Chapter 14

PROBLEM SOLUTIONS

14.1 Since $v_{\text{light}} >> v_{\text{sound}}$, the time required for the flash of light to reach the observer is negligible in comparison to the time required for the sound to arrive. Thus, we can ignore the time required for the lightning flash to arrive, and knowledge of the actual speed of light is not needed. Then,

$$d \approx (343\ \text{m/s})(16.2\ \text{s}) = 5.56 \times 10^3\ \text{m} = \boxed{5.56\ \text{km}}$$

14.2 The speed of longitudinal waves in a fluid is $v = \sqrt{B/\rho}$. Considering the Earth's crust to consist of a very viscous fluid, our estimate of the average bulk modulus of the material in Earth's crust is

$$B = \rho v^2 = (2\ 500\ \text{kg/m}^3)(7 \times 10^3\ \text{m/s})^2 = \boxed{1 \times 10^{11}\ \text{Pa}}$$

14.3 The Celsius temperature was $T_C = \frac{5}{9}(T_F - 32) = \frac{5}{9}(-128.6 - 32) = -89.2°\text{C}$, and the absolute temperature was $T_K = -89.2°\text{C} + 273 = 184\ \text{K}$ and the speed of sound in the air would have been

$$v = (331\ \text{m/s})\sqrt{\frac{184\ \text{K}}{273\ \text{K}}} = \boxed{272\ \text{m/s}}$$

14.4 The speed of sound in seawater at 25°C is $1\ 530\ \text{m/s}$. Therefore, the time for the sound to reach the sea floor and return is

$$t = \frac{2d}{v} = \frac{2(150\ \text{m})}{1530\ \text{m/s}} = \boxed{0.196\ \text{s}}$$

14.5 Since the sound had to travel the distance between the hikers and the mountain twice, the time required for a one-way trip was 1.50 s. The speed of sound in air at $T = 22.0°C = 295$ K is

$$v = 331\ \text{m/s}\ \sqrt{\frac{T}{273\ K}} = 331\ \text{m/s}\ \sqrt{\frac{295\ \text{K}}{273\ \text{K}}} = 3.44\ \text{m/s}$$

and the distance the sound traveled to the mountain was

$$d = 344\ \text{m/s}\quad 1.50\ \text{s} = \boxed{516\ \text{m}}$$

14.6 At $T = 27°C = 300$ K, the speed of sound in air is

$$v = 331\ \text{m/s}\ \sqrt{\frac{T}{273\ K}} = 331\ \text{m/s}\ \sqrt{\frac{300\ \text{K}}{273\ \text{K}}} = 347\ \text{m/s}$$

The wavelength of the 20 Hz sound is

$$\lambda = \frac{v}{f} = \frac{347\ \text{m/s}}{20\ \text{Hz}} = 17\ \text{m}$$

and that of the 20 000 Hz is

$$\lambda = \frac{347\ \text{m/s}}{20\ 000\ \text{Hz}} = 1.7 \times 10^{-2}\ \text{m} = 1.7\ \text{cm}\,.$$

Thus, range of wavelengths of audible sounds at 27°C is $\boxed{1.7\ \text{cm to } 17\ \text{m}}$.

14.7 From Table 14.1, the speed of sound in the saltwater is $v_w = 1530$ m/s. At $T = 20°C = 293$ K, the speed of the sound in air is

$$v_a = 331\ \text{m/s}\ \sqrt{\frac{T}{273\ \text{K}}} = 331\ \text{m/s}\ \sqrt{\frac{293\ \text{K}}{273\ \text{K}}} = 343\ \text{m/s}$$

If d is the width of the inlet, the transit time for the sound in the water is $t_w = d/v_w$, and that for the sound in the air is $t_a = t_w + 4.50\ \text{s} = d/v_a$. Thus,

$$\frac{d}{v_a} = \frac{d}{v_w} + 4.50\ \text{s}\,,\ \text{or}\ d = (4.50\ \text{s})\left(\frac{v_w v_a}{v_w - v_a}\right)$$

$$d = 4.50\text{ s}\left[\frac{1\,530\text{ m/s}\quad 343\text{ m/s}}{1\,530 - 343\quad\text{m/s}}\right] = 1.99 \times 10^3\text{ m} = \boxed{1.99\text{ km}}$$

14.8 At a temperature of $T = 10.0°\text{C} = 283$ K, the speed of sound in air is

$$v = 331\text{ m/s}\sqrt{\frac{T}{273\text{ K}}} = 331\text{ m/s}\sqrt{\frac{283\text{ K}}{273\text{ K}}} = 337\text{ m/s}$$

The elapsed time between when the stone was released and when the sound is heard is the sum of the time t_1 required for the stone to fall distance h and the time t_2 required for sound to travel distance h in air on the return up the well. That is, $t_1 + t_2 = 2.00$ s. The distance the stone falls, starting from rest, in time t_1 is

$$h = \frac{gt_1^2}{2}$$

Also, the time for the sound to travel back up the well is

$$t_2 = \frac{h}{v} = 2.00\text{ s} - t_1$$

Combining these two equations yields

$$\left(\frac{g}{2v}\right)t_1^2 = 2.00\text{ s} - t_1$$

With $v = 337\text{ m/s}$ and $g = 9.80\text{ m/s}^2$, this becomes $1.45 \times 10^{-2}\text{ s}^{-1}\ t_1^2 + t_1 - 2.00\text{ s} = 0.$

Applying the quadratic formula yields one positive solution of $t_1 = 1.95$ s, so the depth of the well is

$$h = \frac{gt_1^2}{2} = \frac{9.80\text{ m/s}^2\quad 1.95\text{ s}^{\ 2}}{2} = \boxed{18.6\text{ m}}$$

14.9 (a) The speed of sound in air at an absolute temperature of $T = T_C + 273 = 65 + 273 = 338$ K is

$$v = 331\ \text{m/s}\ \sqrt{\frac{T}{273\ \text{K}}} = 331\ \text{m/s}\ \sqrt{\frac{338\ \text{K}}{273\ \text{K}}} = \boxed{368\ \text{m/s}}$$

(b) When $T_C = 65°\text{C}$ and the speed of sound is $v = 368\ \text{m/s}$, the wavelength of sound having a frequency $f = 845$ Hz is

$$\lambda = \frac{v}{f} = \frac{368\ \text{m/s}}{845\ \text{Hz}} = \boxed{0.436\ \text{m}} = \boxed{43.6\ \text{cm}}$$

14.10 (a) The decibel level, β, of a sound is given $\beta = 10\log\left(I/I_0\right)$, where I is the intensity of the sound, and $I_0 = 1.0 \times 10^{-12}\ \text{W/m}^2$ is the reference intensity. Therefore, if $\beta = 150$ dB, the intensity is

$$I = I_0 \times 10^{\beta/10} = \left(1.0 \times 10^{-12}\ \text{W/m}^2\right) \times 10^{15} = \boxed{1.0 \times 10^{3}\ \text{W/m}^2}$$

(b) The threshold of pain is $I = 1\ \text{W/m}^2$ and the answer to part (a) is 1 000 times greater than this, explaining why some airport employees must wear hearing protection equipment.

14.11 If the intensity of this sound varied inversely with the square of the distance from the source $\left(I = \text{constant}/r^2\right)$, the ratio of the intensities at distances $r_1 = 161$ km and $r_2 = 4\ 800$ km from the source is given by

$$\frac{I_2}{I_1} = \left(\frac{\cancel{\text{constant}}}{r_2^2}\right)\left(\frac{r_1^2}{\cancel{\text{constant}}}\right) = \left(\frac{r_1}{r_2}\right)^2 = \left(\frac{161\ \text{km}}{4\ 800\ \text{km}}\right)^2$$

The difference in the decibel levels at distances r_1 and r_2 from this source was then

$$\beta_2 - \beta_1 = 10\cdot\log\left(\frac{I_2}{I_0}\right) - 10\cdot\log\left(\frac{I_1}{I_0}\right) = 10\cdot\log\left(\frac{I_2}{\cancel{I_0}}\cdot\frac{\cancel{I_0}}{I_1}\right) = 10\cdot\log\left(\frac{I_2}{I_1}\right) = 10\cdot\log\left(\frac{161\ \text{km}}{4\ 800\ \text{km}}\right)^2$$

or

$$\beta_2 - \beta_1 = -29.5\ \text{dB} \qquad \text{giving} \qquad \beta_2 = \beta_1 - 29.5\ \text{dB} = 180\ \text{dB} - 29.5\ \text{dB} \approx \boxed{150\ \text{dB}}$$

14.12 The decibel level due to the first siren is

$$\beta_1 = 10 \cdot \log\left(\frac{100.0\ \text{W/m}^2}{1.0 \times 10^{-12}\ \text{W/m}^2}\right) = 140\ \text{dB}.$$

Thus, the decibel level of the sound from the ambulance is

$$\beta_2 = \beta_1 + 10\ \text{dB} = 140\ \text{dB} + 10\ \text{dB} = \boxed{150\ \text{dB}}$$

14.13 In terms of their intensities, the difference in the decibel level of 2 sounds is

$$\beta_2 - \beta_1 = 10 \cdot \log\left(\frac{I_2}{I_0}\right) - 10 \cdot \log\left(\frac{I_1}{I_0}\right) = 10 \cdot \log\left(\frac{I_2}{\cancel{I_0}} \cdot \frac{\cancel{I_0}}{I_1}\right) = 10 \cdot \log\left(\frac{I_2}{I_1}\right)$$

Thus,

$$\frac{I_2}{I_1} = 10^{(\beta_2 - \beta_1)/10} \qquad \text{or} \qquad I_2 = I_1 \times 10^{(\beta_2 - \beta_1)/10}$$

If $\beta_2 - \beta_1 = 30\ \text{dB}$ and $I_1 = 3.0 \times 10^{-11}\ \text{W/m}^2$, then

$$I_2 = \left(3.0 \times 10^{-11}\ \text{W/m}^2\right) \times 10^3 = \boxed{3.0 \times 10^{-8}\ \text{W/m}^2}$$

14.14 The sound power incident on the eardrum is $P = IA$ where I is the intensity of the sound and $A = 5.0 \times 10^{-5}\ \text{m}^2$ is the area of the eardrum.

