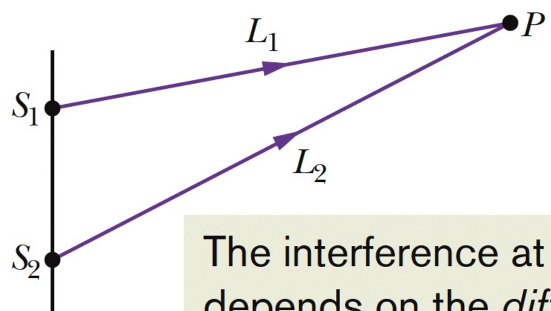
Path Length Difference



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 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**.

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

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

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

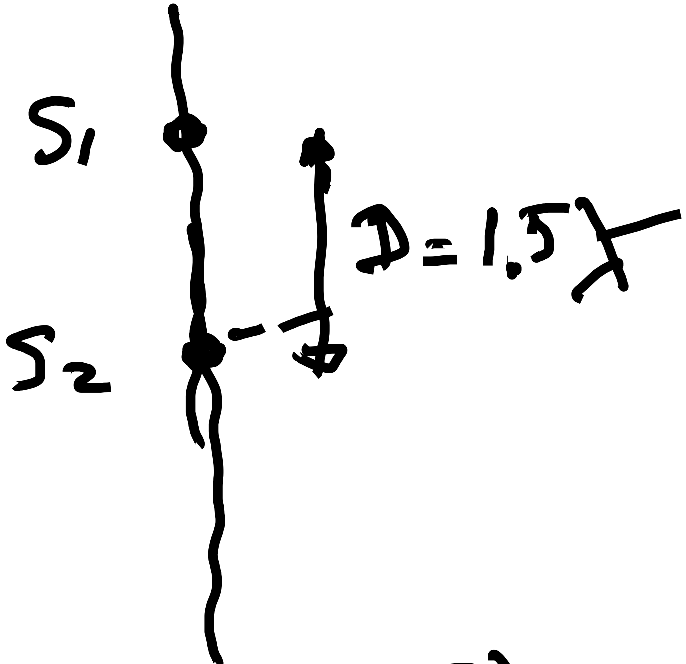
$$\frac{\Delta L}{\lambda} = 0, 1, 2, \ldots \quad \text{(fully constructive interference).}$$

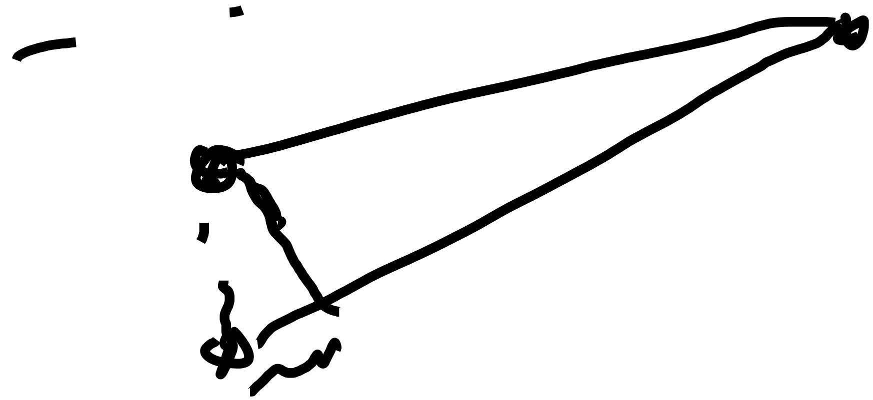
- **Fully destructive interference** occurs when ϕ is an odd multiple of π,

