CHAPTER 14

Refraction

Most of us have seen a rainbow when sunlight hits droplets of water in the air. Sunlight is bent, or *refracted,* as it passes through a raindrop. Longer wavelengths of light (red) are bent the least, and shorter wavelengths of light (violet) are bent the most.

WHAT TO EXPECT

In this chapter, you will study optical phenomena associated with the refraction of light as it passes from one transparent medium to another. You will learn how to analyze *converging* and *diverging* lenses. You will then better understand how optical devices work.

WHY IT MATTERS

Optical devices, such as cameras, microscopes, and telescopes, use the principles of reflection and refraction to create images that we can then use for many artistic and scientific applications. An understanding of how lenses function is also essential to the practice of optometry.

CHAPTER PREVIEW

1 Refraction
- Refraction of Light
- The Law of Refraction

2 Thin Lenses
- Types of Lenses
- Characteristics of Lenses
- The Thin-Lens Equation and Magnification
- Eyeglasses and Contact Lenses
- Combination of Thin Lenses

3 Optical Phenomena
- Total Internal Reflection
- Atmospheric Refraction
- Dispersion
- Lens Aberrations

Refraction

SECTION OBJECTIVES

- Recognize situations in which refraction will occur.
- Identify which direction light will bend when it passes from one medium to another.
- Solve problems using Snell's law.

refraction

the bending of a wave front as the wave front passes between two substances in which the speed of the wave differs

Figure 1
The flower looks small when viewed through the water droplet. The light from the flower is bent because of the shape of the water droplet and the change in material as the light passes through the water.

REFRACTION OF LIGHT

Look at the tiny image of the flower that appears in the water droplet in **Figure 1.** The blurred flower can be seen in the background of the photo. Why does the flower look different when viewed through the droplet? This phenomenon occurs because light is bent at the boundary between the water and the air around it. The bending of light as it travels from one medium to another is called **refraction.**

If light travels from one transparent medium to another at any angle other than straight on (normal to the surface), the light ray changes direction when it meets the boundary. As in the case of reflection, the angles of the incoming and refracted rays are measured with respect to the normal. For studying refraction, the normal line is extended into the refracting medium, as shown in **Figure 2.** The angle between the refracted ray and the normal is called the *angle of refraction,* θ_r, and the angle of incidence is designated as θ_i.

Refraction occurs when light's velocity changes

Glass, water, ice, diamonds, and quartz are all examples of transparent media through which light can pass. The speed of light in each of these materials is different. The speed of light in water, for instance, is less than the speed of light in air. And the speed of light in glass is less than the speed of light in water.

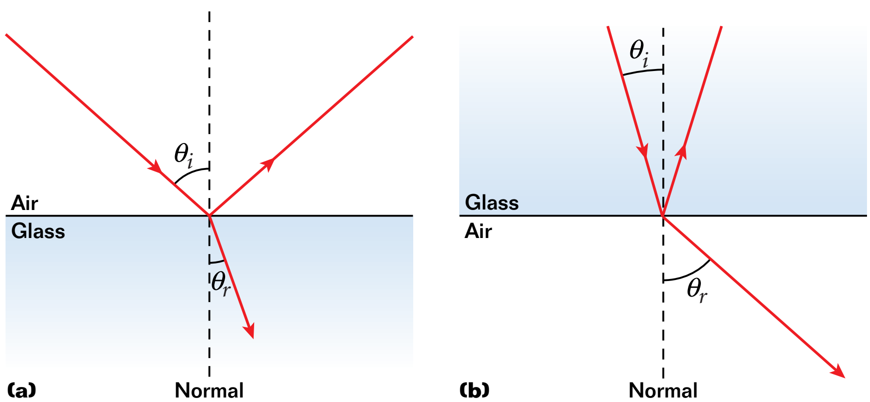


Figure 2
When light moves from one medium to another, part of it is reflected and part is refracted. **(a)** When the light ray moves from air into glass, the refracted portion is bent toward the normal, **(b)** whereas the path of the light ray moving from glass into air is bent away from the normal.

When light moves from a material in which its speed is higher to a material in which its speed is lower, such as from air to glass, the ray is bent toward the normal, as shown in **Figure 2(a).** If the ray moves from a material in which its speed is lower to one in which its speed is higher, as in **Figure 2(b),** the ray is bent away from the normal. If the incident ray of light is parallel to the normal, then no refraction (bending) occurs in either case.

Note that the path of a light ray that crosses a boundary between two different media is reversible. If the ray in **Figure 2(a)** originated inside the glass block, it would follow the same path as shown in the figure, but the reflected ray would be inside the block.

Refraction can be explained in terms of the wave model of light

In the previous chapter on light and refraction, you learned how to use wave fronts and light rays to approximate light waves. This analogy can be extended to light passing from one medium into another. In **Figure 3,** the wave fronts are shown in red and are assumed to be spherical. The combined wave front (dotted line connecting the individual wave fronts) is a superposition of all the spherical wave fronts. The direction of propagation of the wave is perpendicular to the wave front and is what we call the *light ray.*

Consider wave fronts of a plane wave of light traveling at an angle to the surface of a block of glass, as shown in **Figure 3.** As the light enters the glass, the wave fronts slow down, but the wave fronts that have not yet reached the surface of the glass continue traveling at the speed of light in air. During this time, the slower wave fronts travel a smaller distance than do the wave fronts in the air, so the entire plane wave changes directions.

Note the difference in wavelength (the space between the wave fronts) between the plane wave in air and the plane wave in the glass. Because the wave fronts inside the glass are traveling more slowly, in the same time interval they move through a shorter distance than the wave fronts that are still traveling in air. Thus, the wavelength of the light in the glass, λ_{glass}, is shorter than the wavelength of the incoming light, λ_{air}. The frequency of the light does *not* change when the light passes from one medium to another.

Did you know?

The speed of light in a vacuum, *c*, is an important constant used by physicists. It has been measured to be about 3.00×10^8 m/s. Inside of other mediums, such as air, glass, or water, the speed of light is different and is less than *c*.

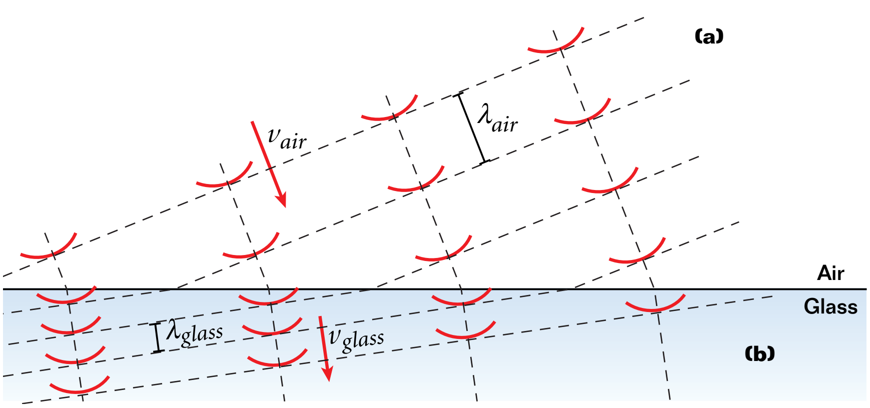


Figure 3
A plane wave traveling in air **(a)** has a wavelength of λ_{air} and velocity of v_{air}. Each wave front turns as it strikes the glass. Because the speed of the wave fronts in the glass **(b)**, v_{glass}, is slower, the wavelength of the light becomes shorter, and the wave fronts change direction.

THE LAW OF REFRACTION

index of refraction

the ratio of the speed of light in a vacuum to the speed of light in a given transparent medium

An important property of transparent substances is the **index of refraction.** The index of refraction for a substance is the ratio of the speed of light in a vacuum to the speed of light in that substance.

INDEX OF REFRACTION

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

$$\text{index of refraction} = \frac{\text{speed of light in vacuum}}{\text{speed of light in medium}}$$

From this definition, we see that the index of refraction is a dimensionless number that is always greater than 1 because light always travels slower in a substance than in a vacuum. **Table 1** lists the indices of refraction for different substances. Note that the larger the index of refraction is, the slower light travels in that substance and the more a light ray will bend when it passes from a vacuum into that material.

Imagine, as an example, light passing between air and water. When light begins in the air (high speed of light and low index of refraction) and travels into the water (lower speed of light and higher index of refraction), the light rays are bent toward the normal. Conversely, when light passes from the water to the air, the light rays are bent away from the normal.

Note that the value for the index of refraction of air is nearly that of a vacuum. For simplicity, *use the value $n = 1.00$ for air when solving problems.*

Did you know?

The index of refraction of any medium can also be expressed as the ratio of the wavelength of light in a vacuum, λ_0, to the wavelength of light in that medium, λ_n, as shown in the following relation.

$$n = \frac{\lambda_0}{\lambda_n}$$

Table 1 Indices of Refraction for Various Substances*

Solids at 20°C	*n*	Liquids at 20°C	*n*
Cubic zirconia	2.20	Benzene	1.501
Diamond	2.419	Carbon disulfide	1.628
Fluorite	1.434	Carbon tetrachloride	1.461
Fused quartz	1.458	Ethyl alcohol	1.361
Glass, crown	1.52	Glycerine	1.473
Glass, flint	1.66	Water	1.333
Ice (at 0°C)	1.309		
Polystyrene	1.49		
Sodium chloride	1.544		
Zircon	1.923		

Gases at 0°C, 1 atm	*n*
Air	1.000 293
Carbon dioxide	1.000 450

*measured with light of vacuum wavelength = 589 nm

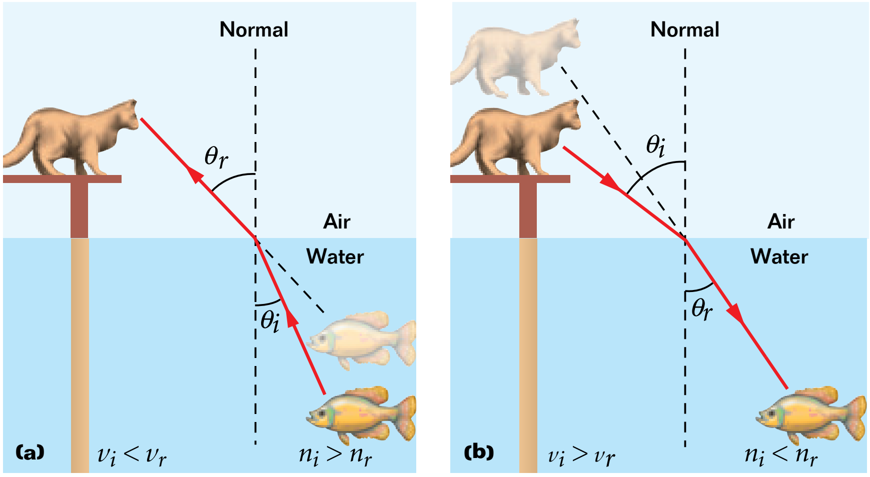


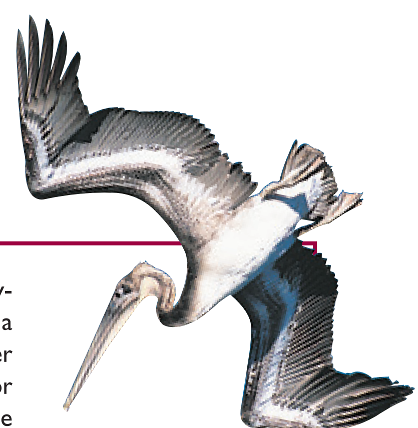
Figure 4
(a) To the cat on the pier, the fish looks closer to the surface than it really is. **(b)** To the fish, the cat seems to be farther from the surface than it actually is.

Objects appear to be in different positions due to refraction

When looking at a fish underwater, a cat sitting on a pier perceives the fish to be closer to the water's surface than it actually is, as shown in **Figure 4(a).** Conversely, the fish perceives the cat on the pier to be farther from the water's surface than it actually is, as shown in **Figure 4(b).**

Because of the reversibility of refraction, both the fish and the cat see along the same path, as shown by the solid lines in both figures. However, the light ray that reaches the fish forms a smaller angle with respect to the normal than does the light ray from the cat to the water's surface. The reason is that light is bent toward the normal when it travels from a medium with a lower index of refraction (the air) to one with a higher index of refraction (the water). Extending this ray along a straight line shows the cat's image to be above the cat's actual position.

