Sound Wave

Sound – **longitudinal** waves.
It can travel through any kind of **matter**, but not through a vacuum.
The speed of sound is different in different materials; in general, it is slowest in gases, faster in liquids, and **fastest in solids**.

The speed depends somewhat on temperature, especially for gases.

$$v \approx (331 + 0.60T)m/s$$

$$T = 0^o C \Rightarrow v = 331 m/s$$

$$T = 20^o C \Rightarrow v = 343 m/s$$

TABLE 12–1 Speed of Sound in Various Materials (20°C and 1 atm)

Material	Speed (m/s)
Air	343
Air (0°C)	331
Helium	1005
Hydrogen	1300
Water	1440
Sea water	1560
Iron and steel	≈5000
Glass	≈4500
Aluminum	≈5100
Hardwood	≈4000
Concrete	≈3000

Loudness: related to **intensity** of the sound wave

Pitch: related to **frequency**.

Loudness and Pitch

Pitch - frequency

Audible range: about 20 Hz to 20,000 Hz; upper limit decreases with age

Ultrasound: above 20,000 Hz
Infrasound: below 20 Hz

Loudness - intensity

The intensity of a wave is the energy transported per unit time across a unit area.
(energy is proportional to the wave amplitude squared)

$$I = \frac{energy/time}{area} = \frac{power}{area} = \frac{P}{4\pi r^2} \Rightarrow \begin{cases} I \propto \dfrac{1}{r^2} \\ I \propto A^2 \end{cases} \qquad \frac{I_2}{I_1} = \frac{r_1^2}{r_2^2}$$

The human ear can detect sounds with an intensity as low as 10^{-12} W/m^2 and as high as 1 W/m^2.

Perceived loudness (**SOUND LEVEL**), however, ***is not proportional*** to the intensity.

Sound Level

The level of a sound is related to the **logarithm** of the intensity.

Sound level is measured in **bel**, or **decibels (dB),** and is defined:

$$\beta\ (\text{in dB}) = 10 \log \frac{I}{I_0}$$

*More on **log** in appendix A*

I_0 is taken to be the threshold of hearing: $I_0 = 1.0 \times 10^{-12}\ \text{W/m}^2$

What is the sound level of a sound whose intensity is $I = 1.0 \times 10^{-10} W/m^2$?

$$\beta = 10 \log\left(\frac{1.0 \times 10^{-10} W/m^2}{1.0 \times 10^{-12} W/m^2}\right) = 10 \log 100 = 20 dB$$

The sound level at the threshold of hearing is 0 dB:

$$\beta = 10 \log\left(\frac{1.0 \times 10^{-12} W/m^2}{1.0 \times 10^{-12} W/m^2}\right) = 10 \log 1 = 0 dB$$

$$\log_b a = x \Rightarrow b^x = a$$
$$\log a = x \Rightarrow 10^x = a$$

$$\log a + \log b = \log(a.b)$$
$$\log a - \log b = \log(a/b)$$

Exercises

Ex. At a busy street corner, the sound level is 70 dB. What is the intensity of sound there?

$$I = 1.0 \times 10^{-5} W / m^2$$

Ex. If the level sound is increased by 3 dB, what is the ratio between the final and the initial intensity?

$$\frac{I_2}{I_1} = 2.0$$

In open areas, the intensity of sound diminishes with distance: $I \propto \frac{1}{r^2}$

Ex. The sound level measured 30 m from a jet plane is 140 dB. What is the sound level at 300 m?

120 dB

Decibels, sound level, change in intensity

Many veteran rockers suffer from acute hearing damage because of the high sound levels they endured for years while playing music near loudspeakers or listening to music on headphones. Some, like Ted Nugent, can no longer hear in a damaged ear. Others, like Peter Townshend of the Who, have a continuous ringing sensation (tinnitus). Recently, many rockers, such as Lars Ulrich of Metallica (Fig. 17-11), began wearing special earplugs to protect their hearing during performances. If an earplug decreases the sound level of the sound waves by 20 dB, what is the ratio of the final intensity I_f of the waves to their initial intensity I_i?

Fig. 17-11 Lars Ulrich of Metallica is an advocate for the organization HEAR (Hearing Education and Awareness for Rockers), which warns about the damage high sound levels can have on hearing. *(Tim Mosenfelder/Getty Images News and Sport Services)*

KEY IDEA

For both the final and initial waves, the sound level β is related to the intensity by the definition of sound level in Eq. 17-29.

Calculations: For the final waves we have

$$\beta_f = (10\text{ dB}) \log \frac{I_f}{I_0},$$

and for the initial waves we have

$$\beta_i = (10\text{ dB}) \log \frac{I_i}{I_0}.$$

The difference in the sound levels is

$$\beta_f - \beta_i = (10\text{ dB}) \left(\log \frac{I_f}{I_0} - \log \frac{I_i}{I_0} \right). \qquad (17\text{-}36)$$

Using the identity

$$\log \frac{a}{b} - \log \frac{c}{d} = \log \frac{ad}{bc},$$

we can rewrite Eq. 17-36 as

$$\beta_f - \beta_i = (10\text{ dB}) \log \frac{I_f}{I_i}. \qquad (17\text{-}37)$$

Rearranging and then substituting the given decrease in sound level as $\beta_f - \beta_i = -20$ dB, we find

$$\log \frac{I_f}{I_i} = \frac{\beta_f - \beta_i}{10\text{ dB}} = \frac{-20\text{ dB}}{10\text{ dB}} = -2.0.$$

We next take the antilog of the far left and far right sides of this equation. (Although the antilog $10^{-2.0}$ can be evaluated mentally, you could use a calculator by keying in 10^-2.0 or using the 10^x key.) We find

$$\frac{I_f}{I_i} = \log^{-1}(-2.0) = 0.010. \qquad \text{(Answer)}$$

Thus, the earplug reduces the intensity of the sound waves to 0.010 of their initial intensity, which is a decrease of two orders of magnitude.

