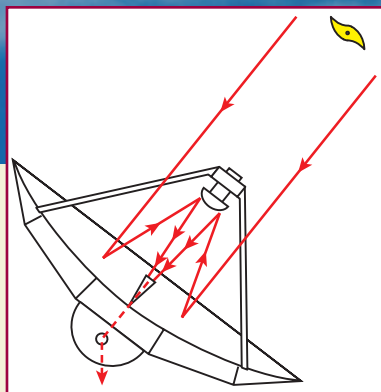# Light and Reflection

The Very Large Array, located near Socorro, New Mexico, consists of 27 radio antennas, each 25 meters in diameter. These antennas detect *electromagnetic radiation* in the radio and microwave regions of the spectrum. The dish of a radio telescope reflects the radio waves and focuses the rays at the receiver poised above the dish.

WHAT TO EXPECT

In this chapter, you will learn about the characteristics of light and other forms of electromagnetic radiation. You will learn how flat and curved mirrors can be used to reflect light and create real and virtual images of objects.

WHY IT MATTERS

Mirrors have many applications both for scientists and in everyday life. For example, a reflector telescope uses two mirrors to gather, focus, and reflect light onto the eyepiece. The reflector telescope remains one of the most popular designs used by amateur astronomers, even though it was invented over 300 years ago.

CHAPTER PREVIEW

Characteristics of Light

ELECTROMAGNETIC WAVES

When most people think of light, they think of the light that they can see. Some examples include the bright, white light that is produced by a light bulb or the sun. However, there is more to light than these examples.

When you hold a piece of green glass or plastic in front of a source of white light, you see green light pass through. This phenomenon is also true for other colors. What your eyes recognize as "white" light is actually light that can be separated into six elementary colors of the visible *spectrum:* red, orange, yellow, green, blue, and violet.

If you examine a glass prism, such as the one shown in **Figure 1,** or any thick, triangular-shaped piece of glass, you will find that sunlight passes through the glass and emerges as a rainbowlike band of colors.

The spectrum includes more than visible light

Not all light is visible to the human eye. If you were to use certain types of photographic film to examine the light dispersed through a prism, you would find that the film records a much wider spectrum than the one you see. A variety of forms of radiation—including X rays, microwaves, and radio waves—have many of the same properties as visible light. The reason is that they are all examples of **electromagnetic waves.**

Light has been described as a particle, as a wave, and even as a combination of the two. Although the current model incorporates aspects of both particle and wave theories, the wave model is best suited for an introductory discussion of light, and it is the one that will be used in this section.
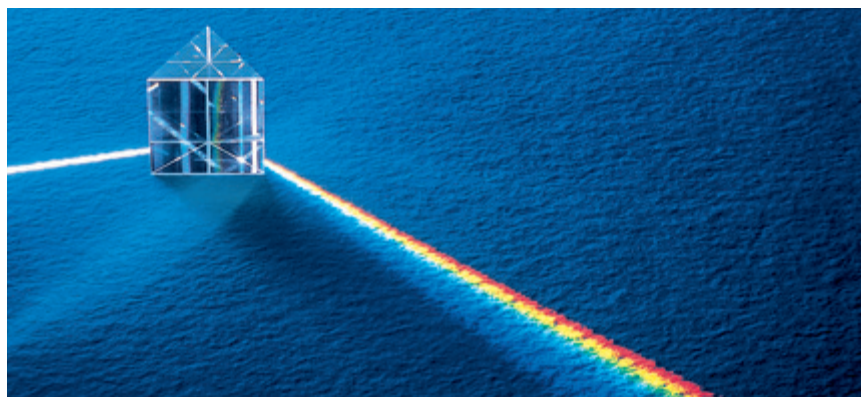
electromagnetic wave

a wave that consists of oscillating electric and magnetic fields, which radiate outward from the source at the speed of light

Figure 1
A prism separates light into its component colors.

Electromagnetic waves vary depending on frequency and wavelength

In classical electromagnetic wave theory, light is considered to be a wave composed of oscillating electric and magnetic fields. These fields are perpendicular to the direction in which the wave moves, as shown in **Figure 2.** Therefore, electromagnetic waves are transverse waves. The electric and magnetic fields are also at right angles to each other.

Electromagnetic waves are distinguished by their different frequencies and wavelengths. In visible light, these differences in frequency and wavelength account for different colors. The difference in frequencies and wavelengths also distinguishes visible light from invisible electromagnetic radiation, such as X rays.

Types of electromagnetic waves are listed in **Table 1.** Note the wide range of wavelengths and frequencies. Although specific ranges are indicated in the table, the electromagnetic spectrum is, in reality, continuous. There is no sharp division between one kind of wave and the next. Some types of waves even have overlapping ranges.
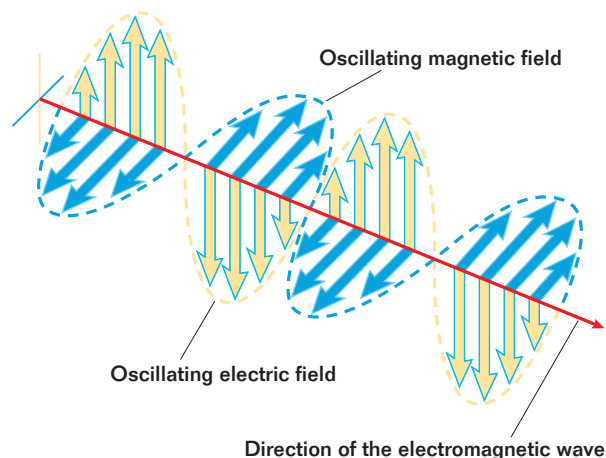

Oscillating magnetic field

Oscillating electric field

Direction of the electromagnetic wave

Figure 2
An electromagnetic wave consists of electric and magnetic field waves at right angles to each other.

Table 1   The Electromagnetic Spectrum

Classification	Range	Applications
radio waves	$\lambda > 30$ cm $f < 1.0 \times 10^9$ Hz	AM and FM radio; television
microwaves	30 cm $> \lambda > 1$ mm 1.0×10^9 Hz $< f < 3.0 \times 10^{11}$ Hz	radar; atomic and molecular research; aircraft navigation; microwave ovens
infrared (IR) waves	1 mm $> \lambda > 700$ nm 3.0×10^{11} Hz $< f < 4.3 \times 10^{14}$ Hz	molecular vibrational spectra; infrared photography; physical therapy
visible light	700 nm (red) $> \lambda > 400$ nm (violet) 4.3×10^{14} Hz $< f < 7.5 \times 10^{14}$ Hz	visible-light photography; optical microscopy; optical astronomy
ultraviolet (UV) light	400 nm $> \lambda > 60$ nm 7.5×10^{14} Hz $< f < 5.0 \times 10^{15}$ Hz	sterilization of medical instruments; identification of fluorescent minerals
X rays	60 nm $> \lambda > 10^{-4}$ nm 5.0×10^{15} Hz $< f < 3.0 \times 10^{21}$ Hz	medical examination of bones, teeth, and vital organs; treatment for types of cancer
gamma rays	0.1 nm $> \lambda > 10^{-5}$ nm 3.0×10^{18} Hz $< f < 3.0 \times 10^{22}$ Hz	examination of thick materials for structural flaws; treatment of types of cancer; food irradiation

All electromagnetic waves move at the speed of light

All forms of electromagnetic radiation travel at a single high speed in a vacuum. Early experimental attempts to determine the speed of light failed because this speed is so great. As experimental techniques improved, especially during the nineteenth and early twentieth centuries, the speed of light was determined with increasing accuracy and precision. By the mid-twentieth century, the experimental error was less than 0.001 percent. The currently accepted value for light traveling in a vacuum is $2.997\ 924\ 58 \times 10^8$ m/s. Light travels slightly slower in air, with a speed of $2.997\ 09 \times 10^8$ m/s. For calculations in this book, the value used for both situations will be 3.00×10^8 m/s.

The relationship between frequency, wavelength, and speed described in the chapter on vibrations and waves also holds true for light waves.

WAVE SPEED EQUATION

$$c = f\lambda$$

$$\text{speed of light} = \text{frequency} \times \text{wavelength}$$

SAMPLE PROBLEM A

Electromagnetic Waves

PROBLEM

The AM radio band extends from 5.4×10^5 Hz to 1.7×10^6 Hz. What are the longest and shortest wavelengths in this frequency range?

SOLUTION

Given: $f_1 = 5.4 \times 10^5$ Hz $f_2 = 1.7 \times 10^6$ Hz $c = 3.00 \times 10^8$ m/s

Unknown: $\lambda_1 = ?$ $\lambda_2 = ?$

Use the wave speed equation on this page to find the wavelengths:

$$c = f\lambda \quad \lambda = \frac{c}{f}$$

$$\lambda_1 = \frac{3.00 \times 10^8 \text{ m/s}}{5.4 \times 10^5 \text{ Hz}}$$

$$\boxed{\lambda_1 = 5.6 \times 10^2 \text{ m}}$$

$$\lambda_2 = \frac{3.00 \times 10^8 \text{ m/s}}{1.7 \times 10^6 \text{ Hz}}$$

$$\boxed{\lambda_2 = 1.8 \times 10^2 \text{ m}}$$

CALCULATOR SOLUTION

Although the calculator solutions are 555.5555556 m and 176.470588 m, both answers must be rounded to two digits because the frequencies have only two significant figures.

Electromagnetic Waves

1. Gamma-ray bursters are objects in the universe that emit pulses of gamma rays with high energies. The frequency of the most energetic bursts has been measured at around 3.0×10^{21} Hz. What is the wavelength of these gamma rays?

2. What is the wavelength range for the FM radio band (88 MHz–108 MHz)?

3. Shortwave radio is broadcast between 3.50 and 29.7 MHz. To what range of wavelengths does this correspond? Why do you suppose this part of the spectrum is called shortwave radio?

4. What is the frequency of an electromagnetic wave if it has a wavelength of 1.0 km?

5. The portion of the visible spectrum that appears brightest to the human eye is around 560 nm in wavelength, which corresponds to yellow-green. What is the frequency of 560 nm light?

6. What is the frequency of highly energetic ultraviolet radiation that has a wavelength of 125 nm?

Waves can be approximated as rays

Consider an ocean wave coming toward the shore. The broad crest of the wave that is perpendicular to the wave's motion consists of a line of water particles. Similarly, another line of water particles forms a low-lying trough in the wave, and still another line of particles forms the crest of a second wave. In any type of wave, these lines of particles are called *wave fronts.*

All the points on the wave front of a plane wave can be treated as point sources, that is, coming from a source of neglibible size. A few of these points are shown on the initial wave front in **Figure 3.** Each of these point sources produces a circular or spherical secondary wave, or *wavelet.* The radii of these wavelets are indicated by the blue arrows in **Figure 3.** The line that is tangent to each of these wavelets at some later time determines the new position of the initial wave front (the new wave front in **Figure 3**). This approach to analyzing waves is called *Huygens' principle,* named for the physicist Christian Huygens, who developed it.

Huygens' principle can be used to derive the properties of any wave (including light) that interacts with matter, but the same results can be obtained by treating the propagating wave as a straight line perpendicular to the wave front. This line is called a *ray,* and this simplification is called the *ray approximation.*
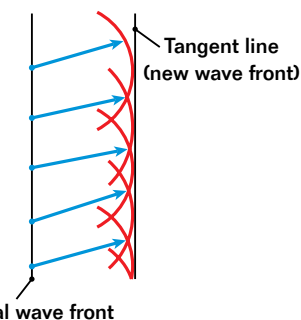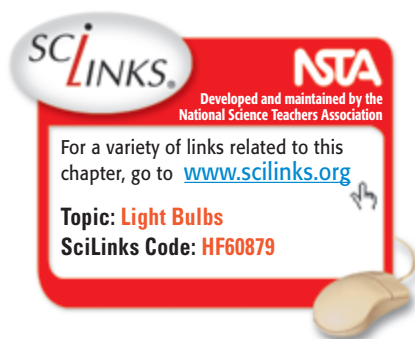

Figure 3
According to Huygens' principle, a wave front can be divided into point sources. The line tangent to the wavelets from these sources marks the wave front's new position.

Illuminance decreases as the square of the distance from the source

You have probably noticed that it is easier to read a book beside a lamp using a 100 W bulb rather than a 25 W bulb. It is also easier to read nearer to a lamp than farther from a lamp. These experiences suggest that the intensity of light depends on both the amount of light energy emitted from a source and the distance from the light source.

