14
Sound

QUICK QUIZZES

1. Choice (c). The speed of sound in air is given by $v = (331\ \text{m/s})\sqrt{T/273\ \text{K}}$. Thus, increasing the absolute temperature, T, will increase the speed of sound. Changes in frequency, amplitude, or air pressure have no effect on the speed of sound.

2. Choice (c). The distance between you and the buzzer is increasing. Therefore, the intensity at your location is decreasing. As the buzzer falls, it moves away from you with increasing speed. This causes the detected frequency to decrease.

3. Choice (b). The speed of sound increases in the warmer air, while the speed of the sound source (the plane) remains constant. Therefore, the ratio of the speed of the source to that of sound (that is, the Mach number) decreases.

4. Choices (b) and (e). A string fastened at both ends can resonate at any integer multiple of the fundamental frequency. Of the choices listed, only 300 Hz and 600 Hz are integer multiples of the 150 Hz fundamental frequency.

5. Choice (d). In the fundamental mode, an open pipe has a node at the center and antinodes at each end. The fundamental wavelength of the open pipe is then twice the length of the pipe and the fundamental frequency is $f_{\text{open}} = v/2L$. When one end of the pipe is closed, the fundamental mode has a node at the closed end and an antinode at the open end. In this case, the fundamental wavelength is four times the length of the pipe and the fundamental frequency is $f_{\text{close}} = v/4L$.

6. Choice (a). The change in the length of the pipe, and hence the fundamental wavelength, is negligible. As the temperature increases, the speed of sound in air increases and this causes an increase in the fundamental frequency, $f_0 = v/\lambda_0$.

7. Choice (b). Since the beat frequency is steadily increasing, you are increasing the difference between the frequency of the string and the frequency of the tuning fork. Thus, your action is counterproductive and you should reverse course by loosening the string.

ANSWERS TO WARM-UP EXERCISES

1. (a) We take the logarithm (base 10) of both sides:

$$\log_{10}\left(10^x\right) = \log_{10}(5)$$

or

$$x = \log_{10}(5) = \boxed{0.699}$$

(b) We exponentiate both sides:

$$10^{\log(3x)} = 10^2$$

which gives

$$3x = 10^2 \qquad \rightarrow \qquad x = \boxed{33.3}$$

2. Dividing both sides of the equation gives

$$7.5\ \text{dB} = \log\left(\frac{I}{10^{-12}\ \text{W/m}^2}\right)$$

Exponentiating both sides then yields

$$10^{7.5\ \text{dB}} = 10^{\log\left(\frac{I}{10^{-12}\ \text{W/m}^2}\right)}$$

or

$$\frac{I}{10^{-12}\ \text{W/m}^2} = 10^{7.5}$$

which gives

$$I = \left(10^{-12}\ \text{W/m}^2\right)\left(10^{7.5}\right) = 3.16\times10^{-5}\ \text{W/m}^2$$

3. From Equation 13.17,

$$\lambda = \frac{\upsilon}{f} = \frac{343\ \text{m/s}}{440\ \text{Hz}} = \boxed{0.780\ \text{m}}$$

4. (a) The linear mass density of the string is

$$\mu = \frac{m}{L} = \frac{12.0\times10^{-3}\ \text{kg}}{1.50\ \text{m}} = \boxed{8.00\times10^{-3}\ \text{kg/m}}$$

(b) From Equation 13.18,

$$\upsilon = \sqrt{\frac{F}{\mu}} = \sqrt{\frac{85.0\ \text{N}}{8.00\times10^{-3}\ \text{kg/m}}} = \boxed{103\ \text{m/s}}$$

5. The dependence of the speed of sound in air on temperature is obtained from Equation 14.4:

$$\upsilon = (331\ \text{m/s})\sqrt{\frac{T}{273\ \text{K}}} = (331\ \text{m/s})\sqrt{\frac{331\ \text{K}}{273\ \text{K}}} = \boxed{364\ \text{m/s}}$$

6. (a) The speed of sound in a fluid is obtained from Equation 14.1:

$$\upsilon = \sqrt{\frac{B}{\rho}} = \sqrt{\frac{1.0\times10^{9}\ \text{Pa}}{0.806\times10^{3}\ \text{kg/m}^3}} = \boxed{1\,100\ \text{m/s}}$$

(b) Table 9.1 gives the density of aluminum as 2.7×10^3 kg/m^3, and Table 9.2 gives the bulk modulus of aluminum as 7.0×10^{10} Pa. Then,

$$\upsilon = \sqrt{\frac{B}{\rho}} = \sqrt{\frac{7.0\times10^{10}\ \text{Pa}}{2.7\times10^{3}\ \text{kg/m}^3}} = \boxed{5.1\times10^{3}\ \text{m/s}}$$

7. We use the equation for intensity level in decibels:

$$\beta = 10\log\left(\frac{I}{I_0}\right)$$

Substituting $\beta = 105\ \text{dB},$ we obtain

$$\frac{105}{10} = \log\left(\frac{I}{I_0}\right)$$

exponentiating both sides yields

$$10^{10.5} = 10^{\log\left(\frac{I}{I_0}\right)} = \frac{I}{I_0}$$

or $\quad I = 10^{10.5} I_0 = 10^{10.5}\left(10^{-12}\ \text{W/m}^2\right) = \boxed{3.16\times10^{-2}\ \text{W/m}^2}$

8. (a) We use the equation for intensity level in decibels:

$$\beta = 10\log\left(\frac{I}{I_0}\right)$$

Substituting $\beta = 118$ dB, we obtain

$$\frac{118}{10} = \log\left(\frac{I}{I_0}\right)$$

exponentiating both sides yields

$$10^{11.8} = 10^{\log\left(\frac{I}{I_0}\right)} = \frac{I}{I_0}$$

or $I = 10^{11.8} I_0 = 10^{11.8}\left(10^{-12}\ \text{W/m}^2\right) = \boxed{0.631\ \text{W/m}^2}$

(b) Intensity is defined as power per unit area. If the sound from the travels as a spherical wave, then the power supplied by the amplifiers is spread over the surface of a sphere of radius 32.0 m. Then,

$$P = IA = I\left(4\pi r^2\right) = \left(0.631\ \text{W/m}^2\right)\left[4\pi(32.0\ \text{m})^2\right]$$
$$= \boxed{8.12\times10^3\ \text{W}}$$

9. (a) The dependence of the speed of sound in air on temperature is obtained from Equation 14.4:

$$v = (331\ \text{m/s})\sqrt{\frac{T}{273\ \text{K}}} = (331\ \text{m/s})\sqrt{\frac{308\ \text{K}}{273\ \text{K}}} = \boxed{352\ \text{m/s}}$$

(b) We use Equation 14.10 for an observer moving away from a stationary source, and substitute $-v_\text{O}$ to obtain

$$f_O = f_s\left(\frac{v - v_o}{v}\right)$$

substituting the value of v found in part (a), we obtain

$$f_O = f_s\left(\frac{v - v_o}{v}\right) = \left(3.30\times10^2\ \text{Hz}\right)\left(\frac{352\ \text{m/s} - 67.1\ \text{m/s}}{352\ \text{m/s}}\right)$$
$$= \boxed{267\ \text{Hz}}$$

10. We use Equation 14.11 for a stationary observer and a source moving toward the observer:

$$f_O = f_s\left(\frac{v}{v - v_S}\right) = (675\ \text{Hz})\left(\frac{343\ \text{m/s}}{343\ \text{m/s} - 30.0\ \text{m/s}}\right) = \boxed{740\ \text{Hz}}$$

11. (a) From Equation 13.17,

$$\lambda = \frac{v}{f} = \frac{331\ \text{m/s}}{225\ \text{Hz}} = \boxed{1.47\ \text{m}}$$

(b) Constructive interference occurs when the path difference for the sound emitted by the two speakers is an integer multiple of the wavelength. If the man moves ½ wavelength toward one speaker, he has moved ½ wavelength away from the second speaker for a total of one wavelength of path difference. Thus, to reach the next maximum, the man travels a distance of

$$\frac{1}{2}\lambda = \frac{1}{2}(1.47\ \text{m}) = \boxed{0.735\ \text{m}}$$

12. (a) The mass per unit length of the string is

$$\mu = \frac{m}{L} = \frac{0.025\ 0\ \text{kg}}{2.00\ \text{m}} = \boxed{1.25\times10^{-2}\ \text{kg/m}}$$