Sources of Sound

The source of any sound is a **vibrating** object – almost any object can vibrate and hence be a source of sound

Musical instruments produce sounds in various ways – vibrating strings, vibrating membranes, vibrating metal or wood shapes, vibrating air columns.

The vibration may be started by plucking, striking, bowing, or blowing. At resonant frequencies – standing waves are produced.

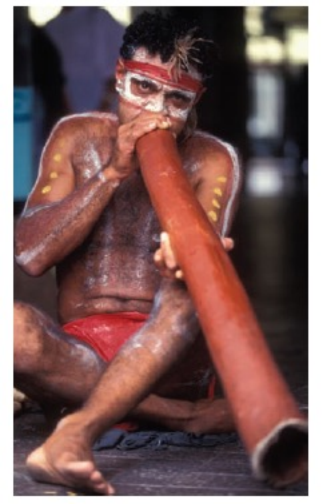
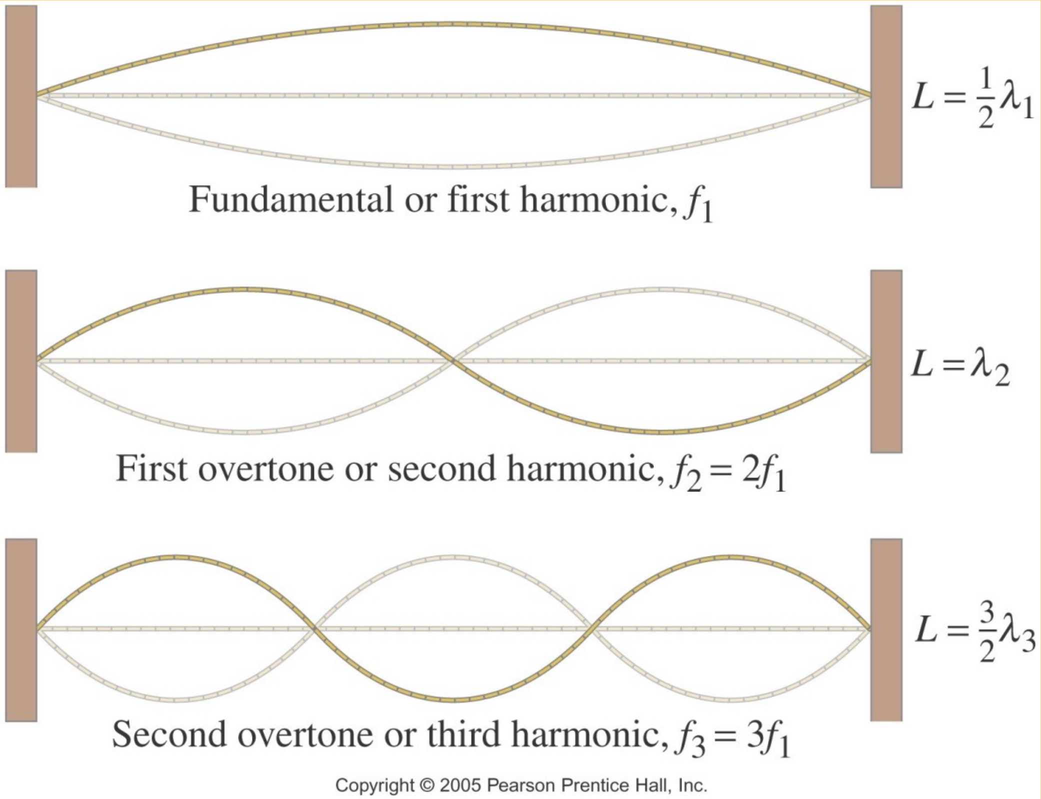


TABLE 12–3 Equally Tempered Chromatic Scale[†]

Note	Frequency (Hz)
C	262
C♯ or D♭	277
D	294
D♯ or E♭	311
E	330
F	349
F♯ or G♭	370
G	392
G♯ or A♭	415
A	440
A♯ or B♭	466
B	494
C′	524

[†] Only one octave is included.

Vibrating Strings



$$\lambda_n = \frac{2L}{n}, \qquad n = 1, 2, 3, \cdots$$

$$f_n = \frac{v}{\lambda_n} = n\frac{v}{2L} = nf_1$$

The pitch is determined by the lowest resonant frequency, the **fundamental**, which corresponds to nodes only at the ends.

The strings on a guitar can be effectively shortened by fingering, **raising** the fundamental pitch.

$$v = \sqrt{\frac{F_T}{m/L}} \Rightarrow$$

The pitch of a string of a given length can also be altered by using a string of different **density**.

Natural frequencies are also called **harmonics**.

First harmonic = **fundamental**
Second harmonic or **first overtone** = twice the fundamental; etc

Exercises

Ex. The highest key on a piano corresponds to a frequency about 150 times that of the lowest key. If the string for the highest note is 5.0 cm long, how long would the string for the lowest note have to be if it had the same mass per unit length and was under the same tension?

