1. Does Huygens' principle apply to sound waves? To water waves?

1. Yes, Huygens' principle applies to all waves, including sound and water waves.

7. 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.

7. Blue light has a shorter wavelength than red light. The angles to each of the bright fringes for the blue light would be smaller than for the corresponding orders for the red light, so the bright fringes would be closer together for the blue light.

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

12. As the thickness of the film increases, the number of different wavelengths in the visible range that meet the constructive interference criteria increases. For a thick piece of glass, many different wavelengths will undergo constructive interference and these will all combine to produce white light.

2. (I) Monochromatic light falling on two slits 0.018 mm apart produces the fifth-order bright fringe at a 9.8° angle. What is the wavelength of the light used?

3. (I) The third-order bright fringe of 610 nm light is observed at an angle of 28° when the light falls on two narrow slits. How far apart are the slits?

2. For constructive interference, the path difference is a multiple of the wavelength, as given by Eq. 34-2a. Apply this to the fifth order.

$$d\sin\theta = m\lambda \quad\to\quad \lambda = \frac{d\sin\theta}{m} = \frac{\left(1.8\times10^{-5}\,\text{m}\right)\sin 9.8^\circ}{5} = \boxed{6.1\times10^{-7}\,\text{m}}$$

3. For constructive interference, the path difference is a multiple of the wavelength, as given by Eq. 34-2a. Apply this to the third order.

$$d\sin\theta = m\lambda \quad\to\quad d = \frac{m\lambda}{\sin\theta} = \frac{3\left(610\times10^{-9}\,\text{m}\right)}{\sin 28^\circ} = \boxed{3.9\times10^{-6}\,\text{m}}$$

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 3.8 m away?

9. For constructive interference, the path difference is a multiple of the wavelength, as given by Eq. 34-2a. The location on the screen is given by $x = \ell\tan\theta$, as seen in Fig. 34-7(c). For small angles, we have $\sin\theta \approx \tan\theta \approx x/\ell$. For adjacent fringes, $\Delta m = 1$.

$$d\sin\theta = m\lambda \quad\to\quad d\frac{x}{\ell} = m\lambda \quad\to\quad x = \frac{\lambda m\ell}{d} \quad\to$$

$$\Delta x = \Delta m\frac{\lambda\ell}{d} = (1)\frac{\left(633\times10^{-9}\,\text{m}\right)(3.8\,\text{m})}{\left(6.8\times10^{-5}\,\text{m}\right)} = 0.035\,\text{m} = \boxed{3.5\,\text{cm}}$$

15. (II) Light of wavelength 470 nm in air falls on two slits 6.00×10^{-2} mm apart. The slits are immersed in water, as is a viewing screen 50.0 cm away. How far apart are the fringes on the screen?

15. The presence of the water changes the wavelength according to Eq. 34-1, and so we must change λ to $\lambda_n = \lambda/n$. For constructive interference, the path difference is a multiple of the wavelength, as given by Eq. 34-2a. The location on the screen is given by $x = \ell \tan\theta$, as seen in Fig. 34-7(c). For small angles, we have $\sin\theta \approx \tan\theta \approx x/\ell$. Adjacent fringes will have $\Delta m = 1$.

$$d\sin\theta = m\lambda_n \rightarrow d\frac{x}{\ell} = m\lambda_n \rightarrow x = \frac{\lambda_n m\ell}{d} \; ; \; x_1 = \frac{\lambda m_1 \ell}{d} \; ; \; x_2 = \frac{\lambda(m+1)\ell}{d} \rightarrow$$

$$\Delta x = x_2 - x_1 = \frac{\lambda_n(m+1)\ell}{d} - \frac{\lambda_n m\ell}{d} = \frac{\lambda_n \ell}{d} = \frac{\lambda\ell}{nd} = \frac{(470\times10^{-9}\,\text{m})(0.500\,\text{m})}{(1.33)(6.00\times10^{-5}\,\text{m})} = \boxed{2.94\times10^{-3}\,\text{m}}$$

***19.** (II) Show that the angular full width at half maximum of the central peak in a double-slit interference pattern is given by $\Delta\theta = \lambda/2d$ if $\lambda \ll d$.

