Physics 207, Lecture 22, Nov. 20

- Agenda: Chapter 17, Sound
  - ❖ Longitudinal Waves
  - ❖ Loudness
  - ❖ Plane waves, spherical waves
  - ❖ Doppler Effect
  - ❖ Shock waves
- Chapter 18, Superposition and Standing Waves
  - ❖ Standing Wave, nodes and antinodes

Assignments:

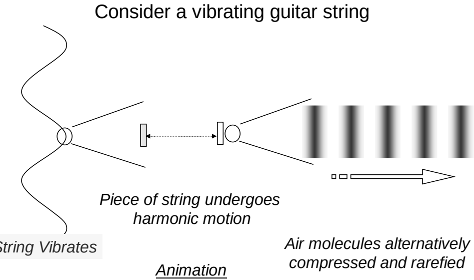
- Problem Set 8, due Wed. noon

Ch. 16: 3, 18, 30, 40, 58, **59** (Honors) Ch. 17: 3, 15, 34, 38, 40

- Nov. 22, Chapter 18, Superposition and Standing Waves
- Mid-Term 3, Chapters 14-17 (plus elastic modulus)

Chapter 17: Sound, A special kind of longitudinal wave

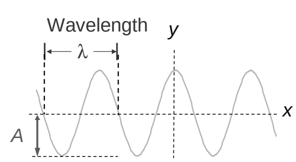
Consider a vibrating guitar string



Wave Properties

- Wavelength: The distance λ between identical points on the wave.
- Amplitude: The maximum displacement *A* of a point on the wave.
- A wave varies in time and space.

$$y(x,t) = A\cos[(2\pi/\lambda)\,x - \omega t)]$$



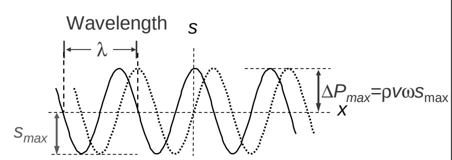
Sound Wave Properties

- Displacement: The maximum relative displacement *s* of a point on the wave. Displacement is longitudinal.
- Maximum displacement has minimum velocity

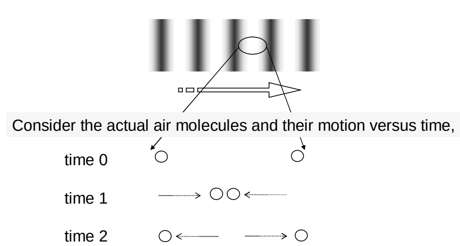
$$s(x,t) = s_{\max}\,\cos[(2\pi/\lambda)\,x - \omega t)]$$

$$ds\,/\,dt = \omega s_{\max}\,\sin[(2\pi/\lambda)\,x - \omega t)]$$

Molecules "pile up" where the relative velocity is maximum (i.e., $ds/dt = s_{max}$)



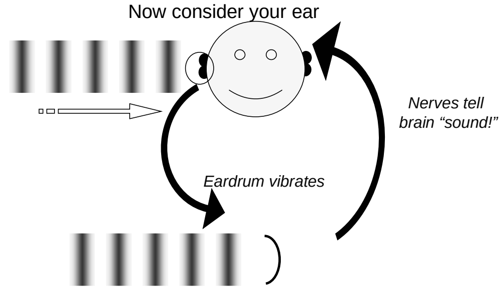
Sound



Individual molecules undergo harmonic motion with displacement in same direction as wave motion.

Sound

Now consider your ear



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:

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

Waves on a string → $v = \sqrt{\frac{T}{\mu}}$

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

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

Medium	Speed (m/s)
Air	343
Helium	972
Water	1500
Steel (solid)	5600

Speed of Sound in a Solid Rod

- The Young's modulus of the material is *Y*
- The density of the material is ρ
- The speed of sound in the rod is

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

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

$$v = (331\text{ m/s})\sqrt{1 + \frac{T_c}{273^\circ\text{C}}}$$

Lecture 22, *Exercise 1*
Comparing Waves, He vs. Air

A sound wave having frequency f_0, speed v_0 and wavelength λ_0, is traveling through air when in encounters a large helium-filled balloon. Inside the balloon the frequency of the wave is f_1, its speed is v_1, and its wavelength is λ_1

