CHAPTER 16: Sound

Responses to Questions

1. Sound exhibits diffraction, refraction, and interference effects that are characteristic of waves. Sound also requires a medium, a characteristic of mechanical waves.

2. Sound can cause objects to vibrate, which is evidence that sound is a form of energy. In extreme cases, sound waves can even break objects. (See Figure 14-24 showing a goblet shattering from the sound of a trumpet.)

3. Sound waves generated in the first cup cause the bottom of the cup to vibrate. These vibrations excite vibrations in the stretched string which are transmitted down the string to the second cup, where they cause the bottom of the second cup to vibrate, generating sound waves which are heard by the second child.

4. The wavelength will change. The frequency cannot change at the boundary since the media on both sides of the boundary are oscillating together. If the frequency were to somehow change, there would be a "pile-up" of wave crests on one side of the boundary.

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, 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. Helium is much less dense than air, so the speed of sound in the helium is higher than in air. The wavelength of the sound produced does not change, because it is determined by the length of the vocal cords and other properties of the resonating cavity. The frequency therefore increases, increasing the pitch of the voice.

7. The speed of sound in a medium is equal to $v = \sqrt{B/\rho}$, where B is the bulk modulus and ρ is the density of the medium. The bulk moduli of air and hydrogen are very nearly the same. The density of hydrogen is less than the density of air. The reduced density is the main reason why sound travels faster in hydrogen than in air.

8. The intensity of a sound wave is proportional to the square of the frequency, so the higher-frequency tuning fork will produce more intense sound.

9. Variations in temperature will cause changes in the speed of sound and in the length of the pipes. As the temperature rises, the speed of sound in air increases, increasing the resonance frequency of the pipes, and raising the pitch of the sound. But the pipes get slightly longer, increasing the resonance wavelength and decreasing the resonance frequency of the pipes and lowering the pitch. As the temperature decreases, the speed of sound decreases, decreasing the resonance frequency of the pipes, and lowering the pitch of the sound. But the pipes contract, decreasing the resonance wavelength and increasing the resonance frequency of the pipes and raising the pitch. These effects compete, but the effect of temperature change on the speed of sound dominates.

10. A tube will have certain resonance frequencies associated with it, depending on the length of the tube and the temperature of the air in the tube. Sounds at frequencies far from the resonance

frequencies will not undergo resonance and will not persist. By choosing a length for the tube that isn't resonant for specific frequencies you can reduce the amplitude of those frequencies.

11. As you press on frets closer to the bridge, you are generating higher frequency (and shorter wavelength) sounds. The difference in the wavelength of the resonant standing waves decreases as the wavelengths decrease, so the frets must be closer together as you move toward the bridge.

12. Sound waves can diffract around obstacles such as buildings if the wavelength of the wave is large enough in comparison to the size of the obstacle. Higher frequency corresponds to shorter wavelength. When the truck is behind the building, the lower frequency (longer wavelength) waves bend around the building and reach you, but the higher frequency (shorter wavelength) waves do not. Once the truck has emerged from behind the building, all the different frequencies can reach you.

13. Standing waves are generated by a wave and its reflection. The two waves have a constant phase relationship with each other. The interference depends only on where you are along the string, on your position in space. Beats are generated by two waves whose frequencies are close but not equal. The two waves have a varying phase relationship, and the interference varies with time rather than position.

14. The points would move farther apart. A lower frequency corresponds to a longer wavelength, so the distance between points where destructive and constructive interference occur would increase.

15. According to the principle of superposition, adding a wave and its inverse produces zero displacement of the medium. Adding a sound wave and its inverse effectively cancels out the sound wave and substantially reduces the sound level heard by the worker.

16. (a) The closer the two component frequencies are to each other, the longer the wavelength of the beat. If the two frequencies are very close together, then the waves very nearly overlap, and the distance between a point where the waves interfere constructively and a point where they interfere destructively will be very large.

17. No. The Doppler shift is caused by relative motion between the source and observer.

18. No. The Doppler shift is caused by relative motion between the source and observer. If the wind is blowing, both the wavelength and the velocity of the sound will change, but the frequency of the sound will not.

19. The child will hear the highest frequency at position C, where her speed toward the whistle is the greatest.

20. The human ear can detect frequencies from about 20 Hz to about 20,000 Hz. One octave corresponds to a doubling of frequency. Beginning with 20 Hz, it takes about 10 doublings to reach 20,000 Hz. So, there are approximately 10 octaves in the human audible range.

21. If the frequency of the sound is halved, then the ratio of the frequency of the sound as the car recedes to the frequency of the sound as the car approaches is equal to ½. Substituting the appropriate Doppler shift equations in for the frequencies yields a speed for the car of $^1/_3$ the speed of sound.

Solutions to Problems

In these solutions, we usually treat frequencies as if they are significant to the whole number of units. For example, 20 Hz is taken as to the nearest Hz, and 20 kHz is taken as to the nearest kHz. We also treat all decibel values as good to whole number of decibels. So 120 dB is good to the nearest decibel.

1. 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 to determine the length of the lake.

$$d = vt = (343\,\text{m/s})(1.0\text{ s}) = 343\text{ m} \approx \boxed{340\,\text{m}}$$

2. 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 in water to determine the depth of the lake.

$$d = vt = (1560\,\text{m/s})(1.25\text{ s}) = 1950\text{ m} = \boxed{2.0\times10^{3}\,\text{m}}$$

3. (*a*) $\lambda_{20\text{ Hz}} = \dfrac{v}{f} = \dfrac{343\,\text{m/s}}{20\text{ Hz}} = \boxed{17\text{ m}}$ $\quad \lambda_{20\text{ kHz}} = \dfrac{v}{f} = \dfrac{343\,\text{m/s}}{2.0\times10^{4}\,\text{Hz}} = \boxed{1.7\times10^{-2}\,\text{m}}$

So the range is from 1.7 cm to 17 m.

(*b*) $\lambda = \dfrac{v}{f} = \dfrac{343\,\text{m/s}}{15\times10^{6}\,\text{Hz}} = \boxed{2.3\times10^{-5}\,\text{m}}$

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

$$d = v_1t_1 = v_2t_2 \;\rightarrow\; \left[(331 + 0.6(27))\,\text{m/s}\right](4.70\,\text{s}) = \left[(331 + 0.6(T_2))\,\text{m/s}\right](5.20\,\text{s}) \;\rightarrow$$

$$T_2 = \boxed{-29^\circ\text{C}}$$

5. (*a*) The ultrasonic pulse travels at the speed of sound, and the round trip distance is twice the distance *d* to the object.

$$2d_{\text{min}} = vt_{\text{min}} \;\rightarrow\; d_{\text{min}} = \tfrac{1}{2}vt_{\text{min}} = \tfrac{1}{2}(343\,\text{m/s})(1.0\times10^{-3}\,\text{s}) = \boxed{0.17\,\text{m}}$$

(*b*) The measurement must take no longer than 1/15 s. Again, the round trip distance is twice the distance to the object.

$$2d_{\text{max}} = vt_{\text{max}} \;\rightarrow\; d_{\text{max}} = \tfrac{1}{2}vt_{\text{max}} = \tfrac{1}{2}(343\,\text{m/s})(\tfrac{1}{15}\,\text{s}) = \boxed{11\,\text{m}}$$

(*c*) The distance is proportional to the speed of sound. So the percentage error in distance is the same as the percentage error in the speed of sound. We assume the device is calibrated to work at 20°C.

$$\frac{\Delta d}{d} = \frac{\Delta v}{v} = \frac{v_{23^\circ\text{C}} - v_{20^\circ\text{C}}}{v_{20^\circ\text{C}}} = \frac{\left[331 + 0.60(23)\right]\text{m/s} - 343\,\text{m/s}}{343\,\text{m/s}} = 0.005248 \approx \boxed{0.5\%}$$

6. (*a*) For the fish, the speed of sound in seawater must be used.

$$d = vt \;\rightarrow\; t = \frac{d}{v} = \frac{1350\,\text{m}}{1560\,\text{m/s}} = \boxed{0.865\,\text{s}}$$

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

$$d = vt \;\rightarrow\; t = \frac{d}{v} = \frac{1350\,\text{m}}{343\,\text{m/s}} = \boxed{3.94\,\text{s}}$$

7. The total time T is the time for the stone to fall $\left(t_{\text{down}}\right)$ plus the time for the sound to come back to the top of the cliff $\left(t_{\text{up}}\right)$: $T = t_{\text{up}} + t_{\text{down}}$. 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.

$$\text{down: } y = y_0 + v_0 t_{\text{down}} + \tfrac{1}{2}at_{\text{down}}^2 \rightarrow h = \tfrac{1}{2}gt_{\text{down}}^2 \qquad \text{up: } h = v_{\text{snd}}t_{\text{up}} \rightarrow t_{\text{up}} = \frac{h}{v_{\text{snd}}}$$

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

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.

$$h^2 - 2\left(343\,\text{m/s}\right)\left(\frac{343\,\text{m/s}}{9.80\,\text{m/s}^2} + 3.0\,\text{s}\right)h + \left(3.0\,\text{s}\right)^2\left(343\,\text{m/s}\right)^2 = 0 \rightarrow$$

$$h^2 - \left(26068\,\text{m}\right)h + 1.0588\times10^6\,\text{m}^2 = 0 \rightarrow h = 26028\,\text{m}\,,\ 41\,\text{m}$$

The larger root is impossible since it takes more than 3.0 sec for the rock to fall that distance, so the correct result is $h = \boxed{41\,\text{m}}$.

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

$$d = v_{\text{air}}t_{\text{air}} = v_{\text{concrete}}t_{\text{concrete}} = v_{\text{concrete}}\left(t_{\text{air}} - 0.75\,\text{s}\right) \rightarrow t_{\text{air}} = \frac{v_{\text{concrete}}}{v_{\text{concrete}} - v_{\text{air}}}0.75\,\text{s}$$

$$d = v_{\text{air}}t_{\text{air}} = v_{\text{air}}\left(\frac{v_{\text{concrete}}}{v_{\text{concrete}} - v_{\text{air}}}0.75\,\text{s}\right)$$

The speed of sound in concrete is obtained from Table 16-1 as 3000 m/s.

$$d = \left(343\,\text{m/s}\right)\left(\frac{3000\,\text{m/s}}{3000\,\text{m/s} - 343\,\text{m/s}}\left(0.75\,\text{s}\right)\right) = \boxed{290\,\text{m}}$$

9. The "5 second rule" says that for every 5 seconds between seeing a lightning strike and hearing the associated sound, the lightning is 1 mile distant. We assume that there are 5 seconds between seeing the lightning and hearing the sound.

