16.6 • (a) In a liquid with density 1300 kg/m^3, longitudinal waves with frequency 400 Hz are found to have wavelength 8.00 m. Calculate the bulk modulus of the liquid. (b) A metal bar with a length of 1.50 m has density 6400 kg/m^3. Longitudinal sound waves take 3.90×10^{-4} s to travel from one end of the bar to the other. What is Young's modulus for this metal?

16.6. IDENTIFY: $v = f\lambda$. Apply $v = \sqrt{\frac{B}{\rho}}$ for the waves in the liquid and $v = \sqrt{\frac{Y}{\rho}}$ for the waves in the metal bar.

SET UP: In part (b) the wave speed is $v = \frac{d}{t} = \frac{1.50 \text{ m}}{3.90 \times 10^{-4} \text{ s}}$.

EXECUTE: **(a)** Using $v = \sqrt{\frac{B}{\rho}}$, we have $B = v^2\rho = (\lambda f)^2\rho$, so

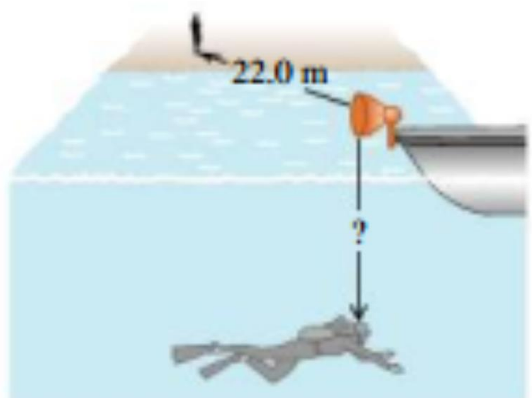
$B = [(8 \text{ m})(400 \text{ Hz})]^2(1300 \text{ kg/m}^3) = 1.33 \times 10^{10}$ Pa.

(b) Using $v = \sqrt{\frac{Y}{\rho}}$, we have $Y = v^2\rho = (L/t)^2\rho = [(1.50 \text{ m})/(3.90 \times 10^{-4} \text{ s})]^2(6400 \text{ kg/m}^3) = 9.47 \times 10^{10}$ Pa.

EVALUATE: In the liquid, $v = 3200$ m/s and in the metal, $v = 3850$ m/s. Both these speeds are much greater than the speed of sound in air.

16.7 • A submerged scuba diver hears the sound of a boat horn directly above her on the surface of the lake. At the same time, a friend on dry land 22.0 m from the boat also hears the horn (Fig. E16.7). The horn is 1.2 m above the surface of the water. What is the distance (labeled "?") from the horn to the diver? Both air and water are at 20°C.

Figure E16.7



16.7. IDENTIFY: $d = vt$ for the sound waves in air and in water.

SET UP: Use $v_{\text{water}} = 1482\text{ m/s}$ at $20°\text{C}$, as given in Table 16.1. In air, $v = 344\text{ m/s}$.

EXECUTE: Since along the path to the diver the sound travels 1.2 m in air, the sound wave travels in water for the same time as the wave travels a distance $22.0\text{ m} - 1.20\text{ m} = 20.8\text{ m}$ in air. The depth of the diver is

$(20.8\text{ m})\dfrac{v_{\text{water}}}{v_{\text{air}}} = (20.8\text{ m})\dfrac{1482\text{ m/s}}{344\text{ m/s}} = 89.6\text{ m}.$ This is the depth of the diver; the distance from the horn is 90.8 m.

EVALUATE: The time it takes the sound to travel from the horn to the person on shore is

$t_1 = \dfrac{22.0\text{ m}}{344\text{ m/s}} = 0.0640\text{ s}.$ The time it takes the sound to travel from the horn to the diver is

$t_2 = \dfrac{1.2\text{ m}}{344\text{ m/s}} + \dfrac{89.6\text{ m}}{1482\text{ m/s}} = 0.0035\text{ s} + 0.0605\text{ s} = 0.0640\text{ s}.$ These times are indeed the same. For three figure accuracy the distance of the horn above the water can't be neglected.

16.11 •• A 60.0-m-long brass rod is struck at one end. A person at the other end hears two sounds as a result of two longitudinal waves, one traveling in the metal rod and the other traveling in air. What is the time interval between the two sounds? (The speed of sound in air is 344 m/s; see Tables 11.1 and 12.1 for relevant information about brass.)

