CHAPTER 18 Refraction and Lenses

Practice Problems

18.1 Refraction of Light pages 485–492

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1. A laser beam in air is incident upon ethanol at an angle of incidence of 37.0°. What is the angle of refraction?

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

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

$$= \sin^{-1}\left(\frac{(1.00)(\sin 37.0°)}{1.36}\right)$$

$$= 26.3°$$

2. Light in air is incident upon a piece of crown glass at an angle of incidence of 45.0°. What is the angle of refraction?

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

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

$$= \sin^{-1}\left(\frac{(1.00)(\sin 45.0°)}{1.52}\right)$$

$$= 27.7°$$

3. Light passes from air into water at 30.0° to the normal. Find the angle of refraction.

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

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

$$= \sin^{-1}\left(\frac{(1.00)(\sin 30.0°)}{1.33}\right)$$

$$= 22.1°$$

4. Light is incident upon a diamond facet at 45.0°. What is the angle of refraction?

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

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

$$= \sin^{-1}\left(\frac{(1.00)(\sin 45.0°)}{2.42}\right) = 17.0°$$

5. A block of unknown material is submerged in water. Light in the water is incident on the block at an angle of incidence of 31°. The angle of refraction of the light in the block is 27°. What is the index of refraction of the material of the block?

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

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

$$= \frac{(1.33)(\sin 31°)}{\sin 27°}$$

$$= 1.5$$

Section Review

18.1 Refraction of Light pages 485–492

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

$n_{water} < n_{liquid} < n_{crown\ glass}$, therefore, n_{liquid} must be between 1.33 and 1.52.

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

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

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

$$= \frac{(1.00)(\sin 30.0°)}{\sin 20.0°}$$

$$= 1.46$$

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

No, it would mean the speed of light in the medium is faster than it is in a vacuum.

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

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

$$v_{\text{chloroform}} = \frac{c}{n_{\text{chloroform}}}$$

$$= \frac{3.00\times10^8 \text{ m/s}}{1.51}$$

$$= 1.99\times10^8 \text{ m/s}$$

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

crown glass because it has a lower index of refraction and would produce total internal reflection

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

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

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

$$= \sin^{-1}\left(\frac{(1.33)(\sin 57.5°)}{1.50}\right)$$

$$= 48.4°$$

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

Yes, because $n_{\text{glass}} > n_{\text{water}}$. No.

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

because of bending of light rays in the atmosphere; refraction

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

In the east, because the Sun sets in the west and sunlight must shine from behind you in order for you to see a rainbow.

Practice Problems

18.2 Convex and Concave Lenses pages 493–499

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

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

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

$$= \frac{(8.5 \text{ cm})(5.5 \text{ cm})}{8.5 \text{ cm} - 5.5 \text{ cm}}$$

$$= 15.6 \text{ cm, or } 16 \text{ cm}$$

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

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

$$= \frac{-(15.6 \text{ cm})(2.25 \text{ cm})}{8.5 \text{ cm}}$$

$$= -4.1 \text{ cm}$$

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

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

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

$$= \frac{(10.4 \text{ cm})(6.8 \text{ cm})}{10.4 \text{ cm} - 6.8 \text{ cm}}$$

$$= 2.0\times10^1 \text{ cm}$$

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

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

$= \frac{-(19.6 \text{ cm})(-1.8 \text{ cm})}{10.4 \text{ cm}}$

$= 3.4 \text{ cm}$

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

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

with $d_o = d_i$ **because**

$m = \frac{-d_i}{d_o}$ **and** $m = -1$

Therefore,

$\frac{1}{f} = \frac{2}{d_i}$

$d_i = 2f$

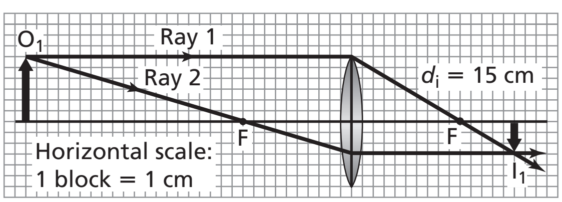
$= 2(25 \text{ mm})$

$= 5.0\times10^1 \text{ mm}$

$d_o = d_i = 5.0\times10^1 \text{ mm}$

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

$d_i = 15 \text{ cm}$



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

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

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

$= \frac{(25 \text{ cm})(5.0 \text{ cm})}{25 \text{ cm} - 5.0 \text{ cm}}$

$= 6.2 \text{ cm}$

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

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

$= \frac{-(6.2 \text{ cm})(2.0 \text{ cm})}{25 \text{ cm}}$

$= -0.50 \text{ cm}$ **(inverted image)**

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

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

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

$= \frac{(6.0 \text{ cm})(20.0 \text{ cm})}{6.0 \text{ cm} - 20.0 \text{ cm}}$

$= -8.6 \text{ cm}$

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

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

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

$= \frac{(3.4 \text{ cm})(12.0 \text{ cm})}{3.4 \text{ cm} - 12.0 \text{ cm}}$

$= -4.7 \text{ cm}$

$h_i = \frac{-h_o d_i}{d_o} = \frac{-(2.0 \text{ cm})(-4.7 \text{ cm})}{3.4 \text{ cm}}$

$= 2.8 \text{ cm}$

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

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

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

$$= \frac{(10.0\text{ cm})(22.0\text{ cm})}{10.0\text{ cm} - 22.0\text{ cm}}$$

$$= -18.3\text{ cm}$$

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

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

$$= \frac{-(-18.3\text{ cm})(15.0\text{ cm})}{10.0\text{ cm}}$$

$$= 27.5\text{ cm (upright image)}$$

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

$$m = \frac{-d_i}{d_o}$$

$$d_i = -md_o = -(4.0)(3.5\text{ cm})$$

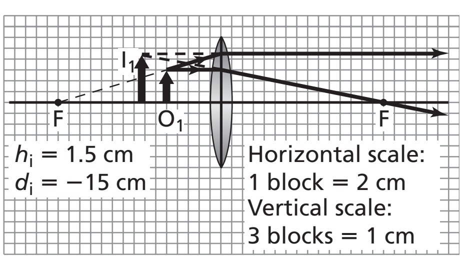
$$= -14\text{ cm}$$

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

$$f = \frac{d_o d_i}{d_o + d_i} = \frac{(3.5\text{ cm})(-14\text{ cm})}{3.5\text{ cm} + (-14\text{ cm})}$$

$$= 4.7\text{ cm}$$

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



The location should be about 15 cm on the same side of the lens (−15 cm) and the image should be upright and about 1.5 cm tall.