Compare the speed of the sound wave inside and outside the balloon

(A) $v_1 < v_0$ (B) $v_1 = v_0$ (C) $v_1 > v_0$

Compare the frequency of the sound wave inside and outside the balloon

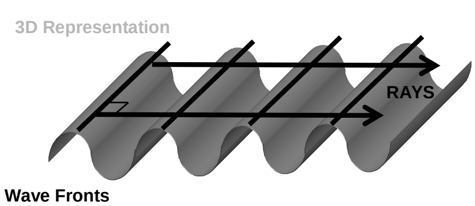
(A) $f_1 < f_0$ (B) $f_1 = f_0$ (C) $f_1 > f_0$

Compare the wavelength of the sound wave inside and outside the balloon

(A) $\lambda_1 < \lambda_0$ (B) $\lambda_1 = \lambda_0$ (C) $\lambda_1 > \lambda_0$

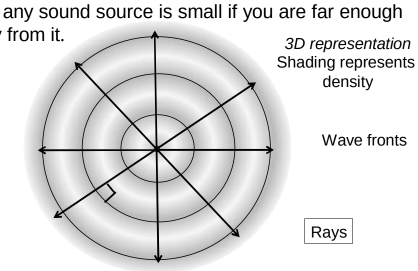
Waves, Wavefronts, and Rays

- Up to now we have only considered waves in 1D but we live in a 3D world.
- The 1D equations are applicable for a 3D **plane wave**.
- A plane wave travels in the +***x*** direction (for example) and has no dependence on ***y*** or ***z***,



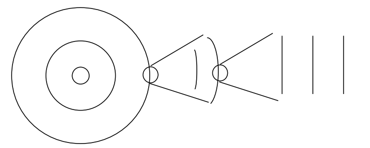
Waves, Wavefronts, and Rays

- Sound radiates away from a source in all directions.
- A small source of sound produces a spherical wave.
- Note any sound source is small if you are far enough away from it.



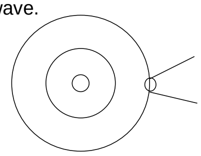
Waves, Wavefronts, and Rays

- Note that a small portion of a spherical wave front is well represented as a plane wave.

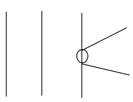


Waves, Wavefronts, and Rays

- If the power output of a source is constant, the total power of any wave front is constant.
- The Intensity at any point depends on the type of wave.



$$I = \frac{P_{\text{av}}}{A} = \frac{P_{\text{av}}}{4\pi R^2}$$



$$I = \frac{P_{\text{av}}}{A} = \frac{P_{\text{av}}}{\text{const}}$$

Lecture 22, *Exercise 2*
Spherical Waves

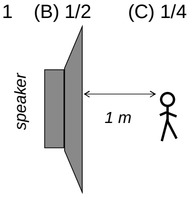
- You are standing 10 m away from a very loud, small speaker. The noise hurts your ears. In order to reduce the intensity to 1/4 its original value, how far away do you need to stand?

(A) 14 m (B) 20 m (C) 30 m (D) 40 m

Lecture 22, *Exercise 3*
Plane Waves

- You are standing 1 m away from a ***very*** large wall hanging speaker. The noise hurts your ears. In order to reduce the intensity you walk back to 1 m away. What is the ratio of the new sound intensity to the original?

(A) 1 (B) 1/2 (C) 1/4 (D) 1/8



Intensity of sounds

- The amplitude of pressure wave depends on
  - ❖ Frequency ω of harmonic sound wave
  - ❖ Speed of sound v and density of medium ρ of medium
  - ❖ Displacement amplitude s_{max} of element of medium

$$\Delta P_{\max} = \omega v \rho s_{\max}$$

- Intensity of a sound wave is

$$\mathrm{I} = \frac{\Delta P_{\max}^2}{2\rho\, \mathrm{v}}$$

  - ❖ Proportional to (amplitude)^2
  - ❖ This is a general result (not only for sound)
- Threshold of human hearing: $I_0 = 10^{-12}$ W/m^2

Sound Level: How loud is loud?

