Chapter 14

Sound

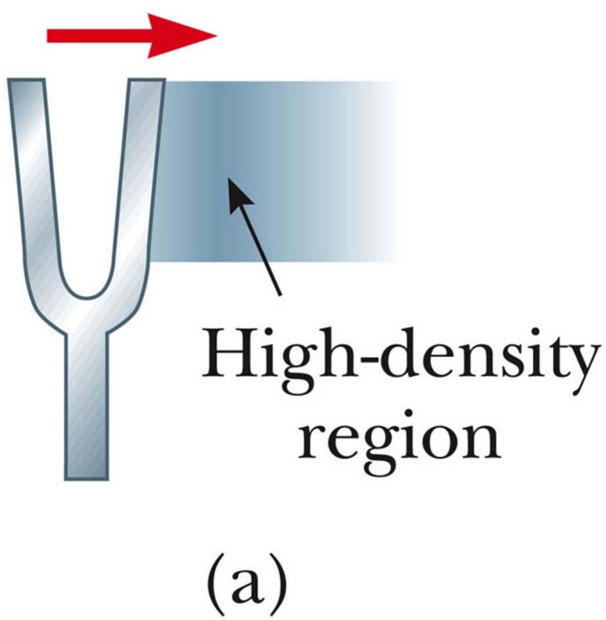
Producing a Sound Wave

- Sound waves are longitudinal waves traveling through a medium
- A tuning fork can be used as an example of producing a sound wave

This picture is not in the new version, but fits very nicely. Either omit or see if it can stay.

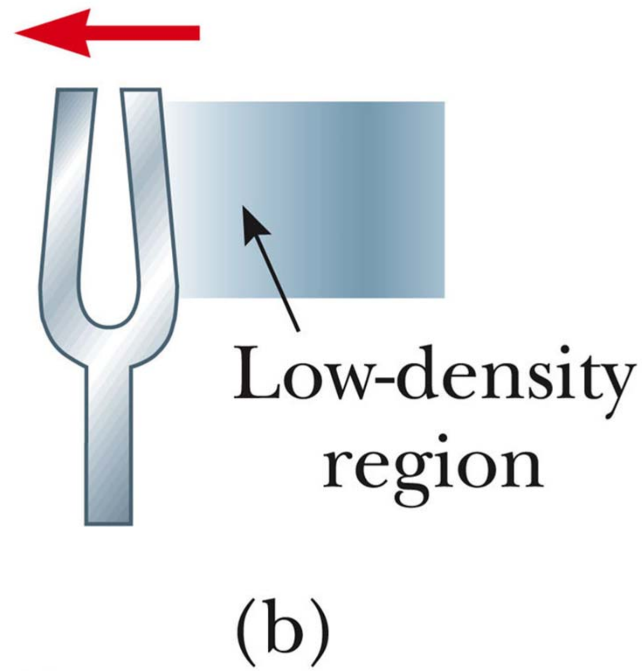
Using a Tuning Fork to Produce a Sound Wave

- A tuning fork will produce a pure musical note
- As the tines vibrate, they disturb the air near them
- As the tine swings to the right, it forces the air molecules near it closer together
- This produces a high density area in the air
  - This is an area of compression

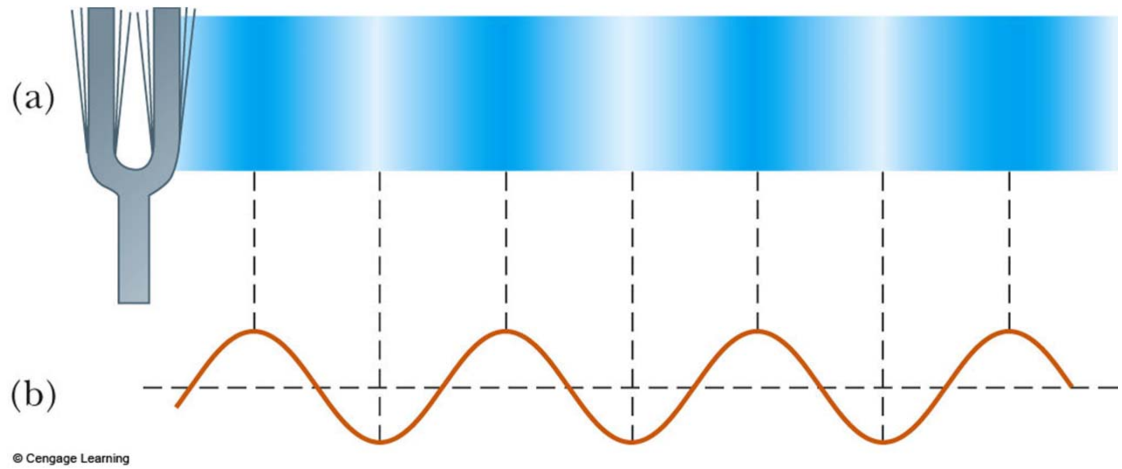


Using a Tuning Fork, cont.

- As the tine moves toward the left, the air molecules to the right of the tine spread out
- This produces an area of low density
  - This area is called a *rarefaction*



Using a Tuning Fork, final



- As the tuning fork continues to vibrate, a succession of compressions and rarefactions spread out from the fork
- A sinusoidal curve can be used to represent the longitudinal wave
  - Crests correspond to compressions and troughs to rarefactions

Categories of Sound Waves

- Audible waves
  - Lay within the normal range of hearing of the human ear
  - Normally between 20 Hz to 20,000 Hz
- Infrasonic waves
  - Frequencies are below the audible range
  - Earthquakes are an example
- Ultrasonic waves
  - Frequencies are above the audible range
  - Dog whistles are an example

Applications of Ultrasound

- Can be used to produce images of small objects
- Widely used as a diagnostic and treatment tool in medicine
  - Ultrasonic flow meter to measure blood flow
  - May use *piezoelectric* devices that transform electrical energy into mechanical energy
    - Reversible: mechanical to electrical
  - Ultrasounds to observe babies in the womb
  - Cavitron Ultrasonic Surgical Aspirator (CUSA) used to surgically remove brain tumors
- Ultrasonic ranging unit for cameras

Speed of Sound in a Liquid

- In a liquid, the speed depends on the liquid's compressibility and inertia

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

  - B is the Bulk Modulus of the liquid
  - ρ is the density of the liquid
  - Compares with the equation for a transverse wave on a string

Speed of Sound in a Solid Rod

- The speed depends on the rod's compressibility and inertial properties

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

  - Y is the Young's Modulus of the material
  - ρ is the density of the material

Speed of Sound, General

$$v = \sqrt{\frac{\text{elastic property}}{\text{inertial property}}}$$

- The speed of sound is higher in solids than in gases
  - The molecules in a solid interact more strongly
- The speed is slower in liquids than in solids
  - Liquids are more compressible

Speed of Sound in Air

$$v = \left(331\,\frac{m}{s}\right)\sqrt{\frac{T}{273\,K}}$$

- 331 m/s is the speed of sound at 0° C
- T is the absolute temperature

Speeds of Sound in Various Media

Medium	v (m/s)
Gases	
Air (0°C)	331
Air (100°C)	386
Hydrogen (0°C)	1 290
Oxygen (0°C)	317
Helium (0°C)	972
Liquids at 25°C	
Water	1 490
Methyl alcohol	1 140
Sea water	1 530
Solids	
Aluminum	5 100
Copper	3 560
Iron	5 130
Lead	1 320
Vulcanized rubber	54

Example

An explosion occurs 275 m above an 867-m-thick ice sheet the lies over ocean water. If the air temperature is $-7^{o}C$, how long does it take the sound to reach a research vessel 1250 m below the ice? Neglect any changes of bulk modulus and density with temperature and depth. Use $B_{ice} = 9.2 \times 10^{9}$ Pa, density of ice = 917 kg/m^3 and $v_{water} = 1530$ m/s

Example

A violin string 16.0 cm long and fixed at both ends oscillates in its n=1 mode. The speed of the waves on the string is 225 m/s and the speed of the sound in air is 343 m/s. What is the wavelength of the emitted sound wave?

