Chapter 24

The Wave Nature of Light

Questions

1. Does Huygens’ principle apply to sound waves? To water waves? Explain how Huygens’ principle makes sense for water waves, where each point vibrates up and down.

2. Why is light sometimes described as rays and sometimes as waves?

3. We can hear sounds around corners but we cannot see around corners; yet both sound and light are waves. Explain the difference.

4. Two rays of light from the same source destructively interfere if their path lengths differ by how much?

5. Monochromatic red light is incident on a double slit, and the interference pattern is viewed on a screen some distance away. Explain how the fringe pattern would change if the red light source is replaced by a blue light source.

6. If Young’s double-slit experiment were submerged in water, how would the fringe pattern be changed?

7. Why doesn’t the light from the two headlights of a distant car produce an interference pattern?

8. Why are interference fringes noticeable only for a thin film like a soap bubble and not for a thick piece of glass?

9. Why are the fringes of Newton’s rings (Fig. 24–31) closer together as you look farther from the center?
10. Some coated lenses appear greenish yellow when seen by reflected light. What reflected wavelengths do you suppose the coating is designed to eliminate completely?

11. A drop of oil on a pond appears bright at its edges, where its thickness is much less than the wavelengths of visible light. What can you say about the index of refraction of the oil compared to that of water?

12. Radio waves and visible light are both electromagnetic waves. Why can a radio receive a signal behind a hill when we cannot see the transmitting antenna?

13. Hold one hand close to your eye and focus on a distant light source through a narrow slit between two fingers. (Adjust your fingers to obtain the best pattern.) Describe the pattern that you see.

14. For diffraction by a single slit, what is the effect of increasing (a) the slit width, (b) the wavelength?

15. Describe the single-slit diffraction pattern produced when white light falls on a slit having a width of (a) 60 nm, (b) 60,000 nm.

16. What happens to the diffraction pattern of a single slit if the whole apparatus is immersed in (a) water, (b) a vacuum, instead of in air.

17. What is the difference in the interference patterns formed by two slits 10^{-4} cm apart as compared to a diffraction grating containing 10^{-4} slits/cm?

18. For a diffraction grating, what is the advantage of (a) many slits, (b) closely spaced slits?

19. White light strikes (a) a diffraction grating and (b) a prism. A rainbow appears on a wall just below the direction of the horizontal incident beam in each case. What is the color of the top of the rainbow in each case? Explain.

20. What does polarization tell us about the nature of light?

21. Explain the advantage of polarized sunglasses over plain tinted sunglasses.
22. How can you tell if a pair of sunglasses is polarizing or not?

*23. What would be the color of the sky if the Earth had no atmosphere?

*24. If the Earth’s atmosphere were 50 times denser than it is, would sunlight still be white, or would it be some other color?

**MisConceptual Questions**

1. Light passing through a double-slit arrangement is viewed on a distant screen. The interference pattern observed on the screen would have the widest spaced fringes for the case of
   (a) red light and a small slit spacing.
   (b) blue light and a small slit spacing.
   (c) red light and a large slit spacing.
   (d) blue light and a large slit spacing.

2. Light from a green laser of wavelength 530 nm passes through two slits that are 400 nm apart. The resulting pattern formed on a screen in front of the slits is shown in Fig. 24–55. If point A is the same distance from both slits, how much closer is point B to one slit than to the other?
   (a) 530 nm.
   (b) 265 nm.
   (c) 400 nm.
   (d) 0 nm.
   (e) It depends on the distance to the screen.

3. The colors in a rainbow are caused by
   (a) the interaction of the light reflected from different raindrops.
   (b) different amounts of absorption for light of different colors by the water in the raindrops.
   (c) different amounts of refraction for light of different colors by the water in the raindrops.
(d) the downward motion of the raindrops.

