Lecture 45

(Ch. 14: 1-3)

Figure 11.1

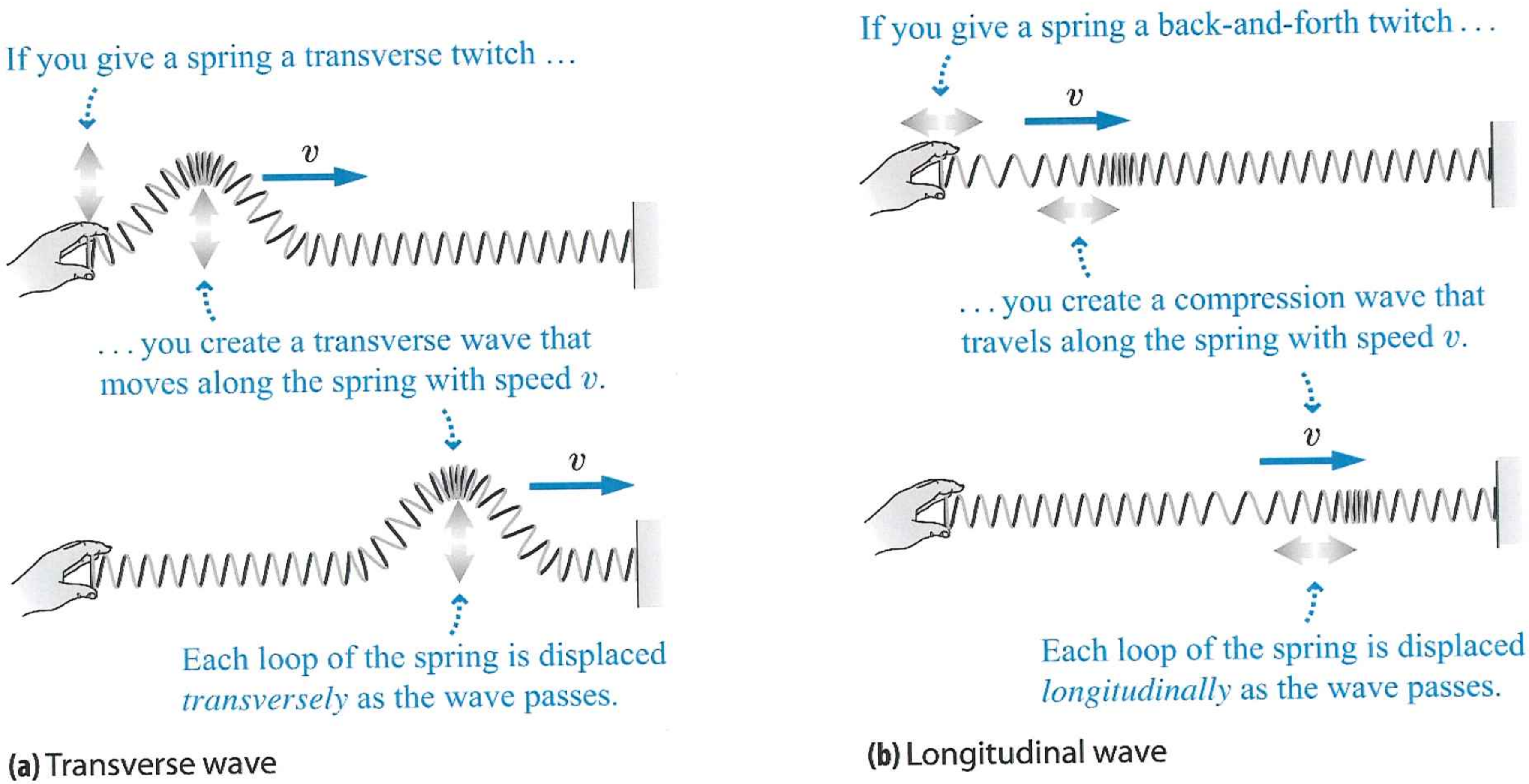
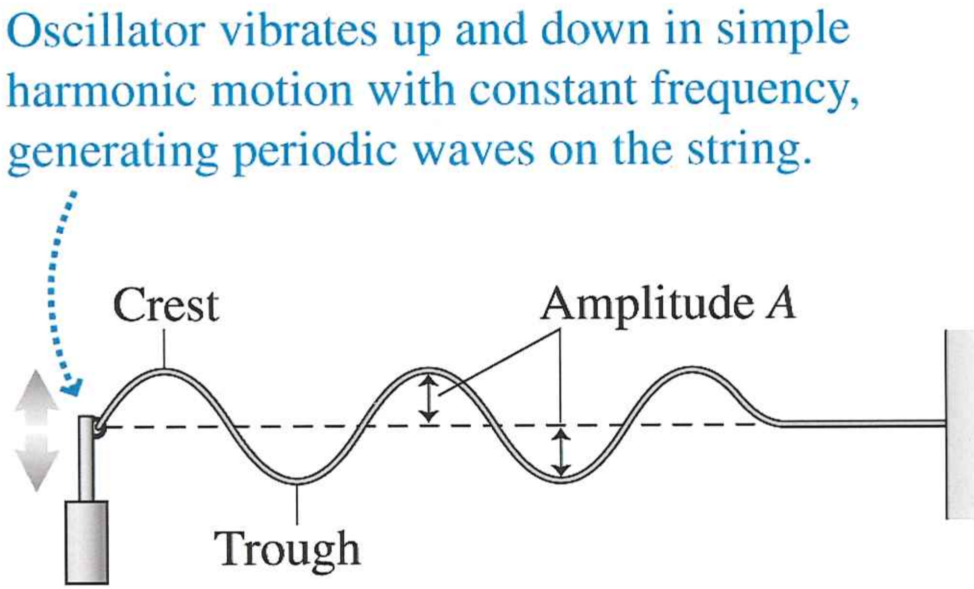
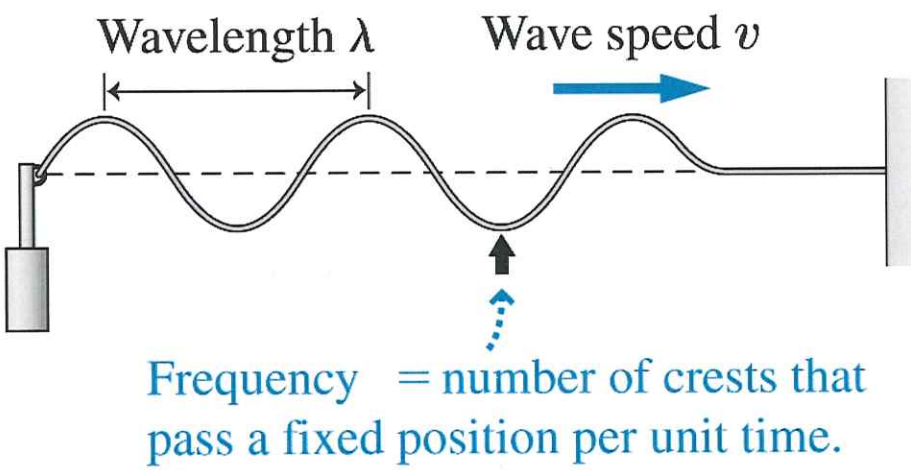

