Chapter 16

Sound Waves

PHYS 2321
Week 13: Sound

Day 3 Outline

1) Hwk: Ch. 16, P. Due Mon after break

2) Ch. 16 – Sound
   * Speed of sound – temperature dependence
   * (Sound waves in terms of P, ρ, s) - skim
   * Energy and Intensity of sound waves

Notes:

Introduction to Sound Waves

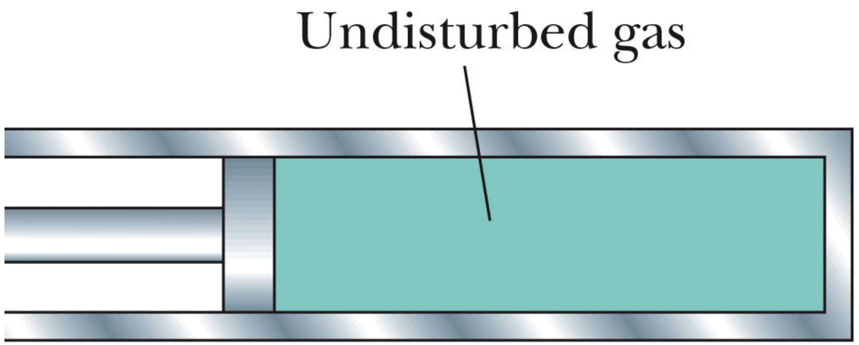
- Sound waves are longitudinal waves
- They travel through any material medium
- The speed of the wave depends on the properties of the medium
- The mathematical description of sinusoidal sound waves is very similar to sinusoidal waves on a string

Categories of Sound Waves

- The categories cover different frequency ranges
- **Audible waves** are within the sensitivity of the human ear
  - Range is approximately 20 Hz to 20 kHz
- **Infrasonic waves** have frequencies below the audible range
- **Ultrasonic waves** have frequencies above the audible range

Speed of Sound Waves

- Use a compressible gas as an example with a setup as shown at right
- Before the piston is moved, the gas has uniform density
- When the piston is suddenly moved to the right, the gas just in front of it is compressed
  - Darker region in the diagram



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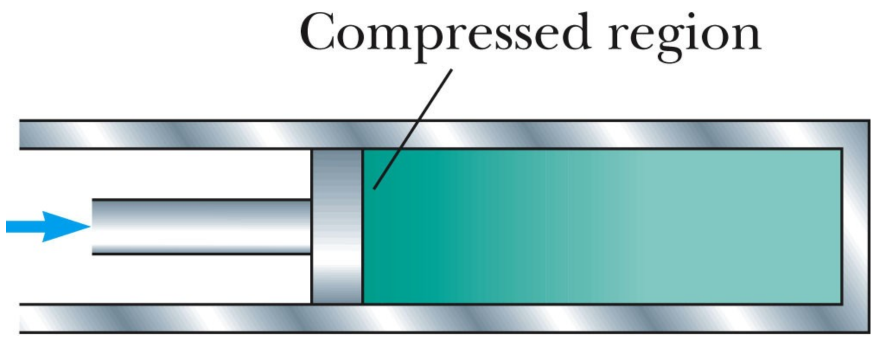

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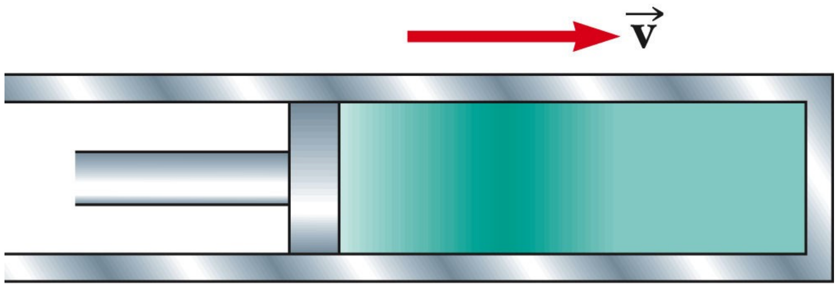
Speed of Sound Waves, cont

- When the piston comes to rest, the compression region of the gas continues to move
  - This corresponds to a longitudinal pulse traveling through the tube with speed *v*
  - The speed of the piston is not the same as the speed of the wave



