17

Sound Waves

CHAPTER OUTLINE

ANSWERS TO QUESTIONS

***Q17.1** Answer (b). The typically higher density would by itself make the speed of sound lower in a solid compared to a gas.

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 $343\ \text{m/s}$, 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 $340\ \text{m/s}$. 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** (i) Answer (b). 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.

(ii) Answer (c).

***Q17.6** (i) Answer (c). Every crest in air produces one crest in water immediately as it reaches the interface, so there must be 500 in every second.

(ii) Answer (a). The speed increases greatly so the wavelength must increase.

Q17.7 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.

***Q17.8** Answer (a). 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** Answer (d). The drop in intensity is what we should expect according to the inverse-square law: $4\pi r_1^2 \mathcal{P}_1$ and $4\pi r_2^2 \mathcal{P}_2$ should agree. $(300\text{ m})^2(2\ \mu\text{W/m}^2)$ and $(950\text{ m})^2(0.2\ \mu\text{W/m}^2)$ are 0.18 W and 0.18 W, agreeing with each other.

***Q17.10** Answer (c). Normal conversation has an intensity level of about 60 dB.

***Q17.11** Answer (c). The intensity is about 10^{-13} W/m^2.

Q17.12 Our brave Siberian 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 from each other. 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.

Q17.13 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.

***Q17.14** In $f' = (v + v_o)f/(v - v_s)$ we can consider the size of the fraction $(v + v_o)/(v - v_s)$ in each case. The positive direction is defined to run from the observer toward the source.

In (a), $340/340 = 1$ In (b), $340/(340 - 25) = 1.08$ In (c), $340/(340 + 25) = 0.932$ In (d), $(340 + 25)/340 = 1.07$ In (e), $(340 - 25)/340 = 0.926$ In (f), $(340 + 25)/(340 + 25) = 1$ In (g), $(340 - 25)/(340 - 25) = 1$. In order of decreasing size we have b > d > a = f = g > c > e.

***Q17.15** (i) Answer (c). Both observer and source have equal speeds in opposite directions relative to the medium, so in $f' = (v + v_o)f/(v - v_s)$ we would have something like $(340 - 25)f/(340 - 25) = f$.

(ii) Answer (a). The speed of the medium adds to the speed of sound as far as the observer is concerned, to cause an increase in $\lambda = v/f$.

(iii) Answer (a).

Q17.16 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.

SOLUTIONS TO PROBLEMS

Section 17.1 **Speed of Sound Waves**

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

We do not need to know the value of the speed of light. As long as it is very large, the travel time for the light is negligible compared to that for the sound.

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

***P17.3** The sound pulse must travel 150 m before reflection and 150 m after reflection. We have $d = vt$

$$t = \frac{d}{v} = \frac{300 \text{ m}}{1\,533 \text{ m/s}} = \boxed{0.196 \text{ s}}$$

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

Using the chain rule:

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

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

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

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

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

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

P17.5 Sound takes this time to reach the man: $\dfrac{(20.0\text{ m} - 1.75\text{ m})}{343\text{ m/s}} = 5.32\times10^{-2}\text{ s}$

so the warning should be shouted no later than before the pot strikes. $0.300\text{ s} + 5.32\times10^{-2}\text{ s} = 0.353\text{ s}$

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

$t = 1.93\text{ s}$

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 $\frac{1}{2}\left(9.80\text{ m/s}^2\right)(1.58\text{ s})^2 = 12.2\text{ m}$

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

P17.6 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 $h = \dfrac{2(686\text{ m})}{\sqrt{5}} = \boxed{614\text{ m}}$

(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: $v = \dfrac{307\text{ m}}{2.00\text{ s}} = \boxed{153\text{ m/s}}$

P17.7 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

$$\frac{2x_2 - 2x_1}{340\text{ m/s}} = 1.92\text{ s} \qquad \text{and} \qquad \frac{2x_1 + 2x_2 - 2x_2}{340\text{ m/s}} = 1.47\text{ s}$$

Thus

$$x_1 = \frac{1}{2}340\text{ m/s }1.47\text{ s} = 250\text{ m} \qquad \text{and} \qquad \frac{2x_2}{340\text{ m/s}} = 1.92\text{ s} + 1.47\text{ s};\ x_2 = 576\text{ m}$$

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

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

Section 17.2 **Periodic Sound Waves**

***P17.8** (a) The speed gradually changes from $v = (331\text{ m/s})(1 + 27°\text{C}/273°\text{C})^{1/2} = 347$ m/s to $(331\text{ m/s})(1 + 0/273°\text{C})^{1/2} = 331$ m/s, a 4.6% decrease. The cooler air at the same pressure is more dense.

(b) The frequency is unchanged, because every wave crest in the hot air becomes one crest without delay in the cold air.

(c) The wavelength decreases by 4.6%, from $v/f = (347\text{ m/s})/(4\,000/\text{s}) = 86.7$ mm to $(331\text{ m/s})/(4\,000/\text{s}) = 82.8$ mm. The crests are more crowded together when they move slower.

