

17

Sound Waves

CHAPTER OUTLINE

- 17.1 Speed of Sound Waves
- 17.2 Periodic Sound Waves
- 17.3 Intensity of Periodic Sound Waves
- 17.4 The Doppler Effect
- 17.5 Digital Sound Recording
- 17.6 Motion Picture Sound

ANSWERS TO QUESTIONS

Q17.1 Sound waves are longitudinal because elements of the medium—parcels of air—move parallel and antiparallel to the direction of wave motion.

Q17.2 We assume that a perfect vacuum surrounds the clock. The sound waves require a medium for them to travel to your ear. The hammer on the alarm will strike the bell, and the vibration will spread as sound waves through the body of the clock. If a bone of your skull were in contact with the clock, you would hear the bell. However, in the absence of a surrounding medium like air or water, no sound can be radiated away. A larger-scale example of the same effect: Colossal storms raging on the Sun are deathly still for us.

What happens to the sound energy within the clock? Here is the answer: As the sound wave travels through the steel and plastic, traversing joints and going around corners, its energy is converted into additional internal energy, raising the temperature of the materials. After the sound has died away, the clock will glow very slightly brighter in the infrared portion of the electromagnetic spectrum.

Q17.3 If an object is $\frac{1}{2}$ meter from the sonic ranger, then the sensor would have to measure how long it would take for a sound pulse to travel one meter. Since sound of any frequency moves at about 343 m/s, then the sonic ranger would have to be able to measure a time difference of under 0.003 seconds. This small time measurement is possible with modern electronics. But it would be more expensive to outfit sonic rangers with the more sensitive equipment than it is to print “do not use to measure distances less than $\frac{1}{2}$ meter” in the users’ manual.

Q17.4 The speed of sound to two significant figures is 340 m/s. Let’s assume that you can measure time to $\frac{1}{10}$ second by using a stopwatch. To get a speed to two significant figures, you need to measure a time of at least 1.0 seconds. Since $d = vt$, the minimum distance is 340 meters.

Q17.5 The frequency increases by a factor of 2 because the wave speed, which is dependent only on the medium through which the wave travels, remains constant.

- Q17.6** When listening, you are approximately the same distance from all of the members of the group. If different frequencies traveled at different speeds, then you might hear the higher pitched frequencies before you heard the lower ones produced at the same time. Although it might be interesting to think that each listener heard his or her own personal performance depending on where they were seated, a time lag like this could make a Beethoven sonata sound as if it were written by Charles Ives.
- Q17.7** Since air is a viscous fluid, some of the energy of sound vibration is turned into internal energy. At such great distances, the amplitude of the signal is so decreased by this effect you are unable to hear it.
- Q17.8** We suppose that a point source has no structure, and radiates sound equally in all directions (isotropically). The sound wavefronts are expanding spheres, so the area over which the sound energy spreads increases according to $A = 4\pi r^2$. Thus, if the distance is tripled, the area increases by a factor of nine, and the new intensity will be one-ninth of the old intensity. This answer according to the inverse-square law applies if the medium is uniform and unbounded.
 For contrast, suppose that the sound is confined to move in a horizontal layer. (Thermal stratification in an ocean can have this effect on sonar “pings.”) Then the area over which the sound energy is dispersed will only increase according to the circumference of an expanding circle: $A = 2\pi rh$, and so three times the distance will result in one third the intensity.
 In the case of an entirely enclosed speaking tube (such as a ship’s telephone), the area perpendicular to the energy flow stays the same, and increasing the distance will not change the intensity appreciably.
- Q17.9** He saw the first wave he encountered, light traveling at 3.00×10^8 m/s. At the same moment, infrared as well as visible light began warming his skin, but some time was required to raise the temperature of the outer skin layers before he noticed it. The meteor produced compressional waves in the air and in the ground. The wave in the ground, which can be called either sound or a seismic wave, traveled much faster than the wave in air, since the ground is much stiffer against compression. Our witness received it next and noticed it as a little earthquake. He was no doubt unable to distinguish the P and S waves. The first air-compression wave he received was a shock wave with an amplitude on the order of meters. It transported him off his doorstep. Then he could hear some additional direct sound, reflected sound, and perhaps the sound of the falling trees.
- Q17.10** A microwave pulse is reflected from a moving object. The waves that are reflected back are Doppler shifted in frequency according to the speed of the target. The receiver in the radar gun detects the reflected wave and compares its frequency to that of the emitted pulse. Using the frequency shift, the speed can be calculated to high precision. Be forewarned: this technique works if you are either traveling toward or away from your local law enforcement agent!
- Q17.11** As you move towards the canyon wall, the echo of your car horn would be shifted up in frequency; as you move away, the echo would be shifted down in frequency.
- Q17.12** Normal conversation has an intensity level of about 60 dB.
- Q17.13** A rock concert has an intensity level of about 120 dB.
 A cheering crowd has an intensity level of about 90 dB.
 Normal conversation has an intensity level of about 50–60 dB.
 Turning a page in the textbook has an intensity level of about 10–20 dB.

- Q17.14** One would expect the spectra of the light to be Doppler shifted up in frequency (blue shift) as the star approaches us. As the star recedes in its orbit, the frequency spectrum would be shifted down (red shift). While the star is moving perpendicular to our line of sight, there will be no frequency shift at all. Overall, the spectra would oscillate with a period equal to that of the orbiting stars.
- Q17.15** For the sound from a source not to shift in frequency, the radial velocity of the source relative to the observer must be zero; that is, the source must not be moving toward or away from the observer. The source can be moving in a plane perpendicular to the line between it and the observer. Other possibilities: The source and observer might both have zero velocity. They might have equal velocities relative to the medium. The source might be moving around the observer on a sphere of constant radius. Even if the source speeds up on the sphere, slows down, or stops, the frequency heard will be equal to the frequency emitted by the source.
- Q17.16** Wind can change a Doppler shift but cannot cause one. Both v_o and v_s in our equations must be interpreted as speeds of observer and source relative to the air. If source and observer are moving relative to each other, the observer will hear one shifted frequency in still air and a different shifted frequency if wind is blowing. If the distance between source and observer is constant, there will never be a Doppler shift.
- Q17.17** If the object being tracked is moving away from the observer, then the sonic pulse would never reach the object, as the object is moving away faster than the wave speed. If the object being tracked is moving towards the observer, then the object itself would reach the detector before reflected pulse.
- Q17.18** New-fallen snow is a wonderful acoustic absorber as it reflects very little of the sound that reaches it. It is full of tiny intricate air channels and does not spring back when it is distorted. It acts very much like acoustic tile in buildings. So where does the absorbed energy go? It turns into internal energy—albeit a very small amount.
- Q17.19** As a sound wave moves away from the source, its intensity decreases. With an echo, the sound must move from the source to the reflector and then back to the observer, covering a significant distance.
- Q17.20** The observer would most likely hear the sonic boom of the plane itself and then beep, baap, boop. Since the plane is supersonic, the loudspeaker would pull ahead of the leading “boop” wavefront before emitting the “baap”, and so forth.
“How are you?” would be heard as “?uoy era woH”
- Q17.21** This system would be seen as a star moving in an elliptical path. Just like the light from a star in a binary star system, described in the answer to question 14, the spectrum of light from the star would undergo a series of Doppler shifts depending on the star’s speed and direction of motion relative to the observer. The repetition rate of the Doppler shift pattern is the period of the orbit. Information about the orbit size can be calculated from the size of the Doppler shifts.

SOLUTIONS TO PROBLEMS

Section 17.1 Speed of Sound Waves

P17.1 Since $v_{\text{light}} \gg v_{\text{sound}}$: $d \approx (343 \text{ m/s})(16.2 \text{ s}) = \boxed{5.56 \text{ km}}$

P17.2
$$v = \sqrt{\frac{B}{\rho}} = \sqrt{\frac{2.80 \times 10^{10}}{13.6 \times 10^3}} = \boxed{1.43 \text{ km/s}}$$

P17.3 Sound takes this time to reach the man: $\frac{(20.0 \text{ m} - 1.75 \text{ m})}{343 \text{ m/s}} = 5.32 \times 10^{-2} \text{ s}$

so the warning should be shouted no later than $0.300 \text{ s} + 5.32 \times 10^{-2} \text{ s} = 0.353 \text{ s}$ before the pot strikes.

Since the whole time of fall is given by $y = \frac{1}{2}gt^2$: $18.25 \text{ m} = \frac{1}{2}(9.80 \text{ m/s}^2)t^2$

$t = 1.93 \text{ s}$

the warning needs to come $1.93 \text{ s} - 0.353 \text{ s} = 1.58 \text{ s}$

into the fall, when the pot has fallen $\frac{1}{2}(9.80 \text{ m/s}^2)(1.58 \text{ s})^2 = 12.2 \text{ m}$

to be above the ground by $20.0 \text{ m} - 12.2 \text{ m} = \boxed{7.82 \text{ m}}$

P17.4 (a) At 9 000 m, $\Delta T = \left(\frac{9\,000}{150}\right)(-1.00^\circ\text{C}) = -60.0^\circ\text{C}$ so $T = -30.0^\circ\text{C}$.

Using the chain rule:

$$\frac{dv}{dt} = \frac{dv}{dT} \frac{dT}{dx} \frac{dx}{dt} = v \frac{dv}{dT} \frac{dT}{dx} = v(0.607) \left(\frac{1}{150}\right) = \frac{v}{247}, \text{ so } dt = (247 \text{ s}) \frac{dv}{v}$$

$$\int_0^t dt = (247 \text{ s}) \int_{v_i}^{v_f} \frac{dv}{v}$$

$$t = (247 \text{ s}) \ln\left(\frac{v_f}{v_i}\right) = (247 \text{ s}) \ln\left[\frac{331.5 + 0.607(30.0)}{331.5 + 0.607(-30.0)}\right]$$

$$t = \boxed{27.2 \text{ s}} \text{ for sound to reach ground.}$$

(b) $t = \frac{h}{v} = \frac{9\,000}{[331.5 + 0.607(30.0)]} = \boxed{25.7 \text{ s}}$

It takes longer when the air cools off than if it were at a uniform temperature.

