Today's Discussion

- Sound
  - Beats & doppler

Sound

- Sound waves will be this course's favorite longitudinal wave
- So favorite, in fact, that all longitudinal waves will be referred to as sound waves
  - seismic waves are sound
  - sonar is sound
  - music is sound
- We will focus on audible sound waves traveling through air

(For Certain Ears, More Sounds are Audible)

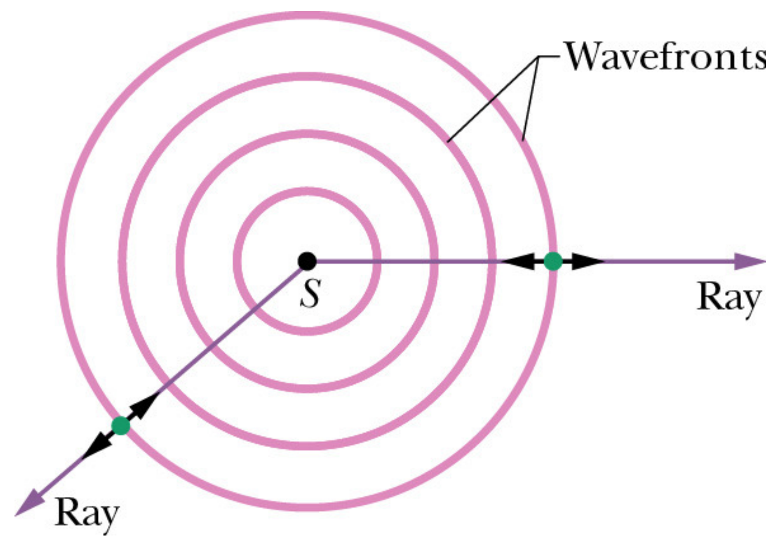
sailfish.exis.net/ ~spook/3bat47.jpg

New meaning to the phrase "I'm all ears"

Some Definitions and Terms

- Imagine a source of sound
  - treat it as a point source, meaning
    - the emitting region is small compared to the distance between source and detector
    - example: the running motor of a farm tractor in the middle of a field
- Picture of a point source
  - 3-d (2-d shown)
  - wavefront:
    - surface where oscillations of the air due to the sound wave are the same
  - ray: $\perp$ to wavefronts

Notice how it starts to look flat, a.k.a. planar



Speed of Sound

- In air at 0°C: 331m/s

$v = (B/\rho)^{\frac{1}{2}}$

- In Helium: 965m/s

  $v = f\lambda \rightarrow v/\lambda$ so your voice is higher-pitched after breathing Helium

- In Water: 1402m/s
- In Steel: 5941m/s
- In Vacuum: 0m/s
- In String $v = \sqrt{T/\mu}$

