Huygens' Principle The three-dimensional transmission of waves, including light, may often be predicted by Huygens’ principle, which states that all points on a wavefront serve as point sources of spherical secondary wavelets. After a time $t$, the new position of the wavefront will be that of a surface tangent to these secondary wavelets.

The law of refraction can be derived from Huygens’ principle by assuming that the index of refraction of any medium is $n = c/v$, in which $v$ is the speed of light in the medium and $c$ is the speed of light in vacuum.

Wavelength and Index of Refraction The wavelength $\lambda_n$ of light in a medium depends on the index of refraction $n$ of the medium:

$$\lambda_n = \frac{\lambda}{n}, \quad (35-8)$$

in which $\lambda$ is the wavelength in vacuum. Because of this dependency, the phase difference between two waves can change if they pass through different materials with different indexes of refraction.

Young’s Experiment In Young’s interference experiment, light passing through a single slit falls on two slits in a screen. The light leaving these slits flares out (by diffraction), and interference occurs in the region beyond the screen. A fringe pattern, due to the interference, forms on a viewing screen.

The light intensity at any point on the viewing screen depends in part on the difference in the path lengths from the slits to that point. If this difference is an integer number of wavelengths, the waves interfere constructively and an intensity maximum results. If it is an odd number of half-wavelengths, there is destructive interference and an intensity minimum occurs. The conditions for maximum and minimum intensity are

$$d \sin \theta = m\lambda, \quad \text{for } m = 0, 1, 2, \ldots \quad (*),$$

(maxima—bright fringes),

$$d \sin \theta = (m + \frac{1}{2})\lambda, \quad \text{for } m = 0, 1, 2, \ldots \quad (**),$$

(minima—dark fringes),

where $\theta$ is the angle the light path makes with a central axis and $d$ is the slit separation.

Coherence If two light waves that meet at a point are to interfere perceptibly, the phase difference between them must remain constant with time; that is, the waves must be coherent. When two coherent waves meet, the resulting intensity may be found by using phasors.

Intensity in Two-Slit Interference In Young’s interference experiment, two waves, each with intensity $I_0$, yield a resultant wave of intensity $I$ at the viewing screen, with

$$I = 4I_0 \cos^2 \frac{\theta}{2}, \quad \text{where } \theta = \frac{2\pi d}{\lambda} \sin \theta. \quad (35-22, 35-23)$$

Equations 35-14 and 35-16, which identify the positions of the fringe maxima and minima, are contained within this relation.

Thin-Film Interference When light is incident on a thin transparent film, the light waves reflected from the front and back surfaces interfere. For near-normal incidence, the wavelength conditions for maximum and minimum intensity of the light reflected from a film in air are

$$2L = \left( m + \frac{1}{2} \right) \frac{\lambda}{n}, \quad \text{for } m = 0, 1, 2, \ldots \quad (35-36)$$

(maxima—bright film in air),

$$2L = m \frac{\lambda}{n}, \quad \text{for } m = 0, 1, 2, \ldots \quad (35-37)$$

(minima—dark film in air),

where $n$ is the index of refraction of the film, $L$ is its thickness, and $\lambda$ is the wavelength of the light in air.

If the light incident at an interface between media with different indexes of refraction is in the medium with the smaller index of refraction, the reflection causes a phase change of $\pi$ rad, or half a wavelength, in the reflected wave. Otherwise, there is no phase change due to the reflection. Refraction causes no phase shift.

The Michelson Interferometer In Michelson’s interferometer a light wave is split into two beams that, after traversing paths of different lengths, are recombined so they interfere and form a fringe pattern. Varying the path length of one of the beams allows distances to be accurately expressed in terms of wavelengths of light, by counting the number of fringes through which the pattern shifts because of the change.

** QUESTIONS **

1. Does the spacing between fringes in a two-slit interference pattern increase, decrease, or stay the same if (a) the slit separation is increased, (b) the color of the light is switched from red to blue, and (c) the whole apparatus is submerged in cooking sherry? (d) If the slits are illuminated with white light, then at any side maximum, does the blue component or the red component peak closer to the central maximum?

2. (a) If you move from one bright fringe in a two-slit interference pattern to the next one farther out, (b) does the path length difference $\Delta L$ increase or decrease and (c) by how much does it change, in wavelengths $\lambda$?

3. Figure 35-22 shows two light rays that are initially exactly in phase and that reflect from several glass surfaces. Neglect the slight
4 In Fig. 35-23, three pulses of light — a, b, and c — of the same wavelength are sent through layers of plastic having the given indexes of refraction and along the paths indicated. Rank the pulses according to their travel time through the plastic layers, greatest first.