***P17.5** Let x_1 represent the cowboy's distance from the nearer canyon wall and x_2 his distance from the farther cliff. The sound for the first echo travels distance $2x_1$. For the second, $2x_2$. For the third, $2x_1 + 2x_2$. For the fourth echo, $2x_1 + 2x_2 + 2x_1$. Then $\frac{2x_2 - 2x_1}{340 \text{ m/s}} = 1.92 \text{ s}$ and $\frac{2x_1 + 2x_2 - 2x_2}{340 \text{ m/s}} = 1.47 \text{ s}$. Thus $x_1 = \frac{1}{2}340 \text{ m/s} \cdot 1.47 \text{ s} = 250 \text{ m}$ and $\frac{2x_2}{340 \text{ m/s}} = 1.92 \text{ s} + 1.47 \text{ s}$; $x_2 = 576 \text{ m}$.

(a) So $x_1 + x_2 = \boxed{826 \text{ m}}$

(b) $\frac{2x_1 + 2x_2 + 2x_1 - (2x_1 + 2x_2)}{340 \text{ m/s}} = \boxed{1.47 \text{ s}}$

P17.6 It is easiest to solve part (b) first:

(b) The distance the sound travels to the plane is $d_s = \sqrt{h^2 + \left(\frac{h}{2}\right)^2} = \frac{h\sqrt{5}}{2}$.

The sound travels this distance in 2.00 s, so

$$d_s = \frac{h\sqrt{5}}{2} = (343 \text{ m/s})(2.00 \text{ s}) = 686 \text{ m}$$

giving the altitude of the plane as $h = \frac{2(686 \text{ m})}{\sqrt{5}} = \boxed{614 \text{ m}}$.

(a) The distance the plane has traveled in 2.00 s is $v(2.00 \text{ s}) = \frac{h}{2} = 307 \text{ m}$.

Thus, the speed of the plane is: $v = \frac{307 \text{ m}}{2.00 \text{ s}} = \boxed{153 \text{ m/s}}$.

Section 17.2 Periodic Sound Waves

P17.7 $\lambda = \frac{v}{f} = \frac{340 \text{ m/s}}{60.0 \times 10^3 \text{ s}^{-1}} = \boxed{5.67 \text{ mm}}$

***P17.8** The sound speed is $v = 331 \text{ m/s} \sqrt{1 + \frac{26^\circ\text{C}}{273^\circ\text{C}}} = 346 \text{ m/s}$

(a) Let t represent the time for the echo to return. Then

$$d = \frac{1}{2}vt = \frac{1}{2}(346 \text{ m/s})(24 \times 10^{-3} \text{ s}) = \boxed{4.16 \text{ m}}$$

(b) Let Δt represent the duration of the pulse:

$$\Delta t = \frac{10\lambda}{v} = \frac{10\lambda}{f\lambda} = \frac{10}{f} = \frac{10}{22 \times 10^6 \text{ 1/s}} = \boxed{0.455 \text{ }\mu\text{s}}$$

(c) $L = 10\lambda = \frac{10v}{f} = \frac{10(346 \text{ m/s})}{22 \times 10^6 \text{ 1/s}} = \boxed{0.157 \text{ mm}}$

***P17.9** If $f = 1 \text{ MHz}$, $\lambda = \frac{v}{f} = \frac{1500 \text{ m/s}}{10^6/\text{s}} = \boxed{1.50 \text{ mm}}$

If $f = 20 \text{ MHz}$, $\lambda = \frac{1500 \text{ m/s}}{2 \times 10^7/\text{s}} = \boxed{75.0 \text{ }\mu\text{m}}$

P17.10 $\Delta P_{\text{max}} = \rho v \omega s_{\text{max}}$

$$s_{\text{max}} = \frac{\Delta P_{\text{max}}}{\rho v \omega} = \frac{(4.00 \times 10^{-3} \text{ N/m}^2)}{(1.20 \text{ kg/m}^3)(343 \text{ m/s})(2\pi)(10.0 \times 10^3 \text{ s}^{-1})} = \boxed{1.55 \times 10^{-10} \text{ m}}$$

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P17.11 (a) $A = \boxed{2.00 \text{ } \mu\text{m}}$

$$\lambda = \frac{2\pi}{15.7} = 0.400 \text{ m} = \boxed{40.0 \text{ cm}}$$

$$v = \frac{\omega}{k} = \frac{858}{15.7} = \boxed{54.6 \text{ m/s}}$$

(b) $s = 2.00 \cos\left[(15.7)(0.0500) - (858)\left(3.00 \times 10^{-3}\right)\right] = \boxed{-0.433 \text{ } \mu\text{m}}$

(c) $v_{\max} = A\omega = (2.00 \text{ } \mu\text{m})(858 \text{ s}^{-1}) = \boxed{1.72 \text{ mm/s}}$

P17.12 (a) $\Delta P = (1.27 \text{ Pa}) \sin\left(\frac{\pi x}{\text{m}} - \frac{340\pi t}{\text{s}}\right)$ (SI units)

The pressure amplitude is: $\Delta P_{\max} = \boxed{1.27 \text{ Pa}}$.

(b) $\omega = 2\pi f = 340\pi/\text{s}$, so $f = \boxed{170 \text{ Hz}}$

(c) $k = \frac{2\pi}{\lambda} = \pi/\text{m}$, giving $\lambda = \boxed{2.00 \text{ m}}$

(d) $v = \lambda f = (2.00 \text{ m})(170 \text{ Hz}) = \boxed{340 \text{ m/s}}$

P17.13 $k = \frac{2\pi}{\lambda} = \frac{2\pi}{(0.100 \text{ m})} = 62.8 \text{ m}^{-1}$

$$\omega = \frac{2\pi v}{\lambda} = \frac{2\pi(343 \text{ m/s})}{(0.100 \text{ m})} = 2.16 \times 10^4 \text{ s}^{-1}$$

Therefore, $\Delta P = (0.200 \text{ Pa}) \sin\left[62.8 x/\text{m} - 2.16 \times 10^4 t/\text{s}\right]$.

P17.14 $\omega = 2\pi f = \frac{2\pi v}{\lambda} = \frac{2\pi(343 \text{ m/s})}{(0.100 \text{ m})} = 2.16 \times 10^4 \text{ rad/s}$

$$s_{\max} = \frac{\Delta P_{\max}}{\rho v \omega} = \frac{(0.200 \text{ Pa})}{(1.20 \text{ kg/m}^3)(343 \text{ m/s})(2.16 \times 10^4 \text{ s}^{-1})} = 2.25 \times 10^{-8} \text{ m}$$

$$k = \frac{2\pi}{\lambda} = \frac{2\pi}{(0.100 \text{ m})} = 62.8 \text{ m}^{-1}$$

Therefore, $s = s_{\max} \cos(kx - \omega t) = (2.25 \times 10^{-8} \text{ m}) \cos(62.8 x/\text{m} - 2.16 \times 10^4 t/\text{s})$.

P17.15 $\Delta P_{\max} = \rho v \omega s_{\max} = \rho v \left(\frac{2\pi v}{\lambda}\right) s_{\max}$

$$\lambda = \frac{2\pi \rho v^2 s_{\max}}{\Delta P_{\max}} = \frac{2\pi(1.20)(343)^2(5.50 \times 10^{-6})}{0.840} = \boxed{5.81 \text{ m}}$$

- P17.16** (a) The sound “pressure” is extra tensile stress for one-half of each cycle. When it becomes $(0.500\%)(13.0 \times 10^{10} \text{ Pa}) = 6.50 \times 10^8 \text{ Pa}$, the rod will break. Then, $\Delta P_{\text{max}} = \rho v \omega s_{\text{max}}$

$$s_{\text{max}} = \frac{\Delta P_{\text{max}}}{\rho v \omega} = \frac{6.50 \times 10^8 \text{ N/m}^2}{(8.92 \times 10^3 \text{ kg/m}^3)(5010 \text{ m/s})(2\pi 500/\text{s})} = \boxed{4.63 \text{ mm}}.$$

- (b) From $s = s_{\text{max}} \cos(kx - \omega t)$

$$v = \frac{\partial s}{\partial t} = -\omega s_{\text{max}} \sin(kx - \omega t)$$

$$v_{\text{max}} = \omega s_{\text{max}} = (2\pi 500/\text{s})(4.63 \text{ mm}) = \boxed{14.5 \text{ m/s}}$$

- (c) $I = \frac{1}{2} \rho v (\omega s_{\text{max}})^2 = \frac{1}{2} \rho v v_{\text{max}}^2 = \frac{1}{2} (8.92 \times 10^3 \text{ kg/m}^3)(5010 \text{ m/s})(14.5 \text{ m/s})^2$
 $= \boxed{4.73 \times 10^9 \text{ W/m}^2}$

- *P17.17** Let $P(x)$ represent absolute pressure as a function of x . The net force to the right on the chunk of air is $+P(x)A - P(x + \Delta x)A$. Atmospheric pressure subtracts out, leaving $[-\Delta P(x + \Delta x) + \Delta P(x)]A = -\frac{\partial \Delta P}{\partial x} \Delta x A$.