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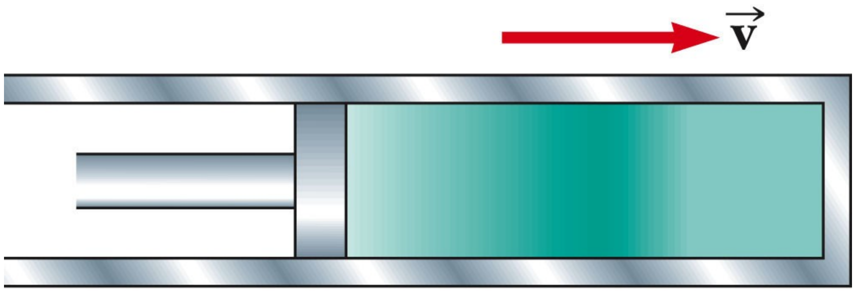

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Speed of Sound Waves, General

- The speed of sound waves in a medium depends on the compressibility and the density of the medium
- The compressibility can sometimes be expressed in terms of the elastic modulus of the material
- The speed of all mechanical waves follows a general form:

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

Speed of Sound in Liquid or Gas

- The bulk modulus of the material is B
- The density of the material is ρ
- The speed of sound in that medium is

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

Speed of Sound in Air

- The speed of sound also depends on the temperature of the medium
- This is particularly important with gases
- For air, the relationship between the speed and temperature is

$$v = (331\, m/s)\left(1 + \frac{Tc}{273}\right)$$

  - The 331 m/s is the speed at 0° C
  - T_C is the air temperature in Celsius

Speed of Sound in Gases, Example Values

Medium	v (m/s)
Gases	
Hydrogen (0°C)	1 286
Helium (0°C)	972
Air (20°C)	343
Air (0°C)	331
Oxygen (0°C)	317

Speed of Sound in Liquids, Example Values

Medium	v (m/s)
Liquids at 25°C	
Glycerol	1 904
Seawater	1 533
Water	1 493
Mercury	1 450
Kerosene	1 324
Methyl alcohol	1 143
Carbon tetrachloride	926

Speeds are in m/s

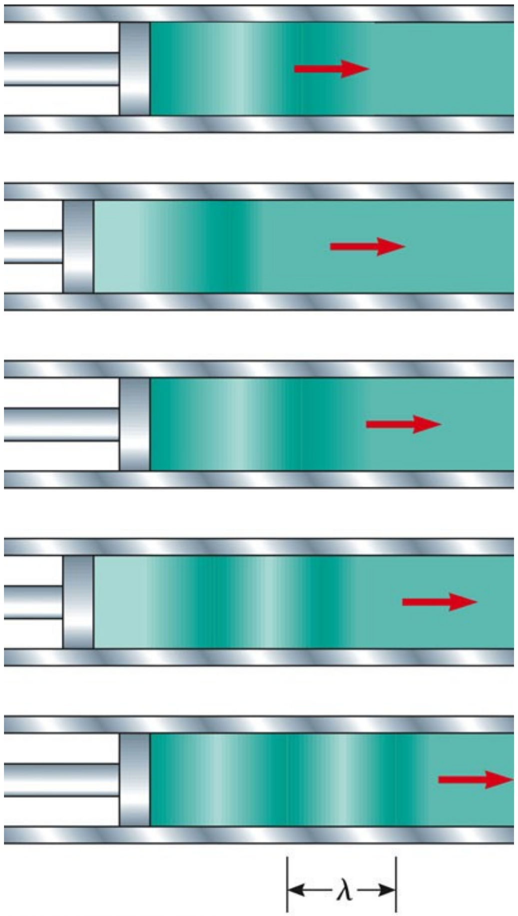
Speed of Sound in Solids, Example Values

Medium	v (m/s)
Solids[a]	
Pyrex glass	5 640
Iron	5 950
Aluminum	6 420
Brass	4 700
Copper	5 010
Gold	3 240
Lucite	2 680
Lead	1 960
Rubber	1 600

Speeds are in m/s; values are for bulk solids

Periodic Sound Waves, Example

- A longitudinal wave is propagating through a gas-filled tube
- The source of the wave is an oscillating piston
- The distance between two successive compressions (or rarefactions) is the wavelength
- Use the active figure to vary the frequency of the piston



Periodic Sound Waves, cont

- As the regions travel through the tube, any small element of the medium moves with simple harmonic motion parallel to the direction of the wave
- The harmonic position function is

$$s(x, t) = s_{max} \cos (kx - \omega t)$$

  - s_{max} is the maximum position from the equilibrium position
  - This is also called the displacement amplitude of the wave