![Fig. 35-23](image)

5 Is there an interference maximum, a minimum, an intermediate state closer to a maximum, or an intermediate state closer to a minimum at point P in Fig. 35-10 if the path length difference of the two rays is (a) 2.2λ, (b) 3.5λ, (c) 1.8λ, and (d) 1.0λ? For each situation, give the value of m associated with the maximum or minimum involved.

6 Figure 35-24a gives intensity I versus position x on the viewing screen for the central portion of a two-slit interference pattern. The other parts of the figure give phasor diagrams for the electric field components of the waves arriving at the screen from the two slits (as in Fig. 35-13a). Which numbered points on the screen best correspond to which phasor diagram?

![Fig. 35-24](image)

7 Figure 35-25 shows two sources S₁ and S₂ that emit radio waves of wavelength λ in all directions. The sources are exactly in phase and are separated by a distance equal to 1.5λ. The vertical broken line is the perpendicular bisector of the distance between the sources. (a) If we start at the indicated start point and travel along path 1, does the interference produce a maximum all along the path, a minimum all along the path, or alternating maxima and minima? Repeat for (b) path 2 (along an axis through the sources) and (c) path 3 (along a perpendicular to that axis).

![Fig. 35-25](image)

8 Figure 35-26 shows two rays of light of wavelength 600 nm that reflect from glass surfaces separated by 150 nm. The rays are initially in phase. (a) What is the path length difference of the rays? (b) When they have cleared the reflection region, are the rays exactly in phase, exactly out of phase, or in some intermediate state?

![Fig. 35-26](image)

9 Light travels along the length of a 1500-nm-long nanostructure. When a peak of the wave is at one end of the nanostructure, is there a peak or a valley at the other end if the wavelength is (a) 500 nm and (b) 1000 nm?

10 Figure 35-27a shows the cross section of a vertical thin film whose width increases downward because gravitation causes slumping. Figure 35-27b is a face-on view of the film, showing four bright (red) interference fringes that result when the film is illuminated with a perpendicular beam of red light. Points in the cross section corresponding to the bright fringes are labeled. In terms of the wavelength of the light inside the film, what is the difference in film thickness between (a) points a and b and (b) points b and d?

![Fig. 35-27](image)

11 Figure 35-28 shows four situations in which light reflects perpendicularly from a thin film of thickness L sandwiched between much thicker materials. The indexes of refraction are given. In which situations does Eq. 35-36 correspond to the reflections yielding maxima (that is, a bright film)?

![Fig. 35-28](image)

12 Figure 35-29 shows the transmission of light through a thin film in air by a perpendicular beam (tilted in the figure for clarity). (a) Did ray r₅ undergo a phase shift due to reflection? (b) In wavelengths, what is the reflection phase shift for ray r₅? (c) If the film thickness is L, what is the path length difference between rays r₅ and r₆?

![Fig. 35-29](image)
sec. 35-2 Light as a Wave

1 In Fig. 35-30, a light wave along ray $r_1$ reflects once from a mirror and a light wave along ray $r_2$ reflects twice from that same mirror and once from a tiny mirror at distance $L$ from the bigger mirror. (Neglect the slight tilt of the rays.) The waves have wavelength 620 nm and are initially in phase. (a) What is the smallest value of $L$ that puts the final light waves exactly out of phase? (b) With the tiny mirror initially at that value of $L$, how far must it be moved away from the bigger mirror to again put the final waves out of phase?

2 In Fig. 35-30, a light wave along ray $r_1$ reflects once from a mirror and a light wave along ray $r_2$ reflects twice from that same mirror and once from a tiny mirror at distance $L$ from the bigger mirror. (Neglect the slight tilt of the rays.) The waves have wavelength $\lambda$ and are initially exactly out of phase. What are the (a) smallest, (b) second smallest, and (c) third smallest values of $L/\lambda$ that result in the final waves being exactly in phase?

3 SSM In Fig. 35-4, assume that two waves of light in air, of wavelength 400 nm, are initially in phase. One travels through a glass layer of index of refraction $n_1 = 1.60$ and thickness $L$. The other travels through an equally thick plastic layer of index of refraction $n_2 = 1.50$. (a) What is the smallest value $L$ should have if the waves are to end up with a phase difference of 5.65 rad? (b) If the waves arrive at some common point with the same amplitude, is their interference fully constructive, fully destructive, intermediate but closer to fully constructive, or intermediate but closer to fully destructive?

