

# Chapter 5

## LIGHT

### **Chapter Check-In**

- Understanding the basic characteristics of light
- Applying the rules of geometric optics to understand mirrors, lens, and refraction
- Analyzing the wave properties of light to understand diffraction and interference

**N**ewton proposed the **particle theory of light** to explain the bending of light upon reflection from a mirror or upon refraction when passing from air into water. In his view, light was a stream of particles emitted from a light source, entering the eye to stimulate sight. Newton's contemporary Christiaan Huygens showed that a **wave theory of light** could explain the laws of reflection and refraction. In the late 1800s, James Clerk Maxwell predicted, and then Gustav Ludwig Hertz verified, the existence of electromagnetic waves traveling at the speed of light. A complete conceptualization of the nature of light includes light as a particle, as a wave, and as electromagnetic radiation.

### **Characteristics of Light**

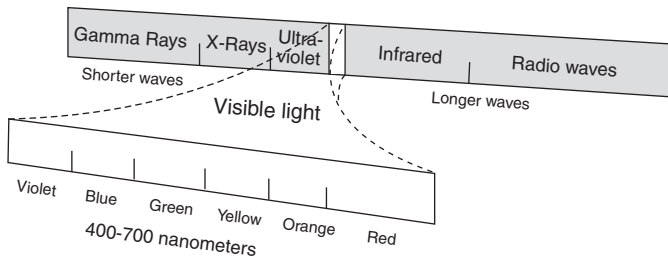
The modern view is that light has a dual nature. To debate whether light is a particle or a wave is inappropriate because in some experiments light acts like a wave and in others it acts like a particle. Perhaps it is most accurate to say that both waves and particles are simplified models of reality and that light is such a complicated phenomena that no one model from our common experience can be devised to explain its nature.

### **Electromagnetic spectrum**

Maxwell's equations united the study of electromagnetism and optics. Light is the relatively narrow frequency band of electromagnetic waves to which

our eyes are sensitive. Figure 5-1 illustrates the spectrum of **visible light**. Wavelengths are usually measured in units of nanometers ( $1\text{ nm} = 10^{-9}\text{ m}$ ) or in units of angstroms ( $1\text{ \AA} = 10^{-10}\text{ m}$ ). The colors of the visible spectrum stretch from violet, with the shortest length, to red, with the longest wavelength.

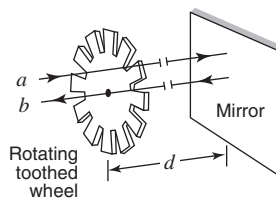
**Figure 5-1** The spectrum of electromagnetic radiation, which includes visible light.



### Speed of light

Light travels at such a high speed,  $3 \times 10^8\text{ m/sec}$ , that historically it was difficult to measure. In the late 1600s, Claus Roemer observed differences in the period of the moons of Jupiter, which varied according to the position of the earth. He correctly assumed a finite speed of light. He deduced the annual variation was due to a changed distance between Jupiter and the earth; so a longer period indicated that the light had farther to travel. His estimate,  $2.1 \times 10^8\text{ m/s}$ , based on his value for the radius of the earth's orbit, was inaccurate, but his theories were sound. Armand Fizeau was the first to measure the speed of light on the earth's surface. In 1849, he used a rotating toothed wheel to find a close approximation of the speed of light,  $3.15 \times 10^8\text{ m/s}$ . As shown in Figure 5-2, a light beam passed through the wheel, was reflected by a mirror a distance ( $d$ ) away, and then again passed through an opening between cogs.

**Figure 5-2** Fizeau's apparatus for measuring the speed of light.



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Assume the speed of the wheel is adjusted so that the light passing through the opening  $a$  then passes through opening  $b$  after reflection. If the toothed wheel spins at an angular velocity  $\omega$  and the angle between the two openings is  $\theta$ , then the time for light to travel  $2d$  is

$$t = \frac{\theta}{\omega}$$

and so the velocity of light may be calculated from

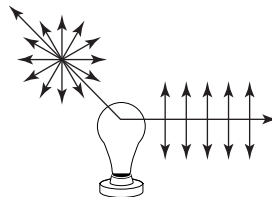
$$c = \frac{2d}{t} = \frac{2\omega d}{\theta}$$

where  $c$  denotes the speed of light. More modern methods with lasers have made measurements accurate to at least nine decimal places.

### Polarization

Light and other electromagnetic radiation can be polarized because the waves are transverse. Recall from the wave motion section in Chapter 2 that an oscillatory motion perpendicular to the direction of motion of the wave is the distinguishing characteristic of transverse waves. Longitudinal waves, such as sound, cannot be polarized. **Polarized** light has vibrations confined to a single plane that is perpendicular to the direction of motion. A beam of light can be represented by a system of light vectors. In Figure 5-3, unpolarized light is radiating from a light bulb. The beam going to the top of the page is viewed along the direction of motion (as end-on). The vectors in the beam traveling to the side of the page are seen perpendicular to the direction of motion (as a side view).

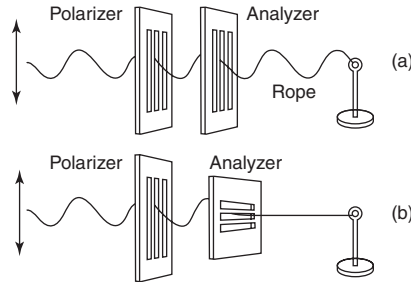
**Figure 5-3** A light bulb emits unpolarized light.