Light bulbs are rated by their power input (measured in watts) and their light output. The rate at which light is emitted from a source is called the *luminous flux* and is measured in *lumens* (lm). Luminous flux is a measure of power output but is weighted to take into account the response of the human eye to light. The idea of luminous flux helps us understand why the illumination on a book page is reduced as you move away from a light source. Imagine spherical surfaces of different sizes with a point light source at the ce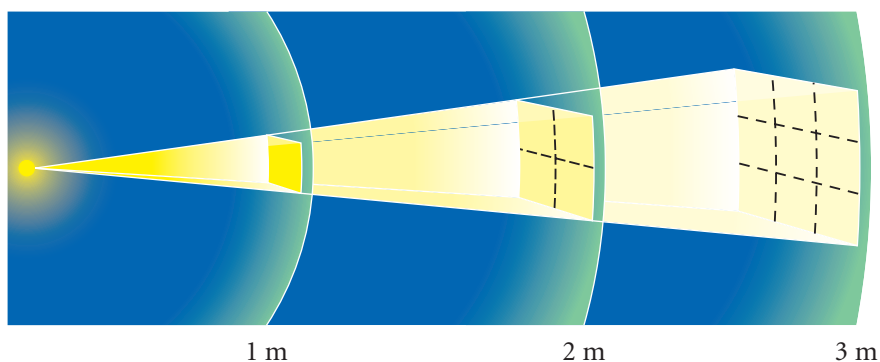nter of the sphere, shown in **Figure 4.** A point source of light provides light equally in all directions. The principle of conservation of energy tells us that the luminous flux is the same on each sphere. However, the luminous flux divided by the area of the surface, which is called the *illuminance* (measured in lm/m^2, or *lux*), decreases as the radius squared when you move away from a light source.

1 m   2 m   3 m

Figure 4
Less light falls on each unit square as the distance from the source increases.

SECTION REVIEW

1. Identify which portions of the electromagnetic spectrum are used in each of the devices listed.
   a. a microwave oven
   b. a television set
   c. a single-lens reflex camera

2. If an electromagnetic wave has a frequency of 7.57×10^{14} Hz, what is its wavelength? To what part of the spectrum does this wave belong?

3. Galileo performed an experiment to measure the speed of light by timing how long it took light to travel from a lamp he was holding to an assistant about 1.5 km away and back again. Why was Galileo unable to conclude that light had a finite speed?

4. **Critical Thinking** How bright would the sun appear to an observer on Earth if the sun were four times farther from Earth than it actually is? Express your answer as a fraction of the sun's brightness on Earth's surface.

Flat Mirrors

REFLECTION OF LIGHT

Suppose you have just had your hair cut and you want to know what the back of your head looks like. You can do this seemingly impossible task by using two mirrors to direct light from behind your head to your eyes. Redirecting light with mirrors reveals a basic property of light's interaction with matter.

Light traveling through a uniform substance, whether it is air, water, or a vacuum, always travels in a straight line. However, when the light encounters a different substance, its path will change. If a material is opaque to the light, such as the dark, highly polished surface of a wooden table, the light will not pass into the table more than a few wavelengths. Part of the light is absorbed, and the rest of it is deflected at the surface. This change in the direction of the light is called **reflection.** All substances absorb at least some incoming light and reflect the rest. A good mirror can reflect about 90 percent of the incident light, but no surface is a perfect reflector. Notice in **Figure 5** that the images of the person get successively darker.

reflection

the change in direction of an electromagnetic wave at a surface that causes it to move away from the surface

The texture of a surface affects how it reflects light

The manner in which light is reflected from a surface depends on the surface's smoothness. Light that is reflected from a rough, textured surface, such as paper, cloth, or unpolished wood, is reflected in many different directions, as shown in **Figure 6(a).** This type of reflection is called *diffuse reflection*. Diffuse reflection will be discussed further in Section 4.

Light reflected from smooth, shiny surfaces, such as a mirror or water in a pond, is reflected in one direction only, as shown in **Figure 6(b).** This type of reflection is called *specular reflection*. A surface is considered smooth if its surface variations are small compared with the wavelength of the incoming light. For our discussion, reflection will be used to mean only specular reflection.
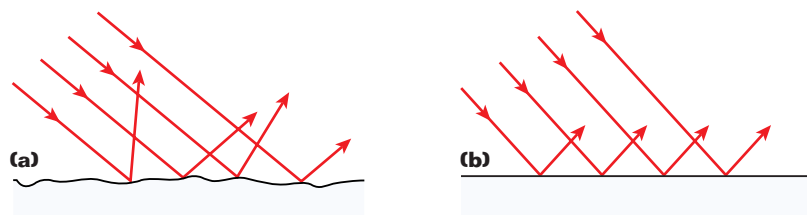
Figure 5

Mirrors reflect nearly all incoming light, so multiple images of an object between two mirrors are easily formed.

Figure 6

Diffusely reflected light is reflected in many directions **(a),** whereas specularly reflected light is reflected in the same forward direction only **(b).**
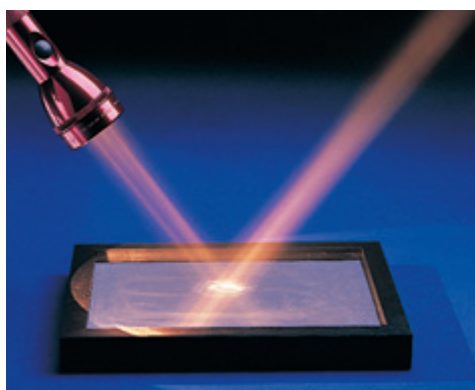
(a)

(b)

Figure 7
The symmetry of reflected light **(a)** is described by the law of reflection, which states that the angles of the incoming and reflected rays are equal **(b).**

Incoming and reflected angles are equal

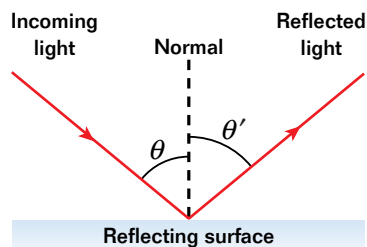You probably have noticed that when incoming rays of light strike a smooth reflecting surface, such as a polished table or mirror, at an angle close to the surface, the reflected rays are also close to the surface. When the incoming rays are high above the reflecting surface, the reflected rays are also high above the surface. An example of this similarity between incoming and reflected rays is shown in **Figure 7(a).**

If a straight line is drawn perpendicular to the reflecting surface at the point where the incoming ray strikes the surface, the **angle of incidence** and the **angle of reflection** can be defined with respect to the line. Careful measurements of the incident and reflected angles θ and θ', respectively, reveal that the angles are equal, as illustrated in **Figure 7(b).**

$$\theta = \theta'$$
angle of incoming light ray = angle of reflected light ray

The line perpendicular to the reflecting surface is referred to as the *normal* to the surface. It therefore follows that the angle between the incoming ray and the surface equals $90° - \theta$, and the angle between the reflected ray and the surface equals $90° - \theta'$.

angle of incidence

the angle between a ray that strikes a surface and the line perpendicular to that surface at the point of contact

angle of reflection

the angle formed by the line perpendicular to a surface and the direction in which a reflected ray moves

FLAT MIRRORS

The simplest mirror is the *flat mirror*. If an object, such as a pencil, is placed at a distance in front of a flat mirror and light is bounced off the pencil, light rays will spread out from the pencil and reflect from the mirror's surface. To an observer looking at the mirror, these rays appear to come from a location on the other side of the mirror. As a convention, an object's image is said to be at this location behind the mirror because the light appears to come from that point. The relationship between the *object distance* from the mirror, which is represented as *p,* and the *image distance,* which is represented as *q,* is such that the object and image distances are equal. Similarly, the image of the object is the same size as the object.

The image formed by rays that appear to come from the image point behind the mirror—but never really do—is called a **virtual image.** As shown in **Figure 8(a),** a flat mirror always forms a virtual image, which always appears as if it is behind the surface of the mirror. For this reason, a virtual image can never be displayed on a physical surface.

Image location can be predicted with ray diagrams

Ray diagrams, such as the one shown in **Figure 8(b),** are drawings that use simple geometry to locate an image formed by a mirror. Suppose you want to make a ray diagram for a pencil placed in front of a flat mirror. First, sketch the situation. Draw the location and arrangement of the mirror and the position of the pencil with respect to the mirror. Construct the drawing so that the object and the image distances (p and q, respectively) are proportional to their actual sizes. To simplify matters, we will consider only the tip of the pencil.

To pinpoint the location of the pencil tip's image, draw two rays on your diagram. Draw the first ray from the pencil tip perpendicular to the mirror's surface. Because this ray makes an angle of $0°$ with a line perpendicular (or *normal*) to the mirror, the angle of reflection also equals $0°$, causing the ray to reflect back on itself. In **Figure 8(b),** this ray is denoted by the number **1** and is shown with arrows pointing in both directions because the incident ray reflects back on itself.

Draw the second ray from the tip of the pencil to the mirror, but this time place the ray at an angle that is not perpendicular to the surface of the mirror. The second ray is denoted in **Figure 8(b)** by the number **2.** Then, draw the reflected ray, keeping in mind that it will reflect away from the surface of the mirror at an angle, θ', equal to the angle of incidence, θ.

Next, trace both reflected rays back to the point from which they appear to have originated, that is, behind the mirror. Use dotted lines when drawing these rays that appear to emerge from behind the mirror to distinguish them from the actual rays of light (the solid lines) in front of the mirror. The point at which these dotted lines meet is the image point, which in this case is where the image of the pencil's tip forms.

By continuing this process for all of the other parts of the pencil, you can locate the complete virtual image of the pencil. Note that the pencil's image appears as far behind the mirror as the pencil is in front of the mirror ($p = q$). Likewise, the object height, h, equals the image height, h'.
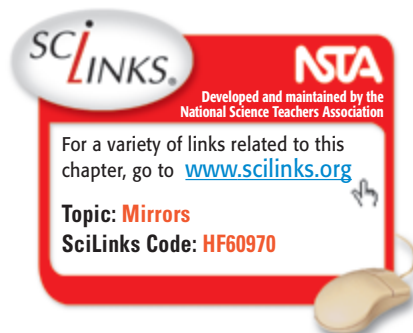
(a)

Figure 8
The position and size of the virtual image that forms in a flat mirror **(a)** can be predicted by constructing a ray diagram **(b).**
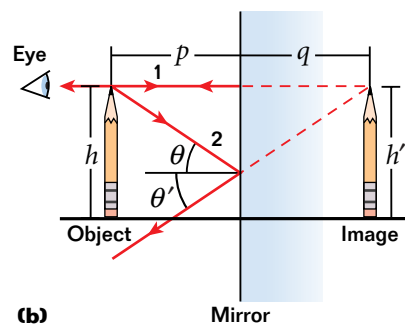
(b)

Figure 9
The front of an object becomes the back of its image.

This ray-tracing procedure will work for any object placed in front of a flat mirror. By selecting a single point on the object (usually its uppermost tip or edge), you can use ray tracing to locate the same point on the image. The rest of the image can be added once the image point and image distance have been determined.

The image formed by a flat mirror appears reversed to an observer in front of the mirror. You can easily observe this effect by placing a piece of writing in front of a mirror, as shown in **Figure 9.** In the mirror, each of the letters is reversed. You may also notice that the angle the word and its reflection make with respect to the mirror is the same.

SECTION REVIEW

1. Which of the following are examples of specular reflection, and which are examples of diffuse reflection?
   a. reflection of light from the surface of a lake on a calm day
   b. reflection of light from a plastic trash bag
   c. reflection of light from the lens of eyeglasses
   d. reflection of light from a carpet

2. Suppose you are holding a flat mirror and standing at the center of a giant clock face built into the floor. Someone standing at 12 o'clock shines a beam of light toward you, and you want to use the mirror to reflect the beam toward an observer standing at 5 o'clock. What should the angle of incidence be to achieve this? What should the angle of reflection be?

3. Some department-store windows are slanted inward at the bottom. This is to decrease the glare from brightly illuminated buildings across the street, which would make it difficult for shoppers to see the display inside and near the bottom of the window. Sketch a light ray reflecting from such a window to show how this technique works.

4. **Interpreting Graphics** The photograph in **Figure 5** shows multiple images that were created by multiple reflections between two flat mirrors. What conclusion can you make about the relative orientation of the mirrors? Explain your answer.

5. **Critical Thinking** If one wall of a room consists of a large flat mirror, how much larger will the room appear to be? Explain your answer.

6. **Critical Thinking** Why does a flat mirror appear to reverse the person looking into a mirror left to right, but not up and down?

Curved Mirrors

CONCAVE SPHERICAL MIRRORS

Small, circular mirrors, such as those used on dressing tables, may appear at first glance to be the same as flat mirrors. However, the images they form differ from those formed by flat mirrors. The images for objects close to the mirror are larger than the object, as shown in **Figure 10(a),** whereas the images of objects far from the mirror are smaller and upside down, as shown in **Figure 10(b).** Images such as these are characteristic of curved mirrors. The image in **Figure 10(a)** is a virtual image like those created by flat mirrors. In contrast, the image in **Figure 10(b)** is a *real* image.

Concave mirrors can be used to form real images

One basic type of curved mirror is the spherical mirror. A spherical mirror, as its name implies, has the shape of part of a sphere's surface. A spherical mirror with light reflecting from its silvered, concave surface (that is, the inner surface of a sphere) is called a **concave spherical mirror.** Concave mirrors are used whenever a magnified image of an object is needed, as in the case of the dressing-table mirror.

One factor that determines where the image will appear in a concave spherical mirror and how large that image will be is the radius of curvature, R, of the mirror. The radius of curvature is the same as the radius of the spherical shell of which the mirror is a small part; R is therefore the distance from the mirror's surface to the center of curvature, C.

SECTION OBJECTIVES

- Calculate distances and focal lengths using the mirror equation for concave and convex spherical mirrors.

- Draw ray diagrams to find the image distance and magnification for concave and convex spherical mirrors.

- Distinguish between real and virtual images.

