CHAPTER

15 Sound

Practice Problems

15.1 Properties and Detection of Sound pages 403–410

page 405

1. Find the wavelength in air at 20°C of an 18-Hz sound wave, which is one of the lowest frequencies that is detectable by the human ear.

   $$\lambda = \frac{v}{f} = \frac{343\ \text{m/s}}{18\ \text{Hz}} = 19\ \text{m}$$

2. What is the wavelength of an 18-Hz sound wave in seawater at 25°C?

   $$\lambda = \frac{v}{f} = \frac{1533\ \text{m/s}}{18\ \text{Hz}} = 85\ \text{m}$$

3. Find the frequency of a sound wave moving through iron at 25°C with a wavelength of 1.25 m.

   $$f = \frac{v}{\lambda} = \frac{5130\ \text{m/s}}{1.25\ \text{m}} = 4.10\times10^{3}\ \text{Hz}$$

4. If you shout across a canyon and hear the echo 0.80 s later, how wide is the canyon?

   $$v = \frac{d}{t}$$

   so $d = vt = (343\ \text{m/s})(0.40\ \text{s}) = 140\ \text{m}$

5. A 2280-Hz sound wave has a wavelength of 0.655 m in an unknown medium. Identify the medium.

   $$\lambda = \frac{v}{f}$$

   so $v = \lambda f = (0.655\ \text{m})(2280\ \text{Hz})$

   $= 1490\ \text{m/s}$

   This speed corresponds to water at 25°C.

page 409

6. Repeat Example Problem 1, but with the car moving away from you. What frequency would you hear?

   $v_s = -24.6\ \text{m/s}$

   $$f_d = 524\ \text{Hz}\left(\frac{1}{1 - \frac{(-24.6\ \text{m/s})}{343\ \text{m/s}}}\right)$$

   $= 489\ \text{Hz}$

7. You are in an auto traveling at 25.0 m/s toward a pole-mounted warning siren. If the siren's frequency is 365 Hz, what frequency do you hear? Use 343 m/s as the speed of sound.

   $v = 343\ \text{m/s}$, $f_s = 365\ \text{Hz}$, $v_s = 0$,

   $v_d = -25.0\ \text{m/s}$

   $$f_d = f_s\left(\frac{v - v_d}{v - v_s}\right)$$

   $$= (365\ \text{Hz})\left(\frac{343\ \text{m/s} + 25.0\ \text{m/s}}{343\ \text{m/s}}\right)$$

   $= 392\ \text{Hz}$

8. You are in an auto traveling at 55 mph (24.6 m/s). A second auto is moving toward you at the same speed. Its horn is sounding at 475 Hz. What frequency do you hear? Use 343 m/s as the speed of sound.

   $v = 343\ \text{m/s}$, $f_s = 475\ \text{Hz}$, $v_s = +24.6\ \text{m/s}$, $v_d = -24.6\ \text{m/s}$

   $$f_d = f_s\left(\frac{v - v_d}{v - v_s}\right)$$

   $$= (475\ \text{Hz})\left(\frac{343\ \text{m/s} + 24.6\ \text{m/s}}{343\ \text{m/s} - 24.6\ \text{m/s}}\right)$$

   $= 548\ \text{Hz}$

9. A submarine is moving toward another submarine at 9.20 m/s. It emits a 3.50-MHz ultrasound. What frequency would the second sub, at rest, detect? The speed of sound in water is 1482 m/s.

   $v = 1482\ \text{m/s}$, $f_s = 3.50\ \text{MHz}$,

   $v_s = 9.20\ \text{m/s}$, $v_d = 0\ \text{m/s}$

   $$f_d = f_s\left(\frac{v - v_d}{v - v_s}\right)$$

$= (3.50 \text{ MHz})\left(\frac{1482 \text{ m/s}}{1482 \text{ m/s} - 9.20 \text{ m/s}}\right)$

= 3.52 MHz

10. A sound source plays middle C (262 Hz). How fast would the source have to go to raise the pitch to C sharp (271 Hz)? Use 343 m/s as the speed of sound.

$v = 343$ m/s, $f_s = 262$ Hz, $f_d = 271$ Hz,

$v_d = 0$ m/s, v_s is unknown

$$f_d = f_s\left(\frac{v - v_d}{v - v_s}\right)$$

Solve this equation for v_s.

$$v_s = v - \frac{f_s}{f_d}(v - v_d)$$

$$= 343 \text{ m/s} - \left(\frac{262 \text{ Hz}}{271 \text{ Hz}}\right)(343 \text{ m/s} - 0 \text{ m/s})$$

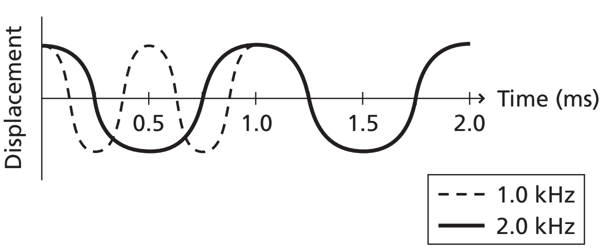
$$= 11.4 \text{ m/s}$$

Section Review

15.1 Properties and Detection of Sound pages 403–410

page 410

11. Graph The eardrum moves back and forth in response to the pressure variations of a sound wave. Sketch a graph of the displacement of the eardrum versus time for two cycles of a 1.0-kHz tone and for two cycles of a 2.0-kHz tone.



12. Effect of Medium List two sound characteristics that are affected by the medium through which the sound passes and two characteristics that are not affected.

affected: speed and wavelength; unaffected: period and frequency

13. Sound Properties What physical characteristic of a sound wave should be changed to change the pitch of the sound? To change the loudness?

frequency; amplitude

14. Decibel Scale How much greater is the sound pressure level of a typical rock band's music (110 dB) than a normal conversation (50 dB)?

The sound pressure level increases by a factor of 10 for every 20-dB increase in sound level. Therefore, 60 dB corresponds to a 1000-fold increase in SPL.

15. Early Detection In the nineteenth century, people put their ears to a railroad track to get an early warning of an approaching train. Why did this work?

The velocity of sound is greater in solids than in gases. Therefore, sound travels faster in steel rails than in air, and the rails help focus the sound so it does not die out as quickly as in air.

16. Bats A bat emits short pulses of high-frequency sound and detects the echoes.

a. In what way would the echoes from large and small insects compare if they were the same distance from the bat?

They would differ in intensity. Larger insects would reflect more of the sound energy back to the bat.

b. In what way would the echo from an insect flying toward the bat differ from that of an insect flying away from the bat?

An insect flying toward the bat would return an echo of higher frequency (Doppler shift). An insect flying away from the bat would return an echo of lower frequency.

17. Critical Thinking Can a trooper using a radar detector at the side of the road determine the speed of a car at the instant the car passes the trooper? Explain.