(*a*) At 30°C, the speed of sound is $\left[331 + 0.60\left(30\right)\right]\text{m/s} = 349\,\text{m/s}$. The actual distance to the lightning is therefore $d = vt = \left(349\,\text{m/s}\right)\left(5\,\text{s}\right) = 1745\ \text{m}$. A mile is 1610 m.

$$\%\ \text{error} = \frac{1745 - 1610}{1745}\left(100\right) \approx \boxed{8\%}$$

(*b*) At 10°C, the speed of sound is $\left[331 + 0.60\left(10\right)\right]\text{m/s} = 337\,\text{m/s}$. The actual distance to the lightning is therefore $d = vt = \left(337\,\text{m/s}\right)\left(5\,\text{s}\right) = 1685\ \text{m}$. A mile is 1610 m.

$$\%\ \text{error} = \frac{1685 - 1610}{1685}\left(100\right) \approx \boxed{4\%}$$

10. The relationship between the pressure and displacement amplitudes is given by Eq. 16-5.

(*a*) $\Delta P_{\text{M}} = 2\pi\rho vAf \quad \rightarrow \quad A = \dfrac{\Delta P_{\text{M}}}{2\pi\rho vf} = \dfrac{3.0\times10^{-3}\,\text{Pa}}{2\pi\left(1.29\,\text{kg/m}^3\right)\left(331\,\text{m/s}\right)\left(150\,\text{Hz}\right)} = \boxed{7.5\times10^{-9}\,\text{m}}$

(*b*) $A = \dfrac{\Delta P_{\text{M}}}{2\pi\rho vf} = \dfrac{3.0\times10^{-3}\,\text{Pa}}{2\pi\left(1.29\,\text{kg/m}^3\right)\left(331\,\text{m/s}\right)\left(15\times10^3\,\text{Hz}\right)} = \boxed{7.5\times10^{-11}\,\text{m}}$

11. The pressure amplitude is found from Eq. 16-5. The density of air is $1.29\,\text{kg/m}^3$.

(*a*) $\Delta P_{\text{M}} = 2\pi\rho vAf = 2\pi\left(1.29\,\text{kg/m}^3\right)\left(331\,\text{m/s}\right)\left(3.0\times10^{-10}\,\text{m}\right)\left(55\,\text{Hz}\right) = \boxed{4.4\times10^{-5}\,\text{Pa}}$

(*b*) $\Delta P_{\text{M}} = 2\pi\rho vAf = 2\pi\left(1.29\,\text{kg/m}^3\right)\left(331\,\text{m/s}\right)\left(3.0\times10^{-10}\,\text{m}\right)\left(5500\,\text{Hz}\right) = \boxed{4.4\times10^{-3}\,\text{Pa}}$

12. The pressure wave can be written as Eq. 16-4.

(*a*) $\Delta P = -\Delta P_{\text{M}}\cos\left(kx - \omega t\right)$

$$\Delta P_{\text{M}} = 4.4\times10^{-5}\,\text{Pa}\ ;\ \omega = 2\pi f = 2\pi\left(55\,\text{Hz}\right) = 110\pi\,\text{rad/s}\ ;\ k = \frac{\omega}{v} = \frac{110\pi\,\text{rad/s}}{331\,\text{m/s}} = 0.33\pi\,\text{m}^{-1}$$

$$\boxed{\Delta P = -\left(4.4\times10^{-5}\,\text{Pa}\right)\cos\left[\left(0.33\pi\,\text{m}^{-1}\right)x - \left(110\pi\,\text{rad/s}\right)t\right]}$$

(*b*) All is the same except for the amplitude and $\omega = 2\pi f = 2\pi\left(5500\ \text{Hz}\right) = 1.1\times10^4\pi\,\text{rad/s}$.

$$\boxed{\Delta P = -\left(4.4\times10^{-3}\,\text{Pa}\right)\cos\left[\left(0.33\pi\,\text{m}^{-1}\right)x - \left(1.1\times10^4\pi\,\text{rad/s}\right)t\right]}$$

13. The pressure wave is $\Delta P = \left(0.0035\,\text{Pa}\right)\sin\left[\left(0.38\pi\,\text{m}^{-1}\right)x - \left(1350\pi\,\text{s}^{-1}\right)t\right]$.

(*a*) $\lambda = \dfrac{2\pi}{k} = \dfrac{2\pi}{0.38\pi\,\text{m}^{-1}} = \boxed{5.3\,\text{m}}$

(*b*) $f = \dfrac{\omega}{2\pi} = \dfrac{1350\pi\,\text{s}^{-1}}{2\pi} = \boxed{675\,\text{Hz}}$

(*c*) $v = \dfrac{\omega}{k} = \dfrac{1350\pi\,\text{s}^{-1}}{0.38\pi\,\text{m}^{-1}} = 3553\,\text{m/s} \approx \boxed{3600\,\text{m/s}}$

(*d*) Use Eq. 16-5 to find the displacement amplitude.

$\Delta P_{\text{M}} = 2\pi\rho vAf \quad \rightarrow$

$$A = \frac{\Delta P_{\text{M}}}{2\pi\rho vf} = \frac{\left(0.0035\,\text{Pa}\right)}{2\pi\left(2300\,\text{kg/m}^3\right)\left(3553\,\text{m/s}\right)\left(675\,\text{Hz}\right)} = \boxed{1.0\times10^{-13}\,\text{m}}$$

14. $120\text{ dB} = 10\log\dfrac{I_{120}}{I_0} \quad \rightarrow \quad I_{120} = 10^{12}I_0 = 10^{12}\left(1.0\times10^{-12}\ \text{W/m}^2\right) = \boxed{1.0\,\text{W/m}^2}$

$20\text{ dB} = 10\log\dfrac{I_{20}}{I_0} \quad \rightarrow \quad I_{20} = 10^{2}I_0 = 10^{2}\left(1.0\times10^{-12}\ \text{W/m}^2\right) = \boxed{1.0\times10^{-10}\ \text{W/m}^2}$

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

15. $\beta = 10\log\frac{I}{I_0} = 10\log\frac{2.0\times10^{-6}\ \text{W/m}^2}{1.0\times10^{-12}\ \text{W/m}^2} = \boxed{63\ \text{dB}}$

16. From Figure 16-6, at 40 dB the low frequency threshold of hearing is about $\boxed{70-80\ \text{Hz}}$. There is no intersection of the threshold of hearing with the 40 dB level on the high frequency side of the chart, and so a 40 dB signal can be heard all the way up to the highest frequency that a human can hear, $\boxed{20,000\ \text{Hz}}$.

17. (*a*) From Figure 16-6, 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 $\frac{5\ \text{W/m}^2}{5\times10^{-9}\ \text{W/m}^2} = \boxed{10^9}$.

    (*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 $\frac{10^{-1}\ \text{W/m}^2}{10^{-13}\ \text{W/m}^2} = \boxed{10^{12}}$.

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

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

$$\beta = 10\log\frac{P_{150}}{P_{100}} = 10\log\frac{150\ \text{W}}{100\ \text{W}} = \boxed{1.8\ \text{dB}}$$

This would barely be perceptible.

$\boxed{19.}$ The intensity can be found from the decibel value.

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

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 *v*, the wave speed. In a time Δt, a volume equal to $\Delta V = Sv\Delta t$ would contain all of the energy that had been transported across the area *S*. Combine these relationships to find the energy in the volume.

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

20. 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 $95\ \text{dB} - 3\ \text{dB} = \boxed{92\ \text{dB}}$.

21. From Example 16-4, 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 127 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 $\boxed{124\ \text{dB}}$.

22. $62\,\text{dB} = 10\log\left(I_{\text{Signal}}/I_{\text{Noise}}\right)_{\text{tape}} \rightarrow \left(I_{\text{Signal}}/I_{\text{Noise}}\right)_{\text{tape}} = 10^{6.2} = \boxed{1.6\times10^{6}}$

$98\,\text{dB} = 10\log\left(I_{\text{Signal}}/I_{\text{Noise}}\right)_{\text{tape}} \rightarrow \left(I_{\text{Signal}}/I_{\text{Noise}}\right)_{\text{tape}} = 10^{9.8} = \boxed{6.3\times10^{9}}$

23. (*a*) According to Table 16-2, the intensity in normal conversation, when about 50 cm from the speaker, is about $3\times10^{-6}\ \text{W/m}^2$. The intensity is the power output per unit area, and so the power output can be found. The area is that of a sphere.

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

(*b*) $75\,\text{W}\left(\dfrac{1\ \text{person}}{9.425\times10^{-6}\,\text{W}}\right) = 7.96\times10^{6} \approx \boxed{8.0\times10^{6}\,\text{people}}$

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

$$50\ \text{dB} = 10\log\frac{I}{I_0} \rightarrow I = 10^{5}I_0 = 10^{5}\left(1.0\times10^{-12}\ \text{W/m}^2\right) = 1.0\times10^{-7}\ \text{W/m}^2$$

$$P = IA = \left(1.0\times10^{-7}\ \text{W/m}^2\right)\left(5.0\times10^{-5}\,\text{m}^2\right) = \boxed{5.0\times10^{-12}\,\text{W}}$$

(*b*) $1\ \text{J}\left(\dfrac{1\ \text{s}}{5.0\times10^{-12}\ \text{J}}\right)\left(\dfrac{1\ \text{yr}}{3.16\times10^{7}\,\text{s}}\right) = \boxed{6.3\times10^{3}\,\text{yr}}$

25. 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*) $I_{250} = \dfrac{250\,\text{W}}{4\pi\left(3.5\,\text{m}\right)^2} = 1.624\,\text{W/m}^2 \qquad \beta_{250} = 10\log\dfrac{I_{250}}{I_0} = 10\log\dfrac{1.624\,\text{W/m}^2}{1.0\times10^{-12}\ \text{W/m}^2} = \boxed{122\,\text{dB}}$

$I_{45} = \dfrac{45\,\text{W}}{4\pi\left(3.5\text{m}\right)^2} = 0.2923\,\text{W/m}^2 \qquad \beta_{45} = 10\log\dfrac{I_{45}}{I_0} = 10\log\dfrac{0.2923\,\text{W/m}^2}{1.0\times10^{-12}\ \text{W/m}^2} = \boxed{115\,\text{dB}}$

(*b*) According to the textbook, for a sound to be perceived as twice as loud as another means that the intensities need to differ by a factor of 10. That is not the case here – they differ only by a factor of $\dfrac{1.624}{0.2598} \approx 6$. $\boxed{\text{The expensive amp will not sound twice as loud as the cheaper one.}}$

26. (*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.

$$\beta = 130\ \text{dB} = 10\log\frac{I_{2.8\text{m}}}{I_0} \rightarrow I_{2.8\text{m}} = 10^{13}I_0 = 10^{13}\left(1.0\times10^{-12}\ \text{W/m}^2\right) = 10\,\text{W/m}^2$$

$$P = IA = 4\pi r^2 I = 4\pi\left(2.2\,\text{m}\right)^2\left(10\,\text{W/m}^2\right) = 608\,\text{W} \approx \boxed{610\,\text{W}}$$

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

$$\beta = 85\,\text{dB} = 10\log\frac{I}{I_0} \rightarrow I = 10^{8.5}I_0 = 10^{8.5}\left(1.0\times10^{-12}\ \text{W/m}^2\right) = 3.16\times10^{-4}\ \text{W/m}^2$$

$$P = 4\pi r^2 I \rightarrow r = \sqrt{\frac{P}{4\pi I}} = \sqrt{\frac{608\,\text{W}}{4\pi\left(3.16\times10^{-4}\ \text{W/m}^2\right)}} = \boxed{390\,\text{m}}$$

27. 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.

$$\frac{I_1}{I_2} = \frac{r_2^2}{r_1^2} = \left[\frac{\sqrt{5}\,(100\,\text{m})}{100\,\text{m}}\right]^2 = 5 \ ; \ \beta = 10\log\frac{I_1}{I_2} = 10\log 5 = \boxed{7.0\,\text{dB}}$$

28. (*a*) The intensity is proportional to the square of the amplitude, so if the amplitude is 2.5 times greater, the intensity will $\boxed{\text{increase by a factor of } 6.25 \approx 6.3}$.