(b) From Equation 13.18,

$$v = \sqrt{\frac{F}{\mu}} = \sqrt{\frac{50.0\ \text{N}}{1.25\times10^{-2}\ \text{kg/m}}} = \boxed{63.2\ \text{m/s}}$$

(c) From Equation 14.15, the fundamental frequency for this string is given by

$$f_1 = \frac{v}{2L} = \frac{63.2\ \text{m/s}}{2(2.00\ \text{m})} = \boxed{15.8\ \text{Hz}}$$

(d) The frequency of the second harmonic is twice that of the fundamental, or

$$f_2 = 2f_1 = 2(15.8\ \text{Hz}) = \boxed{31.6\ \text{Hz}}$$

13. (a) The fundamental frequency for a closed pipe (open on one end, closed on the other) is given by

$$f_1 = \frac{v}{4L} = \frac{343\ \text{m/s}}{4(0.580\ \text{m})} = \boxed{148\ \text{Hz}}$$

(b) For closed pipes, only odd harmonics are possible, so the next harmonic is the third harmonic, with a frequency three times that of the fundamental, or

$$f_3 = 3f_1 = 3(148\ \text{Hz}) = \boxed{444\ \text{Hz}}$$

(c) For a pipe open at both ends,

$$f_1 = \frac{v}{2L} = \frac{343\ \text{m/s}}{2(0.580\ \text{m})} = \boxed{296\ \text{Hz}}$$

14. Beat frequency is given by Equation 14.20 as

$$f_b = |f_1 - f_2|$$

To produce a beat frequency of 3 Hz, the second source has to have a frequency that is 3 Hz higher or 3 Hz lower than the first source, or

$$f_2 = 4.40\times10^2\ \text{Hz} \pm 3\ \text{Hz} = \boxed{437\ \text{Hz or } 443\ \text{Hz}}$$

ANSWERS TO EVEN NUMBERED CONCEPTUAL QUESTIONS

2. The resonant frequency depends on the length of the pipe. Thus, changing the length of the pipe will cause different frequencies to be emphasized in the resulting sound. The shorter the pipe, the higher the fundamental resonance frequency.

4. The speed of light is so high that the arrival of the flash is practically simultaneous with the lightning discharge. Thus, the delay between the flash and the arrival of the sound of thunder is the time sound takes to travel the distance separating the lightning from you. By counting the seconds between the flash and thunder and knowing the approximate speed of sound in air, you have a rough measure of the distance to the lightning bolt.

6. A vibrating string is not able to set very much air into motion when vibrated alone. Thus it will not be very loud. If it is placed on the instrument, however, the string's vibration sets the sounding board of the guitar into vibration. A vibrating piece of wood is able to move a lot of air, and the note is louder.

8. A beam of electromagnetic waves of known frequency is sent toward a speeding car, which reflects the beam back to a detector in the police car. The amount the returning frequency has been shifted depends on the velocity of the oncoming car.

10. Consider the level of fluid in the bottle to be adjusted so that the air column above it resonates at the first harmonic. This is given by $f = v/4L$. This equation indicates that as the length L of the column increases (fluid level decreases), the resonant frequency decreases.

ANSWERS TO EVEN NUMBERED PROBLEMS

2. 1×10^{11} Pa

4. 0.196 s

6. $\lambda = 17$ m for $f = 20$ Hz; $\lambda = 1.7$ cm for $f = 20\,000$ Hz

8. 18.6 m

10. **(a)** 1.0×10^{3} W/m^2

(b) The intensity level is 1 000 times that at the threshold of pain.

12. 150 dB

14. **(a)** 5.0×10^{-17} W **(b)** 5.0×10^{-5} W

16. **(a)** 0.316 W/m^2 **(b)** 1.58 W/m^2 **(c)** 2.47×10^{-2} W/m^2

(d) 104 dB **(e)** 1.26×10^{6} m

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

18. **(a)** 1.32×10^{-4} W/m^2 **(b)** 81.2 dB

20. **(a)** 7.96×10^{-2} W/m^2 **(b)** 109 dB **(c)** 2.82 m

22. **(a)** $I_A/I_B = 2$ **(b)** $I_A/I_C = 5$

24. **(a)** 10.0 kHz **(b)** 3.33 kHz

26. 32.0 m/s

28. **(a)** 3.29 m/s **(b)** Yes, the bat gains on the insect at a rate of 1.71 m/s.

30. **(a)** 2.16×10^{-2} m/s **(b)** 2 000 029 Hz **(c)** 2 000 058 Hz

32. **(a)** $f_O = f_S\left[(v+v_O)/(v-v_S)\right]$ **(b)** the yellow submarine **(c)** the red submarine

(d) increases the time (period), decreases the frequency **(e)** negative

(f) decreases the time (period), increases the frequency **(g)** positive

(h) 5.30×10^{3} Hz

34. **(a)** 0.227 m **(b)** 0.454 m

36. 1.43 m

38. 823.8 N

40. 1.00 cm toward the nut

42. 120 Hz

44. **(a)** $f_A = \frac{n_A}{2L_A}\sqrt{\frac{T_A}{\mu_A}}$ **(b)** $f_B = f_A/2$ **(c)** $T_B = \left(\frac{n_A}{n_A+1}\right)^2 T_A$

(d) $T_B/T_A = 9/16$

46. **(a)** $\mu = 4.9\times10^{-3}$ kg/m **(b)** 2

(c) no standing wave will form

48. 9.00 kHz

50. **(a)** 536 Hz **(b)** 4.29 cm

52. **(a)** $f_n = n(0.0858\text{ Hz})$ $n = 1, 2, 3, \ldots$

(b) Yes. The tunnel can resonate at many closely spaced frequencies, and the sound would be greatly amplified.

54. **(a)** $f_1 = 50.0$ Hz **(b)** open at only one end **(c)** 1.72 m

56. 29.7 cm

58. 3.98 Hz

60. 2.95 cm

62. ~1 000 mosquitoes

64. **(a)** 65.0 dB **(b)** 67.8 dB **(c)** 69.6 dB

66. 21.4 m

68. 1 204 Hz

70. 7.8 m

72. **(a)** 0.655 m **(b)** 13.4°C

74. 1.95 m/s

76. **(a)** 32.2°C **(b)** 3.6×10^2 Hz

PROBLEM SOLUTIONS

14.1 (a) We ignore the time required for the lightning flash to arrive. Then, the distance to the lightning stroke is

$$d = v_{sound}\cdot\Delta t = (343\text{ m/s})(16.2\text{ s}) = 5.56\times10^3\text{ m} = \boxed{5.56\text{ km}}$$

(b) $\boxed{\text{No.}}$ Since $v_{light} >> v_{sound}$, 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, and knowledge of the actual value of the speed of light is not needed.

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

$$B = \rho v^2 = \left(2\,500 \text{ kg/m}^3\right)\left(7\times10^3 \text{ m/s}\right)^2 = \boxed{1\times10^{11} \text{ Pa}}$$

14.3 The Celsius temperature is $T_C = \frac{5}{9}\left(T_F - 32\right) = \frac{5}{9}\left(114-32\right) = 45.6°\text{C}$ and the speed of sound in the air is

$$v = \left(331 \text{ m/s}\right)\sqrt{1+\frac{T_C}{273}} = \left(331 \text{ m/s}\right)\sqrt{1+\frac{45.6}{273}} = \boxed{358 \text{ m/s}}$$

14.4 The speed of sound in seawater at 25°C is 1533 m/s. Therefore, the time for the sound to reach the sea floor and return is

$$t = \frac{2d}{v} = \frac{2(150 \text{ m})}{1\,533 \text{ m/s}} = \boxed{0.196 \text{ s}}$$

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 distance the sound traveled to the mountain was

$$d = \left(343 \text{ m/s}\right)(1.50 \text{ s}) = \boxed{515 \text{ m}}$$

14.6 At $T = 27°\text{C}$, the speed of sound in air is

$$v = \left(331 \text{ m/s}\right)\sqrt{1+\frac{T_C}{273}} = \left(331 \text{ m/s}\right)\sqrt{1+\frac{27}{273}} = 347 \text{ m/s}$$

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

$$\lambda = \frac{347 \text{ m/s}}{20\,000 \text{ Hz}} = 1.7\times10^{-2} \text{ m} = 1.7 \text{ cm}$$

