Chapter 14
Sound

Quick Quizzes

1. (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 affect on the speed of sound.

2. (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. (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. (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. (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. (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. (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 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.

4. Air flowing fast by a rim of the pipe creates a "shshshsh" sound called edgetone noise, a mixture of all frequencies, as the air turbulently switches between flowing on one side of the edge and the other. The air column inside the pipe finds one or more of its resonance frequencies in the noise. The air column starts vibrating with large amplitude in a standing vibration mode and radiates this sound into the surrounding air.

6. The distance around the opening of the bell must be an integer multiple of the wavelength. Actually, the circumference being equal to the wavelength would describe the bell moving from side to side without bending, which it can do without producing any sound. A tuned bell is cast and shaped so that some of these vibrations will have their frequencies constitute higher harmonics of a musical note, the strike tone. This tuning is lost if a crack develops in the bell. The sides of the crack vibrate as antinodes. Energy of vibration may be rapidly lost into thermal energy at the end of the crack, so the bell may not ring for so long a time.

8. 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.

10. Refer to Table 14.2 to see that a rock concert has an intensity level of about 120 dB, the turning of a page in a textbook about 30 dB, a normal conversation is about 50 dB, background noise at a church is about 30 dB. This leaves a cheering crowd at a football game to be about 60 dB.

12. No. Adding two sounds of equal loudness will produce an intensity double that associated with either individual sound. However, the decibel scale is a logarithmic function of intensity, so doubling the intensity only increases the decibel level by $10 \log 2$. Thus, the decibel level with both sounds present will be 53 dB.

14. A beam of radio 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.

16. 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 $f = \frac{v}{4L}$. This equation indicates that as the length L of the column increases (fluid level decreases), the resonant frequency decreases.

18. Walking makes the person's hand vibrate a little. If the frequency of this motion equals the natural frequency of coffee sloshing from side to side in a cup, then a large-amplitude vibration of the coffee will build up in resonance. To get off resonance and back to the normal case of a small-amplitude disturbance producing a small-amplitude result, the person can walk faster, walk slower, vary his speed, or get a larger or smaller cup. Alternatively, even at resonance, he can reduce the amplitude by adding damping, as by stirring high-fiber quick cooking oat meal into the hot coffee.

20. 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.

Answers to Even Numbered Problems

2. 0.196 s

4. 1.7 cm to 17 m

6. 18.5 m

8. 316 K

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

12. 3.01 dB

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

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

18. **(a)** $\frac{I_A}{I_B} = 2$ **(b)** $\frac{I_A}{I_C} = 5$

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

22. 32.1 m/s, behind the car

24. 41 kHz

26. **(a)** 0.0217 m/s **(b)** 2 000 029 Hz **(c)** 2 000 058 Hz

28. **(a)** 57.1 s **(b)** 56.6 km

30. **(a)** 0.431 m **(b)** 0.863 m

32. **(a)** 0.345 m **(b)** constructive interference

34. 824.0 N

36. 2.55 kHz

38. 120 Hz

40. **(a)** 4.9×10^{-3} kg/m **(b)** 2 **(c)** no standing wave will form

42. 9.00 kHz

44. **(a)** 531 Hz **(b)** 4.25 cm

46. $n(206\text{ Hz})$ for $n = 1$ to 9 and
$n(84.5\text{ Hz})$ for $n = 2$ to 23

48. 3.3×10^2 m/s

50. 29.7 cm

52. 3.98 Hz

54. 2.94 cm

56. **(a)** 362 Hz **(b)** 287 Hz **(c)** 0.953 m and 1.20 m

58. 7.8 m

60. 200 m/s

62. **(a)** 0.655 m **(b)** 13.0°C

64. **(a)** 0.233 m **(b)** 14 mm

66. **(a)** a path difference of $\lambda/2$ produces destructive interference

(b) Along a hyperbola given by $\frac{x^2}{16} - \frac{y^2}{9} = 1.00\text{ m}^2$

68. 1.93 m/s

70. **(b)** 531 Hz

72. **(a)** 55.8 m/s **(b)** 2.50 kHz

Problem Solutions

14.1 Since $v_{light} >> v_{sound}$, we ignore the time required for the lightning flash to reach the observer in comparison to the transit time for the sound. 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 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

$$t = \frac{2d}{v} = \frac{2(150\ \text{m})}{1\,530\ \text{m/s}} = \boxed{0.196\ \text{s}}$$

