hill and an inverted image directly below it. Explain how these mirages are formed.

7. In dispersive materials, the angle of refraction for a light ray depends on the wavelength of the light. Does the angle of reflection from the surface of the material depend on the wavelength? Why or why not?

8. The level of water in a clear, colorless glass can easily be observed with the naked eye. The level of liquid helium in a clear glass vessel is extremely difficult to see with the naked eye. Explain. *Hint:* The index of refraction of liquid helium is close to that of air.

9. Suppose you are told that only two colors of light (X and Y) are sent through a glass prism and that X is bent more than Y. Which color travels more slowly in the prism?

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

11. Figure CQ22.11 shows a pencil partially immersed in a cup of water. Why does the pencil appear to be bent?

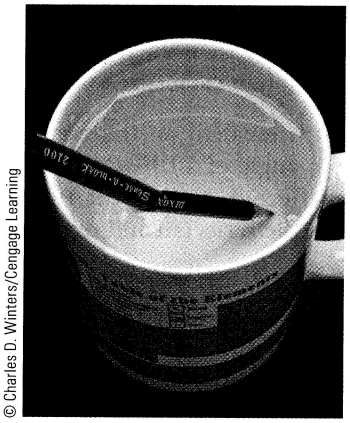

Figure CQ22.11

12. Try this simple experiment on your own. Take two opaque cups, place a coin at the bottom of each cup near the edge, and fill one cup with water. Next, view the cups at some angle from the side so that the coin in water is just visible as shown on the left in Figure CQ22.12. Notice that the coin in air is not visible as shown on the right in Figure CQ22.12. Explain this observation.

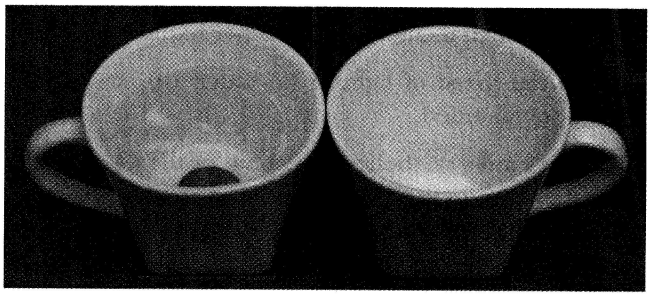

Figure CQ22.12

13. Why do astronomers looking at distant galaxies talk about looking backward in time?

PROBLEMS

ENHANCED **WebAssign** The problems in this chapter may be assigned online in Enhanced WebAssign. Selected problems also have Watch It video solutions.

1. denotes straightforward problem; 2. denotes intermediate problem;
3. denotes challenging problem
1. denotes full solution available in *Student Solutions Manual/Study Guide*

1. denotes problems most often assigned in Enhanced WebAssign
BIO denotes biomedical problems
GP denotes guided problems
M denotes Master It tutorial available in Enhanced WebAssign
Q|C denotes asking for quantitative and conceptual reasoning
S denotes symbolic reasoning problem

22.1 The Nature of Light

1. During the Apollo XI Moon landing, a retroreflecting panel was erected on the Moon's surface. The speed of light can be found by measuring the time it takes a laser beam to travel from Earth, reflect from the panel, and return to Earth. If this interval is found to be 2.51 s, what is the measured speed of light? Take the center-to-center distance from Earth to the Moon to be 3.84×10^8 m. Assume the Moon is directly overhead and do not neglect the sizes of Earth and the Moon.

2. Q|C (a) What is the energy in joules of an x-ray photon with wavelength 1.00×10^{-10} m? (b) Convert the energy to electron volts. (c) If more penetrating x-rays are desired, should the wavelength be increased or decreased? (d) Should the frequency be increased or decreased?

3. M Find the energy of (a) a photon having a frequency of 5.00×10^{17} Hz and (b) a photon having a wavelength of 3.00×10^{2} nm. Express your answers in units of electron volts, noting that 1 eV = 1.60×10^{-19} J.