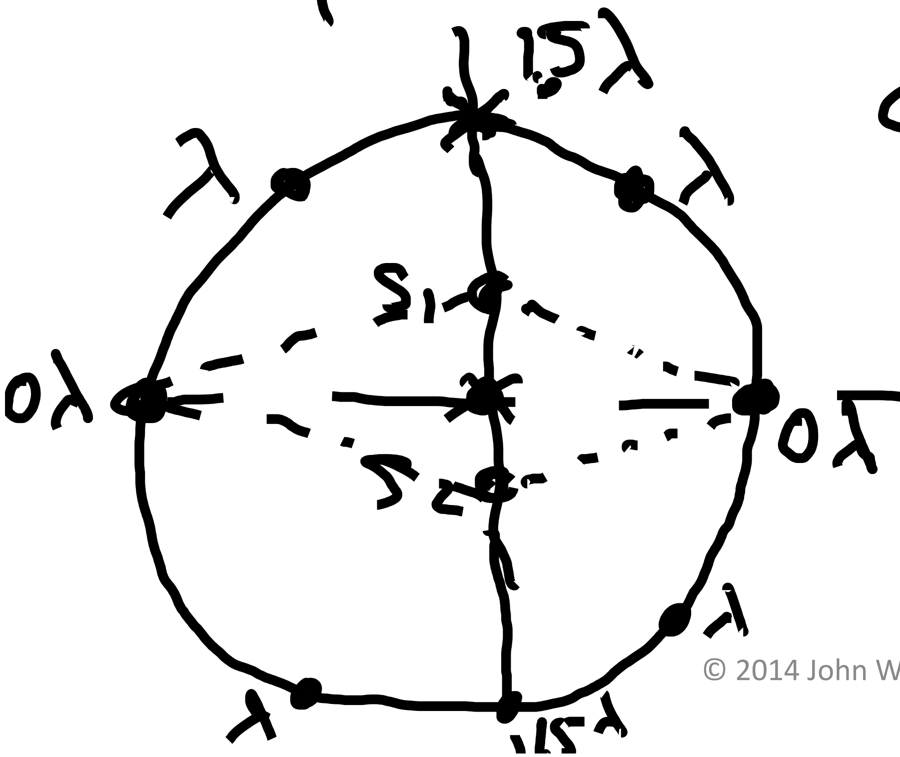
$$\phi = (2m + 1)\pi, \qquad \text{for } m = 0, 1, 2, \ldots,$$

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

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







constructive interference?

6 points

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

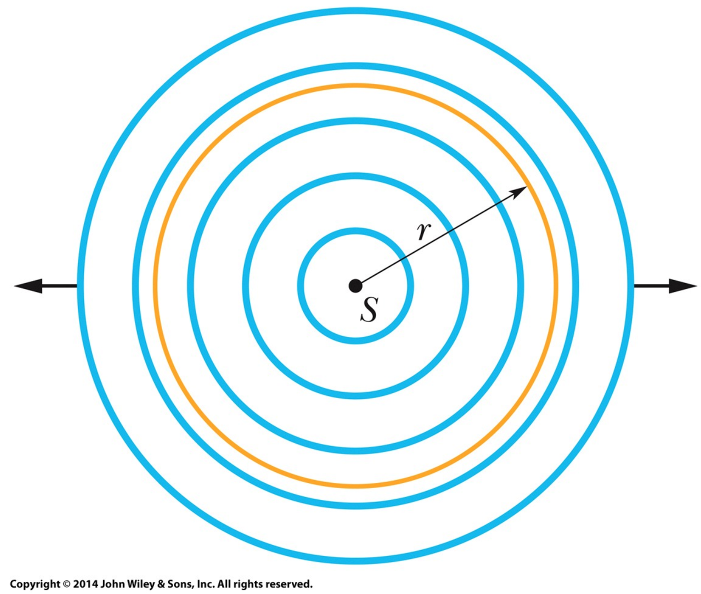
$$I = \tfrac{1}{2}\rho v \omega^2 s_m^2.$$

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*.

17-4 Intensity And Sound Level

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} 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

© Ben Rose

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.

