Fundamentals Physics

Eleventh Edition

Halliday

Chapter 17

Waves - II

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17-1 Speed of Sound (1 of 3)

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.

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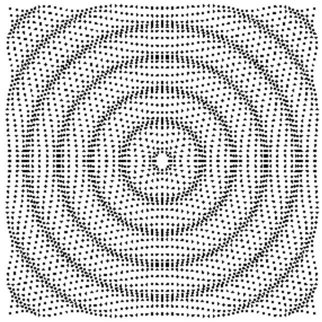
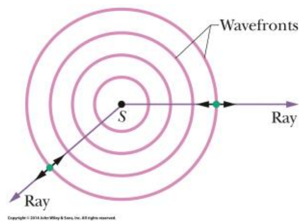
17-1 Speed of Sound (2 of 3)

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 (3 of 3)

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

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

The bulk modulus is the ratio of change in stress (pressure) and volume strain

$$B = \frac{\Delta p}{\Delta V / V}$$

Table 16.1 Speed of Sound in Gases, Liquids, and Solids

Substance	Speed (m/s)
Gases	
Air (0 °C)	331
Air (20 °C)	343
Carbon dioxide (0 °C)	259
Oxygen (0 °C)	316
Helium (0 °C)	965
Liquids	
Chloroform (20 °C)	1004
Ethyl alcohol (20 °C)	1162
Mercury (20 °C)	1450
Fresh water (20 °C)	1482
Seawater (20 °C)	1522
Solids	
Copper	5010
Glass (Pyrex)	5640
Lead	1960
Steel	5960

17-2 Traveling Sound Waves (1 of 6)

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.

17-2 Traveling Sound Waves (2 of 6)

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.

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

17-2 Traveling Sound Waves (3 of 6)

17.11 Apply the relationship between pressure-variation amplitude Δp_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 Δp versus time for a sound wave, determine the amplitude Δp_m and the period *T*.

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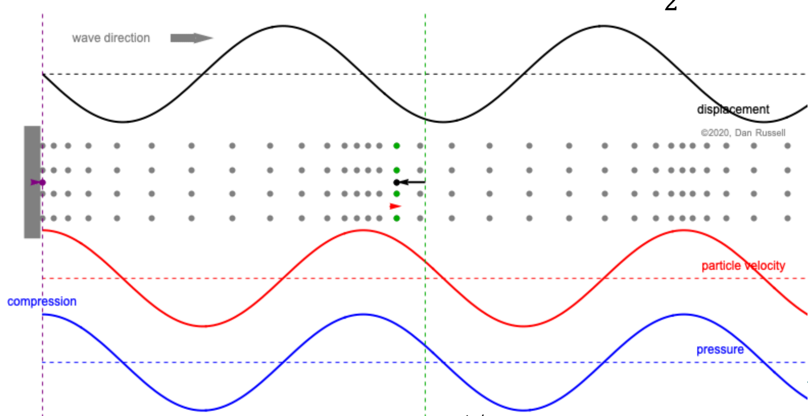
17-2 Traveling Sound Waves (4 of 6)

A sound wave is a **pressure wave**, that is caused by a **longitudinal displacement** of a mass element in a medium.

Pressure and displacement are **out of phase** by $\frac{\pi}{2}$.



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17-2 Traveling Sound Waves (5 of 6)

Longitudinal displacement $s(x,t)$ of a sound wave is given by

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

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

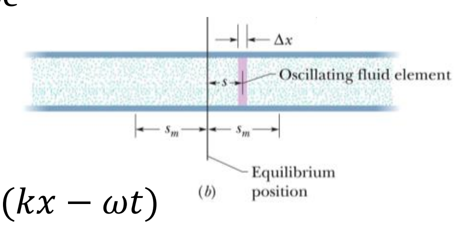
17-2 Traveling Sound Waves (6 of 6)

Pressure: The sound wave also causes a pressure change Δp of the medium from the equilibrium pressure:

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

This pressure wave is related to the displacement from the stress (pressure) – volume strain relationship. Consider a sound wave in an air-filled tube

$$\Delta p = -B\frac{\Delta V}{V}$$
$$= -B\frac{A\Delta s}{A\Delta x}$$
$$= -B\frac{\partial s}{\partial x} = Bks_m \sin(kx - \omega t)$$



17-2 Traveling Sound Waves (6 of 6)

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

Thus, comparing with the last results

$$\Delta p = -B\frac{\Delta V}{V} = -B\frac{\partial s}{\partial x} = Bks_m \sin(kx - \omega t)$$

and recall that the speed of sound is

$$v^2 = \frac{B}{\rho}$$

and the relation $kv = \omega$, we have the pressure amplitude is related to the displacement amplitude as

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

17-3 Interference (1 of 6)

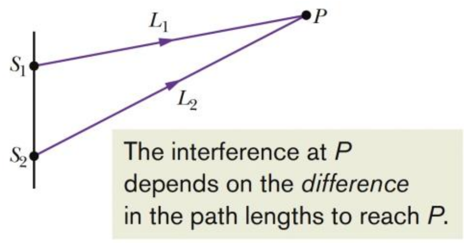
17.14 If two waves with the same wavelength begin in phase but reach a common point by traveling along different paths, calculate their phase difference ϕ at the point by relating the path length difference ΔL to the wavelength λ.

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.

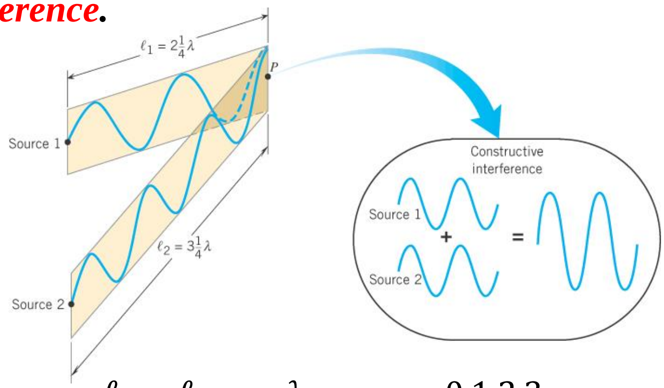
17-3 Interference (2 of 6)

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.



17-3 Interference (2 of 6)

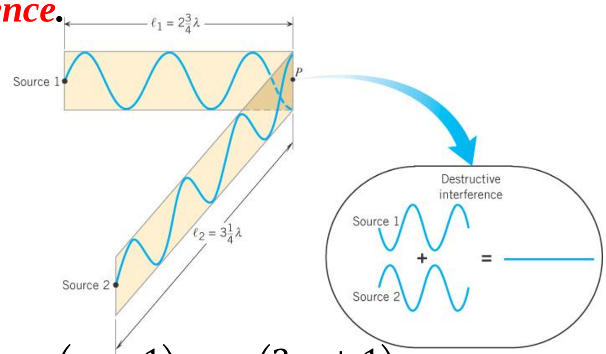
The waves emitted by the sources start out in phase and arrive at point P in phase, leading to ***constructive interference***.



$$\ell_2 - \ell_1 = m\lambda \qquad m = 0,1,2,3,\ldots$$

17-3 Interference (2 of 6)

The waves emitted by the sources start out in phase and arrive at point P out of phase, leading to ***destructive interference***.

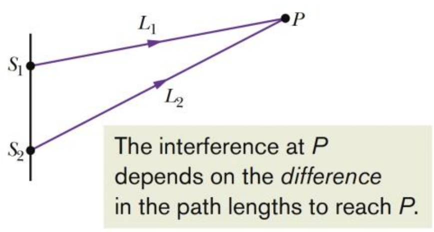


$$\ell_2 - \ell_1 = \left(m + \frac{1}{2}\right)\lambda = \left(\frac{2m+1}{2}\right)\lambda \qquad m = 0,1,2,3,\ldots$$

17-3 Interference (4 of 6)

Path Length Difference

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



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

where ΔL is their **path length difference**.