***P17.9** (a) If $f = 2.4$ MHz, $\lambda = \dfrac{v}{f} = \dfrac{1\,500\text{ m/s}}{2.4\times10^{6}/\text{s}} = \boxed{0.625\text{ mm}}$

(b) If $f = 1$ MHz, $\lambda = \dfrac{v}{f} = \dfrac{1\,500\text{ m/s}}{10^{6}/\text{s}} = \boxed{1.50\text{ mm}}$

If $f = 20$ MHz, $\lambda = \dfrac{1\,500\text{ m/s}}{2\times10^{7}/\text{s}} = \boxed{75.0\ \mu\text{m}}$

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

$$s_{\max} = \frac{\Delta P_{\max}}{\rho v \omega} = \frac{\left(4.00\times10^{-3}\text{ N/m}^2\right)}{\left(1.20\text{ kg/m}^3\right)(343\text{ m/s})(2\pi)\left(10.0\times10^{3}\text{ s}^{-1}\right)} = \boxed{1.55\times10^{-10}\text{ m}}$$

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

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

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

(b) $s = 2.00\cos\left[(15.7)(0.050\,0) - (858)\left(3.00\times10^{-3}\right)\right] = \boxed{-0.433\ \mu\text{m}}$

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

P17.12 (a) $\Delta P = (1.27\text{ Pa})\sin\left(\dfrac{\pi x}{\text{m}} - \dfrac{340\pi t}{\text{s}}\right)$ (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) $k = \dfrac{2\pi}{\lambda} = \pi/\text{m}$, 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,

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

P17.14 (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, $\Delta P_{\max} = \rho v \omega s_{\max}$

$$s_{\max} = \frac{\Delta P_{\max}}{\rho v \omega} = \frac{6.50 \times 10^8\text{ N/m}^2}{(8.92 \times 10^3\text{ kg/m}^3)(5\,010\text{ m/s})(2\pi 500/\text{s})} = \boxed{4.63\text{ mm}}$$

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

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

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

(c) $I = \frac{1}{2}\rho v(\omega s_{\max})^2 = \frac{1}{2}\rho v v_{\max}^2 = \frac{1}{2}(8.92 \times 10^3\text{ kg/m}^3)(5\,010\text{ m/s})(14.5\text{ m/s})^2$

$$= \boxed{4.73 \times 10^9\text{ W/m}^2}$$

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

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

Section 17.3 **Intensity of Periodic Sound Waves**

P17.16 The sound power incident on the eardrum is $\mathcal{P} = IA$ 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

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

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

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

P17.17 $\beta = 10\log\left(\frac{I}{I_0}\right) = 10\log\left(\frac{4.00 \times 10^{-6}}{1.00 \times 10^{-12}}\right) = \boxed{66.0\text{ dB}}$

P17.18 The power necessarily supplied to the speaker is the power carried away by the sound wave:

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

$$= 2\pi^2\left(1.20\ \text{kg/m}^3\right)\pi\left(\frac{0.08\ \text{m}}{2}\right)^2 (343\ \text{m/s})(600\ 1/\text{s})^2\left(0.12\times10^{-2}\ \text{m}\right)^2 = \boxed{21.2\ \text{W}}$$

P17.19 $I = \frac{1}{2}\rho\omega^2 s_{\max}^2 v$

(a) At $f = 2\,500$ Hz, the frequency is increased by a factor of 2.50, so the intensity (at constant $s_{\max}$) increases by $(2.50)^2 = 6.25$.

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

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

P17.20 The original intensity is $I_1 = \frac{1}{2}\rho\omega^2 s_{\max}^2 v = 2\pi^2\rho v f^2 s_{\max}^2$

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

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

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

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

or the $\boxed{\text{intensity is unchanged}}$.

P17.21 (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) $\beta = 10\ \text{dB}\log\left(\frac{I}{10^{-12}\ \text{W/m}^2}\right) = 75$ dB gives $I = 3.16\times10^{-5}\ \text{W/m}^2$

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

$$\Delta P_{\max} = \sqrt{3.16\times10^{-5}\ \text{W/m}^2\, 2\left(1.20\ \text{kg/m}^3\right)(343\ \text{m/s})} = \boxed{0.161\ \text{Pa}}$$

for both low and high notes.

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

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

for the low note, $s_{\max} = \sqrt{\frac{3.16\times10^{-5}\ \text{W/m}^2}{2\pi^2 1.20\ \text{kg/m}^3\ 343\ \text{m/s}}}\frac{1}{146.8/\text{s}}$

$$= \frac{6.24\times10^{-5}}{146.8}\ \text{m} = \boxed{4.25\times10^{-7}\ \text{m}}$$

for the high note, $s_{\max} = \frac{6.24\times10^{-5}}{880}\ \text{m} = \boxed{7.09\times10^{-8}\ \text{m}}$

(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.

