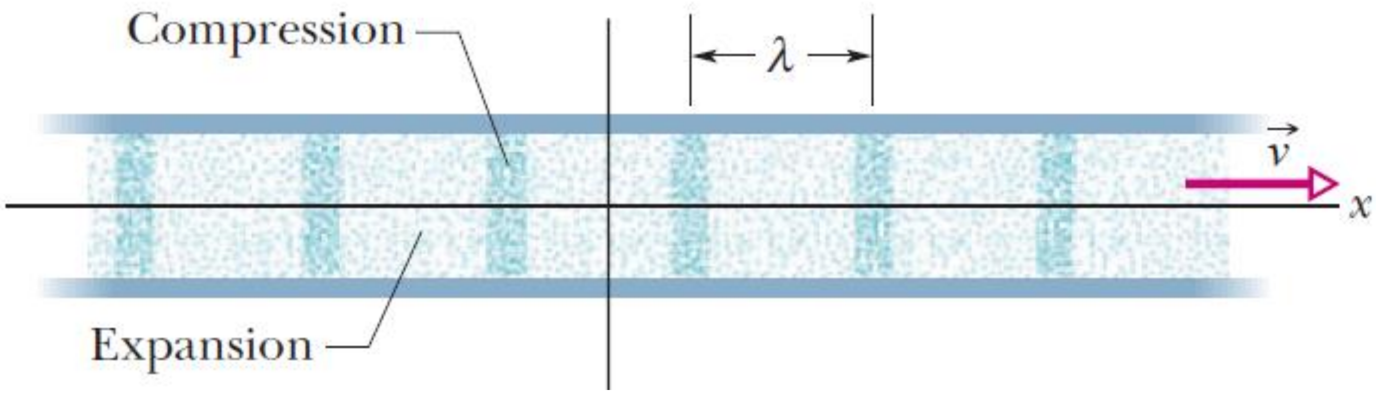
PHYS1001B College Physics IB

Waves II — Sound and Hearing (Ch. 16)

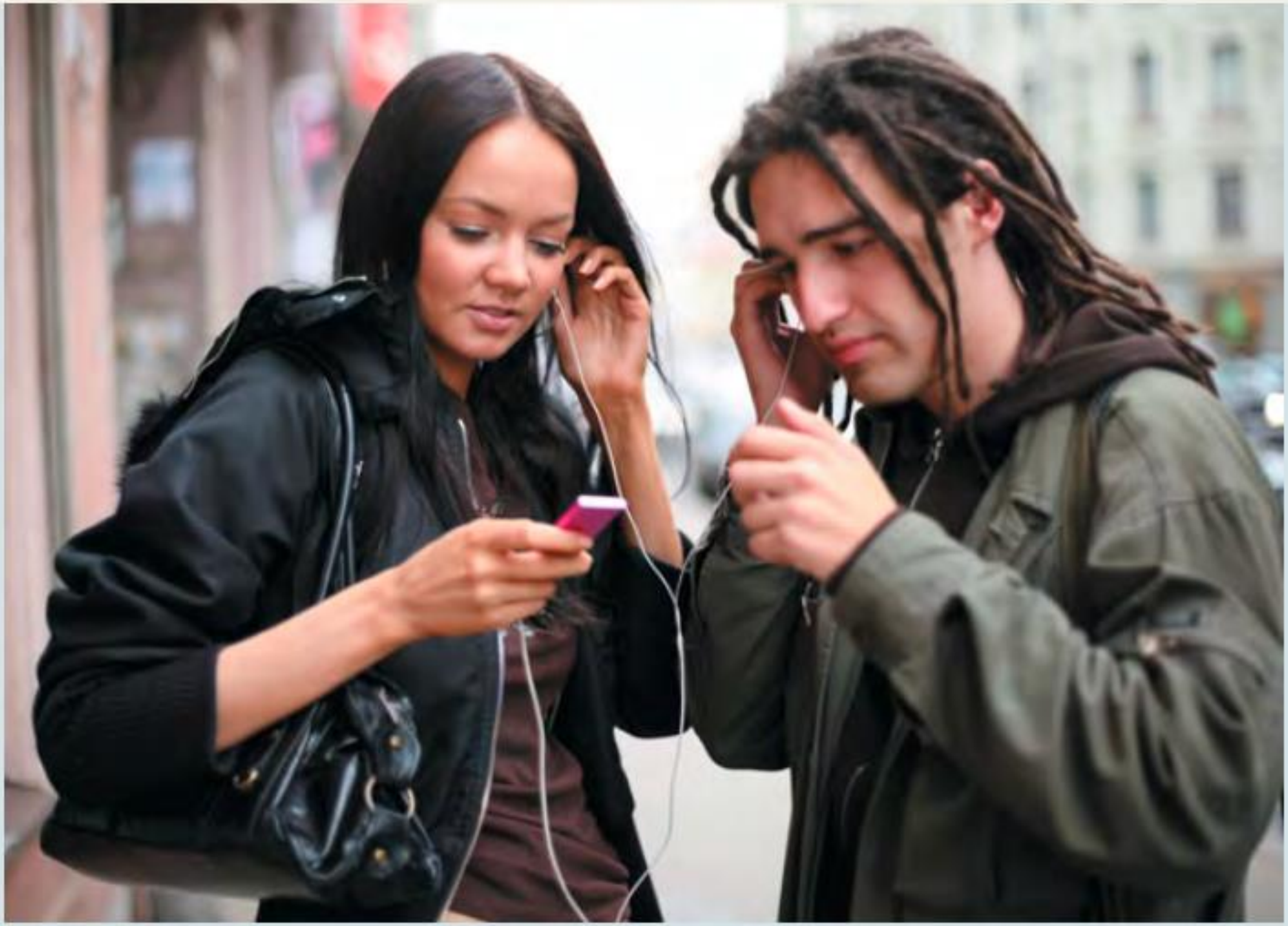
Introduction

- This chapter focuses on sound waves which are *longitudinal waves* involving oscillations parallel to the direction of wave travel



- Similar to string waves, we will study their *interference* and *resonance*

- *Doppler effect* follows



Most people like to listen to music, but hardly anyone likes to listen to noise. What is the physical difference between musical sound and noise?

Outline

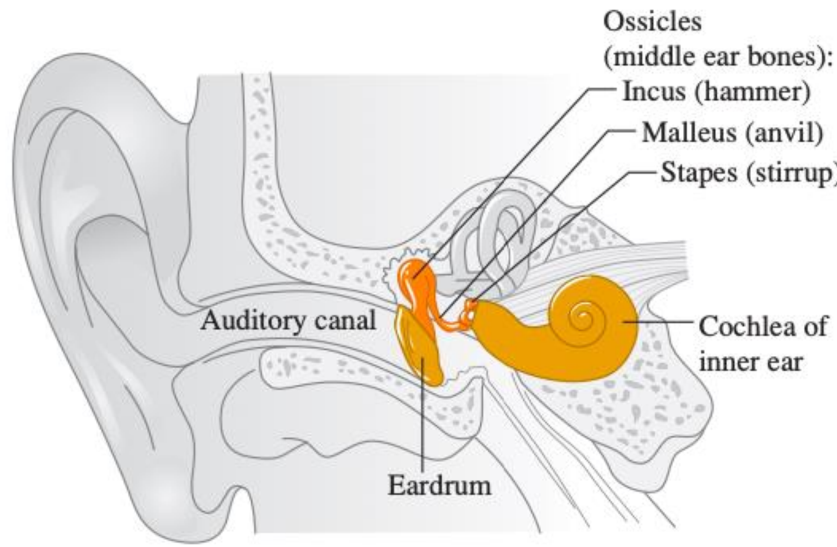
- 16-1 Sound Waves
- 16-2 Speed of Sound Waves
- 16-3 Sound Intensity
- 16-4 Standing Sound Waves and Normal Modes
- 16-6 Interference of Waves
- 16-7 Beats
- 16-8 The Doppler Effect
- 16-9 Shock Waves

16-1 Sound Waves

Sound waves usually travel out in all directions from the source of sound, with an amplitude that depends on the direction and distance from the source

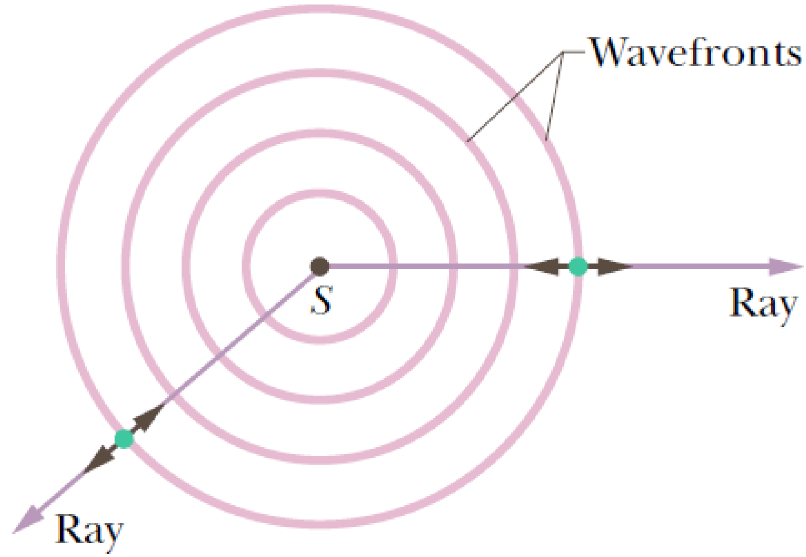
The human ear is sensitive to waves in the frequency range from about 20 to 20,000 Hz, called the **audible range**

“sound” for similar waves with frequencies above **(ultrasonic)** and below **(infrasonic)** the range of human hearing.



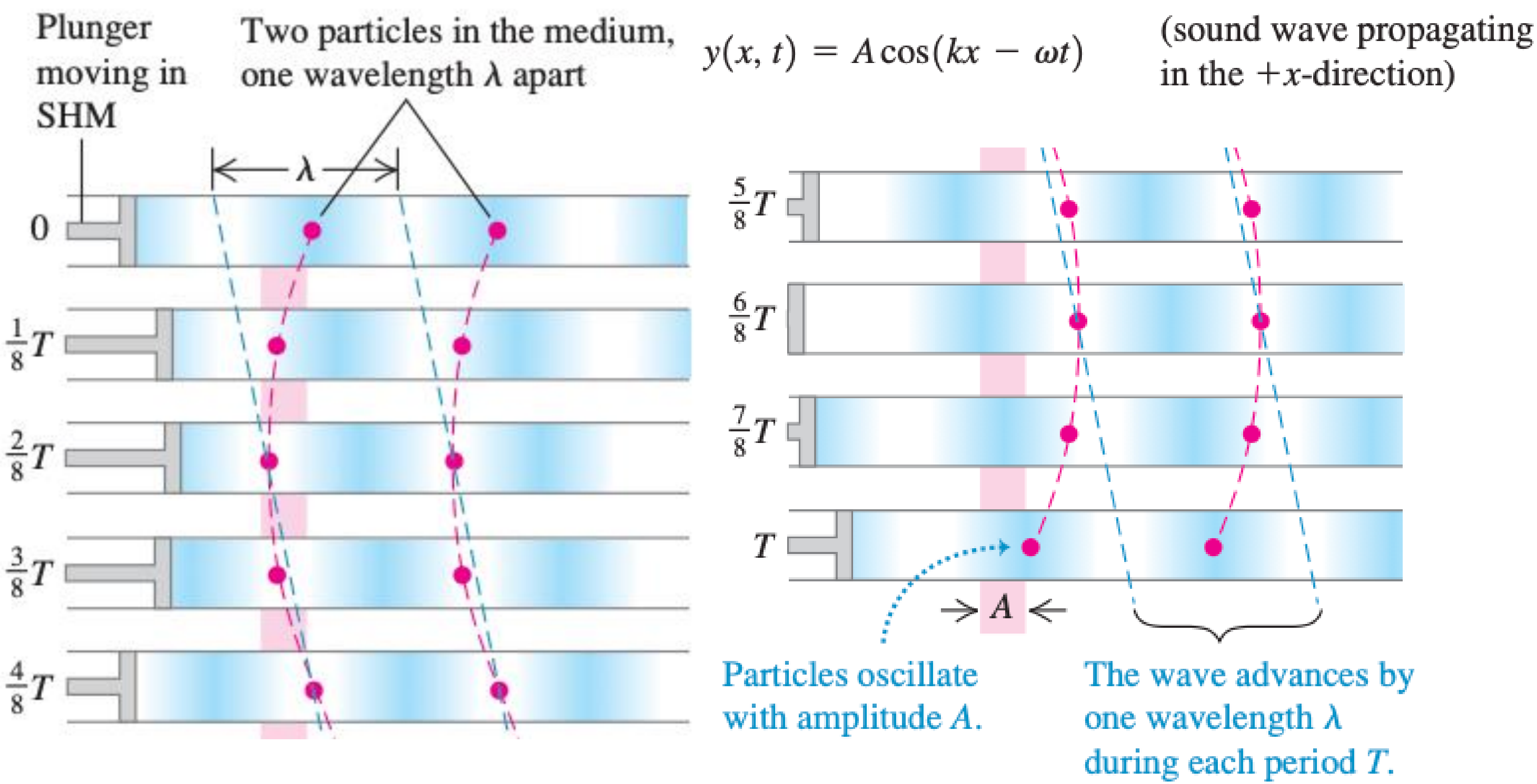
16-1 Sound Waves

A sound wave travels from a point source *S* through a three-dimensional medium. The wavefronts form spheres centered on *S*; the rays are radial to *S*.

