Chapter 12 – Sound

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.

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

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

$$\boxed{T = 20^{o}C \Rightarrow v = 343\,m/s}$$

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

Pitch: related to **frequency**.

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

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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)

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

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. 12-3 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. 12-4 If the level sound is increased by 3 dB, what is the ratio between the final and the initial intensity?

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

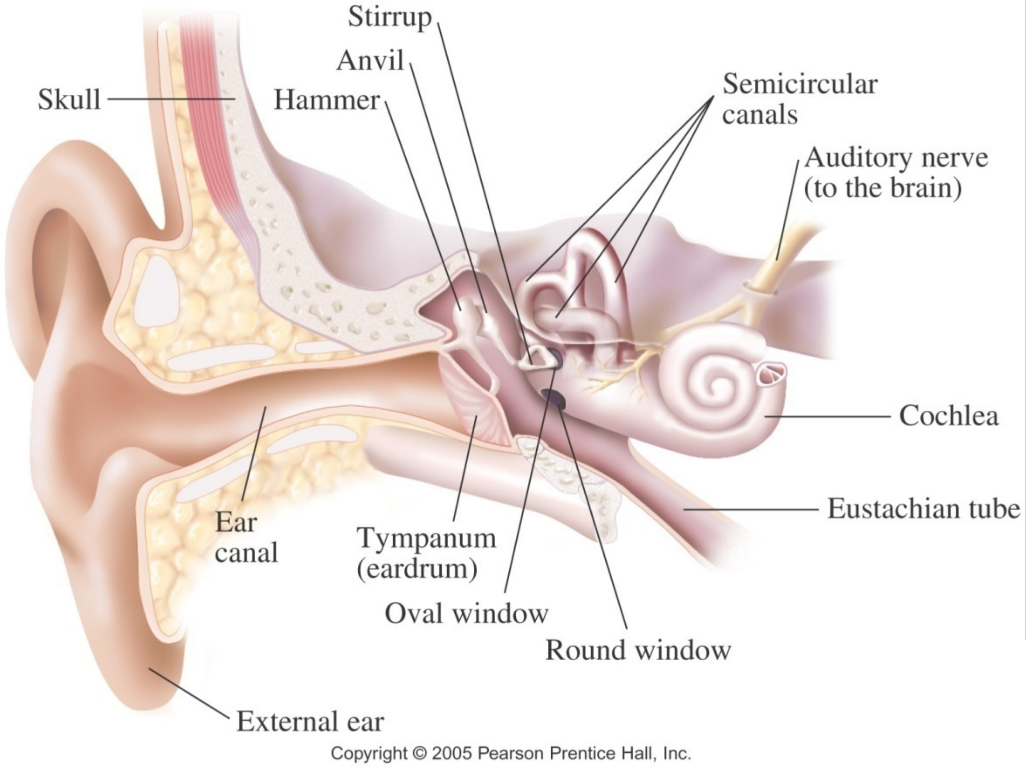
In open areas, the intensity of sound diminishes with distance:

$$I \propto \frac{1}{r^2}$$

Ex. 12-5 The sound level measured 30 m from a jet plane is 140 dB. What is the sound level at 300 m?

120 dB

The Ear and Its Response (extra)

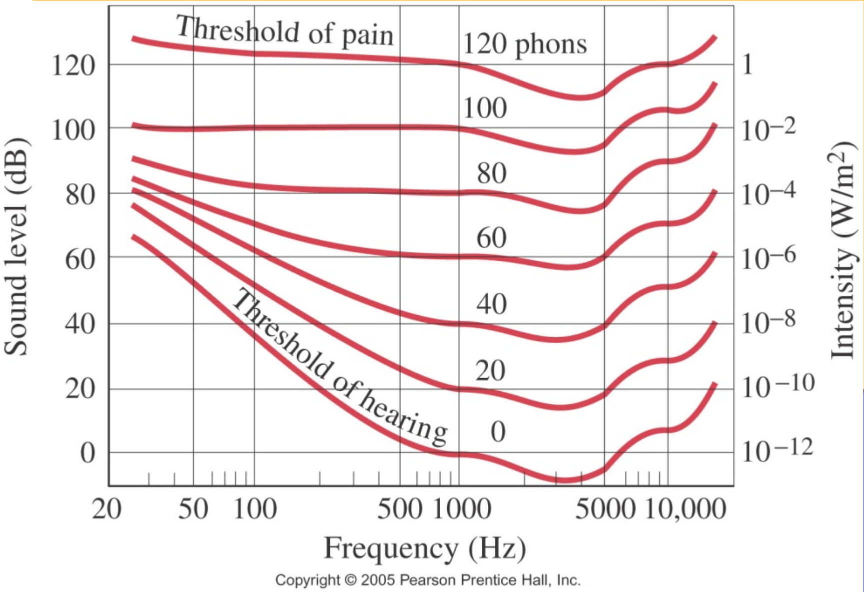


Outer ear: sound waves travel down the ear canal to the eardrum, which vibrates in response