4 In Fig. 35-31(a), a beam of light in material 1 is incident on a boundary at an angle of $30^\circ$. The extent to which the light is bent due to refraction depends, in part, on the index of refraction $n_2$ of material 2. Figure 35-31(b) gives the angle of refraction $\theta_2$ versus $n_2$ for a range of possible $n_2$ values, from $n_2 = 1.30$ to $n_2 = 1.90$. What is the speed of light in material 1?

5 How much faster, in meters per second, does light travel in sapphire than in diamond? See Table 33-1.

6 The wavelength of yellow sodium light in air is 589 nm. (a) What is its frequency? (b) What is its wavelength in glass whose index of refraction is 1.52? (c) From the results of (a) and (b), find its speed in this glass.

7 The speed of yellow light (from a sodium lamp) in a certain liquid is measured to be $1.92 \times 10^8$ m/s. What is the index of refraction of this liquid for the light?

8 In Fig. 35-32, two light pulses are sent through layers of plastic with thicknesses of either $L$ or $2L$ as shown and indexes of refraction $n_1 = 1.55$, $n_2 = 1.70$, $n_3 = 1.60$, $n_4 = 1.45$, $n_5 = 1.59$, $n_6 = 1.65$, and $n_7 = 1.50$. (a) Which pulse travels through the plastic in less time? (b) What multiple of $L/c$ gives the difference in the traversal times of the pulses?

9 In Fig. 35-4, assume that the two light waves, of wavelength 620 nm in air, are initially out of phase by $\pi$ rad. The indexes of refraction of the media are $n_1 = 1.45$ and $n_2 = 1.65$. What are the (a) smallest and (b) second smallest value of $L/\lambda$ that will put the waves exactly in phase once they pass through the two media?

10 In Fig. 35-33, a light ray is incident at angle $\theta_1 = 50^\circ$ on a series of five transparent layers with parallel boundaries. For layers 1 and 3, $L_1 = 20 \mu m$, $L_3 = 25 \mu m$, $n_1 = 1.6$, and $n_3 = 1.45$. (a) At what angle does the light emerge back into air at the right? (b) How much time does the light take to travel through layer 3?

11 Suppose that the two waves in Fig. 35-4 have wavelength $\lambda = 500$ nm in air. What multiple of $\lambda$ gives their phase difference when they emerge if (a) $n_1 = 1.50$, $n_2 = 1.60$, and $L = 8.50 \mu m$; (b) $n_1 = 1.62$, $n_2 = 1.72$, and $L = 8.50 \mu m$; and (c) $n_1 = 1.59$, $n_2 = 1.79$, and $L = 3.25 \mu m$? (d) Suppose that in each of these three situations the waves arrive at a common point (with the same amplitude) after emerging. Rank the situations according to the brightness the waves produce at the common point.

12 In Fig. 35-34, two light rays go through different paths by reflecting from the various flat surfaces shown. The light waves have a wavelength of 420.0 nm and are initially in phase. What are the (a) smallest and (b) second smallest...
value of distance $L$ that will put the waves exactly out of phase as they emerge from the region?

**13. ILW** Two waves of light in air, of wavelength $\lambda = 600.0$ nm, are initially in phase. They then both travel through a layer of plastic as shown in Fig. 35-35, with $L_1 = 4.00 \mu m$, $L_2 = 3.50 \mu m$, $n_1 = 1.40$, and $n_2 = 1.60$. (a) What multiple of $\lambda$ gives their phase difference after they both have emerged from the layers? (b) If the waves later arrive at some common point with the same amplitude, is their interference fully constructive, fully destructive, intermediate but closer to fully constructive, or intermediate but closer to fully destructive?

**35-4 Young's Interference Experiment**

**14.** In a double-slit arrangement the slits are separated by a distance equal to 100 times the wavelength of the light passing through the slits. (a) What is the angular separation in radians between the central maximum and an adjacent maximum? (b) What is the distance between these maxima on a screen 50.0 cm from the slits?

**15. SSM** A double-slit arrangement produces interference fringes for sodium light ($\lambda = 589$ nm) that have an angular separation of $3.50 \times 10^{-3}$ rad. For what wavelength would the angular separation be 10.0% greater?

**16.** A double-slit arrangement produces interference fringes for sodium light ($\lambda = 589$ nm) that are 0.20° apart. What is the angular fringe separation if the entire arrangement is immersed in water ($n = 1.33$)?

