Chapter 18

1. The rule: if you divide the time (in seconds) by 3, then you get (approximately) the straight-line distance d. We note that the speed of sound we are to use is given at the beginning of the problem section in the textbook, and that the speed of light is very much larger than the speed of sound. The proof of our rule is as follows:
$$t = t_{\text{sound}} - t_{\text{light}} \approx t_{\text{sound}} = \frac{d}{v_{\text{sound}}} = \frac{d}{343\,\text{m/s}} = \frac{d}{0.343\,\text{km/s}} \ .$$
Cross-multiplying yields (approximately) $(0.3\,\text{km/s})t = d$ which (since $1/3 \approx 0.3$) demonstrates why the rule works fairly well.

2. We denote the speed of light $c = 3.0 \times 10^8$ m/s. The time t_1 it takes for you to hear the music is $t_1 = D_1/v_s = (300\,\text{m})/(343\,\text{m/s}) = 0.87\,\text{s}$. The time t_2 it takes for a listener 5000 km away to hear the music is $t_2 = D_2/c = 5000\,\text{km}/(3 \times 10^5\,\text{km/s}) = 0.02\,\text{s}$. So the listener 5000 km away actually hears the music first! The time difference is $\Delta t = t_1 - t_2 = 0.87\,\text{s} - 0.02\,\text{s} = 0.85\,\text{s}$.

3. (a) The time for the sound to travel from the kicker to a spectator is given by d/v, where d is the distance and v is the speed of sound. The time for light to travel the same distance is given by d/c, where c is the speed of light. The delay between seeing and hearing the kick is $\Delta t = (d/v) - (d/c)$. The speed of light is so much greater than the speed of sound that the delay can be approximated by $\Delta t = d/v$. This means $d = v\,\Delta t$. The distance from the kicker to the first spectator is $d_1 = v\,\Delta t_1 = (343\,\text{m/s})(0.23\,\text{s}) = 79\,\text{m}$. The distance from the kicker to the second spectator is $d_2 = v\,\Delta t_2 = (343\,\text{m/s})(0.12\,\text{s}) = 41\,\text{m}$.

   (b) Lines from the kicker to each spectator and from one spectator to the other form a right triangle with the line joining the spectators as the hypotenuse, so the distance between the spectators is $D = \sqrt{d_1^2 + d_2^2} = \sqrt{(79\,\text{m})^2 + (41\,\text{m})^2} = 89\,\text{m}$.

4. The time it takes for a soldier in the rear end of the column to switch from the left to the right foot to stride forward is $t = 1\,\text{min}/120 = 1/120\,\text{min} = 0.5\,\text{s}$. This is also the time for the sound of the music to reach from the musicians (who are in the front) to the rear end of the column. Thus the length of the column is
$$l = vt = (343\,\text{m/s})(0.5\,\text{s}) = 1.7 \times 10^2\ \text{m} \ .$$

5. If d is the distance from the location of the earthquake to the seismograph and v_s is the speed of the S waves then the time for these waves to reach the seismograph is $t_s = d/v_s$. Similarly, the time for P waves to reach the seismograph is $t_p = d/v_p$. The time delay is $\Delta t = (d/v_s) - (d/v_p) = d(v_p - v_s)/v_s v_p$, so
$$d = \frac{v_s v_p\,\Delta t}{(v_p - v_s)} = \frac{(4.5\,\text{km/s})(8.0\,\text{km/s})(3.0\,\text{min})(60\,\text{s/min})}{8.0\,\text{km/s} - 4.5\,\text{km/s}} = 1900\ \text{km} \ .$$
We note that values for the speeds were substituted as given, in km/s, but that the value for the time delay was converted from minutes to seconds.

6. (a) The time it takes for sound to travel in air is $t_a = L/v$, while it takes $t_m = L/V$ for the sound to travel in the metal. Thus
$$t = t_a - t_m = \frac{L}{v} - \frac{L}{V} = \frac{L(V-v)}{Vv} \ .$$
(b) Using the values indicated (see Table 18-1), we obtain
$$L = \frac{t}{1/v - 1/V} = \frac{1.00\,\mathrm{s}}{1/(343\,\mathrm{m/s}) - 1/(5941\,\mathrm{m/s})} = 364\,\mathrm{m} \ .$$

7. Let t_f be the time for the stone to fall to the water and t_s be the time for the sound of the splash to travel from the water to the top of the well. Then, the total time elapsed from dropping the stone to hearing the splash is $t = t_f + t_s$. If d is the depth of the well, then the kinematics of free fall gives $d = \frac{1}{2}gt_f^2$, or $t_f = \sqrt{2d/g}$. The sound travels at a constant speed v_s, so $d = v_s t_s$, or $t_s = d/v_s$. Thus the total time is $t = \sqrt{2d/g} + d/v_s$. This equation is to be solved for d. Rewrite it as $\sqrt{2d/g} = t - d/v_s$ and square both sides to obtain $2d/g = t^2 - 2(t/v_s)d + (1/v_s^2)d^2$. Now multiply by gv_s^2 and rearrange to get $gd^2 - 2v_s(gt + v_s)d + gv_s^2t^2 = 0$. This is a quadratic equation for d. Its solutions are
$$d = \frac{2v_s(gt+v_s) \pm \sqrt{4v_s^2(gt+v_s)^2 - 4g^2v_s^2t^2}}{2g} \ .$$
The physical solution must yield $d = 0$ for $t = 0$, so we take the solution with the negative sign in front of the square root. Once values are substituted the result $d = 40.7\,\mathrm{m}$ is obtained.

8. At $f = 20\,\mathrm{Hz}$,
$$\lambda = \frac{v}{f} = \frac{343\,\mathrm{m/s}}{20\,\mathrm{Hz}} = 17 \ \mathrm{m} \ ,$$
and at $f = 20\,\mathrm{kHz}$,
$$\lambda = \frac{v}{f} = \frac{343\,\mathrm{m/s}}{20 \times 10^3\,\mathrm{Hz}} = 1.7 \times 10^{-2} \ \mathrm{m} \ .$$

9. (a) Using $\lambda = v/f$, where v is the speed of sound in air and f is the frequency, we find
$$\lambda = \frac{343\,\mathrm{m/s}}{4.5 \times 10^6\,\mathrm{Hz}} = 7.62 \times 10^{-5} \ \mathrm{m} \ .$$
(b) Now, $\lambda = v/f$, where v is the speed of sound in tissue. The frequency is the same for air and tissue. Thus $\lambda = (1500\,\mathrm{m/s})/(4.5 \times 10^6\,\mathrm{Hz}) = 3.33 \times 10^{-4}\,\mathrm{m}$.

10. (a) Since $\lambda = 24\,\mathrm{cm}$, the wave speed is $v = \lambda f = (0.24\mathrm{m})(25\,\mathrm{Hz}) = 6.0\,\mathrm{m/s}$.
(b) With x in centimeters and t in seconds, the equation for the wave is
$$y = A\sin[2\pi(x/\lambda + ft)] = (0.30\,\mathrm{cm})\sin\left(\frac{\pi}{12}x + 50\pi t\right) \ .$$

11. (a) The amplitude of a sinusoidal wave is the numerical coefficient of the sine (or cosine) function: $p_m = 1.50$ Pa.
(b) From the theory presented in Ch. 17, we identify $k = 0.9\pi$ and $\omega = 315\pi$ (in SI units), which leads to $f = \omega/2\pi = 158$ Hz.
(c) We also obtain $\lambda = 2\pi/k = 2.22$ m.
(d) The speed of the wave is $v = \omega/k = 350$ m/s.

12. It is useful to study Sample Problem 18-3 before working this problem. We label the two point sources 1 and 2 and assume they are on the x axis (a distance $D = 2\lambda$ apart). When we refer to the circle of large radius, we are assuming that a line drawn from source 1 to a point on the circle and a line drawn to it from source 2 are approximately parallel (and thus both at angle θ measured from the y axis). In terms of the theory developed in §18-4, we find that the phase difference at P (on the large circle of radius R) for the two waves emitted from 1 and 2 is

$$\Delta\phi \approx \frac{2\pi\Delta x}{\lambda} = \frac{2\pi D\sin\theta}{\lambda} = 4\pi\sin\theta\ .$$

(a) For maximum signal, we set $\Delta\phi = 2m\pi$ ($m = 0, \pm 1, \pm 2, \ldots$) to obtain $\sin\theta = m/2$. Thus we get a total of 8 possible values of θ between 0 and 2π, given by $\theta = 0,\ \sin^{-1}(1/2) = 30°,\ \sin^{-1}(1) = 90°$ and (using symmetry properties of the sine function) $150°, 180°, 210°, 270°$, and $330°$.

(b) Since there must be a mininum in between two successive maxima, the total number of minima is also eight.

13. Let L_1 be the distance from the closer speaker to the listener. The distance from the other speaker to the listener is $L_2 = \sqrt{L_1^2 + d^2}$, where d is the distance between the speakers. The phase difference at the listener is $\phi = 2\pi(L_2 - L_1)/\lambda$, where λ is the wavelength.

(a) For a minimum in intensity at the listener, $\phi = (2n+1)\pi$, where n is an integer. Thus $\lambda = 2(L_2 - L_1)/(2n+1)$. The frequency is

$$f = \frac{v}{\lambda} = \frac{(2n+1)v}{2\left(\sqrt{L_1^2+d^2} - L_1\right)} = \frac{(2n+1)(343\,\text{m/s})}{2\left(\sqrt{(3.75\,\text{m})^2 + (2.00\,\text{m})^2} - 3.75\,\text{m}\right)} = (2n+1)(343\,\text{Hz})\ .$$

Now $20,000/343 = 58.3$, so $2n+1$ must range from 0 to 57 for the frequency to be in the audible range. This means n ranges from 1 to 28 and $f = 1029$, 1715, ..., 19550 Hz.

(b) For a maximum in intensity at the listener, $\phi = 2n\pi$, where n is any positive integer. Thus $\lambda = (1/n)\left(\sqrt{L_1^2+d^2} - L_1\right)$ and

$$f = \frac{v}{\lambda} = \frac{nv}{\sqrt{L_1^2+d^2} - L_1} = \frac{n(343\,\text{m/s})}{\sqrt{(3.75\,\text{m})^2 + (2.00\,\text{m})^2} - 3.75\,\text{m}} = n(686\,\text{Hz})\ .$$

Since $20,000/686 = 29.2$, n must be in the range from 1 to 29 for the frequency to be audible and $f = 686$, 1372, ..., 19890 Hz.

