Chapter 16
Sound

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Units of Chapter 16

- Characteristics of Sound
- Mathematical Representation of Longitudinal Waves
- Intensity of Sound: Decibels
- Sources of Sound: Vibrating Strings and Air Columns
- Quality of Sound, and Noise; Superposition
- Interference of Sound Waves; Beats

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Units of Chapter 16

- **Doppler Effect**
- **Shock Waves and the Sonic Boom**
- **Applications: Sonar, Ultrasound, and Medical Imaging**

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16-1 Characteristics of Sound

Sound can travel through any kind of **matter**, but not through a **vacuum**.

TABLE 16–1 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

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.

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16-1 Characteristics of Sound

Conceptual Example 16-1: Distance from a lightning strike.

A rule of thumb that tells how close lightning has struck is, "one mile for every five seconds before the thunder is heard." Explain why this works, noting that the speed of light is so high (3×10^8 m/s, almost a million times faster than sound) that the time for light to travel to us is negligible compared to the time for the sound.

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16-1 Characteristics of Sound

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

Pitch: related to **frequency**

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

Ultrasound: above **20,000** Hz; see ultrasonic camera focusing in following example

Infrasound: below **20** Hz

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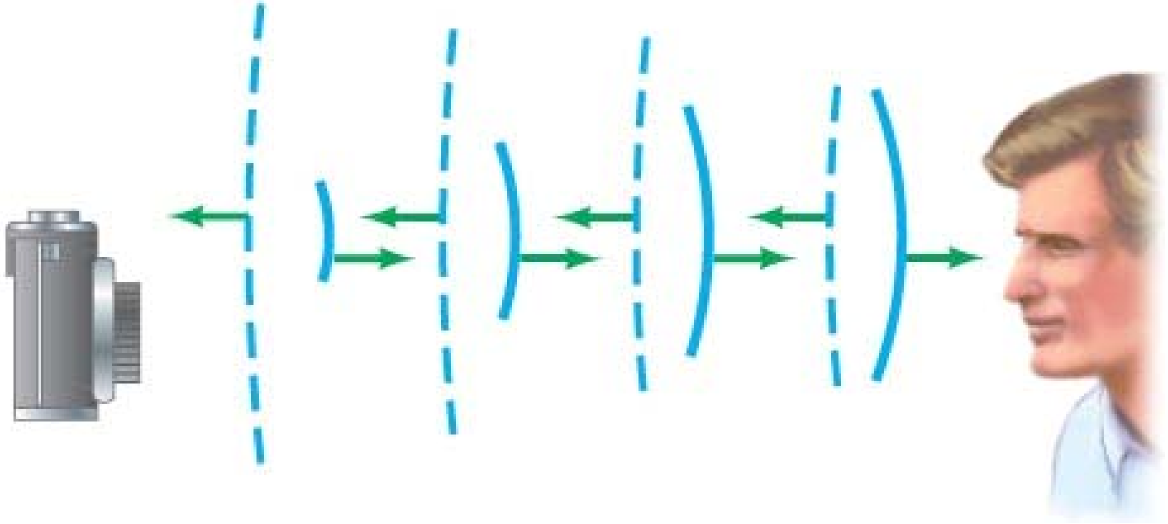
16-1 Characteristics of Sound

Example 16-2: Autofocusing with sound waves.

Older autofocusing cameras determine the distance by emitting a pulse of very high frequency (ultrasonic) sound that travels to the object being photographed, and include a sensor that detects the returning reflected sound. To get an idea of the time sensitivity of the detector, calculate the travel time of the pulse for an object (a) 1.0 m away, and (b) 20 m away.



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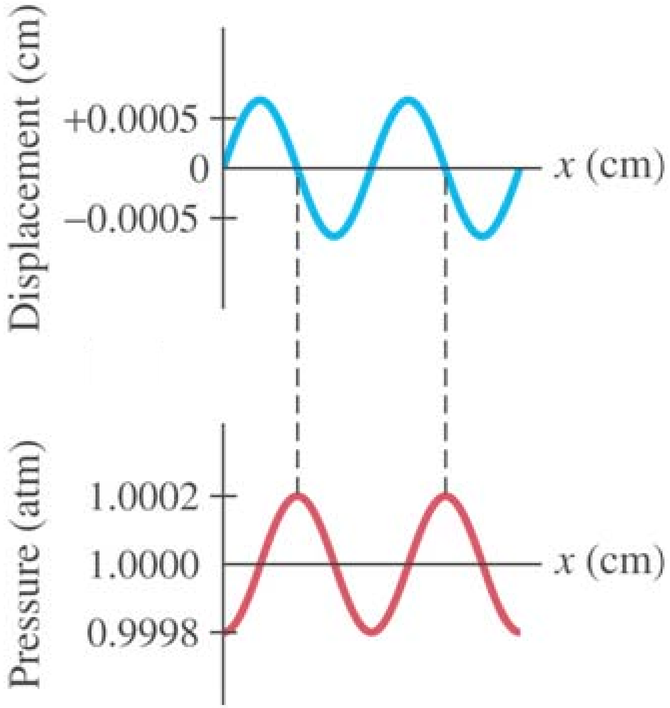
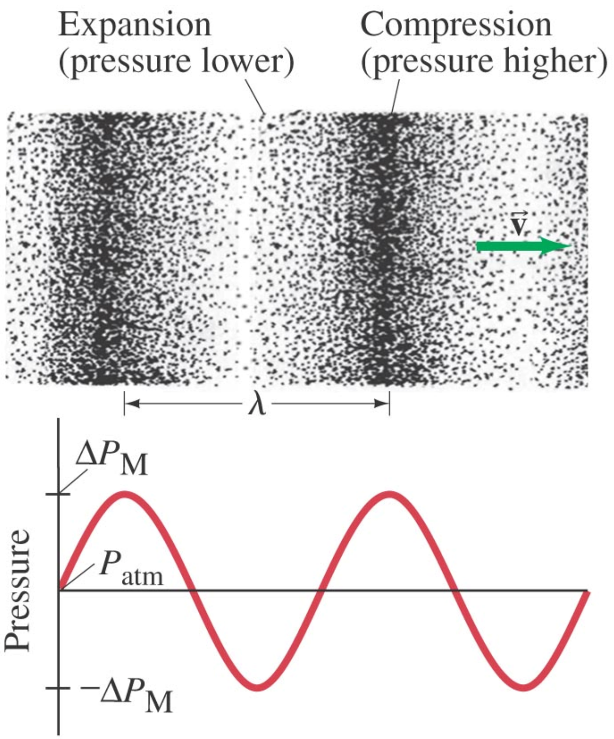
16-2 Mathematical Representation of Longitudinal Waves

Longitudinal waves are often called pressure waves. The displacement is 90° out of phase with the pressure.





