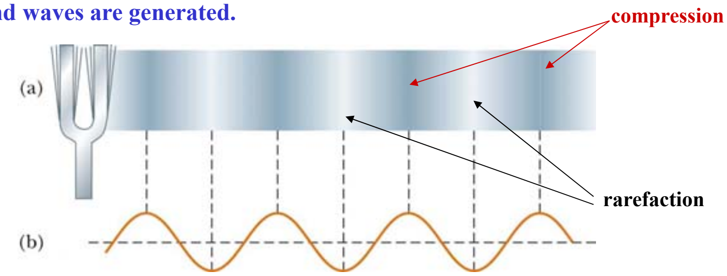
Chapter 17 The Physics of Hearing

Sound waves are longitudinal waves traveling through a medium, such as air. The vibration of an object (drum, tuning fork, etc.) leads to alternate regions of high molecular density (compression) and low molecular density (rarefaction), propagating outward. This is how sound waves are generated.



Audible waves have frequencies in the 20 Hz to 20,000 Hz range.
Ultrasound waves have frequencies higher than 20 kHz.

Generating Longitudinal Waves

Energy and Intensity of Sound Waves

Audible sound: 20Hz – 20 kHz
Velocity of sound in air: ~343 m/s

Sound Intensity I is the sound power P per area that passes perpendicularly through a surface:

$$I = P / A$$

The threshold of hearing of the human ear (at 1 kHz) is about 10^{-12} W/m^2, which amounts to a pressure change of a few parts per billion from the atmospheric pressure. This very small sound intensity is arbitrarily defined as the reference point of sound intensity, I_o.

If a source emits sound uniformly in all directions, the intensity at distance r away from the source is

$$I = P / (4\pi r^2)$$

Logarithmic Scale of Sound Intensity: Decibel (dB)

The intensity level β (expressed in decibels) is defined as

$$\beta = (10\,dB)\ \log\left(\frac{I}{I_o}\right)$$

where I_o is the reference intensity "threshold of hearing" (I_o = 1 x 10^{-12} W/m^2.)   Decibel is dimensionless (a number).

The "human ear" works in a logarithmic scale.

22. If a large housefly 3.0 m away from you makes a noise of 40.0 dB, what is the noise level of 1000 flies at that distance, assuming interference has a negligible effect?

Velocity of Sound

Velocity of sound waves in general is given by $v = \sqrt{B/\rho}$

where B is the bulk modulus of the medium and ρ is the density of the medium. For ideal gases, $v = \sqrt{\gamma P/\rho}$

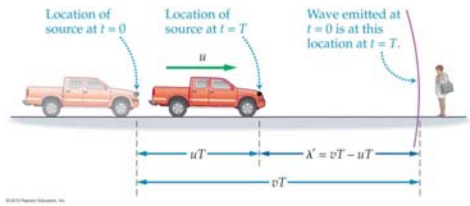
where γ is the ratio of constant volume to constant pressure specific heats and P is the pressure.

Velocity of sound in air is approximately 343 m/s at sea level and 25^{o}C. Sound speed increases with temperature:

$$v_{air} = 331\ (m/s)\ \sqrt{\frac{T}{273}}$$

where T is the absolute temperature

Doppler Effect: Moving Source



Common rule: sound velocity is constant with respect to air.

v = 343 m/s

$$\lambda' = \lambda - u_S\, T$$

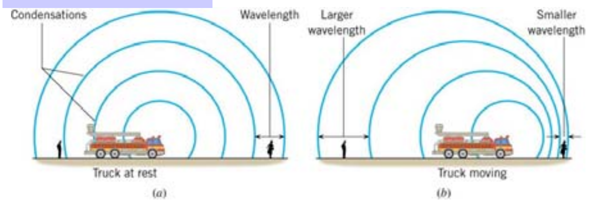
source (s) moving toward stationary observer (o)

$$f_O = \frac{v}{\lambda'} = \frac{f_S \lambda}{\lambda'}$$

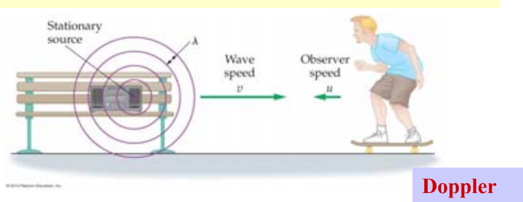
$$f_O = f_S \left(\frac{1}{1 - \frac{u_S}{v}} \right)$$

source (s) moving away from stationary observer (o)

