CHAPTER 16: Sound

Responses to Questions

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.

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.

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.

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.

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.

Solutions to Problems

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

So the range is from 1.7 cm to 17 m.

(*b*) $\lambda = \frac{v}{f} = \frac{343\,\text{m/s}}{15\times 10^6\,\text{Hz}} = \boxed{2.3\times 10^{-5}\,\text{m}}$

$\boxed{7.}$ 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*.

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

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

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.

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

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

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 $h = \boxed{41\,\mathrm{m}}$.

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

$$d = v_{\mathrm{air}}t_{\mathrm{air}} = v_{\mathrm{concrete}}t_{\mathrm{concrete}} = v_{\mathrm{concrete}}(t_{\mathrm{air}} - 0.75\,\mathrm{s}) \quad \rightarrow \quad t_{\mathrm{air}} = \frac{v_{\mathrm{concrete}}}{v_{\mathrm{concrete}} - v_{\mathrm{air}}}0.75\,\mathrm{s}$$

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

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

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

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

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

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

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

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

$$\Delta P_{\mathrm{M}} = 2\pi\rho v A f \quad \rightarrow$$

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

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

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

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

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.

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

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

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 $f = \frac{v}{2l}$.

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

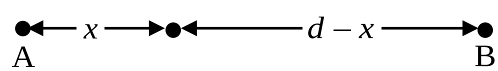
$$l_{\substack{2nd\\fret}}=\frac{l_{\substack{1st\\fret}}}{2^{1/12}}=\frac{l_{unfingered}}{2^{2/12}}\ \rightarrow\ l_{\substack{nth\\fret}}=\frac{l_{unfingered}}{2^{n/12}}\ ;\ x_{\substack{nth\\fret}}=l_{unfingered}-l_{\substack{nth\\fret}}=l_{unfingered}\left(1-2^{-n/12}\right)$$

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

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

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

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.



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.

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

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 $\boxed{0}$.

$\boxed{61.}$ (*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.

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

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

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

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

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:

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

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

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:

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

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

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 $v_{\text{src}} = v_{\text{snd}}$, and use the binomial expansion.

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

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

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

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

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

(*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.

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

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