19. The intensity of the pattern is given by Eq. 34-6. We find the angle where the intensity is half its maximum value.

$$I_\theta = I_0\cos^2\left(\frac{\pi d\sin\theta}{\lambda}\right) = \tfrac{1}{2}I_0 \rightarrow \cos^2\left(\frac{\pi d\sin\theta_{1/2}}{\lambda}\right) = \tfrac{1}{2} \rightarrow \cos\left(\frac{\pi d\sin\theta_{1/2}}{\lambda}\right) = \frac{1}{\sqrt{2}} \rightarrow$$

$$\frac{\pi d\sin\theta_{1/2}}{\lambda} = \cos^{-1}\frac{1}{\sqrt{2}} = \frac{\pi}{4} \rightarrow \sin\theta_{1/2} = \frac{\lambda}{4d}$$

If $\lambda \ll d$, then $\sin\theta = \dfrac{\lambda}{4d} \ll 1$ and so $\sin\theta \approx \theta$. This is the angle from the central maximum to the location of half intensity. The angular displacement from the half-intensity position on one side of the central maximum to the half-intensity position on the other side would be twice this.

$$\Delta\theta = 2\theta_{1/2} = 2\frac{\lambda}{4d} = \boxed{\frac{\lambda}{2d}}$$

*21. (III) Suppose that one slit of a double-slit apparatus is wider than the other so that the intensity of light passing through it is twice as great. Determine the intensity I as a function of position (θ) on the screen for coherent light.

21. A doubling of the intensity means that the electric field amplitude has increased by a factor of $\sqrt{2}$. We set the amplitude of the electric field of one slit equal to E_0 and of the other equal to $\sqrt{2}E_0$. We use Eq. 34-3 to write each of the electric fields, where the phase difference, δ, is given by Eq. 34-4. Summing these two electric fields gives the total electric field.

$$E_\theta = E_0 \sin\omega t + \sqrt{2}E_0 \sin(\omega t + \delta) = E_0 \sin\omega t + \sqrt{2}E_0 \sin\omega t \cos\delta + \sqrt{2}E_0 \cos\omega t \sin\delta$$
$$= E_0\left(1+\sqrt{2}\cos\delta\right)\sin\omega t + \sqrt{2}E_0 \cos\omega t \sin\delta$$

We square the total electric field intensity and integrate over the period to determine the average intensity.

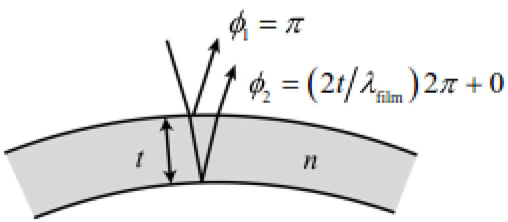
$$\overline{E}_\theta^2 = \frac{1}{T}\int_0^T E_\theta^2 dt = \frac{1}{T}\int_0^T \left[E_0\left(1+\sqrt{2}\cos\delta\right)\sin\omega t + \sqrt{2}E_0\cos\omega t \sin\delta\right]^2 dt$$
$$= \frac{E_0^2}{T}\int_0^T \left[\left(1+\sqrt{2}\cos\delta\right)^2 \sin^2\omega t + 2\cos^2\omega t \sin^2\delta + 2\sqrt{2}\left(1+\sqrt{2}\cos\delta\right)\sin\delta \sin\omega t \cos\omega t\right]dt$$
$$= \frac{E_0^2}{2}\left[\left(1+\sqrt{2}\cos\delta\right)^2 + 2\sin^2\delta\right] = \frac{E_0^2}{2}\left[3+2\sqrt{2}\cos\delta\right]$$

Since the intensity is proportional to this average square of the electric field, and the intensity is maximum when $\delta = 0$, we obtain the relative intensity by dividing the square of the electric field by the maximum square of the electric field.

$$\frac{I_\theta}{I_0} = \frac{\overline{E}_\theta^2}{E_{\delta=0}^2} = \boxed{\frac{3+2\sqrt{2}\cos\delta}{3+2\sqrt{2}}, \text{ with } \delta = \frac{2\pi}{\lambda} d\sin\theta}$$

25. (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 λ, why would the film also appear black?

25. (*a*) An incident wave that reflects from the outer surface of the bubble has a phase change of $\phi_1 = \pi$. An incident wave that reflects from the inner surface of the bubble has a phase change due to the additional path length, so $\phi_2 = \left(\frac{2t}{\lambda_{\text{film}}}\right)2\pi$. For destructive interference with a minimum non-zero thickness of bubble, the net phase change must be π.



$$\phi_{\text{net}} = \phi_2 - \phi_1 = \left[\left(\frac{2t}{\lambda_{\text{film}}}\right)2\pi\right] - \pi = \pi \rightarrow t = \tfrac{1}{2}\lambda_{\text{film}} = \frac{\lambda}{2n} = \frac{480\,\text{nm}}{2(1.33)} = \boxed{180\,\text{nm}}$$

(*b*) For the next two larger thicknesses, the net phase change would be 3π and 5π.

