Chapter 18

Refraction and Lenses

What You'll Learn

- You will learn how light changes direction and speed when it travels through different materials.
- You will compare properties of lenses and the images that they form.
- You will learn about different applications of lenses, including how lenses in your eyes enable you to see.

Why It's Important

Some light travels in a straight path from objects to your eyes. Some light is reflected before it reaches you. Other light follows a path that appears to be bent.

Wavy Trees If you swim underwater, you will notice that things underwater look normal, but objects above the surface of the water appear to be distorted by the waves on the surface.

Think About This ▶

What causes the images of the trees to be wavy?

Physics Online

physicspp.com

Ric Frazier/Masterfile

LAUNCH Lab What does a straw in a liquid look like from the side view?

Question
Does a straw look different when observed through water, oil, and corn syrup?

Procedure

1. Fill one 400-mL beaker with water.
2. Fill a second 400-mL beaker halfway with corn syrup and the rest with water (pour slowly as to avoid mixing the two liquids).
3. Fill a third 400-mL beaker halfway with water and the rest with cooking oil (pour slowly as to avoid mixing the two liquids).
4. Place a straw gently in each beaker and lean it on the spout.
5. Observe each straw through the side of the beaker as you slowly turn the beaker.
6. Make a data table to record descriptions of the straws' appearance in each solution.

Analysis
In which containers does the straw appear to be broken? Are all amounts of break the same? When does the straw not appear to be broken? Explain.

Critical Thinking Form a hypothesis as to when a solid object appears to be broken and when it does not. Be sure to include an explanation of the amount of break.

18.1 Refraction of Light

Looking at the surface of a swimming pool on a summer day, you can see sunlight reflecting off the water. You can see objects that are in the pool because some of the sunlight travels into the water and reflects off the objects. When you look closely at objects in the water, however, you will notice that they look distorted. For example, things beneath the surface look closer than normal, the feet of a person standing still in the pool appear to move back and forth, and lines along the bottom of the pool seem to sway with the movement of the water. These effects occur because light changes direction as it passes from water to air.

As you learned in Chapter 16, the path of light is bent as it crosses the boundary between two media due to refraction. The amount of refraction depends on properties of the two media and on the angle at which the light strikes the boundary. As waves travel along the surface of the water, the boundary between the air and water moves up and down, and tilts back and forth. The path of light leaving the water shifts as the boundary moves, causing objects under the surface to appear to waver.

Objectives

- **Solve** problems involving refraction.
- **Explain** total internal reflection.
- **Explain** some optical effects caused by refraction.

Vocabulary

index of refraction
Snell's law of refraction
critical angle
total internal reflection
dispersion

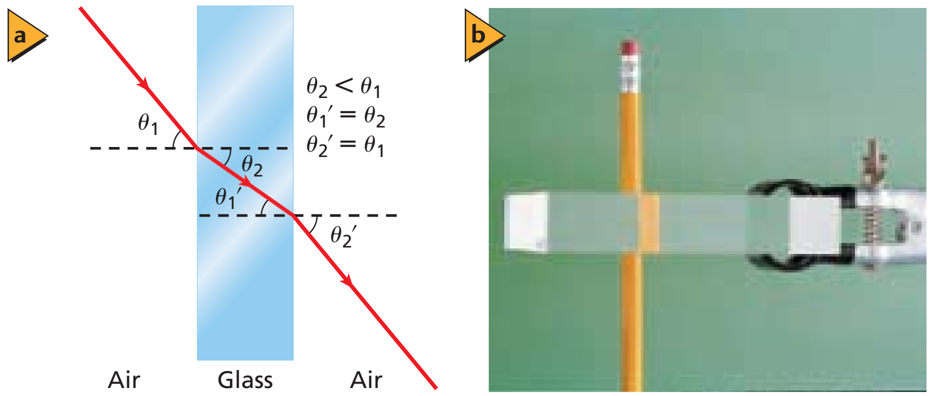


Figure 18-1 Light bends toward the normal as it moves from air to glass and bends away from the normal as it moves from glass to air **(a).** The bending of light makes objects appear to be shifted from their actual locations **(b).**

Snell's Law of Refraction

What happens when you shine a narrow beam of light at the surface of a piece of glass? As you can see in **Figure 18-1,** it bends as it crosses the boundary from air to glass. The bending of light, called refraction, was first studied by René Descartes and Willebrord Snell around the time of Kepler and Galileo.

To discuss the results of Descartes and Snell, you have to define two angles. The angle of incidence, θ_1, is the angle at which the light ray strikes the surface. It is measured from the normal to the surface. The angle of refraction, θ_2, is the angle at which the transmitted light leaves the surface. It also is measured with respect to the normal. In 1621, Snell found that when light passed from air into a transparent substance, the sines of the angles were related by the equation $\sin \theta_1 / \sin \theta_2 = n$. Here n is a constant that depends on the substance, not on the angles, and is called the **index of refraction.** The indices of refraction for some substances are listed in **Table 18-1.** The relationship found by Snell is valid when light goes across a boundary between any two materials. This more general equation is known as **Snell's law of refraction.**

Color Convention

- Refracting media and lenses are light blue.

Snell's Law of Refraction $n_1 \sin \theta_1 = n_2 \sin \theta_2$

The product of the index of refraction of the first medium and the sine of the angle of incidence is equal to the product of the index of refraction of the second medium and the sine of the angle of refraction.

Table 18-1
Indices of Refraction for Yellow Light (λ = 589 nm in vacuum)

Medium	n
Vacuum	1.00
Air	1.0003
Water	1.33
Ethanol	1.36
Crown glass	1.52
Quartz	1.54
Flint glass	1.62
Diamond	2.42

Figure 18-1 shows how Snell's law applies when light travels through a piece of glass with parallel surfaces, such as a windowpane. The light is refracted both when it enters the glass and again when it leaves the glass. When light goes from air to glass it moves from material with a lower index of refraction to one with a higher index of refraction. That is, $n_1 < n_2$. To keep the two sides of the equation equal, one must have $\sin \theta_1 > \sin \theta_2$. The light beam is bent toward the normal to the surface.

When light travels from glass to air it moves from material having a higher index of refraction to one with a lower index. In this case, $n_1 > n_2$. To keep the two sides of the equation equal one must have $\sin \theta_1' < \sin \theta_2'$. That is, the light is bent away from the normal. Note that the direction of the ray when it leaves the glass is the same as it was before it struck the glass, but it is shifted from its original position.

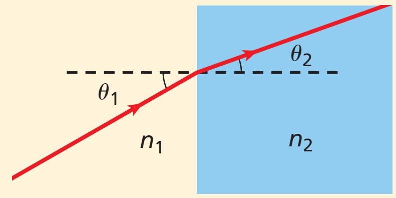
Horizons Companies

EXAMPLE Problem 1

Angle of Refraction A light beam in air hits a sheet of crown glass at an angle of 30.0°. At what angle is the light beam refracted?

1 Analyze and Sketch the Problem

- Make a sketch of the air and crown glass boundary.
- Draw a ray diagram.



Known:	**Unknown:**
$\theta_1 = 30.0°$	$\theta_2 = ?$
$n_1 = 1.00$	
$n_2 = 1.52$	

2 Solve for the Unknown

Use Snell's law to solve for the sine of the angle of refraction.

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

$$\sin \theta_2 = \left(\frac{n_1}{n_2}\right) \sin \theta_1$$

$$\theta_2 = \sin^{-1}\left(\left(\frac{n_1}{n_2}\right) \sin \theta_1\right)$$

$$= \sin^{-1}\left(\left(\frac{1.00}{1.52}\right) \sin 30.0°\right)$$

Substitute n_1 = 1.00, n_2 = 1.52, θ_1 = 30.0°

$$= 19.2°$$

Physics Online

Personal Tutor For an online tutorial on the angle of refraction, visit physicspp.com.

3 Evaluate the Answer

- **Are the units correct?** Angles are expressed in degrees.
- **Is the magnitude realistic?** The index of refraction, n_2, is greater than the index of refraction, n_1. Therefore, the angle of refraction, θ_2, must be less than the angle of incidence, θ_1.

PRACTICE Problems

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

1. A laser beam in air is incident upon ethanol at an angle of incidence of 37.0°. What is the angle of refraction?
2. Light in air is incident upon a piece of crown glass at an angle of incidence of 45.0°. What is the angle of refraction?
3. Light passes from air into water at 30.0° to the normal. Find the angle of refraction.
4. Light in air is incident upon a diamond facet at 45.0°. What is the angle of refraction?
5. A block of unknown material is submerged in water. Light in the water is incident on the block at an angle of incidence of 31°. The angle of refraction of the light in the block is 27°. What is the index of refraction of the material of the block?

Refraction is responsible for the Moon appearing red during a lunar eclipse. A lunar eclipse occurs when Earth blocks sunlight from the Moon. As a result, you might expect the Moon to be completely dark. Instead, light refracts through Earth's atmosphere and bends around Earth toward the Moon. Recall that Earth's atmosphere scatters most of the blue and green light. Thus, mostly red light illuminates the Moon. Because the Moon reflects most colors of light equally well, it reflects the red light back to Earth, and therefore the Moon appears to be red.

Astronomy Connection

Wave Model of Refraction

The wave model of light was developed almost 200 years after Snell published his research. An understanding that light interacts with atoms when traveling through a medium, such that it moves more slowly than in a vacuum, was achieved three hundred years after Snell's work. The wave relationship that you learned in Chapter 16 for light traveling through a vacuum, $\lambda_0 = c/f$, can be rewritten as $\lambda = v/f$, where v is the speed of light in any medium and λ is the wavelength. The frequency of light, f, does not change when it crosses a boundary. That is, the number of oscillations per second that arrive at a boundary is the same as the number that leave the boundary and transmit through the refracting medium. So, the wavelength of light, λ, must decrease when light slows down. Wavelength in a medium is shorter than wavelength in a vacuum.

What happens when light travels from a region with a high speed into one with a low speed, as shown in **Figure 18-2a?** The diagram in **Figure 18-2b** shows a beam of light as being made up of a series of parallel, straight wave fronts. Each wave front represents the crest of a wave and is perpendicular to the direction of the beam. The beam strikes the surface at an angle, θ_1. Consider the triangle PQR. Because the wave fronts are perpendicular to the direction of the beam, $\angle$PQR is a right angle and $\angle$QRP is equal to θ_1. Therefore, $\sin\theta_1$ is equal to the distance between P and Q divided by the distance between P and R.

$$\sin\theta_1 = \frac{\overline{PQ}}{\overline{PR}}$$

The angle of refraction, θ_2, can be related in a similar way to the triangle PSR. In this case

$$\sin\theta_2 = \frac{\overline{RS}}{\overline{PR}}$$

By taking the ratio of the sines of the two angles, $\overline{PR}$ is canceled, leaving the following equation:

$$\frac{\sin\theta_2}{\sin\theta_1} = \frac{\overline{RS}}{\overline{PQ}}$$

Figure 18-2b is drawn such that the distance between P and Q is equal to the length of three wavelengths of light in medium 1, or $\overline{PQ} = 3\lambda_1$. In a similar way, $\overline{RS} = 3\lambda_2$. Substituting these two values into the previous equation and canceling the common factor of 3 provides an equation that relates the angles of incidence and refraction with the wavelength of the light in each medium.

$$\frac{\sin\theta_2}{\sin\theta_1} = \frac{3\lambda_2}{3\lambda_1} = \frac{\lambda_2}{\lambda_1}$$

Using $\lambda = v/f$ in the above equation and canceling the common factor of f, the equation is rewritten as follows:

$$\frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1}$$

Snell's law also can be written as a ratio of the sines of the angles of incidence and refraction.

$$\frac{\sin\theta_2}{\sin\theta_1} = \frac{n_1}{n_2}$$

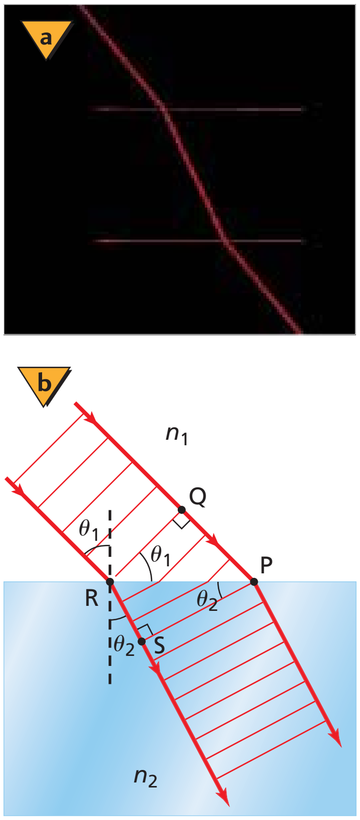


Figure 18-2 Light moves from air to glass to air again **(a).** Light slows down and bends toward the normal when it enters a region of a higher index of refraction **(b).**

CLICK HERE

Index of refraction Using the transitive property of equality, the previous two equations lead to the following equation:

$$\frac{n_1}{n_2} = \frac{v_2}{v_1}$$

In a vacuum, $n = 1$ and $v = c$. If either medium is a vacuum, then the equation is simplified to an equation that relates the index of refraction to the speed of light in a medium.

