CHAPTER 12: Sound

Answers to Questions

1. Sound exhibits several phenomena that give evidence that it is a wave. The phenomenon of interference is a wave phenomenon, and sound produces interference (such as beats). The phenomenon of 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.

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 shatter a glass.

3. The child speaking into a cup creates sound waves which 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 longitudinal waves travel down the string, and cause the bottom of the receiver cup to vibrate. This relatively large vibrating surface moves the adjacent air, and generates sound waves from the bottom of the cup, traveling up into the cup. These waves are incident on the receiver's ear, and they hear the sound from the speaker.

4. If the frequency were to change, the two media could not stay in contact with each other. If one medium vibrates with a certain frequency, and the other medium vibrates with a different frequency, 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, and 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. The wave travels about four times faster in water, so we expect the wavelength in water to be about four times longer than it is in air.

5. Listening to music while seated far away from the source of sound gives evidence that the speed of sound in air does not depend on frequency. If the speed were highly frequency dependent, then high and low sounds created at the same time at the source would arrive at your location at different times, and the music would sound very disjointed. The fact that the music "stays together" is evidence that the speed is independent of frequency.

6. The sound-production anatomy of a person includes various resonating cavities, such as the throat. The relatively fixed geometry of these cavities will determine the relatively fixed wavelengths of sound that a person can produce. Those wavelengths will have associated frequencies given by $f = v/\lambda$. 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 about a factor of 3. This is about a 1.5 octave shift, and so the person sounds very high pitched.

7. The basic equation determining the pitch of the organ pipe is either $f_{\text{closed}} = \frac{nv}{4L}, n = \text{odd integer}$, for a closed pipe, or $f_{\text{open}} = \frac{nv}{2L}, n = \text{integer}$, 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 fixed, the frequency is also a function of temperature. Thus when the temperature changes, the resonant frequencies of the organ pipes change as well. 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 so have a reduced amplitude as compared to the resonant frequencies. The length of the tube can be chosen to thus "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 $f = \frac{v}{2L}$ and so the length of string for a given frequency is $L = \frac{v}{2f}$. 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.

$$L_1 - L_2 = \frac{v}{2f_1} - \frac{v}{2f_2} = \frac{v}{2}\left(\frac{1}{f_1} - \frac{1}{f_2}\right)$$

Now see table 12-3. Each note there would correspond to one fret on the guitar neck. Notice that as the adjacent frequencies get higher, the inter-frequency spacing also increases. The change from C to C# is 15 Hz, while the change from G to G# is 23 Hz. Thus their reciprocals get closer together, and so from the above formula, the length spacing gets closer together. Consider a numeric example.

$$L_{\mathrm{C}} - L_{\mathrm{C\#}} = \frac{v}{2}\left(\frac{1}{262} - \frac{1}{277}\right) = \frac{v}{2}\left(2.07\times10^{-4}\right) \qquad L_{\mathrm{G}} - L_{\mathrm{G\#}} = \frac{v}{2}\left(\frac{1}{392} - \frac{1}{415}\right) = \frac{v}{2}\left(1.41\times10^{-4}\right)$$

$$\frac{L_{\mathrm{G}} - L_{\mathrm{G\#}}}{L_{\mathrm{C}} - L_{\mathrm{C\#}}} = 0.68$$

The G to G# spacing is only about 68% of the C to 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, and 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 (anti-node) to destructive (node). To experience the full range from node to anti-node, 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 (anti-node). 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.

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

13. So-called *active noise reduction* devices work on the principle of interference. If the electronics are fast enough to detect the noise, invert it, and create the opposite wave (180^o 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 hear a net sound signal that is very low in intensity.

14. From the two waves shown, it is seen that the frequency of beating is higher in Figure (a) – the beats occur more frequently. The beat frequency is the difference between the two component frequencies, and so since (a) has a higher beat frequency, the component frequencies are further apart in (a).

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 towards 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, and 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.

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, then 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 towards each other. The child would also hear the lowest frequency of sound at point C, while swinging backwards.

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 42, values of 350 Hz and 355 Hz are used. We took both of those values to have 3 significant figures. We treated the decibel values similarly. For example, in problem 11, we treated the value of 120 dB as having three significant figures.

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.

$$d = vt = (343\,\mathrm{m/s})(1.0\ \mathrm{s}) = 343\ \mathrm{m} \approx \boxed{3.4\times10^2\,\mathrm{m}}$$

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 17 cm to 17 m.

(*b*) $\lambda = \dfrac{v}{f} = \dfrac{343\,\text{m/s}}{10\times10^{6}\text{Hz}} = \boxed{3.4\times10^{-5}\text{m}}$

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

$$d = vt \quad \rightarrow \quad t = \frac{d}{v} = \frac{1.0\times10^{3}\text{ m}}{1560\,\text{m/s}} = \boxed{0.64\text{ s}}$$

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

$$d = vt \quad \rightarrow \quad t = \frac{d}{v} = \frac{1.0\times10^{3}\text{ m}}{343\,\text{m/s}} = \boxed{2.9\text{ s}}$$

5. 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.

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

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

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.

$$h^2 - 2(343\,\text{m/s})\left(\frac{343\,\text{m/s}}{9.80\,\text{m/s}^2} + 3.5\text{ s}\right)h + (3.5\text{ s})^2(343\,\text{m/s})^2 = 0 \rightarrow$$

$$h^2 - (26411\text{ m})h + 1.4412\times10^{6}\text{m}^2 = 0 \rightarrow h = 26356\text{ m}, 55\text{ m}$$

The larger root is impossible since it takes more than 3.5 sec for the rock to fall that distance, so the correct result is $h = \boxed{55\text{ m}}$.

