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

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 2450×10^6 Hz.

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

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

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

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 5.91×10^{12} m?

$\Delta t = \Delta d/c = (5.91 \times 10^{12}\ \text{m})/(3.00 \times 10^{8}\ \text{m/s}) =$ **19 700 s**

Answer: **19 700 s**

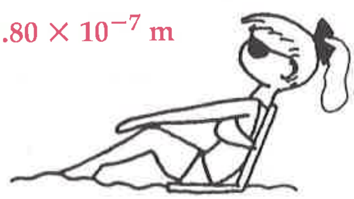
Exercise 2: If a person could travel at the speed of light, it would still take 4.3 years to reach the nearest star, Proxima Centauri. How far away, in meters, is Proxima Centauri? (Ignore any relativistic effects.)

$\Delta d = c\Delta t = (3.00 \times 10^{8}\ \text{m/s})(135\ 604\ 800\ \text{s}) =$ **4.07×10^{16}m**

Answer: **4.07×10^{16} m**

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 7.89×10^{14} Hz?

a) $\lambda = c/f = (3.00 \times 10^{8}\ \text{m/s})/(7.89 \times 10^{14}\ \text{Hz}) =$ **3.80×10^{-7} m**



Answer: **3.80×10^{-7} m**

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 1.00×10^{-6} m?

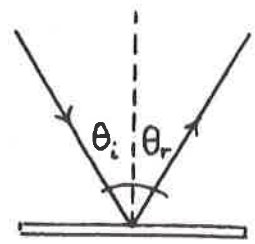
$f = c/\lambda = (3.00 \times 10^{8}\ \text{m/s})/(1.00 \times 10^{-6}\ \text{m}) =$ **3.00×10^{14} Hz**

Answer: **3.00×10^{14} Hz**

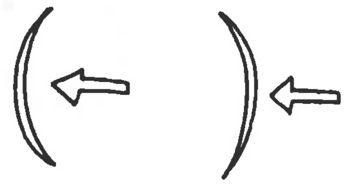
13-2 Reflection

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.

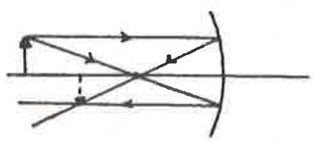


Figure A

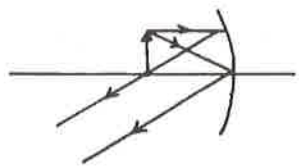


Figure B

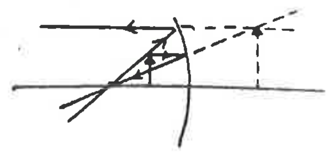
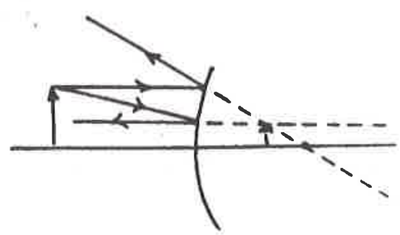


Figure C

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:* $d_o = 15\ \text{cm}$
$d_i = -4.0\ \text{cm}$

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

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

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. $f = \frac{-60\ \text{cm}}{11} = \mathbf{-5.5\ cm}$

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:* $d_o = 6.0\ \text{cm}$
$d_i = -12\ \text{cm}$

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

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

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

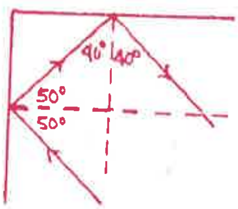
$f = \mathbf{12\ cm}$

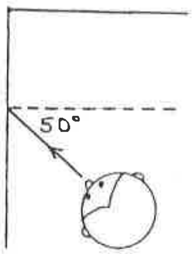
The positive answer means that the bowl was acting as a converging mirror.

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?

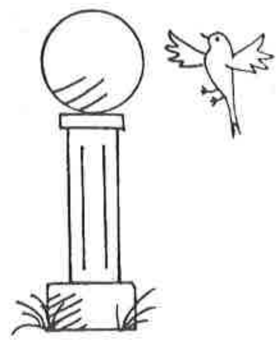




Answer: 40°

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?

a) $1/f = 1/d_o + 1/d_i = 1/(10.0 \text{ cm}) + 1(-5.0 \text{ cm})$
$= -0.10 \text{ cm}^{-1}$ $f = \mathbf{-10. \text{ cm}}$
b) Smaller.



Answer: **a.** **−10. cm**

Answer: **b.** **Smaller**

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.

a) $1/d_i = 1/f - 1/d_o = 1/(18 \text{ cm}) - 1/(12 \text{ cm}) = -0.028 \text{ cm}^{-1}$ $d_i = \mathbf{-36 \text{ cm}}$
b) Yes. She wants to be inside f so that her face is right side up and enlarged.

Answer: **a.** **−36 cm**

Answer: **b.** **closer**

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?

