# 13 Reflection and Refraction

## 13-1 The Speed of Light

An important physical constant is the **speed of light**, $c$. In a vacuum, this speed is $3.00 \times 10^8$ m/s. All calculations in this book will use this value for the speed of light unless otherwise specified in the exercise.

Light has both wave and particle properties. The exercises in this chapter deal with the wave nature of light. For a wave of wavelength $\lambda$ and frequency $f$ traveling at the speed of light, $c$, $c = \lambda f$. The distance that light travels in a given amount of time can be represented by the equation $\Delta d = c\Delta t$.

Note that these two equations are both special cases of the more general equations, $v = \lambda f$ and $\Delta d = v\Delta t$.

### Solved Examples

**Example 1:** How long does it take for light from the sun to reach Earth if the sun is $1.50 \times 10^{11}$ m away?

*Given:* $\Delta d = 1.50 \times 10^{11}$ m
$c = 3.00 \times 10^8$ m/s

*Unknown:* $\Delta t = ?$
*Original equation:* $\Delta d = c\Delta t$

*Solve:* $\Delta t = \dfrac{\Delta d}{c} = \dfrac{1.50 \times 10^{11}\text{ m}}{3.00 \times 10^8\text{ m/s}} = \mathbf{500.\ s}$

This is a little more than 8 min.

**Example 2:** Microwave ovens emit waves of about 2450 MHz. What is the wavelength of this light?

**Solution:** The term MHz stands for Megahertz or $10^6$ Hz. Therefore, the microwaves have a frequency of $2450 \times 10^6$ Hz.

*Given:* $c = 3.00 \times 10^8$ m/s
$f = 2450 \times 10^6$ Hz

*Unknown:* $\lambda = ?$
*Original equation:* $c = \lambda f$

*Solve:* $\lambda = \dfrac{c}{f} = \dfrac{3.00 \times 10^8\text{ m/s}}{2450 \times 10^6\text{ Hz}} = \mathbf{0.122\ m}$

## Practice Exercises

**Exercise 1:** When you look at a distant star or planet, you are looking back in time. How far back in time are you looking when you observe Pluto through the telescope from a distance of $5.91 \times 10^{12}$ m?

Answer: ____________________

**Exercise 2:** If a person could travel at the speed of light, it would still take 4.3 years to reach the nearest star, Proxima Centauri. How far away, in meters, is Proxima Centauri? (Ignore any relativistic effects.)

Answer: ____________________

**Exercise 3:** When you go out in the sun, it is the ultraviolet light that gives you your tan. The pigment in your skin called *melanin* is activated by the enzyme *tyrosinase,* which has been stimulated by ultraviolet light. What is the wavelength of this light if it has a frequency of $7.89 \times 10^{14}$ Hz?

Answer: ____________________

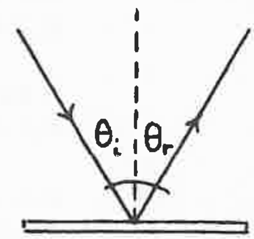
**Exercise 4:** IRAS, the Infrared Astronomy Satellite launched by NASA in 1983, had a detector that was supercooled to enable it to measure infrared or heat radiation from different regions of space. What is the frequency of infrared light that has a wavelength of $1.00 \times 10^{-6}$ m?

Answer: ____________________

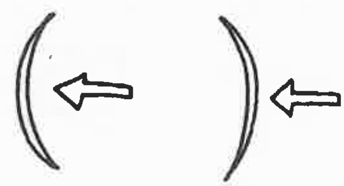
# 13-2 Reflection

*Vocabulary* **Reflection:** The bouncing of light.

The angle a beam of light makes when it strikes a surface is described with respect to the **normal,** an imaginary line drawn perpendicular to the surface. When light shines onto a mirror, the angle at which the light enters the mirror (angle of incidence) is exactly equal to the angle at which the light leaves the mirror (angle of reflection). This is called the **law of reflection** and is easily observed in a plane (flat) mirror.




Due to the curvature of a spherical mirror, light reflected from its surface behaves somewhat differently than it does when reflected from a plane mirror. There are two types of spherical mirrors, **converging** (or concave) and **diverging** (or convex).



Converging Diverging

The following terminology is used when describing how light is reflected from converging and diverging mirrors.

*Vocabulary* **Object distance:** The distance from the mirror to the object. This value is always a positive number.

*Vocabulary* **Image distance:** The distance from the mirror to the image. An image can be **real** (inverted and able to be projected on a screen), or **virtual** (right-side-up and not able to be projected on a screen).

*Vocabulary* **Focal point:** The point where parallel rays meet (or appear to meet) after reflecting from a mirror. The distance from this focal point to the mirror is called the **focal length**. The focal length of a converging mirror always has a positive value while the focal length of a diverging mirror always has a negative value.

*Vocabulary* **Mirror Equation:** $\frac{1}{\textbf{focal length}} = \frac{1}{\textbf{object distance}} + \frac{1}{\textbf{image distance}}$

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

Note: Many situations involving mirrors can also be solved using ray diagrams.

## Converging (Concave) Mirror

If an object is located more than one focal length from a converging mirror as shown in Figure A, the image it forms is real, inverted, and in front of the mirror. You can actually project this image onto a piece of paper. Both $d_o$ and $d_i$ have positive values.

If the object is at the focal point as in figure B, no image is formed because the reflected rays are parallel.

If an object is located less than one focal length from a converging mirror as in figure C, the image it forms is virtual, upright, enlarged, and behind the mirror. In other words, you must look into the mirror to see the image. Here, $d_o$ has a positive value and $d_i$ has a negative value.

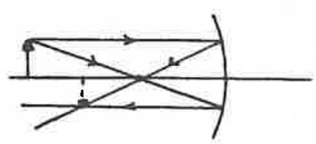


Figure A

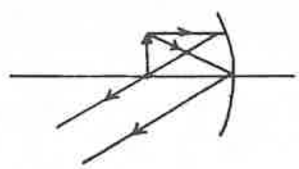


Figure B

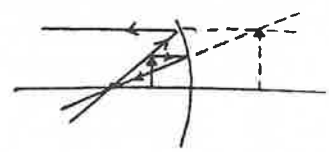
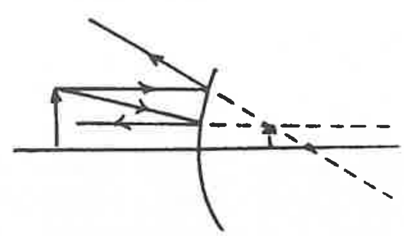


Figure C

## Diverging (Convex) Mirror

The image formed by a diverging mirror is always virtual, upright, smaller, and behind the mirror. The image can be seen only by looking into the mirror. Here $d_o$ has a positive value while $d_i$ has a negative value.