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

$$d = v_{\text{air}} t_{\text{air}} = v_{\text{concrete}} t_{\text{concrete}} = v_{\text{concrete}}(t_{\text{air}} - 1.1\text{ s}) \rightarrow t_{\text{air}} = \frac{v_{\text{concrete}}}{v_{\text{concrete}} - v_{\text{air}}} 1.1\text{ s}$$

$$d = v_{\text{air}} t_{\text{air}} = v_{\text{air}}\left(\frac{v_{\text{concrete}}}{v_{\text{concrete}} - v_{\text{air}}} 1.1\text{ s}\right)$$

The speed of sound in concrete is obtained from Equation (11-14a), Table (9-1), and Table (10-1).

$$v_{\text{concrete}} = \sqrt{\frac{E}{\rho}} = \sqrt{\frac{20\times10^9\ \text{N/m}^2}{2.3\times10^3\ \text{kg/m}^3}} = 2949\,\text{m/s}$$

$$d = v_{\text{air}}t_{\text{air}} = (343\,\text{m/s})\left(\frac{2949\,\text{m/s}}{2949\,\text{m/s}-343\,\text{m/s}}1.1\ \text{s}\right) = 427\text{m} \approx \boxed{4.3\times10^2\,\text{m}}$$

7. 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 $[331+0.60(30)]\,\text{m/s} = 349\,\text{m/s}$. The actual distance to the lightning is therefore $d = vt = (349\,\text{m/s})(5\,\text{s}) = 1745\ \text{m}$. A mile is 1610 m.

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

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

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

$\boxed{8.}$ $$120\ \text{dB} = 10\log\frac{I_{120}}{I_0} \rightarrow I_{120} = 10^{12}I_0 = 10^{12}\left(1.0\times10^{-12}\ \text{W/m}^2\right) = \boxed{1.0\,\text{W/m}^2}$$

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

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

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

10. 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 $95\ \text{dB} - 3\ \text{dB} = \boxed{92\ \text{dB}}$.

11. 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 117 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 $\boxed{114\ \text{dB}}$.

12. $$58\ \text{dB} = 10\log\left(I_{\text{Signal}}/I_{\text{Noise}}\right)_{\text{tape}} \rightarrow \left(I_{\text{Signal}}/I_{\text{Noise}}\right)_{\text{tape}} = 10^{5.8} = \boxed{6.3\times10^5}$$

$$95\ \text{dB} = 10\log\left(I_{\text{Signal}}/I_{\text{Noise}}\right)_{\text{tape}} \rightarrow \left(I_{\text{Signal}}/I_{\text{Noise}}\right)_{\text{tape}} = 10^{9.5} = \boxed{3.2\times10^9}$$

13. (*a*) According to Table 12-2, the intensity in normal conversation, when about 50 cm from the speaker, is about $3\times10^{-6}\ \mathrm{W/m^2}$. The intensity is the power output per unit area, and so the power output can be found. The area is that of a sphere.

$$I=\frac{P}{A}\ \rightarrow\ P=IA=I\left(4\pi r^2\right)=\left(3\times10^{-6}\ \mathrm{W/m^2}\right)4\pi\left(0.50\ \mathrm{m}\right)^2=9.425\times10^{-6}\ \mathrm{W}\approx\boxed{9\times10^{-6}\ \mathrm{W}}$$

(*b*) $$100\ \mathrm{W}\left(\frac{1\ \text{person}}{9.425\times10^{-6}\ \mathrm{W}}\right)=1.06\times10^{7}\approx\boxed{1\times10^{7}\ \text{people}}$$

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

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

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

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

15. 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*) $$I_{250}=\frac{250\ \mathrm{W}}{4\pi\left(3.5\mathrm{m}\right)^2}=1.6\ \mathrm{W/m^2}\qquad \beta_{250}=10\log\frac{I_{250}}{I_0}=10\log\frac{1.6\ \mathrm{W/m^2}}{1.0\times10^{-12}\ \mathrm{W/m^2}}=\boxed{122\ \mathrm{dB}}$$

$$I_{40}=\frac{40\ \mathrm{W}}{4\pi\left(3.5\mathrm{m}\right)^2}=0.26\ \mathrm{W/m^2}\qquad \beta_{40}=10\log\frac{I_{40}}{I_0}=10\log\frac{0.26\ \mathrm{W/m^2}}{1.0\times10^{-12}\ \mathrm{W/m^2}}=\boxed{114\ \mathrm{dB}}$$

(*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 $\frac{1.6}{0.26}\approx 6$. $\boxed{\text{The expensive amp will not sound twice as loud as the cheaper one.}}$

16. (*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.

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

$$P=IA=4\pi r^2 I=4\pi\left(2.8\ \mathrm{m}\right)^2\left(10\ \mathrm{W/m^2}\right)=985\ \mathrm{W}\approx\boxed{9.9\times10^{2}\ \mathrm{W}}$$

(*b*) Find the intensity from the 90 dB value, and then from the power output, find the distance corresponding to that intensity.

$$\beta=90\ \mathrm{dB}=10\log\frac{I}{I_0}\ \rightarrow\ I=10^9 I_0=10^9\left(1.0\times10^{-12}\ \mathrm{W/m^2}\right)=1.0\times10^{-3}\ \mathrm{W/m^2}$$

$$P=4\pi r^2 I\ \rightarrow\ r=\sqrt{\frac{P}{4\pi I}}=\sqrt{\frac{985\ \mathrm{W}}{4\pi\left(1.0\times10^{-3}\ \mathrm{W/m^2}\right)}}=\boxed{2.8\times10^{2}\ \mathrm{m}}$$

17. The intensity is proportional to the square of the amplitude.

$$2.0\text{ dB} = 10\log\frac{I_{2.0}}{I_0} = 10\log\frac{A_{2.0}^2}{A_0^2} = 20\log\frac{A_{2.0}}{A_0} \quad\rightarrow\quad \frac{A_{2.0}}{A_0} = 10^{0.1} = 1.259 \approx \boxed{1.3}$$

18. (*a*) The intensity is proportional to the square of the amplitude, so if the amplitude is tripled, the intensity will $\boxed{\text{increase by a factor of 9}}$.