Light is commonly polarized by selective absorption of a polarizing material. Tourmaline is a naturally occurring crystal that transmits light in only one plane of polarization and absorbs the light vectors in other polarization planes. This type of material is called a **dichroic** substance. A mechanical

analogy illustrates this process. Imagine a rope with transverse pulses passing through two frames of slots, as shown in Figure 5-4. When the second polarizer is turned perpendicular to the first, the wave energy is absorbed.

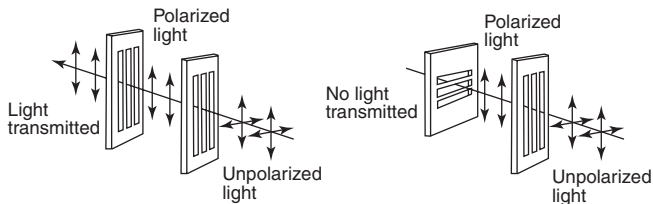
**Figure 5-4** A mechanical analogy of polarization, for a wave on a string.



Polaroid, another dichroic substance, is manufactured from long-chain hydrocarbons with alignment of the chains. As you will recall, electromagnetic waves are crossed electric and magnetic fields propagating through space. The orientation of the electric wave is taken as the direction of polarization. The polaroid molecules can conduct electric charges parallel to their chains; therefore, hydrocarbon molecules in polaroid filters absorb light with an electric field parallel to their length and transmit light with electric field perpendicular to their length.

Figure 5-5 shows the direction of light vectors for a beam of light traveling through two polaroids. The first polaroid is called the **polarizer**, and the second polaroid is called an **analyzer**. When the transmission axes of the polarizing materials are parallel, the polarized light passes through. Light is nearly completely absorbed when passing through two sets of polarizing materials with their transmission axes at right angles.

**Figure 5-5** A sequence of polaroids.



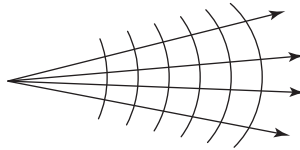
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Light can be polarized by reflection. For this reason, polaroid sunglasses are effective for reducing glare. Sunlight is primarily polarized parallel to the surface after reflection; therefore, the polaroids in sunglasses are oriented so that the reflected polarized light is largely absorbed.

## Geometrical Optics

When an object is dropped in still water, the circular wave fronts that are produced move out from the contact point over the two-dimensional surface. A light source emits light uniformly in all directions of the three-dimensional world. The wave fronts are spherical, and the direction of motion of the wave is perpendicular to the wave front, as depicted in Figure 5-6. This straight line path shown by the arrow is called a **ray**. Depicting light as rays in **ray diagrams** provides a method to explain the images formed by mirrors and lenses.

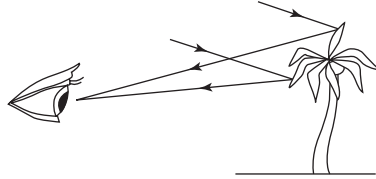
**Figure 5-6** Rays are perpendicular to the spherical wave fronts.



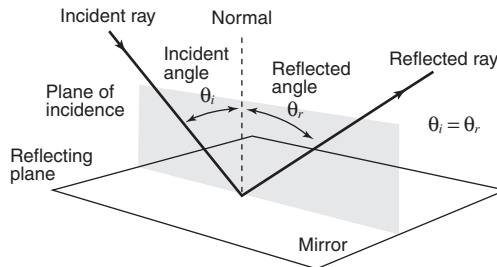
Far from the source, the curvature of the wave front is small, so the wave front appears to be a plane. Then, the light rays will be nearly parallel. Rays from the sun are considered to be parallel when reaching the earth.

### The law of reflection

Most visible objects are seen by reflected light. There are few natural sources of light, such as the sun, stars, and a flame; other sources are man-made, such as electric lights. For an object to be visible, light from a source is reflected off the object into our eyes (except in the special case of phosphors). In Figure 5-7, the light is coming from the sun, parallel due to the distance of the source. The light reflects off the object and travels in straight lines to the viewer. Through experience, the viewer has learned to extend the reflected rays entering the eye back to locate the object.

**Figure 5-7** Vision is the result of light reflected from the object.

As shown in Figure 5-8, light strikes a mirror and is reflected. The original ray is called the **incident ray**, and after reflection, it is called the **reflected ray**. The angles of the incident and reflected rays are always measured from the **normal**. The normal is a line perpendicular to the surface at the point where the incident ray reflects. The incident ray, reflected ray, and normal all lie in the same plane perpendicular to the reflecting surface, known as the **plane of incidence**. The angle measured from the incoming ray to the normal is termed the **incident angle**. The angle measured from the outgoing ray to the normal is called the **reflected angle**. **The law of reflection** states that the angle of incidence equals the angle of reflection. This law applies to all reflecting surfaces.

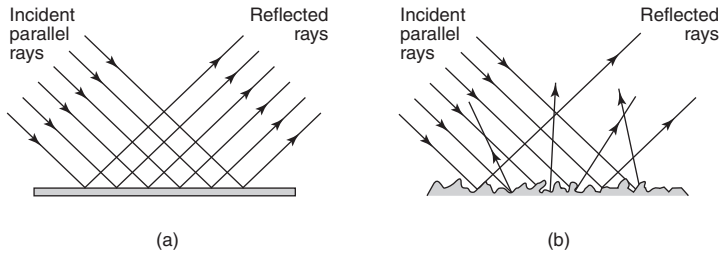
**Figure 5-8** The law of reflection.

Light undergoes either diffuse or regular reflection. The two are illustrated in Figure 5-9.

**Diffuse reflection** occurs when light reflects from a rough surface. **Regular reflection** is reflection from a smooth surface, such as a mirror. The reflected rays are scattered in diffuse reflection. This scattering is because the local direction of the normal to the surface is different for the different rays. By contrast, in regular reflection, the reflected light rays are orderly because each local region of the surface has a normal in the same direction.