## Solved Examples

**Example 3:** Sitting in her parlor one night, Gerty sees the reflection of her cat, Whiskers, in the living room window. If the image of Whiskers makes an angle of 40° with the normal, at what angle does Gerty see him reflected?

**Solution:** Because the angle of incidence equals the angle of reflection, Gerty must see her cat reflected at an angle of 40°.

**Example 4:** Wendy the witch is polishing her crystal ball. It is so shiny that she can see her reflection when she gazes into the ball from a distance of 15 cm. a) What is the focal length of Wendy's crystal ball if she can see her reflection 4.0 cm behind the surface? b) Is this image real or virtual?

**a.** *Given:* $d_o = 15$ cm
$d_i = -4.0$ cm

*Unknown:* $f = ?$
*Original equation:* $\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$

*Solve:* $\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{15 \text{ cm}} + \frac{1}{-4.0 \text{ cm}}$

Getting a common denominator of 60 cm gives $\frac{1}{f} = \frac{4}{60 \text{ cm}} - \frac{15}{60 \text{ cm}} = \frac{-11}{60 \text{ cm}}$

To find $f$, take the reciprocal of this sum. $f = \frac{-60 \text{ cm}}{11} = \mathbf{-5.5 \text{ cm}}$

The minus sign before the answer means that this is the focal length of a diverging mirror.

**b.** The image seen *behind* a curved surface is always a **virtual image.**

**Example 5:** With his face 6.0 cm from his empty water bowl, Spot sees his reflection 12 cm behind the bowl and jumps back. a) What is the focal length of the bowl? b) What was surprising about Spot's reflection that may have caused him to jump?

**a.** *Given:* $d_o = 6.0$ cm
$d_i = -12$ cm

*Unknown:* $f = ?$
*Original equation:* $\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$

*Solve:* $\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{6.0 \text{ cm}} + \frac{1}{-12 \text{ cm}}$

Getting a common denominator of 12 cm gives $\frac{1}{f} = \frac{2}{12 \text{ cm}} - \frac{1}{12 \text{ cm}} = \frac{1}{12 \text{ cm}}$

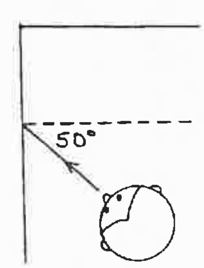
$f = \mathbf{12 \text{ cm}}$

The positive answer means that the bowl was acting as a converging mirror.

**b.** The surprising thing Spot noticed about his reflection was that it appeared larger than life!

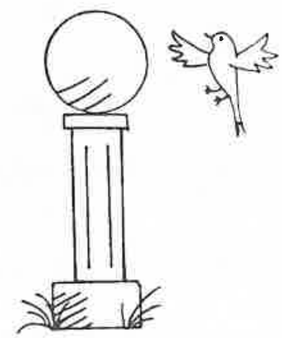
## Practice Exercises

**Exercise 5:** Manish is in a house of mirrors with one of his friends when he comes to two mirrors situated at an angle of 90°. Manish stands so that light shining on his face is incident on one mirror at an angle of 50°, as shown. At what angle will this light reflect from the second mirror?




Answer: ____________________

**Exercise 6:** A popular lawn ornament in the 1960s was a colored reflecting sphere that sat in the yard as a decoration. a) If a bird is 10.0 cm from a blue reflecting sphere and sees its image reflected 5.0 cm behind the sphere, what is the focal length of the spherical reflector? b) Would the bird's image appear larger or smaller than the bird itself?



Answer: **a.** ____________________

Answer: **b.** ____________________

**Exercise 7:** Polly applies her mascara while looking in a concave mirror whose focal length is 18 cm. She looks into it from a distance of 12 cm. a) How far is Polly's image from the mirror? b) Does it matter whether or not Polly's face is closer or farther than one focal length? Explain.

Answer: **a.** ____________________

Answer: **b.** ____________________

**Exercise 8:** A friend is wearing a pair of mirrored sunglasses whose convex surface has a focal length of 20.0 cm. If your face is 40.0 cm from the sunglasses, how far behind the sunglasses is your image?

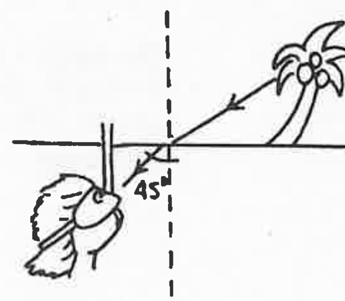
Answer: ____________________

**A-7:** An automobile headlight is made by placing a filament at the focal point of a concave mirrored surface. a) If the focal length of the mirrored surface is 5.0 cm, calculate the image distance. b) Why is this the desired image distance for automobile headlights?

**A-8:** A blue glow from a bug light strikes the Bradford's swimming pool at an angle of 35.0°. At what angle is the light refracted into the pool? ($n_{water} = 1.33$)

**A-9:** The index of refraction of ethyl alcohol is 1.36, while the index of refraction of water is 1.33. a) Does light travel faster in alcohol or in water? b) What is the speed of light in each?

**A-10:** Heather is snorkeling in Oahu's Hanuma Bay when she looks up through the water at a palm tree on the shore. a) If the index of refraction of water is 1.33 and Heather sees the palm tree at an angle of 45°, at what angle is the palm tree really located with respect to the normal?



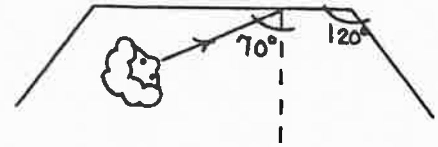

**A-11:** Spenser, a cat, enjoys watching the family goldfish from the top of the fish tank. If the goldfish, swimming in water, appears to be at an angle of 28.0° as seen by Spenser, at what true angle is the goldfish from the normal? ($n_{water} = 1.33$)

**A-12:** Evan has taken Eva out to dinner to propose marriage and he has hidden the engagement ring in her drink as a surprise. When Eva has finished her drink, she spots the ring beneath an ice cube. If Eva looks down into the glass at an angle of 61.0° but the ice cube refracts the ring at an angle of 42.0°, what is the index of refraction of ice?

