12

SOUND

Responses to Questions

1. Sound exhibits several phenomena that give evidence that it is a wave. Interference is a wave phenomenon, and sound produces interference (such as beats). Diffraction is a wave phenomenon, and sound can be diffracted (such as sound being heard around corners). Refraction is a wave phenomenon, and sound exhibits refraction when passing obliquely from one medium to another. Sound also requires a medium, a characteristic of mechanical waves.

2. Evidence that sound is a form of energy is found in the fact that sound can do work. A sound wave created in one location can cause the mechanical vibration of an object at a different location. For example, sound can set eardrums in motion, make windows rattle, or even shatter a glass. See Fig. 11–19 for a photograph of a goblet shattering from the sound of a trumpet.

3. The child speaking into a cup creates sound waves that cause the bottom of the cup to vibrate. Since the string is tightly attached to the bottom of the cup, the vibrations of the cup are transmitted to longitudinal waves in the string. These waves travel down the string and cause the bottom of the receiver's cup to vibrate back and forth. This relatively large vibrating surface moves the adjacent air and generates sound waves from the bottom of the cup that travel up into the cup. These waves are incident on the receiver's ear, and the receiver hears the sound from the speaker.

4. If the frequency were to change, the two media could not stay in contact with each other. If the two media vibrated with different frequencies, then particles from the two media initially in contact could not stay in contact with each other. But particles must be in contact in order for the wave to be transmitted from one medium to the other, so the frequency does not change. Since the wave speed changes in passing from air into water and the frequency does not change, we expect the wavelength to change. Sound waves travel about four times faster in water than in air, so we expect the wavelength in water to be about four times longer than it is in air.

5. If the speed of sound in air depended significantly on frequency, then the sounds that we hear would be separated in time according to frequency. For example, if a chord were played by an orchestra, then we would hear the high notes at one time, the middle notes at another, and the lower notes at still another. This effect is not heard for a large range of distances, indicating that the speed of sound in air does not depend significantly on frequency.

6. The sound-producing anatomy of a person includes various resonating cavities, such as the throat. The relatively fixed geometry of these cavities determines the relatively fixed wavelengths of sound that a person can produce. Those wavelengths have associated frequencies given by $f = \upsilon/\lambda.$ The speed of sound is determined by the gas that is filling the resonant cavities. If the person has inhaled helium, then the speed of sound will be much higher than normal, since the speed of sound waves in helium is about 3 times that in air. Thus, the person's frequencies will go up by about a factor of 3. This is about a 1.5-octave shift, so the person's voice sounds very high pitched.

7. The basic equation determining the pitch of the organ pipe is either $f_{\text{closed}} = \dfrac{n\upsilon}{4\ell}, n = \text{odd integer},$ for a closed pipe, or $f_{\text{open}} = \dfrac{n\upsilon}{2\ell}, n = \text{integer},$ for an open pipe. In each case, the frequency is proportional to the speed of sound in air. Since the speed is a function of temperature, and the length of any particular pipe is very nearly constant over the relatively small range of temperatures in a room, the frequency is also a function of temperature. Thus, when the temperature changes, the resonant frequencies of the organ pipes change. Since the speed of sound increases with temperature, as the temperature increases, the pitch of the pipes increases as well.

8. A tube of a given length will resonate (permit standing waves) at certain frequencies. When a mix of frequencies is input to the tube, only those frequencies close to resonant frequencies will produce sound that persists, because standing waves are created for those frequencies. Frequencies far from resonant frequencies will not persist very long at all—they will "die out" quickly. If, for example, two adjacent resonances of a tube are at 100 Hz and 200 Hz, then sound input near one of those frequencies will persist and sound relatively loud. A sound input near 150 Hz would fade out quickly and thus have a reduced amplitude as compared to the resonant frequencies. The length of the tube can therefore be chosen to "filter" certain frequencies, if those filtered frequencies are not close to resonant frequencies.

9. For a string with fixed ends, the fundamental frequency is given by $f = \dfrac{\upsilon}{2\ell},$ so the length of string for a given frequency is $\ell = \dfrac{\upsilon}{2f}.$ For a string, if the tension is not changed while fretting, the speed of sound waves will be constant. Thus, for two frequencies $f_1 < f_2,$ the spacing between the frets corresponding to those frequencies is given as follows:

$$\ell_1 - \ell_2 = \frac{\upsilon}{2f_1} - \frac{\upsilon}{2f_2} = \frac{\upsilon}{2}\left(\frac{1}{f_1} - \frac{1}{f_2}\right)$$

Now see Table 12–3. Each note there corresponds to one fret on the guitar neck. Notice that as the adjacent frequencies increase, the interfrequency spacing also increases. The change from C to $\text{C}^{\#}$ is 15 Hz, while the change from G to $\text{G}^{\#}$ is 23 Hz. Thus, their reciprocals get closer together, so from the above formula, the length spacing gets closer together. Consider a numerical example.

$$\ell_{\text{C}} - \ell_{\text{C}^{\#}} = \frac{\upsilon}{2}\left(\frac{1}{262} - \frac{1}{277}\right) = \frac{\upsilon}{2}(2.07\times 10^{-4}) \qquad \ell_{\text{G}} - \ell_{\text{G}^{\#}} = \frac{\upsilon}{2}\left(\frac{1}{392} - \frac{1}{415}\right) = \frac{\upsilon}{2}(1.41\times 10^{-4})$$

$$\frac{\ell_{\text{G}} - \ell_{\text{G}^{\#}}}{\ell_{\text{C}} - \ell_{\text{C}^{\#}}} = 0.68$$

The G to $\text{G}^{\#}$ spacing is only about 68% of the C to $\text{C}^{\#}$ spacing.

10. When you first hear the truck, you cannot see it. There is no straight-line path from the truck to you. The sound waves that you are hearing are therefore arriving at your location due to diffraction. Long wavelengths are diffracted more than short wavelengths, so you are initially only hearing sound with long wavelengths, which are low-frequency sounds. After you can see the truck, you are able to receive all frequencies being emitted by the truck, not just the lower frequencies. Thus, the sound "brightens" due to your hearing more high-frequency components.

11. The wave pattern created by standing waves does not "travel" from one place to another. The node locations are fixed in space. Any one point in the medium has the same amplitude at all times. Thus, the interference can be described as "interference in space"—moving the observation point from one location to another changes the interference from constructive (antinode) to destructive (node). To experience the full range from node to antinode, the position of observation must change, but all observations could be made at the same time by a group of observers.

    The wave pattern created by beats does travel from one place to another. Any one point in the medium will at one time have a 0 amplitude (node) and half a beat period later, have a maximum amplitude (antinode). Thus, the interference can be described as "interference in time." To experience the full range from constructive interference to destructive interference, the time of observation must change, but all observations could be made at the same position.

$\boxed{12.}$ If the frequency of the speakers is lowered, then the wavelength will be increased. Each circle in the diagram will be larger, so the points C and D will move farther apart.

13. *Active noise reduction* devices work on the principle of destructive interference. If the electronics are fast enough to detect the noise, invert it, and create the opposite wave (180° out of phase with the original) in significantly less time than one period of the components of the noise, then the original noise and the created noise will be approximately in a destructive interference relationship. The person wearing the headphones will then hear a net sound signal that is very low in intensity.

14. For the two waves shown, the frequency of beating is higher in wave (a)—the beats occur more frequently. The beat frequency is the difference between the two component frequencies, so since (a) has a higher beat frequency, the component frequencies are farther apart in (a).

$\boxed{15.}$ There is no Doppler shift if the source and observer move in the same direction, with the same velocity. Doppler shift is caused by relative motion between source and observer, and if both source and observer move in the same direction with the same velocity, there is no relative motion.

16. If the wind is blowing but the listener is at rest with respect to the source, the listener will not hear a Doppler effect. We analyze the case of the wind blowing from the source toward the listener. The moving air (wind) has the same effect as if the speed of sound had been increased by an amount equal to the wind speed. The wavelength of the sound waves (distance that a wave travels during one period of time) will be increased by the same percentage that the wind speed is relative to the still-air speed of sound. Since the frequency is the speed divided by the wavelength, the frequency does not change, so there is no Doppler effect to hear. Alternatively, the wind has the same effect as if the air were not moving but the source and listener were moving at the same speed in the same direction. See Question 15 for a discussion of that situation. Finally, since there is no relative motion between the source and the listener, there is no Doppler shift.

17. The highest frequency of sound will be heard at position C, while the child is swinging forward. Assuming the child is moving with SHM, the highest speed is at the equilibrium point, point C. And to have an increased pitch, the relative motion of the source and detector must be toward each other. The child would also hear the lowest frequency of sound at point C, while swinging backward.

Responses to MisConceptual Questions

1. (*a*) Students may answer that the speed of sound is the same, if they do not understand that the speed of sound is not constant, but depends upon the temperature of the air. When it is hotter, the speed of sound is greater, so it takes less time for the echo to return.

2. (*d*) Sound waves are longitudinal waves, so (*a*) is incorrect. The sound waves can be characterized either by the longitudinal displacement of the air molecules or by the pressure differences that cause the displacements.

3. (*b*) A common misconception is to treat the sound intensity level as a linear scale instead of a logarithmic scale. If the sound intensity doubles, the intensity level increases by about 3 dB, so the correct answer is 73 dB.

4. (*e*) Students often think that the sound intensity is the same as loudness and therefore mistakenly answer that doubling the intensity will double the loudness. However, the ear interprets loudness on a logarithmic scale. For something to sound twice as loud, it must have an intensity that is 10 times as great.

5. (*b*) The octave is a measure of musical frequency, not loudness. Raising a note by one octave requires doubling the frequency. Therefore, raising a note by two octaves is doubling the frequency twice, which is the same as quadrupling the frequency.

6. (*e*) In a string or open tube the lowest vibration mode is equal to half of a wavelength. In a tube closed at one end the lowest vibration mode is equal to a quarter of a wavelength. Therefore, none of the listed objects have a lowest vibration mode equal to a wavelength.

7. (*e*) A common misconception is that the frequency of a sound changes as it passes from air to water. The frequency is the number of wave crests that pass a certain point per unit time. If this value were to change as it entered the water, then wave crests would build up or be depleted over time. This would make the interface an energy source or sink, which it is not. The speed of sound in water is greater than in air, so the speed of the wave changes. Since the frequency cannot change, the increase in speed results in an increase in wavelength.

8. (*e*) As the string oscillates, it causes the air to vibrate at the same frequency. Therefore, the sound wave will have the same frequency as the guitar string, so answers (*b*) and (*c*) are incorrect. The speed of sound in air at 20°C is 343 m/s. The speed of sound in the string is the product of the wavelength and frequency, 462 m/s, so the sound waves in air have a shorter wavelength than the waves on the string.

9. (*c*) Pushing the string straight down onto a fret does not affect the tension a significant amount, due to the fret being so close to the string. The amplitude of the wave is determined by how hard the string is plucked, not by pushing the string onto the frets. When the string is pushed down, its effective length is shortened, which shortens the wavelength and thus increases the oscillation frequency. (The wave speed on the string doesn't change due to fretting the string.)

10. (*a*) The fundamental wavelength of an open-ended organ pipe is twice the length of the pipe. If one end is closed, then the fundamental wavelength is four times the length of the pipe. Since the wavelength doubles when one end of the pipe is closed off, and the speed of sound remains constant, the fundamental frequency is cut in half.