(*b*) $\beta = 10\log I/I_0 = 10\log 6.25 = \boxed{8\,\text{dB}}$

29. (*a*) The pressure amplitude is seen in Eq. 16-5 to be proportional to the displacement amplitude and to the frequency. Thus $\boxed{\text{the higher frequency wave has the larger pressure amplitude, by a factor of 2.6.}}$

(*b*) The intensity is proportional to the square of the frequency. Thus the ratio of the intensities is the square of the frequency ratio.

$$\frac{I_{2.6f}}{I_f} = \frac{(2.6f)^2}{f^2} = 6.76 \approx \boxed{6.8}$$

30. The intensity is given by Eq. 15-7, $I = 2\pi^2 v\rho f^2 A^2$, using the density of air and the speed of sound in air.

$$I = 2\rho v\pi^2 f^2 A^2 = 2\left(1.29\,\text{kg/m}^3\right)(343\,\text{m/s})\pi^2(380\,\text{Hz})^2\left(1.3\times10^{-4}\,\text{m}\right)^2 = 21.31\,\text{W/m}^2$$

$$\beta = 10\log\frac{I}{I_0} = 10\log\frac{21.31\,\text{W/m}^2}{1.0\times10^{-12}\,\text{W/m}^2} = 133\,\text{dB} \approx \boxed{130\,\text{dB}}$$

Note that this is above the threshold of pain.

31. (*a*) We find the intensity of the sound from the decibel value, and then calculate the displacement amplitude from Eq. 15-7.

$$\beta = 10\log\frac{I}{I_0} \ \rightarrow \ I = 10^{\beta/10} I_0 = 10^{12}\left(10^{-12}\,\text{W/m}^2\right) = 1.0\,\text{W/m}^2$$

$$I = 2\pi^2 v\rho f^2 A^2 \ \rightarrow$$

$$A = \frac{1}{\pi f}\sqrt{\frac{I}{2\rho v}} = \frac{1}{\pi(330\,\text{Hz})}\sqrt{\frac{1.0\,\text{W/m}^2}{2\left(1.29\,\text{kg/m}^3\right)(343\,\text{m/s})}} = \boxed{3.2\times10^{-5}\,\text{m}}$$

(*b*) The pressure amplitude can be found from Eq. 16-7.

$$I = \frac{(\Delta P_M)^2}{2v\rho} \ \rightarrow$$

$$\Delta P_M = \sqrt{2v\rho I} = \sqrt{2(343\,\text{m/s})\left(1.29\,\text{kg/m}^3\right)\left(1.0\,\text{W/m}^2\right)} = \boxed{30\,\text{Pa}\ (2\text{ sig. fig.})}$$

32. (*a*) We assume that there has been no appreciable absorption in this 25 meter distance. The intensity is the power divide by the area of a sphere of radius 25 meters. We express the sound level in dB.

$$I=\frac{P}{4\pi r^2}\ ;\ \beta=10\log\frac{I}{I_0}=10\log\frac{P}{4\pi r^2 I_0}=10\log\frac{\left(5.0\times10^5\,\text{W}\right)}{4\pi\left(25\,\text{m}\right)^2\left(10^{-12}\,\text{W/m}^2\right)}=\boxed{138\,\text{dB}}$$

(*b*) We find the intensity level at the new distance, and subtract due to absorption.

$$\beta=10\log\frac{P}{4\pi r^2 I_0}=10\log\frac{\left(5.0\times10^5\,\text{W}\right)}{4\pi\left(1000\,\text{m}\right)^2\left(10^{-12}\,\text{W/m}^2\right)}=106\,\text{dB}$$

$$\beta_{\substack{\text{with}\\\text{absorption}}}=106\,\text{dB}-\left(1.00\,\text{km}\right)\left(7.0\,\text{dB/km}\right)=\boxed{99\,\text{dB}}$$

(*c*) We find the intensity level at the new distance, and subtract due to absorption.

$$\beta=10\log\frac{P}{4\pi r^2 I_0}=10\log\frac{\left(5.0\times10^5\,\text{W}\right)}{4\pi\left(7500\,\text{m}\right)^2\left(10^{-12}\,\text{W/m}^2\right)}=88.5\,\text{dB}$$

$$\beta_{\substack{\text{with}\\\text{absorption}}}=88.5\,\text{dB}-\left(7.50\,\text{km}\right)\left(7.0\,\text{dB/km}\right)=\boxed{36\,\text{dB}}$$

33. For a closed tube, Figure 16-12 indicates that $f_1=\frac{v}{4\ell}$. We assume the bass clarinet is at room temperature.

$$f_1=\frac{v}{4\ell}\ \rightarrow\ \ell=\frac{v}{4f_1}=\frac{343\,\text{m/s}}{4\left(69.3\,\text{Hz}\right)}=\boxed{1.24\,\text{m}}$$

34. For a vibrating string, the frequency of the fundamental mode is given by $f=\frac{v}{2L}=\frac{1}{2L}\sqrt{\frac{F_T}{m/L}}$.

$$f=\frac{1}{2L}\sqrt{\frac{F_T}{m/L}}\ \rightarrow\ F_T=4Lf^2m=4\left(0.32\,\text{m}\right)\left(440\,\text{Hz}\right)^2\left(3.5\times10^{-4}\,\text{kg}\right)=\boxed{87\,\text{N}}$$

35. (*a*) If the pipe is closed at one end, only the odd harmonic frequencies are present, and are given by $f_n=\frac{nv}{4L}=nf_1, n=1,3,5\cdots$.

$$f_1=\frac{v}{4L}=\frac{343\,\text{m/s}}{4\left(1.24\text{ m}\right)}=\boxed{69.2\text{ Hz}}$$

$$f_3=3f_1=\boxed{207\,\text{Hz}}\qquad f_5=5f_1=\boxed{346\,\text{Hz}}\qquad f_7=7f_1=\boxed{484\,\text{Hz}}$$

(*b*) If the pipe is open at both ends, all the harmonic frequencies are present, and are given by $f_n=\frac{nv}{2\ell}=nf_1$.

$$f_1=\frac{v}{2\ell}=\frac{343\,\text{m/s}}{2\left(1.24\,\text{m}\right)}=138.3\,\text{Hz}\approx\boxed{138\,\text{Hz}}$$

$$f_2=2f_1=\frac{v}{\ell}=\boxed{277\,\text{Hz}}\qquad f_3=3f_1=\frac{3v}{2\ell}=\boxed{415\,\text{Hz}}\qquad f_4=4f_1=\frac{2v}{\ell}=\boxed{553\,\text{Hz}}$$

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

$$f = \frac{v}{\lambda} = \frac{343\,\text{m/s}}{4(0.21\,\text{m})} = \boxed{410\,\text{Hz}}$$

(*b*) If the bottle is one-third full, then the effective length of the air column is reduced to 14 cm.

$$f = \frac{v}{\lambda} = \frac{343\,\text{m/s}}{4(0.14\,\text{m})} = \boxed{610\,\text{Hz}}$$

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

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

38. We approximate the shell as a closed tube of length 20 cm, and calculate the fundamental frequency.

$$f = \frac{v}{4\ell} = \frac{343\,\text{m/s}}{4(0.20\,\text{m})} = 429\,\text{Hz} \approx \boxed{430\,\text{Hz}}$$

39. (*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 $f = \frac{v}{2\ell}$, and so the frequency is inversely proportional to the length.

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

$$f_E\ell_E = f_A\ell_A \quad \rightarrow \quad \ell_A = \ell_E\frac{f_E}{f_A} = (0.73\text{ m})\left(\frac{330\text{ Hz}}{440\text{ Hz}}\right) = 0.5475\text{ m}$$

The string should be fretted a distance $0.73\text{ m} - 0.5475\text{ m} = 0.1825\,\text{m} \approx \boxed{0.18\text{ m}}$ from the nut of the guitar.

(*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. 16-7).

$$\lambda = 2\ell = 2(0.5475\text{ m}) = 1.095\,\text{m} \approx \boxed{1.1\text{ m}}$$

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

$$\lambda = \frac{v}{f} = \frac{343\,\text{m/s}}{440\text{ Hz}} = \boxed{0.78\text{ m}}$$

40. (*a*) At $T = 15^\circ\text{C}$, the speed of sound is given by $v = (331 + 0.60(15))\,\text{m/s} = 340\,\text{m/s}$ (with 3 significant figures). For an open pipe, the fundamental frequency is given by $f = \frac{v}{2\ell}$.

$$f = \frac{v}{2\ell} \quad \rightarrow \quad \ell = \frac{v}{2f} = \frac{340\,\text{m/s}}{2(262\text{ Hz})} = \boxed{0.649\,\text{m}}$$

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

(*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 $\boxed{262\text{ Hz}}$ and the wavelength is $\boxed{1.30\,\text{m}}$.

41. 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.

$$f_{22} = \frac{v_{22}}{\lambda} \qquad f_{5.0} = \frac{v_{5.0}}{\lambda} \qquad \Delta f = f_{5.0} - f_{22} = \frac{v_{5.0} - v_{22}}{\lambda}$$

$$\frac{\Delta f}{f} = \frac{\dfrac{v_{5.0} - v_{22}}{\lambda}}{\dfrac{v_{22}}{\lambda}} = \frac{v_{5.0}}{v_{22}} - 1 = \frac{331 + 0.60(5.0)}{331 + 0.60(22)} - 1 = -2.96\times 10^{-2} = \boxed{-3.0\%}$$

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

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

$\boxed{43.}$ For a tube open at both ends, all harmonics are allowed, with $f_n = nf_1$. Thus consecutive harmonics differ by the fundamental frequency. The four consecutive harmonics give the following values for the fundamental frequency.

$$f_1 = 523\,\text{Hz} - 392\,\text{Hz} = 131\,\text{Hz},\ \ 659\,\text{Hz} - 523\,\text{Hz} = 136\,\text{Hz},\ \ 784\,\text{Hz} - 659\,\text{Hz} = 125\,\text{Hz}$$

The average of these is $f_1 = \frac{1}{3}(131\,\text{Hz} + 136\,\text{Hz} + 125\,\text{Hz}) \approx 131\,\text{Hz}$. We use that for the fundamental frequency.

(*a*) $f_1 = \dfrac{v}{2\ell} \quad\rightarrow\quad \ell = \dfrac{v}{2f_1} = \dfrac{343\,\text{m/s}}{2(131\,\text{Hz})} = \boxed{1.31\,\text{m}}$

Note that the bugle is coiled like a trumpet so that the full length fits in a smaller distance.

(*b*) $f_n = nf_1 \quad\rightarrow\quad n_{\text{G4}} = \dfrac{f_{\text{G4}}}{f_1} = \dfrac{392\,\text{Hz}}{131\,\text{Hz}} = 2.99\ ;\ n_{\text{C5}} = \dfrac{f_{\text{C5}}}{f_1} = \dfrac{523\,\text{Hz}}{131\,\text{Hz}} = 3.99\ ;$

$$n_{\text{E5}} = \frac{f_{\text{E5}}}{f_1} = \frac{659\,\text{Hz}}{131\,\text{Hz}} = 5.03\ ;\ n_{\text{G5}} = \frac{f_{\text{G5}}}{f_1} = \frac{784\,\text{Hz}}{131\,\text{Hz}} = 5.98$$

The harmonics are $\boxed{3,\ 4,\ 5,\ \text{and}\ 6}$.