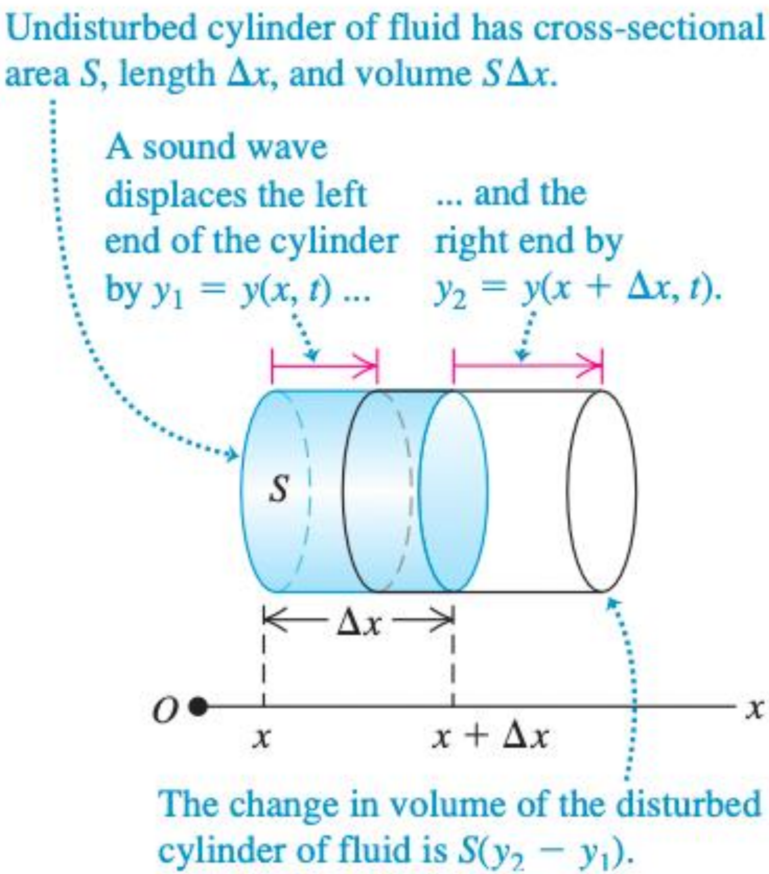


- Wavefronts (波面)
  - are surfaces over which the oscillations due to the sound wave have the *same value*; such surfaces are represented by whole or partial circles in a two-dimensional drawing
- Rays (波線)
  - are directed lines perpendicular to the wavefronts that indicate the *direction* of travel of the wavefronts

16-1 Sound Waves



16-1 Sound Waves



$$\Delta V = S(y_2 - y_1) = S[y(x + \Delta x, t) - y(x, t)]$$

$$\frac{dV}{V} = \lim_{\Delta x \to 0} \frac{S[y(x + \Delta x, t) - y(x, t)]}{S\Delta x} = \frac{\partial y(x, t)}{\partial x}$$

$$B = -p(x, t)/(dV/V)$$

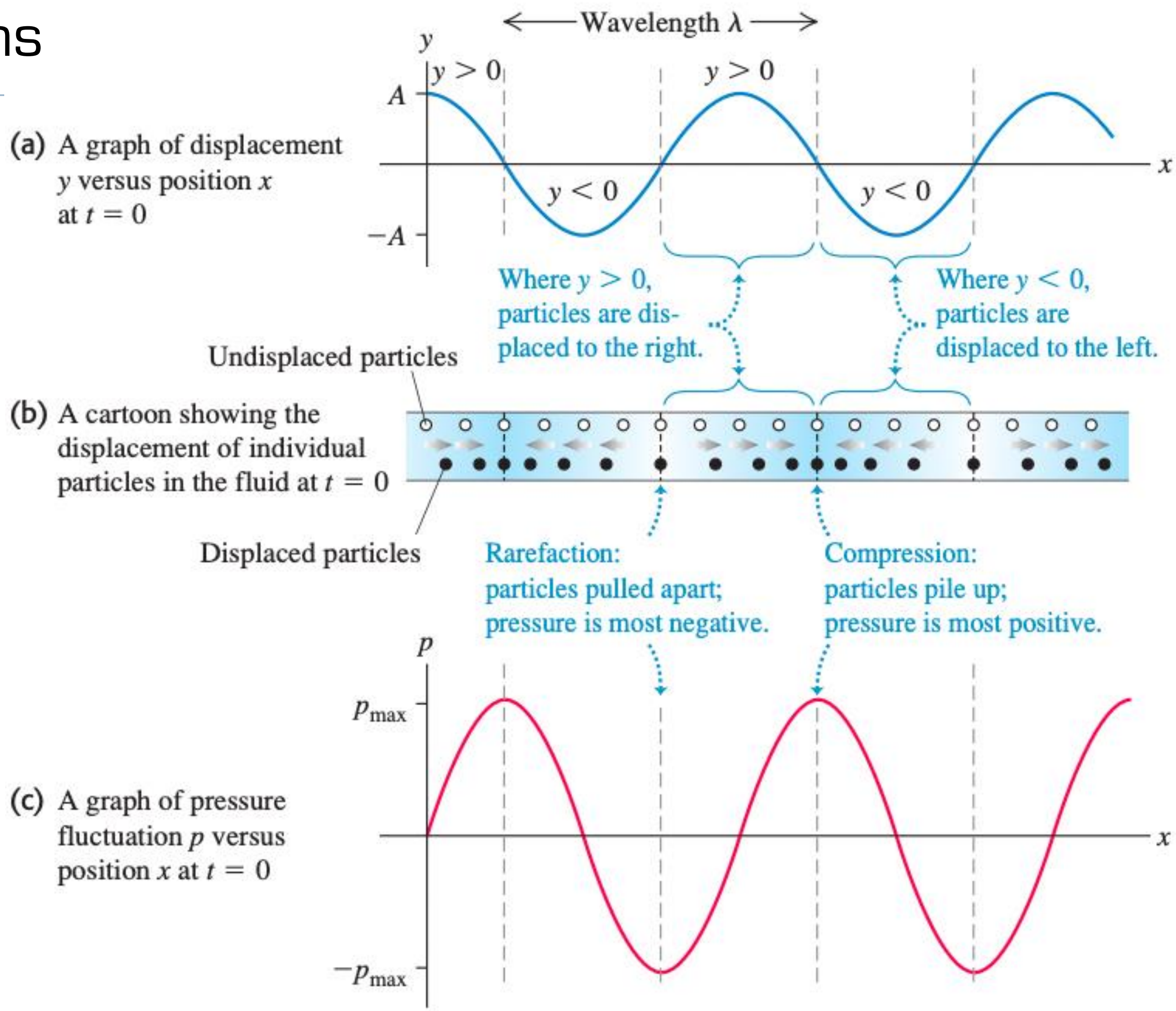
$$p(x, t) = -B\frac{\partial y(x, t)}{\partial x}$$