(a) At the threshold of hearing, $I = 1.0 \times 10^{-12}\ \text{W/m}^2$, and

$$P = \left(1.0 \times 10^{-12}\ \text{W/m}^2\right)\left(5.0 \times 10^{-5}\ \text{m}^2\right) = \boxed{5.0 \times 10^{-17}\ \text{W}}$$

(b) At the threshold of pain, $I = 1.0\ \text{W/m}^2$, and

$$P = \left(1.0\ \text{W/m}^2\right)\left(5.0\times10^{-5}\ \text{m}^2\right) = \boxed{5.0\times10^{-5}\ \text{W}}$$

14.15 The decibel level $\beta = 10\log\left(I/I_0\right)$, where $I_0 = 1.00\times10^{-12}\ \text{W/m}^2$.

(a) If β = 100 dB, then $\log\left(I/I_0\right) = 10$ giving $I = 10^{10}\,I_0 = \boxed{1.00\times10^{-2}\ \text{W/m}^2}$

(b) If all three toadfish sound at the same time, the total intensity of the sound produced is $I' = 3I = 3.00\times10^{-2}\ \text{W/m}^2$, and the decibel level is

$$\beta' = 10\log\left(\frac{3.00\times10^{-2}\ \text{W/m}^2}{1.00\times10^{-12}\ \text{W/m}^2}\right)$$

$$= 10\log\left[\left(3.00\right)\left(10^{10}\right)\right] = 10\left[\log\left(3.00\right)+10\right] = \boxed{105}$$

14.16 (a) From the defining equation of the decibel level, $\beta = 10\cdot\log\left(I/I_0\right)$. We solve for the intensity as $I = I_0\cdot10^{\beta/10}$ and find that

$$I = \left(1.0\times10^{-12}\ \text{W/m}^2\right)\cdot10^{115/10} = 1.0\times10^{-12+11.5}\ \text{W/m}^2 = 10^{-0.5}\ \text{W/m}^2 = \boxed{0.316\ \text{W/m}^2}$$

(b) If 5 trumpets are sounded together, the total intensity of the sound is

$$I_5 = 5I_1 = 5\left(0.316\ \text{W/m}^2\right) = \boxed{1.58\ \text{W/m}^2}$$

(c) If the sound propagates uniformly in all directions, the intensity varies inversely as the square of the distance from the source, $I = \text{constant}/r^2$, and we find that

$$\frac{I_2}{I_1} = \left(\frac{r_1}{r_2}\right)^2 \qquad \text{or}$$

$$I_2 = I_1\left(\frac{r_1}{r_2}\right)^2 = 1.58\ \text{W/m}^2\left(\frac{1.0\ \text{m}}{8.0\ \text{m}}\right)^2 = \boxed{2.47 \times 10^{-2}\ \text{W/m}^2}$$

(d) $$\beta_{row\ 1} = 10 \cdot \log\left(\frac{I_{row\ 1}}{I_0}\right) = 10 \cdot \log\left(\frac{2.47 \times 10^{-2}\ \text{W/m}^2}{1.0 \times 10^{-12}\ \text{W/m}^2}\right) = \boxed{104\ \text{dB}}$$

(e) The intensity of sound at the threshold of hearing is $I_0 = 1.0 \times 10^{-12}\ \text{W/m}^2$, and from the discussion and result of part (c), we have $I_0/I_2 = r_2/r_0{}^2$ and with the intensity being $I_2 = 2.47 \times 10^{-2}\ \text{W/m}^2$ at distance $r_2 = 8.0$ m, the distance at which the intensity would be $I_0 = 1.0 \times 10^{-12}\ \text{W/m}^2$ is

$$r_0 = r_2\sqrt{\frac{I_2}{I_0}} = 8.0\ \text{m}\ \sqrt{\frac{2.47 \times 10^{-2}\ \text{W/m}^2}{1.0 \times 10^{-12}\ \text{W/m}^2}} = \boxed{1.26 \times 10^6\ \text{m}}$$

(f) The sound intensity level falls as the sound wave travels farther from the source until it is much lower than the ambient noise level and is drowned out.

14.17 The intensity of a spherical sound wave at distance r from a point source is $I = P_{av}/4\pi r^2$, where P_{av} is the average power radiated by the source. Thus, at distances $r_1 = 5.0$ m and $r_2 = 10$ km = 10^4, the intensities of the sound wave radiating out from the elephant are

$$I_1 = \frac{P_{av}}{4\pi r_1^2} \quad \text{and} \quad I_2 = \frac{P_{av}}{4\pi r_2^2} \quad \text{giving} \quad I_2 = \left(\frac{r_1}{r_2}\right)^2 I_1$$

From the defining equation, $\beta = 10 \log\left(I/I_o\right)$, the intensity level of the sound at distance r_2 from the elephant is seen to be

$$\beta_2 = 10\log\left(\frac{I_2}{I_0}\right) = 10\log\left[\left(\frac{r_1}{r_2}\right)^2 \frac{I_1}{I_0}\right] = 10\log\left(\frac{r_1}{r_2}\right)^2 + 10\log\left(\frac{I_1}{I_0}\right) = 20\log\left(\frac{r_1}{r_2}\right) + 10\log\left(\frac{I_1}{I_0}\right)$$

or

$$\text{or} \quad \beta_2 = 20\log\left(\frac{5.0 \text{ m}}{10^4 \text{ m}}\right) + \beta_1 = -66 \text{ dB} + 103 \text{ dB} = \boxed{37 \text{ dB}}$$

14.18 (a) The intensity of the sound generated by the orchestra ($\beta = 80$ dB) is $I_{Orch} = I_0 10^{\beta/10} = I_0\left(10^{8.0}\right)$, and that produced by the crying baby ($\beta = 75$ dB) is $I_b = I_0\left(10^{7.5}\right)$. Thus, the total intensity of the sound engulfing you is

$$I = I_{Orch} + I_b = I_0\left(10^{8.0} + 10^{7.5}\right)$$

$$= \left(1.0 \times 10^{-12} \text{ W/m}^2\right)\left(1.32 \times 10^8\right) = \boxed{1.32 \times 10^{-4} \text{ W/m}^2}$$

(b) The combined sound level is

$$\beta = 10\log\left(I/I_0\right) = 10\log\left(1.32 \times 10^8\right) = \boxed{81.2 \text{ dB}}$$

14.19 (a) The intensity of sound at 10 km from the horn (where $\beta = 50$ dB) is

$$I = I_0 10^{\beta/10} = \left(1.0 \times 10^{-12}\ \text{W/m}^2\right)\left(10^{5.0}\right) = 1.0 \times 10^{-7}\ \text{W/m}^2$$

Thus, from $I = P/4\pi r^2$, the power emitted by the source is

$$P = 4\pi r^2 I = 4\pi\left(10 \times 10^3\ \text{m}\right)^2\left(1.0 \times 10^{-7}\ \text{W/m}^2\right) = \boxed{1.3 \times 10^2\ \text{W}}$$

(b) At $r = 50$ m, the intensity of the sound will be

$$I = \frac{P}{4\pi r^2} = \frac{1.3 \times 10^2\ \text{W}}{4\pi\left(50\ \text{m}\right)^2} = 4.0 \times 10^{-3}\ \text{W/m}^2$$

and the sound level is

$$\beta = 10\log\left(\frac{I}{I_0}\right) = 10\log\left(\frac{4.0 \times 10^{-3}\ \text{W/m}^2}{1.0 \times 10^{-12}\ \text{W/m}^2}\right) = 10\log(4.0 \times 10^9) = \boxed{96\ \text{dB}}$$

14.20 (a) $$I = \frac{P}{4\pi r^2} = \frac{100\ W}{4\pi(10.0\ \text{m})^2} = \boxed{7.96 \times 10^{-2}\ \text{W/m}^2}$$

(b) $$\beta = 10\log\left(\frac{I}{I_0}\right) = 10\log\left(\frac{7.96 \times 10^{-2}\ \text{W/m}^2}{1.00 \times 10^{-12}\ \text{W/m}^2}\right)$$

$$= 10\log(7.96 \times 10^{10}) = \boxed{109\ \text{dB}}$$

(c) At the threshold of pain ($\beta = 120$ dB), the intensity is $I = 1.00\ \text{W/m}^2$. Thus, from $I = P/4\pi r^2$, the distance from the speaker is

$$r = \sqrt{\frac{P}{4\pi I}} = \sqrt{\frac{100\ \mathrm{W}}{4\pi\ \ 1.00\ \ \mathrm{W/m^2}}} = \boxed{2.82\ \mathrm{m}}$$

14.21 The sound level for intensity I is $\beta = 10\log\ \ I/I_0$. Therefore,

$$\beta_2 - \beta_1 = 10\log\left(\frac{I_2}{I_0}\right) - 10\log\left(\frac{I_1}{I_0}\right) = 10\log\left(\frac{I_2/I_0}{I_1/I_0}\right) = 10\log\left(\frac{I_2}{I_1}\right)$$

Since

$$I = \frac{P}{4\pi r^2} = \frac{P/4\pi}{r^2}$$

the ratio of intensities is

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

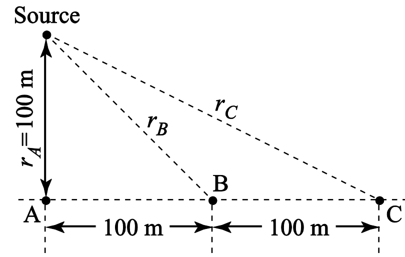
Thus,

$$\beta_2 - \beta_1 = 10\log\left(\frac{r_1^2}{r_2^2}\right) = 10\log\left(\frac{r_1}{r_2}\right)^2 = \boxed{20\log\left(\frac{r_1}{r_2}\right)}$$

14.22 The intensity at distance r from the source is $I = \frac{\tilde{A}}{4\pi r^2} = \frac{\tilde{A}/4\pi}{r^2}$

(a)

$$\frac{I_A}{I_B} = \frac{r_B^2}{r_A^2} = \frac{100\text{ m}^{\,2} + 100\text{ m}^{\,2}}{100\text{ m}^{\,2}} = \boxed{2}$$



(b)

$$\frac{I_A}{I_C} = \frac{r_C^2}{r_A^2} = \frac{100\text{ m}^{\,2} + 200\text{ m}^{\,2}}{100\text{ m}^{\,2}} = \boxed{5}$$

14.23 When a stationary observer $v_0 = 0$ hears a moving source, the observed frequency is

$$f_O = f_S\left(\frac{v + v_O}{v - v_S}\right) = f_S\left(\frac{v}{v - v_S}\right)$$

(a) When the train is approaching, $v_S = +40.0\text{ m/s}$ and

$$f_{O\ approach} = 320\text{ Hz}\left(\frac{345\text{ m/s}}{345\text{ m/s} - 40.0\text{ m/s}}\right) = 362\text{ Hz}$$

After the train passes and is receding, $v_S = -40.0\text{ m/s}$ and

$$f_{O\ recede} = (320\text{ Hz})\left[\frac{345\text{ m/s}}{345\text{ m/s} - \ -40.0\text{ m/s}}\right] = 287\text{ Hz and}$$

Thus, the frequency shift that occurs as the train passes is

$$\Delta f_O = f_{O\ recede} - f_{O\ approach} = -75.2\ \text{Hz}\text{, or it is a } \boxed{75.2\ \text{Hz drop}}$$

(b) As the train approaches, the observed wavelength is

$$\lambda = \frac{v}{f_{O\ approach}} = \frac{345\ \text{m/s}}{362\ \text{Hz}} = \boxed{0.953\ \text{m}}$$

14.24 The general expression for the observed frequency of a sound when the source and/or the observer are in motion is

$$f_O = f_S\left(\frac{v + v_O}{v - v_S}\right)$$

Here, v is the velocity of sound in air, v_O is the velocity of the observer, v_S is the velocity of the source, and f_S is the frequency that would be detected if both the source and observer were stationary.