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

14.7 At $T = 27.0°\text{C}$, the speed of sound in air is

$$v_{27} = \left(331 \text{ m/s}\right)\sqrt{1+\frac{T_C}{273}} = \left(331 \text{ m/s}\right)\sqrt{1+\frac{27.0}{273}} = 347 \text{ m/s}$$

and at $T = 10.0°\text{C}$, the speed is

$$v_{10} = \left(331 \text{ m/s}\right)\sqrt{1+\frac{T_C}{273}} = \left(331 \text{ m/s}\right)\sqrt{1+\frac{10.0}{273}} = 337 \text{ m/s}$$

Since $v = \lambda f$, the change in wavelength will be

$$\Delta\lambda = \frac{v_{10}}{f} - \frac{v_{27}}{f} = \frac{v_{10}-v_{27}}{f} = \frac{(337-347) \text{ m/s}}{4.00\times10^3 \text{ Hz}} = -2.5\times10^{-3} \text{ m} = \boxed{-2.5 \text{ mm}}$$

14.8 At a temperature of $T = 10.0°C$, the speed of sound in air is

$$v = (331 \text{ m/s})\sqrt{1+\frac{T_C}{273}} = (331 \text{ m/s})\sqrt{1+\frac{10.0}{273}} = 337 \text{ m/s}$$

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

With $v = 337$ m/s and $g = 9.80$ m/s^2, this becomes $(1.45\times10^{-2} \text{ s}^{-1})t_1^2 + t_1 - 2.00 \text{ s} = 0$

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

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

14.9 (a) Because the speed of sound in air is $v_{\text{air}} = 343$ m/s while its speed in the steel rail is

$v_{\text{steel}} = 5\,950$ m/s, $\boxed{\text{the pulse traveling in the steel rail arrives first}}$.

(b) The difference in times when the two pulses reach the microphone at the opposite end of the rail is

$$\Delta t = \frac{L}{v_{\text{air}}} - \frac{L}{v_{\text{steel}}} = (8.50 \text{ m})\left(\frac{1}{343 \text{ m/s}} - \frac{1}{5\,950 \text{ m/s}}\right) = 2.34\times10^{-2} \text{ s} = \boxed{23.4 \text{ ms}}$$

14.10 (a) The decibel level, β, of a sound is given $\beta = 10\log(I/I_0)$, where I is the intensity of the sound, and $I_0 = 1.0\times10^{-12}$ W/m^2 is the reference intensity. Therefore, if $\beta = 150$ dB, the intensity is

$$I = I_0 \times 10^{\beta/10} = (1.0\times10^{-12} \text{ W/m}^2)\times10^{15} = \boxed{1.0\times10^3 \text{ W/m}^2}$$

(b) The threshold of pain is $I = 1$ W/m^2 and the answer to part (a) is 1000 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 $(I = \text{constant}/r^2)$, 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 $\beta_2 - \beta_1 = -29.5$ dB. This gives the decibel level on Rodriguez Island as

$$\beta_2 = \beta_1 - 29.5\text{ dB} = 180\text{ dB} - 29.5\text{ dB} = \boxed{151\text{ dB}}$$

14.12 The decibel level due to the first siren is

$$\beta_1 = 10 \cdot \log\left(\frac{100.0\text{ W/m}^2}{1.0\times10^{-12}\text{ W/m}^2}\right) = 140\text{ dB}$$

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

If $\beta_2 - \beta_1 = 30.0$ dB and $I_1 = 3.0\times10^{-11}\text{ W/m}^2$, then

$$I_2 = \left(3.0\times10^{-11}\text{ W/m}^2\right)\times10^{3.00} = \boxed{3.0\times10^{-8}\text{ W/m}^2}$$

14.14 The sound power incident on the eardrum is $P = IA$, where I is the intensity of the sound and $A = 5.0\times10^{-5}\text{ m}^2$ is the area of the eardrum.

(a) At the threshold of hearing, $I = 1.0\times10^{-12}\text{ W/m}^2$, and

$$P = \left(1.0\times10^{-12}\text{ W/m}^2\right)\left(5.0\times10^{-5}\text{ m}^2\right) = \boxed{5.0\times10^{-17}\text{ W}}$$

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

(a) If $\beta = 100$ dB, then $\log(I/I_0) = 10$, 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

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

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

14.16 (a) From the defining equation of the decibel level, $\beta = 10\cdot\log(I/I_0)$, 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

$$\frac{I_2}{I_1} = \left(\frac{r_1}{r_2}\right)^2 \quad \text{or} \quad I_2 = I_1\left(\frac{r_1}{r_2}\right)^2 = \left(1.58\ \text{W/m}^2\right)\left(\frac{1.0\ \text{m}}{8.0\ \text{m}}\right)^2 = \boxed{2.47\times10^{-2}\ \text{W/m}^2}$$

(d) $$\beta_{\text{row 1}} = 10\cdot\log\left(\frac{I_{\text{row 1}}}{I_0}\right) = 10\cdot\log\left(\frac{2.47\times10^{-2}\ \text{W/m}^2}{1.0\times10^{-12}\ \text{W/m}^2}\right) = \boxed{104\ \text{dB}}$$

(e) The intensity of sound at the threshold of hearing is $I_0 = 1.0\times10^{-12}\ \text{W/m}^2$, and from the discussion and result of part (c), we have $I_0/I_2 = \left(r_2/r_0\right)^2$, and with the intensity being $I_2 = 2.47\times10^{-2}\ \text{W/m}^2$ at distance $r_2 = 8.0\ \text{m}$, the distance at which the intensity would be $I_0 = 1.0\times10^{-12}\ \text{W/m}^2$ is

$$r_0 = r_2\sqrt{\frac{I_2}{I_0}} = (8.0\ \text{m})\sqrt{\frac{2.47\times10^{-2}\ \text{W/m}^2}{1.0\times10^{-12}\ \text{W/m}^2}} = \boxed{1.26\times10^6\ \text{m}}$$

(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 $r_1 = 5.0\ \text{m}$ and $r_2 = 10\ \text{km} = 10^4\ \text{m}$, the intensities of the sound wave radiating out from the elephant are $I_1 = P_{av}/4\pi r_1^2$ and $I_2 = P_{av}/4\pi r_2^2$ giving $I_2 = \left(r_1/r_2\right)^2 I_1$. From the defining equation, $\beta = 10\log\left(I/I_0\right)$, 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 $$\beta_2 = 20\log\left(\frac{5.0\ \text{m}}{10^4\ \text{m}}\right) + \beta_1 = -66\ \text{dB} + 103\ \text{dB} = \boxed{37\ \text{dB}}$$

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

$$I = I_{\text{music}} + I_{\text{baby}} = I_0\left(10^{8.0} + 10^{7.5}\right)$$

$$= \left(1.0\times10^{-12}\ \text{W/m}^2\right)\left(1.32\times10^8\right) = \boxed{1.32\times10^{-4}\ \text{W/m}^2}$$

(b) The combined sound level is

$$\beta = 10\log\left(I/I_0\right) = 10\log\left(1.32\times10^8\right) = \boxed{81.2\ \text{dB}}$$

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

$$I = I_0 10^{\beta/10} = \left(1.0\times10^{-12}\ \text{W/m}^2\right)10^{5.0} = 1.0\times10^{-7}\ \text{W/m}^2$$

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

$$P = 4\pi r^2 I = 4\pi\left(10\times10^3\ \text{m}\right)^2\left(1.0\times10^{-7}\ \text{W/m}^2\right) = 4\pi\times10^1\ \text{W} = \boxed{1.3\times10^2\ \text{W}}$$

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

$$I = \frac{P}{4\pi r^2} = \frac{1.3\times10^2 \text{ W}}{4\pi(50 \text{ m})^2} = 4.1\times10^{-3} \text{ W/m}^2$$

and the sound level is

$$\beta = 10\log\left(\frac{I}{I_0}\right) = 10\log\left(\frac{4.1\times10^{-3} \text{ W/m}^2}{1.0\times10^{-12} \text{ W/m}^2}\right) = 10\log\left(4.1\times10^9\right) = \boxed{96 \text{ dB}}$$

14.20 (a) $I = \dfrac{P}{4\pi r^2} = \dfrac{100 \text{ W}}{4\pi(10.0 \text{ m})^2} = \boxed{7.96\times10^{-2} \text{ W/m}^2}$