On the other hand, the light ray that reaches the cat from the water's surface forms a larger angle with respect to the normal, because the light from the fish travels from a medium with a higher index of refraction to one with a lower index of refraction. Note that the fish's image is closer to the water's surface than the fish actually is. An underwater object seen from the air above appears larger than its actual size because the image, which is the same size as the object, is closer to the observer.



Conceptual Challenge

1. The Invisible Man H. G. Wells wrote a famous novel about a man who made himself invisible by changing his index of refraction. What would his index of refraction have to be to accomplish this?

2. Visibility for the Invisible Man Would the invisible man be able to see anything?

3. Fishing When trying to catch a fish, should a pelican dive into the water horizontally in front of or behind the image of the fish it sees?

Wavelength affects the index of refraction

Note that the indices of refraction listed in **Table 1** are only valid for light that has a wavelength of 589 nm in a vacuum. The reason is that the amount that light bends when entering a different medium depends on the wavelength of the light as well as the speed. Thus, a spectrum is produced when white light passes through a prism. Each color of light has a different wavelength. Therefore, each color of the spectrum is refracted by a different amount.

Snell's law determines the angle of refraction

The index of refraction of a material can be used to figure out how much a ray of light will be refracted as it passes from one medium to another. As mentioned, the greater the index of refraction, the more refraction occurs. But how can the angle of refraction be found?

In 1621, Willebrord Snell experimented with light passing through different media. He developed a relationship called Snell's law, which can be used to find the angle of refraction for light traveling between any two media.

SNELL'S LAW

$$n_i \sin \theta_i = n_r \sin \theta_r$$

index of refraction of first medium × sine of the angle of incidence = index of refraction of second medium × sine of the angle of refraction

SAMPLE PROBLEM A

Snell's Law

PROBLEM

A light ray of wavelength 589 nm (produced by a sodium lamp) traveling through air strikes a smooth, flat slab of crown glass at an angle of 30.0° to the normal. Find the angle of refraction, θ_r.

SOLUTION

Given: $\theta_i = 30.0°$ $\quad n_i = 1.00$ $\quad n_r = 1.52$

Unknown: $\theta_r = ?$

Use the equation for Snell's law.

$$n_i \sin \theta_i = n_r \sin \theta_r$$

$$\theta_r = \sin^{-1}\left[\frac{n_i}{n_r}(\sin \theta_i)\right] = \sin^{-1}\left[\frac{1.00}{1.52}(\sin 30.0°)\right]$$

$$\boxed{\theta_r = 19.2°}$$

PRACTICE A

Snell's Law

1. Find the angle of refraction for a ray of light that enters a bucket of water from air at an angle of 25.0° to the normal. (Hint: Use **Table 1.**)

2. For an incoming ray of light of vacuum wavelength 589 nm, fill in the unknown values in the following table. (Hint: Use **Table 1.**)

	from (medium)	to (medium)	θ_i	θ_r
a.	flint glass	crown glass	25.0°	?
b.	air	?	14.5°	9.80°
c.	air	diamond	31.6°	?

3. A ray of light of vacuum wavelength 550 nm traveling in air enters a slab of transparent material. The incoming ray makes an angle of 40.0° with the normal, and the refracted ray makes an angle of 26.0° with the normal. Find the index of refraction of the transparent material. (Assume that the index of refraction of air for light of wavelength 550 nm is 1.00.)

SECTION REVIEW

1. Sunlight passes into a raindrop at an angle of 22.5° from the normal at one point on the droplet. What is the angle of refraction?

2. For each of the following cases, will light rays be bent toward or away from the normal?

a. $n_i > n_r$, where $\theta_i = 20°$
b. $n_i < n_r$, where $\theta_i = 20°$
c. from air to glass with an angle of incidence of 30°
d. from glass to air with an angle of incidence of 30°

3. Find the angle of refraction of a ray of light that enters a diamond from air at an angle of 15.0° to the normal. (Hint: Use **Table 1.**)

4. Critical Thinking In which of the following situations will light from a laser be refracted?

a. traveling from air into a diamond at an angle of 30° to the normal
b. traveling from water into ice along the normal
c. upon striking a metal surface
d. traveling from air into a glass of iced tea at an angle of 25° to the normal

SECTION 2

Thin Lenses

SECTION OBJECTIVES

- Use ray diagrams to find the position of an image produced by a converging or diverging lens, and identify the image as real or virtual.
- Solve problems using the thin-lens equation.
- Calculate the magnification of lenses.
- Describe the positioning of lenses in compound microscopes and refracting telescopes.

TYPES OF LENSES

When light traveling in air enters a pane of glass, it is bent toward the normal. As the light exits the pane of glass, it is bent again. When the light exits, however, its speed increases as it enters the air, so the light bends away from the normal. Because the amount of refraction is the same regardless of whether light is entering or exiting a medium, the light rays are bent as much on exiting the pane of glass as they were on entering.

Curved surfaces change the direction of light

When the surfaces of a medium are curved, the direction of the normal line differs for each spot on the surface of the medium. Thus, when light passes through a medium that has one or more curved surfaces, the change in the direction of the light rays varies from point to point. This principle is applied in media called **lenses.** Like mirrors, lenses form images, but lenses do so by refraction rather than by reflection. The images formed can be either real or virtual, depending on the type of lens and on the placement of the object. Recall that a real image is formed when rays of light actually intersect to form the image. Virtual images form at a point from which light rays appear to come but do not actually come. Real images can be projected onto a screen; virtual images cannot.

lens

a transparent object that refracts light rays such that they converge or diverge to create an image

Lenses are commonly used to form images in optical instruments, such as cameras, telescopes, and microscopes. In fact, transparent tissue in the front of the human eye acts as a lens, converging light toward the light-sensitive retina, which lines the back of the eye.

A typical lens consists of a piece of glass or plastic ground so that each of its two refracting surfaces is a segment of either a sphere or a plane. **Figure 5** shows examples of lenses. Notice that the lenses are shaped differently. The lens that is thicker at the middle than it is at the rim, shown in **Figure 5(a),** is an example of a *converging* lens. The lens that is thinner at the middle than it

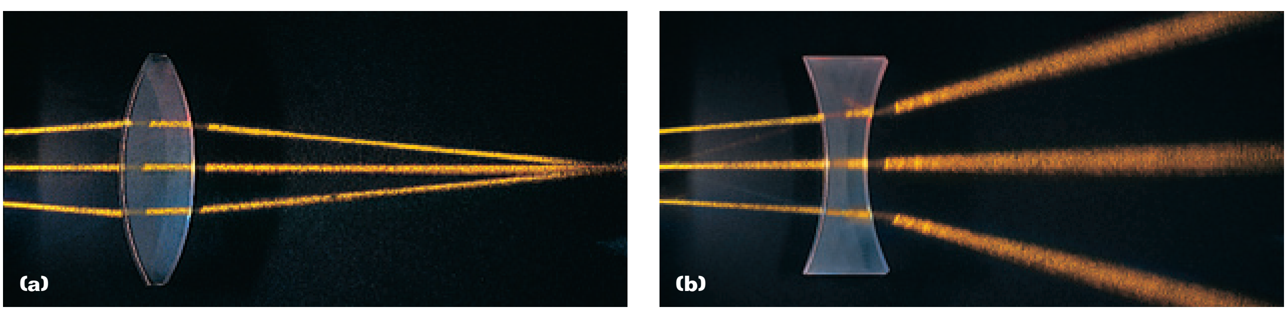


Figure 5
When rays of light pass through **(a)** a converging lens (thicker at the middle), they are bent inward. When they pass through **(b)** a diverging lens (thicker at the edge), they are bent outward.

is at the rim, shown in **Figure 5(b),** is an example of a *diverging* lens. The light rays show why the names *converging* and *diverging* are applied to these lenses.

Focal length is the image distance for an infinite object distance

As with mirrors, it is convenient to define a point called the *focal point* for a lens. Note that light rays from an object far away are nearly parallel. The focal point of a converging lens is the location where the image of an object at an infinite distance from the lens is focused. For example, in **Figure 6(a)** a group of rays parallel to the principal axis passes through a focal point, *F*, after being bent inward by the lens. Unlike mirrors, every lens has a focal point on each side of the lens because light can pass through the lens from either side, as illustrated in **Figure 6.** The distance from the focal point to the center of the lens is called the *focal length, f.* The focal length is the image distance that corresponds to an infinite object distance.

Rays parallel to the principal axis diverge after passing through a diverging lens, as shown in **Figure 6(b).** In this case, the focal point is defined as the point from which the diverged rays appear to originate. Again, the focal length is defined as the distance from the center of the lens to the focal point.

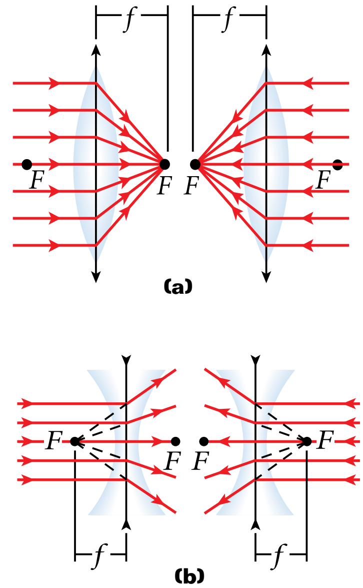


Figure 6
Both **(a)** converging lenses and **(b)** diverging lenses have two focal points but only one focal length.

Ray diagrams of thin-lens systems help identify image height and location

In the chapter on light and reflection, we used a set of standard rays and a ray diagram to predict the characteristics of images formed by spherical mirrors. A similar approach can be used for lenses.

We know, as shown in **Figure 5,** that refraction occurs at a boundary between two materials with different indexes of refraction. However, for *thin lenses* (lenses for which the thickness of the lens is small compared to the radius of curvature of the lens or the distance of the object from the lens), we can represent the front and back boundaries of the lens as a line segment passing through the center of the lens. To draw ray diagrams in the thin-lens approximation, we will use a line segment with arrow ends to indicate a converging lens, as in **Figure 6(a).** To show a diverging lens, we will draw a line segment with "upside-down" arrow ends, as illustrated in **Figure 6(b).** We can then draw ray diagrams using the set of rules outlined in **Table 2.**

Table 2 Rules for Drawing Reference Rays

Ray	From object to lens	From *converging* lens to image	From *diverging* lens to image
Parallel ray	parallel to principal axis	passes through focal point, *F*	directed away from focal point, *F*
Central ray	to the center of the lens	from the center of the lens	from the center of the lens
Focal ray	passes through focal point, *F*	parallel to principal axis	parallel to principal axis

The reasons why these rules work relate to concepts already covered in this textbook. From the definition of a focal point, we know that light traveling parallel to the principal axis (parallel ray) will be focused at the focal point. For a converging lens, this means that light will come together at the focal point in back of the lens. (In this book, the *front* of the lens is defined as the side of the lens that the light rays first encounter. The *back* of the lens refers to the side of the lens opposite where the light rays first encounter the lens.) But a similar ray passing through a diverging lens will exit the lens as if it originated from the focal point in front of the lens. Because refraction is reversible, a ray entering a converging lens from either focal point will be refracted so that it is parallel to the principal axis.

For both lenses, a ray passing through the center of the lens will continue in a straight line with no net refraction. This occurs because both sides of a lens are parallel to one another along any path through the center of the lens. As with a pane of glass, the exiting ray will be parallel to the ray that entered the lens. For ray diagrams, the usual assumption is that the lens is negligibly thin, so it is assumed that the ray is not displaced sideways but instead continues in a straight line.

Quick Lab

Focal Length

MATERIALS LIST

- magnifying glass
- ruler

SAFETY CAUTION

Care should be taken not to focus the sunlight onto a flammable surface or any body parts, such as hands or arms. Also, DO NOT look at the sun through the magnifying glass because serious eye injury can result.