Periodic Sound Waves, Pressure

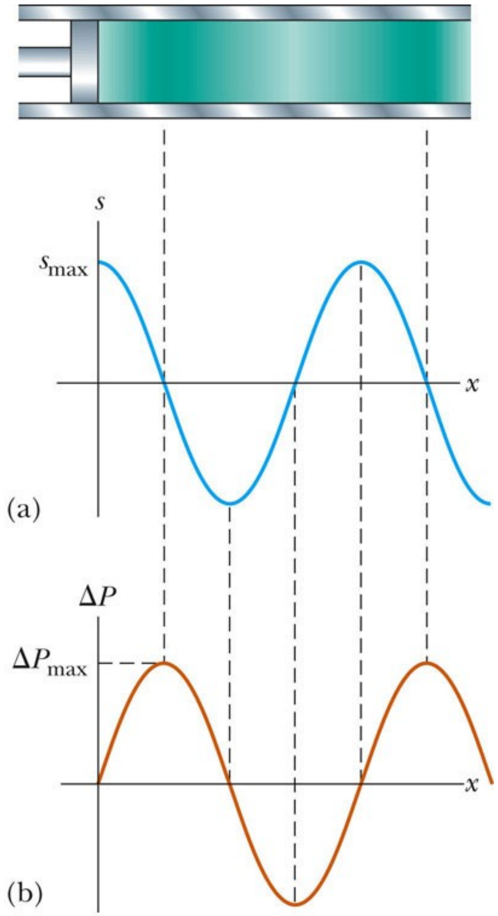
- The variation in gas pressure, ΔP, is also periodic

$$\Delta P = \Delta P_{max} \sin (kx - \omega t)$$

- ΔP_{max} is the pressure amplitude
- It is also given by $\Delta P_{max} = \rho v \omega s_{max}$
- k is the wave number (in both equations)
- ω is the angular frequency (in both equations)

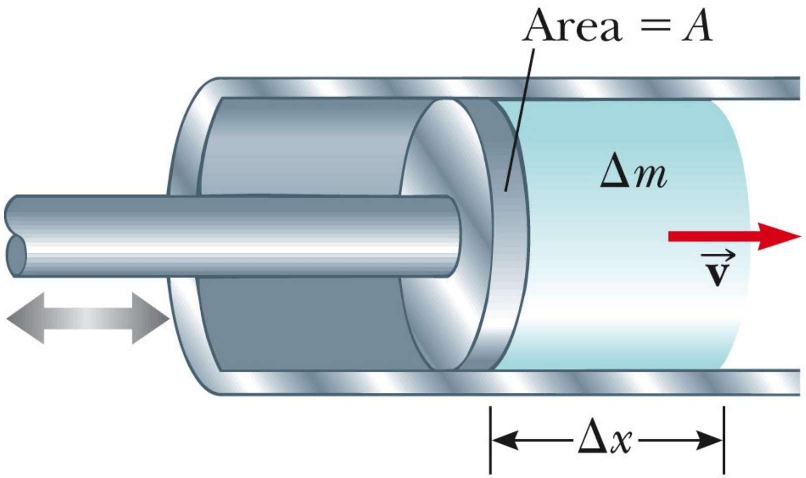
Periodic Sound Waves, final

- A sound wave may be considered either a displacement wave or a pressure wave
- The pressure wave is 90^{o} out of phase with the displacement wave
  - The pressure is a maximum when the displacement is zero, etc.



Energy of Periodic Sound Waves

- Consider an element of air with mass Δm and length Δx
- The piston transmits energy to the element of air in the tube
- This energy is propagated away from the piston by the sound wave



Energy, cont.

- The kinetic energy in one wavelength is
  $K_\lambda = \frac{1}{4}(\rho A)\omega^2 \; s_{max}^2\lambda$
- The total potential energy for one wavelength is the same as the kinetic
- The total mechanical energy is
  $E_\lambda = K_\lambda + U_\lambda = \frac{1}{2}(\rho A)\omega^2 \; s_{max}^2\lambda$

Power of a Periodic Sound Wave

- The rate of energy transfer is the power of the wave

$$\wp = \frac{\Delta E}{\Delta t} = \frac{E_\lambda}{T} = \frac{1}{2}\rho A v \omega^2 s_{\max}{}^2$$

- This is the energy that passes by a given point during one period of oscillation

Intensity of a Periodic Sound Wave

- The **intensity,** *I*, of a wave is defined as the power per unit area
  - This is the rate at which the energy being transported by the wave transfers through a unit area, *A*, perpendicular to the direction of the wave