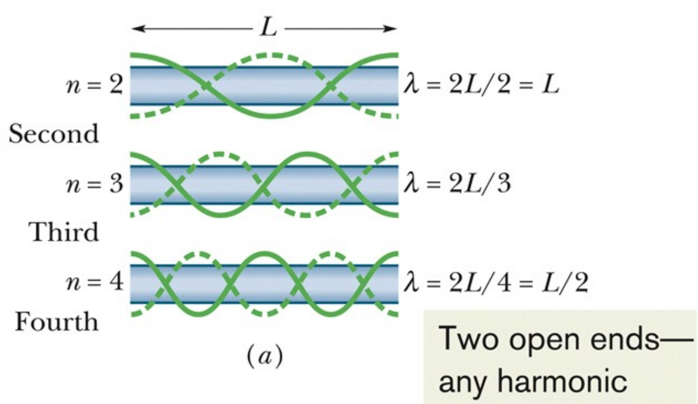
17-5 Sources of Musical Sound

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

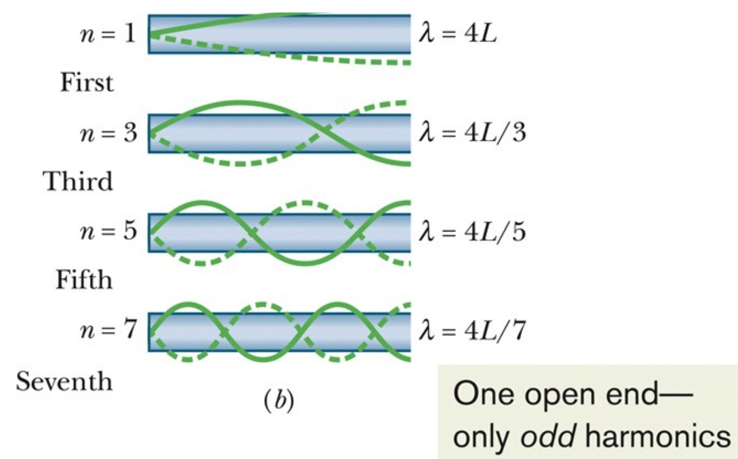
$$f = \frac{v}{\lambda} = \frac{nv}{2L}, \qquad n = 1, 2, 3, \ldots,$$



One Open End.

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

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



$\cos \omega_1 t + \cos \omega_2 t$

17-6 Beats

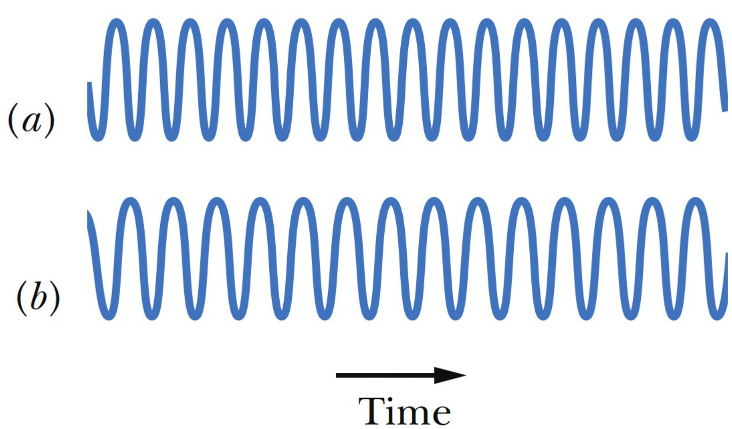
$\cos\alpha + \cos\beta = 2\cos\left(\frac{\alpha-\beta}{2}\right)\cos\frac{\alpha+\beta}{2}$

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

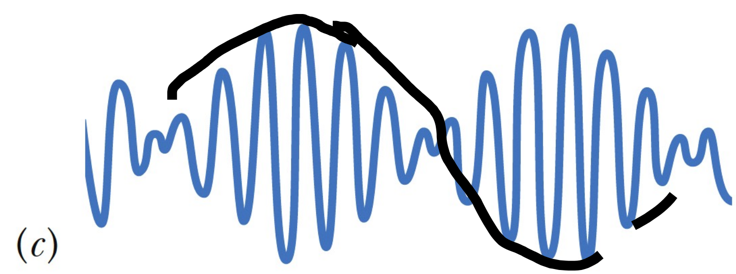
$s = 2 s_m \cos(\omega' t)\cos\omega t$

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

$\omega' = \frac{\omega_1 - \omega_2}{2}$



(a,b) The pressure variations Δp 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