11. (*c*) The two speakers create sound waves that interact as described by the principle of superposition. When the waves overlap, the frequency remains the same; it does not double. If the speakers occupied the same location so that each point in the room were equidistant from the speakers, then the intensity would double everywhere. However, the speakers are separated by a distance of 10 m. Since the path lengths from each speaker to different locations around the room are not the same, at some points in the room the path difference will be an odd integer number of half wavelengths, so the sounds will destructively interfere. At other locations in the room the speakers will be equidistant, or the path difference will be an integral number of whole wavelengths, and the sounds will constructively interfere. This results in dead spots and loud spots in the room.

12. (*c*) A common misconception is that since the cars are moving there must be a Doppler shift. In this situation, however, there is no relative motion between the two vehicles. The two vehicles travel in the same direction at the same speed. Since the distance between them does not change, you and your sister will hear the horn sound at the same frequency.

13. (*e*) As the string vibrates, each part of the string (other than the nodes) oscillates at the same frequency, so answer (*a*) is true. This oscillation excites the air to vibrate at that frequency, so answer (*c*) is true. The wave relationships in answers (*b*) and (*d*) are true for any wave, so both are true in this case as well. However, the speed of the wave on the string is determined by the tension and mass of the string, and the speed of sound in the air is determined by the temperature, pressure, and density of the air. The two speeds are not necessarily the same. Since the sound wave and wave on the string have the same frequencies, but not necessarily the same wave speeds, they do not necessarily have the same wavelengths. Thus, (*e*) is not true.

Solutions to Problems

In solving these problems, the authors did not always follow the rules of significant figures rigidly. We tended to take quoted frequencies as correct to the number of digits shown, especially where other values might indicate that. For example, in Problem 49, values of 350 Hz and 355 Hz are used. We took both of those values to have 3 significant figures.

1. The round-trip time for sound is 2.5 seconds, so the time for sound to travel the length of the lake is 1.25 seconds. Use the time and the speed of sound to determine the length of the lake.

$$d = \upsilon t = (343\text{ m/s})(1.25\text{ s}) = 429\text{ m} \approx \boxed{430\text{ m}}$$

2. The round-trip time for sound is 2.0 seconds, so the time for sound to travel the length of the lake is 1.0 seconds. Use the time and the speed of sound in water to determine the depth of the lake.

$$d = \upsilon t = (1560\text{ m/s})(1.0\text{ s}) = 1560\text{ m} = \boxed{1600\text{ m}}$$

3. (*a*) $$\lambda_{20\text{ Hz}} = \frac{\upsilon}{f} = \frac{343\text{ m/s}}{20\text{ Hz}} = \boxed{17\text{ m}} \quad \lambda_{20\text{ kHz}} = \frac{\upsilon}{f} = \frac{343\text{ m/s}}{2.0\times 10^4\text{ Hz}} = \boxed{1.7\times 10^{-2}\text{ m}}$$

The range is from 1.7 cm to 17 m.

(*b*) $$\lambda = \frac{\upsilon}{f} = \frac{343\text{ m/s}}{18\times 10^6\text{ Hz}} = \boxed{1.9\times 10^{-5}\text{ m}}$$

4. The distance that the sound travels is the same on both days and is equal to the speed of sound times the elapsed time. Use the temperature-dependent relationship for the speed of sound in air.

$$d = \upsilon_1 t_1 = \upsilon_2 t_2 \quad \rightarrow \quad [(331 + 0.6(31))\text{ m/s}](4.80\text{ s}) = [(331 + 0.6(T_2))\text{ m/s}](5.20\text{ s}) \quad \rightarrow$$

$$T_2 = \boxed{-14°\text{C}}$$

5. (*a*) For the fish, the speed of sound in sea water must be used.

$$d = \upsilon t \quad \rightarrow \quad t = \frac{d}{\upsilon} = \frac{1550\text{ m}}{1560\text{ m/s}} = \boxed{0.994\text{ s}}$$

(*b*) For the fishermen, the speed of sound in air must be used.

$$d = \upsilon t \quad \rightarrow \quad t = \frac{d}{\upsilon} = \frac{1550\text{ m}}{343\text{ m/s}} = \boxed{4.52\text{ s}}$$

6. The two sound waves travel the same distance. The sound will travel faster in the concrete and thus take a shorter time.

$$d = \upsilon_{\text{air}} t_{\text{air}} = \upsilon_{\text{concrete}} t_{\text{concrete}} = \upsilon_{\text{concrete}} (t_{\text{air}} - 0.80\text{ s}) \quad \rightarrow \quad t_{\text{air}} = \frac{\upsilon_{\text{concrete}}}{\upsilon_{\text{concrete}} - \upsilon_{\text{air}}}(0.80\text{ s})$$

$$d = \upsilon_{\text{air}} t_{\text{air}} = \upsilon_{\text{air}} \left(\frac{\upsilon_{\text{concrete}}}{\upsilon_{\text{concrete}} - \upsilon_{\text{air}}} \right)(0.80\text{ s})$$

The speed of sound in concrete is obtained from Eq. 11–14a, Table 9–1, and Table 10–1.

$$\upsilon_{\text{concrete}} = \sqrt{\frac{E}{\rho}} = \sqrt{\frac{20 \times 10^9\text{ N/m}^2}{2.3 \times 10^3\text{ kg/m}^3}} = 2949\text{ m/s}$$

$$d = \upsilon_{\text{air}} t_{\text{air}} = (343\text{ m/s}) \left(\frac{2949\text{ m/s}}{2949\text{ m/s} - 343\text{ m/s}} \right)(0.80\text{ s}) = 310.5\text{ m} \approx \boxed{310\text{ m}}$$

7. The total time T is the time for the stone to fall (t_{down}) plus the time for the sound to come back to the top of the cliff (t_{up}): $T = t_{\text{up}} + t_{\text{down}}$. Use constant-acceleration relationships for an object dropped from rest that falls a distance h in order to find t_{down}, with down as the positive direction. Use the constant speed of sound to find t_{up} for the sound to travel a distance h.

$$\text{down: } y = y_0 + \upsilon_0 t_{\text{down}} + \tfrac{1}{2} a t_{\text{down}}^2 \quad \rightarrow \quad h = \tfrac{1}{2} g t_{\text{down}}^2 \qquad \text{up: } h = \upsilon_{\text{snd}} t_{\text{up}} \quad \rightarrow \quad t_{\text{up}} = \frac{h}{\upsilon_{\text{snd}}}$$

$$h = \tfrac{1}{2} g t_{\text{down}}^2 = \tfrac{1}{2} g (T - t_{\text{up}})^2 = \tfrac{1}{2} g \left(T - \frac{h}{\upsilon_{\text{snd}}} \right)^2 \quad \rightarrow \quad h^2 - 2\upsilon_{\text{snd}} \left(\frac{\upsilon_{\text{snd}}}{g} + T \right) h + T^2 \upsilon_{\text{snd}}^2 = 0$$

This is a quadratic equation for the height. This can be solved with the quadratic formula, but be sure to keep several significant digits in the calculations.

$$h^2 - 2(343\text{ m/s}) \left(\frac{343\text{ m/s}}{9.80\text{ m/s}^2} + 2.7\text{ s} \right) h + (2.7\text{ s})^2 (343\text{ m/s})^2 = 0 \quad \rightarrow$$

$$h^2 - (25862\text{ m})h + 8.5766 \times 10^5\text{ m}^2 = 0 \quad \rightarrow \quad h = \frac{25862 \pm 25796}{2} = 25{,}829\text{ m}, \ \boxed{33\text{ m}}$$

The larger root is impossible since it takes more than 2.7 s for the rock to fall that distance, so $\boxed{h = 33\text{ m}}$.

8. $120 \text{ dB} = 10 \log \frac{I_{120}}{I_0} \rightarrow I_{120} = 10^{12} I_0 = 10^{12}(1.0 \times 10^{-12} \text{ W/m}^2) = \boxed{1.0 \text{ W/m}^2}$

$20 \text{ dB} = 10 \log \frac{I_{20}}{I_0} \rightarrow I_{20} = 10^2 I_0 = 10^2(1.0 \times 10^{-12} \text{ W/m}^2) = \boxed{1.0 \times 10^{-10} \text{ W/m}^2}$

The pain level is 10^{10} times more intense than the whisper.

9. $\beta = 10 \log \frac{I}{I_0} = 10 \log \frac{1.5 \times 10^{-6} \text{ W/m}^2}{1.0 \times 10^{-12} \text{ W/m}^2} = 61.76 \text{ dB} \approx \boxed{62 \text{ dB}}$

10. Compare the two power output ratings using the definition of decibels.

$\beta = 10 \log \frac{P_{150}}{P_{100}} = 10 \log \frac{120 \text{ W}}{75 \text{ W}} = \boxed{2.0 \text{ dB}}$

This would barely be perceptible.

11. From Example 12–4, we see that a sound level decrease of 3 dB corresponds to a halving of intensity. Thus, the sound level for one firecracker will be $85 \text{ dB} - 3 \text{ dB} = \boxed{82 \text{ dB}}$.

12. From Example 12–4, we see that a sound level decrease of 3 dB corresponds to a halving of intensity. Thus, if two engines are shut down, the intensity will be cut in half, and the sound level will be 137 dB. Then, if one more engine is shut down, the intensity will be cut in half again, and the sound level will drop by 3 more dB, to a final value of $\boxed{134 \text{ dB}}$.

13. For the 82-dB device: $82 \text{ dB} = 10 \log (I_{\text{signal}}/I_{\text{noise}})_{\text{tape}} \rightarrow (I_{\text{signal}}/I_{\text{noise}})_{\text{tape}} = 10^{8.2} = \boxed{1.6 \times 10^8}$.

For the 98-dB device: $98 \text{ dB} = 10 \log (I_{\text{signal}}/I_{\text{noise}})_{\text{tape}} \rightarrow (I_{\text{signal}}/I_{\text{noise}})_{\text{tape}} = 10^{9.8} = \boxed{6.3 \times 10^9}$.

14. (*a*) The energy absorbed per second is the power of the wave, which is the intensity times the area.

$$55 \text{ dB} = 10 \log \frac{I}{I_0} \rightarrow I = 10^{5.5} I_0 = 10^{5.5}(1.0 \times 10^{-12} \text{ W/m}^2) = 3.162 \times 10^{-7} \text{ W/m}^2$$

$$P = IA = (3.162 \times 10^{-7} \text{ W/m}^2)(5.0 \times 10^{-5} \text{ m}^2) = 1.581 \times 10^{-11} \text{ W} \approx \boxed{1.6 \times 10^{-11} \text{ J/s}}$$

(*b*) $1.0 \text{ J} \left(\frac{1 \text{ s}}{1.581 \times 10^{-11} \text{ J}} \right) \left(\frac{1 \text{ yr}}{3.16 \times 10^7 \text{ s}} \right) = 2001 \text{ yr} \approx \boxed{2.0 \times 10^3 \text{ yr}}$

$\boxed{15.}$ (*a*) Find the intensity from the 130-dB value, and then find the power output corresponding to that intensity at that distance from the speaker.

$$\beta = 130 \text{ dB} = 10 \log \frac{I_{2.8 \text{ m}}}{I_0} \rightarrow I_{2.8 \text{ m}} = 10^{13} I_0 = 10^{13}(1.0 \times 10^{-12} \text{ W/m}^2) = 10 \text{ W/m}^2$$

$$P = IA = 4\pi r^2 I = 4\pi (2.5 \text{ m})^2 (10 \text{ W/m}^2) = 785.4 \text{ W} \approx \boxed{790 \text{ W}}$$

(*b*) Find the intensity from the 85-dB value, and then from the power output, find the distance corresponding to that intensity.

$$\beta = 85\text{ dB} = 10\log\frac{I}{I_0} \quad\rightarrow\quad I = 10^{8.5}\,I_0 = 10^{8.5}(1.0\times10^{-12}\text{ W/m}^2) = 3.162\times10^{-4}\text{ W/m}^2$$

$$P = 4\pi r^2 I \quad\rightarrow\quad r = \sqrt{\frac{P}{4\pi I}} = \sqrt{\frac{785.4\text{ W}}{4\pi(3.162\times10^{-4}\text{ W/m}^2)}} = 444.6\text{ m} \approx \boxed{440\text{ m}}$$

16. The first person is a distance of $r_1 = 100\,\text{m}$ from the explosion, while the second person is a distance $r_2 = \sqrt{5}(100\text{ m})$ from the explosion. The intensity detected away from the explosion is inversely proportional to the square of the distance from the explosion.

$$\frac{I_1}{I_2} = \frac{r_2^2}{r_1^2} = \left[\frac{\sqrt{5}(100\text{ m})}{100\text{ m}}\right]^2 = 5; \quad \beta = 10\log\frac{I_1}{I_2} = 10\log 5 = 6.99\text{ dB} \approx \boxed{7\text{ dB}}$$

17. (*a*) The intensity is proportional to the square of the amplitude, so if the amplitude is 3.5 times greater, the intensity will $\boxed{\text{increase by a factor of } 3.5^2 = 12.25 \approx 12}$.