(b) $\beta = 10\log\left(\dfrac{I}{I_0}\right) = 10\log\left(\dfrac{7.96\times10^{-2} \text{ W/m}^2}{1.00\times10^{-12} \text{ W/m}^2}\right)$

$= 10\log\left(7.96\times10^{10}\right) = \boxed{109 \text{ dB}}$

(c) At the threshold of pain (β = 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

$$r = \sqrt{\frac{P}{4\pi I}} = \sqrt{\frac{100 \text{ W}}{4\pi\left(1.00 \text{ W/m}^2\right)}} = \boxed{2.82 \text{ m}}$$

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

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

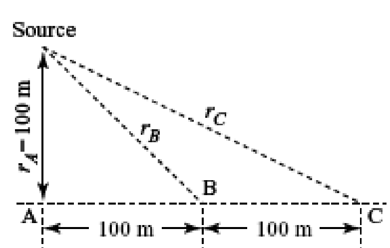
Since $I = P/4\pi r^2 = \left(P/4\pi\right)/r^2$, the ratio of intensities is

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

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

14.22 The intensity at distance r from the source is $I = \dfrac{P}{4\pi r^2} = \dfrac{\left(P/4\pi\right)}{r^2}$

(a) $\dfrac{I_A}{I_B} = \dfrac{r_B^2}{r_A^2} = \dfrac{(100 \text{ m})^2 + (100 \text{ m})^2}{(100 \text{ m})^2} = \boxed{2}$



(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 $(v_O = 0)$ 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

$$(f_O)_{\text{approach}} = (320 \text{ Hz})\left(\frac{343 \text{ m/s}}{343 \text{ m/s} - 40.0 \text{ m/s}}\right) = 362 \text{ Hz}$$

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

$$(f_O)_{\text{recede}} = (320 \text{ Hz})\left[\frac{343 \text{ m/s}}{343 \text{ m/s} - (-40.0 \text{ m/s})}\right] = 287 \text{ Hz}$$

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

$\Delta f_O = (f_O)_{\text{recede}} - (f_O)_{\text{approach}} = -75 \text{ Hz}$, or it is a $\boxed{75 \text{ Hz drop}}$

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

$$\lambda = \frac{v}{(f_O)_{\text{approach}}} = \frac{343 \text{ m/s}}{362 \text{ Hz}} = \boxed{0.948 \text{ m}}$$

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 $f_S = 5.00 \text{ kHz}$ 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 $f_S = 5.00 \text{ kHz}$ and the source moves away from a stationary observer at half the speed of sound $(v_S = -v/2)$, 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

$$v_S = 90.0\ \frac{\text{km}}{\text{h}}\left(\frac{1\ 000\ \text{m}}{1\ \text{km}}\right)\left(\frac{1\ \text{h}}{3\ 600\ \text{s}}\right) = 25.0\ \text{m/s}$$

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

$$f_O = (500\ \text{Hz})\left(\frac{343\ \text{m/s} + 36.1\ \text{m/s}}{343\ \text{m/s} - 25.0\ \text{m/s}}\right) = \boxed{596\ \text{Hz}}$$

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

(b) With the cyclist (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, $v_O = +|v_{\text{cyclist}}| = +|v_{\text{car}}|/3$ and $v_S = -|v_{\text{car}}|$, where $|v_{\text{car}}|$ is the speed of the car.

The observed frequency is

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

giving

$$415\ \text{Hz} = (440\ \text{Hz})\left(\frac{343\ \text{m/s} + |v_{\text{car}}|/3}{343\ \text{m/s} + |v_{\text{car}}|}\right) \quad \text{and} \quad |v_{\text{car}}| = \boxed{32.0\ \text{m/s}}$$

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

$$465\ \text{Hz} = f_S\left(\frac{343\ \text{m/s}}{343\ \text{m/s} - |v_t|}\right) \qquad \textbf{[1]}$$

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

$$441\ \text{Hz} = f_S\left(\frac{343\ \text{m/s}}{343\ \text{m/s} + |v_t|}\right) \qquad \textbf{[2]}$$

Dividing Equation [1] by [2] gives

$$\frac{465}{441} = \frac{343\ \text{m/s} + |v_t|}{343\ \text{m/s} - |v_t|}$$

and solving for the speed of the train yields $|v_t| = \boxed{9.09\ \text{m/s}}$.

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

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

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, $v_S = -|v_{\text{bug}}|$, and the observer (bat) is moving *toward* the source (insect) giving $v_O = +|v_{\text{bat}}|$. The frequency of the return sound received by the bat is then

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

Combing the results of the two 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

$$40.4 \text{ kHz} = (40.0 \text{ kHz})\left(\frac{343 \text{ m/s}-|v_{\text{bug}}|}{343-5.00}\right)\left(\frac{343+5.00}{343 \text{ m/s}+|v_{\text{bug}}|}\right)$$

This reduces to

$$343 \text{ m/s}+|v_{\text{bug}}| = \left(\frac{40.0}{40.4}\right)\left(\frac{348}{338}\right)\left(343 \text{ m/s}-|v_{\text{bug}}|\right)$$

or

$$\left[\left(\frac{40.0}{40.4}\right)\left(\frac{348}{338}\right)+1\right]|v_{\text{bug}}| = (343 \text{ m/s})\left[\left(\frac{40.0}{40.4}\right)\left(\frac{348}{338}\right)-1\right]$$

and yields $|v_{\text{bug}}| = \boxed{3.29 \text{ m/s}}$.

(b) $\boxed{\text{Yes, the bat is gaining on the insect at a rate of } 5.00 \text{ m/s} - 3.29 \text{ m/s} = 1.71 \text{ m/s}}$..

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

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

Thus, the speed the falling tuning fork must reach is

$$|v_S| = v\left(\frac{f_S}{f_O} - 1\right) = (343\ \text{m/s})\left(\frac{512\ \text{Hz}}{485\ \text{Hz}} - 1\right) = 19.1\ \text{m/s}$$

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

$$\Delta y_1 = \frac{v_S^2 - 0}{2a_y} = \frac{(19.1\ \text{m/s})^2 - 0}{2(9.80\ \text{m/s}^2)} = 18.6\ \text{m}$$

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

$$t = \frac{\Delta y_1}{v} = \frac{18.6\ \text{m}}{343\ \text{m/s}} = 0.054\,2\ \text{s}$$

During this time the fork falls an additional distance

$$\Delta y_2 = v_S t + \frac{1}{2}a_y t^2 = (19.1\ \text{m/s})(0.054\,2\ \text{s}) + \frac{1}{2}(9.80\ \text{m/s}^2)(0.054\,2\ \text{s})^2 = 1.05\ \text{m}$$

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

$$\Delta y = \Delta y_1 + \Delta y_2 = 18.6\ \text{m} + 1.05\ \text{m} = \boxed{19.7\ \text{m}}$$

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

and for harmonic motion,

$$(f_{\text{wall}})_{\max} = f_S\left(\frac{v + |v_{\max}|}{v}\right) = (2\,000\,000\ \text{Hz})\left(\frac{1\,500 + 0.021\,6}{1\,500}\right) = \boxed{2\,000\,029\ \text{Hz}}$$

(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

$$(f_{\text{wall}})_{\max} = f_S\left(\frac{v + |v_{\max}|}{v}\right) = (2\,000\,000\ \text{Hz})\left(\frac{1\,500 + 0.021\,6}{1\,500}\right) = \boxed{2\,000\,029\ \text{Hz}}$$

(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

$$f_{\text{echo}} = (f_{\text{wall}})_{\max}\left(\frac{v}{v - |v_{\max}|}\right) = (2\,000\,029\ \text{Hz})\left(\frac{1\,500}{1\,500 - 0.021\,6}\right) = \boxed{2\,000\,058\ \text{Hz}}$$

14.31 (a) For a plane traveling at Mach 3.00, the half-angle of the conical wave front is

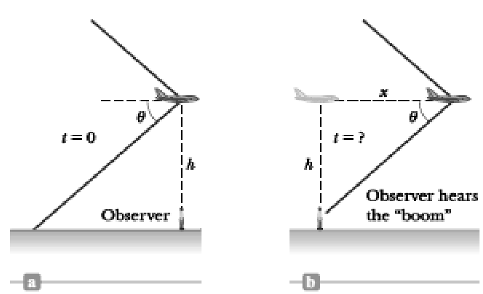


FIGURE P14.31

$$\theta = \sin^{-1}\left(\frac{v_{\text{sound}}}{v_{\text{plane}}}\right) = \sin^{-1}\left(\frac{1}{3.00}\right)$$

The distance the plane has moved when the wave front reaches the observer is $x = h/\tan\theta$, or

$$x = \frac{20.0 \text{ km}}{\tan\left[\sin^{-1}(1/3.00)\right]} = 56.6 \text{ km}$$

The time required for the plane to travel this distance, and hence the time when the shock wave reaches the observer, is

$$t = \frac{x}{v_{\text{plane}}} = \frac{x}{3.00 v_{\text{sound}}} = \frac{56.6\times10^3 \text{ m}}{3.00(335 \text{ m/s})} = \boxed{56.3 \text{ s}}$$

(b) The plane is $\boxed{\text{56.6 km farther along}}$ as computed above.