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

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

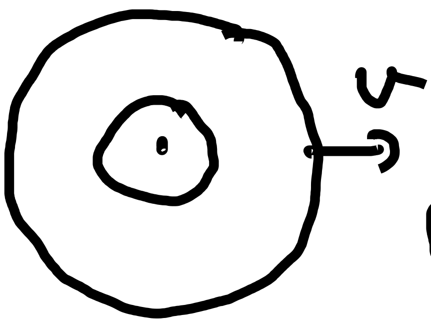
where v is the speed of sound through the air, v_D is the detector's speed relative to the air, and v_S is the source's speed relative to the air.
In the numerator, the plus sign applies when the detector moves toward the source and the minus sign applies when the detector moves away from the source.
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: $f' = f\,\frac{v+v_D}{v} = f\left(1+\frac{v_r}{v}\right)$

Source $f' = f\,\frac{v}{v-v_s} = f\,\frac{1}{1-\frac{v_r}{v}}$

$$\frac{1}{1-\frac{v_r}{v}} = 1+\frac{v_r}{v}+\left(\frac{v_r}{v}\right)^2+\dots$$

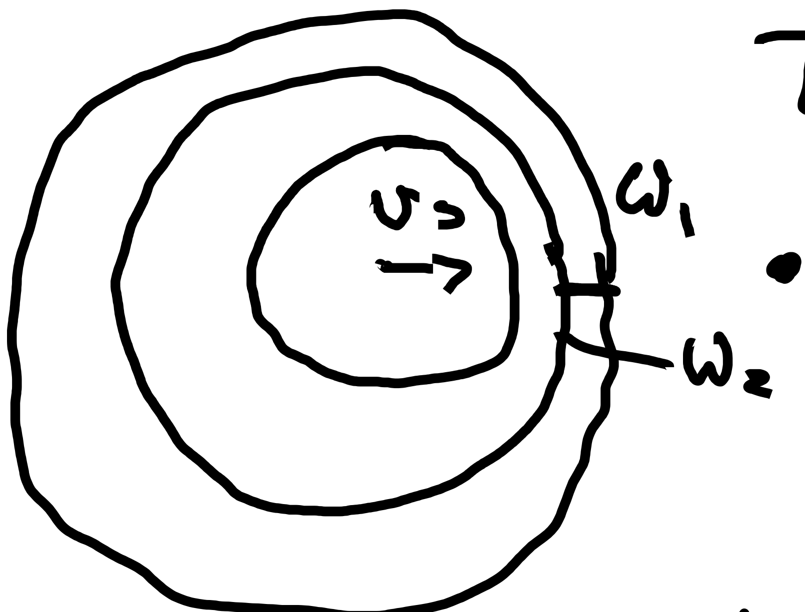
$$\frac{1}{1-x} = 1+x+x^2+\dots$$



$\frac{v_D}{}$

$\frac{vt}{\lambda}$ = # of wavelengths $\qquad v = f\lambda$

$$\frac{\frac{(v+v_D)t}{\lambda}}{t} = f' = \frac{v+v_D}{v}f \qquad \frac{\frac{vt}{\lambda}}{t} = f = \frac{v}{\lambda}$$



