Chapter 17

# Waves - II

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# 17-1 Speed of Sound

## Learning Objectives

**17.01** Distinguish between a longitudinal wave and a transverse wave.

**17.02** Explain wavefronts and rays.

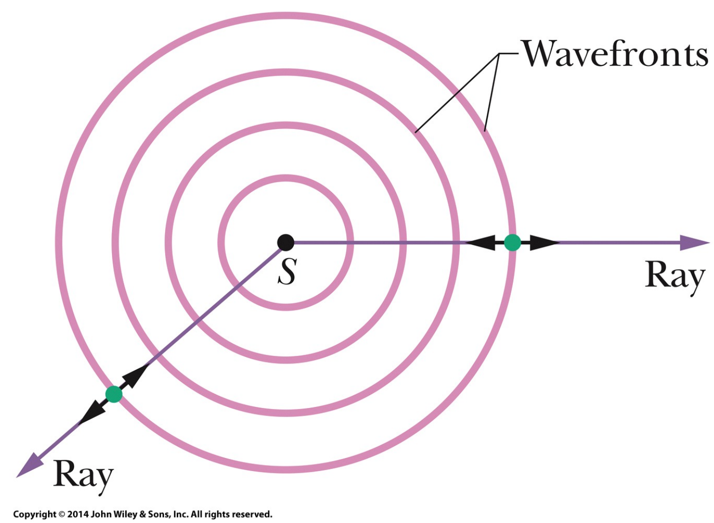
**17.03** Apply the relationship between the speed of sound through a material, the material's bulk modulus, and the material's density.

**17.04** Apply the relationship between the speed of sound, the distance traveled by a sound wave, and the time required to travel that distance.

# 17-1 Speed of Sound

**Sound waves** are longitudinal mechanical waves that can travel through solids, liquids, or gases.

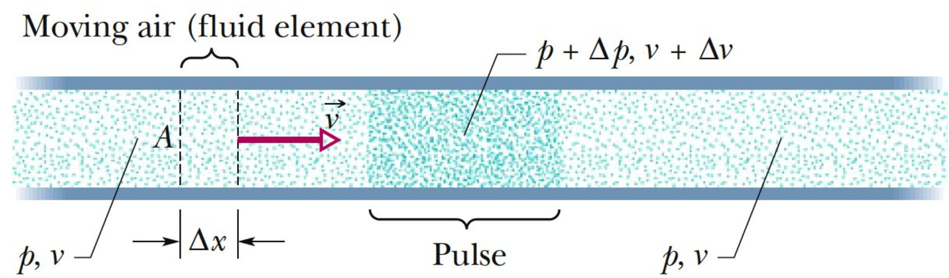
Point S represents a tiny sound source, called a **point source**, that emits sound waves in all directions. A sound wave travels from a point source S through a three-dimensional medium. The **wavefronts (**surfaces over which the oscillations due to the sound wave have the same value) form spheres centered on S; the **rays** are radial to S. The short, double-headed arrows indicate that elements of the medium oscillate parallel to the rays.



# 17-1 Speed of Sound

The speed *v* of a sound wave in a medium having bulk modulus *B* and density *ρ* is

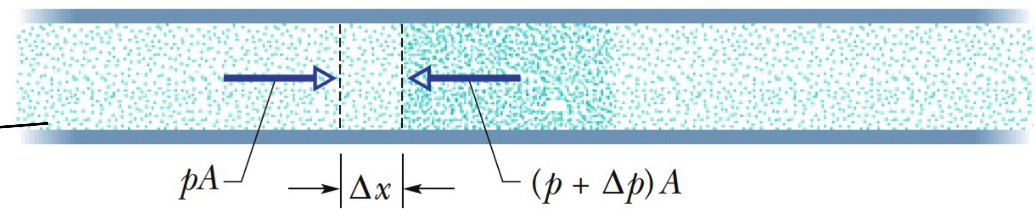
$$v = \sqrt{\frac{B}{\rho}} \qquad \text{(speed of sound)}$$






An element of air of width *Δx* moves toward the pulse with speed *v*.

Through direct application of Newton's Second law.






The leading face of the element enters the pulse. The forces acting on the leading and trailing faces (due to air pressure) are shown.