On a sunny day, hold the magnifying glass, which is a converging lens, above a nonflammable surface, such as a sidewalk, so that a round spot of light is formed on the surface. Move the magnifying glass up and down to find the height at which the spot formed by the lens is most distinct, or smallest. Use the ruler to measure the distance between the magnifying glass and the surface. This distance is the approximate focal length of the lens.

CHARACTERISTICS OF LENSES

Table 3 summarizes the possible relationships between object and image positions for converging lenses. The rules for drawing reference rays were used to create each of these diagrams. Note that applications are listed along with each ray diagram to show the varied uses of the different configurations.

Converging lenses can produce real or virtual images of real objects

An object infinitely far away from a converging lens will create a point image at the focal point, as shown in the first diagram in **Table 3.** This image is real, which means that it can be projected on a screen.

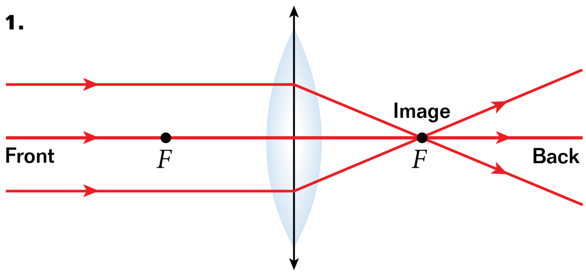
As a distant object approaches the focal point, the image becomes larger and farther away, as shown in the second, third, and fourth diagrams in **Table 3.** When the object is at the focal point, as shown in the fifth diagram, the light rays from the object are refracted so that they exit the lens parallel to each other. (Because the object is at the focal point, it is impossible to draw a third ray that passes through that focal point, the lens, and the tip of the object.)

When the object is between a converging lens and its focal point, the light rays from the object diverge when they pass through the lens, as shown in the sixth diagram in **Table 3.** This image appears to an observer in back of the lens as being on the same side of the lens as the object. In other words, the brain interprets these diverging rays as coming from an object directly along the path of the rays that reach the eye. The ray diagram for this final case is less straightforward than those drawn for the other cases in the table. The first two rays (parallel to the axis and through the center of the lens) are drawn in the usual

Table 3 Images Created by Converging Lenses

Ray diagrams

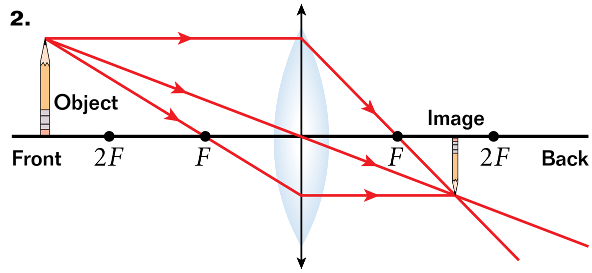
1.



Configuration: object at infinity; point image at *F*

Applications: burning a hole with a magnifying glass

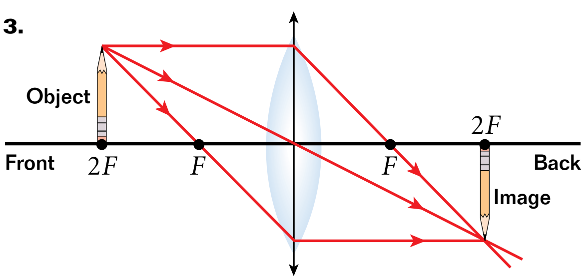
2.



Configuration: object outside 2*F*; real, smaller image between *F* and 2*F*

Applications: lens of a camera, human eyeball lens, and objective lens of a refracting telescope

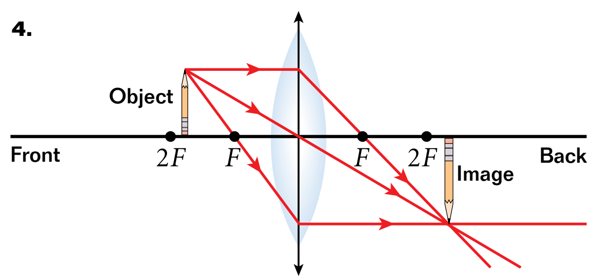
3.



Configuration: object at 2*F*; real image at 2*F* same size as object

Applications: inverting lens of a field telescope

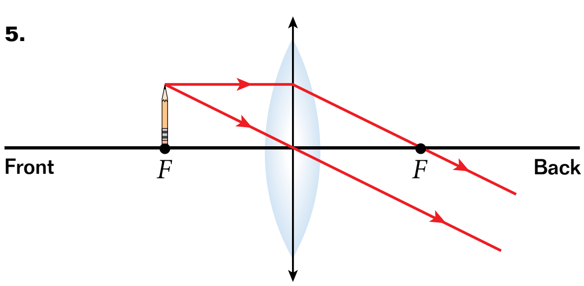
4.



Configuration: object between *F* and 2*F*; magnified real image outside 2*F*

Applications: motion-picture or slide projector and objective lens in a compound microscope

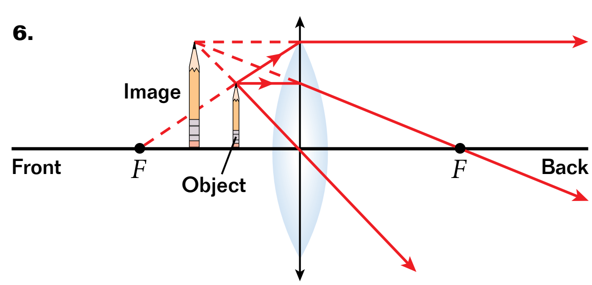
5.



Configuration: object at *F*; image at infinity

Applications: lenses used in lighthouses and searchlights

6.



Configuration: object inside *F*; magnified virtual image on the same side of the lens as the object

Applications: magnifying with a magnifying glass; eye-piece lens of microscope, binoculars, and telescope fashion. The third ray, however, is drawn so that if it were extended, it would connect the focal point in front of the lens, the tip of the object, and the lens in a straight line. To determine where the image is, draw lines extending from the rays exiting the lens back to the point where they would appear to have originated to an observer on the back side of the lens (these lines are dashed in the sixth diagram in **Table 3**).

Diverging lenses produce virtual images from real objects

A diverging lens creates a virtual image of a real object placed anywhere with respect to the lens. The image is upright, and the magnification is always less than one; that is, the image size is reduced. Additionally, the image appears inside the focal point for any placement of the real object.

Did you know?

The lens of a camera forms an inverted image on the film in the back of the camera. Two methods are used to view this image before taking a picture. In one, a system of mirrors and prisms reflects the image to the viewfinder, making the image upright in the process. In the other method, the viewfinder is a diverging lens that is separate from the main lens system. This lens forms an upright virtual image that resembles the image that will be projected onto the film.

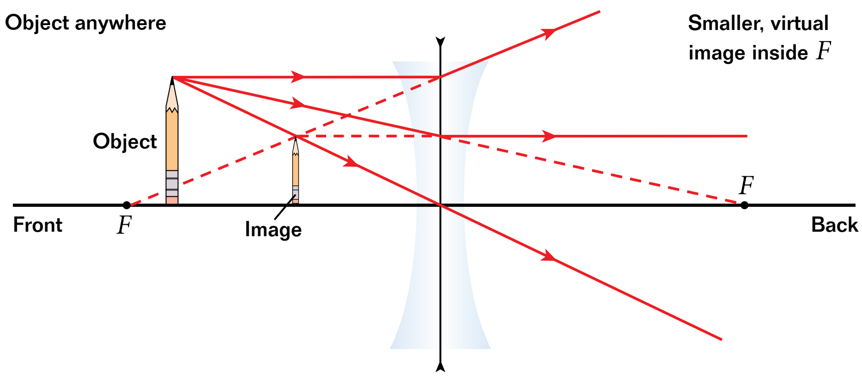


Figure 7
The image created by a diverging lens is always a virtual, smaller image.

The ray diagram shown in **Figure 7** for diverging lenses was created using the rules given in **Table 2.** The first ray, parallel to the axis, appears to come from the focal point on the same side of the lens as the object. This ray is indicated by the oblique dashed line. The second ray passes through the center of the lens and is not refracted. The third ray is drawn as if it were going to the focal point in back of the lens. As this ray passes through the lens, it is refracted parallel to the principal axis and must be extended backward, as shown by the dashed line. The location of the tip of the image is the point at which the three rays appear to have originated.

THE THIN-LENS EQUATION AND MAGNIFICATION

Ray diagrams for lenses give a good estimate of image size and distance, but it is also possible to calculate these values. The equation that relates object and image distances for a lens is called the *thin-lens equation* because it is derived using the assumption that the lens is very thin. In other words, this equation applies when the lens thickness is much smaller than its focal length.

THIN-LENS EQUATION

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

$$\frac{1}{\text{distance from object to lens}} + \frac{1}{\text{distance from image to lens}} = \frac{1}{\text{focal length}}$$

When using the thin-lens equation, we often illustrate it using the ray diagram model in which, for clarity, we magnify the vertical axis and show the lens position as a thin line. Always remember that the actual light rays bend at the lens surfaces and that our diagram showing bending at a single central line is an idealized model, which is quite good for thin lenses. But the model, and the equation, must be modified to deal properly with thick lenses, systems of lenses, and object and image points far from the principal axis.

The thin-lens equation can be applied to both converging and diverging lenses if we adhere to a set of sign conventions. **Table 4** gives the sign conventions for lenses. Under this convention, an image in back of the lens (that is, a real image) has a positive image distance, and an image in front of the lens, or a virtual image, has a negative image distance. A converging lens has a positive focal length and a diverging lens has a negative focal length. Therefore, converging lenses are sometimes called *positive lenses* and diverging lenses are sometimes called *negative lenses.*

Table 4
Sign Conventions for Lenses

	+	−
p	real object in front of the lens	real object in back of the lens
q	virtual image in back of the lens	virtual image in front of the lens
f	converging lens	diverging lens

Magnification by a lens depends on object and image distances

Recall that magnification (M) is defined as the ratio of image height to object height. The following equation can be used to calculate the magnification of both converging and diverging lenses.

MAGNIFICATION OF A LENS

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

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

If close attention is given to the sign conventions defined in **Table 4,** then the magnification will describe the image's size and orientation. When the magnitude of the magnification of an object is less than one, the image is smaller than the object. Conversely, when the magnitude of the magnification is greater than one, the image is larger than the object.

Additionally, a negative sign for the magnification indicates that the image is real and inverted. A positive magnification signifies that the image is upright and virtual.

PHYSICS INTERACTIVE TUTOR

Module 15
"Refraction and Lenses"
provides an interactive lesson with guided problem-solving practice to teach you about the images produced with different types of lenses.

SAMPLE PROBLEM B

Lenses

PROBLEM

An object is placed 30.0 cm in front of a converging lens and then 12.5 cm in front of a diverging lens. Both lenses have a focal length of 10.0 cm. For both cases, find the image distance and the magnification. Describe the images.

SOLUTION

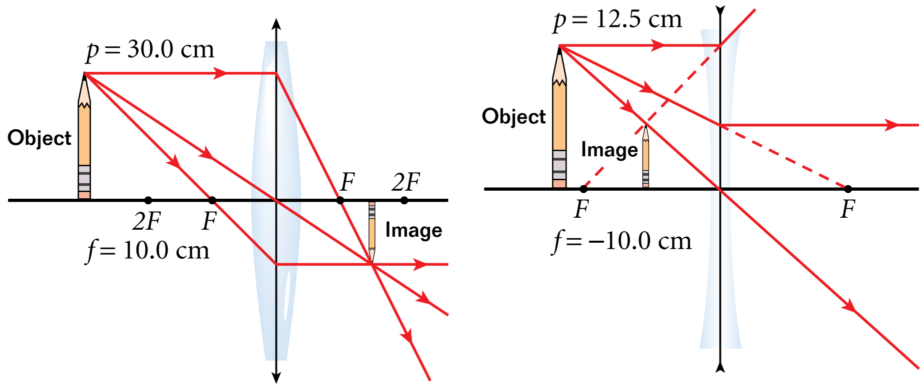
1. DEFINE

Given: $f_{converging} = 10.0$ cm $\quad f_{diverging} = -10.0$ cm

$p_{converging} = 30.0$ cm $\quad p_{diverging} = 12.5$ cm

Unknown: $q_{converging} = ?\quad M = ?\quad q_{diverging} = ?\quad M = ?$

Diagrams:



2. PLAN

Choose an equation or situation:

The thin-lens equation can be used to find the image distance, and the equation for magnification will serve to describe the size and orientation of the image.