14.3 The speed of the sound wave is $v = \lambda f = (0.50\ \text{m})(700\ \text{Hz}) = 3.5 \times 10^2\ \text{m/s}$. Thus, from $v = (331\ \text{m/s})\sqrt{T/273\ \text{K}}$, the temperature of the air is

$$T = (273\ \text{K})\left(\frac{v}{331\ \text{m/s}}\right)^2 = (273\ \text{K})\left(\frac{3.5 \times 10^2\ \text{m/s}}{331\ \text{m/s}}\right)^2 = 305\ \text{K} = \boxed{32°\text{C}}$$

14.4 At $T = 27°\text{C} = 300\ \text{K}$, the speed of sound in air is

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

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 $20\,000\ \text{Hz}$ 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 $\boxed{1.7\ \text{cm to } 17\ \text{m}}$.

14.5 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 $T = 22.0°\text{C} = 295\ \text{K}$ is

$$v = (331\ \text{m/s})\sqrt{\frac{T}{273\ \text{K}}} = (331\ \text{m/s})\sqrt{\frac{295\ \text{K}}{273\ \text{K}}} = 344\ \text{m/s}$$

and the distance the sound traveled to the mountain was

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

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

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

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, $t_1 + t_2 = 2.00\ \text{s}$. 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

$$\left(1.45 \times 10^{-2}\ \text{s}^{-1}\right)t_1^2 + t_1 - 2.00\ \text{s} = 0$$

Applying the quadratic equation yields one positive solution of $t_1 = 1.945\ \text{s}$, so the depth of the well is

$$h = \frac{gt_1^2}{2} = \frac{(9.80\ \text{m/s}^2)(1.945\ \text{s})^2}{2} = \boxed{18.5\ \text{m}}$$

14.7 From Table 14.1, the speed of sound in the saltwater is $v_w = 1\,530\ \text{m/s}$. At $T = 20°\text{C} = 293\ \text{K}$, 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 $t_w = \dfrac{d}{v_w}$, and that for the sound in the air is $t_a = t_w + 4.50\ \text{s} = \dfrac{d}{v_a}$.

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

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

14.8 At absolute temperature T, the speed of sound in air is

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

Thus, if the speed of sound in the air column is measured to be $v = 356\ \text{m/s}$, the temperature of the air in the column must be

$$T = (273\ \text{K})\left(\frac{v}{331\ \text{m/s}}\right)^2 = (273\ \text{K})\left(\frac{356\ \text{m/s}}{331\ \text{m/s}}\right)^2 = \boxed{316\ \text{K}}$$

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

(a) If $\beta = 100$, then $\log(I/I_0) = 10$ giving $I = 10^{10}\, I_0 = \boxed{1.00 \times 10^{-2}\ \text{W/m}^2}$

(b) If all three toadfish sound at the same time, the total intensity of the sound produced is $I' = 3I = 3.00 \times 10^{-2}\ \text{W/m}^2$, and the decibel level is

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

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

14.10 The sound power incident on the eardrum is $\mathcal{P} = IA$ 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

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

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

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

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

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

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

14.12 Observe that $\dfrac{I_2}{I_1} = \dfrac{200\ \text{W/m}^2}{100\ \text{W/m}^2} = 2.00$

Thus, the difference in the intensity levels of these two sounds is

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

or $$\beta_2 - \beta_1 = 10\log(2.00) = 10(0.301) = \boxed{3.01\ \text{dB}}$$

14.13 From $\beta = 10\log(I/I_0)$, the intensity for sound level β is $I = I_0 10^{\beta/10}$

The intensity of sound produced by one machine (β = 80 dB) is

$$I_1 = I_0\left(10^{8.0}\right)$$

The intensity needed to reach β = 90 dB is $I = I_0\left(10^{9.0}\right)$. Thus, the total number of machines the factory can accommodate without exceeding 90 dB is

$$N = \frac{I}{I_1} = \frac{I_0\left(10^{9.0}\right)}{I_0\left(10^{8.0}\right)} = 10$$

Since the factory already contains one of these machines, you can add $\boxed{\text{9 additional machines}}$ without going over the limit.