$$y(x, t) = A\cos(kx - \omega t)$$

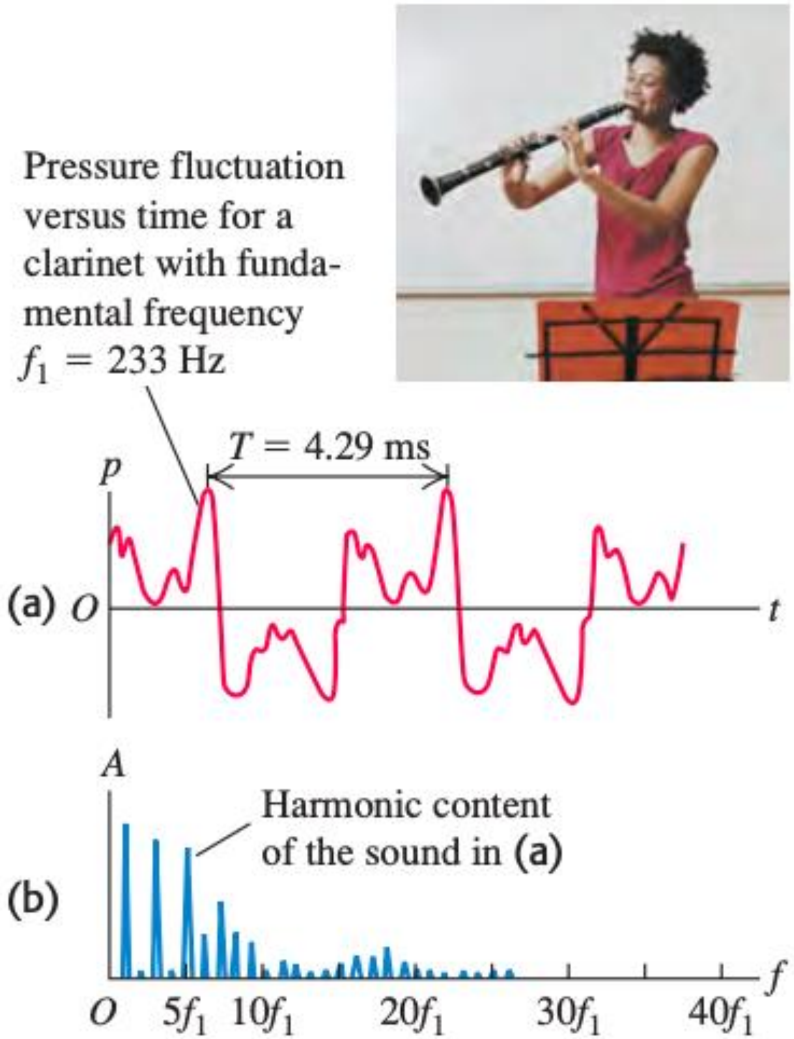
$$p(x, t) = BkA\sin(kx - \omega t)$$

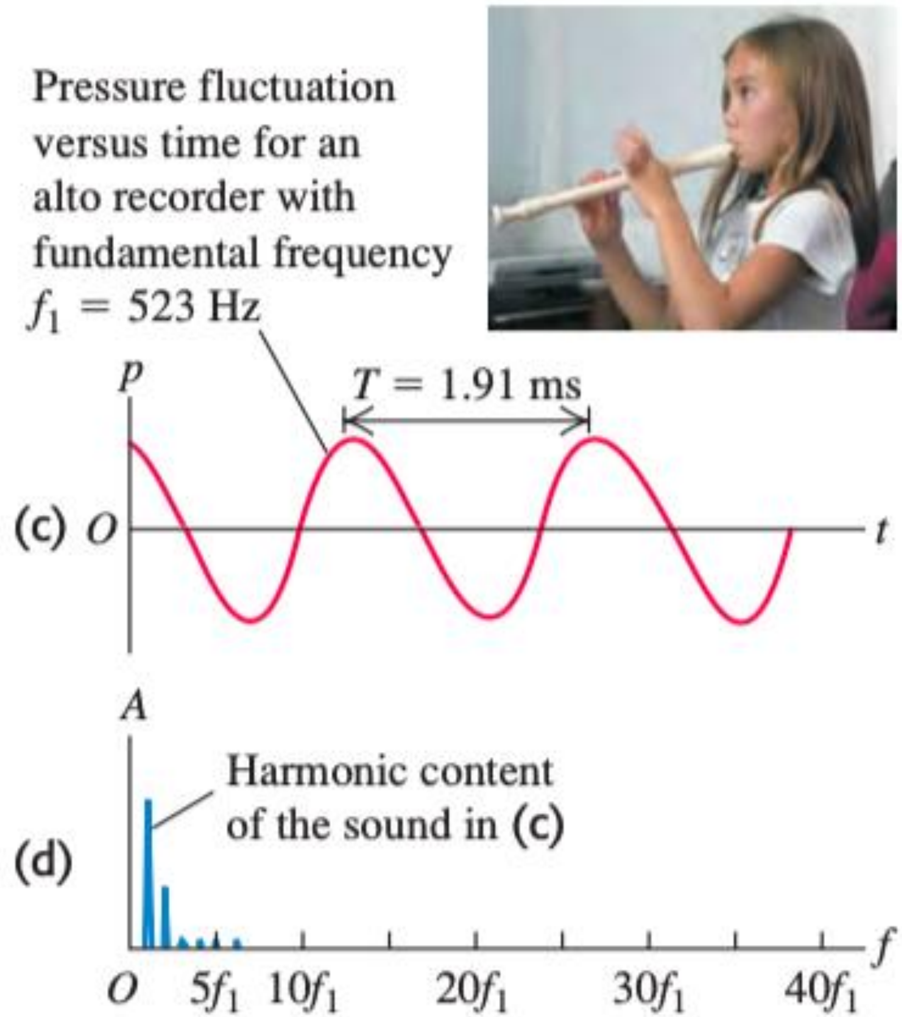
$$p_{max} = BkA \qquad \text{(sinusoidal sound wave)}$$

Sound Waves As Pressure Fluctuations



16-1 Sound Waves





Sample Problem

Example 16.1 **Amplitude of a sound wave in air**

In a sinusoidal sound wave of moderate loudness, the maximum pressure variations are about 3.0×10^{-2} Pa above and below atmospheric pressure. Find the corresponding maximum displacement if the frequency is 1000 Hz. In air at normal atmospheric pressure and density, the speed of sound is 344 m/s and the bulk modulus is 1.42×10^5 Pa.

EXECUTE: From Eq. (15.6),

$$k = \frac{\omega}{v} = \frac{2\pi f}{v} = \frac{(2\pi \text{ rad})(1000 \text{ Hz})}{344 \text{ m/s}} = 18.3 \text{ rad/m}$$

Then from Eq. (16.5), the maximum displacement is

$$A = \frac{p_{\max}}{Bk} = \frac{3.0 \times 10^{-2} \text{ Pa}}{(1.42 \times 10^5 \text{ Pa})(18.3 \text{ rad/m})} = 1.2 \times 10^{-8} \text{ m}$$

16-2 Speed of Sound Waves

- The speed of any mechanical wave depends on both an *inertial property* of the medium (kinetic energy) and an *elastic property* of the medium (potential energy)

$$v = \sqrt{\frac{\text{Restoring force returning the system to equilibrium}}{\text{Inertia resisting the return to equilibrium}}}$$

16-2 Speed of Sound Waves

- Speed of sound in Fluid

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

  - B is the bulk modulus
    - $-\frac{\Delta p}{\Delta V / V}$; pressure change against fractional volume change
  - ρ is the density of medium

Medium	Speed (m/s)
Gases	
Air (0°C)	331
Air (20°C)	343
Helium	965
Hydrogen	1284
Liquids	
Water (0°C)	1402
Water (20°C)	1482
Seawater[b]	1522
Solids	
Aluminum	6420
Steel	5941
Granite	6000

16-2 Speed of Sound Waves

- Speed of sound in solid rod

$$v = \sqrt{\frac{Y}{\rho}}$$

  - Y is the Young's modulus
  - ρ is the density of medium
- Bulk solid: depends also on the shear modulus

sound waves of very high frequency and very short wavelength, called *ultrasound*
More sensitive than x rays

16-2 Speed of Sound Waves

$$v = \sqrt{\frac{\gamma RT}{M}} \qquad \text{(speed of sound in an ideal gas)}$$

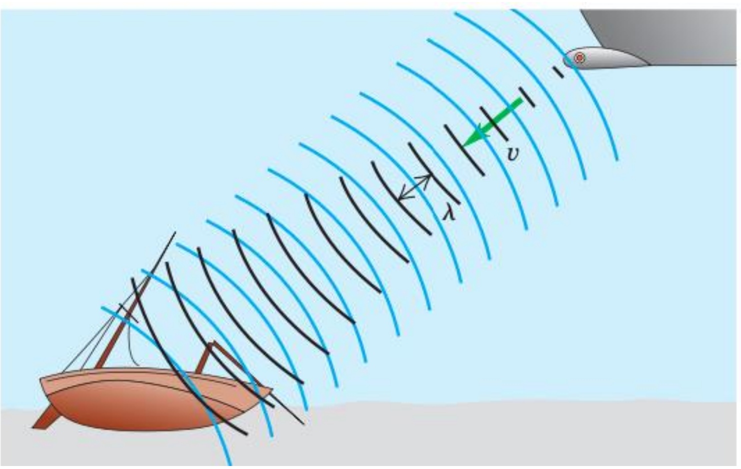
M is the molar mass
R is the *gas constant,* has the same value for all gases
γ is the ratio of heat capacities
T is the temperature

$$R = 8.314472(15)\ \mathrm{J/mol \cdot K}$$

Sample Problem

Example 16.3 **Wavelength of sonar waves**

A ship uses a sonar system (Fig. 16.8) to locate underwater objects. Find the speed of sound waves in water using Eq. (16.7), and find the wavelength of a 262-Hz wave.



EXECUTE: In Example 16.2, we used Table 11.2 to find $B = 2.18 \times 10^9$ Pa. Then

$$v = \sqrt{\frac{B}{\rho}} = \sqrt{\frac{2.18 \times 10^9\ \text{Pa}}{1.00 \times 10^3\ \text{kg/m}^3}} = 1480\ \text{m/s}$$

and

$$\lambda = \frac{v}{f} = \frac{1480\ \text{m/s}}{262\ \text{s}^{-1}} = 5.65\ \text{m}$$

16-3 Sound Intensity

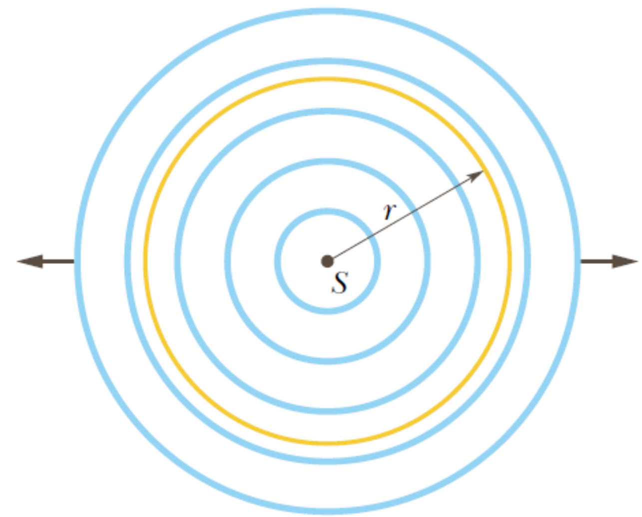
- The intensity *I* of a sound wave at a surface is the average rate per unit area at which energy is transferred by the wave through or onto the surface

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

- where *P* is the time rate of energy transfer (the power) of the sound wave and *A* is the area of the surface intercepting the sound

16-3 Sound Intensity

- 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*



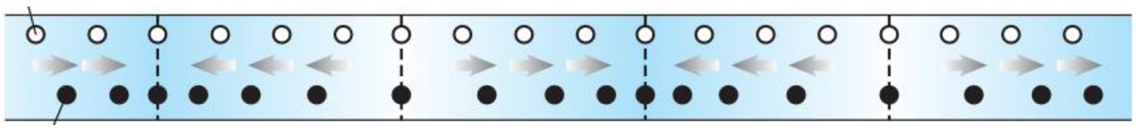
- The intensity I at the sphere is

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

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

- The intensity of sound from an *isotropic* (with equal intensity in all directions) point source decreases with the square of the distance r from the source
  - inverse-square law

16-3 Sound Intensity



A sound wave propagating in the +x-direction

$$v_y(x, t) = \frac{\partial y(x, t)}{\partial t} = \omega A \sin(kx - \omega t)$$

$$p(x, t) v_y(x, t) = [BkA \sin(kx - \omega t)][\omega A \sin(kx - \omega t)]$$

$$= B\omega k A^2 \sin^2(kx - \omega t)$$

The intensity is the time average value of $p(x, t)\, v_y(x, t)$

$$I = \tfrac{1}{2} B\omega k A^2$$

$$I = \tfrac{1}{2}\sqrt{\rho B}\,\omega^2 A^2 \qquad \text{(intensity of a sinusoidal sound wave)}$$

16-3 Sound Intensity

Intensity in term of pressure

$$I = \frac{1}{2}B\omega k A^2 \qquad p_{\max} = BkA$$

$$I = \frac{\omega p_{\max}^{\ 2}}{2Bk} = \frac{v p_{\max}^{\ 2}}{2B}$$

$$v^2 = B/\rho$$

$$I = \frac{p_{\max}^{\ 2}}{2\rho v} = \frac{p_{\max}^{\ 2}}{2\sqrt{\rho B}}$$

16.10 By cupping your hands like this, you direct the sound waves emerging from your mouth so that they don't propagate to the sides. Hence the intensity decreases with distance more slowly than the inverse-square law would predict, and you can be heard at greater distances.

Sample Problem

Example 16.5 **Intensity of a sound wave in air**

Find the intensity of the sound wave in Example 16.1, with $p_{max} = 3.0 \times 10^{-2}$ Pa. Assume the temperature is 20°C so that the density of air is $\rho = 1.20\ \mathrm{kg/m^3}$ and the speed of sound is $v = 344\ \mathrm{m/s}$.