7.5 m

FIRST harmonic in both strings

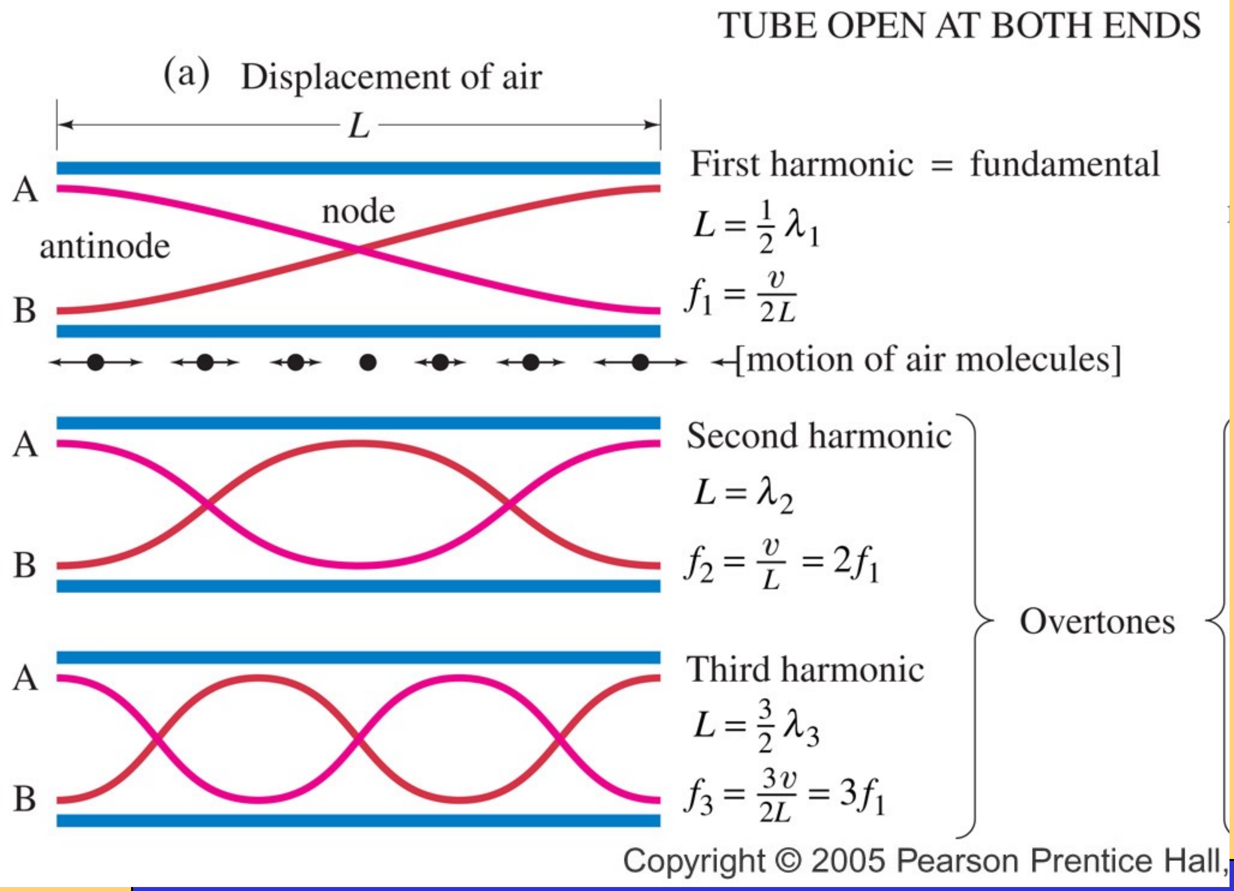
Ex. A 0.32-m-long violin string is tuned to play A above middle C at 440 Hz. (a) What is the wavelength of the fundamental string vibration, and (b) what is the wavelength of the sound wave produced? (c) Why is there a difference? v(sound) = 343 m/s

(a) 64 cm (b) 78 cm (c) wavelength of the sound wave is different from the wavelength of the fundamental string vibration, because the speed of sound in air is different from the speed of the wave on the string

Air Columns – open tube

Wind instruments create sound through standing waves in a column of air.

Blow – make molecules of air vibrate in the tube



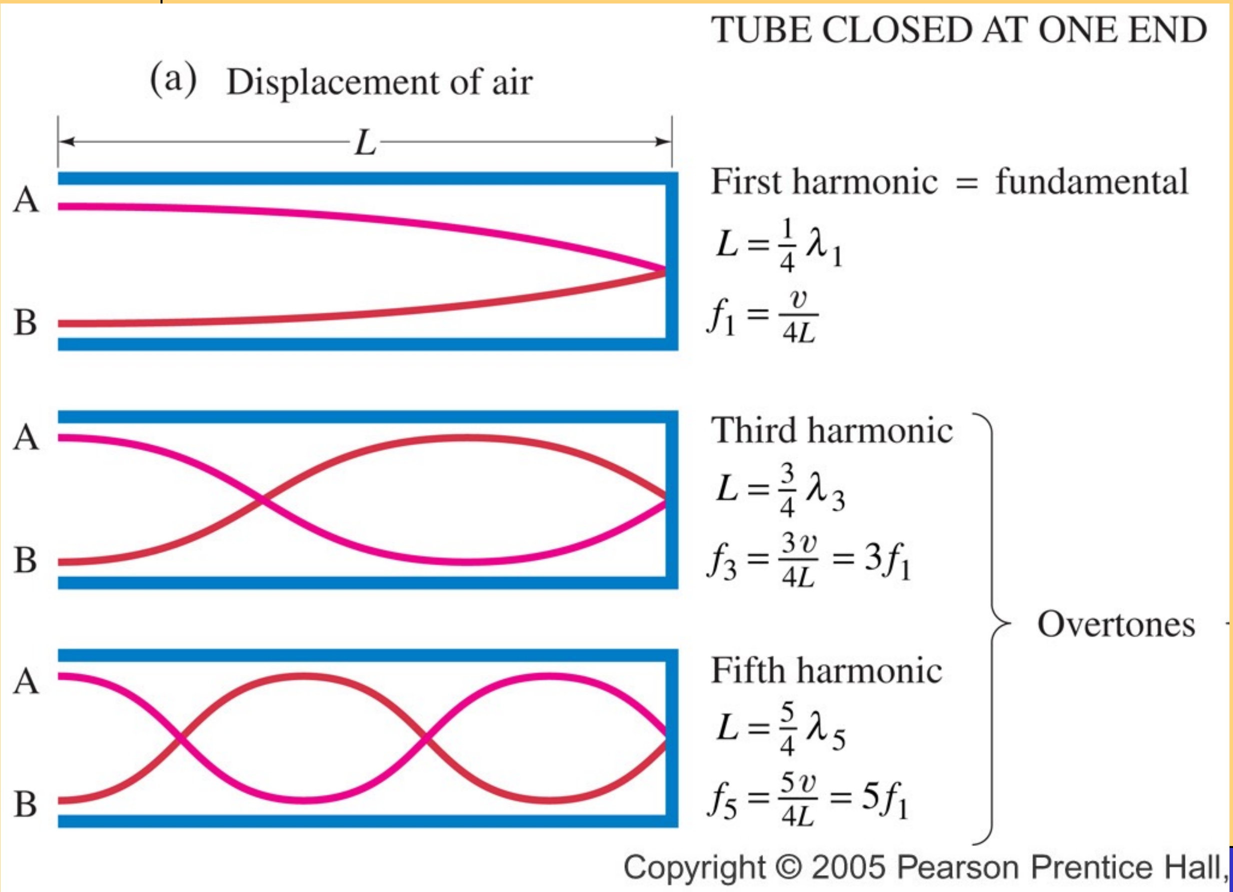
$$L = \frac{n\lambda_n}{2} \quad n = 1,2,3,...$$