4. QC (a) Calculate the wavelength of light in vacuum that has a frequency of 5.45×10^{14} Hz. (b) What is its wavelength in benzene? (c) Calculate the energy of one photon of such light in vacuum. Express the answer in electron volts. (d) Does the energy of the photon change when it enters the benzene? Explain.

5. Find the speed of light in (a) water, (b) crown glass, and (c) diamond.

6. S (a) Find a symbolic expression for the wavelength λ of a photon in terms of its energy E, Planck's constant h, and the speed of light c. (b) What does the equation say about the wavelengths of higher-energy photons?

7. A ray of light travels from air into another medium, making an angle of $\theta_1 = 45.0°$ with the normal as in Figure P22.7. Find the angle of refraction θ_2 if the second medium is (a) fused quartz, (b) carbon disulfide, and (c) water.

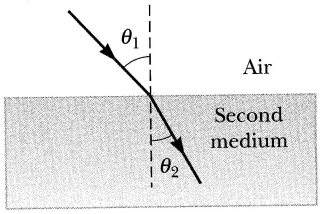

Figure P22.7

22.2 Reflection and Refraction

22.3 The Law of Refraction

8. The two mirrors in Figure P22.8 meet at a right angle. The beam of light in the vertical plane P strikes mirror 1 as shown. (a) Determine the distance the reflected light beam travels before striking mirror 2. (b) In what direction does the light beam travel after being reflected from mirror 2?

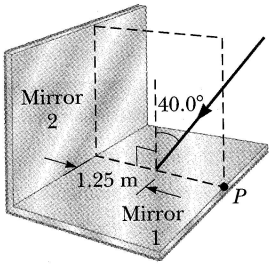

Figure P22.8

9. An underwater scuba diver sees the Sun at an apparent angle of 45.0° from the vertical. What is the actual direction of the Sun?

10. Two plane mirrors are at right angles to each other as shown by the side view in Figure P22.10. A light ray is incident on mirror 1 at an angle θ with the vertical. Using the law of reflection and geometry, show that after the ray is reflected off of both mirrors, the outgoing reflected ray is parallel to the incident ray.

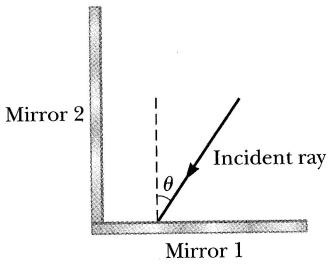

Figure P22.10

11. A laser beam is incident at an angle of 30.0° to the vertical onto a solution of corn syrup in water. If the beam is refracted to 19.24° to the vertical, (a) what is the index of refraction of the syrup solution? Suppose the light is red, with wavelength 632.8 nm in a vacuum. Find its (b) wavelength, (c) frequency, and (d) speed in the solution.

12. Light containing wavelengths of 400 nm, 500 nm, and 650 nm is incident from air on a block of crown glass at an angle of 25.0°. (a) Are all colors refracted alike, or is one color bent more than the others? (b) Calculate the angle of refraction in each case to verify your answer.

13. A ray of light is incident on the surface of a block of clear ice at an angle of 40.0° with the normal. Part of the light is reflected, and part is refracted. Find the angle between the reflected and refracted light.

14. Two plane mirrors are at an angle of $\theta_1 = 50.0°$ with each other as in the side view shown in Figure P22.14. If a horizontal ray is incident on mirror 1, at what angle θ_2 does the outgoing reflected ray make with the surface of mirror 2?

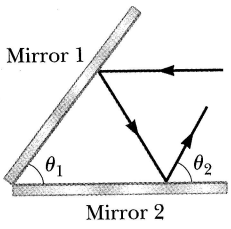

Figure P22.14

15. The light emitted by a helium–neon laser has a wavelength of 632.8 nm in air. As the light travels from air into zircon, find its (a) speed, (b) wavelength, and (c) frequency, all in the zircon.