  T = tension in string &
  $\mu =$ mass/length

Example: Sound Wave Generator

- Tuning Fork

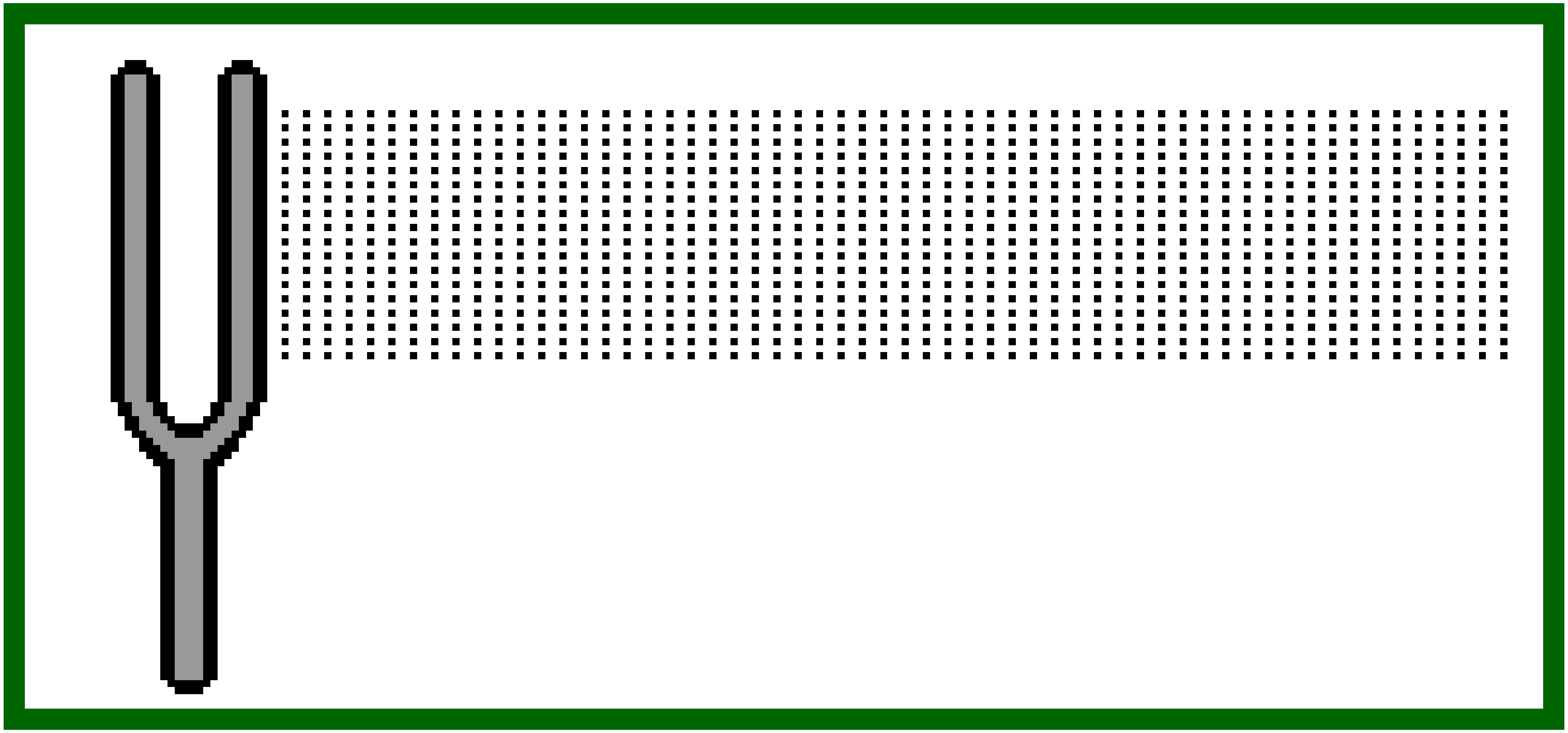
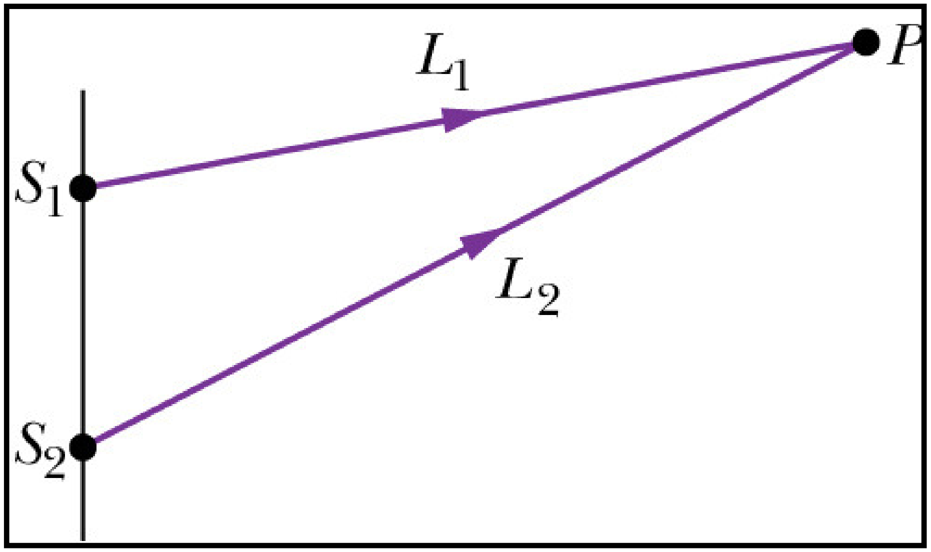