14.32 (a) From Equation 14.12 in the textbook,

$$\boxed{f_o = f_s\left(\frac{v+v_o}{v-v_s}\right)}$$

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 $\boxed{\text{decrease in the observed frequency.}}$

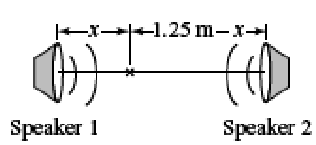
(e) In this case, the sign of v_0 should be $\boxed{\text{negative}}$ to decrease the numerator in Equation 14.12, and thereby decrease the calculated observed frequency.

(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) $$f_o = f_s\left(\frac{v+v_o}{v-v_s}\right) = (5.27\times10^3 \text{ Hz})\left[\frac{1\,533 \text{ m/s}+(-3.00 \text{ m/s})}{1\,533 \text{ m/s}-(+11.0 \text{ m/s})}\right] = \boxed{5.30\times10^3 \text{ Hz}}$$

14.33 The wavelength of the waves generated by the speakers is



$$\lambda = \frac{v}{f} = \frac{343 \text{ m/s}}{800 \text{ Hz}} = 0.429 \text{ m}$$

For the waves from the two speakers to interfere destructively at some point, the difference in the path lengths from the speakers to that point must be an odd multiple of a half-wavelength. Thus, along the line connecting the two speakers, destructive interference (and minima in amplitude) occur where

$$(1.25\text{ m} - x) - x = (2n+1)\frac{\lambda}{2} \quad \text{where } n \text{ is any integer}$$

or where $x = 0.625\text{ m} - (2n+1)\frac{\lambda}{4} = 0.625\text{ m} - \left(\frac{2n+1}{4}\right)(0.429\text{ m})$

This gives $n = 0 \Rightarrow x = 0.518\text{ m}$ $\quad n = -1 \Rightarrow x = 0.732\text{ m}$

$n = 1 \Rightarrow x = 0.303\text{ m}$ $\quad n = -2 \Rightarrow x = 0.947\text{ m}$

$n = 2 \Rightarrow x = 0.089\text{ m}$ $\quad n = -3 \Rightarrow x = 1.16\text{ m}$

Thus, minima occur at distances of

$$\boxed{0.089\text{ m}, 0.303\text{ m}, 0.518\text{ m}, 0.732\text{ m}, 0.947\text{ m, and } 1.16\text{ m}}$$

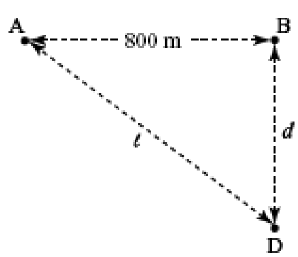
from either speaker.

14.34 The wavelength of the sound emitted by the speaker is $\lambda = \frac{v}{f} = \frac{343\text{ m/s}}{756\text{ Hz}} = 0.454\text{ m}$, and a half wavelength is $\lambda/2 = 0.227\text{ m}$.

(a) If a condition of constructive interference currently exists, this can be changed to a case of destructive interference by adding a distance of $\boxed{\lambda/2 = 0.227\text{ m}}$ 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 $\boxed{\lambda = 0.454\text{ m}}$.

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

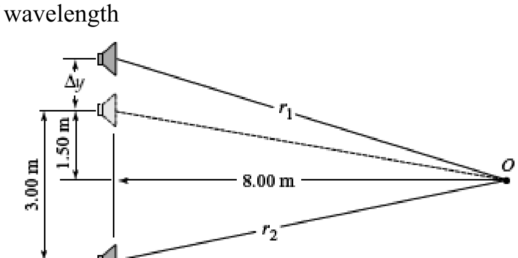


$$\ell = \sqrt{d^2 + (800\text{ m})^2} = \sqrt{(600\text{ m})^2 + (800\text{ m})^2} = 1\,000\text{ m}$$

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

$$l = 2(\ell - d) = 2(1\,000\text{ m} - 600\text{ m}) = \boxed{800\text{ m}}$$

14.36 The speakers emit sound of wavelength



$$\lambda = \frac{v}{f} = \frac{343 \text{ m/s}}{450 \text{ Hz}} = 0.762 \text{ m}$$

so $\lambda/2 = 0.381 \text{ m}$

Initially, $\Delta y = 0$, and

$$r_1 = r_2 = \sqrt{(1.50 \text{ m})^2 + (8.00 \text{ m})^2} = 8.14 \text{ m}$$

To create destructive interference at point *O*, we move the top speaker upward 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

$$r_1 = r_2 + \lambda/2 = 8.14 \text{ m} + 0.381 \text{ m} = 8.52 \text{ m}$$

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

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

14.37 The wavelength of the sound is

$$\lambda = \frac{v}{f} = \frac{343 \text{ m/s}}{686 \text{ Hz}} = 0.500 \text{ m}$$

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

$$r = x + \lambda = x + 0.500 \text{ m}$$

Using the Pythagorean theorem, $r^2 = x^2 + d^2$, or

$$(x + 0.500 \text{ m})^2 = x^2 + (0.700 \text{ m})^2$$

giving $x = \boxed{0.240 \text{ m}}$. .

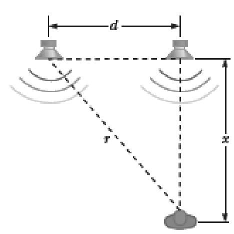


FIGURE P14.37 (modified)

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

$$r = x + \lambda/2 = x + 0.250 \text{ m}$$

Therefore, the Pythagorean theorem yields

$$(x + 0.250 \text{ m})^2 = x^2 + (0.700 \text{ m})^2$$

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

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

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

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

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

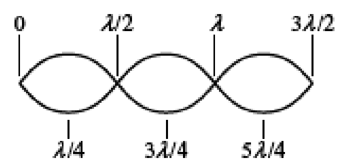
The mass per unit length of the wire is

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

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

$$F = v^2 \mu = (366.2\ \text{m/s})^2 (6.143 \times 10^{-3}\ \text{kg/m}) = \boxed{823.8\ \text{N}}$$

14.39 In the third harmonic, the string of length L forms a standing wave of three loops, each of length $\lambda/2 = L/3$. The wavelength of the wave is then



$$\lambda = \frac{2L}{3} = \frac{16.0\ \text{m}}{3} = 5.33\ \text{m}$$

(a) The nodes in this string, fixed at each end, will occur at distances of $\boxed{0,\ \lambda/2 = 2.67\ \text{m},\ \lambda = 5.33\ \text{m, and}\ 3\lambda/2 = 8.00\ \text{m}}$ from the end.