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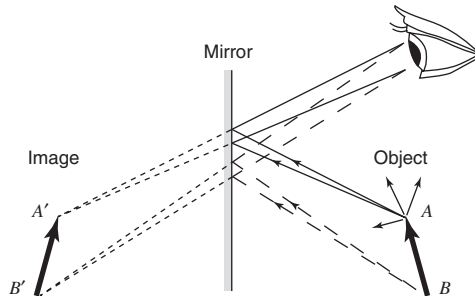
**Figure 5-9** (a) Regular reflection. (b) Diffuse reflection.



### Plane mirrors

Figure 5-10 illustrates the formation of an image by a plane mirror. Light rays are coming from a source and reflecting off each point of the object ( $AB$ ) in all directions. For simplicity, only a few of the rays are drawn. The rays spread upon leaving the object, and then each ray reflects from the mirror according to the law of reflection. The eye extends back the diverging reflected rays to see an image behind the mirror. An image formed in this manner by extending back the reflected diverging rays is called a **virtual** image. A virtual image cannot be projected on a screen. The light does *not* physically come together, but rather, the eye (or camera) interprets the diverging rays as originating from an image behind the mirror. Due to the law of reflection, the image formed by a plane mirror is the same distance behind the mirror as the object is in front of the mirror.

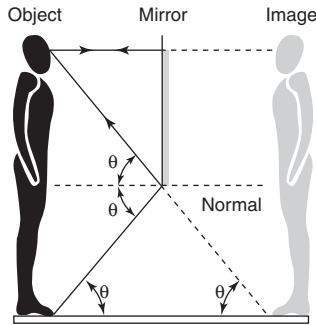
**Figure 5-10** Construction of an image reflected in a mirror.



How tall does a mirror need to be so you can see your entire height? Assume the top of the mirror is in line with the top of your head. Does it matter where you stand? The ray diagram in Figure 5-11 illustrates this situation.

From the law of reflection and basic geometry, it can be proven that the marked angles are all equal; therefore, the necessary height of the mirror is approximately half your height. Draw a figure at a different distance to show that the distance from the person to the mirror does not change the result.

**Figure 5-11** Seeing your own feet in a mirror.



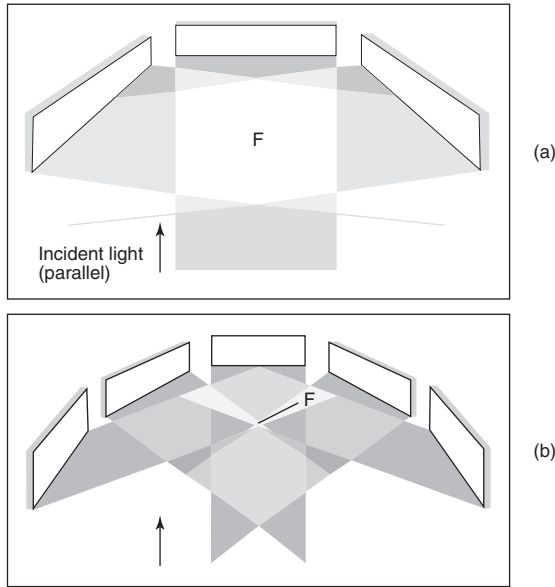
### Concave mirrors

Regular reflection occurs not only for plane (flat) mirrors but also for curved mirrors. Picture a series of plane mirrors arranged in a semicircle as shown in Figure 5-12. The incoming light is from a distant source and, therefore, is nearly parallel, as Figure 5-12(a) shows. After reflection, the light converges on a region. As the number of mirrors increases—Figure 5-12(b)—the converging region of the light beams decreases.

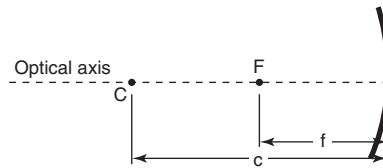
A **concave** mirror reflects its light from the inner curved surface. The mirror can be a portion of a sphere, a cylinder, or shaped as a rotated parabolic curve. The light rays intersect after reflection at a common focus called the **focal point** ( $F$ ). The focal point is on the **optical axis**, the symmetry axis of the mirror. The distance  $f$  from focal point to the mirror is called the **focal length**. For a spherical mirror, the focal length is one-half the radius of the sphere that defines the mirror. This distance  $c$  is called the **radius of curvature**, and the center of the sphere is denoted as  $C$  ( $c = 2f$ ). Figure 5-13 illustrates these definitions.

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**Figure 5-12** A semicircular arrangement of mirrors focuses light in the region  $F$ .



**Figure 5-13** A concave mirror with radius  $c$  and focal length  $f$ .

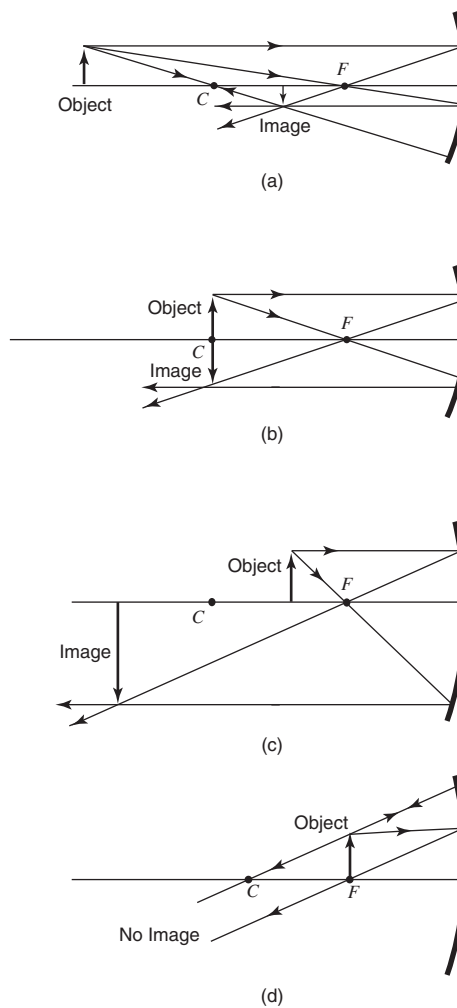


It is helpful to have a geometric system for locating an image formed by rays reflected from a curved mirror. Any reflected ray follows the law of reflection; however, certain rays have easily defined paths so that measuring angles and finding the normals are not necessary. Four of these rays are