P17.22 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, $\beta_2 - \beta_1 = 10\log\left(\frac{r_1}{r_2}\right)^2 = \boxed{20\log\left(\frac{r_1}{r_2}\right)}$

P17.23 (a) $I_1 = \left(1.00\times10^{-12}\ \text{W/m}^2\right)10^{(\beta_1/10)} = \left(1.00\times10^{-12}\ \text{W/m}^2\right)10^{80.0/10}$

or $I_1 = 1.00\times10^{-4}\ \text{W/m}^2$

$I_2 = \left(1.00\times10^{-12}\ \text{W/m}^2\right)10^{(\beta_2/10)} = \left(1.00\times10^{-12}\ \text{W/m}^2\right)10^{75.0/10}$

or $I_2 = 1.00\times10^{-4.5}\ \text{W/m}^2 = 3.16\times10^{-5}\ \text{W/m}^2$

When both sounds are present, the total intensity is

$$I = I_1 + I_2 = 1.00\times10^{-4}\ \text{W/m}^2 + 3.16\times10^{-5}\ \text{W/m}^2 = \boxed{1.32\times10^{-4}\ \text{W/m}^2}$$

(b) The decibel level for the combined sounds is

$$\beta = 10\log\left(\frac{1.32\times10^{-4}\ \text{W/m}^2}{1.00\times10^{-12}\ \text{W/m}^2}\right) = 10\log\left(1.32\times10^{8}\right) = \boxed{81.2\ \text{dB}}$$

P17.24 In $I = \dfrac{\mathcal{P}}{4\pi r^2}$, intensity I is proportional to $\dfrac{1}{r^2}$, so between locations 1 and 2: $\dfrac{I_2}{I_1} = \dfrac{r_1^2}{r_2^2}$

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

Then, $\left(\dfrac{s_2}{s_1}\right)^2 = \left(\dfrac{r_1}{r_2}\right)^2$ or $\left(\dfrac{1}{2}\right)^2 = \left(\dfrac{r_1}{r_2}\right)^2$ 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 $d = \boxed{86.6\text{ m}}$

P17.25 (a) $120\text{ dB} = 10\text{ dB}\log\left[\dfrac{I}{10^{-12}\text{ W/m}^2}\right]$

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

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

We have assumed the speaker is an isotropic point source.

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

$$I = 1.00\times10^{-12}\text{ W/m}^2$$

$$r = \sqrt{\frac{\mathcal{P}}{4\pi I}} = \sqrt{\frac{6.00\text{ W}}{4\pi(1.00\times10^{-12}\text{ W/m}^2)}} = \boxed{691\text{ km}}$$

We have assumed a uniform medium that absorbs no energy.

P17.26 We presume the speakers broadcast equally in all directions.

(a) $r_{AC} = \sqrt{3.00^2 + 4.00^2}\text{ m} = 5.00\text{ m}$

$$I = \frac{\mathcal{P}}{4\pi r^2} = \frac{1.00\times10^{-3}\text{ W}}{4\pi(5.00\text{ m})^2} = 3.18\times10^{-6}\text{ W/m}^2$$

$$\beta = 10\text{ dB}\log\left(\frac{3.18\times10^{-6}\text{ W/m}^2}{10^{-12}\text{ W/m}^2}\right)$$

$$\beta = 10\text{ dB }6.50 = \boxed{65.0\text{ dB}}$$

(b) $r_{BC} = 4.47\text{ m}$

$$I = \frac{1.50\times10^{-3}\text{ W}}{4\pi(4.47\text{ m})^2} = 5.97\times10^{-6}\text{ W/m}^2$$

$$\beta = 10\text{ dB}\log\left(\frac{5.97\times10^{-6}}{10^{-12}}\right)$$

$$\beta = \boxed{67.8\text{ dB}}$$

(c) $I = 3.18\ \mu\text{W/m}^2 + 5.97\ \mu\text{W/m}^2$

$$\beta = 10\text{ dB}\log\left(\frac{9.15\times10^{-6}}{10^{-12}}\right) = \boxed{69.6\text{ dB}}$$

P17.27 Since intensity is inversely proportional to the square of the distance,

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

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.

P17.28 (a) $E = \mathcal{P}t = 4\pi r^2 It = 4\pi(100 \text{ m})^2 (7.00\times 10^{-2} \text{ W/m}^2)(0.200 \text{ s}) = \boxed{1.76 \text{ kJ}}$

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

P17.29 $\beta = 10 \log\left(\frac{I}{10^{-12}}\right)$ $\quad I = \left[10^{(\beta/10)}\right]\left(10^{-12}\right) \text{ W/m}^2$

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

(a) $\mathcal{P} = 4\pi r^2 I$ 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) $r_2 = r_1\left(\frac{I_1}{I_2}\right)^{1/2} = (3.00 \text{ m})\sqrt{\frac{1.00}{1.00\times 10^{-11}}} = \boxed{9.49\times 10^5 \text{ m}}$