$$v = \lambda f$$

$$\lambda_n = 2L/n \Rightarrow \boxed{f_n = n\frac{v}{2L}}$$

Air Columns – closed tube

Only ODD harmonics are present



$$L = \frac{n\lambda_n}{4} \quad n = 1,3,5 \ldots ODD$$

$$v = \lambda f$$

$$\lambda_n = 4L/n \Rightarrow \boxed{f_n = n\frac{v}{4L}}$$

Exercises

Ex. What will be the fundamental frequency and first three overtones for a 26-cm-long organ pipe at 20 Degrees Celsius if it is (a) open and (b) closed?

(a) 660 Hz, and 1320, 1980, 2640 Hz

(a) (b) 330 Hz and 990, 1650, 2310 Hz

Ex. A flute is designed to play middle C (262 Hz) as the fundamental frequency when all the holes are covered. Approximately how long should the distance be from the mouthpiece to the far end of the flute? Assume the temperature is 20 Degrees Celsius.

0.655 m

Exercise

Sound resonance in double-open pipe and single-open pipe

Weak background noises from a room set up the fundamental standing wave in a cardboard tube of length $L = 67.0$ cm with two open ends. Assume that the speed of sound in the air within the tube is 343 m/s.

(a) What frequency do you hear from the tube?

KEY IDEA

With both pipe ends open, we have a symmetric situation in which the standing wave has an antinode at each end of the tube. The standing wave pattern (in string wave style) is that of Fig. 17-13*b*.

Calculation: The frequency is given by Eq. 17-39 with $n = 1$ for the fundamental mode:

$$f = \frac{nv}{2L} = \frac{(1)(343 \text{ m/s})}{2(0.670 \text{ m})} = 256 \text{ Hz.} \qquad \text{(Answer)}$$

If the background noises set up any higher harmonics, such as the second harmonic, you also hear frequencies that are *integer* multiples of 256 Hz. (Thus, the lowest frequency is this fundamental frequency of 256 Hz.)

(b) If you jam your ear against one end of the tube, what fundamental frequency do you hear from the tube?

KEY IDEA

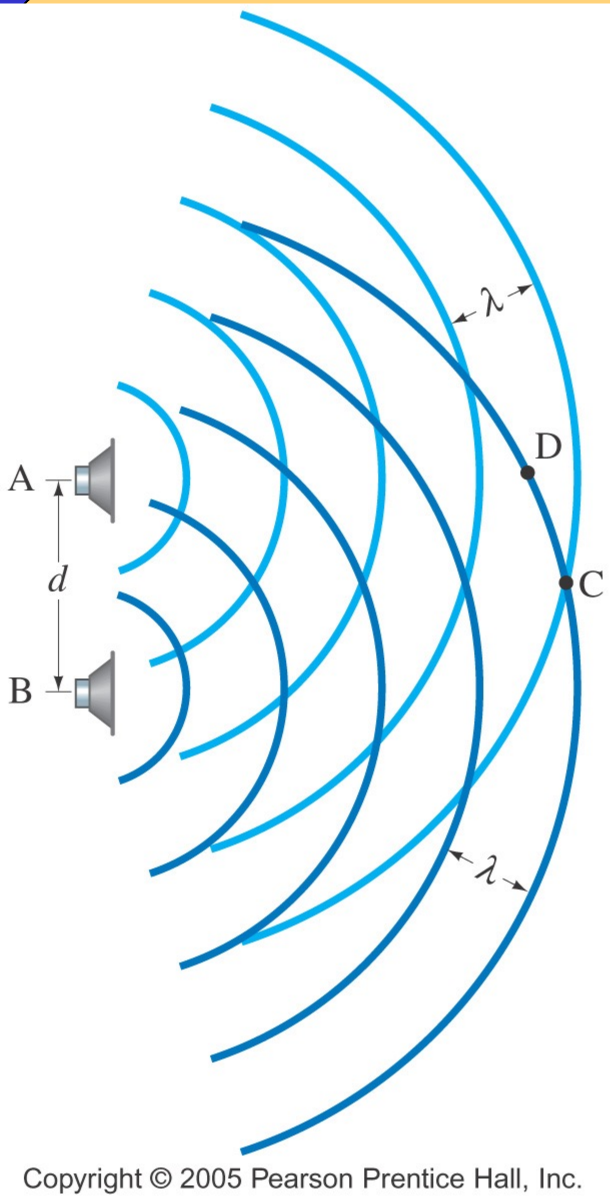
With your ear effectively closing one end of the tube, we have an asymmetric situation—an antinode still exists at the open end, but a node is now at the other (closed) end. The standing wave pattern is the top one in Fig. 17-14*b*.

Calculation: The frequency is given by Eq. 17-41 with $n = 1$ for the fundamental mode:

$$f = \frac{nv}{4L} = \frac{(1)(343 \text{ m/s})}{4(0.670 \text{ m})} = 128 \text{ Hz.} \qquad \text{(Answer)}$$

If the background noises set up any higher harmonics, they will be *odd* multiples of 128 Hz. That means that the frequency of 256 Hz (which is an even multiple) cannot now occur.

Interference of Sound Waves



The two speakers emit sound waves of the same frequency and they are in phase.

