Chapter 17 Organizer

Section/Objectives	Standards: National	Standards: State/Local	Lab and Demo Planning
Chapter Opener	See page 14T for a key to the standards.		
Section 17.1 1. **Explain** the law of reflection. 2. **Distinguish** between specular and diffuse reflection. 3. **Locate** the images formed by plane mirrors.	UCP.1, UCP.2, UCP.3, A.1, A.2, B6		**Student Lab:** **Launch Lab,** p. 457: index card, plane mirror, concave mirror, convex mirror, flashlight **Mini Lab,** p. 462: camera with a manual focus lens, plane mirror **Teacher Demonstration:** **Quick Demo,** p. 459: small flashlight, laser pointer, white marker board, sheet of white paper, plane mirror
Section 17.2 4. **Explain** how concave and convex mirrors form images. 5. **Describe** properties and uses of spherical mirrors. 6. **Determine** the locations and sizes of spherical mirror images.	UCP.1, UCP.2, UCP.3, A.1, A.2, B6, E.1		**Student Lab:** **Additional Mini Lab,** p. 471: small convex mirror, small concave mirror, clay, paper **Physics Lab,** pp. 474–475: concave mirror, flashlight, screen support, mirror holder, two metersticks, four meterstick supports, screen, lamp with 15-W lightbulb **Teacher Demonstration:** **Quick Demo,** p. 470: concave mirror, battery or chemically powered glowing object

Differentiated Instruction

L1 Level 1 activities should be appropriate for students with learning difficulties.

L2 Level 2 activities should be within the ability range of all students.

L3 Level 3 activities are designed for above-average students.

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FAST FILE Chapters 16–20 Resources, Chapter 17 Transparency 17-3 Master, p. 59 Study Guide, pp. 43–48 Reinforcement, p. 51 Section 17-2 Quiz, p. 50 Physics Lab Worksheet, pp. 39–42 **Teaching Transparency 17-3** **Connecting Math to Physics** **Laboratory Manual,** pp. 89–92 **Forensics Laboratory Manual,** pp. 35–38	**Interactive Chalkboard CD-ROM:** Section 17.2 Presentation **TeacherWorks™ CD-ROM** **Problem of the Week at** physicspp.com

Assessment Resources

FAST FILE Chapters 16–20 Resources, Chapter 17
Chapter Assessment, pp. 61–66

Additional Challenge Problems, p. 17
Physics Test Prep, pp. 33–34
Pre-AP/Critical Thinking, pp. 33–34
Supplemental Problems, pp. 33–34

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Chapter 17 Reflection and Mirrors

Chapter Overview

The chapter introduces the law of reflection and applies it to analyze image formation by plane mirrors. Virtual images and their properties are discussed. The law of reflection is applied to image formation by concave and convex mirrors. Real images and their properties are discussed. Finally, the mirror equation is used to quantify relationships between object and image locations and sizes.

Think About This

Light from the Sun reflects off the mountain. Some of these light rays strike the surface of the lake and are reflected off it. If students were present and they looked in the lake, they would see their images upright. However, when the scene is viewed from across the lake, the reflected rays cross and the image appears inverted. This is discussed further on page 463.

▶ Key Terms

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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George Matchneer

LAUNCH Lab

Purpose to observe a real image, explain its properties, and describe which mirrors can produce it

Materials index card, plane mirror, concave mirror, convex mirror, flashlight

Teaching Strategies

CAUTION: Remind students to handle mirrors carefully—sharp edges can cut skin.

- This lab works best on bright, sunny days.
- A candle or flashlight in a darkened room may be substituted for the bright window.

Expected Results The concave mirror should produce a real image. The other mirrors do not.

Analysis Only the concave mirror produces a real image. The image is projected onto a screen and is upside down.

Critical Thinking A concave mirror causes light from the flashlight to converge, so it might be that converging light forms a real image.

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

Horizons Companies

Section 17.1

1 FOCUS

Bellringer Activity

Reflections Place a variety of objects on a desk and have students observe whether they can see their reflections from each object. Include some objects that reflect, such as a metal can, a flat mirror, and a spoon. Also include some objects that do not reflect or that do not reflect well, such as cardboard, a clear plastic cup, and a piece of crumpled aluminum foil. Students will see clear reflections in the smooth, mirrored surfaces, unclear reflections in the non-smooth, mirrored surfaces, faint reflections in the shiny, opaque surfaces, and no reflections in the rough, opaque surfaces. Ask students whether they think light is reflected off the rougher surfaces, and why. **L1 Kinesthetic**

Tie to Prior Knowledge

Angles of Reflection Students learned about the reflection of mechanical waves at a boundary in Chapter 14. In this section, students will apply this concept to determine the angles of reflection of light waves from smooth and rough surfaces.

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17.1 Resource MANAGER

FAST FILE Chapters 16–20 Resources

Transparency 17-1 Master, p. 55
Transparency 17-2 Master, p. 57
Study Guide, pp. 44–45
Enrichment, pp. 53–54
Section 17-1 Quiz, p. 49
Mini Lab Worksheet, p. 37

Teaching Transparency 17-1
Teaching Transparency 17-2
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Technology

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2 TEACH

Identifying Misconceptions

Light Demonstration Students may believe that they are able to see light that is not directed toward their eyes. Explain to students that when light reflects off a surface, they see only the rays that reflect directly toward their eyes. Demonstrate this by having students try to observe the beam of light from a laser pointer that you shine across the room. ***CAUTION: Warn students never to look directly at a laser beam.*** If you shine the light toward an open door, students cannot see the beam. If you shine the light toward a wall, they can see the rays that reflect off the wall toward their eyes. Sprinkle some chalk or talcum powder in the path of the laser beam so that students can now see it. Ask them why they can now see the beam. Some of the laser light is reflected off the dust particles toward their eyes. **L1 Visual-Spatial**

Using Models

Law of Reflection Help students model the law of reflection with a ball reflecting off a wall. First, draw a line normal to the wall. Then draw two other lines that model an incident ray and a reflecting ray—they should be at equal angles to the normal and touch the same point on the wall. Have a student roll the ball, such as a golf ball, on the floor along one angled line. The class should notice that the ball reflects along the other angled line, in the same way that a light ray reflects off a surface. **L1**

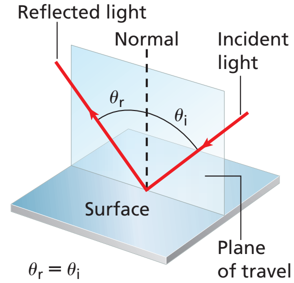


Figure 17-1 The incident ray and the reflected ray are in the same plane of travel.

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 $\theta_r = \theta_i$

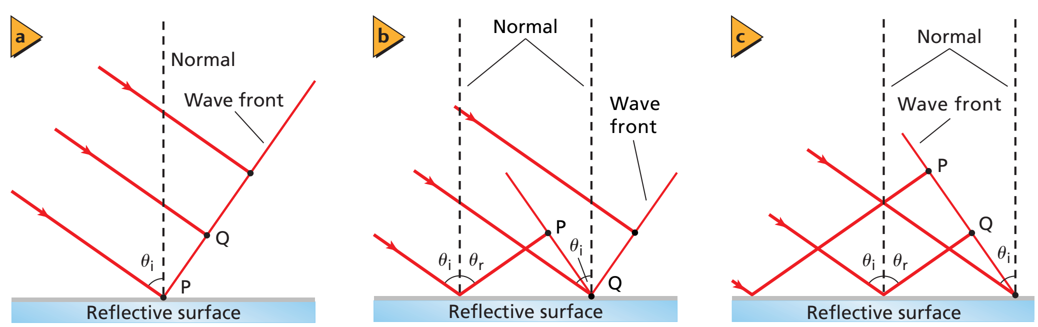
The angle that a reflected ray makes as measured from the normal to a reflective surface equals the angle that the incident ray makes as measured from the same normal.