- Describe how parabolic mirrors differ from spherical mirrors.

concave spherical mirror

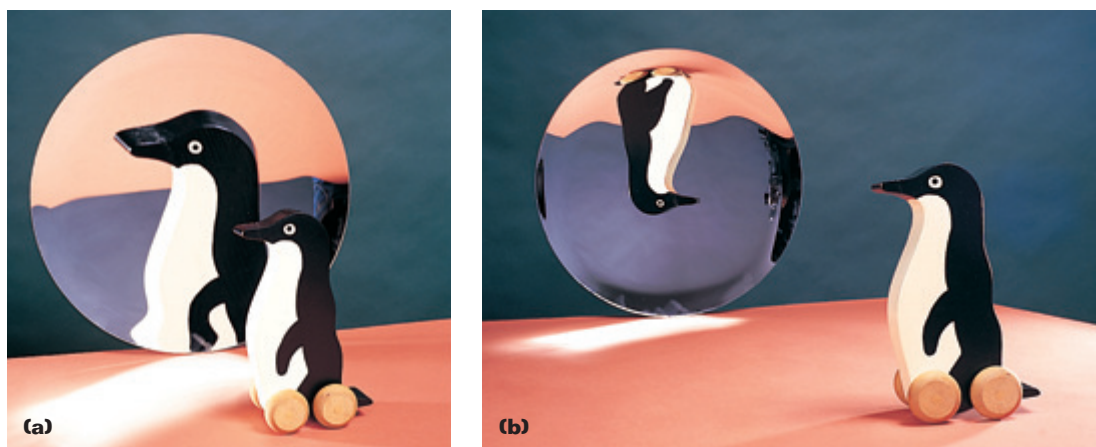*a mirror whose reflecting surface is a segment of the inside of a sphere*

Figure 10
Curved mirrors can be used to form images that are larger **(a)** or smaller **(b)** than the object.
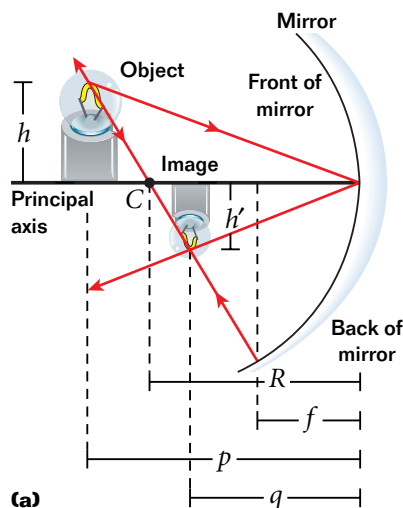
Figure 11

(a) The rays from an object, such as a light bulb, converge to form a real image in front of a concave mirror. **(b)** In this lab setup, the real image of a light-bulb filament appears on a glass plate in front of a concave mirror.

real image

an image formed when rays of light actually pass through a point on the image

Imagine a light bulb placed upright at a distance p from a concave spherical mirror, as shown in **Figure 11(a).** The base of the bulb is along the mirror's principal axis, which is the line that extends infinitely from the center of the mirror's surface through the center of curvature, C. Light rays diverge from the light bulb, reflect from the mirror's surface, and converge at some distance, q, in front of the mirror. Because the light rays reflected by the mirror actually pass through the image point, which in this case is below the principal axis, the image forms in front of the mirror.

If you place a piece of paper at the image point, you will see on the paper a sharp and clear image of the light bulb. As you move the paper in either direction away from the image point, the rays diverge, and the image becomes unfocused. An image of this type is called a **real image.** Unlike the virtual images that appear behind a flat mirror, real images can be displayed on a surface, like the images on a movie screen. **Figure 11(b)** shows a real image of a light-bulb filament on a glass plate in front of a concave mirror. This light bulb itself is outside the photograph, to the left.

Image created by spherical mirrors suffer from spherical aberration

As you draw ray diagrams, you may notice that certain rays do not exactly intersect at the image point. This phenomenon is particularly noticeable for rays that are far from the principal axis and for mirrors with a small radius of curvature. This situation, called *spherical aberration,* also occurs with real light rays and real spherical mirrors and will be discussed further at the end of this section when we introduce *parabolic mirrors.*

In the next pages of this section, you will learn about the mirror equation and ray diagrams. Both of these concepts are valid only for *paraxial rays,* but they do provide quite useful approximations. Paraxial rays are those light rays that are very near the principal axis of the mirror. We will assume that all of the rays used in our drawings and calculations with spherical mirrors are paraxial, even though they may not appear to be so in all of the diagrams accompanying the text.

Image location can be predicted with the mirror equation

By looking at **Figure 11(a),** you can see that object distance, image distance, and radius of curvature are interdependent. If the object distance and radius of curvature of the mirror are known, you can predict where the image will appear. Alternatively, the radius of curvature of a mirror can be determined if you know where the image appears for a given object distance. The following equation relates object distance, p, image distance, q, and the radius of curvature, R, is called *the mirror equation.*

$$\frac{1}{p} + \frac{1}{q} = \frac{2}{R}$$

If the light bulb is placed very far from the mirror, the object distance, p, is great enough compared with R that $1/p$ is almost 0. In this case, q is almost $R/2$, so the image forms about halfway between the center of curvature and the center of the mirror's surface. The image point, as shown in **Figure 12(a)** and **(b),** is in this special case called the *focal point* of the mirror and is denoted by the capital letter F. Because the light rays are reversible, the reflected rays from a light source at the focal point will emerge parallel to each other and will not form an image.

For light emerging from a source very far away from a mirror, the light rays are essentially parallel to one another. In this case, an image forms at the focal point, F, and the image distance is called the *focal length,* denoted by the lowercase letter f. For a spherical mirror, the focal length is equal to half the radius of curvature of the mirror. The mirror equation can therefore be expressed in terms of the focal length.
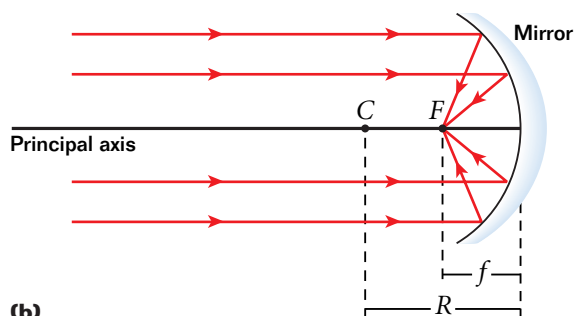
MIRROR EQUATION

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$

$$\frac{1}{\textbf{object distance}} + \frac{1}{\textbf{image distance}} = \frac{1}{\textbf{focal length}}$$

(a)

(b)

Figure 12
Light rays that are parallel converge at a single point **(a),** which can be represented in a diagram **(b),** when the rays are assumed to be from a distant object ($p \approx \infty$).

A set of sign conventions for the three variables must be established for use with the mirror equation. The region in which light rays reflect and form real images is called the front side of the mirror. The other side, where light rays do not exist—and where virtual images are formed—is called the back side of the mirror.

Object and image distances have a positive sign when measured from the center of the mirror to any point on the mirror's front side. Distances for images that form on the back side of the mirror always have a negative sign. Because the mirrored surface is on the front side of a concave mirror, its focal length always has a positive sign. The object and image heights are positive when both are above the principal axis and negative when either is below.

Magnification relates image and object sizes

Unlike flat mirrors, curved mirrors form images that are not the same size as the object. The measure of how large or small the image is with respect to the original object's size is called the *magnification* of the image.

If you know where an object's image will form for a given object distance, you can determine the magnification of the image. Magnification, M, is defined as the ratio of the height of the bulb's image to the bulb's actual height. M also equals the negative of the ratio of the image distance to the object distance. If an image is smaller than the object, the magnitude of its magnification is less than 1. If the image is larger than the object, the magnitude of its magnification is greater than 1. Magnification is a unitless quantity.

EQUATION FOR MAGNIFICATION

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

$$\text{magnification} = \frac{\text{image height}}{\text{object height}} = -\frac{\text{image distance}}{\text{object distance}}$$

For an image in front of the mirror, M is negative and the image is upside down, or *inverted,* with respect to the object. When the image is behind the mirror, M is positive and the image is *upright* with respect to the object. The conventions for magnification are listed in **Table 2.**

Table 2	Sign Conventions for Magnification	
Orientation of image with respect to object	**Sign of M**	**Type of image this applies to**
upright	+	virtual
inverted	−	real

Ray diagrams can be used for concave spherical mirrors

Ray diagrams are useful for checking values calculated from the mirror and magnification equations. The techniques for ray diagrams that were used to locate the image for an object in front of a flat mirror can also be used for concave spherical mirrors. When drawing ray diagrams for concave mirrors, follow the basic procedure for a flat mirror, but also measure all distances along the principal axis and mark the center of curvature, C, and the focal point, F. As with a flat mirror, draw the diagram to scale. For instance, if the object distance is 50 cm, you can draw the object distance as 5 cm.

For spherical mirrors, three reference rays are used to find the image point. The intersection of any *two* rays locates the image. The third ray should intersect at the same point and can be used to check the diagram. These reference rays are described in **Table 3.**

Table 3	Rules for Drawing Reference Rays	
Ray	Line drawn from object to mirror	Line drawn from mirror to image after reflection
1	parallel to principal axis	through focal point F
2	through focal point F	parallel to principal axis
3	through center of curvature C	back along itself through C

The image distance in the diagram should agree with the value for q calculated from the mirror equation. However, the image distance may differ because of inaccuracies that arise from drawing the ray diagrams at a reduced scale and far from the principal axis. Ray diagrams should therefore be used to obtain *approximate* values only; they should not be relied on for the best quantitative results.

Concave mirrors can produce both real and virtual images

When an object is moved toward a concave spherical mirror, its image changes, as shown in **Table 4** on next page. If the object is very far from the mirror, the light rays converge very near the focal point, F, of the mirror and form an image there. For objects at a finite distance greater than the radius of curvature, C, the image is real, smaller than the object, inverted, and located between C and F. When the object is at C, the image is real, located at C, and inverted. For an object at C, the image is the same size as the object. If the object is located between C and F, the image will be real, inverted, larger than the object, and located outside of C. When the object is at the focal point, no image is formed. When the object lies between F and the mirror surface, the image forms again, but now it becomes virtual, upright, and larger.
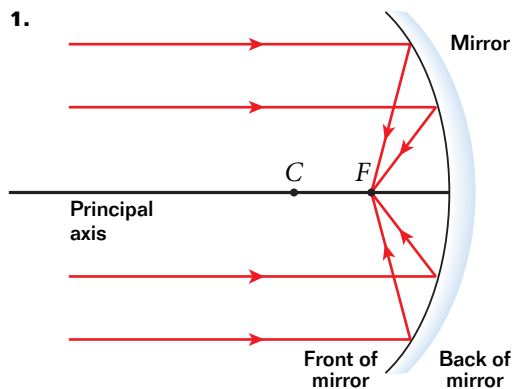
Table 4   Images Created by Concave Mirrors

Ray diagrams

1.

Configuration: object at infinity

Image: real image at *F*

2.
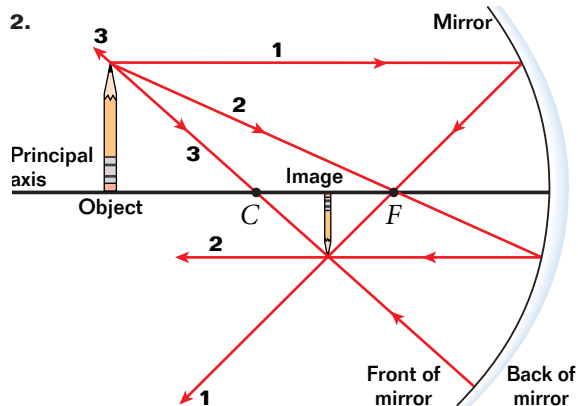
Configuration: object outside *C*

Image: real image between *C* and *F*, inverted with magnification < 1

3.
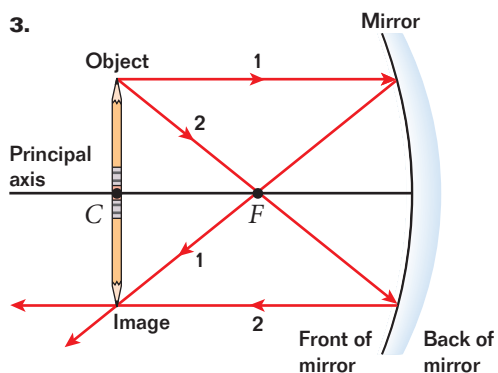
Configuration: object at *C*

Image: real image at *C*, inverted with magnification = 1

4.
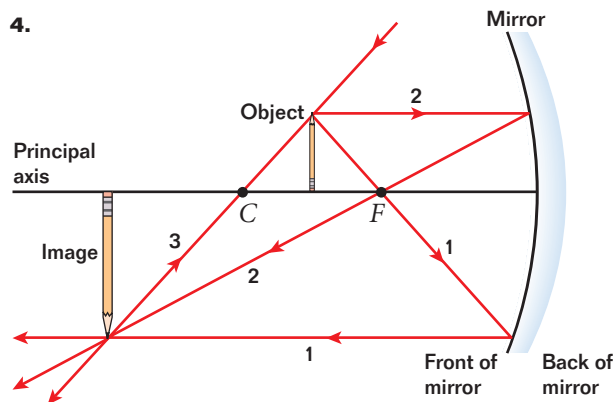
Configuration: object between *C* and *F*