Middle ear: hammer, anvil, and stirrup transfer vibrations to inner ear

Inner ear: cochlea transforms vibrational energy to electrical energy and sends signals to the brain

The ear's sensitivity varies with frequency. These curves translate the intensity into sound level at different frequencies.



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.

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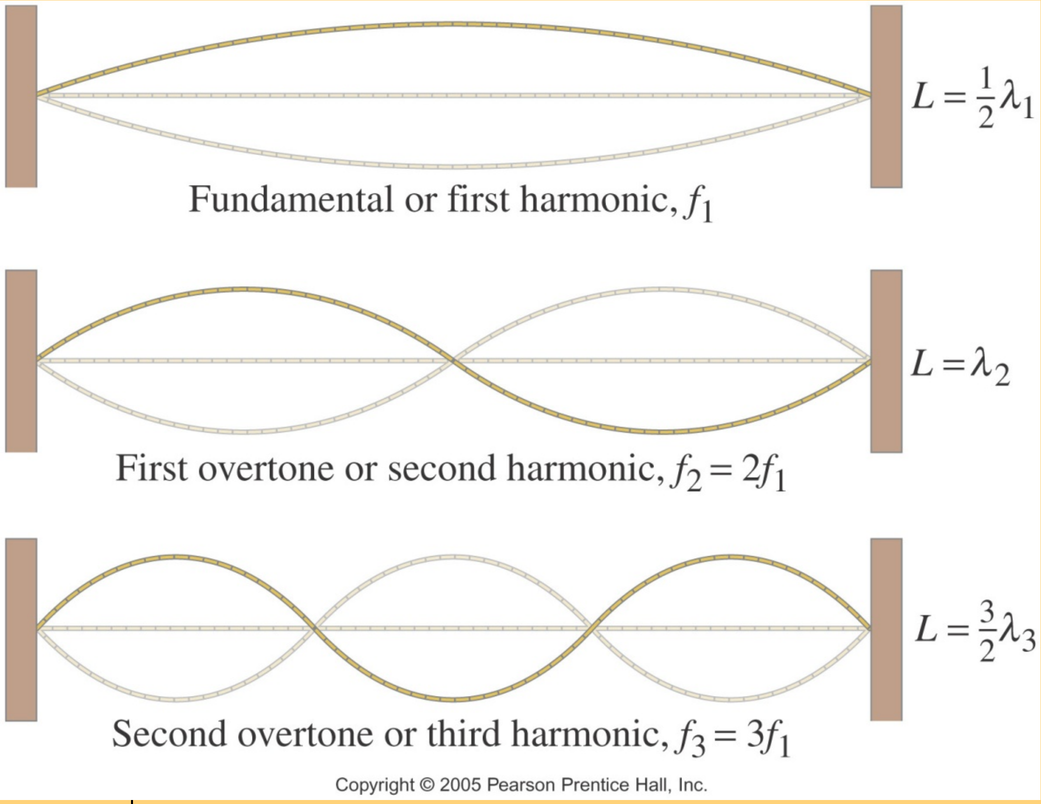
Vibrating Strings



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

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

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. 12-7 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