Index of Refraction $n = \frac{c}{v}$

The index of refraction of a medium is equal to the speed of light in a vacuum divided by the speed of light in the medium.

This definition of the index of refraction can be used to find the wavelength of light in a medium compared to the wavelength the light would have in a vacuum. In a medium with an index of refraction n the speed of light is given by $v = c/n$. The wavelength of the light in a vacuum is $\lambda_0 = c/f$. Solve for frequency, and substitute $f = c/\lambda_0$ and $v = c/n$ into $\lambda = v/f$. $\lambda = (c/n)/(c/\lambda_0) = \lambda_0/n$, and thus the wavelength of light in a medium is smaller than the wavelength in a vacuum.

Total Internal Reflection

The angle of refraction is larger than the angle of incidence when light passes into a medium of a lower index of refraction, as shown in **Figure 18-3a.** This leads to an interesting phenomenon. As the angle of incidence increases, the angle of refraction increases. At a certain angle of incidence known as the **critical angle,** θ_c, the refracted light ray lies along the boundary of the two media, as shown in **Figure 18-3b.**

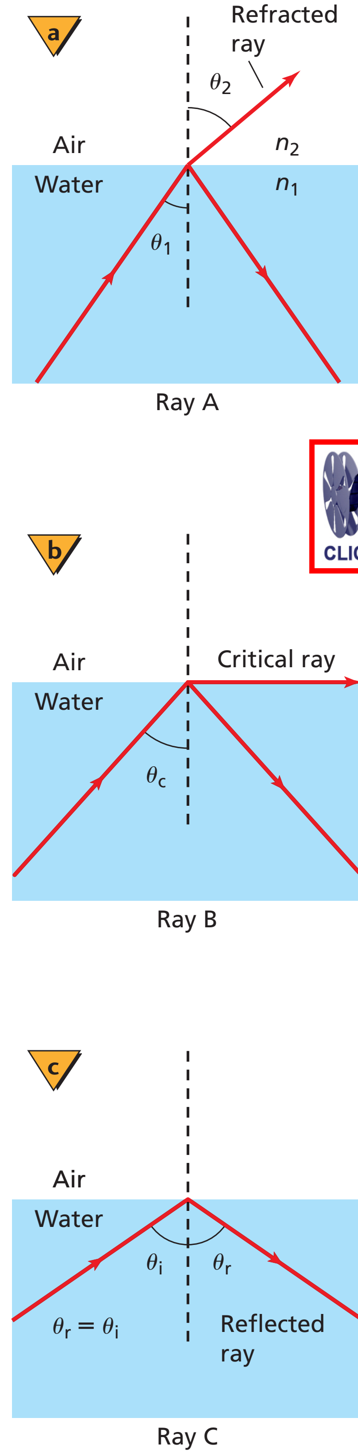
Recall from Chapter 16 that when light strikes a transparent boundary, even though much of the light is transmitted, some is reflected. **Total internal reflection** occurs when light traveling from a region of a higher index of refraction to a region of a lower index of refraction strikes the boundary at an angle greater than the critical angle such that all light reflects back into the region of the higher index of refraction, as shown in **Figure 18-3c.** To construct an equation for the critical angle of any boundary, you can use Snell's law and substitute $\theta_1 = \theta_c$ and $\theta_2 = 90.0°$.

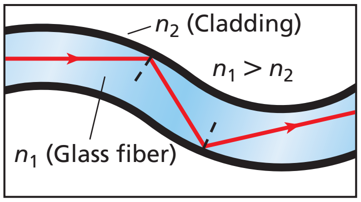
Critical Angle for Total Internal Reflection $\sin \theta_c = \frac{n_2}{n_1}$

The sine of the critical angle is equal to the index of refraction of the refracting medium divided by the index of refraction of the incident medium.

Total internal reflection causes some curious effects. Suppose that you are looking up at the surface from underwater in a calm pool. You might see an upside-down reflection of another nearby object that also is underwater or a reflection of the bottom of the pool itself. The surface of the water acts like a mirror. Likewise, when you are standing on the side of a pool, it is possible for things below the surface of the water to not be visible to you. When a swimmer is underwater, near the surface, and on the opposite side of the pool from you, you might not see him or her. This is because the light from his or her body is reflected.

■ **Figure 18-3** Ray A is partially refracted and partially reflected **(a).** Ray B is refracted along the boundary of the medium and forms the critical angle **(b).** An angle of incidence greater than the critical angle results in the total internal reflection of Ray C, which follows the law of reflection **(c).**





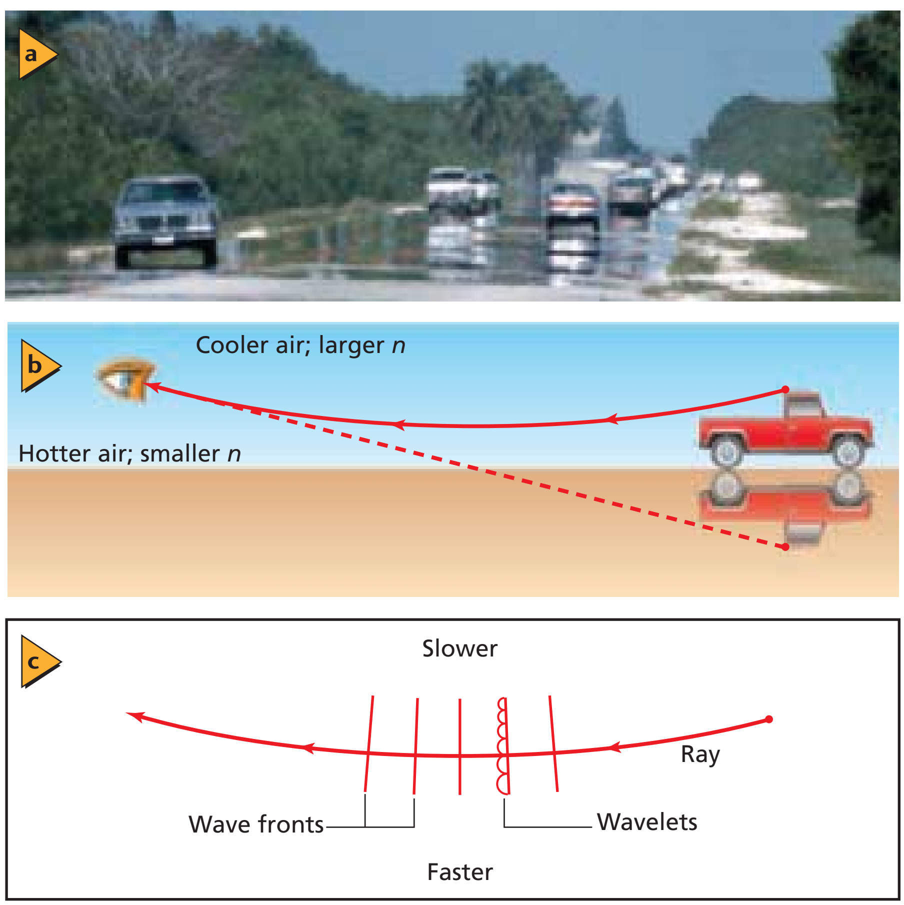
■ **Figure 18-4** Light impulses from a source enter one end of the optical fiber. Each time the light strikes the surface, the angle of incidence is larger than the critical angle, and, therefore, the light is kept within the fiber.

Optical fibers are an important technical application of total internal reflection. As shown in **Figure 18-4,** the light traveling through the transparent fiber always hits the internal boundary of the optical fiber at an angle greater than the critical angle, so all of the light is reflected and none of the light is transmitted through the boundary. Thus, the light maintains its intensity over the distance of the fiber.

Mirages

On a hot summer day, you sometimes can see the mirage effect shown in **Figure 18-5a.** As you drive down a road, you see what appears to be the reflection of an oncoming car in a pool of water. The pool, however, disappears as you approach it. The mirage is the result of the Sun heating the road. The hot road heats the air above it and produces a thermal layering of air that causes light traveling toward the road to gradually bend upward. This makes the light appear to be coming from a reflection in a pool, as shown in **Figure 18-5b.**

Figure 18-5c shows how this occurs. As light from a distant object travels downward toward the road, the index of refraction of the air decreases as the air gets hotter, but the temperature change is gradual. Recall from Chapter 16 that light wave fronts are comprised of Huygens' wavelets. In the case of a mirage, the Huygens' wavelets closer to the ground travel faster than those higher up, causing the wave fronts to gradually turn upward. A similar phenomenon, called a superior mirage, occurs when a reflection of a distant boat appears above the boat. The water keeps the air that is closer to its surface cooler.



■ **Figure 18-5** A mirage is seen on the surface of a road **(a).** Light from the car bends upward into the eye of the observer **(b).** The bottom of the wave front moves faster than the top **(c).**

John M. Dunay IV/Fundamental Photographs

Dispersion of Light

The speed of light in a medium is determined by interactions between the light and the atoms that make up the medium. Recall from Chapters 12 and 13 that temperature and pressure are related to the energy of particles on the atomic level. The speed of light, and therefore, the index of refraction for a gaseous medium, can change slightly with temperature. In addition, the speed of light and the index of refraction vary for different wavelengths of light in the same liquid or solid medium.

You learned in Chapter 16 that white light separates into a spectrum of colors when it passes through a glass prism, as shown in **Figure 18-6a.** This phenomenon is called **dispersion.** If you look carefully at the light that passes through a prism, you will notice that violet is refracted more than red, as shown in **Figure 18-6b.** This occurs because the speed of violet light through glass is less than the speed of red light through glass. Violet light has a higher frequency than red light, which causes it to interact differently with the atoms of the glass. This results in glass having a slightly higher index of refraction for violet light than it has for red light.

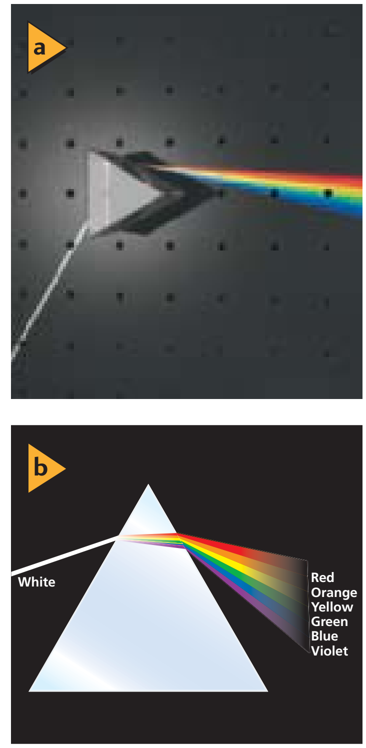


Figure 18-6 White light directed through a prism is dispersed into bands of different colors **(a).** Different colors of light bend different amounts when they enter a medium **(b).**

CLICK HERE

Rainbows A prism is not the only means of dispersing light. A rainbow is a spectrum formed when sunlight is dispersed by water droplets in the atmosphere. Sunlight that falls on a water droplet is refracted. Because of dispersion, each color is refracted at a slightly different angle, as shown in **Figure 18-7a.** At the back surface of the droplet, some of the light undergoes internal reflection. On the way out of the droplet, the light once again is refracted and dispersed.

Although each droplet produces a complete spectrum, an observer positioned between the Sun and the rain will see only a certain wavelength of light from each droplet. The wavelength depends on the relative positions of the Sun, the droplet, and the observer, as shown in **Figure 18-7b.** Because there are many droplets in the sky, a complete spectrum is visible. The droplets reflecting red light make an angle of 42° in relation to the direction of the Sun's rays; the droplets reflecting blue light make an angle of 40°.