P17.30 Assume you are 1 m away from your lawnmower and receiving 100 dB sound from it. The intensity of this sound is given by $100\text{ dB} = 10\text{ dB}\log\dfrac{I}{10^{-12}\text{ W/m}^2}$; $I = 10^{-2}\text{ W/m}^2$. If the lawnmower radiates as a point source, its sound power is given by $I = \dfrac{\mathcal{P}}{4\pi r^2}$

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

Now let your neighbor have an identical lawnmower 20 m away. You receive from it sound with intensity $I = \dfrac{0.126\text{ W}}{4\pi(20\text{ m})^2} = 2.5\times10^{-5}\text{ W/m}^2$. The total sound intensity impinging on you is $10^{-2}\text{ W/m}^2 + 2.5\times10^{-5}\text{ W/m}^2 = 1.002\,5\times10^{-2}\text{ W/m}^2$. So its level is

$$10\text{ dB}\log\frac{1.002\,5\times10^{-2}}{10^{-12}} = 100.01\text{ dB}$$

If the smallest noticeable difference is between 100 dB and 101 dB, this $\boxed{\text{cannot}}$ be heard as a change from 100 dB.

P17.31 (a) The sound intensity inside the church is given by

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

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

$$I = 10^{10.1}\left(10^{-12}\text{ W/m}^2\right) = 10^{-1.90}\text{ W/m}^2 = 0.012\,6\text{ W/m}^2$$

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

$$\mathcal{P} = IA = \left(0.012\,6\text{ W/m}^2\right)\left(22.0\text{ m}^2\right) = 0.277\text{ W}$$

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

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

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

$$A = 2\pi r^2 = 2\pi(1\,000\text{ m})^2 = 2\pi\times10^6\text{ m}^2$$

The intensity at this distance is

$$I = \frac{\mathcal{P}}{A} = \frac{0.277\text{ W}}{2\pi\times10^6\text{ m}^2} = 4.41\times10^{-8}\text{ W/m}^2$$

and the sound intensity level is

$$\beta = (10\text{ dB})\ln\left(\frac{4.41\times10^{-8}\text{ W/m}^2}{1.00\times10^{-12}\text{ W/m}^2}\right) = \boxed{46.4\text{ dB}}$$

Section 17.4 **The Doppler Effect**

P17.32 (a) $\omega = 2\pi f = 2\pi\left(\frac{115/\text{min}}{60.0\ \text{s/min}}\right) = 12.0\ \text{rad/s}$

$$v_{\max} = \omega A = (12.0\ \text{rad/s})(1.80\times 10^{-3}\ \text{m}) = \boxed{0.021\,7\ \text{m/s}}$$

(b) The heart wall is a moving observer.

$$f' = f\left(\frac{v+v_O}{v}\right) = (2\,000\,000\ \text{Hz})\left(\frac{1\,500 + 0.021\,7}{1\,500}\right) = \boxed{2\,000\,028.9\ \text{Hz}}$$

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

$$f'' = f'\left(\frac{v}{v-v_s}\right) = (2\,000\,029\ \text{Hz})\left(\frac{1\,500}{1\,500 - 0.021\,7}\right) = \boxed{2\,000\,057.8\ \text{Hz}}$$

***P17.33** (a) $f' = \frac{f(v+v_o)}{(v-v_s)}$

$$f' = 2\,500\frac{(343+25.0)}{(343-40.0)} = \boxed{3.04\ \text{kHz}}$$

(b) $f' = 2\,500\left(\frac{343+(-25.0)}{343-(-40.0)}\right) = \boxed{2.08\ \text{kHz}}$

(c) $f' = 2\,500\left(\frac{343+(-25.0)}{343-40.0}\right) = \boxed{2.62\ \text{kHz}}$ while police car overtakes

$f' = 2\,500\left(\frac{343+25.0}{343-(-40.0)}\right) = \boxed{2.40\ \text{kHz}}$ after police car passes

P17.34 (a) The maximum speed of the speaker is described by

$$\frac{1}{2}mv_{\max}^2 = \frac{1}{2}kA^2$$

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

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.

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

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

continued on next page

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

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).

Thus,

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

or

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

This gives:

$$60.0\text{ dB} - \beta_{\min} = 10\text{ dB}\log(4.00) = 6.02\text{ dB} \qquad \text{and} \qquad \beta_{\min} = \boxed{54.0\text{ dB}}$$

P17.35 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 $\quad 560\left(1 - \frac{v_S}{v}\right) = 480\left(1 + \frac{v_S}{v}\right)$

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

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

P17.36 (a) $v = (331\text{ m/s}) + 0.6\frac{\text{m}}{\text{s}\cdot{}^\circ\text{C}}(-10^\circ\text{C}) = \boxed{325\text{ m/s}}$

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

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

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

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

P17.37 $f' = f\left(\frac{v}{v - v_s}\right) \qquad 485 = 512\left(\frac{340}{340 - (-9.80t_{\text{fall}})}\right)$

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

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

$d_1 = \frac{1}{2}gt_f^2 = 18.3$ m: $\qquad t_{\text{return}} = \frac{18.3}{340} = 0.053\,8$ s

The fork continues to fall while the sound returns.

$$t_{\text{total fall}} = t_f + t_{\text{return}} = 1.93\text{ s} + 0.053\,8\text{ s} = 1.985\text{ s}$$

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

P17.38 (a) Sound moves upwind with speed $(343-15)$ m/s. Crests pass a stationary upwind point at frequency 900 Hz.