The mass of the air is $\Delta m = \rho \Delta V = \rho A \Delta x$ and its acceleration is $\frac{\partial^2 s}{\partial t^2}$. So

Newton's second law becomes

$$\begin{aligned} -\frac{\partial \Delta P}{\partial x} \Delta x A &= \rho A \Delta x \frac{\partial^2 s}{\partial t^2} \\ -\frac{\partial}{\partial x} \left(-B \frac{\partial s}{\partial x} \right) &= \rho \frac{\partial^2 s}{\partial t^2} \\ \frac{B}{\rho} \frac{\partial^2 s}{\partial x^2} &= \frac{\partial^2 s}{\partial t^2} \end{aligned}$$

Into this wave equation as a trial solution we substitute the wave function $s(x, t) = s_{\text{max}} \cos(kx - \omega t)$ we find

$$\begin{aligned} \frac{\partial s}{\partial x} &= -k s_{\text{max}} \sin(kx - \omega t) \\ \frac{\partial^2 s}{\partial x^2} &= -k^2 s_{\text{max}} \cos(kx - \omega t) \\ \frac{\partial s}{\partial t} &= +\omega s_{\text{max}} \sin(kx - \omega t) \\ \frac{\partial^2 s}{\partial t^2} &= -\omega^2 s_{\text{max}} \cos(kx - \omega t) \end{aligned}$$

$$\frac{B}{\rho} \frac{\partial^2 s}{\partial x^2} = \frac{\partial^2 s}{\partial t^2} \text{ becomes } -\frac{B}{\rho} k^2 s_{\text{max}} \cos(kx - \omega t) = -\omega^2 s_{\text{max}} \cos(kx - \omega t)$$

$$\text{This is true provided } \frac{B}{\rho} \frac{4\pi^2}{\lambda^2} = 4\pi^2 f^2.$$

The sound wave can propagate provided it has $\lambda^2 f^2 = v^2 = \frac{B}{\rho}$; that is, provided it propagates with

$$\text{speed } v = \sqrt{\frac{B}{\rho}}.$$

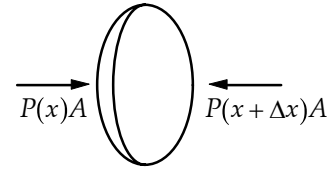


FIG. P17.17

Section 17.3 Intensity of Periodic Sound Waves

***P17.18** The sound power incident on the eardrum is $\wp = IA$ where I is the intensity of the sound and $A = 5.0 \times 10^{-5} \text{ m}^2$ is the area of the eardrum.

(a) At the threshold of hearing, $I = 1.0 \times 10^{-12} \text{ W/m}^2$, and

$$\wp = (1.0 \times 10^{-12} \text{ W/m}^2)(5.0 \times 10^{-5} \text{ m}^2) = \boxed{5.00 \times 10^{-17} \text{ W}}.$$

(b) At the threshold of pain, $I = 1.0 \text{ W/m}^2$, and

$$\wp = (1.0 \text{ W/m}^2)(5.0 \times 10^{-5} \text{ m}^2) = \boxed{5.00 \times 10^{-5} \text{ W}}.$$

$$\textbf{P17.19} \quad \beta = 10 \log \left(\frac{I}{I_0} \right) = 10 \log \left(\frac{4.00 \times 10^{-6}}{1.00 \times 10^{-12}} \right) = \boxed{66.0 \text{ dB}}$$

$$\textbf{P17.20} \quad (\text{a}) \quad 70.0 \text{ dB} = 10 \log \left(\frac{I}{1.00 \times 10^{-12} \text{ W/m}^2} \right)$$

$$\text{Therefore, } I = (1.00 \times 10^{-12} \text{ W/m}^2) 10^{(70.0/10)} = \boxed{1.00 \times 10^{-5} \text{ W/m}^2}.$$

$$(\text{b}) \quad I = \frac{\Delta P_{\text{max}}^2}{2\rho v}, \text{ so}$$

$$\Delta P_{\text{max}} = \sqrt{2\rho v I} = \sqrt{2(1.20 \text{ kg/m}^3)(343 \text{ m/s})(1.00 \times 10^{-5} \text{ W/m}^2)}$$

$$\Delta P_{\text{max}} = \boxed{90.7 \text{ mPa}}$$

$$\textbf{P17.21} \quad I = \frac{1}{2} \rho \omega^2 s_{\text{max}}^2 v$$

(a) At $f = 2500 \text{ Hz}$, the frequency is increased by a factor of 2.50, so the intensity (at constant s_{max}) increases by $(2.50)^2 = 6.25$.

$$\text{Therefore, } 6.25(0.600) = \boxed{3.75 \text{ W/m}^2}.$$

$$(\text{b}) \quad \boxed{0.600 \text{ W/m}^2}$$

$$\textbf{P17.22} \quad \text{The original intensity is } I_1 = \frac{1}{2} \rho \omega^2 s_{\text{max}}^2 v = 2\pi^2 \rho v f^2 s_{\text{max}}^2$$

(a) If the frequency is increased to f' while a constant displacement amplitude is maintained, the new intensity is

$$I_2 = 2\pi^2 \rho v (f')^2 s_{\text{max}}^2 \text{ so } \frac{I_2}{I_1} = \frac{2\pi^2 \rho v (f')^2 s_{\text{max}}^2}{2\pi^2 \rho v f^2 s_{\text{max}}^2} = \left(\frac{f'}{f} \right)^2 \text{ or } \boxed{I_2 = \left(\frac{f'}{f} \right)^2 I_1}.$$

continued on next page

- (b) If the frequency is reduced to $f' = \frac{f}{2}$ while the displacement amplitude is doubled, the new intensity is

$$I_2 = 2\pi^2 \rho v \left(\frac{f}{2}\right)^2 (2s_{\max})^2 = 2\pi^2 \rho v f^2 s_{\max}^2 = I_1$$

or the intensity is unchanged.

***P17.23** (a) For the low note the wavelength is $\lambda = \frac{v}{f} = \frac{343 \text{ m/s}}{146.8/\text{s}} = \boxed{2.34 \text{ m}}$.

For the high note $\lambda = \frac{343 \text{ m/s}}{880/\text{s}} = \boxed{0.390 \text{ m}}$.

We observe that the ratio of the frequencies of these two notes is $\frac{880 \text{ Hz}}{146.8 \text{ Hz}} = 5.99$ nearly equal to a small integer. This fact is associated with the consonance of the notes D and A.

(b) $\beta = 10 \text{ dB} \log\left(\frac{I}{10^{-12} \text{ W/m}^2}\right) = 75 \text{ dB}$ gives $I = 3.16 \times 10^{-5} \text{ W/m}^2$

$$I = \frac{\Delta P_{\max}^2}{2\rho v}$$

$$\Delta P_{\max} = \sqrt{3.16 \times 10^{-5} \text{ W/m}^2 \cdot 2(1.20 \text{ kg/m}^3)(343 \text{ m/s})} = \boxed{0.161 \text{ Pa}}$$

for both low and high notes.

(c) $I = \frac{1}{2} \rho v (\omega s_{\max})^2 = \frac{1}{2} \rho v 4\pi^2 f^2 s_{\max}^2$

$$s_{\max} = \sqrt{\frac{I}{2\pi^2 \rho v f^2}}$$

for the low note,

$$s_{\max} = \sqrt{\frac{3.16 \times 10^{-5} \text{ W/m}^2}{2\pi^2 \cdot 1.20 \text{ kg/m}^3 \cdot 343 \text{ m/s} \cdot 146.8/\text{s}}} \cdot \frac{1}{146.8} \text{ m} = \boxed{4.25 \times 10^{-7} \text{ m}}$$

for the high note,

$$s_{\max} = \frac{6.24 \times 10^{-5}}{880} \text{ m} = \boxed{7.09 \times 10^{-8} \text{ m}}$$

- (d) With both frequencies lower (numerically smaller) by the factor $\frac{146.8}{134.3} = \frac{880}{804.9} = 1.093$, the wavelengths and displacement amplitudes are made 1.093 times larger, and the pressure amplitudes are unchanged.

***P17.24** The power necessarily supplied to the speaker is the power carried away by the sound wave:

$$P = \frac{1}{2} \rho A v (\omega s_{\max})^2 = 2\pi^2 \rho A v f^2 s_{\max}^2$$

$$= 2\pi^2 (1.20 \text{ kg/m}^3) \pi \left(\frac{0.08 \text{ m}}{2}\right)^2 (343 \text{ m/s})(600 \text{ 1/s})^2 (0.12 \times 10^{-2} \text{ m})^2 = \boxed{21.2 \text{ W}}$$

P17.25 (a) $I_1 = (1.00 \times 10^{-12} \text{ W/m}^2) 10^{(\beta_1/10)} = (1.00 \times 10^{-12} \text{ W/m}^2) 10^{80.0/10}$

or $I_1 = 1.00 \times 10^{-4} \text{ W/m}^2$

$$I_2 = (1.00 \times 10^{-12} \text{ W/m}^2) 10^{(\beta_2/10)} = (1.00 \times 10^{-12} \text{ W/m}^2) 10^{75.0/10}$$

or $I_2 = 1.00 \times 10^{-4.5} \text{ W/m}^2 = 3.16 \times 10^{-5} \text{ W/m}^2$

When both sounds are present, the total intensity is

$$I = I_1 + I_2 = 1.00 \times 10^{-4} \text{ W/m}^2 + 3.16 \times 10^{-5} \text{ W/m}^2 = \boxed{1.32 \times 10^{-4} \text{ W/m}^2}.$$

(b) The decibel level for the combined sounds is

$$\beta = 10 \log \left(\frac{1.32 \times 10^{-4} \text{ W/m}^2}{1.00 \times 10^{-12} \text{ W/m}^2} \right) = 10 \log(1.32 \times 10^8) = \boxed{81.2 \text{ dB}}.$$

***P17.26** (a) We have $\lambda = \frac{v}{f}$ and f is the same for all three waves. Since the speed is smallest in air, λ is

smallest in air. It is larger by $\frac{1493 \text{ m/s}}{331 \text{ m/s}} = \boxed{4.51 \text{ times}}$ in water and by

$$\frac{5950}{331} = \boxed{18.0 \text{ times in iron}}.$$

(b) From $I = \frac{1}{2} \rho v \omega^2 s_{\max}^2$; $s_{\max} = \sqrt{\frac{2I_0}{\rho v \omega^2}}$, $s_{\max}$ is smallest in iron, larger in water by

$$\sqrt{\frac{\rho_{\text{iron}} v_{\text{iron}}}{\rho_{\text{water}} v_{\text{water}}}} = \sqrt{\frac{7860 \cdot 5950}{1000 \cdot 1493}} = \boxed{5.60 \text{ times}}, \text{ and larger in air by } \sqrt{\frac{7860 \cdot 5950}{1.29 \cdot 331}} = \boxed{331 \text{ times}}.$$

(c) From $I = \frac{\Delta P_{\max}^2}{2\rho v}$; $\Delta P_{\max} = \sqrt{2I\rho v}$, $\Delta P_{\max}$ is smallest in air, larger in water by

$$\sqrt{\frac{1000 \cdot 1493}{1.29 \cdot 331}} = \boxed{59.1 \text{ times}}, \text{ and larger in iron by } \sqrt{\frac{7860 \cdot 5950}{1.29 \cdot 331}} = \boxed{331 \text{ times}}.$$