(*b*) $\beta = 10\log I/I_0 = 10\log 9 = \boxed{9.5\,\text{dB}}$

19. The intensity is given by $I = 2\rho v\pi^2 f^2 A^2$. 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.

$$\frac{I_{2f}}{I_f} = \frac{(2f)^2}{f^2} = \boxed{4}$$

$\boxed{20.}$ The intensity is given by $I = 2\rho v\pi^2 f^2 A^2$, using the density of air and the speed of sound in air.

$$I = 2\rho v\pi^2 f^2 A^2 = 2\left(1.29\,\text{kg/m}^3\right)\left(343\,\text{m/s}\right)\pi^2\left(300\text{ Hz}\right)^2\left(1.3\times10^{-4}\text{ m}\right)^2 = 13.28\,\text{W/m}^2$$

$$\beta = 10\log\frac{I}{I_0} = 10\log\frac{13.28\,\text{W/m}^2}{1.0\times10^{-12}\text{ W/m}^2} = 131.2\,\text{dB} \approx \boxed{130\text{ dB}}$$

Note that this is above the threshold of pain.

21. From Figure 12-6, a 100-Hz tone at 50 dB has a loudness of about 20 phons. At 6000 Hz, 20 phons corresponds to about $\boxed{25\text{ dB}}$. Answers may vary due to estimation in the reading of the graph.

22. From Figure 12-6, at 30 dB the low frequency threshold of hearing is about $\boxed{150\text{ Hz}}$. There is no intersection of the threshold of hearing with the 30 dB level on the high frequency side of the chart, and so a 30 dB signal can be heard all the way up to the highest frequency that a human can hear, $\boxed{20{,}000\text{ Hz}}$.

23. (*a*) From Figure 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} W/m^2, and the threshold of pain is about 10^{-1} 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.

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

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

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

$$f_1 = \frac{v}{4L} = \frac{343\,\text{m/s}}{4(1.12\text{ m})} = \boxed{76.6\text{ Hz}}$$

$$f_3 = 3f_1 = \boxed{230\text{ Hz}} \quad f_5 = 5f_1 = \boxed{383\text{ Hz}} \quad f_7 = 7f_1 = \boxed{536\text{ Hz}}$$

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

$$f_1 = \frac{v}{2L} = \frac{343\,\text{m/s}}{2(1.12\text{ m})} = \boxed{153\text{ Hz}}$$

$$f_2 = 2f_1 = \boxed{306\text{ Hz}} \quad f_3 = 3f_1 = \boxed{459\text{ Hz}} \quad f_4 = 4f_1 = \boxed{612\text{ Hz}}$$

26. (*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.

$$f = \frac{v}{\lambda} = \frac{343\,\text{m/s}}{4(0.18\text{ m})} = \boxed{480\text{ Hz}}$$

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

$$f = \frac{v}{\lambda} = \frac{343\,\text{m/s}}{4(0.12\text{ m})} = \boxed{710\text{ Hz}}$$

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

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

28. 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 60% of the original length. The fundamental frequency of the vibrating string is also given by $f_1 = \frac{v}{2L}$, and *v* is a constant for the string, assuming its tension is not changed.

$$f_{1_{\text{fingered}}} = \frac{v}{2L_{\text{fingered}}} = \frac{v}{2(0.60)L} = \frac{1}{0.60}f_1 = \frac{180\text{ Hz}}{0.60} = \boxed{300\text{ Hz}}$$

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

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

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

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. 12-7).

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

(*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.

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

30. (*a*) At $T = 21^\circ\text{C}$, the speed of sound is given by $v = (331 + 0.60(21)) \text{ m/s} = 343.6 \text{ m/s}$. For an open pipe, the fundamental frequency is given by $f = \frac{v}{2L}$.

$$f = \frac{v}{2L} \quad \rightarrow \quad L = \frac{v}{2f} = \frac{343.6 \text{ m/s}}{2(262 \text{ Hz})} = \boxed{0.656 \text{ m}}$$

(*b*) The frequency of the standing wave in the tube is $\boxed{262 \text{ Hz}}$. The wavelength is twice the length of the pipe, $\boxed{1.31 \text{ m}}$

(*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 $\boxed{1.31 \text{ m}}$

31. 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.

$$f_{20} = \frac{v_{20}}{\lambda} \qquad f_{5.0} = \frac{v_{5.0}}{\lambda} \qquad \Delta f = f_{5.0} - f_{20} = \frac{v_{5.0} - v_{20}}{\lambda}$$

$$\frac{\Delta f}{f} = \frac{\frac{v_{5.0} - v_{20}}{\lambda}}{\frac{v_{20}}{\lambda}} = \frac{v_{5.0}}{v_{20}} - 1 = \frac{331 + 0.60(5.0)}{331 + 0.60(20)} - 1 = -2.6 \times 10^{-2} = \boxed{-2.6\%}$$

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

$$f=\frac{v}{2L} \quad\rightarrow\quad L=\frac{v}{2f}=\frac{343\,\text{m/s}}{2(294\text{ Hz})}=\boxed{0.583\text{ m}}$$

33. (*a*) At $T=20^{\circ}\text{C}$, the speed of sound is $343\,\text{m/s}$. For an open pipe, the fundamental frequency is given by $f=\dfrac{v}{2L}$.

$$f=\frac{v}{2L} \quad\rightarrow\quad L=\frac{v}{2f}=\frac{343\,\text{m/s}}{2(294\text{ Hz})}=\boxed{0.583\text{ m}}$$

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

$$f=\frac{v}{2L}=\frac{1005\,\text{m/s}}{2(0.583\text{ m})}=\boxed{862\text{ Hz}}$$

34. (*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 $\boxed{88.0\text{ Hz}}$. 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.