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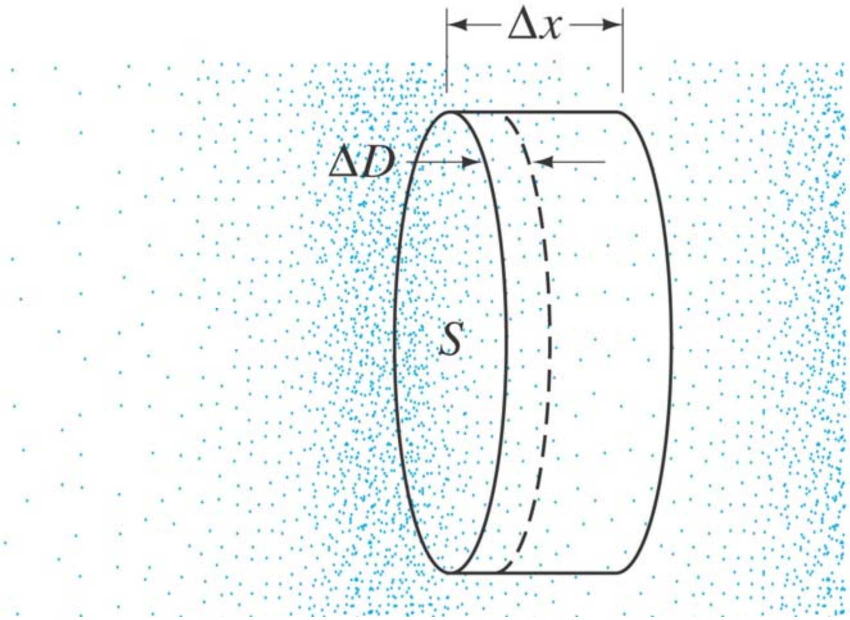
16-2 Mathematical Representation of Longitudinal Waves

By considering a small cylinder within the fluid, we see that the change in pressure is given by (B is the bulk modulus):

$$\Delta P = -B\frac{\partial D}{\partial x}.$$



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16-2 Mathematical Representation of Longitudinal Waves

If the displacement is sinusoidal, we have

$$\Delta P = -(BAk)\cos(kx - \omega t),$$

where

$$v = \sqrt{\frac{B}{\rho}},$$

and

$$v = \frac{\omega}{k}.$$

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16-3 Intensity of Sound: Decibels

TABLE 16–2
Intensity of Various Sounds

Source of the Sound	Sound Level (dB)	Intensity (W/m^2)
Jet plane at 30 m	140	100
Threshold of pain	120	1
Loud rock concert	120	1
Siren at 30 m	100	1×10^{-2}
Truck traffic	90	1×10^{-3}
Busy street traffic	80	1×10^{-4}
Noisy restaurant	70	1×10^{-5}
Talk, at 50 cm	65	3×10^{-6}
Quiet radio	40	1×10^{-8}
Whisper	30	1×10^{-9}
Rustle of leaves	10	1×10^{-11}
Threshold of hearing	0	1×10^{-12}

The **intensity** of a wave is the **energy** transported per unit **time** across a unit **area**.

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**, however, is not proportional to the intensity.

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16-3 Intensity of Sound: Decibels

The loudness of a sound is much more closely related to the **logarithm** of the intensity.

Sound level is measured in **decibels** (dB) and is defined as:

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

I_0 is taken to be the **threshold** of hearing:

$$I_0 = 1.0 \times 10^{-12}\ \text{W/m}^2.$$

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16-3 Intensity of Sound: Decibels

Example 16-3: Sound intensity on the street.

At a busy street corner, the sound level is 75 dB. What is the intensity of sound there?

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16-3 Intensity of Sound: Decibels

Example 16-4: Loudspeaker response.

A high-quality loudspeaker is advertised to reproduce, at full volume, frequencies from 30 Hz to 18,000 Hz with uniform sound level ± 3 dB. That is, over this frequency range, the sound level output does not vary by more than 3 dB for a given input level. By what factor does the intensity change for the maximum change of 3 dB in output sound level?

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16-3 Intensity of Sound: Decibels

Conceptual Example 16-5: Trumpet players.

A trumpeter plays at a sound level of 75 dB. Three equally loud trumpet players join in. What is the new sound level?

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16-3 Intensity of Sound: Decibels

An increase in sound level of 3 dB, which is a **doubling** in intensity, is a very small change in loudness.

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

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

However, in **enclosed** spaces this is complicated by **reflections**, and if sound travels through air, the higher frequencies get preferentially **absorbed**.

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16-3 Intensity of Sound: Decibels

Example 16-6: Airplane roar.

The sound level measured 30 m from a jet plane is 140 dB. What is the sound level at 300 m? (Ignore reflections from the ground.)

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16-3 Intensity of Sound: Decibels

Example 16-7: How tiny the displacement is.

(a) Calculate the displacement of air molecules for a sound having a frequency of 1000 Hz at the threshold of hearing.

(b) Determine the maximum pressure variation in such a sound wave.

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16-3 Intensity of Sound: Decibels

The intensity can be written in terms of the maximum pressure variation. With some algebraic manipulation, we find:

$$I = 2\pi^2 v\rho f^2 A^2 = 2\pi^2 v\rho f^2 \left(\frac{\Delta P_{\mathrm{M}}}{2\pi\rho v f}\right)^2$$

$$I = \frac{\left(\Delta P_{\mathrm{M}}\right)^2}{2v\rho}.$$

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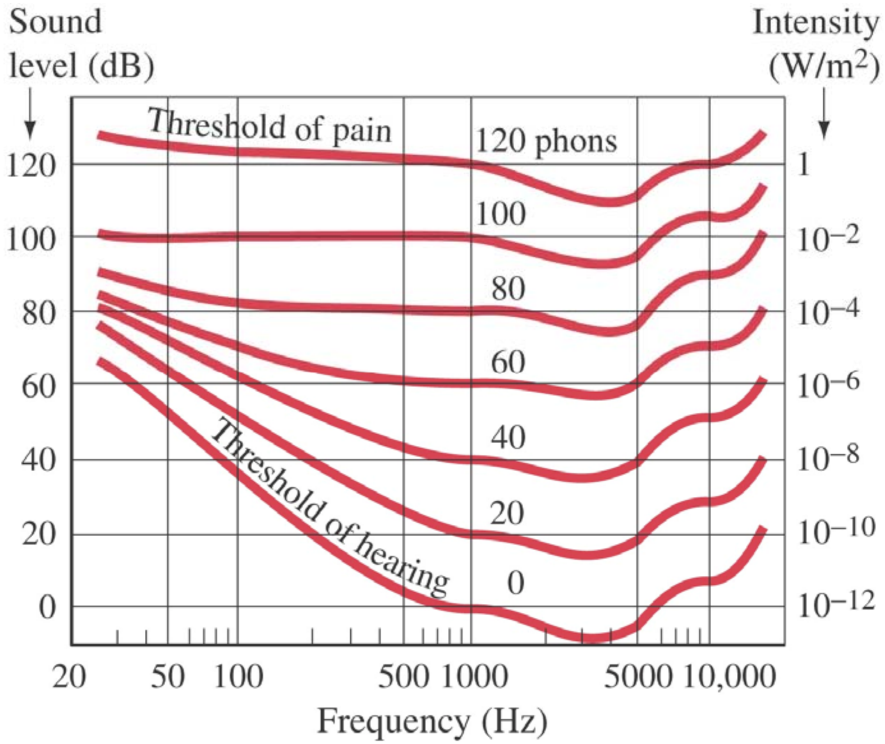
16-3 Intensity of Sound: Decibels

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



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16-4 Sources of Sound: Vibrating Strings and Air Columns

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. The vibrations are transmitted to the air and then to our ears.

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16-4 Sources of Sound: Vibrating Strings and Air Columns

TABLE 16–3 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.

This table gives frequencies for the octave beginning with middle C. The equally tempered scale is designed so that music sounds the same regardless of what key it is transposed into.