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f} \qquad M = -\frac{q}{p}$$

Rearrange the equation to isolate the unknown:

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

3. CALCULATE

For the converging lens:

$$\frac{1}{q} = \frac{1}{f} - \frac{1}{p} = \frac{1}{10.0\text{ cm}} - \frac{1}{30.0\text{ cm}} = \frac{2}{30.0\text{ cm}}$$

$$\boxed{q = 15.0\text{ cm}}$$

$$M = -\frac{q}{p} = -\frac{15.0\text{ cm}}{30.0\text{ cm}}$$

$$\boxed{M = -0.500}$$

For the diverging lens:

$$\frac{1}{q} = \frac{1}{f} - \frac{1}{p} = \frac{1}{-10.0\text{ cm}} - \frac{1}{12.5\text{ cm}} = -\frac{22.5}{125\text{ cm}}$$

$$\boxed{q = -5.56\text{ cm}}$$

$$M = -\frac{q}{p} = -\frac{-5.56\text{ cm}}{12.5\text{ cm}}$$

$$\boxed{M = 0.445}$$

4. EVALUATE These values and signs for the converging lens indicate a real, inverted, smaller image. This is expected because the object distance is longer than twice the focal length of the converging lens. The values and signs for the diverging lens indicate a virtual, upright, smaller image formed inside the focal point. This is the only kind of image diverging lenses form.

PRACTICE B

Lenses

1. An object is placed 20.0 cm in front of a converging lens of focal length 10.0 cm. Find the image distance and the magnification. Describe the image.
2. Sherlock Holmes examines a clue by holding his magnifying glass at arm's length and 10.0 cm away from an object. The magnifying glass has a focal length of 15.0 cm. Find the image distance and the magnification. Describe the image that he observes.
3. An object is placed 20.0 cm in front of a diverging lens of focal length 10.0 cm. Find the image distance and the magnification. Describe the image.
4. Fill in the missing values in the following table.

	f	p	q	M
	Converging lens			
a.	6.0 cm	?	–3.0 cm	?
b.	2.9 cm	?	7.0 cm	?
	Diverging lens			
c.	–6.0 cm	4.0 cm	?	?
d.	?	5.0 cm	?	0.50

Quick Lab

Prescription Glasses

MATERIALS LIST

- several pairs of prescription eyeglasses

Hold a pair of prescription glasses at various distances from your eye, and look at different objects through the lenses. Try this with different types of glasses, such as those for farsightedness and nearsightedness, and describe what effect the differences have on the image you see. If you have bifocals, how do the images produced by the top and bottom portions of the bifocal lens compare?

EYEGLASSES AND CONTACT LENSES

The transparent front of the eye, called the *cornea,* acts like a lens, directing light rays toward the light-sensitive *retina* in the back of the eye. Although most of the refraction of light occurs at the cornea, the eye also contains a small lens, called the *crystalline lens,* that refracts light as well.

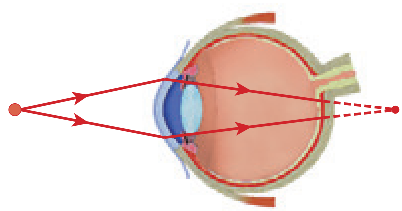
When the eye attempts to produce a focused image of a nearby object but the image position is behind the retina, the abnormality is known as *hyperopia,* and the person is said to be *farsighted.* With this defect, distant objects are seen clearly, but near objects are blurred. Either the hyperopic eye is too short or the ciliary muscle that adjusts the shape of the lens cannot adjust enough to properly focus the image. **Table 5** shows how hyperopia can be corrected with a converging lens.

Another condition, known as *myopia,* or *nearsightedness,* occurs either when the eye is longer than normal or when the maximum focal length of the lens is insufficient to produce a clear image on the retina. In this case, light from a distant object is focused in front of the retina. The distinguishing feature of this imperfection is that distant objects are not seen clearly. Nearsightedness can be corrected with a diverging lens, as shown in **Table 5.**

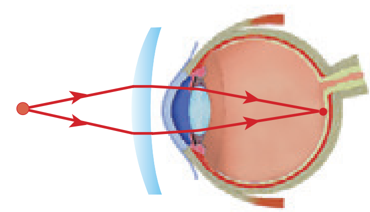
A contact lens is simply a lens worn directly over the cornea of the eye. The lens floats on a thin layer of tears.

Table 5 Farsighted and Nearsighted

Farsighted

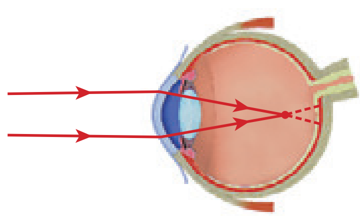


Hyperopia

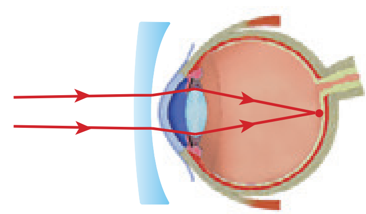


Corrected with a converging lens

Nearsighted



Myopia



Corrected with a diverging lens

COMBINATION OF THIN LENSES

If two lenses are used to form an image, the system can be treated in the following manner. First, the image of the first lens is calculated as though the second lens were not present. The light then approaches the second lens as if it had come from the image formed by the first lens. Hence, *the image formed by the first lens is treated as the object for the second lens.* The image formed by the second lens is the final image of the system. The overall magnification of a system of lenses is the product of the magnifications of the separate lenses. If the image formed by the first lens is in back of the second lens, then the image is treated as a virtual object for the second lens (that is, p is negative). The same procedure can be extended to a system of three or more lenses.

Compound microscopes use two converging lenses

A simple magnifier, such as a magnifying glass, provides only limited assistance when inspecting the minute details of an object. Greater magnification can be achieved by combining two lenses in a device called a *compound microscope.* It consists of two lenses: an objective lens (near the object) with a focal length of less than 1 cm and an eyepiece with a focal length of a few centimeters. As shown in **Figure 8,** the object placed just outside the focal point of the objective lens forms a real, inverted, and enlarged image that is at or just inside the focal point of the eyepiece. The eyepiece, which serves as a simple magnifier, uses this enlarged image as its object and produces an even more enlarged virtual image. The image viewed through a microscope is upside-down with respect to the actual orientation of the specimen, as shown in **Figure 8.**

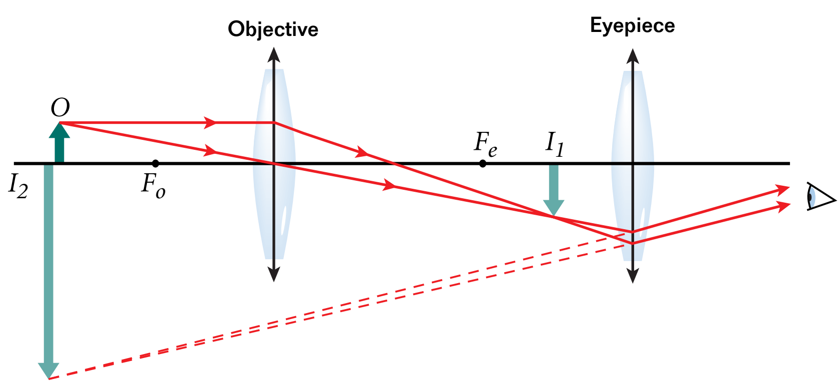


Figure 8
In a compound microscope, the real, inverted image produced by the objective lens is used as the object for the eyepiece lens.

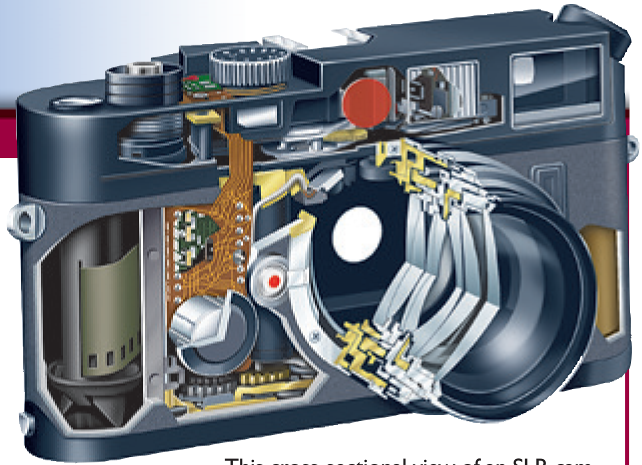
The microscope has extended our vision into the previously unknown realm of incredibly small objects. A question that is often asked about microscopes is, "With extreme patience and care, would it be possible to construct a microscope that would enable us to see an atom?" As long as visible light is used to illuminate the object, the answer is no. In order to be seen, the object under a microscope must be at least as large as a wavelength of light. An atom is many times smaller than a wavelength of visible light, so its mysteries must be probed through other techniques.

The Inside Story on Cameras

Cameras come in many types and sizes, from the small and simple "point-and-shoot" camera you might use to snap photos on a vacation to the large and complex video camera used to film a Hollywood motion picture. Most cameras have at least one lens, and more complex cameras may have 30 or more lenses and may even contain mirrors and prisms. However, the simplest camera, called a *pinhole camera,* consists of a closed, light-tight box with a small (about 0.5 mm) hole in it. A surprisingly good image can be made with a pinhole camera! The film is placed on the wall opposite the hole and must be exposed for quite a long time because not much light passes through the hole.

Making the hole a bit larger and adding a single, converging lens and a shutter, which opens and closes quickly to allow light to pass through the lens and expose the film, can make another simple camera called a *fixed-focus camera.* The film is located at the focal length of the lens, and a typical disposable camera is of this kind. This type of camera usually gives good images only for objects far from the camera. For close objects, the focus falls behind the film. Because the film location is fixed, the lens must be able to be moved away from the film and thus be "focused."

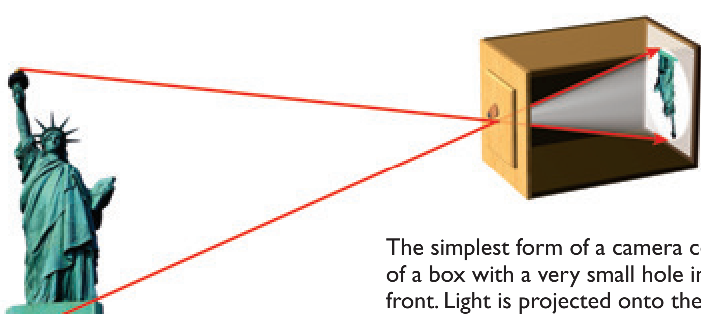
There are many types of camera lenses, and they are easily interchangeable on most *single-lens reflex* (SLR) cameras. A normal lens is one that provides about the same field of view as a human eye. Sometimes, however, a photographer wants to photograph distant objects with more detail or capture a larger object without taking multiple shots. A *wide-angle lens* has a very short focal length and can capture a larger field of view than a normal lens. A *telephoto lens* has a long focal length and increases magnification. Telephoto lenses have a narrow angle of view. *Zoom lenses* allow you to change the focal length without changing lenses. These camera lenses contain multiple lenses that can be moved relative to one another.



This cross-sectional view of an SLR camera shows the many optical elements used to form an image on the film.

High-quality cameras contain quite a few lenses, both converging and diverging, to minimize the *distortions* and *aberrations* that are created by a single converging lens. The most prevalent aberration occurs because lenses bend light of different colors by different amounts, causing, in effect, rainbows to appear in the image.

You may be wondering how the optics change for digital cameras. The lenses and shutters are essentially the same as those used in film cameras. However, the film is replaced by a *charge-coupled device* (CCD) array, an array of tiny sensors that produce a current when hit by light from the subject being photographed. Lenses must still focus the light coming from the subject onto the CCD array, as they must on film.



The simplest form of a camera consists of a box with a very small hole in the front. Light is projected onto the inside back of the box.