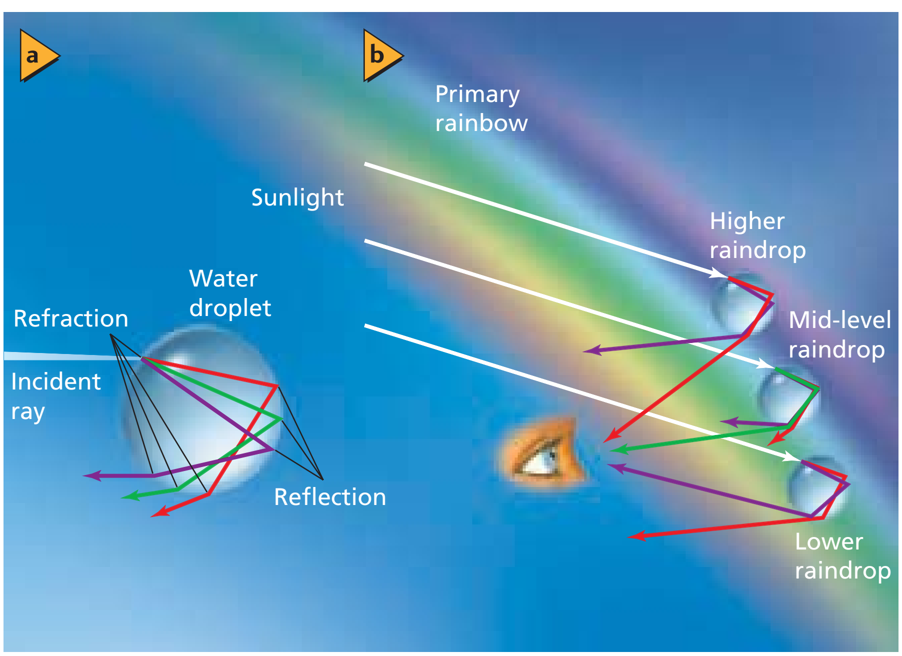


Figure 18-7 Rainbows form because white light is dispersed as it enters, reflects at the inside boundary, and exits the raindrops **(a).** Because of dispersion, only one color from each raindrop reaches an observer **(b).** (Illustration not to scale)

David Parker/Photo Researchers

Figure 18-8 A mist across your view allows for light comprising the entire spectrum of colors to reach your eyes in the form of a rainbow. Reflection from the raindrops sometimes enables you to see a second rainbow with the colors reversed.

Sometimes, you can see a faint second-order rainbow like the one shown in **Figure 18-8.** The second rainbow is outside of the first, is fainter, and has the order of the colors reversed. Light rays that are reflected twice inside water droplets produce this effect. Very rarely, a third rainbow is visible outside the second. What is your prediction about how many times light is reflected in the water droplets and the order of appearance of the colors for the third rainbow?

18.1 Section Review

6. **Index of Refraction** You notice that when a light ray enters a certain liquid from water, it is bent toward the normal, but when it enters the same liquid from crown glass, it is bent away from the normal. What can you conclude about the liquid's index of refraction?

7. **Index of Refraction** A ray of light in air has an angle of incidence of 30.0° on a block of unknown material and an angle of refraction of 20.0°. What is the index of refraction of the material?

8. **Speed of Light** Could an index of refraction ever be less than 1? What would this imply about the speed of light in that medium?

9. **Speed of Light** What is the speed of light in chloroform ($n = 1.51$)?

10. **Total Internal Reflection** If you were to use quartz and crown glass to make an optical fiber, which would you use for the cladding layer? Why?

11. **Angle of Refraction** A beam of light passes from water into polyethylene with $n = 1.50$. If $\theta_i = 57.5°$, what is the angle of refraction in the polyethylene?

12. **Critical Angle** Is there a critical angle for light traveling from glass to water? From water to glass?

13. **Dispersion** Why can you see the image of the Sun just above the horizon when the Sun itself has already set?

14. **Critical Thinking** In what direction can you see a rainbow on a rainy late afternoon? Explain.

Physics Online physicspp.com/self_check_quiz

18.2 Convex and Concave Lenses

The refraction of light in nature that forms rainbows and red lunar eclipses is beautiful, but refraction also is useful. In 1303, French physician Bernard of Gordon wrote of the use of lenses to correct eyesight. Around 1610, Galileo used two lenses to make a telescope, with which he discovered the moons of Jupiter. Since Galileo's time, lenses have been used in many instruments, such as microscopes and cameras. Lenses are probably the most useful of all optical devices.

▶ **Objectives**

- **Describe** how real and virtual images are formed by single convex and concave lenses.
- **Locate** images formed by lenses using ray tracing and equations.
- **Explain** how chromatic aberration can be reduced.

▶ **Vocabulary**

lens
convex lens
concave lens
thin lens equation
chromatic aberration
achromatic lens

Types of Lenses

A **lens** is a piece of transparent material, such as glass or plastic, that is used to focus light and form an image. Each of a lens's two faces might be either curved or flat. The lens in **Figure 18-9a** is called a **convex lens** because it is thicker at the center than at the edges. A convex lens often is called a converging lens because when surrounded by material with a lower index of refraction it refracts parallel light rays so that the rays meet at a point. The lens in **Figure 18-9b** is called a **concave lens** because it is thinner in the middle than at the edges. A concave lens often is called a diverging lens because when surrounded by material with a lower index of refraction rays passing through it spread out.

When light passes through a lens, refraction occurs at the two lens surfaces. Using Snell's law and geometry, you can predict the paths of rays passing through lenses. To simplify such problems, assume that all refraction occurs on a plane, called the principal plane, that passes through the center of the lens. This approximation, called the thin lens model, applies to all the lenses that you will learn about in this chapter section.

Lens equations The problems that you will solve involve spherical thin lenses, lenses that have faces with the same curvature as a sphere. Based on the thin lens model, as well as the other simplifications used in solving problems for spherical mirrors, equations have been developed that look exactly like the equations for spherical mirrors. The **thin lens equation** relates the focal length of a spherical thin lens to the object position and the image position.

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

The inverse of the focal length of a spherical lens is equal to the sum of the inverses of the image position and the object position.

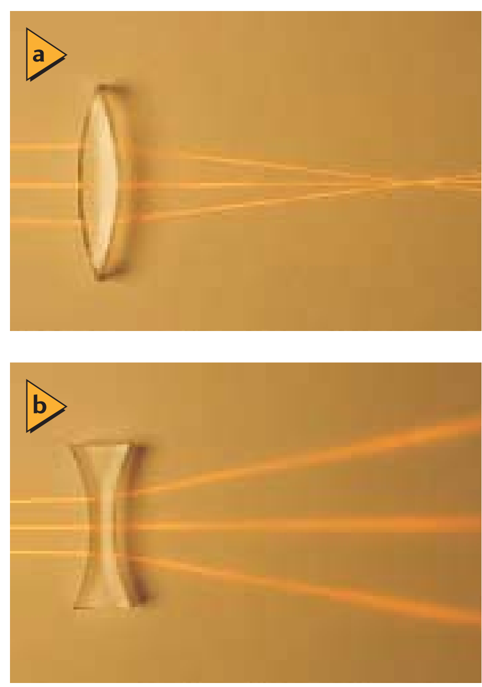
The magnification equation for spherical mirrors used in Chapter 17 also can be used for spherical thin lenses. It is used to determine the height and orientation of the image formed by a spherical thin lens.

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

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

CLICK HERE

CLICK HERE



■ **Figure 18-9** A convex lens causes rays of light to converge **(a).** A concave lens causes rays of light to diverge **(b).**

Horizons Companies

Table 18-2					
Properties of a Single Spherical Lens System					
Lens Type	**f**	**d_o**	**d_i**	**m**	**Image**
Convex	$+$	$d_o > 2f$	$2f > d_i > f$	Reduced Inverted	Real
		$2f > d_o > f$	$d_i > 2f$	Enlarged Inverted	Real
		$f > d_o > 0$	$\lvert d_i \rvert > d_o$ (negative)	Enlarged	Virtual
Concave	$-$	$d_o > 0$	$\lvert f \rvert > \lvert d_i \rvert > 0$ (negative)	Reduced	Virtual

Using the equations for lenses It is important that you use the proper sign conventions when using these equations. **Table 18-2** shows a comparison of the image position, magnification, and type of image formed by single convex and concave lenses when an object is placed at various object positions, d_o, relative to the lens. Notice the similarity of this table to Table 17-1 for mirrors. As with mirrors, the distance from the principal plane of a lens to its focal point is the focal length, f. The focal length depends upon the shape of the lens and the index of refraction of the lens material. Focal lengths and image positions can be negative.

For lenses, virtual images are always on the same side of the lens as the object, which means that the image position is negative. When the absolute value of a magnification is between zero and one, the image is smaller than the object. Magnifications with absolute values greater than one represent images that are larger than the objects. A negative magnification means the image is inverted compared to the object. Notice that a concave lens produces only virtual images, whereas a convex lens can produce real images or virtual images.

Convex Lenses and Real Images

As shown in **Figure 18-10a,** paper can be ignited by producing a real image of the Sun on the paper. Recall from Chapter 17 that the rays of the Sun are almost exactly parallel when they reach Earth. After being refracted by the lens, the rays converge at the focal point, F, of the lens. **Figure 18-10b** shows two focal points, one on each side of the lens. You could turn the lens around, and it will work the same.

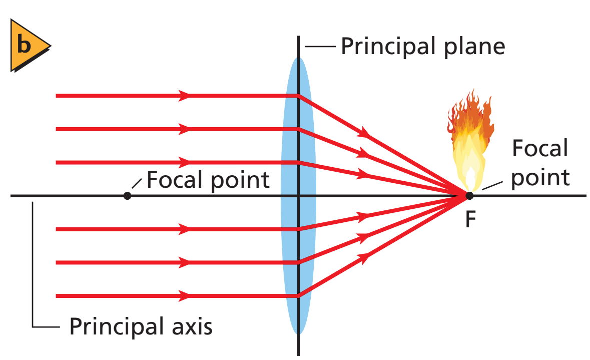
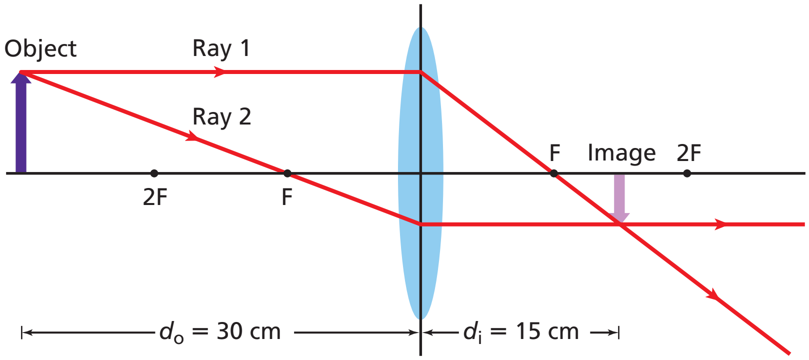


Figure 18-10 A converging lens can be used to ignite paper **(a).** Light entering parallel to the principal axis converges at the focal point of the lens, concentrating solar energy **(b).**



■ **Figure 18-11** When an object is placed at a distance greater than twice the focal length of the lens, a real image is produced that is inverted and smaller compared to the object. If the object is placed at the location of the image, you could locate the new image by tracing the same rays in the opposite direction.

Concepts In Motion

Interactive Figure To see an animation on ray diagrams, visit physicspp.com.

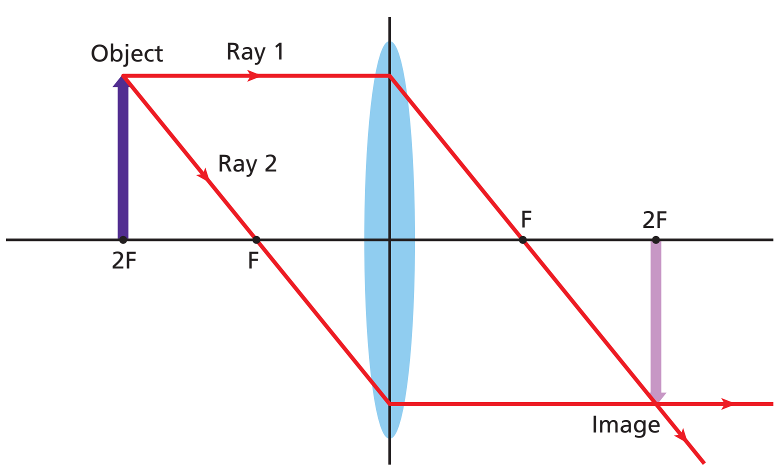
CLICK HERE

Ray diagrams In **Figure 18-11,** rays are traced from an object located far from a convex lens. For the purpose of locating the image, you only need to use two rays. Ray 1 is parallel to the principal axis. It refracts and passes through F on the other side of the lens. Ray 2 passes through F on its way to the lens. After refraction, its path is parallel to the principal axis. The two rays intersect at a point beyond F and locate the image. Rays selected from other points on the object converge at corresponding points to form the complete image. Note that this is a real image that is inverted and smaller compared to the object.