No. The car must be approaching or

receding from the detector for the Doppler effect to be observed. Transverse motion produces no Doppler effect.

Practice Problems

15.2 The Physics of Music pages 411–419

page 416

18. A 440-Hz tuning fork is held above a closed pipe. Find the spacing between the resonances when the air temperature is 20°C.

Resonance spacing = $\frac{\lambda}{2}$ so using $\lambda = \frac{v}{f}$ the resonance spacing is

$$\frac{\lambda}{2} = \frac{v}{2f} = \frac{343\text{ m/s}}{(2)(440\text{ Hz})} = 0.39\text{ m}$$

19. A 440-Hz tuning fork is used with a resonating column to determine the velocity of sound in helium gas. If the spacings between resonances are 110 cm, what is the velocity of sound in helium gas?

Resonance spacing = $\frac{\lambda}{2}$ = 1.1 m

so λ = 2.2 m

$$v = \lambda f = (2.2\text{ m})(440\text{ Hz}) = 970\text{ m/s}$$

20. The frequency of a tuning fork is unknown. A student uses an air column at 27°C and finds resonances spaced by 20.2 cm. What is the frequency of the tuning fork? Use the speed calculated in Example Problem 2 for the speed of sound in air at 27°C.

v = 347 m/s at 27°C

Resonance spacing gives $\frac{\lambda}{2}$ = 0.202 m, or λ = 0.404 m

$$f = \frac{v}{\lambda} = \frac{347\text{ m/s}}{0.404\text{ m}} = 859\text{ Hz}$$

21. A bugle can be thought of as an open pipe. If a bugle were straightened out, it would be 2.65-m long.

a. If the speed of sound is 343 m/s, find the lowest frequency that is resonant for a bugle (ignoring end corrections).

$$\lambda_1 = 2L = (2)(2.65\text{ m}) = 5.30\text{ m}$$

The lowest frequency is

$$f_1 = \frac{v}{\lambda_1} = \frac{343\text{ m/s}}{5.30\text{ m}} = 64.7\text{ Hz}$$

b. Find the next two resonant frequencies for the bugle.

$$f_2 = \frac{v}{\lambda_2} = \frac{v}{L} = \frac{343\text{ m/s}}{2.65\text{ m}} = 129\text{ Hz}$$

$$f_3 = \frac{v}{\lambda_3} = \frac{3v}{2L} = \frac{(3)(343\text{ m/s})}{(2)(2.65\text{ m})} = 194\text{ Hz}$$

Section Review

15.2 The Physics of Music pages 411–419

page 419

22. Origins of Sound What is the vibrating object that produces sounds in each of the following?

a. a human voice

vocal cords

b. a clarinet

a reed

c. a tuba

the player's lips

d. a violin

a string

23. Resonance in Air Columns Why is the tube from which a tuba is made much longer than that of a cornet?

The longer the tube, the lower the resonant frequency it will produce.

24. Resonance in Open Tubes How must the length of an open tube compare to the wavelength of the sound to produce the strongest resonance?

The length of the tube should be one-half the wavelength.

25. Resonance on Strings A violin sounds a note of F sharp, with a pitch of 370 Hz. What are the frequencies of the next three harmonics produced with this note?

A string's harmonics are whole number multiples of the fundamental, so the frequencies are:

$f_2 = 2f_1 = (2)(370\text{ Hz}) = 740\text{ Hz}$

$f_3 = 3f_1 = (3)(370\text{ Hz}) = 1110\text{ Hz}$
$= 1100\text{ Hz}$

$f_4 = 4f_1 = (4)(370\text{ Hz}) = 1480\text{ Hz}$
$= 1500\text{ Hz}$

26. **Resonance in Closed Pipes** One closed organ pipe has a length of 2.40 m.

a. What is the frequency of the note played by this pipe?

$\lambda = 4L = (4)(2.40\text{ m}) = 9.60\text{ m}$

$\lambda = \frac{v}{f}$

$f = \frac{v}{\lambda} = \frac{343\text{ m/s}}{9.60\text{ m}} = 35.7\text{ Hz}$

b. When a second pipe is played at the same time, a 1.40-Hz beat note is heard. By how much is the second pipe too long?

$f = 35.7\text{ Hz} - 1.40\text{ Hz} = 34.3\text{ Hz}$

$\lambda = \frac{v}{f} = \frac{343\text{ m/s}}{34.3\text{ Hz}} = 10.0\text{ m}$

$\lambda = 4L$

$L = \frac{\lambda}{4} = \frac{10.0\text{ m}}{4} = 2.50\text{ m}$

The difference in lengths is
$2.50\text{ m} - 2.40\text{ m} = 0.10\text{ m}$

27. **Timbre** Why do various instruments sound different even when they play the same note?

Each instrument produces its own set of fundamental and harmonic frequencies, so they have different timbres.

28. **Beats** A tuning fork produces three beats per second with a second, 392-Hz tuning fork. What is the frequency of the first tuning fork?

It is either 389 Hz or 395 Hz. You can't tell which without more information.

29. **Critical Thinking** Strike a tuning fork with a rubber hammer and hold it at arm's length. Then press its handle against a desk, a door, a filing cabinet, and other objects. What do you hear? Why?

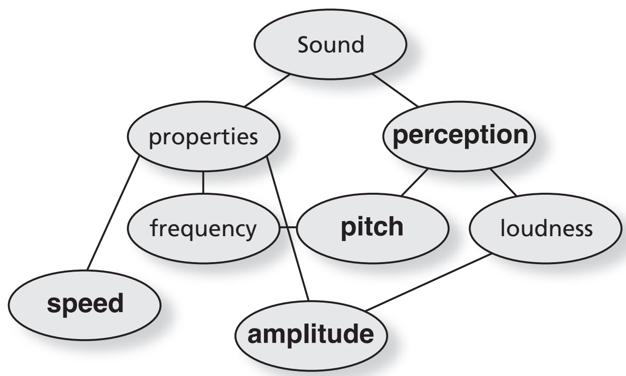
The tuning fork's sound is amplified greatly when it is pressed against other objects because they resonate like a sounding board. They sound different because they resonate with different harmonics; therefore, they have different timbres.

Chapter Assessment

Concept Mapping

page 424

30. Complete the concept map below using the following terms: *amplitude, perception, pitch, speed.*



Mastering Concepts

page 424

31. What are the physical characteristics of sound waves? (15.1)

Sound waves can be described by frequency, wavelength, amplitude, and speed.

32. When timing the 100-m run, officials at the finish line are instructed to start their stopwatches at the sight of smoke from the starter's pistol and not at the sound of its firing. Explain. What would happen to the times for the runners if the timing started when sound was heard? (15.1)

Light travels at 3.00×10^8 m/s, while sound travels at 343 m/s. Officials would see the smoke before they would hear the pistol fire. The times would be less than actual if sound were used.