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

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

(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.

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

P17.39 (b) $\sin\theta = \dfrac{v}{v_S} = \dfrac{1}{3.00}$; $\theta = 19.5°$

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

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

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

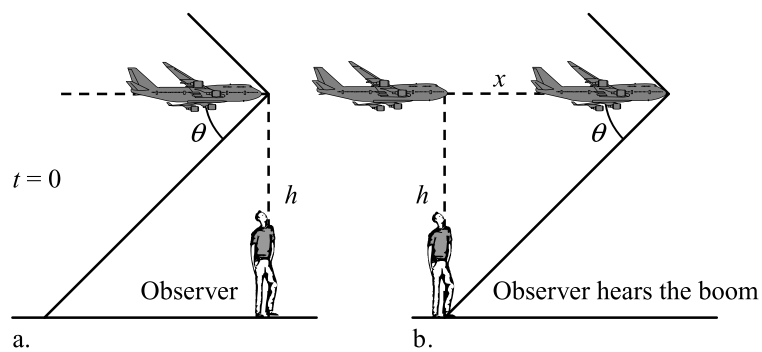

FIG. P17.39(a)

P17.40 $$\theta = \sin^{-1}\frac{v}{v_S} = \sin^{-1}\frac{1}{1.38} = \boxed{46.4°}$$

P17.41 The *half angle* of the shock wave cone is given by $\sin\theta = \dfrac{v_{\text{light}}}{v_S}$

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

Section 17.5 **Digital Sound Recording**

Section 17.6 **Motion Picture Sound**

P17.42 For a 40-dB sound,

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

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

$$\Delta P_{\max} = \sqrt{2\rho v I} = \sqrt{2\left(1.20\ \text{kg/m}^3\right)\left(343\ \text{m/s}\right)10^{-8}\ \text{W/m}^2} = 2.87\times10^{-3}\ \text{N/m}^2$$

(a) $\text{code} = \dfrac{2.87\times10^{-3}\ \text{N/m}^2}{28.7\ \text{N/m}^2}65\,536 = \boxed{7}$

(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.

Additional Problems

***P17.43** The gliders stick together and move with final speed given by momentum conservation for the two-glider system:

$$0.15\ \text{kg}\ 2.3\ \text{m/s} + 0 = (0.15 + 0.2)\ \text{kg}\ v \qquad v = 0.986\ \text{m/s}$$

The missing mechanical energy is

$$(1/2)(0.15\ \text{kg})(2.3\ \text{m/s})^2 - (1/2)(0.35\ \text{kg})(0.986\ \text{m/s})^2 = 0.397\ \text{J} - 0.170\ \text{J} = 0.227\ \text{J}$$

We imagine one-half of 227 mJ going into internal energy and half into sound radiated isotropically in 7 ms. Its intensity 0.8 m away is

$$I = E/At = 0.5(0.227\ \text{J})/[4\pi(0.8\ \text{m})^2\ 0.007\ \text{s}] = 2.01\ \text{W/m}^2$$

Its intensity level is $\beta = 10\log(2.01/10^{-12}) = 123\ \text{dB}$

The sound of air track gliders latching together is many orders of magnitude less intense. The idea is unreasonable. Nearly all of the missing mechanical energy becomes internal energy in the latch.

***P17.44** The wave moves outward equally in all directions. (We can tell it is outward because of the negative sign in $1.36\,r - 2030\,t$.) Its amplitude is inversely proportional to its distance from the center. Its intensity is proportional to the square of the amplitude, so the intensity follows the inverse-square law, with no absorption of energy by the medium. Its speed is constant at $v = f\lambda = \omega/k = (2030/\text{s})/(1.36/\text{m}) = 1.49$ km/s. By comparison to the table in the chapter, it can be moving through water at 25°C, and we assume that it is. Its frequency is constant at $(2030/\text{s})/2\pi = 323$ Hz. Its wavelength is constant at $2\pi/k = 2\pi/(1.36/\text{m}) = 4.62$ m. Its pressure amplitude is 25.0 Pa at radius 1 m. Its intensity at this distance is

$$I = \frac{\Delta P_{\max}^2}{2\rho v} = \frac{\left(25\ \text{N/m}^2\right)^2}{2(1000\ \text{kg/m}^3)(1490\ \text{m/s})} = 209\ \mu\text{W/m}^2$$

so the power of the source and the net power of the wave at all distances is $\mathcal{P} = I4\pi r^2 = \left(2.09\times10^{-4}\ \text{W/m}^2\right)4\pi(1\ \text{m})^2 = 2.63$ mW.