(a) If $f_S = 5.00$ kHz and the observer is stationary ($v_O = 0$), the frequency detected when the source moves toward the observer at half the speed of sound $v_S = +v/2$ is

$$f_O = (5.00\ \text{kHz})\left(\frac{v + 0}{v - v/2}\right) = (5.00\ \text{kHz})\ 2 = \boxed{10.0\ \text{kHz}}$$

(b) When $f_S = 5.00$ kHz and the source moves away from a stationary observer at half the speed of sound $v = 343\ \text{m/s}$, the observed frequency is

$$f_O = (5.00\text{ kHz})\left(\frac{v+0}{v+v/2}\right) = (5.00\text{ kHz})\left(\frac{2}{3}\right) = \boxed{3.33\text{ kHz}}$$

14.25 Both source and observer are in motion, so

$$f_O = f_S\left(\frac{v+v_O}{v-v_S}\right)$$

Since each train moves *toward* the other, $v_O > 0$ and $v_S > 0$. The speed of the source (train 2) is

$$v_S = 90.0\ \frac{\text{km}}{\text{h}}\left(\frac{1000\text{ m}}{1\text{ km}}\right)\left(\frac{1\text{ h}}{3600\text{ s}}\right) = 25.0\text{ m/s}$$

and that of the observer (train 1) is $v_O = 130\text{ km/h} = 36.1\text{ m/s}$. Thus, the observed frequency is

$$f_O = (500\text{ Hz})\left(\frac{345\text{ m/s}+36.1\text{ m/s}}{345\text{ m/s}-25.0\text{ m/s}}\right) = \boxed{595\text{ Hz}}$$

14.26 Since the observer hears a reduced frequency, the source and observer are getting farther apart. Hence, the bicyclist is $\boxed{\text{behind the car}}$.

With the bicyclist (observer) behind the car (source) and both moving in the same direction, the observer moves *toward* the source ($v_O > 0$) while the source moves *away from* the observer ($v_S > 0$). Thus, $v_O = +|v_{bicyclist}| = +|v_{car}|/3$ and $v_S = -|v_{car}|$ where $|v_{car}|$ is the speed of the car.

The observed frequency is

$$f_O = f_S\left(\frac{v + v_O}{v - v_S}\right) = f_S\left[\frac{v + |v_{car}|/3}{v - \ -|v_{car}|}\right] = f_S\left(\frac{v + |v_{car}|/3}{v + |v_{car}|}\right),$$

giving

$$415 \text{ Hz} = 440 \text{ Hz}\left(\frac{345 \text{ m/s} + |v_{car}|/3}{345 \text{ m/s} + |v_{car}|}\right) \text{ and } |v_{car}| = \boxed{32.1 \text{ m/s}}$$

14.27 With the train *approaching* the stationary observer ($v_O = 0$) at speed $|v_t|$, the source velocity is $v_S = +|v_t|$ and the observed frequency is

$$442 \text{ Hz} = f_S\left(\frac{345 \text{ m/s}}{345 \text{ m/s} - |v_t|}\right) \qquad [1]$$

As the train *recedes*, the source velocity is $v_S = -|v_t|$ and the observed frequency is

$$441 \text{ Hz} = f_S\left(\frac{345 \text{ m/s}}{345 \text{ m/s} + |v_t|}\right) \qquad [2]$$

Dividing equation [1] by [2] gives

$$\frac{442}{441} = \frac{345 \text{ m/s} + |v_t|}{345 \text{ m/s} - |v_t|}$$

and solving for the speed of the train yields $|v_t| = \boxed{0.391 \text{ m/s}}$

14.28 We let the speed of the insect be $|v_{bug}|$ and the speed of the bat be $|v_{bat}| = 5.00 \text{ m/s}$, and break the action into 2 steps. In the first step, the bat is the sound source flying *toward* the observer (the insect), so $v_S = +|v_{bat}|$, while the insect (observer) is flying *away* from the source, making $v_O = -|v_{bug}|$. If f_0 is the actual frequency sound emitted by the bat, the frequency detected (and reflected) by the moving insect is

$$f_{reflect} = f_0\left(\frac{v + v_O}{v - v_S}\right) = f_0\left[\frac{v + -|v_{bug}|}{v - +|v_{bat}|}\right] \quad \text{or} \quad f_{reflect} = f_0\left(\frac{v - |v_{bug}|}{v - |v_{bat}|}\right)$$

In the second step of the action, the insect acts as a sound source, reflecting a wave of frequency f_{reflect} back to the bat which acts as a moving observer. Since the source (insect) is moving *away* from the observer, $v_S = -|v_{bug}|$, and the observer (bat) is moving *toward* the source (insect) giving $v_O = +|v_{bat}|$. The frequency of the return sound received by the bat is then

$$f_{\text{return}} = f_{\text{reflect}}\left(\frac{v + v_O}{v - v_S}\right) = f_{\text{reflect}}\left[\frac{v + +|v_{\text{bat}}|}{v - -|v_{\text{bug}}|}\right] \quad \text{or}$$

$$f_{\text{return}} = f_{\text{reflect}}\left(\frac{v + |v_{\text{bat}}|}{v + |v_{\text{bug}}|}\right)$$

Combing the results of the 2 steps gives

$$f_{\text{return}} = f_0\left(\frac{v - |v_{\text{bug}}|}{v - |v_{\text{bat}}|}\right)\left(\frac{v + |v_{\text{bat}}|}{v + |v_{\text{bug}}|}\right)$$

or

$$40.4\text{ kHz} = 40.0\text{ kHz}\left(\frac{340\text{ m/s} - |v_{\text{bug}}|}{340 - 5.00}\right)\left(\frac{340 + 5.00}{340\text{ m/s} + |v_{\text{bug}}|}\right)$$

This reduces to

$$340\text{ m/s} + |v_{\text{bug}}| = \left(\frac{40.0}{40.4}\right)\left(\frac{345}{335}\right)\ 340\text{ m/s} - |v_{\text{bug}}|$$

or

$$\left[\left(\frac{40.0}{40.4}\right)\left(\frac{345}{335}\right) + 1\right]|v_{\text{bug}}| = 340\text{ m/s}\left[\left(\frac{40.0}{40.4}\right)\left(\frac{345}{335}\right) - 1\right]$$

and yields $|v_{bug}| = \boxed{3.31\text{ m/s}}$.

Thus, the bat is gaining on the insect at a rate of $5.00\text{ m/s} - 3.31\text{ m/s} = 1.69\text{ m/s}$.

14.29 For a source *receding* from a stationary observer,

$$f_O = f_S\left(\frac{v}{v - \ -|v_S|}\right) = f_S\left(\frac{v}{v + |v_S|}\right).$$

Thus, the speed the falling tuning fork must reach is

$$|v_S| = v\left(\frac{f_S}{f_O} - 1\right) = 340\ \text{m/s}\left(\frac{512\ \text{Hz}}{485\ \text{Hz}} - 1\right) = 18.9\ \text{m/s}$$

The distance it has fallen from rest before reaching this speed is

$$\Delta y_1 = \frac{v_S^2 - 0}{2\,a_y} = \frac{18.9\ \text{m/s}\ ^2 - 0}{2\ \ 9.80\ \text{m/s}^2} = 18.3\ \text{m}$$

The time required for the 485 Hz sound to reach the observer is

$$t = \frac{\Delta y_1}{v} = \frac{18.3\ \text{m}}{340\ \text{m/s}} = 0.0538\ \text{s}$$

During this time the fork falls an additional distance

$$\Delta y_2 = v_S t + \frac{1}{2} a_y t^2 = 18.9\ \text{m/s}\quad 0.0538\ \text{s}\ + \frac{1}{2}\ 9.80\ \text{m/s}^2\quad 0.0538\ \text{s}\ ^2 = 1.03\ \text{m}$$

The total distance fallen before the 485 Hz sound reaches the observer is

$$\Delta y = \Delta y_1 + \Delta y_2 = 18.3\ \text{m} + 1.03\ \text{m} = \boxed{19.3\ \text{m}}$$

14.30 (a) $\omega = 2\pi f = 2\pi\left(\dfrac{115/\text{min}}{60.0\ \text{s/min}}\right) = 12.0\ \text{rad/s}$

and for harmonic motion,

$$v_{\max} = \omega A = (12.0 \text{ rad/s})(1.80 \times 10^{-3} \text{ m}) = \boxed{0.0217 \text{ m/s}}$$

(b) The heart wall is a moving observer ($v_O = +|v_{\max}|$) and the detector a stationary source, so the maximum frequency reflected by the heart wall is

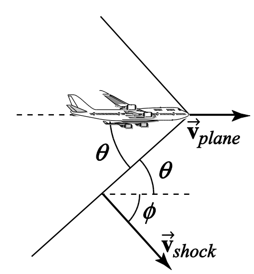
$$(f_{\text{wall}})_{\max} = f_S\left(\frac{v + |v_{\max}|}{v}\right) = (2\ 000\ 000 \text{ Hz})\left(\frac{1500 + 0.0217}{1500}\right) = \boxed{2\ 000\ 029 \text{ Hz}}$$

(c) Now, the heart wall is a moving source ($v_S = +|v_{\max}|$) and the detector a stationary observer. The observed frequency of the returning echo is

$$f_{\text{echo}} = (f_{\text{wall}})_{\max}\left(\frac{v}{v - |v_{\max}|}\right) = (2\ 000\ 029 \text{ Hz})\left(\frac{1500}{1500 - 0.0217}\right) = \boxed{2\ 000\ 058 \text{ Hz}}$$

14.31 The half-angle of the cone of the shock wave is θ where

$$\theta = \sin^{-1}\left(\frac{v_{\text{sound}}}{v_{\text{source}}}\right) = \sin^{-1}\left(\frac{1}{1.5}\right) = 42°$$



As shown in the sketch, the angle between the direction of propagation of the shock wave and the direction of the plane's velocity is

$$\phi = 90^\circ - \theta = 90^\circ - 42^\circ = \boxed{48^\circ}$$

14.32 (a) Equation 14.12 is

$$\boxed{f_O = f_S\left(\frac{v + v_O}{v - v_S}\right)}$$

where f_S is the frequency emitted by the source, f_O is the frequency detected by the observer, v is the speed of the wave in the propagating medium, v_O is the velocity of the observer relative to the medium, and v_S is the velocity of the source relative to the propagating medium.