- The ray directed parallel to the optical axis will reflect through  $F$ .
- The ray directed through  $F$  will reflect parallel to the optical axis.
- The ray directed to the center of the mirror will reflect at the same angle to the optical axis.
- The ray directed along the radius of the sphere will reflect back on itself.

Light rays are drawn for four different positions in Figure 5-14: (a) far from  $F$ , (b) at nearly  $2F$ , (c) between  $F$  and  $2F$ , and (d) at  $F$ . It is only necessary to find the intersection of two reflected rays from a point on the object to define the corresponding point on the image. A third one can be used as a check. Sometimes one or another of the rays may be difficult to draw, and so choices can be made.

**Figure 5-14** Images from a concave mirror.



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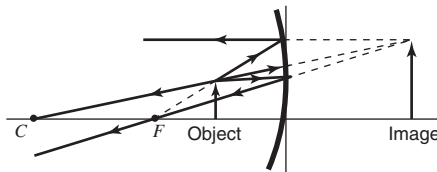
Notice that images are formed for the first three cases but not for the last one. No image is formed when the object is at the focal point or, alternatively, the image is formed at infinity and cannot be seen. The three images are all **real images**. Real images can be shown on a screen because the light physically comes together at a point in space. Note that real images are formed by light that converges after reflection. Also, real images are always inverted—upside down—with regard to the original object. In Figure 5-14, the light rays from the bottom of the object are not drawn. Light traveling along the optical axis will reflect back along the axis, and so if a point of the object is on the optical axis, the corresponding image point will also be on the optical axis.

The images formed can be characterized by size and placement. Let the distance from the object to the mirror be given by  $O$ . Then the image characteristics can be summarized as follows:

- If  $O > 2F$ , the image is inverted, smaller, and located between  $F$  and  $2F$ .
- If  $O = 2F$  (at  $C$ ), the image is inverted, the same size as the object, and located at  $2F$ ; that is, the distances of both the object and image to the mirror are equal.
- If  $2F < O < F$ , the image is inverted, larger than the object, and located  $>2F$ . Light paths are reversible. If the object is placed in the position of its former image, the image will then be located where the object was originally; that is, the two will exchange positions.

Figure 5-15 shows the diagram for the case when the object is between the focal point ( $F$ ) and the mirror. In this case, a **virtual image** is formed because the reflected rays diverge from the surface of the mirror. The virtual image is upright, enlarged, and behind the mirror. Virtual images are *never* inverted.

**Figure 5-15** Formation of a virtual image in a concave mirror.



The following approximate **mirror equation** relates the distances from the object to the mirror ( $O$ ), the distance from the image to the mirror ( $I$ ), and the focal length ( $f$ ):

$$\frac{1}{O} + \frac{1}{I} = \frac{1}{f}$$

The sign of  $f$  is positive if it is on the same side as the mirror (a concave mirror) and negative otherwise (convex mirror). Both  $O$  and  $I$  are positive in sign if they lie on the same side of the mirror as the incident light and negative if they lie on the opposite side.

The magnification is defined as the ratio of the image size to the object size. This ratio is the same as the ratio of the distances:

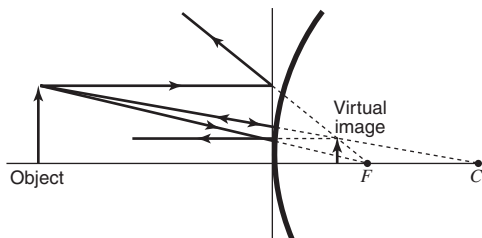
$$\text{magnification} = \frac{I}{O}$$

Thus, a magnification of  $10\times$  means the image seen is 10 times the size of the object when viewed without a magnifying device.

### Convex mirrors

The graphical technique for locating the image of a convex mirror is shown in Figure 5-16. For convex mirrors, the image on the opposite side of the mirror is virtual, and the images on the same side of the mirror are real. Figure 5-16 shows a virtual, upright, and smaller image. In comparison to the virtual image of the concave mirror, the virtual image of the convex mirror is still upright, but it is diminished (smaller) instead of enlarged and on the opposite side of the mirror instead of the same side. Again, the virtual image is formed by extending back the reflected diverging rays.

**Figure 5-16** Formation of a virtual image in a convex mirror.

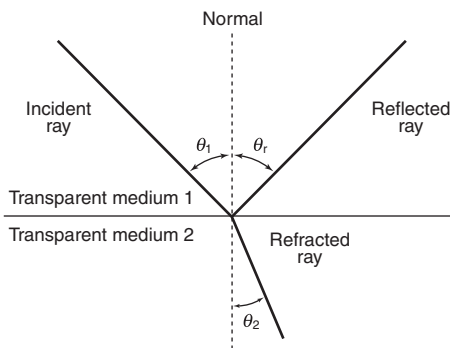


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### The law of refraction

**Refraction** is the bending of light when the beam passes from one **transparent** medium into another. A transparent object allows the transmission of light, in contrast to an **opaque** object, which does not. Some of the light will also be reflected. The incident ray, reflected ray, normal, and **refracted ray** are shown in Figure 5-17.