Color Convention

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

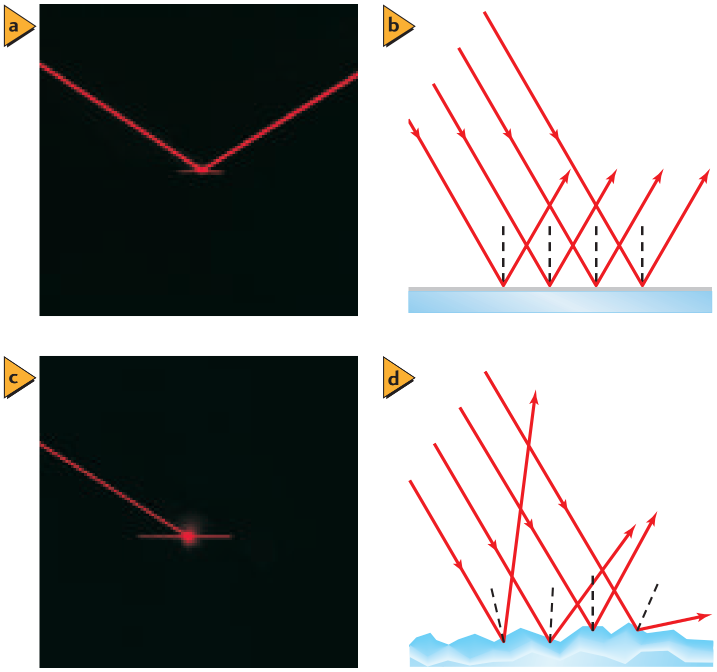
This law can be explained in terms of the wave model of light. **Figure 17-2** shows a wave front of light approaching a reflective surface. As each point along the wave front reaches the surface, it reflects off at the same angle as the preceding point. Because all points are traveling at the same speed, 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).**



CHALLENGE Activity

Illusions Magicians often use mirrors to create illusions for audiences. Directors of older movies sometimes used mirrors to produce special effects. Ask students to investigate the ways in which mirrors can be used to create these effects. Have them work in groups or as individuals to create and perform a skit or trick using a mirror illusion for the class. Interested students may even try to get pointers by visiting a local magic shop or interviewing a magician who performs in their area. **L2 Kinesthetic**



■ **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.

Henry Leap/James Lehman

QUICK DEMO

Reflecting Surfaces

Estimated Time 5 minutes

Materials small flashlight, white marker board, sheet of white paper, plane mirror, laser pointer

Procedure

1. In a dimly lit room, shine the flashlight directly toward a white board. Some light may reflect along the board because of scratches and imperfections in the board.

2. ***CAUTION: Warn students never to look directly at a laser pointer.*** Lay the paper on a desk next to a wall. Shine the laser pointer at about a 45° angle toward the paper. Ask students why they see diffuse, reflected light on the wall. The surface of the paper is rough, and the reflected light is scattered.

3. Lay the mirror on the desk next to a wall. Then, shine the laser pointer at about a 45° angle toward the mirror. Ask students why they see a dot of light reflected onto the wall. The smooth surface of the mirror reflects the light in a narrow beam.

Concept Development

Silvered Mirrors Most of the reflection from an ordinary mirror occurs at the silver coating on the underside of the glass. A little light does reflect from the front surface, which sometimes produces a faint image. Front-silvered or front-surfaced mirrors produce higher-quality images because light reflects directly off the silver coating without passing through glass. Therefore, they produce only one reflection, which is a major reason for their use.

Teacher F.Y.I. CONTENT BACKGROUND

Mirror Coatings The first mirrors, dating back to antiquity, were made of polished metal such as bronze, tin, or silver. Glass mirrors were introduced in fourteenth-century Venice. By the sixteenth and seventeenth centuries, mirrors were made by pressing an amalgam of mercury and tin onto a sheet of glass and later draining off the excess mercury. The method on which modern mirror coatings are based was developed by German chemist Justus von Liebig in 1835. A compound of silver and ammonia was poured onto the glass surface. Then, a reducing agent, such as formaldehyde, was added to reduce the compound to metallic silver. Present-day mirrors are made by spraying molten aluminum or silver onto plate glass in a vacuum.

▶ IN-CLASS Example

Question A light ray strikes a plane mirror at an angle of 15° to the normal. The mirror then rotates 20° around the point where the beam strikes the mirror so that the ray's angle of incidence increases. The axis of rotation is perpendicular to the plane of the incident and to the reflected rays. What is the final angle of reflection of the light ray?

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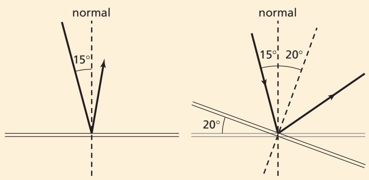


Answer
$\theta_{r,final} = 35°$

▶ PRACTICE Problems

1. Polishing makes the surfaces smoother.
2. **a.** 42° **b.** 48° **c.** 84°
3. 35°
4. 51°
5. 60°

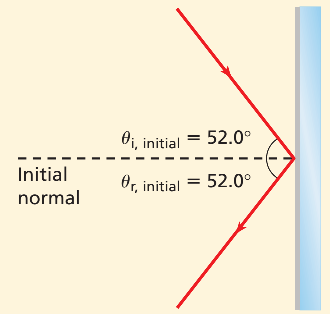
Discussion

Question Ask students the following questions: A good mirror must be smooth, and it must reflect most of the light that strikes it, but is this enough? Why doesn't a smooth, white surface make a good mirror?

Answer A typical mirror reflects well because of its silvered backing. Although a white surface reflects well, it appears white because it is mostly diffuse reflection. It is not as smooth as a silvered surface. L2

▶ 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?

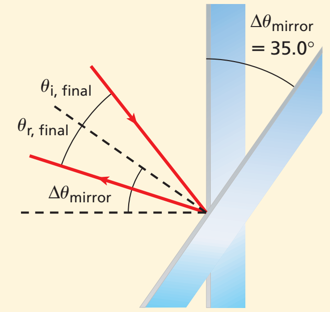


1 Analyze and Sketch the Problem

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

Known:	Unknown:
$\theta_{i,\ initial} = 52.0°$	$\Delta\theta_r = ?$
$\Delta\theta_{mirror} = 35.0°$	

2 Solve for the Unknown



For the angle of incidence to reduce, rotate clockwise.

$$\theta_{i,\ final} = \theta_{i,\ initial} - \Delta\theta_{mirror}$$
$$= 52.0° - 35.0°$$ **Substitute $\theta_{i,\ initial} = 52.0°$, $\Delta\theta_{mirror} = 35.0°$**
$$= 17.0° \text{ clockwise from the new normal}$$

Apply the law of reflection.

$$\theta_{r,\ final} = \theta_{i,\ final}$$
$$= 17.0° \text{ counterclockwise from the new normal}$$ **Substitute $\theta_{i,\ final} = 17.0°$**

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

$$\Delta\theta_r = 52.0° + 35.0° - 17.0°$$
$$= 70.0° \text{ clockwise from the original angle}$$

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

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?

REAL-LIFE PHYSICS Activity

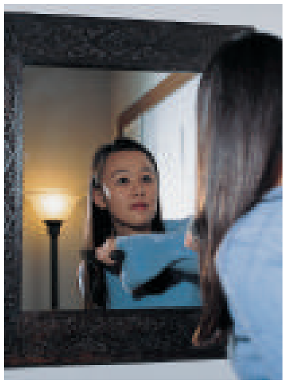
Multiple Plane Mirrors Using information covered on page 461, have students study how plane mirrors can be used in combination to make multiple images. For example, they can study a three-plane mirror in a clothing store and draw a ray diagram, using ray tracing to determine the location of each image in the three-plane mirror. Students also can research other uses of combinations of plane mirrors and draw ray diagrams for them. L2 **Visual-Spatial**

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.

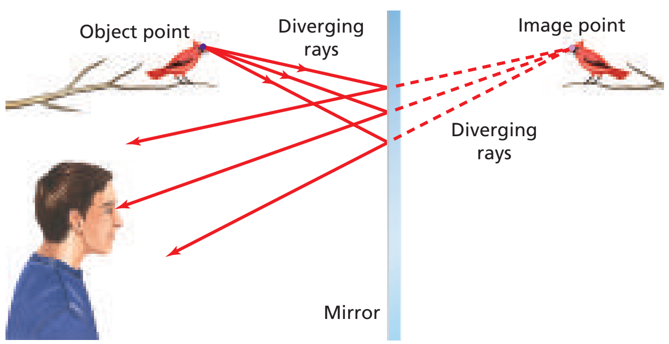
The boy in Figure 17-5 sees rays of light that come from many points on the bird. The combination of the image points produced by reflected light rays forms the **image** of the bird. It is a **virtual image,** which is a type of image formed by diverging light rays. A virtual image is always on the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



■ **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.

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

Laura Sifferlin

Discussion

Question Ask students why you can see your reflection if you look out a window at night, but not during the day. Why is it easier to see outside at night if the inside lights are off?

Answer Window glass transmits most light, but some light is reflected. This reflected light is not as visible during the day because it is much dimmer than the sunlight that is transmitted in from outside. At night, the reflected light is visible because there is very little light outside. L2

Critical Thinking

Reflection Demo Set up two small mirrors about 10 cm apart so that they face each other. Scrape a small hole in the paint on the back of one mirror about one-third of the way down from the top. Place a soda can or other object halfway between the mirrors. Have students look through the hole and describe the reflections. It appears that reflections continue to infinity, with the sizes of the images getting smaller. Have students explain this effect. The first image in each mirror is of the real soda can. The second image in each mirror is a reflection of the first image of the other mirror. Each of the first images are three times farther away from the opposite mirrors than the real can, so the second images appear to be three times farther behind the mirrors than the first images. This repeats, with each image appearing to be smaller because it is farther away behind the mirror. L2 **Visual-Spatial**

Teacher F.Y.I.