You can use Figure 18-11 to locate the image of an object that is closer to the lens than the object in the figure. If a refracted ray is reversed in direction, it will follow its original path in the reverse direction. This means that the image and object may be interchanged by changing the direction of the rays. Imagine that the path of light through the lens in Figure 18-11 is reversed and the object is at a distance of 15 cm from the right side of the lens. The new image, located 30 cm from the left side of the lens, is a real image that is inverted and larger compared to the object.

If the object is placed at twice the focal length from the lens at the point 2F, as shown in **Figure 18-12,** the image also is found at 2F. Because of symmetry, the image and object have the same size. Thus, you can conclude that if an object is more than twice the focal length from the lens, the image is smaller than the object. If the object is between F and 2F, then the image is larger than the object.

■ **Figure 18-12** When an object is placed at a distance equal to twice the focal length from the lens, the image is the same size as the object.



MINI LAB

Lens Masking Effects

What happens when you mask, or cover, part of a lens? Does this cause only part of a real image to be formed by the lens?

1. Stick the edge of a convex lens into a ball of clay and place the lens on a tabletop. ***CAUTION: Lenses have sharp edges. Handle carefully.***

2. Use a small lamp on one side and a screen on the other side to get a sharp image of the lamp's lightbulb. ***CAUTION: Lamps get hot and can burn skin.***

3. Predict what will happen to the image if you place your hand over the top half of the lens. This is called masking.

4. Observe the effects of masking more of the lens and masking less of the lens.

Analyze and Conclude

5. How much of the lens is needed for a complete image?

6. What is the effect of masking the lens?

EXAMPLE Problem 2

An Image Formed by a Convex Lens An object is placed 32.0 cm from a convex lens that has a focal length of 8.0 cm.

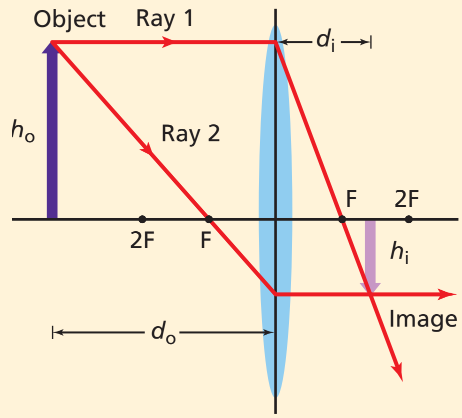
a. Where is the image?

b. If the object is 3.0 cm high, how tall is the image?

c. What is the orientation of the image?

1 Analyze and Sketch the Problem

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



Known:	**Unknown:**
$d_o = 32.0$ cm	$d_i = ?$
$h_o = 3.0$ cm	$h_i = ?$
$f = 8.0$ cm	

2 Solve for the Unknown

a. Use the thin lens equation to determine d_i.

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

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

$$= \frac{(8.0\text{ cm})(32.0\text{ cm})}{32.0\text{ cm} - 8.0\text{ cm}}$$ Substitute $f = 8.0$ cm, $d_o = 32.0$ cm

$= 11$ cm (11 cm away from the lens on the side opposite the object)

b. Use the magnification equation and solve for image height.

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

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

$$= \frac{-(11\text{ cm})(3.0\text{ cm})}{32.0\text{ cm}}$$ Substitute $d_i = 11$ cm, $h_o = 3.0$ cm, $d_o = 32.0$ cm

$= -1.0$ cm (1.0 cm tall)

Math Handbook
Operations with Significant Digits
pages 835–836

c. The negative sign in part **b** means that the image is inverted.

3 Evaluate the Answer

- **Are the units correct?** All are in centimeters.
- **Do the signs make sense?** Image position is positive (real image) and image height is negative (inverted compared to the object), which make sense for a convex lens.

PRACTICE Problems

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

15. A 2.25-cm-tall object is 8.5 cm to the left of a convex lens of 5.5-cm focal length. Find the image position and height.

16. An object near a convex lens produces a 1.8-cm-tall real image that is 10.4 cm from the lens and inverted. If the focal length of the lens is 6.8 cm, what are the object position and height?

17. An object is placed to the left of a convex lens with a 25-mm focal length so that its image is the same size as the object. What are the image and object positions?

18. Use a scale ray diagram to find the image position of an object that is 30 cm to the left of a convex lens with a 10-cm focal length.

19. Calculate the image position and height of a 2.0-cm-tall object located 25 cm from a convex lens with a focal length of 5.0 cm. What is the orientation of the image?

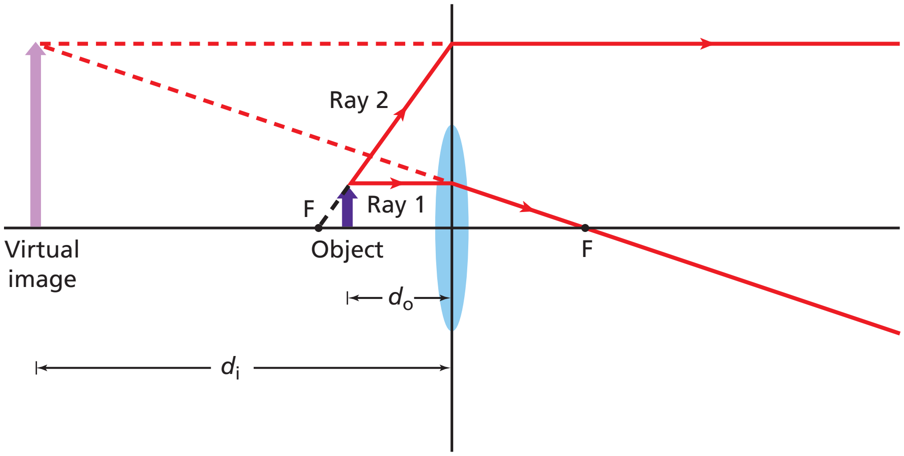


Figure 18-13 The two principal rays show that a convex lens forms a virtual image that is upright and larger compared to the object when the object is located between the lens and the focal point. Because the principal rays are simply part of a model to help locate an image, they do not have to pass through the picture of the lens in a diagram. In reality, the image is formed only by the light that passes through the actual lens.

Convex Lenses and Virtual Images

When an object is placed at the focal point of a convex lens, the refracted rays will emerge in a parallel beam and no image will be seen. When the object is brought closer to the lens, the rays will diverge on the opposite side of the lens, and the rays will appear to an observer to come from a spot on the same side of the lens as the object. This is a virtual image that is upright and larger compared to the object.

Figure 18-13 shows how a convex lens forms a virtual image. The object is located between F and the lens. Ray 1, as usual, approaches the lens parallel to the principal axis and is refracted through the focal point, F. Ray 2 travels from the tip of the object, in the direction it would have if it had started at F on the object side of the lens. The dashed line from F to the object shows you how to draw ray 2. Ray 2 leaves the lens parallel to the principal axis. Rays 1 and 2 diverge as they leave the lens. Thus, no real image is possible. Drawing sight lines for the two rays back to their apparent intersection locates the virtual image. It is on the same side of the lens as the object, and it is upright and larger compared to the object. Note that the actual image is formed by light that passes through the lens, but you can still determine the location of the image by drawing rays that do not have to pass through the lens.

PRACTICE Problems

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

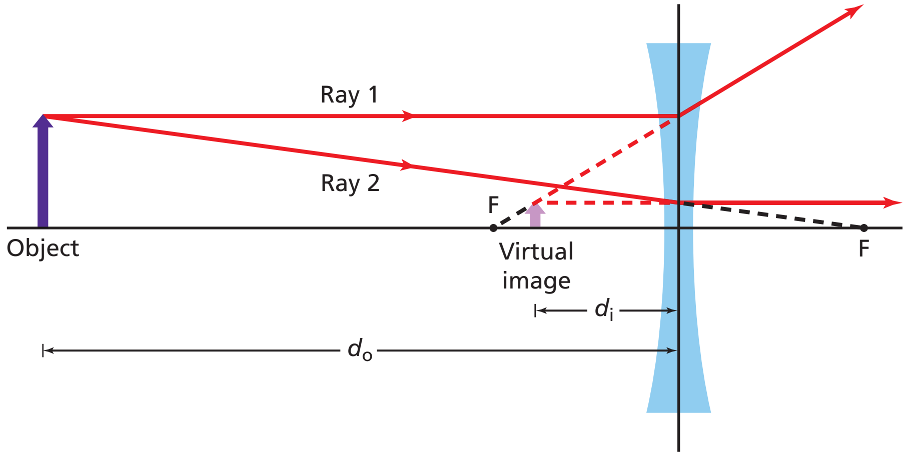
20. A newspaper is held 6.0 cm from a convex lens of 20.0-cm focal length. Find the image position of the newsprint image.

21. A magnifying glass has a focal length of 12.0 cm. A coin, 2.0 cm in diameter, is placed 3.4 cm from the lens. Locate the image of the coin. What is the diameter of the image?

22. A convex lens with a focal length of 22.0 cm is used to view a 15.0-cm-long pencil located 10.0 cm away. Find the height and orientation of the image.

23. A stamp collector wants to magnify a stamp by 4.0 when the stamp is 3.5 cm from the lens. What focal length is needed for the lens?

24. A magnifier with a focal length of 30 cm is used to view a 1-cm-tall object. Use ray tracing to determine the location and size of the image when the magnifier is positioned 10 cm from the object.



■ **Figure 18-14** Concave lenses produce only virtual images that are upright and smaller compared to their objects.

Concave Lenses

A concave lens causes all rays to diverge. **Figure 18-14** shows how such a lens forms a virtual image. Ray 1 approaches the lens parallel to the principal axis. It leaves the lens along a line that extends back through the focal point. Ray 2 approaches the lens as if it is going to pass through the focal point on the opposite side, and leaves the lens parallel to the principal axis. The sight lines of rays 1 and 2 intersect on the same side of the lens as the object. Because the rays diverge, they produce a virtual image. The image is located at the point from where the two rays apparently diverge. The image also is upright and smaller compared to the object. This is true no matter how far from the lens the object is located. The focal length of a concave lens is negative.

When solving problems for concave lenses using the thin lens equation, you should remember that the sign convention for focal length is different from that of convex lenses. If the focal point for a concave lens is 24 cm from the lens, you should use the value $f = -24$ cm in the thin lens equation. All images for a concave lens are virtual. Thus, if an image distance is given as 20 cm from the lens, then you should use $d_i = -20$ cm. The object position always will be positive.

Defects of Spherical Lenses

Throughout this section, you have studied lenses that produce perfect images at specific positions. In reality, spherical lenses, just like spherical mirrors, have intrinsic defects that cause problems with the focus and color of images. Spherical lenses exhibit an aberration associated with their spherical design, just as mirrors do. In addition, the dispersion of light through a spherical lens causes an aberration that mirrors do not exhibit.

Spherical aberration The model that you have used for drawing rays through spherical lenses suggests that all parallel rays focus at the same position. However, this is only an approximation. In reality, parallel rays that pass through the edges of a spherical lens focus at positions different from those of parallel rays that pass through the center. This inability of a spherical lens to focus all parallel rays to a single point is called spherical aberration. Making lens surfaces aspherical, such as in cameras, eliminates spherical aberration. In high-precision instruments, many lenses, often five or more, are used to form sharp, well-defined images.

Chromatic aberration Lenses have a second defect that mirrors do not have. A lens is like a prism, so different wavelengths of light are refracted at slightly different angles, as you can see in **Figure 18-15a.** Thus, the light that passes through a lens, especially near the edges, is slightly dispersed. An object viewed through a lens appears to be ringed with color. This effect is called **chromatic aberration.** The term *chromatic* comes from the Greek word *chromo,* which means "color."

Chromatic aberration is always present when a single lens is used. However, this defect can be greatly reduced by an **achromatic lens,** which is a system of two or more lenses, such as a convex lens with a concave lens, that have different indices of refraction. Such a combination of lenses is shown in **Figure 18-15b.** Both lenses in the figure disperse light, but the dispersion caused by the convex lens is almost canceled by the dispersion caused by the concave lens. The index of refraction of the convex lens is chosen so that the combination of lenses still converges the light.

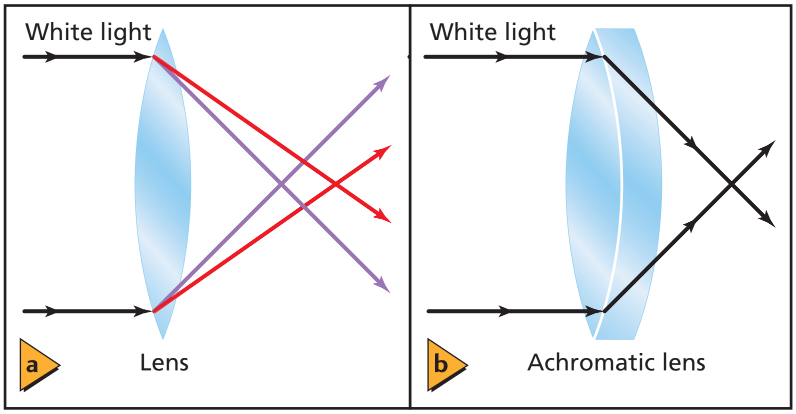


Figure 18-15 All simple lenses have chromatic aberration, in which light of different wavelengths is focused at different points **(a).** An achromatic lens is a combination of lenses, which minimizes the chromatic defect **(b).**

18.2 Section Review

25. Magnification Magnifying glasses normally are used to produce images that are larger than the related objects, but they also can produce images that are smaller than the related objects. Explain.