(d) $\lambda = \frac{v}{f} = \frac{v2\pi}{\omega} = \frac{(331 \text{ m/s})2\pi}{2000 \pi/\text{s}} = \boxed{0.331 \text{ m}}$ in air

$$\lambda = \frac{1493 \text{ m/s}}{1000/\text{s}} = \boxed{1.49 \text{ m}} \text{ in water} \quad \lambda = \frac{5950 \text{ m/s}}{1000/\text{s}} = \boxed{5.95 \text{ m}} \text{ in iron}$$

$$s_{\max} = \sqrt{\frac{2I_0}{\rho v \omega^2}} = \sqrt{\frac{2 \times 10^{-6} \text{ W/m}^2}{(1.29 \text{ kg/m}^3)(331 \text{ m/s})(6283 \text{ 1/s})^2}} = \boxed{1.09 \times 10^{-8} \text{ m}} \text{ in air}$$

$$s_{\max} = \sqrt{\frac{2 \times 10^{-6}}{1000(1493)} \frac{1}{6283}} = \boxed{1.84 \times 10^{-10} \text{ m}} \text{ in water}$$

$$s_{\max} = \sqrt{\frac{2 \times 10^{-6}}{7860(5950)} \frac{1}{6283}} = \boxed{3.29 \times 10^{-11} \text{ m}} \text{ in iron}$$

$$\Delta P_{\max} = \sqrt{2I\rho v} = \sqrt{2(10^{-6} \text{ W/m}^2)(1.29 \text{ kg/m}^3)331 \text{ m/s}} = \boxed{0.0292 \text{ Pa}} \text{ in air}$$

$$\Delta P_{\max} = \sqrt{2 \times 10^{-6}(1000)1493} = \boxed{1.73 \text{ Pa}} \text{ in water}$$

$$\Delta P_{\max} = \sqrt{2 \times 10^{-6}(7860)(5950)} = \boxed{9.67 \text{ Pa}} \text{ in iron}$$

P17.27 (a) $120 \text{ dB} = 10 \text{ dB} \log \left[\frac{I}{10^{-12} \text{ W/m}^2} \right]$

$$I = 1.00 \text{ W/m}^2 = \frac{\mathcal{P}}{4\pi r^2}$$

$$r = \sqrt{\frac{\mathcal{P}}{4\pi I}} = \sqrt{\frac{6.00 \text{ W}}{4\pi(1.00 \text{ W/m}^2)}} = \boxed{0.691 \text{ m}}$$

We have assumed the speaker is an isotropic point source.

(b) $0 \text{ dB} = 10 \text{ dB} \log \left(\frac{I}{10^{-12} \text{ W/m}^2} \right)$

$$I = 1.00 \times 10^{-12} \text{ W/m}^2$$

$$r = \sqrt{\frac{\mathcal{P}}{4\pi I}} = \sqrt{\frac{6.00 \text{ W}}{4\pi(1.00 \times 10^{-12} \text{ W/m}^2)}} = \boxed{691 \text{ km}}$$

We have assumed a uniform medium that absorbs no energy.

P17.28 We begin with $\beta_2 = 10 \log \left(\frac{I_2}{I_0} \right)$, and $\beta_1 = 10 \log \left(\frac{I_1}{I_0} \right)$, so

$$\beta_2 - \beta_1 = 10 \log \left(\frac{I_2}{I_1} \right).$$

Also, $I_2 = \frac{\mathcal{P}}{4\pi r_2^2}$, and $I_1 = \frac{\mathcal{P}}{4\pi r_1^2}$, giving $\frac{I_2}{I_1} = \left(\frac{r_1}{r_2} \right)^2$.

Then, $\beta_2 - \beta_1 = 10 \log \left(\frac{r_1}{r_2} \right)^2 = \boxed{20 \log \left(\frac{r_1}{r_2} \right)}$.

P17.29 Since intensity is inversely proportional to the square of the distance,

$$I_4 = \frac{1}{100} I_{0.4} \text{ and } I_{0.4} = \frac{\Delta P_{\text{max}}^2}{2\rho v} = \frac{(10.0)^2}{2(1.20)(343)} = 0.121 \text{ W/m}^2.$$

The difference in sound intensity level is

$$\Delta\beta = 10 \log \left(\frac{I_{4 \text{ km}}}{I_{0.4 \text{ km}}} \right) = 10(-2.00) = -20.0 \text{ dB}.$$

At 0.400 km,

$$\beta_{0.4} = 10 \log \left(\frac{0.121 \text{ W/m}^2}{10^{-12} \text{ W/m}^2} \right) = 110.8 \text{ dB}.$$

At 4.00 km,

$$\beta_4 = \beta_{0.4} + \Delta\beta = (110.8 - 20.0) \text{ dB} = 90.8 \text{ dB}.$$

Allowing for absorption of the wave over the distance traveled,

$$\beta'_4 = \beta_4 - (7.00 \text{ dB/km})(3.60 \text{ km}) = \boxed{65.6 \text{ dB}}.$$

This is equivalent to the sound intensity level of heavy traffic.

P17.30 Let r_1 and r_2 be the distance from the speaker to the observer that hears 60.0 dB and 80.0 dB, respectively. Use the result of problem 28,

$$\beta_2 - \beta_1 = 20 \log \left(\frac{r_1}{r_2} \right), \text{ to obtain } 80.0 - 60.0 = 20 \log \left(\frac{r_1}{r_2} \right).$$

Thus, $\log \left(\frac{r_1}{r_2} \right) = 1$, so $r_1 = 10.0 r_2$. Also: $r_1 + r_2 = 110 \text{ m}$, so

$$10.0 r_2 + r_2 = 110 \text{ m giving } \boxed{r_2 = 10.0 \text{ m}}, \text{ and } \boxed{r_1 = 100 \text{ m}}.$$

P17.31 We presume the speakers broadcast equally in all directions.

$$\begin{aligned} \text{(a)} \quad r_{AC} &= \sqrt{3.00^2 + 4.00^2} \text{ m} = 5.00 \text{ m} \\ I &= \frac{\mathcal{P}}{4\pi r^2} = \frac{1.00 \times 10^{-3} \text{ W}}{4\pi (5.00 \text{ m})^2} = 3.18 \times 10^{-6} \text{ W/m}^2 \\ \beta &= 10 \text{ dB} \log \left(\frac{3.18 \times 10^{-6} \text{ W/m}^2}{10^{-12} \text{ W/m}^2} \right) \\ \beta &= 10 \text{ dB } 6.50 = \boxed{65.0 \text{ dB}} \end{aligned}$$

$$\begin{aligned} \text{(b)} \quad r_{BC} &= 4.47 \text{ m} \\ I &= \frac{1.50 \times 10^{-3} \text{ W}}{4\pi (4.47 \text{ m})^2} = 5.97 \times 10^{-6} \text{ W/m}^2 \\ \beta &= 10 \text{ dB} \log \left(\frac{5.97 \times 10^{-6}}{10^{-12}} \right) \\ \beta &= \boxed{67.8 \text{ dB}} \end{aligned}$$

$$\begin{aligned} \text{(c)} \quad I &= 3.18 \text{ } \mu\text{W/m}^2 + 5.97 \text{ } \mu\text{W/m}^2 \\ \beta &= 10 \text{ dB} \log \left(\frac{9.15 \times 10^{-6}}{10^{-12}} \right) = \boxed{69.6 \text{ dB}} \end{aligned}$$

P17.32 In $I = \frac{\mathcal{P}}{4\pi r^2}$, intensity I is proportional to $\frac{1}{r^2}$,

so between locations 1 and 2: $\frac{I_2}{I_1} = \frac{r_1^2}{r_2^2}$.

In $I = \frac{1}{2} \rho v (\omega s_{\max})^2$, intensity is proportional to $s_{\max}^2$, so $\frac{I_2}{I_1} = \frac{s_2^2}{s_1^2}$.

Then, $\left(\frac{s_2}{s_1} \right)^2 = \left(\frac{r_1}{r_2} \right)^2$ or $\left(\frac{1}{2} \right)^2 = \left(\frac{r_1}{r_2} \right)^2$, giving $r_2 = 2r_1 = 2(50.0 \text{ m}) = 100 \text{ m}$.

But, $r_2 = \sqrt{(50.0 \text{ m})^2 + d^2}$ yields $d = \boxed{86.6 \text{ m}}$.

P17.33 $\beta = 10 \log \left(\frac{I}{10^{-12}} \right) \quad I = \left[10^{(\beta/10)} \right] (10^{-12}) \text{ W/m}^2$

$$I_{(120 \text{ dB})} = 1.00 \text{ W/m}^2; I_{(100 \text{ dB})} = 1.00 \times 10^{-2} \text{ W/m}^2; I_{(10 \text{ dB})} = 1.00 \times 10^{-11} \text{ W/m}^2$$

(a) $\phi = 4\pi r^2 I$ so that $r_1^2 I_1 = r_2^2 I_2$

$$r_2 = r_1 \left(\frac{I_1}{I_2} \right)^{1/2} = (3.00 \text{ m}) \sqrt{\frac{1.00}{1.00 \times 10^{-2}}} = \boxed{30.0 \text{ m}}$$

(b) $r_2 = r_1 \left(\frac{I_1}{I_2} \right)^{1/2} = (3.00 \text{ m}) \sqrt{\frac{1.00}{1.00 \times 10^{-11}}} = \boxed{9.49 \times 10^5 \text{ m}}$

P17.34 (a) $E = \phi t = 4\pi r^2 I t = 4\pi (100 \text{ m})^2 (7.00 \times 10^{-2} \text{ W/m}^2) (0.200 \text{ s}) = \boxed{1.76 \text{ kJ}}$

(b) $\beta = 10 \log \left(\frac{7.00 \times 10^{-2}}{1.00 \times 10^{-12}} \right) = \boxed{108 \text{ dB}}$

P17.35 (a) The sound intensity inside the church is given by

$$\beta = 10 \ln \left(\frac{I}{I_0} \right)$$

$$101 \text{ dB} = (10 \text{ dB}) \ln \left(\frac{I}{10^{-12} \text{ W/m}^2} \right)$$

$$I = 10^{10.1} (10^{-12} \text{ W/m}^2) = 10^{-1.90} \text{ W/m}^2 = 0.0126 \text{ W/m}^2$$