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

Intensity, cont

- In the case of our example wave in air,

  $I = \frac{1}{2} \rho v(\omega s_{max})^2$
- Therefore, the intensity of a periodic sound wave is proportional to the
  - Square of the displacement amplitude
  - Square of the angular frequency
- In terms of the pressure amplitude,

$$I = \frac{(\Delta P_{max})^2}{2\rho v}$$

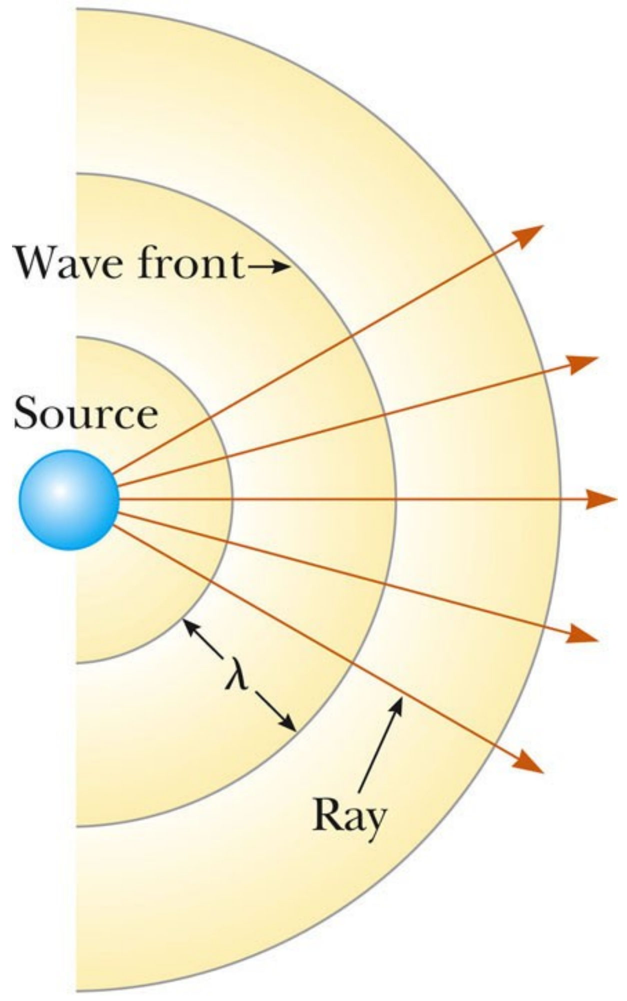
Intensity of a Point Source

- A **point source** will emit sound waves equally in all directions
  - This results in a **spherical wave**
- Identify an imaginary sphere of radius r centered on the source
- The power will be distributed equally through the area of the sphere

Intensity of a Point Source, cont

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

- This is an inverse-square law
  - The intensity decreases in proportion to the square of the distance from the source



Sound Level

- The range of intensities detectable by the human ear is very large
- It is convenient to use a logarithmic scale to determine the intensity level, β

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

Sound Level, cont

- I_0 is called the **reference intensity**
  - It is taken to be the threshold of hearing
  - $I_0 = 1.00 \times 10^{-12}$ W/ m^2
  - I is the intensity of the sound whose level is to be determined
- β is in decibels (dB)
- Threshold of pain: I = 1.00 W/m^2; β = 120 dB
- Threshold of hearing: $I_0 = 1.00 \times 10^{-12}$ W/ m^2 corresponds to β = 0 dB

Sound Level, Example

- What is the sound level that corresponds to an intensity of 2.0×10^{-7} W/m^2 ?

$\beta = 10 \log (2.0 \times 10^{-7}\ \text{W/m}^2 / 1.0 \times 10^{-12}\ \text{W/m}^2) = 10 \log 2.0 \times 10^{5} = 53$ dB

- Rule of thumb: A doubling in the intensity is approximately equivalent to an increase of 3 dB

Sound Levels

TABLE 17.2

Sound Levels

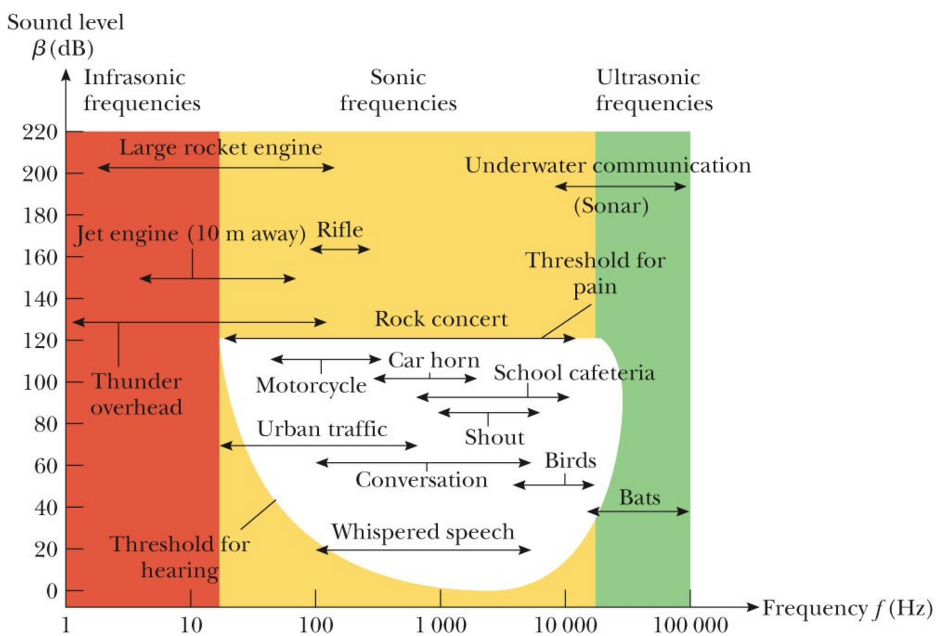
Source of Sound	β (dB)
Nearby jet airplane	150
Jackhammer; machine gun	130
Siren; rock concert	120
Subway; power lawn mower	100
Busy traffic	80
Vacuum cleaner	70
Normal conversation	50
Mosquito buzzing	40
Whisper	30
Rustling leaves	10
Threshold of hearing	0