4. A double-slit experiment yields an interference pattern due to the path length difference from light traveling through one slit versus the other. Why does a single slit show a diffraction pattern?
(a) There is a path length difference from waves originating at different parts of the slit.
(b) The wavelength of the light is shorter than the slit.
(c) The light passing through the slit interferes with light that does not pass through.
(d) The single slit must have something in the middle of it, causing it to act like a double slit.

5. If you hold two fingers very close together and look at a bright light, you see lines between the fingers. What is happening?
(a) You are holding your fingers too close to your eye to be able to focus on it.
(b) You are seeing a diffraction pattern.
(c) This is a quantum-mechanical tunneling effect.
(d) The brightness of the light is overwhelming your eye.

6. Light passes through a slit that is about $5 \times 10^{-3}$ m high and $5 \times 10^{-7}$ m wide. The central bright light visible on a distant screen will be
(a) about $5 \times 10^{-3}$ m high and about $5 \times 10^{-7}$ m wide.
(b) about $5 \times 10^{-3}$ m high and wider than $5 \times 10^{-7}$ m.
(c) about $5 \times 10^{-3}$ m high and narrower than $5 \times 10^{-7}$ m.
(d) taller than $5 \times 10^{-3}$ m high and wider than $5 \times 10^{-7}$ m.
(e) taller than $5 \times 10^{-3}$ m high and about $5 \times 10^{-7}$ m wide.

7. Blue light of wavelength $A$ passes through a single slit of width $d$ and forms a diffraction pattern on a screen. If we replace the blue light by red
light of wavelength $2\lambda$, we can retain the original diffraction pattern if we change the slit width
(a) to $d/4$.
(b) to $d/2$.
(c) not at all.
(d) to $2d$.
(e) to $4d$.

8. Imagine holding a circular disk in a beam of monochromatic light (Fig. 24–56). If diffraction occurs at the edge of the disk, the center of the shadow is
(a) darker than the rest of the shadow.
(b) a bright spot.
(c) bright or dark, depending on the wavelength.
(d) bright or dark, depending on the distance to the screen.

9. If someone is around a corner from you, what is the main reason you can hear him speaking but can’t see him?
(a) Sound travels farther in air than light does.
(b) Sound can travel through walls, but light cannot.
(c) Sound waves have long enough wavelengths to bend around a corner; light wavelengths are too short to bend much.
(d) Sound waves reflect off walls, but light cannot.

10. When a CD is held at an angle, the reflected light contains many colors. What causes these colors?
(a) An anti-theft encoding intended to prevent copying of the CD.
(b) The different colors correspond to different data bits.
(c) Light reflected from the closely spaced grooves adds constructively for different wavelengths at different angles.
(d) It is part of the decorative label on the CD.
11. If a thin film has a thickness that is
   
   (a) \( \frac{1}{4} \) of a wavelength, constructive interference will always occur.
   
   (b) \( \frac{1}{4} \) of a wavelength, destructive interference will always occur.
   
   (c) \( \frac{1}{2} \) of a wavelength, constructive interference will always occur.
   
   (d) \( \frac{1}{2} \) of a wavelength, destructive interference will always occur.
   
   (e) None of the above is always true.

12. If unpolarized light is incident from the left on three polarizers as shown in Fig. 24–57, in which case will some light get through?
   
   (a) Case 1 only.
   
   (b) Case 2 only.
   
   (c) Case 3 only.
   
   (d) Cases 1 and 3.
   
   (e) All three cases.

For assigned homework and other learning materials, go to the MasteringPhysics website.

**Problems**

**24–3 Double-Slit Interference**

1. (I) Monochromatic light falling on two slits 0.018 mm apart produces the fifth-order bright fringe at an 8.6° angle. What is the wavelength of the light used?

2. (I) The third-order bright fringe of 610-nm light is observed at an angle of 31° when the light falls on two narrow slits. How far apart are the slits?
3. (II) Monochromatic light falls on two very narrow slits 0.048 mm apart. Successive fringes on a screen 6.50 m away are 8.5 cm apart near the center of the pattern. Determine the wavelength and frequency of the light.