Section Review

18.2 Convex and Concave Lenses pages 493–499

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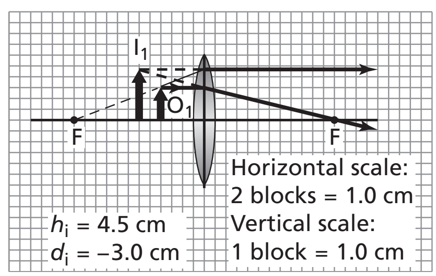
25. Magnification Magnifying glasses normally are used to produce images that are larger than the related objects, but they also can produce images that are smaller than the related objects. Explain.

If the object is located farther than twice the focal length from the lens, the size of the image is smaller than the size of the object.

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



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

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

$$= \frac{(2.0\text{ cm})(6.0\text{ cm})}{2.0\text{ cm} - 6.0\text{ cm}}$$

$$= -3.0\text{ cm}$$

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

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

$$= \frac{-(-3.0\text{ cm})(3.0\text{ cm})}{2.0\text{ cm}}$$

$$= 4.5\text{ cm}$$

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

■ **Figure 18-16**

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

Lenses a and c are converging.

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

Lenses b and d are diverging.

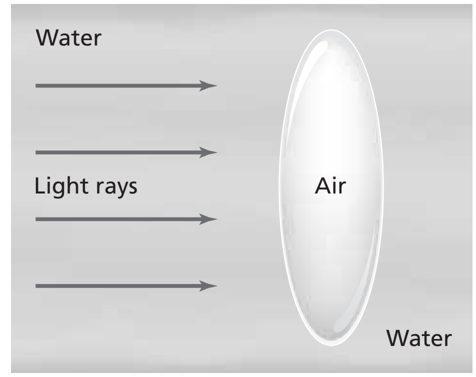
28. Chromatic Aberration All simple lenses have chromatic aberration. Explain, then, why you do not see this effect when you look through a microscope.

All precision optical instruments use a combination of lenses, called an achromatic lens, to minimize chromatic aberration.

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

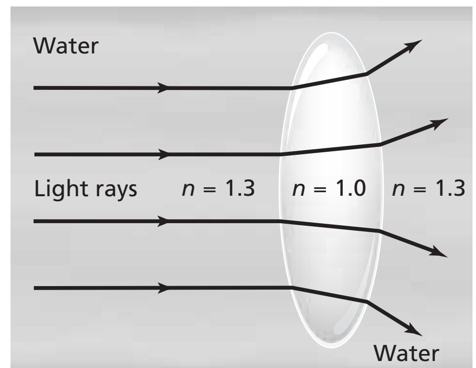
closer to the lens

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



■ **Figure 18-17**

The light rays will diverge.



Section Review

18.3 Applications of Lenses pages 500–503

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

The difference in index of refraction between the air and the cornea is greater than any other difference that light rays encounter when traveling toward the retina.

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

A nearsighted person should use a concave lens. A farsighted person should use a convex lens.

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

Closer; real images are always farther from the lens than the focal point. The farther away the object is, the closer the image is to the focal point.

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

After the light rays pass through the objective lens, they cross, forming an image that is inverted. The eyepiece maintains this orientation when it uses this image as its object.

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

The prisms extend the light's path length to make the binoculars more compact, invert light rays so that the viewer sees an upright image, and increase separation between objective lenses to improve the three-dimensional view.

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

You are using the light that strikes only a small area of the object. A brighter lamp could be used.

Chapter Assessment

Concept Mapping

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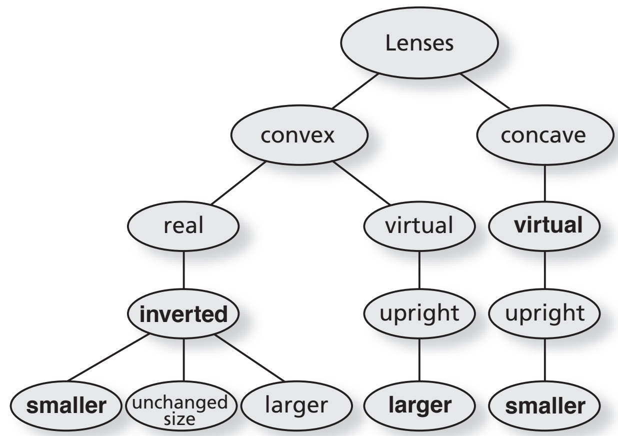
37. Complete the following concept map using the following terms: *inverted, larger, smaller, virtual.*



Mastering Concepts

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

The angle of incidence is larger than the angle of refraction, because air has a smaller index of refraction.

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

The angle of incidence is smaller than the angle of refraction, because glass has a larger index of refraction.

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

The term *critical angle* refers to the incident angle that causes the refracted ray to lie right along the boundary of the substance when a ray is passing from a region of higher index of refraction to a region of lower index of refraction. If the incident angle exceeds the critical angle, total internal reflection will occur.

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

The speeds of the different colors of light traveling through air are the same.

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

During a lunar eclipse, Earth blocks the Sun's rays from the Moon. However, sunlight refracting off Earth's atmosphere is directed inward toward the Moon. Because blue wavelengths of light are dispersed more, red wavelengths of light reflect off the Moon toward Earth.

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

Convex lenses are thicker at the center than at the edges. Concave lenses are thinner in the middle than at the edges.

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

It is a real image that is located between F and 2F, and that is inverted and smaller compared to the object.

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

The index of refraction of the material from which the lens is made also determines the focus.

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

Another lens is included in the optics system of the projector to invert the image again. As a result, the image is upright compared to the original object.

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

All lenses have chromatic aberration, which means different wavelengths of light are bent at slightly different angles near their edges. An achromatic lens is a combination of two or more lenses with different indices of refraction that reduce this effect.