Image: real image at *C*, inverted with magnification > 1

5.
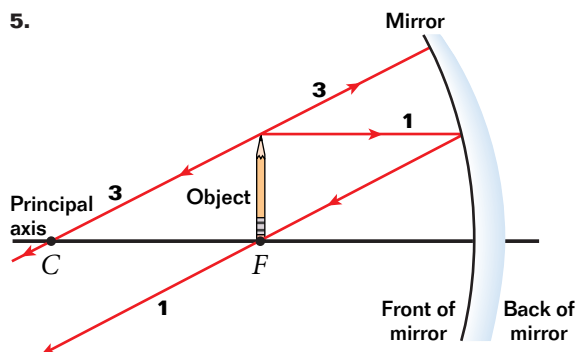
Configuration: object at *F*

Image: image at infinity (no image)

6.
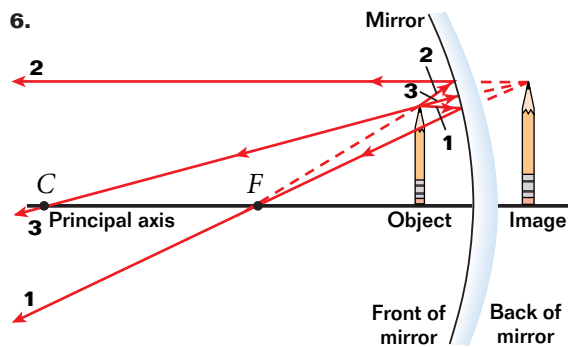
Configuration: object inside *F*

Image: virtual, upright image at *C* with magnification >1

STRATEGY Imaging with Concave Mirrors

PROBLEM

A concave spherical mirror has a focal length of 10.0 cm. Locate the image of a pencil that is placed upright 30.0 cm from the mirror. Find the magnification of the image. Draw a ray diagram to confirm your answer.
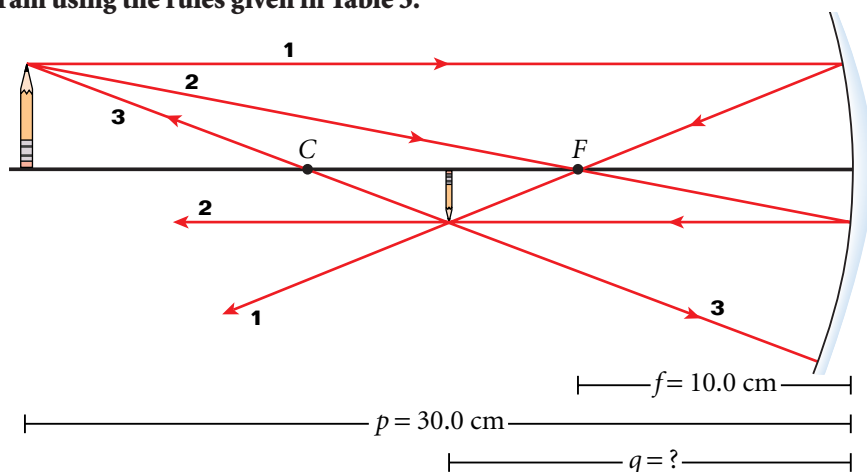
SOLUTION

1. **Determine the sign and magnitude of the focal length and object size.**

$f = +10.0$ cm $p = +30.0$ cm

The mirror is concave, so f is positive. The object is in front of the mirror, so p is positive.

2. **Draw a ray diagram using the rules given in Table 3.**

3. **Use the mirror equation to relate the object and image distances to the focal length.**

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$

4. **Use the magnification equation in terms of object and image distances.**

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

5. **Rearrange the equation to isolate the image distance, and calculate.**

Subtract the reciprocal of the object distance from the reciprocal of the focal length to obtain an expression for the unknown image distance.

$$\frac{1}{q} = \frac{1}{f} - \frac{1}{p}$$

Substitute the values for f and p into the mirror equation and the magnification equation to find the image distance and magnification.

$$\frac{1}{q} = \frac{1}{10.0\ \text{cm}} - \frac{1}{30.0\ \text{cm}} = \frac{0.100}{1\ \text{cm}} - \frac{0.033}{1\ \text{cm}} = \frac{0.067}{1\ \text{cm}}$$

$$\boxed{q = 15\ \text{cm}}$$

$$\boxed{M = -\frac{q}{p} = -\frac{15\ \text{cm}}{30.0\ \text{cm}} = -0.50}$$

6. **Evaluate your answer in terms of the image location and size.**
The image appears between the focal point (10.0 cm) and the center of curvature (20.0 cm), as confirmed by the ray diagram. The image is smaller than the object and inverted ($-1 < M < 0$), as is also confirmed by the ray diagram. The image is therefore real.

PRACTICE B

Imaging with Concave Mirrors

1. Find the image distance and magnification of the mirror in the sample problem when the object distances are 10.0 cm and 5.00 cm. Are the images real or virtual? Are the images inverted or upright? Draw a ray diagram for each case to confirm your results.

2. A concave shaving mirror has a focal length of 33 cm. Calculate the image position of a cologne bottle placed in front of the mirror at a distance of 93 cm. Calculate the magnification of the image. Is the image real or virtual? Is the image inverted or upright? Draw a ray diagram to show where the image forms and how large it is with respect to the object.

3. A concave makeup mirror is designed so that a person 25.0 cm in front of it sees an upright image at a distance of 50.0 cm behind the mirror. What is the radius of curvature of the mirror? What is the magnification of the image? Is the image real or virtual?

4. A pen placed 11.0 cm from a concave spherical mirror produces a real image 13.2 cm from the mirror. What is the focal length of the mirror? What is the magnification of the image? If the pen is placed 27.0 cm from the mirror, what is the new position of the image? What is the magnification of the new image? Is the new image real or virtual? Draw ray diagrams to confirm your results.
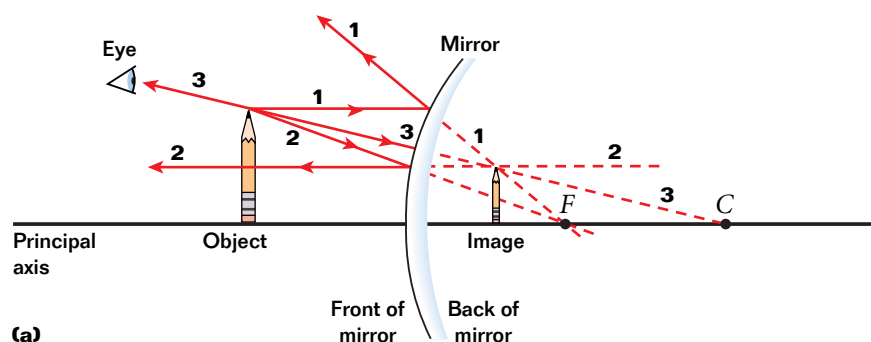
CONVEX SPHERICAL MIRRORS

On recent models of automobiles, there is a side-view mirror on the passenger's side of the car. Unlike the flat mirror on the driver's side, which produces unmagnified images, the passenger's mirror bulges outward at the center. Images in this mirror are distorted near the mirror's edges, and the image is smaller than the object. This type of mirror is called a <mark>convex spherical mirror.</mark>

A convex spherical mirror is a segment of a sphere that is silvered so that light is reflected from the sphere's outer, convex surface. This type of mirror is also called a diverging mirror because the incoming rays diverge after reflection as though they were coming from some point behind the mirror. The resulting image is therefore always virtual, and the image distance is always negative. Because the mirrored surface is on the side opposite the radius of curvature, a convex spherical mirror also has a negative focal length. The sign conventions for all mirrors are summarized in **Table 5.**

The technique for drawing ray diagrams for a convex mirror differs slightly from that for concave mirrors. The focal point and center of curvature are situated behind the mirror's surface. Dotted lines are extended along the reflected reference rays to points behind the mirror, as shown in **Figure 13(a).** A virtual, upright image forms where the three rays apparently intersect. Magnification for convex mirrors is always less than 1, as shown in **Figure 13(b).**

Convex spherical mirrors take the objects in a large field of view and produce a small image, so they are well suited for providing a fixed observer with a complete view of a large area. Convex mirrors are often placed in stores to help employees monitor customers and at the intersections of busy hallways so that people in both hallways can tell when others are approaching.

The side-view mirror on the passenger's side of a car is another application of the convex mirror. This mirror usually carries the warning, "objects are closer than they appear." Without this warning, a driver might think that he or she is looking into a flat mirror, which does not alter the size of the image. The driver could therefore be fooled into believing that a vehicle is farther away than it is because the image is smaller than the actual object.

convex spherical mirror

a mirror whose reflecting surface is an outward-curved segment of a sphere

(a)

(b)

Figure 13
Light rays diverge upon reflection from a convex mirror **(a)**, forming a virtual image that is always smaller than the object **(b).**
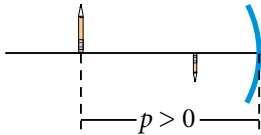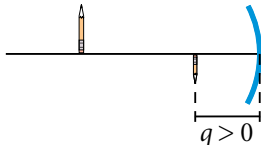
Table 5   Sign Conventions for Mirrors

Symbol	Situation	Sign	
p	object is in front of the mirror (real object)	+	$p > 0$
q	image is in front of the mirror (real image)	+	$q > 0$
q	image is behind the mirror (virtual image)	−	$q < 0$
R, f	center of curvature is in front of the mirror (concave spherical mirror)	+	$R > 0$ $f > 0$
R, f	center of curvature is behind the mirror (convex spherical mirror)	−	$R < 0$ $f < 0$
R, f	mirror has no curvature (flat mirror)	∞	$R, f \rightarrow \infty$
h'	image is above the principal axis	+	$h, h' > 0$
h'	image is below the principal axis	−	$h > 0, h' < 0$

SAMPLE PROBLEM C

Convex Mirrors

PROBLEM

An upright pencil is placed in front of a convex spherical mirror with a focal length of 8.00 cm. An erect image 2.50 cm tall is formed 4.44 cm behind the mirror. Find the position of the object, the magnification of the image, and the height of the pencil.

SOLUTION

1. DEFINE   **Given:** $f = -8.00$ cm $q = -4.44$ cm $h' = 2.50$ cm

Because the mirror is convex, the focal length is negative.
The image is behind the mirror, so q is also negative.

Unknown: $p = ?$ $h = ?$ $M = ?$

Diagram: Construct a ray diagram.

2. PLAN
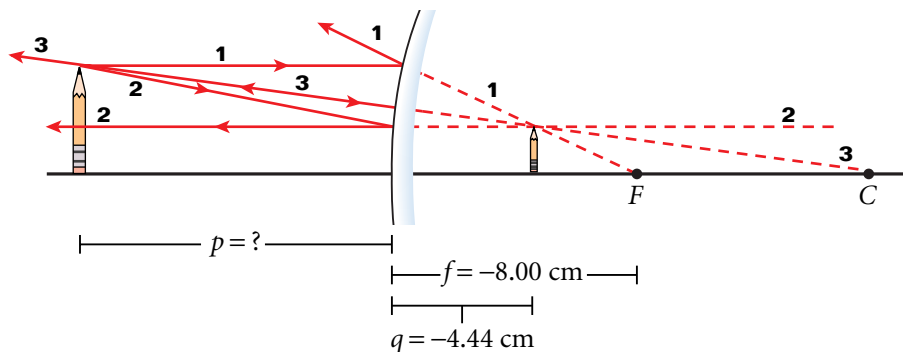
Choose an equation or situation: Use the mirror equation.

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$

Use the magnification formula.

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

Rearrange the equation to isolate the unknown:

$$\frac{1}{p} = \frac{1}{f} - \frac{1}{q} \quad \text{and} \quad h = -\frac{p}{q} h'$$

3. CALCULATE   **Substitute the values into the equation and solve:**

$$\frac{1}{p} = \frac{1}{-8.00 \text{ cm}} - \frac{1}{-4.44 \text{ cm}}$$

$$\frac{1}{p} = \frac{-0.125}{1 \text{ cm}} - \frac{-0.225}{1 \text{ cm}} = \frac{0.100}{1 \text{ cm}}$$

continued on
next page

$$\boxed{p = 10.0 \text{ cm}}$$

Light and Reflection   **465**

Substitute the values for p and q to find the magnification of the image.

$$M = -\frac{q}{p} = -\frac{-4.44 \text{ cm}}{10.0 \text{ cm}}$$

$$\boxed{M = 0.444}$$

Substitute the values for p, q, and h' to find the height of the object.

$$h = -\frac{p}{q}h' = -\frac{10.0 \text{ cm}}{-4.44 \text{ cm}} (2.50 \text{ cm})$$

$$\boxed{h = 5.63 \text{ cm}}$$

PRACTICE C

Convex Mirrors

1. The image of a crayon appears to be 23.0 cm behind the surface of a convex mirror and is 1.70 cm tall. If the mirror's focal length is 46.0 cm, how far in front of the mirror is the crayon positioned? What is the magnification of the image? Is the image virtual or real? Is the image inverted or upright? How tall is the actual crayon?