4. (II) If 720-nm and 660-nm light passes through two slits 0.62 mm apart, how far apart are the second-order fringes for these two wavelengths on a screen 1.0 m away?

5. (II) Water waves having parallel crests 4.5 cm apart pass through two openings 7.5 cm apart in a board. At a point 3.0 m beyond the board, at what angle relative to the “straight-through” direction would there be little or no wave action?

6. (II) A red laser from the physics lab is marked as producing 632.8-nm light. When light from this laser falls on two closely spaced slits, an interference pattern formed on a wall several meters away has bright red fringes spaced 5.00 mm apart near the center of the pattern. When the laser is replaced by a small laser pointer, the fringes are 5.14 mm apart. What is the wavelength of light produced by the laser pointer?

7. (II) Light of wavelength 680 nm falls on two slits and produces an interference pattern in which the third-order bright red fringe is 38 mm from the central fringe on a screen 2.8 m away. What is the separation of the two slits?

8. (II) Light of wavelength $\lambda$ passes through a pair of slits separated by 0.17 mm, forming a double-slit interference pattern on a screen located a distance 37 cm away. Suppose that the image in Fig. 24–9a is an actual-size reproduction of this interference pattern. Use a ruler to measure a pertinent distance on this image; then utilize this measured value to determine $\lambda$ (nm).
9. (II) A parallel beam of light from a He-Ne laser, with a wavelength 633 nm, falls on two very narrow slits 0.068 mm apart. How far apart are the fringes in the center of the pattern on a screen 3.3 m away?

10. (II) A physics professor wants to perform a lecture demonstration of Young’s double-slit experiment for her class using the 633-nm light from a He-Ne laser. Because the lecture hall is very large, the interference pattern will be projected on a wall that is 5.0 m from the slits. For easy viewing by all students in the class, the professor wants the distance between the $m = 0$ and $m = 1$ maxima to be 35 cm. What slit separation is required in order to produce the desired interference pattern?

11. (II) Suppose a thin piece of glass is placed in front of the lower slit in Fig. 24–7 so that the two waves enter the slits 180° out of phase (Fig. 24–58). Draw in detail the interference pattern seen on the screen.

12. (II) In a double-slit experiment it is found that blue light of wavelength 480 nm gives a second-order maximum at a certain location on the screen. What wavelength of visible light would have a minimum at the same location?

13. (II) Two narrow slits separated by 1.0 mm are illuminated by 544-nm light. Find the distance between adjacent bright fringes on a screen 4.0 m from the slits.

14. (II) Assume that light of a single color, rather than white light, passes through the two-slit setup described in Example 24–3. If the distance from the central fringe to a first-order fringe is measured to be 2.9 mm on the screen, determine the light’s wavelength (in nm) and color (see Fig. 24–12).

15. (II) In a double-slit experiment, the third-order maximum for light of wavelength 480 nm is located 16 mm from the central bright spot on a screen 1.6 m from the slits. Light of wavelength 650 nm is then projected
through the same slits. How far from the central bright spot will the second-order maximum of this light be located?

16. (II) Light of wavelength 470 nm in air shines on two slits 6.00 \times 10^{-2} \text{ mm} apart. The slits are immersed in water, as is a viewing screen 40.0 \text{ cm} away. How far apart are the fringes on the screen?

17. (III) A very thin sheet of plastic (n = 1.60) covers one slit of a double-slit apparatus illuminated by 680-nm light. The center point on the screen, instead of being a maximum, is dark. What is the (minimum) thickness of the plastic?

24–4 Visible Spectrum; Dispersion

18. (I) By what percent is the speed of blue light (450 nm) less than the speed of red light (680 nm), in silicate flint glass (see Fig. 24–14)?

19. (II) A light beam strikes a piece of glass at a 65.00° incident angle. The beam contains two wavelengths, 450.0 nm and 700.0 nm, for which the index of refraction of the glass is 1.4831 and 1.4754, respectively. What is the angle between the two refracted beams?

