**20.1. Model**: The wave is a traveling wave on a stretched string.

**Solve:** The wave speed on a stretched string with linear density $\mu$ is $v_{\text{string}} = \sqrt{T_S / \mu}$. The wave speed if the tension is doubled will be

$$v'_{\text{string}} = \sqrt{\frac{2T_S}{\mu}} = \sqrt{2}v_{\text{string}} = \sqrt{2}\left(200 \text{ m/s}\right) = 283 \text{ m/s}$$

**20.2. Model:** The wave is a traveling wave on a stretched string.

**Solve:** The wave speed on a stretched string with linear density $\mu$ is

$$v_{\text{string}} = \sqrt{\frac{T_S}{\mu}} \Rightarrow 150 \text{ m/s} = \sqrt{\frac{75 \text{ N}}{\mu}} \Rightarrow \mu = 3.333 \times 10^{-3} \text{ kg/m}$$

For a wave speed of 180 m/s, the required tension will be

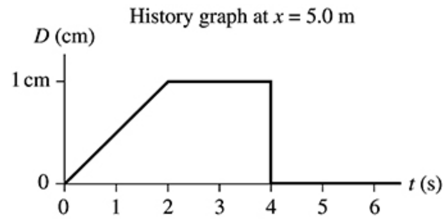
$$T_S = \mu v_{\text{string}}^2 = (3.333 \times 10^{-3} \text{ kg/m})(180 \text{ m/s})^2 = 110 \text{ N}$$

**20.3. Model:** The wave pulse is a traveling wave on a stretched string.

**Solve:** The wave speed on a stretched string with linear density $\mu$ is

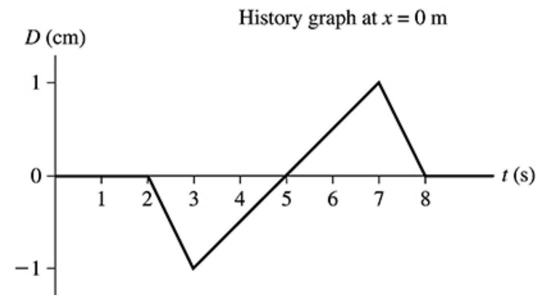
$$v_{\text{string}} = \sqrt{\frac{T_S}{\mu}} = \sqrt{\frac{T_S}{m/L}} = \sqrt{\frac{LT_S}{m}} \Rightarrow \frac{2.0\text{ m}}{50\times10^{-3}\text{ s}} = \sqrt{\frac{(2.0\text{ m})(20\text{ N})}{m}} \Rightarrow m = 0.025\text{ kg} = 25\text{ g}$$

**20.4. Model:** This is a wave traveling at constant speed. The pulse moves 1 m to the right every second.
**Visualize:** The snapshot graph shows the wave at all points on the $x$-axis at $t = 0$ s. The wave is just reaching $x = 5.0$. The first part of the wave causes an upward displacement of the medium. The rising portion of the wave is 2 m wide, so it will take 2 s to pass the $x = 5.0$ m point. The constant part of the wave, whose width is 2 m, will take 2 seconds to pass $x = 5.0$ m and during this time the displacement of the medium will be a constant ($\Delta y = 1$ cm). The trailing edge of the pulse arrives at $t = 4$ s at $x = 5.0$ m. The displacement now becomes zero and stays zero for all later times.



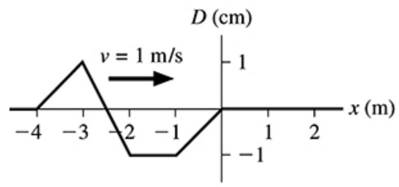
**20.5. Model:** This is a wave traveling at constant speed. The pulse moves 1 m to the left every second.

**Visualize:** This snapshot graph shows the wave at all points on the $x$-axis at $t = 2$ s. You can see that the leading edge of the wave at $t = 2$ s is precisely at $x = 0$ m. That is, in the first 2 seconds, the displacement is zero at $x = 0$ m. The first part of the wave causes a downward displacement of the medium, so immediately after $t = 2$ s the displacement at $x = 0$ m will be negative. The negative portion of the wave pulse is 3 m wide and takes 3 s to pass $x = 0$ m. The positive portion begins to pass through $x = 0$ m at $t = 5$ s and until $t = 8$ s the displacement of the medium is positive. The displacement at $x = 0$ m returns to zero at $t = 8$ s and remains zero for all later times.



**20.6. Model:** This is a wave traveling at constant speed to the right at 1 m/s.

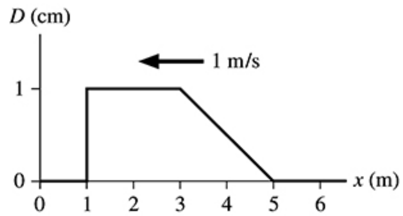
**Visualize:** This is the history graph of a wave at $x$ = 0 m. The graph shows that the $x$ = 0 m point of the medium first sees the negative portion of the pulse wave at $t$ = 1.0 s. Thus, the snapshot graph of this wave at $t$ = 1.0 s must have the leading negative portion of the wave at $x$ = 0 m.




Snapshot graph at $t$ = 1.0 s

**20.7. Model:** This is a wave traveling at constant speed to the left at 1 m/s.

**Visualize:** This is the history graph of a wave at $x = 2$ m. Because the wave is moving to the left at 1 m/s, the wave passes the $x = 2$ m position a distance of 1 m in 1 s. Because the flat part of the history graph takes 2 s to pass the $x = 2$ m position, its width is 2 m. Similarly, the width of the linearly increasing part of the history graph is 2 m. The center of the flat part of the history graph corresponds to both $t = 0$ s and $x = 2$ m.




Snapshot graph at $t = 0$ s

**20.8. Visualize**:

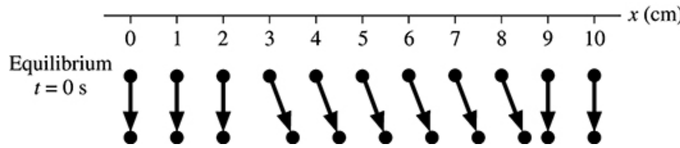
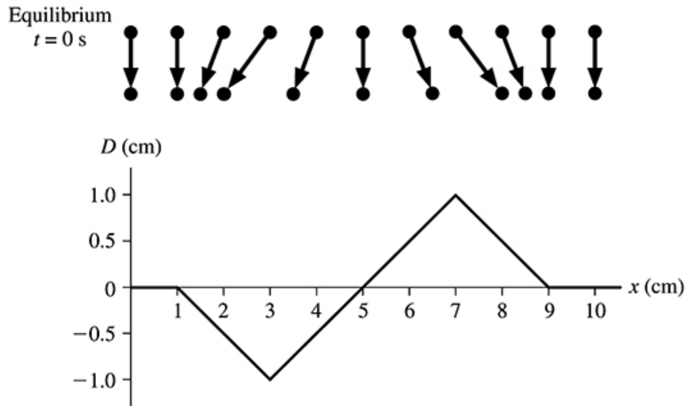



Figure EX20.8 shows a snapshot graph at $t = 0$ s of a longitudinal wave. This diagram shows a row of particles with an inter-particle separation of 1.0 cm at equilibrium. Because the longitudinal wave has a positive amplitude of 0.5 cm between $x = 3$ cm and $x = 8$ cm, the particles at $x = 3$, 4, 5, 6, 7 and 8 cm are displaced to the right by 0.5 cm.

**20.9. Visualize**:




We first draw the particles of the medium in the equilibrium positions, with an inter-particle spacing of 1.0 cm. Just underneath, the positions of the particles as a longitudinal wave is passing through are shown at time $t$ = 0 s. It is clear that relative to the equilibrium the particle positions are displaced negatively on the left side and positively on the right side. For example, the particles at $x$ = 0 cm and $x$ = 1 cm are at equilibrium, the particle at $x$ = 2 cm is displaced left by 0.5 cm, the particle at $x$ = 3 cm is displaced left by 1.0 cm, the particle at $x$ = 4 cm is displaced left by 0.5 cm, and the particle at $x$ = 5 cm is undisplaced. The behavior of particles for $x > 5$ cm is opposite of that for $x < 5$ cm.

**20.10. Solve:** **(a)** The wave number is

$$k = \frac{2\pi}{\lambda} = \frac{2\pi}{2.0 \text{ m}} = 3.1 \text{ rad/m}$$

**(b)** The wave speed is

$$v = \lambda f = \lambda\left(\frac{\omega}{2\pi}\right) = (2.0 \text{ m})\left(\frac{30 \text{ rad/s}}{2\pi}\right) = 9.5 \text{ m/s}$$

**20.11. Solve: (a)** The wavelength is

$$\lambda = \frac{2\pi}{k} = \frac{2\pi}{1.5 \text{ rad/m}} = 4.2 \text{ m}$$

**(b)** The frequency is

$$f = \frac{v}{\lambda} = \frac{200 \text{ m/s}}{4.19 \text{ m}} = 48 \text{ Hz}$$

**20.12.** **Model:** The wave is a traveling wave.

**Solve:** **(a)** A comparison of the wave equation with Equation 20.14 yields: $A$ = 3.5 cm, $k$ = 2.7 rad/m, $\omega$ = 124 rad/s, and $\phi_0 = 0$ rad. The frequency is

$$f = \frac{\omega}{2\pi} = \frac{124 \text{ rad/s}}{2\pi} = 19.7 \text{ Hz} \approx 20 \text{ Hz}$$

**(b)** The wavelength is

$$\lambda = \frac{2\pi}{k} = \frac{2\pi}{2.7 \text{ rad/m}} = 2.33 \text{ m} \approx 2.3 \text{ m}$$

**(c)** The wave speed $v = \lambda f = 46 \text{ m/s}$ .

**20.13. Model:** The wave is a traveling wave.

**Solve:** **(a)** A comparison of the wave equation with Equation 20.14 yields: $A$ = 5.2 cm, $k$ = 5.5 rad/m, $\omega$ = 72 rad/s, and $\phi_0 = 0$ rad. The frequency is

$$f = \frac{\omega}{2\pi} = \frac{72 \text{ rad/s}}{2\pi} = 11.5 \text{ Hz} \approx 11 \text{ Hz}$$

**(b)** The wavelength is

$$\lambda = \frac{2\pi}{k} = \frac{2\pi}{5.5 \text{ rad/m}} = 1.14 \text{ m} \approx 1.1 \text{ m}$$