2. A convex mirror with a focal length of 0.25 m forms a 0.080 m tall image of an automobile at a distance of 0.24 m behind the mirror. What is the magnification of the image? Where is the car located, and what is its height? Is the image real or virtual? Is the image upright or inverted?

3. A convex mirror of focal length 33 cm forms an image of a soda bottle at a distance of 19 cm behind the mirror. If the height of the image is 7.0 cm, where is the object located, and how tall is it? What is the magnification of the image? Is the image virtual or real? Is the image inverted or upright? Draw a ray diagram to confirm your results.

4. A convex mirror with a radius of curvature of 0.550 m is placed above the aisles in a store. Determine the image distance and magnification of a customer lying on the floor 3.1 m below the mirror. Is the image virtual or real? Is the image inverted or upright?

5. A spherical glass ornament is 6.00 cm in diameter. If an object is placed 10.5 cm away from the ornament, where will its image form? What is the magnification? Is the image virtual or real? Is the image inverted or upright?

6. A candle is 49 cm in front of a convex spherical mirror that has a focal length of 35 cm. What are the image distance and magnification? Is the image virtual or real? Is the image inverted or upright? Draw a ray diagram to confirm your results.

PARABOLIC MIRRORS

You have probably noticed that certain rays in ray diagrams do not intersect exactly at the image point. This occurs especially with rays that reflect at the mirror's surface far from the principal axis. The situation also occurs with real light rays and real spherical mirrors.

If light rays from an object are near the principal axis, all of the reflected rays pass through the image point. Rays that reflect at points on the mirror far from the principal axis converge at slightly different points on the principal axis, as shown in **Figure 14.** This produces a blurred image. This effect, called *spherical aberration,* is present to some extent in any spherical mirror.

Parabolic mirrors eliminate spherical aberration

A simple way to reduce the effect of spherical aberration is to use a mirror with a small diameter; that way, the rays are never far from the principal axis. If the mirror is large to begin with, shielding its outer portion will limit how much of the mirror is used and thus will accomplish the same effect. However, many concave mirrors, such as those used in astronomical telescopes, are made large so that they will collect a large amount of light. Therefore, it is not desirable to limit how much of the mirror is used in order to reduce spherical aberration. An alternative approach is to use a mirror that is not a segment of a sphere but still focuses light rays in a manner similar to a small spherical concave mirror. This is accomplished with a parabolic mirror.

Parabolic mirrors are segments of a paraboloid (a three-dimensional parabola) whose inner surface is reflecting. All rays parallel to the principal axis converge at the focal point regardless of where on the mirror's surface the rays reflect. Thus, a real image forms without spherical aberration, as illustrated in **Figure 15.** Similarly, light rays from an object at the focal point of a parabolic mirror will be reflected from the mirror in parallel rays. Parabolic reflectors are ideal for flashlights and automobile headlights.

Reflecting telescopes use parabolic mirrors

A telescope permits you to view distant objects, whether they are buildings a few kilometers away or galaxies that are millions of light-years from Earth. Not all telescopes are intended for visible light. Because all electromagnetic radiation obeys the law of reflection, parabolic surfaces can be constructed to reflect and focus electromagnetic radiation of different wavelengths. For instance, a radio telescope consists of a large metal parabolic surface that reflects radio waves in order to receive radio signals from objects in space.

There are two types of telescopes that use visible light. One type, called a *refracting telescope,* uses a combination of lenses to form an image. The other kind uses a curved mirror and small lenses to form an image. This type of telescope is called a *reflecting telescope.*
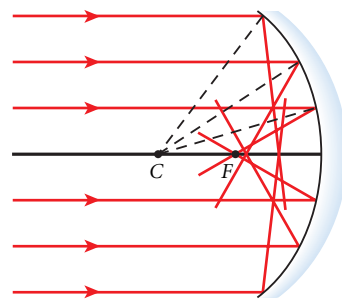
Figure 14
Spherical aberration occurs when parallel rays far from the principal axis converge away from the mirror's focal point.
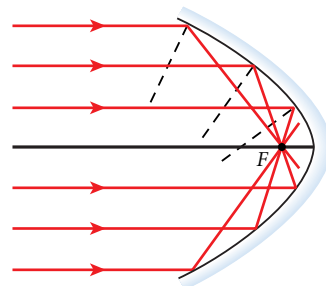
Figure 15
All parallel rays converge at a parabolic mirror's focal point. The curvature in this figure is much greater than it is in real parabolic mirrors.

SCILINKS.

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For a variety of links related to this chapter, go to www.scilinks.org

Topic: Telescopes
SciLinks Code: HF61500
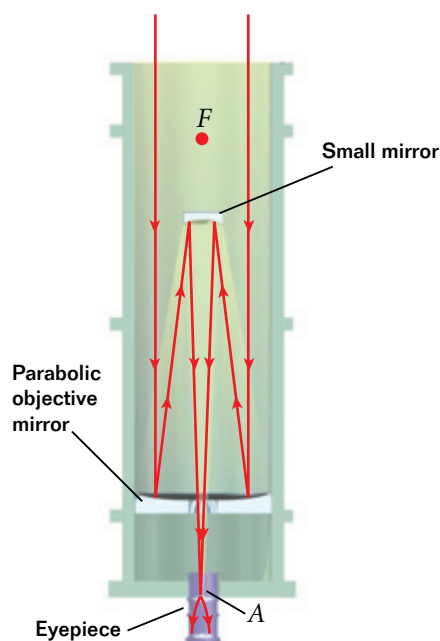
Figure 16
The parabolic objective mirror in a Cassegrain reflector focuses incoming light.

Reflecting telescopes employ a parabolic mirror (called an *objective mirror*) to focus light. One type of reflecting telescope, called a *Cassegrain reflector,* is shown in **Figure 16.** Parallel light rays pass down the barrel of the telescope and are reflected by the parabolic objective mirror at the telescope's base. These rays converge toward the objective mirror's focal point, *F,* where a real image would normally form. However, a small curved mirror that lies in the path of the light rays reflects the light back toward the center of the objective mirror. The light then passes through a small hole in the center of the objective mirror and comes to a focus at point *A.* An eyepiece near point *A* magnifies the image.

You may wonder how a hole can be placed in the objective mirror without affecting the final image formed by the telescope. Each part of the mirror's surface reflects light from distant objects, so a complete image is always formed. The presence of the hole merely reduces the amount of light that is reflected. Even that is not severely affected by the hole because the light-gathering capacity of an objective mirror is dependent on the mirror's area. For instance, a 1 m diameter hole in a mirror that is 4 m in diameter reduces the mirror's reflecting surface by only $\frac{1}{16}$, or 6.25 percent.

SECTION REVIEW

1. A steel ball bearing with a radius of 1.5 cm forms an image of an object that has been placed 1.1 cm away from the bearing's surface. Determine the image distance and magnification. Is the image virtual or real? Is the image inverted or upright? Draw a ray diagram to confirm your results.

2. A spherical mirror is to be used in a motion-picture projector to form an inverted, real image 95 times as tall as the picture in a single frame of film. The image is projected onto a screen 13 m from the mirror. What type of mirror is required, and how far should it be from the film?

3. Which of the following images are real and which are virtual?
   a. the image of a distant illuminated building projected onto a piece of heavy, white cardboard by a small reflecting telescope
   b. the image of an automobile in a flat rearview mirror
   c. the image of shop aisles in a convex observation mirror

4. **Critical Thinking** Why is an image formed by a parabolic mirror sharper than the image of the same object formed by a concave spherical mirror?

5. **Critical Thinking** The reflector of the radio telescope at Arecibo has a radius of curvature of 265.0 m. How far above the reflector must the radio-detecting equipment be placed in order to obtain clear radio images?

Color and Polarization

COLOR

You have probably noticed that the color of an object can appear different under different lighting conditions. These differences are due to differences in the reflecting and light-absorbing properties of the object being illuminated.

So far, we have assumed that objects are either like mirrors, which reflect almost all light uniformly, or like rough objects, which reflect light diffusely in several directions. But, as mentioned in Section 1, objects absorb certain wavelengths from the light striking them and reflect the rest. The color of an object depends on which wavelengths of light shine on the object and which wavelengths are reflected (see **Figure 17**).

If all wavelengths of incoming light are completely reflected by an object, that object appears to have the same color as the light illuminating it. This gives the object the same appearance as a white object illuminated by the light. An object of a particular color, such as the green leaf in **Figure 17,** absorbs light of all colors except the light whose color is the same as the object's color. By contrast, an object that reflects no light appears black. In truth, leaves appear green only when their primary pigment, chlorophyll, is present. In the autumn, when the green pigment is destroyed, other colors are reflected by the leaves.

Additive primary colors produce white light when combined

Because white light can be dispersed into its elementary colors, it is reasonable to suppose that elementary colors can be combined to form white light. One way of doing this is to use a lens to recombine light that has been dispersed by a prism. Another way is to combine light that has been passed through red, green, and blue filters. These colors are called the *additive primary colors* because when they are added in varying proportions, they can form all of the colors of the spectrum.
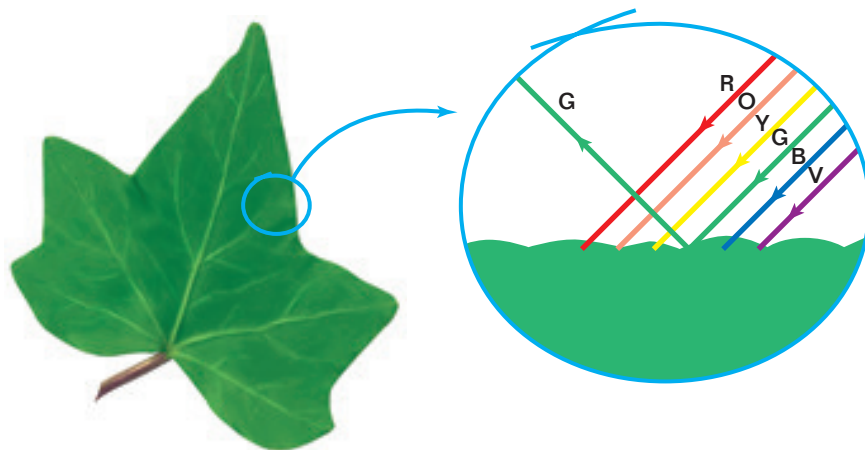
SECTION OBJECTIVES

- **Recognize how additive colors affect the color of light.**
- **Recognize how pigments affect the color of reflected light.**
- **Explain how linearly polarized light is formed and detected.**

SC**LINKS.** NSTA

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Topic: Color
SciLinks Code: HF60313

extension

Integrating Biology
Visit go.hrw.com for the activity "How Does Sunscreen Work?"

Keyword HF6LGTX

Figure 17
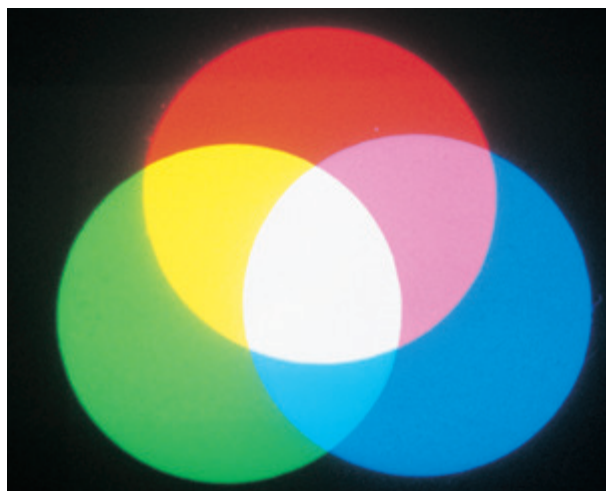A leaf appears green under white light because the primary pigment in the leaf reflects only green light.

Figure 18
The combination of the additive primary colors in any two circles produces the complementary color of the third additive primary color.

Figure 19
The brightness of the red, green, and blue pixels of a color television screen are adjusted such that, from a distance, all of the colors in a single picture appear.

When light passed through a red filter is combined with green light produced with a green filter, a patch of yellow light appears. If this yellow light is combined with blue light, the resulting light will be colorless, or "white," as shown in **Figure 18.** Because yellow is the color added to the primary additive color blue to produce white light, yellow is called the *complementary* color of blue. Two primary colors combine to produce the complement of the third primary color, as indicated in **Table 6.**

One application of additive primary colors is the use of certain chemical compounds to give color to glass. Iron compounds give glass a green color. Manganese compounds give glass a magenta, or reddish blue, color. Green and magenta are complementary colors, so the right proportion of these compounds produces an equal combination of green and magenta light, and the resulting glass appears colorless.

Another example of additive colors is the image produced on a color television screen. A television screen consists of small, luminous dots, or *pixels,* that glow either red, green, or blue when they are struck by electrons (see **Figure 19**). Varying the brightness of different pixels in different parts of the picture produces a picture that appears to have many colors present at the same time.

Humans can see in color because there are three kinds of color receptors in the eye. Each receptor, called a *cone cell,* is sensitive to either red, green, or blue light. Light of different wavelengths stimulates a combination of these receptors so that a wide range of colors can be perceived.