20. (III) A parallel beam of light containing two wavelengths, \( \lambda_1 = 455 \text{ nm} \) and \( \lambda_2 = 642 \text{ nm} \), enters the silicate flint glass of an equilateral prism as shown in Fig. 24–59. At what angles, \( \theta_1 \) and \( \theta_2 \), does each beam leave the prism (give angle with normal to the face)? See Fig. 24–14.

24–5 Single-Slit Diffraction

21. (I) If 680-nm light falls on a slit 0.0425 mm wide, what is the angular width of the central diffraction peak?

22. (I) Monochromatic light falls on a slit that is \( 2.60 \times 10^{-3} \text{ mm} \) wide. If the angle between the first dark fringes on either side of the central maximum
is 28.0° (dark fringe to dark fringe), what is the wavelength of the light used?

23. (II) When blue light of wavelength 440 nm falls on a single slit, the first dark bands on either side of center are separated by 51.0°. Determine the width of the slit.

24. (II) A single slit 1.0 mm wide is illuminated by 450-nm light. What is the width of the central maximum (in cm) in the diffraction pattern on a screen 6.0 m away?

25. (II) How wide is the central diffraction peak on a screen 2.30 m behind a 0.0348-mm-wide slit illuminated by 558-nm light?

26. (II) Consider microwaves which are incident perpendicular to a metal plate which has a 1.6-cm slit in it. Discuss the angles at which there are diffraction minima for wavelengths of (a) 0.50 cm, (b) 1.0 cm, and (c) 3.0 cm.

27. (II) (a) For a given wavelength A, what is the minimum slit width for which there will be no diffraction minima? (b) What is the minimum slit width so that no visible light exhibits a diffraction minimum?

28. (II) Light of wavelength 620 nm falls on a slit that is $3.80 \times 10^{-3}$ mm wide. Estimate how far the first bright diffraction fringe is from the strong central maximum if the screen is 10.0 m away.

29. (II) Monochromatic light of wavelength 633 nm falls on a slit. If the angle between the first two bright fringes on either side of the central maximum is 32°, estimate the slit width.

30. (II) Coherent light from a laser diode is emitted through a rectangular area 3.0 $\mu$m $\times$ 1.5 $\mu$m (horizontal-by-vertical). If the laser light has a wavelength of 780 nm, determine the angle between the first diffraction minima (a) above and below the central maximum, (b) to the left and right of the central maximum.
31. (III) If parallel light falls on a single slit of width $D$ at a 28.0° angle to the normal, describe the diffraction pattern.

24–6 and 24–7 Diffraction Gratings

32. (I) At what angle will 510-nm light produce a second-order maximum when falling on a grating whose slits are $1.35 \times 10^{-3}$ cm apart?

33. (I) A grating that has 3800 slits per cm produces a third-order fringe at a 22.0° angle. What wavelength of light is being used?

34. (I) A grating has 7400 slits/cm. How many spectral orders can be seen (400 to 700 nm) when it is illuminated by white light?

35. (II) Red laser light from a He-Ne laser ($\lambda = 632.8$ nm) creates a second-order fringe at 53.2° after passing through the grating. What is the wavelength $\lambda$ of light that creates a first-order fringe at 20.6°?

36. (II) How many slits per centimeter does a grating have if the third order occurs at a 15.0° angle for 620-nm light?

37. (II) A source produces first-order lines when incident normally on a 9800-slit/cm diffraction grating at angles 28.8°, 36.7°, 38.6°, and 41.2°. What are the wavelengths?

38. (II) White light containing wavelengths from 410 nm to 750 nm falls on a grating with 7800 slits/cm. How wide is the first-order spectrum on a screen 3.40 m away?

39. (II) A diffraction grating has $6.5 \times 10^5$ slits/m. Find the angular spread in the second-order spectrum between red light of wavelength $7.0 \times 10^{-7}$ m and blue light of wavelength $4.5 \times 10^{-7}$ m.