35. (*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 $f_1=\dfrac{v}{2L}$. Solve this for the speed of sound.

$$v=2Lf_1=2(1.80\text{ m})(55\text{ Hz})=198\,\text{m/s}\approx\boxed{2.0\times10^2\text{ m/s}}$$

36. 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 $\boxed{\text{open pipe}}$.

$$f=\frac{v}{2L} \quad\rightarrow\quad L=\frac{v}{2f}=\frac{343\,\text{m/s}}{2(40\text{ Hz})}=\boxed{4.3\text{ m}}$$

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

$$\frac{nv}{2L}<2\times10^4\,\text{Hz} \quad\rightarrow\quad n<\frac{2(2.14\text{ m})(2\times10^4\,\text{Hz})}{343\,\text{m/s}}=249.6$$

Since there are 249 harmonics, there are $\boxed{248\text{ overtones}}$

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

$$\frac{nv}{4L} < 2\times10^4\,\text{Hz} \rightarrow n < \frac{4(2.14\text{ m})(2\times10^4\,\text{Hz})}{343\,\text{m/s}} = 499.1$$

The values of *n* must be odd, so *n* = 1, 3, 5, …, 499. There are 250 harmonics, and so there are $\boxed{\text{249 overtones}}$

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

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

$$\boxed{f_1 = 3430\text{ Hz} \quad f_3 = 10300\text{ Hz} \quad f_5 = 17200\text{ Hz}}$$

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.

39. 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 $\boxed{\pm0.50\text{ Hz}}$. The beating does not tell the tuner whether the second string is too high or too low.

40. 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 $\frac{1}{4}(15\text{ Hz}) = 3.75\,\text{Hz} \approx \boxed{3.8\text{ Hz}}$.

41. 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 be in the audible range for humans. Since it cannot be heard by humans, the brand X whistle must be 5000 Hz higher than the known frequency whistle. Thus the brand X frequency is $23.5\text{ kHz} + 5\text{ kHz} = \boxed{28.5\text{ kHz}}$

42. 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 $\boxed{346\text{ Hz}}$.

43. The fundamental frequency of the violin string is given by $f = \frac{v}{2L} = \frac{1}{2L}\sqrt{\frac{F_T}{m/L}} = 294\text{ Hz}$. Change the tension to find the new frequency, and then subtract the two frequencies to find the beat frequency.

$$f' = \frac{1}{2L}\sqrt{\frac{(0.98)F_T}{m/L}} = \sqrt{0.98}\,\frac{1}{2L}\sqrt{\frac{F_T}{m/L}} = \sqrt{0.98}\,f$$

$$\Delta f = f - f' = f\left(1-\sqrt{0.98}\right) = (294\text{ Hz})\left(1-\sqrt{0.98}\right) = \boxed{3.0\text{ Hz}}$$

44. Beats will be heard because the difference in the speed of sound for the two flutes will result in two different frequencies. We assume that the flute at 25.0°C will accurately play the middle C.

$$f_1 = \frac{v_1}{2L} \rightarrow L = \frac{v_1}{2f_1} = \frac{[331+0.6(25.0)]\text{m/s}}{2(262\text{ Hz})} = 0.660\text{ m}$$

$$f_2 = \frac{v_2}{2L} = \frac{[331+0.6(5.0)]\text{m/s}}{2(0.660\text{ m})} = 253\text{ Hz} \qquad \Delta f = 262\text{ Hz} - 253\text{ Hz} = \boxed{9\text{ beats/sec}}$$

45. Tuning fork A must have a frequency of 3 Hz either higher or lower than the 441 Hz fork B. Tuning fork C must have a frequency of 4 Hz either higher or lower than the 441 Hz fork B.

$$\boxed{f_A = 438\text{ Hz or }444\text{ Hz} \qquad f_C = 437\text{ Hz or }445\text{ Hz}}$$

The possible beat frequencies are found by subtracting all possible frequencies of A and C.

$$\boxed{|f_A - f_C| = 1\text{ Hz or }7\text{ Hz}}$$

46. (*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.

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

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

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

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

47. The beat frequency is 3 beats per 2 seconds, or 1.5 Hz.

(*a*) The other string must be either $132\text{ Hz} - 1.5\text{ Hz} = \boxed{130.5\text{ Hz}}$ or $132\text{ Hz} + 1.5\text{ Hz} = \boxed{133.5\text{ Hz}}$.

(*b*) Since $f = \frac{v}{2L} = \frac{\sqrt{\frac{F_T}{m/L}}}{2L}$, we have $f \propto \sqrt{F_T} \rightarrow \frac{f}{\sqrt{F_T}} = \frac{f'}{\sqrt{F_T'}} \rightarrow F' = F_T\left(\frac{f'}{f}\right)^2$.

To change 130.5 Hz to 132 Hz: $F' = F_T\left(\frac{132}{130.5}\right)^2 = 1.023$, $\boxed{2.3\%\text{ increase}}$

To change 133.5 Hz to 132 Hz: $F' = F_T\left(\frac{132}{133.5}\right)^2 = 0.978$, $\boxed{2.2\%\text{ decrease}}$

48. To find the beat frequency, calculate the frequency of each sound, and then subtract the two frequencies.

$$f_{\text{beat}} = \left|f_1 - f_2\right| = \left|\frac{v}{\lambda_1} - \frac{v}{\lambda_2}\right| = (343\,\text{m/s})\left|\frac{1}{2.64\text{ m}} - \frac{1}{2.76\text{ m}}\right| = 5.649 \approx \boxed{5.6\text{ Hz}}$$

49. (*a*) Observer moving towards stationary source.