Figure by Tom Henderson, Glenbrook High School

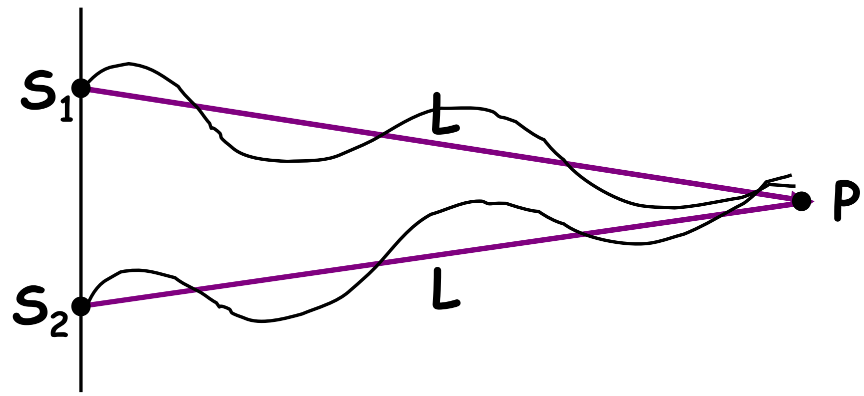
Interference

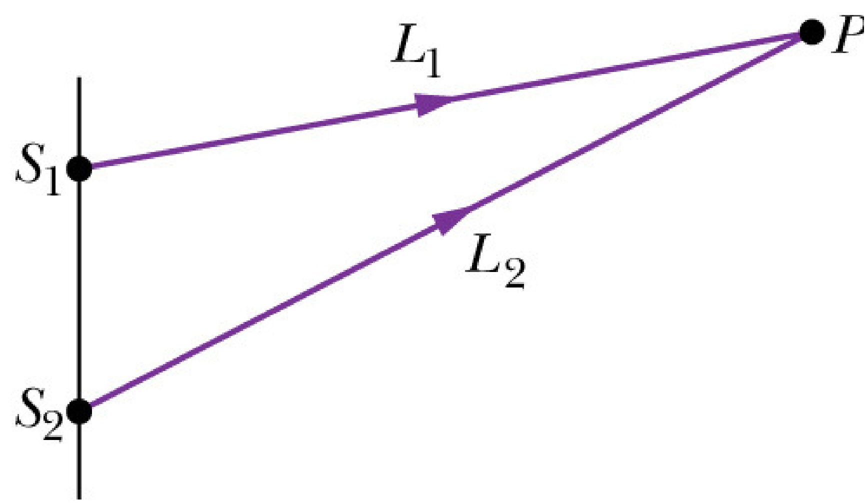
- Simplest case
  - Two identical sources of sound emitting in phase
- What is detected at a point some distance from both sources?



Interference

- If distant point "P" is equidistant from both sources, there will be constructive interference
- If not, there might not be!





Interference: Quantitative

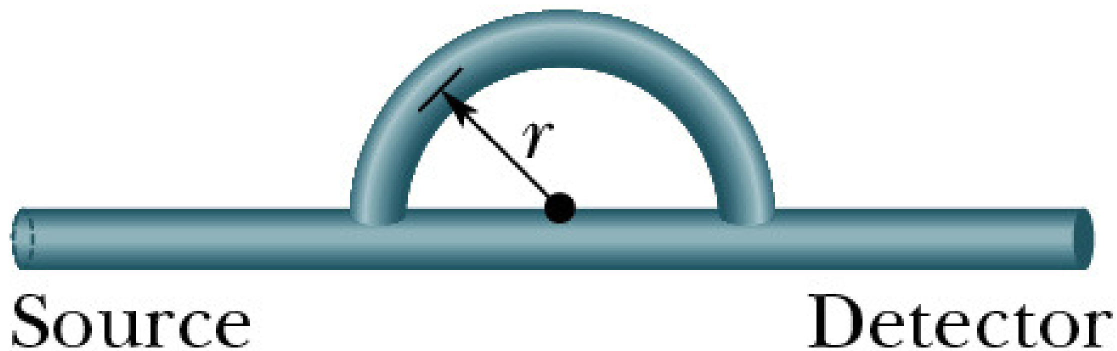
- The phase difference in the waves at the detection point is directly related to $\Delta L = |L_1 - L_2|$, the pathlength difference
- One full wavelength difference corresponds to 2π phase difference:

  $\phi/2\pi = \Delta L/\lambda \rightarrow \phi = 2\pi(\Delta L/\lambda)$

  - fully constructive: $\phi = m(2\pi)$
    - I.e., $\Delta L/\lambda = 0, 1, 2, \ldots$
  - fully destructive: $\phi = (2m+1)\pi$
    - I.e., $\Delta L/\lambda = 0.5,\ 1.5,\ 2.5$

Interference : example

Sound of wavelength λ travels rightward from a source through the tube structure shown below. What is the smallest value of the radius r for which an intensity minimum is detected by the detector?