16. Figure P22.16 shows a light ray traveling in a slab of crown glass surrounded by air. The ray is incident on the right surface at an angle of 55° with the normal and then reflects from points A, B, and C. (a) At which of these points does part of the ray enter the air? (b) If the glass slab is surrounded by carbon disulfide, at which point does part of the ray enter the carbon disulfide?

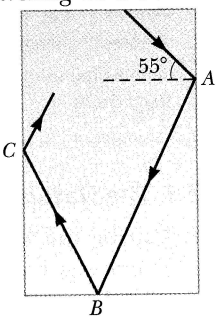

Figure P22.16

17. How many times will the incident beam shown in Figure P22.17 be reflected by each of the parallel mirrors?

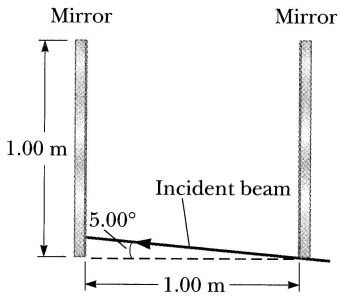

Figure P22.17

18. **Q C** A ray of light strikes a flat, 2.00-cm-thick block of glass ($n = 1.50$) at an angle of 30.0° with respect to the normal (Fig. P22.18). (a) Find the angle of refraction at the top surface. (b) Find the angle of incidence at the bottom surface and the refracted angle. (c) Find the lateral distance d by which the light beam is shifted. (d) Calculate the speed of light in the glass and (e) the time required for the light to pass through the glass block. (f) Is the travel time through the block affected by the angle of incidence? Explain.

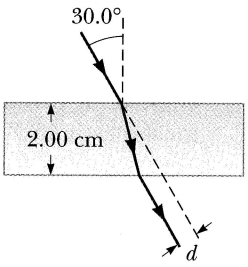

Figure P22.18

19. **M** The light beam shown in Figure P22.19 makes an angle of 20.0° with the normal line NN' in the linseed oil. Determine the angles θ and θ'. (The refractive index for linseed oil is 1.48.)

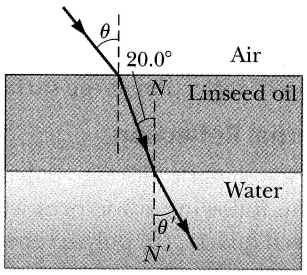

Figure P22.19

20. A laser beam is incident on a 45°–45°–90° prism perpendicular to one of its faces, as shown in Figure P22.20. The transmitted beam that exits the hypotenuse of the prism makes an angle of $\theta = 15.0°$ with the direction of the incident beam. Find the index of refraction of the prism.

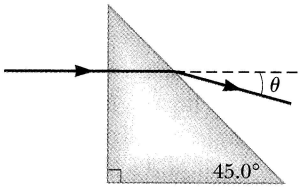

Figure P22.20

21. A block of crown glass is immersed in water as in Figure P22.21. A light ray is incident on the top face at an angle of $\theta_1 = 42.0°$ with the normal and exits the block at point P. (a) Find the vertical distance y from the top of the block to P. (b) Find the angle of refraction θ_2 of the light ray leaving the block at P.

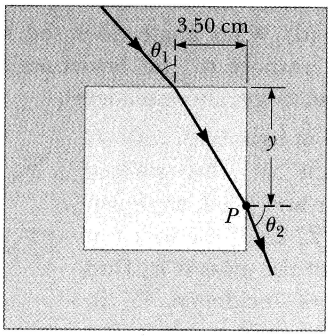

Figure P22.21

22. **BIO** A narrow beam of ultrasonic waves reflects off the liver tumor in Figure P22.22. If the speed of the wave is 10.0% less in the liver than in the surrounding medium, determine the depth of the tumor.