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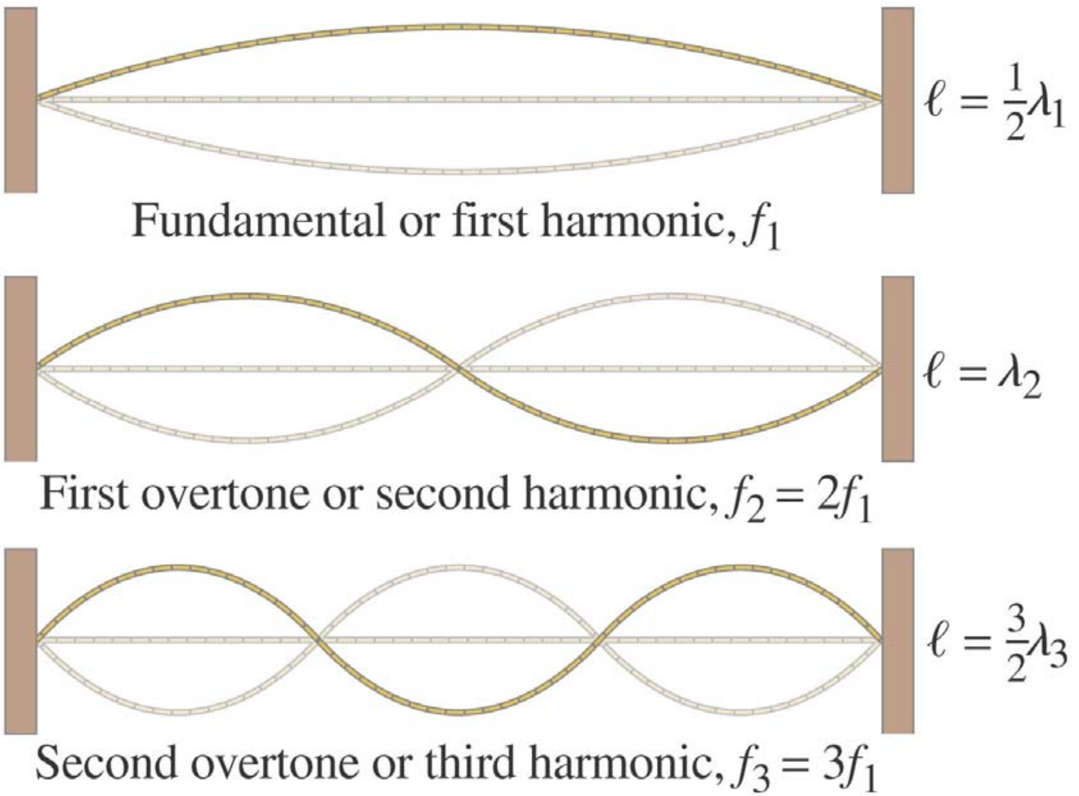
16-4 Sources of Sound: Vibrating Strings and Air Columns

This figure shows the first three standing waves, or harmonics, on a fixed string.



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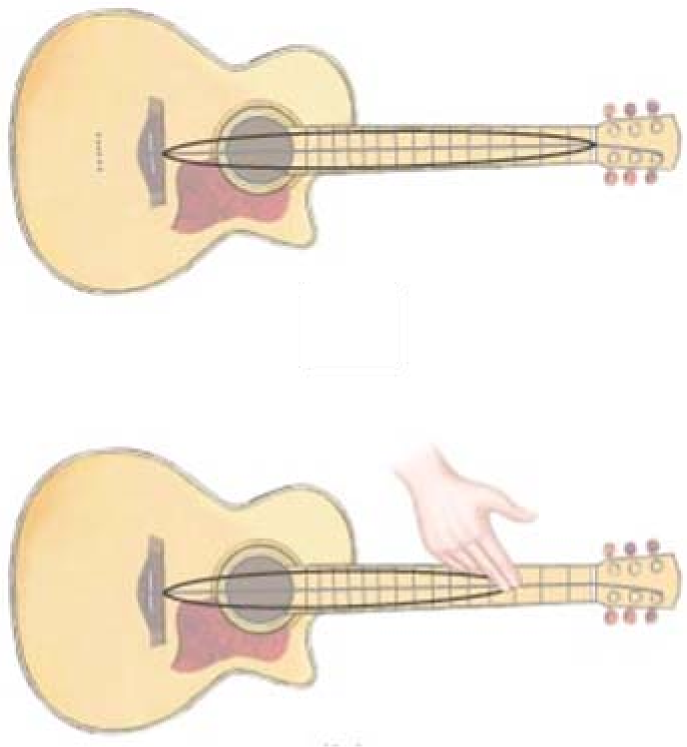
16-4 Sources of Sound: Vibrating Strings and Air Columns



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

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

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16-4 Sources of Sound: Vibrating Strings and Air Columns

Example 16-8: Piano strings.

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?

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16-4 Sources of Sound: Vibrating Strings and Air Columns

Example 16-9: Frequencies and wavelengths in the violin.

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 are the frequency and wavelength of the sound wave produced?

(c) Why is there a difference?

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16-4 Sources of Sound: Vibrating Strings and Air Columns

The sound waves from vibrating strings need to be amplified in order to be of a practical loudness; this is done in acoustical instruments by using a sounding board or box, creating a resonant chamber. The sound can also be amplified electronically.

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16-4 Sources of Sound: Vibrating Strings and Air Columns

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

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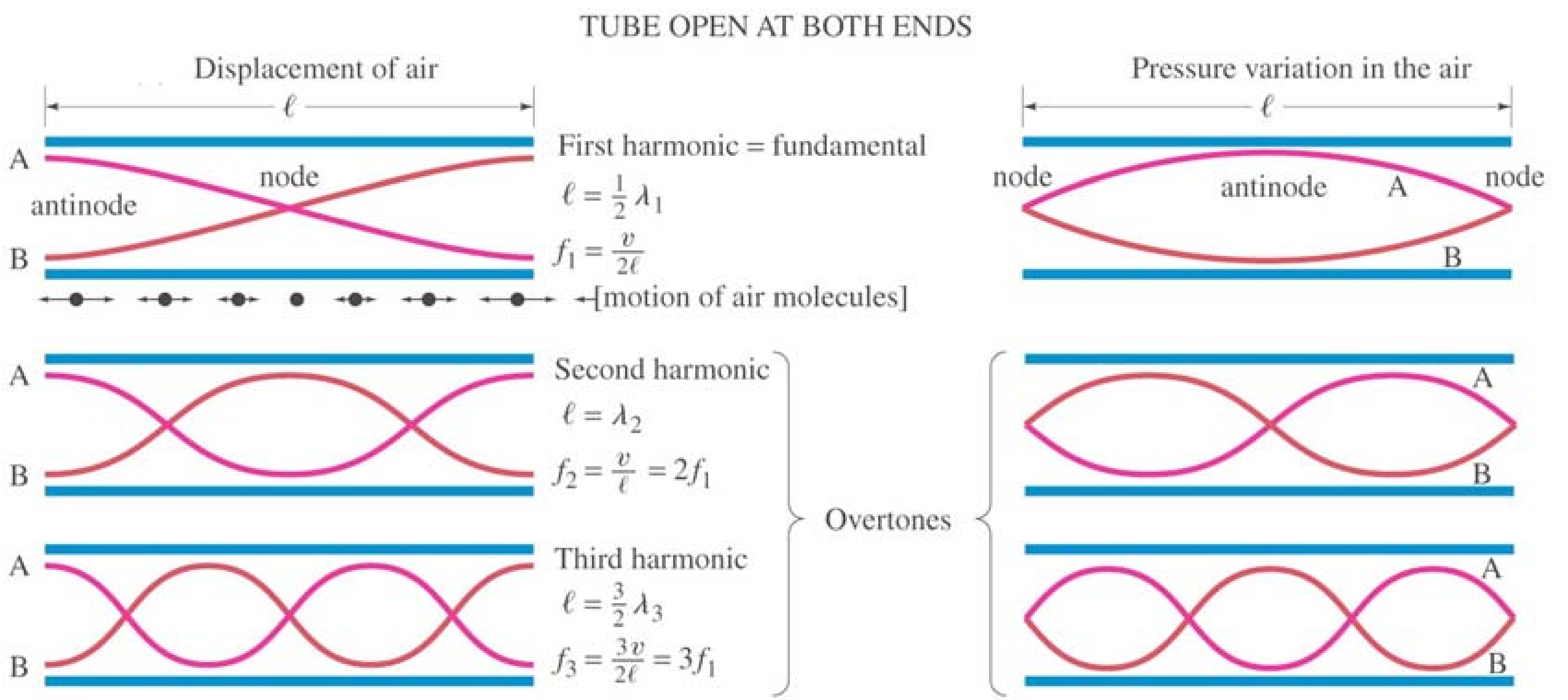
16-4 Sources of Sound: Vibrating Strings and Air Columns

A tube **open** at both ends (most wind instruments) has pressure **nodes**, and therefore displacement **antinodes**, at the ends.