40. (II) Two first-order spectrum lines are measured by a 9650-slit/cm spectroscope at angles, on each side of center, of $+26°38’$, $+41°02’$ and $-26°18’$, $-40°27’$. Calculate the wavelengths based on these data.
41. (II) What is the highest spectral order that can be seen if a grating with 6500 slits per cm is illuminated with 633-nm laser light? Assume normal incidence.

42. (II) The first-order line of 589-nm light falling on a diffraction grating is observed at a 14.5° angle. How far apart are the slits? At what angle will the third order be observed?

43. (II) Two (and only two) full spectral orders can be seen on either side of the central maximum when white light is sent through a diffraction grating. What is the maximum number of slits per cm for the grating?

24–8 Thin-Film Interference

44. (I) If a soap bubble is 120 nm thick, what wavelength is most strongly reflected at the center of the outer surface when illuminated normally by white light? Assume that \( n = 1.32 \).

45. (I) How far apart are the dark bands in Example 24–10 if the glass plates are each 21.5 cm long?

46. (II) (a) What is the smallest thickness of a soap film (\( n = 1.33 \)) that would appear black if illuminated with 480-nm light? Assume there is air on both sides of the soap film. (b) What are two other possible thicknesses for the film to appear black? (c) If the thickness \( t \) was much less than \( A \), why would the film also appear black?

47. (II) A lens appears greenish yellow (\( \lambda = 570 \) nm is strongest) when white light reflects from it. What minimum thickness of coating (\( n = 1.25 \)) do you think is used on such a glass lens (\( n = 1.52 \)), and why?

48. (II) A thin film of oil (\( n_o = 1.50 \)) with varying thickness floats on water (\( n_w = 1.33 \)). When it is illuminated from above by white light, the reflected colors are as shown in Fig. 24–60. In air, the wavelength of yellow light is
580 nm. (a) Why are there no reflected colors at point A? (b) What is the oil’s thickness $t$ at point B?

49. (II) How many uncoated thin lenses in an optical instrument would reduce the amount of light passing through the instrument to 50% or less? (Assume the same transmission percent at each of the two surfaces—see page 697.)

50. (II) A total of 35 bright and 35 dark Newton’s rings (not counting the dark spot at the center) are observed when 560-nm light falls normally on a planoconvex lens resting on a flat glass surface (Fig. 24–31). How much thicker is the lens at the center than the edges?

51. (II) If the wedge between the glass plates of Example 24–10 is filled with some transparent substance other than air—say, water—the pattern shifts because the wavelength of the light changes. In a material where the index of refraction is $n$, the wavelength is $\lambda_n = \lambda/n$, where $\lambda$ is the wavelength in vacuum (Eq. 24–1). How many dark bands would there be if the wedge of Example 24–10 were filled with water?

52. (II) A fine metal foil separates one end of two pieces of optically flat glass, as in Fig. 24–33. When light of wavelength 670 nm is incident normally, 24 dark bands are observed (with one at each end). How thick is the foil?

53. (II) How thick (minimum) should the air layer be between two flat glass surfaces if the glass is to appear bright when 450-nm light is incident normally? What if the glass is to appear dark?

54. (III) A thin oil slick ($n_o = 1.50$) floats on water ($n_w = 1.33$). When a beam of white light strikes this film at normal incidence from air, the only enhanced reflected colors are red (650 nm) and violet (390 nm). From this information, deduce the (minimum) thickness $t$ of the oil slick.
55. (III) A uniform thin film of alcohol \(n = 1.36\) lies on a flat glass plate \(n = 1.56\). When monochromatic light, whose wavelength can be changed, is incident normally, the reflected light is a minimum for \(\lambda = 525\) nm and a maximum for \(\lambda = 655\) nm. What is the minimum thickness of the film?