26. Image Position and Height A 3.0-cm-tall object is located 2.0 cm from a convex lens having a focal length of 6.0 cm. Draw a ray diagram to determine the location and size of the image. Use the thin lens equation and the magnification equation to verify your answer.

27. Types of Lenses The cross sections of four different thin lenses are shown in **Figure 18-16.**

a. Which of these lenses, if any, are convex, or converging, lenses?

b. Which of these lenses, if any, are concave, or diverging, lenses?

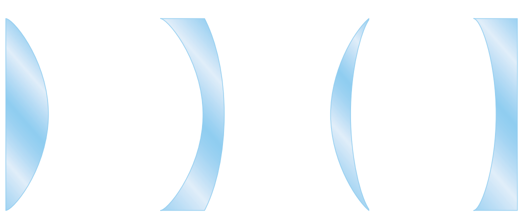


Figure 18-16

28. Chromatic Aberration All simple lenses have chromatic aberration. Explain, then, why you do not see this effect when you look through a microscope.

29. Chromatic Aberration You shine white light through a convex lens onto a screen and adjust the distance of the screen from the lens to focus the red light. Which direction should you move the screen to focus the blue light?

30. Critical Thinking An air lens constructed of two watch glasses is placed in a tank of water. Copy **Figure 18-17** and draw the effect of this lens on parallel light rays incident on the lens.

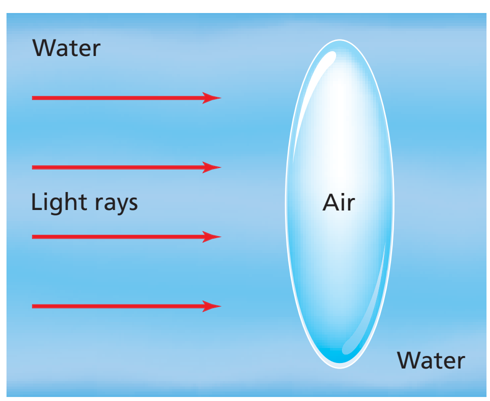


Figure 18-17

18.3 Applications of Lenses

▶ **Objectives**

- **Describe** how the eye focuses light to form an image.
- **Explain** nearsightedness and farsightedness and how eyeglass lenses correct these defects.
- **Describe** the optical systems in some common optical instruments.

▶ **Vocabulary**

nearsightedness
farsightedness

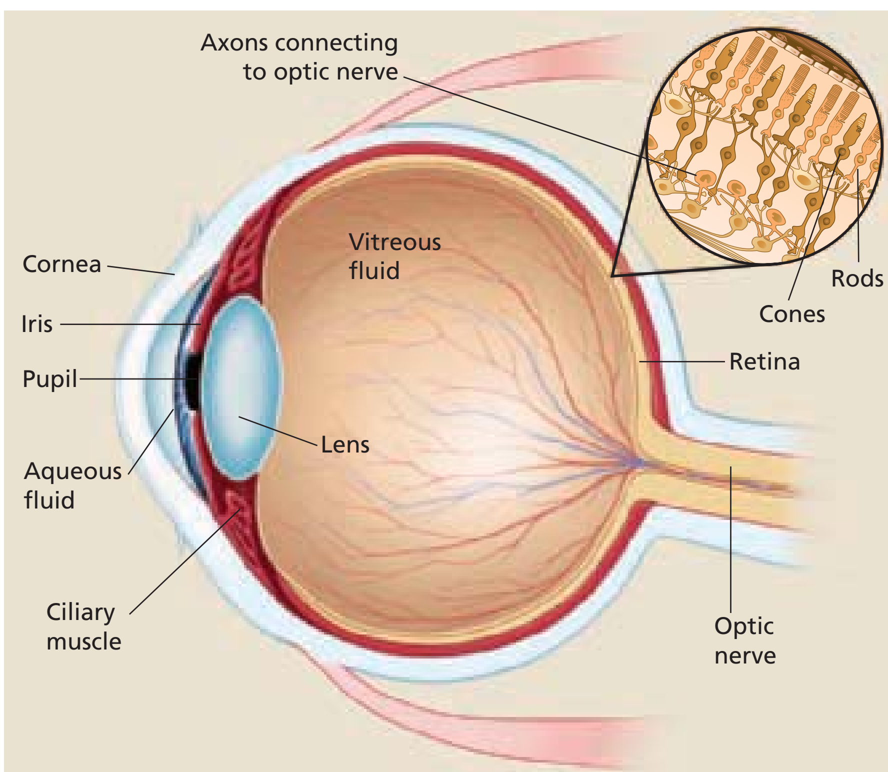
The properties that you have learned for the refraction of light through lenses are used in almost every optical instrument. In many cases, a combination of lenses and mirrors is used to produce clear images of small or faraway objects. Telescopes, binoculars, cameras, microscopes, and even your eyes contain lenses.

Lenses in Eyes

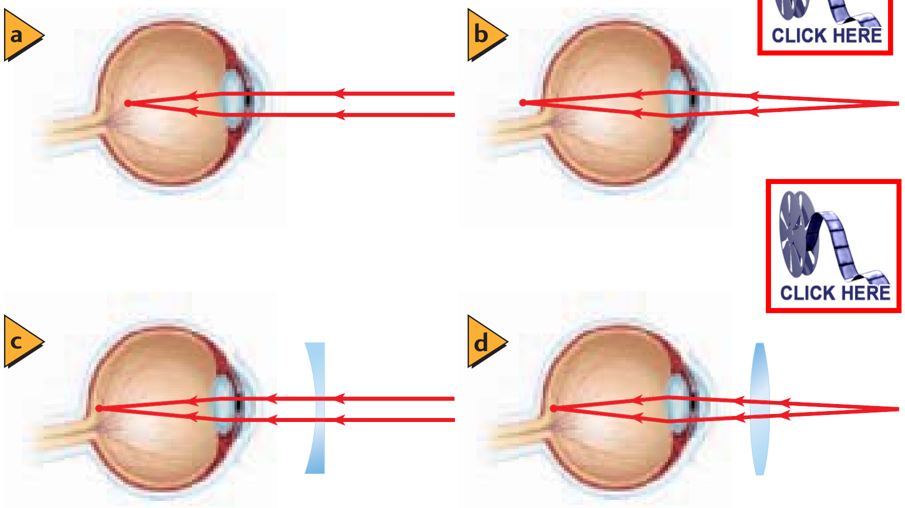
The eye is a remarkable optical device. As shown in **Figure 18-18,** the eye is a fluid-filled, almost spherical vessel. Light that is emitted or reflected off an object travels into the eye through the cornea. The light then passes through the lens and focuses onto the retina that is at the back of the eye. Specialized cells on the retina absorb this light and send information about the image along the optic nerve to the brain.

Focusing images Because of its name, you might assume that the lens of an eye is responsible for focusing light onto the retina. In fact, light entering the eye is primarily focused by the cornea because the air-cornea surface has the greatest difference in indices of refraction. The lens is responsible for the fine focus that allows you to clearly see both distant and nearby objects. Using a process called accommodation, muscles surrounding the lens can contract or relax, thereby changing the shape of the lens. This, in turn, changes the focal length of the eye. When the muscles are relaxed, the image of distant objects is focused on the retina. When the muscles contract, the focal length is shortened, and this allows images of closer objects to be focused on the retina.

Biology Connection



■ **Figure 18-18** The human eye is complex and has many components that must work together.



■ **Figure 18-19** A nearsighted person cannot see distant objects clearly because images are focused in front of the retina **(a).** A concave lens corrects this defect **(c).** A farsighted person cannot see close objects clearly because images are focused behind the retina **(b).** A convex lens corrects this defect **(d).**

Nearsightedness and farsightedness The eyes of many people do not focus sharp images on the retina. Instead, images are focused either in front of the retina or behind it. External lenses, in the form of eyeglasses or contact lenses, are needed to adjust the focal length and move images to the retina. **Figure 18-19a** shows the condition of **nearsightedness,** or myopia, whereby the focal length of the eye is too short to focus light on the retina. Images are formed in front of the retina. As shown in **Figure 18-19b,** concave lenses correct this by diverging light, thereby increasing images' distances from the lens, and forming images on the retina.

You also can see in **Figure 18-19c** that **farsightedness,** or hyperopia, is the condition in which the focal length of the eye is too long. Images are therefore formed past the retina. A similar result is caused by the increasing rigidity of the lenses in the eyes of people who are more than about 45 years old. Their muscles cannot shorten the focal length enough to focus images of close objects on the retina. For either defect, convex lenses produce virtual images farther from the eye than the associated objects, as shown in **Figure 18-19d.** The images then become the objects for the eye lens and can be focused on the retina, thereby correcting the defect.

APPLYING PHYSICS

▶ **Contacts** Contact lenses produce the same results as eyeglasses do. These small, thin lenses are placed directly on the corneas. A thin layer of tears between the cornea and lens keeps the lens in place. Most of the refraction occurs at the air-lens surface, where the difference in indices of refraction is greatest. ◀

CHALLENGE PROBLEM

As light enters the eye, it first encounters the air/cornea interface. Consider a ray of light that strikes the interface between the air and a person's cornea at an angle of 30.0° to the normal. The index of refraction of the cornea is approximately 1.4.

1. Use Snell's law to calculate the angle of refraction.
2. What would the angle of refraction be if the person was swimming underwater?
3. Is the refraction greater in air or in water? Does this mean that objects under water seem closer or more distant than they would in air?
4. If you want the angle of refraction for the light ray in water to be the same as it is for air, what should the new angle of incidence be?

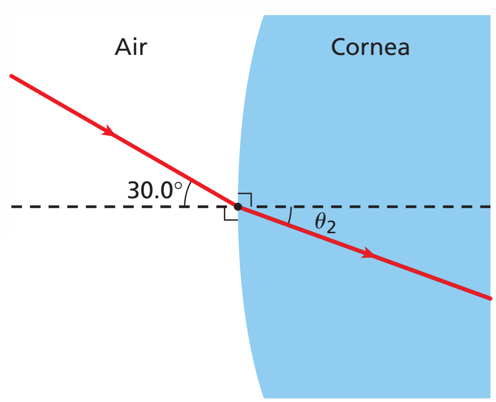
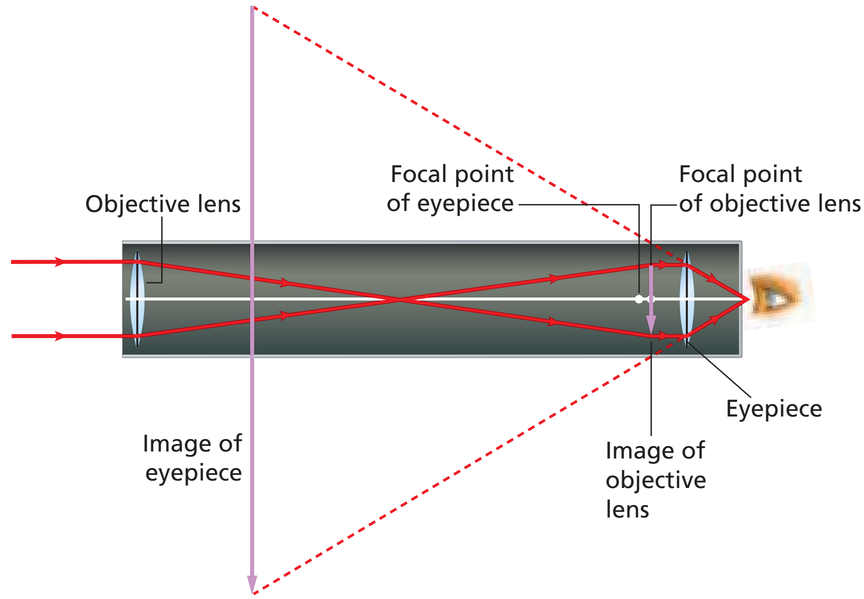


Figure 18-20 An astronomical refracting telescope creates a virtual image that is inverted compared to the object. (Illustration not to scale)

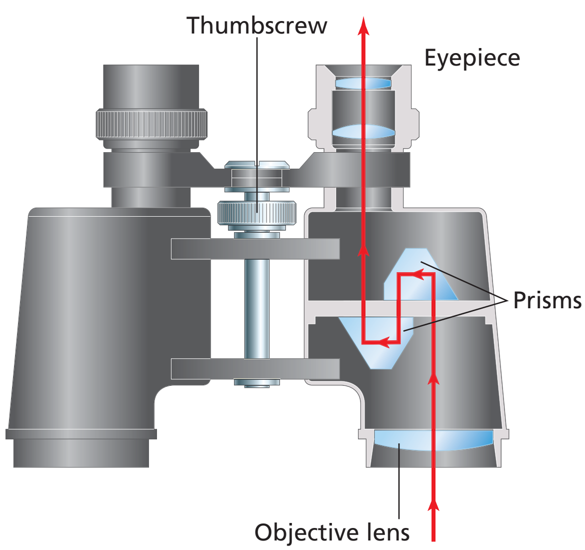


Refracting Telescopes

An astronomical refracting telescope uses lenses to magnify distant objects. **Figure 18-20** shows the optical system for a Keplerian telescope. Light from stars and other astronomical objects is so far away that the rays can be considered parallel. The parallel rays of light enter the objective convex lens and are focused as a real image at the focal point of the objective lens. The image is inverted compared to the object. This image then becomes the object for the convex lens of the eyepiece. Notice that the eyepiece lens is positioned so that the focal point of the objective lens is between the eyepiece lens and its focal point. This means that a virtual image is produced that is upright and larger than the first image. However, because the first image was already inverted, the final image is still inverted. For viewing astronomical objects, an image that is inverted is acceptable.