33. Name two types of perception of sound and the physical characteristics of sound waves that correspond to them. (15.1)

pitch—frequency, loudness—amplitude

34. Does the Doppler shift occur for only some types of waves or for all types of waves? (15.1)

all types of waves

35. Sound waves with frequencies higher than can be heard by humans, called ultrasound, can be transmitted through the human body. How could ultrasound be used to measure the speed of blood flowing in veins or arteries? Explain how the waves change to make this measurement possible. (15.1)

Doctors can measure the Doppler shift from sound reflected by the moving blood cells. Because the blood is moving, sound gets Doppler shifted, the compressions either get piled up or spaced apart. This alters the frequency of the wave.

36. What is necessary for the production and transmission of sound? (15.2)

a vibrating object and a material medium

37. **Singing** How can a certain note sung by an opera singer cause a crystal glass to shatter? (15.2)

The frequency of the note is the same as the natural resonance of the crystal, causing its molecules to increase their amplitude of vibration as energy from the sound is accepted.

38. **Marching** In the military, as marching soldiers approach a bridge, the command "route step" is given. The soldiers then walk out-of-step with each other as they cross the bridge. Explain. (15.2)

While marching in step, a certain frequency is established that could resonate the bridge into destructive oscillation. No single frequency is maintained under "route step."

39. **Musical Instruments** Why don't most musical instruments sound like tuning forks? (15.2)

Tuning forks produce simple, single-frequency waves. Musical instruments produce complex waves containing many different frequencies. This gives them their timbres.

40. **Musical Instruments** What property distinguishes notes played on both a trumpet and a clarinet if they have the same pitch and loudness? (15.2)

the sound quality or timbre

41. **Trombones** Explain how the slide of a trombone, shown in **Figure 15-21,** changes the pitch of the sound in terms of a trombone being a resonance tube. (15.2)

■ **Figure 15-21**

The slide of a trombone varies pitch by changing the length of the resonating column of vibrating air.

Applying Concepts

pages 424–425

42. **Estimation** To estimate the distance in kilometers between you and a lightning flash, count the seconds between the flash and the thunder and divide by 3. Explain how this rule works. Devise a similar rule for miles.

The speed of sound = 343 m/s = 0.343 km/s = (1/2.92) km/s; or, sound travels approximately 1 km in 3 s. Therefore, divide the number of seconds by three. For miles, sound travels approximately 1 mile in 5 s. Therefore, divide the number of seconds by five.

43. The speed of sound increases by about 0.6 m/s for each degree Celsius when the air temperature rises. For a given sound, as the temperature increases, what happens to the following?

a. the frequency

There is no change in frequency.

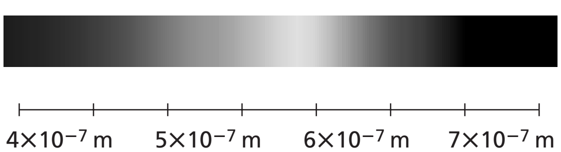
b. the wavelength

The wavelength increases.

44. **Movies** In a science-fiction movie, a satellite blows up. The crew of a nearby ship immediately hears and sees the explosion. If you had been hired as an advisor, what two physics errors would you have noticed and corrected?

First, if you had heard a sound, you would have heard it after you saw the explosion. Sound waves travel much more slowly than electromagnetic waves. Second, in space the density of matter is so small that the sound waves do not propagate. Consequently, no sound should have been heard.

45. **The Redshift** Astronomers have observed that the light coming from distant galaxies appears redder than light coming from nearer galaxies. With the help of **Figure 15-22,** which shows the visible spectrum, explain why astronomers conclude that distant galaxies are moving away from Earth.



■ **Figure 15-23**

Red light has a longer wavelength and therefore, a lower frequency than other colors. The Doppler shift of their light to lower frequencies indicates that distant galaxies are moving away from us.

46. Does a sound of 40 dB have a factor of 100 (10^2) times greater pressure variation than the threshold of hearing, or a factor of 40 times greater?

A 40-dB sound has sound pressures 100 times greater.

47. If the pitch of sound is increased, what are the changes in the following?

a. the frequency

Frequency will increase.

b. the wavelength

Wavelength will decrease.

c. the wave velocity

Wave velocity will remain the same.

d. the amplitude of the wave

Amplitude will remain the same.

48. The speed of sound increases with temperature. Would the pitch of a closed pipe increase or decrease when the temperature of the air rises? Assume that the length of the pipe does not change.

$\lambda = 4l$ **and** $v = f\lambda$ **so** $v = 4fl$**. If** v **increases and** l **remains unchanged,** f **increases and pitch increases.**

49. **Marching Bands** Two flutists are tuning up. If the conductor hears the beat frequency increasing, are the two flute frequencies getting closer together or farther apart?

The frequencies are getting farther apart.

50. **Musical Instruments** A covered organ pipe plays a certain note. If the cover is removed to make it an open pipe, is the pitch increased or decreased?

The pitch is increased; the frequency is twice as high for an open pipe as for a closed pipe.

51. **Stringed Instruments** On a harp, **Figure 15-23a,** long strings produce low notes and short strings produce high notes. On a guitar, **Figure 15-23b,** the strings are all the same length. How can they produce notes of different pitches?

■ **Figure 15-23**

The strings have different tensions and masses per unit length. Thinner, tighter strings produce higher notes than do thicker, looser strings.

Mastering Problems

15.1 Properties and Detection of Sound
pages 425–426

Level 1

52. You hear the sound of the firing of a distant cannon 5.0 s after seeing the flash. How far are you from the cannon?

$\boldsymbol{d = vt = (343\ \text{m/s})(5.0\ \text{s}) = 1.7\ \text{km}}$

53. If you shout across a canyon and hear an echo 3.0 s later, how wide is the canyon?

$d = vt = (343\ \text{m/s})(3.0\ \text{s})$ is the total distance traveled. The distance to the wall is $\frac{1}{2}(343\ \text{m/s})(3.0\ \text{s}) = 5.1\times10^2\ \text{m}$

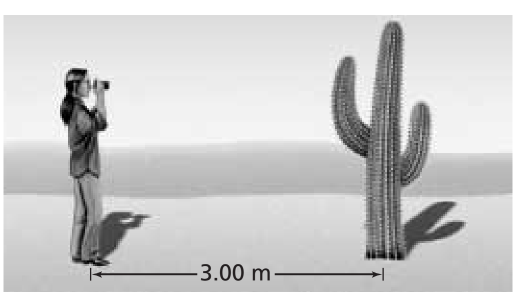
54. A sound wave has a frequency of 4700 Hz and travels along a steel rod. If the distance between compressions, or regions of high pressure, is 1.1 m, what is the speed of the wave?