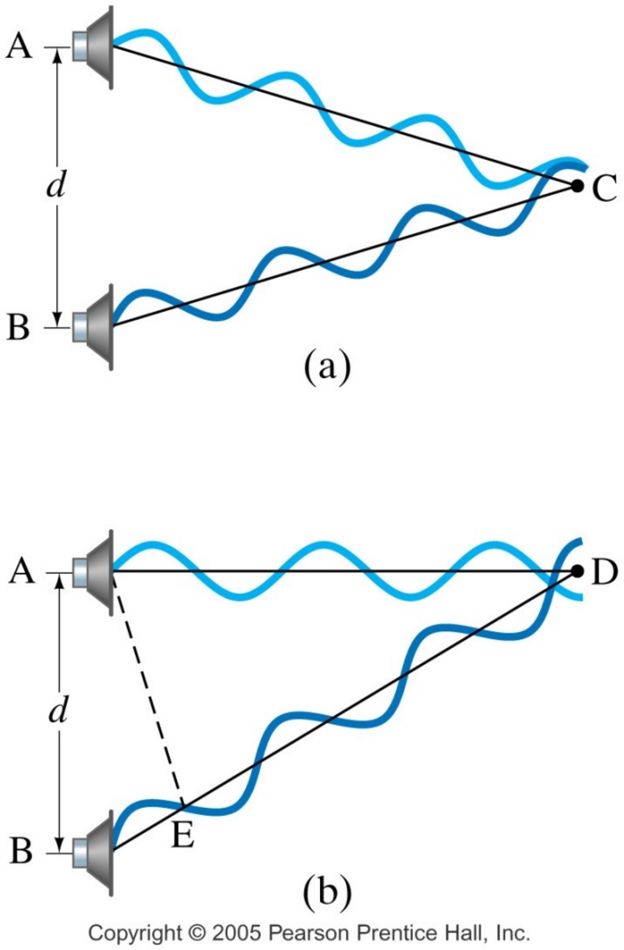
The curves represent the crests from each speaker at one instant of time.

C = constructive interference

AC=BC

D = destructive interference

AD=ED, BE is half of the wavelength of sound



Interference in Position

Ex Two loudspeakers are 1.00 m apart. A person stands 4.00 m from one speaker. How far must this person be from the 2nd speaker to detect destructive interference when the speakers emit an 1150-Hz sound? Assume the temperature is 20 Degrees Celsius (v=343m/s).

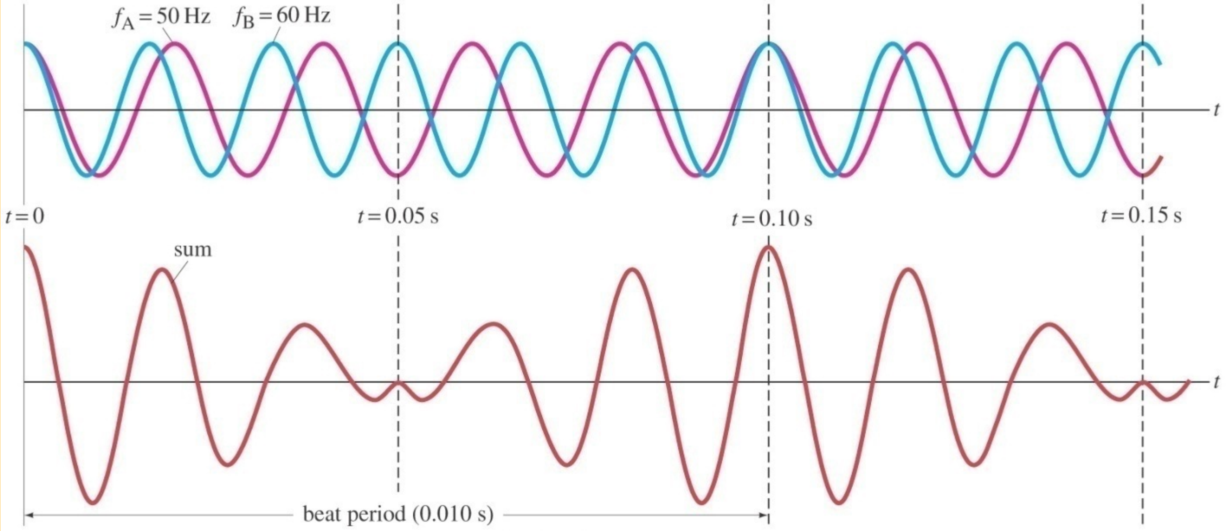
at 3.85 m or 4.15 m

Interference in Time: beats

Waves can also interfere in time, causing a phenomenon called beats.

Beats are the slow "envelope" around two waves that are relatively close in frequency.

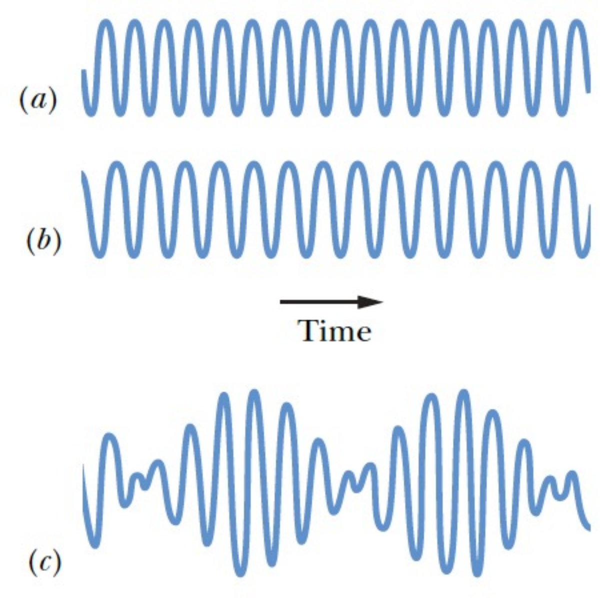
In the figure: beats are 0.10 s apart --- the beat frequency is $f_B - f_A = 10$ Hz



Beats

Waves can also interfere in time, causing a phenomenon called beats.