(*b*) $\beta = 10\log I/I_0 = 10\log 12.25 = 10.88\text{ dB} \approx \boxed{11\text{ dB}}$

18. The intensity is given by Eq. 11–18, $I = 2\rho\upsilon\pi^2 f^2 A^2$. If the only difference in two sound waves is their frequencies, then the ratio of the intensities is the ratio of the square of the frequencies.

$$\frac{I_{2f}}{I_f} = \frac{(2.2f)^2}{f^2} = \boxed{4.8}$$

$\boxed{19.}$ The intensity is given by Eq. 11–18, $I = 2\pi^2\upsilon\rho f^2 A^2$, using the density of air (from Table 10–1) and the speed of sound in air.

$$I = 2\rho\upsilon\pi^2 f^2 A^2 = 2(1.29\text{ kg/m}^3)(343\text{ m/s})\pi^2(440\text{ Hz})^2(1.3\times10^{-4}\text{ m})^2 = 28.57\,6\text{ W/m}^2$$

$$\beta = 10\log\frac{I}{I_0} = 10\log\frac{28.576\text{ W/m}^2}{1.0\times10^{-12}\text{ W/m}^2} = 134.56\text{ dB} \approx \boxed{130\text{ dB}}$$

Note that according to Fig. 12–6, this is above the threshold of pain at that frequency.

20. (*a*) According to Table 12–2, the intensity of normal conversation, at a distance of about 50 cm from the speaker, is about $3\times10^{-6}\text{ W/m}^2$. The intensity is the power output per unit area, so the power output can be found. The area to use is the surface area of a sphere.

$$I = \frac{P}{A} \quad\rightarrow\quad P = IA = I(4\pi r^2) = (3\times10^{-6}\text{ W/m}^2)4\pi(0.50\text{ m})^2 = 9.425\times10^{-6}\text{ W} \approx \boxed{9.4\times10^{-6}\text{ W}}$$

(*b*) $60\text{ W}\left(\dfrac{1\text{ person}}{9.425\times10^{-6}\text{ W}}\right) = 6.37\times10^6 \approx \boxed{6\text{ million people}}$

21. The intensity of the sound is defined to be the power per unit area. We assume that the sound spreads out spherically from the loudspeaker.

(*a*) $$I_{220} = \frac{220\ \text{W}}{4\pi(3.5\ \text{m})^2} = 1.429\ \text{W/m}^2 \quad I_{45} = \frac{45\ \text{W}}{4\pi(3.5\ \text{m})^2} = 0.292\ \text{W/m}^2$$

$$\beta_{220} = 10\log\frac{I_{220}}{I_0} = 10\log\frac{1.429\ \text{W/m}^2}{1.0\times10^{-12}\ \text{W/m}^2} = 121.55\ \text{dB} \approx \boxed{122\ \text{dB}}$$

$$\beta_{45} = 10\log\frac{I_{45}}{I_0} = 10\log\frac{0.292\ \text{W/m}^2}{1.0\times10^{-12}\ \text{W/m}^2} = 114.66\ \text{dB} \approx \boxed{115\ \text{dB}}$$

(*b*) According to the textbook, for a sound to be perceived as twice as loud as another, the intensities need to differ by a factor of 10, or differ by 10 dB. They differ by only about 7 dB. $\boxed{\text{The expensive amp will not sound twice as loud as the cheaper one.}}$

22. From Fig. 12–6, a 100-Hz tone at 50 dB has a loudness of about 20 phons. At 5000 Hz, 20 phons corresponds to about $\boxed{20\ \text{dB}}$. Answers may vary due to estimation in the reading of the graph.

23. From Fig. 12–6, at 40 dB the low-frequency threshold of hearing is about $\boxed{70\text{–}80\ \text{Hz}}$. There is no intersection of the threshold of hearing with the 40-dB level on the high-frequency side of the chart, so we assume that a 40-dB signal can be heard all the way up to the highest frequency that a human can hear, $\boxed{20{,}000\ \text{Hz}}$. Answers may vary due to estimation in the reading of the graph.

24. (*a*) From Fig. 12–6, at 100 Hz, the threshold of hearing (the lowest detectable intensity by the ear) is approximately $5\times10^{-9}\ \text{W/m}^2$. The threshold of pain is about $5\ \text{W/m}^2$. The ratio of highest to lowest intensity is thus $\dfrac{5\ \text{W/m}^2}{5\times10^{-9}\ \text{W/m}^2} = \boxed{10^9}$.

(*b*) At 5000 Hz, the threshold of hearing is about $10^{-13}\ \text{W/m}^2$, and the threshold of pain is about $10^{-1}\ \text{W/m}^2$. The ratio of highest to lowest intensity is $\dfrac{10^{-1}\ \text{W/m}^2}{10^{-13}\ \text{W/m}^2} = \boxed{10^{12}}$.

Answers may vary due to estimation in the reading of the graph.

25. Each octave is a doubling of frequency. The number of octaves, *n*, can be found from the following:

$$20{,}000\ \text{Hz} = 2^n(20\ \text{Hz}) \quad\rightarrow\quad 1000 = 2^n \quad\rightarrow\quad \log 1000 = n\log 2 \quad\rightarrow$$
$$n = \frac{\log 1000}{\log 2} = 9.97 \approx \boxed{10\ \text{octaves}}$$

26. For a closed tube, Fig. 12–12 indicates that $f_1 = \dfrac{\upsilon}{4\ell}$. We assume the bass clarinet is at room temperature.

$$f_1 = \frac{\upsilon}{4\ell} \quad\rightarrow\quad \ell = \frac{\upsilon}{4f_1} = \frac{343\ \text{m/s}}{4(69\ \text{Hz})} = \boxed{1.2\ \text{m}}$$

27. For a vibrating string, the frequency of the fundamental mode is given by Eq. 11–19b combined with Eq. 11–13.

$$f = \frac{\upsilon}{2\ell} = \frac{1}{2\ell}\sqrt{\frac{F_T}{\mu}} = \frac{1}{2\ell}\sqrt{\frac{F_T}{m/\ell}} \rightarrow F_T = 4\ell f^2 m = 4(0.32\text{ m})(440\text{ Hz})^2(3.5\times10^{-4}\text{ kg}) = \boxed{87\text{ N}}$$

$\boxed{28.}$ (*a*) If the pipe is closed at one end, only the odd harmonic frequencies are present.

$$f_n = \frac{n\ell}{4\ell} = nf_1,\ n = 1, 3, 5, \cdots \rightarrow f_1 = \frac{\upsilon}{4\ell} = \frac{343\text{ m/s}}{4(1.16\text{ m})} = \boxed{73.9\text{ Hz}}$$

$$f_3 = 3f_1 = \boxed{222\text{ Hz}} \quad f_5 = 5f_1 = \boxed{370\text{ Hz}} \quad f_7 = 7f_1 = \boxed{517\text{ Hz}}$$

(*b*) If the pipe is open at both ends, then all the harmonic frequencies are present.

$$f_n = \frac{n\upsilon}{2\ell} = nf_1,\ n = 1, 3, 5, \cdots \rightarrow f_1 = \frac{\upsilon}{2\ell} = \frac{343\text{ m/s}}{2(1.16\text{ m})} = \boxed{148\text{ Hz}}$$

$$f_2 = 2f_1 = \boxed{296\text{ Hz}} \quad f_3 = 3f_1 = \boxed{444\text{ Hz}} \quad f_4 = 4f_1 = \boxed{591\text{ Hz}}$$

29. (*a*) The length of the tube is one-fourth of a wavelength for this (one end closed) tube, so the wavelength is four times the length of the tube.

$$f = \frac{\upsilon}{\lambda} = \frac{343\text{ m/s}}{4(0.24\text{ m})} = \boxed{360\text{ Hz}}$$

(*b*) If the bottle is one-third full, then the effective length of the air column is reduced to 12 cm.

$$f = \frac{\upsilon}{\lambda} = \frac{343\text{ m/s}}{4(0.16\text{ m})} = \boxed{540\text{ Hz}}$$

30. For a pipe open at both ends, the fundamental frequency is given by $f_1 = \frac{\upsilon}{2\ell}$, so the length for a given fundamental frequency is $\ell = \frac{\upsilon}{2f_1}$.

$$\ell_{20\text{ Hz}} = \frac{343\text{ m/s}}{2(20\text{ Hz})} = \boxed{8.6\text{ m}} \qquad \ell_{20\text{ kHz}} = \frac{343\text{ m/s}}{2(20{,}000\text{ Hz})} = \boxed{8.6\times10^{-3}\text{ m}}$$

31. For a fixed string, the frequency of the *n*th harmonic is given by $f_n = nf_1$. Thus, the fundamental for this string is $f_1 = f_3/3 = 540\text{ Hz}/3 = 180\text{ Hz}$. When the string is fingered, it has a new length of 70% of the original length. The fundamental frequency of the vibrating string is also given by $f_1 = \frac{\upsilon}{2\ell}$, and υ is constant for the string, assuming its tension is not changed.

$$f_{1\,\text{fingered}} = \frac{\upsilon}{2\ell_{\text{fingered}}} = \frac{\upsilon}{2(0.70)\ell} = \frac{1}{0.70}f_1 = \frac{180\text{ Hz}}{0.70} = \boxed{260\text{ Hz}}$$

32. We approximate the shell as a closed tube of length 15 cm and calculate the fundamental frequency.

$$f = \frac{\upsilon}{4\ell} = \frac{343\text{ m/s}}{4(0.15\text{ m})} = 572\text{ Hz} \approx \boxed{570\text{ Hz}}$$

33. (*a*) We assume that the speed of waves on the guitar string does not change when the string is fretted. The fundamental frequency is given by $f = \frac{\upsilon}{2\ell}$, so the frequency is inversely proportional to the length.

$$f \propto \frac{1}{\ell} \quad \rightarrow \quad f\ell = \text{constant}$$

$$f_{\mathrm{E}}\ell_{\mathrm{E}} = f_{\mathrm{A}}\ell_{\mathrm{A}} \quad \rightarrow \quad \ell_{\mathrm{A}} = \ell_{\mathrm{E}}\frac{f_{\mathrm{E}}}{f_{\mathrm{A}}} = (0.68\ \mathrm{m})\left(\frac{330\ \mathrm{Hz}}{440\ \mathrm{Hz}}\right) = 0.51\ \mathrm{m}$$

The string should be fretted a distance $0.68\ \mathrm{m} - 0.51\ \mathrm{m} = \boxed{0.17\ \mathrm{m}}$ from the tuning nut of the guitar: (at the right-hand node in Fig. 12–8a of the textbook).