44. (*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, and 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 3 times the fundamental, 440 Hz is 5 times the fundamental, and 616 Hz is 7 times the fundamental.

45. 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 $f = \frac{v}{2\ell}$.

$$f = \frac{v}{2\ell} \quad \rightarrow \quad \frac{f_{\substack{\text{1st}\\\text{fret}}}}{f_{\text{unfingered}}} = \frac{\dfrac{v}{2\ell_{\substack{\text{1st}\\\text{fret}}}}}{\dfrac{v}{2\ell_{\text{unfingered}}}} = 2^{1/12} \quad \rightarrow \quad \ell_{\substack{\text{1st}\\\text{fret}}} = \frac{\ell_{\text{unfingered}}}{2^{1/12}} = \frac{65.0\,\text{cm}}{2^{1/12}} = 61.35\,\text{cm}$$

$$\ell_{\substack{\text{2nd}\\\text{fret}}} = \frac{\ell_{\substack{\text{1st}\\\text{fret}}}}{2^{1/12}} = \frac{\ell_{\text{unfingered}}}{2^{2/12}} \quad \rightarrow \quad \ell_{\substack{\text{nth}\\\text{fret}}} = \frac{\ell_{\text{unfingered}}}{2^{n/12}} \; ; \; x_{\substack{\text{nth}\\\text{fret}}} = \ell_{\text{unfingered}} - \ell_{\substack{\text{nth}\\\text{fret}}} = \ell_{\text{unfingered}}\left(1 - 2^{-n/12}\right)$$

$$x_1 = (65.0\,\text{cm})\left(1 - 2^{-1/12}\right) = \boxed{3.6\,\text{cm}} \; ; \; x_2 = (65.0\,\text{cm})\left(1 - 2^{-2/12}\right) = \boxed{7.1\,\text{cm}}$$

$$x_3 = (65.0\,\text{cm})\left(1 - 2^{-3/12}\right) = \boxed{10.3\,\text{cm}} \; ; \; x_4 = (65.0\,\text{cm})\left(1 - 2^{-4/12}\right) = \boxed{13.4\,\text{cm}}$$

$$x_5 = (65.0\,\text{cm})\left(1 - 2^{-5/12}\right) = \boxed{16.3\,\text{cm}} \; ; \; x_6 = (65.0\,\text{cm})\left(1 - 2^{-6/12}\right) = \boxed{19.0\,\text{cm}}$$

46. (*a*) The difference between successive overtones for an open pipe is the fundamental frequency.

$$f_1 = 330\,\text{Hz} - 275\,\text{Hz} = \boxed{55\text{ Hz}}$$

(*b*) The fundamental frequency is given by $f_1 = \frac{v}{2\ell}$. Solve this for the speed of sound.

$$v = 2\ell f_1 = 2(1.80\text{ m})(55\text{ Hz}) = 198\,\text{m/s} \approx \boxed{2.0\times10^2\text{ m/s}}$$

47. The difference in frequency for two successive harmonics is 40 Hz. For an open pipe, two successive harmonics differ by the fundamental, so the fundamental could be 40 Hz, with 240 Hz being the 6th harmonic and 280 Hz being the 7th harmonic. For a closed pipe, two successive harmonics differ by twice the fundamental, so the fundamental could be 20 Hz. But the overtones of a closed pipe are odd multiples of the fundamental, and both overtones are even multiples of 30 Hz. So the pipe must be an $\boxed{\text{open pipe}}$.

$$f = \frac{v}{2\ell} \quad \rightarrow \quad \ell = \frac{v}{2f} = \frac{[331 + 0.60(23.0)]\,\text{m/s}}{2(40\,\text{Hz})} = \boxed{4.3\,\text{m}}$$

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

$$\frac{nv}{2\ell} < 2\times10^4\,\text{Hz} \quad \rightarrow \quad n < \frac{2(2.48\,\text{m})(2\times10^4\,\text{Hz})}{343\,\text{m/s}} = 289.2$$

Since there are 289 harmonics, there are $\boxed{\text{288 overtones}}$.

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

$$\frac{nv}{4\ell} < 2\times10^4\,\text{Hz} \quad \rightarrow \quad n < \frac{4(2.48\,\text{m})(2\times10^4\,\text{Hz})}{343\,\text{m/s}} = 578.4$$

The values of n must be odd, so n = 1, 3, 5, …, 577. There are 289 harmonics, and so there are $\boxed{\text{288 overtones}}$.

49. A tube closed at both ends will have standing waves with displacement nodes at each end, and so 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, $\lambda_1 = 2\ell = 16.0\,\text{m}$.

$$f_1 = \frac{v}{\lambda_1} = \frac{343\,\text{m/s}}{16.0\,\text{m}} = \boxed{21.4\,\text{Hz}} \;;\; f_2 = 2f_1 = \boxed{42.8\,\text{Hz}}$$

50. To operate with the first harmonic, we see from the figure that the thickness must be half of a wavelength, so the wavelength is twice the thickness. The speed of sound in the quartz is given by $v = \sqrt{G/\rho}$, analogous to Eqs. 15-3 and 15-4.

$$t = \tfrac{1}{2}\lambda = \tfrac{1}{2}\frac{v}{f} = \tfrac{1}{2}\frac{\sqrt{G/\rho}}{f} = \tfrac{1}{2}\frac{\sqrt{\left(2.95\times10^{10}\,\text{N/m}^2\right)/\left(2650\,\text{kg/m}^2\right)}}{12.0\times10^6\,\text{Hz}} = \boxed{1.39\times10^{-4}\,\text{m}}$$

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

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

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

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.

52. From Eq. 15-7, the intensity is proportional to the square of the amplitude and the square of the frequency. From Fig. 16-14, the relative amplitudes are $\frac{A_2}{A_1} \approx 0.4$ and $\frac{A_3}{A_1} \approx 0.15$.

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

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

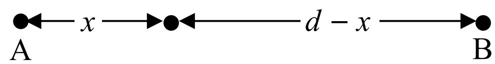
$$\beta_{2-1} = 10\log\frac{I_2}{I_1} = 10\log 0.64 = \boxed{-2\,\text{dB}} \;;\; \beta_{3-1} = 10\log\frac{I_3}{I_1} = 10\log 0.24 = \boxed{-7\,\text{dB}}$$

53. 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.

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

55. Since there are 4 beats/s when sounded with the 350 Hz tuning fork, the guitar string must have a frequency of either 346 Hz or 354 Hz. Since there are 9 beats/s when sounded with the 355 Hz tuning fork, the guitar string must have a frequency of either 346 Hz or 364 Hz. The common value is $\boxed{346\text{ Hz}}$.

56. (*a*) Since the sounds are initially 180° out of phase, another 180° of phase must be added by a path length difference. Thus the difference of the distances from the speakers to the point of constructive interference must be half of a wavelength. See the diagram.



$$(d-x)-x=\tfrac{1}{2}\lambda \rightarrow d=2x+\tfrac{1}{2}\lambda \rightarrow d_{\text{min}}=\tfrac{1}{2}\lambda=\frac{v}{2f}=\frac{343\text{ m/s}}{2(294\text{ Hz})}=\boxed{0.583\text{ m}}$$

This minimum distance occurs when the observer is right at one of the speakers. If the speakers are separated by more than 0.583 m, the location of constructive interference will be moved away from the speakers, along the line between the speakers.

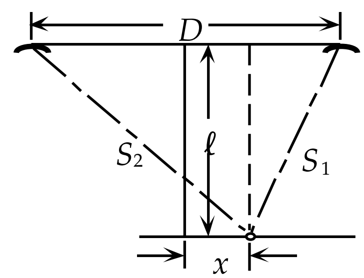
(*b*) Since the sounds are already 180° out of phase, as long as the listener is equidistant from the speakers, there will be completely destructive interference. So even if the speakers have a tiny separation, the point midway between them will be a point of completely destructive interference. The minimum separation between the speakers is $\boxed{0}$.

57. Beats will be heard because the difference in the speed of sound for the two flutes will result in two different frequencies.

$$f_1=\frac{v_1}{2\ell}=\frac{[331+0.60(28)]\text{ m/s}}{2(0.66\text{ m})}=263.4\text{ Hz}$$

$$f_2=\frac{v_2}{2\ell}=\frac{[331+0.60(5.0)]\text{ m/s}}{2(0.66\text{ m})}=253.0\text{ Hz} \qquad \Delta f=263.4\text{ Hz}-253.0\text{ Hz}=\boxed{10\text{ beats/sec}}$$

58. (*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.



$$S_2-S_1=\tfrac{1}{2}\lambda \rightarrow$$

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

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

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

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

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

The values are $D=3.00\text{ m}$, $\ell=3.20\text{ m}$, and $\lambda=v/f=(343\text{ m/s})/(494\text{ Hz})=0.694\text{ m}$.

$$x=(0.694\text{ m})\sqrt{\frac{\tfrac{1}{4}(3.00\text{ m})^2+(3.20\text{ m})^2-\tfrac{1}{16}(0.694\text{ m})^2}{4(3.00\text{ m})^2-(0.694\text{ m})^2}}=\boxed{0.411\text{ m}}$$

(*b*) When the speakers are exactly out of phase, the maxima and minima will be interchanged. The intensity $\boxed{\text{maxima are 0.411 m to the left or right of the midpoint}}$, and the intensity $\boxed{\text{minimum is at the midpoint}}$.

59. The beat frequency is 3 beats per 2 seconds, or 1.5 Hz. We assume the strings are the same length and the same mass density.

(*a*) The other string must be either $220.0\,\text{Hz} - 1.5\,\text{Hz} = \boxed{218.5\,\text{Hz}}$ or $220.0\,\text{Hz} + 1.5\,\text{Hz} = \boxed{221.5\text{ Hz}}$.

(*b*) Since $f = \dfrac{v}{2\ell} = \dfrac{1}{2\ell}\sqrt{\dfrac{F_T}{\mu}}$, we have $f \propto \sqrt{F_T} \rightarrow \dfrac{f}{\sqrt{F_T}} = \dfrac{f'}{\sqrt{F_T'}} \rightarrow F_T' = F_T\left(\dfrac{f'}{f}\right)^2$.

To change 218.5 Hz to 220.0 Hz: $F' = F_T\left(\dfrac{220.0}{218.5}\right)^2 = 1.014$, $\boxed{1.4\%\text{ increase}}$.

To change 221.5 Hz to 220.0 Hz: $F' = F_T\left(\dfrac{220.0}{221.5}\right)^2 = 0.9865$, $\boxed{1.3\%\text{ decrease}}$.