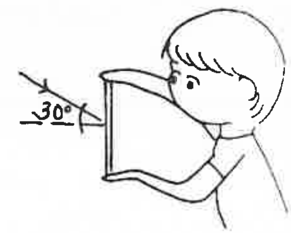
**A-13:** In her bedroom, Mia has a fiber optic light that glows as hundreds of fiber optic cables are lit from below. a) If each fiber optic cable has an index of refraction of 1.48, at what critical angle must light enter the cable in order for total internal reflection to occur? b) Explain why total internal reflection is important to a fiber optic lamp.

## Challenge Exercises for Further Study

**B-1:** Marian admires a new dress in a department store dressing room mirror. If Marian stands as shown, making an angle of 70° with the center mirror, at what angle will the light be reflected from the mirror on the right?



**B-2:** Your friend is stranded 10.0 m high in a tall tree with a hungry tiger beneath, while you lie on the beach a distance away. He has only a mirror, which he uses to signal you by holding it perpendicular to the horizon as shown. If the sun hits the mirror at a 30.0° angle to the normal and reflects back in your eye, how far away are you from the tree?



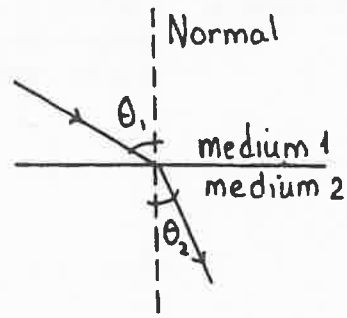

**B-3:** As you are walking toward a swimming pool on a hot summer day, you suddenly notice a glare of sunlight off the water's surface that is so bright it makes you close your eyes. If the angle of incidence of the incoming sunlight is 70.0° and you stand 1.80 m tall, how far (horizontally) are you standing from the point where the incident ray hits the water?

**B-4:** The deepest section of ocean in the world is the Marianas Trench, located in the Pacific Ocean. Here, the ocean floor is as low as 10 918 m below the surface. If the index of refraction of water is 1.33, how long would it take a laser beam to reach the bottom of the trench?

# 13-3 Refraction

*Vocabulary*

**Refraction:** The change in direction of light due to a change in speed as it passes from one medium to another.




The path of light is described with respect to the normal. If light is slowed down as it enters a new medium, it bends toward the normal. If it speeds up, it bends away from the normal.

The amount of bending is represented with the letter $n$, which stands for the **index of refraction**. The index of refraction for a particular medium is a ratio of the speed of light in a vacuum to the speed of light in the medium.

$$\textbf{index of refraction} = \frac{\textbf{speed of light in a vacuum}}{\textbf{speed of light in another medium}} \quad \text{or} \quad n = \frac{c}{v}$$

Because light travels fastest in a vacuum, the index of refraction for any other medium is always greater than 1. Although the index of refraction for air is 1.0003, in this chapter the value will be written simply as 1.00.

The angle to which light will bend upon passing from one medium to another depends upon the index of refraction of each of the two media, $n_1$ and $n_2$, and the light's angle of incidence.

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

The symbols $\theta_1$ and $\theta_2$ stand for the angle of incidence and the angle of refraction, respectively.

A special case of this equation is used when light travels from a more-dense medium to a less-dense medium and the refracted ray makes an angle of 90.0° with the normal as it skims along the boundary of the two media. When this happens, the incident angle $\theta_1$ is called the **critical angle,** $\theta_c$.

$$n_1 \sin \theta_c = n_2 \sin 90.0°$$

If the incident angle is any bigger than the critical angle, there is no refraction. Instead, all the light is reflected back inside the object. This is called **total internal reflection**.

## Solved Examples

**Example 6:** Hickory, a watchmaker, is interested in an old timepiece that's been brought in for a cleaning. If light travels at $1.90 \times 10^8$ m/s in the crystal, what is the crystal's index of refraction?

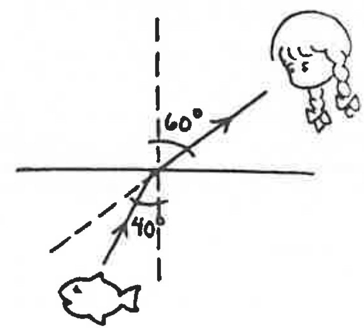
*Given:* $c = 3.00 \times 10^8$ m/s
$v = 1.90 \times 10^8$ m

*Unknown:* $n = ?$
*Original equation:* $n = \frac{c}{v}$

*Solve:* $n = \frac{c}{v} = \frac{3.00 \times 10^8 \text{ m/s}}{1.90 \times 10^8 \text{ m/s}} = \mathbf{1.58}$

Remember, the index of refraction has no units. It is just a ratio of the speed of light in two different media.

**Example 7:** While fishing out on the lake one summer afternoon, Amy spots a large trout just below the surface of the water at an angle of 60.0° to the vertical, and she tries to scoop it out of the water with her net. a) Draw the fish where Amy sees it. b) At what angle should Amy aim for the fish? ($n_{water} = 1.33$).




**Solution: a.** The fish will appear to be straight ahead according to Amy. However, because light travels slower in water than in air, the fish is closer to Amy than she thinks.

**b.** *Given:* $n_1 = 1.33$ (water)
$n_2 = 1.00$ (air)
$\theta_2 = 60.0°$

*Unknown:* $\theta_2 = ?$
*Original equation:* $n_1 \sin \theta_1 = n_2 \sin \theta_2$

*Solve:* $\sin \theta_1 = \frac{n_2 \sin \theta_2}{n_1} = \frac{(1.00) \sin 60.0°}{1.33} = 0.651$ $\quad \theta_1 = \sin^{-1} 0.651 = \mathbf{40.6°}$

**Example 8:** Binoculars contain prisms inside that reflect light entering at an angle larger than the critical angle. If the index of refraction of a glass prism is 1.58, what is the critical angle for light entering the prism?