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

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

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

(b) The combined sound level is

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

14.15 If the intensity of a sound is $I = 4.00\ \mu\text{W/m}^2 = 4.00\times10^{-6}\ \text{W/m}^2$, the sound level in decibels is

$$\beta = 10\log\left(\frac{I}{I_0}\right) = 10\log\left(\frac{4.00\times10^{-6}\ \text{W/m}^2}{1.00\times10^{-12}\ \text{W/m}^2}\right) = 10\log\left(4.00\times10^{6}\right) = \boxed{66.0\ \text{dB}}$$

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

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

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

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

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

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

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

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

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

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

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

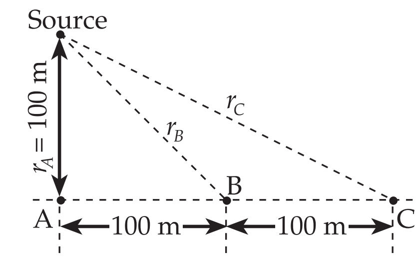
and the sound level is

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

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

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



14.19 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 $I = \dfrac{\mathcal{P}}{4\pi r^2} = \dfrac{(\mathcal{P}/4\pi)}{r^2}$, the ratio of intensities is

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

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

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

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

14.21 When a stationary observer $(v_O = 0)$ hears a moving source, the observed frequency is $f_O = f_S\left(\dfrac{v+v_O}{v-v_S}\right) = f_S\left(\dfrac{v}{v-v_S}\right)$.

(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

$$(f_O)_{recede} = (320\text{ Hz})\left[\frac{345\text{ m/s}}{345\text{ m/s} - (-40.0\text{ m/s})}\right] = 287\text{ Hz}.$$

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

$$\lambda = \frac{v}{(f_O)_{approach}} = \frac{345\text{ m/s}}{362\text{ Hz}} = \boxed{0.953\text{ m}}$$

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

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

14.23 Both source and observer are in motion, so $f_O = f_S\left(\dfrac{v+v_O}{v-v_S}\right)$. 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

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

14.24 It is useful to consider this echo in two steps. First, consider the wall to be a stationary observer $(v_O = 0)$ with the source (the bat) *approaching* at $v_S = v_{bat}$. The frequency of the wave reflecting from the wall is $f_{reflect} = f_S\left(\dfrac{v}{v - v_{bat}}\right)$. Next, consider the wall as a stationary source $(v_S = 0)$ of the reflected wave and the bat to be the *approaching* observer $(v_O = +v_{bat})$ of this wave. The frequency detected by the bat will be $f_O = f_{reflect}\left(\dfrac{v + v_{bat}}{v}\right)$.

Combining gives the frequency of the echo detected by the bat as

$$f_O = \left[f_S\left(\frac{v}{v - v_{bat}}\right)\right]\left(\frac{v + v_{bat}}{v}\right) = f_S\left(\frac{v + v_{bat}}{v - v_{bat}}\right) = (40\text{ kHz})\left(\frac{345 + 5.0}{345 - 5.0}\right) = \boxed{41\text{ kHz}}$$

14.25 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

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

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

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

Dividing equation (1) by (2) gives $\dfrac{442}{441} = \dfrac{345\text{ m/s} + |v_t|}{345\text{ m/s} - |v_t|}$,

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

14.26 (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

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

(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

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

14.27 For a source *receding* from a stationary observer, $f_O = f_S\left(\dfrac{v}{v-\left(-|v_S|\right)}\right) = f_S\left(\dfrac{v}{v+|v_S|}\right)$. Thus, the speed the falling tuning fork must reach is

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

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

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

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

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

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

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

14.28 (b) The half angle of the shock wave is given by

$$\sin\theta = v_{\text{sound}}/v_{\text{source}} = 1/3$$

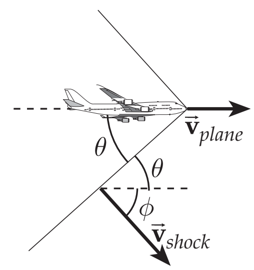
Thus, $\theta = 19.47°$. In Figure P14.28(b), we have

$$x = \frac{h}{\tan\theta} = \frac{20\,000 \text{ m}}{\tan 19.47°} = 56.6\times10^{3} \text{ m} = \boxed{56.6 \text{ km}}$$

(a) The time required for the plane to travel the distance found above is

$$t = \frac{x}{v_{\text{plane}}} = \frac{56.6\times10^{3} \text{ m}}{3(330 \text{ m/s})} = \boxed{57.1 \text{ s}}$$