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# 17-2 Traveling Sound Waves

## Learning Objectives

**17.05** For any particular time and position, calculate the displacement *s(x,t)* of an element of air as a sound wave travels through its location.

**17.06** Given a displacement function *s(x,t)* for a sound wave, calculate the time between two given displacements.

**17.07** Apply the relationships between wave speed *v*, angular frequency *ω*, angular wave number *k*, wavelength *λ*, period *T*, and frequency *f*.

**17.08** Sketch a graph of the displacement *s(x)* of an element of air as a function of position, and identify the amplitude $s_m$ and wavelength *λ*.

**17.09** For any particular time and position, calculate the pressure variation *Δp* (variation from atmospheric pressure) of an element of air as a sound wave travels through its location.

# 17-2 Traveling Sound Waves

## Learning Objectives (Continued)

**17.10** Sketch a graph of the pressure variation $\Delta p(x)$ of an element as a function of position, and identify the amplitude $\Delta p_m$ and wavelength $\lambda$.

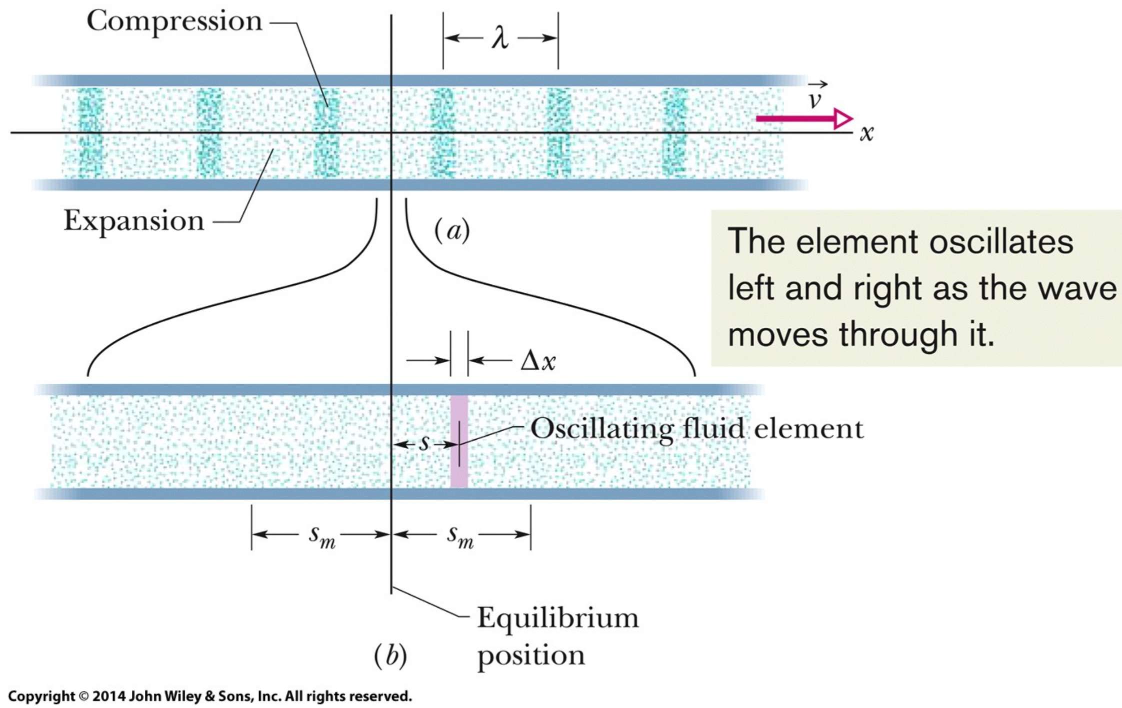
**17.11** Apply the relationship between pressure-variation amplitude $\Delta p_m$ and displacement amplitude $s_m$.

**17.12** Given a graph of position $s$ versus time for a sound wave, determine the amplitude $s_m$ and the period $T$.

**17.13** Given a graph of pressure variation $\Delta p$ versus time for a sound wave, determine the amplitude $\Delta p_m$ and the period $T$.