Intensity of Sound Waves

- The average *intensity* I of a wave on a given surface is defined as the rate at which the energy flows through the surface divided by the surface area, A

$$I = \frac{1}{A}\frac{\Delta E}{\Delta t} = \frac{\wp}{A}$$

- The direction of energy flow is perpendicular to the surface at every point
- The rate of energy transfer is the power
- Units are W/m^2

Various Intensities of Sound

- Threshold of hearing
  - Faintest sound most humans can hear
  - About 1×10^{-12} W/m^2
- Threshold of pain
  - Loudest sound most humans can tolerate
  - About 1 W/m^2
- The ear is a very sensitive detector of sound waves
  - It can detect pressure fluctuations as small as about 3 parts in 10^{10}

Intensity Level of Sound Waves

- The sensation of loudness is logarithmic in the human hear
- β is the intensity level or the decibel level of the sound

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

- I_o is the threshold of hearing

Various Intensity Levels

- Threshold of hearing is 0 dB
- Threshold of pain is 120 dB
- Jet airplanes are about 150 dB
- Table 14.2 lists intensity levels of various sounds
  - Multiplying a given intensity by 10 adds 10 dB to the intensity level

Various Intensity Levels

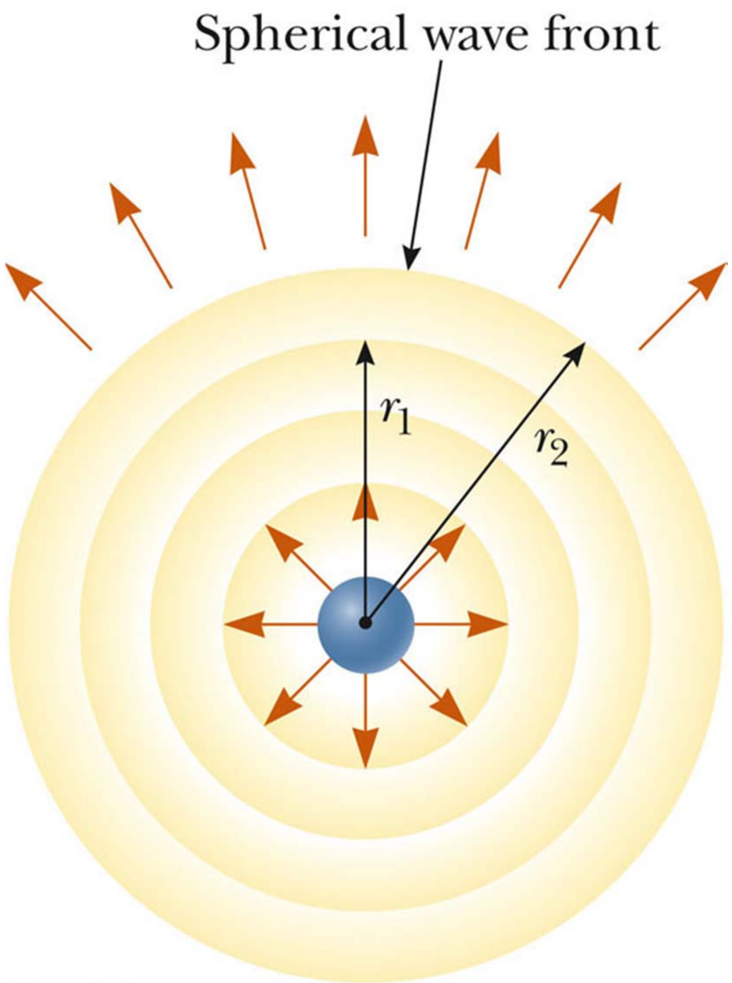
Intensity Levels in Decibels for Different Sources

Source of Sound	β (dB)
Nearby jet airplane	150
Jackhammer, machine gun	130
Siren, rock concert	120
Subway, power mower	100
Busy traffic	80
Vacuum cleaner	70
Normal conversation	50
Mosquito buzzing	40
Whisper	30
Rustling leaves	10
Threshold of hearing	0

Spherical Waves

- A spherical wave propagates radially outward from the oscillating sphere
- The energy propagates equally in all directions
- The intensity is

$$I = \frac{\wp_{av}}{A} = \frac{\wp_{av}}{4\pi r^2}$$



Example

The intensity of a certain sound wave is $6x10^{-8}$ W/m^2. a. Find its intensity level. B. If its intensity is raised by 40 decibels, what is the new intensity in W/m^2?

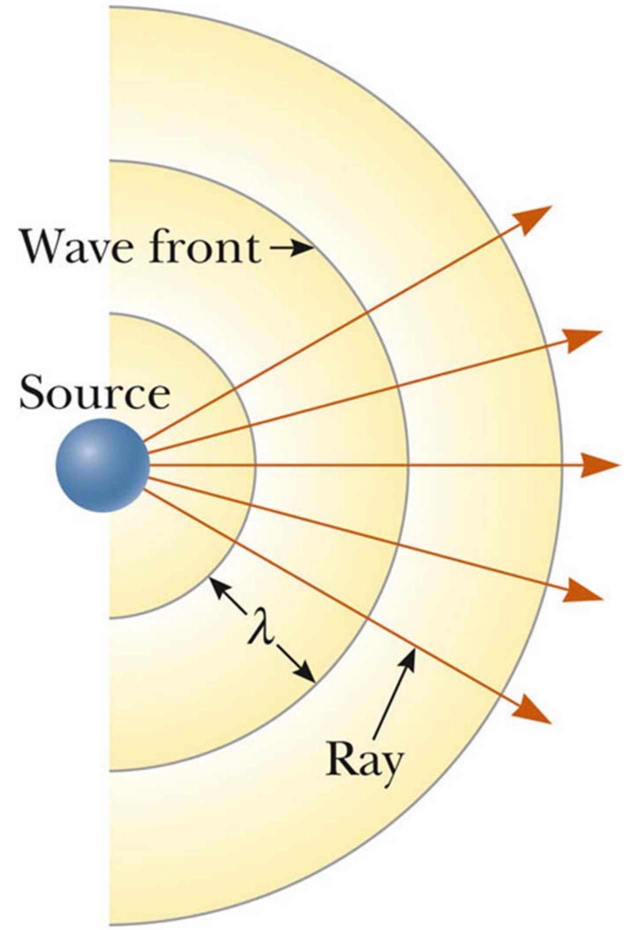
Intensity of a Point Source

- Since the intensity varies as $1/r^2$, this is an *inverse square relationship*
- The average power is the same through any spherical surface centered on the source
- To compare intensities at two locations, the inverse square relationship can be used