We suppose that sound comes perpendicularly out through the windows and doors. Then, the radiated power is

$$\phi = IA = (0.0126 \text{ W/m}^2)(22.0 \text{ m}^2) = 0.277 \text{ W}.$$

Are you surprised by how small this is? The energy radiated in 20.0 minutes is

$$E = \phi t = (0.277 \text{ J/s})(20.0 \text{ min}) \left(\frac{60.0 \text{ s}}{1.00 \text{ min}} \right) = \boxed{332 \text{ J}}.$$

(b) If the ground reflects all sound energy headed downward, the sound power, $\phi = 0.277 \text{ W}$, covers the area of a hemisphere. One kilometer away, this area is

$$A = 2\pi r^2 = 2\pi (1000 \text{ m})^2 = 2\pi \times 10^6 \text{ m}^2.$$

The intensity at this distance is

$$I = \frac{\phi}{A} = \frac{0.277 \text{ W}}{2\pi \times 10^6 \text{ m}^2} = 4.41 \times 10^{-8} \text{ W/m}^2$$

and the sound intensity level is

$$\beta = (10 \text{ dB}) \ln \left(\frac{4.41 \times 10^{-8} \text{ W/m}^2}{1.00 \times 10^{-12} \text{ W/m}^2} \right) = \boxed{46.4 \text{ dB}}.$$

510 Sound Waves

- *P17.36** Assume you are 1 m away from your lawnmower and receiving 100 dB sound from it. The intensity of this sound is given by $100 \text{ dB} = 10 \text{ dB} \log \frac{I}{10^{-12} \text{ W/m}^2}$; $I = 10^{-2} \text{ W/m}^2$. If the lawnmower radiates as a point source, its sound power is given by $I = \frac{\wp}{4\pi r^2}$.

$$\wp = 4\pi(1 \text{ m})^2 10^{-2} \text{ W/m}^2 = 0.126 \text{ W}$$

Now let your neighbor have an identical lawnmower 20 m away. You receive from it sound with intensity $I = \frac{0.126 \text{ W}}{4\pi(20 \text{ m})^2} = 2.5 \times 10^{-5} \text{ W/m}^2$. The total sound intensity impinging on you is $10^{-2} \text{ W/m}^2 + 2.5 \times 10^{-5} \text{ W/m}^2 = 1.0025 \times 10^{-2} \text{ W/m}^2$. So its level is

$$10 \text{ dB} \log \frac{1.0025 \times 10^{-2}}{10^{-12}} = 100.01 \text{ dB}.$$

If the smallest noticeable difference is between 100 dB and 101 dB, this cannot be heard as a change from 100 dB.

Section 17.4 The Doppler Effect

P17.37 $f' = f \frac{(v \pm v_O)}{(v \pm v_S)}$

(a) $f' = 320 \frac{(343 + 40.0)}{(343 + 20.0)} = \boxed{338 \text{ Hz}}$

(b) $f' = 510 \frac{(343 + 20.0)}{(343 + 40.0)} = \boxed{483 \text{ Hz}}$

P17.38 (a) $\omega = 2\pi f = 2\pi \left(\frac{115/\text{min}}{60.0 \text{ s/min}} \right) = 12.0 \text{ rad/s}$

$$v_{\max} = \omega A = (12.0 \text{ rad/s})(1.80 \times 10^{-3} \text{ m}) = \boxed{0.0217 \text{ m/s}}$$

(b) The heart wall is a moving observer.

$$f' = f \left(\frac{v + v_O}{v} \right) = (2\,000\,000 \text{ Hz}) \left(\frac{1\,500 + 0.0217}{1\,500} \right) = \boxed{2\,000\,028.9 \text{ Hz}}$$

(c) Now the heart wall is a moving source.

$$f'' = f' \left(\frac{v}{v - v_s} \right) = (2\,000\,029 \text{ Hz}) \left(\frac{1\,500}{1\,500 - 0.0217} \right) = \boxed{2\,000\,057.8 \text{ Hz}}$$

P17.39 Approaching ambulance:

$$f' = \frac{f}{(1 - v_s/v)}$$

Departing ambulance:

$$f'' = \frac{f}{(1 - (-v_s/v))}$$

Since $f' = 560$ Hz and $f'' = 480$ Hz

$$560 \left(1 - \frac{v_s}{v} \right) = 480 \left(1 + \frac{v_s}{v} \right)$$

$$1\,040 \frac{v_s}{v} = 80.0$$

$$v_s = \frac{80.0(343)}{1\,040} \text{ m/s} = \boxed{26.4 \text{ m/s}}$$

P17.40 (a) The maximum speed of the speaker is described by

$$\frac{1}{2} m v_{\max}^2 = \frac{1}{2} k A^2$$

$$v_{\max} = \sqrt{\frac{k}{m}} A = \sqrt{\frac{20.0 \text{ N/m}}{5.00 \text{ kg}}} (0.500 \text{ m}) = 1.00 \text{ m/s}$$

The frequencies heard by the stationary observer range from

$$f'_{\min} = f \left(\frac{v}{v + v_{\max}} \right) \text{ to } f'_{\max} = f \left(\frac{v}{v - v_{\max}} \right)$$

where v is the speed of sound.

$$f'_{\min} = 440 \text{ Hz} \left(\frac{343 \text{ m/s}}{343 \text{ m/s} + 1.00 \text{ m/s}} \right) = \boxed{439 \text{ Hz}}$$

$$f'_{\max} = 440 \text{ Hz} \left(\frac{343 \text{ m/s}}{343 \text{ m/s} - 1.00 \text{ m/s}} \right) = \boxed{441 \text{ Hz}}$$

$$(b) \quad \beta = 10 \text{ dB} \log \left(\frac{I}{I_0} \right) = 10 \text{ dB} \log \left(\frac{\wp / 4\pi r^2}{I_0} \right)$$

The maximum intensity level (of 60.0 dB) occurs at $r = r_{\min} = 1.00$ m. The minimum intensity level occurs when the speaker is farthest from the listener (i.e., when $r = r_{\max} = r_{\min} + 2A = 2.00$ m).

$$\text{Thus, } \beta_{\max} - \beta_{\min} = 10 \text{ dB} \log \left(\frac{\wp}{4\pi I_0 r_{\min}^2} \right) - 10 \text{ dB} \log \left(\frac{\wp}{4\pi I_0 r_{\max}^2} \right)$$

$$\text{or } \beta_{\max} - \beta_{\min} = 10 \text{ dB} \log \left(\frac{\wp}{4\pi I_0 r_{\min}^2} \frac{4\pi I_0 r_{\max}^2}{\wp} \right) = 10 \text{ dB} \log \left(\frac{r_{\max}^2}{r_{\min}^2} \right).$$

This gives: $60.0 \text{ dB} - \beta_{\min} = 10 \text{ dB} \log(4.00) = 6.02 \text{ dB}$, and $\beta_{\min} = \boxed{54.0 \text{ dB}}$.

512 Sound Waves

$$\text{P17.41} \quad f' = f \left(\frac{v}{v - v_s} \right) \quad 485 = 512 \left(\frac{340}{340 - (-9.80 t_{\text{fall}})} \right)$$

$$485(340) + (485)(9.80 t_f) = (512)(340)$$

$$t_f = \left(\frac{512 - 485}{485} \right) \frac{340}{9.80} = 1.93 \text{ s}$$

$$d_1 = \frac{1}{2} g t_f^2 = 18.3 \text{ m}; \quad t_{\text{return}} = \frac{18.3}{340} = 0.0538 \text{ s}$$

The fork continues to fall while the sound returns.

$$t_{\text{total fall}} = t_f + t_{\text{return}} = 1.93 \text{ s} + 0.0538 \text{ s} = 1.985 \text{ s}$$

$$d_{\text{total}} = \frac{1}{2} g t_{\text{total fall}}^2 = \boxed{19.3 \text{ m}}$$

$$\text{P17.42} \quad (\text{a}) \quad v = (331 \text{ m/s}) + 0.6 \frac{\text{m}}{\text{s} \cdot ^\circ\text{C}} (-10^\circ\text{C}) = \boxed{325 \text{ m/s}}$$

$$(\text{b}) \quad \text{Approaching the bell, the athlete hears a frequency of} \quad f' = f \left(\frac{v + v_O}{v} \right)$$

$$\text{After passing the bell, she hears a lower frequency of} \quad f'' = f \left(\frac{v + (-v_O)}{v} \right)$$

$$\text{The ratio is} \quad \frac{f''}{f'} = \frac{v - v_O}{v + v_O} = \frac{5}{6}$$

$$\text{which gives } 6v - 6v_O = 5v + 5v_O \text{ or} \quad v_O = \frac{v}{11} = \frac{325 \text{ m/s}}{11} = \boxed{29.5 \text{ m/s}}$$

***P17.43** (a) Sound moves upwind with speed $(343 - 15) \text{ m/s}$. Crests pass a stationary upwind point at frequency 900 Hz .

$$\text{Then} \quad \lambda = \frac{v}{f} = \frac{328 \text{ m/s}}{900/\text{s}} = \boxed{0.364 \text{ m}}$$

$$(\text{b}) \quad \text{By similar logic,} \quad \lambda = \frac{v}{f} = \frac{(343 + 15) \text{ m/s}}{900/\text{s}} = \boxed{0.398 \text{ m}}$$

(c) The source is moving through the air at 15 m/s toward the observer. The observer is stationary relative to the air.

$$f' = f \left(\frac{v + v_o}{v - v_s} \right) = 900 \text{ Hz} \left(\frac{343 + 0}{343 - 15} \right) = \boxed{941 \text{ Hz}}$$

(d) The source is moving through the air at 15 m/s away from the downwind firefighter. Her speed relative to the air is 30 m/s toward the source.

$$f' = f \left(\frac{v + v_o}{v - v_s} \right) = 900 \text{ Hz} \left(\frac{343 + 30}{343 - (-15)} \right) = 900 \text{ Hz} \left(\frac{373}{358} \right) = \boxed{938 \text{ Hz}}$$