**17. SSM** In Fig. 35-36, two radio-frequency point sources $S_1$ and $S_2$, separated by distance $d = 2.0$ m, are radiating in phase with $\lambda = 0.50$ m. A detector moves in a large circular path around the two sources in a plane containing them. How many maxima does it detect?

**18.** In the two-slit experiment of Fig. 35-10, let angle $\theta$ be 20.0°, the slit separation be 4.24 $\mu m$, and the wavelength be $\lambda = 500$ nm. (a) What multiple of $\lambda$ gives the phase difference between the waves of rays $r_1$ and $r_2$ when they arrive at point $P$ on the distant screen? (b) What is the phase difference in radians? (c) Determine where in the interference pattern point $P$ lies by giving the maximum or minimum on which it lies, or the maximum and minimum between which it lies.

**19. SSM ILW** Suppose that Young's experiment is performed with blue-green light of wavelength 500 nm. The slits are 1.20 mm apart, and the viewing screen is 5.40 m from the slits. How far apart are the bright fringes near the center of the interference pattern?

**20.** Monochromatic green light, of wavelength 550 nm, illuminates two parallel narrow slits 7.70 $\mu m$ apart. Calculate the angular deviation ($\theta$ in Fig. 35-10) of the third-order ($m = 3$) bright fringe (a) in radians and (b) in degrees.

**21.** In a double-slit experiment, the distance between slits is 5.0 mm and the slits are 1.0 m from the screen. Two interference patterns can be seen on the screen: one due to light of wavelength 480 nm, and the other due to light of wavelength 600 nm. What is the separation on the screen between the third-order ($m = 3$) bright fringes of the two interference patterns?

**22. ILW** In Fig. 35-36, two isotropic point sources $S_1$ and $S_2$ emit identical light waves in phase at wavelength $\lambda$. The sources lie at separation $d$ on an $x$ axis, and a light detector is moved in a circle of large radius around the midpoint between them. It detects 30 points of zero intensity, including two on the $x$ axis, one of them to the left of the sources and the other to the right of the sources. What is the value of $d/\lambda$?

**23.** In Fig. 35-37, sources $A$ and $B$ emit long-range radio waves of wavelength 400 m, with the phase of the emission from $A$ ahead of that from source $B$ by 90°. The distance $r_A$ from $A$ to detector $D$ is greater than the corresponding distance $r_B$ by 100 m. What is the phase difference of the waves at $D$?

**24. ILW** In Fig. 35-38, two isotropic point sources $S_1$ and $S_2$ emit light in phase at wavelength $\lambda$ and at the same amplitude. The sources are separated by distance $2d = 6.00\lambda$. They lie on an axis that is parallel to an $x$ axis, which runs along a viewing screen at distance $D = 20.0\lambda$. The origin lies on the perpendicular bisector between the sources. The figure shows two rays reaching point $P$ on the screen, at position $x_P$. (a) At what value of $x_P$ do the rays have the minimum possible phase difference? (b) What multiple of $\lambda$ gives that minimum phase difference? (c) At what value of $x_P$ do the rays have the maximum possible phase difference? What multiple of $\lambda$ gives (d) that maximum phase difference and (e) the phase difference when $x_P = 6.00\lambda$? (f) When $x_P = 6.00\lambda$, is the resulting intensity at point $P$, maximum, minimum, intermediate but closer to maximum, or intermediate but closer to minimum?

**25.** In Fig. 35-39, two isotropic point sources of light ($S_1$ and $S_2$) are separated by distance 2.70 $\mu m$ along a $y$ axis and emit in phase at wavelength 900 nm and at the same amplitude. A light detector is located at point $P$ at coordinate $x_P$ on the $x$ axis. What is the greatest value of $x_P$ at which the detected light is minimum due to destructive interference?

**26.** In a double-slit experiment, the fourth-order maximum for a wavelength of 450 nm occurs at an angle of $\theta = 90°$. Thus, it is on the verge of being eliminated from the pattern because $\theta$ cannot exceed 90° in Eq. 35-14. (a) What range of wavelengths in the visible range (400 nm to 700 nm) are not present in the third-order maxima? To eliminate all of the visible light in the fourth-order maximum, (b) should the slit separation be increased or decreased and (c) what least change in separation is needed?