EXECUTE: From Eq. (16.14),

$$I = \frac{p_{max}{}^2}{2\rho v} = \frac{(3.0 \times 10^{-2}\ \mathrm{Pa})^2}{2(1.20\ \mathrm{kg/m^3})(344\ \mathrm{m/s})}$$
$$= 1.1 \times 10^{-6}\ \mathrm{J/(s \cdot m^2)} = 1.1 \times 10^{-6}\ \mathrm{W/m^2}$$

16-3 Sound Intensity

- Sound level

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

  - dB is the abbreviation for decibel (分貝), the unit of sound level
  - I_0 is the standard reference intensity ($I_0 = 10^{-12} \text{ W/m}^2$), which is the lower limit of the human range of hearing

- For $I = I_0, \beta = 10 \log 1 = 0$, so our standard reference level corresponds to zero decibels

16-3 Sound Intensity

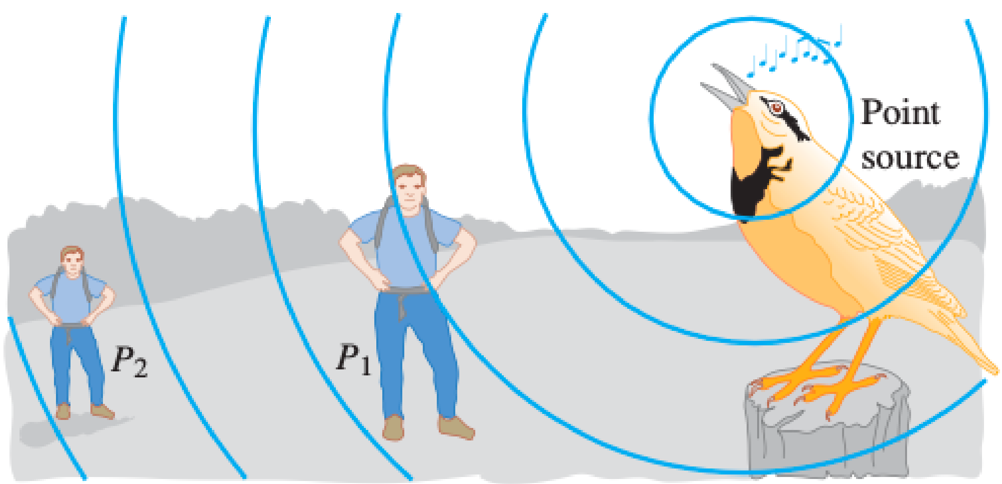
Table 16.2 Sound Intensity Levels from Various Sources (Representative Values)

Source or Description of Sound		Sound Intensity Level, β (dB)	Intensity, I (W/m^2)
Military jet aircraft 30 m away	Immediate danger	140	10^{2}
Threshold of pain		120	1
Riveter		95	3.2×10^{-3}
Elevated train		90	10^{-3}
Busy street traffic	Long period damage	70	10^{-5}
Ordinary conversation		65	3.2×10^{-6}
Quiet automobile		50	10^{-7}
Quiet radio in home		40	10^{-8}
Average whisper		20	10^{-10}
Rustle of leaves		10	10^{-11}
Threshold of hearing at 1000 Hz		0	10^{-12}

Sample Problem

Example 16.9 **A bird sings in a meadow**

Consider an idealized bird (treated as a point source) that emits constant sound power, with intensity obeying the inverse-square law (Fig. 16.11). If you move twice the distance from the bird, by how many decibels does the sound intensity level drop?



Sample Problem

EXECUTE: The difference $\beta_2 - \beta_1$ between any two sound intensity levels is related to the corresponding intensities by

$$\beta_2 - \beta_1 = (10\ \text{dB})\left(\log\frac{I_2}{I_0} - \log\frac{I_1}{I_0}\right)$$
$$= (10\ \text{dB})\left[(\log I_2 - \log I_0) - (\log I_1 - \log I_0)\right]$$
$$= (10\ \text{dB})\log\frac{I_2}{I_1}$$

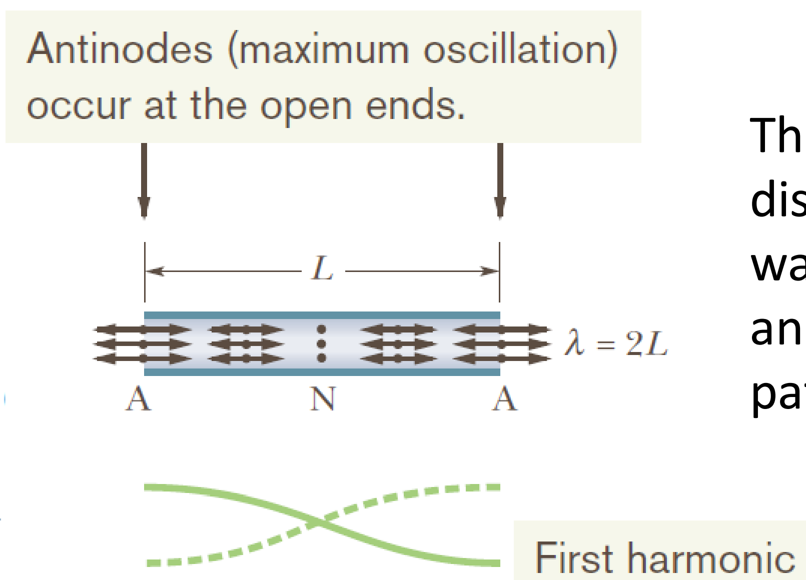
For this inverse-square-law source, Eq. (15.26) yields $I_2/I_1 = {r_1}^2/{r_2}^2 = \frac{1}{4}$, so

$$\beta_2 - \beta_1 = (10\ \text{dB})\log\frac{I_1}{I_2} = (10\ \text{dB})\log\tfrac{1}{4} = -6.0\ \text{dB}$$

16-4 Standing Sound Waves and Normal Modes

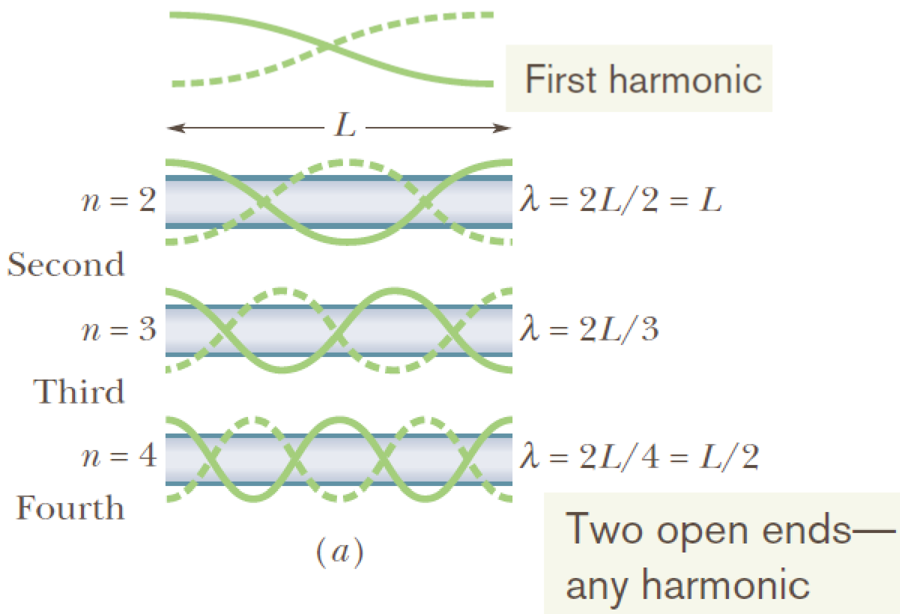
- Musical sounds can be set up by oscillating strings (guitar), membranes (drum), air columns (pipe organ),…

- The advantage of setting up standing waves is that the air particles oscillate with a large, sustained amplitude, thus generating a noticeable sound at *resonant frequencies*



The simplest standing wave pattern of displacement for (longitudinal) sound waves in a pipe with both ends open and the corresponding standing wave pattern for (transverse) string waves

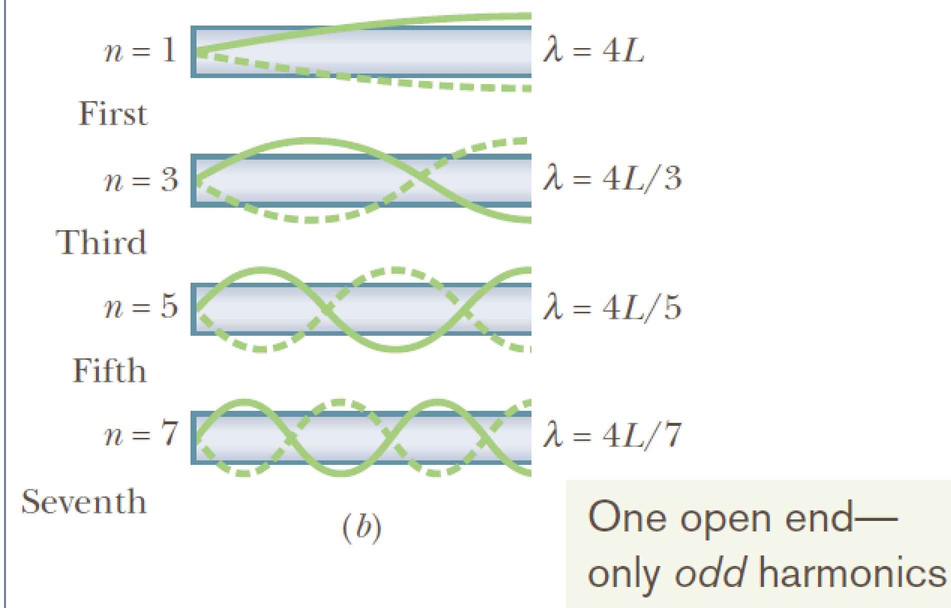
(*a*) Pipe opens at both ends



$$\lambda = \frac{2L}{n}, \qquad for\, n = 1, 2,3, \ldots$$

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

(b) Pipe opens at one end only



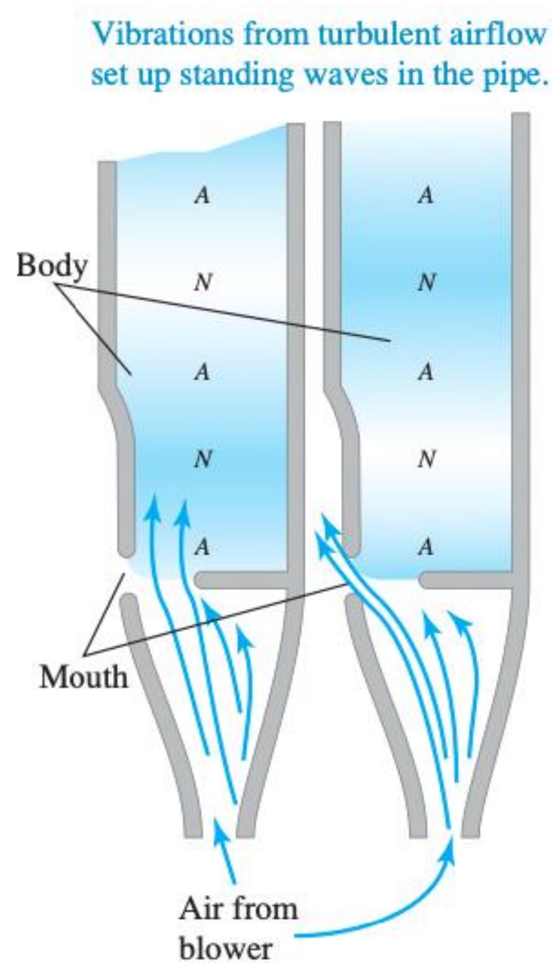
$$\lambda = \frac{4L}{n}, \qquad for\, n = 1, 3,5, \ldots$$