REAL-LIFE CAREERS

Optical Engineers Students who enjoy astronomy and do well in optical physics may be interested in a career as an optical engineer at a space observatory. Optical engineers are responsible for the design, alignment, and maintenance of optical systems in the telescopes. In addition to understanding mirror and lens systems, optical engineers must be able to use and maintain the instrumentation that supports the system. (Lenses will be covered in Chapter 18.) Students interested in this field should obtain at least a bachelor's degree in engineering or physics. They also should learn as much mathematics as possible.

Reinforcement

Perspective Demo Be sure students understand that being able to see an image behind a plane mirror is dependent on the viewer being in a position from which the image is visible. To emphasize this, place a mirror against a wall in the middle of the classroom. Have one student stand in front of the mirror and another student stand far to the right of the mirror. Place an object far to left of the mirror so that the first student cannot see the image of it, but the second student can. Let each student in the class stand at each position to reinforce how perspective of the viewer affects what can be seen using a mirror.
L1 **Kinesthetic**

MINI LAB

Virtual Image Position

See page 37 of **FAST FILE Chapters 16–20 Resources** *for the accompanying Mini Lab Worksheet.*

CAUTION: Remind students to handle mirrors carefully—sharp edges can cut skin.

Purpose to estimate the distance of an image from a plane mirror

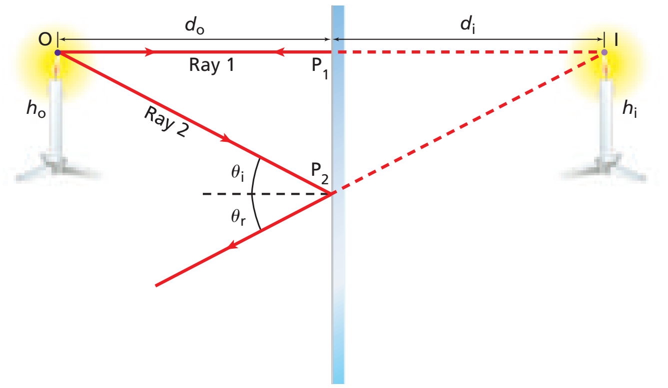
Materials camera with a manual focus lens, plane mirror

Expected Results The reading on the focus ring is 2.0 m.

Analyze and Conclude

4. The image is 1.0 m behind the mirror.

5. The camera is capturing light that is diverging from the mirror's surface as if the light originated from 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, OP_1P_2 and 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.

DIFFERENTIATED INSTRUCTION Activity

Visually Impaired When performing the Mini Lab, pair a visually impaired student with another student who can describe the distances and image properties. Visually impaired students may understand the concept of plane-mirror images better if you allow them to walk from the position of an object to the plane mirror. Explain to them that if they could continue walking into the mirror, the image would be the same distance behind the mirror as the distance they just walked. However, the image would not really be there when they arrived because it is a virtual image. **L1** **Kinesthetic**

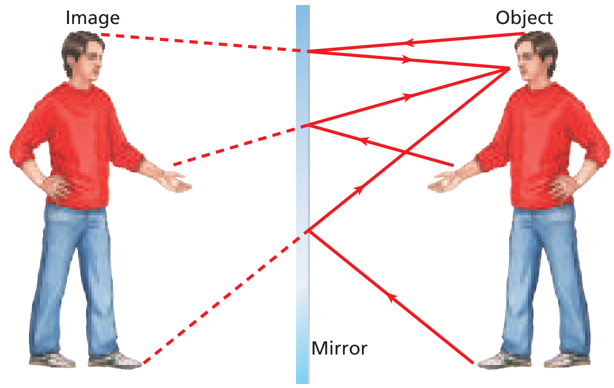


Figure 17-7 The image formed in a plane mirror is the same size as the object and is the same distance behind the mirror as the object is in front. However, when the boy blinks his right eye, the left eye of his image blinks.

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.

Physics Online physicspp.com/self_check_quiz

17.1 Section Review

6. 10°
7. The law of reflection applies to individual rays of light. Rough surfaces make the light rays reflect in many different directions.
8. Specular: window glass, smooth water, polished metal; diffuse: paper, rough metal, ground glass, plastic milk jug
9. 3 m from the mirror, 50 cm tall, virtual
10. Diagrams should show that the Sun's position directly overhead would likely reflect light into the driver's eyes, according to the law of reflection.
11. The incoming light reflects off the surface of the object in all directions. This enables you to view the object from any location.

Using Figure 17-7

Ask students how tall a mirror must be so that you can see your entire reflection. To answer this question, have a student stand in front of a full-length mirror within reaching distance. Have the student point at his or her head and feet. Point out that the top of the mirror must be at the student's height and that the bottom of the mirror can be no more than half the student's height from the ground. Have students study the angles formed by the light rays in Figure 17-6 to study this effect. By applying the law of reflection, they should see that the student observes a full-sized image in a mirror half of his or her height. **L2 Visual-Spatial**

3 ASSESS

Check for Understanding

Image Location Demo Ask students whether the point on the surface of a mirror at which light from an object reflects is the same as the location of the image formed by the reflected light. The image is behind the plane mirror, not on or in the surface of the mirror. One way to demonstrate this is to have students hold a small mirror and place their thumbs on the front of the mirror. By applying their thumbs directly to the surface, they can see clearly that the reflection is behind the surface of the mirror. **L1 Visual-Spatial**

Reteach

Mirror Image Activity Help students make paper cutouts of their hands. Have them flip the cutouts vertically. Ask students if flipping the cutouts produces mirror images. The flipped cutouts reverse from left to right and front to back, unlike a mirror image that reflects left to left and right to right. **L1 Kinesthetic**

Section 17.2

1 FOCUS

Bellringer Activity

Different Types of Mirrors Have students look into a plane mirror and then look into the front and back sides of a shiny spoon. Point out that the shape of a reflecting surface affects the image it produces.
L1 Kinesthetic

Tie to Prior Knowledge

Image Properties Students studied properties of images produced by flat reflecting surfaces in Section 17.1. In this section, they will extend these concepts to curved reflecting surfaces. They will learn how the focal length is related to object and image position.

2 TEACH

Reinforcement

Focal Point Emphasize the difference between the focal point, F, and the focal length, *f*. The focal length is the distance between the mirror and the focal point.

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.

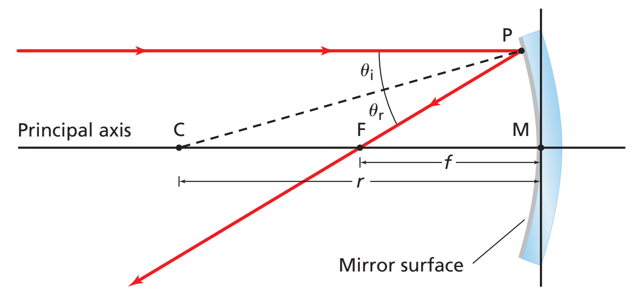


Figure 17-8 The focal point of a spherical concave mirror is located halfway between the center of curvature and the mirror surface. Rays entering parallel to the principal axis are reflected to converge at the focal point, F.

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.

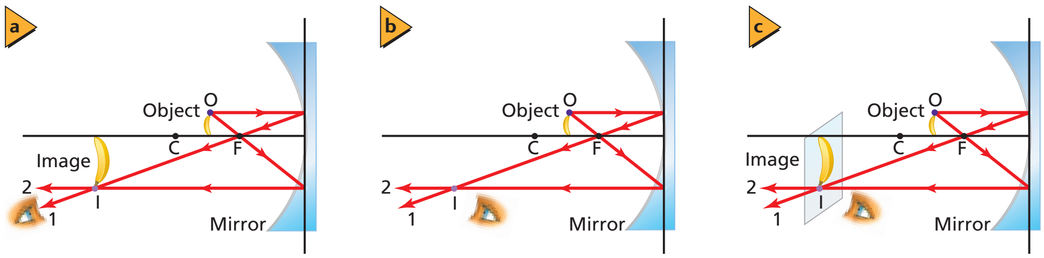
When a ray strikes a mirror, it is reflected according to the law of reflection. Figure 17-8 shows that a ray parallel to the principal axis is reflected and crosses the principal axis at point F, the focal point. F is at the halfway point between M and C. The **focal length,** *f*, is the position of 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.