Beats are the slow "envelope" around two waves that are relatively close in frequency



$$s_1 = s_m \cos \omega_1 t \qquad \text{and} \qquad s_2 = s_m \cos \omega_2 t,$$

$$\omega_1 > \omega_2$$

$$s = s_1 + s_2 = s_m(\cos \omega_1 t + \cos \omega_2 t)$$

$$\cos \alpha + \cos \beta = 2 \cos[\tfrac{1}{2}(\alpha - \beta)] \cos[\tfrac{1}{2}(\alpha + \beta)]$$

$$s = 2s_m \cos[\tfrac{1}{2}(\omega_1 - \omega_2)t] \cos[\tfrac{1}{2}(\omega_1 + \omega_2)t]$$

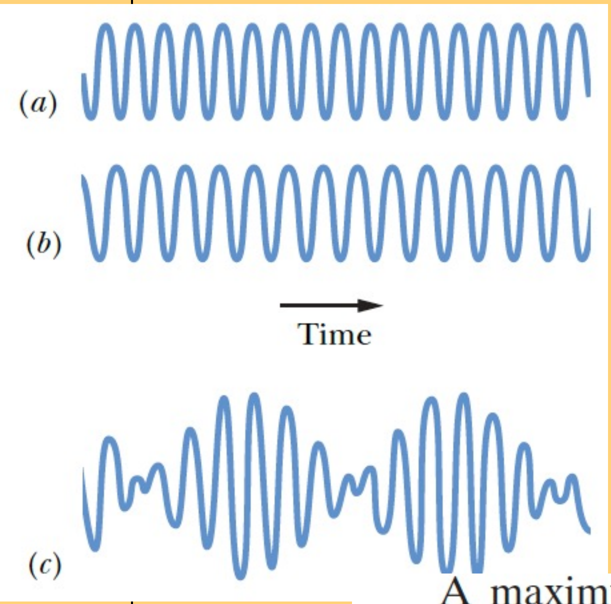
$$\omega' = \tfrac{1}{2}(\omega_1 - \omega_2) \qquad \text{and} \qquad \omega = \tfrac{1}{2}(\omega_1 + \omega_2)$$

$$s(t) = [2s_m \cos \omega' t] \cos \omega t$$

$$\omega \gg \omega'$$

Beats

Waves can also interfere in time, causing a phenomenon called beats.
Beats are the slow "envelope" around two waves that are relatively close in frequency



$$s(t) = [2s_m \cos \omega' t] \cos \omega t$$

$$\omega' = \tfrac{1}{2}(\omega_1 - \omega_2) \quad \text{and} \quad \omega = \tfrac{1}{2}(\omega_1 + \omega_2)$$

$\omega \gg \omega'$

NOTE: ω' is a small frequency,
It is related to the frequency of the ENVELOPE!

A maximum amplitude will occur whenever $\cos \omega' t$ in Eq. 17-45 has the value +1 or −1, which happens twice in each repetition of the cosine function. Because $\cos \omega' t$ has angular frequency ω', the angular frequency ω_{beat} at which beats occur is $\omega_{beat} = 2\omega'$. Then, with the aid of Eq. 17-44, we can write

$$\omega_{beat} = 2\omega' = (2)(\tfrac{1}{2})(\omega_1 - \omega_2) = \omega_1 - \omega_2.$$

$$f_{beat} = f_1 - f_2 \qquad \text{(beat frequency)}$$

Interference in Time: beats

Waves can also interfere in time, causing a phenomenon called beats.
Beats are the slow "envelope" around two waves that are relatively close in frequency

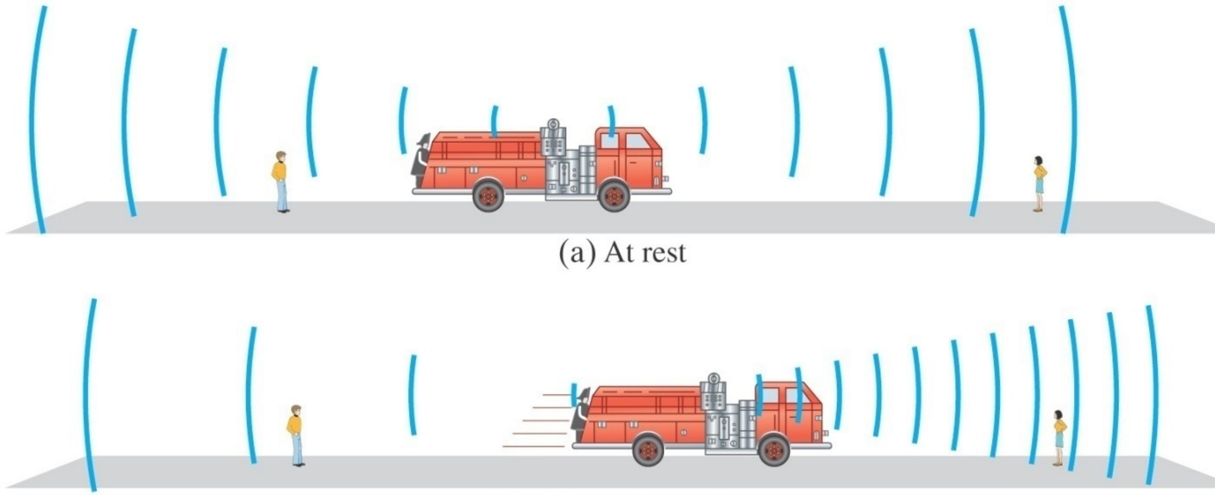
Ex. A tuning fork produces a steady 400-Hz tone. When this tuning fork is struck and held near a vibrating guitar string, twenty beats are counted in five seconds. What are the possible frequencies produced by the guitar string?