$\boldsymbol{v = \lambda f = (1.1\ \text{m})(4700\ \text{Hz}) = 5200\ \text{m/s}}$

55. **Bats** The sound emitted by bats has a wavelength of 3.5 mm. What is the sound's frequency in air?

$$f = \frac{v}{\lambda} = \frac{343\ \text{m/s}}{0.0035\ \text{m}} = 9.8\times10^4\ \text{Hz}$$

56. **Photography** As shown in **Figure 15-24,** some cameras determine the distance to the subject by sending out a sound wave and measuring the time needed for the echo to return to the camera. How long would it take the sound wave to return to such a camera if the subject were 3.00 m away?



■ **Figure 15-24**

The total distance the sound must travel is 6.00 m.

$$v = \frac{d}{t}$$

$$\text{so } t = \frac{d}{v} = \frac{6.00\ \text{m}}{343\ \text{m/s}} = 0.0175\ \text{s}$$

57. Sound with a frequency of 261.6 Hz travels through water at 25°C. Find the sound's wavelength in water. Do not confuse sound waves moving through water with surface waves moving through water.

$$\lambda = \frac{v}{f} = \frac{1493\ \text{m/s}}{261.6\ \text{Hz}} = 5.707\ \text{m}$$

58. If the wavelength of a 4.40×10^2-Hz sound in freshwater is 3.30 m, what is the speed of sound in freshwater?

$$v = \lambda f = (3.30\ \text{m})(4.40\times10^2\ \text{Hz}) = 1.45\times10^3\ \text{m/s}$$

59. Sound with a frequency of 442 Hz travels through an iron beam. Find the wavelength of the sound in iron.

$$\lambda = \frac{v}{f} = \frac{5130\ \text{m/s}}{442\ \text{Hz}} = 11.6\ \text{m}$$

60. **Aircraft** Adam, an airport employee, is working near a jet plane taking off. He experiences a sound level of 150 dB.

a. If Adam wears ear protectors that reduce the sound level to that of a typical rock concert, what decrease in dB is provided?

A typical rock concert is 110 dB, so 40 dB reduction is needed.

b. If Adam then hears something that sounds like a barely audible whisper, what will a person not wearing the ear protectors hear?

A barely audible whisper is 10 dB, so the actual level would be 50 dB, or that of an average classroom.

61. **Rock Music** A rock band plays at an 80-dB sound level. How many times greater is the sound pressure from another rock band playing at each of the following sound levels?

a. 100 dB

Each 20 dB increases pressure by a factor of 10, so 10 times greater pressure.

b. 120 dB

(10)(10) = 100 times greater pressure

62. A coiled-spring toy is shaken at a frequency of 4.0 Hz such that standing waves are observed with a wavelength of 0.50 m. What is the speed of propagation of the wave?

$v = \lambda f = (0.50 \text{ m})(4.0 \text{ s}^{-1}) = 2.0 \text{ m/s}$

63. A baseball fan on a warm summer day (30°C) sits in the bleachers 152 m away from home plate.

a. What is the speed of sound in air at 30°C?

The speed increases 0.6 m/s per °C, so the increase from 20°C to 30°C is 6 m/s. Thus, the speed is 343 + 6 = 349 m/s.

b. How long after seeing the ball hit the bat does the fan hear the crack of the bat?

$t = \frac{d}{v} = \frac{152 \text{ m}}{349 \text{ m}} = 0.436 \text{ s}$

64. On a day when the temperature is 15°C, a person stands some distance, *d*, as shown in **Figure 15-25,** from a cliff and claps his hands. The echo returns in 2.0 s. How far away is the cliff?

■ **Figure 15-25**

At 15°C, the speed of sound is 3 m/s slower than at 20°C. Thus, the speed of sound is 340 m/s.

$v = 340 \text{ m/s}$ **and** $2t = 2.0 \text{ s}$

$d = vt = (340 \text{ m/s})(1.0 \text{ s}) = 3.4\times10^{2} \text{ m}$

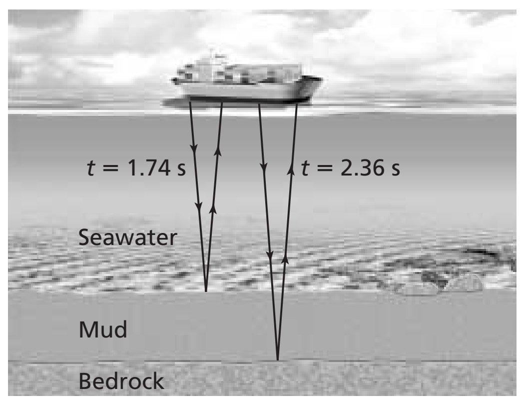
Level 2

65. Medical Imaging Ultrasound with a frequency of 4.25 MHz can be used to produce images of the human body. If the speed of sound in the body is the same as in salt water, 1.50 km/s, what is the length of a 4.25-MHz pressure wave in the body?

$\lambda = \frac{v}{f} = \frac{1.50\times10^{3} \text{ m/s}}{4.25\times10^{6} \text{ Hz}} = 3.53\times10^{-4} \text{ m}$

$= 0.353 \text{ mm}$

66. Sonar A ship surveying the ocean bottom sends sonar waves straight down into the seawater from the surface. As illustrated in **Figure 15-26,** the first reflection, off of the mud at the sea floor, is received 1.74 s after it was sent. The second reflection, from the bedrock beneath the mud, returns after 2.36 s. The seawater is at a temperature of 25°C, and the speed of sound in mud is 1875 m/s.



■ **Figure 15-26**

a. How deep is the water?

The speed of sound in the seawater is 1533 m/s and the time for a one-way trip is 0.87 s, so

$d_w = vt_w = (1533 \text{ m/s})(0.87 \text{ s})$

$= 1300 \text{ m}$

b. How thick is the mud?

The round-trip time in the mud is

2.36 s − 1.74 s = 0.62 s

The one-way time in the mud is 0.31 s,

so $d_m = vt_m = (1875 \text{ m/s})(0.31 \text{ s})$

$= 580 \text{ m}$

67. Determine the variation in sound pressure of a conversation being held at a sound level of 60 dB.

The pressure variation at 0 dB is 2×10^{-5} Pa. For every 20-dB increase, the pressure variation increases by a factor of 10. Therefore, 60 dB has a pressure variation amplitude of 2×10^{-2} Pa.

68. A fire truck is moving at 35 m/s, and a car in front of the truck is moving in the same direction at 15 m/s. If a 327-Hz siren blares from the truck, what frequency is heard by the driver of the car?