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

Light entering the eye is primarily focused by the cornea. Fine focusing occurs when muscles change the shape of the lens, allowing the eye to focus on either near or far objects.

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

nearsightedness

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

real image, inverted

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

It improves the three-dimensional view.

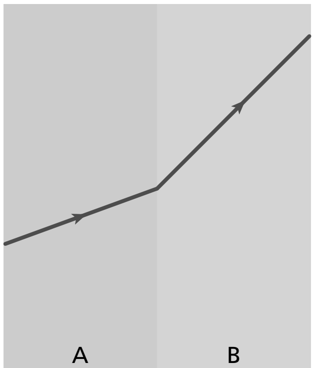
52. What is the purpose of a camera's reflex mirror? (18.3)

The reflex mirror diverts the image onto a prism so that it can be viewed before taking a photograph. When the shutter release button is pressed, the reflex mirror moves out of the way so that the lens focuses the image onto the film or other photodetector.

Applying Concepts

pages 508–509

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



■ **Figure 18-24**

The angle in substance A is smaller, so it has the larger index of refraction.

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

An angle of incidence of 0° allows the light to go through unchanged. Or if the angle of incidence is greater than the critical angle there is total internal reflection.

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

As the index of refraction of a material increases, the speed of light in that material decreases.

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

The critical angle decreases as the index of refraction increases.

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

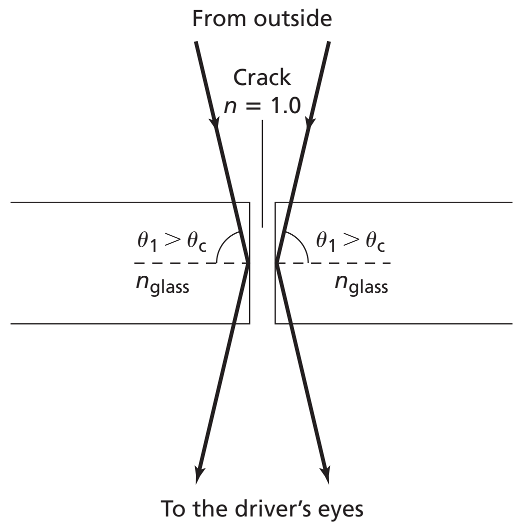
$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

$$\theta_{c,\text{ water/air}} = \sin^{-1}\left(\frac{1.00}{1.33}\right) = 48.8°$$

$$\theta_{c,\text{ glass/air}} = \sin^{-1}\left(\frac{1.00}{1.52}\right) = 41.1°$$

Air and glass have the smaller critical angle of 41.1°. The critical angle for air and water is 48.8°.

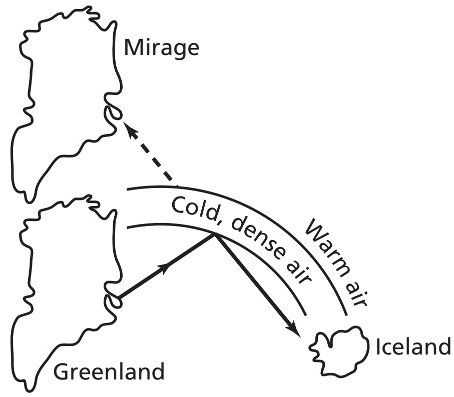
58. **Cracked Windshield** If you crack the windshield of your car, you will see a silvery line along the crack. The glass has separated at the crack, and there is air in the crack. The silvery line indicates that light is reflecting off the crack. Draw a ray diagram to explain why this occurs. What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



This illustrates light reflected at angles larger than the critical angle, or total internal reflection.

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

Even though Greenland is below the horizon, it is visible as a mirage due to the refraction of light.



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

Violet light travels slower in a prism than red light does.

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

You can see a rainbow only when the Sun's rays come from behind you at an angle not greater than 42° with the horizon. When you are facing south in the northern hemisphere, the Sun is never behind you at an angle of 42° or less.

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

The location of the image depends on the focal length of the lens and the distance of the object from the lens. Therefore, the location of the image doesn't change.

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

The magnification is much less in water than in air. The difference in the indices of refraction for water and glass is much less than the difference for air and glass.

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

Chromatic aberration for lenses is due to the dispersion of light (different wavelengths of light have different speeds in the lens and refract with slightly different angles). Mirrors reflect, and reflection is independent of wavelength.

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

Eyes can focus better in bright light because rays that are refracted into larger angles are cut off by the iris. Therefore, all rays converge at a narrow angle, so there is less spherical aberration.

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

Each side of the binoculars is like a refracting telescope. Therefore, the objective lens image must be between the eyepiece lens and its focal point to magnify the image.

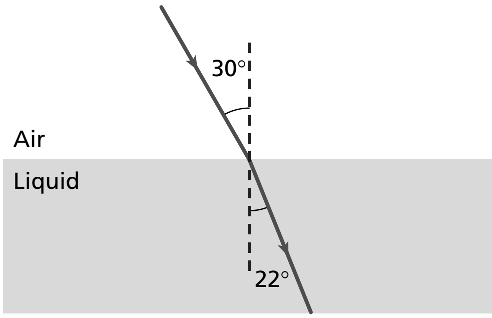
Mastering Problems

18.1 Refraction of Light

pages 509–510

Level 1

67. A ray of light travels from air into a liquid, as shown in **Figure 18-25.** The ray is incident upon the liquid at an angle of 30.0°. The angle of refraction is 22.0°.



■ **Figure 18-25**

a. Using Snell's law, calculate the index of refraction of the liquid.