# 17-2 Traveling Sound Waves

(a) A sound wave, traveling through a long air-filled tube with speed *v*, consists of a moving, periodic pattern of expansions and compressions of the air. The wave is shown at an arbitrary instant.




(b) A horizontally expanded view of a short piece of the tube. As the wave passes, an air element of thickness $\Delta x$ oscillates left and right in simple harmonic motion about its equilibrium position. At the instant shown in (b), the element happens to be displaced a distance $s$ to the right of its equilibrium position. Its maximum displacement, either right or left, is $s_m$.

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# 17-2 Traveling Sound Waves

**Displacement**: A sound wave causes a longitudinal displacement s of a mass element in a medium as given by

$$s(x, t) = s_m \cos(kx - \omega t).$$

where $s_m$ is the displacement amplitude (maximum displacement) from equilibrium, $k = 2\pi/\lambda$, and $\omega = 2\pi f$, $\lambda$ and $f$ being the wavelength and frequency, respectively, of the sound wave.

**Pressure**: The sound wave also causes a pressure change $\Delta p$ of the medium from the equilibrium pressure:

$$\Delta p(x, t) = \Delta p_m \sin(kx - \omega t).$$

where the pressure amplitude is

$$\Delta p_m = (v\rho\omega)s_m.$$

# 17-3 Interference

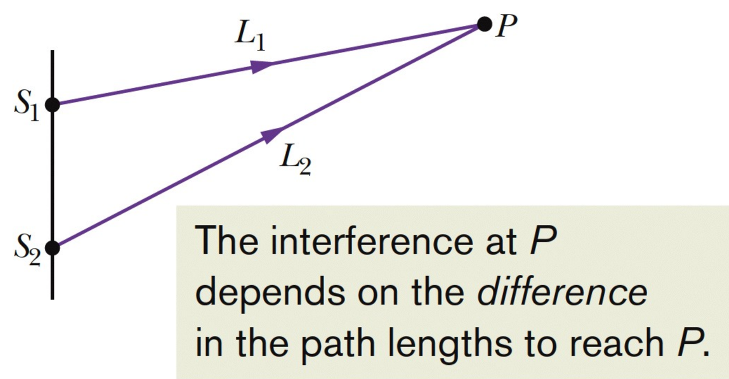
## Learning Objectives

**17.14** If two waves with the same wavelength begin in phase but reach a common point by traveling along different paths, calculate their phase difference $\Phi$ at that point by relating the path length difference $\Delta L$ to the wavelength $\lambda$.

**17.15** Given the phase difference between two sound waves with the same amplitude, wavelength, and travel direction, determine the type of interference between the waves (fully destructive interference, fully constructive interference, or indeterminate interference).

**17.16** Convert a phase difference between radians, degrees, and number of wavelengths.

# 17-3 Interference

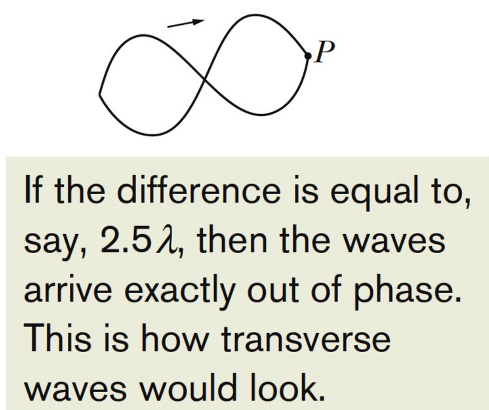





Two point sources $S_1$ and $S_2$ emit spherical sound waves in phase. The rays indicate that the waves pass through a common point *P*. The waves (represented with transverse waves) arrive at *P*.