Loudness and Intensity

- Sound level in decibels relates to a *physical measurement* of the strength of a sound
- We can also describe a *psychological "measurement"* of the strength of a sound
- Our bodies "calibrate" a sound by comparing it to a reference sound
- This would be the threshold of hearing
- Actually, the threshold of hearing is this value for 1000 Hz

Loudness and Frequency, cont

- There is a complex relationship between loudness and frequency
- The white area shows average human response to sound
- The lower curve of the white area shows the threshold of hearing
- The upper curve shows the threshold of pain

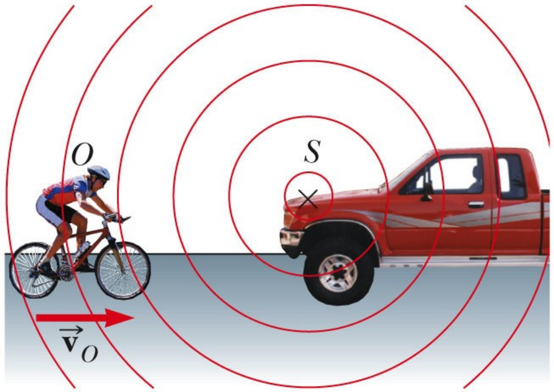


The Doppler Effect

- The **Doppler effect** is the apparent change in frequency (or wavelength) that occurs because of motion of the source or observer of a wave
  - When the relative speed of the source and observer is higher than the speed of the wave, the frequency appears to increase
  - When the relative speed of the source and observer is lower than the speed of the wave, the frequency appears to decrease

Doppler Effect, Observer Moving

- The observer moves with a speed of v_o
- Assume a point source that remains stationary relative to the air
- It is convenient to represent the waves with a series of circular arcs concentric to the source
    - These surfaces are called ***wave fronts***



Doppler Effect, Observer Moving, cont

- The distance between adjacent wave fronts is the wavelength
- The speed of the sound is v, the frequency is f, and the wavelength is λ
- When the observer moves toward the source, the speed of the waves relative to the observer is $v' = v + v_o$
  - The wavelength is unchanged

Doppler Effect, Observer Moving, final

- The frequency heard by the observer, f', appears higher when the observer approaches the source

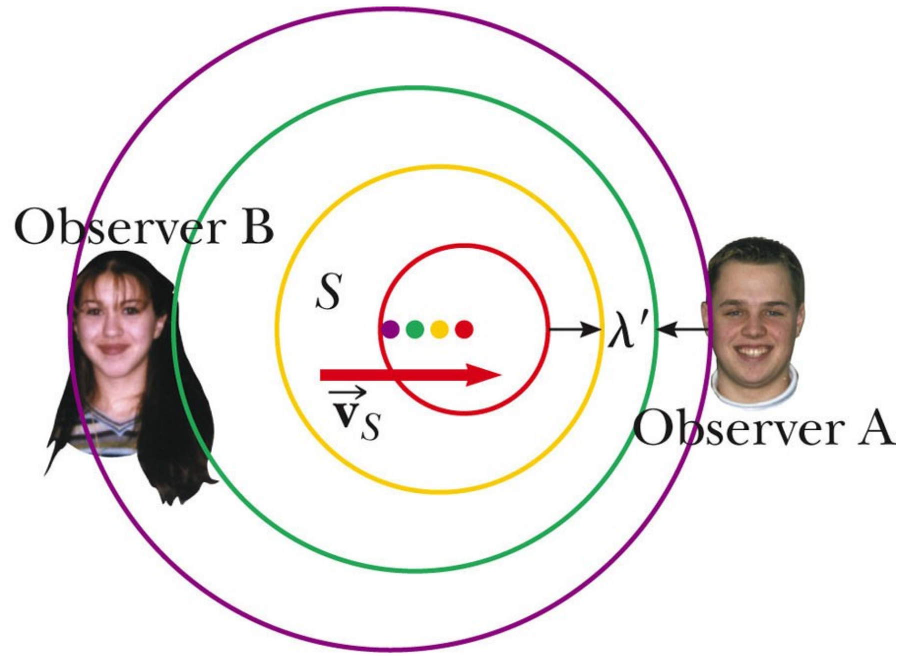
$$f' = \left(\frac{v + v_o}{v}\right) f$$