Beats

- If two slightly-different frequencies are emitted from a point source (say, two closely-spaced speakers) what is heard some distance away?
  - $s_1 = s_m \cos(\omega_1 t)$ and $s_2 = s_m \cos(\omega_2 t)$
  - $s = s_1 + s_2 = s_m(\cos(\omega_1 t) + \cos(\omega_2 t))$
  - using trigonometry
    - $s = 2s_m \cos(\frac{1}{2}(\omega_1 - \omega_2)t) \cos(\frac{1}{2}(\omega_1 + \omega_2)t)$
      - call $\omega' = \frac{1}{2}(\omega_1 - \omega_2)$ and $\omega = \frac{1}{2}(\omega_1 + \omega_2)$
    - $s = 2s_m \cos(\omega' t) \cos(\omega t)$
  - Prediction: will hear two different frequencies, the average and the half the difference

Beats

- The difference frequency is also called the "beat" frequency
- For two frequencies close together, beat frequency is low and easy to hear
  - used to tune instruments to a standard

Intensity and Sound Level

- How can we measure how loud something is?
  - Not as easy as it seems—we need to cover many orders of magnitude
  - To surmount this problem, use logarithms
  - Reminder: if y=log(x) then
    - when x increases by 10, y increases by 1
    - when x increases by 10^{12}, y increases by 12
- Define the sound level as

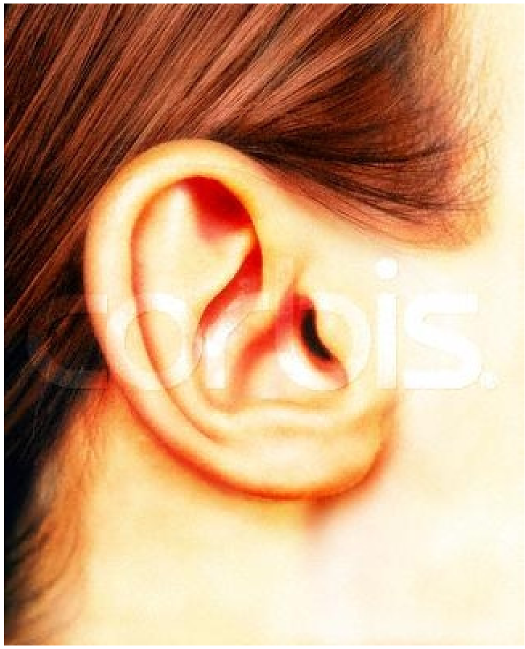
  β = (10 db) $\log(I/I_o)$
  - units: “decibels”
  - I_o=“standard reference intensity”=10^{-12}W/m^2

Expression for Intensity & Variation of Intensity w/Distance

- $I = \frac{1}{2}\rho v \omega^2 s_m^2$
  - derived in text
- Ignoring echos, and with sound emitted isotropically (w/equal intensity in all directions), and assuming mechanical energy of wave is conserved…
  - $I = P_s/(4\pi r^2)$ (P_s: power of source)

Inverse square law!

The Human Ear



- The range of human hearing
  - The faintest audible sounds at 1kHz have an intensity of $I=I_o=10^{-12}W/m^2$
  - The pain threshold is at $I=1W/m^2$

The Who

- As detailed in the text, The Who set a record for the loudest concert—the sound level was 120db 46m from the stage (0.03 mi)
- How far away would you have to be to hear this concert as if it was a conversation, which is at about 60 db?