404 Hz or 396 Hz

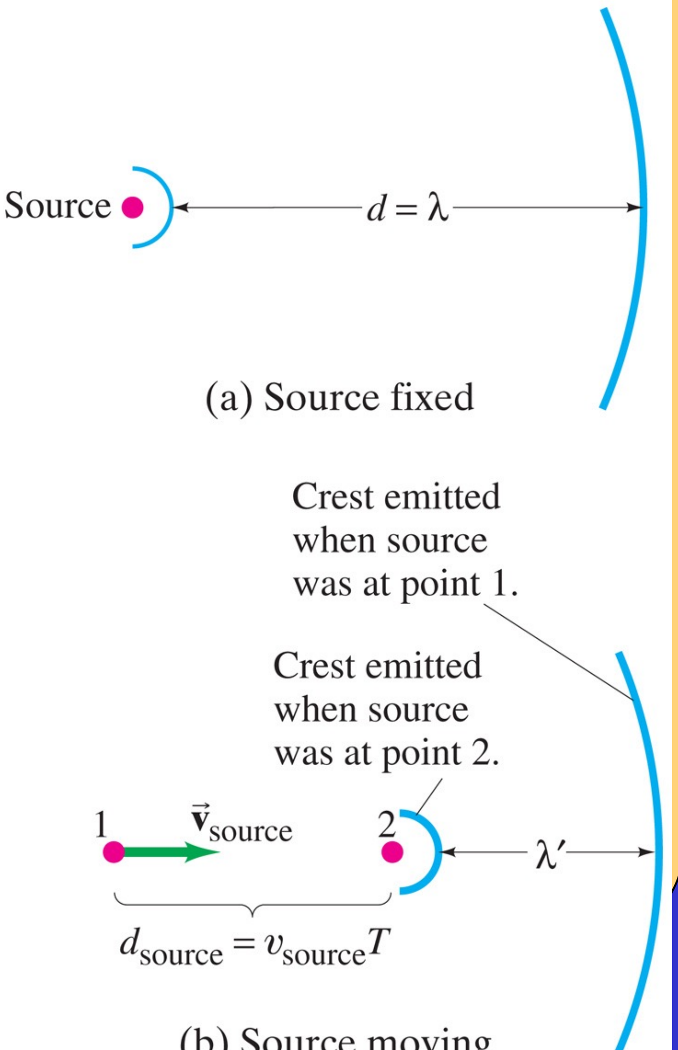
Doppler Effect

The **Doppler effect** occurs when a source of sound is moving with respect to an observer.

A source moving **toward** an observer has a **higher frequency** and **shorter wavelength**; the opposite is true when a source is moving away from an observer.


(a) At rest

(b) Firetruck moving



(a) Source fixed

(b) Source moving

Doppler Effect

Source at **rest**: $T = \frac{1}{f} = \frac{\lambda}{v_{snd}};\ v_{snd} = \lambda f$ where vsnd is the speed of sound

Source moving **toward** the observer; the change in the wavelength is given by:

$$\begin{aligned}\lambda' &= d - d_{\text{source}} \\ &= \lambda - v_{\text{source}} T \\ &= \lambda - v_{\text{source}} \frac{\lambda}{v_{\text{snd}}} \\ &= \lambda\left(1 - \frac{v_{\text{source}}}{v_{\text{snd}}}\right)\end{aligned}$$

$$f' = \frac{v_{\text{snd}}}{\lambda'} = \frac{f}{\left(1 - \frac{v_{\text{source}}}{v_{\text{snd}}}\right)}$$

Therefore, **toward**: f’>f

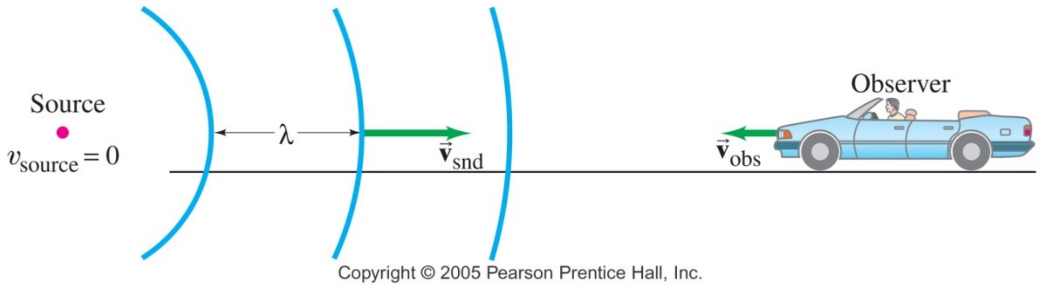
Source moving **away** from the observer:

$$f' = \frac{f}{\left(1 + \frac{v_{\text{source}}}{v_{\text{snd}}}\right)}$$

Therefore, **away**: f’<f

Doppler Effect

Doppler effect also occurs when the source is at rest and the observer is in motion.
If the observer moves **toward** the source: the pitch is **higher**; **away -- lower**.
Quantitatively things are a bit different. The *wavelength remains the same*, but the ***wave speed is different*** for the observer.



$$\left.\begin{aligned} f' &= \frac{v'}{\lambda} \\ v_{snd} &= \lambda f \end{aligned}\right\} f' = f\,\frac{v'}{v_{snd}}$$

Observer moving **towards** a stationary source: the speed v' of the wave relative to the observer is an addition of velocities $v' = v_{snd} + v_{obs}$

$$f' = \left(1 + \frac{v_{obs}}{v_{snd}}\right) f$$

Observer moving **away** $v' = v_{snd} - v_{obs}$

$$f' = \left(1 - \frac{v_{obs}}{v_{snd}}\right) f$$

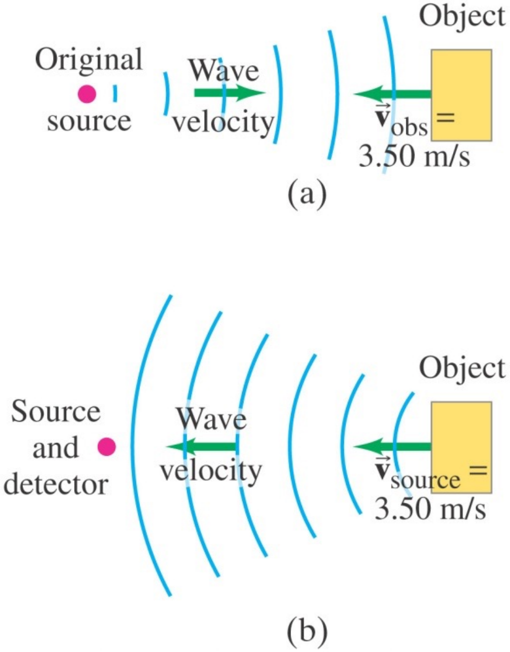
Exercises

Ex. The siren of a police car at rest emits at a predominant frequency of 1600 Hz. What frequency will you hear if you are at rest and the police car moves at 25.0 m/s (a) toward you, and (b) away from you?