**Figure 5-17** The law of refraction.



When Willebrod Snell (1580–1626) observed light traveling from air into another transparent material, he found a constant ratio of the sines of the angles measured from the normal to the light ray in the material:

$$n = \frac{\sin \theta_{\text{air}}}{\sin \theta_{\text{material}}}$$

The constant ( $n$ ) is called the **index of refraction** and depends only upon the optical properties of the material. The index of refraction gives a measure of the amount of bending occurring when light travels from air into the material. It is a dimensionless number and can be located in tables of properties of materials. For example, the index of refraction of water is 1.33, and the index of refraction of crown glass varies from 1.50 to 1.62, depending upon the composition of the glass.

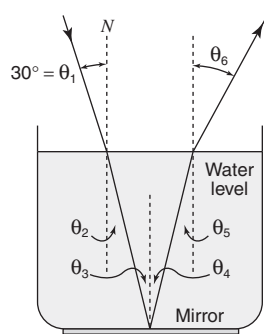
For the more general case of light traveling from medium 1 to medium 2, **Snell's law** can be written  $n_1 \sin \theta_1 = n_2 \sin \theta_2$ , where the subscripts 1 and 2 refer respectively to the angles and indices of the refraction for material 1 and material 2 respectively. A light ray traveling along the normal, with an incident angle of zero, will not be bent.

The index of refraction is also the ratio of the speed of light in a vacuum ( $c$ ) and the speed of light in that medium ( $v$ ); thus,

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

Consider the following problem involving both reflection and refraction. Imagine light entering an aquarium and reflecting off a mirror at the bottom. First, what will be the angle of refraction in the water if the angle in air is 30 degrees? Second, at what angle will the beam leave the water? See the setup in Figure 5-18.

**Figure 5-18** A problem combining refraction and reflection.

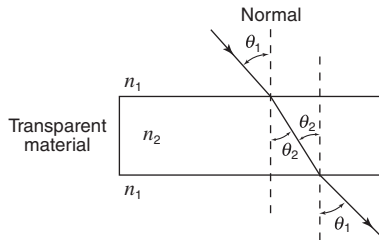


Angle  $\theta_2$  is determined from  $\theta_1$ , using Snell's law of refraction. Angle  $\theta_3 = \theta_2$  by geometry,  $\theta_3 = \theta_2$  by law of reflection, and  $\theta_4 = \theta_2$  by geometry.  $\theta_5$  is related to  $\theta_2$  by Snell's law of refraction, in the same ratio as  $\theta_1$  to  $\theta_6$ . Therefore,  $\theta_6$ —the angle of the ray leaving the water—must be 30 degrees. The problem is symmetrical.

A light ray passing through a rectangular block of transparent material will simply be displaced from its original path. For example, in passing from air to glass, the ray will bend toward the normal. Upon leaving the glass block, the ray will bend away from the normal so that the measured angles in the air on each side of the block are the same (Figure 5-19).

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**Figure 5-19** A light ray is displaced after passing through a refracting medium.



### Brewster's angle

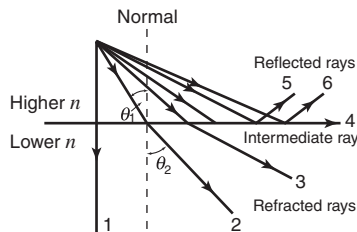
In the earlier section “Polarization,” it was stated that light reflected from the surface of a material is partially polarized. A ray incident on a transparent surface at a certain angle will be partly refracted and partly reflected in a plane polarized ray. This angle of maximum plane polarization is called **Brewster's angle**, named for Sir David Brewster (1781–1868). The equation is  $\tan \theta = n$ , where  $n$  is the index of refraction of the reflecting surface.

### Total internal reflection

When light travels from a material with a higher  $n$  to one with a lower  $n$ , at certain angles all of the light is reflected. This effect is called **total internal reflection**.

**Example 1:** Figure 5-20 illustrates ray 1 along the normal (no bending), rays 2 and 3 are refracted, and rays 5 and 6 are reflected. Ray 4 is intermediate between reflection and refraction with an angle of refraction of 90 degrees. The incident angle for this case is called the **critical angle** ( $\theta_c$ ). If the angle of incidence is less than  $\theta_c$ , the light will refract, and if it is greater, the light will reflect.

**Figure 5-20** Total internal reflection at the interface of two different media.



The equation is

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

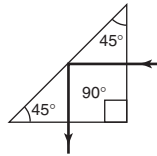
where  $n_1 > n_2$ . Find the critical angle from glass to air.

**Solution:**  $\theta = \sin^{-1} \left( \frac{n_2}{n_1} \right) = \sin^{-1} \left( \frac{1.00}{1.52} \right)$

$$\theta = 41.1^\circ$$

Therefore, if the incident ray on a glass to air interface is greater than 42 degrees, total internal reflection will occur. Figure 5-21 shows the light rays entering and leaving a 45-45-90 glass prism. This phenomenon has broad applications where a mirror is needed, but a silvered surface might corrode after a period of time.