Refracting telescopes also use two converging lenses

As mentioned in the chapter on light and reflection, there are two types of telescopes, reflecting and refracting. In a refracting telescope, an image is formed at the eye in much the same manner as is done with a microscope. A small, inverted image is formed at the focal point of the objective lens, F_0, because the object is essentially at infinity. The eyepiece is positioned so that its focal point lies very close to the focal point of the objective lens, where the image is formed, as shown in **Figure 9.** Because the image is now just inside the focal point of the eyepiece, F_e, the eyepiece acts like a simple magnifier and allows the viewer to examine the object in detail.

extension

Integrating Astronomy
Visit go.hrw.com for the activity "The Refracting Telescope at Yerkes."
Keyword HF6REFX

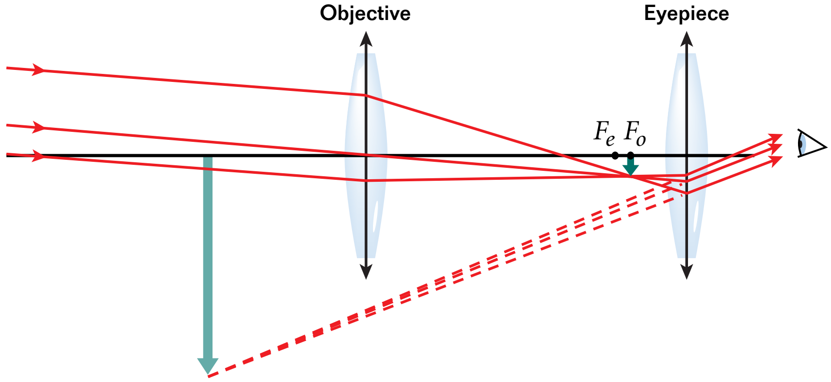


Figure 9
The image produced by the objective lens of a refracting telescope is a real, inverted image that is at its focal point. This inverted image, in turn, is the object from which the eyepiece creates a magnified, virtual image.

SECTION REVIEW

1. What type of image is produced by the cornea and the lens on the retina?

2. What type of image, virtual or real, is produced in the following cases?
  a. an object inside the focal point of a camera lens
  b. an object outside the focal point of a refracting telescope's objective lens
  c. an object outside the focal point of a camera's viewfinder

3. Find the image position for an object placed 3.0 cm outside the focal point of a converging lens with a 4.0 cm focal length.

4. What is the magnification of the object from item 3?

5. Interpreting Graphics Using a ray diagram, find the position and height of an image produced by a viewfinder in a camera with a focal length of 5.0 cm if the object is 1.0 cm tall and 10.0 cm in front of the lens. A camera viewfinder is a diverging lens.

6. Critical Thinking Compare the length of a refracting telescope with the sum of the focal lengths of its two lenses.

SECTION 3

Optical Phenomena

SECTION OBJECTIVES

- **Predict whether light will be refracted or undergo total internal reflection.**
- **Recognize atmospheric conditions that cause refraction.**
- **Explain dispersion and phenomena such as rainbows in terms of the relationship between the index of refraction and the wavelength.**

TOTAL INTERNAL REFLECTION

An interesting effect called **total internal reflection** can occur when light moves along a path from a medium with a *higher* index of refraction to one with a *lower* index of refraction. Consider light rays traveling from water into air, as shown in **Figure 10(a).** Four possible directions of the rays are shown in the figure.

At some particular angle of incidence, called the **critical angle,** the refracted ray moves parallel to the boundary, making the angle of refraction equal to 90°, as shown in **Figure 10(b).** For angles of incidence greater than the critical angle, the ray is entirely reflected at the boundary, as shown in **Figure 10.** This ray is reflected at the boundary as though it had struck a perfectly reflecting surface. Its path and the path of all rays like it can be predicted by the law of reflection; that is, the angle of incidence equals the angle of reflection.

In optical equipment, prisms are arranged so that light entering the prism is totally internally reflected off the back surface of the prism. Prisms are used in place of silvered or aluminized mirrors because they reflect light more efficiently and are more scratch resistant.

Snell's law can be used to find the critical angle. As mentioned above, when the angle of incidence, θ_i, equals the critical angle, θ_c, then the angle of refraction, θ_r, equals 90°. Substituting these values into Snell's law gives the following relation.

$$n_i \sin \theta_c = n_r \sin 90°$$

total internal reflection

the complete reflection that takes place within a substance when the angle of incidence of light striking the surface boundary is greater than the critical angle

critical angle

the angle of incidence at which the refracted light makes an angle of 90° with the normal

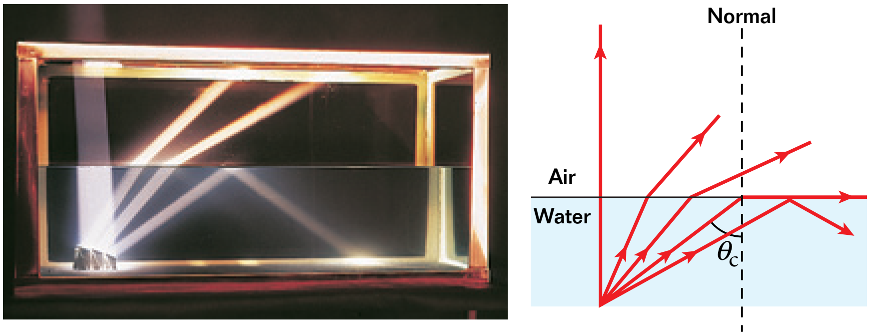


Figure 10
(a) This photo demonstrates several different paths of light radiated from the bottom of an aquarium. **(b)** At the critical angle, θ_c, a light ray will travel parallel to the boundary. Any rays with an angle of incidence greater than θ_c will be totally internally reflected at the boundary.

Because the sine of 90° equals 1, the following relationship results.

CRITICAL ANGLE

$$\sin \theta_c = \frac{n_r}{n_i} \quad \text{for } n_i > n_r$$

$$\text{sine (critical angle)} = \frac{\text{index of refraction of second medium}}{\text{index of refraction of first medium}}$$

but only if index of refraction of first medium > index of refraction of second medium

Note that this equation can be used only when n_i is greater than n_r. In other words, *total internal reflection occurs only when light moves along a path from a medium of higher index of refraction to a medium of lower index of refraction.* If n_i were less than n_r, this equation would give $\sin \theta_c > 1$, which is an impossible result because by definition the sine of an angle can never be greater than 1.

When the second substance is air, the critical angle is small for substances with large indices of refraction. Diamonds, which have an index of refraction of 2.419, have a critical angle of 24.4°. By comparison, the critical angle for crown glass, a very clear optical glass, where $n = 1.52$, is 41.0°. Because diamonds have such a small critical angle, most of the light that enters a cut diamond is totally internally reflected. The reflected light eventually exits the diamond from the most visible faces of the diamond. Jewelers cut diamonds so that the maximum light entering the upper surface is reflected back to these faces.

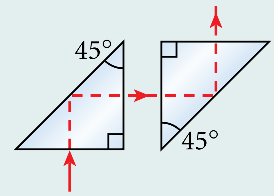
Quick Lab

Periscope

MATERIALS LIST

- two 90° prisms

Align the two prisms side by side as shown below.



Note that this configuration can be used like a periscope to see an object above your line of sight if the configuration is oriented vertically and to see around a corner if it is oriented horizontally. How would you arrange the prisms to see behind you? Draw your design on paper and test it.

SAMPLE PROBLEM C

Critical Angle

PROBLEM

Find the critical angle for a water-air boundary if the index of refraction of water is 1.333.

SOLUTION

Given: $n_i = 1.333 \quad n_r = 1.000$

Unknown: $\theta_c = ?$

Use the equation for critical angle on this page.

$$\sin \theta_c = \frac{n_r}{n_i}$$

$$\theta_c = \sin^{-1}\left(\frac{n_r}{n_i}\right) = \sin^{-1}\left(\frac{1.00}{1.333}\right)$$

$$\boxed{\theta_c = 48.6°}$$

TIP *Remember that the critical angle equation is valid only if the light is moving from a higher to a lower index of refraction.*

PRACTICE C

Critical Angle

1. Glycerine is used to make soap and other personal care products. Find the critical angle for light traveling from glycerine ($n = 1.473$) into air.

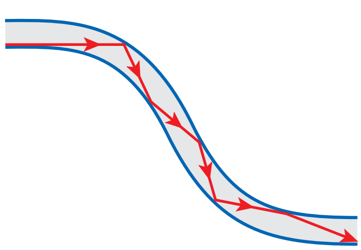
2. Calculate the critical angle for light traveling from glycerine ($n = 1.473$) into water ($n = 1.333$).

3. Ice has a lower index of refraction than water. Find the critical angle for light traveling from ice ($n = 1.309$) into air.

4. Which has a smaller critical angle in air, diamond ($n = 2.419$) or cubic zirconia ($n = 2.20$)? Show your work.

The Inside Story on Fiber Optics

Another interesting application of total internal reflection is the use of glass or transparent plastic rods, like the ones shown in the photograph, to transfer light from one place to another. As indicated in the illustration below, light is confined to traveling within the rods, even around gentle curves, as a result of successive internal reflections. Such a *light pipe* can be flexible if thin fibers rather than thick rods are used. If a bundle of parallel fibers is used to construct an optical transmission line, images can be transferred from one point to another.



Light is guided along a fiber by multiple internal reflections.

This technique is used in a technology known as *fiber optics*. Very little light intensity is lost in these fibers as a result of reflections on the sides. Any loss of intensity is due essentially to reflections from the two ends and absorption by the fiber material. Fiber-optic devices are particularly useful for viewing images produced at inaccessible locations. For example, a fiber-optic cable can be threaded through the esophagus and into the stomach to look for ulcers.

Fiber optic cables are widely used in telecommunications because the fibers can carry much higher volumes of telephone calls and computer signals than can electrical wires.

ATMOSPHERIC REFRACTION

We see an example of refraction every day: the sun can be seen even after it has passed below the horizon. Rays of light from the sun strike Earth's atmosphere and are bent because the atmosphere has an index of refraction different from that of the near-vacuum of space. The bending in this situation is gradual and continuous because the light moves through layers of air that have a continuously changing index of refraction. Our eyes follow them back along the direction from which they appear to have come.

Refracted light produces mirages

The *mirage* is another phenomenon of nature produced by refraction in the atmosphere. A mirage can be observed when the ground is so hot that the air directly above it is warmer than the air at higher elevations.

These layers of air at different heights above Earth have different densities and different refractive indices. The effect this can have is pictured in **Figure 11.** In this situation, the observer sees a tree in two different ways. One group of light rays reaches the observer by the straight-line path *A*, and the eye traces these rays back to see the tree in the normal fashion. A second group of rays travels along the curved path *B*. These rays are directed toward the ground and are then bent as a result of refraction. Consequently, the observer also sees an inverted image of the tree by tracing these rays back to the point at which they appear to have originated. Because both an upright image and an inverted image are seen when the image of a tree is observed in a reflecting pool of water, the observer subconsciously calls upon this past experience and concludes that a pool of water must be in front of the tree.

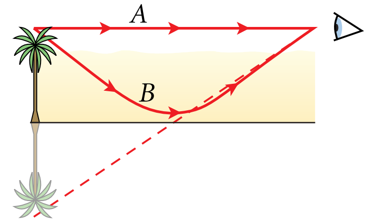


Figure 11
A mirage is produced by the bending of light rays in the atmosphere when there are large temperature differences between the ground and the air.

DISPERSION

An important property of the index of refraction is that its value in anything but a vacuum depends on the wavelength of light. Because the index of refraction is a function of wavelength, Snell's law indicates that incoming light of different wavelengths is bent at different angles as it moves into a refracting material. This phenomenon is called **dispersion.** As mentioned in Section 1, the index of refraction decreases with increasing wavelength. For instance, blue light ($\lambda \approx 470$ nm) bends more than red light ($\lambda \approx 650$ nm) when passing into a refracting material.

dispersion

the process of separating polychromatic light into its component wavelengths

White light passed through a prism produces a visible spectrum

To understand how dispersion can affect light, consider what happens when light strikes a prism, as in **Figure 12.** Because of dispersion, the blue component of the incoming ray is bent more than the red component, and the rays that emerge from the second face of the prism fan out in a series of colors known as a *visible spectrum*. These colors, in order of decreasing wavelength, are red, orange, yellow, green, blue, and violet.