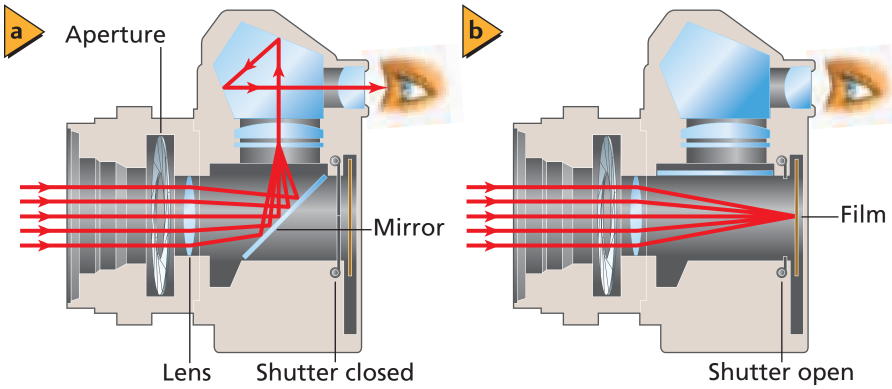
In a telescope, the convex lens of the eyepiece is almost always an achromatic lens. Recall that an achromatic lens is a combination of lenses that function as one lens. The combination of lenses eliminates the peripheral colors, or chromatic aberration, that can form on images.

Figure 18-21 Binoculars are like two side-by-side refracting telescopes.



Binoculars

Binoculars, like telescopes, produce magnified images of faraway objects. **Figure 18-21** shows a typical binocular design. Each side of the binoculars is like a small telescope: light enters a convex objective lens, which inverts the image. The light then travels through two prisms that use total internal reflection to invert the image again, so that the viewer sees an image that is upright compared to the object. The prisms also extend the path along which the light travels and direct it toward the eyepiece of the binoculars. Just as the separation of your two eyes gives you a sense of three dimensions and depth, the prisms allow a greater separation of the objective lenses, thereby improving the three-dimensional view of a distant object.



■ **Figure 18-22** The single-lens reflex camera shown here can divert the image formed by the lens through a prism for viewing **(a)** or directly to the film **(b).**

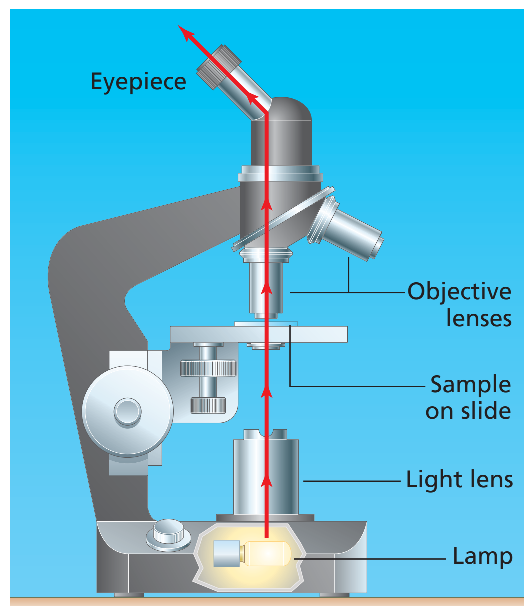
Cameras

Figure 18-22a shows the optical system used in a single-lens reflex camera. As light enters the camera, it passes through an achromatic lens. This lens system refracts the light much like a single convex lens would, forming an image that is inverted on the reflex mirror. The image is reflected upward to a prism that inverts and redirects the light to the viewfinder. When the person holding the camera takes a photograph, he or she presses the shutter-release button, which briefly raises the mirror, as shown in **Figure 18-22b.** The light, instead of being diverted upward to the prism, then travels along a straight path to form an image on the film.

CLICK HERE

■ **Figure 18-23** The objective lens and the eyepiece in this simple microscope produce an image that is inverted and larger compared to the object.

Concepts In Motion
Interactive Figure To see an animation on how a simple microscope works, visit physicspp.com.



Microscopes

Like a telescope, a microscope has both an objective convex lens and a convex eyepiece. However, microscopes are used to view small objects. **Figure 18-23** shows the optical system used in a simple compound microscope. The object is located between one and two focal lengths from the objective lens. A real image is produced that is inverted and larger than the object. As with a telescope, this image then becomes the object for the eyepiece. This image is between the eyepiece and its focal point. A virtual image is produced that is upright and larger than the image of the objective lens. Thus, the viewer sees an image that is inverted and greatly larger than the original object.

18.3 Section Review

31. Refraction Explain why the cornea is the primary focusing element in the eye.

32. Lens Types Which type of lens, convex or concave, should a nearsighted person use? Which type should a farsighted person use?

33. Focal Length Suppose your camera is focused on a person who is 2 m away. You now want to focus it on a tree that is farther away. Should you move the lens closer to the film or farther away?

34. Image Why is the image that you observe in a refracting telescope inverted?

35. Prisms What are three benefits of having prisms in binoculars?

36. Critical Thinking When you use the highest magnification on a microscope, the image is much darker than it is at lower magnifications. What are some possible reasons for the darker image? What could you do to obtain a brighter image?

Physics Online physicspp.com/self_check_quiz

PHYSICS LAB

Convex Lenses and Focal Length

The thin lens equation states that the inverse of the focal length is equal to the sum of the inverses of the image position from the lens and the object position from the lens.

QUESTION

How is the image position with a thin convex lens related to the object position and the focal length?

Objectives

- **Make and use graphs** to describe the relationship between the image position with a thin convex lens and the object position.
- **Use models** to show that no matter the image position, the focal length is a constant.

Safety Precautions

- **Ensure the lamp is turned off before plugging and unplugging it from the electrical outlet.**
- **Use caution when handling lamps. They get hot and can burn the skin.**
- **Lenses have sharp edges. Handle carefully.**

Materials

25-W straight-line filament bulb
lamp base
thin convex lens
meterstick
lens holder
index card

Procedure

1. Place a meterstick on your lab table so that it is balancing on the thin side and the metric numbers are right side up.
2. Place a convex lens in a lens holder and set it on the meterstick on or between the 10-cm and 40-cm marks on the meterstick. (Distances will vary depending on the focal length of the lens used.)
3. Turn on the lamp and set it next to the meterstick so that the center of the lightbulb is even with the 0-cm end of the meterstick.
4. Hold an index card so that the lens is between the lamp and the index card.
5. Move the index card back and forth until an upside-down image of the lightbulb is as sharp as possible.
6. Record the distance of the lightbulb from the lens (d_o) and the distance of the image from the lens (d_i).
7. Move the lens to another spot between 10 cm and 40 cm and repeat steps 5 and 6. (Distances will vary depending on the focal length of the lens used.)
8. Repeat step 7 three more times.

Data Table

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

Calculation Table

Trial	$\frac{1}{d_o}$ (cm^{-1})	$\frac{1}{d_i}$ (cm^{-1})	$\frac{1}{d_o} + \frac{1}{d_i}$ (cm^{-1})	f (cm)
1				
2				
3				
4				
5				

Analyze

1. **Make and Use Graphs** Make a scatter-plot graph of the image position (vertical axis) versus the object position (horizontal axis). Use a computer or calculator to construct the graph if possible.
2. **Use Numbers** Calculate $1/d_o$ and $1/d_i$ and enter the values in the calculation table.
3. **Use Numbers** Calculate the sum of $1/d_o$ and $1/d_i$ and enter the values in the calculation table. Calculate the reciprocal of this number and enter it in the calculation table as f.

Conclude and Apply

1. **Interpret Data** Looking at the graph, describe the relationship between d_o and d_i.
2. **Interpret Data** Find out the actual focal length of the lens from your teacher. How accurate are your calculations of f?
3. **Interpret Data** Compare the results of your focal length calculations of the five trials. Are your results similar?
4. **Lab Techniques** Why do you suppose you were instructed not to hold your lens closer than 10 cm or farther than 40 cm?

Going Further

1. Which measurement is more precise: d_o or d_i? Why do you think so?
2. What can you do to make either (or both) measurement(s) more accurate?

Real-World Physics

1. If you were to take a picture with a camera, first of a distant scene, then of an object less than a meter away, how should the distance between the lens and film be changed?
2. What are two ways in which the image projected onto your retina differs from the object you look at? (Remember the lens in your eye is also convex.)

Physics Online

To find out more about lenses and refraction, visit the Web site: physicspp.com

eXtreme physics

Gravitational Lenses

In 1979, astronomers at the Jodrell Bank Observatory in Great Britain discovered two quasars that were separated by only 7 arc seconds (seven 0.36th's of a degree). Measurements showed they should have been 500,000 light years apart. The two quasars seemed to fluctuate in brightness and in rhythm with each other. The most amazing thing, however, was that the quasars had identical spectra. There appeared to be two different objects, but the two objects were the same.

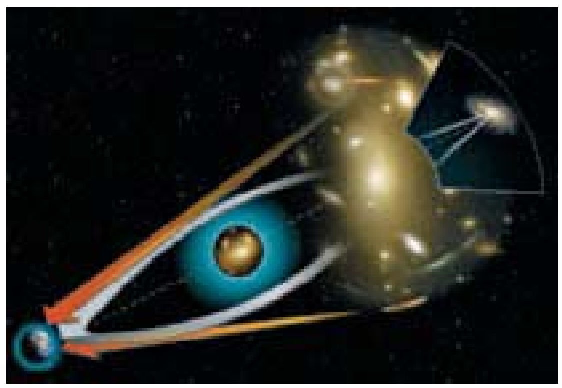
The blue shapes are multiple images of the same galaxy produced by gravitational lensing from galaxy cluster 0024+1654 in the center of the photo.

Further work by astronomers around the world confirmed that there was just a single quasar, and that its light was being distorted by a cluster of galaxies dominated by a massive elliptical galaxy lying in the line of sight between the quasar and Earth. The astronomers realized that they were seeing two images of one quasar. The galaxy acted like an imperfect convex lens, focusing the deflected light in such a way that two images were formed from one object. Why would they think that the light was bent?

Gravity and Light The astronomers remembered the work of Albert Einstein and his theory of relativity. Einstein proposed that light would be bent by the gravitational fields of massive objects. In the classical theory of space, known as Euclidean space, light travels in a straight line. According to Einstein, light bends when it comes near a massive object. In 1919, comparison of starlight before and during a solar eclipse proved Einstein's theory to be true.

In 1936, Einstein proposed the phenomenon of the gravitational lens. Because light can be bent by the gravitational fields of massive objects, virtual images of rings should be seen by observers on Earth when a massive object is between Earth and the object being observed. Einstein never observed such a phenomenon, but his theory of relativity supported the possible existence of gravitational lenses.

The illustration shows how light from a distant galaxy is bent around a galaxy cluster before reaching Earth.



The Evidence As often occurs in science, once someone discovers something for the first time, many more supporting discoveries are made soon after. Since Einstein's proposals, and the discovery in 1979 of the double-image quasar, many more gravitational lenses have been observed. Both Einstein's rings and multiple images have been observed. Einstein's rings result when the gravitational lens and the light from the object are in near-perfect alignment. Multiple images are formed when the gravitational lens and the light from the object are not in perfect alignment. Over 50 gravitational lenses have been discovered.