(A) 0.3 mi (B) 3 mi
(C) 30 mi (D) 300 mi

The Who

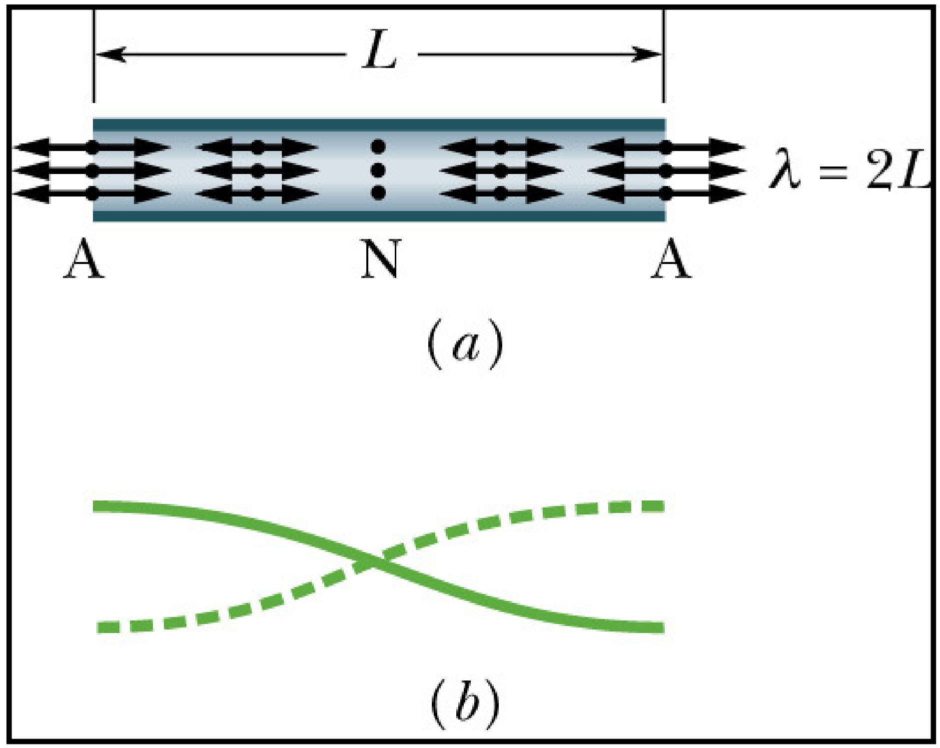
- $120db = 10db \log(I/I_o)$ at 46m
  - $I = 1\ W/m^2$ at 46m
- $I = P_s/(4\pi r^2)$
  - $P_s = 26.6kW$
- At 60db, conversation level:
  - $I = 10^{-6}\ W/m^2$
- At what distance?
  - $26{,}600W = (10^{-6}\ W/m^2)(4\pi r^2)$
    - r = 46km!!! ~ 30 mi

Musical Sound: Organ Pipes

- Recall:
  - a string (e.g., a guitar string) attached at both ends can support standing waves
    - for suitable wavelengths, waves traveling from one end reflect off the other end & all the waves interfere with one another to produce a standing wave
    - A standing wave is what you hear—all other wavelengths get removed by destructive interference