## Fully Destructive Interference

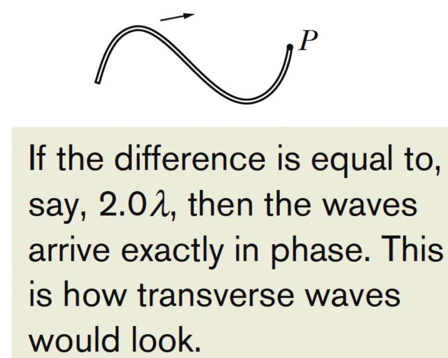
(exactly out of phase)






## Fully Constructive Interference

(exactly in phase)



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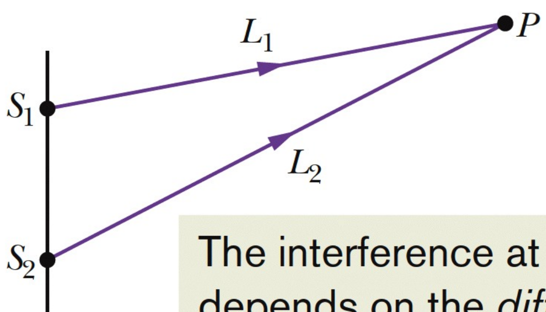
# 17-3 Interference

## Path Length Difference




The interference at *P* depends on the *difference* in the path lengths to reach *P*.



- The interference of two sound waves with identical wavelengths passing through a common point depends on their phase difference there $\phi$ . If the sound waves were emitted in phase and are traveling in approximately the same direction, $\phi$ is given by

$$\phi = \frac{\Delta L}{\lambda} 2\pi.$$

where $\Delta L$ is their **path length difference**.

## 17-3 Interference

- **Fully constructive interference** occurs when $\phi$ is an integer and multiple of $2\pi$,

$$\phi = m(2\pi), \qquad \text{for } m = 0, 1, 2, \ldots,$$

and, equivalently, when $\Delta L$ is related to wavelength $\lambda$ by

$$\frac{\Delta L}{\lambda} = 0, 1, 2, \ldots \quad \text{(fully constructive interference).}$$

- **Fully destructive interference** occurs when $\phi$ is an odd multiple of $\pi$,

$$\phi = (2m + 1)\pi, \qquad \text{for } m = 0, 1, 2, \ldots,$$

and, equivalently, when $\Delta L$ is related to wavelength $\lambda$ by

$$\frac{\Delta L}{\lambda} = 0.5, 1.5, 2.5, \ldots \quad \text{(fully destructive interference).}$$

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# 17-4 Intensity And Sound Level

## Learning Objectives

**17.17** Calculate the sound intensity $I$ at a surface as the ratio of the power $P$ to the surface area $A$.

**17.18** Apply the relationship between the sound intensity $I$ and the displacement amplitude $s_m$ of the sound wave.

**17.19** Identify an isotropic point source of sound.

**17.20** For an isotropic point source, apply the relationship involving the emitting power $P_s$, the distance $r$ to a detector, and the sound intensity $I$ at the detector.

**17.21** Apply the relationship between the sound level $\beta$, the sound intensity $I$, and the standard reference intensity $I_0$.

**17.22** Evaluate a logarithm function (log) and an antilogarithm function ($\log^{-1}$).

**17.23** Relate the change in a sound level to the change in sound intensity.

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# 17-4 Intensity And Sound Level

- The **intensity** $I$ of a sound wave at a surface is the average rate per unit area at which energy is transferred by the wave through or onto the surface

$$I = \frac{P}{A},$$

where $P$ is the time rate of energy transfer (**power**) of the sound wave and $A$ is the area of the surface intercepting the sound. The intensity $I$ is related to the displacement amplitude $s_m$ of the sound wave by

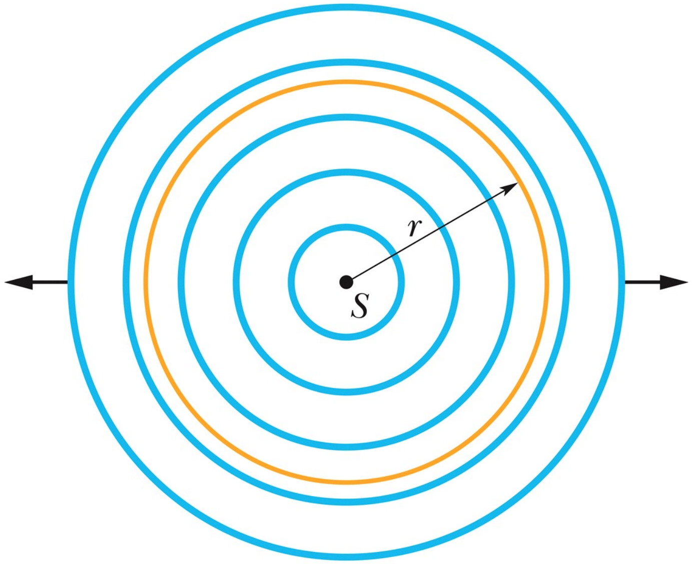
$$I = \tfrac{1}{2}\rho v \omega^2 s_m^2.$$