**24–9 Michelson Interferometer**

*56. (II) How far must the mirror \(M_1\) in a Michelson interferometer be moved if 680 fringes of 589-nm light are to pass by a reference line?*

*57. (II) What is the wavelength of the light entering an interferometer if 362 bright fringes are counted when the movable mirror moves 0.125 mm?*

*58. (II) A micrometer is connected to the movable mirror of an interferometer. When the micrometer is tightened down on a thin metal foil, the net number of bright fringes that move, compared to closing the empty micrometer, is 296. What is the thickness of the foil? The wavelength of light used is 589 nm.

*59. (III) One of the beams of an interferometer (Fig. 24–61) passes through a small evacuated glass container 1.155 cm deep. When a gas is allowed to slowly fill the container, a total of 158 dark fringes are counted to move past a reference line. The light used has a wavelength of 632.8 nm. Calculate the index of refraction of the gas at its final density, assuming that the interferometer is in vacuum.

**24–10 Polarization**

60. (I) Two polarizers are oriented at 72° to one another. Unpolarized light falls on them. What fraction of the light intensity is transmitted?

61. (I) What is Brewster’s angle for an air-glass \((n = 1.56)\) surface?

62. (II) At what angle should the axes of two Polaroids be placed so as to reduce the intensity of the incident unpo-larized light to \((a) \frac{1}{3}\), \((b) \frac{1}{10}\)?
63. (II) Two polarizers are oriented at 42.0° to one another. Light polarized at a 21.0° angle to each polarizer passes through both. What is the transmitted intensity (%)?

64. (II) Three perfectly polarizing sheets are spaced 2 cm apart and in parallel planes. The transmission axis of the second sheet is 30° relative to the first one. The transmission axis of the third sheet is 90° relative to the first one. Unpolarized light impinges on the first polarizing sheet. What percent of this light is transmitted out through the third polarizer?

65. (II) A piece of material, suspected of being a stolen diamond \((n = 2.42)\), is submerged in oil of refractive index 1.43 and illuminated by unpolarized light. It is found that the reflected light is completely polarized at an angle of 62°. Is it diamond? Explain.

66. (II) Two Polaroids are aligned so that the initially unpolarized light passing through them is a maximum. At what angle should one of them be placed so the transmitted intensity is subsequently reduced by half?

67. (II) What is Brewster’s angle for a diamond submerged in water?

68. (II) The critical angle for total internal reflection at a boundary between two materials is 58°. What is Brewster’s angle at this boundary? Give two answers, one for each material.

69. (II) What would Brewster’s angle be for reflections off the surface of water for light coming from beneath the surface? Compare to the angle for total internal reflection, and to Brewster’s angle from above the surface.

70. (II) Unpolarized light of intensity \(l_0\) passes through six successive Polaroid sheets each of whose axis makes a 35° angle with the previous one. What is the intensity of the transmitted beam?

71. (III) Two polarizers are oriented at 48° to each other and plane-polarized light is incident on them. If only 35% of the light gets through both of them, what was the initial polarization direction of the incident light?
72. (III) Four polarizers are placed in succession with their axes vertical, at
30.0° to the vertical, at 60.0° to the vertical, and at 90.0° to the vertical. (a)
Calculate what fraction of the incident unpolarized light is transmitted by
the four polarizers. (b) Can the transmitted light be decreased by removing
one of the polarizers? If so, which one? (c) Can the transmitted light
intensity be extinguished by removing polarizers? If so, which one(s)?

General Problems

73. Light of wavelength 5.0 \times 10^{-7} \text{ m} passes through two parallel slits and
falls on a screen 5.0 \text{ m} away. Adjacent bright bands of the interference
pattern are 2.0 \text{ cm} apart. (a) Find the distance between the slits. (b) The
same two slits are next illuminated by light of a different wavelength, and
the fifth-order minimum for this light occurs at the same point on the
screen as the fourth-order minimum for the previous light. What is the
wavelength of the second source of light?