$$f' = \left(1 + \frac{v_{\text{obs}}}{v_{\text{snd}}}\right) f = \left(1 + \frac{30.0\,\text{m/s}}{343\,\text{m/s}}\right)(1550\text{ Hz}) = \boxed{1690\text{ Hz}}$$

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

$$f' = \left(1 - \frac{v_{\text{obs}}}{v_{\text{snd}}}\right) f = \left(1 - \frac{30.0\,\text{m/s}}{343\,\text{m/s}}\right)(1550\text{ Hz}) = \boxed{1410\text{ Hz}}$$

50. (*a*) Source moving towards stationary observer.

$$f' = \frac{f}{\left(1 - \frac{v_{\text{src}}}{v_{\text{snd}}}\right)} = \frac{(1550\text{ Hz})}{\left(1 - \frac{32\,\text{m/s}}{343\,\text{m/s}}\right)} = \boxed{1710\text{ Hz}}$$

(*b*) Source moving away from stationary observer.

$$f' = \frac{f}{\left(1 + \frac{v_{\text{src}}}{v_{\text{snd}}}\right)} = \frac{(1550\text{ Hz})}{\left(1 + \frac{32\,\text{m/s}}{343\,\text{m/s}}\right)} = \boxed{1420\text{ Hz}}$$

51. (*a*) For the 15 m/s relative velocity:

$$f'_{\substack{\text{source}\\\text{moving}}} = f\frac{1}{\left(1 - \frac{v_{\text{src}}}{v_{\text{snd}}}\right)} = (2000\text{ Hz})\frac{1}{\left(1 - \frac{15\,\text{m/s}}{343\,\text{m/s}}\right)} = \boxed{2091\text{ Hz}}$$

$$f'_{\substack{\text{observer}\\\text{moving}}} = f\left(1 + \frac{v_{\text{src}}}{v_{\text{snd}}}\right) = (2000\text{ Hz})\left(1 + \frac{15\,\text{m/s}}{343\,\text{m/s}}\right) = \boxed{2087\text{ Hz}}$$

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. To 3 significant figures they are the same.

(*b*) For the 150 m/s relative velocity:

$$f'_{\substack{\text{source}\\\text{moving}}} = f\frac{1}{\left(1 - \frac{v_{\text{src}}}{v_{\text{snd}}}\right)} = (2000\text{ Hz})\frac{1}{\left(1 - \frac{150\,\text{m/s}}{343\,\text{m/s}}\right)} = \boxed{3.55\times10^{3}\,\text{Hz}}$$

$$f'_{\substack{\text{observer}\\\text{moving}}} = f\left(1 + \frac{v_{\text{src}}}{v_{\text{snd}}}\right) = (2000\text{ Hz})\left(1 + \frac{150\,\text{m/s}}{343\,\text{m/s}}\right) = \boxed{2.87\times10^{3}\,\text{Hz}}$$

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

(*c*) For the 300 m/s relative velocity:

$$f'_{\substack{\text{source}\\ \text{moving}}} = f\frac{1}{\left(1-\frac{v_{\text{src}}}{v_{\text{snd}}}\right)} = (2000\text{ Hz})\frac{1}{\left(1-\frac{300\text{ m/s}}{343\text{ m/s}}\right)} = \boxed{16.0\times10^{3}\text{ Hz}}$$

$$f'_{\substack{\text{observer}\\ \text{moving}}} = f\left(1+\frac{v_{\text{src}}}{v_{\text{snd}}}\right) = (2000\text{ Hz})\left(1+\frac{300\text{ m/s}}{343\text{ m/s}}\right) = \boxed{3.75\times10^{3}\text{ Hz}}$$

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

. 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. As the source moves toward the observer with speeds approaching the speed of sound, the observed frequency tends towards infinity. As the observer moves toward the source with speeds approaching the speed of sound, the observed frequency tends towards twice the emitted frequency.

52. The frequency received by the stationary car is higher than the frequency emitted by the stationary car, by $\Delta f = 5.5\text{ Hz}$.

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

$$f_{\text{source}} = \Delta f\left(\frac{v_{\text{snd}}}{v_{\text{source}}}-1\right) = (5.5\text{ Hz})\left(\frac{343\text{ m/s}}{15\text{ m/s}}-1\right) = \boxed{120\text{ Hz}}$$

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.

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

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

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

$$= (5.00\times10^{4}\text{ Hz})\frac{343\text{ m/s}-25.0\text{ m/s}}{343\text{ m/s}+25.0\text{ m/s}} = \boxed{4.32\times10^{4}\text{ Hz}}$$

54. 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.

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

$$= \left(3.00\times10^{4}\,\text{Hz}\right)\frac{343\,\text{m/s}+5.0\,\text{m/s}}{343\,\text{m/s}-5.0\,\text{m/s}} = \boxed{3.09\times10^{4}\,\text{Hz}}$$

55. 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

$$f_{\text{obs}} = \frac{f_{\text{source}}}{\left(1-\frac{v_{\text{source}}}{v_{\text{snd}}}\right)} = \frac{75\text{ Hz}}{\left(1-\frac{10.0\,\text{m/s}}{343\,\text{m/s}}\right)} = 77\text{ Hz} \qquad f_{\text{beat}} = 77\text{ Hz} - 75\text{ Hz} = \boxed{2\text{ Hz}}.$$

56. 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).

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

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

$$= \left(3.5\times10^{6}\,\text{Hz}\right)\frac{2\left(2.0\times10^{-2}\right)}{\left(1.54\times10^{3}\text{ m/s}+2.0\times10^{-2}\right)} = \boxed{91\,\text{Hz}}$$

57. 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).