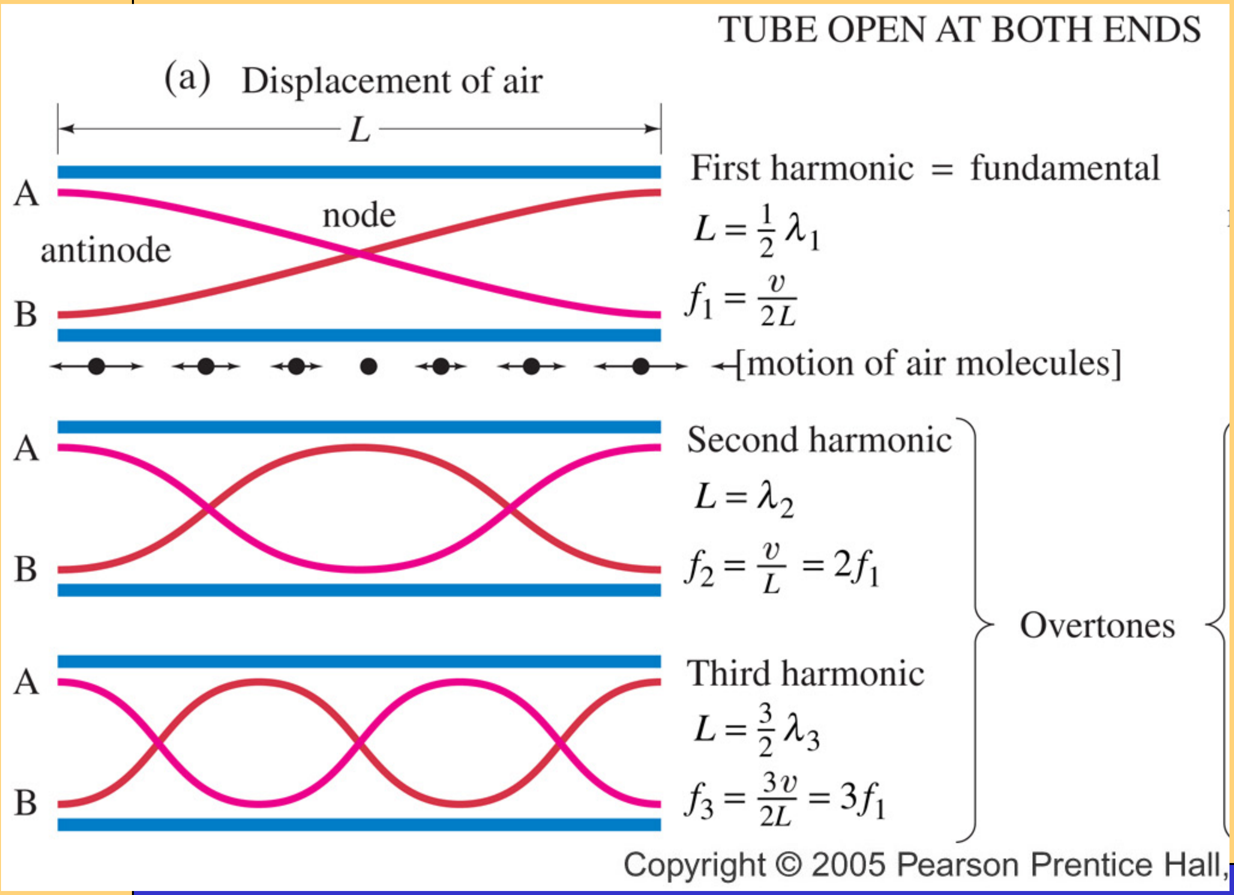
Ex. 12-8 A 0.32-m-long violin string is tuned to play A above middle C at 440 Hz. (a) What is the wavelength of the fundamental string vibration, and (b) what is the wavelength of the sound wave produced? (c) Why is there a difference? v(sound) = 343 m/s