$$f_O = f_S \left(\frac{1}{1 + \frac{u_S}{v}} \right)$$



Doppler Effect: Moving Observer



Doppler

observer moving toward stationary source

$$T' = \frac{\lambda}{v + u_O} \qquad f_O = \frac{1}{T'}$$

$$f_O = f_S \left(1 + \frac{u_O}{v} \right)$$

observer moving away from stationary source

$$f_O = f_S \left(1 - \frac{u_O}{v} \right)$$

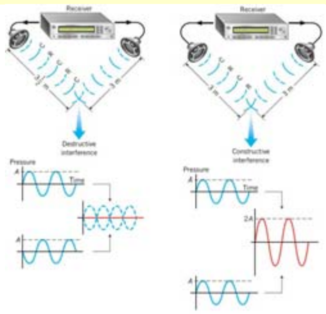
source and observer both moving

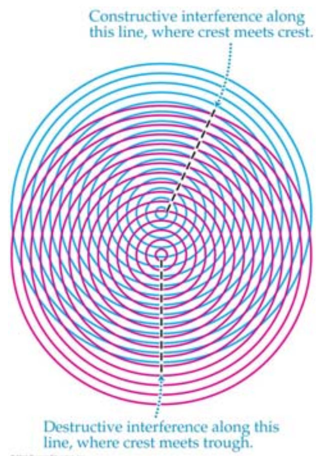
$$f_O = f_S \left(\frac{1 \pm \frac{u_O}{v}}{1 \mp \frac{u_S}{v}} \right)$$

What is the frequency of the alarm of a speeding fire engine, as heard by a firefighter riding in the same vehicle?

Answer: as if the engine were not moving.

Interference of Sound Waves



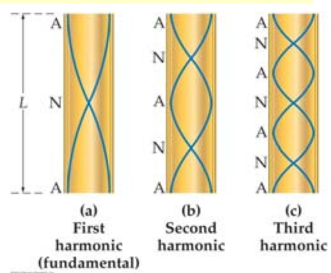


Only coherent sources can produce interference effect. For two wave sources vibrating in phase, a difference in path lengths that is zero or an integer number {1,2,3,..} of wavelengths leads to constructive interference; a difference in path lengths that is a half-integer number {0.5, 1.5, 2.5, ...} of wavelengths leads to destructive interference.

Standing Waves in Air Columns

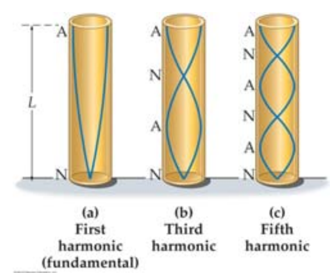
Sound waves exiting the open end of a tube are reflected back. However, the standing wave set up inside the tube has an antinode, rather than a node, on the location of the open end. This means that the standing wave frequencies for a tube of length L, with two open ends, are

$f_n = n\, v / (2\, L)$ n= 1, 2, 3, ...



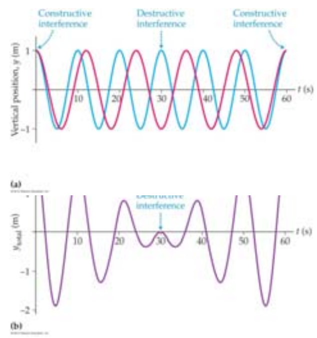
If the tube of length L is sealed on one end. A node is forced to be present at the sealed end, while an antinode exists at the open end. Thus, the natural resonant frequencies are

$f_n = n\, v / (4\, L)$ n = 1, 3, 5, ...



Beats

Two oscillations close in frequency leads to periods of approximate constructive interference and destructive interference. The volume of the sound appears to flip between "large" and "small", forming "beats".



Beats

What is the beat frequency?

Suppose at time t=0, the two primary sounds are "in phase" (maximum). We want to know the next time when the two sounds are again "in phase". The time elapsed, T_{beat}, is then obviously the "period" of the beats. This happens when the sound with the higher frequency (f_1) has gone one full cycle more than the slower wave (f_2).

$$f_1 T_{beat} - f_2 T_{beat} = 1$$

$$T_{beat} = (f_1 - f_2)^{-1}$$

$$f_{beat} = f_1 - f_2$$

$$f_{beat} = | f_1 - f_2 |$$

Example Problems

36. Two eagles fly directly toward one another, the first at 15.0 m/s and the second at 20.0 m/s. Both screech, the first one emitting a frequency of 3200 Hz and the second one emitting a frequency of 3800 Hz. What frequencies do they receive if the speed of sound is 330 m/s?

53. (a) Students in a physics lab are asked to find the length of an air column in a tube closed at one end that has a fundamental frequency of 256 Hz. They hold the tube vertically and fill it with water to the top, then lower the water while a 256-Hz tuning fork is rung and listen for the first resonance. What is the air temperature if the resonance occurs for a length of 0.336 m? (b) At what length will they observe the second resonance (first overtone)?

Summary of Chapter 17

• **Intensity of sound:** $$I = \frac{P}{A}$$

• **Intensity level, in decibels:** $$\beta = 10 \log(I/I_0)$$

• **Doppler effect: change in frequency due to relative motion of sound source and receiver**

$$f' = \left(\frac{1 \pm u_o/v}{1 \mp u_s/v}\right)f$$

• **Standing waves in a half-closed column of air:**

$$f_n = nf_1 = n(v/4L) \qquad n = 1, 3, 5, \ldots$$
$$\lambda_n = \lambda_1/n = 4L/n$$

• **Standing waves in a fully open column of air:**

$$f_n = nf_1 = n(v/2L) \qquad n = 1, 2, 3, \ldots$$
$$\lambda_n = \lambda_1/n = 2L/n$$