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



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

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

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

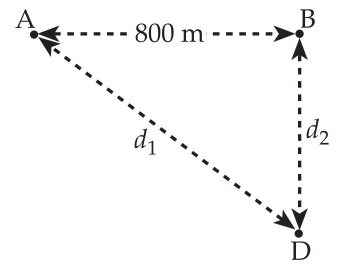
14.30 The wavelength of the sound produced by the speaker is

$$\lambda = \frac{v}{f} = \frac{345 \text{ m/s}}{400 \text{ Hz}} = 0.863 \text{ m}$$

(a) If destructive interference is now occurring, one can increase the path length by $\lambda/2 = \boxed{0.431 \text{ m}}$ to produce constructive interference. This is done by sliding the U-tube out a distance of $0.431 \text{ m}/2 = 0.216 \text{ m}$.

(b) With destructive interference currently taking place, one can increase the path length by a full wavelength $\lambda = \boxed{0.863 \text{ m}}$ to produce destructive interference again.

14.31 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

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

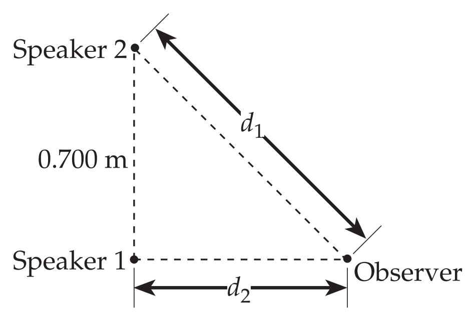
14.32 The wavelength of the sound produced by the speakers is

$$\lambda = \frac{v}{f} = \frac{345\text{ m/s}}{500\text{ Hz}} = 0.690\text{ m}$$

(a) To produce destructive interference, the speaker should be moved back a distance of $d = \dfrac{\lambda}{2} = \boxed{0.345\text{ m}}$.

(b) The speakers will now be separated by a full wavelength and $\boxed{\text{constructive interference}}$ will again occur.

14.33 The wavelength of the sound is $\lambda = \dfrac{v}{f} = \dfrac{345\text{ m/s}}{690\text{ Hz}} = 0.500\text{ m}$.



(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

$$(d_2 + 0.250\text{ m})^2 = d_2^2 + (0.700\text{ m})^2\text{, or } d_2 = \boxed{0.855\text{ m}}$$

14.34 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 $f = 261.6 \text{ Hz}$, the speed of the waves must be

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

With $\mu = \frac{m}{L} = \frac{4.300 \times 10^{-3} \text{ kg}}{0.700\,0 \text{ m}} = 6.143 \times 10^{-3} \text{ kg/m}$, the required tension is given by $v = \sqrt{F/\mu}$ as

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

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

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

14.36 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

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

14.37 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 $\dfrac{1.25\text{ m}}{2} = 0.625\text{ m}$ from either speaker.

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

a node at $0.518\text{ m} - 0.214\text{ m} = \boxed{0.303\text{ m}}$,

a node at $0.303\text{ m} - 0.214\text{ m} = \boxed{0.0891\text{ m}}$,

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

a node at $0.732\text{ m} + 0.214\text{ m} = \boxed{0.947\text{ m}}$, and

a node at $0.947\text{ m} + 0.214\text{ m} = \boxed{1.16\text{ m}}$ from one speaker.

14.38 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

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

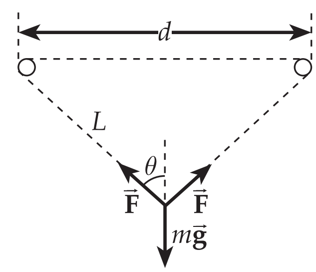
If we have two wires with the same mass per unit length, one of length L and under tension F while the second has length $2L$ and tension $4F$, the ratio of the fundamental frequencies of the two wires is

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

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

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

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



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

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

$$v = \sqrt{\frac{F}{\mu}} = \sqrt{\frac{79\ \text{N}}{0.0010\ \text{kg/m}}} = 2.8\times 10^{2}\ \text{m/s}$$

For the pattern shown, $3(\lambda/2) = d$, so $\lambda = \dfrac{2d}{3} = \dfrac{4.0\ \text{m}}{3}$