Table 6	Additive and Subtractive Primary Colors	
Colors	**Additive (mixing light)**	**Subtractive (mixing pigments)**
red	primary	complementary to cyan
green	primary	complementary to magenta
blue	primary	complementary to yellow
cyan (blue green)	complementary to red	primary
magenta (red blue)	complementary to green	primary
yellow	complementary to blue	primary

Subtractive primary colors filter out all light when combined

When blue light and yellow light are mixed, white light results. However, if you mix a blue pigment (such as paint or the colored wax of a crayon) with a yellow pigment, the resulting color is green, not white. This difference is due to the fact that pigments rely on colors of light that are absorbed, or subtracted, from the incoming light.

For example, yellow pigment subtracts blue and violet colors from white light and reflects red, orange, yellow, and green light. Blue pigment subtracts red, orange, and yellow from the light and reflects green, blue, and violet. When yellow and blue pigments are combined, only green light is reflected.

When pigments are mixed, each one subtracts certain colors from white light, and the resulting color depends on the frequencies that are not absorbed. The primary pigments (or *primary subtractive colors,* as they are sometimes called) are cyan, magenta, and yellow. These are the same colors that are complementary to the additive primary colors (see **Table 6**). When any two primary subtractive colors are combined, they produce either red, green, or blue pigments. When the three primary pigments are mixed together in the proper proportions, all of the colors are subtracted from white light, and the mixture is black, as shown in **Figure 20.**

Combining yellow pigment and its complementary color, blue, should produce a black pigment. Yet earlier, blue and yellow were combined to produce green. The difference between these two situations is explained by the broad use of color names. The "blue" pigment that is added to a "yellow" pigment to produce green is not a pure blue. If it were, only blue light would be reflected from it. Similarly, a pure yellow pigment will reflect only yellow light. Because most pigments found in paints and dyes are combinations of different substances, they reflect light from nearby parts of the visible spectrum. Without knowledge of the light-absorption characteristics of these pigments, it is hard to predict exactly what colors will result from different combinations.

Figure 20
The combination of the subtractive primary colors by any two filters produces the complementary color of the third subtractive primary color.

Conceptual Challenge

1. Colors in a Blanket   Brown is a mixture of yellow with small amounts of red and green. If you shine red light on a brown woolen blanket, what color will the blanket appear? Will it appear lighter or darker than it would under white light? Explain your answers.

2. Blueprints   If a blueprint (a blue drawing on a white background) is viewed under blue light, will you still be able to perceive the drawing? What will the blueprint look like under yellow light?
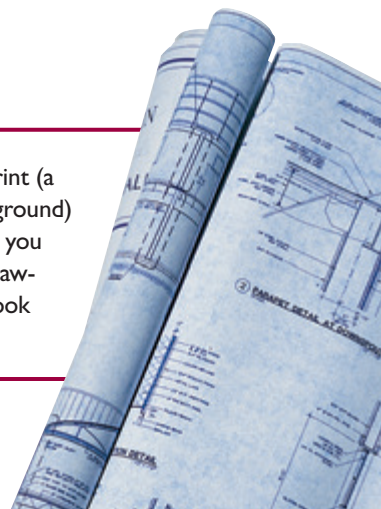
POLARIZATION OF LIGHT WAVES

You have probably seen sunglasses with polarized lenses that reduce glare without blocking the light entirely. There is a property of light that allows some of the light to be filtered by certain materials in the lenses.

In an electromagnetic wave, the electric field is at right angles to both the magnetic field and the direction of propagation. Light from a typical source consists of waves that have electric fields oscillating in random directions, as shown in **Figure 21.** Light of this sort is said to be *unpolarized.*

Electric-field oscillations of unpolarized light waves can be treated as combinations of vertical and horizontal electric-field oscillations. There are certain processes that separate waves with electric-field oscillations in the vertical direction from those in the horizontal direction, producing a beam of light with electric field waves oriented in the same direction, as shown in **Figure 22.** These waves are said to have **linear polarization.**

linear polarization

the alignment of electromagnetic waves in such a way that the vibrations of the electric fields in each of the waves are parallel to each other

Light can be linearly polarized through transmission

Certain transparent crystals cause unpolarized light that passes through them to become linearly polarized. The direction in which the electric fields are polarized is determined by the arrangement of the atoms or molecules in the
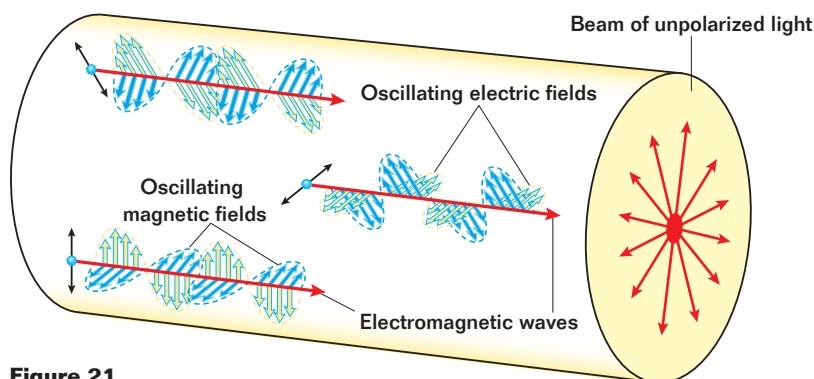

Figure 21
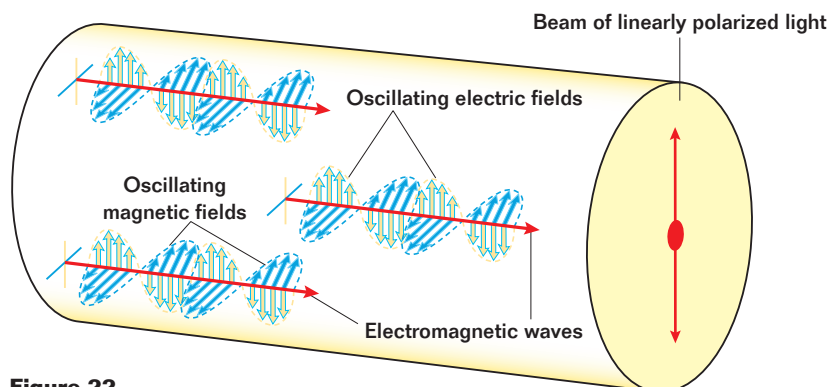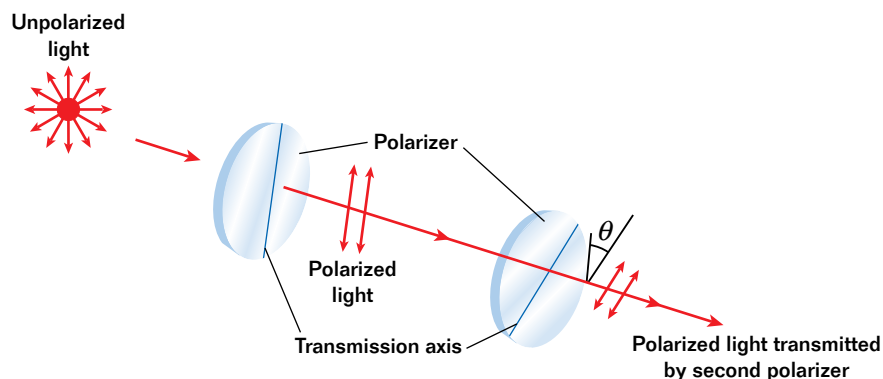Randomly oscillating electric fields produce unpolarized light.

Figure 22
Light waves with aligned electric fields are linearly polarized.

crystal. For substances that polarize light by transmission, the line along which light is polarized is called the *transmission axis* of the substance. Only light waves that are linearly polarized with respect to the transmission axis of the polarizing substance can pass freely through the substance. All light that is polarized at an angle of 90° to the transmission axis does not pass through.

When two polarizing films are held with the transmission axes parallel, light will pass through the films, as shown in **Figure 23(a).** If they are held with the transmission axes perpendicular to each other, as in **Figure 23(b),** no light will pass through the films.

A polarizing substance can be used not only to linearly polarize light but also to determine if and how light is linearly polarized. By rotating a polarizing substance as a beam of polarized light passes through it, a change in the intensity of the light can be seen (see **Figure 24**). The light is brightest when its plane of polarization is parallel to the transmission axis. The larger the angle is between the electric-field waves and the transmission axis, the smaller the component of light that passes through the polarizer will be and the less bright the light will be. When the transmission axis is perpendicular to the plane of polarization for the light, no light passes through.

(a)

(b)

Figure 23
(a) Light will pass through a pair of polarizing films when their polarization axes are aligned in the same direction. **(b)** When the axes are at right angles to one another, light will not get through.

Unpolarized light · Polarizer · Polarized light · Transmission axis · Polarized light transmitted by second polarizer · θ

Figure 24
The brightness of the polarized light decreases as the angle, θ, increases between the transmission axis of the second polarizer and the plane of polarization of the light.

Light can be polarized by reflection and scattering

When light is reflected at a certain angle from a surface, the reflected light is completely polarized parallel to the reflecting surface. If the surface is parallel to the ground, the light is polarized horizontally. This is the case with glaring light that reflects at a low angle from roads, bodies of water, and car hoods.

Quick Lab

Polarization of Sunlight

MATERIALS LIST

• a sheet of polarizing filter or sunglasses with polarizing lenses

SAFETY CAUTION

Never look directly at the sun.

During mid-morning or mid-afternoon, when the sun is well above the horizon but not directly overhead, look directly up at the sky through the polarizing filter. Note how the light's intensity is reduced.

Rotate the polarizer. Take note of which orientations of the polarizer make the sky darker and thus best reduce the amount of transmitted light.

Repeat the test with light from other parts of the sky. Test light reflected off a table near a window. Compare the results of these various experiments.

Because the light that causes glare is in most cases horizontally polarized, it can be filtered out by a polarizing substance whose transmission axis is oriented vertically. This is the case with polarizing sunglasses. As shown in **Figure 25,** the angle between the polarized reflected light and the transmission axis of the polarizer is 90°. Thus, none of the polarized light passes through.

In addition to reflection and absorption, scattering can also polarize light. Scattering, or the absorption and reradiation of light by particles in the atmosphere, causes sunlight to be polarized, as shown in **Figure 26.** When an unpolarized beam of sunlight strikes air molecules, the electrons in the molecules begin vibrating with the electric field of the incoming wave. A horizontally polarized wave is emitted by the electrons as a result of their horizontal motion, and a vertically polarized wave is emitted parallel to Earth as a result of their vertical motion. Thus, an observer with his or her back to the sun will see polarized light when looking up toward the sky.
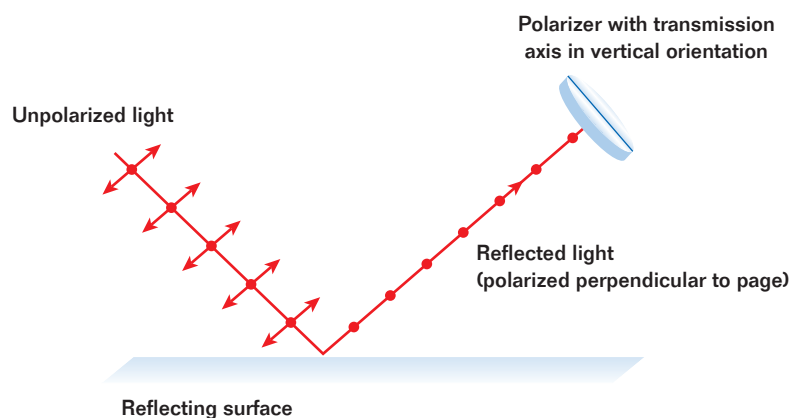
Figure 25
At a particular angle, reflected light is polarized horizontally. This light can be blocked by aligning the transmission axes of the sunglasses vertically.
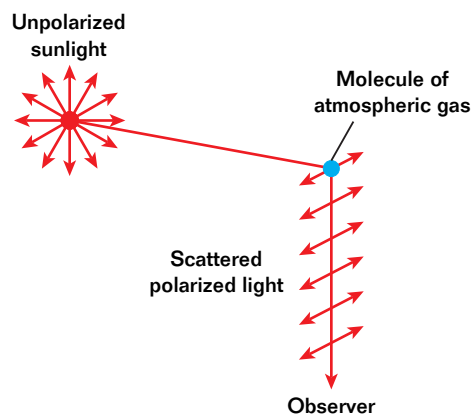
Figure 26
The sunlight scattered by air molecules is polarized for an observer on Earth's surface.

SECTION REVIEW

1. A lens for a spotlight is coated so that it does not transmit yellow light. If the light source is white, what color is the spotlight?

2. A house is painted with pigments that reflect red and blue light but absorb all other colors. What color does the house appear to be when it is illuminated by white light? What color does it appear to be under red light?

3. What primary pigments would an artist need to mix to obtain a pale yellow green color? What primary additive colors would a theater-lighting designer need to mix in order to produce the same color with light?

4. **Critical Thinking** The light reflected from the surface of a pool of water is observed through a polarizer. How can you tell if the reflected light is polarized?

KEY IDEAS

Section 1   Characteristics of Light
- Light is electromagnetic radiation that consists of oscillating electric and magnetic fields with different wavelengths.
- The frequency times the wavelength of electromagnetic radiation is equal to *c,* the speed of light.
- The brightness of light is inversely proportional to the square of the distance from the light source.