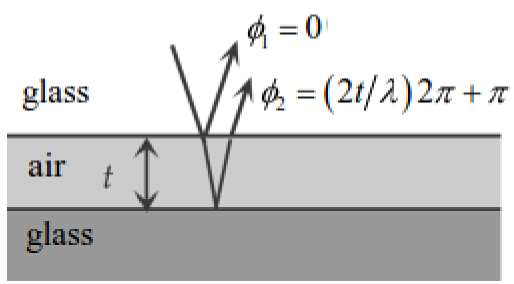
$$\phi_{\text{net}} = \phi_2 - \phi_1 = \left[\left(\frac{2t}{\lambda_{\text{film}}}\right)2\pi\right] - \pi = 3\pi \rightarrow t = \lambda_{\text{film}} = \frac{\lambda}{n} = \frac{480\,\text{nm}}{(1.33)} = \boxed{361\,\text{nm}}$$

$$\phi_{\text{net}} = \phi_2 - \phi_1 = \left[\left(\frac{2t}{\lambda_{\text{film}}}\right)2\pi\right] - \pi = 5\pi \rightarrow t = \lambda_{\text{film}} = \frac{\lambda}{n} = \tfrac{3}{2}\frac{480\,\text{nm}}{(1.33)} = \boxed{541\,\text{nm}}$$

(*c*) If the thickness were much less than one wavelength, then there would be very little phase change introduced by additional path length, and so the two reflected waves would have a phase difference of about $\phi_1 = \pi$. This would produce destructive interference.

31. (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?

31. With respect to the incident wave, the wave that reflects from the air at the top surface of the air layer has a phase change of $\phi_1 = 0$. With respect to the incident wave, the wave that reflects from the glass at the bottom surface of the air layer has a phase change due to both the additional path length and reflection, so $\phi_2 = \left(\frac{2t}{\lambda}\right)2\pi + \pi$. For constructive interference, the net phase change must be an even non-zero integer multiple of π.



$$\phi_{net} = \phi_2 - \phi_1 = \left[\left(\frac{2t}{\lambda}\right)2\pi + \pi\right] - 0 = 2m\pi \rightarrow t = \tfrac{1}{2}\left(m - \tfrac{1}{2}\right)\lambda,\ m = 1, 2, \cdots.$$

The minimum thickness is with $m = 1$.

$$t_{min} = \tfrac{1}{2}(450\,\text{nm})\left(1 - \tfrac{1}{2}\right) = \boxed{113\,\text{nm}}$$

For destructive interference, the net phase change must be an odd-integer multiple of π.

$$\phi_{net} = \phi_2 - \phi_1 = \left[\left(\frac{2t}{\lambda}\right)2\pi + \pi\right] - 0 = (2m+1)\pi \rightarrow t = \tfrac{1}{2}m\lambda,\ = 0, 1, 2, \cdots$$

The minimum non-zero thickness is $t_{min} = \tfrac{1}{2}(450\,\text{nm})(1) = \boxed{225\,\text{nm}}$.

*__45.__ (II) The *luminous efficiency* of a lightbulb is the ratio of luminous flux to electric power input. (*a*) What is the luminous efficiency (%) of a 100-W, 1700-lm bulb? (*b*) How many 40-W, 60-lm/W fluorescent lamps would be needed to provide an illuminance of $250\,\mathrm{lm/m^2}$ on a factory floor of area $25\,\mathrm{m} \times 30\,\mathrm{m}$? Assume the lights are 10 m above the floor and that half their flux reaches the floor.

45. (*a*) The wattage of the bulb is the electric power input to the bulb.

$$\text{luminous efficiency} = \frac{F_\ell}{P} = \frac{1700\,\mathrm{lm}}{100\,\mathrm{W}} = \boxed{17\,\mathrm{lm/W}}$$

(*b*) The illuminance is the luminous flux incident on a surface, divided by the area of the surface. Let N represent the number of lamps, each contributing an identical amount of luminous flux.

$$E_\ell = \frac{F_\ell}{A} = \frac{N\left[\frac{1}{2}(\text{luminous efficiency})P\right]}{A} \rightarrow$$

$$N = \frac{2E_\ell A}{(\text{luminous efficiency})P} = \frac{2(250\,\mathrm{lm/m^2})(25\,\mathrm{m})(30\,\mathrm{m})}{(60\,\mathrm{lm/W})(40\,\mathrm{W})} = 156\,\text{lamps} \approx \boxed{160\,\text{lamps}}$$

49. Light of wavelength 690 nm passes through two narrow slits 0.66 mm apart. The screen is 1.60 m away. A second source of unknown wavelength produces its second-order fringe 1.23 mm closer to the central maximum than the 690-nm light. What is the wavelength of the unknown light?

49. For constructive interference, the path difference is a multiple of the wavelength, as given by Eq. 34-2a. The location on the screen is given by $x = \ell \tan\theta$, as seen in Fig. 34-7(c). For small angles, we have $\sin\theta \approx \tan\theta \approx x/\ell$. Second order means $m = 2$.