(*b*) The string is fixed at both ends and is vibrating in its fundamental mode. Thus, the wavelength is twice the length of the string (see Fig. 12–7).

$$\lambda = 2\ell = 2(0.51\ \mathrm{m}) = \boxed{1.02\ \mathrm{m}}$$

(*c*) The frequency of the sound will be the same as that of the string, $\boxed{440\ \mathrm{Hz}}$. The wavelength is given by the following:

$$\lambda = \frac{\upsilon}{f} = \frac{343\ \mathrm{m/s}}{440\ \mathrm{Hz}} = \boxed{0.78\ \mathrm{m}}$$

34. (*a*) At $T = 18°\mathrm{C}$, the speed of sound is given by $\upsilon = (331 + 0.60(18))\ \mathrm{m/s} = 341.8\ \mathrm{m/s}$. For an open pipe, the fundamental frequency is given by $f = \frac{\upsilon}{2\ell}$.

$$f = \frac{\upsilon}{2\ell} \quad \rightarrow \quad \ell = \frac{\upsilon}{2f} = \frac{341.8\ \mathrm{m/s}}{2(262\ \mathrm{Hz})} = \boxed{0.652\ \mathrm{m}}$$

(*b*) The frequency of the standing wave in the tube is $\boxed{262\ \mathrm{Hz}}$. The wavelength is twice the length of the pipe, $\boxed{1.30\ \mathrm{m}}$.

(*c*) The wavelength and frequency are the same in the air, because it is air that is resonating in the organ pipe. The frequency is $\boxed{262\ \mathrm{Hz}}$ and the wavelength is $\boxed{1.30\ \mathrm{m}}$.

35. The speed of sound will change as the temperature changes, and that will change the frequency of the organ. Assume that the length of the pipe (and thus the resonant wavelength) does not change.

$$f_{22.0} = \frac{\upsilon_{22.0}}{\lambda} \qquad f_{11} = \frac{\upsilon_{11}}{\lambda} \qquad \Delta f = f_{11} - f_{22.0} = \frac{\upsilon_{11} - \upsilon_{22.0}}{\lambda}$$

$$\frac{\Delta f}{f} = \frac{\frac{\upsilon_{11} - \upsilon_{22.0}}{\lambda}}{\frac{\upsilon_{22.0}}{\lambda}} = \frac{\upsilon_{11}}{\vee\ \upsilon_{22.0}} - 1 = \frac{331 + 0.60(11)}{331 + 0.60(22.0)} - 1 = -1.92 \times 10^{-2} = \boxed{-1.9\%}$$

36. A flute is a tube that is open at both ends, so the fundamental frequency is given by $f = \frac{\upsilon}{2\ell}$, where ℓ is the distance from the mouthpiece (antinode) to the first open side hole in the flute tube (antinode).

$$f = \frac{\upsilon}{2\ell} \quad \rightarrow \quad \ell = \frac{\upsilon}{2f} = \frac{343\ \mathrm{m/s}}{2(349\ \mathrm{Hz})} = \boxed{0.491\ \mathrm{m}}$$

37. (*a*) At $T = 22°\text{C}$, the speed of sound is $\upsilon = (331 + 0.60(22))\ \text{m/s} = 344.2\ \text{m/s}$. For an open pipe, the fundamental frequency is given by $f = \dfrac{\upsilon}{2\ell}$.

$$f = \frac{\upsilon}{2\ell} \quad \rightarrow \quad \ell = \frac{\upsilon}{2f} = \frac{344.2\ \text{m/s}}{2(294\ \text{Hz})} = 0.58537\ \text{m} \approx \boxed{0.585\ \text{m}}$$

(*b*) The speed of sound in helium is given in Table 12–1 as 1005 m/s. Use this and the pipe's length to find the pipe's fundamental frequency.

$$f = \frac{\upsilon}{2\ell} = \frac{1005\ \text{m/s}}{2(0.58537\ \text{m})} = 858.43\ \text{Hz} \approx \boxed{858\ \text{Hz}}$$

38. (*a*) The difference between successive overtones for this pipe is 176 Hz. The difference between successive overtones for an open pipe is the fundamental frequency, and each overtone is an integer multiple of the fundamental. Since 264 Hz is not a multiple of 176 Hz, 176 Hz cannot be the fundamental, so the pipe cannot be open. Thus, it must be a $\boxed{\text{closed}}$ pipe.

(*b*) For a closed pipe, the successive overtones differ by twice the fundamental frequency. Thus, 176 Hz must be twice the fundamental, so the fundamental is $\boxed{88\ \text{Hz}}$. This is verified since 264 Hz is three times the fundamental, 440 Hz is five times the fundamental, and 616 Hz is seven times the fundamental.

39. (*a*) The harmonics for the open pipe are $f_n = \dfrac{n\upsilon}{2\ell}$. To be audible, they must be below 20 kHz.

$$\frac{n\upsilon}{2\ell} < 2\times10^4\ \text{Hz} \quad \rightarrow \quad n < \frac{2(2.18\ \text{m})(2\times10^4\ \text{Hz})}{343\ \text{m/s}} = 254.2$$

Since there are 254 harmonics, there are $\boxed{253\ \text{overtones}}$.

(*b*) The harmonics for the closed pipe are $f_n = \dfrac{n\upsilon}{4\ell}$, n odd. Again, they must be below 20 kHz.

$$\frac{n\upsilon}{4\ell} < 2\times10^4\ \text{Hz} \quad \rightarrow \quad n < \frac{4(2.18\ \text{m})(2\times10^4\ \text{Hz})}{343\ \text{m/s}} = 508.5$$

The values of n must be odd, so $n = 1, 3, 5, \cdots, 507$. There are 254 harmonics, so there are $\boxed{253\ \text{overtones}}$.

40. A tube closed at both ends will have standing waves with displacement nodes at each end, so it has the same harmonic structure as a string that is fastened at both ends. Thus, the wavelength of the fundamental frequency is twice the length of the hallway, $\lambda_1 = 2\ell = 18\ \text{m}$.

$$f_1 = \frac{\upsilon}{\lambda_1} = \frac{343\ \text{m/s}}{18\ \text{m}} = 19.056\ \text{Hz} \approx \boxed{19\ \text{Hz}};\ f_2 = 2f_1 = \boxed{38\ \text{Hz}}$$

41. The tension and mass density of the string do not change, so the wave speed is constant. The frequency ratio for two adjacent notes is to be $2^{1/12}$. The frequency is given by $f = \dfrac{\upsilon}{2\ell}$.

$$f = \frac{\upsilon}{2\ell} \rightarrow \frac{f_{\substack{\text{1st}\\\text{fret}}}}{f_{\text{unfingered}}} = \frac{\dfrac{\upsilon}{2\ell_{\substack{\text{1st}\\\text{fret}}}}}{\dfrac{\upsilon}{2\ell_{\text{unfingered}}}} = 2^{1/12} \rightarrow \ell_{\substack{\text{1st}\\\text{fret}}} = \frac{\ell_{\text{unfingered}}}{2^{1/12}} = \frac{75.0\text{ cm}}{2^{1/12}} = 70.79\text{ cm}$$

$$\ell_{\substack{\text{2nd}\\\text{fret}}} = \frac{\ell_{\substack{\text{1st}\\\text{fret}}}}{2^{1/12}} = \frac{\ell_{\text{unfingered}}}{2^{2/12}} \rightarrow \ell_{\substack{n\text{th}\\\text{fret}}} = \frac{\ell_{\text{unfingered}}}{2^{n/12}};\quad x_{\substack{n\text{th}\\\text{fret}}} = \ell_{\text{unfingerd}} - \ell_{\substack{n\text{th}\\\text{fret}}} = \ell_{\text{unf ingered}}(1-2^{-n/12})$$

$$x_1 = (75.0\text{ cm})(1-2^{-1/12}) = \boxed{4.2\text{ cm}};\quad x_2 = (75.0\text{ cm})(1-2^{-2/12}) = \boxed{8.2\text{ cm}}$$

$$x_3 = (75.0\text{ cm})(1-2^{-3/12}) = \boxed{11.9\text{ cm}};\quad x_4 = (75.0\text{ cm})(1-2^{-4/12}) = \boxed{15.5\text{ cm}}$$

$$x_5 = (75.0\text{ cm})(1-2^{-5/12}) = \boxed{18.8\text{ cm}};\quad x_6 = (75.0\text{ cm})(1-2^{-6/12}) = \boxed{22.0\text{ cm}}$$

42. The ear canal can be modeled as a closed pipe of length 2.5 cm. The resonant frequencies are given by $f_n = \frac{n\upsilon}{4\ell}$, n odd. The first several frequencies are calculated here.

$$f_n = \frac{n\upsilon}{4\ell} = \frac{n(343\text{ m/s})}{4(2.5\times10^{-2}\text{ m})} = n(3430\text{ Hz}), n\text{ odd}$$

$$\boxed{f_1 = 3430\text{ Hz}\quad f_3 = 10{,}300\text{ Hz}\quad f_5 = 17{,}200\text{ Hz}}$$

In the graph, the most sensitive frequency is between 3000 and 4000 Hz. This corresponds to the fundamental resonant frequency of the ear canal. The sensitivity decrease above 4000 Hz, but is seen to “flatten out” around 10,000 Hz again, indicating higher sensitivity near 10,000 Hz than at surrounding frequencies. This 10,000-Hz relatively sensitive region corresponds to the first overtone resonant frequency of the ear canal.

43. From Eq. 11–18, the intensity is proportional to the square of the amplitude and the square of the frequency. From Fig. 12–15, the relative amplitudes are $\frac{A_2}{A_1} \approx 0.4$ and $\frac{A_3}{A_1} \approx 0.15$.

$$I = 2\pi^2\upsilon\rho f^2A^2 \rightarrow \frac{I_2}{I_1} = \frac{2\pi^2\upsilon\rho f_2^2A_2^2}{2\pi^2\upsilon\rho f_1^2A_1^2} = \frac{f_2^2A_2^2}{f_1^2A_1^2} = \left(\frac{f_2}{f_1}\right)^2\left(\frac{A_2}{A_1}\right)^2 = 2^2(0.4)^2 = \boxed{0.64}$$

$$\frac{I_3}{I_1} = \left(\frac{f_3}{f_1}\right)^2\left(\frac{A_3}{A_1}\right)^2 = 3^2(0.15)^2 = \boxed{0.20}$$

$$\beta_{2-1} = 10\log\frac{I_2}{I_1} = 10\log 0.64 = \boxed{-2\text{ dB}};\quad \beta_{3-1} = 10\log\frac{I_3}{I_1} = 10\log 0.24 = \boxed{-7\text{ dB}}$$

Answers may vary due to the reading of the figure.

44. The beat period is 2.0 seconds, so the beat frequency is the reciprocal of that, 0.50 Hz. Thus, the other string is off in frequency by $\boxed{\pm 0.50\text{ Hz}}$. The beating does not tell the tuner whether the second string is too high or too low.