T = period

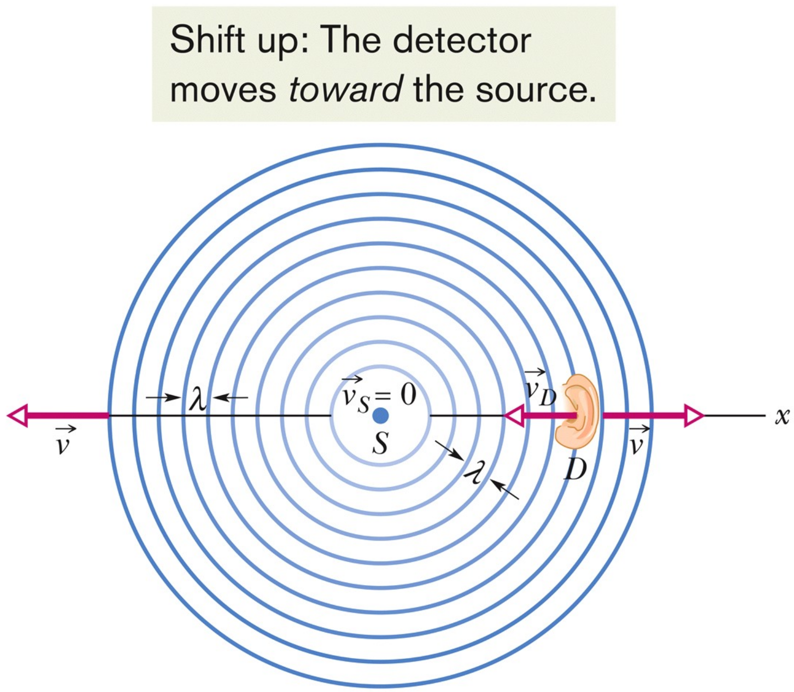
in T, source moved $v_s T$

$$\lambda' = (v - v_s)T$$

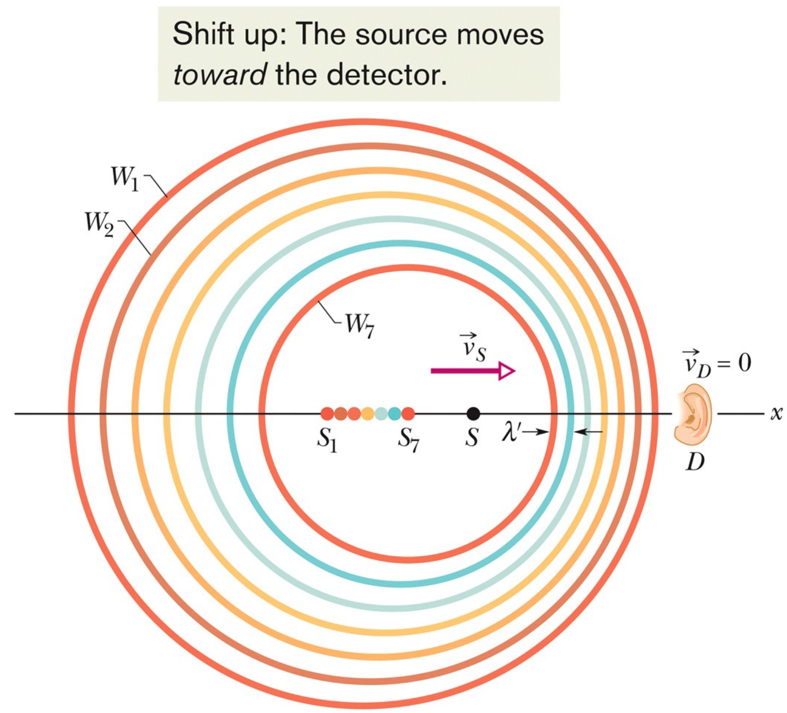
$$f' = \frac{v}{\lambda'} = \frac{v}{(v-v_s)T} = \frac{v}{v-v_s} \cdot f$$