If you give a spring a transverse twitch …
v
… you create a transverse wave that moves along the spring with speed v.
v
Each loop of the spring is displaced *transversely* as the wave passes.
(a) Transverse wave
If you give a spring a back-and-forth twitch . . .
v
. . . you create a compression wave that travels along the spring with speed v.
v
Each loop of the spring is displaced *longitudinally* as the wave passes.
(b) Longitudinal wave

Figure 11.3



(a) Generating periodic waves on a string



(b) Wavelength, wave speed, and frequency

$\lambda = V \cdot T$

$V = \lambda \cdot f = \lambda / T$

v [m/s]

λ [m]

T [sec]

f [Hz]

Radio FM = 98.1 MHz; $C = 3 * 10^8$ m/s

$\lambda = ?$

We are given the frequency f and the velocity c.

The fundamental relationship is:

$\lambda = V . T \rightarrow V = \frac{\Delta}{T} = \lambda . f$

$$v = \lambda f$$

Solving for *lambda*: $\lambda = \frac{v}{f}$

Additional notes: Frequency is given in units of $\text{MHz} = 10^6\ \text{Hz}$

SOLVE Plugging in values:

$$\lambda = \frac{3.0 \times 10^8\ \text{m/s}}{98.1 \times 10^6\ \text{Hz}} = 3.1\ \text{m}$$

REFLECT Another straightforward application of the fundamental relationship with a slight wrinkle of units. We learn that the wavelength of an FM radio station is around 3 meters. This wavelength gives an idea of the size of objects that the waves can diffract (or "bend") around and why you cannot receive FM radio under a bridge.