$v_s = 35$ m/s, $v = 343$ m/s, $v_d = 15$ m/s, $f_s = 327$ Hz

$$f_d = f_s\left(\frac{v - v_d}{v - v_s}\right)$$

$$= (327\text{ Hz})\left(\frac{343 - 15}{343 - 35}\right) = 350\text{ Hz}$$

Level 3

69. A train moving toward a sound detector at 31.0 m/s blows a 305-Hz whistle. What frequency is detected on each of the following?

a. a stationary train

$$f_d = f_s\left(\frac{v - v_d}{v - v_s}\right)$$

$$= \frac{(305\text{ Hz})(343\text{ m/s} - 0)}{343\text{ m/s} - 31.0\text{ m/s}}$$

$$= 335\text{ Hz}$$

b. a train moving toward the first train at 21.0 m/s

$$f_d = f_s\left(\frac{v - v_d}{v - v_s}\right)$$

$$= \frac{(305\text{ Hz})(343\text{ m/s} - (-21.0\text{ m/s}))}{343\text{ m/s} - 31.0\text{ m/s}}$$

$$= 356\text{ Hz}$$

70. The train in the previous problem is moving away from the detector. What frequency is now detected on each of the following?

a. a stationary train

$$f_d = f_s\left(\frac{v - v_d}{v - v_s}\right)$$

$$= \frac{(305\text{ Hz})(343\text{ m/s} - 0)}{343\text{ m/s} - (-31.0\text{ m/s})}$$

$$= 2.80\times10^2\text{ Hz}$$

b. a train moving away from the first train at a speed of 21.0 m/s

$$f_d = f_s\left(\frac{v - v_d}{v - v_s}\right)$$

$$= \frac{(305\text{ Hz})(343\text{ m/s} - 21.0\text{ m/s})}{343\text{ m/s} - (-31.0\text{ m/s})}$$

$$= 2.63\times10^2\text{ Hz}$$

15.2 The Physics of Music

pages 426–427

Level 1

71. A vertical tube with a tap at the base is filled with water, and a tuning fork vibrates over its mouth. As the water level is lowered in the tube, resonance is heard when the water level has dropped 17 cm, and again after 49 cm of distance exists from the water to the top of the tube. What is the frequency of the tuning fork?

49 cm − 17 cm = 32 cm or 0.32 m

$\frac{1}{2}\lambda$ **exists between points of resonance**

$$\frac{1}{2}\lambda = 0.32\text{ m}$$

$$\lambda = 0.64\text{ m}$$

$$f = \frac{v}{\lambda} = \frac{343\text{ m/s}}{0.64\text{ m}} = 540\text{ Hz}$$

72. Human Hearing The auditory canal leading to the eardrum is a closed pipe that is 3.0 cm long. Find the approximate value (ignoring end correction) of the lowest resonance frequency.

$$L = \frac{\lambda}{4}$$

$$\lambda = \frac{v}{f}$$

$$f = \frac{v}{4L} = \frac{343\text{ m/s}}{(4)(0.030\text{ m})} = 2.9\text{ kHz}$$

73. If you hold a 1.2-m aluminum rod in the center and hit one end with a hammer, it will oscillate like an open pipe. Antinodes of pressure correspond to nodes of molecular motion, so there is a pressure antinode in the center of the bar. The speed of sound in aluminum is 5150 m/s. What would be the bar's lowest frequency of oscillation?

The rod length is $\frac{1}{2}\lambda$, so λ = 2.4 m

$$f = \frac{v}{\lambda} = \frac{5150 \text{ m/s}}{2.4 \text{ m}} = 2.1 \text{ kHz}$$

74. One tuning fork has a 445-Hz pitch. When a second fork is struck, beat notes occur with a frequency of 3 Hz. What are the two possible frequencies of the second fork?

445 Hz − 3 Hz = 442 Hz

and 445 Hz + 3 Hz = 448 Hz

75. **Flutes** A flute acts as an open pipe. If a flute sounds a note with a 370-Hz pitch, what are the frequencies of the second, third, and fourth harmonics of this pitch?

$f_2 = 2f_1 = (2)(370 \text{ Hz}) = 740 \text{ Hz}$

$f_3 = 3f_1 = (3)(370 \text{ Hz}) = 1110 \text{ Hz}$

$= 1100 \text{ Hz}$

$f_4 = 4f_1 = (4)(370 \text{ Hz}) = 1480 \text{ Hz}$

$= 1500 \text{ Hz}$

76. **Clarinets** A clarinet sounds the same note, with a pitch of 370 Hz, as in the previous problem. The clarinet, however, acts as a closed pipe. What are the frequencies of the lowest three harmonics produced by this instrument?

$3f_1 = (3)(370 \text{ Hz}) = 1110 \text{ Hz} = 1100 \text{ Hz}$

$5f_1 = (5)(370 \text{ Hz}) = 1850 \text{ Hz} = 1800 \text{ Hz}$

$7f_1 = (7)(370 \text{ Hz}) = 2590 \text{ Hz} = 2600 \text{ Hz}$

77. **String Instruments** A guitar string is 65.0 cm long and is tuned to produce a lowest frequency of 196 Hz.

a. What is the speed of the wave on the string?

$\lambda_1 = 2L = (2)(0.650 \text{ m}) = 1.30 \text{ m}$

$v = \lambda f = (1.30 \text{ m})(196 \text{ Hz}) = 255 \text{ m/s}$

b. What are the next two higher resonant frequencies for this string?

$f_2 = 2f_1 = (2)(196 \text{ Hz}) = 392 \text{ Hz}$

$f_3 = 3f_1 = (3)(196 \text{ Hz}) = 588 \text{ Hz}$

78. **Musical Instruments** The lowest note on an organ is 16.4 Hz.

a. What is the shortest open organ pipe that will resonate at this frequency?

$\lambda = \frac{v}{f} = \frac{343 \text{ m/s}}{16.4 \text{ Hz}} = 20.9$ **m and**

$L = \frac{\lambda}{2}$, **so**

$L = \frac{v}{2f} = \frac{343 \text{ m/s}}{(2)(16.4\text{Hz})} = 10.5 \text{ m}$

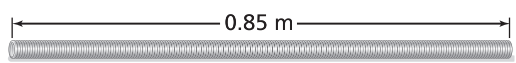
b. What is the pitch if the same organ pipe is closed?

Since a closed pipe produces a fundamental with a wavelength twice as long as that of an open pipe of the same length, the frequency would be $\frac{1}{2}$(16.4 Hz) = 8.20 Hz.

79. **Musical Instruments** Two instruments are playing musical A (440.0 Hz). A beat note with a frequency of 2.5 Hz is heard. Assuming that one instrument is playing the correct pitch, what is the frequency of the pitch played by the second instrument?

It could be either 440.0 + 2.5 = 442.5 Hz or 440.0 − 2.5 = 437.5 Hz.

80. A flexible, corrugated, plastic tube, shown in **Figure 15-27,** is 0.85 m long. When it is swung around, it creates a tone that is the lowest pitch for an open pipe of this length. What is the frequency?



■ **Figure 15-27**

$L = 0.85 \text{ m} = \frac{\lambda}{2}$, **so** $\lambda = 1.7 \text{ m}$

$f = \frac{v}{\lambda} = \frac{343 \text{ m/s}}{1.7 \text{ m}} = 2.0\times10^2 \text{ Hz}$

81. The tube from the previous problem is swung faster, producing a higher pitch. What is the new frequency?

$f_2 = 2f_1 = (2)(2.0\times10^2 \text{ Hz}) = 4.0\times10^2 \text{ Hz}$

Level 2

82. During normal conversation, the amplitude of a pressure wave is 0.020 Pa.

a. If the area of an eardrum is 0.52 cm^2, what is the force on the eardrum?