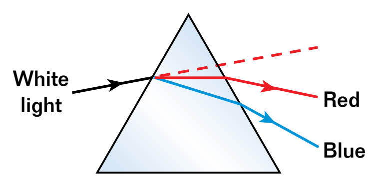


Figure 12
When white light enters a prism, the blue light is bent more than the red, and the prism disperses the white light into its various spectral components.

Rainbows are created by dispersion of light in water droplets

The dispersion of light into a spectrum is demonstrated most vividly in nature by a rainbow, often seen by an observer positioned between the sun and a rain shower. When a ray of sunlight strikes a drop of water in the atmosphere, it is first refracted at the front surface of the drop, with the violet light refracting the most and the red light the least. Then, at the back surface of the drop, the

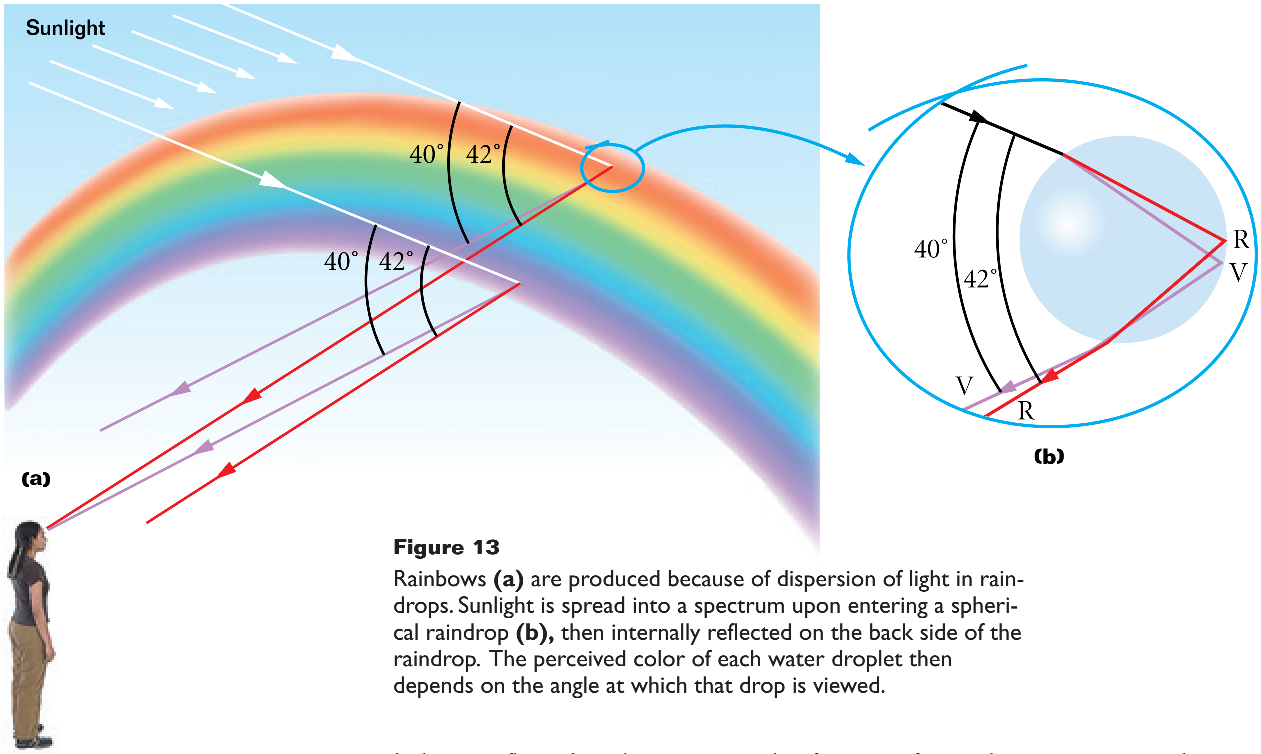


Figure 13
Rainbows **(a)** are produced because of dispersion of light in raindrops. Sunlight is spread into a spectrum upon entering a spherical raindrop **(b),** then internally reflected on the back side of the raindrop. The perceived color of each water droplet then depends on the angle at which that drop is viewed.

light is reflected and returns to the front surface, where it again undergoes refraction as it moves from water into air. The rays leave the drop so that the angle between the incident white light and the returning violet ray is 40° and the angle between the white light and the returning red ray is 42°, as shown in **Figure 13(b).**

Now, consider **Figure 13(a).** When an observer views a raindrop high in the sky, the red light reaches the observer, but the violet light, like the other spectral colors, passes over the observer because it deviates from the path of the white light more than the red light does. Hence, the observer sees this drop as being red. Similarly, a drop lower in the sky would direct violet light toward the observer and appear to be violet. (The red light from this drop would strike the ground and not be seen.) The remaining colors of the spectrum would reach the observer from raindrops lying between these two extreme positions.

Note that rainbows are most commonly seen above the horizon, where the ends of the rainbow disappear into the ground. However, if an observer is at an elevated vantage point, such as on an airplane or at the rim of a canyon, a complete circular rainbow can be seen.

LENS ABERRATIONS

One of the basic problems of lenses and lens systems is the imperfect quality of the images. The simple theory of mirrors and lenses assumes that rays make small angles with the principal axis and that all rays reaching the lens or mirror from a point source are focused at a single point, producing a sharp image. Clearly, this is not always true in the real world. Where the approximations used in this theory do not hold, imperfect images are formed.

As with spherical mirrors, *spherical aberration* occurs for lenses also. It results from the fact that the focal points of light rays far from the principal axis of a spherical lens are different from the focal points of rays with the same wavelength passing near the axis. Rays near the middle of the lens are focused farther from the lens than rays at the edges.

Another type of aberration, called **chromatic aberration,** arises from the wavelength dependence of refraction. Because the index of refraction of a material varies with wavelength, different wavelengths of light are focused at different focal points by a lens. For example, when white light passes through a lens, violet light is refracted more than red light, as shown in **Figure 14;** thus, the focal length for red light is greater than that for violet light. Other colors' wavelengths have intermediate focal points. Because a diverging lens has the opposite shape, the chromatic aberration for a diverging lens is opposite that for a converging lens. Chromatic aberration can be greatly reduced by the use of a combination of converging and diverging lenses made from two different types of glass.

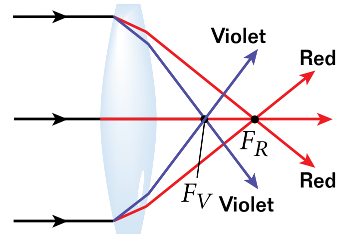


Figure 14
Because of dispersion, white light passing through a converging lens is focused at different focal points for each wavelength of light. (The angles in this figure are exaggerated for clarity.)

chromatic aberration

the focusing of different colors of light at different distances behind a lens

SECTION REVIEW

1. Find the critical angle for light traveling from water ($n = 1.333$) into ice ($n = 1.309$).
2. Which of the following describe places where a mirage is likely to appear?
   a. above a warm lake on a warm day
   b. above an asphalt road on a hot day
   c. above a ski slope on a cold day
   d. above the sand on a beach on a hot day
   e. above a black car on a sunny day
3. When white light passes through a prism, which will be bent more, the red or green light?
4. **Critical Thinking** After a storm, a man walks out onto his porch. Looking to the east, he sees a rainbow that has formed above his neighbor's house. What time of day is it, morning or evening?

PHYSICS CAREERS

Optometrist

The job of an optometrist is to correct imperfect vision using optical devices such as eyeglasses or contact lenses. Optometrists also treat diseases of the eye such as glaucoma. To learn more about optometry as a career, read the interview with Dewey Handy, O.D.

Dr. Dewey Handy uses optical devices to test the vision of a patient.

How did you decide to become an optometrist?

For a while, I didn't know what career I was going to choose. In high school, I had a great love for geometry and an interest in science and anatomy. In college, I was looking for a challenge, so I ended up majoring in physics—almost by accident.

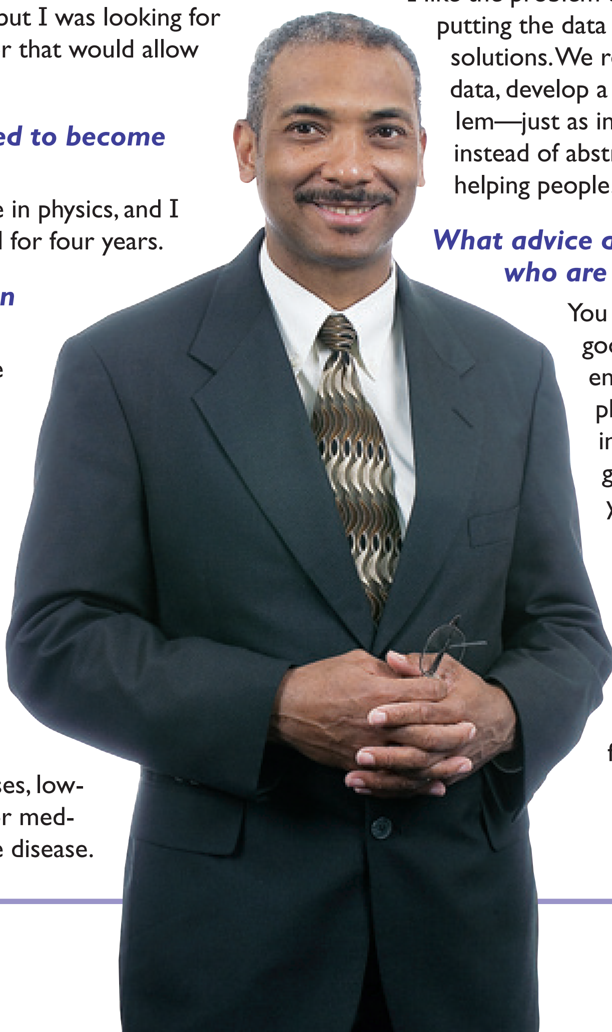
In college, I decided to apply my abilities in science to directly help people. I wasn't excited about dentistry or general medicine, but I was looking for something in a health career that would allow me to use physics.

What education is required to become an optometrist?

I have a bachelor of science in physics, and I attended optometry school for four years.

What sort of work does an optometrist do?

After taking a complete eye and medical history, the doctor may use prisms and/or lenses to determine the proper prescription for the patient. Then, a series of neurological, health, and binocular vision tests are done. After the history and data have been collected, a diagnosis and treatment plan are developed. This treatment may include glasses, contact lenses, low-vision aids, vision training, or medication for treatment of eye disease.



What do you enjoy most about your job?

I like the problem-solving nature of the work, putting the data together to come up with solutions. We read the problem, compile data, develop a formula, and solve the problem—just as in physics, but with people instead of abstract problems. I also like helping people.

What advice do you have for students who are interested in optometry?

You definitely need to have a good background in basic science: chemistry, biology, and physics. Even if you don't major in science, you need to have a good grasp of it by the time you get to optometry school.

Being well rounded will help you get into optometry school—and get out, too. You have to be comfortable doing the science, but you also have to be comfortable dealing with people.

CHAPTER 14 Highlights

KEY IDEAS

Section 1 Refraction

- According to Snell's law, as a light ray travels from one medium into another medium where its speed is different, the light ray will change its direction unless it travels along the normal.
- When light passes from a medium with a smaller index of refraction to one with a larger index of refraction, the ray bends toward the normal. For the opposite situation, the ray bends away from the normal.

Section 2 Thin Lenses

- The image produced by a converging lens is real and inverted when the object is outside the focal point and virtual and upright when the object is inside the focal point. Diverging lenses always produce upright, virtual images.
- The location of an image created by a lens can be found using either a ray diagram or the thin-lens equation.

Section 3 Optical Phenomena

- Total internal reflection can occur when light attempts to move from a material with a higher index of refraction to one with a lower index of refraction. If the angle of incidence of a ray is greater than the critical angle, the ray is totally reflected at the boundary.
- Mirages and the visibility of the sun after it has physically set are natural phenomena that can be attributed to refraction of light in Earth's atmosphere.