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

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

$$v_{blood} = v_{snd} \frac{\Delta f}{2 f_{original} - \Delta f} = \left(1.54\times10^{3}\ \text{m/s}\right)\frac{500\ \text{Hz}}{2\left(2.25\times10^{6}\ \text{Hz}\right) - 500\ \text{Hz}} = \boxed{0.171\ \text{m/s}}$$

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

58. 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, and the wavelength of the waves by the same factor, while the frequency is unchanged.

(*a*), (*b*), (*c*), (*d*) $\boxed{f' = f = 570\ \text{Hz}}$

(*e*) The wind makes an effective speed of sound in air of 343 + 12.0 = 355 m/s, and the observer is moving towards a stationary source with a speed of 15.0 m/s.

$$f' = f\left(1+\frac{v_{obs}}{v_{sns}}\right) = \left(570\ \text{Hz}\right)\left(1+\frac{15.0\ \text{m/s}}{355\ \text{m/s}}\right) = \boxed{594\ \text{Hz}}$$

(*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 15.0 m/s.

$$f' = f\left(1+\frac{v_{obs}}{v_{sns}}\right) = \left(570\ \text{Hz}\right)\left(1+\frac{15.0\ \text{m/s}}{343\ \text{m/s}}\right) = \boxed{595\ \text{Hz}}$$

59. (*a*) We represent the Mach number by the symbol *M*.

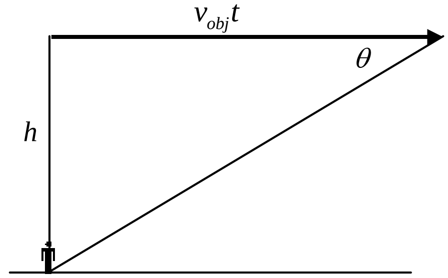
$$M = \frac{v_{obj}}{v_{snd}} \rightarrow v_{obj} = M v_{snd} = \left(0.33\right)\left(343\ \text{m/s}\right) = \boxed{110\ \text{m/s}}$$

(*b*) $M = \frac{v_{obj}}{v_{snd}} \rightarrow v_{snd} = \frac{v_{obj}}{M} = \frac{3000\ \text{km/h}}{3.2} = 937.5\ \text{km/h}\left(\frac{1\ \text{m/s}}{3.6\ \text{km/h}}\right) = \boxed{260\ \text{m/s}}$

60. (*a*) The angle of the shock wave front relative to the direction of motion is given by Eq. 12-7.

$$\sin\theta = \frac{v_{snd}}{v_{obj}} = \frac{v_{snd}}{2.3 v_{snd}} = \frac{1}{2.3} \rightarrow \theta = \sin^{-1}\frac{1}{2.3} = 25.77^{\circ} = \boxed{26^{\circ}}$$

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



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

$$= \frac{7100\ \text{m}}{\left(2.3\right)\left(310\ \text{m/s}\right)\tan 25.77^{\circ}} = 20.63\ \text{s} \approx \boxed{21\ \text{s}}$$

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

$$M = \frac{v_{obs}}{v_{sound}} = \frac{\left(1.5\times10^{4}\ \text{km/hr}\right)\left(\dfrac{1\,\text{m/s}}{3.6\,\text{km/hr}}\right)}{35\,\text{m/s}} = 119.05 \approx \boxed{120}$$

(*b*) Use Eq. 12.5 to find the angle.

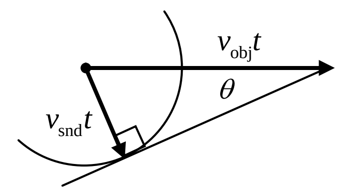
$$\theta = \sin^{-1}\frac{v_{snd}}{v_{obj}} = \sin^{-1}\frac{1}{M} = \sin^{-1}\frac{1}{119.05} = \boxed{0.48^{\circ}}$$

62. From Eq. 12-7, $\sin\theta = \dfrac{v_{snd}}{v_{obj}}$.

(*a*) $\theta = \sin^{-1}\dfrac{v_{snd}}{v_{obj}} = \sin^{-1}\dfrac{343\,\text{m/s}}{8500\,\text{m/s}} = \boxed{2.3^{\circ}}$

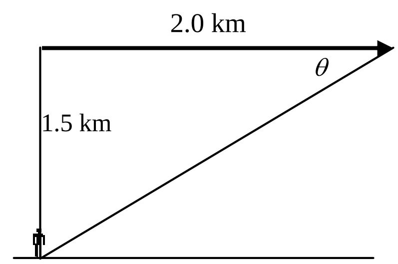
(*b*) $\theta = \sin^{-1}\dfrac{v_{snd}}{v_{obj}} = \sin^{-1}\dfrac{1560\,\text{m/s}}{8500\,\text{m/s}} = \boxed{11^{\circ}}$

63. 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.



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

64. (*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, using Eq. 12-7.



$$\tan\theta = \frac{1.5\text{ km}}{2.0\text{ km}} \rightarrow \theta = \tan^{-1}\frac{1.5}{2.0} = \boxed{37^{\circ}}$$

(*b*) $M = \dfrac{v_{obj}}{v_{snd}} = \dfrac{1}{\sin\theta} = \dfrac{1}{\sin 37^{\circ}} = \boxed{1.7}$

65. 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 400 m, at the speed of sound in fresh water, 1440 m/s.

$$d = vt \rightarrow t = \frac{d}{v} = \frac{400\,\text{m}}{1440\,\text{m/s}} = \boxed{0.28\,\text{s}}$$

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

$$20,000 \text{ Hz} = 2^n (20 \text{ Hz}) \rightarrow 1000 = 2^n \rightarrow \log 1000 = n \log 2 \rightarrow$$

$$n = \frac{\log 1000}{\log 2} = 9.97 \approx \boxed{10 \text{ octaves}}$$

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

(*a*)

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

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

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

(*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.