**27.** A thin flake of mica ($n = 1.58$) is used to cover one slit of a double-slit interference arrangement. The central point on the viewing screen is now occupied by what had been the seventh bright side fringe ($m = 7$). If $\lambda = 550$ nm, what is the thickness of the mica?
sec. 35-6  **Intensity in Double-Slit Interference**

**28** Figure 35-39 shows two isotropic point sources of light ($S_1$ and $S_2$) that emit in phase at wavelength 400 nm and at the same amplitude. A detection point $P$ is shown on an $x$ axis that extends through source $S_1$. The phase difference $\phi$ between the light arriving at point $P$ from the two sources is to be measured as $P$ is moved along the $x$ axis from $x = 0$ out to $x = +\infty$. The results out to $x = 10 \times 10^{-7}$ m are given in Fig. 35-40. On the way out to $+\infty$, what is the greatest value of $x$ at which the light arriving at $P$ from $S_1$ is exactly out of phase with the light arriving at $P$ from $S_2$?

**29** SSM Two waves of the same frequency have amplitudes 1.00 and 2.00. They interfere at a point where their phase difference is 60.0°. What is the resultant amplitude?

**30** Find the sum $y$ of the following quantities:

$$y_1 = 10 \sin(\omega t) \quad \text{and} \quad y_2 = 8.0 \sin(\omega t + 30°).$$

**31** ILW Add the quantities $y_1 = 10 \sin(\omega t), y_3 = 15 \sin(\omega t + 30°)$, and $y_4 = 5.0 \sin(\omega t - 45°)$ using the phasor method.

**32** In the double-slit experiment of Fig. 35-10, the electric fields of the waves arriving at point $P$ are given by

$$E_1 = (2.00 \mu V/m) \sin[(1.26 \times 10^{15})t],$$

$$E_2 = (2.00 \mu V/m) \sin[(1.26 \times 10^{15})t + 39.6 \text{ rad}],$$

where time $t$ is in seconds. (a) What is the amplitude of the resultant electric field at point $P$? (b) What is the ratio of the intensity $I_P$ at point $P$ to the intensity $I_{on}$ at the center of the interference pattern? (c) Describe where point $P$ is in the interference pattern by giving the maximum or minimum on which it lies, or the maximum and minimum between which it lies. In a phasor diagram of the electric fields, (d) at what rate would the phasors rotate around the origin and (e) what is the angle between the phasors?

**33** Three electromagnetic waves travel through a certain point $P$ along an $x$ axis. They are polarized parallel to a $y$ axis, with the following variations in their amplitudes. Find their resultant at $P$:

$$E_1 = (10.0 \mu V/m) \sin[2.0 \times 10^{14} \text{ rad/s} t],$$

$$E_2 = (5.00 \mu V/m) \sin[2.0 \times 10^{14} \text{ rad/s} t + 45.0°],$$

$$E_3 = (5.00 \mu V/m) \sin[2.0 \times 10^{14} \text{ rad/s} t - 45.0°].$$

**34** In the double-slit experiment of Fig. 35-10, the viewing screen is at distance $D = 4.00$ m, point $P$ lies at distance $y = 20.5$ cm from the center of the pattern, the slit separation $d$ is $4.50 \mu m$, and the wavelength $\lambda$ is 580 nm. (a) Determine where point $Q$ is in the interference pattern by giving the maximum or minimum on which it lies, or the maximum and minimum between which it lies. (b) What is the ratio of the intensity $I_Q$ at point $Q$ to the intensity $I_{on}$ at the center of the pattern?

sec. 35-7  **Interference from Thin Films**

**35** SSM We wish to coat flat glass ($n = 1.50$) with a transparent material ($n = 1.25$) so that reflection of light at wavelength 600 nm is eliminated by interference. What minimum thickness can the coating have to do this?

**36** A 600-nm-thick soap film ($n = 1.40$) in air is illuminated with white light in a direction perpendicular to the film. For how many different wavelengths in the 300 to 700 nm range is there (a) fully constructive interference and (b) fully destructive interference in the reflected light?

**37** The rhinestones in costume jewelry are glass with index of refraction 1.50. To make them more reflective, they are often coated with a layer of silicon monoxide of index of refraction 2.00. What is the minimum coating thickness needed to ensure that light of wavelength 560 nm and of perpendicular incidence will be reflected from the two surfaces of the coating with fully constructive interference?

**38** White light is sent downward onto a horizontal thin film that is sandwiched between two materials. The indexes of refraction are 1.80 for the top material, 1.70 for the thin film, and 1.50 for the bottom material. The film thickness is $5.00 \times 10^{-7}$ m. Of the visible wavelengths (400 to 700 nm) that result in fully constructive interference at an observer above the film, which is the (a) longer and (b) shorter wavelength? The materials and film are then heated so that the film thickness increases. (c) Does the light resulting in fully constructive interference shift toward longer or shorter wavelengths?