Section 2   Flat Mirrors
- Light obeys the law of reflection, which states that the incident and reflected angles of light are equal.
- Flat mirrors form virtual images that are the same distance from the mirror's surface as the object is.

Section 3   Curved Mirrors
- The mirror equation relates object distance, image distance, and focal length of a spherical mirror.
- The magnification equation relates image height or distance to object height or distance, respectively.

Section 4   Color and Polarization
- Light of different colors can be produced by adding light consisting of the primary additive colors (red, green, and blue).
- Pigments can be produced by combining subtractive colors (magenta, yellow, and cyan).
- Light can be linearly polarized by transmission, reflection, or scattering.

KEY TERMS

electromagnetic wave (p. 446)

reflection (p. 451)

angle of incidence (p. 452)

angle of reflection (p. 452)

virtual image (p. 453)

concave spherical mirror (p. 455)

real image (p. 456)

convex spherical mirror (p. 463)

linear polarization (p. 472)

PROBLEM SOLVING

See **Appendix D: Equations** for a summary of the equations introduced in this chapter. If you need more problem-solving practice, see **Appendix I: Additional Problems.**

Diagram Symbols

Light rays (real)	
Light rays (apparent)	
Normal lines	
Flat mirror	
Concave mirror	Convex mirror

Variable Symbols

Quantities		Units	
p	object distance	m	meters
q	image distance	m	meters
R	radius of curvature	m	meters
f	focal length	m	meters
M	magnification		(unitless)

CHARACTERISTICS OF LIGHT

Review Questions

1. Which band of the electromagnetic spectrum has
  a. the lowest frequency?
  b. the shortest wavelength?

2. Which of the following electromagnetic waves has the highest frequency?
  a. radio
  b. ultraviolet radiation
  c. blue light
  d. infrared radiation

3. Why can light be used to measure distances accurately? What must be known in order to make distance measurements?

4. For the diagram below, use Huygens' principle to show what the wave front at point *A* will look like at point *B*. How would you represent this wave front in the ray approximation?

Source   New wavefront
             position
A   B
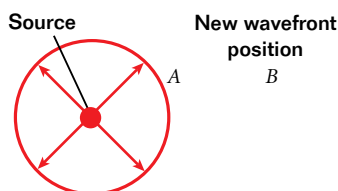
5. What is the relationship between the actual brightness of a light source and its apparent brightness from where you see it?

Conceptual Questions

6. Suppose an intelligent society capable of receiving and transmitting radio signals lives on a planet orbiting Procyon, a star 95 light-years away from Earth. If a signal were sent toward Procyon in 1999, what is the earliest year that Earth could expect to receive a return message? (Hint: A light-year is the distance a ray of light travels in one year.)

7. How fast do X rays travel in a vacuum?

8. Why do astronomers observing distant galaxies talk about looking backward in time?

9. Do the brightest stars that you see in the night sky necessarily give off more light than dimmer stars? Explain your answer.

Practice Problems

For problems 10–13, see Sample Problem A.

10. The compound eyes of bees and other insects are highly sensitive to light in the ultraviolet portion of the spectrum, particularly light with frequencies between 7.5×10^{14} Hz and 1.0×10^{15} Hz. To what wavelengths do these frequencies correspond?

11. The brightest light detected from the star Antares has a frequency of about 3×10^{14} Hz. What is the wavelength of this light?

12. What is the wavelength for an FM radio signal if the number on the dial reads 99.5 MHz?

13. What is the wavelength of a radar signal that has a frequency of 33 GHz?
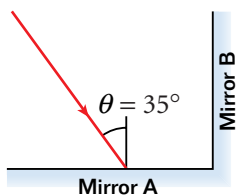
FLAT MIRRORS

Review Questions

14. For each of the objects listed below, identify whether light is reflected diffusely or specularly.
  a. a concrete driveway
  b. an undisturbed pond
  c. a polished silver tray
  d. a sheet of paper
  e. a mercury column in a thermometer

15. If you are stranded on an island, where would you align a mirror to use sunlight to signal a searching aircraft?

16. If you are standing 2 m in front of a flat mirror, how far behind the mirror is your image? What is the magnification of the image?

Conceptual Questions

17. When you shine a flashlight across a room, you see the beam of light on the wall. Why do you not see the light in the air?

18. How can an object be a specular reflector for some electromagnetic waves yet be diffuse for others?

19. A flat mirror that is 0.85 m tall is attached to a wall so that its upper edge is 1.7 m above the floor. Use the law of reflection and a ray diagram to determine if this mirror will show a person who is 1.7 m tall his or her complete reflection.

20. Two flat mirrors make an angle of 90.0° with each other, as diagrammed at right. An incoming ray makes an angle of 35° with the normal of mirror A. Use the law of reflection to determine the angle of reflection from mirror B. What is unusual about the incoming and reflected rays of light for this arrangement of mirrors?

$\theta = 35°$
Mirror A
Mirror B

21. If you walk 1.2 m/s toward a flat mirror, how fast does your image move with respect to the mirror? In what direction does your image move with respect to you?

22. Why do the images produced by two opposing flat mirrors appear to be progressively smaller?

CURVED MIRRORS

Review Questions

23. Which type of mirror should be used to project movie images on a large screen?

24. If an object is placed outside the focal length of a concave mirror, which type of image will be formed? Will it appear in front of or behind the mirror?

25. Can you use a convex mirror to burn a hole in paper by focusing light rays from the sun at the mirror's focal point?

26. A convex mirror forms an image from a real object. Can the image ever be larger than the object?

27. Why are parabolic mirrors preferred over spherical concave mirrors for use in reflecting telescopes?

Conceptual Questions

28. Where does a ray of light that is parallel to the principal axis of a concave mirror go after it is reflected at the mirror's surface?

29. What happens to the real image produced by a concave mirror if you move the original object to the location of the image?

30. Consider a concave spherical mirror and a real object. Is the image always inverted? Is the image always real? Give conditions for your answers.

31. Explain why enlarged images seem dimmer than the original objects.

32. What test could you perform to determine if an image is real or virtual?

33. You've been given a concave mirror that may or may not be parabolic. What test could you perform to determine whether it is parabolic?

Practice Problems

For problems 34–35, see Sample Problem B.

34. A concave shaving mirror has a radius of curvature of 25.0 cm. For each of the following cases, find the magnification, and determine whether the image formed is real or virtual and upright or inverted.
  a. an upright pencil placed 45.0 cm from the mirror
  b. an upright pencil placed 25.0 cm from the mirror
  c. an upright pencil placed 5.00 cm from the mirror

35. A concave spherical mirror can be used to project an image onto a sheet of paper, allowing the magnified image of an illuminated real object to be accurately traced. If you have a concave mirror with a focal length of 8.5 cm, where would you place a sheet of paper so that the image projected onto it is twice as far from the mirror as the object is? Is the image upright or inverted, real or virtual? What would the magnification of the image be?

For problem 36, see Sample Problem C.

36. A convex mirror with a radius of curvature of 45.0 cm forms a 1.70 cm tall image of a pencil at a distance of 15.8 cm behind the mirror. Calculate the object distance for the pencil and its height. Is the image real or virtual? What is the magnification? Is the image inverted or upright?

COLOR AND POLARIZATION

Review Questions

37. What are the three primary additive colors? What happens when you mix them?

38. What are the three primary subtractive colors (or primary pigments)? What happens when you mix them?

39. Explain why a polarizing disk used to analyze light can block light from a beam that has been passed through another polarizer. What is the relative orientation of the two polarizing disks?

Conceptual Questions

40. Explain what could happen when you mix the following:
   a. cyan and yellow pigment
   b. blue and yellow light
   c. pure blue and pure yellow pigment
   d. green and red light
   e. green and blue light

41. What color would an opaque magenta shirt appear to be under the following colors of light?
   a. white   **d.** green
   b. red   **e.** yellow
   c. cyan

42. A substance is known to reflect green and blue light. What color would it appear to be when it is illuminated by white light? by blue light?

43. How can you tell if a pair of sunglasses has polarizing lenses?

44. Why would sunglasses with polarizing lenses remove the glare from your view of the hood of your car or a distant body of water but not from a tall metal tank used for storing liquids?
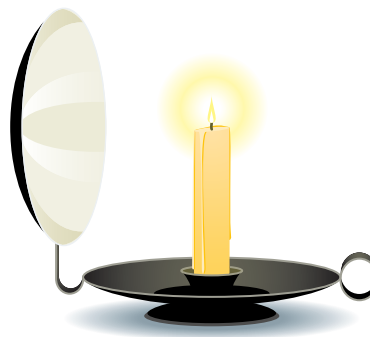
45. Is light from the sky polarized? Why do clouds seen through polarizing glasses stand out in bold contrast to the sky?

MIXED REVIEW

46. The real image of a tree is magnified −0.085 times by a telescope's primary mirror. If the tree's image forms 35 cm in front of the mirror, what is the distance between the mirror and the tree? What is the focal length of the mirror? What is the value for the mirror's radius of curvature? Is the image virtual or real? Is the image inverted or upright?

47. A candlestick holder has a concave reflector behind the candle, as shown below. The reflector magnifies a candle −0.75 times and forms an image 4.6 cm away from the reflector's surface. Is the image inverted or upright? What are the object distance and the reflector's focal length? Is the image virtual or real?


48. A child holds a candy bar 15.5 cm in front of the convex side-view mirror of an automobile. The image height is reduced by one-half. What is the radius of curvature of the mirror?

49. A glowing electric light bulb placed 15 cm from a concave spherical mirror produces a real image 8.5 cm from the mirror. If the light bulb is moved to a position 25 cm from the mirror, what is the position of the image? Is the final image real or virtual? What are the magnifications of the first and final images? Are the two images inverted or upright?

50. A convex mirror is placed on the ceiling at the intersection of two hallways. If a person stands directly underneath the mirror, the person's shoe is a distance of 195 cm from the mirror. The mirror forms an image of the shoe that appears 12.8 cm behind the mirror's surface. What is the mirror's focal length? What is the magnification of the image? Is the image real or virtual? Is the image upright or inverted?

51. The side-view mirror of an automobile has a radius of curvature of 11.3 cm. The mirror produces a virtual image one-third the size of the object. How far is the object from the mirror?

52. An object is placed 10.0 cm in front of a mirror. What type must the mirror be to form an image of the object on a wall 2.00 m away from the mirror? What is the magnification of the image? Is the image real or virtual? Is the image inverted or upright?

53. The reflecting surfaces of two intersecting flat mirrors are at an angle of θ $(0° < \theta < 90°)$, as shown in the figure below. A light ray strikes the horizontal mirror. Use the law of reflection to show that the emerging ray will intersect the incident ray at an angle of $\phi = 180° - 2\theta$.
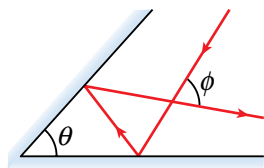
54. Show that if a flat mirror is assumed to have an "infinite" radius of curvature, the mirror equation reduces to $q = -p$.

55. A real object is placed at the zero end of a meterstick. A large concave mirror at the 100.0 cm end of the meterstick forms an image of the object at the 70.0 cm position. A small convex mirror placed at the 20.0 cm position forms a final image at the 10.0 cm point. What is the radius of curvature of the convex mirror? (Hint: The first image created by the concave mirror acts as an object for the convex mirror.)

56. A dedicated sports-car enthusiast polishes the inside and outside surfaces of a hubcap that is a section of a sphere. When he looks into one side of the hubcap, he sees an image of his face 30.0 cm behind the hubcap. He then turns the hubcap over and sees another image of his face 10.0 cm behind the hubcap.

  a. How far is his face from the hubcap?
  b. What is the radius of curvature of the hubcap?
  c. What is the magnification for each image?
  d. Are the images real or virtual?
  e. Are the images upright or inverted?

57. An object 2.70 cm tall is placed 12.0 cm in front of a mirror. What type of mirror and what radius of curvature are needed to create an upright image that is 5.40 cm in height? What is the magnification of the image? Is the image real or virtual?

58. A "floating coin" illusion consists of two parabolic mirrors, each with a focal length of 7.5 cm, facing each other so that their centers are 7.5 cm apart (see the figure below). If a few coins are placed on the lower mirror, an image of the coins forms in the small opening at the center of the top mirror. Use the mirror equation, and draw a ray diagram to show that the final image forms at that location. Show that the magnification is 1 and that the image is real and upright. (Note: A flashlight beam shined on these images has a very startling effect. Even at a glancing angle, the incoming light beam is seemingly reflected off the images of the coins. Do you understand why?)
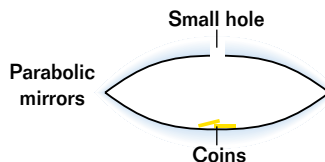
59. Use the mirror equation and the equation for magnification to prove that the image of a real object formed by a convex mirror is always upright, virtual, and smaller than the object. Use the same equations to prove that the image of a real object placed in front of any spherical mirror is always virtual and upright when $p < |f|$.

60. Use trigonometry to derive the mirror and magnification equations. (Hint: Note that the incoming ray between the object and the mirror forms the hypotenuse of a right triangle. The reflected ray between the image point and the mirror is also the hypotenuse of a right triangle.)