(b) The $\boxed{\text{yellow submarine}}$ is the source or emitter of the sound waves.

(c) The $\boxed{\text{red submarine}}$ is the observer or receiver of the sound waves.

(d) The motion of the observer away from the source tends to increase the time observed between arrivals of successive pressure maxima. This effect tends to cause an $\boxed{\text{increase in the observed period}}$ and a $\boxed{\text{decrease in the observed frequency.}}$

(e) In this case, the sign of v_O should be $\boxed{\text{negative}}$ to decrease the numerator in Equation 14.12, and thereby decrease the calculated observed frequency.

(f) The motion of the source toward the observer tends to decrease the time between the arrival of successive pressure maxima, $\boxed{\text{decreasing the observed period}}$, and $\boxed{\text{increasing the observed frequency.}}$

(g) In this case, the sign of v_S should be $\boxed{\text{positive}}$ to decrease the denominator in Equation 14.12, and thereby increase the calculated observed frequency.

(h) $$f_O = f_S\left(\frac{v + v_O}{v - v_S}\right) = 5.27 \times 10^3\ \text{Hz}\left[\frac{1\,531a\ \text{m/s} + \ -3.00\ \text{m/s}}{1\,531\ \text{m/s} - \ +11.0\ \text{m/s}}\right] = \boxed{5.30 \times 10^3\ \text{Hz}}$$

14.33 The wavelength of the waves being generated by the speakers is

$$\lambda = \frac{v}{f} = \frac{343\ \text{m/s}}{343\ \text{Hz}} = 1.00\ \text{m} \qquad \text{so} \qquad \frac{\lambda}{2} = 0.500\ \text{m}$$

Since the two speakers are driven by the same sound source or oscillator, they must vibrate in phase with each other. This means that the point at $x = 2.00$ m, being equidistant from the two speakers must be a point of constructive interference. Other points of constructive interference along the line connecting the speakers will be at integral multiples of a half wavelength from this antinode. This means that constructive interference occurs at

$x = 2.00$ m, $2.00\ \text{m} \pm 1\ \ \lambda/2$, $2.00\ \text{m} \pm 2\ \ \lambda/2$, and $2.00\ \text{m} \pm 3\ \ \lambda/2$, or at

$$\boxed{x = 0.500\ \text{m}, 1.00\ \text{m}, 1.50\ \text{m}, 2.00\ \text{m}, 2.50\ \text{m}, 3.00\ \text{m}, \text{and } 3.50\ \text{m}}$$

14.34 The wavelength of the sound emitted by the speaker is

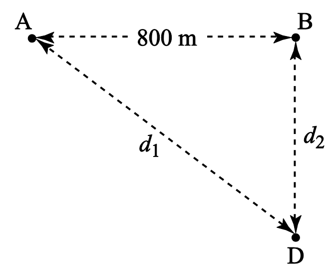
$$\lambda = \frac{v}{f} = \frac{345\ \text{m/s}}{756\ \text{Hz}} = 0.456\ \text{m}$$

and a half wavelength is $\lambda/2 = 0.228$ m .

(a) If a condition of constructive interference currently exists, this can be changed to a case of destructive interference by adding a distance of $\boxed{\lambda/2 = 0.228\text{ m}}$ to the path length through the upper arm.

(b) To move from a case of constructive interference to the next occurrence of constructive interference, one should increase the path length through the upper arm by a full wavelength, or by $\boxed{\lambda = 0.456\text{ m}}$.

14.35 At point D, the distance of the ship from point A is



$$d_1 = \sqrt{d_2^2 + (800\text{ m})^2} = \sqrt{(600\text{ m})^2 + (800\text{ m})^2} = 1000\text{ m}$$

Since destructive interference occurs for the first time when the ship reaches D, it is necessary that $d_1 - d_2 = \lambda/2$, or

$$\lambda = 2(d_1 - d_2) = 2(1000\text{ m} - 600\text{ m}) = \boxed{800\text{ m}}$$

14.36 The speakers emit sound of wavelength $\lambda = v/f = (345\text{ m/s})/450\text{ Hz} = 0.767\text{ m}$, so $\lambda/2 = 0.383\text{ m}$ .At point *O*, $r_1 = r_2 = \sqrt{(1.50\text{ m})^2 + (8.00\text{ m})^2} = 8.14\text{ m}$. To create destructive interference at point *O*, we move the top speaker upward a distance Δy from its original location until we have $r_1 - r_2 = \lambda/2$. Since this did not change r_2, we must now have

$$r_1 = r_2 + \lambda/2 = 8.14\text{ m} + 0.383\text{ m} = 8.52\text{ m}$$

But, after moving the speaker, this gives

$$r_1 = \sqrt{(1.50 \text{ m} + \Delta y)^2 + (8.00 \text{ m})^2} = 8.52 \text{ m}$$

or

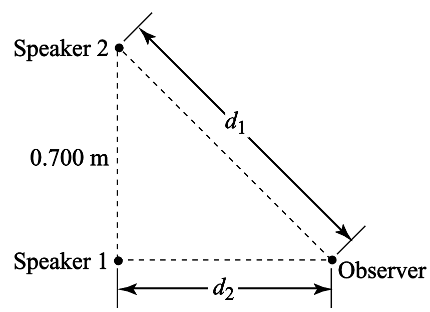
$$(1.50 \text{ m} + \Delta y)^2 = (8.52 \text{ m})^2 - (8.00 \text{ m})^2 = 8.59 \text{ m}^2$$

and

$$\Delta y = \sqrt{8.59 \text{ m}^2} - 1.50 \text{ m} = \boxed{1.43 \text{ m}}$$

14.37 The wavelength of the sound is

$$\lambda = \frac{v}{f} = \frac{345 \text{ m/s}}{690 \text{ Hz}} = 0.500 \text{ m}$$



(a) At the first relative maximum (constructive interference),

$$d_1 = d_2 + \lambda = d_2 + 0.500 \text{ m}$$

Using the Pythagorean theorem,

$$(d_2 + 0.500 \text{ m})^2 = d_2^2 + (0.700 \text{ m})^2, \text{ giving } d_2 = \boxed{0.240 \text{ m}}$$

(b) At the first relative minimum (destructive interference),

$$d_1 = d_2 + \lambda/2 = d_2 + 0.250 \text{ m}$$

Therefore, the Pythagorean theorem yields

$$\left(d_2 + 0.250 \text{ m}\right)^2 = d_2^2 + \left(0.700 \text{ m}\right)^2,$$

or $d_2 = \boxed{0.855 \text{ m}}$

14.38 In the fundamental mode of vibration, the wavelength of waves in the wire is

$$\lambda = 2L = 2\left(0.700\ 0 \text{ m}\right) = 1.400 \text{ m}$$

If the wire is to vibrate at $f = 261.6 \text{ Hz}$, the speed of the waves must be

$$v = \lambda f = \left(1.400 \text{ m}\right)\left(261.6 \text{ Hz}\right) = 366.2 \text{ m/s}$$

With

$$\mu = \frac{m}{L} = \frac{\left(4.300 \times 10^{-3} \text{ kg}\right)}{0.700\ 0 \text{ m}} = 6.143 \times 10^{-3} \text{ kg/m}$$

the required tension is given by $v = \sqrt{F/\mu}$ as

$$F = v^2\mu = \left(366.2 \text{ m/s}\right)^2\left(6.143 \times 10^{-3} \text{ kg/m}\right) = \boxed{824.0 \text{ N}}$$

14.39 In the third harmonic, the string forms a standing wave of three loops, each of length $\lambda/2 = 8.00 \text{ m}/3 = 2.67 \text{ m}$. The wavelength of the wave is then $\lambda = 5.33$ m.

(a) The nodes in this string fixed at each end will occur at distances of $\boxed{0,\ 2.67 \text{ m},\ 5.33 \text{ m, and } 8.00 \text{ m}}$ from the end. Antinodes occur halfway between each pair of adjacent nodes, or at $\boxed{1.33 \text{ m},\ 4.00 \text{ m, and } 6.67 \text{ m}}$ from the end.

(b) The linear density is

$$\mu = \frac{m}{L} = \frac{40.0 \times 10^{-3} \text{ kg}}{8.00 \text{ m}} = 5.00 \times 10^{-3} \text{ kg/m}$$

and the wave speed is

$$v = \sqrt{\frac{F}{\mu}} = \sqrt{\frac{49.0 \text{ N}}{5.00 \times 10^{-3} \text{ kg/m}}} = 99.0 \text{ m/s}$$

Thus, the frequency is

$$f = \frac{v}{\lambda} = \frac{99.0 \text{ m/s}}{5.33 \text{ m}} = \boxed{18.6 \text{ Hz}}$$

14.40 With antinodes at each end and a single node located at the center of the rod, the length of the rod is one-half wavelength, or

$$\lambda = 2L = 2\ 1.00 \text{ m} = 2.00 \text{ m}$$

The speed of sound in aluminum is $v = 5\,100 \text{ m/s}$ (see Table 14.1 in the textbook), so the frequency of the resonance in the rod is

$$f = \frac{v}{\lambda} = \frac{5\,100 \text{ m/s}}{2.00 \text{ m}} = 2.55 \times 10^3 \text{ Hz} = \boxed{2.55 \text{ kHz}}$$

14.41 The facing speakers produce a standing wave in the space between them, with the spacing between nodes being

$$d_{\text{NN}} = \frac{\lambda}{2} = \frac{1}{2}\left(\frac{v}{f}\right) = \frac{343 \text{ m/s}}{2\;800 \text{ Hz}} = 0.214 \text{ m}$$

If the speakers vibrate in phase, the point halfway between them is an antinode of pressure, at $1.25 \text{ m}/2 = 0.625 \text{ m}$ from either speaker.

Then there is a node at $0.625 \text{ m} - 0.214 \text{ m}/2 = \boxed{0.518 \text{ m}}$, and nodes at

$$0.518 \text{ m} - 0.214 \text{ m} = \boxed{0.303 \text{ m}}$$

$$0.303 \text{ m} - 0.214 \text{ m} = \boxed{0.0891 \text{ m}}$$

$$0.518 \text{ m} + 0.214 \text{ m} = \boxed{0.732 \text{ m}},$$

$$0.732 \text{ m} + 0.214 \text{ m} = \boxed{0.947 \text{ m}}$$

and

$$0.947 \text{ m} + 0.214 \text{ m} = \boxed{1.16 \text{ m}}$$

from one speaker.