(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



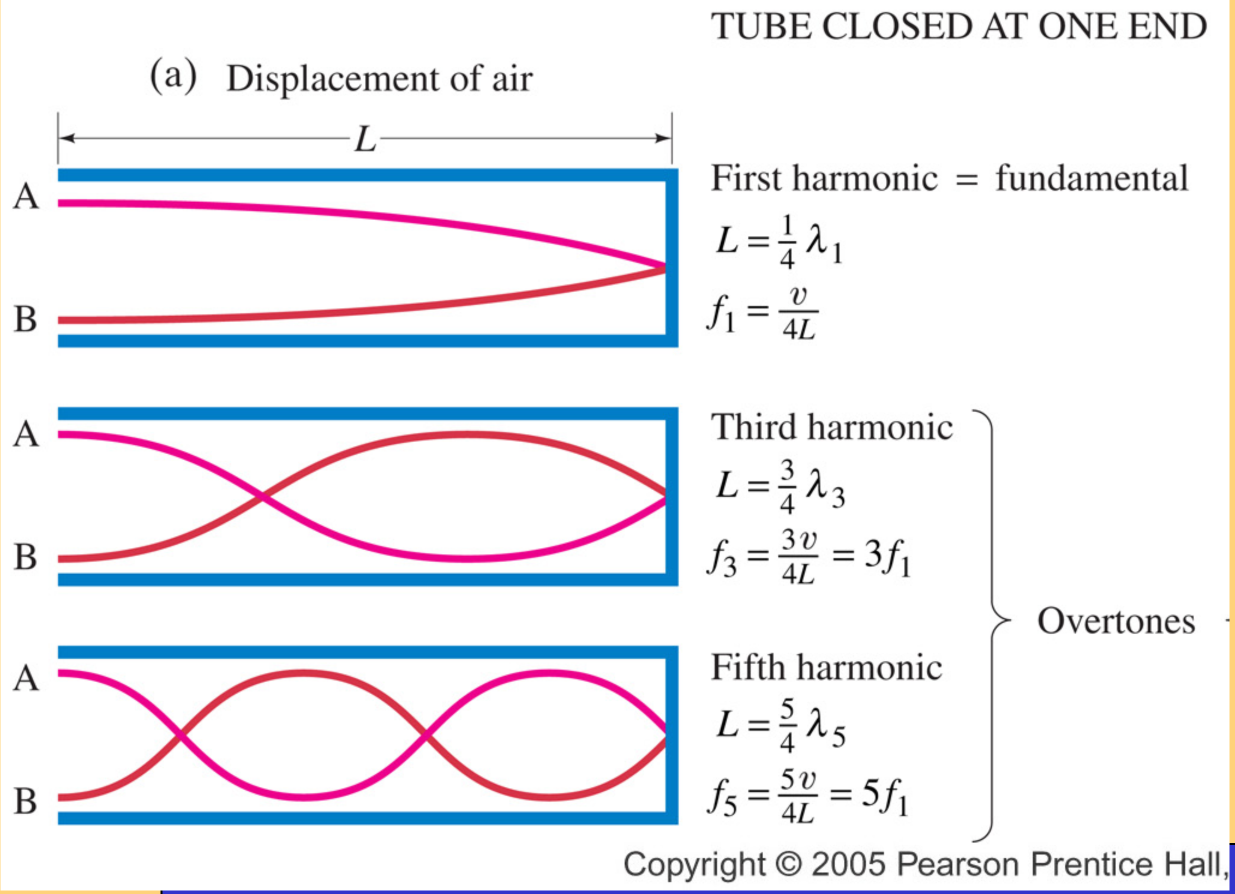
$$L = \frac{n\lambda_n}{2} \quad n = 1,2,3,\ldots$$

$$v = \lambda f$$

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

Air Columns – closed tube

Only ODD harmonics are present



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

$$v = \lambda f$$

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

Exercises

Ex. 12-9 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 (b) 330 Hz and 990, 1650, 2310 Hz

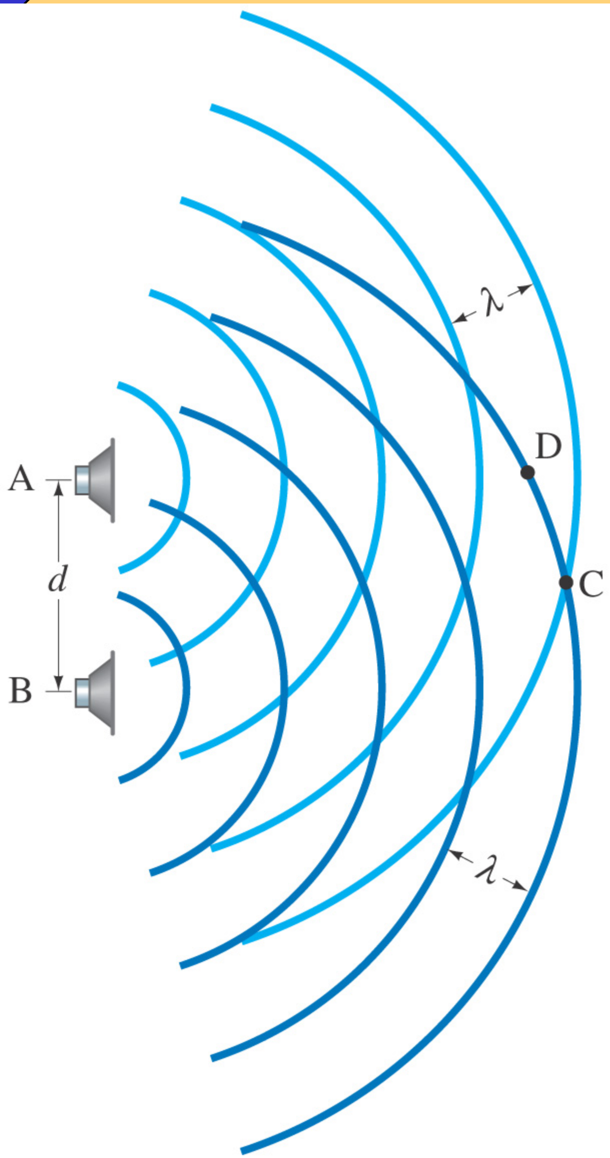
Ex. 12-10 A flute is designed to play middle C (262 Hz) as the fundamental frequency when all the holes are covered. Approximately how long should the distance be from the mouthpiece to the far end of the flute? Assume the temperature is 20 Degrees Celsius.