60. (*a*) To find the beat frequency, calculate the frequency of each sound, and then subtract the two frequencies.

$$f_{\text{beat}} = |f_1 - f_2| = \left|\frac{v}{\lambda_1} - \frac{v}{\lambda_2}\right| = (343\,\text{m/s})\left|\frac{1}{2.64\,\text{m}} - \frac{1}{2.72\,\text{m}}\right| = 3.821\,\text{Hz} \approx \boxed{4\,\text{Hz}}$$

(*b*) The speed of sound is 343 m/s, and the beat frequency is 3.821 Hz. The regions of maximum intensity are one "beat wavelength" apart.

$$\lambda = \frac{v}{f} = \frac{343\,\text{m/s}}{3.821\,\text{Hz}} = 89.79\,\text{m} \approx \boxed{90\,\text{m}}\ (2\text{ sig. fig.})$$

$\boxed{61.}$ (*a*) Observer moving towards stationary source.

$$f' = \left(1 + \frac{v_{\text{obs}}}{v_{\text{snd}}}\right)f = \left(1 + \frac{30.0\,\text{m/s}}{343\,\text{m/s}}\right)(1350\text{ Hz}) = \boxed{1470\text{ Hz}}$$

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

$$f' = \left(1 - \frac{v_{\text{obs}}}{v_{\text{snd}}}\right)f = \left(1 - \frac{30.0\,\text{m/s}}{343\,\text{m/s}}\right)(1350\text{ Hz}) = \boxed{1230\text{ Hz}}$$

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

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

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

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

$$= \left(5.00\times10^{4}\,\text{Hz}\right)\frac{343\,\text{m/s}-30.0\,\text{m/s}}{343\,\text{m/s}+30.0\,\text{m/s}} = \boxed{4.20\times10^{4}\,\text{Hz}}$$

63. (*a*) For the 18 m/s relative velocity:

$$f'_{\substack{\text{source}\\\text{moving}}} = f\frac{1}{\left(1-\dfrac{v_{\text{src}}}{v_{\text{snd}}}\right)} = \left(2300\ \text{Hz}\right)\frac{1}{\left(1-\dfrac{18\,\text{m/s}}{343\,\text{m/s}}\right)} = 2427\,\text{Hz} \approx \boxed{2430\,\text{Hz}}$$

$$f'_{\substack{\text{observer}\\\text{moving}}} = f\left(1+\frac{v_{\text{src}}}{v_{\text{snd}}}\right) = \left(2300\ \text{Hz}\right)\left(1+\frac{18\,\text{m/s}}{343\,\text{m/s}}\right) = 2421\,\text{Hz} \approx \boxed{2420\,\text{Hz}}$$

The frequency shifts are slightly different, with $f'_{\substack{\text{source}\\\text{moving}}} > f'_{\substack{\text{observer}\\\text{moving}}}$. The two frequencies are close, but they are not identical. As a means of comparison, calculate the spread in frequencies divided by the original frequency.

$$\frac{f'_{\substack{\text{source}\\\text{moving}}} - f'_{\substack{\text{observer}\\\text{moving}}}}{f_{\text{source}}} = \frac{2427\,\text{Hz}-2421\,\text{Hz}}{2300\,\text{Hz}} = 0.0026 = 0.26\%$$

(*b*) For the 160 m/s relative velocity:

$$f'_{\substack{\text{source}\\\text{moving}}} = f\frac{1}{\left(1-\dfrac{v_{\text{src}}}{v_{\text{snd}}}\right)} = \left(2300\ \text{Hz}\right)\frac{1}{\left(1-\dfrac{160\,\text{m/s}}{343\,\text{m/s}}\right)} = 4311\,\text{Hz} \approx \boxed{4310\,\text{Hz}}$$

$$f'_{\substack{\text{observer}\\\text{moving}}} = f\left(1+\frac{v_{\text{src}}}{v_{\text{snd}}}\right) = \left(2300\ \text{Hz}\right)\left(1+\frac{160\,\text{m/s}}{343\,\text{m/s}}\right) = 3372\ \text{Hz} \approx \boxed{3370\,\text{Hz}}$$

The difference in the frequency shifts is much larger this time, still with $f'_{\substack{\text{source}\\\text{moving}}} > f'_{\substack{\text{observer}\\\text{moving}}}$.

$$\frac{f'_{\substack{\text{source}\\\text{moving}}} - f'_{\substack{\text{observer}\\\text{moving}}}}{f_{\text{source}}} = \frac{4311\,\text{Hz}-3372\,\text{Hz}}{2300\,\text{Hz}} = 0.4083 = 41\%$$

(*c*) For the 320 m/s relative velocity:

$$f'_{\substack{\text{source}\\\text{moving}}} = f\frac{1}{\left(1-\dfrac{v_{\text{src}}}{v_{\text{snd}}}\right)} = \left(2300\ \text{Hz}\right)\frac{1}{\left(1-\dfrac{320\,\text{m/s}}{343\,\text{m/s}}\right)} = \boxed{34{,}300\,\text{Hz}}$$

$$f'_{\substack{\text{observer}\\\text{moving}}} = f\left(1+\frac{v_{\text{src}}}{v_{\text{snd}}}\right) = \left(2300\ \text{Hz}\right)\left(1+\frac{320\,\text{m/s}}{343\,\text{m/s}}\right) = 4446\,\text{Hz} \approx \boxed{4450\,\text{Hz}}$$

The difference in the frequency shifts is quite large, still with $f'_{\substack{\text{source}\\\text{moving}}} > f'_{\substack{\text{observer}\\\text{moving}}}$.

$$\frac{f'_{\substack{\text{source}\\\text{moving}}} - f'_{\substack{\text{observer}\\\text{moving}}}}{f_{\text{source}}} = \frac{34{,}300\,\text{Hz}-4446\,\text{Hz}}{2300\,\text{Hz}} = 12.98 = 1300\%$$

(*d*) The Doppler formulas are asymmetric, with a larger shift for the moving source than for the moving observer, when the two are getting closer to each other. In the following derivation, assume $v_{\text{src}} \ll v_{\text{snd}}$, and use the binomial expansion.

$$f'_{\substack{\text{source}\\\text{moving}}} = f\frac{1}{\left(1-\dfrac{v_{\text{src}}}{v_{\text{snd}}}\right)} = f\left(1-\frac{v_{\text{src}}}{v_{\text{snd}}}\right)^{-1} \approx f\left(1+\frac{v_{\text{src}}}{v_{\text{snd}}}\right) = f'_{\substack{\text{observer}\\\text{moving}}}$$

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

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

$$f_{\text{source}} = \Delta f\left(\frac{v_{\text{snd}}}{v_{\text{source}}}-1\right) = (4.5\text{ Hz})\left(\frac{343\text{ m/s}}{15\text{ m/s}}-1\right) = \boxed{98\text{ Hz}}$$

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

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

$$f'_{\substack{\text{source}\\\text{moving}\\\text{towards}}} = f\frac{1}{\left(1-\dfrac{v_{\text{src}}}{v_{\text{snd}}}\right)} = (1280\text{ Hz})\frac{1}{\left(1-\dfrac{33.33\text{ m/s}}{343\text{ m/s}}\right)} = \boxed{1420\text{ Hz}}$$

$$f'_{\substack{\text{source}\\\text{moving}\\\text{away}}} = f\frac{1}{\left(1+\dfrac{v_{\text{src}}}{v_{\text{snd}}}\right)} = (1280\text{ Hz})\frac{1}{\left(1+\dfrac{33.33\text{ m/s}}{343\text{ m/s}}\right)} = \boxed{1170\text{ Hz}}$$

(*b*) Both the observer and the source are moving, and so use Eq. 16-11.

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

$$f'_{\text{approaching}} = f\frac{(v_{\text{snd}}+v_{\text{obs}})}{(v_{\text{snd}}-v_{\text{src}})} = (1280\text{ Hz})\frac{(343\text{ m/s}+25\text{ m/s})}{(343\text{ m/s}-33.33\text{ m/s})} = \boxed{1520\text{ Hz}}$$

$$f'_{\text{receding}} = f\frac{(v_{\text{snd}}-v_{\text{obs}})}{(v_{\text{snd}}+v_{\text{src}})} = (1280\text{ Hz})\frac{(343\text{ m/s}-25\text{ m/s})}{(343\text{ m/s}+33.33\text{ m/s})} = \boxed{1080\text{ Hz}}$$

(*c*) Both the observer and the source are moving, and so again use Eq. 16-11.

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

$$f'_{\substack{\text{police}\\\text{car}\\\text{approaching}}} = f\frac{(v_{\text{snd}}-v_{\text{obs}})}{(v_{\text{snd}}-v_{\text{src}})} = (1280\text{ Hz})\frac{(343\text{ m/s}-22.22\text{ m/s})}{(343\text{ m/s}-33.33\text{ m/s})} = \boxed{1330\text{ Hz}}$$

$$f'_{\substack{\text{police}\\\text{car}\\\text{receding}}} = f\frac{(v_{\text{snd}}+v_{\text{obs}})}{(v_{\text{snd}}+v_{\text{src}})} = (1280\text{ Hz})\frac{(343\text{ m/s}+22.22\text{ m/s})}{(343\text{ m/s}+33.33\text{ m/s})} = \boxed{1240\text{ Hz}}$$

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

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

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.

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

$$= \left(3.00\times10^4\,\text{Hz}\right)\frac{343\,\text{m/s} + 7.0\,\text{m/s}}{343\,\text{m/s} - 7.0\,\text{m/s}} = \boxed{3.13\times10^4\,\text{Hz}}$$

67. We assume that the comparison is to be made from the frame of reference of the stationary tuba. The stationary observers would observe a frequency from the moving tuba of

$$f_{\text{obs}} = \frac{f_{\text{source}}}{\left(1 - \frac{v_{\text{source}}}{v_{\text{snd}}}\right)} = \frac{75\,\text{Hz}}{\left(1 - \frac{12.0\,\text{m/s}}{343\,\text{m/s}}\right)} = 78\,\text{Hz} \qquad f_{\text{beat}} = 78\,\text{Hz} - 75\,\text{Hz} = \boxed{3\,\text{Hz}}.$$

68. For the sound to be shifted up by one note, we must have $f'_{\substack{\text{source}\\\text{moving}}} = f\left(2^{1/12}\right)$.

$$f'_{\substack{\text{source}\\\text{moving}}} = f\frac{1}{\left(1 - \frac{v_{\text{src}}}{v_{\text{snd}}}\right)} = f\left(2^{1/12}\right) \rightarrow$$

$$v_{\text{src}} = \left(1 - \frac{1}{2^{1/12}}\right)v_{\text{snd}} = \left(1 - \frac{1}{2^{1/12}}\right)(343\,\text{m/s}) = 19.25\,\text{m/s}\left(\frac{3.6\,\text{km/h}}{\text{m/s}}\right) = \boxed{69.3\,\text{km/h}}$$

69. The ocean wave has $\lambda = 44\,\text{m}$ and $v = 18\,\text{m/s}$ relative to the ocean floor. The frequency of the ocean wave is then $f = \frac{v}{\lambda} = \frac{18\,\text{m/s}}{44\,\text{m}} = 0.409\,\text{Hz}$.

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

$$f'_{\substack{\text{observer}\\\text{moving}}} = \left(1 + \frac{v_{\text{obs}}}{v_{\text{snd}}}\right)f = \left(1 + \frac{15\,\text{m/s}}{18\,\text{m/s}}\right)(0.409\,\text{Hz}) = 0.750\,\text{Hz} \rightarrow$$

$$T = \frac{1}{f} = \frac{1}{0.750\,\text{Hz}} = \boxed{1.3\,\text{s}}$$

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

$$f'_{\substack{\text{observer}\\\text{moving}}} = \left(1 - \frac{v_{\text{obs}}}{v_{\text{snd}}}\right) f = \left(1 - \frac{15\,\text{m/s}}{18\,\text{m/s}}\right)(0.409\,\text{Hz}) = 0.0682\,\text{Hz} \rightarrow$$

$$T = \frac{1}{f} = \frac{1}{0.0682\,\text{Hz}} = \boxed{15\,\text{s}}$$

70. 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 and 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, and so 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 $v_{\text{snd}} - v_{\text{wind}}$. The wavelength of the waves traveling towards the observer is $\lambda_a = (v_{\text{snd}} - v_{\text{wind}})/f_0$, where f_0 is the frequency emitted by the factory whistle. This wavelength approaches the observer at a relative speed of $v_{\text{snd}} - v_{\text{wind}}$. Thus the observer hears the frequency calculated here.

$$f_a = \frac{v_{\text{snd}} - v_{\text{wind}}}{\lambda_a} = \frac{v_{\text{snd}} - v_{\text{wind}}}{\dfrac{v_{\text{snd}} - v_{\text{wind}}}{f_0}} = f_0 = \boxed{720\,\text{Hz}}$$

(*b*) Because the wind is blowing towards the observer, the effective speed of sound is $v_{\text{snd}} + v_{\text{wind}}$. The same kind of analysis as applied in part (a) gives that $f_b = \boxed{720\,\text{Hz}}$.