17-3 Interference (5 of 6)

- **Fully constructive interference** occurs when ϕ is an integer multiple of 2π

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

and, equivalently, when ΔL is related to wavelength λ by

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

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17-3 Interference (5 of 6)

- **Fully destructive interference** occurs when ϕ is an odd multiple of π

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

and, equivalently, when ΔL is related to wavelength λ by

$$\frac{\Delta L}{\lambda} = \frac{1}{2},\frac{3}{2},\frac{5}{2}\ldots \quad \text{(fully constructive interference).}$$

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17-4 Intensity and Sound Level (1 of 6)

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.

17-4 Intensity and Sound Level (2 of 6)

17.21 Apply the relationship between the sound level β, the sound intensity I, and the standard reference intensity I_0.

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

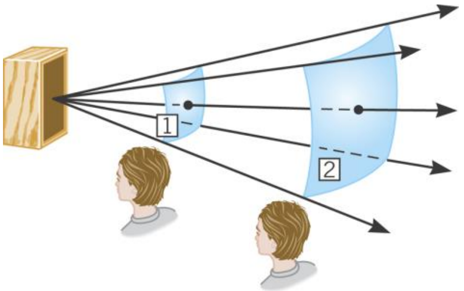
17.23 Relate the change in a sound level to the change in sound intensity.

17-4 Intensity and Sound Level (3 of 6)

- 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

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

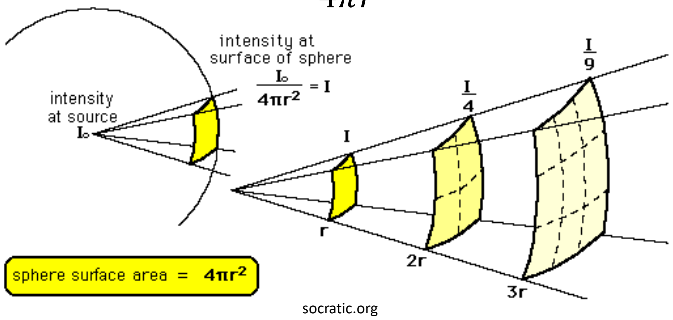
where P is the time rate of energy transfer (**power**) of the sound wave and A is the area of the surface intercepting the sound.



17-4 Intensity and Sound Level (4 of 6)

- 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,

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



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17-4 Intensity and Sound Level (3 of 6)

- The intensity I is related to the displacement amplitude s_m of the sound wave by

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

- Recall the similarity with average power of wave traveling on a string

$$P_{avg} = 2\left(\frac{dK}{dt}\right)_{avg} = \frac{1}{2}\mu v \omega^2 y_m^2$$

17-4 Intensity and Sound Level (5 of 6)

The Decibel Scale

- The sound level β in decibels (dB) is defined as

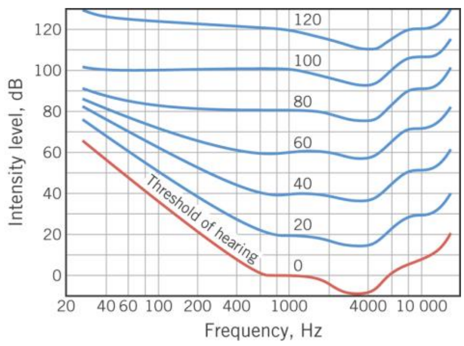
$$\beta = (10 \text{ dB}) \log \frac{I}{I_0}.$$

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

17-4 Intensity and Sound Level (6 of 6)

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



17-5 Sources of Musical Sound (1 of 3)

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.

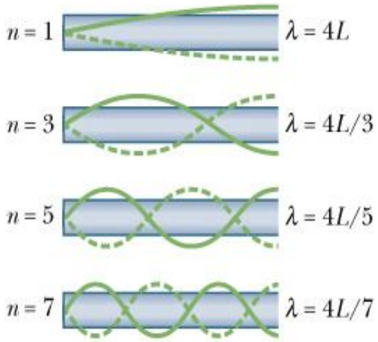
17.27 For any given harmonic and for a pipe with only one open end or with two open ends, apply the relationships between the pipe length L, the speed of sound v, the wavelength λ the harmonic frequency f, and the harmonic number n.