14. Let the separation between the point and the two sources (labeled 1 and 2) be x_1 and x_2, respectively. Then the phase difference is

$$\begin{aligned}\Delta\phi &= \phi_1 - \phi_2 = 2\pi\left(\frac{x_1}{\lambda} + ft\right) - 2\pi\left(\frac{x_2}{\lambda} + ft\right) = \frac{2\pi(x_1 - x_2)}{\lambda} \\ &= \frac{2\pi(4.40\,\text{m} - 4.00\,\text{m})}{(330\,\text{m/s})/540\,\text{Hz}} = 4.12\ \text{rad}\ .\end{aligned}$$

15. (a) Building on the theory developed in $\S 18-4$, we set $\Delta L/\lambda = \frac{1}{2}$(odd numbers) in order to have destructive interference. Since $v = f\lambda$, we can write this in terms of frequency:

$$f = \frac{(\text{odd number})v}{2\Delta L} = \begin{cases} 143\,\text{Hz} & \text{for } n = 1 \\ 429\,\text{Hz} & \text{for } n = 3 \\ 715\,\text{Hz} & \text{for } n = 5 \end{cases}$$

where we have used $v = 343$ m/s (note the remarks made in the textbook at the beginning of the exercises and problems section) and $\Delta L = 19.5 - 18.3 = 1.2$ m.

(b) Now we set $\Delta L/\lambda = \frac{1}{2}$(even numbers) – which can be written more simply as "(all integers)" – in order to establish constructive interference. Thus,

$$f = \frac{(\text{integer})v}{\Delta L} = \begin{cases} 286\,\text{Hz} & \text{for } n = 1 \\ 572\,\text{Hz} & \text{for } n = 2 \\ 858\,\text{Hz} & \text{for } n = 3 \end{cases} .$$

16. At the location of the detector, the phase difference between the wave which traveled straight down the tube and the other one which took the semi-circular detour is

$$\Delta\phi = k\Delta d = \frac{2\pi}{\lambda}(\pi r - 2r) .$$

For $r = r_{\text{min}}$ we have $\Delta\phi = \pi$, which is the smallest phase difference for a destructive interference to occur. Thus

$$r_{\text{min}} = \frac{\lambda}{2(\pi - 2)} = \frac{40.0\,\text{cm}}{2(\pi - 2)} = 17.5 \text{ cm} .$$

17. The intensity is the rate of energy flow per unit area perpendicular to the flow. The rate at which energy flows across every sphere centered at the source is the same, regardless of the sphere radius, and is the same as the power output of the source. If P is the power output and I is the intensity a distance r from the source, then $P = IA = 4\pi r^2 I$, where A $(= 4\pi r^2)$ is the surface area of a sphere of radius r. Thus $P = 4\pi(2.50\,\text{m})^2(1.91 \times 10^{-4}\,\text{W/m}^2) = 1.50 \times 10^{-2}\,\text{W}$.

18. (a) Since intensity is power divided by area, and for an isotropic source the area may be written $A = 4\pi r^2$ (the area of a sphere), then we have

$$I = \frac{P}{A} = \frac{1.0\,\text{W}}{4\pi(1.0\,\text{m})^2} = 0.080 \text{ W/m}^2 .$$

(b) This calculation may be done exactly as shown in part (a) (but with $r = 2.5$ m instead of $r = 1.0$ m), or it may be done by setting up a ratio. We illustrate the latter approach. Thus,

$$\frac{I'}{I} = \frac{P/4\pi(r')^2}{P/4\pi r^2} = \left(\frac{r}{r'}\right)^2$$

leads to $I' = (0.080\,\text{W/m}^2)(1/2.5)^2 = 0.013\,\text{W/m}^2$.

19. The intensity is given by $I = \frac{1}{2}\rho v \omega^2 s_m^2$, where ρ is the density of air, v is the speed of sound in air, ω is the angular frequency, and s_m is the displacement amplitude for the sound wave. Replace ω with $2\pi f$ and solve for s_m:

$$s_m = \sqrt{\frac{I}{2\pi^2 \rho v f^2}} = \sqrt{\frac{1.00 \times 10^{-6}\,\text{W/m}^2}{2\pi^2(1.21\,\text{kg/m}^3)(343\,\text{m/s})(300\,\text{Hz})^2}} = 3.68 \times 10^{-8} \text{ m} .$$

20. Sample Problem 18-5 shows that a decibel difference $\Delta\beta$ is directly related to an intensity ratio (which we write as $\mathcal{R} = I'/I$). Thus,

$$\Delta\beta = 10\log(\mathcal{R}) \implies \mathcal{R} = 10^{\Delta\beta/10} = 10^{0.1} = 1.26 .$$

21. (a) Let I_1 be the original intensity and I_2 be the final intensity. The original sound level is $\beta_1 = (10\,\text{dB})\log(I_1/I_0)$ and the final sound level is $\beta_2 = (10\,\text{dB})\log(I_2/I_0)$, where I_0 is the reference intensity. Since $\beta_2 = \beta_1 + 30\,\text{dB}$, $(10\,\text{dB})\log(I_2/I_0) = (10\,\text{dB})\log(I_1/I_0) + 30\,\text{dB}$, or $(10\,\text{dB})\log(I_2/I_0) - (10\,\text{dB})\log(I_1/I_0) = 30\,\text{dB}$. Divide by 10 dB and use $\log(I_2/I_0) - \log(I_1/I_0) = \log(I_2/I_1)$ to obtain $\log(I_2/I_1) = 3$. Now use each side as an exponent of 10 and recognize that $10^{\log(I_2/I_1)} = I_2/I_1$. The result is $I_2/I_1 = 10^3$. The intensity is increased by a factor of 1000.

(b) The pressure amplitude is proportional to the square root of the intensity so it is increased by a factor of $\sqrt{1000} = 32$.

22. (a) The intensity is given by $I = P/4\pi r^2$ when the source is "point-like." Therefore, at $r = 3.00$ m,

$$I = \frac{1.00 \times 10^{-6}\,\mathrm{W}}{4\pi(3.00\,\mathrm{m})^2} = 8.84 \times 10^{-9}\ \mathrm{W/m^2}\ .$$

(b) The sound level there is

$$\beta = 10\ \log\left(\frac{8.84 \times 10^{-9}\,\mathrm{W/m^2}}{1.00 \times 10^{-12}\,\mathrm{W/m^2}}\right) = 39.5\,\mathrm{dB}\ .$$

23. (a) The intensity is given by $I = \frac{1}{2}\rho v \omega^2 s_m^2$, where ρ is the density of the medium, v is the speed of sound, ω is the angular frequency, and s_m is the displacement amplitude. The displacement and pressure amplitudes are related by $\Delta p_m = \rho v \omega s_m$, so $s_m = \Delta p_m/\rho v \omega$ and $I = (\Delta p_m)^2/2\rho v$. For waves of the same frequency the ratio of the intensity for propagation in water to the intensity for propagation in air is

$$\frac{I_w}{I_a} = \left(\frac{\Delta p_{mw}}{\Delta p_{ma}}\right)^2 \frac{\rho_a v_a}{\rho_w v_w}\ ,$$

where the subscript a denotes air and the subscript w denotes water. Since $I_a = I_w$,

$$\frac{\Delta p_{mw}}{\Delta p_{ma}} = \sqrt{\frac{\rho_w v_w}{\rho_a v_a}} = \sqrt{\frac{(0.998 \times 10^3\,\mathrm{kg/m^3})(1482\,\mathrm{m/s})}{(1.21\,\mathrm{kg/m^3})(343\,\mathrm{m/s})}} = 59.7\ .$$

The speeds of sound are given in Table 18–1 and the densities are given in Table 15–1.

(b) Now, $\Delta p_{mw} = \Delta p_{ma}$, so

$$\frac{I_w}{I_a} = \frac{\rho_a v_a}{\rho_w v_w} = \frac{(1.21\,\mathrm{kg/m^3})(343\,\mathrm{m/s})}{(0.998 \times 10^3\,\mathrm{kg/m^3})(1482\,\mathrm{m/s})} = 2.81 \times 10^{-4}\ .$$

24. Since the power of the sound emitted from a section of the source with unit length is related to I by $P = IA = 2\pi r I(r)$, then we have $I(r) = P/(2\pi r) \propto r^{-1}$. And since $s_m \propto \sqrt{I}$ (by Eq. 18-27), then the fact that $I \propto r^{-1}$ in this situation leads to $s_m \propto r^{-1/2}$.

25. (a) We take the wave to be a plane wave and consider a region formed by the surface of a rectangular solid, with two plane faces of area A perpendicular to the direction of travel and separated by a distance d, along the direction of travel. The energy contained in this region is $U = uAd$. If the wave speed is v then all the energy passes through one end of the region in time $t = d/v$. The energy passing through per unit time is $U/t = uAdv/d = uvA$. The intensity is the energy passing through per unit time, per unit area, or $I = U/tA = uv$.

(b) The power output P of the source equals the rate at which energy crosses the surface of any sphere centered at the source. It is related to the intensity I a distance r away by $P = AI = 4\pi r^2 I$, where A $(= 4\pi r^2)$ is the surface area of a sphere of radius r. Substitute $I = uv$ to obtain $P = 4\pi r^2 uv$, then solve for u:

$$u = \frac{P}{4\pi r^2 v} = \frac{50,000\,\mathrm{W}}{4\pi(480 \times 10^3\,\mathrm{m})^2(3.00 \times 10^8\,\mathrm{m/s})} = 5.76 \times 10^{-17}\ \mathrm{J/m^3}\ .$$

26. We use $\Delta\beta_{12} = \beta_1 - \beta_2 = (10\,\mathrm{dB})\log(I_1/I_2)$.

(a) Since $\Delta\beta_{12} = (10\,\mathrm{dB})\log(I_1/I_2) = 37\,\mathrm{dB}$, we get $I_1/I_2 = 10^{37\,\mathrm{dB}/10\,\mathrm{dB}} = 10^{3.7} = 5.0 \times 10^3$.

(b) Since $\Delta p_m \propto s_m \propto \sqrt{I}$, we have $\Delta p_{m\,1}/\Delta p_{m\,2} = \sqrt{I_1/I_2} = \sqrt{5.0 \times 10^3} = 71$.

(c) The displacement amplitude ratio is $s_{m\,1}/s_{m\,2} = \sqrt{I_1/I_2} = 71$.