- The frequency heard by the observer, f', appears lower when the observer moves away from the source

$$f' = \left(\frac{v - v_o}{v}\right) f$$

Doppler Effect, Source Moving

- Consider the source being in motion while the observer is at rest
- As the source moves toward the observer, the wavelength appears shorter
- As the source moves away, the wavelength appears longer
    - Use the active figure to adjust the speed and observe the results



(a)

Doppler Effect, Source Moving, cont

- When the source is moving toward the observer, the apparent frequency is higher

$$f' = \left(\frac{v}{v - v_s}\right) f$$

- When the source is moving away from the observer, the apparent frequency is lower

$$f' = \left(\frac{v}{v + v_s}\right) f$$

Doppler Effect, General

- Combining the motions of the observer and the source

$$f' = \left(\frac{v + v_o}{v - v_s} \right) f$$

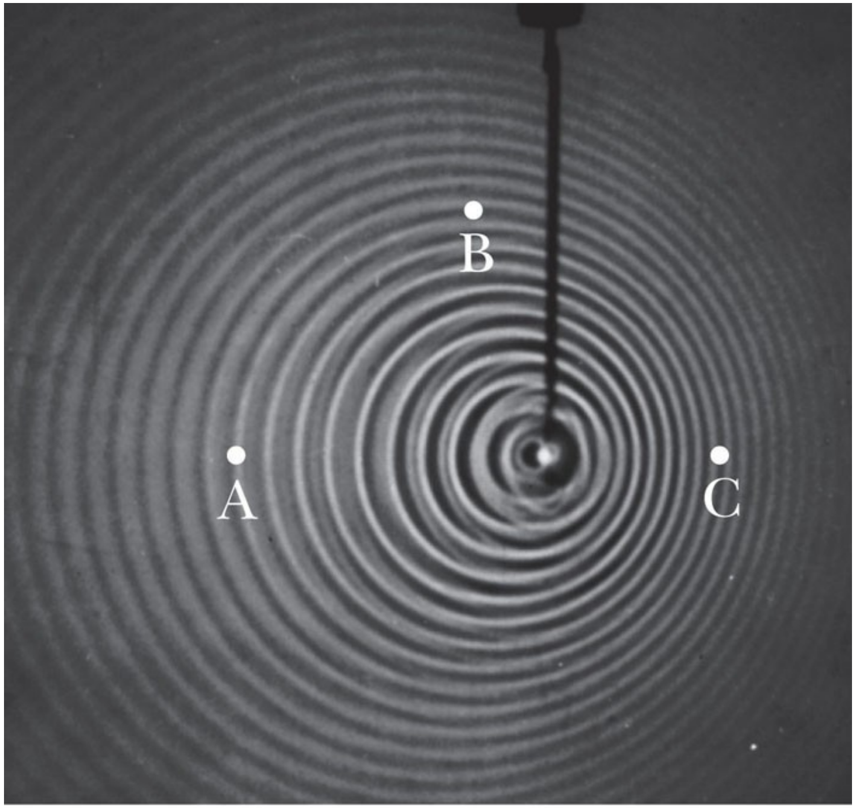
- The signs depend on the direction of the velocity
  - A positive value is used for motion of the observer or the source *toward* the other
  - A negative sign is used for motion of one *away from* the other

Doppler Effect, final

- Convenient rule for signs
  - The word “toward” is associated with an increase in the observed frequency
  - The words “away from” are associated with a decrease in the observed frequency
- The Doppler effect is common to all waves
- The Doppler effect does not depend on distance

Doppler Effect, Water Example

- A point source is moving to the right
- The wave fronts are closer on the right
- The wave fronts are farther apart on the left



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Doppler Effect, Submarine Example

- Sub A (source) travels at 8.00 m/s emitting at a frequency of 1400 Hz
- The speed of sound is 1533 m/s
- Sub B (observer) travels at 9.00 m/s
- What is the apparent frequency heard by the observer as the subs approach each other? Then as they recede from each other?