Alternative Assessment

1. Suntan lotions include compounds that absorb the ultraviolet radiation in sunlight and therefore prevent the ultraviolet radiation from damaging skin cells. Design experiments to test the properties of varying grades (SPFs) of suntan lotions. Plan to use blueprint paper, film, plants, or other light-sensitive items. Write down the questions that will guide your inquiry, the materials you will need, the procedures you plan to follow, and the measurements you will take. If your teacher approves your plan, perform the experiments and report or demonstrate your findings in class.

2. The Egyptian scholar Alhazen studied lenses, mirrors, rainbows, and other light phenomena early in the Middle Ages. Research his scholarly work, his life, and his relationship with the Caliph al-Hakim. How advanced were Alhazen's inventions and theories? Summarize your findings and report them to the class.

3. Work in cooperative groups to explore the use of corner and ceiling mirrors as low-tech surveillance devices. Make a floor plan of an existing store, or devise a floor plan for an imaginary one. Determine how much of the store could be monitored by a clerk if flat mirrors were placed in the corners. If you could use curved mirrors in such a system, would you use concave or convex mirrors? Where would you place them? Identify which parts of the store could be observed with the curved mirrors in place. Note any disadvantages that your choice of mirrors may have.

4. Research the characteristics, effects, and applications of a specific type of electromagnetic wave in the spectrum. Find information about the range of wavelengths, frequencies, and energies; natural and artificial sources of the waves; and the methods used to detect them. Find out how they were discovered and how they affect matter. Learn about any dangers associated with them and about their uses in technology. Work together with others in the class who are researching other parts of the spectrum to build a group presentation, brochure, chart, or Web page that covers the entire spectrum.

5. The Chinese astronomer Chang Heng (78–139 CE) recognized that moonlight was a reflection of sunlight. He applied this theory to explain lunar eclipses. Make diagrams showing how Heng might have represented the moon's illumination and the path of light when the Earth, moon, and sun were in various positions on ordinary nights and on nights when there were lunar eclipses. Find out more about Heng's other scientific work, and report your findings to the class.

6. Explore how many images are produced when you stand between two flat mirrors whose reflecting surfaces face each other. What are the locations of the images? Are they identical? Investigate these questions with diagrams and calculations. Then test your calculated results with parallel mirrors, perpendicular mirrors, and mirrors at angles in between. Which angles produce one, two, three, five, and seven images? Summarize your results with a chart, diagram, or computer presentation.

Graphing Calculator Practice

Mirrors

Mirrors produce many types of images: virtual or real, enlarged or reduced, and upright or inverted. The mirror equation and the magnification equation can help sort things out. The mirror equation relates the object distance (p), image distance (q), and focal length (f) to one another.

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$

Image size can be determined from the magnification equation.

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

Magnification values that are greater than 1 or less than −1 indicate that the image of an object is larger than the object itself. Negative magnification values indicate that an image is real and inverted, while positive magnification values indicate that an image is virtual and upright.

In this graphing calculator activity, the calculator will produce a table of image distance and magnification for various object distances for a mirror with a known focal length. You will use this table to determine the characteristics of the images produced by a variety of mirrors and object distances.

Visit go.hrw.com and enter the keyword **HF6LGTX** to find this graphing calculator activity. Refer to **Appendix B** for instructions on downloading the program for this activity.

MULTIPLE CHOICE

1. Which equation is correct for calculating the focal point of a spherical mirror?
   A. $1/f = 1/p - 1/q$
   B. $1/f = 1/p + 1/q$
   C. $1/p = 1/f + 1/q$
   D. $1/q = 1/f + 1/p$

2. Which of the following statements is true about the speeds of gamma rays and radio waves in a vacuum?
   F. Gamma rays travel faster than radio waves.
   G. Radio rays travel faster than gamma rays.
   H. Gamma rays and radio waves travel at the same speed in a vacuum.
   J. The speed of gamma rays and radio waves in a vacuum depends on their frequencies.

3. Which of the following correctly states the law of reflection?
   A. The angle between an incident ray of light and the normal to the mirror's surface equals the angle between the mirror's surface and the reflected light ray.
   B. The angle between an incident ray of light and the mirror's surface equals the angle between the normal to the mirror's surface and the reflected light ray.
   C. The angle between an incident ray of light and the normal to the mirror's surface equals the angle between the normal and the reflected light ray.
   D. The angle between an incident ray of light and the normal to the mirror's surface is complementary to the angle between the normal and the reflected light ray.

4. Which of the following processes does not linearly polarize light?
   F. scattering
   G. transmission
   H. refraction
   J. reflection

Use the ray diagram below to answer questions 5–7.

$p = 15.0$ cm $q = -6.00$ cm
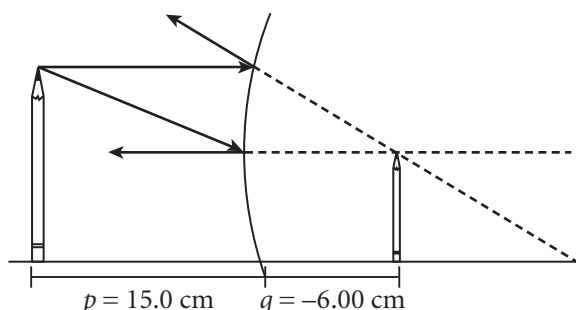
5. Which kind of mirror is shown in the ray diagram?
   A. flat
   B. convex
   C. concave
   D. Not enough information is available to draw a conclusion.

6. What is true of the image formed by the mirror?
   F. virtual, upright, and diminished
   G. real, inverted, and diminished
   H. virtual, upright, and enlarged
   J. real, inverted, and enlarged

7. What is the focal length of the mirror?
   A. −10.0 cm
   B. −4.30 cm
   C. 4.30 cm
   D. 10.0 cm

8. Which combination of primary additive colors will produce magenta-colored light?
   F. green and blue
   G. red and blue
   H. green and red
   J. cyan and yellow

9. What is the frequency of an infrared wave that has a vacuum wavelength of 5.5 μm?

A. 165 Hz
B. 5.5×10^{10} Hz
**C.** 5.5×10^{13} Hz
D. 5.5×10^{16} Hz

10. If the distance from a light source is increased by a factor of 5, by how many times brighter does the light appear?

F. 25
G. 5
H. 1/5
J. 1/25

SHORT RESPONSE

11. White light is passed through a filter that allows only yellow, green, and blue light to pass through it. This light is then shone on a piece of blue fabric and on a piece of red fabric. Which colors do the two pieces of fabric appear to have under this light?

12. The clothing department of a store has a mirror that consists of three flat mirrors, each arranged so that a person standing before the mirrors can see how an article of clothing looks from the side and back. Suppose a ray from a flashlight is shined on the mirror on the left. If the incident ray makes an angle of 65° with respect to the normal to the mirror's surface, what will be the angle θ of the ray reflected from the mirror on the right?
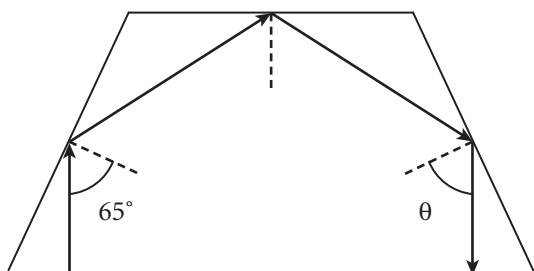
13. X rays emitted from material around compact massive stars, such as neutron stars or black holes, serve to help locate and identify such objects. What would be the wavelength of the X rays emitted from material around such an object if the X rays have a frequency of 5.0×10^{19} Hz?

EXTENDED RESPONSE

14. Explain how you can use a piece of polarizing plastic to determine if light is linearly polarized.

Use the ray diagram below to answer questions 15–19.

A candle is placed 30.0 cm from the reflecting surface of a concave mirror. The radius of curvature of the mirror is 20.0 cm.
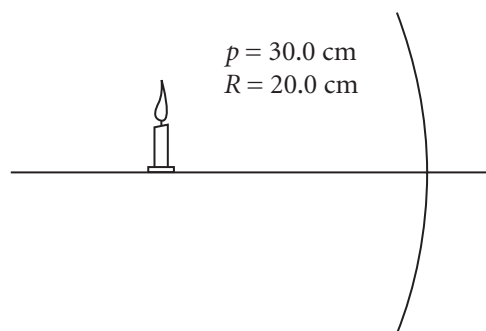
15. What is the distance between the surface of the mirror and the image?

16. What is the focal length of the mirror?

17. What is the magnification of the image?

18. If the candle is 12 cm tall, what is the image height?

19. Is the image real or virtual? Is it upright or inverted?

$p = 30.0$ cm
$R = 20.0$ cm

Test TIP Double-check the signs of all values to be used in the mirror and magnification equations.

Skills Practice Lab | Brightness of Light

OBJECTIVES

- **Determine** the relationship between the intensity of the light emitted by a light source and the distance from the source.
- **Explore** the inverse square law in terms of the intensity of light.

MATERIALS LIST

- black aperture tube for light meter
- black paper aperture stop for light meter
- black tube to cover bulb and socket
- black paper square
- clamp for support stand
- light meter
- meterstick
- meterstick-mounted bulb socket
- meterstick supports
- power supply
- small, clear incandescent bulb
- support stand
- masking tape

The measured brightness of a light depends on the distance between the light meter and the light source. In this lab, you will use a light meter to measure the intensity of light at different distances from a light source in order to investigate the relationship between the distance and the brightness of a light source.

SAFETY

- Use a hot mitt to handle resistors, light sources, and other equipment that may be hot. Allow all equipment to cool before storing it.
- If a bulb breaks, notify your teacher immediately. Do not remove broken bulbs from sockets.
- Never put broken glass in a regular waste container. Use a dustpan, brush, and heavy gloves to carefully pick up broken pieces, and dispose of them in a container specifically provided for this purpose.
- Avoid looking directly at a light source. Looking directly at a light source may cause permanent eye damage. Put on goggles.

PROCEDURE

Preparation

1. If you are not using a datasheet provided by your teacher, prepare a data table in your lab notebook with two columns and nine rows. In the first row, label the columns *Distance (m)* and *Intensity*. In the first column of your data table, label the second through ninth rows *0.20, 0.25, 0.30, 0.35, 0.40, 0.50, 0.75,* and *1.00*.

Brightness of Light

2. Set up the meterstick, meterstick supports, light source (bulb and socket), power supply, and light meter with aperture as shown in **Figure 1.** Carefully screw the bulb into the socket. Tape the meterstick and supports to the lab table. Set the 0.00 m mark on the meterstick directly below the face of the light meter as shown.

3. Set the bulb socket 0.20 m away from the light meter. Align the clamp and the aperture of the meter so that the aperture is level, parallel to the meterstick, and at the same height as the hole in the tube covering the bulb. Adjust the bulb socket to the 0.20 m mark on the meterstick.
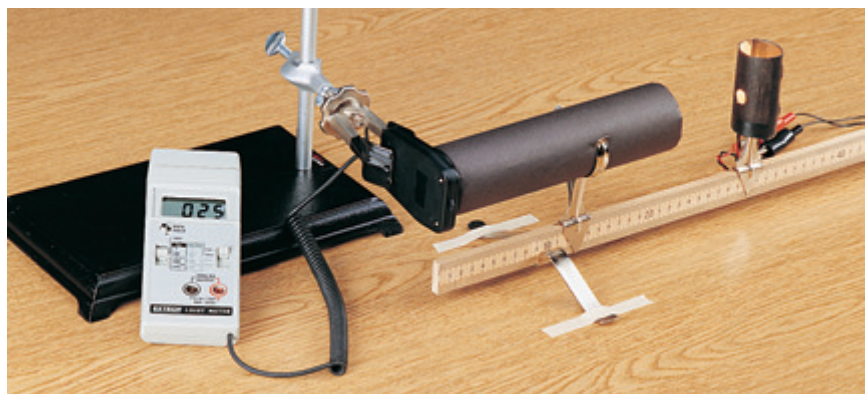
4. Carefully connect the power supply to the wires from the light socket, and adjust the power supply to 5.0 V. ***Do not plug in the power supply until your teacher has approved your setup.*** When your teacher has approved your setup, carefully plug the power supply into the wall outlet to light the lamp.

5. Use the light meter to read the intensity. Select the "fast" mode, and use the "data hold" option if the intensity values continually fluctuate. Record the intensity value for that distance in your data table.

6. Repeat this procedure for all other bulb distances recorded in your data table.

7. After the last trial turn off the light source. Cover the opening of the phototube with the piece of black paper. Draw a line above or below your data table, and label it *Background.* Use this space to record the intensity reading of the light meter without the bulb illuminated.

8. Clean up your work area. Put equipment away as directed by your teacher.

ANALYSIS

1. **Organizing Data**   For each trial, find the real value of the measured light intensity by subtracting the background from the measured value.

2. **Constructing Graphs**   Make a graph of the intensity plotted against the distance. Use a graphing calculator, computer, or graph paper.

3. **Organizing Data**   For each trial, calculate $1/(Distance^2)$. This value represents the inverse of the distance squared.

4. **Constructing Graphs**   Make a graph of the intensity plotted against the inverse of the distance squared.

CONCLUSIONS

5. **Analyzing**   Based on your graphs, what is the relationship between the intensity of the light and the distance from the light source? Explain how your graphs support your answer.