17.2 Resource MANAGER

FAST FILE Chapters 16–20 Resources
- Transparency 17-3 Master, p. 59
- Study Guide, pp. 46–48
- Reinforcement, p. 51
- Section Quiz, p. 50
- Physics Lab Worksheet, pp. 39–42

Teaching Transparency 17-3
Connecting Math to Physics

Technology
TeacherWorks™ CD-ROM
Interactive Chalkboard CD-ROM
Exam*View*® Pro Testmaker CD-ROM
physicspp.com
physicspp.com/vocabulary_puzzlemaker



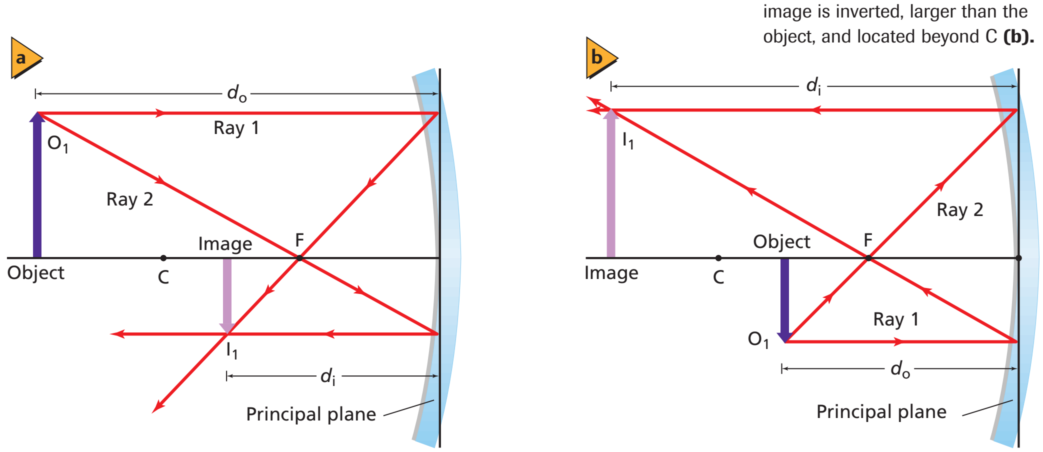
■ **Figure 17-9** The real image, as seen by the unaided eye **(a).** The unaided eye cannot see the real image if it is not in a location to catch the rays that form the image **(b).** The real image as seen on a white opaque screen **(c).**

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 17-10** 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).**



Using an Analogy

Focal Point Demo Demonstrate the concept of a focal point by wrapping a rubber band loosely around the middle of about 20 pieces of thin skewers or uncooked spaghetti. Spread the skewers out on both sides of the rubber band. Point out that the skewers converge at the rubber band and then spread out, just as light reflects off a concave mirror, converges at the focal point, and then spreads out again.

■ Using Figure 17-9

Students may notice that the rays in this figure are drawn to the plane perpendicular to the principal axis, rather than to the face of the mirror. Explain that this is an approximation and they will study the reason for it later in this section. For now, tell students to be sure to draw this plane on the surface of the mirror at the point where the principal axis intersects the face of the mirror. L2

PHYSICS PROJECT Activity

Uses of Mirrors Have students look through astronomy magazines or other science and technology periodicals to find an article about a modern technology that uses concave mirrors, such as the *Hubble Space Telescope.* Encourage them to read the article, learn as much as they can about how the technology uses mirrors, and prepare a presentation. Perhaps they could write an advertisement "selling" their technology. L2 **Linguistic**

Identifying Misconceptions

Demonstrating Ray Diagrams When drawing ray diagrams, students will sometimes find that a ray does not intersect the picture of the mirror on the paper. Students might believe that the diagram is impossible to draw or that the mirror cannot form a full image of the object. Demonstrate how they can extend the plane perpendicular to the principal axis as far as necessary, up or down. The reflection of the ray occurs at this plane, just as if it had intersected the mirror. Using this model, the mirror is shown to form a full image, just as in reality. Demonstrate that even in the case of a spoon, a student will be able to see the entire upper part of his or her body, which is obviously taller than the bowl of the spoon.

Critical Thinking

Image Dimming Ask students whether they think a mirror is a perfect reflector. Suggest that a mirror might reflect 90 percent of the light incident upon it. Have students imagine light bouncing off three such mirrors, one after the other. Ask students what percentage of the original light would bounce off the third mirror. Because about 90 percent of the incoming light reflects from each mirror surface, the total amount after three reflections is $0.90 \times 0.90 \times 0.90 = 0.73$, or 73 percent. Ask students how a curved mirror could be used to rebrighten an image. A large curved mirror can make the image appear brighter by putting the same amount of light into a smaller area. L2

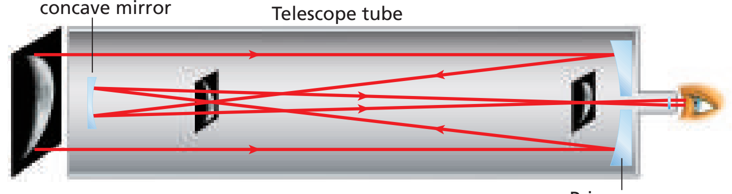


Figure 17-11 A Gregorian telescope produces a real image that is upright.

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

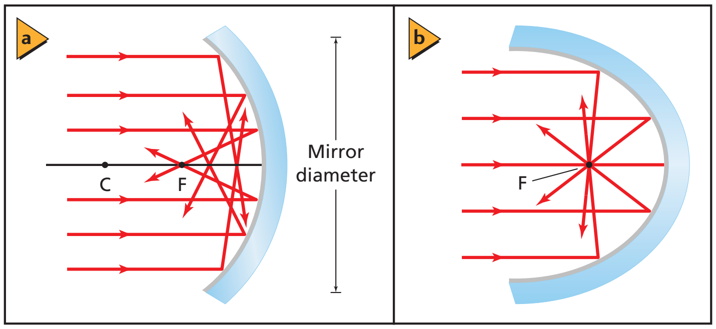
Use the following strategies for spherical-mirror problems. Refer to Figure 17-10.

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.

Lick Observatory

HELPING STRUGGLING STUDENTS Activity

Constructing Ray Diagrams Drawing ray diagrams can be confusing to students when they first encounter it, but obtaining this skill is important to solving optical problems. Divide the class into small groups and provide each group with two or three problems involving concave mirrors. Have each group apply the above Problem-Solving Strategies step-by-step to solve the problems. Students should draw the ray diagrams independently, but they can benefit from discussing each step with the group. L1 Interpersonal



■ **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. ◄

ACTIVITY

■ **Spherical Aberration** Have students investigate spherical aberration of real images using large demonstration-sized concave mirrors. First, have students mask the outer regions of the mirror with manila file folders. They should notice that the image is less intense, but that it suffers less spherical aberration. Next, have them mask the center of the mirror. Again the image is less intense, but the spherical aberration is more noticeable. It is interesting to use a hole with a diameter of about 5 cm as a mask and to move the hole around over the surface of the mirror. Students should compare the images produced by different regions of the mirror's surface.
L2 Kinesthetic

APPLYING PHYSICS

► A malfunction in a measuring device during polishing made the outer edge of the *Hubble Space Telescope's* primary mirror too flat. Although the imperfection was only about the depth of $\frac{1}{50}$ of a human hair, it was enough to make *Hubble's* viewing only slightly better than that of a land-based telescope. COSTAR (Corrective Optics Space Telescope Axial Replacement) positioned five pairs of corrective mirrors at locations that successfully countered *Hubble's* spherical aberration. Have interested students research and prepare a class presentation about COSTAR and other optical improvements made on *Hubble Space Telescope.*
L2 ◄

Teacher F.Y.I.

CONTENT BACKGROUND

Spherical Aberration Students should understand that spherical aberration is an intrinsic defect, not an imperfection in a mirror. It occurs even in perfectly shaped spherical mirrors. Spherical aberration can be avoided by producing aspherical mirrors. However, the production of aspherical surfaces for precise astronomical uses is difficult because the glass surfaces must be ground and polished. For applications in which less-precise images are acceptable, a molded, aspherical plastic base for a mirror can be easily produced.

Concept Development

Disappearing Image Discuss what happens to the image produced by a concave mirror as the object position approaches the focal point from the direction of the mirror and from a large distance from the mirror. The image height gets larger and larger, and then it disappears as the object reaches the focal point. The light rays are reflected as parallel rays that never meet. The mirror and magnification equations suggest that the image is infinitely far away and infinitely large. **L2**

Identifying Misconceptions

Object Location Students may believe that it is necessary for an object to be on the principal axis of a concave mirror for the mirror to be able to form an image. For a concave mirror, the object can be to the side as long as any amount of mirror surface is visible from the location of the object. Have students use a concave magnifying mirror to investigate this concept.

L1

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:

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

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 positon 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.