Thus, the frequency is $f = \dfrac{v}{\lambda} = \dfrac{3(2.8\times 10^{2}\ \text{m/s})}{4.0\ \text{m}} = \boxed{2.1\times 10^{2}\ \text{Hz}}$

14.40 (a) For a standing wave of 6 loops, $6\left(\dfrac{\lambda}{2}\right) = L$, or $\lambda = \dfrac{L}{3} = \dfrac{2.0\ \text{m}}{3}$

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 $F = mg = (5.0\ \text{kg})(9.80\ \text{m/s}^2) = 49\ \text{N}$

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

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

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

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

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

and $n = \dfrac{L}{\lambda/2} = \dfrac{2.0\ \text{m}}{0.47\ \text{m}}$ is not an integer,

so $\boxed{\text{no standing wave will form}}$.

14.41 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 $f_{339} = 19\,976\ \text{Hz} = \boxed{19.976\ \text{kHz}}$

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

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

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

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

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

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

$$\lambda = 4(5.0\text{ ft}) = 2.0\times10^{1}\text{ ft}$$

and $$f = \frac{v}{\lambda} = \frac{(353\text{ m/s})}{2.0\times10^{1}\text{ ft}}\left(\frac{3.281\text{ ft}}{1\text{ m}}\right) = \boxed{58\text{ Hz}}$$

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

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

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

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

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

14.46 For a closed box, the resonant frequencies will have nodes at both sides, so the permitted wavelengths will be $L = \frac{n\lambda}{2} = \frac{nv}{2f}$, $(n = 1, 2, 3, \ldots)$.

Thus, $f_n = \frac{nv}{2L}$. With $L = 0.860\text{ m}$ and $L' = 2.10\text{ m}$, the resonant frequencies are:

$$f_n = \boxed{n(206\text{ Hz})}\text{ for } L = 0.860\text{ m for each } n \text{ from 1 to 9}$$

and $$f_n = \boxed{n(84.5\text{ Hz})}\text{ for } L' = 2.10\text{ m for each } n \text{ from 2 to 23}$$

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

$$\lambda_1 = 2L = \frac{v}{f_1} \text{ giving } L = \frac{v}{2f_1} = \frac{331\text{ m/s}}{2(300\text{ Hz})} = \boxed{0.552\text{ m}}$$

(b) At $T = 30\text{ °C} = 303\text{ K}$, $v = (331\text{ m/s})\sqrt{\dfrac{T}{273\text{ K}}} = (331\text{ m/s})\sqrt{\dfrac{303\text{ K}}{273\text{ K}}} = 349\text{ m/s}$

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

14.48 For a pipe open at both ends, the frequency of the nth harmonic is, $f_n = n(v/2L)$. Thus, the difference between two successive resonant frequencies is

$$\Delta f = f_{n+1} - f_n = (n+1)\left(\frac{v}{2L}\right) - n\left(\frac{v}{2L}\right) = \frac{v}{2L}$$

In this case, $L = 2.00\text{ m}$ and $\Delta f = 492\text{ Hz} - 410\text{ Hz} = 82\text{ Hz}$. Thus, the speed of sound in the pipe is

$$v = 2L(\Delta f) = 2(2.00\text{ m})(82\text{ Hz}) = \boxed{3.3 \times 10^2\text{ m/s}}$$

14.49 Since the lengths, and hence the wavelengths of the first harmonics, of the strings are identical, the ratio of their fundamental frequencies is

$$\frac{f_1'}{f_1} = \frac{v'/\lambda_1}{v/\lambda_1} = \frac{v'}{v}, \text{ or } f_1' = f_1\left(\frac{v'}{v}\right)$$

Thus, the beat frequency heard when the two strings are sounded simultaneously is

$$f_{beat} = f_1 - f_1' = f_1(1 - v'/v)$$

From $v = \sqrt{F/\mu}$, the speeds of transverse waves in the two strings are

$$v = \sqrt{\frac{200\text{ N}}{\mu}} \text{ and } v' = \sqrt{\frac{196\text{ N}}{\mu}}, \text{ so } \frac{v'}{v} = \sqrt{\frac{196\text{ N}}{200\text{ N}}} = \sqrt{0.980}$$

Therefore, $f_{beat} = (523\text{ Hz})\left(1 - \sqrt{0.980}\right) = \boxed{5.26\text{ Hz}}$

14.50 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.