Table 11.1

Material	**Young's Modulus, Y (Pa)**	**Bulk Modulus, B (Pa)**	**Shear Modulus, S (Pa)**
Brass	9.0×10^{10}	6.0×10^{10}	3.5×10^{10}

Table 12.1

Material	**Density (kg/m^3)**
Brass	8.6×10^{3}

16.11. IDENTIFY and SET UP: Use $t = \text{distance/speed}$. Calculate the time it takes each sound wave to travel the $L = 60.0\text{ m}$ length of the pipe. Use $v = \sqrt{\dfrac{Y}{\rho}}$ to calculate the speed of sound in the brass rod.

EXECUTE: Wave in air: $t = (60.0\text{ m})/(344\text{ m/s}) = 0.1744\text{ s}.$

Wave in the metal: $v = \sqrt{\dfrac{Y}{\rho}} = \sqrt{\dfrac{9.0\times10^{10}\text{ Pa}}{8600\text{ kg/m}^3}} = 3235\text{ m/s},$ so $t = \dfrac{60.0\text{ m}}{3235\text{ m/s}} = 0.01855\text{ s}.$

The time interval between the two sounds is $\Delta t = 0.1744\text{ s} - 0.01855\text{ s} = 0.156\text{ s}.$

EVALUATE: The restoring forces that propagate the sound waves are much greater in solid brass than in air, so v is much larger in brass.

16.15 •• **Eavesdropping!** You are trying to overhear a juicy conversation, but from your distance of 15.0 m, it sounds like only an average whisper of 20.0 dB. How close should you move to the chatterboxes for the sound level to be 60.0 dB?

16.15. IDENTIFY and SET UP: We want the sound intensity level to increase from 20.0 dB to 60.0 dB. The previous problem showed that $\beta_2 - \beta_1 = (10\ \text{dB})\log\left(\dfrac{I_2}{I_1}\right)$. We also know that $\dfrac{I_2}{I_1} = \dfrac{r_1^2}{r_2^2}$.

EXECUTE: Using $\beta_2 - \beta_1 = (10\ \text{dB})\log\left(\dfrac{I_2}{I_1}\right)$, we have $\Delta\beta = +40.0\ \text{dB}$. Therefore $\log\left(\dfrac{I_2}{I_1}\right) = 4.00$, so $\dfrac{I_2}{I_1} = 1.00\times 10^4$. Using $\dfrac{I_2}{I_1} = \dfrac{r_1^2}{r_2^2}$ and solving for r_2, we get $r_2 = r_1\sqrt{\dfrac{I_1}{I_2}} = (15.0\ \text{m})\sqrt{\dfrac{1}{1.00\times 10^4}} = 15.0\ \text{cm}$.

EVALUATE: A change of 10^2 in distance gives a change of 10^4 in intensity. Our analysis assumes that the sound spreads from the source uniformly in all directions.

16.20 •• The intensity due to a number of independent sound sources is the sum of the individual intensities. (a) When four quadruplets cry simultaneously, how many decibels greater is the sound intensity level than when a single one cries? (b) To increase the sound intensity level again by the same number of decibels as in part (a), how many more crying babies are required?

16.20. IDENTIFY and SET UP: Apply the relation $\beta_2 - \beta_1 = (10\ \text{dB})\log(I_2/I_1)$ that is derived in Example 16.9.

EXECUTE: **(a)** $\Delta\beta = (10\ \text{dB})\log\left(\dfrac{4I}{I}\right) = 6.0\ \text{dB}$

(b) The total number of crying babies must be multiplied by four, for an increase of 12 kids.

EVALUATE: For $I_2 = \alpha I_1$, where α is some factor, the increase in sound intensity level is $\Delta\beta = (10\ \text{dB})\log\alpha$. For $\alpha = 4$, $\Delta\beta = 6.0\ \text{dB}$.

16.25 • Standing sound waves are produced in a pipe that is 1.20 m long. For the fundamental and first two overtones, determine the locations along the pipe (measured from the left end) of the displacement nodes and the pressure nodes if (a) the pipe is open at both ends and (b) the pipe is closed at the left end and open at the right end.