***P17.44** The half-angle of the cone of the shock wave is θ where

$$\theta = \sin^{-1}\left(\frac{v_{\text{sound}}}{v_{\text{source}}}\right) = \sin^{-1}\left(\frac{1}{1.5}\right) = 41.8^\circ.$$

As shown in the sketch, the angle between the direction of propagation of the shock wave and the direction of the plane's velocity is

$$\phi = 90^\circ - \theta = 90^\circ - 41.8^\circ = \boxed{48.2^\circ}.$$

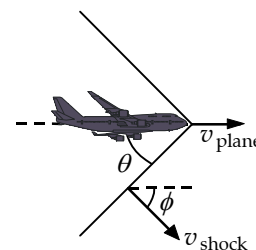


FIG. P17.44

P17.45 The *half angle* of the shock wave cone is given by $\sin \theta = \frac{v_{\text{light}}}{v_s}$.

$$v_s = \frac{v_{\text{light}}}{\sin \theta} = \frac{2.25 \times 10^8 \text{ m/s}}{\sin(53.0^\circ)} = \boxed{2.82 \times 10^8 \text{ m/s}}$$

P17.46 $\theta = \sin^{-1} \frac{v}{v_s} = \sin^{-1} \frac{1}{1.38} = \boxed{46.4^\circ}$

P17.47 (b) $\sin \theta = \frac{v}{v_s} = \frac{1}{3.00}; \theta = 19.5^\circ$

$$\tan \theta = \frac{h}{x}; x = \frac{h}{\tan \theta}$$

$$x = \frac{20\,000 \text{ m}}{\tan 19.5^\circ} = 5.66 \times 10^4 \text{ m} = \boxed{56.6 \text{ km}}$$

(a) It takes the plane $t = \frac{x}{v_s} = \frac{5.66 \times 10^4 \text{ m}}{3.00(335 \text{ m/s})} = \boxed{56.3 \text{ s}}$ to travel this distance.

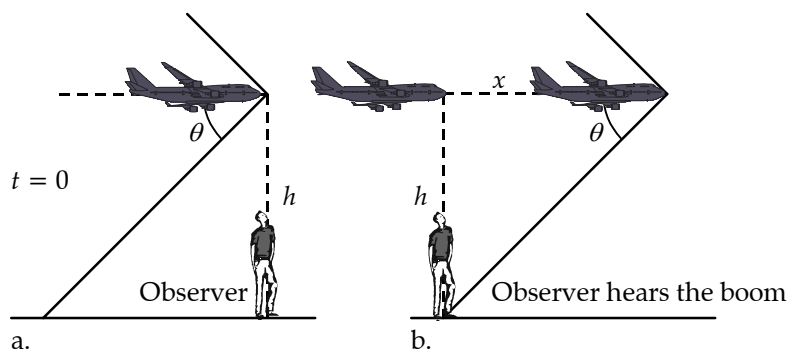


FIG. P17.47(a)

Section 17.5 Digital Sound Recording

Section 17.6 Motion Picture Sound

*P17.48 For a 40-dB sound,

$$40 \text{ dB} = 10 \text{ dB} \log \left[\frac{I}{10^{-12} \text{ W/m}^2} \right]$$

$$I = 10^{-8} \text{ W/m}^2 = \frac{\Delta P_{\text{max}}^2}{2\rho v}$$

$$\Delta P_{\text{max}} = \sqrt{2\rho v I} = \sqrt{2(1.20 \text{ kg/m}^3)(343 \text{ m/s})10^{-8} \text{ W/m}^2} = 2.87 \times 10^{-3} \text{ N/m}^2$$

$$(a) \quad \text{code} = \frac{2.87 \times 10^{-3} \text{ N/m}^2}{28.7 \text{ N/m}^2} 65\,536 = \boxed{7}$$

(b) For sounds of 40 dB or softer, too few digital words are available to represent the wave form with good fidelity.

(c) In a sound wave ΔP is negative half of the time but this coding scheme has no words available for negative pressure variations.

*P17.49 If the source is to the left at angle θ from the direction you are facing, the sound must travel an extra distance $d \sin \theta$ to reach your right ear as shown, where d is the distance between your ears. The delay time is Δt in $v = \frac{d \sin \theta}{\Delta t}$. Then

$$\theta = \sin^{-1} \frac{v \Delta t}{d} = \sin^{-1} \frac{(343 \text{ m/s}) 210 \times 10^{-6} \text{ s}}{0.19 \text{ m}} = \boxed{22.3^\circ \text{ left of center}}$$

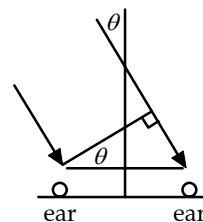


FIG. P17.49

$$*P17.50 \quad 103 \text{ dB} = 10 \text{ dB} \log \left[\frac{I}{10^{-12} \text{ W/m}^2} \right]$$

$$(a) \quad I = 2.00 \times 10^{-2} \text{ W/m}^2 = \frac{\wp}{4\pi r^2} = \frac{\wp}{4\pi(1.6 \text{ m})^2}$$

$$\wp = \boxed{0.642 \text{ W}}$$

$$(b) \quad \text{efficiency} = \frac{\text{sound output power}}{\text{total input power}} = \frac{0.642 \text{ W}}{150 \text{ W}} = \boxed{0.004\,28}$$

Additional Problems

P17.51 Model your loud, sharp sound impulse as a single narrow peak in a graph of air pressure versus time. It is a noise with no pitch, no frequency, wavelength, or period. It radiates away from you in all directions and some of it is incident on each one of the solid vertical risers of the bleachers. Suppose that, at the ambient temperature, sound moves at 340 m/s; and suppose that the horizontal width of each row of seats is 60 cm. Then there is a time delay of

$$\frac{0.6 \text{ m}}{(340 \text{ m/s})} = 0.002 \text{ s}$$

continued on next page

between your sound impulse reaching each riser and the next. Whatever its material, each will reflect much of the sound that reaches it. The reflected wave sounds very different from the sharp pop you made. If there are twenty rows of seats, you hear from the bleachers a tone with twenty crests, each separated from the next in time by

$$\frac{2(0.6 \text{ m})}{(340 \text{ m/s})} = 0.004 \text{ s}.$$

This is the extra time for it to cross the width of one seat twice, once as an incident pulse and once again after its reflection. Thus, you hear a sound of definite pitch, with period about 0.004 s, frequency

$$\frac{1}{0.0035 \text{ s}} \sim 300 \text{ Hz}$$

wavelength

$$\lambda = \frac{v}{f} = \frac{(340 \text{ m/s})}{(300/\text{s})} = 1.2 \text{ m} \sim 10^0 \text{ m}$$

and duration

$$20(0.004 \text{ s}) \sim 10^{-1} \text{ s}.$$

P17.52 (a) $\lambda = \frac{v}{f} = \frac{343 \text{ m/s}}{1480 \text{ s}^{-1}} = 0.232 \text{ m}$

(b) $\beta = 81.0 \text{ dB} = 10 \text{ dB} \log \left[\frac{I}{10^{-12} \text{ W/m}^2} \right]$

$$I = (10^{-12} \text{ W/m}^2) 10^{8.10} = 10^{-3.90} \text{ W/m}^2 = 1.26 \times 10^{-4} \text{ W/m}^2 = \frac{1}{2} \rho v \omega^2 s_{\text{max}}^2$$

$$s_{\text{max}} = \sqrt{\frac{2I}{\rho v \omega^2}} = \sqrt{\frac{2(1.26 \times 10^{-4} \text{ W/m}^2)}{(1.20 \text{ kg/m}^3)(343 \text{ m/s})4\pi^2(1480 \text{ s}^{-1})^2}} = 8.41 \times 10^{-8} \text{ m}$$

(c) $\lambda' = \frac{v}{f'} = \frac{343 \text{ m/s}}{1397 \text{ s}^{-1}} = 0.246 \text{ m} \quad \Delta\lambda = \lambda' - \lambda = 13.8 \text{ mm}$

P17.53 Since $\cos^2 \theta + \sin^2 \theta = 1$, $\sin \theta = \pm \sqrt{1 - \cos^2 \theta}$ (each sign applying half the time)

$$\Delta P = \Delta P_{\text{max}} \sin(kx - \omega t) = \pm \rho v \omega s_{\text{max}} \sqrt{1 - \cos^2(kx - \omega t)}$$

Therefore $\Delta P = \pm \rho v \omega \sqrt{s_{\text{max}}^2 - s^2} \cos^2(kx - \omega t) = \pm \rho v \omega \sqrt{s_{\text{max}}^2 - s^2}$

P17.54 The trucks form a train analogous to a wave train of crests with speed $v = 19.7 \text{ m/s}$ and unshifted frequency $f = \frac{2}{3.00 \text{ min}} = 0.667 \text{ min}^{-1}$.

(a) The cyclist as observer measures a lower Doppler-shifted frequency:

$$f' = f \left(\frac{v + v_o}{v} \right) = (0.667 \text{ min}^{-1}) \left(\frac{19.7 + (-4.47)}{19.7} \right) = 0.515/\text{min}$$

(b) $f'' = f \left(\frac{v + v'_o}{v} \right) = (0.667 \text{ min}^{-1}) \left(\frac{19.7 + (-1.56)}{19.7} \right) = 0.614/\text{min}$

The cyclist's speed has decreased very significantly, but there is only a modest increase in the frequency of trucks passing him.