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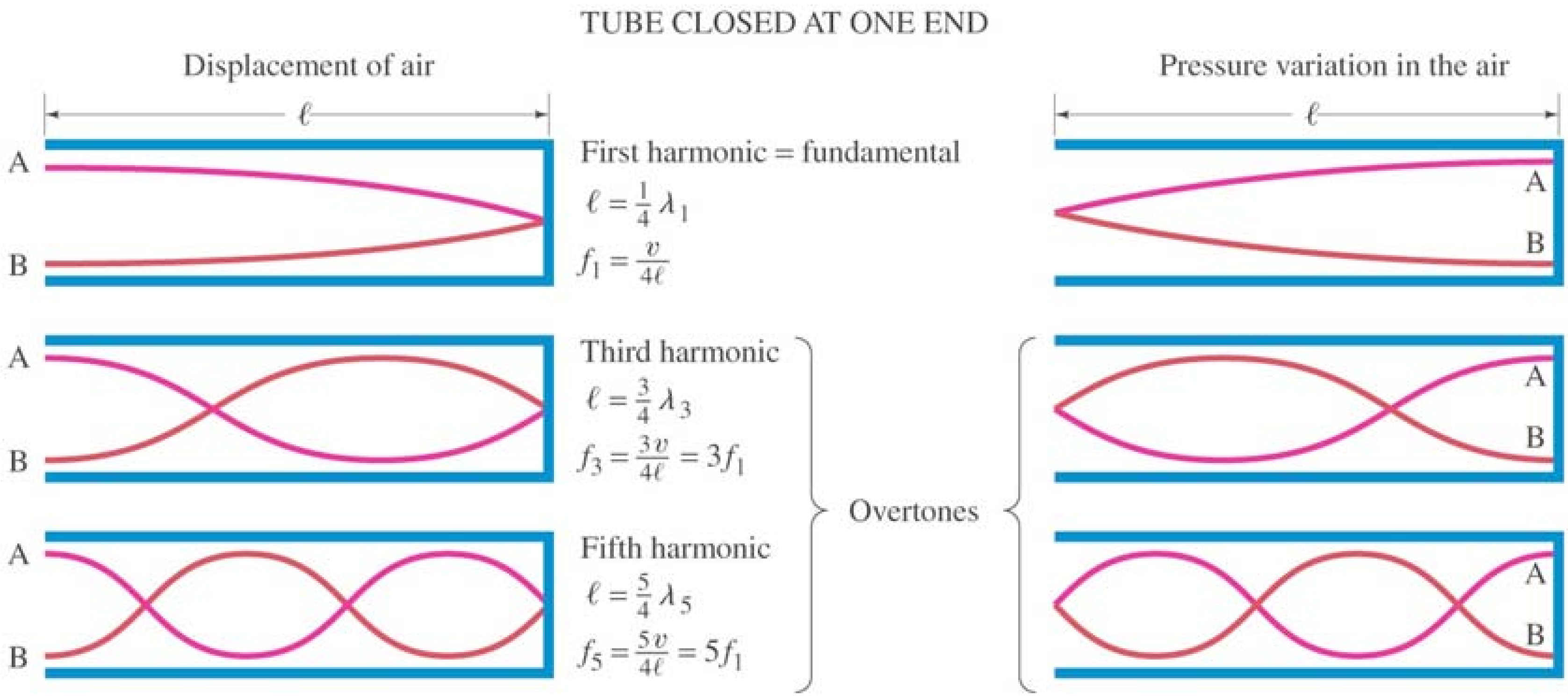
16-4 Sources of Sound: Vibrating Strings and Air Columns

A tube closed at one end (some organ pipes) has a displacement node (and pressure antinode) at the closed end.



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16-4 Sources of Sound: Vibrating Strings and Air Columns

Example 16-10: Organ pipes.

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

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16-4 Sources of Sound: Vibrating Strings and Air Columns

Example 16-11: Flute.

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? (This is only approximate since the antinode does not occur precisely at the mouthpiece.) Assume the temperature is 20°C.

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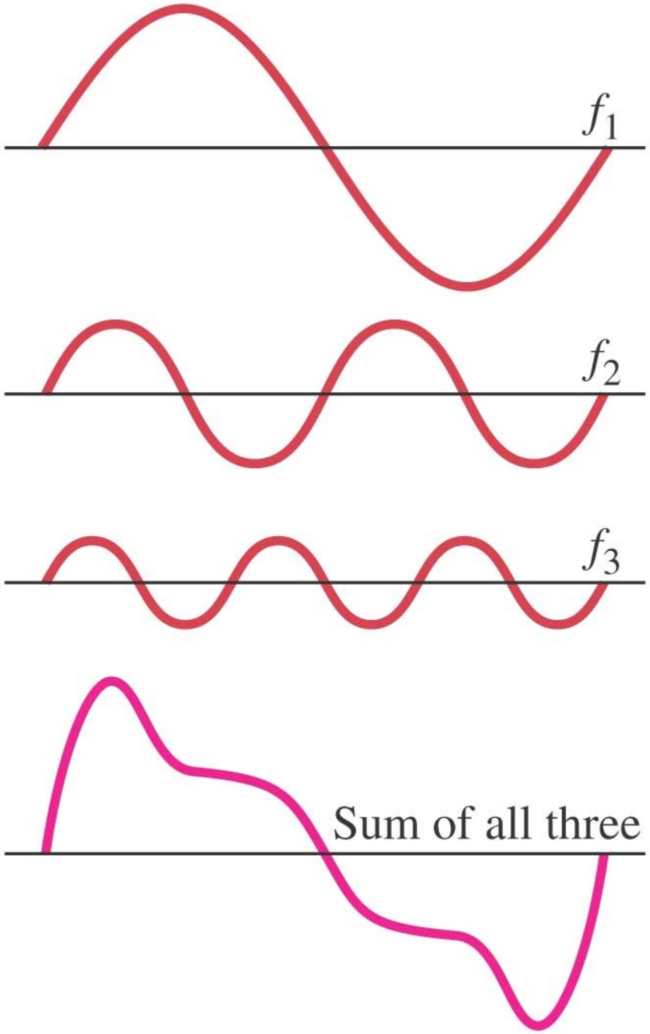
16-5 Quality of Sound, and Noise; Superposition

So why does a trumpet sound different from a flute? The answer lies in **overtones**—which ones are present, and how strong they are, makes a big difference. The sound wave is the superposition of the fundamental and all the harmonics.