HELPING STRUGGLING STUDENTS Activity

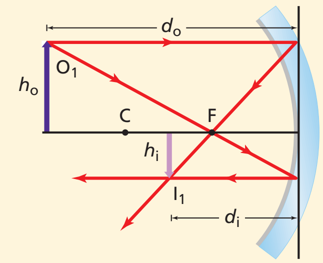
Magnification Some students might need help understanding the concept of image magnification by curved mirrors. Cut a manila folder into several rectangles of different dimensions. Give one rectangle to each pair of students. Demonstrate how students can use a ruler to draw an object using a simple magnification ratio such as 2:5. Students should include the scales on their drawings. Pairs of students should then exchange diagrams and determine the height of the original objects from the scale drawings. **L2** **Visual-Spatial**

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:	Unknown:
$h_o = 2.0$ cm	$d_i = ?$
$d_o = 30.0$ cm	$h_i = ?$
$r = 20.0$ cm	

2 Solve for the Unknown

Focal length is half the radius of curvature.

$$f = \frac{r}{2}$$

$$= \frac{20.0\text{ cm}}{2} \quad \text{Substitute } r = 20.0\text{ cm}$$

$$= 10.0\text{ cm}$$

Use the mirror equation and solve for image position.

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

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

$$= \frac{(10.0\text{ cm})(30.0\text{ cm})}{30.0\text{ cm} - 10.0\text{ cm}} \quad \text{Substitute } f = 10.0\text{ cm}, d_o = 30.0\text{ cm}$$

$$= 15.0\text{ cm (real image, in front of the mirror)}$$

Math Handbook
Fractions
page 837

Use the magnification equation and solve for image height.

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

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

$$= \frac{-(15.0\text{ cm})(2.0\text{ cm})}{30.0\text{ cm}} \quad \text{Substitute } d_i = 15.0\text{ cm}, h_o = 2.0\text{ cm}, d_o = 30.0\text{ cm}$$

$$= -1.0\text{ cm (inverted, smaller image)}$$

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

12. Use a ray diagram, drawn to scale, to solve Example Problem 2.

13. An object is 36.0 cm in front of a concave mirror with a 16.0-cm focal length. Determine the image position.

14. 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.

15. 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.

16. 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?

REAL-LIFE PHYSICS

Liquid Mirrors Have students imagine swirling milk in a cereal bowl until the milk has a parabolic shape. Explain that scientists use this concept to produce liquid telescopes. Mercury, a highly reflective metal that is liquid at room temperature, is placed in a large container. As the container is spun, the mercury becomes a parabolic concave mirror. A bowl of compressed air cushions the mercury from outside vibrations, and smooth plastic film on the surface of the mercury prevents air disturbances. Although liquid telescopes are inexpensive compared to those that employ solid mirrors, they have a limited viewing area because they must be positioned facing straight upward.

IN-CLASS Example

INTERACTIVE CHALKBOARD with Image Bank
PowerPoint® Presentations

Question A concave mirror has a radius of curvature of 24.0 cm. A 6.4-cm-tall object is held 26.0 cm from the mirror. Where is the image and how tall is the image?

Answer
d_i = 22.3 cm. The image is 22.3 cm in front of the mirror.

h_i = −5.5 cm. The image is 5.5 cm tall and inverted.

PRACTICE Problems

12. See Solutions Manual

13. 28.8 cm

14. position: 13.3 cm; height: −2.0 cm

15. −1.9 cm

16. position: 26.7 cm; height: 5.0 cm

Concept Development

- **Benefits of Ray Diagrams** Be sure to point out that the ray-drawing techniques serve as a check on algebraic methods and vice versa. The two methods should agree.
- **Image Height Equation** The equation $h_i = -d_i h_o/d_o$ is used frequently for solving problems involving concave mirrors. Students will profit from deriving this equation from the magnification equation. To solve for image height, h_i, students simply need to multiply the ratios in the magnification equation by the object height, h_o.

$$m = h_i/h_o = -d_i/d_o$$

$$(h_o)(h_i/h_o) = (-d_i/d_o)(h_o)$$

$$h_i = -d_i h_o/d_o$$

L2

QUICK DEMO

Image Position

Estimated Time 10 minutes

Materials concave mirror, battery-powered or chemically powered glowing object

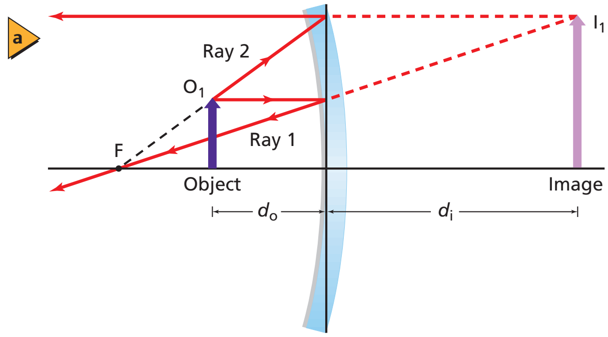
Procedure

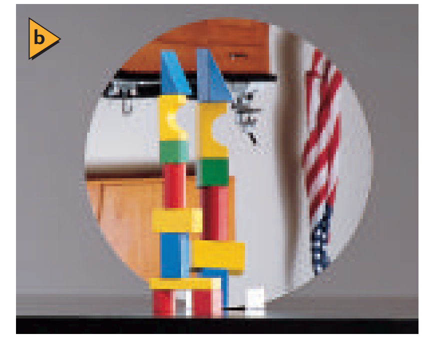
1. Dim the lights and hold the object in one hand and the concave mirror in the other.
2. Face the mirror toward a white board or wall. Hold the object off the principal axis between C and F, but close to the focal point. A large inverted image of the object will appear on the wall.
3. Hold the object beyond C. You will have to angle the mirror face slightly away from the wall. A small inverted image will be formed on the wall between C and F.
4. Hold the object between F and the mirror. No real image will be formed.

Discussion

Question Ask students if they would expect a difference in brightness between enlarged and reduced images.

Answer Yes. As light rays diverge, the light is spread over a greater area. As light rays converge, the light is concentrated on a smaller area. As a result, enlarged images are dimmer and reduced images are brighter. This explains why the focal point of a concave mirror can be located by finding the brightest spot of reflected light. The focal point for a concave mirror is where rays that were parallel before striking the mirror come together. L2





■ **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

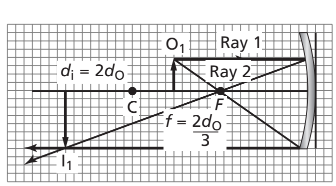
An object of height h_o is located at d_o relative to a concave mirror with focal length f.

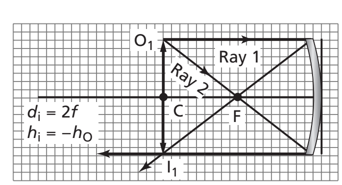
1. Draw and label a ray diagram showing the focal length and location of the object if the image is located twice as far from the mirror as the object. Prove your answer mathematically. Calculate the focal length as a function of object position for this placement.
2. Draw and label a ray diagram showing 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?

Horizons Companies

CHALLENGE PROBLEM

1.



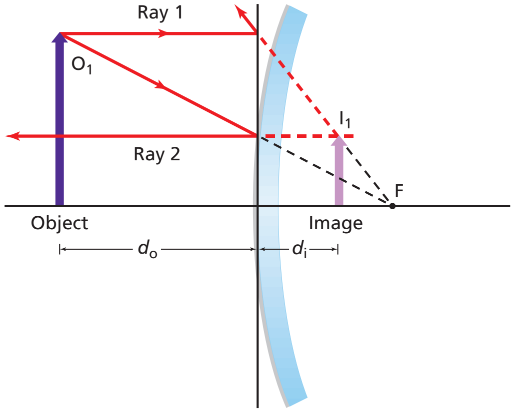


$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$$

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

$$f = \frac{d_o(2d_o)}{d_o + 2d_o}$$

$$f = \frac{2d_o}{3}$$



■ **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.

Additional MINI LAB

Finding the Focal Point

Purpose To observe the focal point of curved mirrors

Materials small convex mirror, small concave mirror, clay, paper

CAUTION: Remind students to handle mirrors carefully—sharp edges can cut skin.

Procedure

1. Take the concave mirror into an area of direct sunlight. Use a piece of clay to hold the mirror on a flat surface, such that it is at an angle to the Sun. ***CAUTION: Do not look directly into a mirror at a reflection of the Sun.***

2. Have each student in turn move a paper toward or away from the mirror in the area of reflected light to find the brightest spot. ***CAUTION: Do not hold the paper at the focal point for too long or it might ignite.*** This is the focal point of the mirror.

3. Replace the concave mirror with the convex mirror. Have students repeat Step 2 using this mirror. No bright spot will be found.

Assessment

1. Why does the concave mirror form a bright spot, but the convex mirror does not? The concave mirror causes light to converge to a single point. The convex mirror causes light to diverge, so no bright spot is formed.