27. (a) Let P be the power output of the source. This is the rate at which energy crosses the surface of any sphere centered at the source and is therefore equal to the product of the intensity I at the sphere surface and the area of the sphere. For a sphere of radius r, $P = 4\pi r^2 I$ and $I = P/4\pi r^2$. The intensity is proportional to the square of the displacement amplitude s_m. If we write $I = Cs_m^2$, where C is a constant of proportionality, then $Cs_m^2 = P/4\pi r^2$. Thus $s_m = \sqrt{P/4\pi r^2 C} = \left(\sqrt{P/4\pi C}\right)(1/r)$. The displacement amplitude is proportional to the reciprocal of the distance from the source. We take the wave to be sinusoidal. It travels radially outward from the source, with points on a sphere of radius r in phase. If ω is the angular frequency and k is the angular wave number then the time dependence is $\sin(kr - \omega t)$. Letting $b = \sqrt{P/4\pi C}$, the displacement wave is then given by

$$s(r,t) = \sqrt{\frac{P}{4\pi C}}\,\frac{1}{r}\sin(kr - \omega t) = \frac{b}{r}\sin(kr - \omega t)\ .$$

(b) Since s and r both have dimensions of length and the trigonometric function is dimensionless, the dimensions of b must be length squared.

28. (a) The intensity is

$$I = \frac{P}{4\pi r^2} = \frac{30.0\,\mathrm{W}}{(4\pi)(200\,\mathrm{m})^2} = 5.97 \times 10^{-5}\ \mathrm{W/m^2}\ .$$

(b) Let $A\,(= 0.750\,\mathrm{cm^2})$ be the cross-sectional area of the microphone. Then the power intercepted by the microphone is

$$P' = IA = 0 = \left(6.0 \times 10^{-5}\,\mathrm{W/m^2}\right)\left(0.750\,\mathrm{cm^2}\right)\left(10^{-4}\,\mathrm{m^2/cm^2}\right) = 4.48 \times 10^{-9}\ \mathrm{W}\ .$$

29. (a) When the right side of the instrument is pulled out a distance d the path length for sound waves increases by $2d$. Since the interference pattern changes from a minimum to the next maximum, this distance must be half a wavelength of the sound. So $2d = \lambda/2$, where λ is the wavelength. Thus $\lambda = 4d$ and, if v is the speed of sound, the frequency is $f = v/\lambda = v/4d = (343\,\mathrm{m/s})/4(0.0165\,\mathrm{m}) = 5.2 \times 10^3\,\mathrm{Hz}$.

(b) The displacement amplitude is proportional to the square root of the intensity (see Eq. 18–27). Write $\sqrt{I} = Cs_m$, where I is the intensity, s_m is the displacement amplitude, and C is a constant of proportionality. At the minimum, interference is destructive and the displacement amplitude is the difference in the amplitudes of the individual waves: $s_m = s_{SAD} - s_{SBD}$, where the subscripts indicate the paths of the waves. At the maximum, the waves interfere constructively and the displacement amplitude is the sum of the amplitudes of the individual waves: $s_m = s_{SAD} + s_{SBD}$. Solve $\sqrt{100} = C(s_{SAD} - s_{SBD})$ and $\sqrt{900} = C(s_{SAD} + s_{SBD})$ for s_{SAD} and s_{SBD}. Add the equations to obtain $s_{SAD} = (\sqrt{100} + \sqrt{900})/2C = 20/C$, then subtract them to obtain $s_{SBD} = (\sqrt{900} - \sqrt{100})/2C = 10/C$. The ratio of the amplitudes is $s_{SAD}/s_{SBD} = 2$.

(c) Any energy losses, such as might be caused by frictional forces of the walls on the air in the tubes, result in a decrease in the displacement amplitude. Those losses are greater on path B since it is longer than path A.

30. (a) From Eq. 17-53, we have

$$f = \frac{nv}{2L} = \frac{(1)(250\,\mathrm{m/s})}{2(0.150\,\mathrm{m})} = 833\ \mathrm{Hz}\ .$$

(b) The frequency of the wave on the string is the same as the frequency of the sound wave it produces during its vibration. Consequently, the wavelength in air is

$$\lambda = \frac{v_{\mathrm{sound}}}{f} = \frac{348\,\mathrm{m/s}}{833\,\mathrm{Hz}} = 0.418\ \mathrm{m}\ .$$

31. At the beginning of the exercises and problems section in the textbook, we are told to assume $v_{\text{sound}} = 343$ m/s unless told otherwise. The second harmonic of pipe A is found from Eq. 18-39 with $n = 2$ and $L = L_A$, and the third harmonic of pipe B is found from Eq. 18-41 with $n = 3$ and $L = L_B$. Since these frequencies are equal, we have

$$\frac{2v_{\text{sound}}}{2L_A} = \frac{3v_{\text{sound}}}{4L_B} \implies L_B = \frac{3}{4}L_A .$$

   (a) Since the fundamental frequency for pipe A is 300 Hz, we immediately know that the second harmonic has $f = 2(300) = 600$ Hz. Using this, Eq. 18-39 gives $L_A = (2)(343)/2(600) = 0.572$ m.

   (b) The length of pipe B is $L_B = \frac{3}{4}L_A = 0.429$ m.

32. The frequency is $f = 686$ Hz. At the beginning of the exercises and problems section in the textbook, we are told to assume $v_{\text{sound}} = 343$ m/s unless told otherwise. If L is the length of the air-column (so that the water height is $h = 1.00\,\text{m} - L$) then Eq. 18-41 leads to

$$L = \frac{nv}{4f} \implies h = 1.00 - L = \begin{cases} 0.875\,\text{m} & \text{for } n = 1 \\ 0.625\,\text{m} & \text{for } n = 3 \\ 0.375\,\text{m} & \text{for } n = 5 \\ 0.125\,\text{m} & \text{for } n = 7 \end{cases} .$$

33. (a) When the string (fixed at both ends) is vibrating at its lowest resonant frequency, exactly one-half of a wavelength fits between the ends. Thus, $\lambda = 2L$. We obtain $v = f\lambda = 2Lf = 2(0.220\,\text{m})(920\,\text{Hz}) = 405\,\text{m/s}$.

   (b) The wave speed is given by $v = \sqrt{\tau/\mu}$, where τ is the tension in the string and μ is the linear mass density of the string. If M is the mass of the (uniform) string, then $\mu = M/L$. Thus $\tau = \mu v^2 = (M/L)v^2 = \left[(800 \times 10^{-6}\,\text{kg})/(0.220\,\text{m})\right](405\,\text{m/s})^2 = 596\,\text{N}$.

   (c) The wavelength is $\lambda = 2L = 2(0.220\,\text{m}) = 0.440\,\text{m}$.

   (d) The frequency of the sound wave in air is the same as the frequency of oscillation of the string. The wavelength is different because the wave speed is different. If v_a is the speed of sound in air the wavelength in air is $\lambda_a = v_a/f = (343\,\text{m/s})/(920\,\text{Hz}) = 0.373\,\text{m}$.

34. (a) The fundamental frequency of a string can be increased (for instance, going from A up to C) by shortening the length of the vibrating portion of the string. When the note C is played, the vibrating length is (using Eq. 17-53)

$$\frac{f'}{f} = \frac{nv/2L'}{nv/2L} \implies L = (30\,\text{cm})\left(\frac{440\,\text{Hz}}{528\,\text{Hz}}\right) = 25\text{ cm} .$$

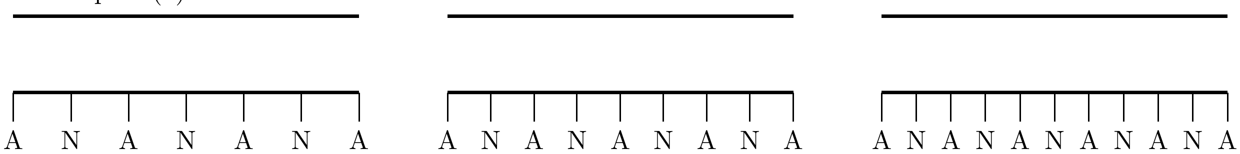
   Thus, one should place his finger a distance of $30\,\text{cm} - 25\,\text{cm} = 5\,\text{cm}$ from one end of the string.

   (b) Since $v = f\lambda$, the ratio of wavelengths is the reciprocal of the frequency ratio, so that $\lambda_{\text{A}}/\lambda_{\text{C}} = 528\,\text{Hz}/440\,\text{Hz} = 1.2$.

   (c) This has the same answer as part (b), due to the fact that the frequencies are the same on the string and the air (transmitting a signal from one medium to another does not generally change its frequency. Both wavelengths are larger (*much* larger) in the air than on the string, but their ratio (due to $v = f\lambda$) remains the same.

35. (a) Since the pipe is open at both ends there are displacement antinodes at both ends and an integer number of half-wavelengths fit into the length of the pipe. If L is the pipe length and λ is the wavelength then $\lambda = 2L/n$, where n is an integer. If v is the speed of sound then the resonant frequencies are given by $f = v/\lambda = nv/2L$. Now $L = 0.457\,\text{m}$, so $f = n(344\,\text{m/s})/2(0.457\,\text{m}) = 376.4n\,\text{Hz}$. To find the resonant frequencies that lie between 1000 Hz and 2000 Hz, first set $f = 1000\,\text{Hz}$ and solve for n, then set $f = 2000\,\text{Hz}$ and again solve for n. You should get 2.66 and 5.32. This means $n = 3$, 4, and 5 are the appropriate values of n. For $n = 3$, $f = 3(376.4\,\text{Hz}) = 1129\,\text{Hz}$; for $n = 4$, $f = 4(376.4\,\text{Hz}) = 1526\,\text{Hz}$; and for $n = 5$, $f = 5(376.4\,\text{Hz}) = 1882\,\text{Hz}$.

(b) For any integer value of n the displacement has n nodes and $n+1$ antinodes, counting the ends. The nodes (N) and antinodes (A) are marked on the diagrams below for the three resonances found in part (a).



$n = 3$ $n = 4$ $n = 5$

36. (a) Using Eq. 17-53 with $n = 1$ (for the fundamental mode of vibration), we obtain

$$\frac{f'}{f} = \frac{(1)v/2L'}{(1)v/2L} = \frac{L}{L'}$$

so that $f' = rf$ (where r is a pure number) implies $L' = L/r$. Thus, the amount if must be shortened is $l = \Delta L = L - L' = L(1 - 1/r)$.

(b) With $L = 80$ cm and $r = 1.2$, this yields $l = 13$ cm.