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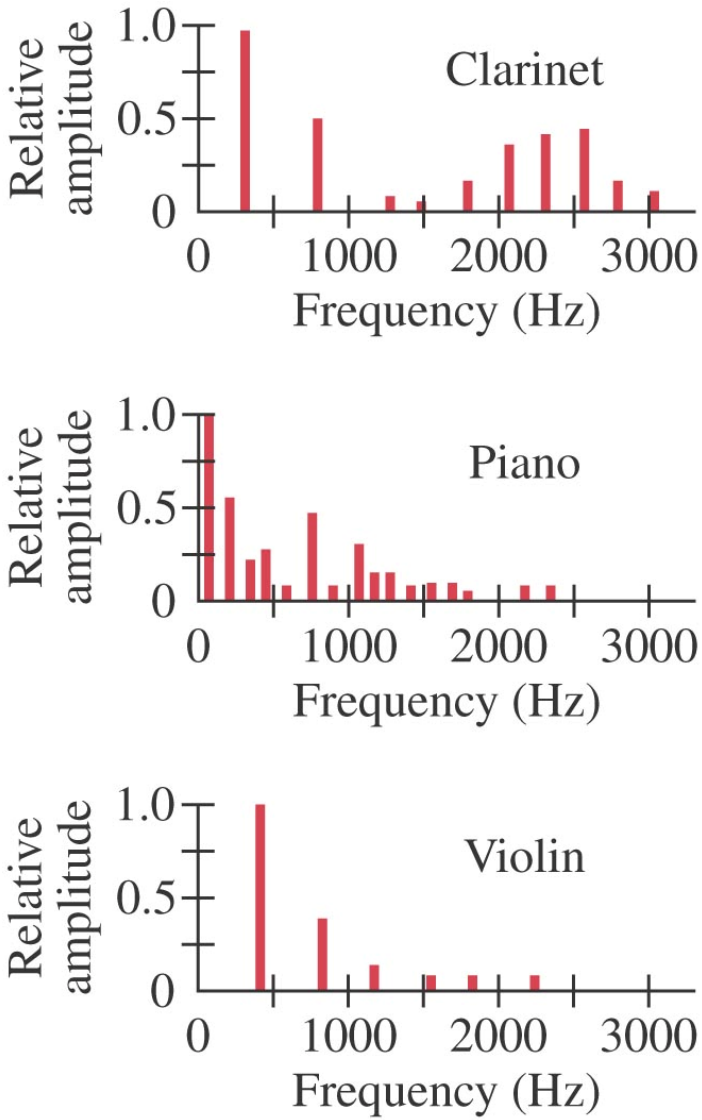
16-5 Quality of Sound, and Noise; Superposition

This plot shows **frequency** spectra for a **clarinet**, a **piano**, and a **violin**. The differences in overtone strength are apparent.



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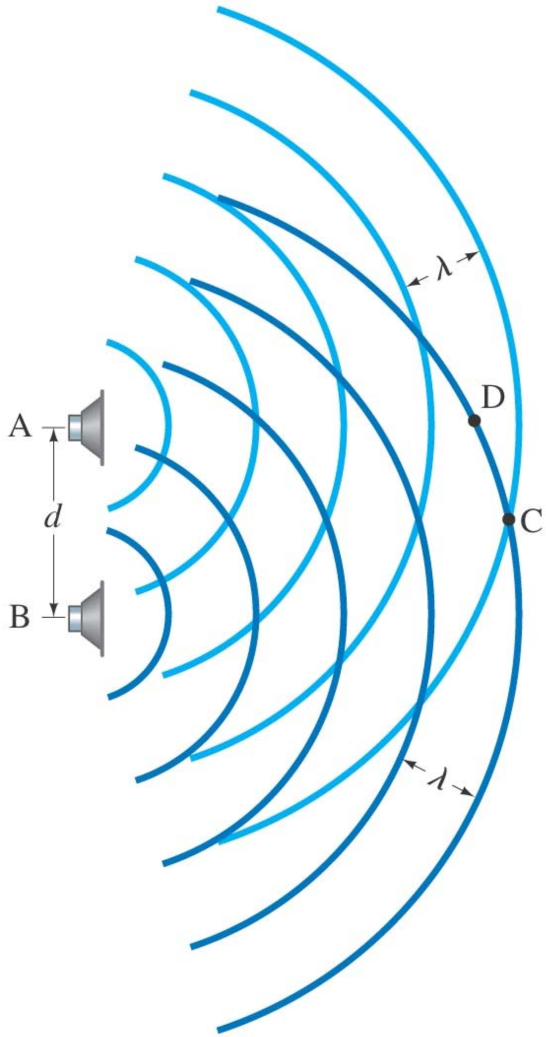
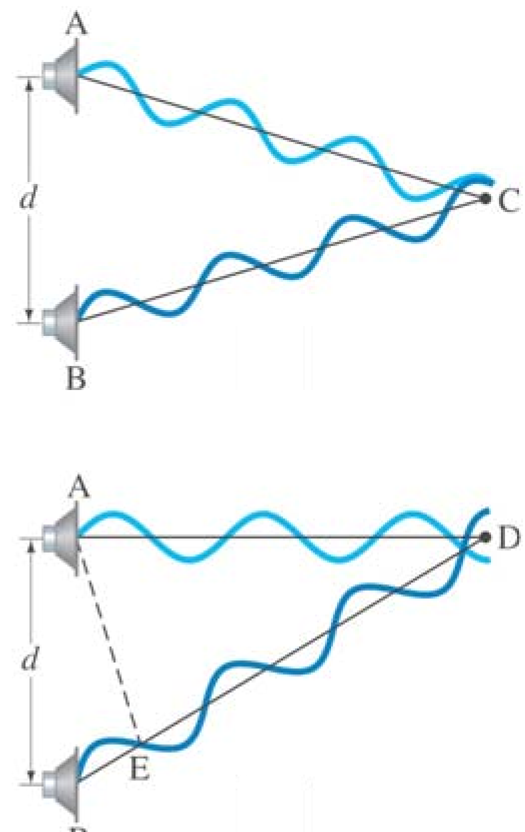
16-6 Interference of Sound Waves; Beats

Sound waves **interfere** in the same way that other waves do in space.





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16-6 Interference of Sound Waves; Beats

Example 16-12: Loudspeakers' interference.

Two loudspeakers are 1.00 m apart. A person stands 4.00 m from one speaker. How far must this person be from the second speaker to detect destructive interference when the speakers emit an 1150-Hz sound? Assume the temperature is 20°C.

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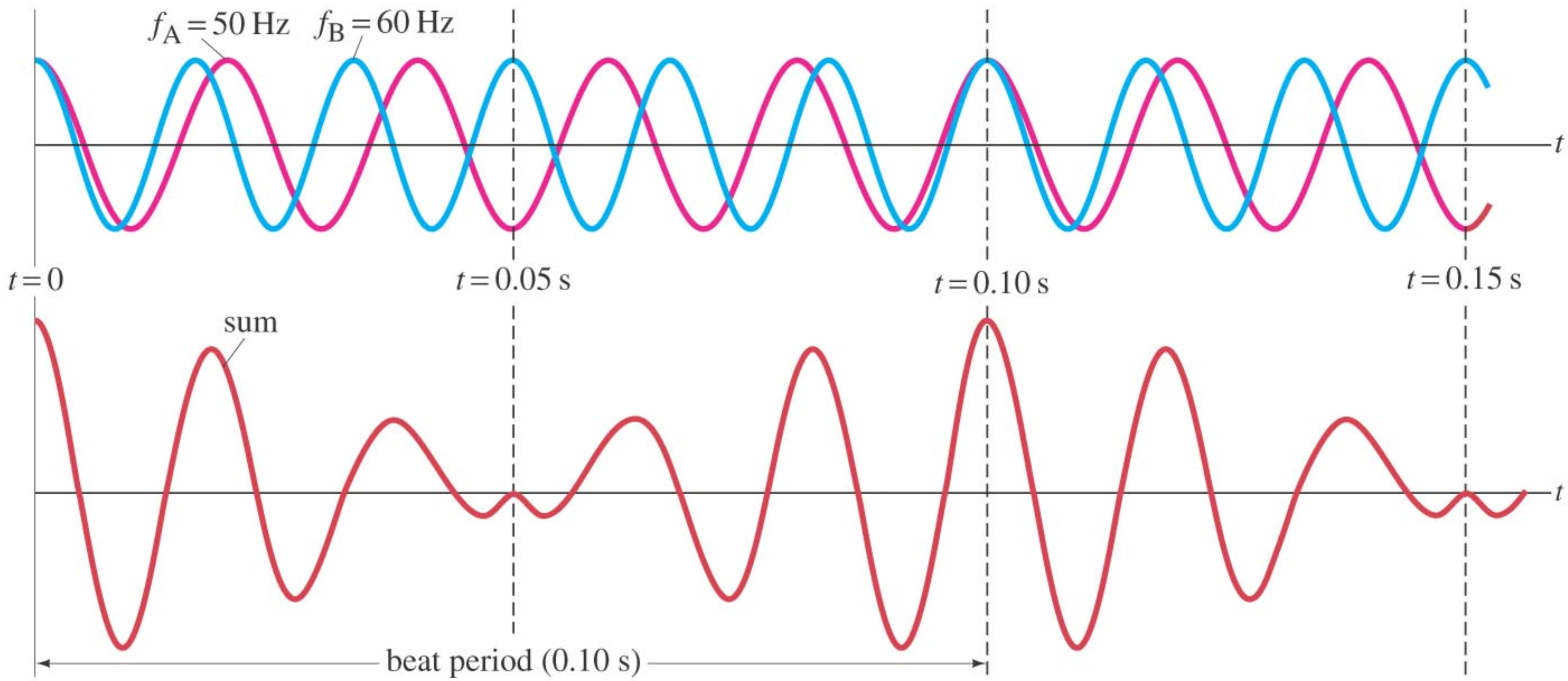
16-6 Interference of Sound Waves; Beats