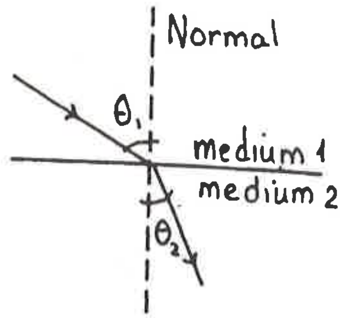
$1/d_i = 1/f - 1/d_o = 1/(-20.0 \text{ cm}) - 1/(40.0 \text{ cm}) = -0.0750 \text{ cm}^{-1}$
$d_i = \mathbf{-13.3 \text{ cm}}$

Answer: **−13.3 cm**

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 θ_1 and θ_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 θ_1 is called the **critical angle,** θ_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 1.90×10^8 m/s in the crystal, what is the crystal's index of refraction?

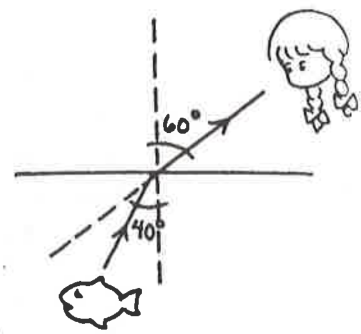
Given: $c = 3.00 \times 10^8$ m/s
$v = 1.90 \times 10^8$ m

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

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

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? ($n_{water} = 1.33$)

$\sin \theta_2 = n_1 \sin \theta_1 / n_2 = (1.00) \sin 40.0° / 1.33 = 0.483$ $\quad \boldsymbol{\theta_2 = 28.9°}$

Answer: **28.9°**

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? ($n_{water} = 1.33$)

$\sin \theta_2 = n_1 \sin \theta_1 / n_2 = (1.00) \sin 70.0° / 1.33 = 0.707$ $\quad \boldsymbol{\theta_2 = 45.0°}$

Answer: **45.0°**

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?

$n_1 = n_2 \sin \theta_2 / \sin \theta_1 = (1.00) \sin 44.0° / \sin 30.0° = \mathbf{1.39}$

Answer: **1.39**

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? ($n_{diamond} = 2.41$, $n_{zircon} = 1.92$)

$n_2 = n_1 \sin 90.0° / \sin \theta_c = (1.00) \sin 90.0° / \sin 31.3° =$ **1.92. It is zircon!**

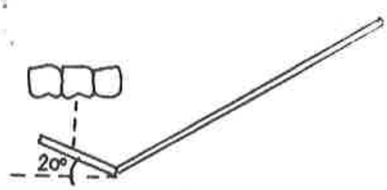
Answer: **1.92. It is zircon!**

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 7.8×10^{10} m from Earth?

A-2: At the doctor's office, an X-ray of your hand is taken with electromagnetic radiation of frequency 3.00×10^{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?

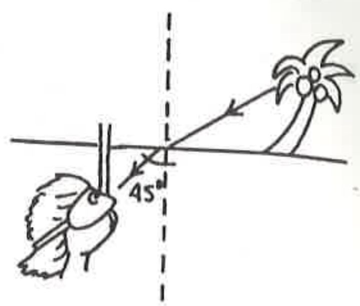
A-6: Wes stands in his hotel room in Cancun and admires his tan in a mirror that allows him to look "larger than life." a) What type of mirror is Wes using? b) Where should Wes stand in relation to the focal point of the mirror in order to appear enlarged? c) If the mirror has a focal length of 75.0 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?

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?



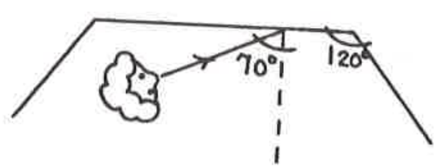
A-11: Spenser, a cat, enjoys watching the family goldfish from the top of the fish tank. If the goldfish, swimming in water, appears to be at an angle of 28.0° as seen by Spenser, at what true angle is the goldfish from the normal? (n_{water} = 1.33)

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?

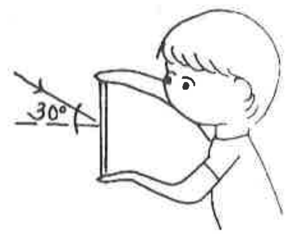
A-13: In her bedroom, Mia has a fiber optic light that glows as hundreds of fiber optic cables are lit from below. a) If each fiber optic cable has an index of refraction of 1.48, at what critical angle must light enter the cable in order for total internal reflection to occur? b) Explain why total internal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

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**.

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

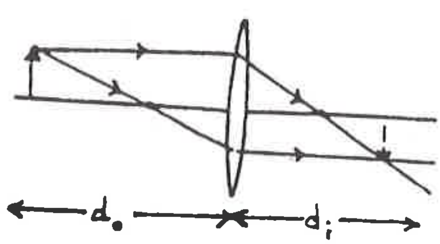
or $$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$$

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

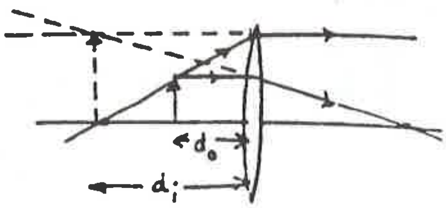
The Converging (Positive) Lens

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

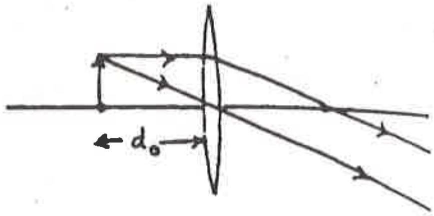
If an object is located outside the focal point of a converging lens, the image it forms is real, inverted, and on the opposite side of the lens. Both d_o and d_i are positive numbers.