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

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

$$= \frac{(1.00)(\sin 30.0°)}{\sin 22.0°}$$

$$= 1.33$$

b. Compare the calculated index of refraction to those in Table 18-1. What might the liquid be?

water

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

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

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

$$= \sin^{-1}\left(\frac{(1.36)(\sin 25.0°)}{1.62}\right)$$

$$= 20.8°$$

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

a. At what angle does the beam enter the glass?

$$n_A \sin \theta_A = n_g \sin \theta_g$$

$$\theta_g = \sin^{-1}\left(\frac{n_A \sin \theta_A}{n_g}\right)$$

$$= \sin^{-1}\left(\frac{(1.00)(\sin 40.0°)}{1.50}\right)$$

$$= 25.4°$$

b. At what angle does the beam enter the water?

$$n_g \sin \theta_g = n_w \sin \theta_w$$

$$\theta_w = \sin^{-1}\left(\frac{n_g \sin \theta_g}{n_w}\right)$$

$$= \sin^{-1}\left(\frac{(1.50)(\sin 25.4°)}{1.33}\right)$$

$$= 28.9°$$

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

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

$$v_{\text{diamond}} = \frac{c}{n_{\text{diamond}}}$$

$$= \frac{3.00\times10^8 \text{ m/s}}{2.42}$$

$$= 1.24\times10^8 \text{ m/s}$$

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

$$\theta_{\text{c, diamond/air}} = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

$$= \sin^{-1}\left(\frac{1.00}{2.42}\right)$$

$$= 24.4°$$

Level 2

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

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

$$n_{\text{water}} \sin \theta_{\text{water}} = n_{\text{plastic}} \sin \theta_{\text{plastic}}$$

$$\theta_{\text{plastic}} = \sin^{-1}\left(\frac{n_{\text{water}} \sin \theta_{\text{water}}}{n_{\text{plastic}}}\right)$$

$$= \sin^{-1}\left(\frac{(1.33)(\sin 35.0°)}{1.500}\right)$$

$$= 30.57°$$

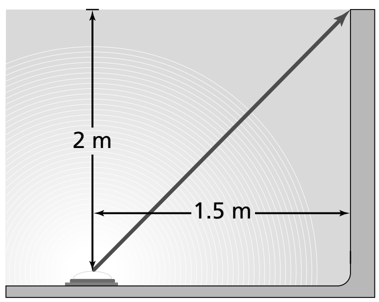
$$n_{\text{plastic}} \sin \theta_{\text{plastic}} = n_{\text{air}} \sin \theta_{\text{air}}$$

$$\theta_{air} = \sin^{-1}\left(\frac{n_{plastic} \sin \theta_{plastic}}{n_{air}}\right)$$

$$= \sin^{-1}\left(\frac{(1.500)(\sin 30.57°)}{1.00}\right)$$

$$= 49.7°$$

73. Swimming-Pool Lights A light source is located 2.0 m below the surface of a swimming pool and 1.5 m from one edge of the pool, as shown in **Figure 18-26.** The pool is filled to the top with water.



■ **Figure 18-26**

a. At what angle does the light reaching the edge of the pool leave the water?

$$\theta_i = \tan^{-1}\left(\frac{1.5\text{ m}}{2.0\text{ m}}\right)$$

$$= 37°$$

Then find the angle in air.

$$n_A \sin \theta_A = n_w \sin \theta_w$$

$$\theta_A = \sin^{-1}\left(\frac{n_w \sin \theta_w}{n_A}\right)$$

$$= \sin^{-1}\left(\frac{(1.33)(\sin 37°)}{1.00}\right)$$

$$= 53°$$

b. Does this cause the light viewed from this angle to appear deeper or shallower than it actually is?

$$\tan 53° = \frac{\text{side opposite}}{\text{side adjacent}}$$

$$\text{side adjacent} = \frac{\text{side opposite}}{\tan 53°}$$

$$= \frac{1.5\text{ m}}{\tan 53°}$$

$$= 1.1\text{ m, shallower}$$

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

$$n_A \sin \theta_A = n_d \sin \theta_d$$

$$\theta_d = \sin^{-1}\left(\frac{n_A \sin \theta_A}{n_d}\right)$$

For red light

$$\theta_d = \sin^{-1}\left(\frac{(1.00)(\sin 30.0°)}{2.410}\right)$$

$$= 12.0°$$

For blue light

$$\theta_d = \sin^{-1}\left(\frac{(1.00)(\sin 30.0°)}{2.450}\right)$$

$$= 11.8°$$

75. The index of refraction of crown glass is 1.53 for violet light, and it is 1.51 for red light.

a. What is the speed of violet light in crown glass?

$$v = \frac{c}{n} = \frac{3.00\times10^8\text{ m/s}}{1.53}$$

$$= 1.96\times10^8\text{ m/s}$$

b. What is the speed of red light in crown glass?

$$v = \frac{c}{n} = \frac{3.00\times10^8\text{ m/s}}{1.51}$$

$$= 1.99\times10^8\text{ m/s}$$

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

$$\sin \theta_{c,\,air} = \frac{n_A}{n_g}$$

$$n_g = \frac{n_A}{\sin \theta_{c,\,air}} = \frac{1.00}{\sin 41.0°} = 1.524$$

$$\sin \theta_{c,\,water} = \frac{n_w}{n_g}$$

$$\theta_{c,\,water} = \sin^{-1}\left(\frac{n_w}{n_g}\right)$$

$$= \sin^{-1}\left(\frac{1.33}{1.524}\right)$$

$$= 60.8°$$

Level 3

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

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

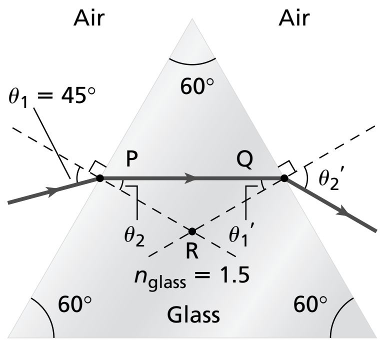
$$\theta_2 = \sin^{-1}\left(\frac{n_1 \sin \theta_1}{n_2}\right)$$

$$= \sin^{-1}\left(\frac{(1.33)(\sin 55.0°)}{1.00}\right)$$

$$= \sin^{-1}(1.09)$$

The value $\sin \theta_2 = 1.09$ is not defined. Therefore, total internal reflection occurs.