Thus, $\lambda_1' f_1' = \lambda_1 f_1$, or $\lambda_1' = \lambda_1 \left(f_1 / f_1' \right)$. Since the fundamental wavelength of a string fixed at both ends is $\lambda = 2L$, this yields

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

14.51 If the second train is moving *toward* the stationary observer with speed $|v_S|$, the Doppler effect gives $f_O = f_S\left(\dfrac{v}{v - |v_S|}\right) > f_S$

Therefore, $f_O = f_S + f_{beat} = 180\ \text{Hz} + 2\ \text{Hz} = 182\ \text{Hz}$, and the speed of the train is

$$|v_S| = v\left(1 - \frac{f_S}{f_O}\right) = (345\ \text{m/s})\left(1 - \frac{180}{182}\right) = 3.79\ \text{m/s}$$

and the velocity of the train is $v_S = \boxed{3.79\ \text{m/s toward the station}}$

If the second train is moving *away from* the stationary observer $\left(v_S = -|v_S|\right)$, then

$$f_O = f_S\left(\frac{v}{v + |v_S|}\right) < f_S \text{, giving } f_O = f_S - f_{beat} = 180\ \text{Hz} - 2\ \text{Hz} = 178\ \text{Hz}$$

Thus,

$$|v_S| = v\left(\frac{f_S}{f_O} - 1\right) = (345\ \text{m/s})\left(\frac{180}{178} - 1\right) = 3.88\ \text{m/s}$$

and the velocity of the train is $v_S = \boxed{3.88\ \text{m/s away from the station}}$

14.52 The temperatures of the air in the two pipes are $T_1 = 27°\text{C} = 300\text{ K}$ and $T_2 = 32°\text{C} = 305\text{ K}$. 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 $f_{beat} = f_2 - f_1 = f_1\left(\frac{v_2}{v_1} - 1\right) = f_1\left(\sqrt{\frac{T_2}{T_1}} - 1\right)$

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

14.53 (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

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

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

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

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

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

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

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

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

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

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

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

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

Thus, the wavelength of 3 000 Hz sound is $\lambda = \dfrac{v}{f} = \dfrac{353 \text{ m/s}}{3\,000 \text{ Hz}} = 0.118 \text{ m}$

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

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

14.55 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 $20\,000 \text{ Hz}$ 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 $\boxed{1.76 \text{ cm}}$

14.56 (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 $f_O = f_S\left(v+v_O\right)/\left(v-v_S\right)$ 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, $f_S = 320\text{ Hz}, v_O = 0,$ 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, $v_S = -40.0\text{ m/s}$ 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

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

14.57 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

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

14.58 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 $t_1 = \dfrac{18.3\text{ m}}{345\text{ m/s}} = 0.0529\text{ s}$, 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

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

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

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

14.60 The length of the air column when the first resonance is heard is $L_1 = \lambda_a/4$, where λ_a is the wavelength of the sound in air. Thus, $\lambda_a = 4L_1 = 4(0.340\text{ m}) = 1.36\text{ m}$

The frequency of the sound wave, and hence the vibrating wire producing the sound, is

$$f = \frac{v_{sound}}{\lambda_a} = \frac{340\text{ m/s}}{1.36\text{ m}} = 250\text{ Hz}$$

When the wire vibrates in its third harmonic, its length is $L_w = (3/2)\lambda_w$ where λ_w is the wavelength of the waves traveling in the wire.

Therefore, $\lambda_w = \dfrac{2L_w}{3} = \dfrac{2(1.20\text{ m})}{3} = 0.800\text{ m}$, and the speed of transverse waves in the wire is $v_w = \lambda_w f = (0.800\text{ m})(250\text{ Hz}) = \boxed{200\text{ m/s}}$

14.61 The maximum speed of the oscillating block and speaker is

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

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

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

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

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

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

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

The first harmonic or fundamental of the flute (a pipe open at both ends) is given by $\lambda_1 = 2L = \dfrac{v}{f_1} = \dfrac{343\ \text{m/s}}{261.6\ \text{Hz}} = 1.31\ \text{m}$. 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, $\lambda_1' = \lambda_1 = 1.31\text{ m}$). 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

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

14.63 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

$$v_2 = v\left(1 - \frac{f_S}{(f_O)_2}\right) = (345\text{ m/s})\left(1 - \frac{300\text{ Hz}}{331.6\text{ Hz}}\right) = \boxed{32.9\text{ m/s}}$$