16.25. **IDENTIFY** and **SET UP:** An open end is a displacement antinode and a closed end is a displacement node. Sketch the standing wave pattern and use the sketch to relate the node-to-antinode distance to the length of the pipe. A displacement node is a pressure antinode and a displacement antinode is a pressure node.
EXECUTE: **(a)** The placement of the displacement nodes and antinodes along the pipe is as sketched in Figure 16.25a. The open ends are displacement antinodes.

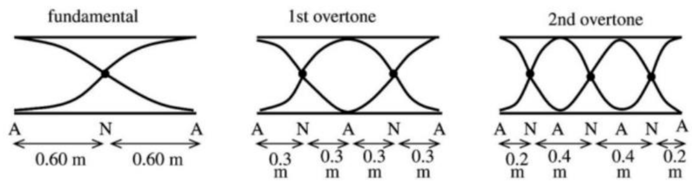


Figure 16.25a

Location of the displacement nodes (N) measured from the left end:
fundamental 0.60 m
1st overtone 0.30 m, 0.90 m
2nd overtone 0.20 m, 0.60 m, 1.00 m

Location of the pressure nodes (displacement antinodes (A)) measured from the left end:
fundamental 0, 1.20 m
1st overtone 0, 0.60 m, 1.20 m
2nd overtone 0, 0.40 m, 0.80 m, 1.20 m

(b) The open end is a displacement antinode and the closed end is a displacement node. The placement of the displacement nodes and antinodes along the pipe is sketched in Figure 16.25b.

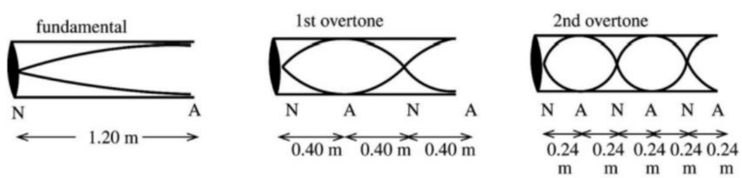


Figure 16.25b

Location of the displacement nodes (N) measured from the closed end:
fundamental 0
1st overtone 0, 0.80 m
2nd overtone 0, 0.48 m, 0.96 m

Location of the pressure nodes (displacement antinodes (A)) measured from the closed end:
fundamental 1.20 m
1st overtone 0.40 m, 1.20 m
2nd overtone 0.24 m, 0.72 m, 1.20 m
EVALUATE: The node-to-node or antinode-to-antinode distance is $\lambda/2$. For the higher overtones the frequency is higher and the wavelength is smaller.

16.30 • **Singing in the Shower.** A pipe closed at both ends can have standing waves inside of it, but you normally don't hear them because little of the sound can get out. But you *can* hear them if you are *inside* the pipe, such as someone singing in the shower. (a) Show that the wavelengths of standing waves in a pipe of length L that is closed at both ends are $\lambda_n = 2L/n$ and the frequencies are given by $f_n = nv/2L = nf_1$, where $n = 1, 2, 3, \ldots$. (b) Modeling it as a pipe, find the frequency of the fundamental and the first two overtones for a shower 2.50 m tall. Are these frequencies audible?

16.30. **IDENTIFY:** There must be a node at each end of the pipe. For the fundamental there are no additional nodes and each successive overtone has one additional node. $v = f\lambda$.

SET UP: $v = 344$ m/s. The node to node distance is $\lambda/2$.

EXECUTE: **(a)** $\frac{\lambda_1}{2} = L$ so $\lambda_1 = 2L$. Each successive overtone adds an additional $\lambda/2$ along the pipe, so $n\left(\frac{\lambda_n}{2}\right) = L$ and $\lambda_n = \frac{2L}{n}$, where $n = 1, 2, 3, \ldots$ $f_n = \frac{v}{\lambda_n} = \frac{nv}{2L}$.

(b) $f_1 = \frac{v}{2L} = \frac{344 \text{ m/s}}{2(2.50 \text{ m})} = 68.8$ Hz. $f_2 = 2f_1 = 138$ Hz. $f_3 = 3f_1 = 206$ Hz. All three of these frequencies are audible.

EVALUATE: A pipe of length L closed at both ends has the same standing wave wavelengths, frequencies and nodal patterns as for a string of length L that is fixed at both ends.