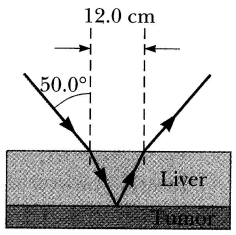

Figure P22.22

23. **S** A person looking into an empty container is able to see the far edge of the container's bottom, as shown in Figure P22.23a. The height of the container is h, and its width is d. When the container is completely filled with a fluid of index of refraction n and viewed from the same angle, the person can see the center of a coin at the middle of the container's bottom, as shown in Figure P22.23b. (a) Show that the ratio h/d is given by

$$\frac{h}{d} = \sqrt{\frac{n^2 - 1}{4 - n^2}}$$

(b) Assuming the container has a width of 8.00 cm and is filled with water, use the expression above to find the height of the container.

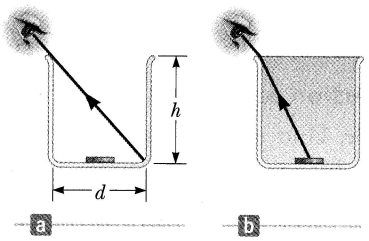

Figure P22.23

24. **GP** A submarine is 3.00×10^2 m horizontally from shore and 1.00×10^2 m beneath the surface of the water. A laser beam is sent from the submarine so that the beam strikes the surface of the water 2.10×10^2 m from the shore. A building stands on the shore, and the laser beam hits a target at the top of the building. The goal is to find the height of the target above sea

level. (a) Draw a diagram of the situation, identifying the two triangles that are important to finding the solution. (b) Find the angle of incidence of the beam striking the water–air interface. (c) Find the angle of refraction. (d) What angle does the refracted beam make with respect to the horizontal? (e) Find the height of the target above sea level.

25. S A beam of light both reflects and refracts at the surface between air and glass, as shown in Figure P22.25. If the index of refraction of the glass is n_g, find the angle of incidence, θ_1, in the air that would result in the reflected ray and the refracted ray being perpendicular to each other. *Hint:* Remember the identity $\sin(90° - \theta) = \cos\theta$.

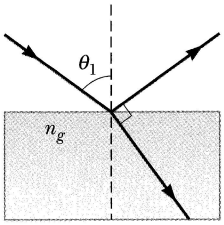

Figure P22.25

26. Figure P22.26 shows a light ray incident on a series of slabs having different refractive indices, where $n_1 < n_2 < n_3 < n_4$. Notice that the path of the ray steadily bends toward the normal. If the variation in n were continuous, the path would form a smooth curve. Use this idea and a ray diagram to explain why you can see the Sun at sunset after it has fallen below the horizon.

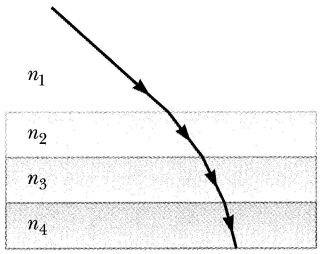

Figure P22.26 Problems 26 and 39

27. M An opaque cylindrical tank with an open top has a diameter of 3.00 m and is completely filled with water. When the afternoon Sun reaches an angle of 28.0° above the horizon, sunlight ceases to illuminate the bottom of the tank. How deep is the tank?

22.4 Dispersion and Prisms

28. A certain kind of glass has an index of refraction of 1.650 for blue light of wavelength 430 nm and an index of 1.615 for red light of wavelength 680 nm. If a beam containing these two colors is incident at an angle of 30.00° on a piece of this glass, what is the angle between the two beams inside the glass?

29. The index of refraction for red light in water is 1.331 and that for blue light is 1.340. If a ray of white light enters the water at an angle of incidence of 83.00°, what are the underwater angles of refraction for the (a) blue and (b) red components of the light?

30. The index of refraction for crown glass is 1.512 at a wavelength of 660 nm (red), whereas its index of refraction is 1.530 at a wavelength of 410 nm (violet). If both wavelengths are incident on a slab of crown glass at the same angle of incidence, 60.0°, what is the angle of refraction for each wavelength?