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.



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16-6 Interference of Sound Waves; Beats

If we consider two waves of the same amplitude and phase, with different frequencies, we can find the beat frequency when we add them:

$$D = \left[2A\cos 2\pi\left(\frac{f_1 - f_2}{2}\right)t\right]\sin 2\pi\left(\frac{f_1 + f_2}{2}\right)t.$$

This represents a wave vibrating at the average frequency, with an “envelope” at the difference of the frequencies.

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16-6 Interference of Sound Waves; Beats

Example 16-13: Beats.

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?

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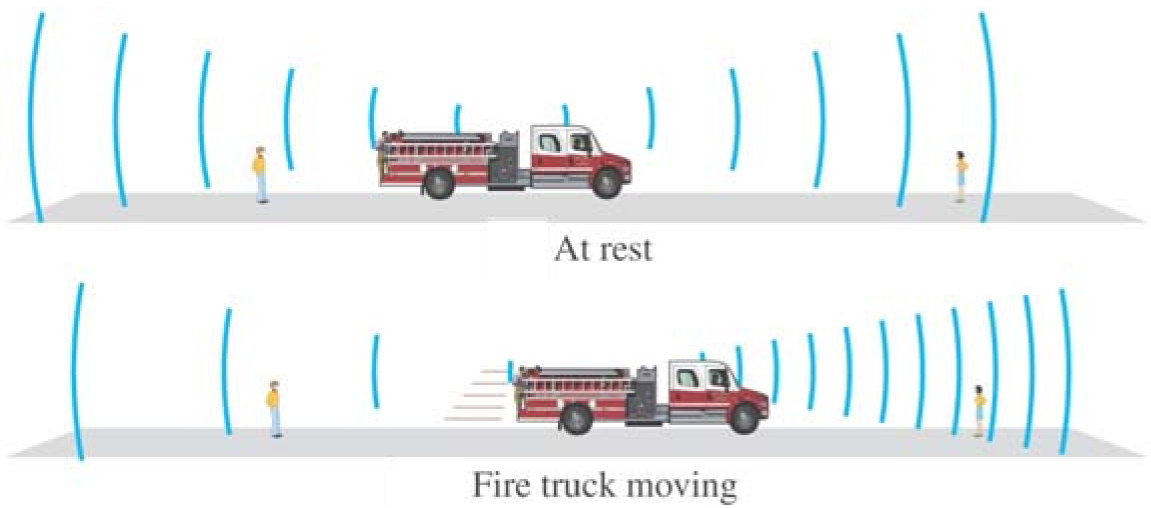
16-7 Doppler Effect

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

A source moving **toward** an observer appears to have a **higher** frequency and **shorter** wavelength; a source moving **away** from an observer appears to have a **lower** frequency and **longer** wavelength.



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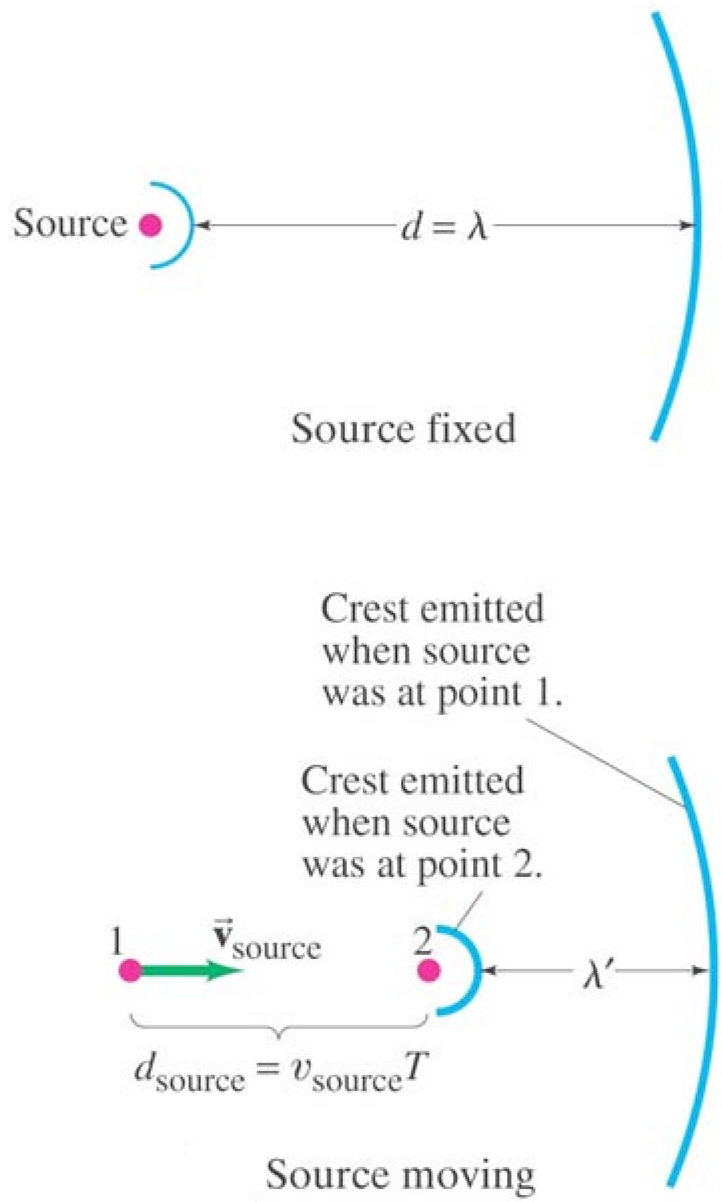
16-7 Doppler Effect



If we can figure out what the **change** in the **wavelength** is, we also know the change in the **frequency**.