45. The 5000-Hz shrill whine is the beat frequency generated by the combination of the two sounds. This means that the brand X whistle is either 5000 Hz higher or 5000 Hz lower than the known-frequency whistle. If it were 5000 Hz lower, then it would just barely be in the audible range for humans. Since humans cannot hear it, the brand X whistle must be 5000 Hz higher than the known frequency whistle.

Thus, the brand X frequency is $23.5\text{ kHz} + 5\text{ kHz} = \boxed{28.5\text{ kHz}}$. Since the original frequencies are good to 0.1 KHz, we assume that the 5000-Hz value is 5.0 kHz.

46. The beat frequency is the difference in the two frequencies, or $277\text{ Hz} - 262\text{ Hz} = \boxed{15\text{ Hz}}$. If both frequencies are reduced by a factor of 4, then the difference between the two frequencies will also be reduced by a factor of 4, so the beat frequency will be $\frac{1}{4}(15\text{ Hz}) = 3.75\text{ Hz} \approx \boxed{3.8\text{ Hz}}$.

47. Since there are 3 beats/s when sounded with the 350-Hz tuning fork, the guitar string must have a frequency of either 347 Hz or 353 Hz. Since there are 8 beats/s when sounded with the 355-Hz tuning fork, the guitar string must have a frequency of either 347 Hz or 363 Hz. The common value is $\boxed{347\text{ Hz}}$.

48. The fundamental frequency of the violin string is given by $f = \frac{\upsilon}{2\ell} = \frac{1}{2\ell}\sqrt{\frac{F_\text{T}}{\mu}} = 294\text{ Hz}$. Change the tension to find the new frequency and then subtract the two frequencies to find the beat frequency.

$$f' = \frac{1}{2\ell}\sqrt{\frac{(0.975)F_\text{T}}{\mu}} = \sqrt{0.975}\,\frac{1}{2\ell}\sqrt{\frac{F_\text{T}}{\mu}} = \sqrt{0.975}f$$

$$\Delta f = f - f' = f(1 - \sqrt{0.975}) = (294\text{ Hz})(1 - \sqrt{0.975}) = \boxed{3.7\text{ Hz}}$$

49. The beat frequency is 3 beats per 2.5 seconds, or 1.2 Hz. We assume the strings are the same length and the same mass density.

(*a*) The other string is either $220.0\text{ Hz} - 1.2\text{ Hz} = \boxed{218.8\text{ Hz}}$ or $220.0\text{ Hz} + 1.2\text{ Hz} = \boxed{221.2\text{ Hz}}$.

(*b*) Since $f = \frac{\upsilon}{2\ell} = \frac{1}{2\ell}\sqrt{\frac{F_\text{T}}{\mu}}$, we have $f \propto \sqrt{F_\text{T}} \rightarrow \frac{f}{\sqrt{F_\text{T}}} = \frac{f'}{\sqrt{F'_\text{T}}} \rightarrow F'_\text{T} = F_\text{T}\left(\frac{f'}{f}\right)^2$.

To change 218.8 Hz to 220.0 Hz: $F' = F_\text{T}\left(\frac{220.0}{218.8}\right)^2 = 1.011F_\text{T}$, $\boxed{1.1\%\text{ increase}}$.

To change 221.2 Hz to 220.0 Hz: $F' = F_\text{T}\left(\frac{220.0}{221.2}\right)^2 = 0.9892F_\text{T}$, $\boxed{1.1\%\text{ decrease}}$.

50. (a) For destructive interference, the smallest path difference must be one-half wavelength. Thus, the wavelength in this situation must be twice the path difference, or 1.00 m.

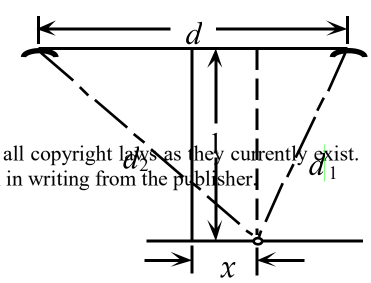
$$f = \frac{\upsilon}{\lambda} = \frac{343\text{ m/s}}{1.00\text{ m}} = \boxed{343\text{ Hz}}$$

(*b*) There will also be destructive interference if the path difference is 1.5 wavelengths, 2.5 wavelengths, etc.

$$\Delta\ell = 1.5\lambda \rightarrow \lambda = \frac{0.50\text{ m}}{1.5} = 0.333\text{ m} \rightarrow f = \frac{\upsilon}{\lambda} = \frac{343\text{ m/s}}{0.33\text{ m}} = 1029\text{ Hz} \approx \boxed{1000\text{ Hz}}$$

$$\Delta\ell = 2.5\lambda \rightarrow \lambda = \frac{0.50\text{ m}}{2.5} = 0.20\text{ m} \rightarrow f = \frac{\upsilon}{\lambda} = \frac{343\text{ m/s}}{0.20\text{ m}} = 1715\text{ Hz} \approx \boxed{1700\text{ Hz}}$$

51. (*a*) The microphone must be moved to the right until the difference



in distances from the two sources is half a wavelength. See the diagram. We square the expression, collect terms, isolate the remaining square root, and square again.

$$d_2 - d_1 = \tfrac{1}{2}\lambda \quad \rightarrow$$

$$\sqrt{\left(\tfrac{1}{2}d + x\right)^2 + \ell^2} - \sqrt{\left(\tfrac{1}{2}d - x\right)^2 + \ell^2} = \tfrac{1}{2}\lambda \quad \rightarrow$$

$$\sqrt{\left(\tfrac{1}{2}d + x\right)^2 + \ell^2} = \tfrac{1}{2}\lambda + \sqrt{\left(\tfrac{1}{2}d - x\right)^2 + \ell^2} \quad \rightarrow$$

$$\left(\tfrac{1}{2}d + x\right)^2 + \ell^2 = \tfrac{1}{4}\lambda^2 + 2\left(\tfrac{1}{2}\lambda\right)\sqrt{\left(\tfrac{1}{2}d - x\right)^2 + \ell^2} + \left(\tfrac{1}{2}d - x\right)^2 + \ell^2 \quad \rightarrow$$

$$2dx - \tfrac{1}{4}\lambda^2 = \lambda\sqrt{\left(\tfrac{1}{2}d - x\right)^2 + \ell^2} \quad \rightarrow \quad 4d^2x^2 - 2(2dx)\tfrac{1}{4}\lambda^2 + \tfrac{1}{16}\lambda^4 = \lambda^2\left[\left(\tfrac{1}{2}d - x\right)^2 + \ell^2\right]$$

$$4d^2x^2 - dx\lambda^2 + \tfrac{1}{16}\lambda^4 = \tfrac{1}{4}d^2\lambda^2 - dx\lambda^2 + x^2\lambda^2 + \lambda^2\ell^2 \quad \rightarrow \quad x = \lambda\sqrt{\frac{\left(\tfrac{1}{4}d^2 + \ell^2 - \tfrac{1}{16}\lambda^2\right)}{(4d^2 - \lambda^2)}}$$

The values are $d = 3.00\text{ m}$, $\ell = 3.20\text{ m}$, and $\lambda = \upsilon/f = (343\text{ m/s})/(474\text{ Hz}) = 0.7236\text{ m}$.

$$x = (0.7236\text{ m})\sqrt{\frac{\tfrac{1}{4}(3.00\text{ m})^2 + (3.20\text{ m})^2 - \tfrac{1}{16}(0.7236\text{ m})^2}{4(3.00\text{ m})^2 - (0.7236\text{ m})^2}} = \boxed{0.429\text{ m}}$$

(*b*) When the speakers are exactly out of phase, the maxima and minima will be interchanged. The intensity maxima are 0.429 m to the left or right of the midpoint, and the intensity minimum is at the midpoint.

52. (*a*) Observer moving toward stationary source:

$$f' = \left(1 + \frac{\upsilon_{\text{obs}}}{\upsilon_{\text{snd}}}\right)f = \left(1 + \frac{30.0\text{ m/s}}{343\text{ m/s}}\right)(1650\text{ Hz}) = \boxed{1790\text{ Hz}}$$

(*b*) Observer moving away from stationary source:

$$f' = \left(1 - \frac{\upsilon_{\text{obs}}}{\upsilon_{\text{snd}}}\right)f = \left(1 - \frac{30.0\text{ m/s}}{343\text{ m/s}}\right)(1650\text{ Hz}) = \boxed{1510\text{ Hz}}$$

53. The moving object can be treated as a moving "observer" for calculating the frequency it receives and reflects. The bat (the source) is stationary.

$$f'_{\text{object}} = f_{\text{bat}}\left(1 - \frac{\upsilon_{\text{object}}}{\upsilon_{\text{snd}}}\right)$$

Then the object can be treated as a moving source emitting the frequency f'_{object} and the bat as a stationary observer.

$$f''_{\text{bat}} = \frac{f'_{\text{object}}}{\left(1+\dfrac{v_{\text{object}}}{v_{\text{snd}}}\right)} = f_{\text{bat}}\frac{\left(1-\dfrac{v_{\text{object}}}{v_{\text{snd}}}\right)}{\left(1+\dfrac{v_{\text{object}}}{v_{\text{snd}}}\right)} = f_{\text{bat}}\frac{(v_{\text{snd}} - v_{\text{object}})}{(v_{\text{snd}} + v_{\text{object}})}$$

$$= (5.00\times10^4\ \text{Hz})\left(\frac{343\ \text{m/s} - 27.0\ \text{m/s}}{343\ \text{m/s} + 27.0\ \text{m/s}}\right) = \boxed{4.27\times10^4\ \text{Hz}}$$

54. The frequency received by the stationary car is higher than the frequency emitted by the stationary car, by $\Delta f = 4.5$ Hz.

$$f_{\text{obs}} = f_{\text{source}} + \Delta f = \frac{f_{\text{source}}}{\left(1-\dfrac{v_{\text{source}}}{v_{\text{snd}}}\right)} \quad \rightarrow$$

$$f_{\text{source}} = \Delta f\left(\frac{v_{\text{snd}}}{v_{\text{source}}} - 1\right) = (4.5\ \text{Hz})\left(\frac{343\ \text{m/s}}{18\ \text{m/s}} - 1\right) = 81.25\ \text{Hz} \approx \boxed{81\ \text{Hz}}$$

55. The wall can be treated as a stationary "observer" for calculating the frequency it receives. The bat is flying toward the wall.

$$f'_{\text{wall}} = f_{\text{bat}}\frac{1}{\left(1-\dfrac{v_{\text{bat}}}{v_{\text{snd}}}\right)}$$

Then the wall can be treated as a stationary source emitting the frequency f'_{wall} and the bat as a moving observer, flying toward the wall.

$$f''_{\text{bat}} = f'_{\text{wall}}\left(1+\frac{v_{\text{bat}}}{v_{\text{snd}}}\right) = f_{\text{bat}}\frac{1}{\left(1-\dfrac{v_{\text{bat}}}{v_{\text{snd}}}\right)}\left(1+\frac{v_{\text{bat}}}{v_{\text{snd}}}\right) = f_{\text{bat}}\frac{(v_{\text{snd}} + v_{\text{bat}})}{(v_{\text{snd}} - v_{\text{bat}})}$$

$$= (3.00\times10^4\ \text{Hz})\frac{343\ \text{m/s} + 6.0\ \text{m/s}}{343\ \text{m/s} - 6.0\ \text{m/s}} = \boxed{3.11\times10^4\ \text{Hz}}$$

56. The ocean wave has $\lambda = 44$ m and $v = 18$ m/s relative to the ocean floor. The frequency of the ocean wave is then $f = \dfrac{v}{\lambda} = \dfrac{18\ \text{m/s}}{44\ \text{m}} = 0.4091$ Hz.