68. The single mosquito creates a sound intensity of $I_0 = 1 \times 10^{-12} \text{ W/m}^2$. Thus 1000 mosquitoes will create a sound intensity of 1000 times that of a single mosquito.

$$I = 1000 I_0 \qquad \beta = 10 \log \frac{1000 I_0}{I_0} = 10 \log 1000 = \boxed{30 \text{ dB}}.$$

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

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

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

$$I_{\text{total}} = I_{82} + I_{87} = (6.597 \times 10^8) I_0 \rightarrow$$

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

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

$$105 \text{ dB} = 10 \log \frac{I}{I_0} \rightarrow I = 10^{10.5} I_0 = 10^{10.5} (1.0 \times 10^{-12} \text{ W/m}^2) = 3.162 \times 10^{-2} \text{ W/m}^2$$

$$I = \frac{P}{A} = \frac{P}{4\pi r^2} \rightarrow P = 4\pi r^2 I = 4\pi (12.0 \text{ m})^2 (3.162 \times 10^{-2} \text{ W/m}^2) = \boxed{57.2 \text{ W}}$$

71. Relative to the 1000 Hz output, the 15 kHz output is –10 dB.

$$-10\text{ dB} = 10\log\frac{P_{15\text{ kHz}}}{150\text{ W}} \;\rightarrow\; -1 = \log\frac{P_{15\text{ kHz}}}{150\text{ W}} \;\rightarrow\; 0.1 = \frac{P_{15\text{ kHz}}}{150\text{ W}} \;\rightarrow\; P_{15\text{ kHz}} = \boxed{15\text{ W}}$$

72. The 140 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.

$$\beta = 140\text{ dB} = 10\log\frac{I}{I_0} \;\rightarrow\; I = 10^{14} I_0 = 10^{14}\left(1.0\times10^{-12}\text{ W/m}^2\right) = 1.0\times10^{2}\text{ W/m}^2$$

$$P = IA = I\pi r^2 = \left(1.0\times10^{2}\text{ W/m}^2\right)\pi\left(2.0\times10^{-2}\right)^2 = \boxed{0.13\text{ W}}$$

73. The gain is given by $\beta = 10\log\frac{P_{\text{out}}}{P_{\text{in}}} = 10\log\frac{100\text{ W}}{1\times10^{-3}\text{ W}} = \boxed{50\text{ dB}}$.

74. 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 $f_1 = \frac{v}{2L} = \frac{1}{2L}\sqrt{\frac{F_T}{\mu}}$.

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

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

$$f_D = 1.5 f_C = (1.5)^4 f_A \;\rightarrow\; \frac{1}{2L}\sqrt{\frac{F_T}{\mu_D}} = (1.5)^4\frac{1}{2L}\sqrt{\frac{F_T}{\mu_A}} \;\rightarrow\; \mu_D = \frac{\mu_A}{(1.5)^8} = \boxed{0.039\mu_A}$$

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

$$f = \frac{v}{2L} \;\rightarrow\; v = 2Lf = 2(0.32\text{ m})(440\text{ Hz}) = 281.6 = \boxed{2.8\times10^{2}\text{ m/s}}$$

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

$$v = \sqrt{\frac{F_T}{\mu}} \;\rightarrow\; F_T = \mu v^2 = \left(6.1\times10^{-4}\text{ kg/m}\right)(281.6\text{ m/s})^2 = \boxed{48\text{ N}}$$

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

$$f = \frac{v}{4L} \;\rightarrow\; L = \frac{v}{4f} = \frac{343\text{ m/s}}{4(440\text{ Hz})} = \boxed{0.195\text{ m}}$$

(*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. $\boxed{1320\text{ Hz}}$

76. 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.

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

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

77. The frequency of the guitar string is to be the same as the third harmonic (n = 3) of the closed tube. The resonance frequencies of a closed tube are given by $f_n = \dfrac{nv}{4L}$, $n = 1, 3, 5 \cdots$, and the frequency of a stretched string is given by $f = \dfrac{1}{2L}\sqrt{\dfrac{F_T}{m/L}}$. Equate the two frequencies and solve for the tension.

$$\frac{1}{2L_{\text{string}}}\sqrt{\frac{F_T}{m/L_{\text{string}}}} = \frac{3v}{4L_{\text{tube}}} \quad \rightarrow \quad F_T = \frac{9v^2 m}{4L_{\text{string}}} = \frac{9(343\,\text{m/s})^2(2.10\times10^{-3}\,\text{kg})}{4(0.75\,\text{m})} = \boxed{7.4\times10^2\,\text{N}}$$

78. By anchoring the overpass to the ground in the middle, the center of the overpass is now a node point. This forces the lowest frequency for the bridge to be twice the fundamental frequency, and so now **the resonant frequency is 8.0 Hz**. Since the earthquakes don't do significant shaking above 6 Hz, this modification should be effective.

79. 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.

$$0.34\ \text{m} = \lambda/2 \quad \rightarrow \quad \lambda = 0.68\ \text{m} \qquad f = v/\lambda = 343\,\text{m/s}/0.68\ \text{m} = \boxed{504\ \text{Hz}}$$

$$0.34\ \text{m} = 3\lambda/2 \quad \rightarrow \quad \lambda = 0.227\ \text{m} \qquad f = v/\lambda = 343\,\text{m/s}/0.227\ \text{m} = 1513\ \text{Hz}\ (\text{out of range})$$

80. The Doppler shift is 3.0 Hz, and the emitted frequency from both trains is 424 Hz. Thus the frequency received by the conductor on the stationary train is 427 Hz. Use this to find the moving train's speed.

$$f' = f\frac{v_{\text{snd}}}{(v_{\text{snd}} - v_{\text{source}})} \quad \rightarrow \quad v_{\text{source}} = \left(1 - \frac{f}{f'}\right)v_{\text{snd}} = \left(1 - \frac{424\ \text{Hz}}{427\ \text{Hz}}\right)(343\,\text{m/s}) = \boxed{2.41\,\text{m/s}}$$

81. 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}.