14.42 In a wire of length ℓ is fixed at both ends, the wavelength of the fundamental mode of vibration is $\lambda_1 = 2\ell$. The speed of transverse waves in the wire is $v = \sqrt{F/\mu}$, where F is the tension in the wire and μ is the mass per unit length of the wire. The fundamental frequency for the wire is then

$$f_1 = \frac{v}{\lambda_1} = \frac{1}{2\ell}\sqrt{\frac{F}{\mu}}$$

If we have two wires with the same mass per unit length, one of length L and under tension F while the second has length $2L$ and tension $4F$, the ratio of the fundamental frequencies of the two wires is

$$\frac{f_{1,\text{ long}}}{f_{1,\text{ short}}} = \frac{1/2L\ \sqrt{4F/\mu}}{1/L\ \sqrt{F/\mu}} = \frac{1}{2}\sqrt{4} = 1$$

or the two wires have the same fundamental frequency of vibration. If this frequency is $f_1 = 60$ Hz, then the frequency of the second harmonic for both wires is

$$f_2 = 2f_1 = 2\ \ 60\text{ Hz}\ = \boxed{120\text{ Hz}}$$

14.43 (a) The linear density is

$$\mu = \frac{m}{L} = \frac{25.0\times10^{-3}\text{ kg}}{1.35\text{ m}} = \boxed{1.85\times10^{-2}\text{ kg/m}}$$

(b) In a string fixed at both ends, the fundamental mode has a node at each end and a single antinode in the center, so that $L = \lambda/2$, or $\lambda = 2L = 2(1.10\text{ m}) = 2.20\text{ m}$.

Then, the wave speed in the wire is $v = \lambda f = (2.20\text{ m})(41.2\text{ Hz}) = \boxed{90.6\text{ m/s}}$

(c) The speed of transverse waves in a string is $v = \sqrt{F/\mu}$, so the required tension is

$$F = \mu v^2 = (1.85\times10^{-2}\text{ kg/m})(90.6\text{ m/s})^2 = \boxed{152\text{ N}}$$

(d) $\lambda = 2L = 2(1.10\text{ m}) = \boxed{2.20\text{ m}}$ [See part (b) above.]

(e) The wavelength of the longitudinal sound waves produced in air by the vibrating string is

$$\lambda_{air} = \frac{v_{air}}{f} = \frac{343\text{ m/s}}{41.2\text{ Hz}} = \boxed{8.33\text{ m}}$$

14.44 (a) A string fixed at each end forms standing wave patterns with a node at each end and an integer number of loops, each of length $\lambda/2$ and with an antinode at its center, between the two ends. Thus, $L = n(\lambda/2)$ or $\lambda = 2L/n$.

If the string has tension F and mass per unit length μ, the speed of transverse waves is $v = \lambda f = \sqrt{T/\mu}$. Thus, when the string forms a standing wave of n loops (and hence n antinodes), the frequency of vibration is

$$f = \frac{v}{\lambda} = \frac{\sqrt{T/\mu}}{2L/n} = \frac{n}{2L}\sqrt{\frac{T}{\mu}} \qquad \Rightarrow \qquad \boxed{f_A = \frac{n_A}{2L_A}\sqrt{\frac{T_A}{\mu}}}$$

(b) Assume the length is doubled, $L_B = 2\,L_A$, and a new standing wave is formed having $n_B = n_A$ and $T_B = T_A$. Then,

$$f_B = \frac{n_B}{2L_B}\sqrt{\frac{T_B}{\mu}} = \frac{n_A}{2\ 2L_A}\sqrt{\frac{T_A}{\mu}} = \frac{1}{2}\left(\frac{n_A}{2L_A}\sqrt{\frac{T_A}{\mu}}\right) = \boxed{\frac{f_A}{2}}$$

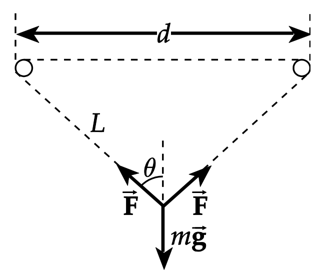
(c) Solving the general result obtained in part (a) for the tension in the string gives $T = 4\mu f^2 L^2/n^2$. Thus, if $f_B = f_A$, $L_B = L_A$, and $n_B = n_A + 1$, we find

$$T_B = \frac{4\mu f_B^2 L_B^2}{n_B^2} = \frac{4\mu f_A^2 L_A^2}{(n_A+1)^2} = \frac{n_A^2}{(n_A+1)^2}\left(\frac{4\mu f_A^2 L_A^2}{n_A^2}\right) = \frac{n_A^2}{(n_A+1)^2}T_A = \boxed{\left(\frac{n_A}{n_A+1}\right)^2 T_A}$$

(d) If now we have $f_B = 3f_A$, $L_B = L_A$, $L_B = L_A/2$, and $n_B = 2n_A$, then

$$T_B = \frac{4\mu f_B^2 L_B^2}{n_B^2} = \frac{4\mu\ 9f_A^2\ \ L_A^2/4}{4n_A^2} = \frac{9}{16}\left(\frac{4\mu f_A^2 L_A^2}{n_A^2}\right) = \frac{9}{16}T_A \text{ or } \boxed{\frac{T_B}{T_A} = \frac{9}{16}}$$

14.45 (a) From the sketch at the right, notice that when



$$d = 2.0\text{ m},\ L = \frac{5.0\text{ m} - d}{2} = 1.5\text{ m},$$

and

$$\theta = \sin^{-1}\left(\frac{d/2}{L}\right) = 42°$$

Then evaluating the net vertical force on the lowest bit of string,

$\Sigma F_y = 2F\cos\theta - mg = 0$ gives the tension in the string as

$$F = \frac{mg}{2\cos\theta} = \frac{(12\text{ kg})(9.80\text{ m/s}^2)}{2\cos(42°)} = \boxed{79\text{ N}}$$

(b) The speed of transverse waves in the string is

$$v = \sqrt{\frac{F}{\mu}} = \sqrt{\frac{79\text{ N}}{0.001\,0\text{ kg/m}}} = 2.8\times10^2\text{ m/s}$$

For the pattern shown,

$$3(\lambda/2) = d\text{, so } \lambda = \frac{2d}{3} = \frac{4.0\text{ m}}{3}$$

Thus, the frequency is

$$f = \frac{v}{\lambda} = \frac{3(2.8\times10^2\text{ m/s})}{4.0\text{ m}} = \boxed{2.1\times10^2\text{ Hz}}$$

14.46 (a) For a standing wave of 6 loops, $6(\lambda/2) = L$, or

$$\lambda = \frac{L}{3} = \frac{2.0\text{ m}}{3}$$

The speed of the waves in the string is then

$$v = \lambda f = \left(\frac{2.0\ \text{m}}{3}\right)(150\ \text{Hz}) = 1.0 \times 10^2\ \text{m/s}$$

Since the tension in the string is $F = mg = (5.0\ \text{kg})(9.80\ \text{m/s}^2) = 49\ \text{N}$, $v = \sqrt{F/\mu}$ gives

$$\mu = \frac{F}{v^2} = \frac{49\ \text{N}}{(1.0 \times 10^2\ \text{m})^2} = \boxed{4.9 \times 10^{-3}\ \text{kg/m}}$$

(b) If $m = 45\ \text{kg}$, then $F = (45\ \text{kg})(9.80\ \text{m/s}^2) = 4.4 \times 10^2\ \text{N}$, and

$$v = \sqrt{\frac{4.4 \times 10^2\ \text{N}}{4.9 \times 10^{-3}\ \text{kg/m}}} = 3.0 \times 10^2\ \text{m/s}$$

Thus,

$$\lambda = \frac{v}{f} = \frac{3.0 \times 10^2\ \text{m/s}}{150\ \text{Hz}} = 2.0\ \text{m}$$

and the number of loops is

$$n = \frac{L}{\lambda/2} = \frac{2.0\ \text{m}}{1.0\ \text{m}} = \boxed{2}$$

(c) If $m = 10$ kg, the tension is $F = (10\ \text{kg})(9.80\ \text{m/s}^2) = 98\ \text{N}$, and

$$v = \sqrt{\frac{98 \text{ N}}{4.9 \times 10^{-3} \text{ kg/m}}} = 1.4 \times 10^{2} \text{ m/s}$$

Then,

$$\lambda = \frac{v}{f} = \frac{1.4 \times 10^{2} \text{ m/s}}{150 \text{ Hz}} = 0.94 \text{ m}$$

and $n = L/\lambda/2 = 2.0\,\text{m}/0.47\,\text{m}$ is not an integer, so $\boxed{\text{no standing wave will form}}$.

14.47 The speed of transverse waves in the string is

$$v = \sqrt{\frac{F}{\mu}} = \sqrt{\frac{50.000 \text{ N}}{1.000\ 0 \times 10^{-2} \text{ kg/m}}} = 70.711 \text{ m/s}$$

The fundamental wavelength is $\lambda_1 = 2L = 1.200\ 0$ m and its frequency is

$$f_1 = \frac{v}{\lambda_1} = \frac{70.711 \text{ m/s}}{1.200\ 0 \text{ m}} = 58.926 \text{ Hz}$$

The harmonic frequencies are then $f_n = nf_1 = n\ 58.926 \text{ Hz}$, with n being an integer.

The largest one under $20\,000$ Hz is $f_{339} = 19\ 976 \text{ Hz} = \boxed{19.976 \text{ kHz}}$

14.48 The distance between adjacent nodes is one-quarter of the circumference.

$$d_{\text{NN}} = d_{\text{AA}} = \frac{\lambda}{2} = \frac{20.0\text{ cm}}{4} = 5.00\text{ cm}$$

so $\lambda = 10.0$ cm = 0.100 m, and

$$f = \frac{v}{\lambda} = \frac{900\text{ m/s}}{0.100\text{ m}} = 9.00 \times 10^3\text{ Hz} = \boxed{9.00\text{ kHz}}$$

The singer must match this frequency quite precisely for some interval of time to feed enough energy into the glass to crack it.

14.49 Assuming an air temperature of $T = 37°\text{C} = 310\ K$, the speed of sound inside the pipe is

$$v = 331\text{ m/s}\sqrt{\frac{T}{273\text{ K}}} = 331\text{ m/s}\sqrt{\frac{310\text{ K}}{273\text{ K}}} = 353\text{ m/s}$$

In the fundamental resonant mode, the wavelength of sound waves in a pipe closed at one end is $\lambda = 4\,L$. Thus, for the whooping crane

$$\lambda = 4\ \ 5.0\text{ ft}\ \ = 2.0 \times 10^1\text{ ft}$$

and

$$f = \frac{v}{\lambda} = \frac{353\text{ m/s}}{2.0 \times 10^1\text{ ft}}\left(\frac{3.281\text{ ft}}{1\text{ m}}\right) = \boxed{58\text{ Hz}}$$

14.50 (a) In the fundamental resonant mode of a pipe open at both ends, the distance between antinodes is $d_{\text{AA}} = \lambda/2 = L$.