(c) Since $v = f\lambda$, the ratio of wavelengths is the reciprocal of the ratio of frequencies: $\lambda'/\lambda = f/f' = 1/1.2 = 5/6$. This ratio applies to the wavelength ratio for the vibrating string and also for the wavelength ratio for the emitted sound waves (due to the fact that the frequency of a signal is generally not altered when transmitted from one medium to another).

37. The top of the water is a displacement node and the top of the well is a displacement antinode. At the lowest resonant frequency exactly one-fourth of a wavelength fits into the depth of the well. If d is the depth and λ is the wavelength then $\lambda = 4d$. The frequency is $f = v/\lambda = v/4d$, where v is the speed of sound. The speed of sound is given by $v = \sqrt{B/\rho}$, where B is the bulk modulus and ρ is the density of air in the well. Thus $f = (1/4d)\sqrt{B/\rho}$ and

$$d = \frac{1}{4f}\sqrt{\frac{B}{\rho}} = \left[\frac{1}{4(7.00\,\text{Hz})}\right]\sqrt{\frac{1.33\times10^5\,\text{Pa}}{1.10\,\text{kg/m}^3}} = 12.4\text{ m} .$$

38. (a) Using Eq. 18-39 with $n = 1$ (for the fundamental mode of vibration) and 343 m/s for the speed of sound, we obtain

$$f = \frac{(1)v_{\text{sound}}}{4L_{\text{tube}}} = \frac{343\,\text{m/s}}{4(1.20\,\text{m})} = 71.5\text{ Hz} .$$

(b) For the wire (using Eq. 17-53) we have

$$f' = \frac{nv_{\text{wire}}}{2L_{\text{wire}}} = \frac{1}{2L_{\text{wire}}}\sqrt{\frac{\tau}{\mu}}$$

where $\mu = m_{\text{wire}}/L_{\text{wire}}$. Recognizing that $f = f'$ (both the wire and the air in the tube vibrate at the same frequency), we solve this for the tension τ:

$$\tau = (2L_{\text{wire}}f)^2\left(\frac{m_{\text{wire}}}{L_{\text{wire}}}\right) = 4f^2 m_{\text{wire}}L_{\text{wire}} = 4(71.5\,\text{Hz})^2\left(9.60\times10^{-3}\,\text{kg}\right)(0.33\,\text{m}) = 64.8\text{ N} .$$

39. (a) We expect the center of the star to be a displacement node. The star has spherical symmetry and the waves are spherical. If matter at the center moved it would move equally in all directions and this is not possible.

(b) We assume the oscillation is at the lowest resonance frequency. Then, exactly one-fourth of a wavelength fits the star radius. If λ is the wavelength and R is the star radius then $\lambda = 4R$. The frequency is $f = v/\lambda = v/4R$, where v is the speed of sound in the star. The period is $T = 1/f = 4R/v$.

(c) The speed of sound is $v = \sqrt{B/\rho}$, where B is the bulk modulus and ρ is the density of stellar material. The radius is $R = 9.0 \times 10^{-3} R_s$, where R_s is the radius of the Sun (6.96×10^8 m). Thus

$$T = 4R\sqrt{\frac{\rho}{B}} = 4(9.0 \times 10^{-3})(6.96 \times 10^8\,\text{m})\sqrt{\frac{1.0 \times 10^{10}\,\text{kg/m}^3}{1.33 \times 10^{22}\,\text{Pa}}} = 22\ \text{s} .$$

40. We observe that "third lowest ... frequency" corresponds to harmonic number $n = 3$ for a pipe open at both ends. Also, "second lowest ... frequency" corresponds to harmonic number $n = 3$ for a pipe closed at one end.

(a) Since $\lambda = 2L/n$ for pipe A, where $L = 1.2$ m, then $\lambda = 0.80$ m for this mode. The change from node to antinode requires a distance of $\lambda/4$ so that every increment of 0.20 m along the x axis involves a switch between node and antinode. Since the opening is a displacement antinode, then the locations for displacement nodes are at $x = 0.20$ m, $x = 0.60$ m, and $x = 1.0$ m.

(b) The waves in both pipes have the same wavespeed (sound in air) and frequency, so the standing waves in both pipes have the same wavelength (0.80 m). Therefore, using Eq. 18-38 for pipe B, we find $L = 3\lambda/4 = 0.60$ m.

(c) Using $v = 343$ m/s, we find $f_3 = v/\lambda = 429$ Hz. Now, we find the fundamental resonant frequency by dividing by the harmonic number, $f_1 = f_3/3 = 143$ Hz.

41. The string is fixed at both ends so the resonant wavelengths are given by $\lambda = 2L/n$, where L is the length of the string and n is an integer. The resonant frequencies are given by $f = v/\lambda = nv/2L$, where v is the wave speed on the string. Now $v = \sqrt{\tau/\mu}$, where τ is the tension in the string and μ is the linear mass density of the string. Thus $f = (n/2L)\sqrt{\tau/\mu}$. Suppose the lower frequency is associated with $n = n_1$ and the higher frequency is associated with $n = n_1 + 1$. There are no resonant frequencies between so you know that the integers associated with the given frequencies differ by 1. Thus $f_1 = (n_1/2L)\sqrt{\tau/\mu}$ and

$$f_2 = \frac{n_1+1}{2L}\sqrt{\frac{\tau}{\mu}} = \frac{n_1}{2L}\sqrt{\frac{\tau}{\mu}} + \frac{1}{2L}\sqrt{\frac{\tau}{\mu}} = f_1 + \frac{1}{2L}\sqrt{\frac{\tau}{\mu}} .$$

This means $f_2 - f_1 = (1/2L)\sqrt{\tau/\mu}$ and

$$\begin{aligned}\tau &= 4L^2\mu(f_2 - f_1)^2 \\ &= 4(0.300\,\text{m})^2(0.650 \times 10^{-3}\,\text{kg/m})(1320\,\text{Hz} - 880\,\text{Hz})^2 \\ &= 45.3\ \text{N} .\end{aligned}$$

42. Let the period be T. Then the beat frequency is $\frac{1}{T} - 440\,\text{Hz} = 4.00\,\text{beats/s}$. Therefore, $T = 2.25 \times 10^{-3}$ s. The string that is "too tightly stretched" has the higher tension and thus the higher (fundamental) frequency.

43. Since the beat frequency equals the difference between the frequencies of the two tuning forks, the frequency of the first fork is either 381 Hz or 387 Hz. When mass is added to this fork its frequency decreases (recall, for example, that the frequency of a mass-spring oscillator is proportional to $1/\sqrt{m}$). Since the beat frequency also decreases the frequency of the first fork must be greater than the frequency of the second. It must be 387 Hz.

44. (a) The number of different ways of picking up a pair of tuning forks out of a set of five is $5!/(2!3!) = 10$. For each of the pairs selected, there will be one beat frequency. If these frequencies are all different from each other, we get the maximum possible number of 10.

(b) First, we note that the minimum number occurs when the frequencies of these forks, labeled 1 through 5, increase in equal increments: $f_n = f_1 + n\Delta f$, where $n = 2, 3, 4, 5$. Now, there are only 4 different beat frequencies: $f_{\text{beat}} = n\Delta f$, where $n = 1, 2, 3, 4$.

45. Each wire is vibrating in its fundamental mode so the wavelength is twice the length of the wire ($\lambda = 2L$) and the frequency is $f = v/\lambda = (1/2L)\sqrt{\tau/\mu}$, where v $(= \sqrt{\tau/\mu})$ is the wave speed for the wire, τ is the tension in the wire, and μ is the linear mass density of the wire. Suppose the tension in one wire is τ and the oscillation frequency of that wire is f_1. The tension in the other wire is $\tau + \Delta\tau$ and its frequency is f_2. You want to calculate $\Delta\tau/\tau$ for $f_1 = 600\,\text{Hz}$ and $f_2 = 606\,\text{Hz}$. Now, $f_1 = (1/2L)\sqrt{\tau/\mu}$ and $f_2 = (1/2L)\sqrt{(\tau + \Delta\tau)/\mu}$, so

$$f_2/f_1 = \sqrt{(\tau + \Delta\tau)/\tau} = \sqrt{1 + (\Delta\tau/\tau)}\ .$$

This leads to

$$\Delta\tau/\tau = (f_2/f_1)^2 - 1 = [(606\,\text{Hz})/(600\,\text{Hz})]^2 - 1 = 0.020\ .$$

46. The Doppler effect formula, Eq. 18-47, and its accompanying rule for choosing $\pm$ signs, are discussed in §18-8. Using that notation, we have $v = 343$ m/s, $v_D = v_S = 160000/3600 = 44.4$ m/s, and $f = 500$ Hz. Thus,

$$f' = (500)\left(\frac{343 - 44.4}{343 - 44.4}\right) = 500\,\text{Hz} \quad\Longrightarrow\quad \Delta f = 0\ .$$

47. The detector (the second plane) is moving toward the source (the first plane). This tends to increase the frequency, so we use the plus sign in the numerator of Eq. 18-47. The source is moving away from the detector. This tends to decrease the frequency, so we use the plus sign in the denominator of Eq. 18-47. Thus

$$f' = f\,\frac{v + v_D}{v + v_S} = (16000\,\text{Hz})\left(\frac{343\,\text{m/s} + 250\,\text{m/s}}{343\,\text{m/s} + 200\,\text{m/s}}\right) = 17500\ \text{Hz}\ .$$

48. The Doppler effect formula, Eq. 18-47, and its accompanying rule for choosing $\pm$ signs, are discussed in §18-8. Using that notation, we have $v = 343$ m/s, $v_D = 2.44$ m/s, $f' = 1590$ Hz and $f = 1600$ Hz. Thus,

$$f' = f\left(\frac{v + v_D}{v + v_S}\right) \quad\Longrightarrow\quad v_S = \frac{f}{f'}\,(v + v_D) - v = 4.61\ \text{m/s}\ .$$

49. We use $v_S = r\omega$ (with $r = 0.600$ m and $\omega = 15.0$ rad/s) for the linear speed during circular motion, and Eq. 18-47 for the Doppler effect (where $f = 540$ Hz, and $v = 343$ m/s for the speed of sound).

$$f' = f\left(\frac{v + 0}{v \pm v_S}\right) = \begin{cases} 526\,\text{Hz} & \text{for } + \text{ choice} \\ 555\,\text{Hz} & \text{for } - \text{ choice} \end{cases}$$