*Given:* $n_1 = 1.58$ (glass)
$n_2 = 1.00$ (air)

*Unknown:* $\theta_c = ?$
*Original equation:* $n_1 \sin \theta_c = n_2 \sin 90.0°$

*Solve:* $\sin \theta_c = \frac{n_2 \sin \theta_2}{n_1} = \frac{(1.00) \sin 90.0°}{1.58} = 0.633$ $\quad \theta_c = \sin^{-1} 0.633 = \mathbf{39.3°}$

## Practice Exercises

**Exercise 9:** Alison sees a coin at the bottom of her swimming pool at an angle of 40.0° to the normal and she dives in to retrieve it. However, Alison doesn't like to open her eyes in the water so she must rely on her initial observation of the coin made in the air. At what angle does the light from the coin travel as it moves toward the surface? ($n_{water} = 1.33$)

Answer: ____________________

**Exercise 10:** Here's an interesting trick to try. Place a penny in the bottom of a cup and stand so that the penny is just out of sight, as shown. Then pour water into the cup. Without moving, you will suddenly see the penny magically appear. If you look into the cup at an angle of 70.0° to the normal, at what angle to the normal must the penny be located in order for it to just appear in the bottom of the cup when the cup is filled with water? ($n_{water} = 1.33$)

Answer: ____________________

**Exercise 11:** Rohit makes his girlfriend a romantic candlelight dinner and tops it off with a dessert of gelatin filled with blueberries. If a blueberry that appears at an angle of 44.0° to the normal in air is really located at 30.0° to the normal in the gelatin, what is the index of refraction of the gelatin?

Answer: ____________________

**Exercise 12:** A jeweler must decide whether the stone in Mrs. Smigelski's ring is a real diamond or a less-precious zircon. He measures the critical angle of the gem and finds that it is 31.3°. Is the stone really a diamond or just a good imitation? ($n_{diamond} = 2.41$, $n_{zircon} = 1.92$)

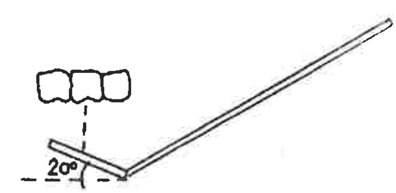
Answer: ____________________

## Additional Exercises

**A-1:** Radio waves travel at the speed of light. How long would it take the Russians to send a message to a spacecraft orbiting Mars at a distance of $7.8 \times 10^{10}$ m from Earth?

**A-2:** At the doctor's office, an X-ray of your hand is taken with electromagnetic radiation of frequency $3.00 \times 10^{17}$ Hz. What is the wavelength of this radiation?

**A-3:** In order to see your back teeth more easily, your dentist uses a small mirrored instrument that can be easily manipulated in your mouth. If the dentist places this mirror directly under a real molar, and tilts it 20°, at what angle to the normal will the dentist need to look into the mirror in order to see the tooth?




**A-4:** While decorating his Christmas tree, Vinnie discovers that he can see his reflection in a Christmas tree ball. a) If Vinnie looks into the ornament from a distance of 20.0 cm and focuses on his reflection 4.0 cm behind the ball, what is the focal length of the Christmas ball? b) Is Vinnie's image upright or inverted? c) Is his image larger or smaller?

**A-5:** Some rear-view mirrors on cars and trucks are curved to allow for a wider field of view. a) Would these mirrors be converging or diverging? b) Why might this be a little dangerous for a driver unaccustomed to this type of mirror? c) If the mirror has a focal length of 20.0 cm and the truck driver looks in the mirror from a distance of 30.0 cm, where does he see his image?

**A-6:** Wes stands in his hotel room in Cancun and admires his tan in a mirror that allows him to look "larger than life." a) What type of mirror is Wes using? b) Where should Wes stand in relation to the focal point of the mirror in order to appear enlarged? c) If the mirror has a focal length of 75.0 cm, and Wes stands 50.0 cm from the mirror's surface, how far behind the mirror is his image? d) Where does he see his image if he stands 200. cm from the mirror?

# 14 Lenses, Diffraction, and Interference

## 14-1 Lenses, Telescopes, and Magnifying Glasses

When light shines through a lens, it is **refracted** or bent due to the shape and material of the lens. Parallel rays of light passed through some lenses will eventually converge at the **focal point**. The terminology used for lenses is much the same as that used for mirrors in Chapter 13.

*Vocabulary* **Object distance:** The distance from the center of the lens to the object.

*Vocabulary* **Image distance:** The distance from the center of the lens to the image. An image can be **real** (able to be projected on a screen), or **virtual** (not able to be projected on a screen).

*Vocabulary* **Focal point:** The point where parallel rays meet (or appear to meet) after passing through a lens. The distance from this focal point to the center of the lens is called the **focal length**.

$$\textbf{Thin Lens Equation: } \frac{1}{\text{focal length}} = \frac{1}{\text{object distance}} + \frac{1}{\text{image distance}}$$

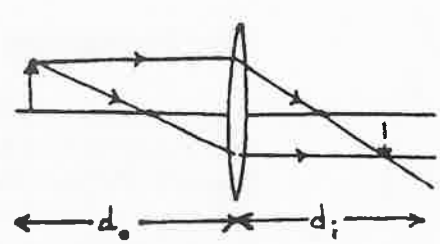
or $$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$$

NOTE: Many situations involving lenses can also be solved using ray diagrams.

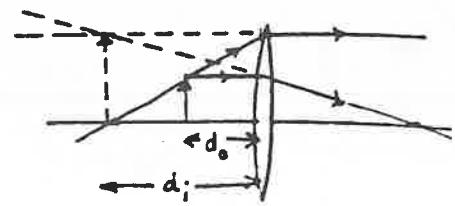
### The Converging (Positive) Lens

The focal length of a converging lens is always a positive number.

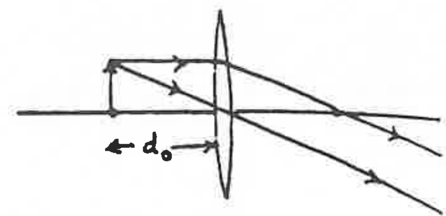
If an object is located outside the focal point of a converging lens, the image it forms is real, inverted, and on the opposite side of the lens. Both $d_o$ and $d_i$ are positive numbers.



If an object is located inside the focal point of a converging lens, the image it forms is virtual, upright, enlarged, and on the same side as the object. In this instance, $d_o$ is positive and $d_i$ is negative.



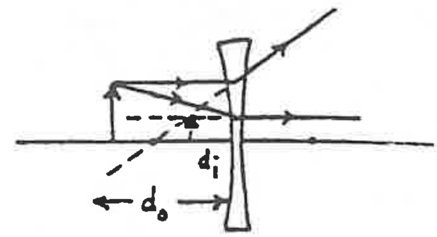

If the object is at the focal point, the rays do not converge and therefore no image is formed.