74. Television and radio waves reflecting from mountains or airplanes can
interfere with the direct signal from the station. (a) What kind of
interference will occur when 75-MHz television signals arrive at a receiver
directly from a distant station, and are reflected from a nearby airplane
122 \text{ m} directly above the receiver? Assume \( \frac{1}{2} \lambda \) change in phase of the
signal upon reflection. (b) What kind of interference will occur if the plane
is 22 \text{ m} closer to the receiver?

75. Red light from three separate sources passes through a diffraction grating
with 3.60 \times 10^5 \text{ slits/m}. The wavelengths of the three lines are 6.56 \times 10^{-7}
\text{ m} (hydrogen), 6.50 \times 10^{-7} \text{ m} (neon), and 6.97 \times 10^{-7} \text{ m} (argon). Calculate
the angles for the first-order diffraction line of each source.
76. What is the index of refraction of a clear material if a minimum thickness of 125 nm, when laid on glass, is needed to reduce reflection to nearly zero when light of 675 nm is incident normally upon it? Do you have a choice for an answer?

77. Light of wavelength 650 nm passes through two narrow slits 0.66 mm apart. The screen is 2.40 m away. A second source of unknown wavelength produces its second-order fringe 1.23 mm closer to the central maximum than the 650-nm light. What is the wavelength of the unknown light?

78. Monochromatic light of variable wavelength is incident normally on a thin sheet of plastic film in air. The reflected light is a maximum only for \( \lambda = 491.4 \) nm and \( \lambda = 688.0 \) nm in the visible spectrum. What is the thickness of the film \( (n = 1.58) \)? [Hint: Assume successive values of m.]

79. Show that the second- and third-order spectra of white light produced by a diffraction grating always overlap. What wavelengths overlap?

80. A radio station operating at 90.3 MHz broadcasts from two identical antennas at the same elevation but separated by a 9.0-m horizontal distance \( d \), Fig. 24–62. A maximum signal is found along the midline, perpendicular to \( d \) at its midpoint and extending horizontally in both directions. If the midline is taken as 0°, at what other angle(s) \( \theta \) is a maximum signal detected? A minimum signal? Assume all measurements are made much farther than 9.0 m from the antenna towers.

81. Calculate the minimum thickness needed for an antireflective coating \( (n = 1.38) \) applied to a glass lens in order to eliminate \( (a) \) blue (450 nm), or \( (b) \) red (720 nm) reflections for light at normal incidence.

82. Stealth aircraft are designed to not reflect radar, whose wavelength is typically 2 cm, by using an antireflecting coating. Ignoring any change in wavelength in the coating, estimate its thickness.
83. A laser beam passes through a slit of width 1.0 cm and is pointed at the Moon, which is approximately 380,000 km from the Earth. Assume the laser emits waves of wavelength 633 nm (the red light of a He-Ne laser). Estimate the width of the beam when it reaches the Moon due to diffraction.

84. A thin film of soap \((n = 1.34)\) coats a piece of flat glass \((n = 1.52)\). How thick is the film if it reflects 643-nm red light most strongly when illuminated normally by white light?

85. When violet light of wavelength 415 nm falls on a single slit, it creates a central diffraction peak that is 8.20 cm wide on a screen that is 3.15 m away. How wide is the slit?

86. A series of polarizers are each rotated 10° from the previous polarizer. Unpolarized light is incident on this series of polarizers. How many polarizers does the light have to go through before it is \(\frac{1}{5}\) of its original intensity?

87. The wings of a certain beetle have a series of parallel lines across them. When normally incident 480-nm light is reflected from the wing, the wing appears bright when viewed at an angle of 56°. How far apart are the lines?

88. A teacher stands well back from an outside doorway 0.88 m wide, and blows a whistle of frequency 950 Hz. Ignoring reflections, estimate at what angle(s) it is not possible to hear the whistle clearly on the playground outside the doorway. Assume 340 m/s for the speed of sound.