50. We are combining two effects: the reception of a moving object (the truck of speed $u = 45.0$ m/s) of waves emitted by a stationary object (the motion detector), and the subsequent emission of those waves by the moving object (the truck) which are picked up by the stationary detector. This could be figured in two steps, but is more compactly computed in one step as shown here:

$$f_{\text{final}} \;=\; f_{\text{initial}}\left(\frac{v + u}{v - u}\right) = (0.150\,\text{MHz})\left(\frac{343\,\text{m/s} + 45\,\text{m/s}}{343\,\text{m/s} - 45\,\text{m/s}}\right) = 0.195\ \text{MHz}\ .$$

51. We denote the speed of the French submarine by u_1 and that of the U.S. sub by u_2.

   (a) The frequency as detected by the U.S. sub is

$$f_1' = f_1\left(\frac{v + u_2}{v - u_1}\right) = (1000\,\text{Hz})\left(\frac{5470 + 70}{5470 - 50}\right) = 1.02 \times 10^3\ \text{Hz}\ .$$

(b) If the French sub were stationary, the frequency of the reflected wave would be $f_r = f_1(v+u_2)/(v-u_2)$. Since the French sub is moving towards the reflected signal with speed u_1, then

$$\begin{aligned} f_r' &= f_r\left(\frac{v+u_1}{v}\right) = f_1\frac{(v+u_1)(v+u_2)}{v(v-u_2)} \\ &= \frac{(1000\,\text{Hz})(5470+50)(5470+70)}{(5470)(5470-70)} \\ &= 1.04\times 10^3\ \text{Hz}\ . \end{aligned}$$

52. We use Eq. 18-47 with $f = 1200$ Hz and $v = 329$ m/s.

(a) In this case, $v_D = 65.8$ m/s and $v_S = 29.9$ m/s, and we choose signs so that f' is larger than f:

$$f' = f\left(\frac{329+65.8}{329-29.9}\right) = 1584\ \text{Hz}\ .$$

(b) The wavelength is $\lambda = v/f' = 0.208$ m.

(c) The wave (of frequency f') "emitted" by the moving reflector (now treated as a "source," so $v_S = 65.8$ m/s) is returned to the detector (now treated as a detector, so $v_D = 29.9$ m/s) and registered as a new frequency f'':

$$f'' = f'\left(\frac{329+29.9}{329-65.8}\right) = 2160\ \text{Hz}\ .$$

(d) This has wavelength $v/f'' = 0.152$ m.

53. In this case, the intruder is moving *away* from the source with a speed u satisfying $u/v \ll 1$. The Doppler shift (with $u = -0.950\,\text{m/s}$) leads to

$$f_{\text{beat}} = |f_r - f_s| \approx \frac{2|u|}{v} f_s = \frac{2(0.95\,\text{m/s})(28.0\,\text{kHz})}{343\,\text{m/s}}) = 155\ \text{Hz}\ .$$

54. As a result of the Doppler effect, the frequency of the reflected sound as heard by the bat is

$$f_r = f'\left(\frac{v+u_{\text{bat}}}{v-u_{\text{bat}}}\right) = (39000\,\text{Hz})\left(\frac{v+v/40}{v-v/40}\right) = 41000\ \text{Hz}\ .$$

55. (a) The expression for the Doppler shifted frequency is

$$f' = f\,\frac{v\pm v_D}{v\mp v_S}\ ,$$

where f is the unshifted frequency, v is the speed of sound, v_D is the speed of the detector (the uncle), and v_S is the speed of the source (the locomotive). All speeds are relative to the air. The uncle is at rest with respect to the air, so $v_D = 0$. The speed of the source is $v_S = 10\,\text{m/s}$. Since the locomotive is moving away from the uncle the frequency decreases and we use the plus sign in the denominator. Thus

$$f' = f\,\frac{v}{v+v_S} = (500.0\,\text{Hz})\left(\frac{343\,\text{m/s}}{343\,\text{m/s}+10.00\,\text{m/s}}\right) = 485.8\ \text{Hz}\ .$$

(b) The girl is now the detector. Relative to the air she is moving with speed $v_D = 10.00\,\text{m/s}$ toward the source. This tends to increase the frequency and we use the plus sign in the numerator. The source is moving at $v_S = 10.00\,\text{m/s}$ away from the girl. This tends to decrease the frequency and we use the plus sign in the denominator. Thus $(v+v_D) = (v+v_S)$ and $f' = f = 500.0\,\text{Hz}$.

(c) Relative to the air the locomotive is moving at $v_S = 20.00\,\mathrm{m/s}$ away from the uncle. Use the plus sign in the denominator. Relative to the air the uncle is moving at $v_D = 10.00\,\mathrm{m/s}$ toward the locomotive. Use the plus sign in the numerator. Thus

$$f' = f\,\frac{v + v_D}{v + v_S} = (500.0\,\mathrm{Hz})\left(\frac{343\,\mathrm{m/s} + 10.00\,\mathrm{m/s}}{343\,\mathrm{m/s} + 20.00\,\mathrm{m/s}}\right) = 486.2\,\mathrm{Hz}\ .$$

(d) Relative to the air the locomotive is moving at $v_S = 20.00\,\mathrm{m/s}$ away from the girl and the girl is moving at $v_D = 20.00\,\mathrm{m/s}$ toward the locomotive. Use the plus signs in both the numerator and the denominator. Thus $(v + v_D) = (v + v_S)$ and $f' = f = 500.0\,\mathrm{Hz}$.

56. The Doppler shift formula, Eq. 18-47, is valid only when both u_S and u_D are measured with respect to a stationary medium (i.e., no wind). To modify this formula in the presence of a wind, we switch to a new reference frame in which there is no wind.

(a) When the wind is blowing from the source to the observer with a speed w, we have $u'_S = u'_D = w$ in the new reference frame that moves together with the wind. Since the observer is now approaching the source while the source is backing off from the observer, we have, in the new reference frame,

$$f' = f\left(\frac{v + u'_D}{v + u'_S}\right) = f\left(\frac{v + w}{v + w}\right) = 2000\ \mathrm{Hz}\ .$$

In other words, there is no Doppler shift.

(b) In this case, all we need to do is to reverse the signs in front of both u'_D and u'_S. The result is that there is still no Doppler shift:

$$f' = f\left(\frac{v - u'_D}{v - u'_S}\right) = f\left(\frac{v - w}{v - w}\right) = 2000\ \mathrm{Hz}\ .$$

In general, there will always be no Doppler shift as long as there is no relative motion between the observer and the source, regardless of whether a wind is present or not.

57. We use Eq. 18-47 with $f = 500$ Hz and $v = 343$ m/s. We choose signs to produce $f' > f$.

(a) The frequency heard in still air is

$$f' = 500\left(\frac{343 + 30.5}{343 - 30.5}\right) = 598\ \mathrm{Hz}\ .$$

(b) In a frame of reference where the air seems still, the velocity of the detector is $30.5 - 30.5 = 0$, and that of the source is $2(30.5)$. Therefore,

$$f' = 500\left(\frac{343 + 0}{343 - 2(30.5)}\right) = 608\ \mathrm{Hz}\ .$$

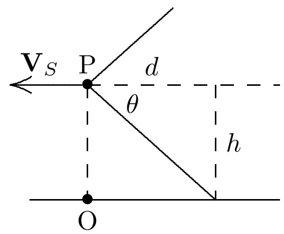
(c) We again pick a frame of reference where the air seems still. Now, the velocity of the source is $30.5 - 30.5 = 0$, and that of the detector is $2(30.5)$. Consequently,

$$f' = 500\left(\frac{343 + 2(30.5)}{343 - 0)}\right) = 589\ \mathrm{Hz}\ .$$

58. The angle is $\sin^{-1}(v/v_s) = sin^{-1}(343/685) = 30°$.

59. (a) The half angle θ of the Mach cone is given by $\sin\theta = v/v_S$, where v is the speed of sound and v_S is the speed of the plane. Since $v_S = 1.5v$, $\sin\theta = v/1.5v = 1/1.5$. This means $\theta = 42°$.

(b) Let h be the altitude of the plane and suppose the Mach cone intersects Earth's surface a distance d behind the plane. The situation is shown on the diagram below, with P indicating the plane and O indicating the observer. The cone angle is related to h and d by $\tan\theta = h/d$, so $d = h/\tan\theta$. The shock wave reaches O in the time the plane takes to fly the distance d: $t = d/v = h/v\tan\theta = (5000\,\text{m})/1.5(331\,\text{m/s})\tan 42° = 11\,\text{s}$.



60. The altitude H and the horizontal distance x for the legs of a right triangle, so we have

$$H = x\tan\theta = v_p t\tan\theta = 1.25vt\sin\theta$$

where v is the speed of sound, v_p is the speed of the plane and

$$\theta = \sin^{-1}\left(\frac{v}{v_p}\right) = \sin^{-1}\left(\frac{v}{1.25v}\right) = 53.1° \ .$$

Thus the altitude is

$$H = x\tan\theta = (1.25)(330\,\text{m/s})(60\,\text{s})(\tan 53.1°) = 3.30 \times 10^4 \text{ m} \ .$$

61. We use $\beta = 10\log(I/I_\text{o})$ with $I_\text{o} = 1 \times 10^{-12}\,\text{W/m}^2$ and $I = P/4\pi r^2$ (an assumption we are asked to make in the problem). We estimate $r \approx 0.3$ m (distance from knuckle to ear) and find

$$P \approx 4\pi(0.3\,\text{m})^2\left(1 \times 10^{-12}\,\text{W/m}^2\right)10^{6.2} = 2 \times 10^{-6} \text{ W} \ .$$

62. (a) Using Eq. 18-39 with $v = 343$ m/s and $n = 1$, we find $f = nv/2L = 86$ Hz for the fundamental frequency in a nasal passage of length $L = 2.0$ m (subject to various assumptions about the nature of the passage as a "bent tube open at both ends").

(b) The sound would be perceptible as *sound* (as opposed to just a general vibration) of very low frequency.

(c) Smaller L implies larger f by the formula cited above. Thus, the female's sound is of higher pitch (frequency).

63. (a) Since $\omega = 2\pi f$, Eq. 18-15 leads to

$$\Delta p_m = v\rho(2\pi f)s_m \quad \Longrightarrow \quad s_m = \frac{1.13 \times 10^{-3}\,\text{Pa}}{2\pi(1665\,\text{Hz})(343\,\text{m/s})(1.21\,\text{kg/m}^3)}$$

which yields $s_m = 0.26$ nm. The nano prefix represents 10^{-9}. We use the speed of sound and air density values given at the beginning of the exercises and problems section in the textbook.