(*a*) For the boat traveling west, the boat will encounter a Doppler shifted frequency, for an observer moving toward a stationary source. The speed $v = 18$ m/s represents the speed of the waves in the stationary medium, so it corresponds to the speed of sound in the Doppler formula. The time between encountering waves is the period of the Doppler shifted frequency.

$$f'_{\substack{\text{observer}\\ \text{moving}}} = \left(1+\frac{v_{\text{obs}}}{v_{\text{snd}}}\right)f = \left(1+\frac{14\ \text{m/s}}{18\ \text{m/s}}\right)(0.4091\ \text{Hz}) = 0.7273\ \text{Hz} \quad \rightarrow$$

$$T = \frac{1}{f} = \frac{1}{0.7273\ \text{Hz}} = 1.375\ \text{s} \approx \boxed{1.4\ \text{s}}$$

(*b*) For the boat traveling east, the boat will encounter a Doppler shifted frequency, for an observer moving away from a stationary source.

$$f'_{\substack{\text{observer}\\\text{moving}}} = \left(1 - \frac{\upsilon_{\text{obs}}}{\upsilon_{\text{snd}}}\right) f = \left(1 - \frac{14\text{ m/s}}{18\text{ m/s}}\right)(0.4091\text{ Hz}) = 0.09091\text{ Hz} \quad \to$$

$$T = \frac{1}{f} = \frac{1}{0.09091\text{ Hz}} = \boxed{11\text{ s}}$$

57. (*a*) The observer is stationary, and the source is moving. First the source is approaching, and then the source is receding.

$$120.0\text{ km/h}\left(\frac{1\text{ m/s}}{3.6\text{ km/h}}\right) = 33.33\text{ m/s}$$

$$f'_{\substack{\text{source}\\\text{moving}\\\text{toward}}} = f\frac{1}{\left(1 - \frac{\upsilon_{\text{src}}}{\upsilon_{\text{snd}}}\right)} = (1580\text{ Hz})\frac{1}{\left(1 - \frac{33.33\text{ m/s}}{343\text{ m/s}}\right)} = \boxed{1750\text{ Hz}}$$

$$f'_{\substack{\text{source}\\\text{moving}\\\text{away}}} = f\frac{1}{\left(1 + \frac{\upsilon_{\text{src}}}{\upsilon_{\text{snd}}}\right)} = (1580\text{ Hz})\frac{1}{\left(1 + \frac{33.33\text{ m/s}}{343\text{ m/s}}\right)} = \boxed{1440\text{ Hz}}$$

(*b*) Both the observer and the source are moving, so use Eq. 12–4.

$$90.0\text{ km/h}\left(\frac{1\text{ m/s}}{3.6\text{ km/h}}\right) = 25\text{ m/s}$$

$$f'_{\text{approaching}} = f\frac{(\upsilon_{\text{snd}} + \upsilon_{\text{obs}})}{(\upsilon_{\text{snd}} - \upsilon_{\text{src}})} = (1580\text{ Hz})\frac{(343\text{ m/s} + 25\text{ m/s})}{(343\text{ m/s} - 33.33\text{ m/s})} = \boxed{1880\text{ Hz}}$$

$$f'_{\text{receding}} = f\frac{(\upsilon_{\text{snd}} - \upsilon_{\text{obs}})}{(\upsilon_{\text{snd}} + \upsilon_{\text{src}})} = (1580\text{ Hz})\frac{(343\text{ m/s} - 25\text{ m/s})}{(343\text{ m/s} + 33.33\text{ m/s})} = \boxed{1340\text{ Hz}}$$

(*c*) Both the observer and the source are moving, so again use Eq. 12–4.

$$80.0\text{ km/h}\left(\frac{1\text{ m/s}}{3.6\text{ km/h}}\right) = 22.22\text{ m/s}$$

$$f'_{\substack{\text{police}\\\text{car}\\\text{approaching}}} = f\frac{(\upsilon_{\text{snd}} - \upsilon_{\text{obs}})}{(\upsilon_{\text{snd}} - \upsilon_{\text{src}})} = (1580\text{ Hz})\frac{(343\text{ m/s} - 22.22\text{ m/s})}{(343\text{ m/s} - 33.33\text{ m/s})} = \boxed{1640\text{ Hz}}$$

$$f'_{\substack{\text{police}\\\text{car}\\\text{receding}}} = f\frac{(\upsilon_{\text{snd}} - \upsilon_{\text{obs}})}{(\upsilon_{\text{snd}} - \upsilon_{\text{src}})} = (1580\text{ Hz})\frac{(343\text{ m/s} + 22.22\text{ m/s})}{(343\text{ m/s} + 33.33\text{ m/s})} = \boxed{1530\text{ Hz}}$$

58. The maximum Doppler shift occurs when the heart has its maximum velocity. Assume that the heart is moving away from the original source of sound. The beats arise from the combining of the original 2.25-MHz frequency with the reflected signal which has been Doppler shifted. There are two Doppler shifts—one for the heart receiving the original signal (observer moving away from stationary source) and one for the detector receiving the reflected signal (source moving away from stationary observer).

$$f'_{\text{heart}} = f_{\text{original}}\left(1-\frac{\upsilon_{\text{heart}}}{\upsilon_{\text{snd}}}\right); \quad f''_{\text{detector}} = \frac{f'_{\text{heart}}}{\left(1+\dfrac{\upsilon_{\text{heart}}}{\upsilon_{\text{snd}}}\right)} = f_{\text{original}}\frac{\left(1-\dfrac{\upsilon_{\text{heart}}}{\upsilon_{\text{snd}}}\right)}{\left(1+\dfrac{\upsilon_{\text{heart}}}{\upsilon_{\text{snd}}}\right)} = f_{\text{original}}\frac{(\upsilon_{\text{snd}}-\upsilon_{\text{heart}})}{(\upsilon_{\text{snd}}+\upsilon_{\text{heart}})}$$

$$\Delta f = f_{\text{original}} - f''_{\text{detector}} = f_{\text{original}} - f_{\text{original}}\frac{(\upsilon_{\text{snd}}-\upsilon_{\text{blood}})}{(\upsilon_{\text{snd}}+\upsilon_{\text{blood}})} = f_{\text{original}}\frac{2\upsilon_{\text{blood}}}{(\upsilon_{\text{snd}}+\upsilon_{\text{blood}})} \rightarrow$$

$$\upsilon_{\text{blood}} = \upsilon_{\text{snd}}\frac{\Delta f}{2f_{\text{original}}-\Delta f} = (1.54\times10^3\text{ m/s})\frac{240\text{ Hz}}{2(2.25\times10^6\text{ Hz})-240\text{ Hz}} = \boxed{0.0821\text{ m/s}}$$

If instead we had assumed that the heart was moving toward the original source of sound, we would get $\upsilon_{\text{blood}} = \upsilon_{\text{snd}}\dfrac{\Delta f}{2f_{\text{original}}+\Delta f}$. Since the beat frequency is much smaller than the original frequency, the Δf term in the denominator does not significantly affect the answer.

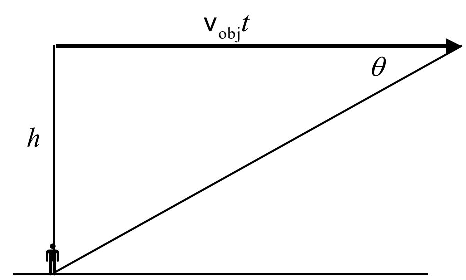
59. The speed is found from Eq. 12–5.

$$\sin\theta = \frac{\upsilon_{\text{wave}}}{\upsilon_{\text{obj}}} \rightarrow \upsilon_{\text{obj}} = \frac{\upsilon_{\text{wave}}}{\sin\theta} = \frac{2.2\text{ km/h}}{\sin 12^\circ} = 10.58\text{ km/h} \approx \boxed{11\text{ km/h}}$$

60. (*a*) The angle of the shock wave front relative to the direction of motion is given by Eq. 12–5.

$$\sin\theta = \frac{\upsilon_{\text{snd}}}{\upsilon_{\text{obj}}} = \frac{\upsilon_{\text{snd}}}{2.1\upsilon_{\text{snd}}} = \frac{1}{2.1} \rightarrow \theta = \sin^{-1}\frac{1}{2.1} = 28.44^\circ = \boxed{28^\circ}$$

(*b*) The displacement of the plane $(\upsilon_{\text{obj}}t)$ from the time it passes overhead to the time the shock wave reaches the observer is shown, along with the shock wave front. From the displacement and height of the plane, the time is found.



$$\tan\theta = \frac{h}{\upsilon_{\text{obj}}t} \rightarrow$$

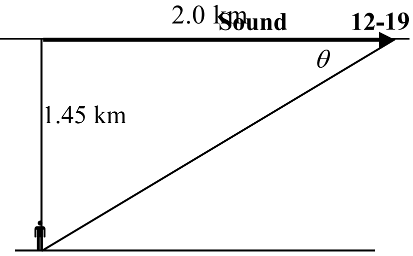
$$t = \frac{h}{\upsilon_{\text{obj}}\tan\theta} = \frac{6500\text{ m}}{(2.1)(310\text{ m/s})\tan 28.44^\circ} = 18\ 44\text{ s} \approx \boxed{18\text{ s}}$$

61. From Eq. 12–7, $\sin\theta = \dfrac{\upsilon_{\text{snd}}}{\upsilon_{\text{obj}}}$. The speed of sound in the ocean is taken from Table 12–1.

(*a*) $$\theta = \sin^{-1}\frac{\upsilon_{\text{snd}}}{\upsilon_{\text{obj}}} = \sin^{-1}\frac{343\text{ m/s}}{9200\text{ m/s}} = \boxed{2.1^\circ}$$

(*b*) $$\theta = \sin^{-1}\frac{\upsilon_{\text{snd}}}{\upsilon_{\text{obj}}} = \sin^{-1}\frac{1560\text{ m/s}}{9200\text{ m/s}} = \boxed{9.8^\circ}$$

62. (*a*) The displacement of the plane from the time it passes overhead to the time the shock wave reaches the listener is shown, along with the shock wave front. From the displacement and height of the plane, the angle of the shock wave front relative to the direction of motion can be found.