$F = PA$

$= (0.020\ \text{N/m}^2)(0.52\times10^{-4}\ \text{m}^2)$

$= 1.0\times10^{-6}\ \text{N}$

b. The mechanical advantage of the three bones in the middle ear is 1.5. If the force in part **a** is transmitted undiminished to the bones, what force do the bones exert on the oval window, the membrane to which the third bone is attached?

$MA = \frac{F_r}{F_e}$ so $F_r = (MA)(F_e)$

$F_r = (1.5)(1.0\times10^{-6}\ \text{N}) = 1.5\times10^{-6}\ \text{N}$

c. The area of the oval window is 0.026 cm^2. What is the pressure increase transmitted to the liquid in the cochlea?

$P = \frac{F}{A} = \frac{1.5\times10^{-6}\ \text{N}}{0.026\times10^{-4}\ \text{m}^2} = 0.58\ \text{Pa}$

83. Musical Instruments One open organ pipe has a length of 836 mm. A second open pipe should have a pitch that is one major third higher. How long should the second pipe be?

$L = \frac{\lambda}{2}$, so $\lambda = 2L$ and $\lambda = \frac{v}{f}$

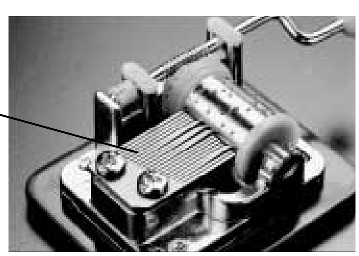
$f = \frac{v}{2L} = \frac{343\ \text{m/s}}{(2)(0.836\ \text{m})} = 205\ \text{Hz}$

The ratio of a frequency one major third higher is 5:4, so $(205\ \text{Hz})\left(\frac{5}{4}\right) = 256\ \text{Hz}$.

The length of the second pipe is

$L = \frac{v}{2f} = \frac{343\ \text{m/s}}{(2)(256\ \text{Hz})} = 6.70\times10^2\ \text{mm}$

84. As shown in **Figure 15-28,** a music box contains a set of steel fingers clamped at one end and plucked on the other end by pins on a rotating drum. What is the speed of a wave on a finger that is 2.4 cm long and plays a note of 1760 Hz?



■ **Figure 15-28**

The length of the steel finger clamped at one end and free to vibrate at the other is $\frac{1}{4}$ **wavelength. Therefore,**

$\lambda = 4L = 4(0.024\ \text{m}) = 0.096\ \text{m}$, and

$v = f\lambda = (1760\ \text{Hz})(0.096\ \text{m})$

$= 1.7\times10^2\ \text{m/s}$

Mixed Review

pages 427–428

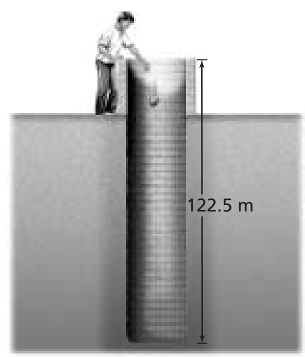
Level 1

85. An open organ pipe is 1.65 m long. What fundamental frequency note will it produce if it is played in helium at 0°C?

An open pipe has a length equal to one-half its fundamental wavelength. Therefore, $\lambda = 3.30\ \text{m}$**. The speed of sound in helium is 972 m/s. Therefore,**

$f = \frac{v}{\lambda} = \frac{972\ \text{m/s}}{3.30\ \text{m}} = 295\ \text{Hz}$

86. If you drop a stone into a well that is 122.5 m deep, as illustrated in **Figure 15-29,** how soon after you drop the stone will you hear it hit the bottom of the well?



■ **Figure 15-29**

First find the time it takes the stone to fall down the shaft by $d = \frac{1}{2}gt^2$, **so**

$t = \sqrt{\frac{d}{\frac{1}{2}g}} = \sqrt{\frac{122.5\ \text{m}}{\left(\frac{1}{2}\right)(9.80\ \text{m/s}^2)}} = 5.00\ \text{s}$

The time it takes the sound to comes back up is found with $d = v_s t$, **so**

$t = \frac{d}{v_s} = \frac{122.5\ \text{m}}{343\ \text{m/s}} = 0.357\ \text{s}$

The total time is 5.00 s + 0.357 s = 5.36 s.

87. A bird on a newly discovered planet flies toward a surprised astronaut at a speed of 19.5 m/s while singing at a pitch of 945 Hz. The astronaut hears a tone of 985 Hz. What is the speed of sound in the atmosphere of this planet?

f_d = 985 Hz, f_s = 945 Hz, v_s = 19.5 m/s, v = ?

$$\frac{f_d}{f_s} = \frac{v}{v - v_s} = \frac{1}{1 - \frac{v_s}{v}}$$

So $\frac{v_s}{v} = 1 - \frac{f_s}{f_d}$,

or $v = \frac{v_s}{1 - \frac{f_s}{f_d}} = \frac{19.5\text{ m/s}}{1 - \left(\frac{945\text{ Hz}}{985\text{ Hz}}\right)}$

$= 4.80\times10^2$ m/s

88. In North America, one of the hottest outdoor temperatures ever recorded is 57°C and one of the coldest is −62°C. What are the speeds of sound at those two temperatures?

$v(T) = v(0°C) + (0.6\text{ m/s})T$, where $v(0°C)$ = 331 m/s. So, $v(57°C)$

$= (331\text{ m/s}) + \left(\frac{0.6\text{ m/s}}{°C}\right)(57°C)$

$= 365$ m/s

$v(-62°C) = (331\text{ m/s}) + \left(\frac{0.6\text{ m/s}}{°C}\right)(-62°C)$

$= 294$ m/s

Level 2

89. A ship's sonar uses a frequency of 22.5 kHz. The speed of sound in seawater is 1533 m/s. What is the frequency received on the ship that was reflected from a whale traveling at 4.15 m/s away from the ship? Assume that the ship is at rest.

Part 1. From ship to whale:

v_d = +4.15 m/s, v = 1533 m/s, f_s = 22.5 kHz, v_s = 0

$$f_d = f_s\left(\frac{v - v_d}{v - v_s}\right) = (22.5\text{ kHz})\left(\frac{1533 - 4.15}{1533}\right)$$

$= 22.4$ kHz

Part 2. From whale to ship:

v_s = −4.15 m/s, v = 1533 m/s, f_s = 22.4 kHz, v_d = 0

$$f_d = f_s\left(\frac{v - v_d}{v - v_s}\right) = (22.4\text{ kHz})\left(\frac{1533}{1533 + 4.15}\right)$$

$= 22.3$ kHz

90. When a wet finger is rubbed around the rim of a glass, a loud tone of frequency 2100 Hz is produced. If the glass has a diameter of 6.2 cm and the vibration contains one wavelength around its rim, what is the speed of the wave in the glass?