**Figure 5-21** Total internal reflection in a glass prism.



## Optical lenses

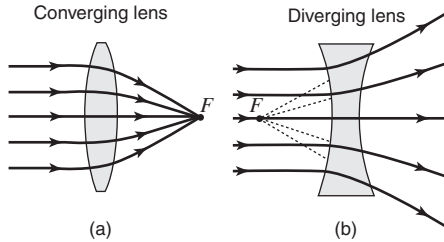
An optical lens functions by refracting light at its interfaces. In these examples, the lens will be assumed to be thin, in which case the thickness of the lens is negligible compared with its focal length. Lenses are basically of two types. A **converging lens** causes parallel rays to converge, and a **diverging lens** causes parallel rays to diverge. Figure 5-22 illustrates the paths of the rays through the lens and the focal point for each case. The definitions for optical axis, focal point, and focal length given for curved mirrors hold true for lenses, with the addition that lenses have focal points on each side of the lens.

Ray diagrams can be made for lenses similar to those drawn for curved mirrors. These three rays can be drawn to locate the image formed by the lens.

- The ray directed parallel to the optical axis refracts through  $F$  on the far side.
- The ray directed to the near  $F$  refracts parallel to the optical axis.
- The ray directed to the center of the lens is undeviated (in the thin lens approximation).

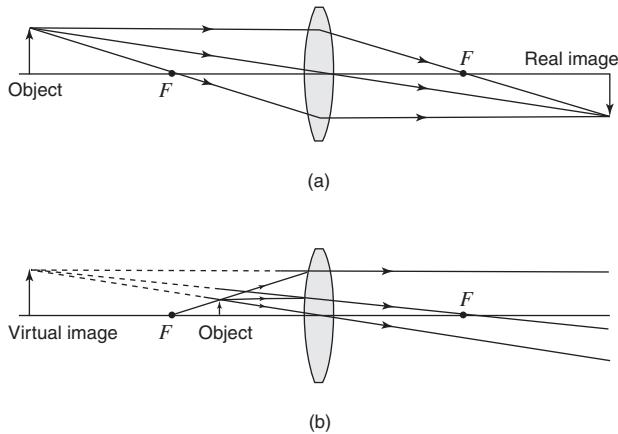
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**Figure 5-22** Thin lenses function by refracting light.



The ray diagrams for two cases of a converging lens are shown in Figure 5-23.

**Figure 5-23** Ray diagrams for a converging lens, showing the formation of (a) a real image or (b) a virtual image.



In Figure 5-23(a), a real image is formed, and in Figure 5-23(b), a virtual image is formed. The lens setup in Figure 5-23(b) is called a simple magnifier. With lenses as with mirrors, virtual images are right side up, and real images are inverted. (This is why slides inserted into a projector are inverted; the projector lens reinverts the image on the screen.)

The **lens equation** is the same relationship used for curved mirrors:

$$\frac{1}{O} + \frac{1}{I} = \frac{1}{f}$$

as is the equation for magnification:

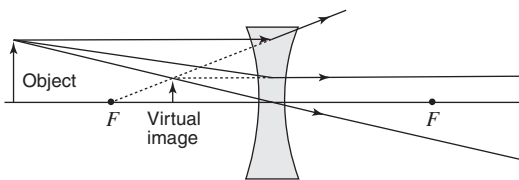
$$\text{magnification} = \frac{I}{O}$$

The focal length is positive for a converging lens and negative for a diverging lens. The object and image distances are positive if they are on opposite sides of the lens and negative if they are on the same side. The relative sizes and positions of the object and image for a converging lens are similar to the four cases reviewed for the concave mirror.

- If  $O > 2F$ , the image is inverted, smaller, and located between  $F$  and  $2F$ , on the opposite side.
- If  $O = 2F$ , the image is inverted, the same size as the object, and located at  $2F$ ; that is, the distances of both the object and image to the lens are equal but on opposite sides of the lens.
- If  $2F < O < F$ , the image is inverted, larger than the object, and located  $> 2F$ .
- If  $O < F$ , the image is virtual, enlarged, and located on the same side of the lens where  $I > F$ .

Figure 5-24 shows the ray diagram for a diverging lens. The image formed by this lens is always virtual, upright, and diminished.

**Figure 5-24** Ray diagram for a diverging lens.



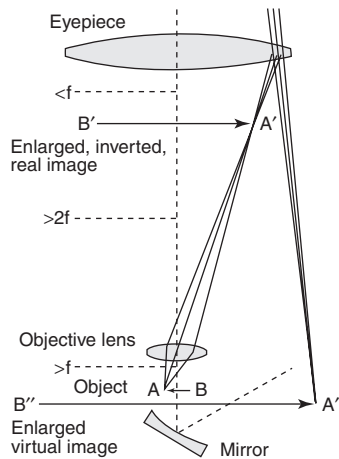
### The compound microscope

When lenses are used in combinations, the image given by one lens becomes the object for a second lens. The **compound microscope** is an example of the use of several lenses to magnify an object. An **objective** lens near the object forms an enlarged image. This image is then further magnified by the second lens, called the **eyepiece**. Both are converging lenses.

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In Figure 5-25, the object ( $AB$ ) is placed just below the focal point of the objective lens. The objective lens forms an enlarged, real, and inverted image at a distance greater than  $2f$  from the first lens. This image ( $A'B'$ ) falls inside the focal point of the eyepiece lens; therefore, an enlarged, virtual image is formed by the eyepiece ( $A''B''$ ). The total magnification is the product of the magnifications of each lens.

**Figure 5-25** A compound microscope.

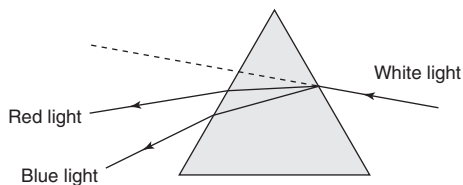


## Dispersion and prisms

An important property of the index of refraction is that it is slightly dependent upon wavelength. For a given material—for example, glass— $n$  decreases with increasing wavelength; thus, blue light bends more than red light. This effect is called **dispersion**.