$$\frac{I_1}{I_2} = \frac{r_2^2}{r_1^2}$$

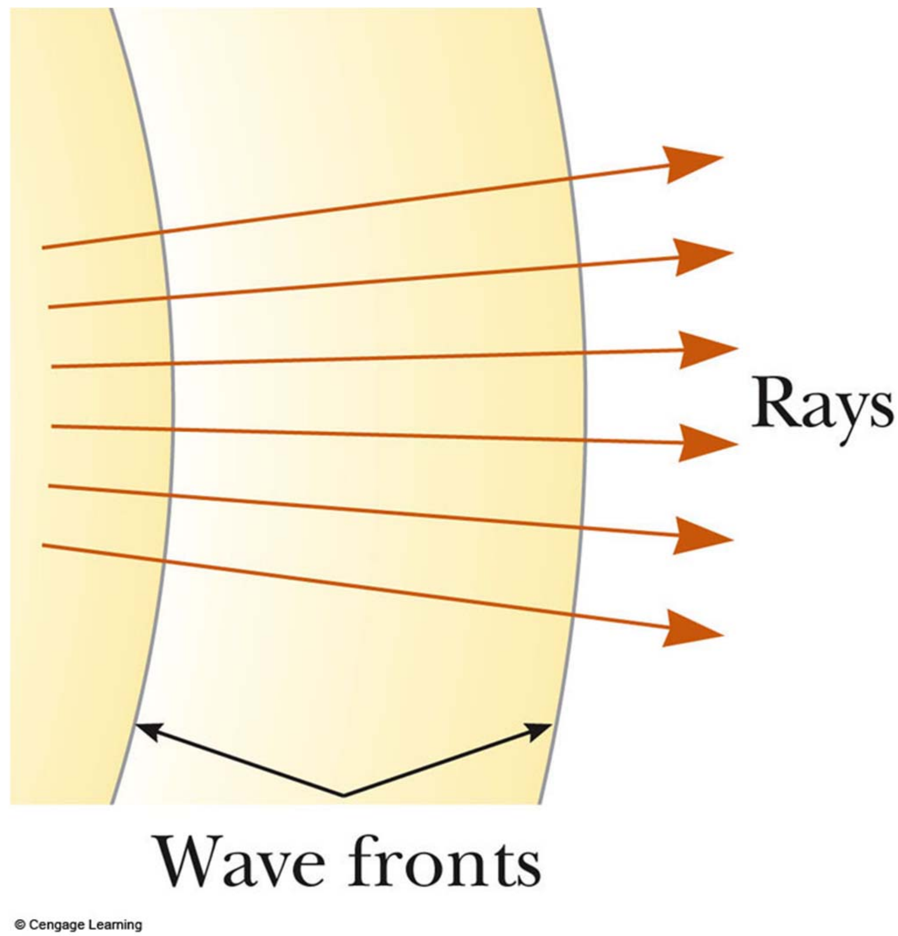
Representations of Waves

- *Wave fronts* are the concentric arcs
  - The distance between successive wave fronts is the wavelength
- *Rays* are the radial lines pointing out from the source and perpendicular to the wave fronts



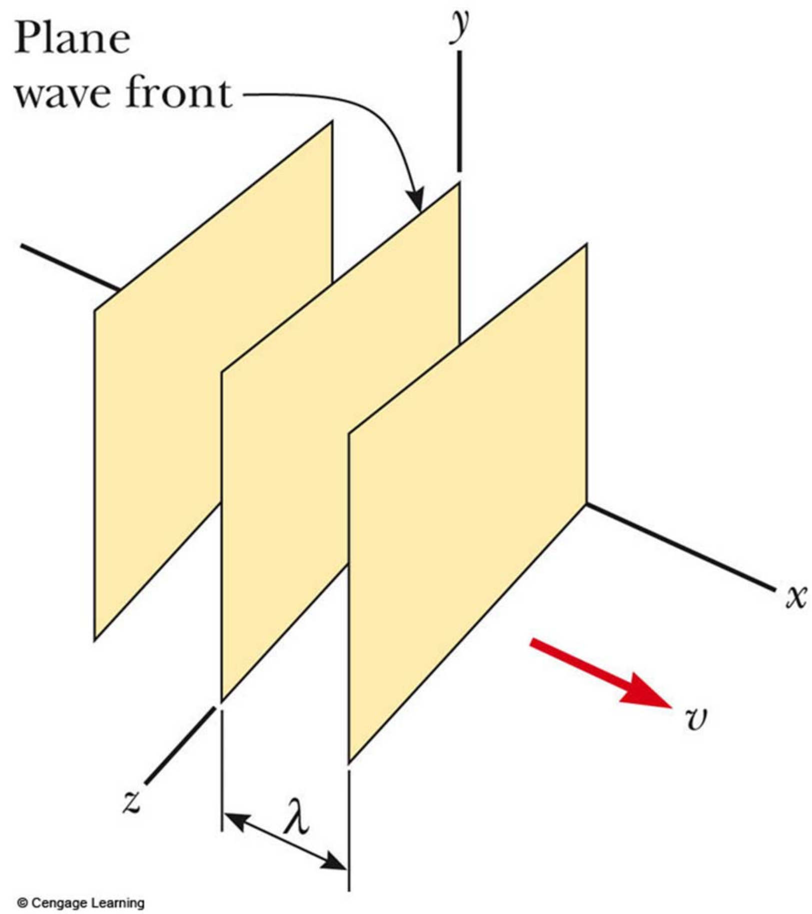
Plane Wave

- Far away from the source, the wave fronts are nearly parallel planes
- The rays are nearly parallel lines
- A small segment of the wave front is approximately a plane wave



Plane Waves, cont

- Any small portion of a spherical wave that is far from the source can be considered a plane wave
- This shows a plane wave moving in the positive x direction
  - The wave fronts are parallel to the yz plane



Doppler Effect

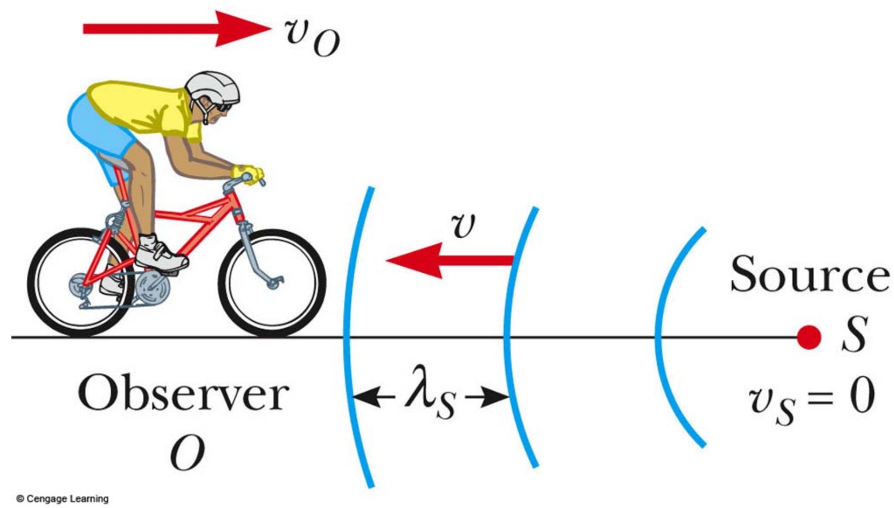
- A Doppler effect is experienced whenever there is relative motion between a source of waves and an observer.
  - When the source and the observer are moving toward each other, the observer hears a higher frequency
  - When the source and the observer are moving away from each other, the observer hears a lower frequency

Doppler Effect, cont.