***P17.45** 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

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

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

$$\frac{1}{0.003\,5\ \text{s}} = 300\ \text{Hz}\ \boxed{\sim \text{a few hundred Hz}}$$

wavelength

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

and duration

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

(b) Yes. With the steps narrower, the frequency can be close to 1000 Hz. If the person clapping his hands is at the base of the pyramid, the echo can drop somewhat in frequency and in loudness as sound returns, with the later cycles coming from the smaller and more distant upper risers. The sound could imitate some particular bird, and could in fact constitute a recording of the call.

***P17.46** (a) The distance is larger by 240/60 = 4 times. The intensity is 16 times smaller at the larger distance, because the sound power is spread over a 4^2 times larger area.

(b) The amplitude is 4 times smaller at the larger distance, because intensity is proportional to the square of amplitude.

(c) The extra distance is (240 – 60)/45 = 4 wavelengths. The phase is the same at both points, because they are separated by an integer number of wavelengths.

P17.47 Since $\cos^2\theta + \sin^2\theta = 1$, $\quad \sin\theta = \pm\sqrt{1-\cos^2\theta}$ (each sign applying half the time)

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

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

P17.48 (a) $\lambda = \dfrac{v}{f} = \dfrac{343\ \text{m/s}}{1\,480\ \text{s}^{-1}} = \boxed{0.232\ \text{m}}$

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

$$I = \left(10^{-12}\ \text{W/m}^2\right)10^{8.10} = 10^{-3.90}\ \text{W/m}^2 = 1.26\times10^{-4}\ \text{W/m}^2 = \frac{1}{2}\rho v\omega^2 s_{\max}^2$$

$$s_{\max} = \sqrt{\frac{2I}{\rho v\omega^2}} = \sqrt{\frac{2\left(1.26\times10^{-4}\ \text{W/m}^2\right)}{\left(1.20\ \text{kg/m}^3\right)(343\ \text{m/s})4\pi^2\left(1\,480\ \text{s}^{-1}\right)^2}} = \boxed{8.41\times10^{-8}\ \text{m}}$$

(c) $\lambda' = \dfrac{v}{f'} = \dfrac{343\ \text{m/s}}{1\,397\ \text{s}^{-1}} = 0.246\ \text{m} \qquad \Delta\lambda = \lambda' - \lambda = \boxed{13.8\ \text{mm}}$

P17.49 The trucks form a train analogous to a wave train of crests with speed $v = 19.7\ \text{m/s}$ and unshifted frequency $f = \dfrac{2}{3.00\ \text{min}} = 0.667\ \text{min}^{-1}$

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

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

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

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

P17.50 (a) The speed of a compression wave in a bar is

$$v = \sqrt{\frac{Y}{\rho}} = \sqrt{\frac{20.0\times10^{10}\ \text{N/m}^2}{7\,860\ \text{kg/m}^3}} = \boxed{5.04\times10^3\ \text{m/s}}$$

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

$$t = \frac{L}{v} = \frac{0.800\ \text{m}}{5.04\times10^3\ \text{m/s}} = \boxed{1.59\times10^{-4}\ \text{s}}$$

continued on next page

(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

$$\Delta L = v_i t = (12.0 \text{ m/s})(1.59\times10^{-4} \text{ s}) = 1.90\times10^{-3} \text{ m} = \boxed{1.90 \text{ mm}}$$

(d) The strain in the rod is: $\dfrac{\Delta L}{L} = \dfrac{1.90\times10^{-3} \text{ m}}{0.800 \text{ m}} = \boxed{2.38\times10^{-3}}$

(e) The stress in the rod is: $\sigma = Y\left(\dfrac{\Delta L}{L}\right) = (20.0\times10^{10} \text{ N/m}^2)(2.38\times10^{-3}) = \boxed{476 \text{ MPa}}$

Since $\sigma > 400$ 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 $v = \sqrt{\dfrac{Y}{\rho}}$

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

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

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

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

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

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.

P17.51 (a) $f' = f\dfrac{v}{(v - v_{\text{diver}})}$

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

with $v = 343 \text{ m/s}$, $f = 1\,800$ Hz and $f' = 2\,150$ Hz

we find $v_{\text{diver}} = 343\left(1 - \dfrac{1\,800}{2\,150}\right) = \boxed{55.8 \text{ m/s}}$

(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 $f'' = 1\,800\dfrac{(343 + 55.8)}{(343 - 55.8)} = \boxed{2\,500 \text{ Hz}}$

P17.52 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 $\left[-\Delta P(x+\Delta x) + \Delta P(x)\right]A = -\dfrac{\partial \Delta P}{\partial x}\Delta x A$. The mass of the air is $\Delta m = \rho \Delta V = \rho A \Delta x$ and its acceleration is $\dfrac{\partial^2 s}{\partial t^2}$. So Newton's second law becomes

$$-\frac{\partial \Delta P}{\partial x}\Delta x A = \rho A \Delta x \frac{\partial^2 s}{\partial t^2}$$

$$-\frac{\partial}{\partial x}\left(-B\frac{\partial s}{\partial x}\right) = \rho \frac{\partial^2 s}{\partial t^2}$$

$$\frac{B}{\rho}\frac{\partial^2 s}{\partial x^2} = \frac{\partial^2 s}{\partial t^2}$$