0.655 m

Ex. 12-11 Wind can be noisy – it can howl in trees; it can moan in chimneys. What is causing the noise and about what range of frequencies would you expect to hear?

recitation

Interference of Sound Waves



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

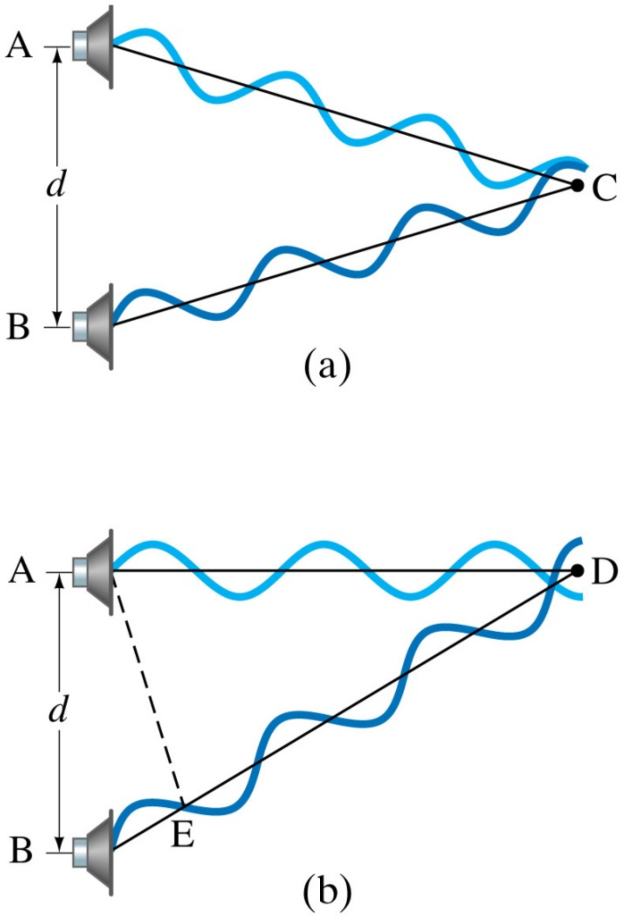
The curves represent the crests from each speaker at one instant of time.