Going Further

1. **Infer** Why was the discovery of gravitational lenses important?
2. **Compare and Contrast** How are gravitational lenses similar to convex lenses? How are they different?

Chapter 18

Study Guide

18.1 Refraction of Light

Vocabulary

- index of refraction (p. 486)
- Snell's law of refraction (p. 486)
- critical angle (p. 489)
- total internal reflection (p. 489)
- dispersion (p. 491)

Key Concepts

- The path of travel of light bends when it passes from a medium with an index of refraction, n_1, into a medium with a different index of refraction, n_2.

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

- The ratio of the speed of light in a vacuum, c, to the speed of light in any medium, v, is the index of refraction, n, of the medium.

$$n = \frac{c}{v}$$

- When light traveling through a medium hits a boundary of a medium with a smaller index of refraction, if the angle of incidence exceeds the critical angle, θ_c, the light will be reflected back into the original medium by total internal reflection.

$$\sin \theta_c = \frac{n_2}{n_1}$$

18.2 Convex and Concave Lenses

Vocabulary

- lens (p. 493)
- convex lens (p. 493)
- concave lens (p. 493)
- thin lens equation (p. 493)
- chromatic aberration (p. 499)
- achromatic lens (p. 499)

Key Concepts

- The focal length, f; the object position, d_o; and the image position, d_i, for a lens are related by the thin lens equation.

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

- The magnification, m, of an image by a lens is defined in the same way as the magnification of an image by a mirror.

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

- A single convex lens produces a real image that is inverted when the object position is greater than the focal length. The image is reduced or enlarged, depending on the object position.
- A single convex lens produces a virtual image that is upright and larger than the object when the object is located between the lens and the focal point.
- A single concave lens always produces a virtual image that is upright and smaller than the object.
- All simple lenses have chromatic aberration. All lenses made with spherical surfaces have spherical aberration.

18.3 Applications of Lenses

Vocabulary

- nearsightedness (p. 501)
- farsightedness (p. 501)

Key Concepts

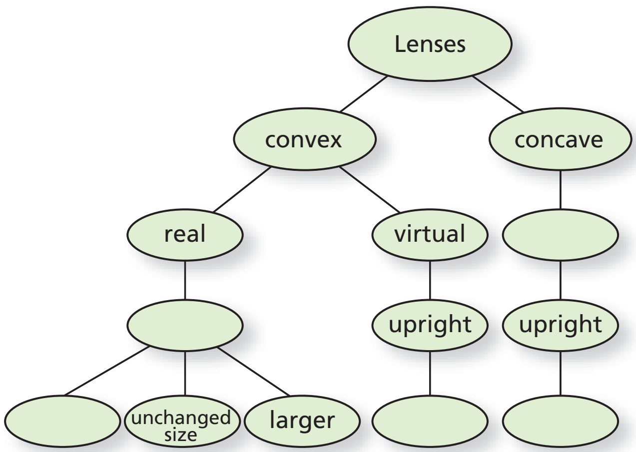
- Differences in indices of refraction between air and the cornea are primarily responsible for focusing light in the eye.
- Optical instruments use combinations of lenses to obtain clear images of small or distant objects.

Chapter 18

Assessment

Concept Mapping

37. Complete the following concept map using the following terms: *inverted, larger, smaller, virtual.*



Mastering Concepts

38. How does the angle of incidence compare with the angle of refraction when a light ray passes from air into glass at a nonzero angle? (18.1)

39. How does the angle of incidence compare with the angle of refraction when a light ray leaves glass and enters air at a nonzero angle? (18.1)

40. Regarding refraction, what is the critical angle? (18.1)

41. Although the light coming from the Sun is refracted while passing through Earth's atmosphere, the light is not separated into its spectrum. What does this indicate about the speeds of different colors of light traveling through air? (18.1)

42. Explain why the Moon looks red during a lunar eclipse. (18.1)

43. How do the shapes of convex and concave lenses differ? (18.2)

44. Locate and describe the physical properties of the image produced by a convex lens when an object is placed some distance beyond 2F. (18.2)

45. What factor, other than the curvature of the surfaces of a lens, determines the location of the focal point of the lens? (18.2)

46. To project an image from a movie projector onto a screen, the film is placed between F and 2F of a converging lens. This arrangement produces an image that is inverted. Why does the filmed scene appear to be upright when the film is viewed? (18.2)

47. Describe why precision optical instruments use achromatic lenses. (18.2)

48. Describe how the eye focuses light. (18.3)

49. What is the condition in which the focal length of the eye is too short to focus light on the retina? (18.3)

50. What type of image is produced by the objective lens in a refracting telescope? (18.3)

51. The prisms in binoculars increase the distance between the objective lenses. Why is this useful? (18.3)

52. What is the purpose of a camera's reflex mirror? (18.3)

Applying Concepts

53. Which substance, A or B, in **Figure 18-24** has a larger index of refraction? Explain.

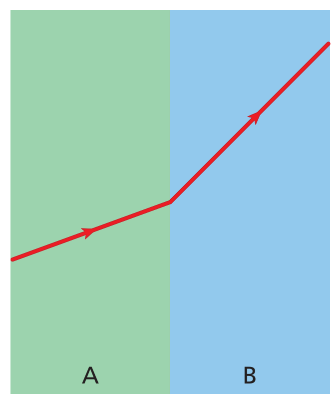


Figure 18-24

54. A light ray strikes the boundary between two transparent media. What is the angle of incidence for which there is no refraction?

55. How does the speed of light change as the index of refraction increases?

56. How does the size of the critical angle change as the index of refraction increases?

57. Which pair of media, air and water or air and glass, has the smaller critical angle?

58. **Cracked Windshield** If you crack the windshield of your car, you will see a silvery line along the crack. The glass has separated at the crack, and there is air in the crack. The silvery line indicates that light is reflecting off the crack. Draw a ray diagram to explain why this occurs. What phenomenon does this illustrate?

59. **Legendary Mirage** According to legend, Eric the Red sailed from Iceland and discovered Greenland after he had seen the island in a mirage. Describe how the mirage might have occurred.

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

60. A prism bends violet light more than it bends red light. Explain.

61. **Rainbows** Why would you never see a rainbow in the southern sky if you were in the northern hemisphere? In which direction should you look to see rainbows if you are in the southern hemisphere?

62. Suppose that Figure 18-14 is redrawn with a lens of the same focal length but a larger diameter. Explain why the location of the image does not change. Would the image be affected in any way?

63. A swimmer uses a magnifying glass to observe a small object on the bottom of a swimming pool. She discovers that the magnifying glass does not magnify the object very well. Explain why the magnifying glass is not functioning as it would in air.

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

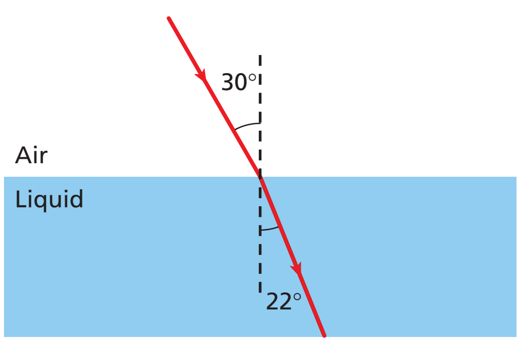
65. When subjected to bright sunlight, the pupils of your eyes are smaller than when they are subjected to dimmer light. Explain why your eyes can focus better in bright light.

66. **Binoculars** The objective lenses in binoculars form real images that are upright compared to their objects. Where are the images located relative to the eyepiece lenses?

Mastering Problems

18.1 Refraction of Light

67. A ray of light travels from air into a liquid, as shown in **Figure 18-25.** The ray is incident upon the liquid at an angle of 30.0°. The angle of refraction is 22.0°.
   a. Using Snell's law, calculate the index of refraction of the liquid.
   b. Compare the calculated index of refraction to those in Table 18-1. What might the liquid be?



■ **Figure 18-25**

68. Light travels from flint glass into ethanol. The angle of refraction in the ethanol is 25.0°. What is the angle of incidence in the glass?

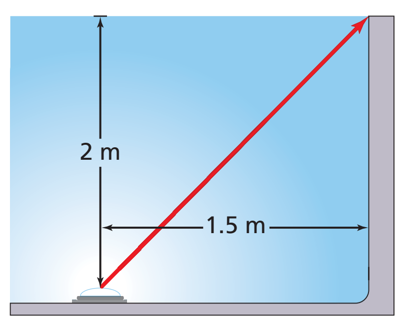
69. A beam of light strikes the flat, glass side of a water-filled aquarium at an angle of 40.0° to the normal. For glass, $n = 1.50$.
   a. At what angle does the beam enter the glass?
   b. At what angle does the beam enter the water?

70. Refer to Table 18-1. Use the index of refraction of diamond to calculate the speed of light in diamond.

71. Refer to Table 18-1. Find the critical angle for a diamond in air.

72. **Aquarium Tank** A thick sheet of plastic, $n = 1.500$, is used as the side of an aquarium tank. Light reflected from a fish in the water has an angle of incidence of 35.0°. At what angle does the light enter the air?

73. **Swimming-Pool Lights** A light source is located 2.0 m below the surface of a swimming pool and 1.5 m from one edge of the pool, as shown in **Figure 18-26.** The pool is filled to the top with water.
   a. At what angle does the light reaching the edge of the pool leave the water?
   b. Does this cause the light viewed from this angle to appear deeper or shallower than it actually is?



■ **Figure 18-26 (Not to scale)**

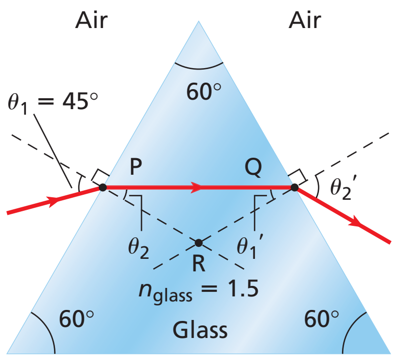
74. A diamond's index of refraction for red light, 656 nm, is 2.410, while that for blue light, 434 nm, is 2.450. Suppose that white light is incident on the diamond at 30.0°. Find the angles of refraction for red and blue light.

75. The index of refraction of crown glass is 1.53 for violet light, and it is 1.51 for red light.
   a. What is the speed of violet light in crown glass?
   b. What is the speed of red light in crown glass?

76. The critical angle for a special glass in air is 41.0°. What is the critical angle if the glass is immersed in water?

77. A ray of light in a tank of water has an angle of incidence of 55.0°. What is the angle of refraction in air?

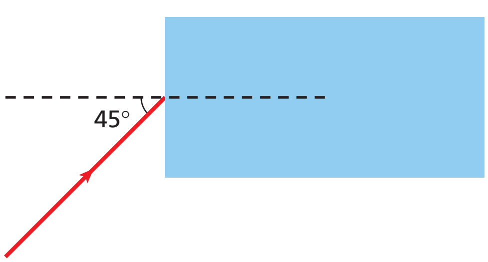
78. The ray of light shown in **Figure 18-27** is incident upon a 60°-60°-60° glass prism, $n = 1.5$.
 a. Using Snell's law of refraction, determine the angle, θ_2, to the nearest degree.
 b. Using elementary geometry, determine the value of θ_1'.
 c. Determine θ_2'.



■ **Figure 18-27**

79. The speed of light in a clear plastic is 1.90×10^8 m/s. A ray of light strikes the plastic at an angle of 22.0°. At what angle is the ray refracted?

80. A light ray enters a block of crown glass, as illustrated in **Figure 18-28.** Use a ray diagram to trace the path of the ray until it leaves the glass.



■ **Figure 18-28**

18.2 Convex and Concave Lenses

81. The focal length of a convex lens is 17 cm. A candle is placed 34 cm in front of the lens. Make a ray diagram to locate the image.

82. A converging lens has a focal length of 25.5 cm. If it is placed 72.5 cm from an object, at what distance from the lens will the image be?

83. If an object is 10.0 cm from a converging lens that has a focal length of 5.00 cm, how far from the lens will the image be?

84. A convex lens is needed to produce an image that is 0.75 times the size of the object and located 24 cm from the lens on the other side. What focal length should be specified?

85. An object is located 14.0 cm from a convex lens that has a focal length of 6.0 cm. The object is 2.4 cm high.
 a. Draw a ray diagram to determine the location, size, and orientation of the image.
 b. Solve the problem mathematically.

86. A 3.0-cm-tall object is placed 22 cm in front of a converging lens. A real image is formed 11 cm from the lens. What is the size of the image?

87. A 3.0-cm-tall object is placed 15.0 cm in front of a converging lens. A real image is formed 10.0 cm from the lens.
 a. What is the focal length of the lens?
 b. If the original lens is replaced with a lens having twice the focal length, what are the image position, size, and orientation?