(*c*) Because the wind is blowing perpendicular to the line towards the observer, the effective speed of sound along that line is v_{snd}. Since there is no relative motion of the whistle and observer, there will be no change in frequency, and so $f_c = \boxed{720\,\text{Hz}}$.

(*d*) This is just like part (*c*), and so $f_d = \boxed{720\,\text{Hz}}$.

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

$$f_e = \frac{(v_{\text{snd}} + v_{\text{wind}} + v_{\text{cycle}})}{\lambda_e} = \frac{(v_{\text{snd}} + v_{\text{wind}} + v_{\text{cycle}})}{(v_{\text{snd}} + v_{\text{wind}})} f_0 = \frac{(343 + 15.0 + 12.0)\,\text{m/s}}{(343 + 15.0)}(720\,\text{Hz})$$

$$= \boxed{744\,\text{Hz}}$$

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

$$f' = f\left(1 + \frac{v_{\text{obs}}}{v_{\text{sns}}}\right) = (720\ \text{Hz})\left(1 + \frac{12.0\,\text{m/s}}{343\,\text{m/s}}\right) = \boxed{745\,\text{Hz}}$$

71. 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).

$$f'_{\text{heart}} = f_{\text{original}}\left(1-\frac{v_{\text{heart}}}{v_{\text{snd}}}\right) \qquad f''_{\text{detector}} = \frac{f'_{\text{heart}}}{\left(1+\frac{v_{\text{heart}}}{v_{\text{snd}}}\right)} = f_{\text{original}}\frac{\left(1-\frac{v_{\text{heart}}}{v_{\text{snd}}}\right)}{\left(1+\frac{v_{\text{heart}}}{v_{\text{snd}}}\right)} = f_{\text{original}}\frac{\left(v_{\text{snd}}-v_{\text{heart}}\right)}{\left(v_{\text{snd}}+v_{\text{heart}}\right)}$$

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

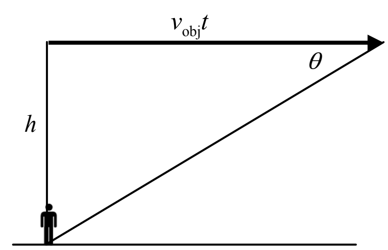
$$v_{\text{blood}} = v_{\text{snd}}\frac{\Delta f}{2f_{\text{original}}-\Delta f} = \left(1.54\times10^{3}\ \text{m/s}\right)\frac{260\ \text{Hz}}{2\left(2.25\times10^{6}\ \text{Hz}\right)-260\ \text{Hz}} = \boxed{8.9\times10^{-2}\ \text{m/s}}$$

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

72. (*a*) The angle of the shock wave front relative to the direction of motion is given by Eq. 16-12.

$$\sin\theta = \frac{v_{\text{snd}}}{v_{\text{obj}}} = \frac{v_{\text{snd}}}{2.0v_{\text{snd}}} = \frac{1}{2.0} \rightarrow \theta = \sin^{-1}\frac{1}{2.0} = \boxed{30^\circ} \text{ (2 sig. fig.)}$$

(*b*) The displacement of the plane $\left(v_{\text{obj}}t\right)$ 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.



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

$$= \frac{6500\ \text{m}}{(2.0)(310\ \text{m/s})\tan30^\circ} = \boxed{18\ \text{s}}$$

73. (*a*) The Mach number is the ratio of the object's speed to the speed of sound.

$$M = \frac{v_{\text{obs}}}{v_{\text{sound}}} = \frac{\left(1.5\times10^{4}\ \text{km/hr}\right)\left(\frac{1\ \text{m/s}}{3.6\ \text{km/hr}}\right)}{45\ \text{m/s}} = 92.59 \approx \boxed{93}$$

(*b*) Use Eq. 16-125 to find the angle.

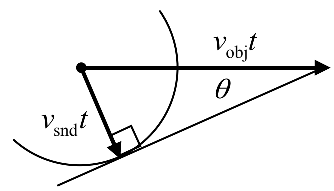
$$\theta = \sin^{-1}\frac{v_{\text{snd}}}{v_{\text{obj}}} = \sin^{-1}\frac{1}{M} = \sin^{-1}\frac{1}{92.59} = \boxed{0.62^\circ}$$

74. From Eq. 16-12, $\sin\theta = \frac{v_{snd}}{v_{obj}}$.

(*a*) $\theta = \sin^{-1}\frac{v_{snd}}{v_{obj}} = \sin^{-1}\frac{343\,\text{m/s}}{8800\,\text{m/s}} = \boxed{2.2^\circ}$

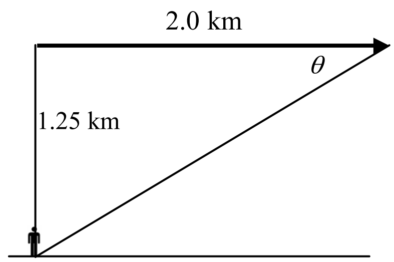
(*b*) $\theta = \sin^{-1}\frac{v_{snd}}{v_{obj}} = \sin^{-1}\frac{1560\,\text{m/s}}{8800\,\text{m/s}} = \boxed{10^\circ}$ (2 sig. fig.)

75. Consider one particular wave as shown in the diagram, created at the location of the black dot. After a time *t* has elapsed from the creation of that wave, the supersonic source has moved a distance $v_{obj}t$, and the wave front has moved a distance $v_{snd}t$. The line from the position of the source at time *t* is tangent to all of the wave fronts, showing the location of the shock wave. A tangent to a circle at a point is perpendicular to the radius connecting that point to the center, and so a right angle is formed. From the right triangle, the angle θ can be defined.



$$\boxed{\sin\theta = \frac{v_{snd}t}{v_{obj}t} = \frac{v_{snd}}{v_{obj}}}$$

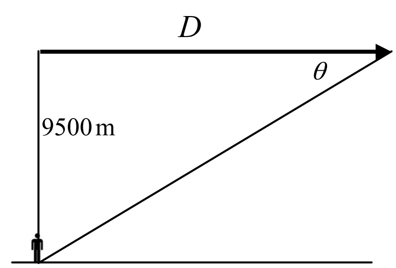
76. (*a*) The displacement of the plane from the time it passes overhead to the time the shock wave reaches the listener is shown, along with the shock wave front. From the displacement and height of the plane, the angle of the shock wave front relative to the direction of motion can be found. Then use Eq. 16-12.



$$\tan\theta = \frac{1.25\text{ km}}{2.0\text{ km}} \rightarrow \theta = \tan^{-1}\frac{1.25}{2.0} = \boxed{32^\circ}$$

(*b*) $M = \frac{v_{obj}}{v_{snd}} = \frac{1}{\sin\theta} = \frac{1}{\sin 32^\circ} = \boxed{1.9}$

77. Find the angle of the shock wave, and then find the distance the plane has traveled when the shock wave reaches the observer. Use Eq. 16-12.



$$\theta = \sin^{-1}\frac{v_{snd}}{v_{obj}} = \sin^{-1}\frac{v_{snd}}{2.2v_{snd}} = \sin^{-1}\frac{1}{2.2} = 27^\circ$$

$$\tan\theta = \frac{9500\,\text{m}}{D} \rightarrow D = \frac{9500\,\text{m}}{\tan 27^\circ} = 18616\,\text{m} = \boxed{19\,\text{km}}$$

78. 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 150 m, at the speed of sound in fresh water, 1440 m/s.

$$d = vt \rightarrow t = \frac{d}{v} = \frac{150\,\text{m}}{1440\,\text{m/s}} = \boxed{0.10\,\text{s}}$$

79. Assume that only the fundamental frequency is heard. The fundamental frequency of an open pipe is given by $f = \frac{v}{2L}$.

(*a*) $f_{3.0} = \frac{v}{2L} = \frac{343\,\text{m/s}}{2(3.0\text{ m})} = \boxed{57\text{ Hz}}$ $\quad f_{2.5} = \frac{v}{2L} = \frac{343\,\text{m/s}}{2(2.5\text{ m})} = \boxed{69\text{ Hz}}$

$f_{2.0} = \frac{v}{2L} = \frac{343\,\text{m/s}}{2(2.0\text{ m})} = \boxed{86\text{ Hz}}$ $\quad f_{1.5} = \frac{v}{2L} = \frac{343\,\text{m/s}}{2(1.5\text{ m})} = 114.3\,\text{Hz} \approx \boxed{110\text{ Hz}}$

$f_{1.0} = \frac{v}{2L} = \frac{343\,\text{m/s}}{2(1.0\text{ m})} = 171.5\text{ Hz} \approx \boxed{170\text{ Hz}}$

(*b*) On a noisy day, there are a large number of component frequencies to the sounds that are being made – more people walking, more people talking, etc. Thus it is more likely that the frequencies listed above will be a component of the overall sound, and then the resonance will be more prominent to the hearer. If the day is quiet, there might be very little sound at the desired frequencies, and then the tubes will not have any standing waves in them to detect.

80. The single mosquito creates a sound intensity of $I_0 = 1\times10^{-12}\text{ W/m}^2$. Thus 100 mosquitoes will create a sound intensity of 100 times that of a single mosquito.

$I = 100I_0 \quad \beta = 10\log\frac{100I_0}{I_0} = 10\log 100 = \boxed{20\,\text{dB}}$.

81. The two sound level values must be converted to intensities, then the intensities added, and then converted back to sound level.

$I_{82}: \;\; 82\,\text{dB} = 10\log\frac{I_{82}}{I_0} \;\rightarrow\; I_{82} = 10^{8.2}I_0 = 1.585\times10^8 I_0$

$I_{89}: \;\; 89\,\text{dB} = 10\log\frac{I_{87}}{I_0} \;\rightarrow\; I_{89} = 10^{8.9}I_0 = 7.943\times10^8 I_0$

$I_{\text{total}} = I_{82} + I_{89} = \left(9.528\times10^8\right)I_0 \;\rightarrow$

$\beta_{\text{total}} = 10\log\frac{9.528\times10^8 I_0}{I_0} = 10\log 6.597\times10^8 = 89.8\,\text{dB} \approx \boxed{90\,\text{dB}} \;\; (2\text{ sig. fig.})$

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

$115\text{ dB} = 10\log\frac{I}{I_0} \;\rightarrow\; I = 10^{11.5}I_0 = 10^{11.5}\left(1.0\times10^{-12}\text{ W/m}^2\right) = 3.162\times10^{-1}\text{ W/m}^2$

$I = \frac{P}{A} = \frac{P}{4\pi r^2} \;\rightarrow\; P = 4\pi r^2 I = 4\pi(9.00\text{ m})^2\left(3.162\times10^{-1}\text{ W/m}^2\right) = \boxed{322\text{ W}}$

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

$-12\text{ dB} = 10\log\frac{P_{15\text{ kHz}}}{175\text{ W}} \;\rightarrow\; -1.2 = \log\frac{P_{15\text{ kHz}}}{175\text{ W}} \;\rightarrow\; 10^{-1.2} = \frac{P_{15\text{ kHz}}}{175\text{ W}} \;\rightarrow\; P_{15\text{ kHz}} = \boxed{11\text{ W}}$

84. 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.