The wavelength is equal to the circumference of the glass rim, $\lambda = \pi d$

Therefore, the speed is

$v = \lambda f = \pi d f$

$= \pi(0.062\text{ m})(2100\text{ Hz}) = 4.1\times10^2$ m/s

91. **History of Science** In 1845, Dutch scientist Christoph Buys-Ballot developed a test of the Doppler effect. He had a trumpet player sound an A note at 440 Hz while riding on a flatcar pulled by a locomotive. At the same time, a stationary trumpeter played the same note. Buys-Ballot heard 3.0 beats per second. How fast was the train moving toward him?

f_d = 440 Hz + 3.0 Hz = 443 Hz

$$f_d = f_s\left(\frac{v - v_d}{v - v_s}\right)$$

so $(v - v_s)f_d = (v - v_d)f_s$ **and**

$$v_s = v - \frac{(v - v_d)f_s}{f_d}$$

$= 343\text{ m/s} - \frac{(343\text{ m/s} - 0)(440\text{ Hz})}{443\text{ Hz}}$

$= 2.3$ m/s

92. You try to repeat Buys-Ballot's experiment from the previous problem. You plan to have a trumpet played in a rapidly moving car. Rather than listening for beat notes, however, you want to have the car move fast enough so that the moving trumpet sounds one major third above a stationary trumpet.

a. How fast would the car have to move?

major third ratio $= \frac{5}{4}$

$$f_d = f_s\left(\frac{v - v_d}{v - v_s}\right)$$

so $(v - v_s)f_d = (v - v_d)f_s$

and $v_s = v - \frac{(v - v_d)f_s}{f_d}$

$= 343 \text{ m/s} - (343 \text{ m/s} - 0)\left(\frac{4}{5}\right)$

$= 68.6 \text{ m/s}$

b. Should you try the experiment? Explain.

$v = (68.6 \text{ m/s})\left(\frac{3600 \text{ s}}{1 \text{ h}}\right)\left(\frac{1 \text{ mi}}{1609 \text{ m}}\right)$

$= 153 \text{ mph}$,

so the car would be moving dangerously fast. Do not try the experiment.

Level 3

93. Guitar Strings The equation for the speed of a wave on a string is $v = \sqrt{\frac{F_T}{\mu}}$, where F_T is the tension in the string and μ is the mass per unit length of the string. A guitar string has a mass of 3.2 g and is 65 cm long. What must be the tension in the string to produce a note whose fundamental frequency is 147 Hz?

$\mu = \frac{0.0032 \text{ kg}}{0.65 \text{ m}} = 4.9\times10^{-3} \text{ kg/m}$

$\lambda = 2L = 2(0.65 \text{ m}) = 1.30 \text{ m}$

$v = f\lambda = (147 \text{ Hz})(1.30 \text{ m}) = 191 \text{ m/s}$

$F_T = v^2\mu = (191 \text{ m/s})^2(4.9\times10^{-3} \text{ kg/m})$

$= 180 \text{ N}$

94. A train speeding toward a tunnel at 37.5 m/s sounds its horn at 327 Hz. The sound bounces off the tunnel mouth. What is the frequency of the reflected sound heard on the train? *Hint: Solve the problem in two parts. First, assume that the tunnel is a stationary observer and find the frequency. Then, assume that the tunnel is a stationary source and find the frequency measured on the train.*

Part 1. $v_s = +37.5 \text{ m/s}$, $v = 343 \text{ m/s}$,

$f_s = 327 \text{ Hz}$

$f_d = f_s\left(\frac{v - v_d}{v - v_s}\right) = (327 \text{ Hz})\left(\frac{343}{343 - 37.5}\right)$

$= 367 \text{ Hz}$

Part 2. $v_d = -37.5 \text{ m/s}$, $v = 343 \text{ m/s}$,

$f_s = 367 \text{ Hz}$

$f_d = f_s\left(\frac{v - v_d}{v - v_s}\right) = (367 \text{ Hz})\left(\frac{343 - (-37.5)}{343}\right)$

$= 407 \text{ Hz}$

Thinking Critically

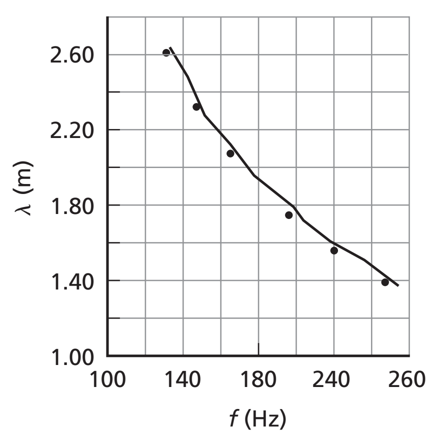
page 428

95. Make and Use Graphs The wavelengths of the sound waves produced by a set of tuning forks with given frequencies are shown in **Table 15-2** below.

Table 15-2	
Tuning Forks	
Frequency (Hz)	Wavelength (m)
131	2.62
147	2.33
165	2.08
196	1.75
220	1.56
247	1.39

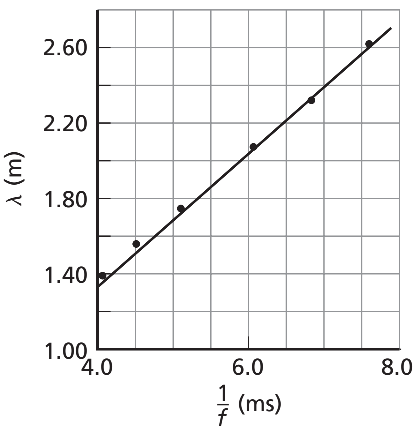
a. Plot a graph of the wavelength versus the frequency (controlled variable). What type of relationship does the graph show?

The graph shows an inverse relationship between frequency and wavelength.



b. Plot a graph of the wavelength versus the inverse of the frequency (1/*f*). What kind of graph is this? Determine the speed of sound from this graph.

The graph shows a direct relationship between period (1/*f*) and wavelength. The speed of sound is represented by the slope, ~343 m/s.



96. Make Graphs Suppose that the frequency of a car horn is 300 Hz when it is stationary. What would the graph of the frequency versus time look like as the car approached and then moved past you? Complete a rough sketch.

The graph should show a fairly steady frequency above 300 Hz as it approaches and a fairly steady frequency below 300 Hz as it moves away.

97. Analyze and Conclude Describe how you could use a stopwatch to estimate the speed of sound if you were near the green on a 200-m golf hole as another group of golfers hit their tee shots. Would your estimate of the speed of sound be too large or too small?