Variable Symbols

	Quantities	Units	
θ_i	angle of incidence	°	degrees
θ_r	angle of refraction	°	degrees
n	index of refraction		
p	distance from object to lens	m	meters
q	distance from image to lens	m	meters
h'	image height	m	meters
h	object height	m	meters
θ_c	critical angle	°	degrees

KEY TERMS

refraction (p. 488)

index of refraction (p. 490)

lens (p. 494)

total internal reflection (p. 506)

critical angle (p. 506)

dispersion (p. 509)

chromatic aberration (p. 511)

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.**

CHAPTER 14 Review

REFRACTION AND SNELL'S LAW

Review Questions

1. Does a light ray traveling from one medium into another always bend toward the normal?

2. As light travels from a vacuum ($n = 1$) to a medium such as glass ($n > 1$), does its wavelength change? Does its speed change? Does its frequency change?

3. What is the relationship between the speed of light and the index of refraction of a transparent substance?

4. Why does a clear stream always appear to be shallower than it actually is?

5. What are the three conditions that must be met for refraction to occur?

Conceptual Questions

6. Two colors of light (X and Y) are sent through a glass prism, and X is bent more than Y. Which color travels more slowly in the prism?

7. Why does an oar appear to be bent when part of it is in the water?

8. A friend throws a coin into a pool. You close your eyes and dive toward the spot where you saw it from the edge of the pool. When you reach the bottom, will the coin be in front of you or behind you?

9. The level of water ($n = 1.33$) in a clear glass container is easily observed with the naked eye. The level of liquid helium ($n = 1.03$) in a clear glass container is extremely difficult to see with the naked eye. Explain why.

Practice Problems

For problems 10–14, see Sample Problem A.

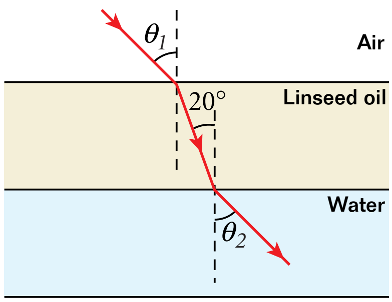
10. Light passes from air into water at an angle of incidence of 42.3°. Determine the angle of refraction in the water.

11. A ray of light enters the top of a glass of water at an angle of 36° with the vertical. What is the angle between the refracted ray and the vertical?

12. A narrow ray of yellow light from glowing sodium ($\lambda_0 = 589$ nm) traveling in air strikes a smooth surface of water at an angle of $\theta_i = 35.0°$. Determine the angle of refraction, θ_r.

13. A ray of light traveling in air strikes a flat 2.00 cm thick block of glass ($n = 1.50$) at an angle of 30.0° with the normal. Trace the light ray through the glass, and find the angles of incidence and refraction at each surface.

14. The light ray shown in the figure below makes an angle of 20.0° with the normal line at the boundary of linseed oil and water. Determine the angles θ_1 and θ_2. Note that $n = 1.48$ for linseed oil.



RAY DIAGRAMS AND THIN LENSES

Review Questions

15. Which type of lens can focus the sun's rays?

16. Why is no image formed when an object is at the focal point of a converging lens?

17. Consider the image formed by a thin converging lens. Under what conditions will the image be
    a. inverted?
    b. upright?
    c. real?
    d. virtual?
    e. larger than the object?
    f. smaller than the object?

18. Repeat a–f of item 17 for a thin diverging lens.

19. Explain this statement: The focal point of a converging lens is the location of an image of a point object at infinity. Based on this statement, can you think of a quick method for determining the focal length of a positive lens?

Conceptual Questions

20. If a glass converging lens is submerged in water, will its focal length be longer or shorter than when the lens is in air?

21. In order to get an upright image, slides must be placed upside down in a slide projector. What type of lens must the slide projector have? Is the slide inside or outside the focal point of the lens?

22. If there are two converging lenses in a compound microscope, why is the image still inverted?

23. In a Jules Verne novel, a piece of ice is shaped into the form of a magnifying lens to focus sunlight and thereby start a fire. Is this possible?

Practice Problems

For problems 24–26, see Sample Problem B.

24. An object is placed in front of a diverging lens with a focal length of 20.0 cm. For each object distance, find the image distance and the magnification. Describe each image.
    a. 40.0 cm
    b. 20.0 cm
    c. 10.0 cm

25. A person looks at a gem using a converging lens with a focal length of 12.5 cm. The lens forms a virtual image 30.0 cm from the lens. Determine the magnification. Is the image upright or inverted?

26. An object is placed in front of a converging lens with a focal length of 20.0 cm. For each object distance, find the image distance and the magnification. Describe each image.
    a. 40.0 cm
    b. 10.0 cm

TOTAL INTERNAL REFLECTION, ATMOSPHERIC REFRACTION, AND ABERRATIONS

Review Questions

27. Is it possible to have total internal reflection for light incident from air on water? Explain.

28. What are the conditions necessary for the occurrence of a mirage?

29. On a hot day, what is it that we are seeing when we observe a "water on the road" mirage?

30. Why does the arc of a rainbow appear with red colors on top and violet colors on the bottom?

31. What type of aberration is involved in each of the following situations?
    a. The edges of the image appear reddish.
    b. The central portion of the image cannot be clearly focused.
    c. The outer portion of the image cannot be clearly focused.
    d. The central portion of the image is enlarged relative to the outer portions.

Conceptual Questions

32. A laser beam passing through a nonhomogeneous sugar solution follows a curved path. Explain.

33. On a warm day, the image of a boat floating on cold water appears above the boat. Explain.

34. Explain why a mirror cannot give rise to chromatic aberration.

35. Why does a diamond show flashes of color when observed under ordinary white light?

Practice Problems

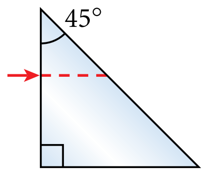
For problems 36–38, see Sample Problem C.

36. Calculate the critical angle for light going from glycerine into air.

37. Assuming that $\lambda = 589$ nm, calculate the critical angles for the following materials when they are surrounded by air:

a. zircon
b. fluorite
c. ice

38. Light traveling in air enters the flat side of a prism made of crown glass ($n = 1.52$), as shown at right. Will the light pass through the other side of the prism or will it be totally internally reflected? Be sure to show your work.



MIXED REVIEW

39. The angle of incidence and the angle of refraction for light going from air into a material with a higher index of refraction are 63.5° and 42.9°, respectively. What is the index of refraction of this material?

40. A person shines a light at a friend who is swimming underwater. If the ray in the water makes an angle of 36.2° with the normal, what is the angle of incidence?

41. What is the index of refraction of a material in which the speed of light is 1.85×10^8 m/s? Look at the indices of refraction in **Table 1** to identify this material.

42. Light moves from flint glass into water at an angle of incidence of 28.7°.

a. What is the angle of refraction?
b. At what angle would the light have to be incident to give an angle of refraction of 90.0°?

43. A magnifying glass has a converging lens of focal length 15.0 cm. At what distance from a nickel should you hold this lens to get an image with a magnification of +2.00?

44. The image of the United States postage stamps in the figure above is 1.50 times the size of the actual stamps in front of the lens. Determine the focal length of the lens if the distance from the lens to the stamps is 2.84 cm.

45. Where must an object be placed to have a magnification of 2.00 in each of the following cases? Show your work.

a. a converging lens of focal length 12.0 cm
b. a diverging lens of focal length 12.0 cm

46. A diverging lens is used to form a virtual image of an object. The object is 80.0 cm in front of the lens, and the image is 40.0 cm in front of the lens. Determine the focal length of the lens.

47. A microscope slide is placed in front of a converging lens with a focal length of 2.44 cm. The lens forms an image of the slide 12.9 cm from the slide.

a. How far is the lens from the slide if the image is real?
b. How far is the lens from the slide if the image is virtual?

48. Where must an object be placed to form an image 30.0 cm from a diverging lens with a focal length of 40.0 cm? Determine the magnification of the image.

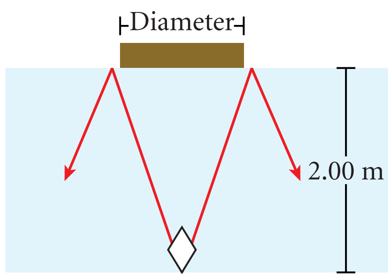
49. The index of refraction for red light in water is 1.331, and that for blue light is 1.340. If a ray of white light traveling in air enters the water at an angle of incidence of 83.0°, what are the angles of refraction for the red and blue components of the light?

50. A ray of light traveling in air strikes the surface of mineral oil at an angle of 23.1° with the normal to the surface. If the light travels at 2.17×10^8 m/s through the oil, what is the angle of refraction? (Hint: Remember the definition of the index of refraction.)

51. A ray of light traveling in air strikes the surface of a liquid. If the angle of incidence is 30.0° and the angle of refraction is 22.0°, find the critical angle for light traveling from the liquid back into the air.

52. The laws of refraction and reflection are the same for sound and for light. The speed of sound is 340 m/s in air and 1510 m/s in water. If a sound wave that is traveling in air approaches a flat water surface with an angle of incidence of 12.0°, what is the angle of refraction?

53. A jewel thief decides to hide a stolen diamond by placing it at the bottom of a crystal-clear fountain. He places a circular piece of wood on the surface of the water and anchors it directly above the diamond at the bottom of the fountain, as shown below. If the fountain is 2.00 m deep, find the minimum diameter of the piece of wood that would prevent the diamond from being seen from outside the water.



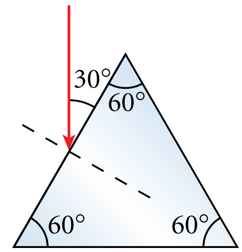
54. A ray of light traveling in air strikes the surface of a block of clear ice at an angle of 40.0° with the normal. Part of the light is reflected, and part is refracted. Find the angle between the reflected and refracted light.

55. An object's distance from a converging lens is 10 times the focal length. How far is the image from the lens? Express the answer as a fraction of the focal length.

56. A fiber-optic cable used for telecommunications has an index of refraction of 1.53. For total internal reflection of light inside the cable, what is the minimum angle of incidence to the inside wall of the cable if the cable is in the following:

a. air

b. water

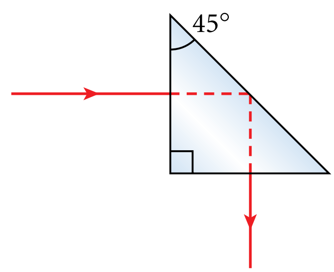


57. A ray of light traveling in air strikes the midpoint of one face of an equiangular glass prism ($n = 1.50$) at an angle of exactly 30.0°, as shown above.

a. Trace the path of the light ray through the glass, and find the angle of incidence of the ray at the bottom of the prism.

b. Will the ray pass through the bottom surface of the prism, or will it be totally internally reflected?

58. Light strikes the surface of a prism, $n = 1.8$, as shown in the figure below. If the prism is surrounded by a fluid, what is the maximum index of refraction of the fluid that will still cause total internal reflection within the prism?

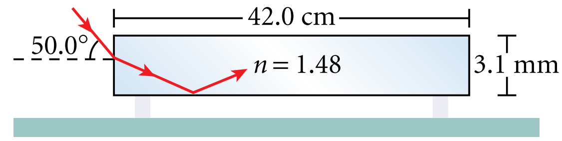


59. A fiber-optic rod consists of a central strand of material surrounded by an outer coating. The interior portion of the rod has an index of refraction of 1.60. If all rays striking the interior walls of the rod with incident angles greater than 59.5° are subject to total internal reflection, what is the index of refraction of the coating?

60. A flashlight on the bottom of a 4.00 m deep swimming pool sends a ray upward and at an angle so that the ray strikes the surface of the water 2.00 m from the point directly above the flashlight. What angle (in air) does the emerging ray make with the water's surface? (Hint: To determine the angle of incidence, consider the right triangle formed by the light ray, the pool bottom, and the imaginary line straight down from where the ray strikes the surface of the water.)

61. A submarine is 325 m horizontally out from the shore and 115 m beneath the surface of the water. A laser beam is sent from the submarine so that it strikes the surface of the water at a point 205 m from the shore. If the beam strikes the top of a building standing directly at the water's edge, find the height of the building. (Hint: To determine the angle of incidence, consider the right triangle formed by the light beam, the horizontal line drawn at the depth of the submarine, and the imaginary line straight down from where the beam strikes the surface of the water.)