16.32 •• **CP** You have a stopped pipe of adjustable length close to a taut 62.0-cm, 7.25-g wire under a tension of 4110 N. You want to adjust the length of the pipe so that, when it produces sound at its fundamental frequency, this sound causes the wire to vibrate in its second *overtone* with very large amplitude. How long should the pipe be?

16.32. **IDENTIFY:** The wire will vibrate in its second overtone with frequency f_3^{wire} when $f_3^{\text{wire}} = f_1^{\text{pipe}}$. For a stopped pipe, $f_1^{\text{pipe}} = \dfrac{v}{4L_{\text{pipe}}}$. The second overtone standing wave frequency for a wire fixed at both ends is $f_3^{\text{wire}} = 3\left(\dfrac{v_{\text{wire}}}{2L_{\text{wire}}}\right)$. $v_{\text{wire}} = \sqrt{F/\mu}$.

SET UP: The wire has $\mu = \dfrac{m}{L_{\text{wire}}} = \dfrac{7.25 \times 10^{-3}\text{ kg}}{0.620\text{ m}} = 1.169 \times 10^{-2}\text{ kg/m}$. The speed of sound in air is $v = 344\text{ m/s}$.

EXECUTE: $v_{\text{wire}} = \sqrt{\dfrac{4110\text{ N}}{1.169 \times 10^{-2}\text{ kg/m}}} = 592.85\text{ m/s}$. $f_3^{\text{wire}} = f_1^{\text{pipe}}$ gives $3\dfrac{v_{\text{wire}}}{2L_{\text{wire}}} = \dfrac{v}{4L_{\text{pipe}}}$.

$$L_{\text{pipe}} = \frac{2L_{\text{wire}}v}{12v_{\text{wire}}} = \frac{2(0.620\text{ m})(344\text{ m/s})}{12(592.85\text{ m/s})} = 0.0600\text{ m} = 6.00\text{ cm}.$$

EVALUATE: The fundamental for the pipe has the same frequency as the third harmonic of the wire. But the wave speeds for the two objects are different and the two standing waves have different wavelengths.

16.33 •• A 75.0-cm-long wire of mass 5.625 g is tied at both ends and adjusted to a tension of 35.0 N. When it is vibrating in its second overtone, find (a) the frequency and wavelength at which it is vibrating and (b) the frequency and wavelength of the sound waves it is producing.

16.33. **IDENTIFY:** The second overtone is the third harmonic, with $f = 3f_1$.

SET UP: $v = \sqrt{\dfrac{F}{\mu}}$. $f_1 = v/2L$. $v = f\lambda$. $\lambda_n = 2L/n$, so $\dfrac{3\lambda}{2} = L$ for the third harmonic.

EXECUTE: **(a)** $v = \sqrt{\dfrac{35.0\text{ N}}{(5.625 \times 10^{-3}\text{ kg})/(0.750\text{ m})}} = 68.3\text{ m/s}$.

$$f = \frac{3v}{2L} = \frac{3(68.3\text{ m/s})}{2(0.750\text{ m})} = 137\text{ Hz}$$

$$\lambda = \frac{v}{f} = \frac{68.3\text{ m/s}}{137\text{ Hz}} = 0.50\text{ m}$$

(b) $f = 137\text{ Hz}$, the same as for the wire, so $\lambda = \dfrac{v}{f} = \dfrac{344\text{ m/s}}{137\text{ Hz}} = 2.51\text{ m}$.

EVALUATE: λ is larger in air because v is larger there.

16.37 ·· Two loudspeakers, A and B, are driven by the same amplifier and emit sinusoidal waves in phase. Speaker B is 12.0 m to the right of speaker A. The frequency of the waves emitted by each speaker is 688 Hz. You are standing between the speakers, along the line connecting them, and are at a point of constructive interference. How far must you walk toward speaker B to move to a point of destructive interference?

16.37. IDENTIFY: For constructive interference the path difference is an integer number of wavelengths and for destructive interference the path difference is a half-integer number of wavelengths.

SET UP: $\lambda = v/f = (344\text{ m/s})/(688\text{ Hz}) = 0.500\text{ m}$

EXECUTE: To move from constructive interference to destructive interference, the path difference must change by $\lambda/2$. If you move a distance x toward speaker B, the distance to B gets shorter by x and the distance to A gets longer by x so the path difference changes by $2x$. $2x = \lambda/2$ and $x = \lambda/4 = 0.125\text{ m}$.