Antinodes occur halfway between each pair of adjacent nodes, or at distances of $\boxed{\lambda/4 = 1.33\ \text{m},\ 3\lambda/4 = 4.00\ \text{m, and}\ 5\lambda/4 = 6.67\ \text{m}}$ 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 $f = \dfrac{v}{\lambda} = \dfrac{99.0\ \text{m/s}}{5.33\ \text{m}} = \boxed{18.6\ \text{Hz}}$

14.40 In the fundamental mode, the distance from the finger of the cellist to the far end of the string is one-half of the wavelength for the transverse waves in the string. Thus, when the string resonates at 449 Hz,

$$\lambda = 2(68.0\ \text{cm} - 20.0\ \text{cm}) = 96.0\ \text{cm}$$

The speed of transverse waves in the string is therefore

$$v = \lambda f = (0.960 \text{ m})(449 \text{ Hz}) = 431 \text{ m/s}$$

For a resonance frequency of 440 Hz, the wavelength would be

$$\lambda' = \frac{v}{f'} = \frac{431 \text{ m/s}}{440 \text{ Hz}} = 0.980 \text{ m} = 98.0 \text{ cm}$$

To produce this tone, the cellist should position her finger at a distance of

$$x = L - \frac{\lambda}{2} = 68.0 \text{ cm} - \frac{98.0 \text{ cm}}{2} = 19.0 \text{ cm}$$

from the nut. Thus, she should $\boxed{\text{move her finger 1.00 cm toward the nut.}}$

14.41 When the string vibrates in the fifth harmonic (i.e., in five equal segments) at a frequency of $f_5 = 630 \text{ Hz}$, we have $L = 5(\lambda_5/2)$, or the wavelength is $\lambda_5 = 2L/5$. The speed of transverse waves in the string is then

$$v = \lambda_5 f_5 = (2L/5) f_5$$

For the string to vibrate in three segments (i.e., third harmonic), the wavelength must be such that $L = 3(\lambda_3/2)$ or $\lambda_3 = 2L/3$. The new frequency would then be

$$f_3 = \frac{v}{\lambda_3} = \frac{(2L/5) f_5}{2L/3} = \frac{3}{5} f_5 = \frac{3}{5}(630 \text{ Hz}) = \boxed{378 \text{ Hz}}$$

14.42 If 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

$$f_1 = \frac{v}{\lambda_1} = \frac{1}{2\ell}\sqrt{\frac{F}{\mu}} = \frac{1}{2}\left(\frac{1}{\ell}\right)\sqrt{\frac{F}{\mu}}$$

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

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

or the two wires have the same fundamental frequency of vibration. If this frequency is $f_1 = 60 \text{ Hz}$, 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 $\mu = \dfrac{m}{L} = \dfrac{25.0 \times 10^{-3} \text{ kg}}{1.35 \text{ m}} = \boxed{1.85 \times 10^{-2} \text{ kg/m}}$

(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 desired 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

$$F = \mu v^2 = (1.85 \times 10^{-2} \text{ kg/m})(90.6 \text{ m/s})^2 = \boxed{152 \text{ N}}$$

(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

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

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 loop of length $\lambda/2$, with an antinode at its center. Thus, $L = n(\lambda/2)$ or $\lambda = 2L/n$.

If the string has tension T 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

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

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

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

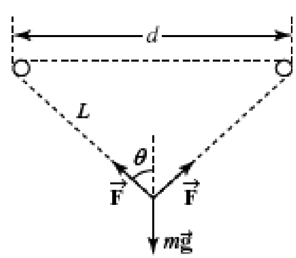
(c) Solving the general result obtained in part (a) for the tension in the string gives $T = 4\mu f^2 L^2/n^2$. Thus, if $f_B = f_A$, $L_B = L_A$, and $n_B = n_A + 1$, we find

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

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

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

14.45 (a) From the sketch at the right, notice that when $d = 2.00$ m,



$$L = \frac{5.00 \text{ m} - d}{2} = 1.50 \text{ m},$$

and

$$\theta = \sin^{-1}\left(\frac{d/2}{L}\right) = 41.8∝$$

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

$$F = \frac{mg}{2\cos\theta} = \frac{(12.0 \text{ kg})(9.80 \text{ m/s}^2)}{2\cos(41.8°)} = \boxed{78.9 \text{ N}}$$

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

$$v=\sqrt{\frac{F}{\mu}}=\sqrt{\frac{78.9\text{ N}}{0.00100\text{ kg/m}}}=2.81\times10^{2}\text{ m/s}$$

For the pattern shown,

$$3(\lambda/2)=d,\text{ so }\lambda=\frac{2d}{3}=\frac{4.00\text{ m}}{3}$$

Thus, the frequency is

$$f=\frac{v}{\lambda}=\frac{3(2.81\times10^{2}\text{ m/s})}{4.00\text{ m}}=\boxed{2.11\times10^{2}\text{ Hz}}$$

14.46 (a) For a standing wave of 6 loops, $6(\lambda/2)=L$, or $\lambda=L/3=(2.0\text{ m})/3$.

The speed of the waves in the string is then

$$v=\lambda f=\left(\frac{2.0\text{ m}}{3}\right)(150\text{ Hz})=1.0\times10^{2}\text{ m/s}$$

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

$$\mu=\frac{F}{v^2}=\frac{49\text{ N}}{(1.0\times10^{2}\text{ m})^2}=\boxed{4.9\times10^{-3}\text{ kg/m}}$$

(b) If $m=45\text{ kg}$, then $F=(45\text{ kg})(9.80\text{ m/s}^2)=4.4\times10^{2}\text{ N}$, and

$$v=\sqrt{\frac{4.4\times10^{2}\text{ N}}{4.9\times10^{-3}\text{ kg/m}}}=3.0\times10^{2}\text{ m/s}$$

Thus, the wavelength will be

$$\lambda=\frac{v}{f}=\frac{3.0\times10^{2}\text{ m/s}}{150\text{ Hz}}=2.0\text{ m}$$

and the number of loops is $n=\dfrac{L}{\lambda/2}=\dfrac{2.0\text{ m}}{1.0\text{ m}}=\boxed{2}$

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

$$v=\sqrt{\frac{98\text{ N}}{4.9\times10^{-3}\text{ kg/m}}}=1.4\times10^{2}\text{ m/s}$$

Then, $\lambda=\dfrac{v}{f}=\dfrac{1.4\times10^{2}\text{ m/s}}{150\text{ Hz}}=0.93\text{ m}$

and $n=\dfrac{L}{\lambda/2}=\dfrac{2.0\text{ m}}{0.47\text{ m}}$ 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 $\lambda_1 = 2L = 1.200\,0 \text{ m}$ 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 $20\,000 \text{ Hz}$ is $f_{339} = 19\,976 \text{ Hz} = \boxed{19.976 \text{ kHz}}$.

14.48 The distance between adjacent nodes (and between adjacent antinodes) is one-quarter of the circumference.

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

so $\lambda = 10.0 \text{ cm} = 0.100 \text{ m}$,

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

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

In the fundamental resonant mode, the wavelength of sound waves in a pipe closed at one end is $\lambda = 4L$. 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 $d_{AA} = \lambda/2 = L$.

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

and $f = \frac{v}{\lambda} = \frac{343 \text{ m/s}}{0.640 \text{ m}} = \boxed{536 \text{ Hz}}$

(b) $d_{AA} = \frac{\lambda}{2} = \frac{1}{2}\left(\frac{v}{f}\right) = \frac{1}{2}\left(\frac{343 \text{ m/s}}{4\,000 \text{ Hz}}\right) = 4.29 \times 10^{-2} \text{ m} = \boxed{4.29 \text{ cm}}$

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

and $f = \frac{v}{\lambda} = \frac{343 \text{ m/s}}{4(2.8 \text{ cm})}\left(\frac{100 \text{ cm}}{1 \text{ m}}\right) = 3.1\times 10^3 \text{ Hz} = \boxed{3.1 \text{ kHz}}$

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

$$f_n = \frac{v_{\substack{\text{sound}\\ \text{in air}}}}{\lambda_n} = \frac{343 \text{ m/s}}{2L/n} = n\left(\frac{343 \text{ m/s}}{2(2.00\times 10^3 \text{ m})}\right) = \boxed{n(0.0858 \text{ Hz})} \quad n = 1,\ 2,\ 3,\ \ldots$$

(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 fundamental wavelength of the pipe open at both ends is $\lambda_1 = 2L = v/f_1$. Since the speed of sound is 331 m/s at 0°C, the length of the pipe is

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

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

$$v = (331 \text{ m/s})\sqrt{\frac{T_K}{273}} = (331 \text{ m/s})\sqrt{\frac{303}{273}} = 349 \text{ m/s}$$

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 (a) 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 $\boxed{f_1 = 50.0 \text{ Hz}}$.

(b) 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 $\boxed{\text{open at only one end}}$ and closed at the other.