- Although the Doppler Effect is commonly experienced with sound waves, it is a phenomena common to all waves
- Assumptions:
  - The air is stationary
  - All speed measurements are made relative to the stationary medium

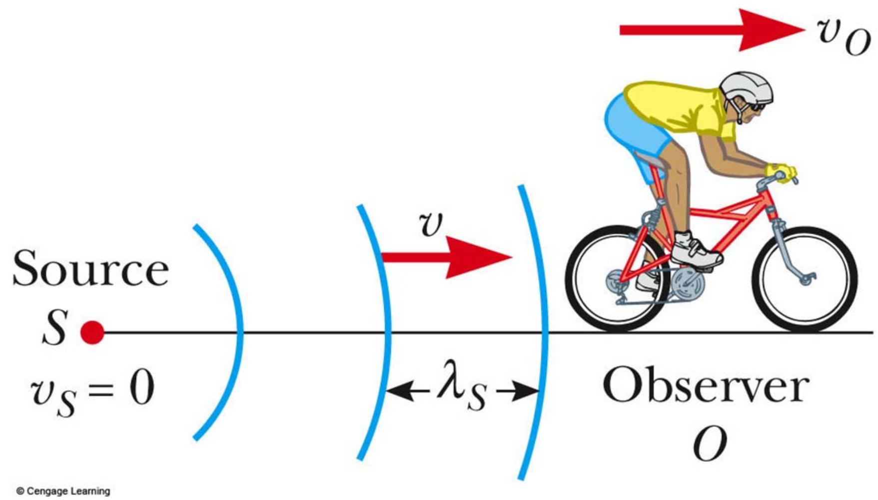
Doppler Effect, Case 1 (Observer Toward Source)

- An observer is moving toward a stationary source
- Due to his movement, the observer detects an additional number of wave fronts
- The frequency heard is increased



Doppler Effect, Case 1 (Observer Away from Source)

- An observer is moving away from a stationary source
- The observer detects fewer wave fronts per second
- The frequency appears lower



Doppler Effect, Case 1 – Equation

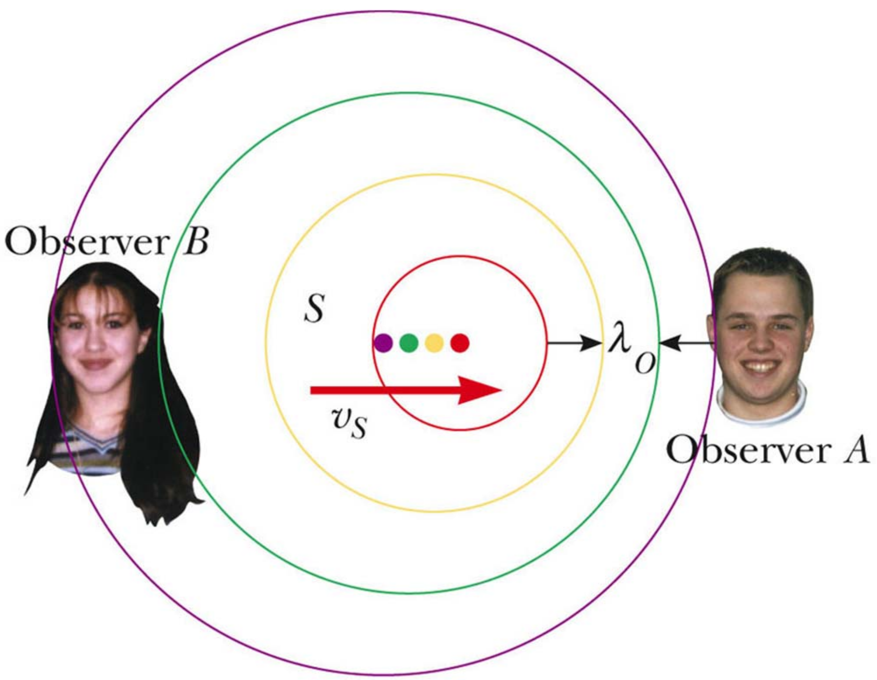
- When moving toward the stationary source, the observed frequency is

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

- When moving away from the stationary source, substitute $-v_o$ for v_o in the above equation

Doppler Effect, Case 2 (Source in Motion)

- As the source moves toward the observer (A), the wavelength appears shorter and the frequency increases
- As the source moves away from the observer (B), the wavelength appears longer and the frequency appears to be lower



(a)

Doppler Effect, Source Moving – Equation

$$f_o = f_s\left(\frac{v}{v - v_s}\right)$$

- Use the $-v_s$ when the source is moving toward the observer and $+v_s$ when the source is moving away from the observer

Doppler Effect, General Case

- Both the source and the observer could be moving

$$f_o = f_s\left(\frac{v + v_o}{v - v_s}\right)$$

- Use positive values of v_o and v_s if the motion is toward
  - Frequency appears higher
- Use negative values of v_o and v_s if the motion is away
  - Frequency appears lower

Example

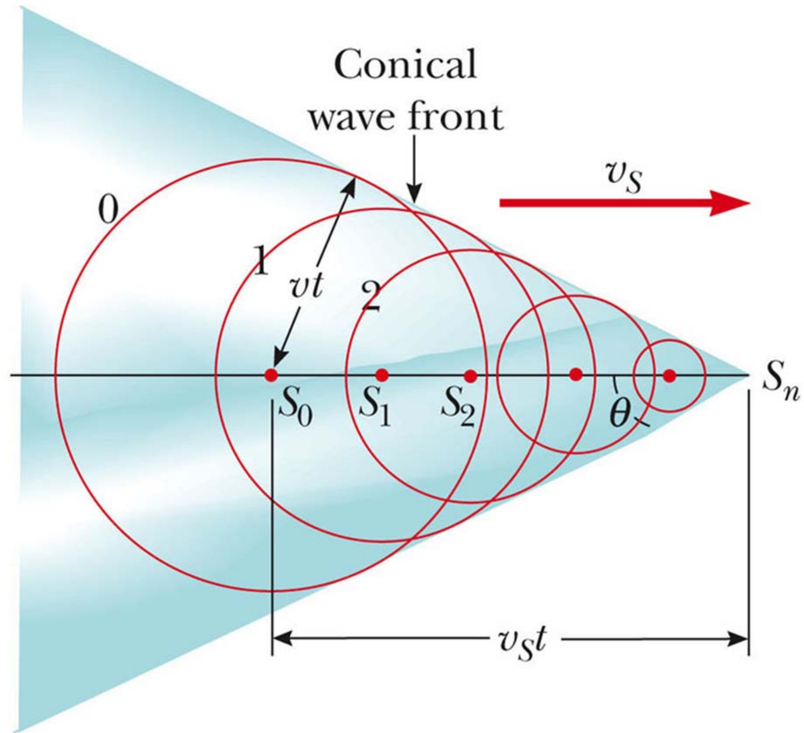
Two cars traveling with the same speed of 25 m/s move directly away from one another. One car sounds a horn whose frequency is 245 Hz. Calculate the frequency heard the driver in the second car.

Doppler Effect, Final Notes

- The Doppler Effect does not depend on distance
  - As you get closer, the intensity will increase
  - The apparent frequency will not change

Shock Waves

- A shock wave results when the source velocity exceeds the speed of the wave itself
- The circles represent the wave fronts emitted by the source



(a)

Shock Waves, cont

- Tangent lines are drawn from S_n to the wave front centered on S_o
- The angle between one of these tangent lines and the direction of travel is given by $\sin \theta = v / v_s$
- The ratio v/v_s is called the *Mach Number*
- The conical wave front is the *shock wave*

Shock Waves, final

- Shock waves carry energy concentrated on the surface of the cone, with correspondingly great pressure variations
- A jet produces a shock wave seen as a fog

(b)

Interference of Sound Waves

- Sound waves interfere
  - **Constructive interference** occurs when the path difference between two waves' motion is zero or some integer multiple of wavelengths
    - **Path difference = $n\lambda$**
  - **Destructive interference** occurs when the path difference between two waves' motion is an odd half wavelength
    - **Path difference = $(n + \frac{1}{2})\lambda$**

Example

A pair of in-phase speakers is placed side-by-side, 2.2 m apart. A listener stand directly in front of one of the speakers, 3.2 m from the speaker. What is the smallest frequency that will produce destructive interference at listeners location?