Light is refracted twice as it enters and leaves the prism, as shown in Figure 5-26.

**Figure 5-26** Dispersion of white light in a prism.



A given ray is bent from its original direction of travel by an angle ( $\delta$ ), called the **angle of deviation**. The angle of deviation for the red light is less than that for the blue light; therefore, the prism spreads the light into the colors of the **spectrum**. These colors are commonly called red, orange, yellow, green, blue, indigo, and violet (often abbreviated with the mnemonic Roy G Biv).

Rainbows are formed by dispersion and total internal reflection of sunlight in raindrops. The critical angle for water to air is approximately 40 degrees. The sunlight enters the drop and is reflected off the side of the drop away from the viewer. Due to dispersion, the violet ray emerges above the red ray. Figure 5-27 shows the refraction of sunlight on one idealized raindrop.

**Figure 5-27** Dispersion and internal reflection of light passing through a raindrop.

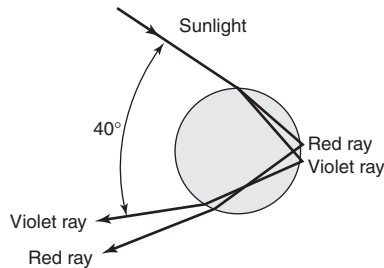
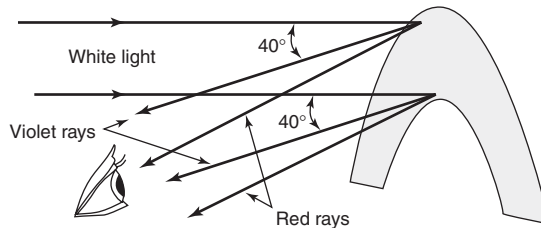


Figure 5-28 shows how the viewer sees the rainbow. The rainbow is in the shape of an arc because the circle of drops at the angle of about 40 degrees is in existence only above the ground. It is possible to see a circular rainbow from an airplane in the correct position relative to the sunlight and raindrops.

**Figure 5-28** Formation of a rainbow due to total internal reflection and dispersion.



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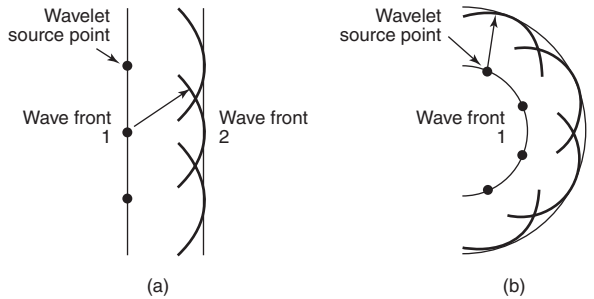
### Wave Optics

To explain some phenomena, such as interference and diffraction of light, it is necessary to go beyond geometrical optics.

#### Huygens' principle

As mentioned earlier, Huygens considered light to be a wave. He envisioned a wave crest advancing by imagining each point along the wave crest to be source point for small, circular, expanding wavelets, which expand with the speed of the wave. The surface tangent to these wavelets determines the contour of the advancing wave. Figure 5-29 illustrates Huygens' construction for a plane wave (a) and for a spherical wave (b).

**Figure 5-29** Huygens' principle for (a) a plane wave and (b) a spherical wave.



Huygens' principle can be used to derive the law of reflection and the law of refraction. Note that the observed laws of geometric optics follow from the assumption that light is a wave.

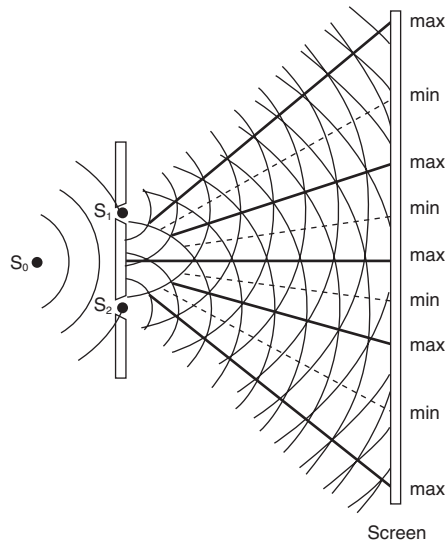
#### Interference

Because light is a wave, the superposition principle discussed in the wave motion section of Chapter 2 is valid to determine the constructive and destructive interferences for light waves. Interference in light waves is not easy to observe because the wavelengths are so short. For constructive interference, two waves must have the two contributing crests and the two troughs arriving at the same time. For destructive interference, a crest from one wave and a trough from the other must arrive at a given point at the same time.

### Young's experiment

Thomas Young first demonstrated interference from light waves with a double slit. The schematic diagram for this experiment is shown in Figure 5-30.

**Figure 5-30** Schematic diagram of Young's experiment, demonstrating interference between light waves.

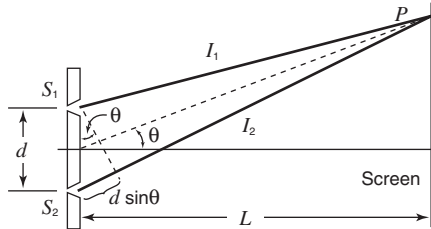


The single light source is located at  $S_0$ , and the light goes through two very narrow openings at  $S_1$  and  $S_2$ . (A single light source is necessary because the light waves must have identical frequency and phase. The light beam is also considered to be of one color.) Each of the slits act as a source for circular expanding waves. The points of intersection of two crests, one from each slit, are points of constructive interference. The point of intersection of a crest from one slit and a trough from the other slit is a point of destructive interference. Therefore, the interference pattern called fringes, consisting of alternating light and dark bars, will be seen on the screen.