Thus, $\lambda = 2\,L = 2\,(0.320\text{ m}) = 0.640\text{ m}$, and

$$f = \frac{v}{\lambda} = \frac{340\text{ m/s}}{0.640\text{ m}} = \boxed{531\text{ Hz}}$$

(b) $$d_{AA} = \frac{\lambda}{2} = \frac{1}{2}\left(\frac{v}{f}\right) = \frac{1}{2}\left(\frac{340\text{ m/s}}{4\ 000\text{ Hz}}\right) = 0.042\ 5\text{ m} = \boxed{4.25\text{ cm}}$$

14.51 Hearing would be best at the fundamental resonance, so $\lambda = 4\,L = 4\,(2.8\text{ cm})$

and $$f = \frac{v}{\lambda} = \frac{340\text{ m/s}}{4\ 2.8\text{ cm}}\left(\frac{100\text{ cm}}{1\text{ m}}\right) = 3.0\times10^{3}\text{ Hz} = \boxed{3.0\text{ kHz}}$$

14.52 (a) To form a standing wave in the tunnel, open at both ends, one must have an antinode at each end, a node at the middle of the tunnel, and the length of the tunnel must be equal to an integral number of half-wavelengths [$L = n\ \lambda/2$ or $\lambda = 2L/n$]. The resonance frequencies of the tunnel are then

$$f_n = \frac{v_{\substack{\text{sound}\\ \text{in air}}}}{\lambda_n} = \frac{345\text{ m/s}}{2L/n} = n\left(\frac{345\text{ m/s}}{2\ 2.00\times10^{3}\text{ m}}\right) = \boxed{n\ 0.0863\text{ Hz}} \quad n = 1,\ 2,\ 3,\ \ldots$$

(b) It would be good to make such a rule. Any car horn would produce several closely spaced resonance frequencies of the air in the tunnel, so the sound would be greatly amplified. Other drivers might be frightened directly into dangerous behavior or might blow their horns also.

14.53 (a) The speed of sound is 331 m/s at 0°C, so the fundamental wavelength of the pipe open at both ends is

$$\lambda_1 = 2L = \frac{v}{f_1}$$

giving

$$L = \frac{v}{2f_1} = \frac{331 \text{ m/s}}{2 \ 300 \text{ Hz}} = \boxed{0.552 \text{ m}}$$

(b) At $T = 30°\text{C} = 303 \text{ K}$,

$$v = 331 \text{ m/s} \sqrt{\frac{T}{273 \text{ K}}} = 331 \text{ m/s} \sqrt{\frac{303 \text{ K}}{273 \text{ K}}} = 349 \text{ m/s}$$

and

$$f_1 = \frac{v}{\lambda_1} = \frac{v}{2L} = \frac{349 \text{ m/s}}{2 \ 0.552 \text{ m}} = \boxed{316 \text{ Hz}}$$

14.54 Observe from Equations 14.18 and 14.19 in the textbook that the difference between successive resonance frequencies is constant, regardless of whether the pipe is open at both ends or is closed at one end. Thus, the resonance frequencies of 650 Hz or less for this pipe must be 650 Hz, 550 Hz, 450 Hz, 350 Hz, 250 Hz, 150 Hz, and 50.0 Hz, with the lowest or fundamental frequency being $\boxed{f_1 = 50.0 \text{ Hz}}$.

Note, from the list given above, the resonance frequencies are only the *odd* multiples of the fundamental frequency. This is a characteristic of a pipe that is $\boxed{\text{closed at one end}}$ and open at the other. The length of such a pipe (with an antinode at the open end and a node at the closed end) is one-quarter of the wavelength of the fundamental frequency, so the length of this pipe must be

$$L = \frac{\lambda_1}{4} = \frac{v_{\text{sound}}}{4f_1} = \frac{340 \text{ m/s}}{4\ 50.0 \text{ Hz}} = \boxed{1.70 \text{ m}}$$

14.55 In a string fixed at both ends, the length of the string is equal to a half-wavelength of the fundamental resonance frequency, so $\lambda_1 = 2L$. The fundamental frequency may then be written as

$$f_1 = \frac{v}{\lambda_1} = \frac{1}{2L}\sqrt{\frac{T}{\mu}} = \sqrt{\frac{T}{4L^2\mu}}$$

If a second identical string with tension $T' < T$ is struck, the fundamental frequency of vibration would be

$$f_1' = \sqrt{\frac{T'}{4L^2\mu}} = \sqrt{\left(\frac{T}{4L^2\mu}\right)\frac{T'}{T}} = f_1\sqrt{\frac{T'}{T}}$$

When the two strings are sounded together, the beat frequency heard will be

$$f_{beat} = f_1 - f_1' = f_1\left(1 - \sqrt{\frac{T'}{T}}\right) = 1.10 \times 10^2 \text{ Hz}\left(1 - \sqrt{\frac{5.40 \times 10^2 \text{ N}}{6.00 \times 10^2 \text{ N}}}\right) = \boxed{5.64 \text{ beats/s}}$$

14.56 By shortening her string, the second violinist increases its fundamental frequency. Thus, $f_1' = f_1 + f_{beat} = 196 + 2.00 \text{ Hz} = 198\text{Hz}$. Since the tension and the linear density are both identical for the two strings, the speed of transverse waves, $v = \sqrt{F/\mu}$, has the same value for both strings. Therefore, $\lambda_1' f_1' = \lambda_1 f_1$, or $\lambda_1' = \lambda_1\ f_1/f_1'$. The fundamental wavelength of a string fixed at both ends is $\lambda = 2L$, and this yields

$$L' = L\left(\frac{f_1}{f_1'}\right) = 30.0 \text{ cm}\left(\frac{196}{198}\right) = \boxed{29.7 \text{ cm}}$$

14.57 The commuter, stationary relative to the station and the first train, hears the actual source frequency ($f_{0,1} = f_S = 180$ Hz) from the first train. The frequency the commuter hears from the second train, moving relative to the station and commuter, is given by

$$f_{O,2} = f_S \pm f_{beat} = 180 \text{ Hz} \pm 2 \text{ Hz} = 178 \text{ Hz or } 182 \text{ Hz}$$

This stationary observer ($v_0 = 0$) hears the lower frequency ($f_{0,2} = 178$ Hz) if the second train is moving *away* from the station $v_S = -|v_S|$, so $f_O = f_S\left(\frac{v + v_O}{v - v_S}\right)$ gives the speed of the receding second train as

$$178 \text{ Hz} = 180 \text{ Hz}\left(\frac{345 \text{ m/s} + 0}{345 \text{ m/s} - \; -|v_S|}\right) = 180 \text{ Hz}\left(\frac{345 \text{ m/s} + 0}{345 \text{ m/s} + |v_S|}\right)$$

or

$$345 \text{ m/s} + |v_S| = 345 \text{ m/s}\left(\frac{180 \text{ Hz}}{178 \text{ Hz}}\right)$$

and

$$|v_S| = 345 \text{ m/s}\left[\left(\frac{180 \text{ Hz}}{178 \text{ Hz}}\right) - 1\right] = 3.88 \text{ m/s}$$

so one possibility for the second train is $\boxed{v_S = 3.88 \text{ m/s away from the station}}$

The other possibility is that the second train is moving toward the station $v_S = +|v_S|$ and the commuter is detecting the higher of the possible frequencies ($f_{0,2}$ = 182 Hz). In this coase, $f_O = f_S[(v + v_O)/(v - v_S)]$ yields

$$182\text{ Hz} = 180\text{ Hz}\left(\frac{345\text{ m/s} + 0}{345\text{ m/s} - |v_S|}\right)$$

and

$$345\text{ m/s} - |v_S| = 345\text{ m/s}\left(\frac{180\text{ Hz}}{182\text{ Hz}}\right)$$

or

$$|v_S| = 345\text{ m/s}\left[1 - \left(\frac{180\text{ Hz}}{182\text{ Hz}}\right)\right] = 3.79\text{ m/s}$$

In this case, the velocity of the second train is $\boxed{v_S = 3.79\text{ m/s toward the station}}$.

14.58 The temperatures of the air in the two pipes are T_1 = 27 °C = 300 K and T_2 = 32°C = 305 K. The speed of sound in the two pipes is

$$v_1 = 331\text{ m/s}\sqrt{\frac{T_1}{273\text{ K}}} \quad \text{and} \quad v_2 = 331\text{ m/s}\sqrt{\frac{T_2}{273\text{ K}}}$$

Since the pipes have the same length, the fundamental wavelength, $\lambda = 4L$, is the same for them. Thus, from $f = v/\lambda$, the ratio of their fundamental frequencies is seen to be $f_2/f_1 = v_2/v_1$, which gives $f_2 = f_1 \; v_2/v_1$.

The beat frequency produced is then

$$f_{\text{beat}} = f_2 - f_1 = f_1\left(\frac{v_2}{v_1} - 1\right) = f_1\left(\sqrt{\frac{T_2}{T_1}} - 1\right)$$

or

$$f_{\text{beat}} = 480\text{ Hz}\left(\sqrt{\frac{305\text{ K}}{300\text{ K}}} - 1\right) = \boxed{3.98\text{ Hz}}$$

14.59 (a) First consider the wall a stationary observer receiving sound from an *approaching* source having velocity v_a. The frequency received and reflected by the wall is

$$f_{\text{reflect}} = f_S\left(\frac{v}{v - v_a}\right).$$

Now consider the wall as a stationary source emitting sound of frequency f_{reflect} to an observer *approaching* at velocity v_a. The frequency of the wave heard by the observer is

$$f_O = f_{\text{reflect}}\left(\frac{v + v_a}{v}\right) = f_S\left(\frac{v}{v - v_a}\right)\left(\frac{v + v_a}{v}\right) = f_S\left(\frac{v + v_a}{v - v_a}\right)$$

Thus, the beat frequency between the tuning fork and its echo is

$$f_{\text{beat}} = f_O - f_S = f_S\left(\frac{v + v_a}{v - v_a} - 1\right) = f_S\left(\frac{2\,v_a}{v - v_a}\right) = (256\text{ Hz})\left(\frac{2\ \ 1.33}{345 - 1.33}\right) = \boxed{1.98\text{ Hz}}$$

(b) When the student moves away from the wall, v_a changes sign so the beat frequency heard is

$$f_{\text{beat}} = f_S \left(\frac{2 \;\; -|v_a|}{v - \;\; -|v_a|} \right) = \frac{2\, f_S\, |v_a|}{v + |v_a|}$$

giving

$$|v_a| = \frac{v\, f_{\text{beat}}}{2\, f_S - f_{\text{beat}}}$$

The receding speed needed to observe a beat frequency of 5.00 Hz is

$$|v_a| = \frac{345 \text{ m/s} \quad 5.00 \text{ Hz}}{2 \;\; 256 \text{ Hz} \;\; - 5.00 \text{ Hz}} = \boxed{3.40 \text{ m/s}}$$

14.60 The extra sensitivity of the ear at 3000 Hz appears as downward dimples on the curves in Figure 14.29 of the textbook.