78. The ray of light shown in **Figure 18-27** is incident upon a 60°-60°-60° glass prism, $n = 1.5$.



■ **Figure 18-27**

a. Using Snell's law of refraction, determine the angle, θ_2, to the nearest degree.

$$n_{air} \sin \theta_1 = n_{glass} \sin \theta_2$$

$$\theta_2 = \sin^{-1}\left(\frac{n_{air} \sin \theta_1}{n_{glass}}\right)$$

$$= \sin^{-1}\left(\frac{1.00 \sin 45°}{1.5}\right)$$

$$= 28°$$

b. Using elementary geometry, determine the value of θ_1'.

$$\theta_P = 90° - 28° = 62°$$

$$\theta_Q = 180° - 62° - 60° = 58°$$

$$\theta_1' = 90° - 58° = 32°$$

c. Determine θ_2'.

$$n_{air} \sin \theta_2' = n_{glass} \sin \theta_1'$$

$$\theta_2' = \sin^{-1}\left(\frac{n_{glass} \sin \theta_1'}{n_{air}}\right)$$

$$= \sin^{-1}\left(\frac{(1.5)(\sin 32°)}{1.00}\right)$$

$$= 53°$$

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

$n_{air} \sin \theta_{air} = n_p \sin \theta_p$ **and** $n_p = \frac{c}{v_p}$, **so**

$$n_{air} \sin \theta_{air} = \frac{c}{v_p} \sin \theta_p$$

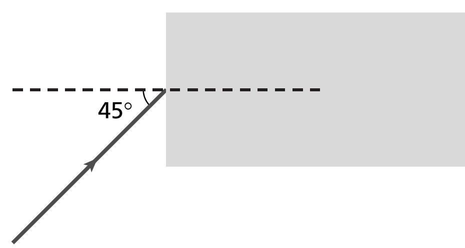
$$\sin \theta_p = \frac{v_p n_{air} \sin \theta_{air}}{c}$$

$$\theta_p = \sin^{-1}\left(\frac{v_p n_{air} \sin \theta_{air}}{c}\right)$$

$$= \sin^{-1}\left(\frac{(1.90\times10^8 \text{ m/s})(1.00)(\sin 22.0°)}{3.00\times10^8 \text{ m/s}}\right)$$

$$= 13.7°$$

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



■ **Figure 18-28**

$$n_A \sin \theta_A = n_g \sin \theta_g$$

$$\theta_g = \sin^{-1}\left(\frac{n_A \sin \theta_A}{n_g}\right)$$

$$= \sin^{-1}\left(\frac{(1.00)(\sin 45°)}{1.52}\right)$$

$$= 28°$$

Find the critical angle for crown glass.

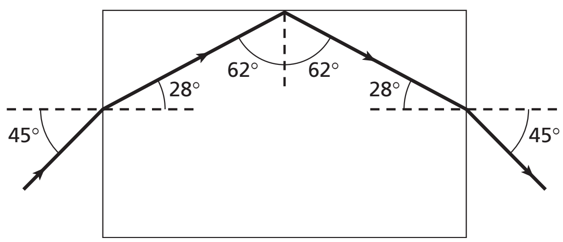
$$\sin \theta_c = \frac{n_A}{n_g}$$

$$\theta_c = \sin^{-1}\left(\frac{n_A}{n_g}\right)$$

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

$$= 41.1°$$

When the light ray in the glass strikes the surface at a 62° angle, total internal reflection occurs.



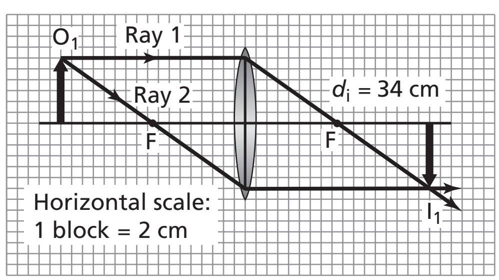
18.2 Convex and Concave Lenses

page 510

Level 1

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

$$d_i = 34 \text{ cm}$$



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

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

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

$$= \frac{(72.5 \text{ cm})(25.5 \text{ cm})}{72.5 \text{ cm} - 25.5 \text{ cm}}$$

$$= 39.3 \text{ cm}$$

The image is 39.3 cm from the lens.

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

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

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

$$= \frac{(10.0 \text{ cm})(5.00 \text{ cm})}{10.0 \text{ cm} - 5.00 \text{ cm}}$$

$$= 10.0 \text{ cm}$$

Level 2

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

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

$$d_o = \frac{-d_i}{m}$$

$$= \frac{-(24 \text{ cm})}{-0.75}$$

$$= 32 \text{ cm}$$

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

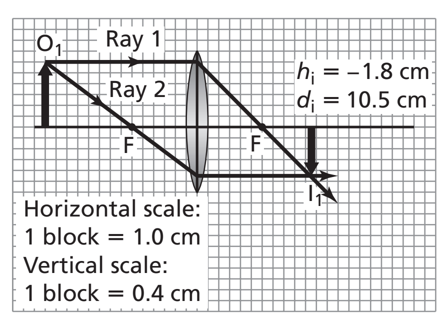
$$f = \frac{d_o d_i}{d_o + d_i}$$

$$= \frac{(32 \text{ cm})(24 \text{ cm})}{32 \text{ cm} + 24 \text{ cm}}$$

$$= 14 \text{ cm}$$

85. An object is located 14.0 cm from a convex lens that has a focal length of 6.0 cm. The object is 2.4 cm high.

a. Draw a ray diagram to determine the location, size, and orientation of the image.



b. Solve the problem mathematically.

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

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

$$= \frac{(14.0\text{ cm})(6.0\text{ cm})}{14.0\text{ cm} - 6.0\text{ cm}}$$

$$= 10.5\text{ cm}$$

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

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

$$= \frac{-(10.5\text{ cm})(2.4\text{ cm})}{14.0\text{ cm}}$$

$= -1.8$ cm, so the image is inverted

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

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

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

$$= \frac{-(11\text{ cm})(3.0\text{ cm})}{22\text{ cm}}$$

$$= -1.5\text{ cm}$$

The image is 1.5 cm tall.

Level 3

87. A 3.0-cm-tall object is placed 15.0 cm in front of a converging lens. A real image is formed 10.0 cm from the lens.

a. What is the focal length of the lens?