Interference of Sound Waves

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    - Path difference = $(n + \frac{1}{2})\lambda$

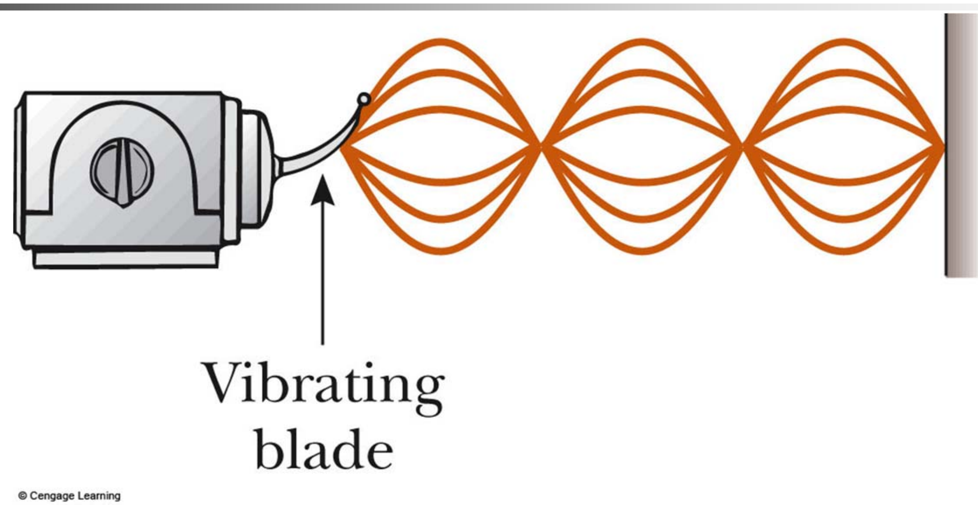
Standing Waves

- When a traveling wave reflects back on itself, it creates traveling waves in both directions
- The wave and its reflection interfere according to the superposition principle
- With exactly the right frequency, the wave will appear to stand still
  - This is called a *standing wave*

Standing Waves, cont

- A *node* occurs where the two traveling waves have the same magnitude of displacement, but the displacements are in opposite directions
  - Net displacement is zero at that point
  - The distance between two nodes is $\frac{1}{2}\lambda$
- An *antinode* occurs where the standing wave vibrates at maximum amplitude

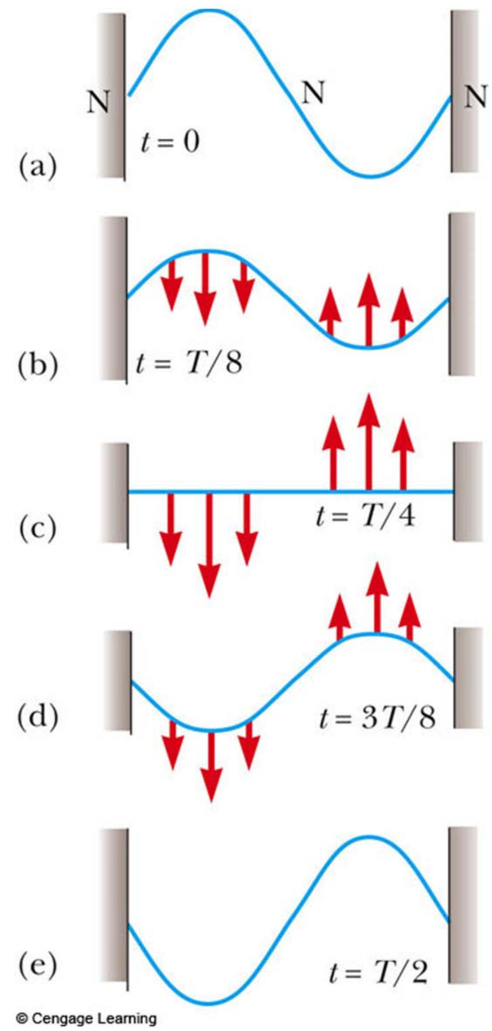
Standing Waves on a String



- Nodes must occur at the ends of the string because these points are fixed

Standing Waves, cont.

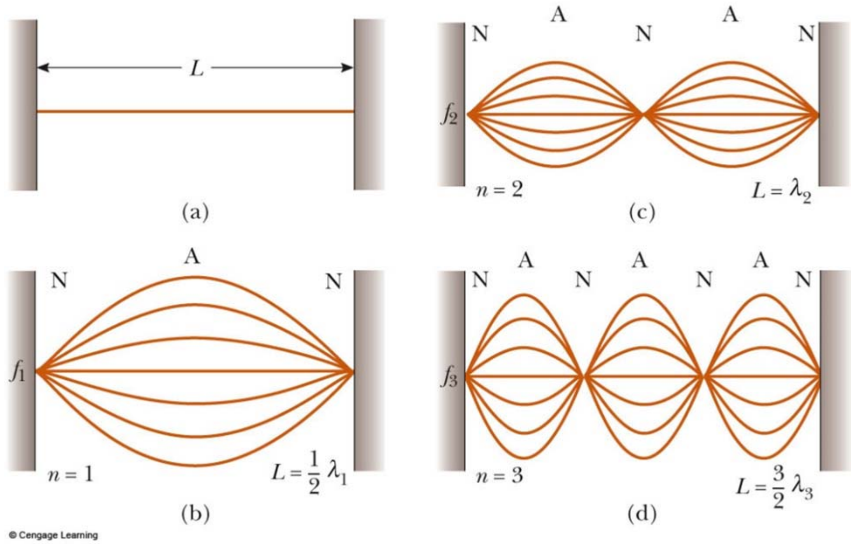
- The pink arrows indicate the direction of motion of the parts of the string
- All points on the string oscillate together vertically with the same frequency, but different points have different amplitudes of motion



Standing Waves on a String, final

- The lowest frequency of vibration (b) is called the *fundamental frequency*

$$f_n = nf_1 = \frac{n}{2L}\sqrt{\frac{F}{\mu}}$$



Standing Waves on a String – Frequencies

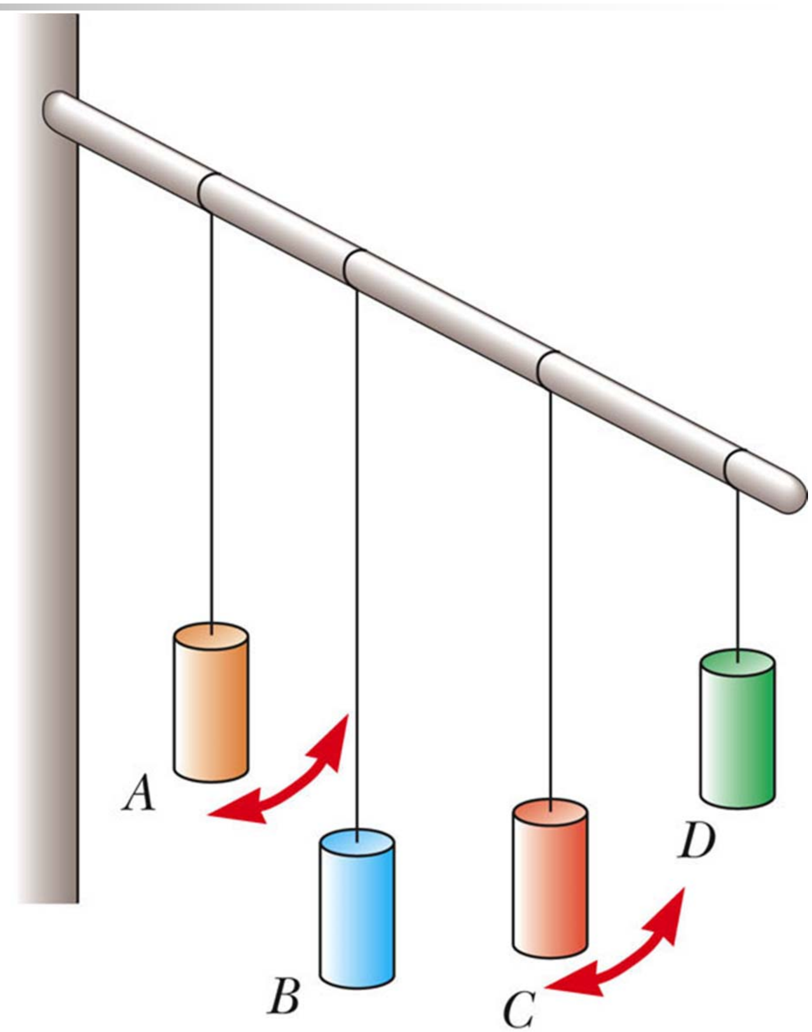
- f_1, f_2, f_3 form a harmonic series
  - f_1 is the fundamental and also the first harmonic
  - f_2 is the second harmonic
- Waves in the string that are not in the harmonic series are quickly damped out
  - In effect, when the string is disturbed, it "selects" the standing wave frequencies