# 17-4 Intensity And Sound Level

- The intensity at a distance *r* from a point source that emits sound waves of power $P_s$ equally in all directions isotropically i.e. with equal intensity in all directions,

$$I = \frac{P_s}{4\pi r^2},$$

where $4\pi r^2$ is the area of the sphere.





A point source S emits sound waves uniformly in all directions. The waves pass through an imaginary sphere of radius *r* that is centered on *S*.

## The Decibel Scale

- The sound level $\beta$ in decibels (dB) is defined as

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

where $I_0$ (= $10^{-12}$ W/m$^2$) is a reference intensity level to which all intensities are compared. For every factor-of-10 increase in intensity, 10 dB is added to the sound level.

**Table 17-2** Some Sound Levels (dB)

| | |
|---|---|
| Hearing threshold | 0 |
| Rustle of leaves | 10 |
| Conversation | 60 |
| Rock concert | 110 |
| Pain threshold | 120 |
| Jet engine | 130 |



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Sound can cause the wall of a drinking glass to oscillate. If the sound produces a standing wave of oscillations and if the intensity of the sound is large enough, the glass will shatter.

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# 17-5 Sources of Musical Sound

## Learning Objectives

**17.24** Using standing wave patterns for string waves, sketch the standing wave patterns for the first several acoustical harmonics of a pipe with only one open end and with two open ends.

**17.25** For a standing wave of sound, relate the distance between nodes and the wavelength.

**17.26** Identify which type of pipe has even harmonics.

**17.27** For any given harmonic and for a pipe with only one open end or with two open ends, apply the relationships between the pipe length *L*, the speed of sound *v*, the wavelength *λ*, the harmonic frequency *f*, and the harmonic number *n*.

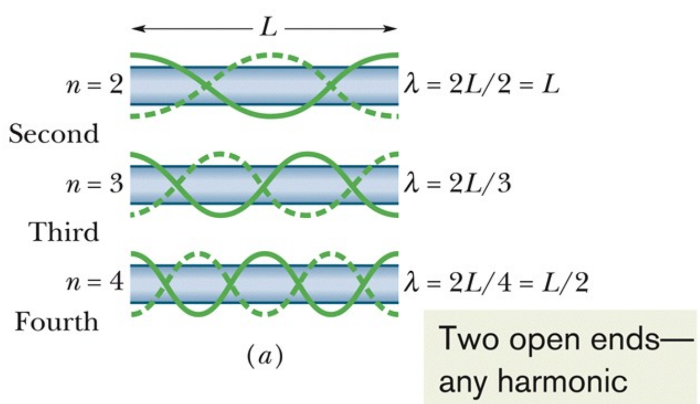
# 17-5 Sources of Musical Sound

Standing sound wave patterns can be set up in pipes (that is, resonance can be set up) if sound of the proper wave- length is introduced in the pipe.

**Two Open Ends.**

A pipe open at both ends will resonate at frequencies

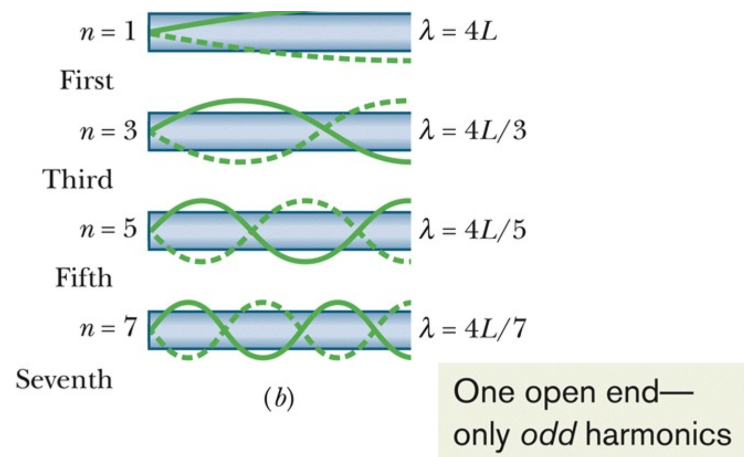
$$f = \frac{v}{\lambda} = \frac{nv}{2L}, \qquad n = 1, 2, 3, \ldots,$$