(a) 1726 Hz (b) 1491 Hz

Ex. A 5000-Hz sound wave is emitted by a stationary source. The sound wave reflects from an object moving 3.50 m/s toward the source. What is the frequency of the wave reflected by the moving object as detected by a detector at rest near the source?

The frequency that is detected by the moving object is 5051 Hz. The moving object now emits (reflects) a sound at this frequency. The detector receives it as 5103 Hz. Thus the frequency shifts by 103 Hz.



Bats navigate and search out prey by emitting, and then detecting reflections of, ultrasonic waves, which are sound waves with frequencies greater than can be heard by a human. Suppose a bat emits ultrasound at frequency $f_{be} = 82.52$ kHz while flying with velocity $\vec{v}_b = (9.00\ \text{m/s})\hat{\text{i}}$ as it chases a moth that flies with velocity $\vec{v}_m = (8.00\ \text{m/s})\hat{\text{i}}$. What frequency f_{md} does the moth detect? What frequency f_{bd} does the bat detect in the returning echo from the moth?

To get the frequency detected by the moth [$v_{source} = v_{net} = (9-8)$m/s]. Source (bat) approaches the observer (moth).

$$f' = \frac{v_{\text{snd}}}{\lambda'} = \frac{f}{\left(1 - \frac{v_{\text{source}}}{v_{\text{snd}}}\right)}$$

To get the frequency detected by the bat [$v_{obs} = v_{net} = (9-8)$m/s]. Observer (bat) approaches the source (moth)

$$f' = \left(1 + \frac{v_{\text{obs}}}{v_{\text{snd}}}\right)f$$

Double Doppler shift in the echoes used by bats

Bats navigate and search out prey by emitting, and then detecting reflections of, ultrasonic waves, which are sound waves with frequencies greater than can be heard by a human. Suppose a bat emits ultrasound at frequency $f_{be} = 82.52$ kHz while flying with velocity $\vec{v}_b = (9.00 \text{ m/s})\hat{i}$ as it chases a moth that flies with velocity $\vec{v}_m = (8.00 \text{ m/s})\hat{i}$. What frequency f_{md} does the moth detect? What frequency f_{bd} does the bat detect in the returning echo from the moth?

KEY IDEAS

The frequency is shifted by the relative motion of the bat and moth. Because they move along a single axis, the shifted frequency is given by Eq. 17-47 for the general Doppler effect. Motion *toward* tends to shift the frequency *up*, and motion *away* tends to shift the frequency *down*.

Detection by moth: The general Doppler equation is

$$f' = f\frac{v \pm v_D}{v \pm v_S}. \qquad (17\text{-}56)$$

Here, the detected frequency f' that we want to find is the frequency f_{md} detected by the moth. On the right side of the equation, the emitted frequency f is the bat's emission frequency $f_{be} = 82.52$ kHz, the speed of sound is $v = 343$ m/s, the speed v_D of the detector is the moth's speed $v_m = 8.00$ m/s, and the speed v_S of the source is the bat's speed $v_b = 9.00$ m/s.

These substitutions into Eq. 17-56 are easy to make. However, the decisions about the plus and minus signs can be tricky. Think in terms of *toward* and *away*. We have the speed of the moth (the detector) in the numerator of Eq. 17-56. The moth moves *away* from the bat, which tends to lower the detected frequency. Because the speed is in the numerator, we choose the minus sign to meet that tendency (the numerator becomes smaller). These reasoning steps are shown in Table 17-3.

We have the speed of the bat in the denominator of Eq. 17-56. The bat moves *toward* the moth, which tends to increase the detected frequency. Because the speed is in the denominator, we choose the minus sign to meet that tendency (the denominator becomes smaller).

With these substitutions and decisions, we have

$$\begin{aligned} f_{md} &= f_{be}\frac{v - v_m}{v - v_b} \\ &= (82.52 \text{ kHz})\frac{343 \text{ m/s} - 8.00 \text{ m/s}}{343 \text{ m/s} - 9.00 \text{ m/s}} \\ &= 82.767 \text{ kHz} \approx 82.8 \text{ kHz.} \qquad \text{(Answer)} \end{aligned}$$

Detection of echo by bat: In the echo back to the bat, the moth acts as a source of sound, emitting at the frequency f_{md} we just calculated. So now the moth is the source (moving *away*) and the bat is the detector (moving *toward*). The reasoning steps are shown in Table 17-3. To find the frequency f_{bd} detected by the bat, we write Eq. 17-56 as

$$\begin{aligned} f_{bd} &= f_{md}\frac{v + v_b}{v + v_m} \\ &= (82.767 \text{ kHz})\frac{343 \text{ m/s} + 9.00 \text{ m/s}}{343 \text{ m/s} + 8.00 \text{ m/s}} \\ &= 83.00 \text{ kHz} \approx 83.0 \text{ kHz.} \qquad \text{(Answer)} \end{aligned}$$

Some moths evade bats by "jamming" the detection system with ultrasonic clicks.

Doppler Effect for Light

Stars emit light. Using a prism or a diffraction grating, we can spread this light out into a spectrum.
If a star is moving towards us, the whole pattern of the spectrum gets shifted to shorter wavelengths, i.e. towards the blue end of the spectrum. This is a BLUESHIFT, and we can measure it very accurately by comparing the apparent wavelengths of the spectral lines with the known laboratory wavelengths. If the star is receding, the pattern moves to longer, redder wavelengths, and this is a REDSHIFT.