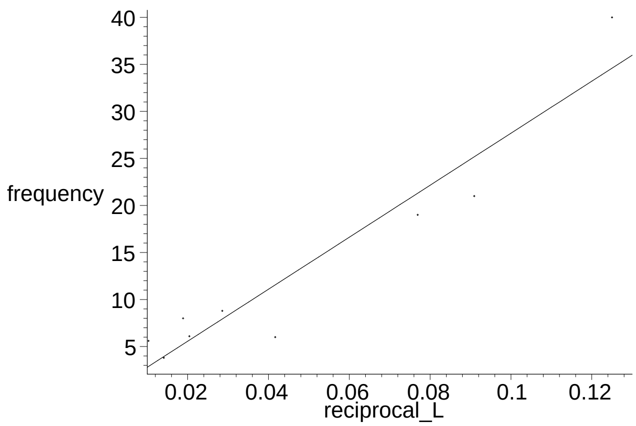
(b) We can plug into Eq. 18-27 or into its equivalent form, rewritten in terms of the pressure amplitude:

$$I = \frac{1}{2}\frac{(\Delta p_m)^2}{\rho v} = \frac{1}{2}\frac{\left(1.13 \times 10^{-3}\,\text{Pa}\right)^2}{(1.21\,\text{kg/m}^3)\,(343\,\text{m/s})} = 1.5 \text{ nW/m}^2 \ .$$

64. We use $\beta = 10\log(I/I_\text{o})$ with $I_\text{o} = 1 \times 10^{-12}\,\text{W/m}^2$ and Eq. 18-27 with $\omega = 2\pi f = 2\pi(260\,\text{Hz})$, $v = 343$ m/s and $\rho = 1.21\,\text{kg/m}^3$.

$$I = I_\text{o}\left(10^{8.5}\right) = \frac{1}{2}\rho v(2\pi f)^2 s_m^2 \quad \Longrightarrow \quad s_m = 7.6 \times 10^{-7} \text{ m} \ .$$

65. The points and the least-squares fit is shown in the graph below. The graph has frequency in Hertz along the vertical axis and $1/L$ in inverse meters along the horizontal axis. The function found by the least squares fit procedure is $f = 276(1/L) + 0.037$. Assuming this fits either the model of an open organ pipe (mathematically similar to a string fixed at both ends) or that of a pipe closed at one end, as discussed in the textbook, then $f = v/2L$ in the former case or $f = v/4L$ in the latter. Thus, if the least-squares slope of 276 fits the first model, then a value of $v = 2(276) = 553$ m/s is implied. In the second model (the pipe with only one end open) we find $v = 4(276) = 1106$ m/s which is more "in the ballpark" of the 1400 m/s value cited in the problem. This suggests that the acoustic resonance involved in this situation is more closely related to the $n = 1$ case of Figure 18-15(b) than to Figure 18-14.



66. The round-trip time is $t = 2L/v$ where we estimate from the chart that the time between clicks is 3 ms. Thus, with $v = 1372$ m/s, we find $L = \frac{1}{2}vt = 2.1$ m.

67. (a) In regions where the speed is constant, it is equal to distance divided by time. Thus, we conclude that the time difference is

$$\Delta t = \left(\frac{L-d}{V} + \frac{d}{V - \Delta V}\right) - \frac{L}{V}$$

where the first term is the travel time through bone and rock and the last term is the expected travel time purely through rock. Solving for d and simplifying, we obtain

$$d = \Delta t\,\frac{V(V - \Delta V)}{\Delta V} \approx \Delta t\,\frac{V^2}{\Delta V}\ .$$

(b) If we estimate $d \approx 10$ cm (as the lower limit of a range that goes up to a diameter of 20 cm), then the above expression (with the numerical values given in the problem) leads to $\Delta t = 0.8\,\mu$s (as the lower limit of a range that goes up to a time difference of $1.6\,\mu$s).

68. (a) Using $m = 7.3 \times 10^7$ kg, the initial gravitational potential energy is $U = mgy = 3.9 \times 10^{11}$ J, where $h = 550$ m. Assuming this converts primarily into kinetic energy during the fall, then $K = 3.9 \times 10^{11}$ J just before impact with the ground. Using instead the mass estimate $m = 1.7 \times 10^8$ kg, we arrive at $K = 9.2 \times 10^{11}$ J.

(b) The process of converting this kinetic energy into other forms of energy (during the impact with the ground) is assumed to take $\Delta t = 0.50$ s (and in the average sense, we take the "power" P to be wave-energy/Δt). With 20% of the energy going into creating a seismic wave, the intensity of the body wave is estimated to be

$$I = \frac{P}{A_{\text{hemisphere}}} = \frac{(0.20)K/\Delta t}{\frac{1}{2}\left(4\pi r^2\right)} = 0.63\ \text{W/m}^2$$

using $r = 200 \times 10^3$ m and the smaller value for K from part (a). Using instead the larger estimate for K, we obtain $I = 1.5$ W/m^2.

(c) The surface area of a cylinder of "height" d is $2\pi rd$, so the intensity of the surface wave is

$$I = \frac{P}{A_{\text{cylinder}}} = \frac{(0.20)K/\Delta t}{(2\pi rd)} = 25 \times 10^3 \text{ W/m}^2$$

using $d = 5.0$ m, $r = 200 \times 10^3$ m and the smaller value for K from part (a). Using instead the larger estimate for K, we obtain $I = 58$ kW/m^2.

(d) Although several factors are involved in determining which seismic waves are most likely to be detected, we observe that on the basis of the above findings we should expect the more intense waves (the surface waves) to be more readily detected.

69. (a) The period is the reciprocal of the frequency: $T = 1/f = 1/(90\,\text{Hz}) = 1.1 \times 10^{-2}$ s.

(b) Using $v = 343$ m/s, we find $\lambda = v/f = 3.8$ m.

70. (a) The blood is moving towards the right (towards the detector), because the Doppler shift in frequency is an *increase*: $\Delta f > 0$.

(b) The reception of the ultrasound by the blood and the subsequent remitting of the signal by the blood back toward the detector is a two step process which may be compactly written as

$$f + \Delta f = f\left(\frac{v + v_x}{v - v_x}\right) \qquad \text{where} \quad v_x = v_{\text{blood}}\cos\theta \ .$$

If we write the ratio of frequencies as $R = (f + \Delta f)/f$, then the solution of the above equation for the speed of the blood is

$$v_{\text{blood}} = \frac{(R-1)v}{(R+1)\cos\theta} = 0.90 \text{ m/s}$$

where $v = 1540$ m/s, $\theta = 20°$, and $R = 1 + 5495/5 \times 10^6$.

(c) We interpret the question as asking how Δf (still taken to be positive, since the detector is in the "forward" direction) changes as the detection angle θ changes. Since larger θ means smaller horizontal component of velocity v_x then we expect Δf to decrease towards zero as θ is increased towards 90°.

71. (a) When the speed is constant, we have $v = d/t$ where $v = 343$ m/s is assumed. Therefore, with $t = \frac{1}{2}(15\,\text{s})$ (the time for sound to travel to the far wall) we obtain $d = (343)(15/2)$ which yields a distance of 2.6 km!

(b) Just as the $\frac{1}{2}$ factor in part (a) was $1/(n+1)$ for $n = 1$ reflection, so also can we write

$$d = (343\,\text{m/s})\left(\frac{15\,\text{s}}{n+1}\right) \quad \Longrightarrow \quad n = \frac{(343)(15)}{d} - 1$$

for multiple reflections (with d in meters). For $d = 25.7$ m, we find $n = 199$.

72. Any phase changes associated with the reflections themselves are rendered inconsequential by the fact that there are an even number of reflections. The additional path length traveled by wave A consists of the vertical legs in the zig-zag path: $2L$. To be (minimally) out of phase means, therefore, that $2L = \lambda/2$ (corresponding to a half-cycle, or 180°, phase difference). Thus, $L = \lambda/4$.

73. The reception of the ultrasound by the structure (moving with speed u) and the subsequent remitting of the signal by the structure back toward the detector is a two step process which may be compactly written as

$$f + \Delta f = f\left(\frac{v + u}{v - u}\right) \quad \Longrightarrow \quad v = \left(\frac{2 + \xi}{\xi}\right)u$$

with $\xi = \Delta f/f$ and where we have assumed that the structure is moving toward the detector. If $u = 1.00 \times 10^{-3}$ m/s and $\xi = 1.30 \times 10^{-6}$, we get $v = 1.54 \times 10^3$ m/s.

74. (a) The wavelength of the sound wave is

$$\lambda = \frac{v}{f} = \frac{343\,\text{m/s}}{1000\,\text{Hz}} = 0.343\ \text{m} .$$

(b) From $\Delta p_m = v^2 \rho k s_m = 2\pi v \rho f s_m$ we find

$$s_m = \frac{\Delta p_m}{2\pi v \rho f} = \frac{10.0\,\text{Pa}}{(2\pi)(343\,\text{m/s})(1.21\,\text{kg/m}^3)(1000\,\text{Hz})} = 3.83 \times 10^{-6}\ \text{m} .$$

(c) The velocity of the particle is the derivative of the sinusoidal wave function with respect to time. Its maximum value is

$$v_\text{m} = 2\pi f s_m = (3.60 \times 10^{-6}\,\text{m})(2\pi)(1000\,\text{Hz}) = 2.41 \times 10^{-2}\ \text{m/s}.$$

(d) From Eq. 18-38, we obtain

$$L = \frac{\lambda}{2} = \frac{0.343\,\text{m}}{2} = 0.172\ \text{m} .$$

75. (a) With the detector stationary, we seek a value of source speed v_S such that the frequency ratio (heard/emitted) is $r = (20\,\text{kHz})/(30\,\text{kHz}) = 2/3$. From the Doppler effect formula, we find

$$f' = f\left(\frac{v+0}{v+v_S}\right) \implies v_S = \left(\frac{1-r}{r}\right) v .$$

If $v = 343$ m/s, we get $v_S = 171.5$ m/s which converts to 617 km/h.

(b) If $r = 20/22$, we find $v_S = 34.3\,\text{m/s} = 123$ km/h.