**(c)** The wave speed $v = \lambda f = 13$ m/s.

**20.14.** **Solve:** The amplitude of the wave is the maximum displacement, which is 6.0 cm. The period of the wave is 0.60 s, so the frequency $f = 1/T = 1/0.60\text{ s} = 1.67\text{ Hz}$. The wavelength is

$$\lambda = \frac{v}{f} = \frac{2\text{ m/s}}{1.667\text{ Hz}} = 1.2\text{ m}$$

**20.15.** **Solve:** According to Equation 20.28, the phase difference between two points on a wave is

$$\Delta\phi = \phi_2 - \phi_1 = 2\pi\frac{\Delta r}{\lambda} = \frac{2\pi}{\lambda}(r_2 - r_1) \Rightarrow (3\pi \text{ rad} - 0 \text{ rad}) = \frac{2\pi}{\lambda}(80 \text{ cm} - 20 \text{ cm}) \Rightarrow \lambda = 40 \text{ cm}$$

**20.16. Solve:** According to Equation 20.28, the phase difference between two points on a wave is

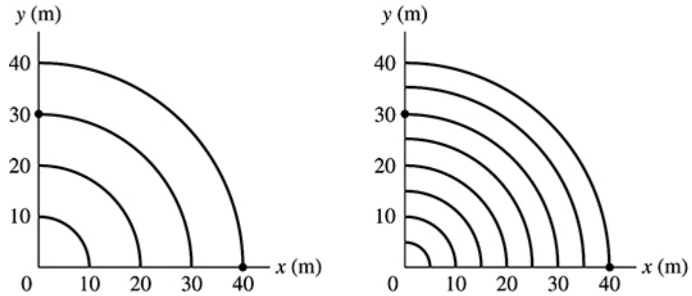
$$\Delta\phi = \phi_2 - \phi_1 = \frac{2\pi}{\lambda}(r_2 - r_1)$$

If $\phi_1 = \pi$ rad at $r_1$ = 4.0 m, we can determine $\phi_2$ at any $r$ value at the same instant using this equation. At $r_2$ = 3.5 m,

$$\phi_2 = \phi_1 + \frac{2\pi}{\lambda}(r_2 - r_1) = \pi \text{ rad} + \frac{2\pi}{2.0 \text{ m}}(3.5 \text{ m} - 4.0 \text{ m}) = \frac{\pi}{2} \text{ rad}$$

At $r_2$ = 4.5 m, $\phi = \frac{3}{2}\pi$ rad.

**20.17. Visualize**:




**Solve:** For a sinusoidal wave, the phase difference between two points on the wave is given by Equation 20.28:

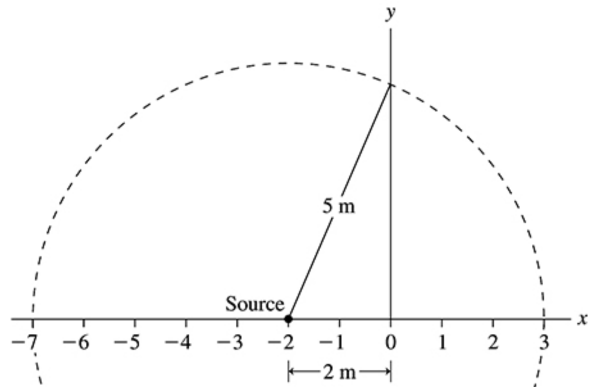
$$\Delta\phi = \phi_2 - \phi_1 = \frac{2\pi}{\lambda}(r_2 - r_1) = \frac{2\pi}{\lambda}(40\text{ m} - 30\text{ m}) \Rightarrow \lambda = \frac{2\pi}{\Delta\phi}(10\text{ m})$$

$\Delta\phi = 2\pi$ for two points on adjacent wavefronts and $\Delta\phi = 4\pi$ for two points separated by $2\lambda$. Thus, $\lambda$ = 10 m when $\Delta\phi = 2\pi$, and $\lambda$ = 5 m when $\Delta\phi = 4\pi$. The crests corresponding to these two wavelengths are shown in the figure. One can see that a crest of the wave passes the 40 m–listener and the 30 m–listener simultaneously. The lowest two possible frequencies will occur for the largest two possible wavelengths, which are 10 m and 5 m. Thus, the lowest frequency is

$$f_1 = \frac{v}{\lambda} = \frac{340\text{ m/s}}{10\text{ m}} = 34\text{ Hz}$$

The next highest frequency is $f_2 = 68$ Hz.

**20.18. Visualize:**




**Solve:** **(a)** Because the same wavefront simultaneously reaches listeners at $x = -7.0$ m and $x = +3.0$ m,

$$\Delta\phi = 0 \text{ rad} = \frac{2\pi}{\lambda}(r_2 - r_1) \Rightarrow r_2 = r_1$$

Thus, the source is at $x = -2.0$ m, so that it is equidistant from the two listeners.

**(b)** The third person is also 5.0 m away from the source. Her $y$-coordinate is thus $y = \sqrt{(5 \text{ m})^2 - (2 \text{ m})^2} = 4.6 \text{ m}$.

**20.19. Solve:** Two pulses of sound are detected because one pulse travels through the metal to the microphone while the other travels through the air to the microphone. The time interval for the sound pulse traveling through the air is

$$\Delta t_{\text{air}} = \frac{\Delta x}{v_{\text{air}}} = \frac{4.0 \text{ m}}{343 \text{ m/s}} = 0.01166 \text{ s} = 11.66 \text{ ms}$$

Sound travels *faster* through solids than gases, so the pulse traveling through the metal will reach the microphone *before* the pulse traveling through the air. Because the pulses are separated in time by 11.0 ms, the pulse traveling through the metal takes $\Delta t_{\text{metal}}$ = 0.66 ms to travel the 4.0 m to the microphone. Thus, the speed of sound in the metal is

$$v_{\text{metal}} = \frac{\Delta x}{\Delta t_{\text{metal}}} = \frac{4.0 \text{ m}}{0.00066 \text{ s}} = 6060 \text{ m/s} \approx 6100 \text{ m/s}$$

**20.20. Solve:** **(a)** In aluminum, the speed of sound is 6420 m/s. The wavelength is thus equal to

$$\lambda = \frac{v}{f} = \frac{6420 \text{ m/s}}{2.0 \times 10^6 \text{ Hz}} = 3.21 \times 10^{-3} \text{ m} = 3.21 \text{ mm} \approx 3.2 \text{ mm}$$

**(b)** The speed of an electromagnetic wave is *c*. The frequency would be

$$f = \frac{c}{\lambda} = \frac{3.0 \times 10^8 \text{ m/s}}{3.21 \times 10^{-3} \text{ m}} = 9.3 \times 10^{10} \text{ Hz}$$

**20.21. Solve:** **(a)** The frequency is

$$f = \frac{v_{\text{air}}}{\lambda} = \frac{343 \text{ m/s}}{0.20 \text{ m}} = 1715 \text{ Hz} \approx 1700 \text{ Hz}$$

**(b)** The frequency is

$$f = \frac{c}{\lambda} = \frac{3.0 \times 10^8 \text{ m/s}}{0.20 \text{ m}} = 1.5 \times 10^9 \text{ Hz} = 1.5 \text{ GHz}$$

**(c)** The speed of a sound wave in water is $v_{\text{water}}$ = 1480 m/s. The wavelength of the sound wave would be $\lambda = \frac{v_{\text{water}}}{f} = \frac{1480 \text{ m/s}}{1.50 \times 10^9 \text{ Hz}} = 9.87 \times 10^{-7} \text{ m} \approx 990 \text{ nm}$

**20.22. Model:** Light is an electromagnetic wave that travels with a speed of $3 \times 10^8$ m/s.

**Solve:** **(a)** The frequency of the blue light is

$$f_{\text{blue}} = \frac{c}{\lambda} = \frac{3.0 \times 10^8 \text{ m/s}}{450 \times 10^{-9} \text{ m}} = 6.67 \times 10^{14} \text{ Hz}$$

**(b)** The frequency of the red light is

$$f_{\text{red}} = \frac{3.0 \times 10^8 \text{ m/s}}{650 \times 10^{-9} \text{ m}} = 4.62 \times 10^{14} \text{ Hz}$$

**(c)** Using Equation 20.30 to calculate the index of refraction,

$$\lambda_{\text{material}} = \frac{\lambda_{\text{vacuum}}}{n} \Rightarrow n = \frac{\lambda_{\text{vacuum}}}{\lambda_{\text{material}}} = \frac{650 \text{ nm}}{450 \text{ nm}} = 1.44$$

**20.23. Model:** Microwaves are electromagnetic waves that travel with a speed of $3 \times 10^8$ m/s.

**Solve:** **(a)** The frequency of the microwave is

$$f_{\text{microwaves}} = \frac{c}{\lambda} = \frac{3.0 \times 10^8 \text{ m/s}}{3.0 \times 10^{-2} \text{ m}} = 1.0 \times 10^{10} \text{ Hz} = 10 \text{ GHz}$$

**(b)** The refractive index of air is 1.0003, so the speed of microwaves in air is $v_{\text{air}} = c/1.00 \approx \text{c}$. The time for the microwave signal to travel is

$$t = \frac{50 \text{ km}}{v_{\text{air}}} = \frac{50 \times 10^3 \text{ m}}{\left(3.0 \times 10^8 \text{ m}/1.00\right)} = 0.167 \text{ ms} \approx 0.17 \text{ ms}$$

**Assess:** A small time of 0.17 ms for the microwaves to cover a distance of 50 km shows that the electromagnetic waves travel very fast.