Topic 14: Sound

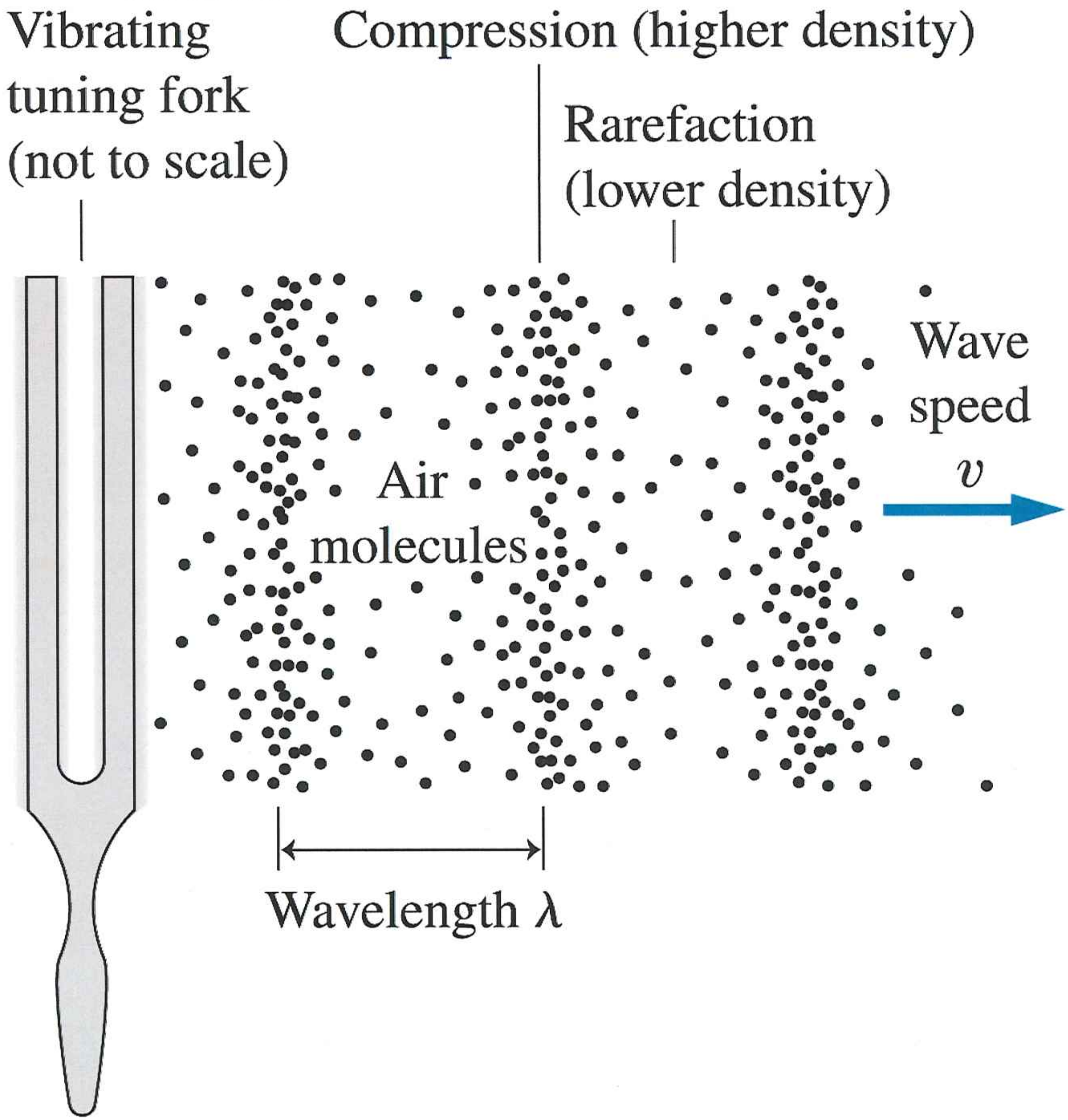
iStockphoto.com/Collin Orthner

College Physics, 11e
Raymond A. Serway;
Chris Vuille

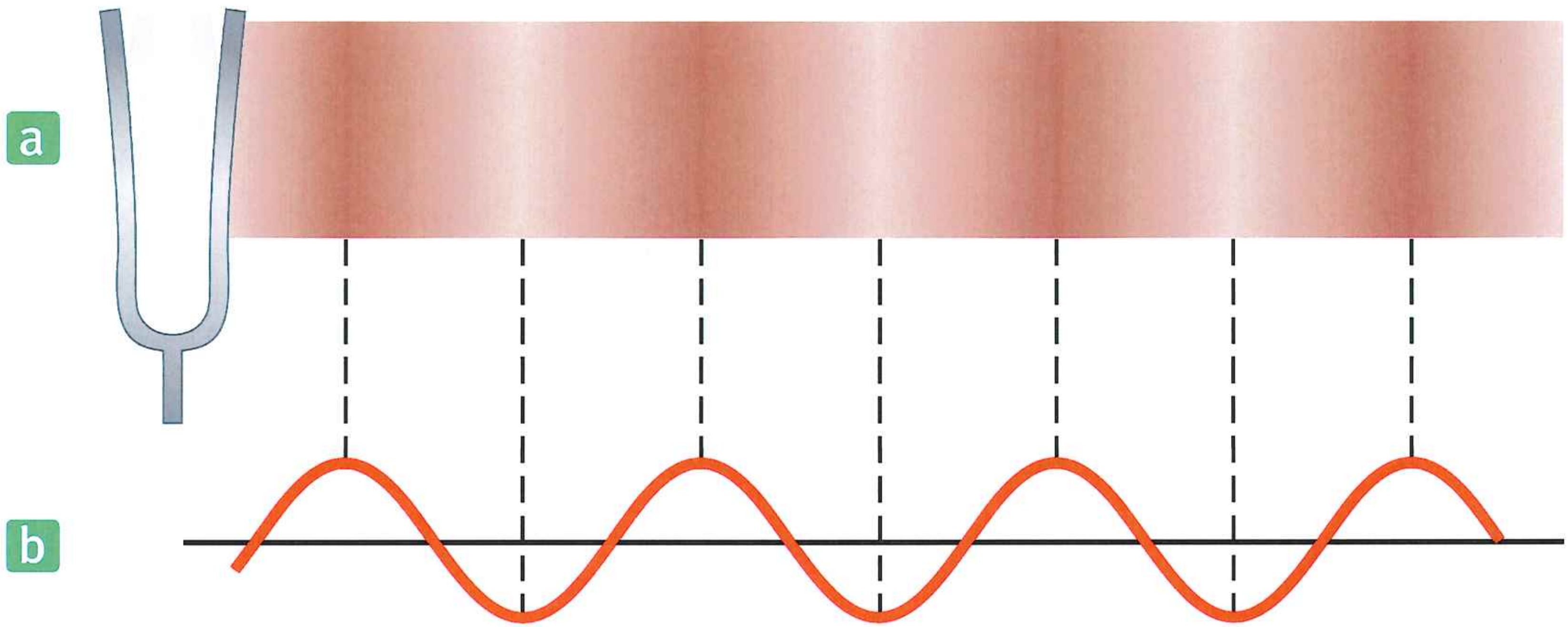
BROOKS/COLE
CENGAGE Learning™

Sound waves

Figure 11.12



Producing a Sound Wave



Categories of Sound Waves

- **Audible waves**
- **Infrasonic waves**
- **Ultrasonic waves**

V CIC Suppose you hear a clap of thunder 16.2 s after seeing the associated lightning stroke. The speed of light in air is 3.00×10^8 m/s.

a. How far are you from the lightning stroke?

Answer

b. Do you need to know the value of the speed of light to answer? Explain.

14.1 **(a)** We ignore the time required for the lightning flash to arrive.