2. How does this relate to the focal point of each mirror? The focal point is in front of the concave mirror and is at the location where the light converges as a bright spot. The focal point of a convex mirror is behind it, so it cannot be found using a paper and reflected light.

2.

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

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

$$d_o = \frac{f(2f)}{2f - f}$$

$$d_o = 2f$$

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

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

$$h_i = \frac{-(2f)h_o}{2f}$$

$$h_i = -h_o$$

3. The object should be placed at the focal point.

▶ IN-CLASS Example

Question A convex mirror has a radius of curvature of 28.4 cm. If you hold a 16-cm-long pencil 23.5 cm in front of the mirror, what will the image position and image height be?

Answer

$d_i = -8.85$ cm; $h_i = 6.0$ cm

▶ PRACTICE Problems

17. See Solutions Manual; −8.57 cm

18. position: −10.7 cm, diameter: 1.1 cm

19. −96 cm

20. position: −12.7 cm, diameter: 4.4 cm

21. −0.60 cm

ACTIVITY

Uses of Mirrors Have students investigate the uses of mirrors, make a list of every mirror that they encounter in a one-day period, and describe each mirror's use. Students could make sketches to help explain how each mirror performs its intended function. If possible, allow students to bring some of the mirrors that they discover to class. **L1 Interpersonal**

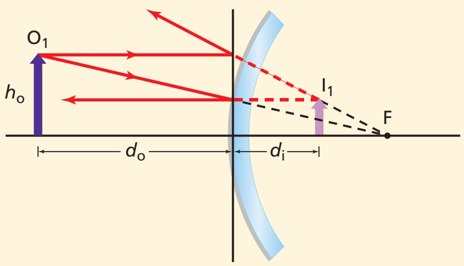
▶ EXAMPLE Problem 3

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:	Unknown:
$h_o = 2.0$ m	$d_i = ?$
$d_o = 5.0$ m	$h_i = ?$
$f = -0.50$ m	



2 Solve for the Unknown

Use the mirror equation and solve for image position.

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

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

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

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

Math Handbook
Isolating a Variable
page 845

Use the magnification equation and solve for image height.

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

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

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

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

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

17. 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.

18. 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?

19. 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?

20. 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?

21. 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?

PHYSICS PROJECT Activity

Systems of Mirrors Many optical devices use systems of mirrors to obtain images with specific properties. Have students work in pairs to design a desktop optical system using two or more mirrors, including plane and curved mirrors. They should be able to explain their system, including information about focal lengths, object locations, and image properties. To further focus the activity, challenge students to devise a system using two plane mirrors that would allow them to undo the reversal of letters seen with a single plane mirror. **L2 Kinesthetic**

Table 17-1					
Single-Mirror System Properties					
Mirror Type	***f***	d_o	d_i	***m***	**Image**
Plane	N/A	$d_o > 0$	$\lvert d_i \rvert = d_o$ (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
		$f > d_o > 0$	$\lvert d_i \rvert > d_o$ (negative)	Enlarged	Virtual
Convex	–	$d_o > 0$	$\lvert f \rvert > \lvert d_i \rvert > 0$ (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.

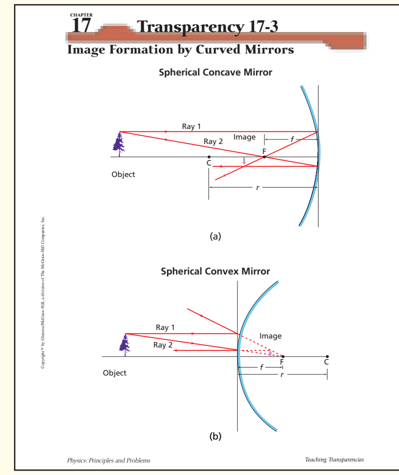
Physics Online physicspp.com/self_check_quiz

17.2 Section Review

22. Place the object between the mirror and the focal point. The image will be virtual.
23. −0.82
24. 26.0 cm
25. See Solutions Manual; position: 26.4 cm, height: −3.6 cm
26. See Solutions Manual; position: −6.46 cm, height: 1.8 cm
27. 29 cm
28. −36 cm
29. It would be less for a mirror whose height is relatively small compared to its radius of curvature; diverging light rays from an object that strike the mirror are more paraxial so they converge more closely to create an image that is not blurred.

Interactive Chalkboard with Image Bank PowerPoint® Presentations

Page 59, FAST FILE Chapters 16–20 Resources



Reinforcement

Properties of Mirrors Divide the class into small groups. Have each group of students write true/false questions about the properties of mirrors on the front of index cards and write the answers with explanations on the back. The groups can exchange cards, and students can use them to quiz each other.
L1 Interpersonal

3 ASSESS

Check for Understanding

Real and Virtual Images Have students each write and illustrate a paragraph comparing real and virtual images formed by a concave mirror. **L1 Linguistic**

Extension

Convex Mirrors in Art Students can research famous paintings that include convex-mirror images. Some examples are *The Arnolfini Marriage* (1434) by Jan van Eyck and *Self-portrait in a Convex Mirror* (1524) by Parmigianino. Have students each write a paragraph describing how the artist used the mirror in the painting. They also should describe the visual effects produced by the convex mirror.
L2 Linguistic

PHYSICS LAB •

Time Allotment
one laboratory period

Process Skills experiment, observe, measure, collect and organize data

Safety Precautions Remind students to handle mirrors carefully—sharp edges can cut skin. Caution students that the lightbulb can get hot enough to burn skin. Do not look at the reflection of the Sun in a mirror or use a large concave mirror to focus sunlight. If using a candle, remind students to be careful of the flame.

Alternative Materials A candle may be substituted for the lamp.

Teaching Strategies
- **Remind students not to look directly at the Sun or reflect sunlight into the eyes of others.**
- **Mirrors may need to be moved back and forth several times to determine the best location of d_i.**

Analyze
Possible answers based on sample data: where $d_o = 95$ cm, $d_i = 65$ cm, $f = 40$ cm

1. $\frac{1}{d_o}\ (\text{cm}^{-1}) = \frac{1}{95}\ (\text{cm}^{-1}) = 1.1\times10^{-2}\ (\text{cm}^{-1})$

$\frac{1}{d_i}\ (\text{cm}^{-1}) = \frac{1}{65}\ (\text{cm}^{-1}) = 1.5\times10^{-2}\ (\text{cm}^{-1})$

2. $\frac{1}{d_o}\ \text{cm} + \frac{1}{d_i}\ \text{cm} = \frac{1}{2.6\times10^{-2}}\ f_{\text{calc}} = \frac{1}{2.6\times10^{-2}}\ \text{cm} = 38.5\ \text{cm}$

3. $\%\ \text{error} = \frac{40 - 38.5}{40\times100} = 3.75\%$

PHYSICS LAB •

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.

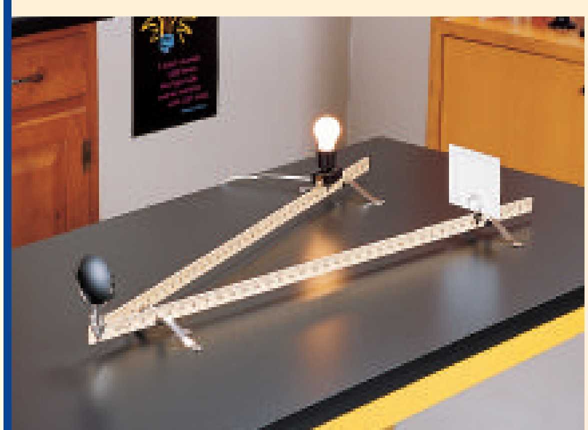
QUESTION
What are the conditions needed to produce real and virtual images using a concave mirror?

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



Horizons Companies

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 mirror and 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.

Sample Data
$f = 40$ cm
Step 7—no image is formed
Step 8—a virtual image is formed in the mirror

Trial	d_o (cm)	d_i (cm)	h_o (cm)	h_i (cm)
1	95	65	1	0.7
2	85	76	1	0.9
3	50	185	1	250
4	40	cannot measure	1	cannot measure
5	30	cannot measure	1	cannot measure

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					

8. 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.
9. 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.
10. 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?
11. 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

1. **Use Numbers** Calculate $1/d_o$ and $1/d_i$ and enter the values in the calculation table.
2. **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}.
3. **Error Analysis** Compare the experimental focal length, f_{calc}, with f, the accepted focal length, by finding the percent error.

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

Conclude and Apply

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

Going Further

1. What are the conditions needed for the image to be larger than the object?
2. 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?

Physics Online

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

Conclude and Apply

1. Trials 1 through 3 produced real images. Trial 4 did not produce an image. Trial 5 produced a virtual image.
2. Real images are formed when the object position is greater than the focal length.
3. Virtual images are formed when the object position is less than the focal length.