31. A light beam containing red and violet wavelengths is incident on a slab of quartz at an angle of incidence of 50.00°. The index of refraction of quartz is 1.455 at 660 nm (red light), and its index of refraction is 1.468 at 410 nm (violet light). Find the dispersion of the slab, which is defined as the difference in the angles of refraction for the two wavelengths.

32. The index of refraction for violet light in silica flint glass is 1.66 and that for red light is 1.62. What is the angular dispersion of visible light passing through an equilateral prism of apex angle 60.0° if the angle of incidence is 50.0°? (See Fig. P22.32.)

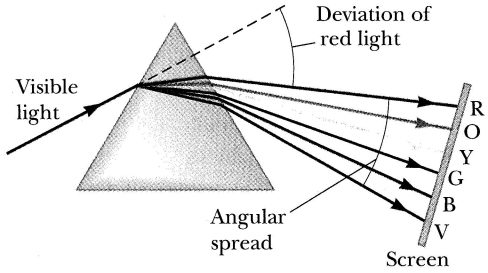

Figure P22.32

33. M A ray of light strikes the midpoint of one face of an equiangular (60°–60°–60°) glass prism ($n = 1.5$) at an angle of incidence of 30°. (a) Trace the path of the light ray through the glass and find the angles of incidence and refraction at each surface. (b) If a small fraction of light is also reflected at each surface, what are the angles of reflection at the surfaces?

22.7 Total Internal Reflection

34. For light of wavelength 589 nm, calculate the critical angles for the following substances when surrounded by air: (a) fused quartz, (b) polystyrene, and (c) sodium chloride.

35. Repeat Problem 34, but this time assume the quartz, polystyrene, and sodium chloride are surrounded by water.

36. M A beam of light is incident from air on the surface of a liquid. If the angle of incidence is 30.0° and the angle of refraction is 22.0°, find the critical angle for the liquid when surrounded by air.

37. A plastic light pipe has an index of refraction of 1.53. For total internal reflection, what is the minimum angle of incidence if the pipe is in (a) air and (b) water?

38. Determine the maximum angle θ for which the light rays incident on the end of the light pipe in Figure P22.38 are

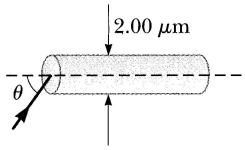

Figure P22.38

subject to total internal reflection along the walls of the pipe. Assume the light pipe has an index of refraction of 1.36 and the outside medium is air.

39. A light ray is incident normally to the long face (the hypotenuse) of a 45°–45°–90° prism surrounded by air, as shown in Figure 22.26b. Calculate the minimum index of refraction of the prism for which the ray will totally internally reflect at each of the two sides making the right angle.

40. **QC** A beam of laser light with wavelength 612 nm is directed through a slab of glass having index of refraction 1.78. (a) For what minimum incident angle would a ray of light undergo total internal reflection? (b) If a layer of water is placed over the glass, what is the minimum angle of incidence on the glass–water interface that will result in total internal reflection at the water–air interface? (c) Does the thickness of the water layer or glass affect the result? (d) Does the index of refraction of the intervening layer affect the result?

41. A room contains air in which the speed of sound is 343 m/s. The walls of the room are made of concrete, in which the speed of sound is 1 850 m/s. (a) Find the critical angle for total internal reflection of sound at the concrete–air boundary. (b) In which medium must the sound be traveling in order to undergo total internal reflection? (c) "A bare concrete wall is a highly efficient mirror for sound." Give evidence for or against this statement.

42. **GP** **QC** Consider a light ray traveling between air and a diamond cut in the shape shown in Figure P22.42. (a) Find the critical angle for total internal reflection for light in the diamond incident on the interface between the diamond and the outside air. (b) Consider the light ray incident normally on the top surface of the diamond as shown in Figure P22.42. Show that the light traveling toward point P in the diamond is totally reflected. (c) If the diamond is immersed in water, find the critical angle at the diamond–water interface? (d) When the diamond is immersed in water, does the light ray entering the top surface in Figure P22.42 undergo total internal reflection at P? Explain. (e) If the light ray entering the diamond remains vertical as shown in Figure P22.42, which way should the diamond in the water be rotated about an axis perpendicular to the page through O so that light will exit the diamond at P? (f) At what angle of rotation in part (e) will light first exit the diamond at point P?