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

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

85. The gain is given by $\beta = 10\log\frac{P_{\text{out}}}{P_{\text{in}}} = 10\log\frac{125\ \text{W}}{1.0\times10^{-3}\,\text{W}} = \boxed{51\,\text{dB}}$.

86. It is desired that the sound from the speaker arrives at a listener 30 ms after the sound from the singer arrives. The fact that the speakers are 3.0 m behind the singer adds in a delay of $\frac{3.0\,\text{m}}{343\,\text{m/s}} =$ $8.7\times10^{-3}\,\text{s}$, or about 9 ms. Thus there must be $\boxed{21\text{ ms}}$ of delay added into the electronic circuitry.

87. The strings are both tuned to the same frequency, and both 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. 15-1 and 15-2.

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

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

88. The strings are both tuned to the same frequency, and both 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. 15-1 and 15-2.

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

$$\frac{F_{\text{T acoustic}}}{F_{\text{T electric}}} = \frac{4\ell^2\rho_{\text{acoustic}} f^2\pi r_{\text{acoustic}}^2}{4\ell^2\rho_{\text{electric}} f^2\pi r_{\text{electric}}^2} = \frac{\rho_{\text{acoustic}} r_{\text{acoustic}}^2}{\rho_{\text{electric}} r_{\text{electric}}^2} = \left(\frac{\rho_{\text{acoustic}}}{\rho_{\text{electric}}}\right)\left(\frac{d_{\text{acoustic}}}{d_{\text{electric}}}\right)^2$$

$$= \left(\frac{7760\,\text{kg/m}^3}{7990\,\text{kg/m}^3}\right)\left(\frac{0.33\,\text{m}}{0.25\,\text{m}}\right)^2 = \boxed{1.7}$$

89. (*a*) The wave speed on the string can be found from the length and the fundamental frequency.

$$f = \frac{v}{2\ell} \quad\rightarrow\quad v = 2\ell f = 2(0.32\ \text{m})(440\ \text{Hz}) = 281.6\,\text{m/s} \approx \boxed{280\,\text{m/s}}$$

The tension is found from the wave speed and the mass per unit length.

$$v = \sqrt{\frac{F_{\text{T}}}{\mu}} \quad\rightarrow\quad F_{\text{T}} = \mu v^2 = \left(7.21\times10^{-4}\ \text{kg/m}\right)(281.6\,\text{m/s})^2 = \boxed{57\,\text{N}}$$

(*b*) The length of the pipe can be found from the fundamental frequency and the speed of sound.

$$f = \frac{v}{4\ell} \quad\rightarrow\quad \ell = \frac{v}{4f} = \frac{343\,\text{m/s}}{4(440\ \text{Hz})} = 0.1949\,\text{m} \approx \boxed{0.19\,\text{m}}$$

(*c*) The first overtone for the string is twice the fundamental. $\boxed{880\text{ Hz}}$

The first overtone for the open pipe is 3 times the fundamental. $\boxed{1320\text{ Hz}}$

90. The apparatus is a closed tube. The water level is the closed end, and so 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.

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

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

$\boxed{91.}$ The fundamental frequency of a tube closed at one end is given by $f_1 = \dfrac{v}{4\ell}$. The change in air temperature will change the speed of sound, resulting in two different frequencies.

$$\frac{f_{30.0^\circ\text{C}}}{f_{25.0^\circ\text{C}}} = \frac{\dfrac{v_{30.0^\circ\text{C}}}{4\ell}}{\dfrac{v_{25.0^\circ\text{C}}}{4\ell}} = \frac{v_{30.0^\circ\text{C}}}{v_{25.0^\circ\text{C}}} \;\rightarrow\; f_{30.0^\circ\text{C}} = f_{25.0^\circ\text{C}}\left(\frac{v_{30.0^\circ\text{C}}}{v_{25.0^\circ\text{C}}}\right)$$

$$\Delta f = f_{30.0^\circ\text{C}} - f_{25.0^\circ\text{C}} = f_{25.0^\circ\text{C}}\left(\frac{v_{30.0^\circ\text{C}}}{v_{25.0^\circ\text{C}}} - 1\right) = \left(349\,\text{Hz}\right)\left(\frac{331 + 0.60\left(30.0\right)}{331 + 0.60\left(25.0\right)} - 1\right) = \boxed{3\,\text{Hz}}$$

92. Call the frequencies of four strings of the violin f_A, f_B, f_C, f_D with f_A the lowest pitch. The mass per unit length will be named μ. All strings are the same length and have the same tension. For a string with both ends fixed, the fundamental frequency is given by $f_1 = \dfrac{v}{2\ell} = \dfrac{1}{2\ell}\sqrt{\dfrac{F_T}{\mu}}$.

$$f_B = 1.5 f_A \;\rightarrow\; \frac{1}{2\ell}\sqrt{\frac{F_T}{\mu_B}} = 1.5\frac{1}{2\ell}\sqrt{\frac{F_T}{\mu_A}} \;\rightarrow\; \mu_B = \frac{\mu_A}{(1.5)^2} = \boxed{0.44\mu_A}$$

$$f_C = 1.5 f_B = (1.5)^2 f_A \;\rightarrow\; \frac{1}{2\ell}\sqrt{\frac{F_T}{\mu_C}} = (1.5)^2\frac{1}{2\ell}\sqrt{\frac{F_T}{\mu_A}} \;\rightarrow\; \mu_C = \frac{\mu_A}{(1.5)^4} = \boxed{0.20\mu_A}$$

$$f_D = 1.5 f_C = (1.5)^3 f_A \;\rightarrow\; \frac{1}{2\ell}\sqrt{\frac{F_T}{\mu_D}} = (1.5)^3\frac{1}{2\ell}\sqrt{\frac{F_T}{\mu_A}} \;\rightarrow\; \mu_D = \frac{\mu_A}{(1.5)^6} = \boxed{0.088\mu_A}$$

93. The effective length of the tube is $\ell_{\text{eff.}} = \ell + \tfrac{1}{3}D = 0.60\,\text{m} + \tfrac{1}{3}\left(0.030\,\text{m}\right) = 0.61\,\text{m}$.

Uncorrected frequencies: $f_n = \dfrac{(2n-1)v}{4\ell}, n = 1,2,3\ldots \;\rightarrow$

$$f_{1-4} = (2n-1)\frac{343\,\text{m/s}}{4\left(0.60\,\text{m}\right)} = 143\,\text{Hz, }429\,\text{Hz, }715\,\text{Hz, }1000\,\text{Hz}$$

Corrected frequencies: $f_n = \dfrac{(2n-1)v}{4\ell_{\text{eff}}}, n = 1,2,3\ldots \;\rightarrow$

$$f_{1-4} = (2n-1)\frac{343\,\text{m/s}}{4\left(0.61\,\text{m}\right)} = \boxed{141\,\text{Hz, }422\,\text{Hz, }703\,\text{Hz, }984\,\text{Hz}}$$

94. Since the sound is loudest at points equidistant from the two sources, the two sources must be in phase. The difference in distance from the two sources must be an odd number of half-wavelengths for destructive interference.

$$0.28\,\text{m} = \lambda/2 \;\rightarrow\; \lambda = 0.56\,\text{m} \qquad f = v/\lambda = 343\,\text{m/s}/0.56\,\text{m} = \boxed{610\,\text{Hz}}$$

$$0.28\,\text{m} = 3\lambda/2 \;\rightarrow\; \lambda = 0.187\,\text{m} \qquad f = v/\lambda = 343\,\text{m/s}/0.187\,\text{m} = 1840\,\text{Hz}\ (\text{out of range})$$

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

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

$$v_{\text{train}} = v_{\text{snd}}\frac{\left(f'_{\text{approach}} - f'_{\text{recede}}\right)}{\left(f'_{\text{approach}} + f'_{\text{recede}}\right)} = (343\,\text{m/s})\frac{(552\,\text{Hz} - 486\,\text{Hz})}{(552\,\text{Hz} + 486\,\text{Hz})} = \boxed{22\,\text{m/s}}$$

96. The Doppler shift is 3.5 Hz, and the emitted frequency from both trains is 516 Hz. Thus the frequency received by the conductor on the stationary train is 519.5 Hz. Use this to find the moving train's speed.

$$f' = f\frac{v_{\text{snd}}}{(v_{\text{snd}} - v_{\text{source}})} \;\rightarrow\; v_{\text{source}} = \left(1 - \frac{f}{f'}\right)v_{\text{snd}} = \left(1 - \frac{516\ \text{Hz}}{519.5\ \text{Hz}}\right)(343\,\text{m/s}) = \boxed{2.31\,\text{m/s}}$$

97. (*a*) Since both speakers are moving towards the observer at the same speed, both frequencies have the same Doppler shift, and the observer hears **no beats**.

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

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

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

$$(348\ \text{Hz})\left[\frac{343\,\text{m/s}}{(343\,\text{m/s} - 10.0\,\text{m/s})} - \frac{343\,\text{m/s}}{(343\,\text{m/s} + 10.0\,\text{m/s})}\right] = \boxed{20\,\text{Hz}}\ (2\ \text{sig. fig.})$$

(*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 **no beats**.

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

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

The longer pipe has a lower frequency. Since the beat frequency is 8.0 Hz, the frequency of the longer pipe must be 63.46 Hz. Use that frequency to find the length of the longer pipe.

$$f = \frac{v}{2\ell} \quad \rightarrow \quad \ell = \frac{v}{2f} = \frac{343\,\text{m/s}}{2(63.46\,\text{Hz})} = \boxed{2.70\,\text{m}}$$

99. Use Eq. 16-11, which applies when both source and observer are in motion. There will be two Doppler shifts in this problem – first for the emitted sound with the bat as the source and the moth as the observer, and then the reflected sound with the moth as the source and the bat as the observer.

$$f'_{\text{moth}} = f_{\text{bat}} \frac{(v_{\text{snd}} + v_{\text{moth}})}{(v_{\text{snd}} - v_{\text{bat}})} \qquad f''_{\text{bat}} = f'_{\text{moth}} \frac{(v_{\text{snd}} + v_{\text{bat}})}{(v_{\text{snd}} - v_{\text{moth}})} = f_{\text{bat}} \frac{(v_{\text{snd}} + v_{\text{moth}})}{(v_{\text{snd}} - v_{\text{bat}})} \frac{(v_{\text{snd}} + v_{\text{bat}})}{(v_{\text{snd}} - v_{\text{moth}})}$$

$$= (51.35\,\text{kHz}) \frac{(343 + 5.0)}{(343 - 7.5)} \frac{(343 + 7.5)}{(343 - 5.0)} = \boxed{55.23\,\text{kHz}}$$

100. The beats arise from the combining of the original 3.80 MHz frequency with the reflected signal which has been Doppler shifted. There are two Doppler shifts – one for the blood cells receiving the original frequency (observer moving away from stationary source) and one for the detector receiving the reflected frequency (source moving away from stationary observer).