**39** ILW Light of wavelength 624 nm is incident perpendicularly on a soap film ($n = 1.33$) suspended in air. What are the (a) least and (b) second least thicknesses of the film for which the reflections from the film undergo fully constructive interference?

**40** A thin film of acetone ($n = 1.25$) coats a thick glass plate ($n = 1.50$). White light is incident normal to the film. In the reflections, fully destructive interference occurs at 600 nm and fully constructive interference at 700 nm. Calculate the thickness of the acetone film.

**41 through 52** SSM 47, 51 **45, 49 Reflection by thin layers.** In Fig. 35-41, light is incident perpendicularly on a thin layer of material 2 that lies between (thicker) materials 1 and 3. (The rays are tilted only for clarity.) The waves of rays $r_1$ and $r_3$ interfere, and here we consider the type of interference to be either maximum (max) or minimum (min). For this situation, each problem in Table 35-2 refers to the indexes of refraction $n_1$, $n_2$, and $n_3$, the type of interference, the thin-layer thickness $L$ in nanometers, and the wavelength $\lambda$ in nanometers of the light as measured in air. Where $\lambda$ is missing, give the wavelength that is in the visible range. Where $L$ is missing, give the second least thickness or the third least thickness as indicated.

**43** The reflection of perpendicularly incident white light by a soap film in air has an interference maximum at 600 nm and a minimum at 450 nm, with no minimum in between. If $n = 1.33$ for the film, what is the film thickness, assumed uniform?

**44** A plane wave of monochromatic light is incident normally on a uniform thin film of oil that covers a glass plate. The wave-
length of the source can be varied continuously. Fully destructive interference of the reflected light is observed for wavelengths of 500 and 700 nm and for no wavelengths in between. If the index of refraction of the oil is 1.30 and that of the glass is 1.50, find the thickness of the oil film.

**55 SSM WWW** A disabled tanker leaks kerosene \((n = 1.20)\) into the Persian Gulf, creating a large slick on top of the water \((n = 1.30)\). (a) If you are looking straight down from an airplane, while the Sun is overhead, at a region of the slick where its thickness is 460 nm, for which wavelength(s) of visible light is the reflection brightest because of constructive interference? (b) If you are scuba diving directly under this same region of the slick, for which wavelength(s) of visible light is the transmitted intensity strongest?

**56** A thin film, with a thickness of 272.7 nm and with air on both sides, is illuminated with a beam of white light. The beam is perpendicular to the film and consists of the full range of wavelengths for the visible spectrum. In the light reflected by the film, light with a wavelength of 600.0 nm undergoes fully constructive interference. At what wavelength does the reflected light undergo fully destructive interference? (Hint: You must make a reasonable assumption about the index of refraction.)

**57 through 68 SSM 59 64, 65 Transmittion through thin layers.** In Fig. 35-42, light is incident perpendicularly on a thin layer of material 2 that lies between (thicker) materials 1 and 3. (The rays are tilted only for clarity.) Part of the light ends up in material 3 as ray \(r_3\) (the light does not reflect inside material 2) and \(r_4\) (the light reflects twice inside material 2). The waves of \(r_3\) and \(r_4\) interfere, and here we consider the type of interference to be either maximum (max) or minimum (min). For this situation, each problem in Table 35-3 refers to the indexes of refraction \(n_1, n_2,\) and \(n_3\), the type of interference, the thin-layer thickness \(L\) in nanometers, and the wavelength \(\lambda\) in nanometers of the light as measured in air. Where \(\lambda\) is missing, give the wavelength that is in the visible range. Where \(L\) is missing, give the second least thickness or the third least thickness as indicated.

**69** In Fig. 35-43, a broad beam of light of wavelength 630 nm is incident at 90° on a thin, wedge-shaped film with index of refraction 1.50. Transmission gives 10 bright and 9 dark fringes along the film’s length. What is the left-to-right change in film thickness?

**70** In Fig. 35-44, a broad beam of light of wavelength 620 nm is sent directly downward through the top plate of a pair of glass plates touching at the left end. The air between the plates acts as a thin film, and an interference pattern can be seen from above the plates. Initially, a dark fringe lies at the left end, a bright fringe lies at the right end, and nine dark fringes lie between those two end fringes. The plates are then very gradually squeezed together at a constant rate to decrease the angle between them. As a result, the fringe at the right side changes between bright to being dark every 15.0 s. (a) At what rate is the spacing between the plates at the right end being changed? (b) By how much has the spacing changed when both left and right ends have a dark fringe and there are five dark fringes between them?