You could start the watch when you saw the hit and stop the watch when the sound reached you. The speed would be calculated by dividing the distance, 200 m, by the measured time. The measured time would be too large because you could anticipate the impact by sight, but you could not anticipate the sound. The calculated speed would be too small.

98. Apply Concepts A light wave coming from a point on the left edge of the Sun is found by astronomers to have a slightly higher frequency than light from the right side. What do these measurements tell you about the Sun's motion?

The Sun must be rotating on its axis in the same manner as Earth. The Doppler shift indicates that the left side of the Sun is coming toward us, while the right side is moving away.

99. Design an Experiment Design an experiment that could test the formula for the speed of a wave on a string. Explain what measurements you would make, how you would make them, and how you would use them to test the formula.

Measure the mass and length of the string to determine μ. Then clamp the string to a table, hang one end over the table edge, and stretch the string by hanging weights on its end to obtain F_T. Calculate the speed of the wave using the formula. Next, pluck the string in its middle and determine the frequency by matching it to a frequency generator, using beats to tune the generator. Multiply the frequency by twice the string length, which is equal to the wavelength, to obtain the speed from the wave equation. Compare the results. Repeat for different tensions and other strings with different masses per unit length. Consider possible causes of error.

Writing in Physics

page 428

100. Research the construction of a musical instrument, such as a violin or French horn. What factors must be considered besides the length of the strings or tube? What is the difference between a quality instrument and a cheaper one? How are they tested for tone quality?

Answers will vary. A report on violin construction might include information about the bridge as a link between the strings and body and information about the role of the body in causing air molecules around the violin to vibrate. Students also might discuss

the ways in which the woods and finishes used in making violins affect the quality of the sound produced by the instruments.

101. Research the use of the Doppler effect in the study of astronomy. What is its role in the big bang theory? How is it used to detect planets around other stars? To study the motions of galaxies?

Students should discuss the work of Edwin Hubble, the redshift and the expanding universe, spectroscopy, and the detection of wobbles in the motion of planet-star systems.

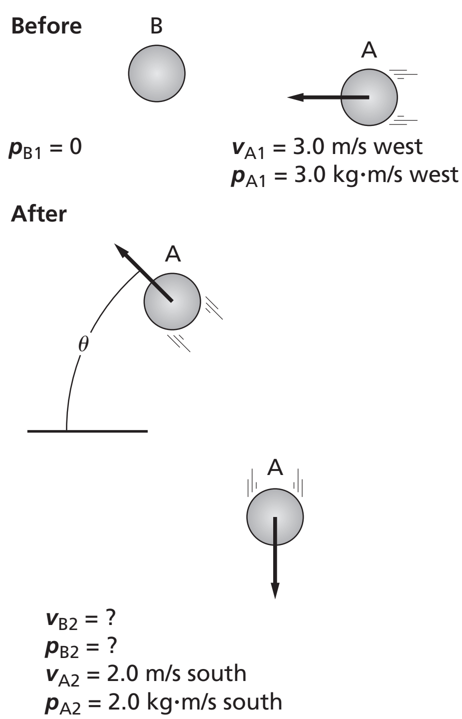
Cumulative Review

page 428

102. Ball A, rolling west at 3.0 m/s, has a mass of 1.0 kg. Ball B has a mass of 2.0 kg and is stationary. After colliding with ball B, ball A moves south at 2.0 m/s. (Chapter 9)

a. Sketch the system, showing the velocities and momenta before and after the collision.

Westward and southward are positive.



b. Calculate the momentum and velocity of ball B after the collision.

Horizontal: $m_A v_{A1} = m_B v_{B2}$

So $m_B v_{B2} = (1.0\text{ kg})(3.0\text{ m/s})$

$= 3.0\text{ kg·m/s}$

Vertical: $0 = m_A v_{A2} + m_B v_{B2}$

So $m_B v_{B2} = -(1.0\text{ kg})(2.0\text{ m/s})$

$= -2.0\text{ kg·m/s}$

The vector sum is

m_v

$= \sqrt{(3.0\text{ kg·m/s})^2 + (-2.0\text{ kg·m/s})^2}$

$= 3.6\text{ kg·m/s}$ **and** $\tan\theta = \frac{2.0\text{ kg·m/s}}{3.0\text{ kg·m/s}}$

so $\theta = 34°$

Therefore, $m_B v_{B2} = 3.6\text{ kg·m/s}$ **at 34° north of west**

$v_{B2} = \frac{3.6\text{ kg·m/s}}{2.0\text{ kg}}$

$= 1.8\text{ m/s}$ **at 34° north of west**

103. Chris carries a 10-N carton of milk along a level hall to the kitchen, a distance of 3.5 m. How much work does Chris do? (Chapter 10)

No work, because the force and the displacement are perpendicular.

104. A movie stunt person jumps from a five-story building (22 m high) onto a large pillow at ground level. The pillow cushions her fall so that she feels a deceleration of no more than 3.0 m/s^2. If she weighs 480 N, how much energy does the pillow have to absorb? How much force does the pillow exert on her? (Chapter 11)

The energy to be absorbed equals the mechanical energy that she had, which equals her initial potential energy.
U = mgh = (480 N)(22 m) = 11 kJ.
The force on her is

$F = ma = \frac{F_g}{g}(a) = \left(\frac{480\text{ N}}{9.80\text{ m/s}^2}\right)(3.0\text{ m/s}^2)$

$= 150\text{ N}$

Challenge Problem

page 417

1. Determine the tension, F_T, in a violin string of mass m and length L that will play the fundamental note at the same frequency as a closed pipe also of length L. Express your answer in terms of m, L, and the speed of sound in air, v. The equation for the speed of a wave on a string is $u = \sqrt{\frac{F_T}{\mu}}$. where F_T is the tension string and μ is the mass per unit length of the string.

   The wavelength of the fundamental in a closed pipe is equal to 4*L*, so the frequency is $f = \frac{v}{4L}$. The wavelength of the fundamental on a string is equal to 2*L*, so the frequency of the string is $f = \frac{u}{2L}$, where *u* is the speed of the wave on the string, $u = \sqrt{\frac{F_T}{\mu}}$. The mass per unit length of the string $\mu = m/L$. Squaring the frequencies and setting them equal gives

   $$\frac{v^2}{16L^2} = \frac{u^2}{4L^2} = \frac{F_T}{4L^2\mu} = \frac{F_TL}{4L^2m} = \frac{F_T}{4Lm}$$

   Finally, rearranging for the tension gives $F_T = \frac{mv^2}{4L}$

2. What is the tension in a string of mass 1.0 g and 40.0 cm long that plays the same note as a closed pipe of the same length?

   For a string of mass 1.0 g and length 0.400 m, the tension is

   $$F_T = \frac{mv^2}{4L} = \frac{(0.0010\text{ kg})(343\text{ m/s})^2}{4(0.400\text{ m})} = 74\text{ N}$$