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

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

$$= \frac{(15.0\text{ cm})(10.0\text{ cm})}{15.0\text{ cm} + 10.0\text{ cm}}$$

$$= 6.00\text{ cm}$$

b. If the original lens is replaced with a lens having twice the focal length, what are the image position, size, and orientation?

$$f_{new} = 2f$$

$$= 2(6.00\text{ cm})$$

$$= 12.0\text{ cm}$$

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

$$d_{i,\,new} = \frac{d_o f_{new}}{d_o - f_{new}}$$

$$= \frac{(15.0\text{ cm})(12.0\text{ cm})}{15.0\text{ cm} - 12.0\text{ cm}}$$

$$= 60.0\text{ cm}$$

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

$$h_{i,\,new} = \frac{-d_{i,\,new} h_o}{d_o}$$

$$= \frac{-(60.0\text{ cm})(3.0\text{ cm})}{15\text{ cm}}$$

$$= -12\text{ cm}$$

The image is inverted compared to the object.

88. A diverging lens has a focal length of 15.0 cm. An object placed near it forms a 2.0-cm-high image at a distance of 5.0 cm from the lens.

a. What are the object position and object height?

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

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

$$= \frac{(-5.0\text{ cm})(-15.0\text{ cm})}{-5.0\text{ cm} - (-15.0\text{ cm})}$$

$$= 7.5\text{ cm}$$

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

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

$$= \frac{-(7.5\text{ cm})(2.0\text{ cm})}{-5.0\text{ cm}}$$

$$= 3.0\text{ cm}$$

b. The diverging lens is now replaced by a converging lens with the same focal length. What are the image position, height, and orientation? Is it a virtual image or a real image?

$$f_{new} = -f$$
$$= -(-15.0\text{ cm})$$
$$= 15.0\text{ cm}$$

$$\frac{1}{f_{new}} = \frac{1}{d_o} + \frac{1}{d_{i,\,new}}$$

$$d_{i,\,new} = \frac{d_o f_{new}}{d_o - f_{new}}$$
$$= \frac{(7.5\text{ cm})(15\text{ cm})}{7.5\text{ cm} - 15\text{ cm}}$$
$$= -15\text{ cm}$$

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

$$h_{i,\,new} = \frac{-d_{i,\,new}h_o}{d_o}$$
$$= \frac{-(-15\text{ cm})(3.0\text{ cm})}{7.5\text{ cm}}$$
$$= 6.0\text{ cm}$$

This is a virtual image that is upright compared to the object.

18.3 Applications of Lenses
pages 510–511
Level 1

89. Camera Lenses Camera lenses are described in terms of their focal length. A 50.0-mm lens has a focal length of 50.0 mm.

a. A camera with a 50.0-mm lens is focused on an object 3.0 m away. What is the image position?

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

$$\text{So } d_i = \frac{d_o f}{d_o - f}$$
$$= \frac{(3.0\times10^3\text{ mm})(50.0\text{ mm})}{3.0\times10^3\text{ mm} - 50.0\text{ mm}}$$
$$= 51\text{ mm}$$

b. A 1000.0-mm lens is focused on an object 125 m away. What is the image position?

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

$$\text{So } d_i = \frac{d_o f}{d_o - f}$$
$$= \frac{(125\text{ m})(1.0000\text{ m})}{125\text{ m} - 1.00\text{ m}}$$
$$= 1.01\text{ m} = 1.01\times10^3\text{ mm}$$

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

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

$$\text{So } f = \frac{d_o d_i}{d_o + d_i}$$
$$= \frac{(25\text{ cm})(-45\text{ cm})}{25\text{ cm} + (-45\text{ cm})}$$
$$= 56\text{ cm}$$

Level 2

91. Copy Machine The convex lens of a copy machine has a focal length of 25.0 cm. A letter to be copied is placed 40.0 cm from the lens.

a. How far from the lens is the copy paper?

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

$$d_i = \frac{d_o f}{d_o - f}$$
$$= \frac{(40.0\text{ cm})(25.0\text{ cm})}{40.0\text{ cm} - 25.0\text{ cm}}$$
$$= 66.7\text{ cm}$$

b. How much larger will the copy be?

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

$$h_i = \frac{-d_i h_o}{d_o} = \frac{-(66.7\text{ cm})(h_o)}{40.0\text{ cm}}$$
$$= -1.67h_o$$

The copy is enlarged and inverted.

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

35 mm; for a distant object, d_o can be considered at ∞, thus $1/d_o$ is zero. According to the thin lens equation, $d_i = f$.

Level 3

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

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

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

$$\text{So } d_i = \frac{d_o f}{d_o - f} = \frac{(12\text{ mm})(10.0\text{ mm})}{12\text{ mm} - 10.0\text{ mm}} = 6.0\times10^1\text{ mm}$$

b. What is the magnification of this image?

$$m_o = \frac{-d_i}{d_o} = \frac{-6.0\times10^1\text{ mm}}{12\text{ mm}} = -5.0$$

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

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

$$d_i = \frac{d_o f}{d_o - f} = \frac{(10.0\text{ mm})(20.0\text{ mm})}{10.0\text{ mm} - 20.0\text{ mm}}$$

$= -20.0$ **mm, or 20.0 mm beneath the eyepiece**

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

$$m_e = \frac{-d_i}{d_o} = \frac{-(-20.0\text{ mm})}{10.0\text{ mm}} = 2.00$$

$$m_{total} = m_o m_e = (-5.0)(2.00) = -1.0\times10^1$$

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

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

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

$$d_i = \frac{d_o f}{d_o - f} = \frac{(425\text{ cm})(20.0\text{ cm})}{425\text{ cm} - 20.0\text{ cm}} = 21.0\text{ cm}$$

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

$$h_i = \frac{-d_i h_o}{d_o} = \frac{-(21.0\text{ cm})(10.0\text{ cm})}{425\text{ cm}} = -0.494\text{ cm}$$

This is a real image that is inverted compared to the object.