## The Diverging (Negative) Lens

The focal length of a diverging lens is always a negative number.

The image formed by a diverging lens is always virtual, upright, smaller, and on the same side of the lens as the object. In this instance, $d_o$ is positive and $d_i$ is negative.




If an object appears taller when seen through a lens, the object is magnified. The **linear magnification** of an object can be found by comparing the image distance to the object distance, or by comparing the image height, $h_i$, to the object height, $h_o$.

$$\textbf{linear magnification} = \frac{\textbf{image distance}}{\textbf{object distance}} = \frac{\textbf{image height}}{\textbf{object height}}$$

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

Note that a negative magnification implies a virtual image.

Linear magnification has no units. It is simply a ratio of image to object distance or a ratio of image to object height.

## The Refracting Telescope

A refracting telescope is a device that uses one lens to produce a real image, and a second lens to produce the virtual image that is seen by your eye. The amount of linear magnification you see when you look at an object through a telescope depends upon the focal length of each of the lenses. The lens that points toward the object is the objective lens and the lens you look through is the eyepiece. The focal lengths of each of these lenses are labeled $f_o$ and $f_e$, respectively.

$$\text{linear magnification} = \frac{\text{focal length of objective lens}}{\text{focal length of eyepiece}} \quad \text{or} \quad m = \frac{f_o}{f_e}$$

## The Magnifying Glass

When using a magnifying glass, the amount of **angular magnification** of an object depends upon how close you hold the magnifying glass to the object. It also depends upon the near point of your own eye, which is the closest point at which an unaided eye can focus on an object. A person's near point increases with age and the eyes lose some of their adaptable, elastic properties. However, for the ease of calculations, assume the near point of the eye is 25 cm unless otherwise noted.

$$\text{angular magnification} = \frac{\text{near point}}{\text{focal length}} \quad \text{or} \quad M = \frac{\text{near point}}{f}$$

## Solved Examples

**Example 1:** Mukluk, an Inuit, makes a converging lens out of ice that will enable him to concentrate light from the sun to start a fire. When he holds the ice lens 1.00 m from a snow-covered wall, an image of his 5.00-m-distant igloo is projected onto the snow. a) What is the focal length of the ice lens? b) Draw a ray diagram of the situation.

**a.** *Given:* $d_o = 5.00 \text{ m}$, $d_i = 1.00 \text{ m}$

*Unknown:* $f = ?$

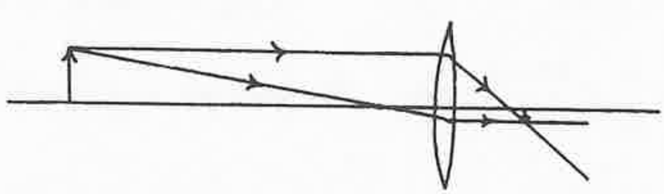
*Original equation:* $\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$

*Solve:* $\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{5.00 \text{ m}} + \frac{1}{1.00 \text{ m}} = 1.20 \text{ m}^{-1}$

Taking the reciprocal gives $f = \frac{1}{1.20 \text{ m}^{-1}} = \mathbf{0.833 \text{ m}}$

The focal length of 0.833 m is close to the image distance of 1.00 m.

**b.**



**Example 2:** A diverging lens is placed 5.0 cm in front of a laser beam to spread the light for the production of a hologram. a) What is the focal length of the lens if the beam of laser light seems to come from a point 2.0 cm behind the lens? b) Draw a ray diagram of the situation.

**a.** *Given:* $d_o = 5.0 \text{ cm}$, $d_i = -2.0 \text{ cm}$

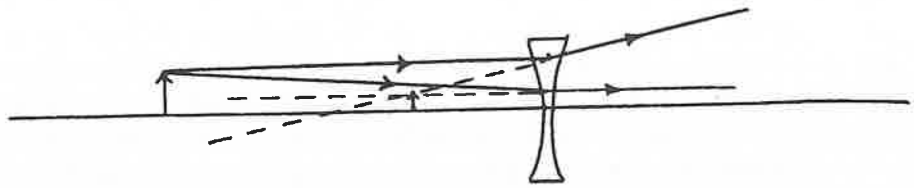
*Unknown:* $f = ?$

*Original equation:* $\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$

*Solve:* $\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{5.0\text{ cm}} + \frac{1}{-2.0\text{ cm}} = \frac{2}{10.\text{ cm}} - \frac{5}{10.0\text{ cm}} = -\frac{3}{10.}\text{ cm}^{-1}$

$f = -\frac{10.}{3}\text{ cm} = \mathbf{-3.3\text{ cm}}$

**b.**



**Example 3:** Irwin, a coin collector, is looking at a rare coin held behind a magnifying glass whose focal length is 5.0 cm. a) If the eyes' near point is 25 cm, what is the angular magnification? b) If the coin is 2.0 cm in diameter, how large will its diameter appear to be when it is held in this position under the magnifying glass?

**a.** *Given:* near point = 25 cm
$f = 5.0$ cm

*Unknown:* $M = ?$
*Original equation:* $M = \frac{\text{near point}}{f}$

*Solve:* $M = \frac{\text{near point}}{f} = \frac{25\text{ cm}}{5.0\text{ cm}} = \mathbf{5.0}$ The coin is magnified 5.0 times.

**b.** *Given:* $m = 5.0$
$h_o = 2.0$ cm

*Unknown:* $h_i = ?$
*Original equation:* $m = \frac{h_i}{h_o}$

*Solve:* $h_i = mh_o = (5.0)(2.0\text{ cm}) = \mathbf{10.\text{ cm}}$

**Example 4:** The ship *Speedwell* brought many early settlers to this country in the 1600s. Oceanus sits high above the ship's deck in the crow's nest watching through a telescope for the first sign of land. How much does the telescope magnify if the eyepiece has a 2.0-cm focal length and the objective lens has a 80.-cm focal length?

*Given:* $f_o = 80.$ cm
$f_e = 2.0$ cm

*Unknown:* $m = ?$
*Original equation:* $m = \frac{f_o}{f_e}$

*Solve:* $m = \frac{f_o}{f_e} = \frac{80.\text{ cm}}{2.0\text{ cm}} = \mathbf{40.}$ The telescope magnifies 40. times.