17-5 Sources of Musical Sound (2 of 3)

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.

Consider a pipe of length *L*, **open at one end**, **closed at the other end.**

At resonance, a **displacement antinode** at the **open end**, and a **displacement node** at the **closed end.**



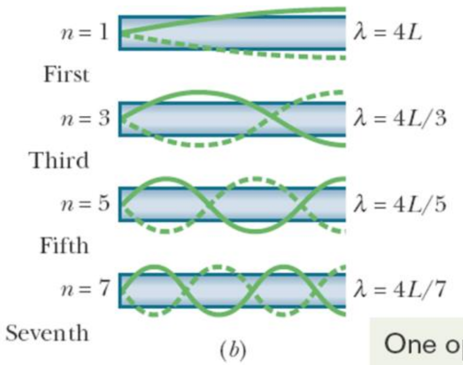
17-5 Sources of Musical Sound (3 of 3)

One Open End.

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

$$f_n = \frac{v}{\lambda} = \frac{nv}{4L}$$

$$n = 1,3,5, \ldots$$



One open end—only *odd* harmonics

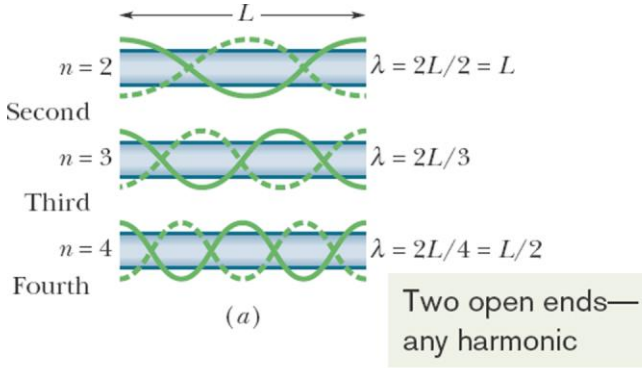
17-5 Sources of Musical Sound (2 of 3)

Two Open Ends or Two Closed Ends

A pipe open at both ends (anti node at both ends) and closed at both ends (node both ends) will resonate at frequencies

$$f_n = \frac{v}{\lambda} = \frac{nv}{2L}$$

$$n = 1,2,3, \ldots$$



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17-5 Sources of Musical Sound (5 of 6)

Example

The water level in a vertical glass tube 1.00 m long can be adjusted to any position in the tube. A tuning fork vibrating at 686 Hz is held just over the open top end of the tube. At what positions of the water level will there be a resonance?

Let L be the length of the air column. Then the condition for resonance is:

$$f_n = n\frac{v}{4L} \text{ or } L_n = \frac{nv}{4f} \qquad n = 1,3,5,\ldots$$

$$L_n = n\frac{343}{4 \times 686} = \frac{1}{8}, \frac{3}{8}, \frac{5}{8}, \frac{7}{8} m$$

$$L_{water} = 1.0 - L_n = 0.875, \; 0.625, \; 0.375, \; 0.125m$$

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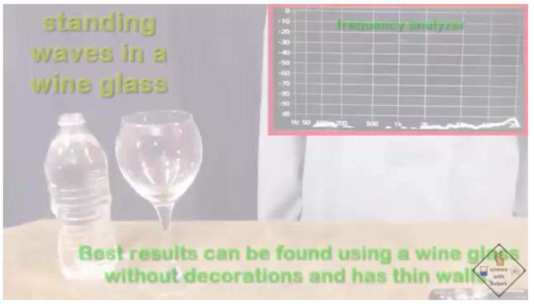
17-5 Sources of Musical Sound (5 of 6)

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.