C = constructive interference

AC=BC

D = destructive interference

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



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Interference in Time: beats

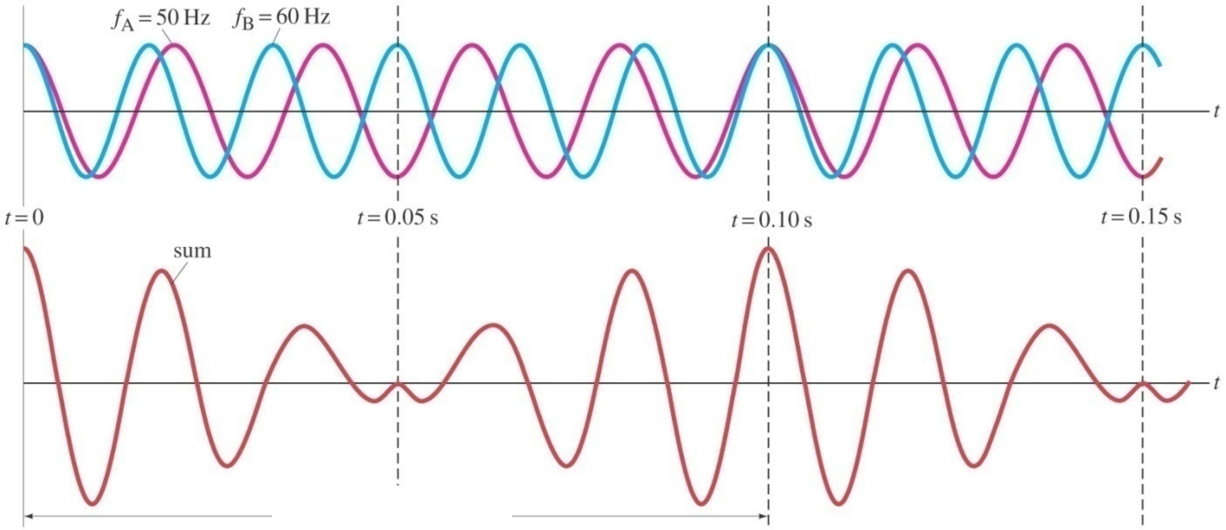
Ex 12-12 Two loudspeakers are 1.00 m apart. A person stands 4.00 m from one speaker. How far must this person be from the 2nd speaker to detect destructive interference when the speakers emit an 1150-Hz sound? Assume the temperature is 20 Degrees Celsius (v=343m/s).

at 3.85 m or 4.15 m

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



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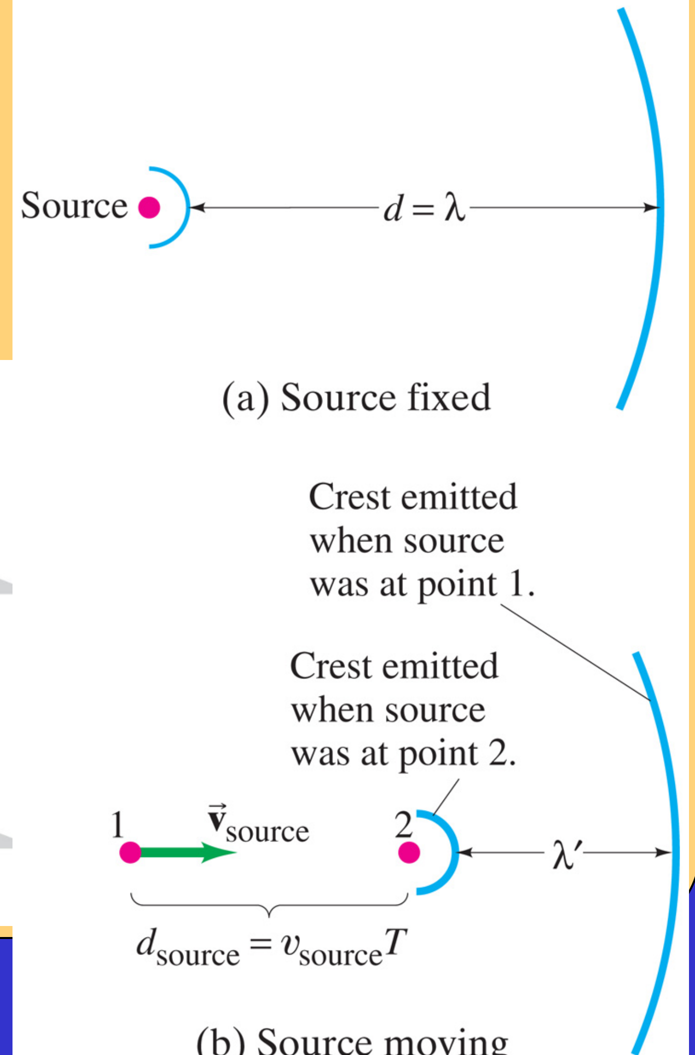
Ex. 12-13 A tuning fork produces a steady 400-Hz tone. When this tuning fork is struck and held near a vibrating guitar string, twenty beats are counted in five seconds. What are the possible frequencies produced by the guitar string?