89. Light is incident on a diffraction grating with 7200 slits/cm and the pattern is viewed on a screen located 2.5 m from the grating. The incident light beam consists of two wavelengths, \(\lambda_1 = 4.4 \times 10^{-7} \text{ m}\) and \(\lambda_2 = 6.8 \times 10^{-7}\)
m. Calculate the linear distance between the first-order bright fringes of these two wavelengths on the screen.

90. How many slits per centimeter must a grating have if there is to be no second-order spectrum for any visible wavelength?

91. When yellow sodium light, \( \lambda = 589 \text{ nm} \), falls on a diffraction grating, its first-order peak on a screen 72.0 cm away falls 3.32 cm from the central peak. Another source produces a line 3.71 cm from the central peak. What is its wavelength? How many slits/cm are on the grating?

92. Two of the lines of the atomic hydrogen spectrum have wavelengths of 656 nm and 410 nm. If these fall at normal incidence on a grating with 7700 slits/cm, what will be the angular separation of the two wavelengths in the first-order spectrum?

93. A tungsten-halogen bulb emits a continuous spectrum of ultraviolet, visible, and infrared light in the wavelength range 360 nm to 2000 nm. Assume that the light from a tungsten-halogen bulb is incident on a diffraction grating with slit spacing \( d \) and that the first-order brightness maximum for the wavelength of 1200 nm occurs at angle \( \theta \). What other wavelengths within the spectrum of incident light will produce a brightness maximum at this same angle \( \theta \)? [Optical filters are used to deal with this bothersome effect when a continuous spectrum of light is measured by a spectrometer.]

94. At what angle above the horizon is the Sun when light reflecting off a smooth lake is polarized most strongly?

95. Unpolarized light falls on two polarizer sheets whose axes are at right angles. (a) What fraction of the incident light intensity is transmitted? (b) What fraction is transmitted if a third polarizer is placed between the first
two so that its axis makes a $56^\circ$ angle with the axis of the first polarizer? (c) What if the third polarizer is in front of the other two?

96. At what angle should the axes of two Polaroids be placed so as to reduce the intensity of the incident unpolarized light by an additional factor (after the first Polaroid cuts it in half) of (a) 4, (b) 10, (c) 100?

**Search and Learn**

1. Compare Figs. 24–5, 24–6, and 24–7, which are different representations of the double-slit experiment. For each figure state the direction the light is traveling. Where are the wave crests in terms of this direction? How are they represented in each figure? Give one advantage of each figure in helping you understand the double-slit experiment and interference.

2. Discuss the similarities, and differences, of double-slit interference and single-slit diffraction.

3. Describe why the various colors of visible light appear as they do in Fig. 24–16, where red is at the top and violet at the bottom, and in Fig. 24–26, where violet is closest to the central maximum and red is farthest from the central maximum.

4. When can we use geometric optics as in Chapter 23, and when do we need to use the more complicated wave model of light discussed in Chapter 24? In particular, what are the physical characteristics that matter in making this decision?

5. A parallel beam of light containing two wavelengths, 420 nm and 650 nm, enters a borate flint glass equilateral prism (Fig. 24–63). (a) What is the angle between the two beams leaving the prism? (b) Repeat part (a) for a diffraction grating with 5800 slits/cm. (c) Discuss two advantages of a diffraction grating, including one that you see from your results.
6. Suppose you viewed the light *transmitted* through a thin coating layered on a flat piece of glass. Draw a diagram, similar to Fig. 24–30 or 24–36, and describe the conditions required for maxima and minima. Consider all possible values of index of refraction. Discuss the relative intensity of the minima compared to the maxima and to zero.

7. What percent of visible light is reflected from plain glass? Assume your answer refers to transmission through each surface, front and back. How does the presence of multiple lenses in a good camera degrade the image? What is suggested in Section 24–8 to reduce this reflection? Explain in words, and sketch how this solution works. For a glass lens in air, about how much improvement does this solution provide?