At $T = 37°\text{C} = 310$ K, the speed of sound in air is

$$v = 331 \text{ m/s} \sqrt{\frac{T}{273 \text{ K}}} = 331 \text{ m/s} \sqrt{\frac{310 \text{ K}}{273 \text{ K}}} = 353 \text{ m/s}$$

Thus, the wavelength of 3 000 Hz sound is

$$\lambda = \frac{v}{f} = \frac{353 \text{ m/s}}{3\ 000 \text{ Hz}} = 0.118 \text{ m}$$

For the fundamental resonant mode in a pipe closed at one end, the length required is

$$L = \frac{\lambda}{4} = \frac{0.118 \text{ m}}{4} = 0.0294 \text{ m} = \boxed{2.94 \text{ cm}}$$

14.61 At normal body temperature of $T = 37°\text{C} = 310 \text{ K}$, the speed of sound in air is

$$v = (331 \text{ m/s})\sqrt{\frac{T}{273 \text{ K}}} = (331 \text{ m/s})\sqrt{\frac{310 \text{ K}}{273 \text{ K}}} = 353 \text{ m/s}$$

and the wavelength of 20 000 Hz sound is

$$\lambda = \frac{v}{f} = \frac{353 \text{ m/s}}{20\ 000 \text{ Hz}} = 1.76 \times 10^{-2} \text{ m} = 1.76 \text{ cm}$$

Thus, the diameter of the eardrum is $\boxed{1.76 \text{ cm}}$

14.62 The decibel level of a sound having intensity I is $\beta = 10 \cdot \log(I/I_0)$, where I_0 is a constant. Solving for the intensity in terms of the decibel level gives $I = I_0\, 10^{\beta/10}$. Thus, if the decibel level of the sound from a single violin is $\beta_1 = 70$ dB, and the decibel level of the sound from the full orchestra is $\beta_2 = 85$ dB, the ratio of the intensity of the full orchestra to that from the single violin is

$$\frac{I_2}{I_1} = \frac{\cancel{I_0} \cdot 10^{\beta_2/10}}{\cancel{I_0} \cdot 10^{\beta_1/10}} = 10^{(\beta_2 - \beta_1)/10} = 10^{\frac{85-70}{10}} = 10^{1.5} = \boxed{32}$$

14.63 (a) With a decibel level of 103 dB, the intensity of the sound at 1.60 m from the speaker is found from $\beta = 10 \cdot \log\left(I/I_0\right)$ as

$$I = I_0 \cdot 10^{\beta/10} = \left(1.00 \times 10^{-12}\ \text{W/m}^2\right) \cdot 10^{10.3} = 2.00 \times 10^{-2}\ \text{W/m}^2$$

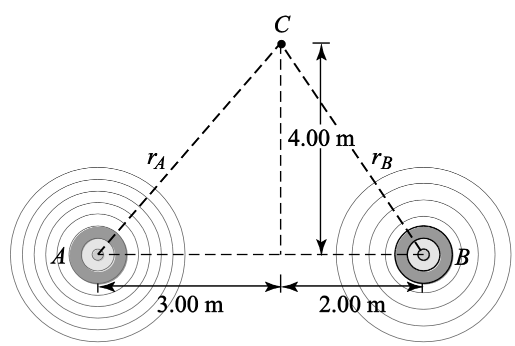
If the speaker broadcasts equally well in all directions, the intensity (power per unit area) at 1.60 m from the speaker is uniformly distributed over a spherical wave front of radius $r = 1.60$ m centered on the speaker. Thus, the power radiated is

$$P = IA = I\left(4\pi r^2\right) = \left(2.00 \times 10^{-2}\ \text{W/m}^2\right)\left[4\pi\left(1.60\ \text{m}\right)^2\right] = \boxed{0.643\ \text{W}}$$

(b) $$\textit{efficiency} = \frac{P_{\text{output}}}{P_{\text{input}}} = \frac{0.643\ \text{W}}{150\ \text{W}} = \boxed{0.0043\ \text{ or }\ 0.43\%}$$

14.64 (a) At point C, the distance from speaker A is

$$r_A = \sqrt{\left(3.00\ \text{m}\right)^2 + \left(4.00\ \text{m}\right)^2} = 5.00\ \text{m}$$



and the intensity of the sound from this speaker is

$$I_A = \frac{P_A}{4\pi r_A^2} = \frac{1.00 \times 10^{-3}\ \text{W}}{4\pi\left(5.00\ \text{m}\right)^2} = 3.18 \times 10^{-6}\ \text{W/m}^2$$

The sound level at C due to speaker A alone is then

$$\beta_A = 10 \cdot \log\left(\frac{I_A}{I_0}\right) = 10 \cdot \log\left(\frac{3.18 \times 10^{-6}\ \text{W/m}^2}{1.00 \times 10^{-12}\ \text{W/m}^2}\right) = \boxed{65.0\ \text{dB}}$$

(b) The distance from point C to speaker B is $r_B = \sqrt{(2.00\ \text{m})^2 + (4.00\ \text{m})^2} = 4.47\ \text{m}$ and the intensity of the sound from this speaker alone is

$$I_B = \frac{P_B}{4\pi r_B^2} = \frac{1.50 \times 10^{-3}\ \text{W}}{4\pi(4.47\ \text{m})^2} = 5.97 \times 10^{-6}\ \text{W/m}^2$$

The sound level at C due to speaker B alone is therefore

$$\beta_B = 10 \cdot \log\left(\frac{I_B}{I_0}\right) = 10 \cdot \log\left(\frac{5.97 \times 10^{-6}\ \text{W/m}^2}{1.00 \times 10^{-12}\ \text{W/m}^2}\right) = \boxed{67.8\ \text{dB}}$$

(c) If both speakers are sounded together, the total sound intensity at point C is

$$I_{AB} = I_A + I_B = 3.18 \times 10^{-6}\ \text{W/m}^2 + 5.97 \times 10^{-6}\ \text{W/m}^2 = 9.15 \times 10^{-6}\ \text{W/m}^2$$

and the total sound level in decibels is

$$\beta_{AB} = 10 \cdot \log\left(\frac{I_{AB}}{I_0}\right) = 10 \cdot \log\left(\frac{9.15 \times 10^{-6}\ \text{W/m}^2}{1.00 \times 10^{-12}\ \text{W/m}^2}\right) = \boxed{69.6\ \text{dB}}$$

14.65 We assume that the average intensity of the sound is directly proportional to the number of cars passing each minute. If the sound level in decibels is $\beta = 10 \cdot \log(I/I_0)$, the intensity of the sound is $I = I_0 \cdot 10^{\beta/10}$, so the average intensity in the afternoon, when 100 cars per minute are passing, is

$$I_{100} = I_0 \cdot 10^{80.0/10} = 1.00 \times 10^{-12}\ \text{W/m}^2 \cdot 10^{8.00} = 1.00 \times 10^{-4}\ \text{W/m}^2$$

The expected average intensity at night, when only 5 cars pass per minute, is given by the ratio $I_5/I_{100} = 5/100 = 1/20$, or

$$I_5 = \frac{I_{100}}{20} = \frac{1.00 \times 10^{-4}\ \text{W/m}^2}{20} = 5.00 \times 10^{-6}\ \text{W/m}^2$$

and the expected sound level in decibels is

$$\beta_5 = 10 \cdot \log\left(\frac{I_5}{I_0}\right) = 10 \cdot \log\left(\frac{5.00 \times 10^{-6}\ \text{W/m}^2}{1.00 \times 10^{-12}\ \text{W/m}^2}\right) = \boxed{67.0\ \text{dB}}$$

14.66 The well will act as a pipe closed at one end (the bottom) and open at the other (top). The resonant frequencies are the *odd integer multiples* of the fundamental frequency, or $f_n = (2n - 1)f_1$ where $n = 1, 2, 3, \ldots$.. Thus, if f_n and f_{n+1} are two successive resonant frequencies, their difference is

$$f_{n+1} - f_n = \left[2\ n + 1\ - 1\right] f_1 - \ 2n - 1\ f_1 = \left(\cancel{2n} + 2 - \cancel{1} - \cancel{2n} + \cancel{1}\right) f_1 = 2 f_1$$

In this case, we have 60.0 Hz–52.0 Hz = $2f_1$, giving the fundamental frequency for the well as f_1 = 4.00 Hz. In the fundamental mode, the well (pipe closed at one end) forms a standing wave pattern with a node at the bottom and the first antinode at the top, making the depth of the well

$$d = \frac{\lambda_1}{4} = \frac{1}{4}\left(\frac{v_{sound}}{f_1}\right) = \frac{1}{4}\left(\frac{345\ \text{m/s}}{4.00\ \text{Hz}}\right) = \boxed{21.6\ \text{m}}$$

14.67 The frequency heard from the first train, moving *toward* the stationary observer at $v_{S\,1} = +30.0\ \text{m/s}$, is

$$f_{O\,1} = f_S\left(\frac{v}{v - v_{S\,1}}\right) = 300\ \text{Hz}\left(\frac{345\ \text{m/s}}{345\ \text{m/s} - 30.0\ \text{m/s}}\right) = 328.6\ \text{Hz}$$

The second train moves *toward the observer* at $v_{S\,2} = +v_2 > 30.0\ \text{m/s}$. The frequency heard from this train must be

$$f_{O\,2} = f_{O\,1} + f_{beat} = 328.6\ \text{Hz} + 3.0\ \text{Hz} = 331.6\ \text{Hz}$$

Then, from

$$f_{O\,2} = f_S\left(\frac{v}{v - v_{S\,2}}\right) = f_S\left(\frac{v}{v - v_2}\right)$$

the speed of the *approaching* second train must be

$$v_2 = v\left(1 - \frac{f_S}{f_{O\,2}}\right) = 345\ \text{m/s}\left(1 - \frac{300\ \text{Hz}}{331.6\ \text{Hz}}\right) = \boxed{32.9\ \text{m/s}}$$

14.68 (a) If a source emits sound of frequency f_S (as detected by an observer stationary relative to the source), the frequency detected by the observer when the source and/or the observer is in motion is $f_O = f_S\ v + v_O \big/ v - v_S$ where v is the velocity of sound in air, v_O is the velocity of the observer, and v_S is the velocity of the source. In the given situation, $f_S = 320$ Hz, $v_O = 0$, and when the train is approaching the observer, $v_S = +40\ \text{m/s}$. Thus, the frequency heard by the observer is

$$f_{O,a} = 320\text{ Hz}\left(\frac{345\text{ m/s} + 0}{345\text{ m/s} - 40.0\text{ m/s}}\right) = \boxed{362\text{ Hz}}$$