Then, the distance to the lightning stroke is

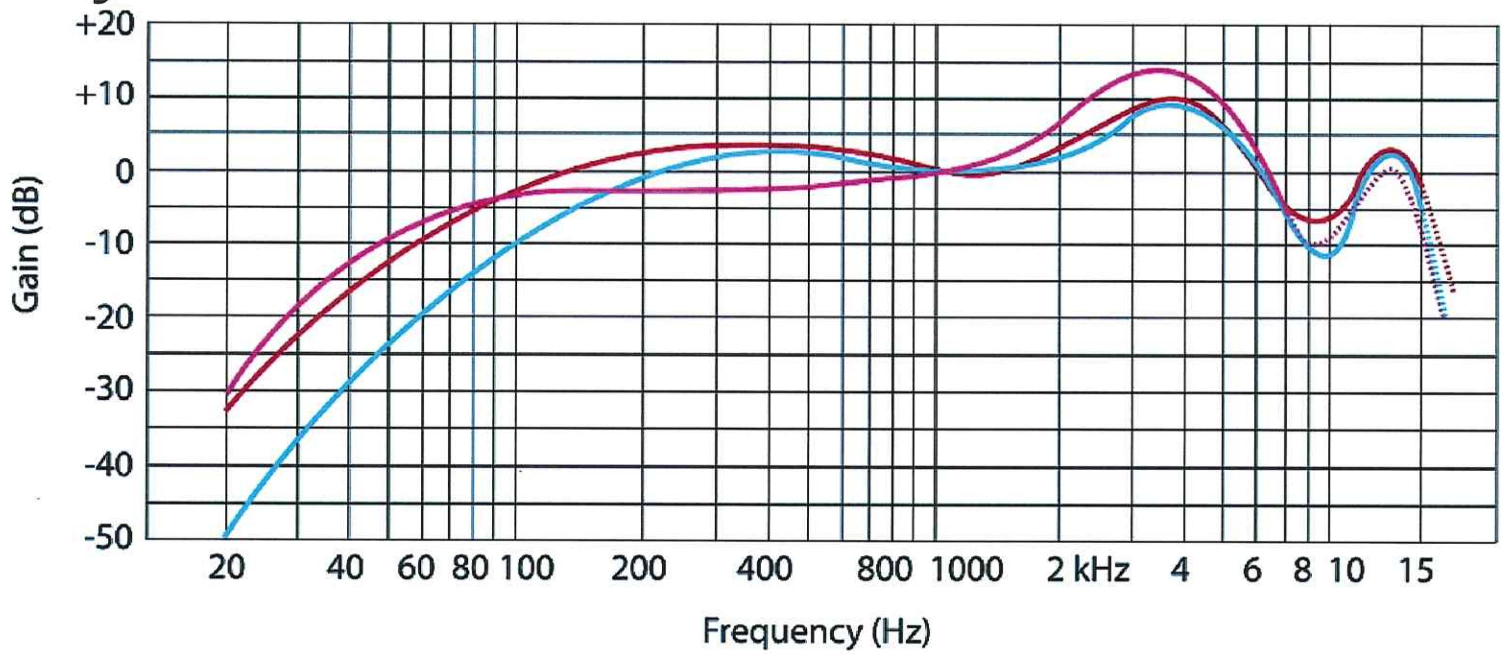
$$d = v_{sound} \cdot \Delta t = (343 \text{ m/s})(16.2 \text{ s}) = 5.56 \times 10^3 \text{ m} = \boxed{5.56 \text{ km}}$$

(b) $\boxed{\text{No.}}$ Since $v_{light} >> v_{sound}$, the time required for the flash of light to reach the observer is negligible in comparison to the time required for the sound to arrive, and knowledge of the actual value of the speed of light is not needed.

Chapter 14: Sound

Sound Waves – Sound Frequency

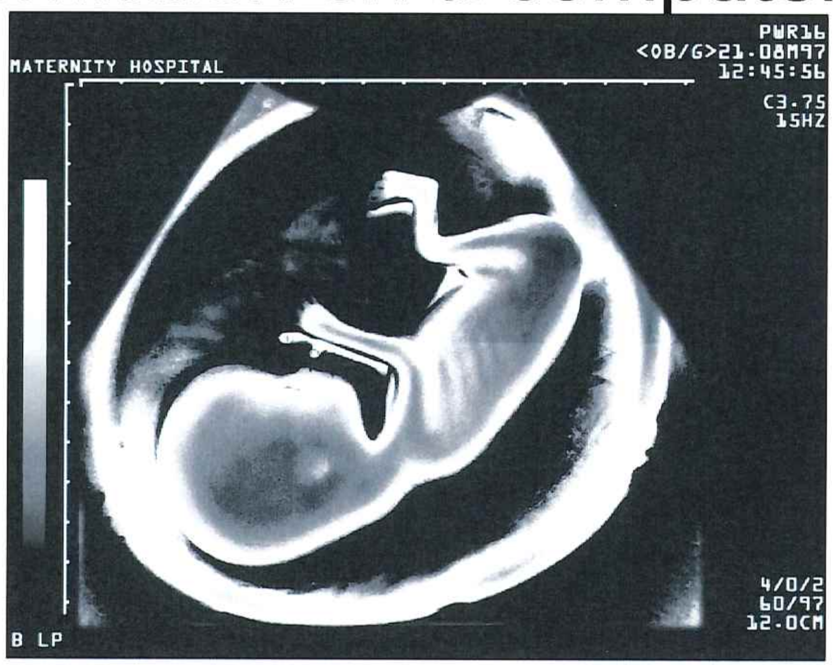
Humans hear in a wide range of frequencies (***pitch***) around 20 Hz – 20 kHz. Some animals use sounds in a wider range both for communication, but also for echolocation. Sounds at frequencies lower than human hearing are called ***infrasounds***, while higher frequency ones are ***ultrasounds***.



Chapter 14: Sound

Sound Waves – Sound Frequency

There are many applications that rely on ultrasounds to provide non-invasive and non-destructive imaging in many fields of medicine, engineering and science. The methods rely on emitting sounds at various high frequencies and recording the reflected waves, then process the information on a computer to generate an image.