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) Source fixed

(b) Source moving

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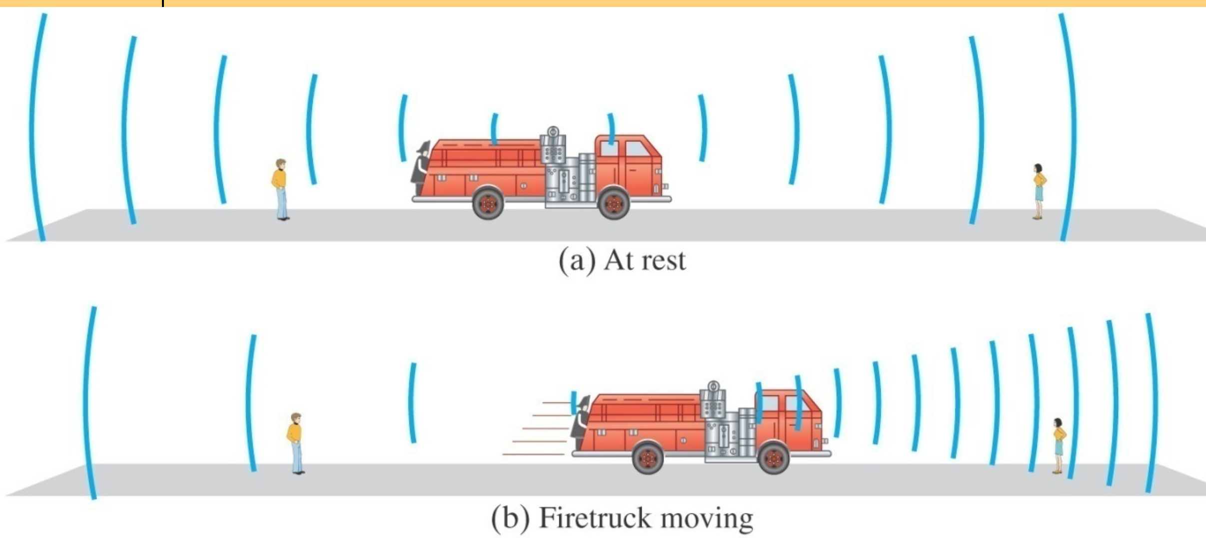

(a) At rest

(b) Firetruck moving

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Doppler Effect

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

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

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

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

Therefore, **toward**: f'>f

Source moving **away** from the observer:

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

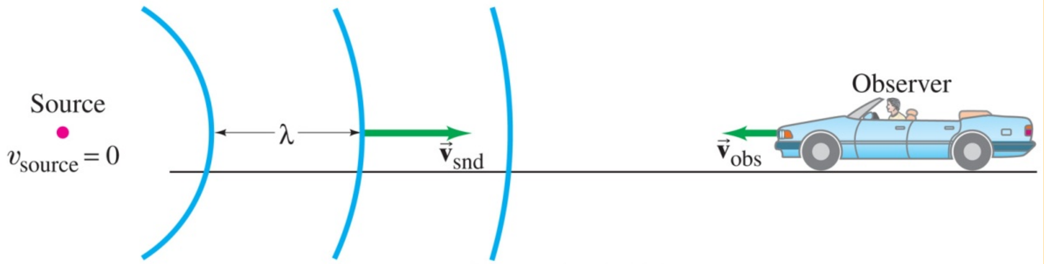
Therefore, **away**: f'<f

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.



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

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** $v' = v_{snd} - v_{obs}$

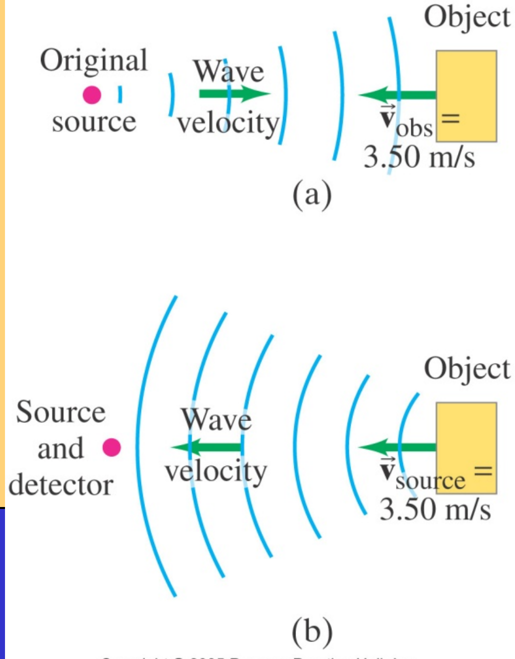
$$f' = \left(1 - \frac{v_{obs}}{v_{snd}}\right) f$$

Exercises

Ex. 12-14 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. 12-15 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?



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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.

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.