**20.24. Model:** Radio waves are electromagnetic waves that travel with speed $c$.

**Solve:** **(a)** The wavelength is

$$\lambda = \frac{c}{f} = \frac{3.0 \times 10^8 \text{ m/s}}{101.3 \text{ MHz}} = 2.96 \text{ m}$$

**(b)** The speed of sound in air at $20°\text{C}$ is 343 m/s. The frequency is

$$f = \frac{v_{\text{sound}}}{\lambda} = \frac{343 \text{ m/s}}{2.96 \text{ m}} = 116 \text{ Hz}$$

**20.25. Model:** Light is an electromagnetic wave.

**Solve:** **(a)** The time light takes is

$$t=\frac{3.0\text{ mm}}{v_{\text{glass}}}=\frac{3.0\times10^{-3}\text{ m}}{c/n}=\frac{3.0\times10^{-3}\text{ m}}{\left(3.0\times10^{8}\text{ m/s}\right)/1.50}=1.5\times10^{-11}\text{ s}$$

**(b)** The thickness of water is

$$d=v_{\text{water}}t=\frac{c}{n_{\text{water}}}t=\frac{3.0\times10^{8}\text{ m/s}}{1.33}\left(1.5\times10^{-11}\text{ s}\right)=3.4\text{ mm}$$

**20.26. Solve: (a)** The speed of light in a material is given by Equation 20.29:

$$n = \frac{c}{v_{\text{mat}}} \Rightarrow v_{\text{mat}} = \frac{c}{n}$$

The refractive index is

$$n = \frac{\lambda_{\text{vac}}}{\lambda_{\text{mat}}} \Rightarrow v_{\text{solid}} = c\frac{\lambda_{\text{solid}}}{\lambda_{\text{vac}}} = \left(3.0\times10^{8}\ \text{m/s}\right)\frac{420\ \text{nm}}{670\ \text{nm}} = 1.88\times10^{8}\ \text{m/s}$$

**(b)** The frequency is

$$f = \frac{v_{\text{solid}}}{\lambda_{\text{solid}}} = \frac{1.88\times10^{8}\ \text{m/s}}{420\ \text{nm}} = 4.48\times10^{14}\ \text{Hz}$$

**20.27. Model:** Assume that the glass has index of refraction $n = 1.5$. This means that $v_{\text{glass}} = c/n = 2 \times 10^8$ m/s.

**Visualize:** We apply $v = \lambda f$ twice, once in air and then in the glass. The frequency will be the same in both cases.

**Solve:** **(a)** In the air

$$f_{\text{air}} = \frac{v_{\text{air}}}{\lambda_{\text{air}}} = \frac{3.0 \times 10^8 \text{ m/s}}{0.35 \text{ m}} = 8.57 \times 10^8 \text{ Hz} \approx 8.6 \times 10^8 \text{ Hz}$$

The frequency is the same in both media, so $f_{\text{glass}} = 8.6 \times 10^8$ Hz.

**(b)** Now that we know $f_{\text{glass}}$ and $v_{\text{glass}}$, we can find $\lambda_{\text{glass}}$.

$$\lambda_{\text{glass}} = \frac{v_{\text{glass}}}{f_{\text{glass}}} = \frac{2.0 \times 10^8 \text{ m/s}}{8.57 \times 10^8 \text{ Hz}} = 23 \text{ cm}$$

**Assess:** We get the same answer from $\lambda_{\text{glass}} = \lambda_{\text{air}}/n_{\text{glass}} = 35 \text{ cm}/1.5 = 23 \text{ cm}$.

**20.28. Solve:** The energy delivered to the eardrum in time $t$ is $E = Pt$, where $P$ is the power of the wave. The intensity of the wave is $I = P/a$ where $a$ is the area of the ear drum. Putting the above information together, we have

$$E = Pt = (Ia)t = I\pi r^2 t = (2.0\times10^{-3}\ \text{W/m}^2)\pi(3.0\times10^{-3}\ \text{m})^2(60\ \text{s}) = 3.4\times10^{-6}\ \text{J}$$

**20.29.** **Solve:** The energy delivered to an area $a$ in time $t$ is $E = Pt,$ where the power $P$ is related to the intensity $I$ as $I = P/a$. Thus, the energy received by your back is

$$E = Pt = Iat = (0.80)(1400\ \text{W/m}^2)(0.30 \times 0.50\ \text{m}^2)(3600\ \text{s}) = 6.0 \times 10^5\ \text{J}$$

**20.30.** **Solve:** If a source of spherical waves radiates uniformly in all directions, the ratio of the intensities at distances $r_1$ and $r_2$ is

$$\frac{I_1}{I_2}=\frac{r_2^2}{r_1^2}\Rightarrow\frac{I_{50\text{ m}}}{I_{2\text{ m}}}=\left(\frac{2\text{ m}}{50\text{ m}}\right)^2=1.6\times10^{-3}$$

$$\Rightarrow I_{50\text{ m}}=I_{2\text{ m}}\left(1.6\times10^{-3}\right)=\left(2.0\text{ W/m}^2\right)\left(1.6\times10^{-3}\right)=3.2\times10^{-3}\text{ W/m}^2$$

**Assess:** The power generated by the sound source is $P = I_{2m}\,[4\pi(2\text{ m})^2] = (2.0\text{ W/m}^2)(50.27) = 101\text{ W}$. This is a significant amount of power.

**20.31. Solve: (a)** The intensity of a uniform spherical source of power $P_{\text{source}}$ a distance $r$ away is $I = P_{\text{source}}/4\pi r^2$. Thus, the intensity at the position of the microphone is

$$I_{50\text{ m}} = \frac{35\text{ W}}{4\pi(50\text{ m})^2} = 1.1\times10^{-3}\text{ W/m}^2$$

**(b)** The sound energy impinging on the microphone per second is

$$P = Ia = \left(1.1\times10^{-3}\text{ W/m}^2\right)\left(1.0\times10^{-4}\text{ m}^2\right) = 1.1\times10^{-7}\text{ W} = 1.1\times10^{-7}\text{ J/s}$$

$$\Rightarrow \text{Energy impinging on the microphone in 1 second} = 1.1\times10^{-7}\text{ J}$$

**20.32. Solve:** Because the sun radiates waves uniformly in all directions, the intensity $I$ of the sun's rays when they impinge upon the earth is

$$I = \frac{P_{\text{sun}}}{4\pi r^2} \Rightarrow I_{\text{earth}} = \frac{P_{\text{sun}}}{4\pi r_{\text{earth}}^2} = \frac{4\times 10^{26}\ \text{W}}{4\pi\left(1.496\times 10^{11}\ \text{m}\right)^2} = 1400\ \text{W/m}^2$$

With $r_{\text{sun-Venus}} = 1.082 \times 10^{11}$ m and $r_{\text{sun-Mars}} = 2.279 \times 10^{11}$ m, the intensities of electromagnetic waves at these planets are $I_{\text{venus}} = 2700\ \text{W/m}^2$ and $I_{\text{Mars}} = 610\ \text{W/m}^2$.

**20.33. Visualize:** Equation 20.35 gives the sound intensity level as

$$\beta = (10\ \text{dB})\log_{10}\left(\frac{I}{I_0}\right)$$

where $I_0 = 1.0\times10^{-12}\ \text{W/m}^2$.

**Solve:**

**(a)**

$$\beta = (10\ \text{dB})\log_{10}\left(\frac{I}{I_0}\right) = (10\ \text{dB})\log_{10}\left(\frac{5.0\times10^{-8}\ \text{W/m}^2}{1.0\times10^{-12}\ \text{W/m}^2}\right) = 47\ \text{dB}$$

**(b)**

$$\beta = (10\ \text{dB})\log_{10}\left(\frac{I}{I_0}\right) = (10\ \text{dB})\log_{10}\left(\frac{5.0\times10^{-2}\ \text{W/m}^2}{1.0\times10^{-12}\ \text{W/m}^2}\right) = 107\ \text{dB}$$

**Assess:** As mentioned in the chapter, each factor of 10 in intensity changes the sound intensity level by 10 dB; between the first and second parts of this problem the intensity changed by a factor of $10^6$, so we expect the sound intensity level to change by 60 dB.

**20.34. Visualize:** We can solve Equation 20.35 for the sound intensity, finding $I = I_0 \times 10^{\beta/10\text{dB}}$.

**Solve:**

**(a)**

$$I = I_0 \times 10^{\beta/10\text{dB}} = (1.0\times10^{-12}\ \text{W/m}^2)\times10^{3.6} = 4.0\times10^{-9}\ \text{W/m}^2$$

**(b)**

$$I = I_0 \times 10^{\beta/10\text{dB}} = (1.0\times10^{-12}\ \text{W/m}^2)\times10^{9.6} = 4.0\times10^{-3}\ \text{W/m}^2$$

**Assess:** Since the sound intensity levels in the two parts of this problem differ by $60\text{dB}$ we expect the sound intensities to differ by a factor of $10^6$.

**20.35. Model:** Assume the pole is tall enough that we don't have to worry about the ground absorbing or reflecting sound.

**Visualize:** The area of a sphere of radius $R$ is $A = 4\pi R^2$. Also recall that $I = P/A$; we are given $P = 5.0\,\text{W}$. We seek $R$ for $\beta = 90\,\text{dB}$.

**Solve:**

$$A = \frac{P}{I} = \frac{P}{I_0 \times 10^{\beta/10\text{dB}}} = \frac{5.0\text{ W}}{(1.0\times10^{-12}\text{ W/m}^2)\times10^{90\text{dB}/10\text{dB}}} = 5000\text{ m}^2$$

$$R = \sqrt{\frac{A}{4\pi}} = \sqrt{\frac{5000\text{ m}^2}{4\pi}} = 20\text{ m}$$

**Assess:** This is a reasonable distance from the loudspeaker for a moderately loud sound.

**20.36. Model:** The frequency of the opera singer's note is altered by the Doppler effect.

**Solve:** **(a)** Using 90 km/h = 25 m/s, the frequency as her convertible approaches the stationary person is

$$f_+ = \frac{f_0}{1 - v_S/v} = \frac{600 \text{ Hz}}{1 - \dfrac{25 \text{ m/s}}{343 \text{ m/s}}} = 650 \text{ Hz}$$

**(b)** The frequency as her convertible recedes from the stationary person is

$$f_- = \frac{f_0}{1 + v_S/v} = \frac{600 \text{ Hz}}{1 + \dfrac{25 \text{ m/s}}{343 \text{ m/s}}} = 560 \text{ Hz}$$

**20.37. Model:** Your friend's frequency is altered by the Doppler effect. The frequency of your friend's note increases as he races towards you (moving source and a stationary observer). The frequency of your note for your approaching friend is also higher (stationary source and a moving observer).

**Solve:** **(a)** The frequency of your friend's note as heard by you is

$$f_+ = \frac{f_0}{1 - \dfrac{v_S}{v}} = \frac{400 \text{ Hz}}{1 - \dfrac{25.0 \text{ m/s}}{340 \text{ m/s}}} = 432 \text{ Hz}$$

**(b)** The frequency heard by your friend of your note is

$$f_+ = f_0\left(1 + \frac{v_0}{v}\right) = (400 \text{ Hz})\left(1 + \frac{25.0 \text{ m/s}}{340 \text{ m/s}}\right) = 429 \text{ Hz}$$

**20.38. Model:** Sound frequency is altered by the Doppler effect. The frequency increases for an observer approaching the source and decreases for an observer receding from a source.