76. Let the frequencies of sound heard by the person from the left and right forks be f_l and f_r, respectively.

(a) If the speeds of both forks are u, then $f_{l,r} = fv/(v \pm u)$ and

$$\begin{aligned} f_\text{beat} &= |f_r - f_l| = fv\left(\frac{1}{v-u} - \frac{1}{v+u}\right) = \frac{2fuv}{v^2-u^2} \\ &= \frac{2(440\,\text{Hz})(30.0\,\text{m/s})(343\,\text{m/s})}{(343\,\text{m/s})^2 - (30.0\,\text{m/s})^2} \\ &= 77.6\ \text{Hz} . \end{aligned}$$

(b) If the speed of the listener is u, then $f_{l,r} = f(v \pm u)/v$ and

$$f_\text{beat} = |f_l - f_r| = 2f\left(\frac{u}{v}\right) = 2(440\,\text{Hz})\left(\frac{30.0\,\text{m/s}}{343\,\text{m/s}}\right) = 77.0\ \text{Hz} .$$

77. (a) Since the source is moving toward the wall, the frequency of the sound as received at the wall is

$$f' = f\left(\frac{v}{v-v_S}\right) = (440\,\text{Hz})\left(\frac{343\,\text{m/s}}{343\,\text{m/s} - 20.0\,\text{m/s}}\right) = 467\ \text{Hz} .$$

(b) Since the person is moving with a speed u toward the reflected sound with frequency f', the frequency registered at the source is

$$f_r = f'\left(\frac{v+u}{v}\right) = (467\,\text{Hz})\left(\frac{343\,\text{m/s} + 20.0\,\text{m/s}}{343\,\text{m/s}}\right) = 494\ \text{Hz} .$$

78. (a) If the destroyer drifts with the current, then it will detect a signal with frequency f' given by

$$\begin{aligned} f' &= f\left(\frac{v}{v-u_1}\right) \\ &= \frac{(1000\,\text{Hz})(5470\,\text{km/h})}{5470\,\text{km/h}-(75.0\,\text{km/h}-30.0\,\text{km/h})} \\ &= 1008.29 \text{ Hz} . \end{aligned}$$

Thus, $\Delta f = f' - f = 8.29\,\text{Hz}$.

(b) If the destroyer is stationary with respect to the ocean floor, then it is moving at $u_2 = 30.0\,\text{km/h}$ relative to the current. The detected frequency then becomes

$$\begin{aligned} f'' &= f\left(\frac{v+u_2}{v-u_1}\right) = \frac{(1000\,\text{Hz})(5470\,\text{km/h}+30.0\,\text{km/h})}{5470\,\text{km/h}-(75.0\,\text{km/h}-30.0\,\text{km/h})} \\ &= 1013.9 \text{ Hz} . \end{aligned}$$

Thus, $\Delta f = f'' - f = 13.9\,\text{Hz}$.

79. (a) With $r = 10$ m in Eq. 18-28, we have

$$I = \frac{P}{4\pi r^2} \implies P = 10\,\text{W} .$$

(b) Using that value of P in Eq. 18-28 with a new value for r, we obtain

$$I = \frac{P}{4\pi(5.0)^2} = 0.032\ \frac{\text{W}}{\text{m}^2}.$$

Alternatively, a ratio $I'/I = (r/r')^2$ could have been used.

(c) Using Eq. 18-29 with $I = 0.0080$ W/m^2, we have

$$\beta = 10\log\frac{I}{I_0} = 99 \text{ dB}$$

where $I_0 = 1\times 10^{-12}$ W/m^2.

80. (a) We proceed by dividing the (velocity) equation involving the new (fundamental) frequency f' by the equation when the frequency f is 440 Hz to obtain

$$\frac{f'\lambda}{f\lambda} = \sqrt{\frac{\frac{\tau'}{\mu}}{\frac{\tau}{\mu}}} \implies \frac{f'}{f} = \sqrt{\frac{\tau'}{\tau}}$$

where we are making an assumption that the mass-per-unit-length of the string does not change significantly. Thus, with $\tau' = 1.2\tau$, we have $f'/440 = \sqrt{1.2}$. Therefore, $f' = 482$ Hz.

(b) In this case, neither tension nor mass-per-unit-length change, so the wavespeed v is unchanged. Hence,

$$f'\lambda' = f\lambda \implies f'(2L') = f(2L)$$

where Eq. 18-38 with $n = 1$ has been used. Since $L' = \frac{2}{3}L$, we obtain $f' = \frac{3}{2}(440) = 660$ Hz.

81. We find the difference in the two applications of the Doppler formula:

$$f_2 - f_1 = 37 = f\left(\frac{340+25}{340-15} - \frac{340}{340-15}\right) = f\left(\frac{25}{340-15}\right)$$

which leads to $f = 481 \approx 480$ Hz.

82. (a) If point P is infinitely far away, then the small distance d between the two sources is of no consequence (they seem effectively to be the same distance away from P). Thus, there is no perceived phase difference.

(b) Since the sources oscillate in phase, then the situation described in part (a) produces constructive interference.

(c) For finite values of x, the difference in source positions becomes significant. The path lengths for waves to travel from S_1 and S_2 become is now different. We interpret the question as asking for the behavior of the absolute value of the phase difference $|\Delta\phi|$, in which case any change from zero (the answer for part (a)) is certainly an increase.

(d) The path length difference for waves traveling from S_1 and S_2 is

$$\Delta\ell = \sqrt{d^2 + x^2} - x \qquad \text{for} \quad x > 0 \ .$$

The phase difference in "cycles" (in absolute value) is therefore

$$|\Delta\phi| = \frac{\Delta\ell}{\lambda} = \frac{\sqrt{d^2 + x^2} - x}{\lambda} \ .$$

Thus, in terms of λ, the phase difference is identical to the path length difference: $|\Delta\phi| = \Delta\ell > 0$. Consider $\Delta\ell = \lambda/2$. Then $\sqrt{d^2 + x^2} = x + \lambda/2$. Squaring both sides, rearranging, and solving, we find

$$x = \frac{d^2}{\lambda} - \frac{\lambda}{4} \ .$$

In general, if $\Delta\ell = \xi\lambda$ for some multiplier $\xi > 0$, we find

$$x = \frac{d^2}{2\xi\lambda} - \frac{1}{2}\xi\lambda \ .$$

Using $d = 16$ m and $\lambda = 2.0$ m, we insert $\xi = \frac{1}{2}, 1, \frac{3}{2}, 2, \frac{5}{2}$ into this expression and find the respective values (in meters) $x = 128, 63, 41, 30, 23$. Since whole cycle phase differences are equivalent (as far as the wave superposition goes) to zero phase difference, then the $\xi = 1, 2$ cases give constructive interference. A shift of a half-cycle brings "troughs" of one wave in superposition with "crests" of the other, thereby canceling the waves; therefore, the $\xi = \frac{1}{2}, \frac{3}{2}, \frac{5}{2}$ cases produce destructive interference.

83. We use $v = \sqrt{B/\rho}$ to find the bulk modulus B:

$$B = v^2\rho = \left(5.4 \times 10^3 \text{ m/s}\right)^2 \left(2.7 \times 10^3 \text{ kg/m}^3\right) = 7.9 \times 10^{10} \text{ Pa} \ .$$

84. Let ℓ be the length of the rod. Then the time of travel for sound in air (speed v_s) will be $t_s = \ell/v_s$. And the time of travel for compressional waves in the rod (speed v_r) will be $t_r = \ell/v_r$. In these terms, the problem tells us that

$$t_s - t_r = 0.12 \text{ s} = \ell \left(\frac{1}{v_s} - \frac{1}{v_r}\right) \ .$$

Thus, with $v_s = 343$ m/s and $v_r = 15v_s = 5145$ m/s, we find $\ell = 44$ m.

85. (a) The frequency at which $\lambda = D$ is

$$f_1 = \frac{v}{D} = \frac{343 \text{ m/s}}{15.0 \times 10^{-2} \text{ m}} = 2.29 \times 10^3 \text{ Hz} \ ,$$

the frequency at which $\lambda = 10D$ is $f_2 = 2.29 \times 10^2$ Hz, and the frequency at which $\lambda = 0.1D$ is $f_3 = 2.29 \times 10^4$ Hz.

(b) Now, $D' = 30.0\,\text{cm}$. The frequency at which $\lambda = D'$ is $f_1' = v/D' = (343\,\text{m/s})/(30.0 \times 10^{-2}\,\text{m}) = 1.14 \times 10^3\,\text{Hz}$, the frequency at which $\lambda = 10D'$ is $f_2' = 1.14 \times 10^2\,\text{Hz}$, and the frequency at which $\lambda = 0.1D'$ is $f_3' = 1.14 \times 10^4\,\text{Hz}$.

86. When $\phi = 0$ it is clear that the superposition wave has amplitude $2\Delta p_m$. For the other cases, it is useful to write

$$\Delta p_1 + \Delta p_2 = \Delta p_m \left(\sin(\omega t) + \sin(\omega t - \phi)\right) = \left(2\Delta p_m \cos\frac{\phi}{2}\right) \sin\left(\omega t - \frac{\phi}{2}\right) .$$

The factor in front of the sine function gives the amplitude for all cases considered: $\phi = \frac{\pi}{2}, \frac{\pi}{3}, \frac{\pi}{4}$ gives $\Delta p_m\sqrt{2}, \Delta p_m\sqrt{3}, \Delta p_m\sqrt{2+\sqrt{2}}$, respectively.

87. The source being isotropic means $A_{\text{sphere}} = 4\pi r^2$ is used in the intensity definition $I = P/A$, which further implies

$$\frac{I_2}{I_1} = \frac{P/4\pi r_2^2}{P/4\pi r_1^2} = \left(\frac{r_1}{r_2}\right)^2 .$$

(a) With $I_1 = 9.60 \times 10^{-4}$ W/m^2, $r_1 = 6.10$ m, and $r_2 = 30.0$ m, we find $I_2 = 0.960(6.10/30.0)^2 = 3.97 \times 10^{-5}$ W/m^2.

(b) Using Eq. 18-27 with $I_1 = 9.60 \times 10^{-4}$ W/m^2, $\omega = 2\pi(2000\,\text{Hz})$, $v = 343$ m/s and $\rho = 1.21\,\text{kg/m}^3$, we obtain

$$s_m = \sqrt{\frac{2I}{\rho v \omega^2}} = 1.71 \times 10^{-7} \text{ m} .$$

(c) Eq. 18-15 gives the pressure amplitude:

$$\Delta p_m = \rho v \omega s_m = 0.893 \text{ Pa} .$$

88. The source being a "point source" means $A_{\text{sphere}} = 4\pi r^2$ is used in the intensity definition $I = P/A$, which further implies

$$\frac{I_2}{I_1} = \frac{P/4\pi r_2^2}{P/4\pi r_1^2} = \left(\frac{r_1}{r_2}\right)^2 .$$

From the discussion in §18-5, we know that the intensity ratio between "barely audible" and the "painful threshold" is $10^{-12} = I_2/I_1$. Thus, with $r_2 = 10000$ m, we find $r_1 = r_2\sqrt{10^{-12}} = 0.01$ m.