**71** In Fig. 35-44, two microscope slides touch at one end and are separated at the other end. When light of wavelength 500 nm
shines vertically down on the slides, an overhead observer sees an interference pattern on the slides with the dark fringes separated by 1.2 mm. What is the angle between the slides?

**72** In Fig. 35-44, a broad beam of monochromatic light is directed perpendicularly through two glass plates that are held together at one end to create a wedge of air between them. An observer intercepting light reflected from the wedge of air, which acts as a thin film, sees 4001 dark fringes along the length of the wedge. When the air between the plates is evacuated, only 4000 dark fringes are seen. Calculate to six significant figures the index of refraction of air from these data.

**73** SSM In Fig. 35-44, a broad beam of light of wavelength 683 nm is sent directly downward through the top plate of a pair of glass plates. The plates are 120 mm long, touch at the left end, and are separated by 48.0 μm at the right end. The air between the plates acts as a thin film. How many bright fringes will be seen by an observer looking down through the top plate?

**74** Two rectangular glass plates (n = 1.60) are in contact along one edge and are separated along the opposite edge (Fig. 35-44). Light with a wavelength of 600 nm is incident perpendicularly onto the top plate. The air between the plates acts as a thin film. Nine dark fringes and eight bright fringes are observed from above the top plate. If the distance between the two plates along the separated edges is increased by 600 nm, how many dark fringes will there then be across the top plate?

**75** SSM ILW Figure 35-45a shows a lens with radius of curvature R lying on a flat glass plate and illuminated from above by light with wavelength λ. Figure 35-45b (a photograph taken from above the lens) shows that circular interference fringes (called Newton’s rings) appear, associated with the variable thickness d of the air film between the lens and the plate. Find the radii r of the interference maxima assuming r/R < 1.

**76** In a Newton’s rings experiment (see Problem 75), the radius of curvature R of the lens is 5.0 m and the lens diameter is 20 mm. (a) How many bright rings are produced? Assume that λ = 589 nm. (b) How many bright rings would be produced if the arrangement were immersed in water (n = 1.33)?

**77** A Newton’s rings apparatus is to be used to determine the radius of curvature of a lens (see Fig. 35-45 and Problem 75). The radii of the nth and (n + 20)th bright rings are measured and found to be 0.162 and 0.368 cm, respectively, in light of wavelength 546 nm. Calculate the radius of curvature of the lower surface of the lens.

**78** A thin film of liquid is held in a horizontal circular ring, with air on both sides of the film. A beam of light at wavelength 550 nm is directed perpendicularly onto the film, and the intensity I of its reflection is monitored. Figure 35-46 gives intensity I as a function of time t; the horizontal scale is set by t₁ = 20.0 s. The intensity changes because of evaporation from the two sides of the film. Assume that the film is flat and has parallel sides, a radius of 1.80 cm, and an index of refraction of 1.40. Also assume that the film’s volume decreases at a constant rate. Find that rate.

**79** If mirror M₁ in a Michelson interferometer (Fig. 35-21) is moved through 0.233 mm, a shift of 792 bright fringes occurs. What is the wavelength of the light producing the fringe pattern?

**80** A thin film with index of refraction n = 1.40 is placed in one arm of a Michelson interferometer, perpendicular to the optical path. If this causes a shift of 7.0 bright fringes of the pattern produced by light of wavelength 589 nm, what is the film thickness?

**81** SSM WWW In Fig. 35-47, an airtight chamber of length d = 5.0 cm is placed in one of the arms of a Michelson interferometer. (The glass window on each end of the chamber has negligible thickness.) Light of wavelength λ = 500 nm is used. Evacuating the air from the chamber causes a shift of 60 bright fringes. From these data and to six significant figures, find the index of refraction of air at atmospheric pressure.

**82** The element sodium can emit light at two wavelengths, λ₁ = 588.9950 nm and λ₂ = 589.5924 nm. Light from sodium is being used in a Michelson interferometer (Fig. 35-21). Through what distance must mirror M₂ be moved if the shift in the fringe pattern for one wavelength is to be 1.00 fringe more than the shift in the fringe pattern for the other wavelength?
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Suppose the water depth changes abruptly at a certain distance from the beach and the wave speed there drops to 3.0 m/s. (a) Close to the beach, what is the angle $\vartheta_2$ between the direction of wave motion and the normal? (Assume the same law of refraction as for light.) (b) Explain why most waves come in normal to a shore even though at large distances they approach at a variety of angles.