(c) The length of 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

$$L = \frac{\lambda_1}{4} = \frac{v_{\text{sound}}}{4f_1} = \frac{343 \text{ m/s}}{4(50.0 \text{ Hz})} = \boxed{1.72 \text{ m}}$$

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

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

If a second identical string with tension $F' < F$ is struck, the fundamental frequency of vibration would be

$$f_1' = \sqrt{\frac{F'}{4L^2\mu}} = \sqrt{\left(\frac{F}{4L^2\mu}\right)\frac{F'}{F}} = f_1\sqrt{\frac{F'}{F}}$$

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

$$f_{\text{beat}} = f_1 - f_1' = f_1\left(1 - \sqrt{\frac{F'}{F}}\right) = \left(1.10\times10^2 \text{ Hz}\right)\left(1 - \sqrt{\frac{5.40\times10^2 \text{ N}}{6.00\times10^2 \text{ N}}}\right) = \boxed{5.64 \text{ beats/s}}$$

14.56 By shortening her string, the second violinist increases its fundamental frequency. Thus, $f_1' = f_1 + f_{\text{beat}} = (196 + 2.00)$ Hz $= 198$ 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 $\lambda_1' = \lambda_1\left(f_1/f_1'\right)$. 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 $\left(f_{O,1} = f_S = 180 \text{ Hz}\right)$ from the first train. The frequency the commuter hears from the second train, moving relative to the station and commuter, is given by

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

This stationary observer $\left(v_O = 0\right)$ hears the lower frequency $\left(f_{O2} = 178 \text{ Hz}\right)$ if the second train is moving *away* from the station $\left(v_S = -\left|v_S\right|\right)$, so $f_O = f_S[(v + v_O)/(v - v_S)]$ gives the speed of the receding second train as

$$178 \text{ Hz} = (180 \text{ Hz})\left(\frac{343 \text{ m/s} + 0}{343 \text{ m/s} - \left(-\left|v_S\right|\right)}\right) = (180 \text{ Hz})\left(\frac{343 \text{ m/s} + 0}{343 \text{ m/s} + \left|v_S\right|}\right)$$

or

$$343 \text{ m/s} + \left|v_S\right| = (343 \text{ m/s})\left(\frac{180 \text{ Hz}}{178 \text{ Hz}}\right) \quad \text{and} \quad \left|v_S\right| = (343 \text{ m/s})\left[\left(\frac{180 \text{ Hz}}{178 \text{ Hz}}\right) - 1\right] = 3.85 \text{ m/s}$$

so one possibility for the second train is $\boxed{v_S = 3.85 \text{ m/s away from the station}}$.

The other possibility is that the second train is moving toward the station $\left(v_S = +\left|v_S\right|\right)$ and the commuter is detecting the higher of the possible frequencies $\left(f_{O2} = 182 \text{ Hz}\right)$. In this case, $f_O = f_S[(v + v_O)/(v - v_S)]$ yields

$$182 \text{ Hz} = (180 \text{ Hz})\left(\frac{343 \text{ m/s} + 0}{343 \text{ m/s} - \left|v_S\right|}\right) \quad \text{and} \quad 343 \text{ m/s} - \left|v_S\right| = (343 \text{ m/s})\left(\frac{180 \text{ Hz}}{182 \text{ Hz}}\right)$$

or $$\left|v_S\right| = (343 \text{ m/s})\left[1 - \left(\frac{180 \text{ Hz}}{182 \text{ Hz}}\right)\right] = 3.77 \text{ m/s}$$

In this case, the velocity of the second train is $\boxed{v_S = 3.77 \text{ m/s toward the station}}$.

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

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 echo heard by the observer is

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

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

$$f_{\text{beat}} = f_{\text{echo}} - f_S = f_S\left(\frac{v + v_a}{v - v_a} - 1\right) = f_S\left(\frac{2v_a}{v - v_a}\right) = (256 \text{ Hz})\left(\frac{2(1.33)}{343 - 1.33}\right) = \boxed{1.99 \text{ Hz}}$$

(b) When the student moves away from the wall, v_a changes sign so the frequency of the echo heard is $f_{\text{echo}} = f_S\left[(v - |v_a|)/(v + |v_a|)\right]$. The beat frequency is then

$$f_{\text{beat}} = f_S - f_{\text{echo}} = f_S\left(1 - \frac{v - |v_a|}{v + |v_a|}\right) = f_S\left(\frac{2|v_a|}{v + |v_a|}\right)$$

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

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

$$|v_a| = \frac{(343 \text{ m/s})(5.00 \text{ Hz})}{2(256 \text{ Hz}) - 5.00 \text{ Hz}} = \boxed{3.38 \text{ m/s}}$$

14.60 The extra sensitivity of the ear at 3 000 Hz appears as downward dimples on the curves in Figure 14.29 of the textbook.

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

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

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

$$L = \frac{\lambda}{4} = \frac{0.118 \text{ m}}{4} = 0.0295 \text{ m} = \boxed{2.95 \text{ cm}}$$

14.61 At normal body temperature of $T = 37.0°\text{C}$, the speed of sound in air is

$$v = (331 \text{ m/s})\sqrt{1 + \frac{T_C}{273}} = (331 \text{ m/s})\sqrt{1 + \frac{37.0}{273}}$$

and the wavelength of sound having a frequency of $f = 20\,000$ Hz is

$$\lambda = \frac{v}{f} = \frac{(331 \text{ m/s})}{(20\,000 \text{ Hz})}\sqrt{1 + \frac{37.0}{273}} = 1.76 \times 10^{-2} \text{ m} = 1.76 \text{ cm}$$

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

14.62 From the defining equation for the decibel level, $\beta = 10 \log(I/I_0)$, the intensity of sound having a decibel level β is

$$I = \left(10^{\beta/10}\right) I_0$$

Thus, the intensity of a 40 dB sound is $I_{40} = (10^{4.0}) I_0$, while that of a 70 dB sound is $I_{70} = (10^{7.0}) I_0$. Since the combined intensity of sound from a swarm of n mosquitoes is $I_{\text{swarm}} = nI_{40}$, we must require that

$$I_{\text{swarm}} = nI_{40} = I_{70}$$

or $$n = \frac{I_{70}}{I_{40}} = \frac{\left(10^{7.0}\right) I_0}{\left(10^{4.0}\right) I_0} = 10^{3.0} = 1\,000$$

We conclude that the swarm should contain $\boxed{\sim 1\,000 \text{ mosquitoes}}$ to yield a 70 dB sound.

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 $\beta = 10 \cdot \log(I/I_0)$ as

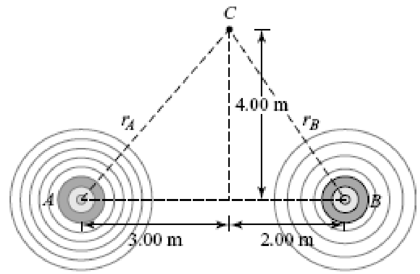
$$I = I_0 \cdot 10^{\beta/10} = \left(1.00 \times 10^{-12} \text{ W/m}^2\right) \cdot 10^{10.3} = 1.00 \times 10^{-1.7} \text{ W/m}^2$$

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

$$P = IA = I\left(4\pi r^2\right) = \left(1.00 \times 10^{-1.7} \text{ W/m}^2\right) 4\pi (1.60 \text{ m})^2 = \boxed{0.642 \text{ W}}$$

(b) $$\textit{efficiency} = \frac{P_{\text{output}}}{P_{\text{input}}} = \frac{0.642 \text{ W}}{150 \text{ W}} = \boxed{0.004\,3 \text{ or } 0.43\%}$$

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



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

and the intensity of the sound from this speaker is

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

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

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

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

$$\beta_5 = 10 \cdot \log\left(\frac{I_5}{I_0}\right) = 10 \cdot \log\left(\frac{5.00\times10^{-6}\ \text{W/m}^2}{1.00\times10^{-12}\ \text{W/m}^2}\right) = \boxed{67.0\ \text{dB}}$$

14.66 The well will act as a pipe closed at one end (the bottom) and open at the other (the 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

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

In this case, we have $60.0\text{ Hz} - 52.0\text{ Hz} = 2f_1$, giving the fundamental frequency for the well as $f_1 = 4.00\text{ Hz}$. 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

$$d = \frac{\lambda_1}{4} = \frac{1}{4}\left(\frac{v_{\text{sound}}}{f_1}\right) = \frac{1}{4}\left(\frac{343\ \text{m/s}}{4.00\ \text{Hz}}\right) = \boxed{21.4\ \text{m}}$$