**Solve:** You need to ride your bicycle away from your friend to lower the frequency of the whistle. The minimum speed you need to travel is calculated as follows:

$$f_{-} = \left(1 - \frac{v_0}{v}\right) f_0 \Rightarrow 20 \text{ kHz} = \left(1 - \frac{v_0}{343 \text{ m/s}}\right)(21 \text{ kHz}) \Rightarrow v_0 = 16.3 \text{ m/s} \approx 16 \text{ m/s}$$

**Assess:** A speed of 16.3 m/s corresponds to approximately 35 mph. This is a possible but very fast speed on a bicycle.

**20.39. Model:** The mother hawk's frequency is altered by the Doppler effect.

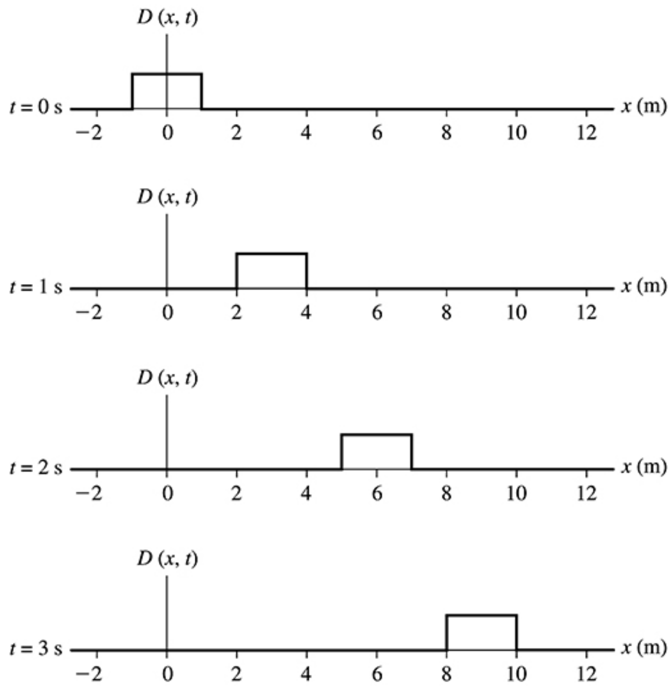
**Solve:** The frequency is $f_+$ as the hawk approaches you is

$$f_+ = \frac{f_0}{1 - v_S/v} \Rightarrow 900 \text{ Hz} = \frac{800 \text{ Hz}}{1 - \dfrac{v_S}{343 \text{ m/s}}} \Rightarrow v_S = 38.1 \text{ m/s}$$

**Assess:** The mother hawk's speed of 38.1 m/s ≈ 80 mph is reasonable.

**20.40. Visualize:** The function $D(x, t)$ represents a pulse that travels in the positive $x$-direction without changing shape.

**Solve: (a)**




**(b)** The leading edge of the pulse moves forward 3 m each second. Thus, the wave speed is 3 m/s.

**(c)** $|x - 3t|$ is a function of the form $D(x - vt)$, so the pulse moves to the right at $v = 3$ m/s.

**20.41.** **Solve:** **(a)** We see from the history graph that the period $T = 0.20$ s and the wave speed $v = 4.0$ m/s. Thus, the wavelength is

$$\lambda = \frac{v}{f} = vT = (4.0 \text{ m/s})(0.20 \text{ s}) = 0.80 \text{ m}$$

**(b)** The phase constant $\phi_0$ is obtained as follows:

$$D(0 \text{ m}, 0 \text{ s}) = A\sin\phi_0 \Rightarrow -2 \text{ mm} = (2 \text{ mm})\sin\phi_0 \Rightarrow \sin\phi_0 = -1 \Rightarrow \phi_0 = -\tfrac{1}{2}\pi \text{ rad}$$

**(c)** The displacement equation for the wave is

$$D(x,\ t) = A\sin\left(\frac{2\pi x}{\lambda} - 2\pi ft + \phi_0\right) = (2.0 \text{ mm})\sin\left(\frac{2\pi x}{0.80 \text{ m}} - \frac{2\pi t}{0.20 \text{ s}} - \frac{\pi}{2}\right) = (2.0 \text{ mm})\sin\left(2.5\pi x - 10\pi t - \tfrac{1}{2}\pi\right)$$

where $x$ and $t$ are in m and s, respectively.

**20.42. Solve: (a)** We can see from the graph that the wavelength is $\lambda = 2.0$ m. We are given that the wave's frequency is $f = 5.0$ Hz. Thus, the wave speed is $v = \lambda f = 10$ m/s.

**(b)** The snapshot graph was made at $t = 0$ s. Reading the graph at $x = 0$ m, we see that the displacement is

$$D(x = 0 \text{ m},\ t = 0 \text{ s}) = D(0 \text{ m},\ 0 \text{ s}) = 0.5 \text{ mm} = \tfrac{1}{2}A$$

Thus

$$D(0 \text{ m}, 0 \text{ s}) = \tfrac{1}{2}A = A\sin\phi_0 \Rightarrow \phi_0 = \sin^{-1}\left(\tfrac{1}{2}\right) = \frac{\pi}{6}\text{rad or } \frac{5\pi}{6}\text{rad}$$

Note that the value of $D$(0 m, 0 s) alone gives two possible values of the phase constant. One of the values will cause the displacement to start at 0.5 mm and increase with distance—as the graph shows—while the other will cause the displacement to start at 0.5 mm but *decrease* with distance. Which is which? The wave equation for $t$ = 0 s is

$$D(x,\ t = 0) = A\sin\left(\frac{2\pi x}{\lambda} + \phi_0\right)$$

If $x$ is a point just to the right of the origin and is very small, the angle $(2\pi x/\lambda + \phi_0)$ is just slightly bigger than the angle $\phi_0$. Now $\sin 31° > \sin 30°$, but $\sin 151° < \sin 150°$, so the value $\phi_0 = \tfrac{1}{6}\pi$ rad is the phase constant for which the displacement increases as $x$ increases.

**(c)** The equation for a sinusoidal traveling wave can be written as

$$D(x,t) = A\sin\left(\frac{2\pi x}{\lambda} - 2\pi ft + \phi_0\right) = A\sin\left[2\pi\left(\frac{x}{\lambda} - ft\right) + \phi_0\right]$$

Substituting in the values found above,

$$D(x,\ t) = (1.0 \text{ mm})\sin\left[2\pi\left(\frac{x}{2.0 \text{ m}} - \left(5.0 \text{ s}^{-1}\right)t\right) + \frac{\pi}{6}\right]$$

**20.43. Solve:** The time for the sound wave to travel down the tube and back is $t = 440\ \mu s$ since 1 division is equal to 100 μs. So, the speed of the sound wave in the liquid is

$$v = \frac{2 \times 25\text{ cm}}{440\ \mu\text{s}} = 1140\text{ m/s} \approx 1100\text{ m/s}$$

**20.44. Model:** The wave is a traveling wave on a stretched string.

**Solve:** The wave speed on a string whose radius is $R$, length is $L$, and mass density is $\rho$ is $v_{\text{string}} = \sqrt{T_S / \mu}$ with

$$\mu = \frac{m}{L} = \frac{\rho V}{L} = \frac{\rho \pi R^2 L}{L} = \rho \pi R^2$$

If the string radius doubles, then

$$v'_{\text{string}} = \sqrt{\frac{T_S}{\rho\pi(2R)^2}} = \frac{v_{\text{string}}}{2} = \frac{280\text{ m/s}}{2} = 140\text{ m/s}$$

**20.45. Model:** The wave pulse is a traveling wave on a stretched string.

**Solve:** While the tension $T_S$ is the same in both the strings, the wave speeds in the two strings are not. We have

$$v_1 = \sqrt{\frac{T_S}{\mu_1}} \quad \text{and} \quad v_2 = \sqrt{\frac{T_S}{\mu_2}} \Rightarrow v_1^2\mu_1 = v_2^2\mu_2 = T_S$$

Because $v_1 = L_1/t_1$ and $v_2 = L_2/t_2$, and because the pulses are to reach the ends of the string simultaneously, the above equation can be simplified to

$$\frac{L_1^2\mu_1}{t^2} = \frac{L_2^2\mu_2}{t^2} \Rightarrow \frac{L_1}{L_2} = \sqrt{\frac{\mu_2}{\mu_1}} = \sqrt{\frac{4.0 \text{ g/m}}{2.0 \text{ g/m}}} = \sqrt{2} \Rightarrow L_1 = \sqrt{2}L_2$$

Since $L_1 + L_2 = 4$ m,

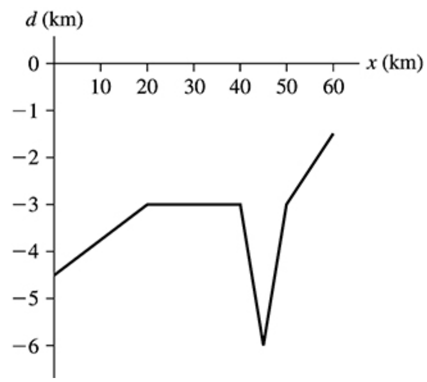
$$\sqrt{2}L_2 + L_2 = 4 \text{ m} \Rightarrow L_2 = 1.66 \text{ m} \approx 1.7 \text{ m} \quad \text{and} \quad L_1 = \sqrt{2}(1.66 \text{ m}) = 2.34 \text{ m} \approx 2.3 \text{ m}$$

**20.46. Solve:** $\Delta t$ is the time the sound wave takes to travel down to the bottom of the ocean and then up to the ocean surface. The depth of the ocean is

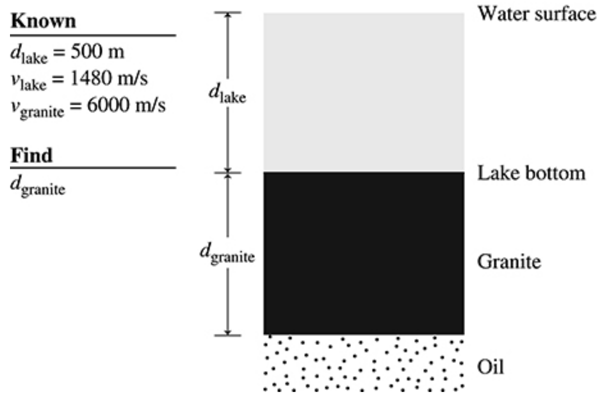
$$2d = (v_{\text{sound in water}})\Delta t \Rightarrow d = (750 \text{ m/s})\Delta t$$