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

$$\beta = 10 \; \log_{10}\left(\frac{I}{I_0}\right)$$

Sound Level

- I_0 is called the **reference intensity**
  - ❖ It is taken to be the threshold of hearing
  - ❖ I_0 = 1.00 x 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 x 10^{-12} W/ m^2 ; β = 0 dB

Intensity of sounds

- Some examples (1 pascal ≅ 10^{-5} atm) :

Sound Intensity	Pressure amplitude (Pa)	Intensity (W/m^2)	level (dB)
Hearing threshold	3×10^{-5}	10^{-12}	0
Classroom	0.01	10^{-7}	50
City street	0.3	10^{-4}	80
Car without muffler	3	10^{-2}	100
Indoor concert	30	1	120
Jet engine at 30 m.	100	10	130

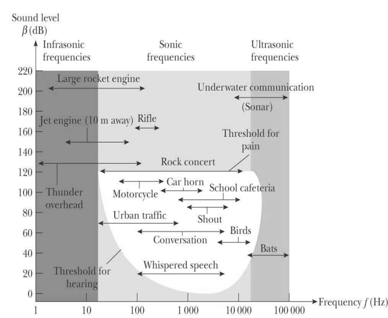
Sound Level, Example

- What is the sound level that corresponds to an intensity of 2.0 x 10^{-7} W/m^2 ?
- β = 10 $\log_{10}$ (2.0 x 10^{-7} W/m^2 / 1.0 x 10^{-12} W/m^2)
  = 10 $\log_{10}$ 2.0 x 10^5 = 53 dB
- Rule of thumb: An apparent "doubling" in the loudness is approximately equivalent to an increase of 10 dB.
- This factor is not linear with intensity

Loudness and Intensity

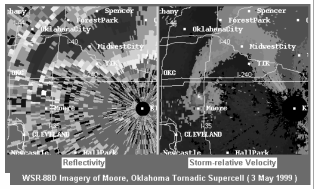
- Sound level in decibels relates to a *physical measurement* of the strength of a sound
- We can also describe a *psychological "measurement"* of the strength of a sound
- Our bodies "calibrate" a sound by comparing it to a reference sound
- This would be the threshold of hearing
- Actually, the threshold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

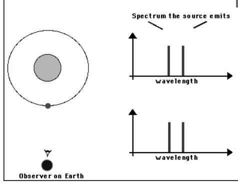
Loudness and Frequency

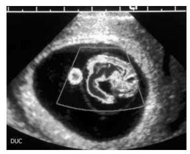


Doppler effect, moving sources/receivers

Christian Doppler (1803-1853)



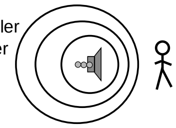




Doppler effect, moving sources/receivers

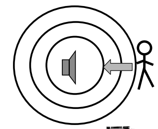
- If the source of sound is moving
  - ❖ Toward the observer ⇒ λ seems smaller
  - ❖ Away from observer ⇒ λ seems larger

$$f_{\text{observer}} = \left(\frac{v}{v \pm v_s}\right) f_{\text{source}}$$



- If the observer is moving
  - ❖ Toward the source ⇒ λ seems smaller
  - ❖ Away from source ⇒ λ seems larger

$$f_{\text{observer}} = \left(\frac{v \pm v_o}{v}\right) f_{\text{source}}$$



- If both are moving $f_{\text{observer}} = \left(\frac{v \pm v_o}{v \mp v_s}\right) f_{\text{source}}$

Doppler Example Audio

- Examples: police car, train, etc. (Recall: v is vector)

Doppler Example Visual

Lecture 22, *Exercise 4*
Plane Waves

A: You are driving along the highway at 65 mph, and behind you a police car, also traveling at 65 mph, has its siren turned on.

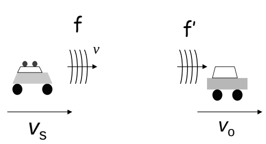
B: You and the police car have both pulled over to the side of the road, but the siren is still turned on.

In which case does the frequency of the siren seem higher to you?

(A) Case A

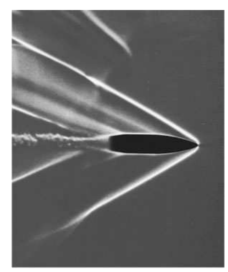
(B) Case B

(C) same



Shock Wave, Sonic Boom

- 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

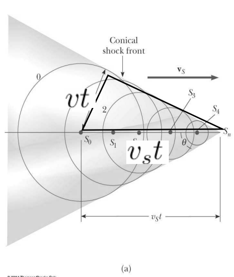


Shock Wave

- 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

  $\sin \theta = v\,t \,/\, v_s\,t$

  - ❖ This is called the *Mach angle*



Recap Lecture 22

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  - ❖ Longitudinal Waves
  - ❖ Loudness
  - ❖ Plane waves, spherical waves
  - ❖ Doppler Effect
  - ❖ Shock waves
- Chapter 18, Superposition and Standing Waves
  - ❖ Standing Wave, nodes and antinodes (Wednesday)

Assignments:

- Problem Set 8 due Nov. 21, Tuesday 11:59 PM

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