Forced Vibrations

- A system with a driving force will force a vibration at its frequency
- When the frequency of the driving force equals the natural frequency of the system, the system is said to be in *resonance*

An Example of Resonance

- Pendulum A is set in motion
- The others begin to vibrate due to the vibrations in the flexible beam
- Pendulum C oscillates at the greatest amplitude since its length, and therefore frequency, matches that of A



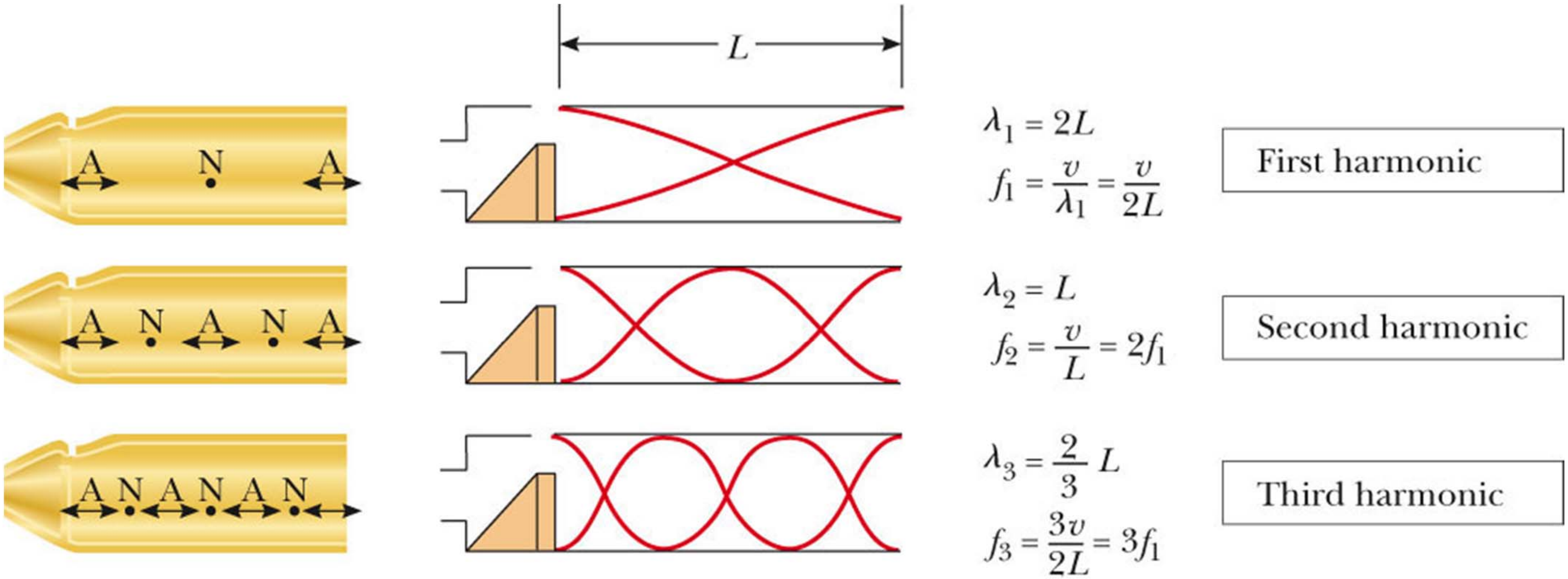
Other Examples of Resonance

- Child being pushed on a swing
- Shattering glasses
- Tacoma Narrows Bridge collapse due to oscillations by the wind
- Upper deck of the Nimitz Freeway collapse due to the Loma Prieta earthquake

Standing Waves in Air Columns

- If one end of the air column is closed, a node must exist at this end since the movement of the air is restricted
- If the end is open, the elements of the air have complete freedom of movement and an antinode exists

Tube Open at Both Ends



(a) Open at both ends

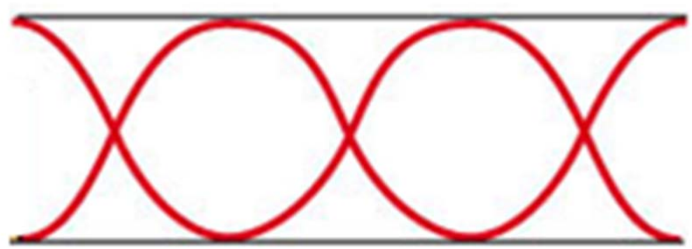
Resonance in Air Column Open at Both Ends

- In a pipe open at both ends, the natural frequency of vibration forms a series whose harmonics are equal to integral multiples of the fundamental frequency

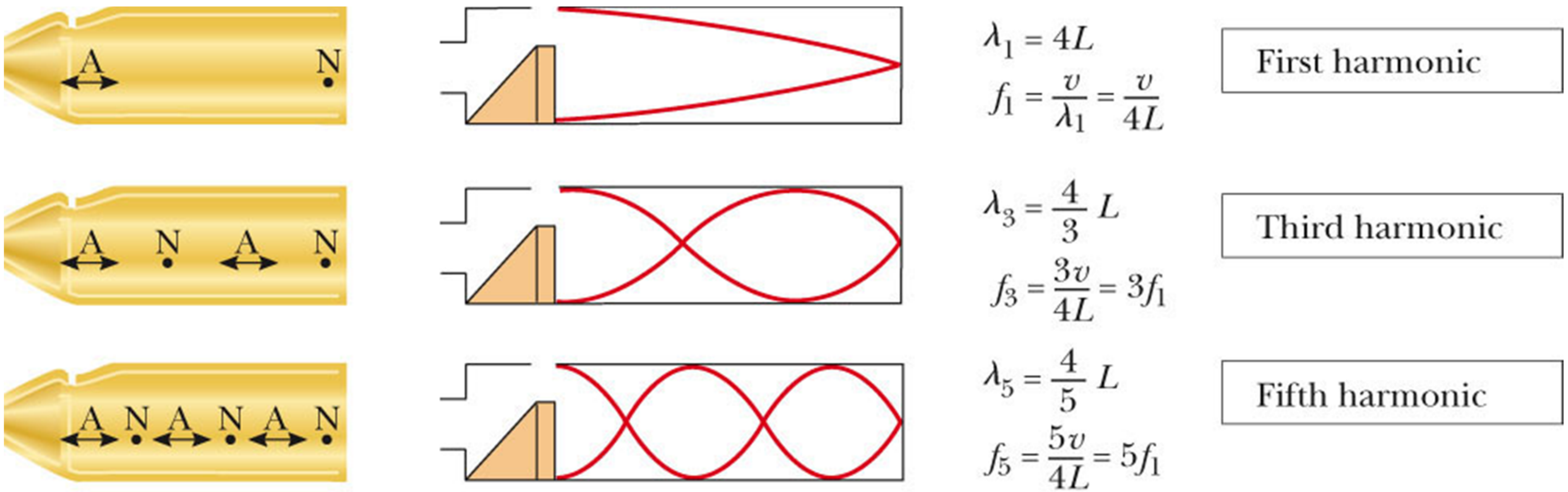
$$f_n = n\frac{v}{2L} = nf_1 \qquad n = 1, 2, 3, \ldots$$

Example

An open pipe shown resonates at 480 Hz. (a) What is the length of the pipe? (b) What is wavelength of the sound wave? What is its fundamental frequency?