Doppler Effect, Submarine Example cont

- Approaching each other:

$$f' = \left(\frac{v + v_o}{v - v_s}\right) f = \left(\frac{1533\ \text{m/s} + (+9.00\ \text{m/s})}{1533\ \text{m/s} - (+8.00\ \text{m/s})}\right)(1400\,Hz)$$

$$= 1416\,Hz$$

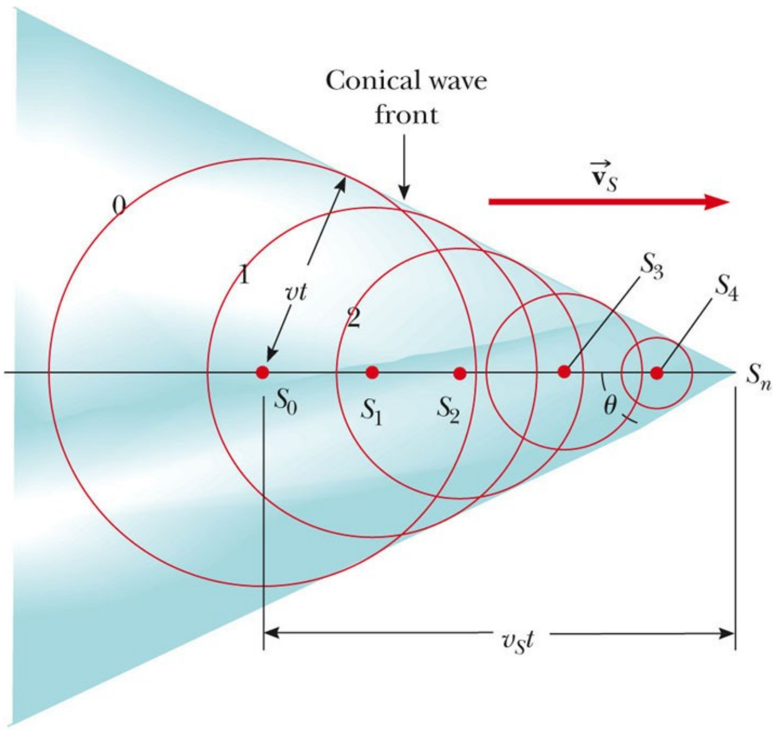
- Receding from each other:

$$f' = \left(\frac{v + v_o}{v - v_s}\right) f = \left(\frac{1533\ \text{m/s} + (-9.00\ \text{m/s})}{1533\ \text{m/s} - (-8.00\ \text{m/s})}\right)(1400\,Hz)$$

$$= 1385\,Hz$$

Shock Wave

- The speed of the source can *exceed* the speed of the wave
- The envelope of these wave fronts is a cone whose apex half-angle is given by $\sin \theta = v/v_S$
  - This is called the *Mach angle*



(a)

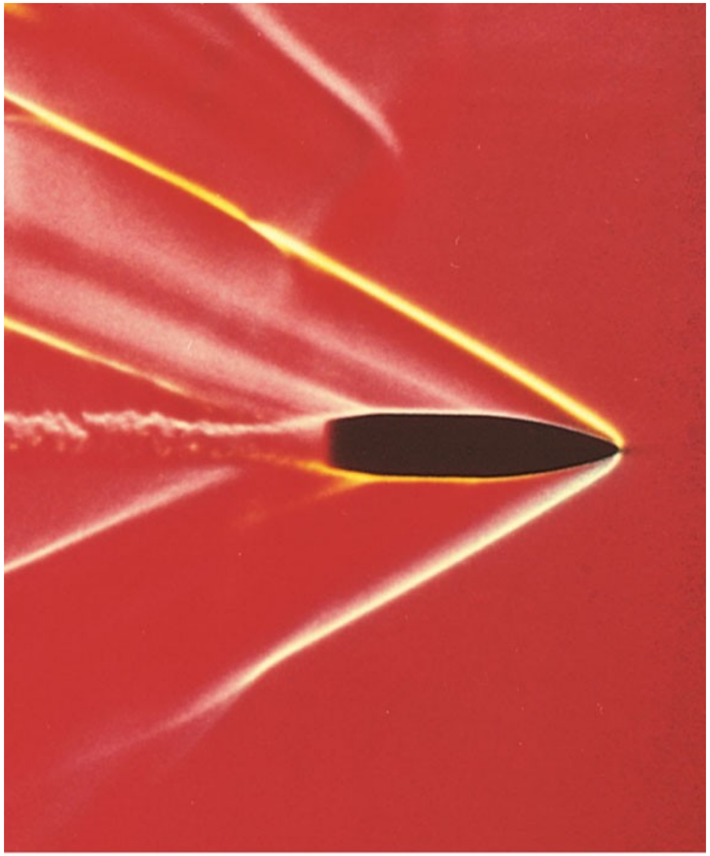
Mach Number

- The ratio v_s / v is referred to as the *Mach number*
- The relationship between the Mach angle and the Mach number is