## Practice Exercises

**Exercise 1:** Harold and Roland find a discarded plastic lens lying on the beach. The boys discuss what they learned in physics last semester and argue whether the lens is a converging or a diverging one. When they look through the lens, they notice that objects are inverted. a) If an object sitting 25.0 cm in front of the lens forms an image 20.0 cm behind the lens, what is the focal length of the lens? b) Is it a converging or a diverging lens?

Answer: **a.** ____________________

Answer: **b.** ____________________

**Exercise 2:** Sadie looks at her friend's face through a diverging lens. a) Is the image real or virtual? b) If her friend's face is 50.0 cm from the lens that forms an image at a distance of 20.0 cm, what is the focal length of the lens? c) Draw a ray diagram of the situation.

Answer: **a.** ____________________

Answer: **b.** ____________________

**Exercise 3:** Giorgio is clicking shots of the fashion model Nadine as she walks toward him across the studio. Giorgio's camera contains a lens with a focal length of 0.0500 m. a) How far back must the film be located when Nadine is 3.00 m from the camera? b) Should the lens be moved in or out as Nadine approaches closer to the photographer? c) Draw a ray diagram of the situation with Nadine at 3.00 m and 1.00 m from the camera.

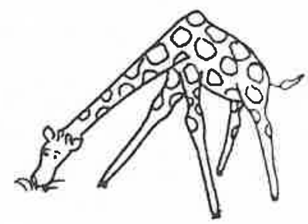
Answer: **a.** ____________________

Answer: **b.** ____________________

**Exercise 4:** Dr. Wasserman is showing slides to his biology class. a) If the slides are positioned 15.5 cm from the projector lens that has a focal length of 15.0 cm, where should the screen be placed to produce the clearest image of the slide? b) Draw a ray diagram of the situation.

Answer: **a.** ____________________

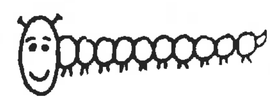
**Exercise 5:** Marlin is out on a safari. Looking through his telescope, he spots a giraffe in the distance. The telescope has an objective lens of 40-cm focal length and an eyepiece of 2-cm focal length. a) What is the magnification of the giraffe? b) How large is the image formed by the telescope if the giraffe appears to be 1.5 cm high to the naked eye?



Answer: **a.** ____________________

Answer: **b.** ____________________

**Exercise 6:** Emilio, an entomologist, studies a millepede that he holds behind a magnifying glass whose focal length is 2.00 cm. a) Assuming Emilio's near point is 25.0 cm, what is the angular magnification? b) Does Emilio have to bring the magnifying glass closer to, or farther from, the millipede in order to make it appear larger?



Answer: **a.** ____________________

Answer: **b.** ____________________

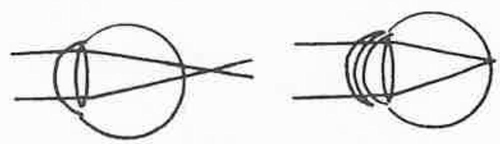
**Exercise 7:** Mr. Crabtree, a jeweler, looks through his jeweler's loupe (a small magnifying glass attached to his glasses) in order to read the engraving on a pewter bowl. The loupe has a focal length of 3 cm. If Mr. Crabtree's near point is 24 cm, what is the angular magnification of the engraving?

Answer: ____________________

# 14-2 Eyeglasses

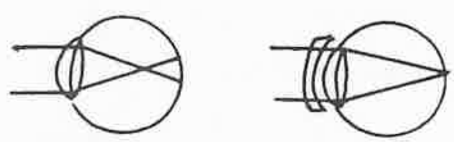
When the eye is unable to focus incoming light directly on the retina (a layer of tissue in the back of the eye that is sensitive to light), eyeglasses or contact lenses are usually prescribed.

If the lens, or cornea, is curved so that light would focus behind the retina, the result is a condition called **farsightedness**, where only objects at a distance can be seen clearly. To correct this problem, glasses for a farsighted person have lenses that are thicker in the middle and thinner near the edges (converging lenses).



Uncorrected Corrected

If the lens, or cornea, is curved so that light would focus in front of the retina, the result is a condition called **nearsightedness**, where only objects close up can be seen clearly. To correct this problem, glasses for a nearsighted person have lenses that are thinner in the middle and thicker near the edges (diverging lenses).



Uncorrected Corrected

The power of a pair of prescription glasses is the reciprocal of the focal length, if the focal length is measured in meters.

$$\textbf{Power} = \frac{\textbf{1}}{\textbf{focal length}} \qquad \text{or} \qquad P = \frac{1}{f}$$

The SI unit for the power of eyeglasses is the **diopter**, which equals the **reciprocal of a meter ($m^{-1}$)**.

For all the following exercises, assume that the preferred far point of the eye is infinity, ∞, and the preferred near point is 25 cm. To find the power of the lenses in a pair of glasses, take the difference between the reciprocal of how far the eye can see without glasses and how far it can see with glasses.

$$\text{power} = \frac{1}{f_{\text{glasses}}} = \frac{1}{d_{o(\text{glasses})}} - \frac{1}{d_{o(\text{no glasses})}}$$

If you wear glasses or contact lenses, ask your doctor about the power of your prescription. You may find that it can be different for each eye!

## Solved Examples

**Example 5:** Craig is nearsighted, so he must wear glasses to see objects that are far away. If his glasses have a focal length of 0.5 m, what is their power in diopters?

**Solution:** The focal length must be written as a negative number because a nearsighted person will always wear glasses with diverging lenses. A diverging lens has a negative focal length.

*Given:* $f_{glasses} = -0.5\text{ m}$

*Unknown:* $P = ?$
*Original equation:* $P = \dfrac{1}{f}$

*Solve:* $P = \dfrac{1}{f} = \dfrac{1}{-0.5\text{ m}} = \mathbf{-2\ diopters}$

**Example 6:** In the previous exercise, if Craig can see to infinity with his glasses on, what is the maximum distance he can see clearly with the glasses off?

*Given:* $f_{glasses} = -0.5\text{ m}$
$d_{o(glasses)} = \infty$

*Unknown:* $d_{o(no\ glasses)} = ?$
*Original equation:*

$$\frac{1}{f_{glasses}} = \frac{1}{d_{o(glasses)}} - \frac{1}{d_{o(no\ glasses)}}$$

*Solve:*

$$\frac{1}{d_{o(no\ glasses)}} = \frac{1}{d_{o(glasses)}} - \frac{1}{f_{glasses}} = \frac{1}{\infty} - \frac{1}{-0.5\text{ m}} = 0 - (-2) = 2\text{ diopters}$$

$$d_{o(no\ glasses)} = \frac{1}{2\text{ diopters}} = \mathbf{0.5\ m}$$

The farthest Craig can see clearly without glasses is 0.5 m.