$$f = \frac{v}{\lambda} = n\frac{v}{4L}, \quad for\, n = 1, 3,5, \ldots$$

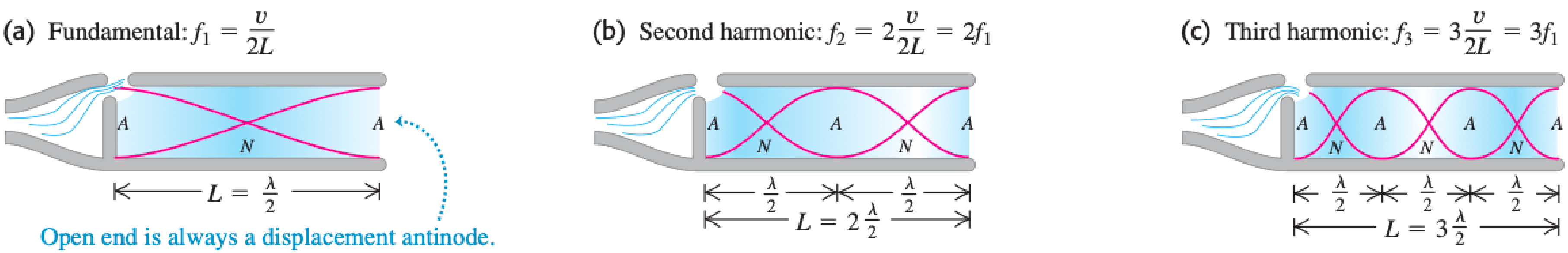
where *n* is the ***harmonic number***

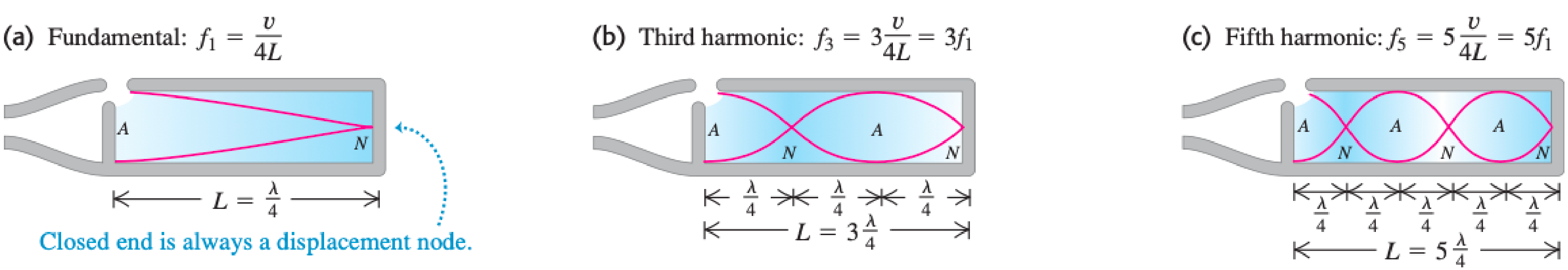
16-4 Standing Sound Waves and Normal Modes

16.15 Organ pipes of different sizes produce tones with different frequencies.



16-4 Standing Sound Waves and Normal Modes



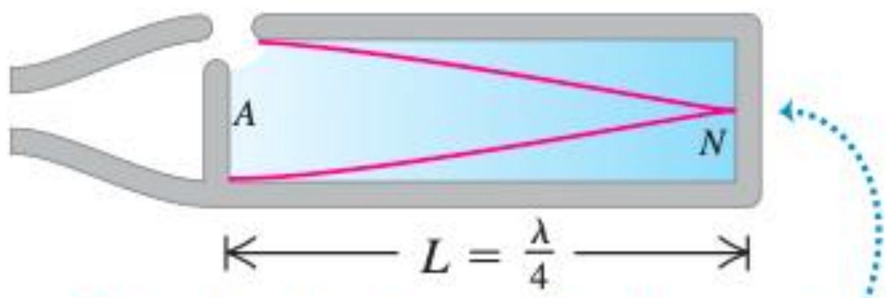


Sample Problem

Example 16.11 **A tale of two pipes**

On a day when the speed of sound is 345 m/s, the fundamental frequency of a particular stopped organ pipe is 220 Hz. (a) How long is this pipe? (b) The second *overtone* of this pipe has the same wavelength as the third *harmonic* of an *open* pipe. How long is the open pipe?

(a) Fundamental: $f_1 = \dfrac{v}{4L}$



Sample Problem

EXECUTE: (a) For a stopped pipe $f_1 = v/4L$, so

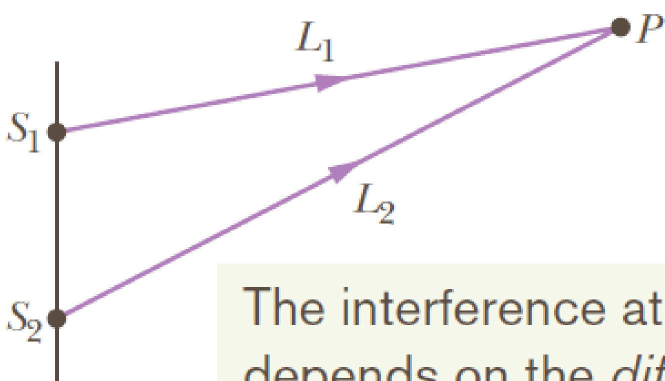
$$L_{\text{stopped}} = \frac{v}{4f_1} = \frac{345\ \text{m/s}}{4(220\ \text{s}^{-1})} = 0.392\ \text{m}$$

(b) The frequency of the second overtone of a stopped pipe (the *third* possible frequency) is $f_5 = 5f_1 = 5(220\ \text{Hz}) = 1100\ \text{Hz}$. If the wavelengths for the two pipes are the same, the frequencies are also the same. Hence the frequency of the third harmonic of the open pipe, which is at $3f_1 = 3(v/2L)$, equals 1100 Hz. Then

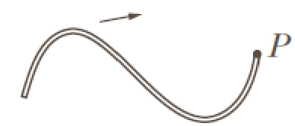
$$1100\ \text{Hz} = 3\left(\frac{345\ \text{m/s}}{2L_{\text{open}}}\right) \quad \text{and} \quad L_{\text{open}} = 0.470\ \text{m}$$

16-6 Interference of Waves

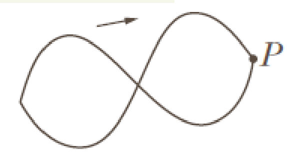
- Sound waves can undergo interference, like transverse waves. Let us consider, in particular, the interference between two identical sound waves travelling in the same direction



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



If the difference is equal to, say, 2.0λ, then the waves arrive exactly in phase. This is how transverse waves would look.



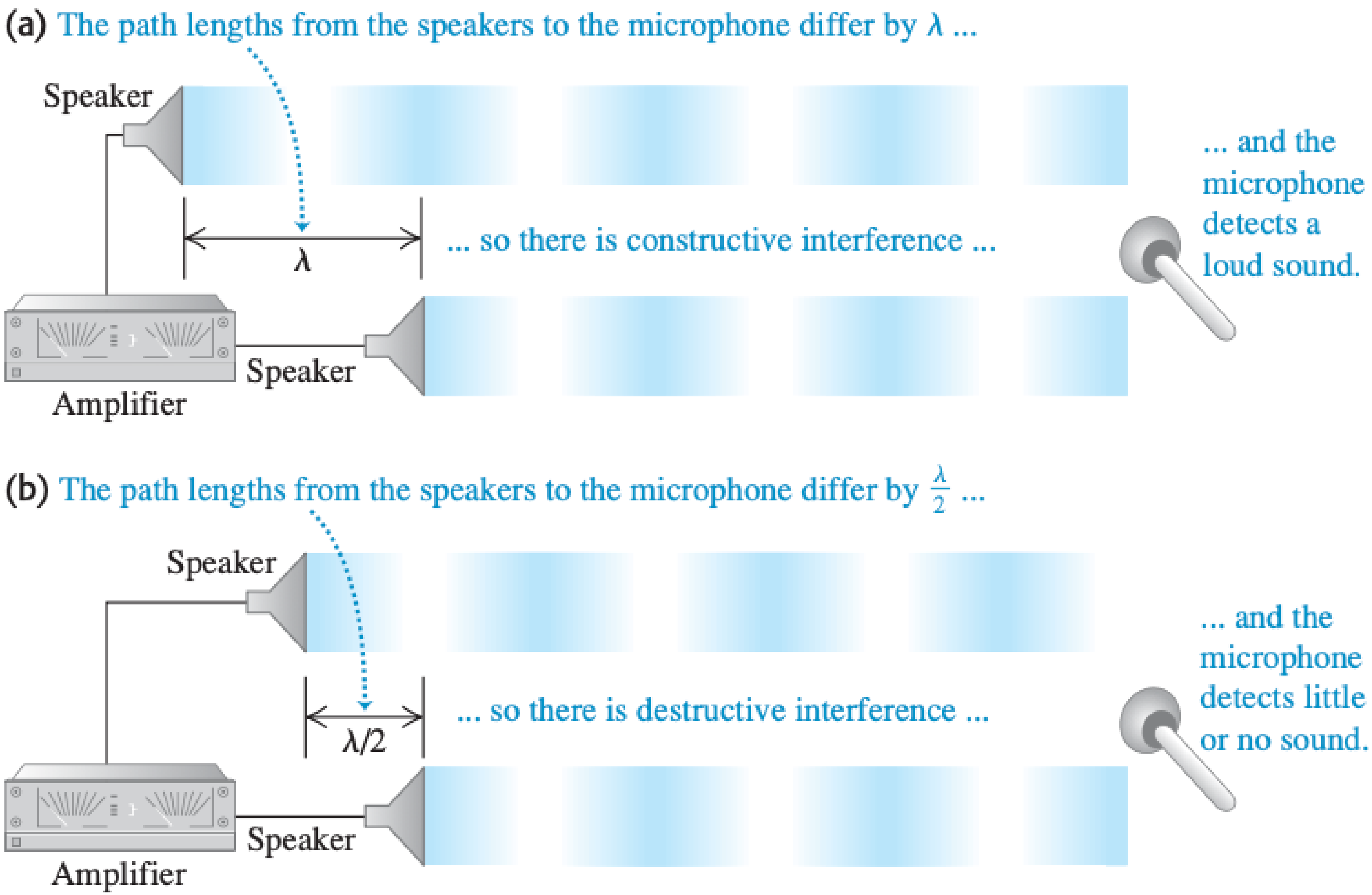
If the difference is equal to, say, 2.5λ, then the waves arrive exactly out of phase. This is how transverse waves would look.

- Path length difference, $\Delta L = |L_2 - L_1|$

16-6 Interference of Waves

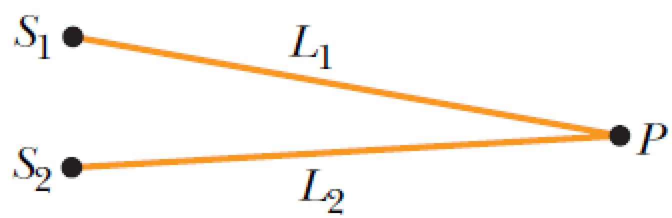
- Phase difference (相差)
  - $\phi = \frac{\Delta L}{\lambda} 2\pi$
  - $\frac{\Delta L}{\lambda} = \frac{\phi}{2\pi}$
- Fully constructive interference (相長干涉)
  - $\phi = m(2\pi), \;\; for\ m = 0,1,2,\ldots$
  - $\frac{\Delta L}{\lambda} = 0,1,2,\ldots$
- Fully destructive interference (相消干涉)
  - $\phi = (2m+1)\pi, \;\; for\ m = 0,1,2,\ldots$
  - $\frac{\Delta L}{\lambda} = 0.5,1.5,2.5,\ldots$

16-6 Interference of Waves



Questions

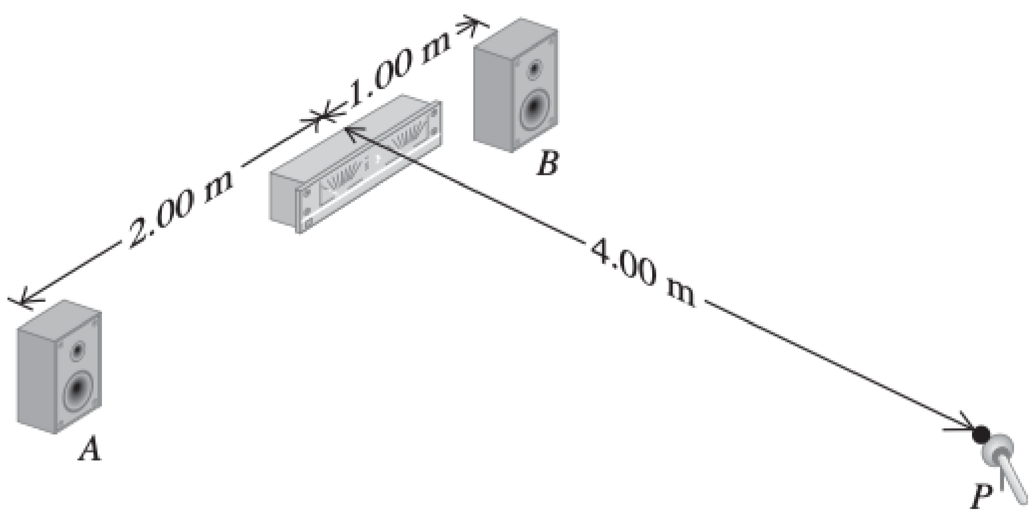
- Two point sources S_1 and S_2, which are in phase, emit identical sound waves of wavelength 2.0 m. In terms of wavelengths, what is the phase difference between the waves arriving at point P if (a) L_1 = 38 m and L_2 = 34 m, and (b) L_1 = 39 m and L_2 = 36 m? (c) Assuming that the source separation is much smaller than L_1 and L_2, what type of interference occurs at P in situations (a) and (b)?