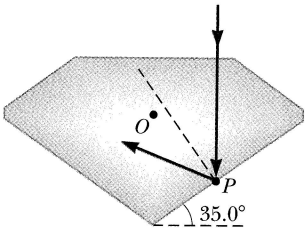

Figure P22.42

43. The light beam in Figure P22.43 strikes surface 2 at the critical angle. Determine the angle of incidence, θ_1.

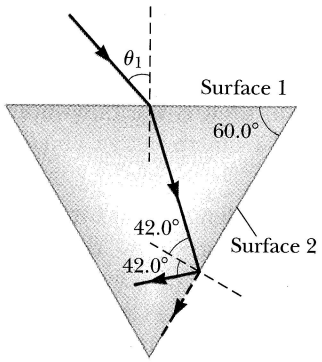

Figure P22.43

44. A jewel thief hides a diamond by placing it on the bottom of a public swimming pool. He places a circular raft on the surface of the water directly above and centered over the diamond, as shown in Figure P22.44. If the surface of the water is calm and the pool is 2.00 m deep, find the minimum diameter of the raft that would prevent the diamond from being seen.

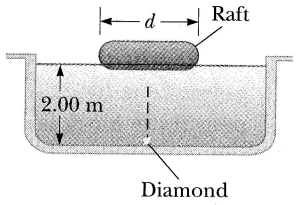

Figure P22.44

Additional Problems

45. A layer of ice having parallel sides floats on water. If light is incident on the upper surface of the ice at an angle of incidence of 30.0°, what is the angle of refraction in the water?

46. **QC** A ray of light is incident at an angle 30.0° on a plane slab of flint glass surrounded by water. (a) Find the refraction angle. (b) Suppose the index of refraction of the surrounding medium can be adjusted, but the incident angle of the light remains the same. As the index of refraction of the medium approaches that of the glass, what happens to the refraction angle? (c) What happens to the refraction angle when the medium's index of refraction exceeds that of the glass?

47. When a man stands near the edge of an empty drainage ditch of depth 2.80 m, he can barely see the boundary between the opposite wall and bottom of the ditch as in Figure P22.47a. The distance from his eyes to the

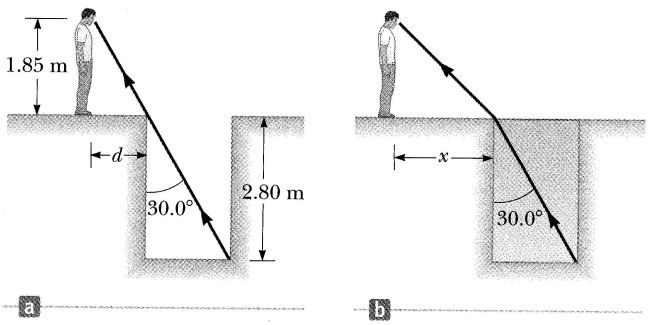

Figure P22.47

ground is 1.85 m. (a) What is the horizontal distance d from the man to the edge of the drainage ditch? (b) After the drainage ditch is filled with water as in Figure P22.47b, what is the maximum distance x the man can stand from the edge and still see the same boundary?

48. A light ray of wavelength 589 nm is incident at an angle θ on the top surface of a block of polystyrene surrounded by air, as shown in Figure P22.48. (a) Find the maximum value of θ for which the refracted ray will undergo total internal reflection at the left vertical face of the block. (b) Repeat the calculation for the case in which the polystyrene block is immersed in water. (c) What happens if the block is immersed in carbon disulfide?