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

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

$$= (3.80 \times 10^6\,\text{Hz}) \frac{2(0.32\,\text{m/s})}{(1.54 \times 10^3\,\text{m/s} + 0.32\,\text{m/s})} = \boxed{1600\,\text{Hz}}$$

101. 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.

$$d = v_{\text{snd}} t = (343\,\text{m/s}) \tfrac{1}{2} (67.0 \times 10^{-3}\,\text{s}) = \boxed{11.5\text{ m}}$$

102. (*a*) We assume that $v_{\text{src}} \ll v_{\text{snd}}$, and use the binomial expansion.

$$f'_{\substack{\text{source}\\\text{moving}}} = f \frac{1}{\left(1 - \frac{v_{\text{src}}}{v_{\text{snd}}}\right)} = f \left(1 - \frac{v_{\text{src}}}{v_{\text{snd}}}\right)^{-1} \approx f \left(1 + \frac{v_{\text{src}}}{v_{\text{snd}}}\right) = f'_{\substack{\text{observer}\\\text{moving}}}$$

(*b*) We calculate the percent error in general, and then substitute in the given relative velocity.

$$\%\,\text{error} = \left(\frac{\text{approx.} - \text{exact}}{\text{exact}}\right)100 = 100\left(\frac{f\left(1+\dfrac{v_{\text{src}}}{v_{\text{snd}}}\right) - f\dfrac{1}{\left(1-\dfrac{v_{\text{src}}}{v_{\text{snd}}}\right)}}{f\dfrac{1}{\left(1-\dfrac{v_{\text{src}}}{v_{\text{snd}}}\right)}}\right)$$

$$= 100\left[\left(1+\frac{v_{\text{src}}}{v_{\text{snd}}}\right)\left(1-\frac{v_{\text{src}}}{v_{\text{snd}}}\right) - 1\right] = -100\left(\frac{v_{\text{src}}}{v_{\text{snd}}}\right)^2 = -100\left(\frac{18.0\,\text{m/s}}{343\,\text{m/s}}\right)^2 = \boxed{-0.28\%}$$

The negative sign indicates that the approximate value is less than the exact value.

103. The person will hear a frequency $f'_{\text{towards}} = f\left(1+\dfrac{v_{\text{walk}}}{v_{\text{snd}}}\right)$ from the speaker that they walk towards.

The person will hear a frequency $f'_{\text{away}} = f\left(1-\dfrac{v_{\text{walk}}}{v_{\text{snd}}}\right)$ from the speaker that they walk away from.

The beat frequency is the difference in those two frequencies.

$$f'_{\text{towards}} - f'_{\text{away}} = f\left(1+\frac{v_{\text{walk}}}{v_{\text{snd}}}\right) - f\left(1-\frac{v_{\text{walk}}}{v_{\text{snd}}}\right) = 2f\frac{v_{\text{walk}}}{v_{\text{snd}}} = 2(282\,\text{Hz})\frac{1.4\,\text{m/s}}{343\,\text{m/s}} = \boxed{2.3\,\text{Hz}}$$

104. There will be two Doppler shifts in this problem – first for a stationary source with a moving "observer" (the blood cells), and then for a moving source (the blood cells) and a stationary "observer" (the receiver). Note that the velocity component of the blood parallel to the sound transmission is $v_{\text{blood}}\cos 45° = \frac{1}{\sqrt{2}}v_{\text{blood}}$. It is that component that causes the Doppler shift.

$$f'_{\text{blood}} = f_{\text{original}}\left(1 - \frac{\frac{1}{\sqrt{2}}v_{\text{blood}}}{v_{\text{snd}}}\right)$$

$$f''_{\text{detector}} = \frac{f'_{\text{blood}}}{\left(1+\dfrac{\frac{1}{\sqrt{2}}v_{\text{blood}}}{v_{\text{snd}}}\right)} = f_{\text{original}}\frac{\left(1-\dfrac{\frac{1}{\sqrt{2}}v_{\text{blood}}}{v_{\text{snd}}}\right)}{\left(1+\dfrac{\frac{1}{\sqrt{2}}v_{\text{blood}}}{v_{\text{snd}}}\right)} = f_{\text{original}}\frac{\left(v_{\text{snd}} - \frac{1}{\sqrt{2}}v_{\text{blood}}\right)}{\left(v_{\text{snd}} + \frac{1}{\sqrt{2}}v_{\text{blood}}\right)} \rightarrow$$

$$v_{\text{blood}} = \sqrt{2}\frac{\left(f_{\text{original}} - f''_{\text{detector}}\right)}{\left(f''_{\text{detector}} + f_{\text{original}}\right)}v_{\text{snd}}$$

Since the cells are moving away from the transmitter / receiver combination, the final frequency received is less than the original frequency, by 780 Hz. Thus $f''_{\text{detector}} = f_{\text{original}} - 780\,\text{Hz}$.

$$v_{\text{blood}} = \sqrt{2}\frac{\left(f_{\text{original}} - f''_{\text{detector}}\right)}{\left(f''_{\text{detector}} + f_{\text{original}}\right)}v_{\text{snd}} = \sqrt{2}\frac{(780\,\text{Hz})}{\left(2f_{\text{original}} - 780\,\text{Hz}\right)}v_{\text{snd}}$$

$$= \sqrt{2}\frac{(780\,\text{Hz})}{\left[2\left(5.0\times10^6\,\text{Hz}\right) - 780\,\text{Hz}\right]}(1540\,\text{m/s}) = \boxed{0.17\,\text{m/s}}$$

105. The apex angle is 15°, so the shock wave angle is 7.5°. The angle of the shock wave is also given by $\sin\theta = v_{\text{wave}}/v_{\text{object}}$.

$$\sin\theta = v_{\text{wave}}/v_{\text{object}} \quad\rightarrow\quad v_{\text{object}} = v_{\text{wave}}/\sin\theta = 2.2\,\text{km/h}/\sin 7.5^{\circ} = \boxed{17\,\text{km/h}}$$

106. First, find the path difference in the original configuration. Then move the obstacle to the right by Δd so that the path difference increases by $\frac{1}{2}\lambda$. Note that the path difference change must be on the same order as the wavelength, and so $\Delta d \ll d, \ell$ since $\lambda \ll \ell, d$.

$$(\Delta D)_{\text{initial}} = 2\sqrt{d^2 + \left(\tfrac{1}{2}\ell\right)^2} - \ell \ ; \ (\Delta D)_{\text{final}} = 2\sqrt{(d+\Delta d)^2 + \left(\tfrac{1}{2}\ell\right)^2} - \ell$$

$$(\Delta D)_{\text{final}} - (\Delta D)_{\text{initial}} = \tfrac{1}{2}\lambda = \left(2\sqrt{(d+\Delta d)^2 + \left(\tfrac{1}{2}\ell\right)^2} - \ell\right) - \left(2\sqrt{d^2 + \left(\tfrac{1}{2}\ell\right)^2} - \ell\right) \rightarrow$$

$$2\sqrt{(d+\Delta d)^2 + \left(\tfrac{1}{2}\ell\right)^2} = \tfrac{1}{2}\lambda + 2\sqrt{d^2 + \left(\tfrac{1}{2}\ell\right)^2}$$

Square the last equation above.

$$4\left[d^2 + 2d\Delta d + (\Delta d)^2 + \left(\tfrac{1}{2}\ell\right)^2\right] = \tfrac{1}{4}\lambda^2 + 2\left(\tfrac{1}{2}\lambda\right)2\sqrt{d^2 + \left(\tfrac{1}{2}\ell\right)^2} + 4\left[d^2 + \left(\tfrac{1}{2}\ell\right)^2\right]$$

We delete terms that are second order in the small quantities Δd and λ.

$$8d\Delta d = 2\lambda\sqrt{d^2 + \left(\tfrac{1}{2}\ell\right)^2} \quad\rightarrow\quad \boxed{\Delta d = \frac{\lambda}{4d}\sqrt{d^2 + \left(\tfrac{1}{2}\ell\right)^2}}$$

107. (*a*) The "singing" rod is manifesting standing waves. By holding the rod at its midpoint, it has a node at its midpoint, and antinodes at its ends. Thus the length of the rod is a half wavelength. The speed of sound in aluminum is found in Table 16-1.

$$f = \frac{v}{\lambda} = \frac{v}{2L} = \frac{5100\,\text{m/s}}{1.50\ \text{m}} = \boxed{3400\ \text{Hz}}$$

(*b*) The wavelength of sound in the rod is twice the length of the rod, $\boxed{1.50\,\text{m}}$.

(*c*) The wavelength of the sound in air is determined by the frequency and the speed of sound in air.

$$\lambda = \frac{v}{f} = \frac{343\,\text{m/s}}{3400\,\text{Hz}} = \boxed{0.10\,\text{m}}$$

108. The displacement amplitude is related to the intensity by Eq. 15-7. The intensity can be calculated from the decibel value. The medium is air.

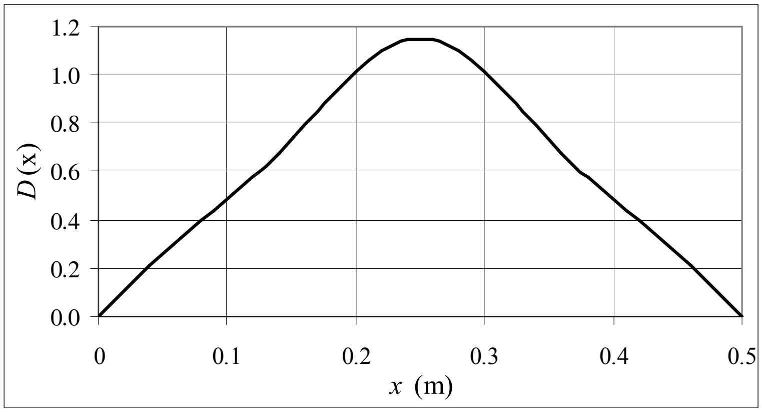
$$\beta = 10\log\frac{I}{I_0} \quad\rightarrow\quad I = \left(10^{\beta/10}\right)I_0 = 10^{10.5}\left(10^{-12}\ \text{W/m}^2\right) = 0.0316\,\text{W/m}^2$$

(*a*) $I = 2\pi^2 v\rho f^2 A^2 \quad\rightarrow$

$$A = \frac{1}{\pi f}\sqrt{\frac{I}{2v\rho}} = \frac{1}{\pi\left(8.0\times10^3\,\text{Hz}\right)}\sqrt{\frac{0.0316\,\text{W/m}^2}{2(343\,\text{m/s})(1.29\,\text{kg/m}^3)}} = \boxed{2.4\times10^{-7}\text{m}}$$

(*b*) $$A = \frac{1}{\pi f}\sqrt{\frac{I}{2v\rho}} = \frac{1}{\pi(35\,\text{Hz})}\sqrt{\frac{0.0316\,\text{W/m}^2}{2(343\,\text{m/s})(1.29\,\text{kg/m}^3)}} = \boxed{5.4\times10^{-5}\text{m}}$$

109. (*a*) The spreadsheet used for this problem can be found on the Media Manager, with filename "PSE4_ISM_CH16.XLS," on tab "Problem 16.109a."



(*b*) The spreadsheet used for this problem can be found on the Media Manager, with filename \ "PSE4_ISM_CH16.XLS," on tab "Problem 16.109b."