Using this relation and the data from Figure P20.46, we can generate the following table for the ocean depth ($d$) at various positions ($x$) of the ship.

| $x$ (km) | $\Delta t$ (s) | $d$ (km) |
|---|---|---|
| 0 | 6 | 4.5 |
| 20 | 4 | 3.0 |
| 40 | 4 | 3.0 |
| 45 | 8 | 6.0 |
| 50 | 4 | 3.0 |
| 60 | 2 | 1.5 |



**20.47. Visualize:**



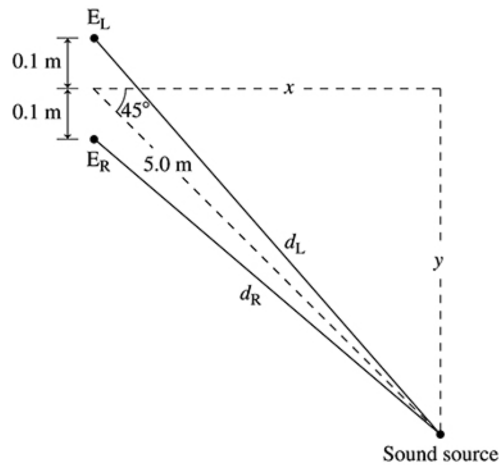

**Solve:** The explosive's sound travels down the lake and into the granite, and then it is reflected by the oil surface. The echo time is thus equal to

$$t_{echo} = t_{water\ down} + t_{granite\ down} + t_{granite\ up} + t_{water\ up}$$

$$0.94 \text{ s} = \frac{500 \text{ m}}{1480 \text{ m/s}} + \frac{d_{granite}}{6000 \text{ m/s}} + \frac{d_{granite}}{6000 \text{ m/s}} + \frac{500 \text{ m}}{1480 \text{ m/s}} \Rightarrow d_{granite} = 790 \text{ m}$$

**20.48. Model:** Assume a room temperature of 20°C.

**Visualize**:




**Solve:** The distance between the source and the left ear ($E_L$) is

$$d_L = \sqrt{x^2 + (y + 0.1\text{ m})^2} = \sqrt{[(5.0\text{ m})\cos 45°]^2 + [(5.0\text{ m})\sin 45° + 0.1\text{ m}]^2} = 5.0712\text{ m}$$

Similarly $d_R = 4.9298$ m. Thus,

$$d_L - d_R = \Delta d = 0.1414\text{ m}$$

For the sound wave with a speed of 343 m/s, the difference in arrival times at your left and right ears is

$$\Delta t = \frac{\Delta d}{343\text{ m/s}} = \frac{0.1414\text{ m}}{343\text{ m/s}} = 410\ \mu\text{s}$$

**20.49. Model:** The laser beam is an electromagnetic wave that travels with the speed of light.
**Solve:** The speed of light in the liquid is

$$v_{\text{liquid}} = \frac{30\times10^{-2}\ \text{m}}{1.38\times10^{-9}\ \text{s}} = 2.174\times10^{8}\ \text{m/s}$$

The liquid's index of refraction is

$$n = \frac{c}{v_{\text{liquid}}} = \frac{3.0\times10^{8}}{2.174\times10^{8}} = 1.38$$

Thus the wavelength of the laser beam in the liquid is

$$\lambda_{\text{liquid}} = \frac{\lambda_{\text{vac}}}{n} = \frac{633\ \text{nm}}{1.38} = 459\ \text{nm}$$

**20.50. Model:** The temperature is 20°C for both air and water.

**Solve:** For the sound speed of $v_{air}$ = 343 m/s, the wavelength of the sound wave in air is

$$\lambda_{air} = \frac{343 \text{ m/s}}{256 \text{ Hz}} = 1.340 \text{ m}$$

On entering water the frequency does not change, so $f_{water} = f_{air}$ and $f_{water}/f_{air} = 1$. The wave speed in water is $v_{water}$ =
1480 m/s, so

$$\frac{v_{water}}{v_{air}} = \frac{1480 \text{ m/s}}{343 \text{ m/s}} = 4.31$$

Finally, the wavelength in water is

$$\lambda_{water} = \frac{v_{water}}{f_{water}} = \frac{1480 \text{ m/s}}{256 \text{ Hz}} = 5.781 \text{ m} \Rightarrow \frac{\lambda_{water}}{\lambda_{air}} = \frac{5.781 \text{ m}}{1.340 \text{ m}} = 4.31$$

**Assess:** This last result is expected because $v = f\lambda$ and the frequency remains unchanged as the wave enters from air into water.

**20.51. Solve:** The difference in the arrival times for the P and S waves is

$$\Delta t = t_S - t_P = \frac{d}{v_S} - \frac{d}{v_P} \Rightarrow 120 \text{ s} = d\left(\frac{1}{4500 \text{ m/s}} - \frac{1}{8000 \text{ m/s}}\right) \Rightarrow d = 1.23\times10^6 \text{ m} = 1230 \text{ km}$$

**Assess:** $d$ is approximately one-fifth of the radius of the earth and is reasonable.

**20.52. Model:** This is a sinusoidal wave.

**Solve:** **(a)** The equation is of the form $D(y,t) = A\sin(ky + \omega t + \phi_0)$, so the wave is traveling along the $y$-axis. Because it is $+\omega t$ rather than $-\omega t$ the wave is traveling in the *negative* $y$-direction.

**(b)** Sound is a longitudinal wave, meaning that the medium is displaced *parallel* to the direction of travel. So the air molecules are oscillating back and forth along the $y$-axis.

**(c)** The wave number is $k = 8.96\ \text{m}^{-1}$, so the wavelength is

$$\lambda = \frac{2\pi}{k} = \frac{2\pi}{8.96\ \text{m}^{-1}} = 0.701\ \text{m}$$

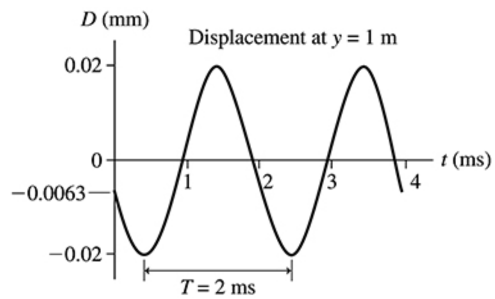
The angular frequency is $\omega = 3140\ \text{s}^{-1}$, so the wave's frequency is

$$f = \frac{\omega}{2\pi} = \frac{3140\ \text{s}^{-1}}{2\pi} = 500\ \text{Hz}$$

Thus, the wave speed $v = \lambda f = (0.70\ \text{m})(500\ \text{Hz}) = 350\ \text{m/s}$. The period $T = 1/f = 0.00200\ \text{s} = 2.00\ \text{ms}$.

**(d)** The interval $t = 0$ s to $t = 4$ ms is exactly 2 cycles of the wave. The initial value at $y = 1$ m is

$$D(y = 1\ \text{m}, t = 0\ \text{s}) = (0.02\ \text{mm})\sin\left(8.96 + \tfrac{1}{4}\pi\right) = -0.0063\ \text{mm}$$




**Assess:** The wave is a sound wave with speed $v = 350$ m/s. This is greater than the room-temperature speed of 343 m/s, so the air temperature must be greater than 20°.

**20.53. Model:** This is a sinusoidal wave.

**Solve:** **(a)** The displacement of a wave traveling in the positive $x$-direction with wave speed $v$ must be of the form $D(x, t) = D(x - vt)$. Since the variables $x$ and $t$ in the given wave equation appear together as $x + vt$, the wave is traveling toward the left, that is, in the $-x$ direction.

**(b)** The speed of the wave is

$$v = \frac{\omega}{k} = \frac{2\pi/0.20 \text{ s}}{2\pi \text{ rad}/2.4 \text{ m}} = 12 \text{ m/s}$$

The frequency is

$$f = \frac{\omega}{2\pi} = \frac{2\pi \text{ rad}/0.20 \text{ s}}{2\pi} = 5.0 \text{ Hz}$$

The wave number is

$$k = \frac{2\pi \text{ rad}}{2.4 \text{ m}} = 2.6 \text{ rad/m}$$

**(c)** The displacement is

$$D(0.20 \text{ m}, 0.50 \text{ s}) = (3.0 \text{ cm})\sin\left[2\pi\left(\frac{0.20 \text{ m}}{2.4 \text{ m}} + \frac{0.50 \text{ s}}{0.20 \text{ s}} + 1\right)\right] = -1.5 \text{ cm}$$

**20.54. Model:** This is a sinusoidal wave traveling on a stretched string in the $+x$ direction.

**Solve:** **(a)** From the displacement equation of the wave, $A = 2.0$ cm, $k = 12.57$ rad/m, and $\omega = 638$ rad/s. Using the equation for the wave speed in a stretched string,

$$v_{\text{string}} = \sqrt{\frac{T_S}{\mu}} \Rightarrow T_S = \mu v_{\text{string}}^2 = \mu\left(\frac{\omega}{k}\right)^2 = \left(5.00\times10^{-3}\ \text{kg/m}^3\right)\left(\frac{638\ \text{rad/s}}{12.57\ \text{rad/m}}\right)^2 = 12.6\ \text{N}$$

**(b)** The maximum displacement is the amplitude $D_{\text{max}}(x,\ t) = 2.00\ \text{cm}$.

**(c)** From Equation 20.17,

$$v_{y\ \text{max}} = \omega A = (638\ \text{rad/s})\left(2.0\times10^{-2}\ \text{m}\right) = 12.8\ \text{m/s}$$

**20.55.** **Solve:** The wave number and frequency are calculated as follows:

$$k = \frac{2\pi}{\lambda} = \frac{2\pi \text{ rad}}{0.50 \text{ m}} = 4\pi \text{ rad/m} \Rightarrow \omega = vk = (4.0 \text{ m/s})(4\pi \text{ rad/m}) = 16\pi \text{ rad/s}$$

Thus, the displacement equation for the wave is

$$D(y, t) = (5.0 \text{ cm})\sin\left[(4\pi \text{ rad/m})y + (16\pi \text{ rad/s})t\right]$$

**Assess:** The positive sign in the sine function's argument indicates motion along the $-y$ direction.

**20.56.** **Solve:** The angular frequency and wave number are calculated as follows:

$$\omega = 2\pi f = 2\pi(200\text{ Hz}) = 400\pi\ \text{ rad/s} \Rightarrow k = \frac{\omega}{v} = \frac{400\pi\ \text{rad/s}}{400\text{ m/s}} = \pi\ \text{rad/m}$$

The displacement equation for the wave is

$$D(x,\ t) = (0.010\text{ mm})\sin\left[(\pi\ \text{rad/m})x - (400\pi\ \text{rad/s})t + \tfrac{1}{2}\pi\ \text{rad}\right]$$

**Assess:** Note the negative sign with $\omega t$ in the sine function's argument. This indicates motion along the $+x$ direction.