17-6 Beats (1 of 2)

Learning Objectives

17.28 Explain how beats are produced.

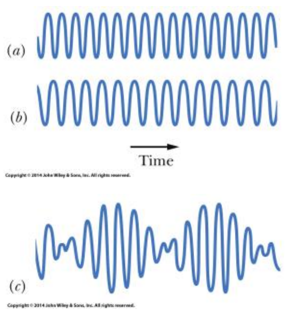
17.29 Add the displacement equations for two sound waves of the same amplitude and slightly different angular frequencies to find the displacement equation of the resultant wave and identify the time-varying amplitude.

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 (2 of 2)

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

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



17-7 The Doppler Effect (1 of 5)

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.

17-7 The Doppler Effect (2 of 5)

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.

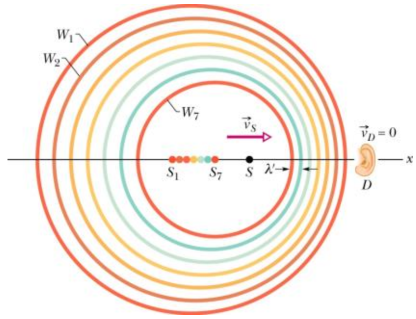
17-7 The Doppler Effect (3 of 5)

The Doppler Effect occurs when there is a **relative motion** between the source and the detector.

The Doppler Effect: the frequency change (either increase or decrease) related to the **motions** of the **source** or/and **detector**

In the following, the **speed** is measured with respect to **the air**, through which the sound wave travels

17-7 The Doppler Effect (3 of 5)



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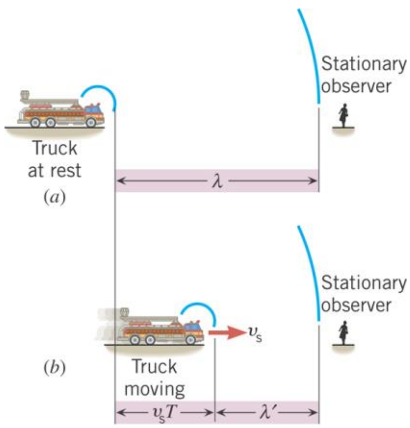
17-7 The Doppler Effect (3 of 5)

Source is moving



$$\lambda' = \lambda - v_s T$$

$$f_o = \frac{v}{\lambda'} = \frac{v}{\lambda - v_s T} = \frac{v}{v/f_s - v_s/f_s}$$

$$v = \lambda f_s$$

$$f_o = f_s\left(\frac{1}{1 - v_s/v}\right)$$ ***source moving toward a stationary observer***

$$f_o = f_s\left(\frac{1}{1 + v_s/v}\right)$$ ***source moving away from a stationary observer***

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17-7 The Doppler Effect (3 of 5)

Example

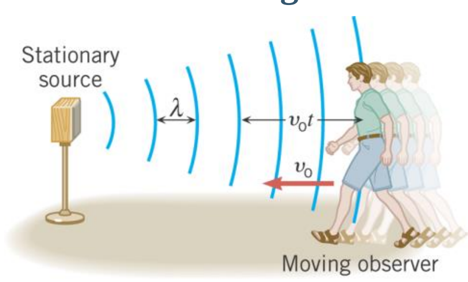
A high-speed train is traveling at a speed of 44.7 m/s when the engineer sounds the 415-Hz warning horn. The speed of sound is 343 m/s. What are the frequency of the sound, as perceived by a person standing at the crossing, when the train is (a) approaching and (b) leaving the crossing?

approaching $$f_o = (415\text{ Hz})\left(\frac{1}{1-\frac{44.7\text{ m/s}}{343\text{ m/s}}}\right) = 477\text{ Hz}$$

leaving $$f_o = (415\text{ Hz})\left(\frac{1}{1+\frac{44.7\text{ m/s}}{343\text{ m/s}}}\right) = 367\text{ Hz}$$

17-7 The Doppler Effect (3 of 5)

Observer is moving



$$f_o = f_s + \frac{v_o}{\lambda} = f_s\left(1 + \frac{v_o}{f_s \lambda}\right)$$

$$= f_s\left(1 + \frac{v_o}{v}\right)$$

Observer moving towards stationary source $$f_o = f_s\left(1 + \frac{v_o}{v}\right)$$