**One Open End.**

A pipe closed at one end and open at the other will resonate at frequencies

$$f = \frac{v}{\lambda} = \frac{nv}{4L}, \qquad n = 1, 3, 5, \ldots.$$



# 17-6 Beats

## Learning Objectives

**17.28** Explain how beats are produced.

**17.29** Add the displacement equations for two sound waves of the same amplitude and slightly different angular frequencies to find the displacement equation of the resultant wave and identify the time-varying amplitude.

**17.30** Apply the relationship between the beat frequency and the frequencies of two sound waves that have the same amplitude when the frequencies (or, equivalently, the angular frequencies) differ by a small amount.

# 17-6 Beats

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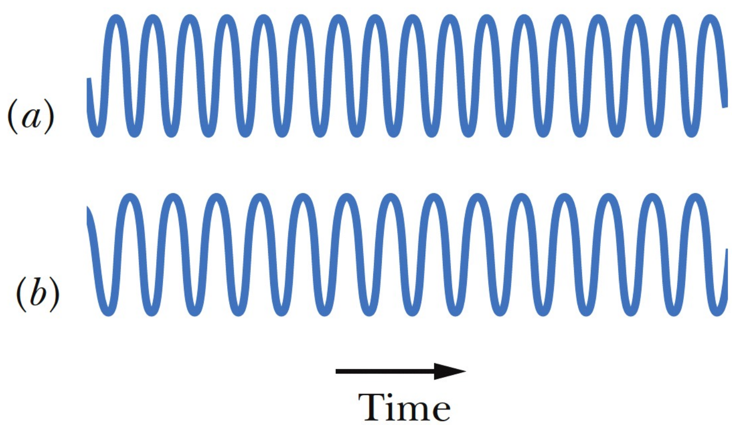
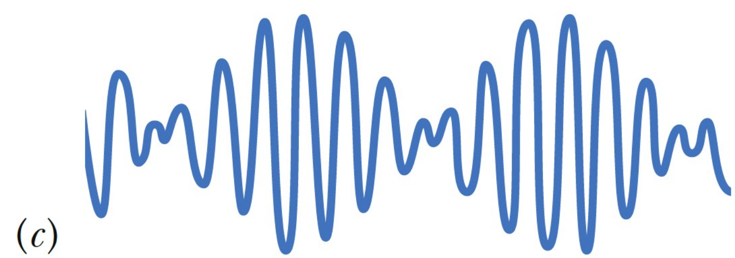
Beats arise when two waves having slightly different frequencies, $f_1$ and $f_2$, are detected together. The beat frequency is

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






(a,b) The pressure variations $\Delta p$ of two sound waves as they would be detected separately. The frequencies of the waves are nearly equal.






(c) The resultant pressure variation if the two waves are detected simultaneously.

# 17-7 The Doppler Effect

## Learning Objectives

**17.31** Identify that the Doppler effect is the shift in the detected frequency from the frequency emitted by a sound source due to the relative motion between the source and the detector.

**17.32** Identify that in calculating the Doppler shift in sound, the speeds are measured relative to the medium (such as air or water), which may be moving.

**17.33** Calculate the shift in sound frequency for (a) a source moving either directly toward or away from a stationary detector, (b) a detector moving either directly toward or away from a stationary source, and (c) both source and detector moving either directly toward each other or directly away from each other.

**17.34** Identify that for relative motion between a sound source and a sound detector, motion *toward* tends to shift the frequency up and motion *away* tends to shift it down.