EVALUATE: If you walk an additional distance of 0.125 m farther, the interference again becomes constructive.

16.43 ·· Two organ pipes, open at one end but closed at the other, are each 1.14 m long. One is now lengthened by 2.00 cm. Find the beat frequency that they produce when playing together in their fundamentals.

16.43. IDENTIFY: $f_{\text{beat}} = |f_a - f_b|$. For a stopped pipe, $f_1 = \frac{v}{4L}$.

SET UP: $v = 344\text{ m/s}$. Let $L_a = 1.14\text{ m}$ and $L_b = 1.16\text{ m}$. $L_b > L_a$ so $f_{1a} > f_{1b}$.

EXECUTE: $f_{1a} - f_{1b} = \frac{v}{4}\left(\frac{1}{L_a} - \frac{1}{L_b}\right) = \frac{v(L_b - L_a)}{4L_aL_b} = \frac{(344\text{ m/s})(2.00\times10^{-2}\text{ m})}{4(1.14\text{ m})(1.16\text{ m})} = 1.3\text{ Hz}$. There are 1.3 beats per second.

EVALUATE: Increasing the length of the pipe increases the wavelength of the fundamental and decreases the frequency.

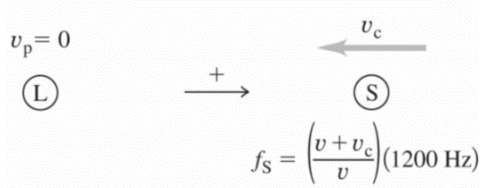
16.55 •• A stationary police car emits a sound of frequency 1200 Hz that bounces off a car on the highway and returns with a frequency of 1250 Hz. The police car is right next to the highway, so the moving car is traveling directly toward or away from it. (a) How fast was the moving car going? Was it moving toward or away from the police car? (b) What frequency would the police car have received if it had been traveling toward the other car at 20.0 m/s?

16.55. **IDENTIFY:** Apply the Doppler shift formulas. We first treat the stationary police car as the source and then as the observer as he receives his own sound reflected from the on-coming car.

SET UP: $f_L = \left(\dfrac{v + v_L}{v + v_S}\right) f_S$.

EXECUTE: **(a)** Since the frequency is increased the moving car must be approaching the police car. Let v_c be the speed of the moving car. The speed v_p of the police car is zero. First consider the moving car as the listener, as shown in Figure 16.55a.

(a)



(b)

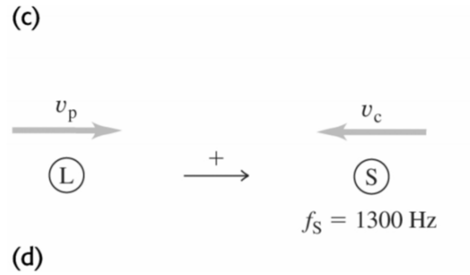


Figure 16.55

$$f_L = \left(\frac{v + v_L}{v + v_S}\right) f_S = \left(\frac{v + v_c}{v}\right)(1200 \text{ Hz})$$

Then consider the moving car as the source and the police car as the listener (Figure 16.55b):

$$f_L = \left(\frac{v + v_L}{v + v_S}\right) f_S \text{ gives } 1250 \text{ Hz} = \left(\frac{v}{v - v_c}\right)\left(\frac{v + v_c}{v}\right)(1200 \text{ Hz}).$$

Solving for v_c gives

$$v_c = \left(\frac{50}{2450}\right) v = \left(\frac{50}{2450}\right)(344 \text{ m/s}) = 7.02 \text{ m/s}$$

(**b**) Repeat the calculation of part (a), but now $v_p = 20.0$ m/s, toward the other car.

Waves received by the car (Figure 16.55c):

$$f_L = \left(\frac{v + v_c}{v - v_p}\right) f_S = \left(\frac{344 \text{ m/s} + 7 \text{ m/s}}{344 \text{ m/s} - 20 \text{ m/s}}\right)(1200 \text{ Hz}) = 1300 \text{ Hz}$$

Waves reflected by the car and received by the police car (Figure 16.55d):

$$f_L = \left(\frac{v + v_p}{v - v_c}\right) f_S = \left(\frac{344 \text{ m/s} + 20 \text{ m/s}}{344 \text{ m/s} - 7 \text{ m/s}}\right)(1300 \text{ Hz}) = 1404 \text{ Hz}$$

EVALUATE: The cars move toward each other with a greater relative speed in (b) and the increase in frequency is much larger there.