(b) When the train is receding from the stationary observer, $v_S = -40.0$ m/s and the detected frequency will be

$$f_{O,b} = 320\text{ Hz}\left(\frac{345\text{ m/s} + 0}{345\text{ m/s} - \ -40.0\text{ m/s}}\right) = 320\text{ Hz}\left(\frac{345\text{ m/s}}{385\text{ m/s}}\right) = \boxed{287\text{ Hz}}$$

c) The wavelengths measured by the observer in each of the 2 cases above are

$$\lambda_a = \frac{v}{f_{O,a}} = \frac{345\text{ m/s}}{362\text{ Hz}} = \boxed{0.953\text{ m}} \text{ and } \lambda_b = \frac{v}{f_{O,b}} = \frac{345\text{ m/s}}{287\text{ Hz}} = \boxed{1.20\text{ m}}$$

14.69 This situation is very similar to the fundamental resonance of an organ pipe that is open at both ends. The wavelength of the standing waves in the crystal is $\lambda = 2t$, where t is the thickness of the crystal, and the frequency is

$$f = \frac{v}{\lambda} = \frac{3.70\times10^{3}\text{ m/s}}{2\ 7.05\times10^{-3}\text{ m}} = 2.62\times10^{5}\text{ Hz} = \boxed{262\text{ kHz}}$$

14.70 The distance from the balcony to the man's head is

$$\Delta y = 20.0\text{ m} - 1.75\text{ m} = 18.3\text{ m}$$

The time for a warning to travel this distance is

$$t_1 = \frac{18.3 \text{ m}}{345 \text{ m/s}} = 0.0529 \text{ s}$$

so the total time needed to receive the warning and react is $t_1' = t_1 + 0.300 \text{ s} = 0.353 \text{ s}$.

The time for the pot to fall this distance, starting from rest, is

$$t_2 = \sqrt{\frac{2 \ \Delta y}{a_y}} = \sqrt{\frac{2 \ -18.3 \text{ m}}{-9.80 \text{ m/s}^2}} = 1.93 \text{ s}$$

Thus, the latest the warning should be sent is at

$$t = t_2 - t_1' = 1.93 \text{ s} - 0.353 \text{ s} = 1.58 \text{ s}$$

into the fall. In this time interval, the pot has fallen

$$\Delta y = \frac{1}{2} g t^2 = \frac{1}{2} \ 9.80 \text{ m/s}^2 \quad 1.58 \text{ s}^{\ 2} = 12.2 \text{ m}$$

and is $h = 20.0 \text{ m} - 12.2 \text{ m} = \boxed{7.8 \text{ m}}$ above the sidewalk.

14.71 On the weekend, there are one-fourth as many cars passing per minute as on a week day. Thus, the intensity, I_2, of the sound on the weekend is one-fourth that, I_1, on a week day. The difference in the decibel levels is therefore:

$$\beta_1 - \beta_2 = 10\log\left(\frac{I_1}{I_o}\right) - 10\log\left(\frac{I_2}{I_o}\right) = 10\log\left(\frac{I_1}{I_2}\right) = 10\log(4) = 6\text{ dB}$$

so,

$$\beta_2 = \beta_1 - 6\text{ dB} = 70\text{ dB} - 6\text{ dB} = \boxed{64\text{ dB}}$$

14.72 (a) At $T = 20°\text{C} = 293$ K, the speed of sound in air is

$$v = 331\text{ m/s}\sqrt{\frac{T}{273\text{ K}}} = 331\text{ m/s}\sqrt{\frac{293\text{ K}}{273\text{ K}}} = 343\text{ m/s}$$

The first harmonic or fundamental of the flute (a pipe open at both ends) is given by

$$\lambda_1 = 2L = \frac{v}{f_1} = \frac{343\text{ m/s}}{261.6\text{ Hz}} = 1.31\text{ m}.$$

Therefore, the length of the flute is

$$L = \frac{\lambda_1}{2} = \frac{1.31\text{ m}}{2} = \boxed{0.655\text{ m}}$$

(b) In the colder room, the length of the flute and hence its fundamental wavelength is essentially unchanged (that is, $\lambda_1 = \lambda_1 = 1.31$ m). However, the speed of sound and thus the frequency of the fundamental will be lowered. At this lower temperature, the frequency must be

$$f_1' = f_1 - f_{beat} = 261.6\text{ Hz} - 3.00\text{ Hz} = 258.6\text{ Hz}$$

The speed of sound in this room is

$$v' = \lambda_1' f_1' = (1.31 \text{ m})(258.6 \text{ Hz}) = 339 \text{ m/s}$$

From $v = (331 \text{ m/s})\sqrt{T/273 \text{ K}}$, the temperature in the colder room is given by

$$T = (273 \text{ K})\left(\frac{v}{331 \text{ m/s}}\right)^2 = (273 \text{ K})\left(\frac{339 \text{ m/s}}{331 \text{ m/s}}\right)^2 = 286 \text{ K} = \boxed{13.0°\text{C}}$$

14.73 The maximum speed of the oscillating block and speaker is

$$v_{\text{max}} = A\omega = A\sqrt{\frac{k}{m}} = (0.500 \text{ m})\sqrt{\frac{20.0 \text{ N/m}}{5.00 \text{ kg}}} = 1.00 \text{ m/s}$$

When the speaker (sound source) moves *toward* the stationary observer, then $v_S = +v_{\text{max}}$ and the maximum frequency heard is

$$(f_O)_{\text{max}} = f_S\left(\frac{v}{v - v_{\text{max}}}\right) = (440 \text{ Hz})\left(\frac{345 \text{ m/s}}{345 \text{ m/s} - 1.00 \text{ m/s}}\right) = \boxed{441 \text{ Hz}}$$

When the speaker moves *away from* the stationary observer, the source velocity is $v_S = -v_{\text{max}}$ and the minimum frequency heard is

$$(f_O)_{\text{min}} = f_S\left(\frac{v}{v + v_{\text{max}}}\right) = (440 \text{ Hz})\left(\frac{345 \text{ m/s}}{345 \text{ m/s} + 1.00 \text{ m/s}}\right) = \boxed{439 \text{ Hz}}$$

14.74 The speed of transverse waves in the wire is

$$v = \sqrt{\frac{F}{\mu}} = \sqrt{\frac{F \cdot L}{m}} = \sqrt{\frac{400\text{ N}\quad 0.750\text{ m}}{2.25 \times 10^{-3}\text{ kg}}} = 365\text{ m/s}$$

When the wire vibrates in its third harmonic, $\lambda = 2L/3 = 0.500$ m, so the frequency of the vibrating wire and the sound produced by the wire is

$$f = \frac{v}{\lambda} = \frac{365\text{ m/s}}{0.500\text{ m}} = 730\text{ Hz}$$

Since both the wire and the wall are stationary, the frequency of the wave reflected from the wall matches that of the waves emitted by the wire. Thus, as the student approaches the wall at speed $|v_O|$, he approaches one stationary source and recedes from another stationary source, both emitting frequency $f_S = 730$ Hz. The two frequencies that will be observed are

$$f_{O\ 1} = f_S\left(\frac{v + |v_O|}{v}\right) \text{ and } f_{O\ 2} = f_S\left(\frac{v - |v_O|}{v}\right)$$

The beat frequency is

$$f_{\text{beat}} = \quad f_{O\ 1} - \quad f_{O\ 2} = f_S\left(\frac{v + |v_O| - \quad v - |v_O|}{v}\right) = \frac{2f_S\,|v_O|}{v}$$

so

$$|v_O| = \left(\frac{f_{\text{beat}}}{2f_S}\right)v = \left[\frac{8.30 \text{ Hz}}{2 \;\; 730 \text{ Hz}}\right] 340 \text{ m/s} = \boxed{1.93 \text{ m/s}}$$

14.75 The speeds of the two types of waves in the rod are

$$v_{\text{long}} = \sqrt{\frac{Y}{\rho}} = \sqrt{\frac{Y}{m/V}} = \sqrt{\frac{Y \;\; A \cdot L}{m}} \text{ and } v_{\text{trans}} = \sqrt{\frac{F}{\mu}} = \sqrt{\frac{F}{m/L}} = \sqrt{\frac{F \cdot L}{m}}$$

Thus, if $v_{\text{long}} = 8v_{\text{trans}}$, we have

$$\frac{Y \;\; A \cdot L}{m} = 64\left(\frac{F \cdot L}{m}\right)$$

or the required tension is

$$F = \frac{Y \cdot A}{64} = \frac{6.80 \times 10^{10} \text{ N/m}^2 \left[\pi \;\; 0.200 \times 10^{-2} \text{ m} \;\; ^2\right]}{64} = \boxed{1.34 \times 10^4 \text{ N}}$$

14.76 (a) As the student walks along the line connecting the locations of the two speakers, she is walking away from the first speaker with velocity $v_O = -|v_O| = -1.50 \text{ m/s}$, and toward the second speaker with velocity $v'_O = +|v_O|$. Thus, she will experience a Doppler shift in the sound from each of the stationary ($v_S = 0$) speakers. The frequency detected from the first speaker is $f_{O,1} = f_S\left[\;\; v - |v_O| \;\; /v\right] = f_S \;\; 1 - |v_O|/v$, and the frequency detected from the second speaker is $f_{O,2} = f_S \;\; 1 + |v_O|/v$. The beat frequency she will hear as she receives these slightly different frequencies together is

$$f_{\text{beat}} = f_{O,2} - f_{O,1} = f_s\left(1 + \frac{|v_O|}{v}\right) - f_s\left(1 - \frac{|v_O|}{v}\right)$$

$$= 2f_s\left(\frac{|v_O|}{v}\right) = 2\ \ 456\ \text{Hz}\ \left(\frac{1.50\ \ \text{m/s}}{345\ \ \text{m/s}}\right) = \boxed{3.97\ \ \text{beats/s}}$$

(b) The wavelength of the sound produced by each of the speakers will be

$$\lambda = \frac{v}{f} = \frac{345\ \ \text{m/s}}{456\ \text{Hz}} = 0.757\ \text{m}$$

In the standing wave pattern that forms along the line connecting the two speakers, successive antinodes will be separated by a distance $\Delta x = \lambda/2 = 0.378\ \text{m}$. As the student walks along this line with speed $|v_O| = 1.50\ \ \text{m/s}$, she will hear an intensity maximum every time she passes an antinode. The time interval (period) between hearing successive maxima is given by $T = \Delta x / |v_O|$, so the number of intensity maxima heard per second (frequency) will be

$$f_{\text{maxima}} = \frac{1}{T} = \frac{|v_O|}{\Delta x} = \frac{1.50\ \ \text{m/s}}{0.378\ \text{m}} = \boxed{3.97\ \text{Hz}}$$

(c) $\boxed{\text{The answers are identical. The models are equally valid.}}$ We may think of the interference of the two waves as interference in space or in time, linked to space by the steady motion of the student.