$f = 4.5$ MHz

$\lambda = V \cdot T = \frac{V}{f}$

$\lambda_{air} = ?$, $V_{tissue} = 1500 \frac{m}{s}$

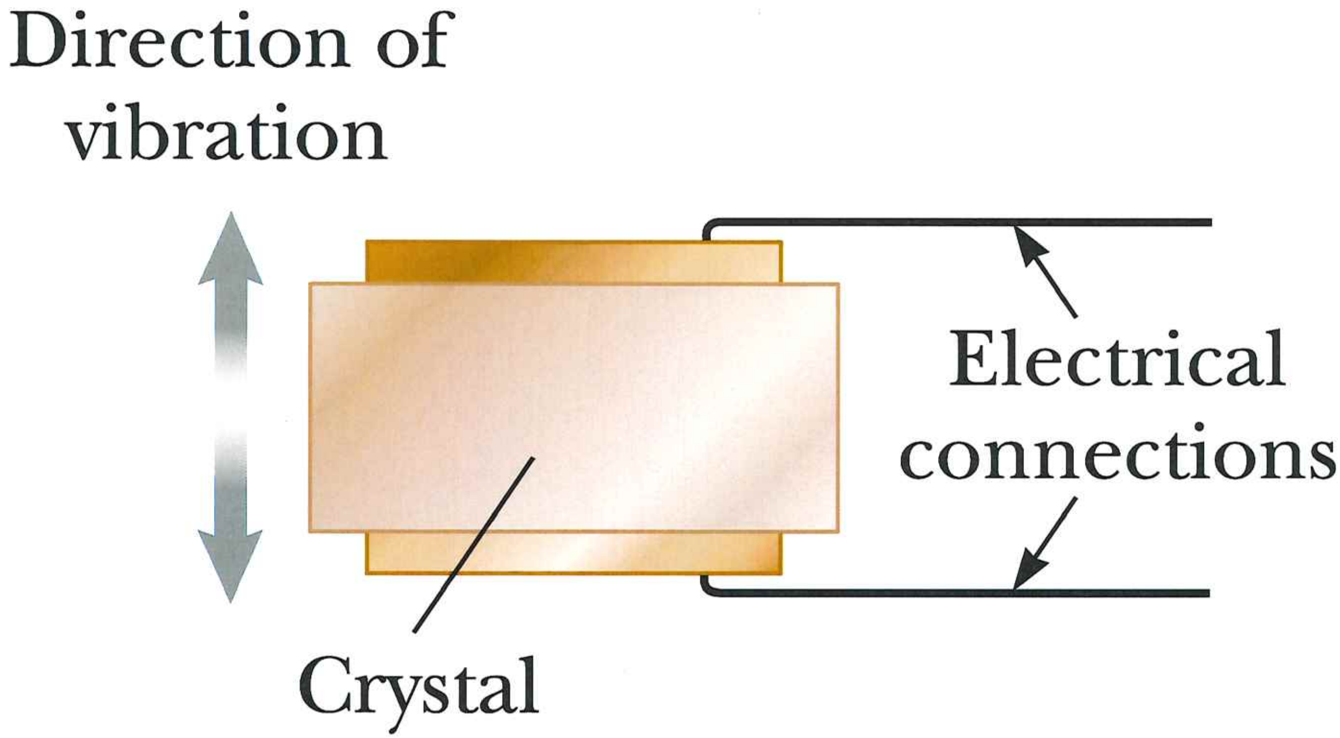
$\lambda_T = ?$ $V_{air} = 343 \frac{m}{s}$

9. (a) Using $\lambda = v/f$, where v is the speed of sound in air and f is the frequency, we find

$$\lambda = \frac{343\,\text{m/s}}{4.5 \times 10^6\,\text{Hz}} = 7.62 \times 10^{-5}\ \text{m}\ .$$

(b) Now, $\lambda = v/f$, where v is the speed of sound in tissue. The frequency is the same for air and tissue. Thus $\lambda = (1500\,\text{m/s})/(4.5 \times 10^6\,\text{Hz}) = 3.33 \times 10^{-4}\,\text{m}$.

Applications of Ultrasound



$$PR = \left(\frac{\rho_i - \rho_t}{\rho_i + \rho_t} \right)^2 \times 100$$

7. BIO Calculate the reflected percentage of an ultrasound wave passing from human muscle into bone. Muscle has a typical density of $1.06 \times 10^3 \text{ kg/m}^3$ and bone has a typical density of $1.90 \times 10^3 \text{ kg/m}^3$.