92 Figure 35-55a shows two light rays that are initially in phase as they travel upward through a block of plastic, with wavelength 400 nm as measured in air. Light ray $r_1$ exits directly into air. However, before light ray $r_2$ exits into air, it travels through a liquid in a hollow cylinder within the plastic. Initially the height $L_{\text{in}}$ of the liquid is 40.0 $\mu$m, but then the liquid begins to evaporate. Let $\phi$ be the phase difference between rays $r_1$ and $r_2$ once they both exit into the air. Figure 35-55b shows $\phi$ versus the liquid’s height $L_{\text{in}}$ until the liquid disappears, with $\phi$ given in terms of wavelength and the horizontal scale set by $L_s = 40.00$ $\mu$m. What are (a) the index of refraction of the plastic and (b) the index of refraction of the liquid?

93 SSM If the distance between the first and tenth minima of a double-slit pattern is 18.0 mm and the slits are separated by 0.150 mm with the screen 50.0 cm from the slits, what is the wavelength of the light used?

94 Figure 35-56 shows an optical fiber in which a central plastic core of index of refraction $n_1 = 1.58$ is surrounded by a plastic sheath of index of refraction $n_2 = 1.53$. Light can travel along different paths within the central core, leading to different travel times through the fiber. This causes an initially short pulse of light to spread as it travels along the fiber, resulting in information loss. Consider light that travels directly along the central axis of the fiber and light that is repeatedly reflected at the critical angle along the core–sheath interface, reflecting from side to side as it travels down the central core. If the fiber length is 300 m, what is the difference in the travel times along these two routes?

95 SSM Two parallel slits are illuminated with monochromatic light of wavelength 500 nm. An interference pattern is formed on a screen some distance from the slits, and the fourth dark band is located 1.68 cm from the central bright band on the screen. (a) What is the path length difference corresponding to the fourth dark band? (b) What is the distance on the screen between the central bright band and the first bright band on either side of the central band? (Hint: The angle to the fourth dark band and the angle to the first bright band are small enough that $\tan \theta = \sin \theta$)

96 A camera lens with index of refraction greater than 1.30 is coated with a thin transparent film of index of refraction 1.25 to eliminate by interference the reflection of light at wavelength $\lambda$ that is incident perpendicularly on the lens. What multiple of $\lambda$ gives the minimum film thickness needed?

97 SSM Light of wavelength $\lambda$ is used in a Michelson interferometer. Let $x$ be the position of the movable mirror, with $x = 0$ when the arms have equal lengths $d_0 = d_1$. Write an expression for the intensity of the observed light as a function of $x$, letting $L_{\text{in}}$ be the maximum intensity.

98 In two experiments, light is to be sent along the two paths shown in Fig. 35-34 by reflecting it from the various flat surfaces shown. In the first experiment, rays 1 and 2 are initially in phase and have a wavelength of 620.0 nm. In the second experiment, rays 1 and 2 are initially in phase and have a wavelength of 496.0 nm. What least value of distance $L$ is required such that the 620.0 nm waves emerge from the region exactly in phase but the 496.0 nm waves emerge exactly out of phase?

99 Figure 35-57 shows the design of a Texas arcade game. Four laser pistols are pointed toward the center of an array of plastic layers where a clay armadillo is the target. The indexes of refraction of the layers are $n_1 = 1.55, n_2 = 1.70, n_3 = 1.45, n_4 = 1.60, n_5 = 1.45, n_6 = 1.61, n_7 = 1.59, n_8 = 1.70$, and $n_9 = 1.60$. The layer thicknesses are either 2.00 mm or 4.00 mm, as drawn. What is the travel time through the layers for the laser burst from (a) pistol 1, (b) pistol 2, (c) pistol 3, and (d) pistol 4? (e) If the pistols are fired simultaneously, which laser burst hits the target first?

100 A thin film suspended in air is 0.410 $\mu$m thick and is illuminated with white light incident perpendicularly on its surface. The index of refraction of the film is 1.50. At what wavelength will visible light that is reflected from the two surfaces of the film undergo fully constructive interference?

101 Find the slit separation of a double-slit arrangement that will produce interference fringes 0.018 rad apart on a distant screen when the light has wavelength $\lambda = 589$ nm.

102 In a phasor diagram for any point on the viewing screen for the two-slit experiment in Fig. 35-10, the resultant-wave phasor rotates $60.0^\circ$ in $2.50 \times 10^{-9}$ s. What is the wavelength?