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16-7 Doppler Effect

The change in the frequency is given by:

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

If the source is moving away from the observer:

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

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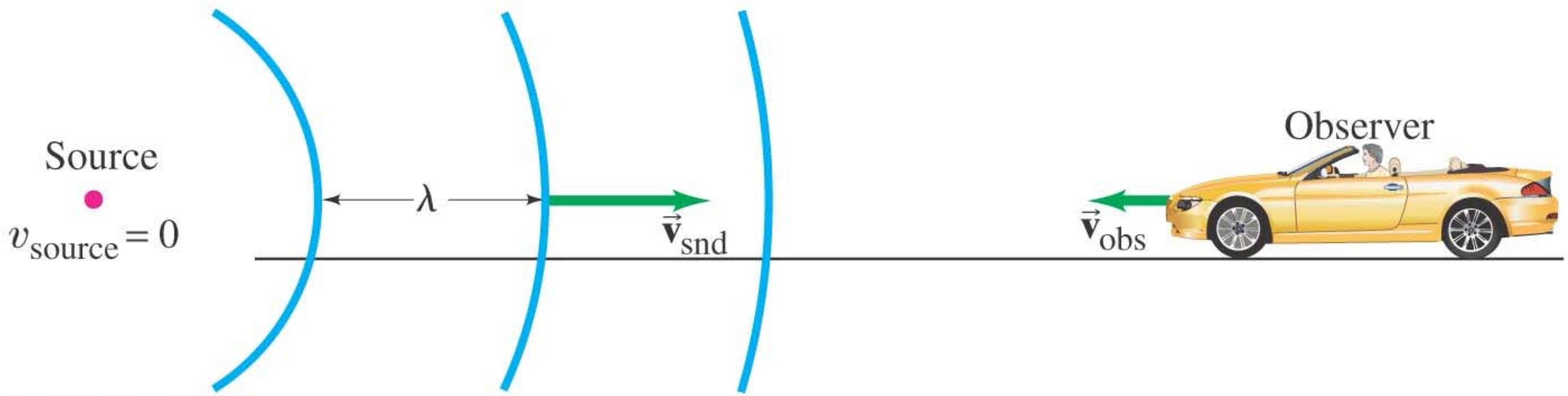
16-7 Doppler Effect

If the **observer** is moving with respect to the source, things are a bit different. The **wavelength** remains the same, but the wave **speed** is different for the observer.



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16-7 Doppler Effect

We find, for an observer moving **toward** a stationary source:

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

And if the observer is moving **away**:

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

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16-7 Doppler Effect

Example 16-14: A moving siren.

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?

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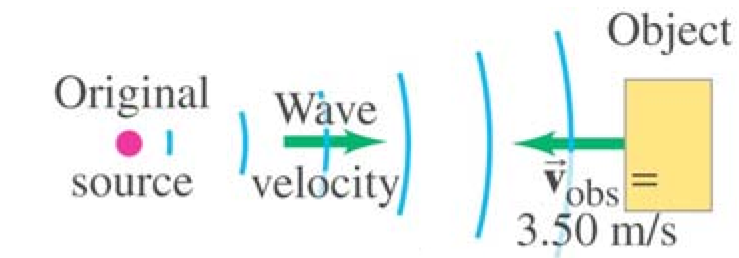
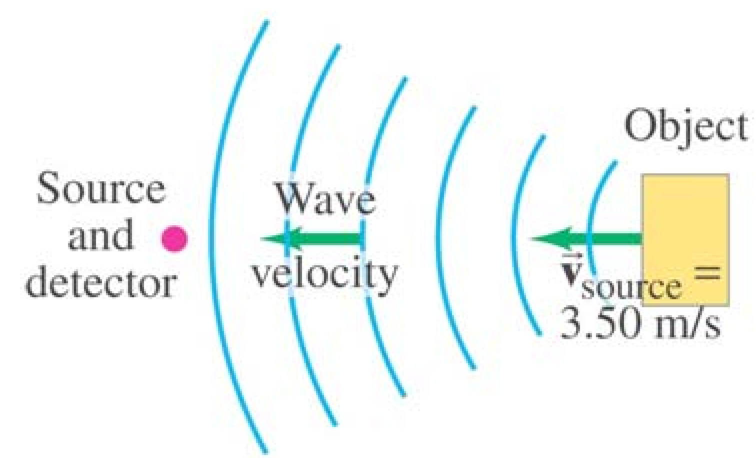
16-7 Doppler Effect

Example 16-15: Two Doppler shifts.

A 5000-Hz sound wave is emitted by a stationary source. This sound wave reflects from an object moving 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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16-7 Doppler Effect

All four equations for the Doppler effect can be combined into one; you just have to keep track of the signs!

$$f' = f\left(\frac{v_{\text{snd}} \pm v_{\text{obs}}}{v_{\text{snd}} \mp v_{\text{source}}}\right).$$

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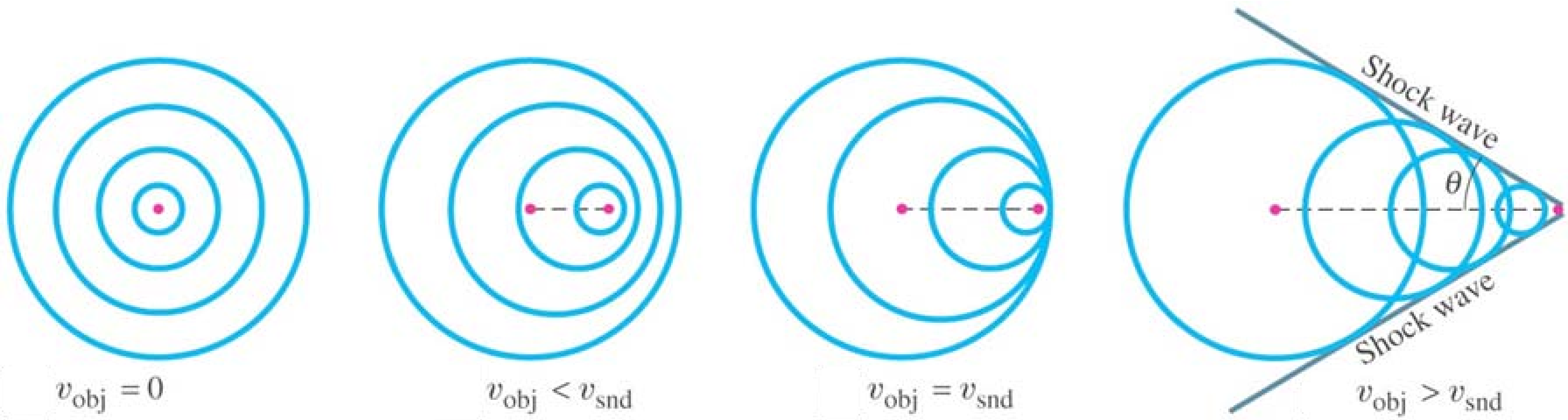
16-8 Shock Waves and the Sonic Boom

If a source is moving **faster** than the **wave speed** in a medium, waves cannot keep up and a **shock wave** is formed.

The angle of the cone is: $$\sin\theta = \frac{v_{\mathrm{snd}}}{v_{\mathrm{obj}}}.$$



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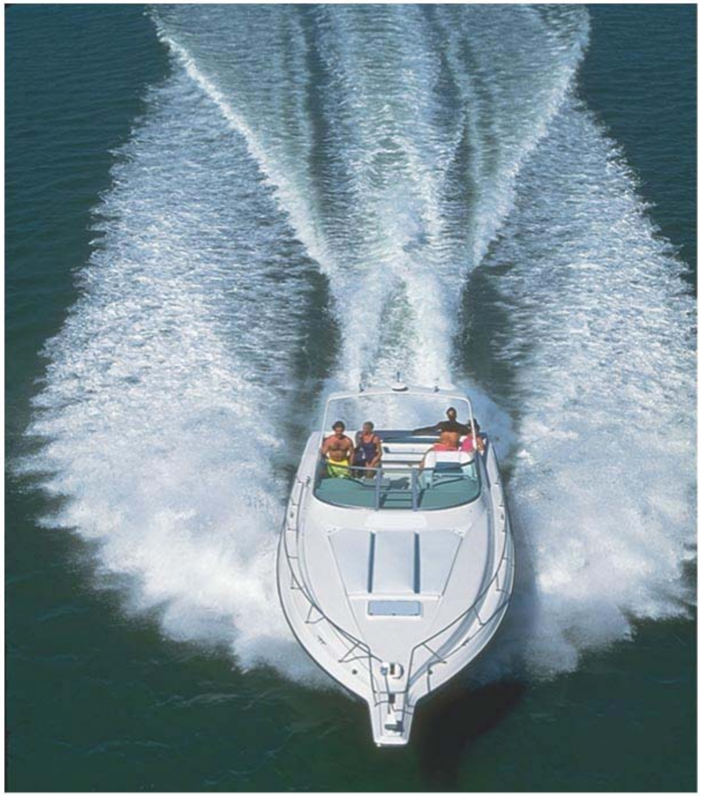
16-8 Shock Waves and the Sonic Boom

Shock waves are analogous to the **bow waves** produced by a boat going faster than the wave speed in water.