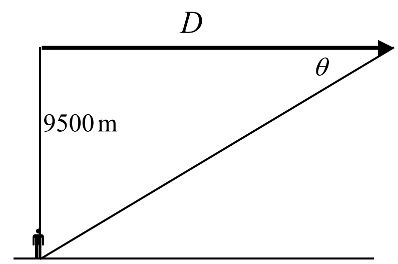
$$\tan\theta = \frac{1.45\text{ km}}{2.0\text{ km}} \quad \to \quad \theta = \tan^{-1}\frac{1.45}{2.0} = 35.94^\circ \approx \boxed{36^\circ}$$

(*b*) The speed and Mach number are found from Eq. 12–5.

$$\upsilon_{\text{obj}} = \frac{\upsilon_{\text{snd}}}{\sin\theta} = \frac{330\text{ m/s}}{\sin 35.94^\circ} = 562.2\text{ m/s} \approx \boxed{560\text{ m/s}}$$

$$M = \frac{\upsilon_{\text{obj}}}{\upsilon_{\text{snd}}} = \frac{1}{\sin\theta} = \frac{1}{\sin 35.94^\circ} = \boxed{1.7}$$

63. Find the angle of the shock wave, then the distance the plane has traveled when the shock wave reaches the observer. Use Eq 12–5.



$$\theta = \sin^{-1}\frac{\upsilon_{\text{snd}}}{\upsilon_{\text{obj}}} = \sin^{-1}\frac{\upsilon_{\text{snd}}}{2.0\upsilon_{\text{snd}}} = \sin^{-1}\frac{1}{2.0} = 30^\circ$$

$$\tan\theta = \frac{9500\text{ m}}{D} \quad \to \quad D = \frac{9500\text{ m}}{\tan 30^\circ} = 16{,}454\text{ m} \approx \boxed{16\text{ km}}$$

64. The minimum time between pulses would be the time for a pulse to travel from the boat to the maximum distance and back again. The total distance traveled by the pulse will be 170 m at the speed of sound in fresh water, 1440 m/s.

$$d = \upsilon t \quad \to \quad t = \frac{d}{\upsilon} = \frac{170\text{ m}}{1440\text{ m/s}} = \boxed{0.12\text{ s}}$$

65. The single mosquito creates a sound intensity of $I_0 = 1\times 10^{-12}\text{ W/m}^2$. Thus, 200 mosquitoes will create a sound intensity of 200 times that of a single mosquito.

$$I = 100 I_0 \quad \beta = 10\log\frac{200 I_0}{I_0} = 10\log 200 = \boxed{23\text{ dB}}$$

66. The two sound level values must be converted to intensities; then the intensities are added and converted back to sound level.

$$I_{82}:\ 81\text{ dB} = 10\log\frac{I_{81}}{I_0} \quad \to \quad I_{81} = 10^{8.1} I_0 = 1.259\times 10^8 I_0$$

$$I_{87}:\ 87\text{ dB} = 10\log\frac{I_{87}}{I_0} \quad \to \quad I_{87} = 10^{8.7} I_0 = 5.012\times 10^8 I_0$$

$$I_{\text{total}} = I_{82} + I_{87} = (6.271\times 10^8) I_0 \quad \to$$

$$\beta_{\text{total}} = 10\log\frac{6.271\times 10^8 I_0}{I_0} = 10\log 6.597\times 10^8 = 87.97 \approx \boxed{88\text{ dB}}$$

67. The power output is found from the intensity, which is the power radiated per unit area.

$$115\text{ dB} = 10\log\frac{I}{I_0} \quad \to \quad I = 10^{11.5} I_0 = 10^{11.5}(1.0\times 10^{-12}\text{ W/m}^2) = 3.162\times 10^{-1}\text{ W/m}^2$$

$$I = \frac{P}{A} = \frac{P}{4\pi r^2} \quad \to \quad P = 4\pi r^2 I = 4\pi(8.25\text{ m})^2(3.162\times 10^{-1}\text{ W/m}^2) = 270.45\text{W} \approx \boxed{270\text{ W}}$$

The answer has 3 significant figures.

68. Relative to the 1000-Hz output, the 15-kHz output is –12 dB.

$$-12\text{ dB} = 10\log\frac{P_{15\text{ kHz}}}{225\text{ W}} \rightarrow -1.2 = \log\frac{P_{15\text{ kHz}}}{225\text{ W}} \rightarrow 10^{-1.2} = \frac{P_{15\text{ kHz}}}{225\text{ W}} \rightarrow$$

$$P_{15\text{ kHz}} = (225\text{ W})(10^{-1.2}) = \boxed{14\text{ W}}$$

69. The 130-dB level is used to find the intensity, and the intensity is used to find the power. It is assumed that the jet airplane engine radiates equally in all directions.

$$\beta = 130\text{ dB} = 10\log\frac{I}{I_0} \rightarrow I = 10^{13}I_0 = 10^{13}(1.0\times10^{-12}\text{ W/m}^2) = 1.0\times10^{1}\text{ W/m}^2$$

$$P = IA = I\pi r^2 = (1.0\times10^{1}\text{ W/m}^2)\pi(2.0\times10^{-2})^2 = \boxed{0.013\text{ W}}$$

70. (*a*) The gain is given by $\beta = 10\log\frac{P_{\text{out}}}{P_{\text{in}}} = 10\log\frac{135\text{ W}}{1.0\times10^{-3}\text{ W}} = \boxed{51\text{ dB}}$.

(*b*) We solve the gain equation for the noise power level.

$$\beta = 10\log\frac{P_{\text{signal}}}{P_{\text{noise}}} \rightarrow P_{\text{noise}} = \frac{P_{\text{signal}}}{10^{\beta/10}} = \frac{10\text{ W}}{10^{93/10}} = \boxed{5\times10^{-9}\text{ W}}$$

71. The strings are both tuned to the same frequency, and they have the same length. The mass per unit length is the density times the cross-sectional area. The frequency is related to the tension by Eqs. 11–13 and 11–19b.

$$f = \frac{\upsilon}{2\ell};\ \upsilon = \sqrt{\frac{F_{\text{T}}}{\mu}} \rightarrow f = \frac{1}{2\ell}\sqrt{\frac{F_{\text{T}}}{\mu}} = \frac{1}{2\ell}\sqrt{\frac{F_{\text{T}}}{\rho\pi r^2}} \rightarrow F_{\text{T}} = 4\ell^2\rho f^2\pi r^2 \rightarrow$$

$$\frac{F_{\text{T high}}}{F_{\text{T low}}} = \frac{4\ell^2\rho f^2\pi r_{\text{high}}^2}{4\ell^2\rho f^2\pi r_{\text{low}}^2} = \left(\frac{r_{\text{high}}}{r_{\text{low}}}\right)^2 = \left(\frac{\frac{1}{2}d_{\text{high}}}{\frac{1}{2}d_{\text{low}}}\right)^2 = \left(\frac{0.724\text{ mm}}{0.699\text{ mm}}\right)^2 = \boxed{1.07}$$

$\boxed{72.}$ The apparatus is a closed tube. The water level is the closed end, so it is a node of air displacement. As the water level lowers, the distance from one resonance level to the next corresponds to the distance between adjacent nodes, which is one-half wavelength.

$$\Delta\ell = \tfrac{1}{2}\lambda \rightarrow \lambda = 2\Delta\ell = 2(0.395\text{ m} - 0.125\text{ m}) = 0.540\text{ m}$$

$$f = \frac{\upsilon}{\lambda} = \frac{343\text{ m/s}}{0.540\text{ m}} = \boxed{635\text{ Hz}}$$

73. We combine the expression for the frequency in a closed tube with the Doppler shift for a source moving away from a stationary observer, Eq. 12–2b.

$$f_1 = \frac{\upsilon_{\text{snd}}}{4\ell}$$

$$f' = \frac{f_1}{\left(1+\frac{\upsilon_{\text{source}}}{\upsilon_{\text{snd}}}\right)} = \frac{\upsilon_{\text{snd}}}{4\ell\left(1+\frac{\upsilon_{\text{source}}}{\upsilon_{\text{snd}}}\right)} = \frac{343\text{ m/s}}{4(7.10\times10^{-2}\text{ m})\left(1+\frac{25\text{ m/s}}{343\text{ m/s}}\right)} = 1127\text{ Hz} \approx \boxed{1130\text{ Hz}}$$

74. The effective length of the tube is $\ell_{\text{eff}} = \ell + \frac{1}{3}D = 0.55\text{ m} + \frac{1}{3}(0.030\text{ m}) = 0.56\text{ m}$.

Uncorrected frequencies: $f_n = \frac{(2n-1)\upsilon}{4\ell}, n = 1, 2, 3, \cdots \rightarrow$

$$f_{1-4} = (2n-1)\frac{343\text{ m/s}}{4(0.55\text{ m})} = 156\text{ Hz, } 468\text{ Hz, } 770\text{ Hz, } 1090\text{ Hz}$$

Corrected frequencies: $f_n = \frac{(2n-1)\upsilon}{4\ell_{\text{eff}}}, n = 1, 2, 3, \cdots \rightarrow$

$$f_{1-4} = (2n-1)\frac{343\text{ m/s}}{4(0.56\text{ m})} = 153\text{ Hz, } 459\text{ Hz, } 766\text{ Hz, } 1070\text{ Hz}$$

$$\approx \boxed{150\text{ Hz, } 460\text{ Hz, } 770\text{ Hz, } 1100\text{ Hz}}$$

75. As the train approaches, the observed frequency is given by $f'_{\text{approach}} = \frac{f}{\left(1-\frac{\upsilon_{\text{train}}}{\upsilon_{\text{snd}}}\right)}$. As the train recedes, the observed frequency is given by $f'_{\text{recede}} = \frac{f}{\left(1+\frac{\upsilon_{\text{train}}}{\upsilon_{\text{snd}}}\right)}$. Solve each expression for f, equate them, and then solve for υ_{train}.

$$f'_{\text{approach}}\left(1-\frac{\upsilon_{\text{train}}}{\upsilon_{\text{snd}}}\right) = f'_{\text{recede}}\left(1+\frac{\upsilon_{\text{train}}}{\upsilon_{\text{snd}}}\right) \rightarrow$$

$$\upsilon_{\text{train}} = \upsilon_{\text{snd}}\frac{(f'_{\text{approach}} - f'_{\text{recede}})}{(f'_{\text{approach}} + f'_{\text{recede}})} = (343\text{ m/s})\frac{(565\text{ Hz} - 486\text{ Hz})}{(565\text{ Hz} + 486\text{ Hz})} = \boxed{26\text{ m/s}}$$

76. The Doppler shift is 3.5 Hz, and the emitted frequency from both trains is 508 Hz. Thus, the frequency received by the conductor on the stationary train is 511.5 Hz. Use this to find the moving train's speed.

$$f' = f\frac{\upsilon_{\text{snd}}}{(\upsilon_{\text{snd}} - \upsilon_{\text{source}})} \rightarrow \upsilon_{\text{source}} = \left(1-\frac{f}{f'}\right)\upsilon_{\text{snd}} = \left(1-\frac{508\text{ Hz}}{511.5\text{ Hz}}\right)(343\text{ m/s}) = \boxed{2.35\text{ m/s}}$$

77. (*a*) Since both speakers are moving toward the observer at the same speed, both frequencies have the same Doppler shift, and the observer hears $\boxed{\text{no beats}}$.

(*b*) The observer will detect an increased frequency from the speaker moving toward him and a decreased frequency from the speaker moving away. The difference in those two frequencies will be the beat frequency that is heard.

$$f'_{\text{towards}} = f\frac{1}{\left(1-\frac{\upsilon_{\text{train}}}{\upsilon_{\text{snd}}}\right)} \qquad f'_{\text{away}} = f\frac{1}{\left(1+\frac{\upsilon_{\text{train}}}{\upsilon_{\text{snd}}}\right)}$$

$$f'_{\text{towards}} - f'_{\text{away}} = f\frac{1}{\left(1-\frac{\upsilon_{\text{train}}}{\upsilon_{\text{snd}}}\right)} - f\frac{1}{\left(1+\frac{\upsilon_{\text{train}}}{\upsilon_{\text{snd}}}\right)} = f\left[\frac{\upsilon_{\text{snd}}}{(\upsilon_{\text{snd}} - \upsilon_{\text{train}})} - \frac{\upsilon_{\text{snd}}}{(\upsilon_{\text{snd}} + \upsilon_{\text{train}})}\right]$$

$$(348\text{ Hz})\left[\frac{343\text{ m/s}}{343\text{ m/s} - 12.0\text{ m/s}} - \frac{343\text{ m/s}}{(343\text{ m/s} + 12.0\text{ m/s})}\right] = 24.38\text{ Hz} \approx \boxed{24\text{ Hz}}$$

(*c*) Since both speakers are moving away from the observer at the same speed, both frequencies have the same Doppler shift, and the observer hears $\boxed{\text{no beats}}$.

