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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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.

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

35. (*a*) If the pipe is closed at one end, only the odd harmonic frequencies are present, and are given by

$$f_n = \frac{nv}{4L} = nf_1, n = 1, 3, 5\text{L} \; .$$

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

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

(*b*) If the pipe is open at both ends, all the harmonic frequencies are present, and are given by

$$f_n = \frac{nv}{2l} = nf_1 .$$

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

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

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.

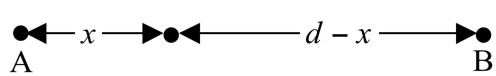
(*b*) For a closed pipe, the successive overtones differ by twice the fundamental frequency. Thus

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.

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.

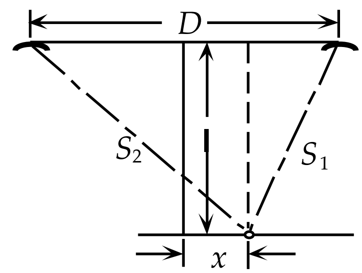


$$(d - x) - x = \tfrac{1}{2}\lambda \;\rightarrow\; d = 2x + \tfrac{1}{2}\lambda \;\rightarrow\; d_{\min} = \tfrac{1}{2}\lambda = \frac{v}{2f} = \frac{343\,\text{m/s}}{2(294\,\text{Hz})} = \boxed{0.583\,\text{m}}$$

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 $\boxed{0}$.

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.



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

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

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

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

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

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

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

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

(*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 $f = \dfrac{v}{2l} = \dfrac{1}{2l}\sqrt{\dfrac{F_\text{T}}{\mu}}$, we have

$$f \propto \sqrt{F_\text{T}} \quad \rightarrow \quad \frac{f}{\sqrt{F_\text{T}}} = \frac{f'}{\sqrt{F'_\text{T}}} \quad \rightarrow \quad F'_\text{T} = F_\text{T}\left(\frac{f'}{f}\right)^2.$$

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

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

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

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

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

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

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

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

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

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.

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

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

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

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

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

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

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

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

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

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.

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

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

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

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.

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

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