Sample Problem

Example 16.13 Loudspeaker interference

Two small loudspeakers, *A* and *B* (Fig. 16.23), are driven by the same amplifier and emit pure sinusoidal waves in phase. (a) For what frequencies does constructive interference occur at point *P*? (b) For what frequencies does destructive interference occur? The speed of sound is 350 m/s.



Sample Problem

EXECUTE: The distance from A to P is $[(2.00\text{ m})^2 + (4.00\text{ m})^2]^{1/2} = 4.47\text{ m}$, and the distance from B to P is $[(1.00\text{ m})^2 + (4.00\text{ m})^2]^{1/2} = 4.12\text{ m}$. The path difference is $d = 4.47\text{ m} - 4.12\text{ m} = 0.35\text{ m}$.

(a) Constructive interference occurs when $d = 0, \lambda, 2\lambda, \ldots$ or $d = 0, v/f, 2v/f, \ldots = nv/f$. So the possible frequencies are

$$f_n = \frac{nv}{d} = n\frac{350\text{ m/s}}{0.35\text{ m}} \qquad (n = 1, 2, 3, \ldots)$$

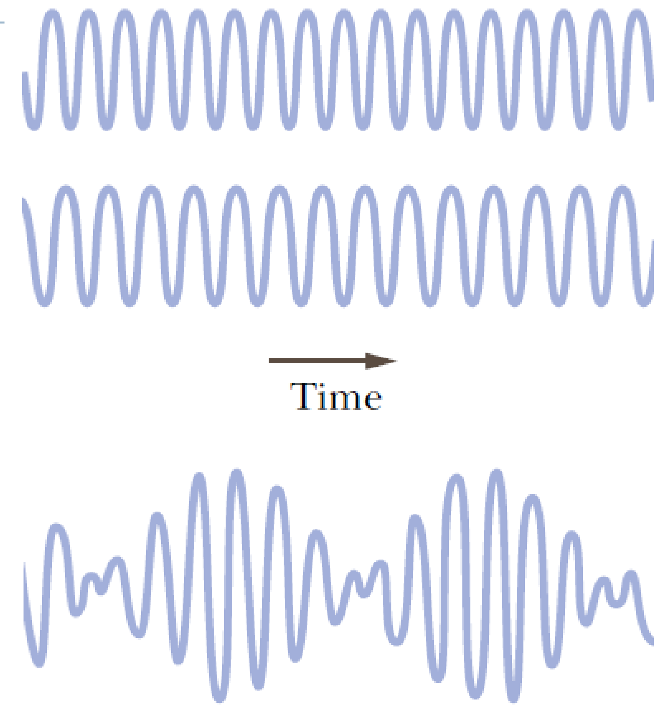
$$= 1000\text{ Hz}, 2000\text{ Hz}, 3000\text{ Hz}, \ldots$$

(b) Destructive interference occurs when $d = \lambda/2, 3\lambda/2, 5\lambda/2, \ldots$ or $d = v/2f, 3v/2f, 5v/2f, \ldots$. The possible frequencies are

$$f_n = \frac{nv}{2d} = n\frac{350\text{ m/s}}{2(0.35\text{ m})} \qquad (n = 1, 3, 5, \ldots)$$

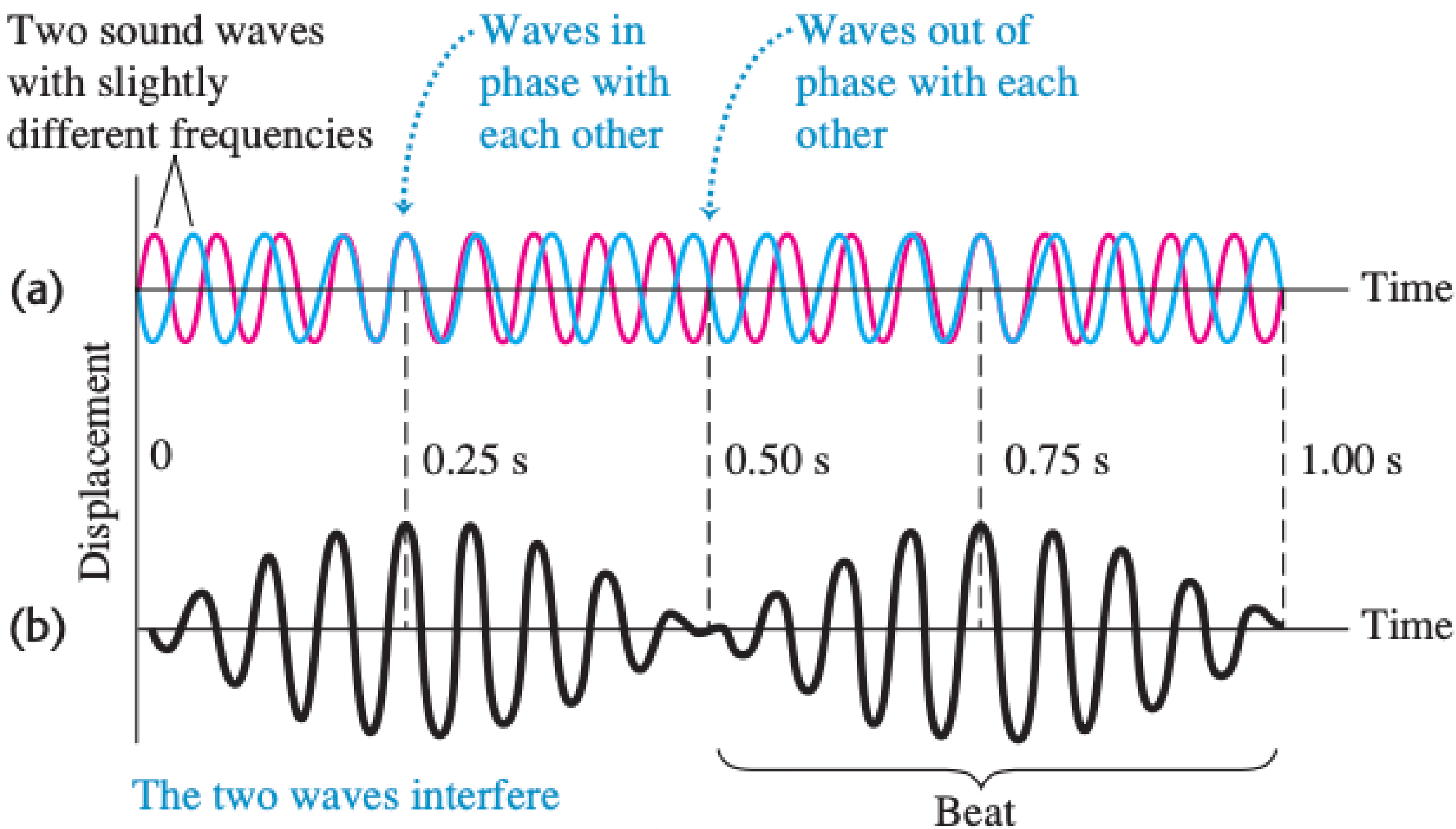
$$= 500\text{ Hz}, 1500\text{ Hz}, 2500\text{ Hz}, \ldots$$

16-7 Beats (拍)



- Beat
  - When two sound waves whose frequencies (f_1 and f_2) are close, but not the same, are superimposed, a variation in the intensity of the resultant sound wave is heard
- Beat frequency
  - At which the wavering of intensity occurs
    - $f_{beat} = |f_1 - f_2|$

16-7 Beats (拍)



The two waves interfere constructively when they are in phase and destructively when they are a half-cycle out of phase. The resultant wave rises and falls in intensity, forming beats.

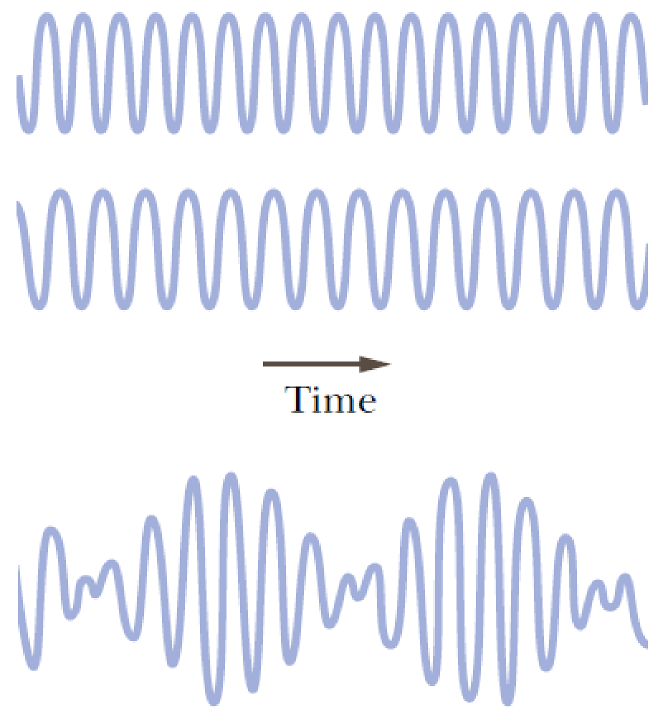
16-7 Beats (拍)

$$T_{\text{beat}} = nT_a \qquad \text{and} \qquad T_{\text{beat}} = (n-1)T_b$$

$$T_{\text{beat}} = \frac{T_a T_b}{T_b - T_a}$$

$$f_{\text{beat}} = \frac{T_b - T_a}{T_a T_b} = \frac{1}{T_a} - \frac{1}{T_b}$$

$$f_{\text{beat}} = f_a - f_b \qquad \text{(beat frequency)}$$



Sample Problem

- A pipe with two open ends. Suppose that the frequency of the first harmonic produced by side *A* is f_{A1} = 432 Hz and the frequency of the first harmonic produced by side *B* is f_{B1} = 371 Hz. What is the beat frequency between those two first-harmonic frequencies and between the two second-harmonic frequencies?