**20.57. Solve:** A sinusoidal traveling wave is represented as $D(x,\ t) = A\sin(kx - \omega t)$. Replacing $t$ with $t + T$ and using the relationship $\omega = 2\pi/T$ between the angular frequency and period,

$$D(x,\ t+T) = A\sin\big(kx - \omega(t+T)\big) = A\sin(kx - \omega t - \omega T) = A\sin(kx - \omega t - 2\pi)$$

$$= A\big[\sin(kx - \omega t)\cos(2\pi) - \cos(kx - \omega t)\sin(2\pi)\big] = A\sin(kx - \omega t) = D(x,\ t)$$

**20.58.** **Solve:** According to Equation 20.28, the phase difference between two points on a wave is $\Delta\phi = 2\pi(r_2 - r_1)/\lambda$. For the first point and second point,

$$r_1 = \sqrt{(1.00 \text{ cm} - 0 \text{ cm})^2 + (3.00 \text{ cm} - 0 \text{ cm})^2 + (2.00 \text{ cm} - 0 \text{ cm})^2} = 3.742 \text{ cm}$$

$$r_2 = \sqrt{(-1.00 \text{ cm} - 0 \text{ cm})^2 + (1.50 \text{ cm} - 0 \text{ cm})^2 + (2.50 \text{ cm} - 0 \text{ cm})^2} = 3.082 \text{ cm}$$

The wavelength is

$$\lambda = \frac{v}{f} = \frac{346 \text{ m/s}}{13{,}100 \text{ Hz}} = 0.02641 \text{ m} = 2.641 \text{ cm}$$

$$\Rightarrow \Delta\phi = \frac{2\pi(3.742 \text{ cm} - 3.082 \text{ cm})}{2.641 \text{ cm}} = \frac{\pi}{2} \text{ rad} = \frac{\pi}{2} \text{ rad} \times \frac{180°}{\pi \text{ rad}} = 90°$$

**20.59. Model:** We have a sinusoidal traveling wave on a stretched string.

**Solve:** **(a)** The wave speed on a string and the wavelength are calculated as follows:

$$v = \sqrt{\frac{T_S}{\mu}} = \sqrt{\frac{20\text{ N}}{0.002\text{ kg/m}}} = 100\text{ m/s} \Rightarrow \lambda = \frac{v}{f} = \frac{100.0\text{ m/s}}{100\text{ Hz}} = 1.0\text{ m}$$

**(b)** The amplitude is determined by the oscillator at the end of the string and is $A$ = 1.0 mm. The phase constant can be obtained from Equation 20.15 as follows:

$$D(0\text{ m, }0\text{ s}) = A\sin\phi_0 \Rightarrow -1.0\text{ mm} = (1.0\text{ mm})\sin\phi_0 \Rightarrow \phi_0 = -\frac{\pi}{2}\text{ rad}$$

**(c)** The wave (as distinct from the oscillator) is described by $D(x,\ t) = A\sin(kx - \omega t + \phi_0)$. In this equation the wave number and angular frequency are

$$k = \frac{2\pi}{\lambda} = \frac{2\pi}{1.0\text{ m}} = 2\pi\text{ rad/m} \qquad \omega = vk = (100.0\text{ m/s})(2\pi\text{ rad/m}) = 200\pi\text{ rad/s}$$

Thus, the wave's displacement equation is

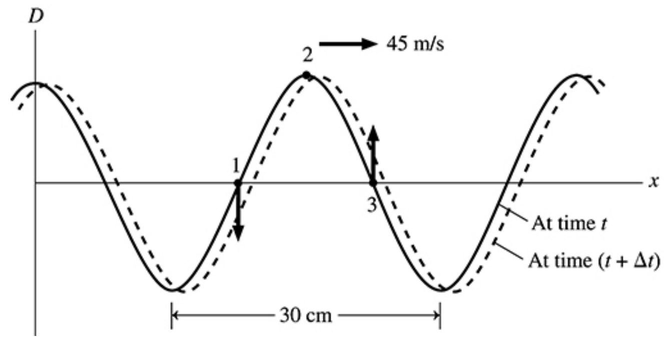
$$D(x,\ t) = (1.0\text{ mm})\sin\left[(2\pi\text{ rad/m})x - (200\pi\text{ rad/s})t - \tfrac{1}{2}\pi\text{ rad}\right]$$

**(d)** The displacement is

$$D(0.50\text{ m, }0.015\text{ s}) = (1.0\text{ mm})\sin\left[(2\pi\text{ rad/s})(0.50\text{ m}) - (200\pi\text{ rad/s})(0.015\text{ s}) - \tfrac{1}{2}\pi\right] = -1.0\text{ mm}$$

**20.60.** **Model:** We have a wave traveling to the right on a string.

**Visualize:**



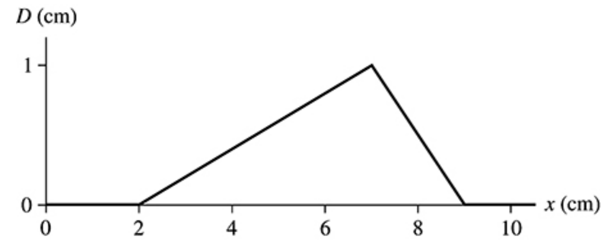

**Solve:** The snapshot of the wave as it travels to the right for an infinitesimally small time $\Delta t$ shows that the velocity at point 1 is downward, at point 3 is upward, and at point 2 is zero. Furthermore, the speed at points 1 and 3 is the maximum speed given by Equation 20.17: $v_1 = v_3 = \omega A$ . The frequency of the wave is

$$\omega = 2\pi f = 2\pi \frac{v}{\lambda} = \frac{2\pi(45 \text{ m/s})}{0.30 \text{ m}} = 300\pi \text{ rad/s} \Rightarrow \omega A = (300\pi \text{ rad/s})(2.0\times10^{-2} \text{ m}) = 19 \text{ m/s}$$

Thus, $v_1 = -19$ m/s, $v_2 = 0$ m/s, and $v_3 = +19$ m/s.

**20.61.** **Model:** This is a wave traveling to the left at a constant speed of 50 cm/s.

**Solve:** The particles at positions between $x = 2$ cm and $x = 7$ cm have a speed of 10 cm/s, and the particles between $x = 7$ cm and $x = 9$ cm have a speed of −25 cm/s. That is, at the time the snapshot of the velocity is shown, the particles of the medium have upward motion for 2 cm $\le x \le$ 7 cm, but downward motion for 7 cm $\le x \le$ 9 cm. The width of the front section of the wave pulse is 7 cm – 2 cm = 5 cm and the width of the rear section is 9 cm – 7 cm = 2 cm. With a wave speed of 50 cm/s, the time taken by the front section to pass through a particular point is $5\text{ cm}/50\text{ cm/s} = 0.1\text{ s}$ and the time taken by the rear section of the wave to pass through a point is $2\text{ cm}/50\text{ cm/s} = 0.04\text{ s}$. Thus the wave causes the upward moving particles to go through a displacement of $A = (10\text{ cm/s})(0.1\text{ s}) = 1.0\text{ cm}$. The downward moving particles have a maximum displacement of $(-25\text{ cm/s})(0.04\text{ s}) = -1.0\text{ cm}$.



**20.62. Model:** The wave is traveling on a stretched string.

**Solve:** The wave speed on the string is

$$v = \sqrt{\frac{T_S}{\mu}} = \sqrt{\frac{50\text{ N}}{0.005\text{ kg/m}}} = 100\text{ m/s}$$

The speed of the particle on the string, however, is given by Equation 20.17. The maximum speed is calculated as follows:

$$v_y = -\omega A\cos(kx - \omega t + \phi_0) \Rightarrow v_{y\ \max} = \omega A = 2\pi fA = 2\pi\frac{v}{\lambda}A = 2\pi\left(\frac{100\text{ m/s}}{2.0\text{ m}}\right)(0.030\text{ m}) = 9.4\text{ m/s}$$

**20.63. Model:** A sinusoidal wave is traveling along a stretched string.

**Solve:** From Equation 20.17 and Equation 20.20, $v_{y\ \max} = \omega A$ and $a_{y\ \max} = \omega^2 A$. These two equations can be combined to give

$$\omega = \frac{a_{y\max}}{v_{y\max}} = \frac{200\ \text{m/s}^2}{2.0\ \text{m/s}} = 100\ \text{rad/s} \Rightarrow f = \frac{\omega}{2\pi} = 15.9\ \text{Hz} \approx 16\ \text{Hz} \Rightarrow A = \frac{v_{y\max}}{\omega} = \frac{2.0\ \text{m/s}}{100\ \text{rad/s}} = 2.0\ \text{cm}$$

**20.64.** **Solve:** **(a)** At a distance $r$ from the bulb, the 5 watts of visible light have spread out to cover the surface of a sphere of radius $r$. The surface area of a sphere is $a = 4\pi r^2$. Thus, the intensity at a distance of 2 m is

$$I = \frac{P}{a} = \frac{P}{4\pi r^2} = \frac{5.0 \text{ W}}{4\pi (2.0 \text{ m})^2} = 0.095 \text{ W/m}^2$$

Note that the presence of the wall has nothing to do with the intensity. The wall allows you to see the light, but the light wave has the same intensity at *all* points 2 m from the bulb whether it is striking a surface or moving through empty space.