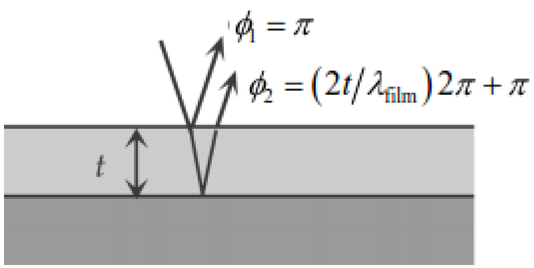
$$d\sin\theta = m\lambda \;\rightarrow\; d\frac{x}{\ell} = m\lambda \;\rightarrow\; x = \frac{\lambda m\ell}{d} \;;\; x_1 = \frac{\lambda_1 m\ell}{d} \;;\; x_2 = \frac{\lambda_2 m\ell}{d} \;\rightarrow$$

$$\Delta x = x_1 - x_2 = \frac{\lambda_1 m\ell}{d} - \frac{\lambda_2 m\ell}{d} \;\rightarrow$$

$$\lambda_2 = \lambda_1 - \frac{d\Delta x}{m\ell} = 690\times10^{-9}\,\text{m} - \frac{(6.6\times10^{-4}\,\text{m})(1.23\times10^{-3}\,\text{m})}{2(1.60\,\text{m})} = 4.36\times10^{-7}\,\text{m} \approx \boxed{440\,\text{nm}}$$

53. 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.

53. With respect to the incident wave, the wave that reflects from the top surface of the coating has a phase change of $\phi_1 = \pi$. With respect to the incident wave, the wave that reflects from the glass $(n \approx 1.5)$ at the bottom surface of the coating has a phase change due to both the additional path length and reflection, so $\phi_2 = \left(\frac{2t}{\lambda_{\text{film}}}\right)2\pi + \pi$. For destructive interference, the net phase change must be an odd-integer multiple of π.



$$\phi_{\text{net}} = \phi_2 - \phi_1 = \left[\left(\frac{2t}{\lambda_{\text{film}}}\right)2\pi + \pi\right] - \pi = (2m+1)\pi \quad \rightarrow$$

$$t = \tfrac{1}{4}(2m+1)\lambda_{\text{film}} = \tfrac{1}{4}(2m+1)\frac{\lambda}{n_{\text{film}}}, \; m = 0, 1, 2, \ldots$$

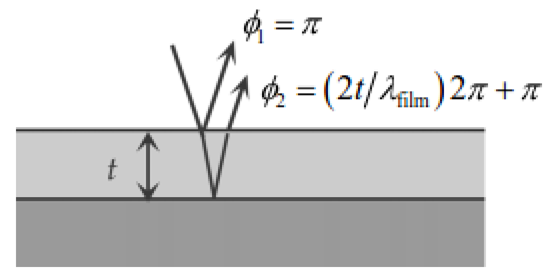
The minimum thickness has $m = 0$, and so $t_{\min} = \tfrac{1}{4}\frac{\lambda}{n_{\text{film}}}$.

(*a*) For the blue light: $t_{\min} = \tfrac{1}{4}\frac{(450\,\text{nm})}{(1.38)} = 81.52\,\text{nm} \approx \boxed{82\,\text{nm}}$.

(*b*) For the red light: $t_{\min} = \tfrac{1}{4}\frac{(700\,\text{nm})}{(1.38)} = 126.8\,\text{nm} \approx \boxed{130\,\text{nm}}$.

61. 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?

61. With respect to the incident wave, the wave that reflects from the top surface of the film has a phase change of $\phi_1 = \pi$. With respect to the incident wave, the wave that reflects from the glass $(n = 1.52)$ at the bottom surface of the film has a phase change due to both the additional path length and reflection, so $\phi_2 = \left(\frac{2t}{\lambda_{\text{film}}}\right)2\pi + \pi$. For constructive interference, the net phase change must be an even non-zero integer multiple of π.



$$\phi_{\text{net}} = \phi_2 - \phi_1 = \left[\left(\frac{2t}{\lambda_{\text{film}}}\right)2\pi + \pi\right] - \pi = m2\pi \rightarrow t = \tfrac{1}{2}m\lambda_{\text{film}} = \tfrac{1}{2}m\frac{\lambda}{n_{\text{film}}}, \; m = 1, 2, 3, \ldots .$$

The minimum non-zero thickness occurs for $m = 1$.

$$t_{\min} = \frac{\lambda}{2n_{\text{film}}} = \frac{643\,\text{nm}}{2(1.34)} = \boxed{240\,\text{nm}}$$