89. The density of oxygen gas is

$$\rho = \frac{0.0320\,\text{kg}}{0.0224\,\text{m}^3} = 1.43\,\text{kg/m}^3 .$$

From $v = \sqrt{B/\rho}$ we find

$$B = v^2\rho = (317\,\text{m/s})^2 \left(1.43\,\text{kg/m}^3\right) = 1.44 \times 10^5 \text{ Pa} .$$

90. The wavelength is

$$\lambda = \frac{v}{f} = \frac{240\,\text{m/s}}{4.2 \times 10^9\,\text{Hz}} = 5.7 \times 10^{-8}\,\text{m} = 57 \text{ nm} .$$

91. Since they oscillate out of phase, then their waves will cancel (producing a node) at a point exactly midway between them (the midpoint of the system, where we choose $x = 0$). We note that Figure 18-14, and the $n = 3$ case of Figure 18-15(a) have this property (of a node at the midpoint). The distance Δx between nodes is $\lambda/2$, where $\lambda = v/f$ and $f = 300$ Hz and $v = 343$ m/s. Thus, $\Delta x == v/2f = 0.572$ m. Therefore, nodes are found at the following positions:

$$\begin{aligned} x &= \pm\Delta x = \pm 0.57 \text{ m} \\ x &= \pm 2\Delta x = \pm 1.14 \text{ m} \\ x &= \pm 3\Delta x = \pm 1.72 \text{ m} \end{aligned}$$

92. (a) Consider a string of pulses returning to the stage. A pulse which came back just before the previous one has traveled an extra distance of $2w$, taking an extra amount of time $\Delta t = 2w/v$. The frequency of the pulse is therefore

$$f = \frac{1}{\Delta t} = \frac{v}{2w} = \frac{343\,\text{m/s}}{2(0.75\,\text{m})} = 2.3 \times 10^2 \text{ Hz} .$$

(b) Since $f \propto 1/w$, the frequency would be higher if w were smaller.

93. The source being isotropic means $A_{\text{sphere}} = 4\pi r^2$ is used in the intensity definition $I = P/A$. Since intensity is proportional to the square of the amplitude (see Eq. 18-27), this further implies

$$\frac{I_2}{I_1} = \left(\frac{s_{m2}}{s_{m1}}\right)^2 = \frac{P/4\pi r_2^2}{P/4\pi r_1^2} = \left(\frac{r_1}{r_2}\right)^2$$

or $s_{m2}/s_{m1} = r_1/r_2$.

(a) With $I = P/4\pi r^2 = (10\,\text{W})/4\pi(3.0\,\text{m})^2 = 0.088\ \text{W/m}^2$.

(b) Using the notation A instead of s_m for the amplitude, we find

$$\frac{A_4}{A_3} = \frac{3.0\,\text{m}}{4.0\,\text{m}} \implies A_4 = \frac{3}{4} A_3 .$$

94. We use $I \propto r^{-2}$ appropriate for an isotropic source. We have

$$\frac{I_{r=d}}{I_{r=D-d}} = \frac{(D-d)^2}{D^2} = \frac{1}{2} ,$$

where $d = 50.0\,\text{m}$. We solve for D: $D = \sqrt{2}d/(\sqrt{2}-1) = \sqrt{2}(50.0\,\text{m})/(\sqrt{2}-1) = 171\,\text{m}$.

95. Let the original tension be τ_1 and the new tension be τ_2. Then

$$\frac{\lambda_{s2}}{\lambda_{s1}} = \frac{v_s/f_2}{v_s/f_1} = \frac{f_1}{f_2} = \frac{v_2/\lambda_1}{v_2/\lambda_2} = \frac{v_1}{v_2} = \sqrt{\frac{\tau_1}{\tau_2}} = \frac{1}{2} .$$

Thus, $\tau_2/\tau_1 = 4$. That is, the tension must be increased by a factor of 4.

96. Since they are approaching each other, the sound produced (of emitted frequency f) by the flatcar-trumpet received by an observer on the ground will be of higher pitch f'. In these terms, we are told $f' - f = 4.0$ Hz, and consequently that $f'/f = 444/440 = 1.0091$. With v_S designating the speed of the flatcar and $v = 343$ m/s being the speed of sound, the Doppler equation leads to

$$\frac{f'}{f} = \frac{v+0}{v-v_S} \implies v_S = (343)\frac{1.0091-1}{1.0091} = 3.1 \text{ m/s} .$$

97. The siren is between you and the cliff, moving away from you and towards the cliff. Both "detectors" (you and the cliff) are stationary, so $v_D = 0$ in Eq. 18-47 (and see the discussion in the textbook immediately after that equation regarding the selection of $\pm$ signs). The source is the siren with $v_S = 10$ m/s. The problem asks us to use $v = 330$ m/s for the speed of sound.

(a) With $f = 1000$ Hz, the frequency f_y you hear becomes

$$f_y = f\left(\frac{v+0}{v+v_S}\right) = 970.6 \approx 9.7 \times 10^2 \text{ Hz} .$$

(b) The frequency heard by an observer at the cliff (and thus the frequency of the sound reflected by the cliff, ultimately reaching your ears at some distance from the cliff) is

$$f_c = f\left(\frac{v+0}{v-v_S}\right) = 1031.3 \approx 1.03 \times 10^2 \text{ Hz} .$$

(c) The beat frequency is $f_c - f_y = 61$ beats/s (which, due to specific features of the human ear, is too large to be perceptible).

98. (a) We observe that "third lowest ... frequency" corresponds to harmonic number $n = 5$ for such a system. Using Eq. 18-41, we have

$$f = \frac{nv}{4L} \implies 750 = \frac{5v}{4(0.60)}$$

so that $v = 360$ m/s.

(b) As noted, $n = 5$; therefore, $f_1 = 750/5 = 150$ Hz.

99. (a) The problem asks for the source frequency f. We use Eq. 18-47 with great care (regarding its $\pm$ sign conventions).

$$f' = f\left(\frac{340-16}{340-40}\right)$$

Therefore, with $f' = 950$ Hz, we obtain $f = 880$ Hz.

(b) We now have

$$f' = f\left(\frac{340+16}{340+40}\right)$$

so that with $f = 880$ Hz, we find $f' = 824$ Hz.

100. (a) Since the speed of sound is lower in air than in water, the speed of sound in the air-water mixture is lower than in pure water (see Table 18-1). Frequency is proportional to the speed of sound (see Eq. 18-39 and Eq. 18-41), so the decrease in speed is "heard" due to the accompanying decrease in frequency.

(b) This follows from Eq. 18-3 and Eq. 18-2 (with Δ's replaced by derivatives). Thus,

$$\frac{1}{v^2} = \frac{\rho}{B} = \frac{\rho}{V\left|\frac{dp}{dV}\right|} = \frac{\rho}{V}\left|\frac{dV}{dp}\right| .$$

(c) Returning to the Δ notation, and letting the absolute values be "understood," we write $\Delta V = \Delta V_w + \Delta V_a$ as indicated in the problem. Subject to the approximations mentioned in the problem, our equation becomes

$$\frac{1}{v^2} = \frac{\rho_w}{V_w}\left(\frac{\Delta V_w}{\Delta p} + \frac{\Delta V_a}{\Delta p}\right) = \frac{\rho_w}{V_w}\frac{\Delta V_w}{\Delta p} + \frac{\rho_w}{\rho_a}\frac{V_a}{V_w}\left(\frac{\rho_a}{V_a}\frac{\Delta V_a}{\Delta p}\right) .$$

In a pure water system or a pure air system, we would have

$$\frac{1}{v_w^2} = \frac{\rho_w}{V_w}\frac{\Delta V_w}{\Delta p} \qquad \text{or} \qquad \frac{1}{v_a^2} = \frac{\rho_a}{V_a}\frac{\Delta V_a}{\Delta p} .$$

Substituting these into the above equation, and using the notation $r = V_a/V_w$, we arrive at

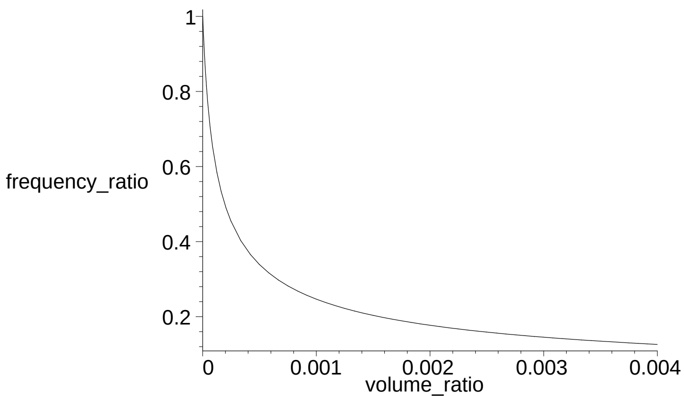
$$\frac{1}{v^2} = \frac{1}{v_w^2} + \frac{\rho_w}{\rho_a}\frac{r}{v_a^2} \implies v = \frac{1}{\sqrt{1/v_w^2 + r(\rho_w/\rho_a)/v_a^2}} .$$

(d) Dividing our result in the previous part by v_w and using the fact that the wave speed is proportional to the frequency, we find

$$\frac{v}{v_w} = \frac{f_{\text{shift}}}{f} = \frac{1}{v_w\sqrt{1/v_w^2 + r(\rho_w/\rho_a)/v_a^2}} = \frac{1}{\sqrt{1 + r(\rho_w/\rho_a)(v_w/v_a)^2}}$$

which becomes the expression shown in the problem when we plug in $\rho_w = 1000\,\text{kg/m}^3$, $\rho_a = 1.21\,\text{kg/m}^3$, $v_w = 1482$ m/s and $v_a = 343$ m/s, and round to three significant figures.

(e) The graph of f_{shift}/f versus r is shown below.



(f) From the graph (or more accurately by solving the equation itself) we find $r = 5.2\times10^{-4}$ corresponds to $f_{\text{shift}}/f = 1/3$.