**(b)** Unlike the light from a light bulb, a laser beam does *not* spread out. We ignore the small diffraction spread of the beam. The laser beam creates a dot of light on the wall that is 2 mm in diameter. The full 5 watts of light is concentrated in this dot of area $a = \pi r^2 = \pi (0.001 \text{ m})^2 = 3.14 \times 10^{-6} \text{ m}^2$. The intensity is

$$I = \frac{P}{a} = \frac{5 \text{ W}}{3.14 \times 10^{-6} \text{ m}^2} = 1.6 \text{ MW/m}^2$$

Although the *power* of the light source is the same in both cases, the laser produces light on the wall whose *intensity* is over 16 million times that of the light bulb.

**20.65. Model:** The radio wave is an electromagnetic wave.

**Solve:** At a distance $r$, the 25 kW power station spreads out waves to cover the surface of a sphere of radius $r$. The surface area of a sphere is $4\pi r^2$. Thus, the intensity of the radio waves is

$$I = \frac{P_{\text{source}}}{4\pi r^2} = \frac{25\times10^3\ \text{W}}{4\pi\left(10\times10^3\ \text{m}\right)^2} = 2.0\times10^{-5}\ \text{W/m}^2$$

**20.66.** **Solve:** **(a)** The peak power of the light pulse is

$$P_{\text{peak}} = \frac{\Delta E}{\Delta t} = \frac{500 \text{ mJ}}{10 \text{ ns}} = \frac{0.50 \text{ J}}{1.0 \times 10^{-8} \text{ s}} = 5.0 \times 10^{7} \text{ W}$$

**(b)** The average power is

$$P_{\text{avg}} = \frac{E_{\text{total}}}{1.0 \text{ s}} = \frac{10 \times 500 \text{ mJ}}{1.0 \text{ s}} = \frac{5.0 \text{ J}}{1.0 \text{ s}} = 5.0 \text{ W}$$

The laser delivers pulses of very high power. But the laser spends most of its time "off," so the *average* power is very much less than the peak power.

**(c)** The intensity is

$$I_{\text{laser}} = \frac{P}{a} = \frac{5.0 \times 10^{7} \text{ W}}{\pi (5.0 \ \mu\text{m})^2} = \frac{5.0 \times 10^{7} \text{ W}}{7.85 \times 10^{-11} \text{ m}^2} = 6.4 \times 10^{17} \text{ W/m}^2$$

**(d)** The ratio is

$$\frac{I_{\text{laser}}}{I_{\text{sun}}} = \frac{6.4 \times 10^{17} \text{ W/m}^2}{1.1 \times 10^{3} \text{ W/m}^2} = 5.8 \times 10^{14}$$

**20.67. Model:** We have a traveling wave radiated by the tornado siren.

**Solve:** **(a)** The power of the source is calculated as follows:

$$I_{50\text{ m}} = 0.10\text{ W/m}^2 = \frac{P_{\text{source}}}{4\pi r^2} = \frac{P_{\text{source}}}{4\pi(50\text{ m})^2} \Rightarrow P_{\text{source}} = \left(0.10\text{ W/m}^2\right)4\pi(50\text{ m})^2 = (1000\pi)\text{ W}$$

The intensity at 1000 m is

$$I_{1000\text{ m}} = \frac{P_{\text{source}}}{4\pi(1000\text{ m})^2} = \frac{(1000\pi)\text{ W}}{4\pi(1000\text{ m})^2} = 250\ \mu\text{W/m}^2$$

**(b)** The maximum distance is calculated as follows:

$$I = \frac{P_{\text{source}}}{4\pi r^2} \Rightarrow 1.0\times10^{-6}\text{ W/m}^2 = \frac{(1000\pi)\text{ W}}{4\pi r^2} \Rightarrow r = 16\text{ km}$$

**20.68. Model:** Assume the saw is far enough off the ground that we don't have to worry about reflected sound.

**Visualize:** First note that $\beta_1 - \beta_2 = 20\,\text{dB} \Rightarrow I_1/I_2 = 10 \cdot 10 = 100$ (a change of 10 dB corresponds to a change in intensity by a factor of 10). Then use $I_1A_1 = P$ and then $P = I_2A_2 \Rightarrow A_2 = P/I_2$, and finally solve for $R_2 = \sqrt{A_2/4\pi}$.

**Solve:** Put all of the above together.

$$R_2 = \sqrt{\frac{A_2}{4\pi}} = \sqrt{\frac{\frac{P}{I_2}}{4\pi}} = \sqrt{\frac{\frac{I_1A_1}{I_2}}{4\pi}} = \sqrt{\frac{\frac{I_1}{I_2}(4\pi R_1^2)}{4\pi}} = R_1\sqrt{\frac{I_1}{I_2}} = R_1\sqrt{100} = (5.0\text{ m})(10) = 50\text{ m}$$

**Assess:** The scaling laws help and the answer is reasonable.

**20.69. Model:** Assume the two loudspeakers broadcast the same power and that the platforms are high enough off the ground that we don't have to worry about reflected sound.

**Visualize:** Call the distance between the loudspeakers $d$. Call the intensity halfway between the speakers (at $d/2$ ) $I_1$ and the sound intensity level there $\beta_1(=75dB)$; call them $I_2$ and $\beta_2$ at 1/4 the distance from one pole and 3/4 the distance from the other pole on the line between them. We seek $\beta_2$.

We first apply a general approach for different sound intensity levels:

$$\Delta\beta = \beta_2 - \beta_1 = (10\,\text{dB})\left[\log_{10}\left(\frac{I_2}{I_0}\right) - \log_{10}\left(\frac{I_1}{I_0}\right)\right] = (10\text{ dB})\log_{10}\left(\frac{I_2/I_0}{I_1/I_0}\right) = (10\text{ dB})\log_{10}\left(\frac{I_2}{I_1}\right)$$

**Solve:** Recall that for the general case of spherical symmetry $I = P/A$, where $P$ is the power emitted by the source and $A = 4\pi R^2$ is the area of the sphere. Now we find the ratio of the intensities $I_2/I_1$ and then plug it in the formula above and add it to 75 dB.

$$I_1 = \frac{P}{4\pi(d/2)^2} + \frac{P}{4\pi(d/2)^2} = \frac{2P}{\pi d^2}$$

$$I_2 = \frac{P}{4\pi(d/4)^2} + \frac{P}{4\pi(3d/4)^2} = \frac{4P}{\pi d^2} + \frac{4P}{9\pi d^2} = \frac{(36+4)P}{9\pi d^2} = \frac{40P}{9\pi d^2} = \frac{20}{9}I_1$$

$$\Delta\beta = (10\text{ dB})\log_{10}\left(\frac{I_2}{I_1}\right) = (10\text{ dB})\log_{10}\left(\frac{20}{9}\right) = 3.48\text{ dB}$$

$$\beta_2 = \beta_1 + \Delta\beta = 75\text{ dB} + 3.48\text{ dB} = 78\text{ dB}$$

**Assess:** An increase of about 3dB corresponds to a doubling of the intensity. 20/9 is close to double.

**20.70. Model:** As suggested, model the bald head as a hemisphere with radius $R = 0.080\,\text{m}$. This means the surface area of the bald head (hemisphere) is $A = 2\pi R^2 = 0.0402\,\text{m}^2$.

**Visualize:** We are given $\beta = 93$ dB and $\Delta E = 0.10$ J. We also know that $I = I_0 \times 10^{\beta/10\,\text{dB}}$ and $P = IA$. Also recall $P = \Delta E \Delta t$.

**Solve:** Put all of the above together to find $\Delta t$.

$$\Delta t = \frac{\Delta E}{P} = \frac{\Delta E}{IA} = \frac{\Delta E}{(I_0 \times 10^{\beta/10\,\text{dB}})(2\pi R^2)} = \frac{0.10\ \text{J}}{(10^{-12}\ \text{W/m}^2 \times 10^{9.3})(0.0402\ \text{m}^2)} = 1250\ \text{s} \approx 21\ \text{min}$$

**Assess:** 21 min seems like quite a while to deliver 0.10 J of energy, but sounds waves don't carry a lot of energy unless the intensity is high.

**20.71. Model:** The bat's chirping frequency is altered by the Doppler effect. The frequency is increased as the bat approaches and it decreases as the bat recedes away.

**Solve:** The bat must fly away from you, so that the chirp frequency observed by you is less than 25 kHz. From Equation 20.38,

$$f_- = \frac{f_0}{1 + v_S / v} \Rightarrow 20{,}000 \text{ Hz} = \frac{25{,}000 \text{ Hz}}{1 + \left(\dfrac{v_S}{343 \text{ m/s}}\right)} \Rightarrow v_S = 85.8 \text{ m/s} \approx 86 \text{ m/s}$$

**Assess:** This is a rather large speed: 85.8 m/s ≈ 180 mph. This is not possible for a bat.

**20.72. Model:** The sound generator's frequency is altered by the Doppler effect. The frequency increases as the generator approaches the student, and it decreases as the generator recedes from the student.
**Solve:** The generator's speed is

$$v_S = r\omega = r(2\pi f) = (1.0 \text{ m})2\pi\left(\frac{100}{60} \text{ rev/s}\right) = 10.47 \text{ m/s}$$

The frequency of the approaching generator is

$$f_+ = \frac{f_0}{1 - v_S/v} = \frac{600 \text{ Hz}}{1 - \dfrac{10.47 \text{ m/s}}{343 \text{ m/s}}} = 619 \text{ Hz} \approx 620 \text{ Hz}$$

Doppler effect for the receding generator, on the other hand, is

$$f_- = \frac{f_0}{1 + v_S/v} = \frac{600 \text{ Hz}}{1 + \dfrac{10.47 \text{ m/s}}{343 \text{ m/s}}} = 582 \text{ Hz} \approx 580 \text{ Hz}$$

Thus, the highest and the lowest frequencies heard by the student are 620 Hz and 580 Hz.