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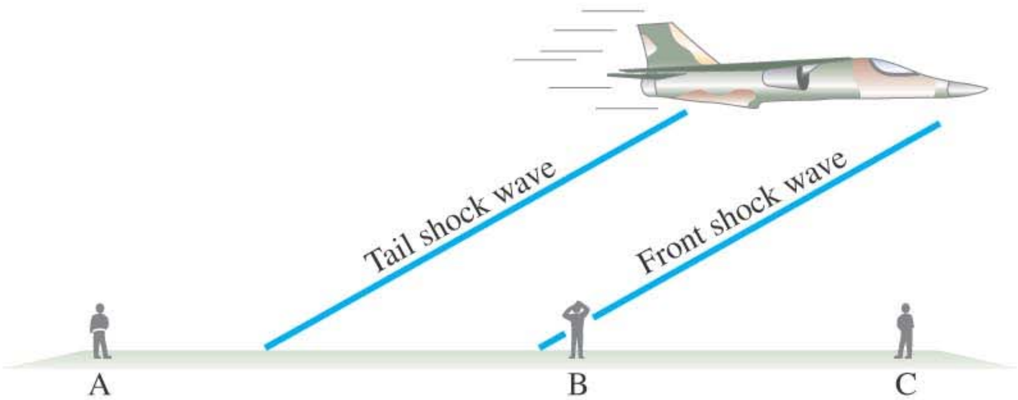
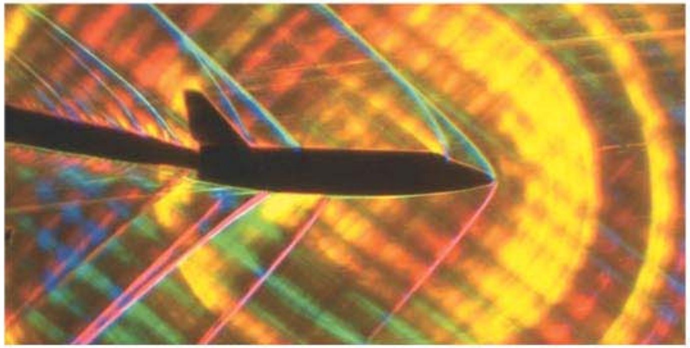
16-8 Shock Waves and the Sonic Boom

Aircraft exceeding the speed of sound in air will produce two **sonic booms**, one from the **front** and one from the **tail**.





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16-9 Applications: Sonar, Ultrasound, and Medical Imaging

Sonar is used to locate objects underwater by measuring the **time** it takes a sound **pulse** to reflect back to the receiver.

Similar techniques can be used to learn about the **internal structure** of the Earth.

Sonar usually uses **ultrasound** waves, as the shorter wavelengths are less likely to be **diffracted** by obstacles.

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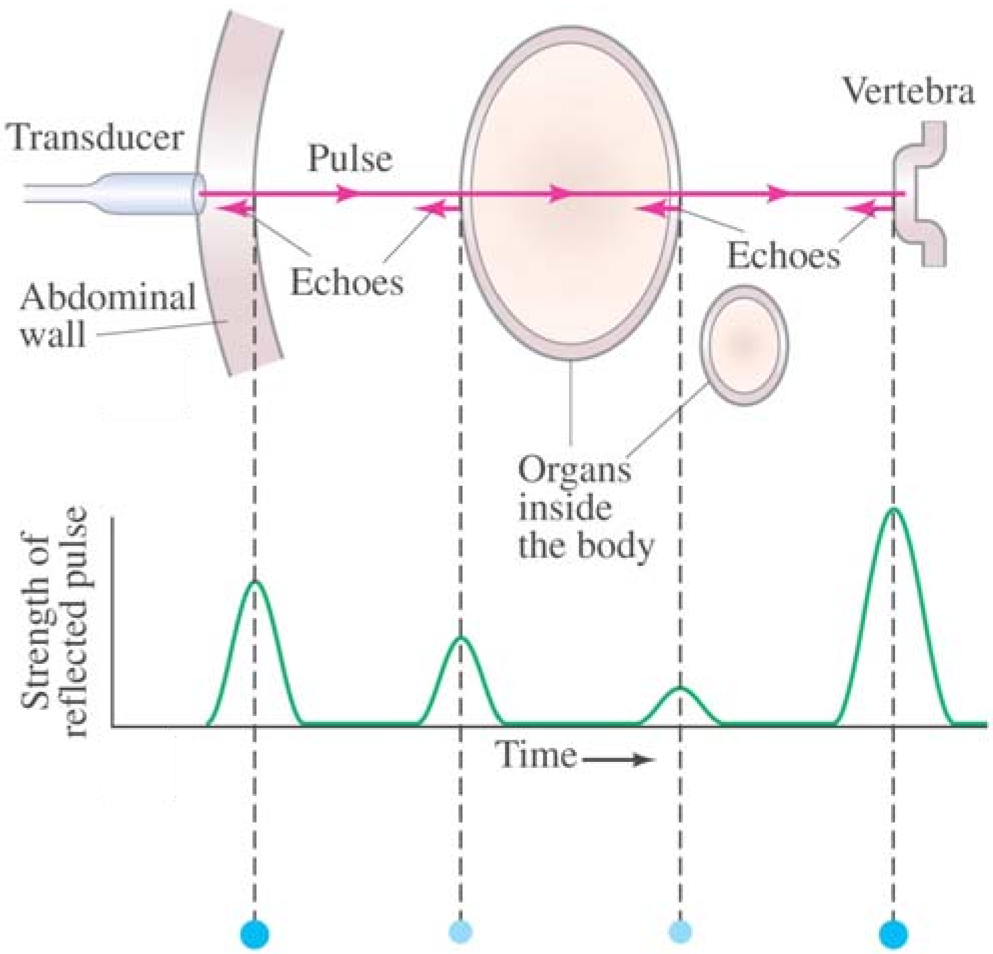
16-9 Applications: Sonar, Ultrasound, and Medical Imaging



Ultrasound is also used for medical imaging. Repeated traces are made as the transducer is moved, and a complete picture is built.

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16-9 Applications: Sonar, Ultrasound, and Medical Imaging

This is an ultrasound image of a human fetus, showing great detail.

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Summary of Chapter 16

- Sound is a longitudinal wave in a medium.
- The pitch of the sound depends on the frequency.
- The loudness of the sound depends on the intensity and also on the sensitivity of the ear.
- The strings on stringed instruments produce a fundamental tone whose wavelength is twice the length of the string; there are also various harmonics present.

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Summary of Chapter 16

- Wind instruments have a vibrating column of air when played. If the tube is open, the fundamental is twice its length; if it is closed, the fundamental is four times the tube length.

- Sound waves exhibit interference; if two sounds are at slightly different frequencies they produce beats.

- The Doppler effect is the shift in frequency of a sound due to motion of the source or the observer.

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