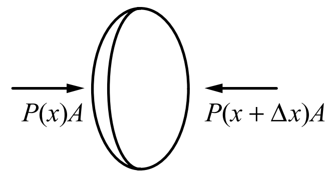

FIG. P17.52

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

$$\frac{\partial s}{\partial x} = -ks_{\max}\sin(kx - \omega t)$$

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

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

$$\frac{\partial^2 s}{\partial t^2} = -\omega^2 s_{\max}\cos(kx - \omega t)$$

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

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

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

P17.53 When observer is moving in front of and in the same direction as the source, $f' = f\dfrac{v - v_O}{v - v_S}$ 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,

$$f' = (1\,200.0\ \text{Hz})\frac{1\,520\ \text{m/s} - 15.3\ \text{m/s}}{1\,520\ \text{m/s} - 20.55\ \text{m/s}} = \boxed{1\,204.2\ \text{Hz}}$$

P17.54 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, $\boxed{\text{the bat is gaining on its prey at 1.69 m/s}}$.

P17.55 $$103\text{ dB} = 10\text{ dB}\log\left[\frac{I}{10^{-12}\ \text{W/m}^2}\right]$$

(a) $$I = 2.00\times10^{-2}\ \text{W/m}^2 = \frac{\mathcal{P}}{4\pi r^2} = \frac{\mathcal{P}}{4\pi(1.6\text{ m})^2}$$

$$\mathcal{P} = \boxed{0.642\text{ W}}$$

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

P17.56 (a)

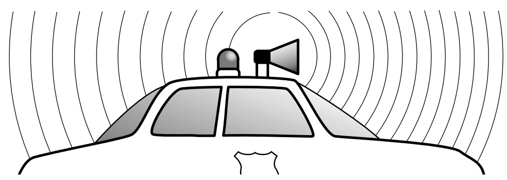

FIG. P17.56(a)

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

(c) $$\lambda' = \frac{v}{f'} = \frac{v}{f}\left(\frac{v - v_S}{v}\right) = \frac{(343-40.0)\text{ m/s}}{1\ 000\text{ s}^{-1}} = \boxed{0.303\text{ m}}$$

(d) $$\lambda'' = \frac{v}{f''} = \frac{v}{f}\left(\frac{v + v_S}{v}\right) = \frac{(343+40.0)\text{ m/s}}{1\ 000\text{ s}^{-1}} = \boxed{0.383\text{ m}}$$

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

***P17.57** (a) $\boxed{\text{The sound through the metal arrives first, because it moves faster than sound in air.}}$

(b) Each travel time is individually given by $\Delta t = L/v$. Then the delay between the pulses' arrivals is

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

and the length of the bar is $$L = \frac{v_{\text{air}}v_{\text{cu}}}{v_{\text{cu}} - v_{\text{air}}}\Delta t = \frac{(331\text{ m/s})(3.56\times10^3\text{ m/s})}{(3\ 560-331)\text{ m/s}}\Delta t = \boxed{(365\text{ m/s})\Delta t}$$

(c) $L = (365\text{ m/s})(0.127\text{ s}) = \boxed{46.3\text{ m}}$

(d) The answer becomes $L = \dfrac{\Delta t}{\dfrac{1}{331\text{ m/s}} - \dfrac{1}{v_r}}$ where v_r is the speed of sound in the rod. As v_r goes to infinity, the travel time in the rod becomes negligible. The answer approaches $(331\text{ m/s})\Delta t$, which is just the distance that the sound travels in air during the delay time.

P17.58 $$\mathcal{P}_2 = \frac{1}{20.0}\mathcal{P}_1 \quad \beta_1 - \beta_2 = 10\log\frac{\mathcal{P}_1}{\mathcal{P}_2}$$

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

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

P17.59 (a) $\theta=\sin^{-1}\left(\dfrac{v_{\text{sound}}}{v_{\text{obj}}}\right)=\sin^{-1}\left(\dfrac{331}{20.0\times10^{3}}\right)=\boxed{0.948^\circ}$

(b) $\theta'=\sin^{-1}\left(\dfrac{1\,533}{20.0\times10^{3}}\right)=\boxed{4.40^\circ}$

P17.60 Let T represent the period of the source vibration, and E be the energy put into each wavefront. Then $\mathcal{P}_{\text{av}}=\dfrac{E}{T}$. 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 $vt-v_St=r$. Then,