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.



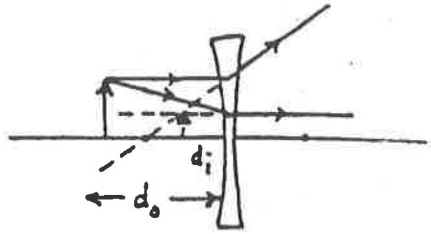
If the object is at the focal point, the rays do not converge and therefore no image is formed.



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:* $d_o = 5.00$ m
$d_i = 1.00$ m

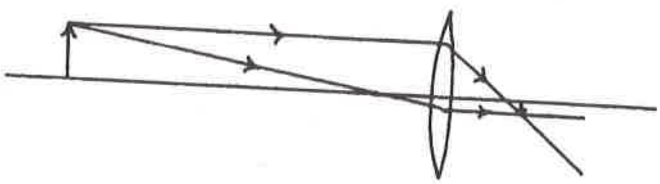
Unknown: $f = ?$
Original equation: $\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$

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.

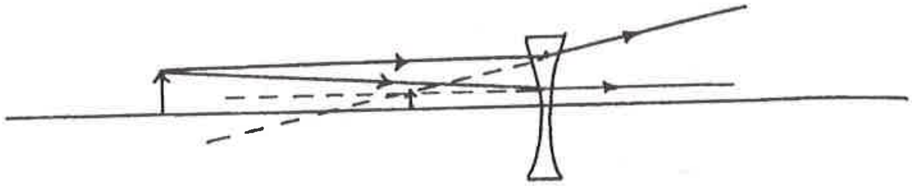
a. *Given:* $d_o = 5.0$ cm
$d_i = -2.0$ cm

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

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

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

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?

a) $1/f = 1/d_o + 1/d_i = 1/(25.0\text{ cm}) + 1/(20.0\text{ cm}) = 0.0900\text{ cm}^{-1}$ $f =$ **11.1 cm**
b) **Converging.**

Answer: **a.** **11.1 cm**

Answer: **b.** **Converging**

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.

a) **Virtual.**
b) $1/f = 1/d_o + 1/d_i$
$= 1/(50.0\text{ cm}) + 1/(-20.0\text{ cm})$
$= -0.0300\text{ cm}^{-1}$ $f =$ **−30.0 cm**

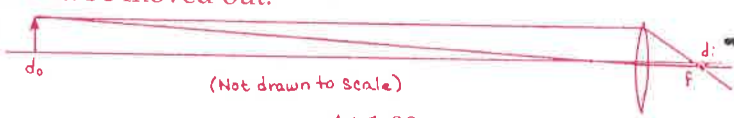
c)

Answer: **a.** **Virtual**

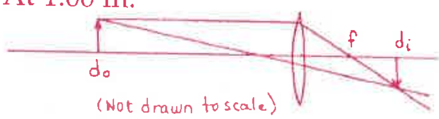
Answer: **b.** **−30.0 cm**

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.

a) $1/d_i = 1/f - 1/d_o = 1/(0.0500\text{ m}) - 1/(3.00\text{ m})$
$= 19.7\text{ m}^{-1}$ $d_i =$ **0.0508 m**
b) The lens should be moved out.
c) At 3.00 m:



At 1.00 m:

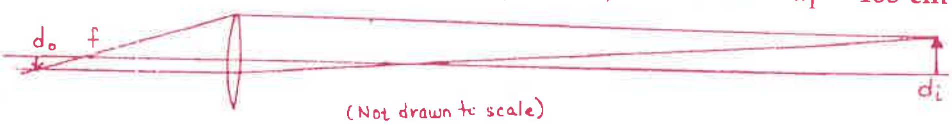


Answer: **a.** **0.0508 m**

Answer: **b.** **Out**

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.

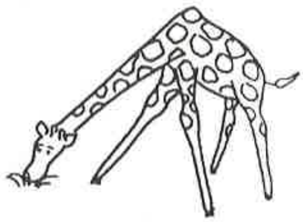
a) $1/d_i = 1/f - 1/d_o = 1/(15.0\text{ cm}) - 1/(15.5\text{ cm}) = 2.15\text{ cm}^{-1}$ $d_i =$ **465 cm**
b)



Answer: **a.** **465 cm**

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?

a) $m = f_o/f_e$ = (40 cm)/(2 cm) = **20 times**
b) $h_i = mh_o$ = (20)(1.5 cm) = **30 cm**



Answer: **a.** **20 times**

Answer: **b.** **30 cm**

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?

a) M = near point/f = (25.0 cm)/(2.00 cm) = **12.5 times**
b) Farther

Answer: **a.** **12.5 times**

Answer: **b.** **Farther**

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?

M = near point/f = (24 cm)/(3 cm) = **8 times**

Answer: **8 times**