**Example 7:** Dorcas must hold the phone book 0.5 m from her eyes in order to find the eye doctor's phone number. a) If Dorcas would like to read the phone book at a more comfortable distance of 0.25 m, what power glasses does she need? b) What type of lenses would these glasses contain?

**a.** *Given:* $d_{o(no\ glasses)} = 0.5\text{ m}$
$d_{o(glasses)} = 0.25\text{ m}$

*Unknown:* $P = ?$
*Original equation:*

$$\frac{1}{f_{glasses}} = \frac{1}{d_{o(glasses)}} - \frac{1}{d_{o(no\ glasses)}}$$

*Solve:*

$$\frac{1}{f_{glasses}} = \frac{1}{d_{o(glasses)}} - \frac{1}{d_{o(no\ glasses)}} = \frac{1}{0.25\text{ m}} - \frac{1}{0.5\text{ m}} = 4 - 2 = \mathbf{2\ diopters}$$

**b.** Because the power of the glasses in this example is a positive number, the lenses must be converging lenses. This is supported by the fact that farsightedness must be corrected with converging lenses.

## Practice Exercises

**Exercise 8:** Beth is farsighted, so she must wear glasses to see objects close by. If her glasses have a focal length of 0.30 m, what is their power in diopters?

Answer: ____________________

**Exercise 9:** Herman is able to read the newspaper at a distance of 0.75 m, but no closer. a) Is he farsighted or nearsighted? b) What power lens should he use to allow him to read the paper at 0.25 m? c) What type of lens does he need?


Answer: **a.** ____________________

Answer: **b.** ____________________

Answer: **c.** ____________________

**Exercise 10:** At the beach, Maria can see Sandy, a surfer, clearly only when he is standing closer than 2.0 m. a) What power prescription sunglasses would Maria need in order to see Sandy when he is out on the ocean riding a wave? b) What type of lenses will her glasses contain?

Answer: **a.** ____________________

Answer: **b.** ____________________

**Exercise 11:** Matt is driving his "18-wheeler" while wearing his new pair of glasses whose focal length is −0.40 m. If the glasses allow Matt to see clearly at an infinite distance for normal driving, how far could Matt see clearly before he bought the glasses?

Answer: ____________________

**Exercise 12:** Moshe has gone to Bermuda for spring vacation and when he is on the beach realizes that he has picked up his father's pair of prescription sunglasses by mistake. The glasses have a power of + 3.0 diopters. a) What type of eye problem does Moshe's father have, and how do you know? b) What is the closest that Moshe's father can see clearly without his glasses? c) Will these glasses produce an image in front of, or behind, the image formed by Moshe's normal eye?

Answer: **a.** ____________________

Answer: **b.** ____________________

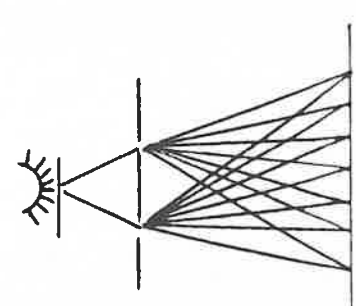
Answer: **c.** ____________________

# 14-3 Diffraction and Interference

*Vocabulary* **Diffraction:** The spreading of a wave as it passes around an obstacle or through an opening.

*Vocabulary* **Interference:** When two waves overlap to produce one new wave.

In 1801, Thomas Young attempted to prove that light was a wave by showing that it has the ability to diffract and interfere. Young passed white light through two closely-spaced slits and noticed that the light spread out as it passed through the openings (diffracted), and overlapped on a screen a few meters away (interfered), to produce alternating bands of light and dark.



Whether light is passed through two slits or through the multiple, closely-spaced slits of a diffraction grating, the grating equation can be written as

$$\textbf{wavelength} = \frac{\textbf{(slit separation)(space between bright bands)}}{\textbf{(distance from slits to screen)}} \quad \text{or} \quad \lambda = \frac{dx}{L}$$

This equation is a good approximation when the angular separation between the bright bands is very small. When used with a diffraction grating, however, it could produce an answer with as much as 10% error. Nevertheless, to simplify calculations and avoid the use of trigonometry, the equation will be used in this form in all exercises.

The common unit for the wavelength of light is the **nanometer (nm)**, which equals $10^{-9}$ m.

## Solved Examples

**Example 8:** Miss McGillivray loses the specifications for her diffraction grating and must recalibrate it in order to determine the grating spacing. She shines a red helium-neon laser, whose wavelength is 633 nm, through the grating. Two bright spots that are each 1.40 m from the central maximum fall on the wall 4.00 m away. What is the space between the grooves on the diffraction grating?

**Solution:** First, convert nm to m. $633 \text{ nm} = 6.33 \times 10^{-7} \text{ m}$

*Given:* $\lambda = 6.33 \times 10^{-7}$ m
$L = 4.00$ m
$x = 1.40$ m

*Unknown:* $d = ?$
*Original equation:* $\lambda = \frac{dx}{L}$

*Solve:* $d = \frac{\lambda L}{x} = \frac{(6.33 \times 10^{-7} \text{ m})(4.00 \text{ m})}{1.40 \text{ m}} = \mathbf{1.81 \times 10^{-6}}$ **m**

**Example 9:** In the previous exercise, Miss McGillivray uses her newly calibrated grating to determine the wavelength of a green helium-neon laser. Keeping the laser at the same distance from the wall as before, the distance from the central maximum to the first bright fringe is 1.20 m. What is the wavelength of the green HeNe laser?

*Given:* $d = 1.81 \times 10^{-6}$ m
$L = 4.00$ m
$x = 1.20$ m

*Unknown:* $\lambda = ?$
*Original equation:* $\lambda = \frac{dx}{L}$

*Solve:* $\lambda = \frac{dx}{L} = \frac{(1.81 \times 10^{-6} \text{ m})(1.20 \text{ m})}{4.00 \text{ m}} = 5.43 \times 10^{-7} \text{ m} =$ **543 nm**

## Practice Exercises

**Exercise 13:** Judy and Earl are sitting under the boardwalk one warm summer evening while the light of a low-pressure sodium vapor lamp whose wavelength is 589 nm passes through two small cracks in a board, producing fringes of light 0.0020 m apart on the ground. a) If the boardwalk is 3.0 m above the sand, what is the distance between the two cracks in the board? b) If the distance between the cracks were smaller, would the fringes of light on the ground be closer together or farther apart?