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

$$v_{\text{train}} = v_{\text{snd}}\frac{(f'_{\text{approach}} - f'_{\text{recede}})}{(f'_{\text{approach}} + f'_{\text{recede}})} = (343\,\text{m/s})\frac{(538\ \text{Hz} - 486\ \text{Hz})}{(538\ \text{Hz} + 486\ \text{Hz})} = \boxed{17\,\text{m/s}}$$

82. The sound is Doppler shifted up as the car approaches, and Doppler shifted down as it recedes. The observer is stationary in both cases. The octave shift down means that $f_{\text{approach}} = 2f_{\text{recede}}$.

$$f'_{\text{approach}} = f_{\text{engine}} \Big/ \left(1 - \frac{v_{\text{car}}}{v_{\text{snd}}}\right) \qquad f'_{\text{recede}} = f_{\text{engine}} \Big/ \left(1 + \frac{v_{\text{car}}}{v_{\text{snd}}}\right) \qquad f_{\text{approach}} = 2f_{\text{recede}} \rightarrow$$

$$f_{\text{engine}} \Big/ \left(1 - \frac{v_{\text{car}}}{v_{\text{snd}}}\right) = 2 f_{\text{engine}} \Big/ \left(1 + \frac{v_{\text{car}}}{v_{\text{snd}}}\right) \rightarrow v_{\text{car}} = \frac{v_{\text{snd}}}{3} = \frac{343\,\text{m/s}}{3} = \boxed{114\,\text{m/s}}$$

83. For each pipe, the fundamental frequency is given by $f = \dfrac{v}{2L}$. Find the frequency of the shortest pipe.

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

The longer pipe has a lower frequency. Since the beat frequency is 11 Hz, the frequency of the longer pipe must be 60.46 Hz. Use that frequency to find the length of the longer pipe.

$$f = \frac{v}{2L} \rightarrow L = \frac{v}{2f} = \frac{343\,\text{m/s}}{2(60.46\,\text{Hz})} = \boxed{2.84\,\text{m}}$$

84. (*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.

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

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

$$(212\text{ Hz})\left[\frac{343\,\text{m/s}}{(343\,\text{m/s} - 10.0\,\text{m/s})} - \frac{343\,\text{m/s}}{(343\,\text{m/s} + 10.0\,\text{m/s})}\right] = \boxed{12\text{ Hz}}$$

(*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 no beats.

85. The beats arise from the combining of the original 5.50 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).

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

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

$$= \left(5.50\times10^{6}\,\text{Hz}\right)\frac{2\left(0.32\,\text{m/s}\right)}{\left(1.54\times10^{3}\,\text{m/s} + 0.32\,\text{m/s}\right)} = \boxed{2.29\times10^{3}\,\text{Hz}}$$

86. Use Eq. 12-4, 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.

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

$$= \left(51.35\text{ kHz}\right)\frac{\left(343+5.0\right)}{\left(343-6.5\right)}\frac{\left(343+6.5\right)}{\left(343-5.0\right)} = \boxed{54.9\text{ kHz}}$$

87. 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.

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

88. The Alpenhorn can be modeled as an open tube, and so the fundamental frequency is $f = \frac{v}{2L}$, and the overtones are given by $f_n = \frac{nv}{2L},\ n = 1, 2, 3, \cdots$.

$$f_1 = \frac{v}{2L} = \frac{343\,\text{m/s}}{2\left(3.4\text{ m}\right)} = 50.44\,\text{Hz} \approx \boxed{50\text{ Hz}}$$

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

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

89. The walls of the room must be air displacement nodes, and so the dimensions of the room between two parallel boundaries corresponds to a half-wavelength of sound. Fundamental frequencies are then given by $f = \frac{v}{2L}$.

Length: $f = \frac{v}{2L} = \frac{343\,\text{m/s}}{2\left(5.0\text{ m}\right)} = \boxed{34\text{ Hz}}$ Width: $f = \frac{v}{2L} = \frac{343\,\text{m/s}}{2\left(4.0\text{ m}\right)} = \boxed{43\text{ Hz}}$

Height: $f = \frac{v}{2L} = \frac{343\,\text{m/s}}{2\left(2.8\text{ m}\right)} = \boxed{61\text{ Hz}}$

90. (*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.

$$f = \frac{v}{\lambda} = \frac{v}{2L} = \frac{5100\,\text{m/s}}{1.80\text{ m}} = 2833\text{ Hz} = \boxed{2.8\times10^{3}\,\text{Hz}}$$

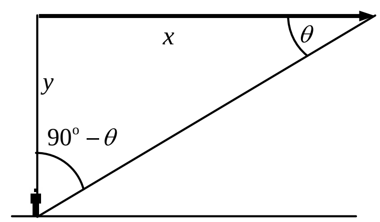
(*b*) The wavelength of sound in the rod is twice the length of the rod, $\boxed{1.80\text{ m}}$.

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

$$\lambda = \frac{v}{f} = \frac{343\,\text{m/s}}{2833\text{ Hz}} = \boxed{0.12\,\text{m}}$$

91. Eq. 11-18 gives the relationship between intensity and the displacement amplitude: $I = 2\pi^2 v\rho f^2 A^2$, 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 $\boxed{10^6}$.

92. The angle between the direction of the airplane and the shock wave front is found from Eq. 12-5.



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

The distance that the plane has traveled horizontally from the observer is found from the time and the speed: $x = v_{\text{obj}}t$. The altitude is found from the angle and the horizontal distance.

$$\tan\theta = y/x \rightarrow y = x\tan\theta = v_{\text{obj}}t\tan 30^\circ = 2(343\,\text{m/s})(90\text{ s})\tan 30^\circ = \boxed{3.6\times10^4\,\text{m}}$$

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

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