17-7 The Doppler Effect

Detector Moving Source Stationary



Source Moving Detector Stationary

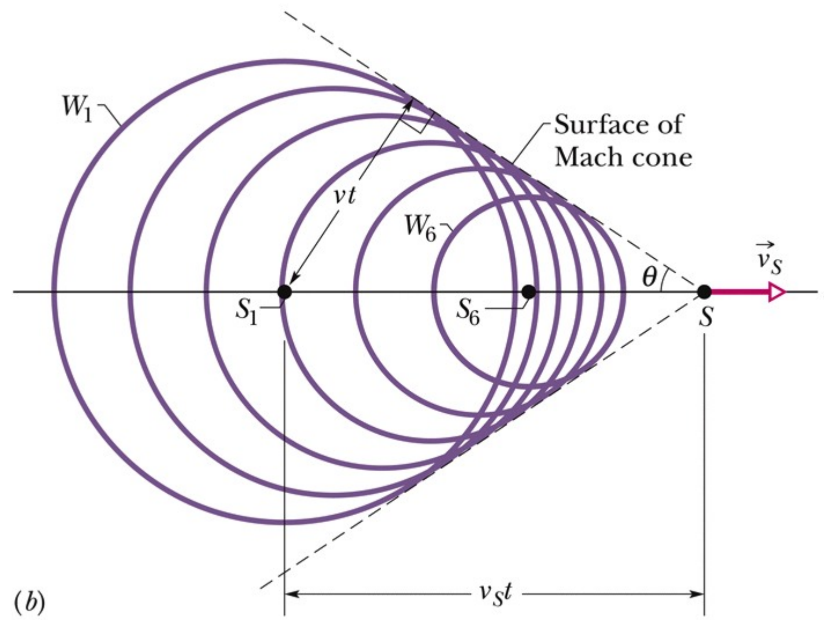


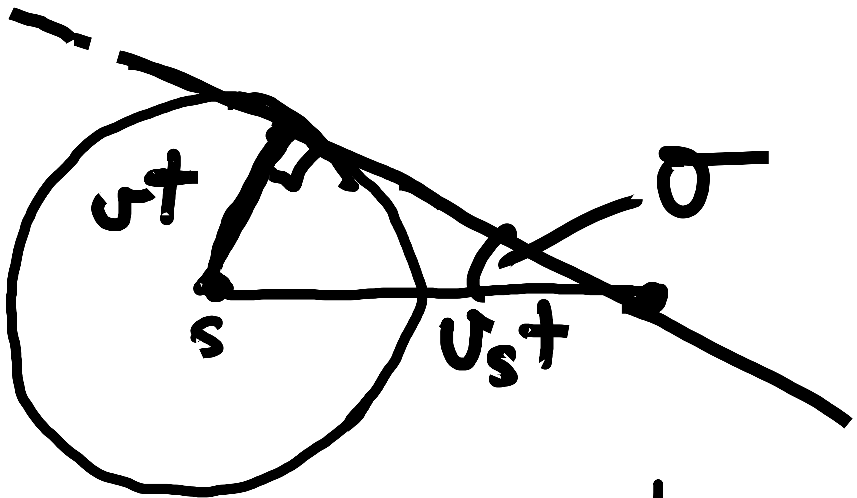
17-8 Supersonic Speeds, Shock Waves

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 ϑ 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 ϑ and is tangent to all the wavefronts.





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

speed of sound in air

$$v = \sqrt{\frac{B}{\rho}} \qquad B = -V\frac{dP}{dV}$$

$$P = \frac{nRT}{V}\ ; \ -\frac{dP}{dV}\Big)_T V = P \implies$$

$$v = \sqrt{\frac{P}{\rho}} \qquad \rho_{air} = 1.225\,kg/m^3$$

$$P = 1.01 \times 10^5\ Pa$$

$$v = \sqrt{\frac{1.225}{1.01\times10^5}}\ m/s = 287\ m/s \longrightarrow 340\,\frac{m}{s}$$

$$PV^\gamma = const \implies P = \frac{const}{V^\gamma}$$

$$B = -V\frac{dP}{dV}\Big)_S = \gamma P \qquad v_s = \sqrt{\gamma}\cdot 287\ m/s$$

$$v_s = 340\ m/s$$

$$\gamma = \frac{C_P}{C_V} = \frac{C_V + R}{C_V} = 1 + \frac{R}{C_V} = 1 + \frac{R}{\frac{5}{2}R} = 1 + \frac{2}{5} = \frac{7}{5}$$

$$v = \sqrt{\frac{\gamma P}{\rho}}$$

$$P = \frac{nRT}{V} \qquad \rho = \frac{M}{V} = \frac{n N_A m}{V}$$

$$\Rightarrow \frac{n}{V} = \frac{\rho}{N_A m} \Rightarrow P = \frac{\rho}{N_A m} k_B N_A T \Rightarrow$$

$$P = \frac{\rho}{m} k_B T \Rightarrow \boxed{v = \sqrt{\frac{\gamma \cdot k_B T}{m}}}$$