Going Further

1. The image is larger than the object when the object is placed between the mirror and the center of curvature of the mirror. Many smaller mirrors may produce an image that is too blurry for a good observation when the object position is within the focal length.
2. It is difficult to accurately estimate the mirror focal length. Answers will vary. Students may state that having a mirror that is larger, not dirty, or free of scratches would be helpful. A front-surface mirror would be a better quality to mention. It is also difficult to accurately determine where the clearest or sharpest image is located.

Real-World Physics

The light rays from distant planets or stars will be arriving parallel to the principal axis, so a sharp image can be obtained.

ALTERNATIVE INQUIRY LAB

To Make this Lab an Inquiry Lab: Have students develop their own procedure for determining the focal length and for investigating images formed by curved mirrors. In addition, they will use what they know about images formed by lenses. Possible materials include 10-cm-focal-length concave mirror, 10-cm-focal-length convex mirror, mirror holders, candle or light source, screen, nail driven into a base of 50-g slotted masses.

Background

The *Hubble Space Telescope* eliminated the problem of atmospheric distortion. A telescope with an adaptive optical system (AOS) on Earth provides images as good as or better than *Hubble*.

Light waves from a distant point source are all parallel. The distortion of the atmosphere deflects the waves slightly, so that they are no longer parallel. Reshaping the mirror makes them parallel again.

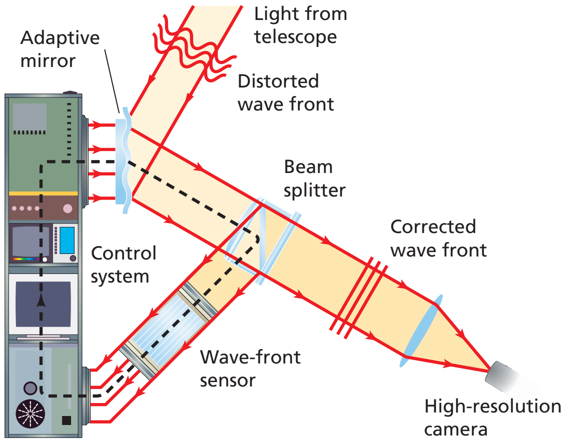
Teaching Strategies

- The twinkling of stars is caused by the convection of heated air, causing the image to waver. Turning on a laboratory burner and letting students look across the surface of it can demonstrate this.
- Many places no longer have dark skies, so students may never have seen the twinkling of a star. It might be helpful to organize an evening field trip on a clear night during winter months. A small telescope or binoculars will be useful. Your local astronomy club will help.

Future Technology

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.



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

Conventional telescope | *Hubble Space Telescope* | Keck telescope with AOS

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.

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.

Activity

Homemade Adaptive Optical System

Construct a flexible mirror using an embroidery hoop and a metal-coated polyester film or a foil balloon. Distort a beam from a laser by shining it through the bottom of a jar. Reflect the distorted laser beam onto a screen using the flexible mirror. Reduce the distortion of the beam by deflecting the flexible mirror gently with your fingers.

Going Further

1. Observatories shine a very powerful laser into the sky to act as an artificial star.
2. A faint laser beam is reflected off the retina. A wave front detector and computer calculate how the eye distorts the beam. Someday, opticians might be able to make eyeglasses to correct the distortion.

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.

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

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.

Physics Online physicspp.com/vocabulary_puzzlemaker

Key Concepts

Summary statements can be used by students to review the major concepts of the chapter.

Physics Online

Visit physicspp.com
/self_check_quiz
/vocabulary_puzzlemaker
/chapter_test
/standardized_test

VOCABULARY PuzzleMaker

For additional help with vocabulary, have students access the Vocabulary PuzzleMaker online.
physicspp.com/vocabulary_puzzlemaker

Concept Mapping

30. See Solutions Manual

Mastering Concepts

31. When parallel light is reflected from a smooth surface, the rays are reflected parallel to each other. The result is an image of the origin of the rays. When light is reflected from a rough surface, it is reflected in many different directions. The rays are diffused or scattered. No image of the source results.

32. any line that is perpendicular to the surface at any point

33. The image is on a line that is perpendicular to the mirror and the same distance behind the mirror as the object is in front of the mirror.

34. A plane mirror is a flat, smooth surface from which light is reflected by specular reflection. The image created by a plane mirror is virtual, upright, and as far behind the mirror as the object is in front of it.

35. No, the rays do not converge at a virtual image. No image forms and the student would not get a picture. Some virtual images are behind the mirror.

36. Place a sheet of plain paper or photographic film at the image location and you should be able to find the image.

37. Object must be located between F and the mirror.

38. Rays parallel to the axis that strike the edges of a concave spherical mirror are not reflected through the focal point. This effect is called spherical aberration.

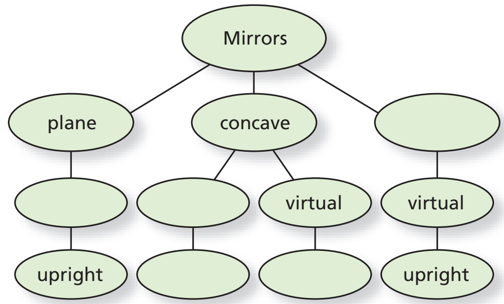
39. $\frac{1}{f} = \frac{1}{d_i} + \frac{1}{d_o}$

40. $C = 2f$

Chapter 17 Assessment

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)

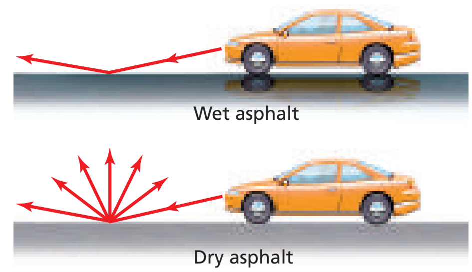
41. If you know the image position and object position relative to a curved mirror, how can you determine the mirror's magnification? (17.2)

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.



Richard Megna/Fundamental Photographs

■ **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**

 For more problems, go to Additional Problems, Appendix B.

41. The magnification is equal to the negative of the image distance divided by the object distance.

42. Convex mirrors are used as rearview mirrors because they allow for a wide range of view, allowing the driver to see a much larger area than is afforded by ordinary mirrors.

43. The light rays always diverge.

Applying Concepts

44. Less light is reflected back to the car from a wet road.

45. Smooth, glossy pages have less diffuse reflection than rougher pages, so the smooth, glossy pages have more glare.

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?

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?

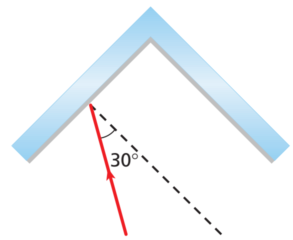
54. A ray of light strikes a mirror at an angle of 53° to the normal.
  a. What is the angle of reflection?
  b. What is the angle between the incident ray and the reflected ray?

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**

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.
  a. What is the angle at which the light ray is reflected from the other mirror?
  b. 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.

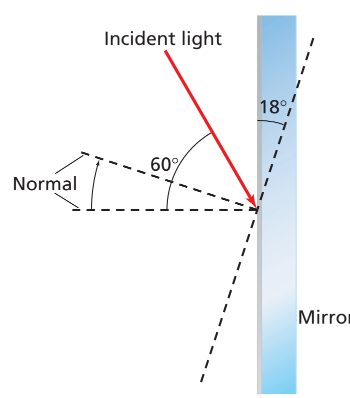


■ **Figure 17-19**

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**

Physics Online physicspp.com/chapter_test

Chapter 17 Assessment

46. The image will be at *C*, the center of curvature, inverted, real, and the same size of the object.

47. The image will be between *C* and *F*, and will be inverted, real, and smaller than the object.

48. You should order a parabolic mirror to eliminate spherical aberrations.

49. The image in a single convex mirror is always virtual, erect, smaller than the object, and located closer to the mirror than the object.

50. You can use only a concave mirror with the object beyond the focal point. A convex mirror will not form a real image.

51. You may use a concave mirror with the object beyond the center of curvature or a convex mirror with the object anywhere.

52. Convex mirror; it provides a wider field of view.

Mastering Problems

17.1 Reflection from Plane Mirrors

Level 1

53. 38°

54. a. 53°
  b. 106°

55. 108°

Level 2

56. The image is 1.2 m behind the mirror, so the camera lens should be set to 2.4 m.

57. a. Reflection from the first mirror: 30°
  Reflection from the second mirror: 60°
  b. See Solutions Manual

58. The ray from the top of the head hits the mirror halfway between the eyes and the top of the head. The ray from feet hits the mirror halfway between the eyes and feet. The distance between the point the two rays hit the mirror is half the total height. See Solutions Manual.