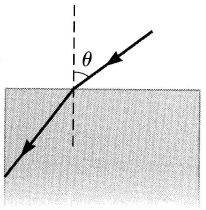

Figure P22.48

49. As shown in Figure P22.49, a light ray is incident normal to one face of a 30°–60°–90° block of flint glass (a prism) that is immersed in water. (a) Determine the exit angle θ_3 of the ray. (b) A substance is dissolved in the water to increase the index of refraction n_2. At what value of n_2 does total internal reflection cease at point P?

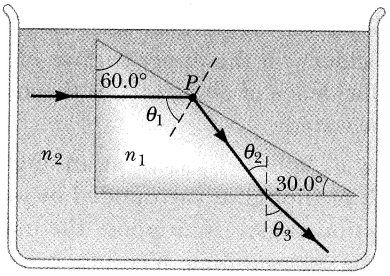

Figure P22.49

50. A narrow beam of light is incident from air onto a glass surface with index of refraction 1.56. Find the angle of incidence for which the corresponding angle of refraction is one-half the angle of incidence. *Hint:* You might want to use the trigonometric identity $\sin 2\theta = 2 \sin\theta \cos\theta$.

51. One technique for measuring the angle of a prism is shown in Figure P22.51. A parallel beam of light is directed onto the apex of the prism so that the beam reflects from opposite faces of the prism. Show that the angular separation of the two reflected beams is given by $B = 2A$.

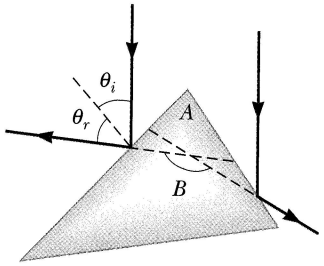

Figure P22.51

52. An optical fiber with index of refraction n and diameter d is surrounded by air. Light is sent into the fiber along its axis, as shown in Figure P22.52. (a) Find the smallest outside radius R permitted for a bend in the fiber if no light is to escape. (b) Does the result for part (a) predict reasonable behavior as d approaches zero? As n increases? As n approaches unity? (c) Evaluate R, assuming the diameter of the fiber is 100 μm and its index of refraction is 1.40.

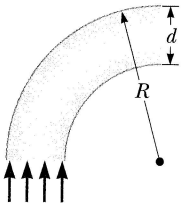

Figure P22.52

53. A piece of wire is bent through an angle θ. The bent wire is partially submerged in benzene (index of refraction = 1.50) so that, to a person looking along the dry part, the wire appears to be straight and makes an angle of 30.0° with the horizontal. Determine the value of θ.

54. A light ray traveling in air is incident on one face of a right-angle prism with index of refraction $n = 1.50$, as shown in Figure P22.54, and the ray follows the path shown in the figure. Assuming $\theta = 60.0°$ and the base of the prism is mirrored, determine the angle ϕ made by the outgoing ray with the normal to the right face of the prism.

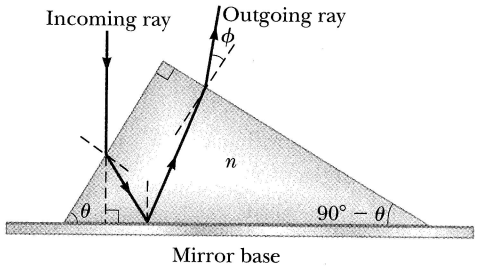

Figure P22.54

55. A transparent cylinder of radius $R = 2.00$ m has a mirrored surface on its right half, as shown in Figure P22.55. A light ray traveling in air is incident on the left side of the cylinder. The incident light ray and the exiting light ray are parallel, and $d = 2.00$ m. Determine the index of refraction of the material.

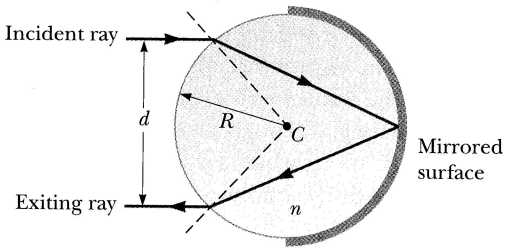

Figure P22.55

56. A laser beam strikes one end of a slab of material, as in Figure P22.56. The index of refraction of the slab is 1.48. Determine the number of internal reflections of the beam before it emerges from the opposite end of the slab.