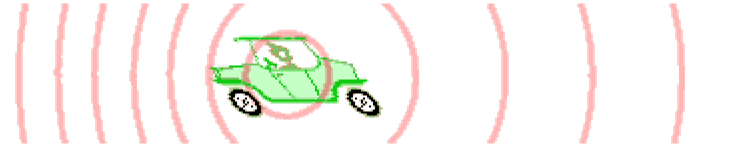
- For the first-harmonic frequencies,

$$\begin{aligned} f_{\text{beat},1} &= f_{A1} - f_{B1} = 432 \text{ Hz} - 371 \text{ Hz} \\ &= 61 \text{ Hz}. \end{aligned}$$

- For the second-harmonic frequencies,

$$\begin{aligned} f_{\text{beat},2} &= f_{A2} - f_{B2} = 2f_{A1} - 2f_{B1} \\ &= 2(432 \text{ Hz}) - 2(371 \text{ Hz}) \\ &= 122 \text{ Hz}. \end{aligned}$$

16-8 The Doppler Effect



- The Doppler effect is the change in frequency of a wave for a detector (observer) moving relative to its source

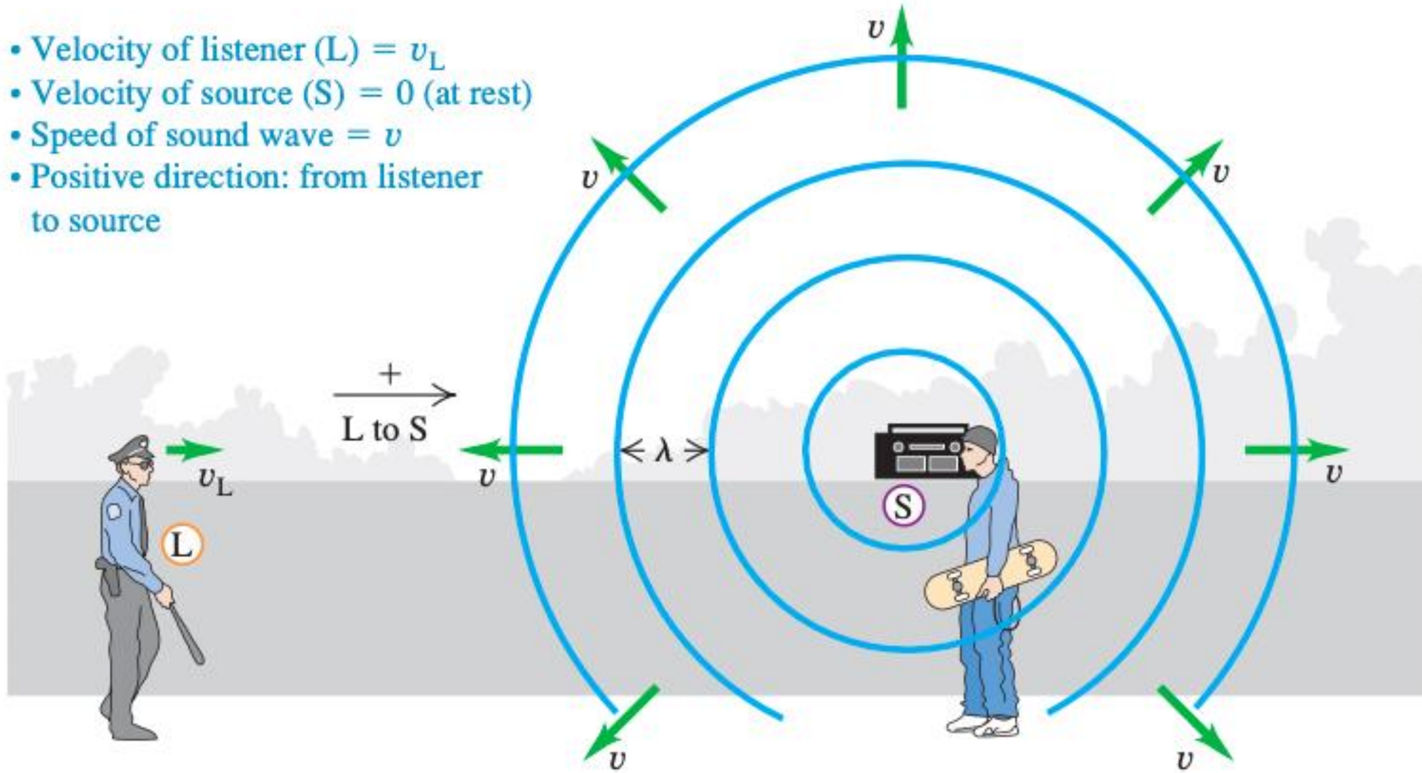
- The *detected frequency* can be related by a general equation

$$f' = f\,\frac{v \pm v_D}{v \pm v_S}$$

  - f is the emitted frequency
  - v is the speed of sound through the medium
  - v_D is the detector's speed *relative to the medium*
  - v_S is the source's speed *relative to the medium*

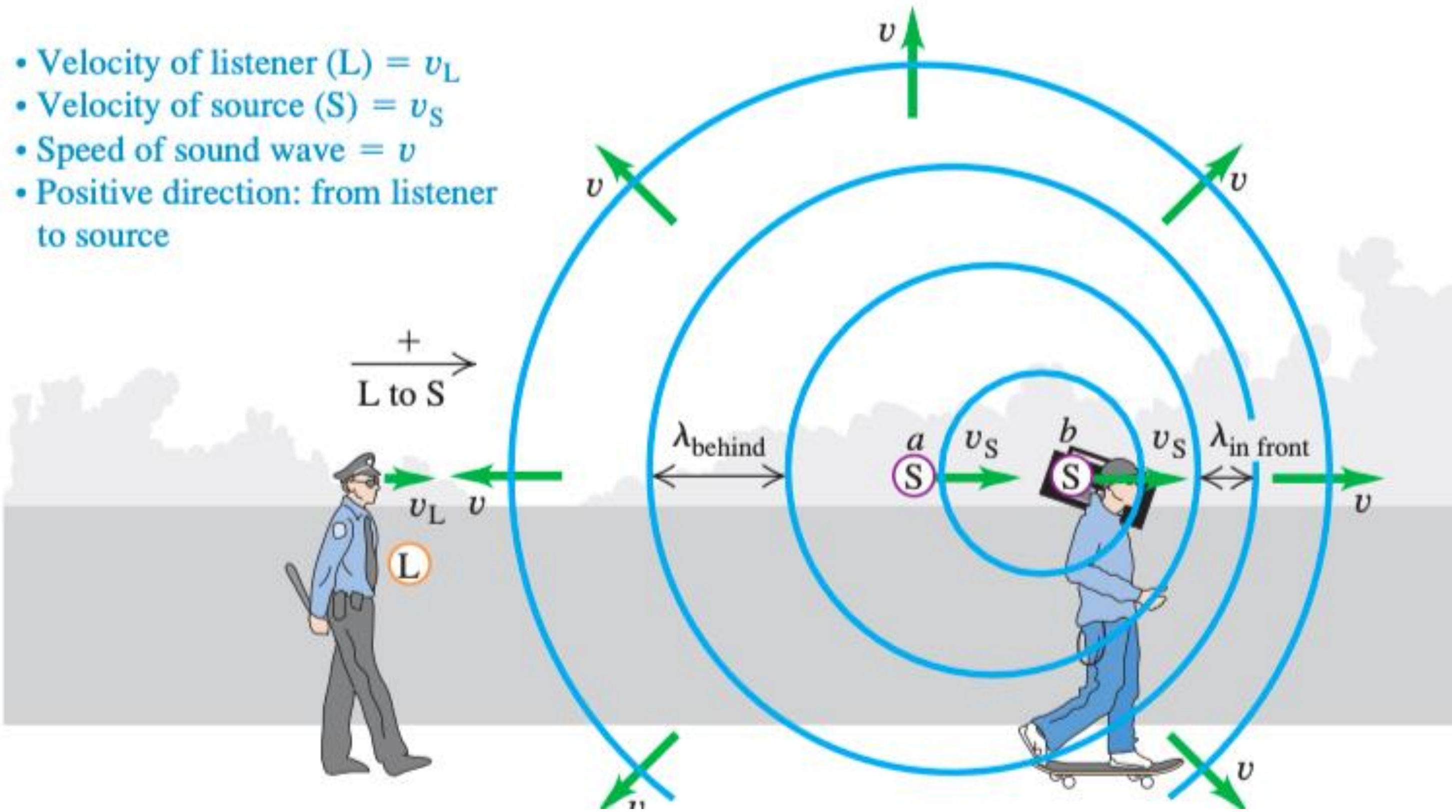
  - When the motion of detector or source is *toward* the other, the sign on its speed must give an *upward shift* in frequency
  - When the motion of detector or source is *away* from the other, the sign on its speed must give a *downward shift* in frequency

16-8 The Doppler Effect



$$f_L = \frac{v + v_L}{\lambda} = \frac{v + v_L}{v/f_S}$$

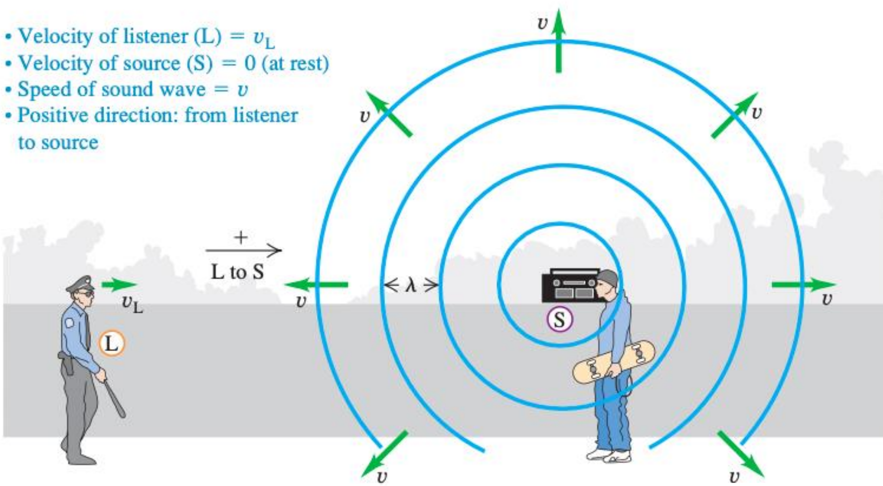
16-8 The Doppler Effect

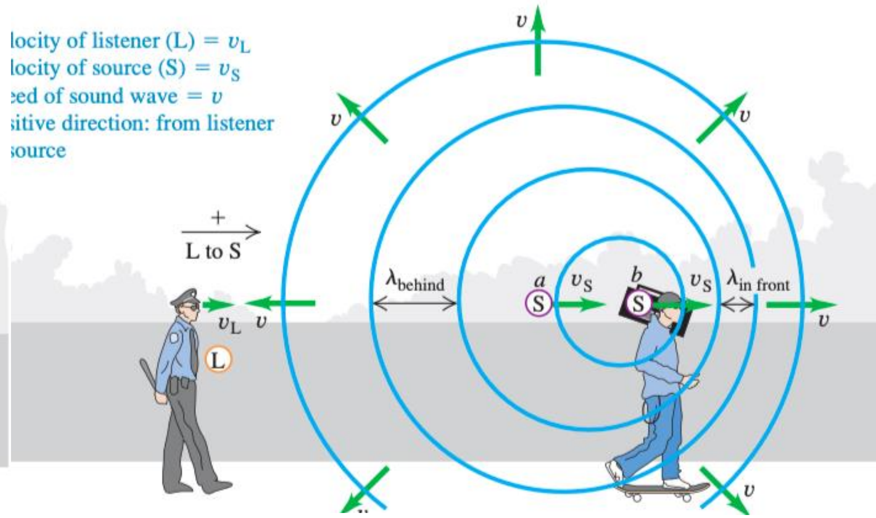


$$\lambda_{in\ front} = \frac{v}{f_S} - \frac{v_S}{f_S} = \frac{v - v_S}{f_S}$$

$$\lambda_{behind} = \frac{v + v_S}{f_S}$$

16-8 The Doppler Effect





$$f_L = \frac{v + v_L}{\lambda_{behind}} = \frac{v + v_L}{(v + v_S)/f_S}$$

$$f_L = \frac{v + v_L}{v + v_S} f_S$$ (Doppler effect, moving source and moving listener)

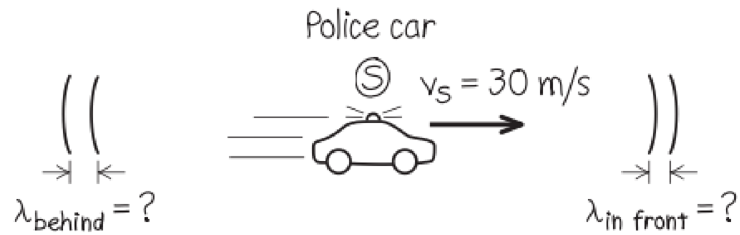
16-8 The Doppler Effect

16.28 The Doppler effect explains why the siren on a fire engine or ambulance has a high pitch ($f_L > f_S$) when it is approaching you ($v_S < 0$) and a low pitch ($f_L < f_S$) when it is moving away ($v_S > 0$).