# 17-7 The Doppler Effect

The Doppler effect is a change in the observed frequency of a wave when the source or the detector moves relative to the transmitting medium (such as air). For sound, the observed frequency $f'$ is given in terms of the source frequency $f$ by

$$f' = f\frac{v \pm v_D}{v \pm v_S} \quad \text{(general Doppler effect)},$$

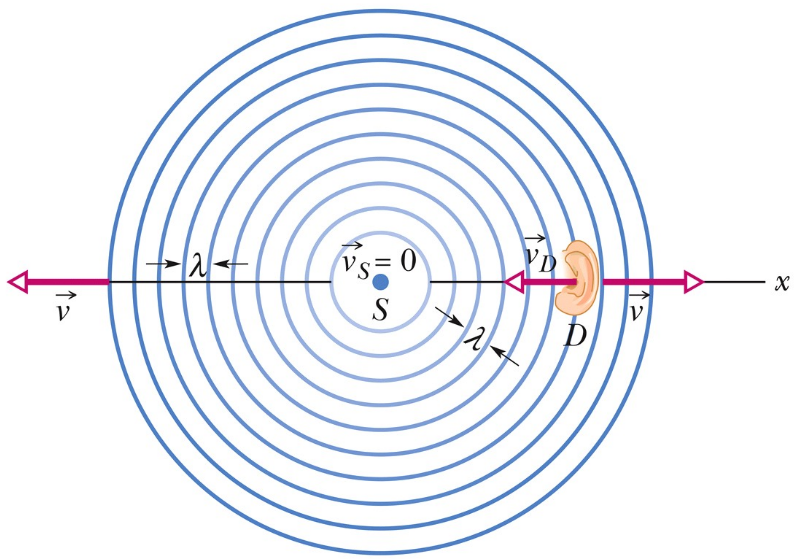
where $v$ is the speed of sound through the air, $v_D$ is the detector's speed relative to the air, and $v_S$ is the source's speed relative to the air.

In the numerator, the plus sign applies when the detector moves toward the source and the minus sign applies when the detector moves away from the source.

In the denominator the minus sign is used when the source moves toward the detector, the plus sign applies when the source moves away from the detector.

## Detector Moving Source Stationary

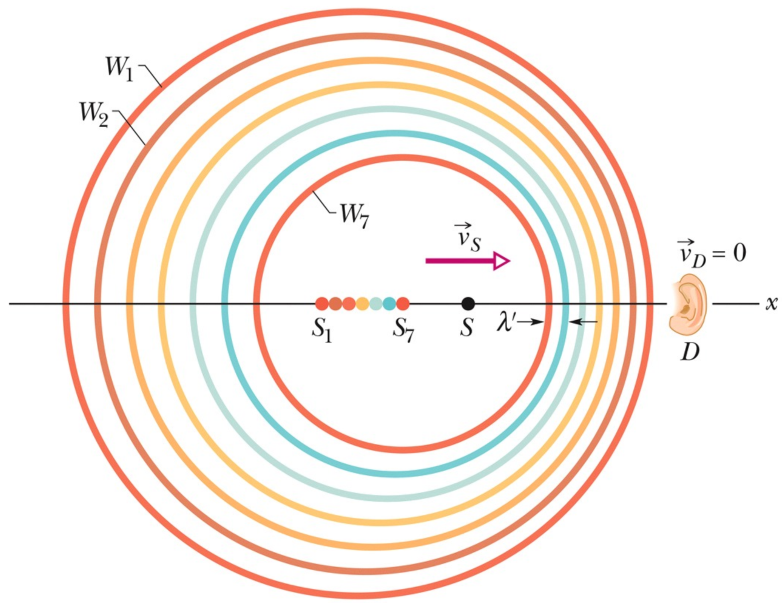
Shift up: The detector moves *toward* the source.






## Source Moving Detector Stationary

Shift up: The source moves *toward* the detector.



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# 17-8 Supersonic Speeds, Shock Waves

## Learning Objectives

**17.35** Sketch the bunching of wavefronts for a sound source traveling at the speed of sound or faster.

**17.36** Calculate the Mach number for a sound source exceeding the speed of sound.

**7.37** For a sound source exceeding the speed of sound, apply the relationship between the Mach cone angle, the speed of sound, and the speed of the source.