To better understand how these points are formed, Figure 5-31 illustrates the rays coming through two slits that are directed to the point  $P$  on the screen.

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**Figure 5-31** The paths of two waves from the slits to the point  $P$ .



The difference in path length of the two rays is given by  $d \sin \theta = l_1 - l_2$ . If the path difference is a whole number of wavelengths, then constructive interference takes place. If the paths differ by a half number of wave lengths, destructive interference occurs. Using  $n$  to represent any integer, the two cases may be written

$$\text{maximum brightness if } n\lambda = d \sin \theta$$

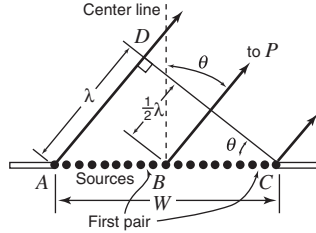
$$\text{minimum brightness if } \left(n + \frac{1}{2}\right)\lambda = d \sin \theta$$

where  $\lambda$  is the wavelength and  $d$  is the distance between the two slits. **Note:** This figure is not to scale: The distance to the screen ( $L$ ) is much greater than the distance between the slits ( $d$ ).

## Diffraction

Young's double-slit experiment shows that light spreads out in wavefronts that can interfere with each other. **Diffraction** is the effect of a wave spreading as it passes through an opening or goes around an object. The diffraction of sound is quite obvious. It is not at all remarkable to hear sound through an open door or even around corners. In contrast, diffraction is quite difficult to observe with light. The difference is that sound waves are long while light waves are extremely short because diffraction is proportional to wave length; it is not easy to observe the bending of light when it passes through a small aperture or goes around a sharp edge.

A single slit yields an interference pattern due to diffraction and interference. Imagine that the slit is wide enough to allow a number of wavelets. Figure 5-32 shows the wave-ray diagram used to analyze the single slit.

**Figure 5-32** Diffraction of light through a single slit.

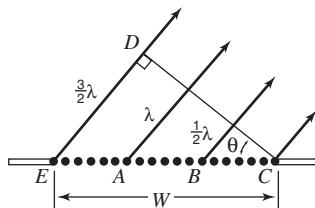
The rays from  $A$  and  $B$  interfere at  $P$  on a distant screen. As shown,  $AP$  exceeds  $BP$  by half a wavelength; therefore, the represented waves destructively interfere. Also for every wave originating between  $A$  and  $B$ , there is another point between  $B$  and  $C$  with a wavelet that will destructively interfere. The wavelets cancel in pairs; thus, point  $P$  is a minimum or dark point on the screen.

The triangle  $ACD$  is nearly a right triangle if  $P$  is quite distant. Applying the definition for sine to the figure yields

$$\sin \theta = \frac{\lambda}{w}$$

where  $\lambda$  is the wavelength and  $w$  is the slit width. Whenever the path difference between  $AP$  and  $CP$  is a whole number of wavelengths, a dark fringe will be produced on the screen because the wavelets can be seen to completely cancel in pairs.

Figure 5-33 illustrates the light rays traveling to another point on the screen.

**Figure 5-33** Diffraction of light through a single slit.

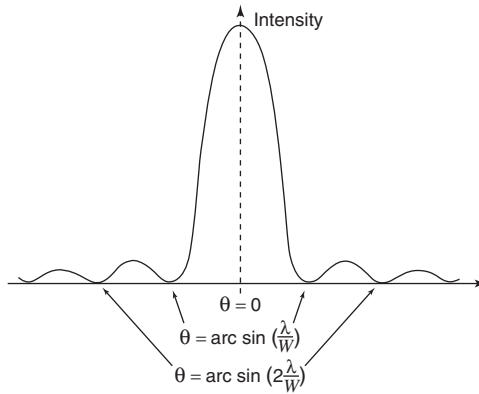
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In this case,

$$\sin \theta = \frac{(3\lambda/2)}{w} = \frac{3\lambda}{2w}$$

The region of wavelets is divided into three. Again, the waves through two regions cancel in pairs, but now the waves from one region constructively interfere to produce a bright point on the screen. This is partial reinforcement. The positions of the light and dark fringes formed by a single slit are summarized in the intensity versus angle sketch shown in Figure 5-34. The center region of the pattern will be the brightest band because the wavelets completely, constructively interfere in the middle.

**Figure 5-34** Position of fringes produced by single-slit diffraction.



When looking through double slits, it is impossible to see only the double-slit pattern because the double-slit is really two single slits; therefore, the actual observed pattern is that of superimposed double- and single-slit patterns.

## **Chapter Checkout**

### **Q&A**

1. True or False: The rules of geometric optics can be applied to explain diffraction of light through a single slit.
2. A fish swims 10 cm below the surface of a pool. Meanwhile, a person views it from above the pool's surface, at an angle of  $30^\circ$  from the normal to the pool. What angle must the light leaving the fish make with the surface of the water? Assume  $n = 1.33$  for water.
3. Fiber optic cable consists of two concentric glass fibers with different indices of refraction. Assume the outer layer has  $n = 1.55$  and the inner layer has  $n = 1.50$ . What angles of light incident on the end of the inner fiber will be propagated down the fiber by total internal reflection?
4. Suppose a light source emits at two wavelengths only: 400 nm and 600 nm. The light is incident on a single-slit diffraction apparatus with a slit width of 1600 nm. What is the angular separation between the first brightness maximums (outside of the central maximum) of the different colors?

**Answers:** 1. False 2.  $22.1^\circ$  3. A cone of total angular width  $30^\circ$  4.  $12.2^\circ$