88. A diverging lens has a focal length of 15.0 cm. An object placed near it forms a 2.0-cm-high image at a distance of 5.0 cm from the lens.
 a. What are the object position and object height?
 b. The diverging lens is now replaced by a converging lens with the same focal length. What are the image position, height, and orientation? Is it a virtual image or a real image?

18.3 Applications of Lenses

89. **Camera Lenses** Camera lenses are described in terms of their focal length. A 50.0-mm lens has a focal length of 50.0 mm.
 a. A camera with a 50.0-mm lens is focused on an object 3.0 m away. What is the image position?
 b. A 1000.0-mm lens is focused on an object 125 m away. What is the image position?

90. **Eyeglasses** To clearly read a book 25 cm away, a farsighted girl needs the image to be 45 cm from her eyes. What focal length is needed for the lenses in her eyeglasses?

91. **Copy Machine** The convex lens of a copy machine has a focal length of 25.0 cm. A letter to be copied is placed 40.0 cm from the lens.
 a. How far from the lens is the copy paper?
 b. How much larger will the copy be?

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

92. Camera A camera lens with a focal length of 35 mm is used to photograph a distant object. How far from the lens is the real image of the object? Explain.

93. Microscope A slide of an onion cell is placed 12 mm from the objective lens of a microscope. The focal length of the objective lens is 10.0 mm.

a. How far from the lens is the image formed?

b. What is the magnification of this image?

c. The real image formed is located 10.0 mm beneath the eyepiece lens. If the focal length of the eyepiece is 20.0 mm, where does the final image appear?

d. What is the final magnification of this compound system?

94. Telescope The optical system of a toy refracting telescope consists of a converging objective lens with a focal length of 20.0 cm, located 25.0 cm from a converging eyepiece lens with a focal length of 4.05 cm. The telescope is used to view a 10.0-cm-high object, located 425 cm from the objective lens.

a. What are the image position, height, and orientation as formed by the objective lens? Is this a real or virtual image?

b. The objective lens image becomes the object for the eyepiece lens. What are the image position, height, and orientation that a person sees when looking into the telescope? Is this a real or virtual image?

c. What is the magnification of the telescope?

Mixed Review

95. A block of glass has a critical angle of 45.0°. What is its index of refraction?

96. Find the speed of light in antimony trioxide if it has an index of refraction of 2.35.

97. A 3.0-cm-tall object is placed 20 cm in front of a converging lens. A real image is formed 10 cm from the lens. What is the focal length of the lens?

98. Derive $n = \sin\theta_1/\sin\theta_2$ from the general form of Snell's law of refraction, $n_1 \sin\theta_1 = n_2 \sin\theta_2$. State any assumptions and restrictions.

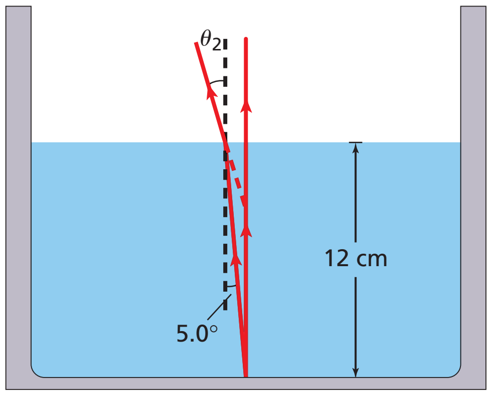
99. Astronomy How many more minutes would it take light from the Sun to reach Earth if the space between them were filled with water rather than a vacuum? The Sun is 1.5×10^8 km from Earth.

100. What is the focal length of the lenses in your eyes when you read a book that is 35.0 cm from them? The distance from each lens to the retina is 0.19 mm.

101. Apparent Depth Sunlight reflects diffusively off the bottom of an aquarium. **Figure 18-29** shows two of the many light rays that would reflect diffusively from a point off the bottom of the tank and travel to the surface. The light rays refract into the air as shown. The red dashed line extending back from the refracted light ray is a sight line that intersects with the vertical ray at the location where an observer would see the image of the bottom of the tank.

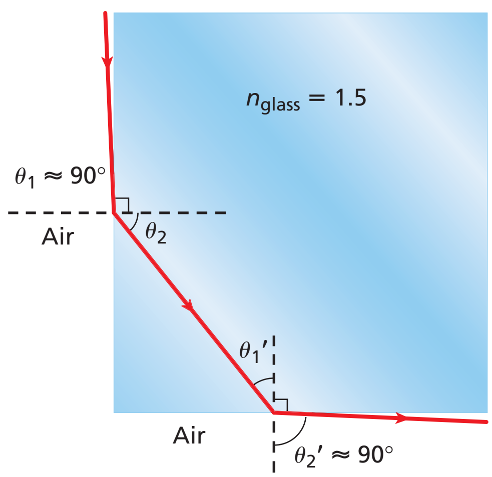
a. Compute the direction that the refracted ray will travel above the surface of the water.

b. At what depth does the bottom of the tank appear to be if you look into the water? Divide this apparent depth into the true depth and compare it to the index of refraction.



■ **Figure 18-29**

102. It is impossible to see through adjacent sides of a square block of glass with an index of refraction of 1.5. The side adjacent to the side that an observer is looking through acts as a mirror. **Figure 18-30** shows the limiting case for the adjacent side to not act like a mirror. Use your knowledge of geometry and critical angles to show that this ray configuration is not achievable when $n_{glass} = 1.5$.



■ **Figure 18-30**

103. Bank Teller Window A 25-mm-thick sheet of plastic, $n = 1.5$, is used in a bank teller's window. A ray of light strikes the sheet at an angle of 45°. The ray leaves the sheet at 45°, but at a different location. Use a ray diagram to find the distance between the ray that leaves and the one that would have left if the plastic were not there.

Thinking Critically

104. Recognize Spatial Relationships White light traveling through air ($n = 1.0003$) enters a slab of glass, incident at exactly 45°. For dense flint glass, $n = 1.7708$ for blue light ($\lambda = 435.8$ nm) and $n = 1.7273$ for red light ($\lambda = 643.8$ nm). What is the angular dispersion of the red and blue light?

105. Compare and Contrast Find the critical angle for ice ($n = 1.31$). In a very cold world, would fiber-optic cables made of ice or those made of glass do a better job of keeping light inside the cable? Explain.

106. Recognize Cause and Effect Your lab partner used a convex lens to produce an image with $d_i = 25$ cm and $h_i = 4.0$ cm. You are examining a concave lens with a focal length of -15 cm. You place the concave lens between the convex lens and the original image, 10 cm from the image. To your surprise, you see a real image on the wall that is larger than the object. You are told that the image from the convex lens is now the object for the concave lens, and because it is on the opposite side of the concave lens, it is a virtual object. Use these hints to find the new image position and image height and to predict whether the concave lens changed the orientation of the original image.

107. Define Operationally Name and describe the effect that causes the rainbow-colored fringe commonly seen at the edges of a spot of white light from a slide or overhead projector.

108. Think Critically A lens is used to project the image of an object onto a screen. Suppose that you cover the right half of the lens. What will happen to the image?

Writing in Physics

109. The process of accommodation, whereby muscles surrounding the lens in the eye contract or relax to enable the eye to focus on close or distant objects, varies for different species. Investigate this effect for different animals. Prepare a report for the class showing how this fine focusing is accomplished for different eye mechanisms.

110. Investigate the lens system used in an optical instrument such as an overhead projector or a particular camera or telescope. Prepare a graphics display for the class explaining how the instrument forms images.

Cumulative Review

111. If you drop a 2.0 kg bag of lead shot from a height of 1.5 m, you could assume that half of the potential energy will be converted into thermal energy in the lead. The other half would go to thermal energy in the floor. How many times would you have to drop the bag to heat it by 10°C? (Chapter 12)

112. A blacksmith puts an iron hoop or tire on the outer rim of a wooden carriage wheel by heating the hoop so that it expands to a diameter greater than the wooden wheel. When the hoop cools, it contracts to hold the rim in place. If a blacksmith has a wooden wheel with a 1.0000-m diameter and wants to put a rim with a 0.9950-m diameter on the wheel, what is the minimum temperature change the iron must experience? ($\alpha_{iron} = 12\times10^{-6}$/°C) (Chapter 13)

113. A car sounds its horn as it approaches a pedestrian in a crosswalk. What does the pedestrian hear as the car brakes to allow him to cross the street? (Chapter 15)

114. Suppose that you could stand on the surface of the Sun and weigh yourself. Also suppose that you could measure the illuminance on your hand from the Sun's visible spectrum produced at that position. Next, imagine yourself traveling to a position 1000 times farther away from the center of the Sun as you were when standing on its surface. (Chapter 16)

a. How would the force of gravity on you from the Sun at the new position compare to what it was at the surface?

b. How would the illuminance on your hand from the Sun at the new position compare to what it was when you were standing on its surface? (For simplicity, assume that the Sun is a point source at both positions.)

c. Compare the effect of distance upon the gravitational force and illuminance.

115. Beautician's Mirror The nose of a customer who is trying some face powder is 3.00-cm high and is located 6.00 cm in front of a concave mirror having a 14.0-cm focal length. Find the image position and height of the customer's nose by means of the following. (Chapter 17)

a. a ray diagram drawn to scale

b. the mirror and magnification equations

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

Standardized Test Practice

Multiple Choice

1. A flashlight beam is directed at a swimming pool in the dark at an angle of 46° with respect to the normal to the surface of the water. What is the angle of refraction of the beam in the water? (The refractive index for water is 1.33.)

   Ⓐ 18° Ⓒ 33°
   Ⓑ 30° Ⓓ 44°

2. The speed of light in diamond is 1.24×10^8 m/s. What is the index of refraction of diamond?

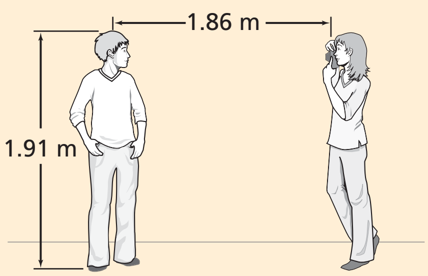
   Ⓐ 0.0422 Ⓒ 1.24
   Ⓑ 0.413 Ⓓ 2.42

3. Which one of the items below is not involved in the formation of rainbows?

   Ⓐ diffraction Ⓒ reflection
   Ⓑ dispersion Ⓓ refraction

4. George's picture is being taken by Cami, as shown in the figure, using a camera which has a convex lens with a focal length of 0.0470 m. Determine George's image position.

   Ⓐ 1.86 cm Ⓒ 4.82 cm
   Ⓑ 4.70 cm Ⓓ 20.7 cm



5. What is the magnification of an object that is 4.15 m in front of a camera that has an image position of 5.0 cm?

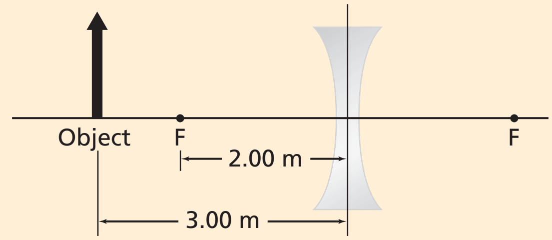
   Ⓐ −0.83 Ⓒ 0.83
   Ⓑ −0.012 Ⓓ 1.2

6. Which one of the items below is not involved in the formation of mirages?

   Ⓐ heating of air near the ground
   Ⓑ Huygens' wavelets
   Ⓒ reflection
   Ⓓ refraction

7. What is the image position for the situation shown in the figure?

   Ⓐ −6.00 m Ⓒ 0.167 m
   Ⓑ −1.20 m Ⓓ 0.833 m



8. What is the critical angle for total internal reflection when light travels from glass (n = 1.52) to water (n = 1.33)?

   Ⓐ 29.0° Ⓒ 48.8°
   Ⓑ 41.2° Ⓓ 61.0°

9. What happens to the image formed by a convex lens when half of the lens is covered?

   Ⓐ half of the image disappears
   Ⓑ the image dims
   Ⓒ the image gets blurry
   Ⓓ the image inverts

Extended Answer

10. The critical angle for total internal reflection at a diamond-air boundary is 24.4°. What is the angle of refraction in the air if light is incident on the boundary at an angle of 20.0°?

11. An object that is 6.98 cm from a lens produces an image that is 2.95 cm from the lens on the same side of the lens. Determine the type of lens that is producing the image and explain how you know.

✓ Test-Taking TIP

Use as Much Time as You Can

You will not get extra points for finishing a test early. Work slowly and carefully to prevent careless errors that can occur when you are hurrying to finish.