P17.55 $v = \frac{2d}{t}$; $d = \frac{vt}{2} = \frac{1}{2}(6.50 \times 10^3 \text{ m/s})(1.85 \text{ s}) = \boxed{6.01 \text{ km}}$

- P17.56** (a) The speed of a compression wave in a bar is

$$v = \sqrt{\frac{Y}{\rho}} = \sqrt{\frac{20.0 \times 10^{10} \text{ N/m}^2}{7860 \text{ kg/m}^3}} = \boxed{5.04 \times 10^3 \text{ m/s}}.$$

- (b) The signal to stop passes between layers of atoms as a sound wave, reaching the back end of the bar in time

$$t = \frac{L}{v} = \frac{0.800 \text{ m}}{5.04 \times 10^3 \text{ m/s}} = \boxed{1.59 \times 10^{-4} \text{ s}}.$$

- (c) As described by Newton's first law, the rearmost layer of steel has continued to move forward with its original speed v_i for this time, compressing the bar by

$$\Delta L = v_i t = (12.0 \text{ m/s})(1.59 \times 10^{-4} \text{ s}) = 1.90 \times 10^{-3} \text{ m} = \boxed{1.90 \text{ mm}}.$$

- (d) The strain in the rod is: $\frac{\Delta L}{L} = \frac{1.90 \times 10^{-3} \text{ m}}{0.800 \text{ m}} = \boxed{2.38 \times 10^{-3}}.$

- (e) The stress in the rod is:

$$\sigma = Y \left(\frac{\Delta L}{L} \right) = (20.0 \times 10^{10} \text{ N/m}^2)(2.38 \times 10^{-3}) = \boxed{476 \text{ MPa}}.$$

Since $\sigma > 400 \text{ MPa}$, the rod will be permanently distorted.

- (f) We go through the same steps as in parts (a) through (e), but use algebraic expressions rather than numbers:

The speed of sound in the rod is $v = \sqrt{\frac{Y}{\rho}}.$

The back end of the rod continues to move forward at speed v_i for a time of $t = \frac{L}{v} = L \sqrt{\frac{\rho}{Y}},$ traveling distance $\Delta L = v_i t$ after the front end hits the wall.

The strain in the rod is: $\frac{\Delta L}{L} = \frac{v_i t}{L} = v_i \sqrt{\frac{\rho}{Y}}.$

The stress is then: $\sigma = Y \left(\frac{\Delta L}{L} \right) = Y v_i \sqrt{\frac{\rho}{Y}} = v_i \sqrt{\rho Y}.$

For this to be less than the yield stress, σ_y , it is necessary that

$$v_i \sqrt{\rho Y} < \sigma_y \text{ or } \boxed{v_i < \frac{\sigma_y}{\sqrt{\rho Y}}}.$$

With the given numbers, this speed is 10.1 m/s. The fact that the length of the rod divides out means that the steel will start to bend right away at the front end of the rod. There it will yield enough so that eventually the remainder of the rod will experience only stress within the elastic range. You can see this effect when sledgehammer blows give a mushroom top to a rod used as a tent stake.

P17.57 (a) $f' = f \frac{v}{(v - v_{\text{diver}})}$

so $1 - \frac{v_{\text{diver}}}{v} = \frac{f}{f'}$

$\Rightarrow v_{\text{diver}} = v \left(1 - \frac{f}{f'} \right)$

with $v = 343 \text{ m/s}$, $f' = 1800 \text{ Hz}$ and $f = 2150 \text{ Hz}$

we find

$$v_{\text{diver}} = 343 \left(1 - \frac{1800}{2150} \right) = \boxed{55.8 \text{ m/s}}.$$

(b) If the waves are reflected, and the skydiver is moving into them, we have

$$f'' = f' \frac{(v + v_{\text{diver}})}{v} \Rightarrow f'' = f \left[\frac{v}{(v - v_{\text{diver}})} \right] \frac{(v + v_{\text{diver}})}{v}$$

so $f'' = 1800 \frac{(343 + 55.8)}{(343 - 55.8)} = \boxed{2500 \text{ Hz}}.$

P17.58 (a) $f' = \frac{fv}{v - u}$ $f'' = \frac{fv}{v - (-u)}$ $f' - f'' = fv \left(\frac{1}{v - u} - \frac{1}{v + u} \right)$

$$\Delta f = \frac{fv(v + u - v + u)}{v^2 - u^2} = \frac{2uvf}{v^2(1 - (u^2/v^2))} = \boxed{\frac{2(u/v)}{1 - (u^2/v^2)} f}$$

(b) $130 \text{ km/h} = 36.1 \text{ m/s}$ $\therefore \Delta f = \frac{2(36.1)(400)}{340[1 - (36.1)^2/340^2]} = \boxed{85.9 \text{ Hz}}$

P17.59 When observer is moving in front of and in the same direction as the source, $f' = f \frac{v - v_O}{v - v_S}$ where v_O

and v_S are measured relative to the medium in which the sound is propagated. In this case the ocean current is opposite the direction of travel of the ships and

$$v_O = 45.0 \text{ km/h} - (-10.0 \text{ km/h}) = 55.0 \text{ km/h} = 15.3 \text{ m/s}, \text{ and}$$

$$v_S = 64.0 \text{ km/h} - (-10.0 \text{ km/h}) = 74.0 \text{ km/h} = 20.55 \text{ m/s}$$

Therefore, $f' = (1200.0 \text{ Hz}) \frac{1520 \text{ m/s} - 15.3 \text{ m/s}}{1520 \text{ m/s} - 20.55 \text{ m/s}} = \boxed{1204.2 \text{ Hz}}.$

P17.60 Use the Doppler formula, and remember that the bat is a moving source.

If the velocity of the insect is v_x ,

$$40.4 = 40.0 \frac{(340 + 5.00)(340 - v_x)}{(340 - 5.00)(340 + v_x)}.$$

Solving,

$$v_x = 3.31 \text{ m/s}.$$

Therefore, the bat is gaining on its prey at 1.69 m/s .

P17.61 $\sin \beta = \frac{v}{v_s} = \frac{1}{N_M}$

$$h = v(12.8 \text{ s})$$

$$x = v_s(10.0 \text{ s})$$

$$\tan \beta = \frac{h}{x} = 1.28 \frac{v}{v_s} = \frac{1.28}{N_M}$$

$$\cos \beta = \frac{\sin \beta}{\tan \beta} = \frac{1}{1.28}$$

$$\beta = 38.6^\circ$$

$$N_M = \frac{1}{\sin \beta} = \boxed{1.60}$$

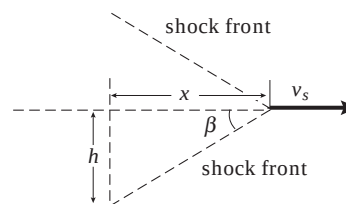


FIG. P17.61

P17.62 (a)

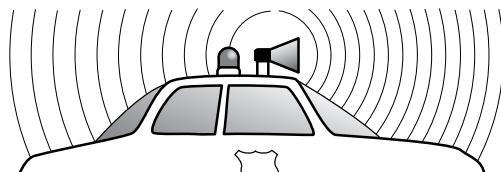


FIG. P17.62(a)

(b) $\lambda = \frac{v}{f} = \frac{343 \text{ m/s}}{1\,000 \text{ s}^{-1}} = \boxed{0.343 \text{ m}}$

(c) $\lambda' = \frac{v}{f'} = \frac{v}{f} \left(\frac{v - v_s}{v} \right) = \frac{(343 - 40.0) \text{ m/s}}{1000 \text{ s}^{-1}} = \boxed{0.303 \text{ m}}$

(d) $\lambda'' = \frac{v}{f''} = \frac{v}{f} \left(\frac{v + v_s}{v} \right) = \frac{(343 + 40.0) \text{ m/s}}{1000 \text{ s}^{-1}} = \boxed{0.383 \text{ m}}$

(e) $f' = f \left(\frac{v - v_o}{v - v_s} \right) = (1\,000\text{ Hz}) \frac{(343 - 30.0)\text{ m/s}}{(343 - 40.0)\text{ m/s}} = \boxed{1.03\text{ kHz}}$

$$\text{P17.63} \quad \Delta t = L \left(\frac{1}{v_{\text{air}}} - \frac{1}{v_{\text{cu}}} \right) = L \frac{v_{\text{cu}} - v_{\text{air}}}{v_{\text{air}} v_{\text{cu}}}$$

$$L = \frac{v_{\text{air}} v_{\text{cu}}}{v_{\text{cu}} - v_{\text{air}}} \Delta t = \frac{(331 \text{ m/s})(3.56 \times 10^3 \text{ m/s})}{(3560 - 331) \text{ m/s}} (6.40 \times 10^{-3} \text{ s})$$

$$\boxed{L = 2.34 \text{ m}}$$

- P17.64** The shock wavefront connects all observers first hearing the plane, including our observer O and the plane P , so here it is vertical. The angle ϕ that the shock wavefront makes with the direction of the plane's line of travel is given by

$$\sin \phi = \frac{v}{v_s} = \frac{340 \text{ m/s}}{1963 \text{ m/s}} = 0.173$$

$$\text{so } \phi = 9.97^\circ.$$

Using the right triangle CPO , the angle θ is seen to be

$$\theta = 90.0^\circ - \phi = 90.0^\circ - 9.97^\circ = \boxed{80.0^\circ}.$$

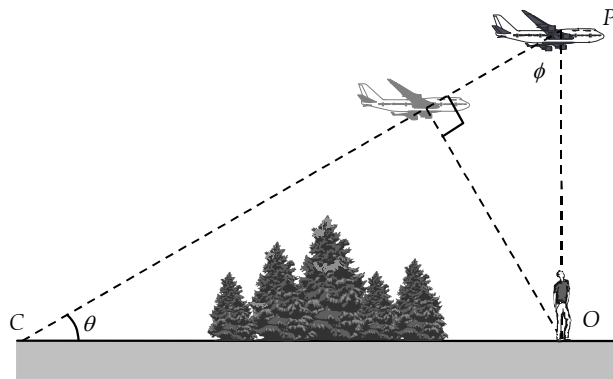


FIG. P17.64

$$\text{P17.65} \quad (\text{a}) \quad \theta = \sin^{-1} \left(\frac{v_{\text{sound}}}{v_{\text{obj}}} \right) = \sin^{-1} \left(\frac{331}{20.0 \times 10^3} \right) = \boxed{0.948^\circ}$$

$$(\text{b}) \quad \theta' = \sin^{-1} \left(\frac{1533}{20.0 \times 10^3} \right) = \boxed{4.40^\circ}$$

$$\text{P17.66} \quad \beta_2 = \frac{1}{20.0} \beta_1 \quad \beta_1 - \beta_2 = 10 \log \frac{\beta_1}{\beta_2}$$

$$80.0 - \beta_2 = 10 \log 20.0 = +13.0$$

$$\beta_2 = \boxed{67.0 \text{ dB}}$$

$$\text{P17.67} \quad \text{For the longitudinal wave } v_L = \left(\frac{Y}{\rho} \right)^{1/2}.$$

$$\text{For the transverse wave } v_T = \left(\frac{T}{\mu} \right)^{1/2}.$$

$$\text{If we require } \frac{v_L}{v_T} = 8.00, \text{ we have } T = \frac{\mu Y}{64.0 \rho} \text{ where } \mu = \frac{m}{L} \text{ and}$$

$$\rho = \frac{\text{mass}}{\text{volume}} = \frac{m}{\pi r^2 L}.$$

$$\text{This gives } T = \frac{\pi r^2 Y}{64.0} = \frac{\pi (2.00 \times 10^{-3} \text{ m})^2 (6.80 \times 10^{10} \text{ N/m}^2)}{64.0} = \boxed{1.34 \times 10^4 \text{ N}}.$$