**20.73. Solve:** We will closely follow the details of section 20.7 in the textbook. Figure 20.29 shows that the wave crests are stretched out behind the source. The wavelength detected by Pablo is $\lambda_- = \frac{1}{3}d$, where $d$ is the distance the wave has moved plus the distance the source has moved at time $t$ = 3$T$. These distances are $\Delta x_{\text{wave}} = vt = 3vT$ and $\Delta x_{\text{source}} = v_S t = 3v_S T$. The wavelength of the wave emitted by a receding source is thus

$$\lambda_- = \frac{d}{3} = \frac{\Delta x_{\text{wave}} + \Delta x_{\text{source}}}{3} = \frac{3vT + 3v_S T}{3} = (v + v_S)T$$

The frequency detected in Pablo's direction is thus

$$f_- = \frac{v}{\lambda_-} = \frac{v}{(v + v_s)T} = \frac{f_0}{1 + v_S/v}$$

**20.74. Model:** We are looking at the Doppler effect for the light of an approaching source.

**Solve: (a)** The time is

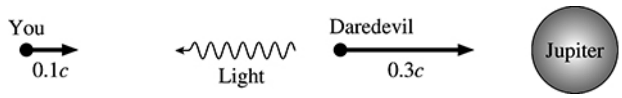
$$t = \frac{54\times10^6\ \text{km}}{3\times10^5\ \text{km/s}} = 180\ \text{s} = 3.0\ \text{min}$$

**(b)** Using Equation 20.40, the observed wavelength is

$$\lambda = \sqrt{\frac{1-v_s/c}{1+v_s/c}}\,\lambda_0 = \sqrt{\frac{1-0.1c/c}{1+0.1c/c}}\,(540\ \text{nm}) = (0.9045)(540\ \text{nm}) = 488\ \text{nm} \approx 490\ \text{nm}$$

**Assess:** 490 nm is slightly blue shifted from green.

**20.75. Model:** We are looking at the Doppler effect for the light of a receding source.
**Visualize:**




Note that the daredevil's tail lights are receding away from your rocket's light detector with a relative speed of 0.2*c*.
**Solve:** Using Equation 20.40, the observed wavelength is

$$\lambda = \sqrt{\frac{1+v_S/c}{1-v_S/c}}\lambda_0 = \sqrt{\frac{1+0.2c/c}{1-0.2c/c}}(650\text{ nm}) = 796\text{ nm} \approx 800\text{ nm}$$

This wavelength is in the infrared region.

**20.76. Model:** The Doppler effect for light of a receding source yields an increased wavelength.

**Solve:** Because the measured wavelengths are 5% longer, that is, $\lambda = 1.05\lambda_0$, the distant galaxy is receding away from the earth. Using Equation 20.40,

$$\lambda = 1.05\lambda_0 = \sqrt{\frac{1+v_s/c}{1-v_s/c}}\lambda_0 \Rightarrow (1.05)^2 = \frac{1+v_s/c}{1-v_s/c} \Rightarrow v_s = 0.049\ c = 1.47\times10^7\ \text{m/s}$$

**20.77.** **Model:** The Doppler effect for light of an approaching source leads to a decreased wavelength.

**Solve:** The red wavelength ($\lambda_0$ = 650 nm) is Doppler shifted to green ($\lambda$ = 540 nm) due to the approaching light source. In relativity theory, the distinction between the motion of the source and the motion of the observer disappears. What matters is the relative approaching or receding motion between the source and the observer. Thus, we can use Equation 20.40 as follows:

$$\lambda = \lambda_0\sqrt{\frac{1-v_s/c}{1+v_s/c}} \Rightarrow 540\text{ nm} = (650\text{ nm})\sqrt{\frac{1-v_s/c}{1+v_s/c}}$$

$$\Rightarrow v_s = 5.5\times10^4\text{ km/s} = 2.0\times10^8\text{ km/h}$$

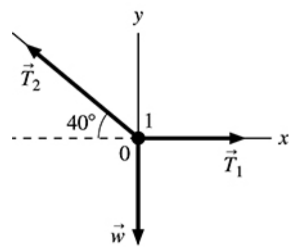
The fine will be

$$\left(2.0\times10^8\text{ km/hr} - 50\text{ km/hr}\right)\left(\frac{1\ \$}{1\text{ km/hr}}\right) = \$200\text{ million}$$

**Assess:** The police officer knew his physics.

**20.78. Model:** The wave pulse is a traveling wave on a stretched string. The two masses hanging from the steel wire are in static equilibrium.

**Visualize:**




**Solve:** The wave speed along the wire is

$$v_{\text{wire}} = \frac{4.0\ \text{m}}{0.024\ \text{s}} = 166.7\ \text{m/s}$$

Using Equation 20.2,

$$v_{\text{wire}} = 166.7\ \text{m/s} = \sqrt{\frac{T_1}{\mu}} = \sqrt{\frac{T_1}{(0.060\ \text{kg}/8.0\ \text{m})}} \Rightarrow T_1 = 208.4\ \text{N}$$

Because point 1 is in static equilibrium, with $\vec{F}_{\text{net}} = \vec{0}$,

$$(F_{\text{net}})_x = T_1 - T_2\cos 40° \Rightarrow T_2 = \frac{T_1}{\cos 40°} = 2721\ \text{N}$$

$$(F_{\text{net}})_y = T_2 \sin 40° - w = 0\ \text{N} \Rightarrow w = mg = T_2 \sin 40° \Rightarrow m = \frac{(272.1\ \text{N})\sin 40°}{9.8\ \text{m/s}^2} = 17.8\ \text{kg}$$

**20.79.** **Solve:** The time for the wave to travel from California to the South Pacific is

$$t = \frac{d}{v} = \frac{8.00 \times 10^6 \text{ m}}{1480 \text{ m/s}} = 5405.4 \text{ s}$$

A time decrease to 5404.4 s implies the speed has changed to $v = \dfrac{d}{t} = 1480.28$ m/s.

Since the 4.0 m/s increase in velocity is due to an increase of 1°C, an increase of 0.28 m/s occurs due to a temperature increase of

$$\left(\frac{1°\text{C}}{4.0 \text{ m/s}}\right)(0.28 \text{ m/s}) = 0.07°\text{C}$$

Thus, a temperature increase of approximately 0.07°C can be detected by the researchers.

**20.80. Solve:** The wave speeds along the two metal wires are

$$v_1 = \sqrt{\frac{T}{\mu_1}} = \sqrt{\frac{2250\text{ N}}{0.009\text{ kg/m}}} = 500\text{ m/s} \qquad v_2 = \sqrt{\frac{T}{\mu_2}} = \sqrt{\frac{2250\text{ N}}{0.025\text{ kg/m}}} = 300\text{ m/s}$$

The wavelengths along the two wires are

$$\lambda_1 = \frac{v_1}{f} = \frac{500\text{ m/s}}{1500\text{ Hz}} = \frac{1}{3}\text{ m} \qquad \lambda_2 = \frac{v_2}{f} = \frac{300\text{ m/s}}{1500\text{ Hz}} = \frac{1}{5}\text{ m}$$

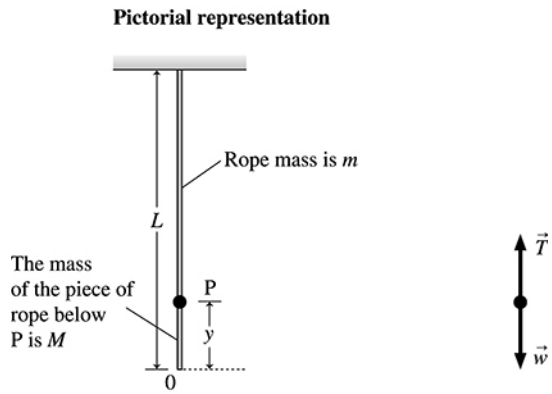
Thus, the number of wavelengths over two sections of the wire are

$$\frac{1.0\text{ m}}{\lambda_1} = \frac{1.0\text{ m}}{\left(\frac{1}{3}\text{ m}\right)} = 3 \qquad \frac{1.0\text{ m}}{\lambda_2} = \frac{1.0\text{ m}}{\left(\frac{1}{5}\text{ m}\right)} = 5$$

The number of complete cycles of the wave in the 2.00-m-long wire is 8.

**20.81. Model:** The wave pulse is a traveling wave on a stretched wire.

**Visualize:**




**Solve: (a)** At a distance $y$ above the lower end of the rope, the point $P$ is in static equilibrium. The upward tension in the rope must balance the weight of the rope that hangs below this point. Thus, at this point

$$T = w = Mg = (\mu y)g$$

where $\mu = m/L$ is the linear density of the entire rope. Using Equation 20.2, we get

$$v = \sqrt{\frac{T}{\mu}} = \sqrt{\frac{\mu y g}{\mu}} = \sqrt{gy}$$

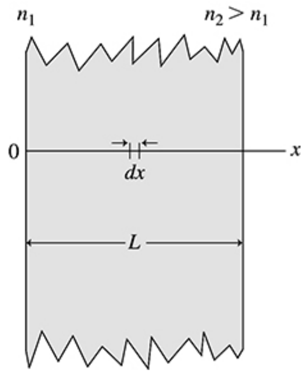
**(b)** The time to travel a distance $dy$ at $y$, where the wave speed is $v = \sqrt{gy}$, is

$$dt = \frac{dy}{v} = \frac{dy}{\sqrt{gy}}$$

Finding the time for a pulse to travel the length of the rope requires integrating from one end of the rope to the other:

$$\Delta t = \int_0^T dt = \int_0^L \frac{dy}{\sqrt{gy}} = \frac{1}{\sqrt{g}}\left(2\sqrt{y}\Big|_0^L\right) = \frac{2}{\sqrt{g}}\sqrt{L} \Rightarrow \Delta t = 2\sqrt{\frac{L}{g}}$$

**20.82. Visualize:**




**Solve: (a)** Using the graph, the refractive index $n$ as a function of distance $x$ can be mathematically expressed as

$$n = n_1 + \frac{n_2 - n_1}{L}x$$

At position $x$, the light speed is $v = c/n$. The time for the light to travel a distance $dx$ at $x$ is

$$dt = \frac{dx}{v} = \frac{n}{c}dx = \frac{1}{c}\left(n_1 + \frac{n_2 - n_1}{L}x\right)dx$$

To find the total time for the light to cover a thickness $L$ of a glass we integrate as follows:

$$T = \int_0^T dt = \frac{1}{c}\int_0^L \left(n_1 + \frac{n_2 - n_1}{L}x\right)dx = \frac{n_1}{c}\int_0^L dx + \frac{(n_2 - n_1)}{cL}\int_0^L x\,dx = \frac{n_1}{c}L + \left(\frac{n_2 - n_1}{cL}\right)\frac{L^2}{2} = \left(\frac{n_1 + n_2}{2c}\right)L$$

**(b)** Substituting the given values into this equation,

$$T = \frac{(1.50 + 1.60)}{2(3.0\times10^8 \text{ m/s})}\times 0.010 \text{ m} = 5.17\times10^{-11} \text{ s}$$