14.64 (a) The wavelength of the original note is

$$\lambda = \frac{v}{f} = \frac{345\ \text{m/s}}{1.480 \times 10^3\ \text{Hz}} = \boxed{0.233\ \text{m}}$$

(b) The wavelength of the transposed note is

$$\lambda' = \frac{v}{f'} = \frac{345\ \text{m/s}}{1.397 \times 10^3\ \text{Hz}} = 0.247\ \text{m}$$

and the increment of change is

$$\Delta\lambda = \lambda' - \lambda = (0.247 - 0.233)\ \text{m=0.014 m=}\boxed{14\ \text{mm}}$$

14.65 The frequency heard from the stationary speaker the student is *approaching* $\left(v_O = +|v_O|\right)$ is

$$(f_O)_1 = f_S\left(\frac{v + |v_O|}{v}\right)$$

The frequency heard from the stationary speaker the student moves *away from* $\left(v_O = -|v_O|\right)$ is

$$(f_O)_2 = f_S\left(\frac{v - |v_O|}{v}\right)$$

Thus, the beat frequency heard is

$$f_{beat} = (f_O)_1 - (f_O)_2 = \frac{2 f_S |v_O|}{v}$$

With $|v_O| = 1.50\ \text{m/s}$, this gives $f_{beat} = \dfrac{2(456\ \text{Hz})(1.50\ \text{m/s})}{345\ \text{m/s}} = \boxed{3.97\ \text{Hz}}$

14.66 (a) The wavelength of the sound generated by the speakers is

$$\lambda = \frac{v}{f} = \frac{344 \text{ m/s}}{21.5 \text{ Hz}} = 16.0 \text{ m}$$

At point A, the distance from the observer to one speaker exceeds the distance to the other speaker by

$$\Delta d = d_1 - d_2 = 9.00 \text{ m} - 1.00 \text{ m} = 8.00 \text{ m}$$

Observe that this path difference is $\boxed{\Delta d = \lambda/2}$. Thus, waves arriving at point A from the two speakers meet out of phase and undergo $\boxed{\text{destructive interference}}$.

(b) The coordinates of points on the path should be so the path difference

$$\Delta d = d_1 - d_2 = \sqrt{(x + 5.00 \text{ m})^2 + y^2} - \sqrt{(x - 5.00 \text{ m})^2 + y^2}$$

will always equal $\lambda/2$.

Thus, we write $\sqrt{(x + 5.00 \text{ m})^2 + y^2} = \sqrt{(x - 5.00 \text{ m})^2 + y^2} + 8.00 \text{ m}$

Square both sides of this equation and simplify to find

$$\frac{5x}{4} - (4.00 \text{ m}) = \sqrt{(x - 5.00 \text{ m})^2 + y^2}$$

Again, square both sides and simplify to obtain $9x^2 - 16y^2 = 144 \text{ m}^2$,

or $\boxed{\frac{x^2}{16} - \frac{y^2}{9} = 1.00 \text{ m}^2}$ This is the equation of a hyperbola.

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

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

Thus, if $v_{long} = 8 v_{trans}$, we have $\frac{Y(A \cdot L)}{m} = 64\left(\frac{F \cdot L}{m}\right)$, or the required tension is

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

14.68 The speed of transverse waves in the wire is

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

When the wire vibrates in its third harmonic, $\lambda = 2L/3 = 0.500\ \text{m}$, 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 $f_S = 730\ \text{Hz}$. 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 $f_{beat} = (f_O)_1 - (f_O)_2 = f_S\left(\frac{v + |v_O| - (v - |v_O|)}{v}\right) = \frac{2f_S|v_O|}{v}$

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

14.69 The speed of the trailing ship (the source) is

$$|v_S| = (64.0\ \text{km/h})\left(\frac{0.278\ \text{m/s}}{1\ \text{km/h}}\right) = 17.8\ \text{m/s}$$

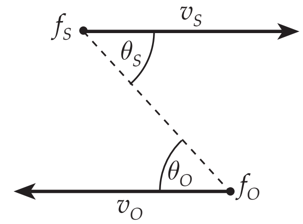
and that of the leading ship (observer) is

$$|v_O| = (45.0\ \text{km/h})\left(\frac{0.278\ \text{m/s}}{1\ \text{km/h}}\right) = 12.5\ \text{m/s}$$