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

The area of the sphere is $4\pi(vt)^2=\dfrac{4\pi v^2r^2}{(v-v_S)^2}$. The energy per unit area over the spherical wavefront is uniform with the value $\dfrac{E}{A}=\dfrac{\mathcal{P}_{\text{av}}T(v-v_S)^2}{4\pi v^2r^2}$. The observer receives parcels of energy with the Doppler shifted frequency $f'=f\left(\dfrac{v}{v-v_S}\right)=\dfrac{v}{T(v-v_S)}$, so the observer receives a wave with intensity

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

P17.61 For the longitudinal wave $v_L=\left(\dfrac{Y}{\rho}\right)^{1/2}$

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

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

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

This gives

$$T=\frac{\pi r^2Y}{64.0}=\frac{\pi\left(2.00\times10^{-3}\text{ m}\right)^2\left(6.80\times10^{10}\text{ N/m}^2\right)}{64.0}=\boxed{1.34\times10^{4}\text{ N}}$$

P17.62 (a) If the source and the observer are moving away from each other, we have: $\theta_S = \theta_0 = 180°$, and since $\cos 180° = -1$, we get Equation (17.13) with negative values for both v_O and v_S.

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

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

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

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

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 between the limits

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

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

P17.63 (a) The time required for a sound pulse to travel distance L at speed v is given by $t = \dfrac{L}{v} = \dfrac{L}{\sqrt{Y/\rho}}$

Using this expression we find

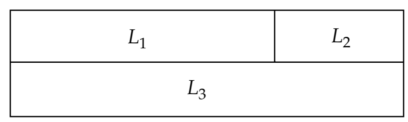

FIG. P17.63

$$t_1 = \frac{L_1}{\sqrt{Y_1/\rho_1}} = \frac{L_1}{\sqrt{(7.00 \times 10^{10} \text{ N/m}^2)/(2\,700 \text{ kg/m}^3)}} = (1.96 \times 10^{-4} L_1) \text{ s}$$

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

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

$$t_3 = \frac{1.50 \text{ m}}{\sqrt{(11.0 \times 10^{10} \text{ N/m}^3)/(8\,800 \text{ kg/m}^3)}}$$

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

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 $L_1 = 1.30$ m and $L_2 = 1.50 - 1.30 = 0.201$ m

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

(b) The ratio of lengths $\dfrac{L_1}{L_2}$ 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 $\boxed{\Delta\phi = 0}$.

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

P14.8 (a) The speed decreases by 4.6%, from 347 m/s to 331 m/s. (b) The frequency is unchanged, because every wave crest in the hot air becomes one crest without delay in the cold air. (c) The wavelength decreases by 4.6%, from 86.7 mm to 82.8 mm. The crests are more crowded together when they move slower.

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 (a) 4.63 mm (b) 14.5 m/s (c) 4.73×10^{9} W/m^2

P17.16 (a) 5.00×10^{-17} W (b) 5.00×10^{-5} W

P17.18 21.2 W

P17.20 (a) $I_2 = \left(\frac{f'}{f}\right)^2 I_1$ (b) $I_2 = I_1$

P17.22 see the solution

P17.24 86.6 m

P17.26 (a) 65.0 dB (b) 67.8 dB (c) 69.6 dB

P17.28 (a) 1.76 kJ (b) 108 dB

P17.30 no

P17.32 (a) 2.17 cm/s (b) 2 000 028.9 Hz (c) 2 000 057.8 Hz

P17.34 (a) 441 Hz; 439 Hz (b) 54.0 dB

P17.36 (a) 325 m/s (b) 29.5 m/s

P17.38 (a) 0.364 m (b) 0.398 m (c) 941 Hz (d) 938 Hz

P17.40 46.4°

P17.42 (a) 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.

P17.44 The wave moves outward equally in all directions. Its amplitude is inversely proportional to its distance from the center so that its intensity follows the inverse-square law, with no absorption of energy by the medium. Its speed is constant at 1.49 km/s, so it can be moving through water at 25°C, and we assume that it is. Its frequency is constant at 323 Hz. Its wavelength is constant at 4.62 m. Its pressure amplitude is 25.0 Pa at radius 1 m. Its intensity at this distance is 209 μW/m^2, so the power of the source and the net power of the wave at all distances is 2.63 mW.

P17.46 (a) The intensity is 16 times smaller at the larger distance, because the sound power is spread over a 4^2 times larger area. (b) The amplitude is 4 times smaller at the larger distance, because intensity is proportional to the square of amplitude. (c) The phase is the same at both points, because they are separated by an integer number of wavelengths.

P17.48 (a) 0.232 m (b) 84.1 nm (c) 13.8 mm

P17.50 (a) 5.04 km/s (b) 159 μs (c) 1.90 mm (d) 0.002 38 (e) 476 MPa (f) see the solution

P17.52 see the solution

P17.54 The gap between bat and insect is closing at 1.69 m/s.

P17.56 (a) see the solution (b) 0.343 m (c) 0.303 m (d) 0.383 m (e) 1.03 kHz

P17.58 67.0 dB

P17.60 see the solution

P17.62 (a) see the solution (b) 531 Hz