16.57 •• A jet plane flies overhead at Mach 1.70 and at a constant altitude of 1250 m. (a) What is the angle α of the shock-wave cone? (b) How much time after the plane passes directly overhead do you hear the sonic boom? Neglect the variation of the speed of sound with altitude.

16.57. **IDENTIFY:** Apply $\sin\alpha = v/v_s$ to calculate α. Use the method of Example 16.19 to calculate t.

SET UP: Mach 1.70 means $v_S/v = 1.70$.

EXECUTE: **(a)** In $\sin\alpha = v/v_s$, $v/v_S = 1/1.70 = 0.588$ and $\alpha = \arcsin(0.588) = 36.0°$.

(b) As in Example 16.19, $t = \dfrac{1250\text{ m}}{(1.70)(344\text{ m/s})(\tan\ 36.0°)} = 2.94\text{ s}.$

EVALUATE: The angle α decreases when the speed v_S of the plane increases.

Example 16.14: A police car's siren emits a sinusoidal wave with frequency f_S = 300 Hz. The speed of sound is 340 m/s and the air is still. The police car is moving toward a warehouse at 30 m/s. What frequency does the driver hear reflected from the warehouse?

EXAMPLE 16.18 DOPPLER EFFECT V: A DOUBLE DOPPLER SHIFT

The police car is moving toward a warehouse at 30 m/s. What frequency does the driver hear reflected from the warehouse?

SOLUTION

IDENTIFY: This situation has *two* Doppler shifts (**Fig. 16.34**). In the first shift, the warehouse is the stationary "listener." The frequency of sound reaching the warehouse, which we call f_W, is greater than 300 Hz because the source is approaching. In the second shift, the warehouse acts as a source of sound with frequency f_W, and the listener is the driver of the police car; she hears a frequency greater than f_W because she is approaching the source.

SET UP: To determine f_W, we use Eq. (16.29) with f_L replaced by f_W. For this part of the problem, $v_L = v_W = 0$ (the warehouse is at rest) and $v_S = -30$ m/s (the siren is moving in the negative direction from source to listener).

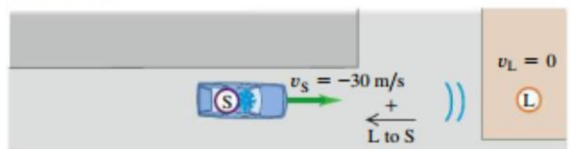
To determine the frequency heard by the driver (our target variable), we again use Eq. (16.29) but now with f_S replaced by f_W. For this second part of the problem, $v_S = 0$ because the stationary warehouse is the source and the velocity of the listener (the driver) is $v_L = +30$ m/s. (The listener's velocity is positive because it is in the direction from listener to source.)

EXECUTE: The frequency reaching the warehouse is

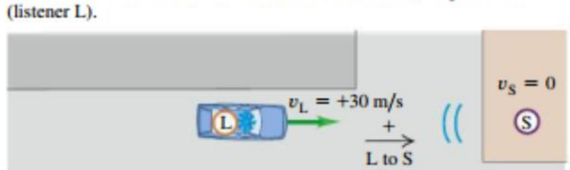
$$f_W = \frac{v}{v + v_S} f_S = \frac{340\text{ m/s}}{340\text{ m/s} + (-30\text{ m/s})}(300\text{ Hz}) = 329\text{ Hz}$$

16.34 Two stages of the sound wave's motion from the police car to the warehouse and back to the police car.

(a) Sound travels from police car's siren (source S) to warehouse ("listener" L).



(b) Reflected sound travels from warehouse (source S) to police car (listener L).



Then the frequency heard by the driver is

$$f_L = \frac{v + v_L}{v} f_W = \frac{340\text{ m/s} + 30\text{ m/s}}{340\text{ m/s}}(329\text{ Hz}) = 358\text{ Hz}$$

EVALUATE: Because there are two Doppler shifts, the reflected sound heard by the driver has an even higher frequency than the sound heard by a stationary listener in the warehouse.