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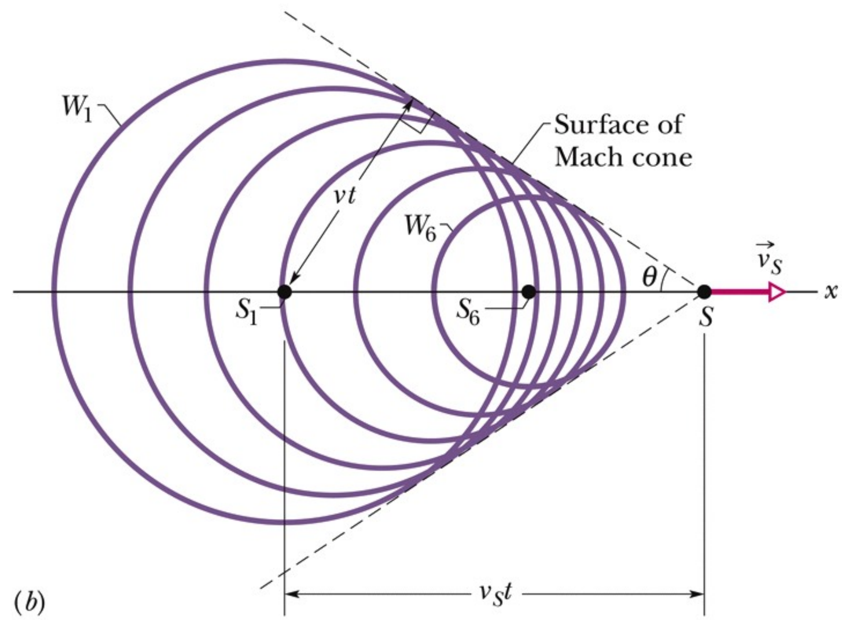
# 17-8 Supersonic Speeds, Shock Waves

If the speed of a source relative to the medium exceeds the speed of sound in the medium, the Doppler equation no longer applies. In such a case, shock waves result. The half-angle $\theta$ of the Mach cone is given by

$$\sin\theta = \frac{vt}{v_S t} = \frac{v}{v_S} \quad \text{(Mach cone angle).}$$

A source $S$ moves at speed $v_S$ faster than the speed of sound and thus faster than the wavefronts. When the source was at position $S_1$ it generated wavefront $W_1$, and at position $S_6$ it generated $W_6$. All the spherical wavefronts expand at the speed of sound $v$ and bunch along the surface of a cone called the Mach cone, forming a shock wave. The surface of the cone has half-angle $\theta$ and is tangent to all the wavefronts.



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# 17 Summary

## Sound Waves

- Speed of sound waves in a medium having bulk modulus and density

$$v = \sqrt{\frac{B}{\rho}}$$ **Eq. (17-3)**

## Interference

- If the sound waves were emitted in phase and are traveling in approximately the same direction, $\phi$ is given by

$$\phi = \frac{\Delta L}{\lambda} 2\pi,$$ **Eq. (17-21)**

## Sound Intensity

- The intensity at a distance r from a point source that emits sound waves of power Ps is

$$I = \frac{P_s}{4\pi r^2}.$$ **Eq. (17-28)**

## Sound Level in Decibel

- The sound level b in decibels (dB) is defined

$$\beta = (10\text{ dB}) \log \frac{I}{I_0},$$ **q. (17-29)**

where $I_0$ (= $10^{-12}$ W/m$^2$) is a reference intensity

# 17 Summary

## Standing Waves in Pipes

- A pipe open at both ends

$$f = \frac{v}{\lambda} = \frac{nv}{2L}, \qquad n = 1, 2, 3, \ldots, \quad \textbf{Eq. (17-39)}$$

- A pipe closed at one end and open at the other

$$f = \frac{v}{\lambda} = \frac{nv}{4L}, \qquad n = 1, 3, 5, \ldots. \quad \textbf{Eq. (17-41)}$$

## The Doppler Effect

- For sound the observed frequency $f'$ is given in terms of the source frequency $f$ by

$$f' = f\frac{v \pm v_D}{v \pm v_S} \qquad \textbf{Eq. (17-47)}$$

## Sound Intensity

- The half-angle $\theta$ of the Mach cone is given by

$$\sin\theta = \frac{v}{v_S} \qquad \textbf{Eq. (17-57)}$$