62. A laser beam traveling in air strikes the midpoint of one end of a slab of material as shown in the figure below. The index of refraction of the slab is 1.48. Determine the number of internal reflections of the laser beam before it finally emerges from the opposite end of the slab.



Alternative Assessment

1. Interview an optometrist, optician, or ophthalmologist. Find out what equipment and tools each uses. What kinds of eye problems is each able to correct? What training is necessary for each career?

2. Obtain permission to use a microscope and slides from your school's biology teacher. Identify the optical components (lenses, mirror, object, and light source) and knobs. Find out how they function at different magnifications and what adjustments must be made to obtain a clear image. Sketch a ray diagram for the microscope's image formation. Estimate the size of the images you see, and calculate the approximate size of the actual cells or microorganisms you observe. How closely do your estimates match the magnification indicated on the microscope?

3. Construct your own telescope with mailing tubes (one small enough to slide inside the other), two lenses, cardboard disks for mounting the lenses, glue, and masking tape. Test your instrument at night. Try to combine different lenses and explore ways to improve your telescope's performance. Keep records of your results to make a brochure documenting the development of your telescope.

4. Research how phone, television, and radio signals are transmitted over long distances through fiber-optic devices. Obtain information from companies that provide telephone or cable television service. What materials are fiber-optic cables made of? What are their most important properties? Are there limits on the kind of light that travels in these cables? What are the advantages of fiber-optic technology over broadcast transmission? Produce a brochure or informational video to explain this technology to consumers.

5. When the Indian physicist Venkata Raman first saw the Mediterranean Sea, he proposed that its blue color was due to the structure of water molecules rather than to the scattering of light from suspended particles. Later, he won the Nobel Prize for work relating to the implications of this hypothesis. Research Raman's life and work. Find out about his background and the challenges and opportunities he met on his way to becoming a physicist. Create a presentation about him in the form of a report, poster, short video, or computer presentation.

63. A nature photographer is using a camera that has a lens with a focal length of 4.80 cm. The photographer is taking pictures of ancient trees in a forest and wants the lens to be focused on a very old tree that is 10.0 m away.

   a. How far must the lens be from the film in order for the resulting picture to be clearly focused?

   b. How much would the lens have to be moved to take a picture of another tree that is only 1.75 m away?

64. The distance from the front to the back of your eye is approximately 1.90 cm. If you can see a clear image of a book when it is 35.0 cm from your eye, what is the focal length of the lens/cornea system?

65. Suppose you look out the window and see your friend, who is standing 15.0 m away. To what focal length must your eye muscles adjust the lens of your eye so that you may see your friend clearly? Remember that the distance from the front to the back of your eye is about 1.90 cm.

Graphing Calculator Practice

Snell's Law

What happens to a light ray that passes from air into a medium whose index of refraction differs from that of air? Snell's law, as you learned earlier in this chapter, describes the relationship between the angle of refraction and the index of refraction.

$$n_i \sin \theta_i = n_r \sin \theta_r$$

In this equation, n_i is the index of refraction of the medium of the incident light ray, and θ_i is the angle of incidence; n_r is the index of refraction of the medium of the refracted light, and θ_r is the angle of refraction.

In this graphing calculator activity, you will enter the angle of incidence and will view a graph of the index of refraction versus the angle of refraction. You can use this graph to better understand the relationship between the index of refraction and the angle of refraction.

Visit go.hrw.com and enter the keyword **HF6REFX** to find this graphing calculator activity. Refer to **Appendix B** for instructions on downloading the program for this activity.

Standardized Test Prep

MULTIPLE CHOICE

1. How is light affected by an increase in the index of refraction?

A. Its frequency increases.
B. Its frequency decreases.
C. Its speed increases.
D. Its speed decreases.

2. Which of the following conditions is *not* necessary for refraction to occur?

F. Both the incident and refracting substances must be transparent.
G. Both substances must have different indices of refraction.
H. The light must have only one wavelength.
J. The light must enter at an angle greater than 0° with respect to the normal.

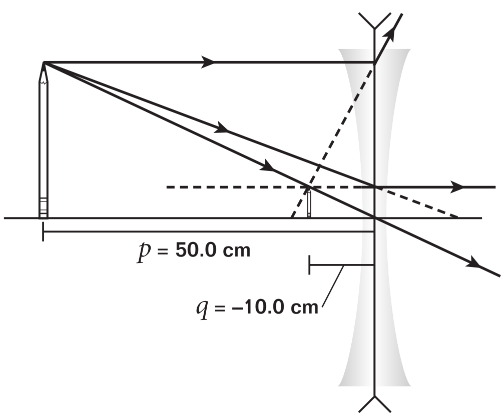
Use the ray diagram below to answer questions 3–4.

3. What is the focal length of the lens?

A. –12.5 cm
B. –8.33 cm
C. 8.33 cm
D. 12.5 cm

4. What is true of the image formed by the lens?

F. real, inverted, and enlarged
G. real, inverted, and diminished
H. virtual, upright, and enlarged
J. virtual, upright, and diminished



5. A block of flint glass with an index of refraction of 1.66 is immersed in oil with an index of refraction of 1.33. How does the critical angle for a refracted light ray in the glass vary from when the glass is surrounded by air?

A. It remains unchanged.
B. It increases.
C. It decreases.
D. No total internal reflection takes place when the glass is placed in the oil.

6. Which color of light is most refracted during dispersion by a prism?

F. red
G. yellow
H. green
J. violet

7. If an object in air is viewed from beneath the surface of water below, where does the object appear to be?

A. The object appears above its true position.
B. The object appears exactly at its true position.
C. The object appears below its true position.
D. The object cannot be viewed from beneath the water's surface.

8. The phenomenon called "looming" is similar to a mirage, except that the inverted image appears above the object instead of below it. What must be true if looming is to occur?

F. The temperature of the air must increase with distance above the surface.
G. The temperature of the air must decrease with distance above the surface.
H. The mass of the air must increase with distance above the surface.
J. The mass of the air must increase with distance above the surface.

9. Light with a vacuum wavelength of 500.0 nm passes into benzene, which has an index of refraction of 1.5. What is the wavelength of the light within the benzene?
   A. 0.0013 nm
   B. 0.0030 nm
   C. 330 nm
   D. 750 nm

10. Which of the following is *not* a necessary condition for seeing a magnified image with a lens?
   F. The object and image are on the same side of the lens.
   G. The lens must be converging.
   H. The observer must be placed within the focal length of the lens.
   J. The object must be placed within the focal length of the lens.

SHORT RESPONSE

11. In both microscopes and telescopes, at least two converging lenses are used: one for the objective and one for the eyepiece. These lenses must be positioned in such a way that the final image is virtual and very much enlarged. In terms of the focal points of the two lenses, how must the lenses be positioned?

12. A beam of light passes from the fused quartz of a bottle ($n = 1.46$) into the ethyl alcohol ($n = 1.36$) that is contained inside the bottle. If the beam of the light inside the quartz makes an angle of 25.0° with respect to the normal of both substances, at what angle to the normal will the light enter the alcohol?

13. A layer of glycerine ($n = 1.47$) covers a zircon slab ($n = 1.92$). At what angle to the normal must a beam of light pass through the zircon toward the glycerine so that the light undergoes total internal reflection?

EXTENDED RESPONSE

14. Explain how light passing through raindrops is reflected and dispersed so that a rainbow is produced. Include in your explanation why the lower band of the rainbow is violet and the outer band is red.

Use the ray diagram below to answer questions 15–18.

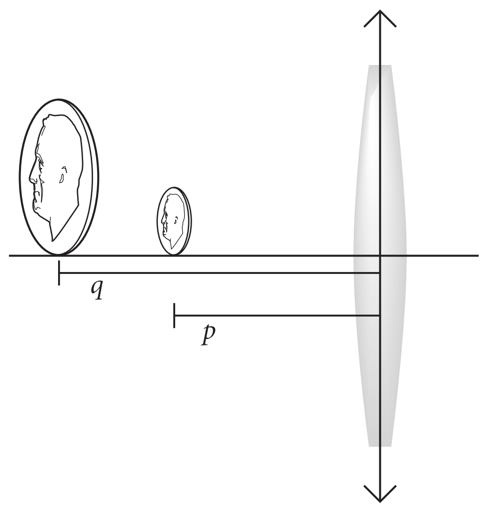
A collector wishes to observe a coin in detail and so places it 5.00 cm in front of a converging lens. An image forms 7.50 cm in front of the lens, as shown in the figure below.

15. What is the focal length of the lens?

16. What is the magnification of the coin's image?

17. If the coin has a diameter of 2.8 cm, what is the diameter of the coin's image?

18. Is the coin's image virtual or real? upright or inverted?



Test TIP When calculating the value of an angle by taking the arcsine of a quantity, recall that the quantity must be positive and no greater than 1.

CHAPTER 14

Skills Practice Lab

Converging Lenses

OBJECTIVE

- **Investigate** the relationships between the positions of the lens and object, and the position and size of the image.

MATERIALS LIST

- 2 screen support riders
- cardboard image screen with metric scale
- converging lens
- dc power supply
- insulated copper wire, 2 lengths
- lens support rider
- meterstick and meterstick supports
- metric ruler
- miniature lamp and base on rider
- object screen

Converging lenses can produce both real and virtual images, and they can produce images that are smaller, the same size as, or larger than the object. In this experiment, you will study image formation using a converging lens.

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.**
- **Never put broken glass or ceramics 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.**

PROCEDURE

Preparation

1. Read the entire lab, and plan what measurements you will take.
2. If you are not using a datasheet provided by your teacher, prepare a data table in your lab notebook with eight columns and six rows. In the first row, label the columns *Trial, Position of Lens (cm), Position of Object (cm), Position of Image (cm), q (cm), p (cm),* h_o *(cm),* and h_i *(cm).* In the first column, label the second through sixth rows *1, 2, 3, 4,* and *5.*

Formation of Images

3. Set up the meterstick, meterstick supports, image screen, and lens as shown in **Figure 1.** Locate and mark the point on the mounted screen where it intercepts the principal axis of the mounted lens.
4. Place the illuminated object screen at one end of the meterstick. Make adjustments so that the center of the object screen coincides with the principal axis of the lens.
5. Place the lens far enough from the object screen to give an object distance greater than twice the focal length of the lens. Move the image screen along the meterstick until the image is as well defined as possible. Read and record in your data table the positions of the object, lens, and image to the nearest millimeter on the meterstick. Also record the object distance, p, the image distance, q, the height of the object, h_o, and the height of the image, h_i.

6. Repeat step 5 four times with the lens at a different position each time. These positions should give the following object distances:

   a. exactly twice the focal length
   b. between one and two focal lengths
   c. exactly one focal length
   d. less than one focal length

   Record all measurements as in step 5. If you do not see an image, place *X*s in your data table for that trial.

7. Set the object distance less than one focal length, remove the image screen, and place your eye close to the lens. Look through the lens at the object, and record your observations.

8. Clean up your work area. Put equipment away safely. Recycle or dispose of used materials as directed by your teacher.

Figure 1

Step 3: Make sure the image screen is securely held in the screen support rider to prevent its moving during the experiment.

Step 4: Use the illuminated object screen as the object for this part of the lab.

ANALYSIS

1. **Organizing Data** For each trial recorded in the data table, perform the following calculations:

   a. Find the reciprocal of the object distance, p.
   b. Find the reciprocal of the image distance, q.
   c. Add the reciprocals found in **(a)** and **(b)**.
   d. Find the inverse of your answer in **(c)**.

2. **Organizing Data** For each trial, perform the following calculations:

   a. Find the ratio between q and p.
   b. Find the ratio between h_i and h_o.

CONCLUSIONS

3. **Recognizing Patterns** Compare the inverse of the sum of the reciprocals for each trial with the focal length of the lens. What is the relationship? Is this true for all trials? Explain.

4. **Recognizing Patterns** For each trial, compare the ratios found in item 2.

   a. Based on your results, what physical quantity is expressed by each of the ratios found in item 2?
   b. What is the relationship between the two ratios for each trial? Is this true for all trials? Explain.