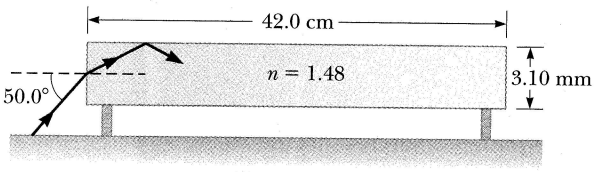

Figure P22.56

57. A light ray enters a rectangular block of plastic at an angle $\theta_1 = 45.0°$ and emerges at an angle $\theta_2 = 76.0°$, as shown in Figure P22.57. (a) Determine the index of refraction of the plastic. (b) If the light ray enters the plastic at a point $L = 50.0$ cm from the bottom edge, how long does it take the light ray to travel through the plastic?

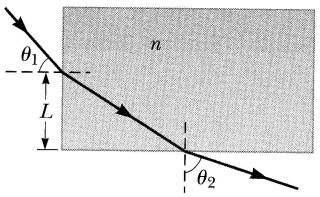

Figure P22.57

58. Students allow a narrow beam of laser light to strike a water surface. They arrange to measure the angle of refraction for selected angles of incidence and record the data shown in the following table:

Angle of Incidence (degrees)	Angle of Refraction (degrees)
10.0	7.5
20.0	15.1
30.0	22.3
40.0	28.7
50.0	35.2
60.0	40.3
70.0	45.3
80.0	47.7

Use the data to verify Snell's law of refraction by plotting the sine of the angle of incidence versus the sine of the angle of refraction. From the resulting plot, deduce the index of refraction of water.

59. Figure P22.59 shows the path of a beam of light through several layers with different indices of refraction. (a) If $\theta_1 = 30.0°$, what is the angle θ_2 of the emerging beam? (b) What must the incident angle θ_1 be to have total internal reflection at the surface between the medium with $n = 1.20$ and the medium with $n = 1.00$?

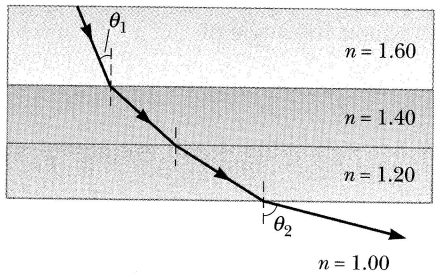

Figure P22.59

60. Three sheets of plastic have unknown indices of refraction. Sheet 1 is placed on top of sheet 2, and a laser beam is directed onto the sheets from above so that it strikes the interface at an angle of 26.5° with the normal. The refracted beam in sheet 2 makes an angle of 31.7° with the normal. The experiment is repeated with sheet 3 on top of sheet 2, and with the same angle of incidence, the refracted beam makes an angle of 36.7° with the normal. If the experiment is repeated again with sheet 1 on top of sheet 3, what is the expected angle of refraction in sheet 3? Assume the same angle of incidence.

61. A thick piece of Lucite ($n = 1.50$) is has the shape of a quarter circle of radius $R = 12.0$ cm as shown in the side view of Figure P22.61. A light ray traveling in air parallel to the base of the Lucite is incident at a distance $h = 6.00$ cm above the base and emerges out of the Lucite at an angle θ with the horizontal. Determine the value of θ.

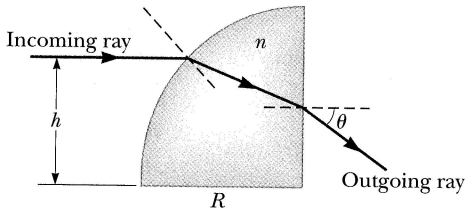

Figure P22.61