Sample Problem

Example 16.14 **Doppler effect I: Wavelengths**

A police car's siren emits a sinusoidal wave with frequency $f_S = 300$ Hz. The speed of sound is 340 m/s and the air is still. (a) Find the wavelength of the waves if the siren is at rest. (b) Find the wavelengths of the waves in front of and behind the siren if it is moving at 30 m/s.



(a) When the source is at rest,

$$\lambda = \frac{v}{f_S} = \frac{340 \text{ m/s}}{300 \text{ Hz}} = 1.13 \text{ m}$$

(b) From Eq. (16.27), in front of the siren

$$\lambda_{\text{in front}} = \frac{v - v_S}{f_S} = \frac{340 \text{ m/s} - 30 \text{ m/s}}{300 \text{ Hz}} = 1.03 \text{ m}$$

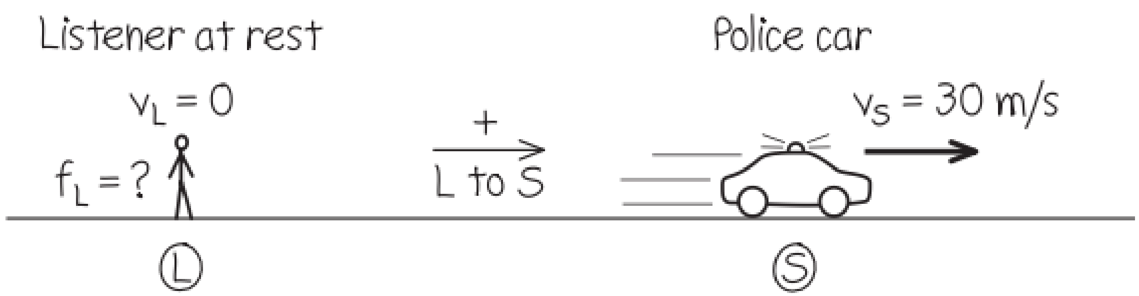
From Eq. (16.28), behind the siren

$$\lambda_{\text{behind}} = \frac{v + v_S}{f_S} = \frac{340 \text{ m/s} + 30 \text{ m/s}}{300 \text{ Hz}} = 1.23 \text{ m}$$

Sample Problem

Example 16.15 Doppler effect II: Frequencies

If a listener L is at rest and the siren in Example 16.14 is moving away from L at 30 m/s, what frequency does the listener hear?



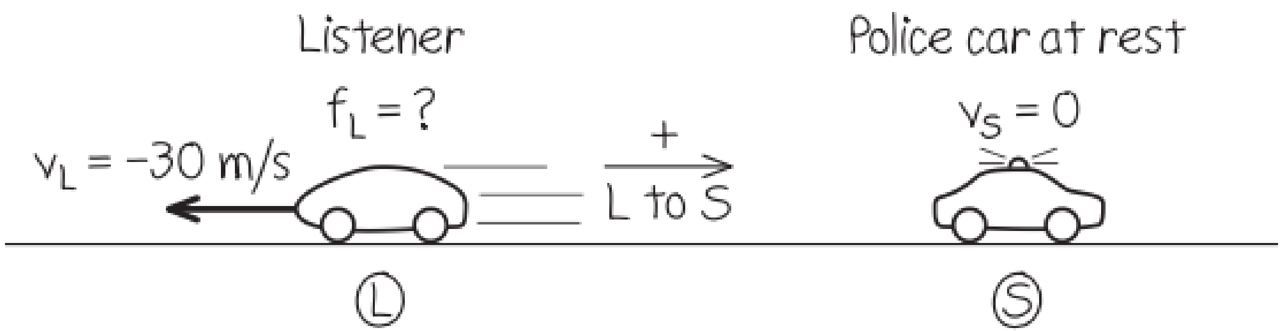
wavelength behind the source (where the listener in Fig. 16.30 is located) is 1.23 m. The wave speed relative to the stationary listener is $v = 340$ m/s even though the source is moving, so

$$f_L = \frac{v}{\lambda} = \frac{340 \text{ m/s}}{1.23 \text{ m}} = 276 \text{ Hz}$$

Sample Problem

Example 16.16 Doppler effect III: A moving listener

If the siren is at rest and the listener is moving away from it at 30 m/s, what frequency does the listener hear?



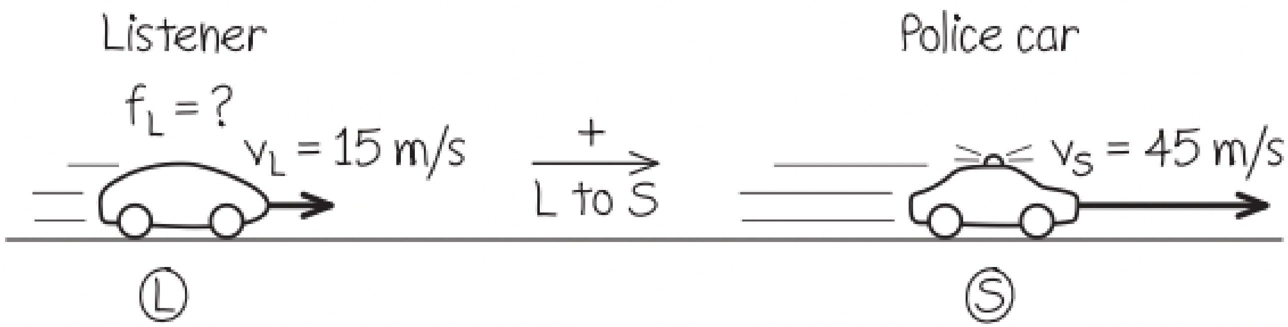
EXECUTE: From Eq. (16.29),

$$f_L = \frac{v + v_L}{v} f_S = \frac{340\ \mathrm{m/s} + (-30\ \mathrm{m/s})}{340\ \mathrm{m/s}} (300\ \mathrm{Hz}) = 274\ \mathrm{Hz}$$

Sample Problem

Example 16.17 **Doppler effect IV: Moving source, moving listener**

The siren is moving away from the listener with a speed of 45 m/s relative to the air, and the listener is moving toward the siren with a speed of 15 m/s relative to the air. What frequency does the listener hear?

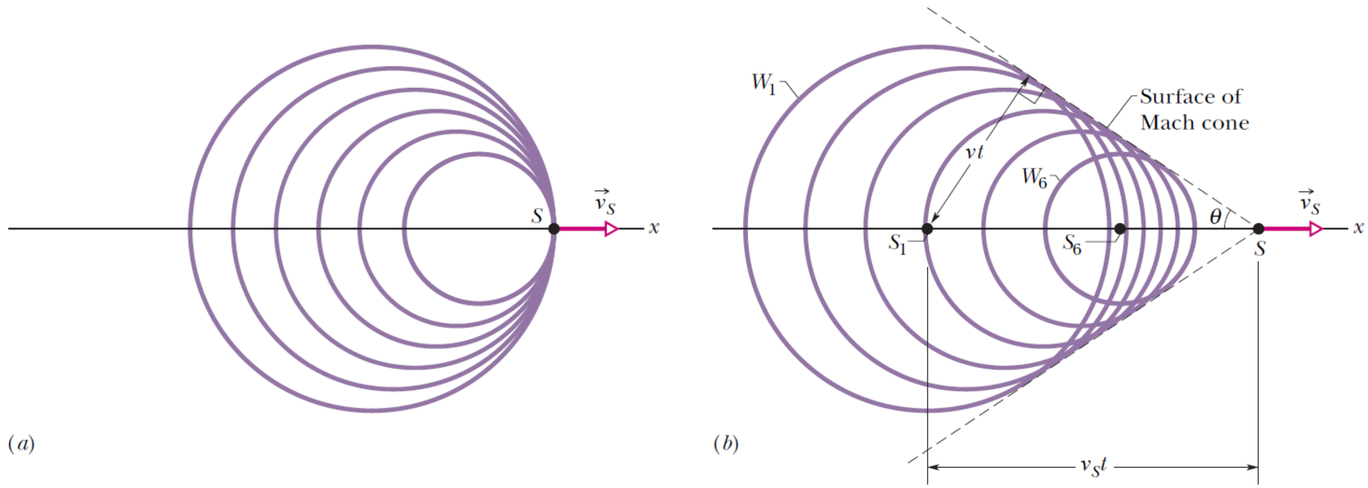


EXECUTE: From Eq. (16.29),

$$f_L = \frac{v + v_L}{v + v_S} f_S = \frac{340 \text{ m/s} + 15 \text{ m/s}}{340 \text{ m/s} + 45 \text{ m/s}} (300 \text{ Hz}) = 277 \text{ Hz}$$

16-9 Shock Waves

- When the speed of the source (v_S), *exceeds the speed of sound* (v), the aforementioned equations no longer apply

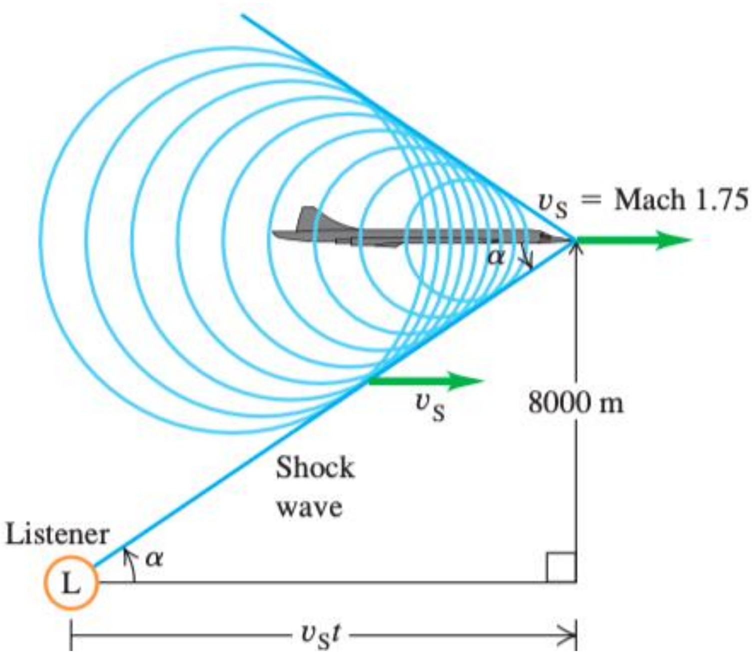


- A shock wave exists along the surface of this cone
  - $\sin\theta = \dfrac{v}{v_S}$
  - Mach number, $M = \dfrac{v_S}{v}\begin{cases} < 1 & (\textit{subsonic}\ 亞/次音速) \\ = 1 & (\textit{sonic}\ 音速) \\ > 1 & (\textit{supersonic}\ 超音速) \end{cases}$

Sample Problem

Example 16.19 **Sonic boom from a supersonic airplane**

An airplane is flying at Mach 1.75 at an altitude of 8000 m, where the speed of sound is 320 m/s. How long after the plane passes directly overhead will you hear the sonic boom?



EXECUTE: From Eq. (16.31) the angle α of the shock cone is

$$\alpha = \arcsin\frac{1}{1.75} = 34.8^\circ$$

The speed of the plane is the speed of sound multiplied by the Mach number:

$$v_S = (1.75)(320\ \text{m/s}) = 560\ \text{m/s}$$

From Fig. 16.37 we have

$$\tan\alpha = \frac{8000\ \text{m}}{v_S t}$$

$$t = \frac{8000\ \text{m}}{(560\ \text{m/s})(\tan 34.8^\circ)} = 20.5\ \text{s}$$