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

Shock Wave, final

- The conical wave front produced when $v_s > v$ is known as a shock wave
  - This is supersonic
- The shock wave carries a great deal of energy concentrated on the surface of the cone
- There are correspondingly great pressure variations



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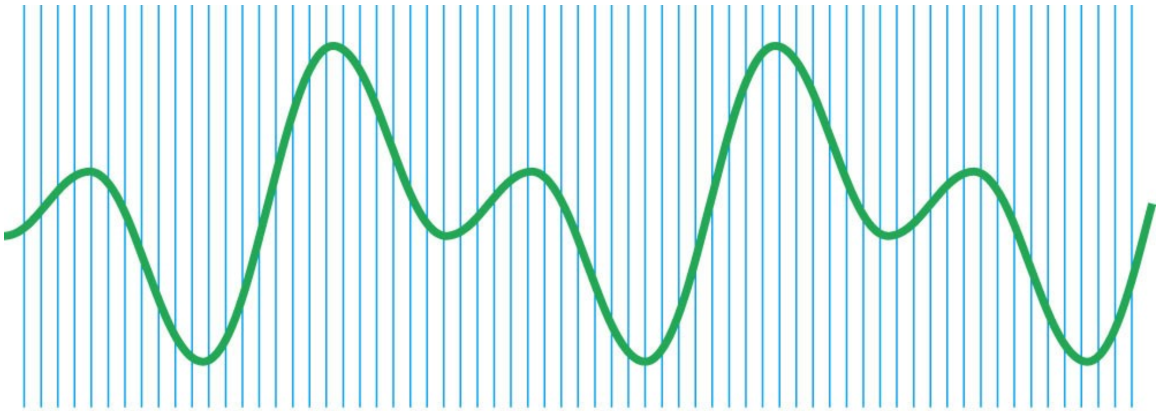
Sound Recording

- Encoding sound waveforms began as variations in depth of a continuous groove cut in tin foil wrapped around a cylinder
- Sound was then recorded on cardboard cylinders coated with wax
- Next were disks made of shellac and clay
- In 1948, plastic phonograph disks were introduced

Digital Recording



(a)

- In digital recording of sound, information is converted to binary code
- The waveforms of the sound are sampled
- During the sampling, the pressure of the wave is sampled and converted into a voltage
- The graph above shows the sampling process

Digital Recording, 2

- These voltage measurements are then converted to binary numbers (1's and 0's)
  - Binary numbers are expressed in base 2
- Generally, the voltages are recorded in 16-bit "words"
  - Each bit is a 1 or a 0
- The number of voltage levels that can be assigned codes is $2^{16} = 65\ 536$

Digital Recording, 3

- The strings of ones and zeroes are recorded on the surface of the compact disc
- There is a laser playback system that detects lands and pits
  - Lands are the untouched regions
    - They are highly reflective
  - Pits are areas burned into the surface
    - They scatter light instead of reflecting it

Digital Recording, final

- The binary numbers from the CD are converted back into voltages
- The waveform is reconstructed
- Advantages
  - High fidelity of the sound
  - There is no mechanical wear on the disc
    - The information is extracted optically

Motion Picture Sound

- Early movies recorded sound on phonograph records
  - They were synchronized with the action on the screen
- Then a variable-area optical soundtrack was introduced
  - The sound was recorded on an optical track on the edge of the film
  - The width of the track varied according to the sound wave

Motion Picture Sound, cont

- A photocell detecting light passing through the track converted the varying light intensity to a sound wave
- Problems
  - Dirt or fingerprints on the track can cause fluctuations and loss of fidelity

Systems of Motion Picture Sound – Original

- Cinema Digital Sound (CDS)
  - First used in 1990
  - No backup
  - No longer used
  - Introduced the use of 5.1 channels of sound:
    - Left, Center, Right, Right Surround, Left Surround and Low Frequency Effects (LFE)

Systems of Motion Picture Sound – Current

- Dolby Digital
  - 5.1 channels stored between sprocket holes on the film
  - Has an analog backup
  - First used in 1992
- Digital Theater Sound (DTS)
  - 5.1 channels stored on a separate CD
  - Synchronized to the film by time codes
  - Has an analog backup
  - First used in 1993

Systems of Motion Picture Sound – Current, cont

- Sony Dynamic Digital Sound (SDDS)
  - Eight full channels
  - Optically stored outside the sprocket holes on both sides of the film
    - Both sides serve as a redundancy
  - Analog optical backup
  - The extra channels are a full channel LFE plus left center and right center behind the screen