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, ϕ 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 as

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

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

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

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

The Doppler Effect

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

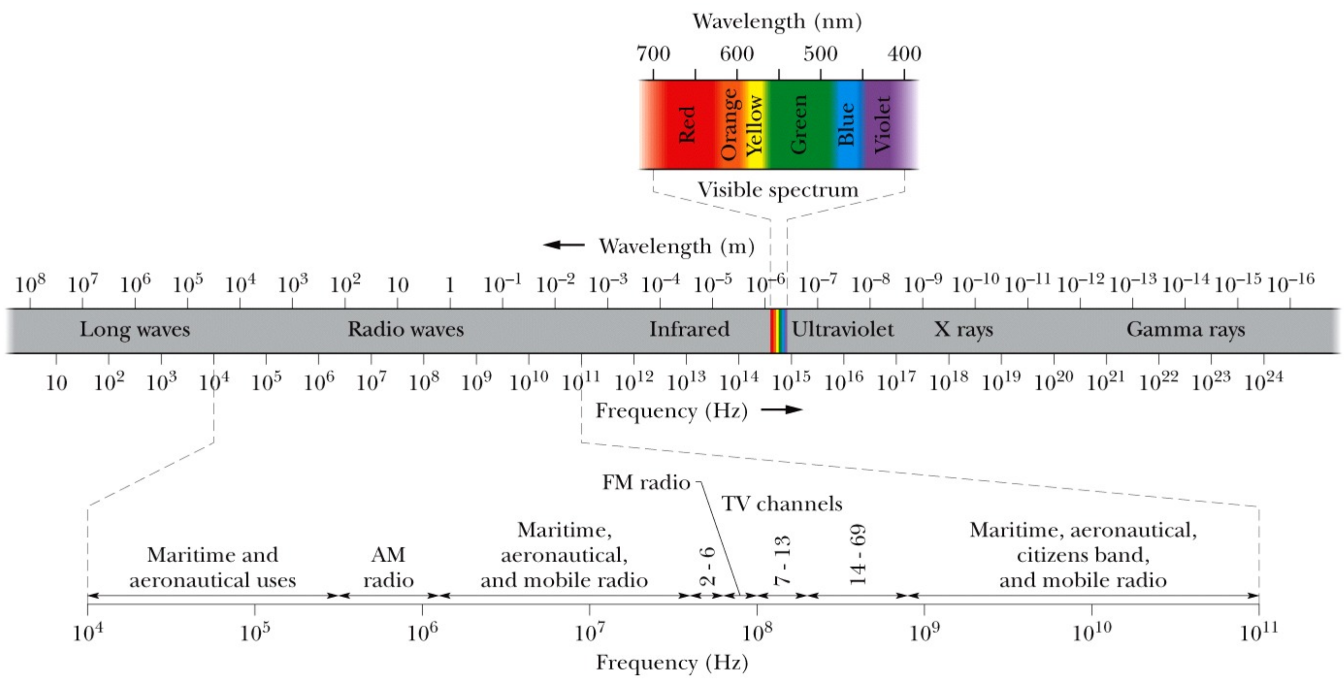
$$f' = f\frac{v \pm v_D}{v \pm v_S} \qquad \textbf{Eq. (17-47)}$$

Sound Intensity

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

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

Maxwell's Rainbow



In Maxwell's time (the mid 1800s), the visible, infrared, and ultraviolet forms of light were the only electromagnetic waves known. Spurred on by Maxwell's work, however, Heinrich Hertz discovered what we now call radio waves and verified that they move through the laboratory at the same speed as visible light, indicating that they have the same basic nature as visible light. As the figure shows, we now know a wide spectrum (or range) of electromagnetic waves: Maxwell's rainbow.