The reflected percentage of an incident ultrasound wave is

$$PR = \left(\frac{\rho_i - \rho_t}{\rho_i + \rho_t} \right)^2 \times 100$$

where ρ_i is the ambient material (muscle tissue, in this case) and ρ_t is

the reflecting material (bone, in this case). Substitute the given values

to find

$$PR = \left(\frac{\rho_i - \rho_t}{\rho_i + \rho_t} \right)^2 \times 100 = \left(\frac{1.06 \times 10^3 \text{ kg/m}^3 - 1.90 \times 10^3 \text{ kg/m}^3}{1.06 \times 10^3 \text{ kg/m}^3 + 1.90 \times 10^3 \text{ kg/m}^3} \right)^2 \times 100$$

$$= \boxed{8.05\%}$$

The Speed of Sound

$$v = \sqrt{\frac{B}{\rho}} \qquad B \equiv -\frac{\Delta P}{\Delta V / V}$$

$$v = \sqrt{\frac{\text{elastic property}}{\text{inertial property}}}$$

$$v = \sqrt{\frac{F}{\mu}} \ \text{(transverse wave on a string)}$$

$$v = \sqrt{\frac{Y}{\rho}} \ \text{(longitudinal wave in a rod)}$$

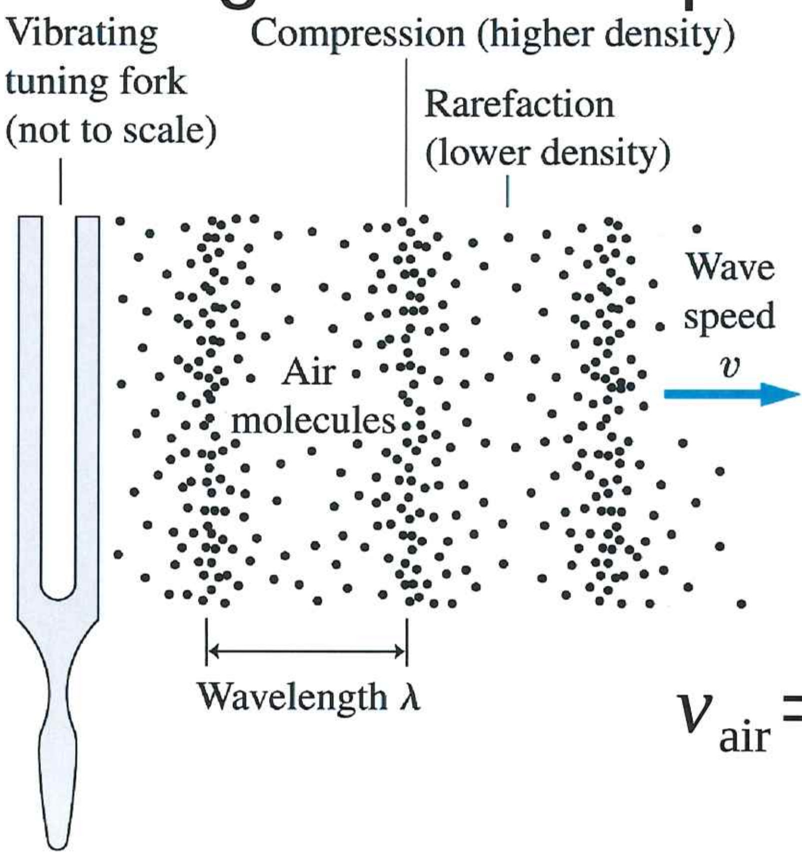
2. Earthquakes at fault lines in Earth's crust create seismic waves, which are longitudinal (P-waves) or transverse (S-waves). The P-waves have a speed of about 7 km/s. Estimate the average bulk modulus of Earth's crust given that the density of rock is about 2 500 kg/m^3.

14.2 The speed of longitudinal waves in a fluid is $v = \sqrt{B/\rho}$. Considering the Earth's crust to consist of a very viscous fluid, our estimate of the average bulk modulus of the material in Earth's crust is

$$B = \rho v^2 = (2\,500 \text{ kg/m}^3)(7 \times 10^3 \text{ m/s})^2 = \boxed{1 \times 10^{11} \text{ Pa}}.$$

Chapter 14: Sound
Sound Waves – Sound Speed

The speed of sound if constant for all frequencies, but this constant is specific for a certain medium. Thus, sound speed in different materials varies, and also changes with temperature.



$$v = \lambda f$$

$$v_{air} = 331\frac{m}{s} + 0.6 \cdot T\,^{o}C$$

Medium	Speed (m/s)
Air (0°C)	331
Air (20°C)	343
Air (100°C)	387
Helium (0°C)	970
Oxygen (0°C)	316
Ethanol	1170
Water	1480
Copper	3500
Glass	5200
Granite	6000
Aluminum	6420

The Speed of Sound

$$v = (331\text{ m/s})\sqrt{\frac{T}{273\text{ K}}}$$

for $T = 293\text{ K}$ (room temperature):

$$v = (331\text{ m/s})\sqrt{\frac{293\text{ K}}{273\text{ K}}} = 343\text{ m/s}$$

5. BIO The range of human hearing extends from approximately 20 Hz to 20 000 Hz. Find the wavelengths of these extremes at a temperature of 27°C.