P17.68 The total output sound energy is $eE = \wp \Delta t$, where $\wp$ is the power radiated.

$$\text{Thus, } \Delta t = \frac{eE}{\wp} = \frac{eE}{IA} = \frac{eE}{(4\pi r^2)I} = \frac{eE}{4\pi d^2 I}.$$

$$\text{But, } \beta = 10 \log \left(\frac{I}{I_0} \right). \text{ Therefore, } I = I_0 (10^{\beta/10}) \text{ and } \Delta t = \boxed{\frac{eE}{4\pi d^2 I_0 10^{\beta/10}}}.$$

P17.69 (a) If the source and the observer are moving away from each other, we have: $\theta_S - \theta_0 = 180^\circ$, and since $\cos 180^\circ = -1$, we get Equation 17.12 with negative values for both v_O and v_S .

$$(b) \quad \text{If } v_O = 0 \text{ m/s then } f' = \frac{v}{v - v_S \cos \theta_S} f$$

Also, when the train is 40.0 m from the intersection, and the car is 30.0 m from the intersection,

$$\cos \theta_S = \frac{4}{5}$$

$$\text{so } f' = \frac{343 \text{ m/s}}{343 \text{ m/s} - 0.800(25.0 \text{ m/s})} (500 \text{ Hz})$$

$$\text{or } f' = \boxed{531 \text{ Hz}}.$$

Note that as the train approaches, passes, and departs from the intersection, θ_S varies from 0° to 180° and the frequency heard by the observer varies from:

$$f'_{\max} = \frac{v}{v - v_S \cos 0^\circ} f = \frac{343 \text{ m/s}}{343 \text{ m/s} - 25.0 \text{ m/s}} (500 \text{ Hz}) = 539 \text{ Hz}$$

$$f'_{\min} = \frac{v}{v - v_S \cos 180^\circ} f = \frac{343 \text{ m/s}}{343 \text{ m/s} + 25.0 \text{ m/s}} (500 \text{ Hz}) = 466 \text{ Hz}$$

P17.70 Let T represent the period of the source vibration, and E be the energy put into each wavefront. Then $\wp_{\text{av}} = \frac{E}{T}$. When the observer is at distance r in front of the source, he is receiving a spherical wavefront of radius vt , where t is the time since this energy was radiated, given by $vt - v_S t = r$. Then,

$$t = \frac{r}{v - v_S}.$$

The area of the sphere is $4\pi(vt)^2 = \frac{4\pi v^2 r^2}{(v - v_S)^2}$. The energy per unit area over the spherical wavefront

$$\text{is uniform with the value } \frac{E}{A} = \frac{\wp_{\text{av}} T (v - v_S)^2}{4\pi v^2 r^2}.$$

The observer receives parcels of energy with the Doppler shifted frequency

$$f' = f \left(\frac{v}{v - v_S} \right) = \frac{v}{T(v - v_S)}, \text{ so the observer receives a wave with intensity}$$

$$I = \left(\frac{E}{A} \right) f' = \left(\frac{\wp_{\text{av}} T (v - v_S)^2}{4\pi v^2 r^2} \right) \left(\frac{v}{T(v - v_S)} \right) = \boxed{\frac{\wp_{\text{av}}}{4\pi r^2} \left(\frac{v - v_S}{v} \right)}.$$

- P17.71** (a) The time required for a sound pulse to travel distance L at speed v is given by $t = \frac{L}{v} = \frac{L}{\sqrt{Y/\rho}}$. Using this expression we find

L_1	L_2
L_3	

FIG. P17.71

$$t_1 = \frac{L_1}{\sqrt{Y_1/\rho_1}} = \frac{L_1}{\sqrt{(7.00 \times 10^{10} \text{ N/m}^2)/(2700 \text{ kg/m}^3)}} = (1.96 \times 10^{-4} L_1) \text{ s}$$

$$t_2 = \frac{1.50 \text{ m} - L_1}{\sqrt{Y_2/\rho_2}} = \frac{1.50 \text{ m} - L_1}{\sqrt{(1.60 \times 10^{10} \text{ N/m}^2)/(11.3 \times 10^3 \text{ kg/m}^3)}}$$

or $t_2 = (1.26 \times 10^{-3} - 8.40 \times 10^{-4} L_1) \text{ s}$

$$t_3 = \frac{1.50 \text{ m}}{\sqrt{(11.0 \times 10^{10} \text{ N/m}^2)/(8800 \text{ kg/m}^3)}}$$

$$t_3 = 4.24 \times 10^{-4} \text{ s}$$

We require $t_1 + t_2 = t_3$, or

$$1.96 \times 10^{-4} L_1 + 1.26 \times 10^{-3} - 8.40 \times 10^{-4} L_1 = 4.24 \times 10^{-4}.$$

This gives $L_1 = 1.30 \text{ m}$ and $L_2 = 1.50 - 1.30 = 0.201 \text{ m}$.

The ratio of lengths is then $\frac{L_1}{L_2} = \boxed{6.45}$.

- (b) The ratio of lengths $\frac{L_1}{L_2}$ is adjusted in part (a) so that $t_1 + t_2 = t_3$. Sound travels the two paths in equal time and the phase difference, $\boxed{\Delta\phi = 0}$.

- P17.72** To find the separation of adjacent molecules, use a model where each molecule occupies a sphere of radius r given by

$$\rho_{\text{air}} = \frac{\text{average mass per molecule}}{\frac{4}{3}\pi r^3}$$

$$\text{or } 1.20 \text{ kg/m}^3 = \frac{4.82 \times 10^{-26} \text{ kg}}{\frac{4}{3}\pi r^3}, \quad r = \left[\frac{3(4.82 \times 10^{-26} \text{ kg})}{4\pi(1.20 \text{ kg/m}^3)} \right]^{1/3} = 2.12 \times 10^{-9} \text{ m}.$$

Intermolecular separation is $2r = 4.25 \times 10^{-9} \text{ m}$, so the highest possible frequency sound wave is

$$f_{\text{max}} = \frac{v}{\lambda_{\text{min}}} = \frac{v}{2r} = \frac{343 \text{ m/s}}{4.25 \times 10^{-9} \text{ m}} = 8.03 \times 10^{10} \text{ Hz} \quad \boxed{\sim 10^{11} \text{ Hz}}.$$

ANSWERS TO EVEN PROBLEMS

- P17.2** 1.43 km/s
- P17.4** (a) 27.2 s; (b) longer than 25.7 s, because the air is cooler
- P17.6** (a) 153 m/s; (b) 614 m
- P17.8** (a) 4.16 m; (b) 0.455 μs ; (c) 0.157 mm
- P17.10** 1.55×10^{-10} m
- P17.12** (a) 1.27 Pa; (b) 170 Hz; (c) 2.00 m; (d) 340 m/s
- P17.14** $s = 22.5 \text{ nm} \cos(62.8x - 2.16 \times 10^4 t)$
- P17.16** (a) 4.63 mm; (b) 14.5 m/s; (c) $4.73 \times 10^9 \text{ W/m}^2$
- P17.18** (a) $5.00 \times 10^{-17} \text{ W}$; (b) $5.00 \times 10^{-5} \text{ W}$
- P17.20** (a) $1.00 \times 10^{-5} \text{ W/m}^2$; (b) 90.7 mPa
- P17.22** (a) $I_2 = \left(\frac{f'}{f}\right)^2 I_1$; (b) $I_2 = I_1$
- P17.24** 21.2 W
- P17.26** (a) 4.51 times larger in water than in air and 18.0 times larger in iron; (b) 5.60 times larger in water than in iron and 331 times larger in air; (c) 59.1 times larger in water than in air and 331 times larger in iron; (d) 0.331 m; 1.49 m; 5.95 m; 10.9 nm; 184 pm; 32.9 pm; 29.2 mPa; 1.73 Pa; 9.67 Pa
- P17.28** see the solution
- P17.30** 10.0 m; 100 m
- P17.32** 86.6 m
- P17.34** (a) 1.76 kJ; (b) 108 dB
- P17.36** no
- P17.38** (a) 2.17 cm/s; (b) 2 000 028.9 Hz; (c) 2 000 057.8 Hz
- P17.40** (a) 441 Hz; 439 Hz; (b) 54.0 dB
- P17.42** (a) 325 m/s; (b) 29.5 m/s
- P17.44** 48.2°
- P17.46** 46.4°
- P17.48** (a) 7; (b) and (c) see the solution
- P17.50** (a) 0.642 W; (b) 0.004 28 = 0.428%
- P17.52** (a) 0.232 m; (b) 84.1 nm; (c) 13.8 mm
- P17.54** (a) 0.515/min; (b) 0.614/min
- P17.56** (a) 5.04 km/s; (b) 159 μs ; (c) 1.90 mm; (d) 0.002 38; (e) 476 MPa; (f) see the solution
- P17.58** (a) see the solution; (b) 85.9 Hz
- P17.60** The gap between bat and insect is closing at 1.69 m/s.
- P17.62** (a) see the solution; (b) 0.343 m; (c) 0.303 m; (d) 0.383 m; (e) 1.03 kHz
- P17.64** 80.0°
- P17.66** 67.0 dB
- P17.68** $\Delta t = \frac{eE}{4\pi d^2 I_0 10^{\beta/10}}$
- P17.70** see the solution
- P17.72** $\sim 10^{11} \text{ Hz}$