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

$$d_{o,\,new} = 25.0\text{ cm} - d_i = 25.0\text{ cm} - 21.0\text{ cm} = 4.0\text{ cm}$$

$$\frac{1}{f_{new}} = \frac{1}{d_{o,\,new}} = \frac{1}{d_{i,\,new}}$$

$$d_{i,\,new} = \frac{d_{o,\,new} f_{new}}{d_{o,\,new} - f_{new}} = \frac{(4.0\text{ cm})(4.05\text{ cm})}{4.0\text{ cm} - 4.05\text{ cm}} = -3.2\times10^2\text{ cm}$$

$$h_{o,\,new} = h_i$$
$$= -0.494 \text{ cm}$$
$$m \equiv \frac{h_i}{h_o} = \frac{-d_i}{d_o}$$
$$h_{i,\,new} = \frac{-d_{i,\,new}h_{o,\,new}}{d_{o,\,new}}$$
$$= \frac{-(-3.2\times10^2 \text{ cm})(-0.494 \text{ cm})}{4.0 \text{ cm}}$$
$$= -4.0\times10^1 \text{ cm}$$

This is a virtual image that is inverted compared to the object.

c. What is the magnification of the telescope?

$$m = \frac{h_{i,\,new}}{h_o}$$
$$= \frac{-4.0\times10^1 \text{ cm}}{10.0 \text{ cm}}$$
$$= -4.0$$

Mixed Review

pages 511–512

Level 1

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

$$\sin\theta_c = \frac{n_2}{n_1}$$
$$n_1 = \frac{n_2}{\sin\theta_c},\ n_2 = 1.00 \text{ for air}$$
$$n_1 = \frac{1.00}{\sin 45.0°}$$
$$= 1.41$$

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

$$n = \frac{c}{v}$$
$$v = \frac{c}{n}$$
$$= \frac{3.00\times10^8 \text{ m/s}}{2.35}$$
$$= 1.28\times10^8 \text{ m/s}$$

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

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$$
$$f = \frac{d_od_i}{d_o + d_i}$$
$$= \frac{(20 \text{ cm})(10 \text{ cm})}{20 \text{ cm} + 10 \text{ cm}}$$
$$= 7 \text{ cm}$$

Level 2

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

The angle of incidence must be in air. If we let substance 1 be air, then n_1 = 1.000. Let $n_2 = n$. Therefore,

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

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

Time through vacuum

$$t = \frac{d}{c} = \frac{(1.5\times10^8 \text{ km})(1000 \text{ m/1 km})}{3.00\times10^8 \text{ m/s}}$$
$$= 5.0\times10^2 \text{ s}$$

Speed through water

$$v = \frac{c}{n} = \frac{3.00\times10^8 \text{ m/s}}{1.33}$$
$$= 2.26\times10^8 \text{ m/s}$$

Time through water

$$t = \frac{d}{v} = \frac{(1.5\times10^8 \text{ km})(1000 \text{ m/1 km})}{2.26\times10^8 \text{ m/s}}$$
$$= 660 \text{ s}$$
$$\Delta t = 660 \text{ s} - 500 \text{ s} = 160 \text{ s}$$
$$= (160 \text{ s})(1 \text{ min/60 s}) = 2.7 \text{ min}$$

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

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

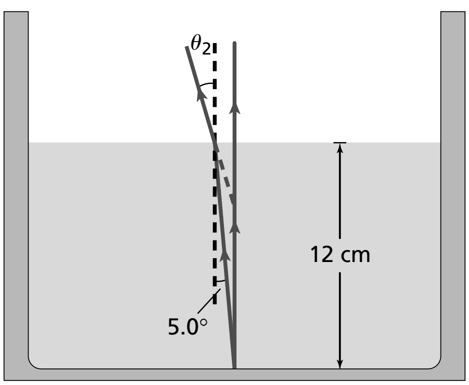
$$f = \frac{d_o d_i}{d_o + d_i}$$

$$= \frac{(350\text{ mm})(0.19\text{ mm})}{350\text{ mm} + 0.19\text{ mm}}$$

$$= \mathbf{0.19\text{ mm}}$$

Level 3

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



■ **Figure 18-29**

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

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

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

$$= \sin^{-1}\left(\frac{(1.33)(\sin 5.0°)}{1.0}\right)$$

$$= 6.7°$$

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

Using right triangle geometry, (actual depth)(tan θ_1) = (apparent depth)(tan θ_2)

$$\text{apparent depth} = (12\text{ cm})\left(\frac{\tan 5.0°}{\tan 6.7°}\right)$$

$$= 8.9\text{ cm}$$

The refracted rays appear to intersect 8.9 cm below the surface; this is the apparent depth.

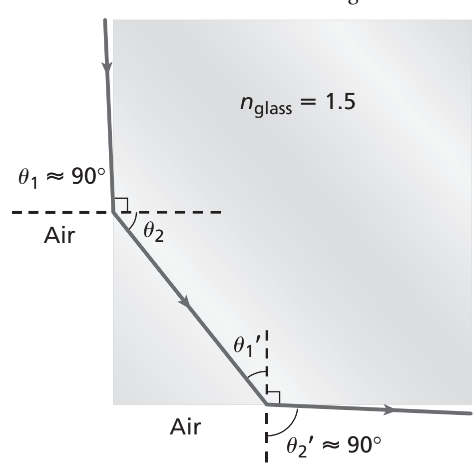
$$\frac{\text{apparent depth}}{\text{true depth}} = \frac{8.9\text{ cm}}{12\text{ cm}} = 0.74$$

Also, $\frac{n_{air}}{n_{water}} = \frac{1.0}{1.33} = 0.75$

Therefore,

$$\frac{\text{apparent depth}}{\text{true depth}} = \frac{n_{air}}{n_{water}}$$

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



■ **Figure 18-30**

The light ray enters the glass at an angle θ_1 and is refracted to an angle θ_2.

$$\theta_2 = \sin^{-1}\left(\frac{n_A \sin \theta_A}{n_g}\right)$$

$$= \sin^{-1}\left(\frac{(1.00)(\sin 90°)}{1.5}\right)$$

$$= 42°$$

Therefore, $\theta_1' = 48°$.