Tube Closed at One End



(b) Closed at one end, open at the other

Resonance in an Air Column Closed at One End

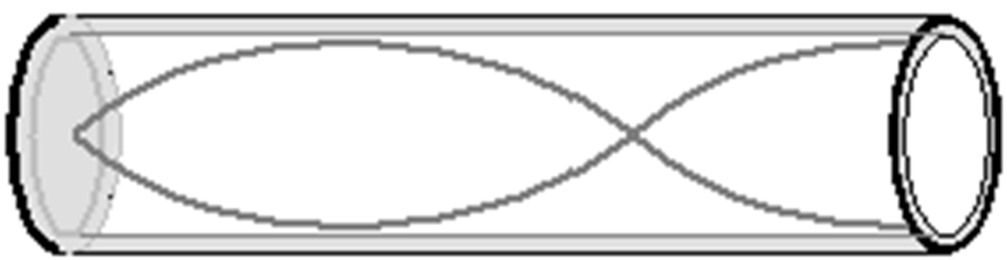
- The closed end must be a node
- The open end is an antinode

$$f_n = n\frac{v}{4L} = nf_1 \qquad n = 1, 3, 5, \ldots$$

- There are no even multiples of the fundamental harmonic

Example

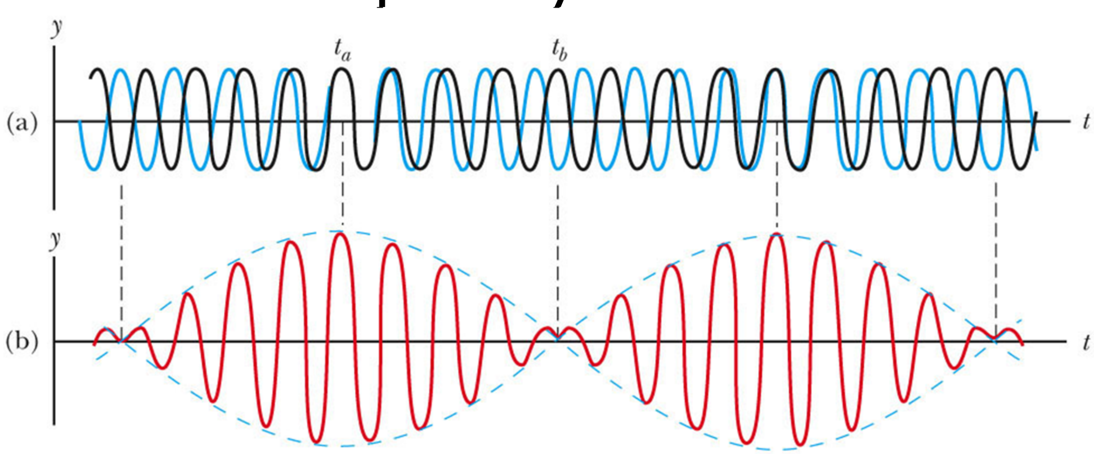
If an organ pipe shown is to resonate at 370 Hz, what is its required length?



Beats

Please replace with active fig. 14.25

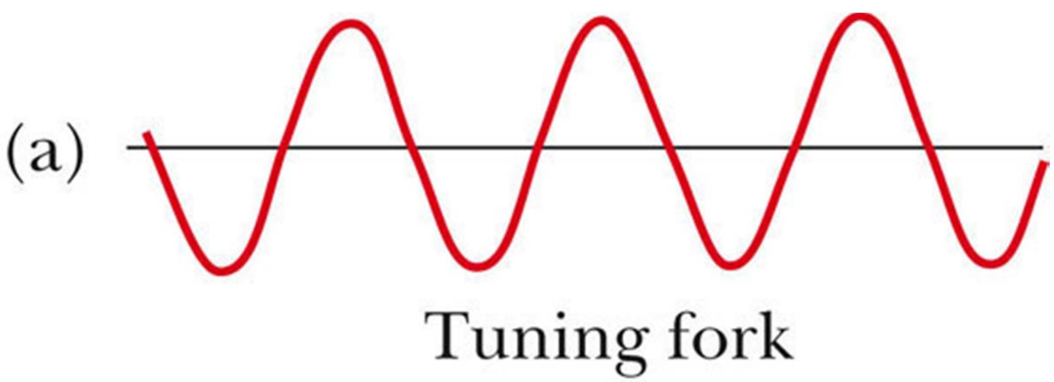
- *Beats* are alternations in loudness, due to interference
- Waves have slightly different frequencies and the time between constructive and destructive interference alternates
- The **beat frequency** equals the difference in frequency between the two sources:

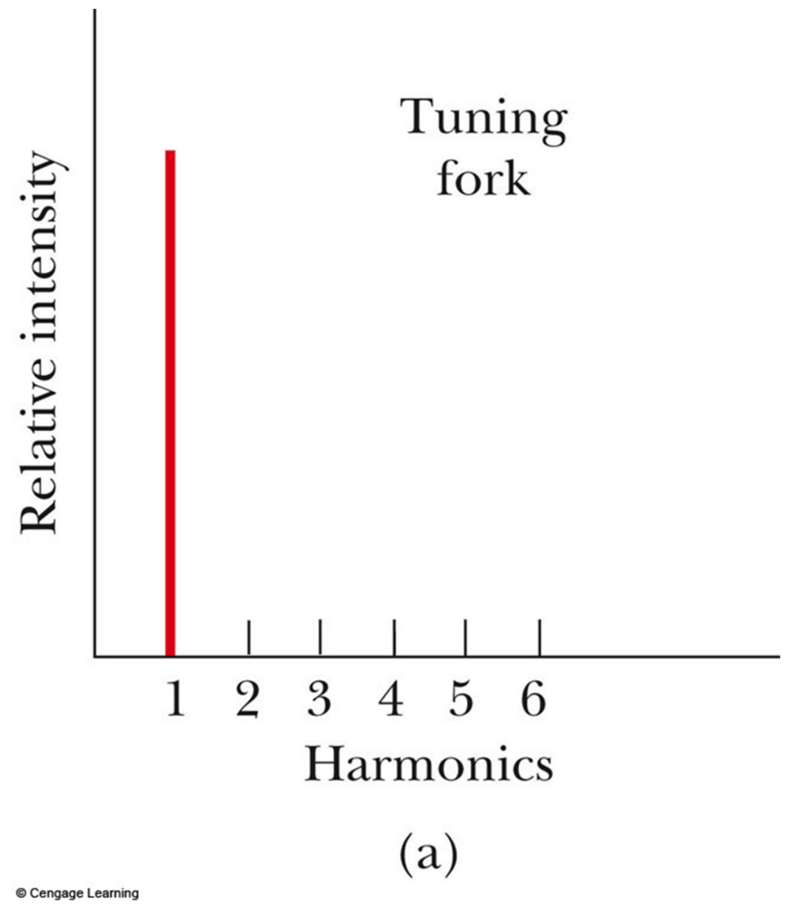


$$f_b = \left| f_2 - f_1 \right|$$

Quality of Sound – Tuning Fork

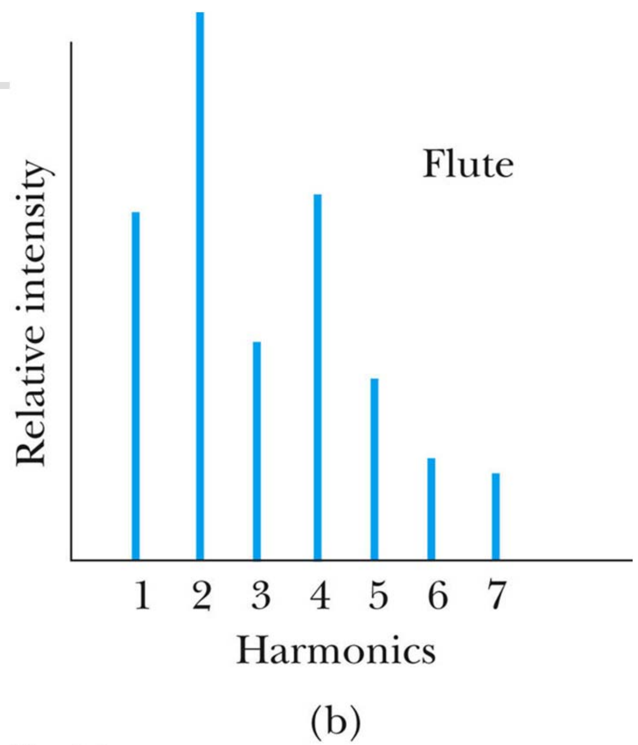
- Tuning fork produces only the fundamental frequency

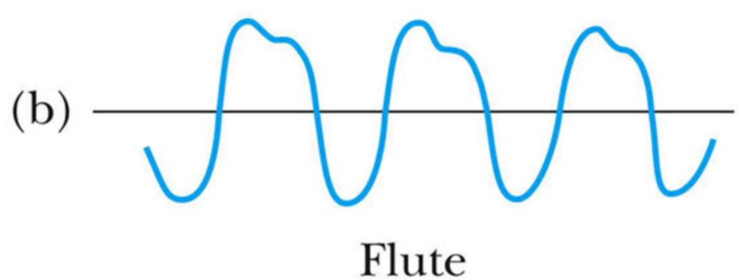




Quality of Sound – Flute

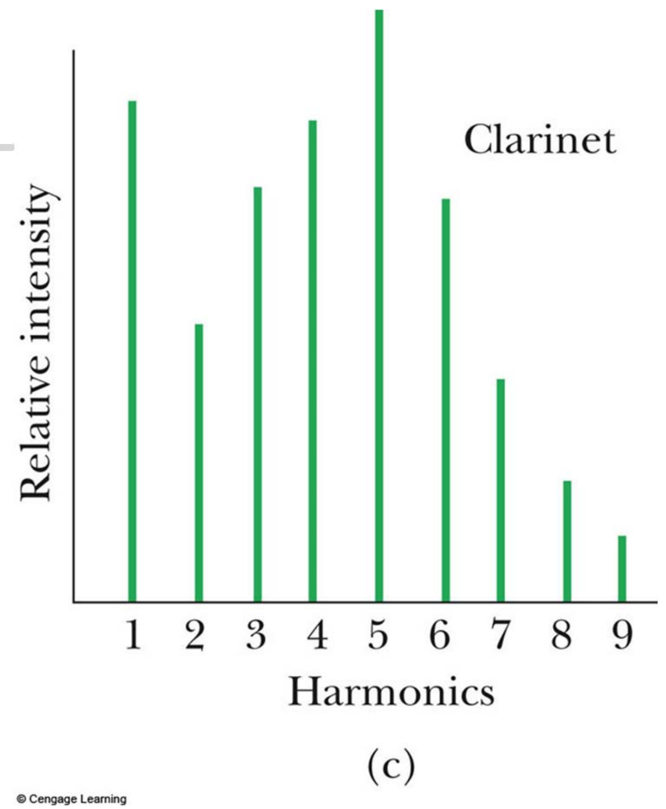
- The same note played on a flute sounds differently
- The second harmonic is very strong
- The fourth harmonic is close in strength to the first

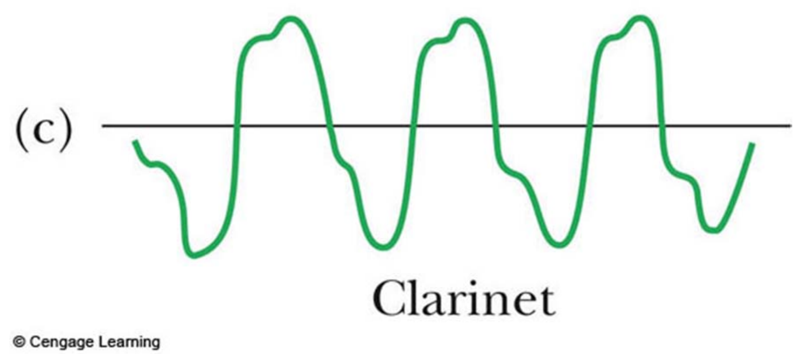




Quality of Sound – Clarinet

- The fifth harmonic is very strong
- The first and fourth harmonics are very similar, with the third being close to them





Timbre

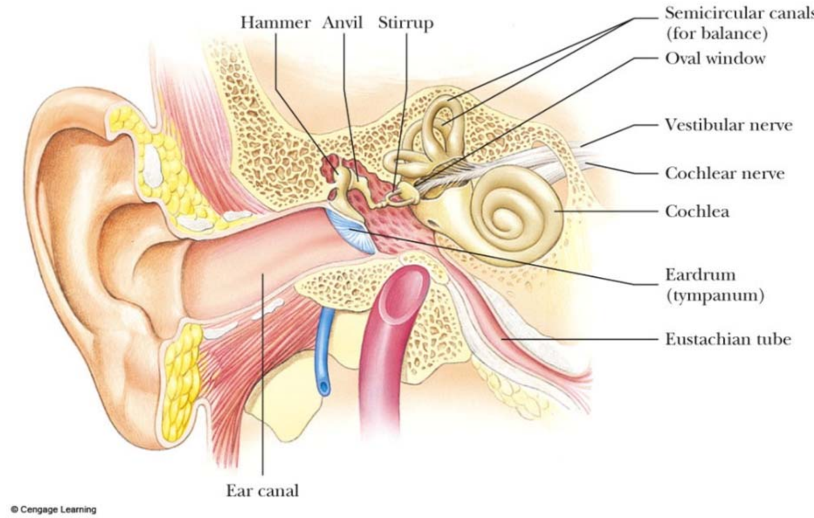
- In music, the characteristic sound of any instrument is referred to as the quality of sound, or the *timbre*, of the sound
- The quality depends on the mixture of harmonics in the sound

Pitch

- Pitch is related mainly, although not completely, to the frequency of the sound
- Pitch is not a physical property of the sound
- Frequency is the stimulus and pitch is the response
  - It is a psychological reaction that allows humans to place the sound on a scale

The Ear

- The outer ear consists of the ear canal that terminates at the eardrum
- Just behind the eardrum is the middle ear
- The bones in the middle ear transmit sounds to the inner ear



Frequency Response Curves

- Bottom curve is the threshold of hearing
  - Threshold of hearing is strongly dependent on frequency
  - Easiest frequency to hear is about 3300 Hz
- When the sound is loud (top curve, threshold of pain) all frequencies can be heard equally well