Answer: **a.** ______________________

Answer: **b.** ______________________

**Exercise 14:** Two large speakers broadcast the sound of a band tuning up before an outdoor concert. While the band plays an A whose wavelength is 0.773 m, Brenda walks to the refreshment stand along a line parallel to the speakers. If the speakers are separated by 12.0 m and Brenda is 24.0 m away, how far must she walk between the "loudspots"?

Answer: ______________________

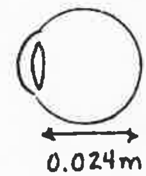
**Exercise 15:** In an attempt to test the particle nature of matter, Claus Jönsson performed an experiment in 1961 that was very similar to Young's Double Slit experiment for light done in 1801. Jönsson sent a beam of electrons through two slits separated by $2.00 \times 10^{-6}$ m onto a fluorescent screen 0.200 m away. Due to their high speed, the electrons behaved like waves with a wavelength of $2.40 \times 10^{-11}$ m. How far apart were the bright lines formed on the screen?

Answer: ______________________

## Additional Exercises

**A-1:** A photocopy machine is set to reduce the size of printed material by 50%. When the print is regular size, both the image and object distance are 16.0 cm. If the lens is then moved 24.0 cm from the object, how large is the new image distance?

**A-2:** The average normal human eye forms an image on the retina at a distance of about 0.0240 m from the lens, as shown. How much must the focal length of the lens change in order to accommodate an object moved from 10.0 m to 0.250 m? (This change in focal length is accomplished by small muscles in the eye called *cilliary muscles.* These muscles actually stretch and relax the lens.)




**A-3:** Lisa is posing for her senior class picture and sits 2.00 m from the camera lens whose focal length is 17.0 cm. The camera lens is positioned 21.0 cm in front of the film. Will the photographer obtain a clear image of Lisa? If not, by how much must the camera lens be moved in our out?

**A-4:** Cindy is lying on the beach focusing her camera on a friend standing 5.00 m away. Her camera has a focal length of 5.00 cm. a) Where must Cindy position the camera lens relative to the film for the sharpest focus? b) What type of lens must her camera have, and why?

**A-5:** Sherlock Holmes discovers some telltale hairs at the scene of a crime. He views the hairs with his magnifying glass from a distance of 6.0 cm. If the hairs are magnified 4.0 times, how far is the magnified image from the lens?

**A-6:** Jacob attaches a solar filter to his telescope and projects an image of the sun through the objective lens that has a focal length of 2.00 m. Jacob can't decide whether to use a 40.0-mm eyepiece or a 16.0-mm eyepiece to study the solar features. a) What amount of magnification will each eyepiece provide? b) Someone may look through a telescope and ask, "What is the magnification of this instrument?" Why is it impossible to give one standard answer to the question? c) If the sun appears to be 1.00 cm across to the naked eye, how large will it appear when viewed with the 16.0-mm eyepiece?

**A-7:** To the naked eye, Jupiter appears to be about 0.10 cm in diameter. In a telescope whose objective lens has a focal length of 2.0 m, Jupiter appears to be 1.2 cm in diameter. What is the focal length of the eyepiece used to produce this image?

**A-8:** Ms. Chang is standing by the slide projector in the back of the room when she realizes that the screen is in the wrong location to get a clear image. a) If the projector has a lens with a focal length of 20.0 cm, and the slides sit 20.6 cm behind the lens, in which direction should one of the students move the screen that sits 7.00 m from the lens? b) How far away should the screen be from the projector lens?

**A-9:** Beverly wears bifocals. She can read close up when she looks through the bottom portion and can read far away when she looks through the top portion. a) The top of her glasses has a focal length of $-0.25$ m. What is the power, in diopters, of this part of the glasses? b) The bottom portion has a power of 3.5 diopters. What is the focal length of this part of the glasses?

**A-10:** In exercise A-9, if Beverly can see to infinity with her glasses on, a) what is the maximum distance she can see clearly with the glasses off? b) If Beverly can see an object at 25 cm with her glasses on, what is the minimum distance she can see clearly with the glasses off?

**A-11:** Rachel brings a note home from school. The note advises her mother that "Rachel is having a difficult time reading the words on the board and can only see the words if she is sitting closer than 2.0 m." If Rachel wants to be able to read the words from 3.0 m away, what power glasses does she need?

**A-12:** Joon puts on a pair of diffraction grating glasses that he bought in a novelty shop and looks at a mercury vapor street lamp that is 5.00 m away. He sees a yellow spectral line 1.16 m on either side of the light source. If the diffraction grating glasses have a slit separation of $2.49 \times 10^{-6}$ m, what is the wavelength of the light Joon is observing?

**A-13:** Radio station WLLH has two transmitters that sit atop nearby hillsides broadcasting a wave that is 214 m long. As Kiesha drives down the interstate parallel to the two transmitters at a distance of 1000. m, she hears an increase in signal from the station every 30.0 m. How far apart are the two transmitters?

## Challenge Exercises for Further Study

**B-1:** The Hale telescope at the Yerkes Observatory in Wisconsin has an objective lens with a focal length of 19 m. (For an object at infinity, the image distance equals the focal length.) If the telescope is used to observe Saturn that is $1275 \times 10^9$ m from Earth, what will be the apparent diameter of the rings if their actual diameter is $27 \times 10^7$ m?

**B-2:** Dr. Kirwan is preparing a slide show that he will present to the executive board at tonight's committee meeting. He places a 3.50-cm slide behind a lens of 20.0 cm focal length in the slide projector. a) How far from the lens should the slide be placed in order to shine on a screen 6.00 m away? b) How wide must the screen be to accommodate the projected image?

**B-3:** Madeline is working for the Eye-Spy Detective Agency and her assignment is to secretly photograph the pages of a journal. Madeline's tiny camera has the film located 2.10 cm behind the lens, and she must fill the entire piece of 1.00-cm film with the picture of the 25.0-cm-tall document. How close must Madeline be to the journal pages to get a clear image on the film?