Level 3

59. 15°

60. 48°

17.2 Curved Mirrors

Level 1

61. 20.0 cm

62. 0.5 cm

63. 1.8 m

64. real; inverted; longer

Level 2

65. 75 cm

66. position: 33 cm; height: −4.1 cm

67. −3.8 m

68. −1.8 cm

69. 5

70. position: 70.5 cm; height: −9.4 cm

Level 3

71. a. −24 cm
b. 9.0 cm

72. a. See Solutions Manual
b. 4.0 cm
c. −8.0 mm

73. position: −9.4 cm; height: 0.75 cm

Mixed Review

Level 1

74. 62°

75. See Solutions Manual
The image height is 1.0 cm, and its location is 2.7 cm from the mirror.

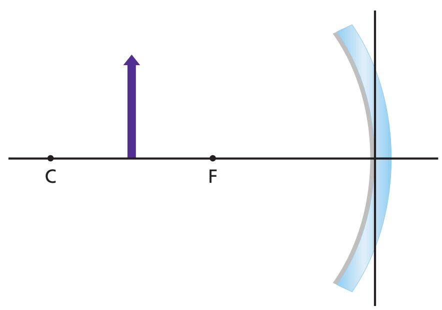
17.2 Curved Mirrors

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?

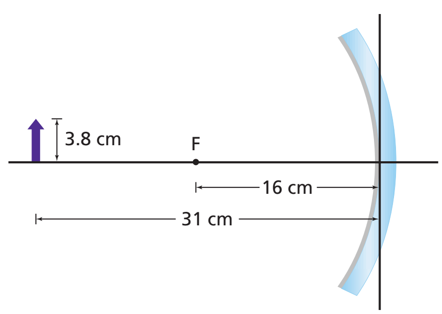
64. Describe the image produced by the object in **Figure 17-21** as real or virtual, inverted or upright, and smaller or larger than the object.



■ **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?

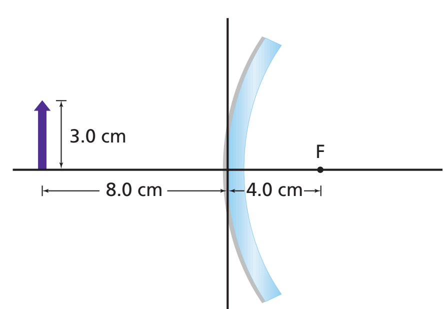
72. Sunlight falls on a concave mirror and forms an image that is 3.0 cm from the mirror. An object that is 24 mm tall is placed 12.0 cm from the mirror.
a. Sketch the ray diagram to show the location of the image.
b. Use the mirror equation to calculate the image position.
c. How tall is the image?

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**

 For more problems, go to Additional Problems, Appendix B.

Level 2

76. −6.9 cm

77. a. 22.9 cm
b. −1.8 cm

78. 58 cm

79. −72 cm

80. a. −1.5 m
b. 0.38 m

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.
   a. Where is the image position?
   b. What is the image height?

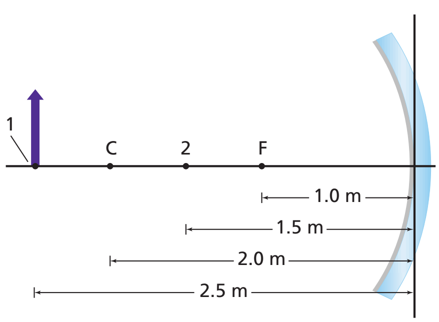
78. What is the radius of curvature of a concave mirror that magnifies an object by a factor of +3.2 when the object is placed 20 cm from the mirror?

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.
   a. What is the image position of a customer who stands 6.5 m in front of the mirror?
   b. 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.
   a. What kind of mirror would do this job?
   b. 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?

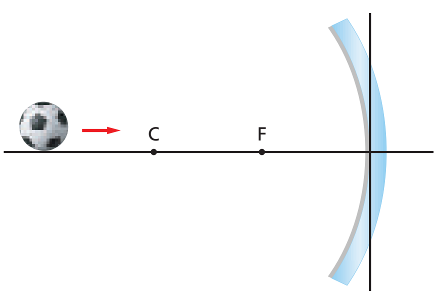
84. A 1.6-m-tall girl stands 3.2 m from a convex mirror. What is the focal length of the mirror if her image appears to be 0.28 m tall?

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.

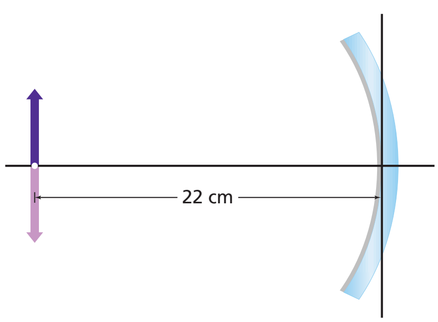
Thinking Critically

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**

Level 3

81. a. An enlarged, upright image results only from a concave mirror, with the object inside the focal length.
b. 32 mm

82. See Solutions Manual

83. $f = 62$ cm. Because the focal length is positive, the spherical mirror is a concave mirror.

84. −0.68

85. See Solutions Manual. The image is 2.4 m tall and it is 14 m from the mirror.

86. See Solutions Manual; −12 cm

Thinking Critically

87. Beyond C, the image is smaller than the ball. As the ball rolls toward the mirror, the image size increases. The image is the same size as the ball when the ball is at C. The image size continues to increase until there is no image when the ball is at F. Past F, the size of the image decreases until it equals the ball's size when the ball touches the mirror.

88. 11 cm

89. As $f \rightarrow \infty$, $\frac{1}{f} \rightarrow 0$. The mirror equation then becomes

$$\frac{1}{d_o} = -\frac{1}{d_i}, \text{ or } d_o = -d_i.$$

90. 1.0×10^{1} cm

91. The smaller mirror is concave to produce a real image at the eyepiece that is upright. The light rays are inverted by the first concave mirror and then inverted again by the secondary concave mirror.

92. a. The convex mirror is placed to intercept the rays from a concave mirror before they converge. The convex mirror places the point of convergence in the opposite direction back toward the concave mirror, and lengthens the total distance the light travels before converging. This effectively increases the focal length compared to using the concave mirror by itself, thus increasing the total magnification.
b. inverted

Writing in Physics

93. Student answers will vary.

94. Student answers will vary.

Cumulative Review

95. 0.18

96. 9.5°C

97. 2.4 kPa

98. 2.8 s

99. a. The resonant frequency of an open pipe is twice that of a closed pipe of the same length. Therefore, the pipes of a closed-pipe organ need be only half as long as open pipes to produce the same range of fundamental frequencies.

b. No. While the two organs will have the same fundamental tones, closed pipes produce only the odd harmonics, so they will have different timbres than open pipes.

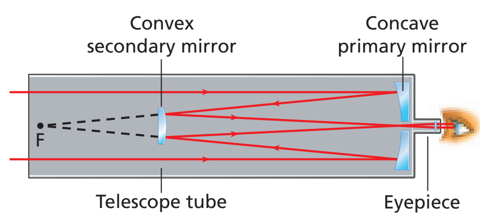
100. Waves can interfere, add, and then pass through unaffected. Chapter 14 showed the amplitude of waves adding. In this case, the waves retain their color information as they cross through each other.

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:

a. the different types of coatings used and the advantages and disadvantages of each

b. 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 1.0×10^4 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 2×10^{-5} 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 7.34×10^{22} kg, and its radius is 1.74×10^{6} 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)

a. Should he design the instrument to have open pipes or closed pipes? Explain.

b. 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

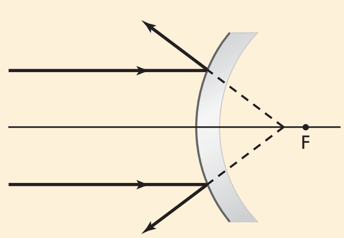
Multiple Choice

1. 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

2. 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

3. 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

4. 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



5. 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°

6. 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

7. 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

8. 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

9. 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

10. 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.

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Standardized Test Practice

Rubric

The following rubric is a sample scoring device for extended response questions.

Extended Response

Points	Description
4	The student demonstrates a thorough understanding of the physics involved. The response may contain minor flaws that do not detract from the demonstration of a thorough understanding.
3	The student demonstrates an understanding of the physics involved. The response is essentially correct and demonstrates an essential but less than thorough understanding of the physics.
2	The student demonstrates only a partial understanding of the physics involved. Although the student may have used the correct approach to a solution or may have provided a correct solution, the work lacks an essential understanding of the underlying physical concepts.
1	The student demonstrates a very limited understanding of the physics involved. The response is incomplete and exhibits many flaws.
0	The student provides a completely incorrect solution or no response at all.

Multiple Choice

1. D **2.** C **3.** D
4. A **5.** C **6.** D
7. D **8.** A **9.** C

Extended Answer

10. $h_i = 2.1$ cm