14.6 At $T = 27°\text{C}$, the speed of sound in air is

$$v = (331\text{ m/s})\sqrt{1+\frac{T_C}{273}} = (331\text{ m/s})\sqrt{1+\frac{27}{273}} = 347\text{ m/s}$$

The wavelength of the 20 Hz sound is

$$\lambda = \frac{v}{f} = \frac{347\text{ m/s}}{20\text{ Hz}} = 17\text{ m}$$

and that of the 20 000 Hz is

$$\lambda = \frac{347\text{ m/s}}{20\ 000\text{ Hz}} = 1.7\times10^{-2}\text{ m} = 1.7\text{ cm}$$

Thus, range of wavelengths of audible sounds at 27°C is $\boxed{1.7\text{ cm to } 17\text{ m}}$.

9. A hammer strikes one end of a thick steel rail of length 8.50 m. A microphone located at the opposite end of the rail detects two pulses of sound, one that travels through the air and a longitudinal wave that travels through the rail.

a. Which pulse reaches the microphone first?

Answer

b. Find the separation in time between the arrivals of the two pulses.

14.9 (a) Because the speed of sound in air is $v_{air} = 343$ m/s while its speed in the steel rail is

$v_{steel} = 5\,950$ m/s, the pulse traveling in the steel rail arrives first.

(b) The difference in times when the two pulses reach the microphone at the opposite end of the rail is

$$\Delta t = \frac{L}{v_{air}} - \frac{L}{v_{steel}} = (8.50\text{ m})\left(\frac{1}{343\text{ m/s}} - \frac{1}{5\,950\text{ m/s}}\right) = 2.34\times10^{-2}\text{ s} = \boxed{23.4\text{ ms}}$$

The Speed of Sound

Table 14.1 Speeds of Sound in Various Media

Medium	v (m/s)
Gases	
Air (0°C)	331
Air (100°C)	386
Hydrogen (0°C)	1 286
Oxygen (0°C)	317
Helium (0°C)	972
Liquids at 25°C	
Water	1 493
Methyl alcohol	1 143
Sea water	1 533
Solids[a]	
Aluminum	6 420
Copper (rolled)	5 010
Steel	5 950
Lead (rolled)	1 960
Synthetic rubber	1 600

[a]Values given are for propagation of longitudinal waves in bulk media. Speeds for longitudinal waves in thin rods are smaller, and speeds of transverse waves in bulk are smaller yet.

8. A stone is dropped from rest into a well. The sound of the splash is heard exactly 2.00 s later. Find the depth of the well if the air temperature is 10.0°C.

14.8 At a temperature of $T = 10.0°C$ the speed of sound in air is

$$v = (331\text{ m/s})\sqrt{1+\frac{T_C}{273}} = (331\text{ m/s})\sqrt{1+\frac{10.0}{273}} = 337\text{ m/s}$$

The elapsed time between when the stone was released and when the sound is heard is the sum of the time t_1 required for the stone to fall distance h and the time t_2 required for sound to travel distance h in air on the return up the well. That is, $t_1 + t_2 = 2.00$ s. The distance the stone falls, starting from rest, in time t_1 is $h = \frac{gt_1^2}{2}$.

Also, the time for the sound to travel back up the well is

$$t_2 = \frac{h}{v} = 2.00\text{ s} - t_1$$

Combining these two equations yields $(g/2v)t_1^2 = 2.00\text{ s} - t_1$.

With $v = 337$ m/s and $g = 9.80\text{ m/s}^2$, this becomes

$$(1.45\times10^{-2}\text{ s}^{-1})t_1^2 + t_1 - 2.00\text{ s} = 0$$

Applying the quadratic formula yields one positive solution of t_1 = 1.95 s, so the depth of the well is

$$h = \frac{gt_1^2}{2} = \frac{(9.80\text{ m/s}^2)(1.95\text{ s})^2}{2} = \boxed{18.6\text{ m}}$$