78. For each pipe, the fundamental frequency is given by $f = \frac{\upsilon}{2\ell}$. Find the frequency of the shortest pipe.

$$f = \frac{\upsilon}{2\ell} = \frac{343\text{ m/s}}{2\,(2.40\text{ m})} = 71.46\text{ Hz}$$

The longer pipe has a lower frequency. Since the beat frequency is 6.0 Hz, the frequency of the longer pipe must be 65.46 Hz. Use that frequency to find the length of the longer pipe.

$$f = \frac{\upsilon}{2\ell} \rightarrow \ell = \frac{\upsilon}{2f} = \frac{343\text{ m/s}}{2(65.46\text{ Hz})} = \boxed{2.62\text{ m}}$$

79. It is 70.0 ms from the start of one chirp to the start of the next. Since the chirp itself is 3.0 ms long, it is 67.0 ms from the end of a chirp to the start of the next. Thus, the time for the pulse to travel to the moth and back again is 67.0 ms. The distance to the moth is half the distance that the sound can travel in 67.0 ms, since the sound must reach the moth and return during the 67.0 ms.

$$d = \upsilon_{\text{snd}}t = (343\text{ m/s})\tfrac{1}{2}(67.0\times10^{-3}\text{s}) = \boxed{11.5\text{ m}}$$

80. The ratio of sound intensity passing through the door to the original sound intensity is a 30-dB decrease.

$$\beta = 10\log I/I_0 = -30 \rightarrow \log I/I_0 = -3 \rightarrow I = 10^{-3}I_0$$

Only $\boxed{1/1000}$ of the sound intensity passes through the door.

81. The alpenhorn can be modeled as an open tube, so the fundamental frequency is $f = \frac{\upsilon}{2\ell}$, and the overtones are given by $f_n = \frac{n\upsilon}{2\ell}$, $n = 1, 2, 3, \ldots$.

$$f_1 = \frac{\upsilon}{2\ell} = \frac{343\text{ m/s}}{2(3.4\text{ m})} = 50.44\text{ Hz} \approx \boxed{50\text{ Hz}}$$

$$f_n = nf_1 = f_{\text{F\#}} \rightarrow n(50.44\text{ Hz}) = 370\text{ Hz} \rightarrow n = \frac{370}{50.44} = 7.34$$

Thus, the 7th harmonic, which is the $\boxed{\text{6th overtone}}$, is close to $\text{F}^{\#}$.

82. The walls of the room must be air displacement nodes, so the dimensions of the room between two parallel boundaries correspond to a half wavelength of sound. Fundamental frequencies are then given by $f = \frac{\upsilon}{2\ell}$.

$$\text{Length: } f = \frac{\upsilon}{2\ell} = \frac{343\text{ m/s}}{2(4.7\text{ m})} = \boxed{36\text{ Hz}} \qquad \text{Width: } f = \frac{\upsilon}{2\ell} = \frac{343\text{ m/s}}{2(3.6\text{ m})} = \boxed{48\text{ Hz}}$$

$$\text{Height: } f = \frac{\upsilon}{2\ell} = \frac{343\text{ m/s}}{2(2.8\text{ m})} = \boxed{61\text{ Hz}}$$

83. Equation 11–18 gives the relationship between intensity and the displacement amplitude: $I = 2\pi^2\upsilon\rho f^2 A^2$, where A is the displacement amplitude. Thus, $I \propto A^2$, or $A \propto \sqrt{I}$. Since the intensity increased by a factor of 10^{12}, the amplitude would increase by a factor of the square root of the intensity increase, or $\boxed{10^6}$.

84. The beats arise from the combining of the original 3.5-MHz frequency with the reflected signal, which has been Doppler shifted. There are two Doppler shifts—one for the blood cells receiving the original signal (observer moving away from stationary source) and one for the detector receiving the reflected signal (source moving away from stationary observer).

$$f'_{\text{blood}} = f_{\text{original}}\left(1-\frac{\upsilon_{\text{blood}}}{\upsilon_{\text{snd}}}\right) \quad f''_{\text{detector}} = \frac{f'_{\text{blood}}}{\left(1+\frac{\upsilon_{\text{blood}}}{\upsilon_{\text{snd}}}\right)} = f_{\text{original}}\frac{\left(1-\frac{\upsilon_{\text{blood}}}{\upsilon_{\text{snd}}}\right)}{\left(1+\frac{\upsilon_{\text{blood}}}{\upsilon_{\text{snd}}}\right)} = f_{\text{original}}\frac{(\upsilon_{\text{snd}}-\upsilon_{\text{blood}})}{(\upsilon_{\text{snd}}+\upsilon_{\text{blood}})}$$

$$\Delta f = f_{\text{original}} - f''_{\text{detector}} = f_{\text{original}} - f_{\text{original}}\frac{(\upsilon_{\text{snd}}-\upsilon_{\text{blood}})}{(\upsilon_{\text{snd}}+\upsilon_{\text{blood}})} = f_{\text{original}}\frac{2\upsilon_{\text{blood}}}{(\upsilon_{\text{snd}}+\upsilon_{\text{blood}})}$$

$$= (3.5\times10^6\ \text{Hz})\frac{2(3.0\times10^{-2})}{(1.54\times10^3\ \text{m/s}+3.0\times10^{-2})} = 136.36\ \text{Hz} \approx \boxed{140\ \text{Hz}}$$

Solutions to Search and Learn Problems

1. The intensity can be found from the sound level in decibels.

$$\beta = 10\log\frac{I}{I_0} \quad\to\quad I = 10^{\beta/10}I_0 = 10^{12}(10^{-12}\ \text{W/m}^2) = 1.0\ \text{W/m}^2$$

Consider a square perpendicular to the direction of travel of the sound wave. The intensity is the energy transported by the wave across a unit area perpendicular to the direction of travel, per unit time. So $I = \frac{\Delta E}{S\Delta t}$, where S is the area of the square. Since the energy is "moving" with the wave, the "speed" of the energy is υ, the wave speed. In a time Δt, a volume equal to $\Delta V = S\upsilon\Delta t$ would contain all of the energy that had been transported across the area S. Combine these relationships to find the energy in the volume.

$$I = \frac{\Delta E}{S\Delta t} \quad\to\quad \Delta E = IS\Delta t = \frac{I\Delta V}{\upsilon} = \frac{(1.0\ \text{W/m}^2)(0.010\ \text{m})^3}{343\ \text{m/s}} = \boxed{2.9\times10^{-9}\ \text{J}}$$

2. As the car approaches, the frequency of the sound from the engine is Doppler shifted up, as given by Eq. 12–2a. As the car moves away, the frequency of the engine sound is Doppler shifted down, as given by Eq. 12–2b. Since the frequency shift is exactly an octave, we know that $f'_{\text{toward}} = 2f'_{\text{away}}$. We then solve for the car's speed.

$$f'_{\text{toward}} = \frac{f}{\left(1-\frac{\upsilon_{\text{source}}}{\upsilon_{\text{snd}}}\right)}; \quad f'_{\text{away}} = \frac{f}{\left(1+\frac{\upsilon_{\text{source}}}{\upsilon_{\text{snd}}}\right)}$$

$$f'_{\text{toward}} = 2f'_{\text{away}} \quad\to\quad \frac{f}{\left(1-\frac{\upsilon_{\text{source}}}{\upsilon_{\text{snd}}}\right)} = 2\frac{f}{\left(1+\frac{\upsilon_{\text{source}}}{\upsilon_{\text{snd}}}\right)} \quad\to\quad \left(1+\frac{\upsilon_{\text{source}}}{\upsilon_{\text{snd}}}\right) = 2\left(1-\frac{\upsilon_{\text{source}}}{\upsilon_{\text{snd}}}\right) \quad\to$$

$$\upsilon_{\text{source}} = \tfrac{1}{3}\upsilon_{\text{snd}} = \tfrac{1}{3}(343\ \text{m/s}) = \boxed{114\ \text{m/s}}$$

3. The Doppler effect occurs only when there is relative motion of the source and the observer along the line connecting them. In the first four parts of this problem, the whistle and the observer are not moving relative to each other, so there is no Doppler shift. The wind speed increases (or decreases) the velocity of the waves in the direction of the wind, as if the speed of sound were different, but the frequency of the waves doesn't change. We do a detailed analysis of this claim in part (*a*).

   (*a*) The wind velocity is a movement of the medium, so it adds or subtracts from the speed of sound in the medium. Because the wind is blowing away from the observer, the effective speed of sound is $\upsilon_{\text{snd}} - \upsilon_{\text{wind}}$. The wavelength of the waves traveling toward the observer is $\lambda_a = (\upsilon_{\text{snd}} - \upsilon_{\text{wind}})/f_0$, where f_0 is the frequency of the sound emitted by the factory whistle. This wavelength approaches the observer at a relative speed of $\upsilon_{\text{snd}} - \upsilon_{\text{wind}}$. Thus, the observer hears the frequency calculated here.

$$f_a = \frac{\upsilon_{\text{snd}} - \upsilon_{\text{wind}}}{\lambda_a} = \frac{\upsilon_{\text{snd}} - \upsilon_{\text{wind}}}{\left(\dfrac{\upsilon_{\text{snd}} - \upsilon_{\text{wind}}}{f_0}\right)} = f_0 = \boxed{770\ \text{Hz}}$$

   (*b*) Because the wind is blowing toward the observer, the effective speed of sound is $\upsilon_{\text{snd}} + \upsilon_{\text{wind}}$. The same kind of analysis as applied in part (*a*) gives $f_b = \boxed{770\ \text{Hz}}$.

   (*c*) Because the wind is blowing perpendicular to the line toward the observer, the effective speed of sound along that line is υ_{snd}. Since there is no relative motion of the whistle and observer, there will be no change in frequency, so $f_c = \boxed{770\ \text{Hz}}$.

   (*d*) This is just like part (*c*), so $f_d = \boxed{770\ \text{Hz}}$.

   (*e*) Because the wind is blowing toward the cyclist, the effective speed of sound is $\upsilon_{\text{snd}} + \upsilon_{\text{wind}}$. The wavelength traveling toward the cyclist is $\lambda_e = (\upsilon_{\text{snd}} + \upsilon_{\text{wind}})/f_0$ and approaches the cyclist at a relative speed of $\upsilon_{\text{snd}} + \upsilon_{\text{wind}} + \upsilon_{\text{cycle}}$. The cyclist will hear the following frequency:

$$f_e = \frac{(\upsilon_{\text{snd}} + \upsilon_{\text{wind}} + \upsilon_{\text{cycle}})}{\lambda_e} = \frac{(\upsilon_{\text{snd}} + \upsilon_{\text{wind}} + \upsilon_{\text{cycle}})}{(\upsilon_{\text{snd}} + \upsilon_{\text{wind}})} f_0 = \frac{(343 + 15.0 + 12.0)\text{m/s}}{(343 + 15.0)}(770\ \text{Hz})$$
$$= \boxed{796\ \text{Hz}}$$

   (*f*) Since the wind is not changing the speed of the sound waves moving toward the cyclist, the speed of sound is 343 m/s. The observer is moving toward a stationary source at 12.0 m/s.

$$f_f = f\left(1 + \frac{\upsilon_{\text{obs}}}{\upsilon_{\text{snd}}}\right) = (770\ \text{Hz})\left(1 + \frac{12.0\ \text{m/s}}{343\ \text{m/s}}\right) = \boxed{797\ \text{Hz}}$$