The trailing ship (source) moves *towtard* the leading ship (observer), so $v_S = +|v_S|$. The observer is moving *away from* the source, so $v_O = -|v_O|$. The observed frequency is therefore

$$f_O = f_S\left(\frac{v+v_O}{v-v_S}\right) = f_S\left(\frac{v-|v_O|}{v-|v_S|}\right) = (1\,200 \text{ Hz})\left(\frac{1\,520 \text{ m/s} - 12.5 \text{ m/s}}{1\,520 \text{ m/s} - 17.8 \text{ m/s}}\right) = \boxed{1\,204 \text{ Hz}}$$

14.70 (a) If the source and the observer are moving away from each other along the same line, the relevant angles as defined in the sketch at the right are $\theta_S = 180°$ and $\theta_O = 180°$.



Thus, $$f_O = \left(\frac{v+|v_O|\cos\theta_O}{v-|v_S|\cos\theta_S}\right) f_S$$

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

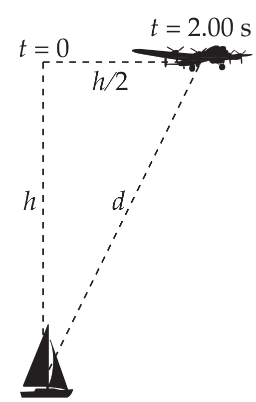
which is the same as Equation 14.12 in the text when both v_O and v_S are negative (that is, when source and observer move away from each other).

(b) When the train is 40.0 m to the left of the crossing and the car is 30.0 m from the tracks, $\theta_S = \tan^{-1}\left(\frac{30.0 \text{ m}}{40.0 \text{ m}}\right) = \tan^{-1}(0.750) = 36.9°$. Then, with $v_O = 0$, the observed frequency is

$$f_O = \left(\frac{v}{v - v_S\cos\theta_S}\right) f_S = \left(\frac{343 \text{ m/s}}{343 \text{ m/s} - (25.0 \text{ m/s})\cos 36.9°}\right)(500 \text{ Hz}) = \boxed{531 \text{ Hz}}$$

14.71 (a) The distance the sound traveled in 2.00 s is

$$d = v_{sound}t = (345 \text{ m/s})(2.00 \text{ s}) = 690 \text{ m}$$



Observe the sketch at the right and apply the Pythagorean theorem to obtain

$$h^2 + \left(\frac{h}{2}\right)^2 = d^2 \quad \text{or} \quad \frac{5}{4}h^2 = d^2$$

Thus, the altitude of the plane is $h = \frac{2d}{\sqrt{5}} = \frac{2(690 \text{ m})}{\sqrt{5}} = \boxed{617 \text{ m}}$

(b) The speed of the plane is $$v=\frac{h/2}{t}=\frac{617\ \text{m}}{2(2.00\ \text{s})}=\boxed{154\ \text{m/s}}$$

14.72 (a) When the observer is stationary with a source emitting sound of frequency $f_S = 1.80\ \text{kHz}$ moving toward it, the frequency detected by the observer is

$$f_O = f_S\left(\frac{v+v_O}{v-v_S}\right)=f_S\left(\frac{v+0}{v-|v_S|}\right)$$

where $|v_S|$ is the speed of the source, and $v = 343\ \text{m/s}$ is the speed of sound in the air. Thus, if the detected frequency is $f_O = 2.15\ \text{kHz}$, the speed of the source is

$$|v_S| = v\left(1-\frac{f_S}{f_O}\right)=(343\ \text{m/s})\left(1-\frac{1.80\ \text{kHz}}{2.15\ \text{kHz}}\right)=\boxed{55.8\ \text{m/s}}$$

(b) In this case, the skydiver is a moving observer with velocity $v_O = +58.8\ \text{m/s}$, moving toward a stationary source (the ground) that is emitting (reflecting) sound of frequency $f_S = 2.15\ \text{kHz}$. The frequency detected by the skydiver will be

$$f_O = f_S\left(\frac{v+v_O}{v-v_S}\right)=(2.15\ \text{kHz})\left(\frac{343\ \text{m/s}+55.8\ \text{m/s}}{343\ \text{m/s}-0}\right)=\boxed{2.50\ \text{kHz}}$$