Observer moving away from stationary source $$f_o = f_s\left(1 - \frac{v_o}{v}\right)$$

17-7 The Doppler Effect (4 of 5)

General Case

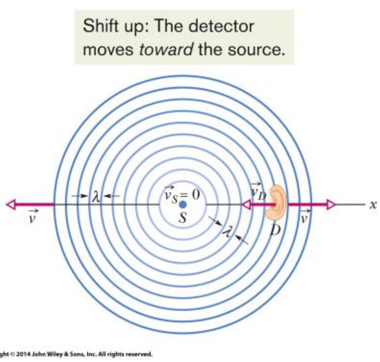
Numerator: plus sign applies when observer moves towards the source

$$f_o = f_s\left(\frac{1 \pm \frac{v_o}{v}}{1 \mp \frac{v_s}{v}}\right)$$

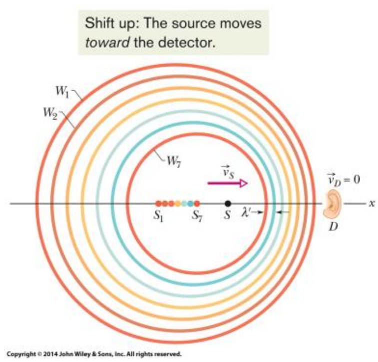
Denominator: minus sign applies when source moves towards the observer

17-7 The Doppler Effect (5 of 5)

Detector Moving Source Stationary



Source Moving Detector Stationary



17-8 Supersonic Speeds, Shock Waves (1 of 3)

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.

17.37 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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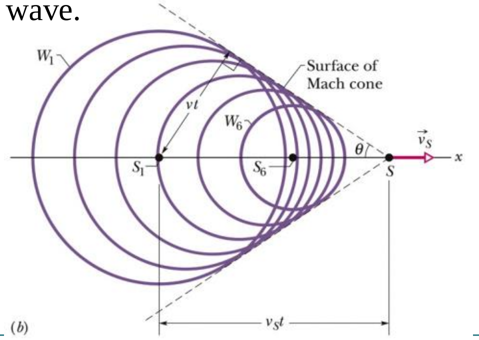
17-8 Supersonic Speeds, Shock Waves (3 of 3)

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.



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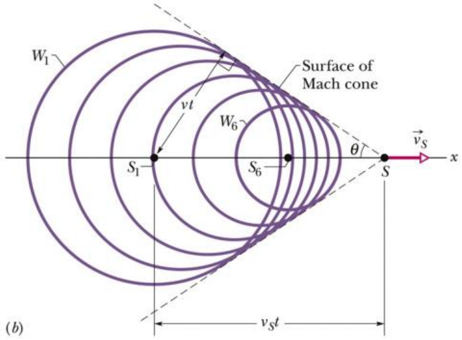
17-8 Supersonic Speeds, Shock Waves (2 of 3)

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 θ of the Mach cone is given by



$$\sin\theta = \frac{vt}{v_S t} = \frac{v}{v_S}$$

17-8 Supersonic Speeds, Shock Waves (3 of 3)

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17 Summary (1 of 4)

Sound Waves

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

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

Interference

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

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

17 Summary (2 of 4)

Sound Intensity

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

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

Sound Level in Decibel

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

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

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

17 Summary (3 of 4)

Standing Waves in Pipes

- A pipe open at both ends

$$f = \frac{v}{\lambda} = \frac{nv}{2L}, \quad n = 1, 2, 3, \ldots,$$ **Equation (17-39)**

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

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

17 Summary (4 of 4)

The Doppler Effect

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

$$f' = f \frac{v \pm v_D}{v \pm v_S}$$ **Equation (17-47)**

Sound Intensity

- The half-angle θ of the Mach cone is given by

$$\sin\theta = \frac{v}{v_S}$$ **Equation (17-57)**

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