14.67 If r_1 and r_2 are the distances of the two observers from the speaker, the intensities of the sound at their locations are

$$I_1 = \frac{P}{4\pi r_1^2} \quad \text{and} \quad I_2 = \frac{P}{4\pi r_2^2}$$

where P is the power output of the speaker. The difference in the decibel levels for the two observers is

$$\beta_1 - \beta_2 = 10\log\left(\frac{I_1}{I_0}\right) - 10\log\left(\frac{I_2}{I_0}\right) = 10\log\left(\frac{I_2}{I_1}\right) = 10\log\left(\frac{r_2^2}{r_1^2}\right) = 10\log\left(\frac{r_2}{r_1}\right)^2 = 20\log\left(\frac{r_2}{r_1}\right)$$

Since $\beta_1 = 80$ dB and $\beta_2 = 60$ dB, we find that $80 - 60 = 20\log(r_2/r_1)$. This yields

$\log(r_2/r_1) = 1.0$ and $r_2/r_1 = 10$ or $r_2 = 10r_1$ **[1]**

We also know that $r_1 + r_2 = 36.0\text{ m}$ **[2]**

Substituting Equation [1] into [2] gives: $11r_1 = 36.0\text{ m}$ or $r_1 = \boxed{36.0\text{ m}/11 \approx 3.3\text{ m}}$

Then, Equation [2] yields $r_2 = 36.0\text{ m} - r_1 = 36.0\text{ m} - 3.3\text{ m} = \boxed{32.7\text{ m}}$

14.68 We take toward the east as the positive direction, so the velocity of the sea water relative to Earth is $\vec{v}_{WE} = -10.0\ \text{km/h}$. The velocity of the trailing ship, which is the sound source (S), relative the propagation medium (sea water) is then

$$\vec{v}_{SW} = \vec{v}_{SE} - \vec{v}_{WE} = +64.0\ \text{km/h} - (-10.0\ \text{km/h}) = +74.0\ \text{km/h}\left(\frac{0.278\ \text{m/s}}{1\ \text{km/h}}\right) = 20.6\ \text{m/s}$$

The velocity of the leading ship, the observer (O) in this case, relative to the water is

$$\vec{v}_{OW} = \vec{v}_{OE} - \vec{v}_{WE} = +45.0\ \text{km/h} - (-10.0\ \text{km/h}) = +55.0\ \text{km/h}\left(\frac{0.278\ \text{m/s}}{1\ \text{km/h}}\right) = 15.3\ \text{m/s}$$

With the source moving toward the observer, but the observer moving away from the source, the frequency detected by the observer is given by Equation 14.12 as

$$f_O = f_S\left(\frac{v + v_O}{v - v_S}\right) = f_S\left(\frac{v + (-|\vec{v}_{OW}|)}{v - (+|\vec{v}_{SW}|)}\right)$$

The speed of sound in sea water is $v = 1\,533 \text{ m/s}$ (Table 14.1) and the frequency emitted by the source is $f_S = 1\,200.0 \text{ Hz}$, so the observed frequency should be

$$f_O = (1\,200.0 \text{ Hz})\left(\frac{1\,533 \text{ m/s} - 15.3 \text{ m/s}}{1\,533 \text{ m/s} - 20.6 \text{ m/s}}\right) = \boxed{1\,204 \text{ Hz}}$$

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 window ledge to the man's head is

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

The time for a warning to travel this distance is $t_1 = (18.3 \text{ m})/(343 \text{ m/s}) = 0.0534 \text{ s}$, 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 elapsed time when the pot, starting from rest, reaches the level of the man's head 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. At this time, the pot has fallen

$$\Delta y = \frac{1}{2}gt^2 = \frac{1}{2}(9.80 \text{ m/s}^2)(1.58 \text{ s})^2 = 12.2 \text{ m}$$

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

14.71 On the weekend, there are one-fourth as many cars passing per minute as on a weekday. Thus, the intensity, I_2, of the sound on the weekend is one-fourth of that, I_1, on a weekday. 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 $T = 20°\text{C} = 293 \text{ K}$, the speed of sound in air is

$$v = (331 \text{ m/s})\sqrt{1 + \frac{T_C}{273}} = (331 \text{ m/s})\sqrt{1 + \frac{20.0}{273}} = 343 \text{ m/s}$$

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

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

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 $v = (331 \text{ m/s})\sqrt{1 + T_C/273}$, the temperature in the colder room is given by

$$T = (273°\text{C})\left[\left(\frac{v}{331 \text{ m/s}}\right)^2 - 1\right] = (273°\text{C})\left[\left(\frac{339 \text{ m/s}}{331 \text{ m/s}}\right)^2 - 1\right] = \boxed{13.4°\text{C}}$$

14.73 The maximum speed of the oscillating block and speaker is

11 $$v_{\max} = A\omega = A\sqrt{\frac{k}{m}} = (0.500 \text{ m})\sqrt{\frac{20.0 \text{ N/m}}{5.00 \text{ kg}}} = 1.00 \text{ m/s}$$

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

$$(f_O)_{\min} = f_S\left(\frac{v}{v + v_{\max}}\right) = (440 \text{ Hz})\left(\frac{343 \text{ m/s}}{343 \text{ m/s} + 1.00 \text{ m/s}}\right) = \boxed{439 \text{ Hz}}$$

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

$$(f_O)_{\max} = f_S\left(\frac{v}{v - v_{\max}}\right) = (440 \text{ Hz})\left(\frac{343 \text{ m/s}}{343 \text{ m/s} - 1.00 \text{ m/s}}\right) = \boxed{441 \text{ Hz}}$$

14.74 The speed of transverse waves in the wire is

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

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

$$f_S = \frac{v_T}{\lambda} = \frac{365 \text{ m/s}}{0.500 \text{ m}} = 730 \text{ Hz}$$

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 $|v_0|$, 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 $f_{\text{beat}} = (f_o)_1 - (f_o)_2 = f_s\left(\frac{v+|v_o|-(v-|v_o|)}{v}\right) = \frac{2f_s|v_o|}{v}$

so $|v_o| = \left(\frac{f_{\text{beat}}}{2f_s}\right)v = \left[\frac{8.30 \text{ Hz}}{2(730 \text{ Hz})}\right](343 \text{ m/s}) = \boxed{1.95 \text{ m/s}}$

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

$$F = \frac{Y\cdot A}{64} = \frac{(6.80\times10^{10} \text{ N/m}^2)\left[\pi(0.200\times10^{-2} \text{ m})^2\right]}{64} = \boxed{1.34\times10^4 \text{ N}}$$

14.76 (a) For the fundamental mode of a pipe open at both ends, $L = \lambda_1/2$ or the wavelength of the waves traveling through the air in the pipe is $\lambda_1 = 2L = 2(0.500 \text{ m}) = 1.00 \text{ m}$.

If the frequency of this fundamental mode is $f_1 = 350 \text{ Hz}$, the speed of sound waves within the pipe must be

$$v = \lambda_1 f_1 = (1.00 \text{ m})(350 \text{ Hz}) = 350 \text{ m/s}$$

From $v = (331 \text{ m/s})\sqrt{1+T_C/273}$, the Celsius temperature of the air in the pipe is

$$T_C = (273°\text{C})\left[\left(\frac{v}{331 \text{ m/s}}\right)^2 - 1\right] = (273°\text{C})\left[\left(\frac{350 \text{ m/s}}{331 \text{ m/s}}\right)^2 - 1\right] = \boxed{32.2°\text{C}}$$

(b) If the temperature rises to $T' = T + 20.0°\text{C} = 52.2°\text{C}$, the speed of sound in the air will be

$v' = (331 \text{ m/s})\sqrt{1+T_C'/273} = (331 \text{ m/s})\sqrt{1+52.2/273}$, and the new length of the pipe will be

$$L' = L_0[1+\alpha(\Delta T)] = (0.500 \text{ m})[1+(19\times10^{-6} \text{ °C}^{-1})(20.0°\text{C})]$$

The new fundamental wavelength is $\lambda_1' = 2L'$, and the new fundamental resonance frequency will be

$$f_1' = \frac{v'}{\lambda_1'} = \frac{(331 \text{ m/s})\sqrt{1+52.2/273}}{2(0.500 \text{ m})[1+(19\times10^{-6} \text{ °C}^{-1})(20.0°\text{C})]} = \boxed{3.6\times10^2 \text{ Hz}}$$