But the critical angle for glass is

$$\theta_c = \sin^{-1}\left(\frac{n_A}{n_g}\right)$$

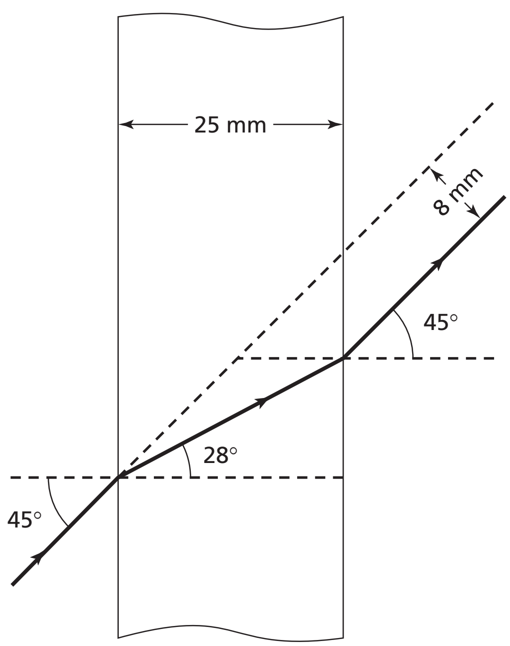
$$= \sin^{-1}\left(\frac{1.00}{1.5}\right)$$

$$= 42°$$

Because $\theta_1' > \theta_c$, the light reflects back into the glass and one cannot see out of an adjacent side.

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

8 mm



Thinking Critically

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

Find the angles of refraction for red and blue light, and find the difference in those angles in degrees.

Use Snell's law, $n_1 \sin \theta_1 = n_2 \sin \theta_2$.

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

For red light

$$\theta_2 = \sin^{-1}\left(\frac{(1.0003)(\sin 45.000°)}{1.7273}\right)$$

$$= 24.173°$$

For blue light

$$\theta_2 = \sin^{-1}\left(\frac{(1.0003)(\sin 45.000°)}{1.7708}\right)$$

$$= 23.543°$$

Difference

$$24.173° - 23.543° = 0.630°$$

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

$$\sin \theta_c = \frac{n_{air}}{n_{ice}}$$

$$\theta_c = \sin^{-1}\left(\frac{n_{air}}{n_{ice}}\right) = \sin^{-1}\left(\frac{1.00}{1.31}\right) = 49.8°$$

In comparison, the critical angle for glass, $n = 1.54$, is 40.5°. The larger critical angle means that fewer rays would be totally internally reflected in an ice core than in a glass core. Thus, they would not be able to transmit as much light. Fiber optic cables made of glass would work better.

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

The new $d_o = -10$ cm. Thus,

$$d_i = \frac{fd_o}{d_o - f} = \frac{(-15\text{ cm})(-10\text{ cm})}{-10\text{ cm} - (-15\text{ cm})}$$

$$= +30\text{ cm}$$

$$m = \frac{-d_i}{d_o} = \frac{-30\text{ cm}}{-10\text{ cm}} = +3$$

$$h_i = mh_o = (3)(4.0\text{ cm}) = 10\text{ cm}$$

The image orientation is not changed.

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

The light that passes through a lens near the edges of the lens is slightly dispersed, since the edges of a lens resemble a prism and refract different wavelengths of light at slightly different angles. The result is that white light is dispersed into its spectrum. The effect is called chromatic aberration.

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

It will get dimmer, because fewer light rays will converge, but you will see a complete image.

Writing in Physics

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

Answers will vary depending on the animals selected by the students.

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

Answers will vary. Students may find that it is necessary to simplify their chosen system for explanation purposes.

Cumulative Review

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

$$PE = mgh$$

$$= (2.0\text{ kg})(9.80\text{ m/s}^2)(1.5\text{ m})$$

$$= 29.4\text{ J}$$

To heat the bag

$$Q = mC\Delta T$$

$$= (2.0\text{ kg})(130\text{ J/kg·°C})(10\text{°C})$$

$$= 2600\text{ J}$$

$$N = \frac{Q}{\frac{1}{2}PE} = \frac{2600\text{ J}}{\frac{1}{2}(29.4\text{ J})}$$

$$= 180\text{ times}$$

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

$\Delta L = \alpha_{iron} L\Delta T$ where L is the diameter of the iron hoop. We want ΔL greater than 0.0050 m.

Therefore,

$$\Delta T = \frac{\Delta L}{\alpha_{iron}L}$$

$$= \frac{0.0050}{(12\times10^{-6}/°C)(0.9950\text{ m})}$$

$$= 420°C$$

Actually he would heat it much hotter to give room to fit over the wheel easily.

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

The pitch of the horn heard by the pedestrian will decrease as the car slows down.

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

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

It is $\frac{1}{(1000)^2} = \frac{1}{1{,}000{,}000} = 1\times10^{-6}$ the value it was originally.

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

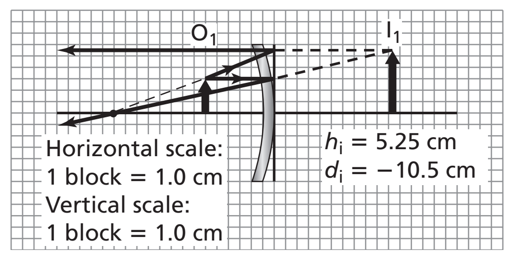
It is $\frac{1}{1000^2} = \frac{1}{1{,}000{,}000} = 1\times10^{-6}$ the value it was originally.

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

They both follow the inverse square law of distance.

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

a. a ray diagram drawn to scale



b. the mirror and magnification equations

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

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

$$= \frac{(6.00\text{ cm})(14.0\text{ cm})}{6.00\text{ cm} - 14.0\text{ cm}}$$

$$= -10.5\text{ cm}$$

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

$$h_i = \frac{-d_ih_o}{d_o}$$

$$= \frac{-(-10.5\text{ cm})(3.00\text{ cm})}{6.00\text{ cm}}$$

$$= 5.25\text{ cm}$$

Challenge Problem

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

1. Use Snell's law to calculate the angle of refraction.

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

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

$$= \sin^{-1}\left(\frac{(1.0)(\sin 30.0°)}{1.4}\right)$$

$$= 21°$$

2. What would the angle of refraction be if the person was swimming underwater?

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

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

$$= \sin^{-1}\left(\frac{(1.33)(\sin 30.0°)}{1.4}\right)$$

$$= 28°$$

3. Is the refraction greater in air or in water? Does this mean that objects under water seem closer or more distant than they would in air?

Refraction is greater in air because the angle to the normal is smaller. Objects seem closer in water.

4. If you want the angle of refraction for the light ray in water to be the same as it is for air, what should the new angle of incidence be?

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

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

$$= \sin^{-1}\left(\frac{(1.4)(\sin 21°)}{1.33}\right)$$

$$= 22°$$