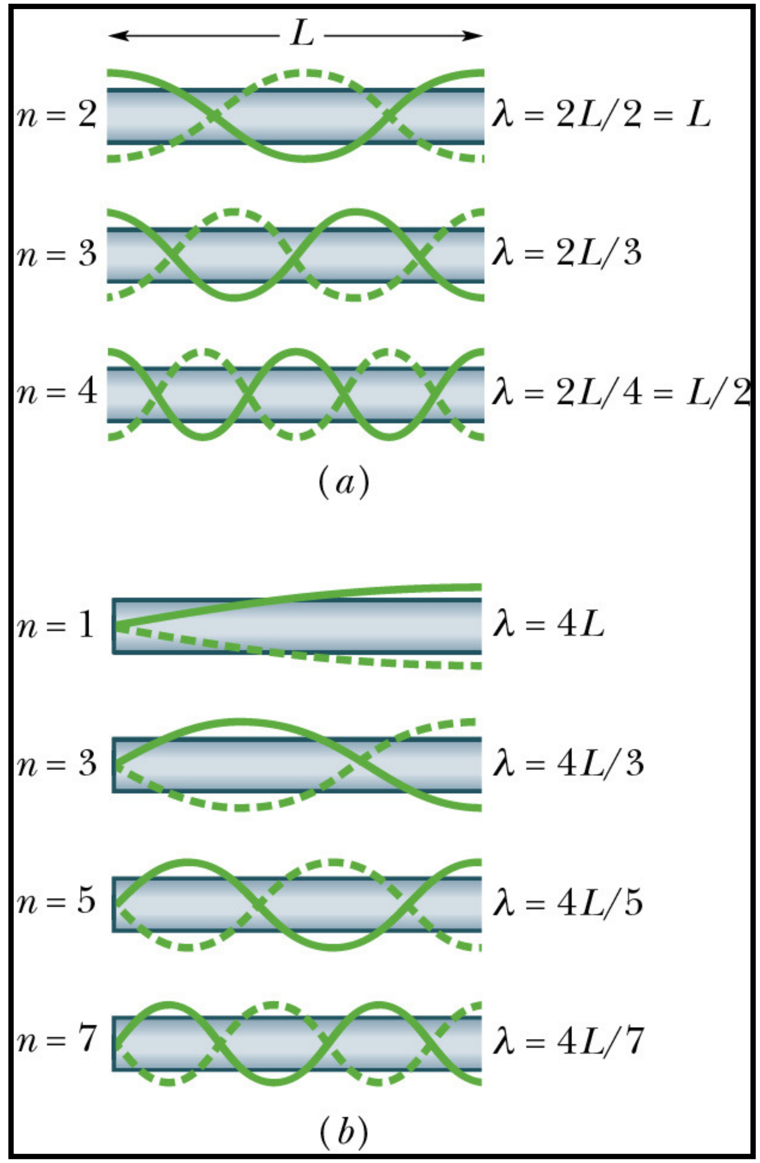
Musical Sound: Organ Pipes

- Other musical instruments operate in a similar way
- Consider standing waves in a pipe
  - if an end of the pipe is closed, that must be a node (zero displacement)
  - if an end is open, that must be an antinode
- For a pipe with two open ends:



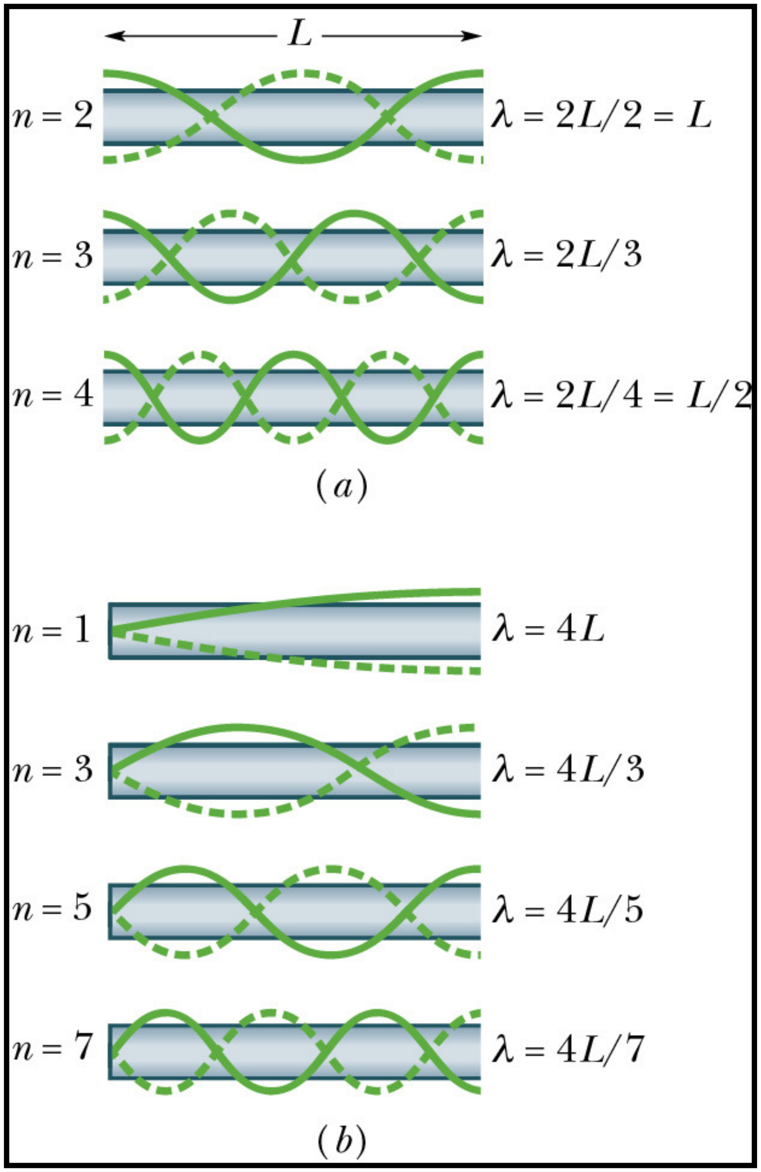
Musical Sound: Organ Pipes

- This is called the "fundamental mode" or "first harmonic"
  - It represents the least wiggly wave pattern that will fit in the pipe
- Can also put in wigglier patterns
  - 2nd harmonic, 3rd harmonic…
- A pipe with one closed end looks a little different



Quantifying Standing Wave Patterns in Pipes

- Pipe with two open ends:
  - $f = v/\lambda = nv/2L$
  - n = 1, 2, 3,…
- Pipe with one open end:
  - $f = v/\lambda = nv/4L$
  - n = 1, 3, 5…



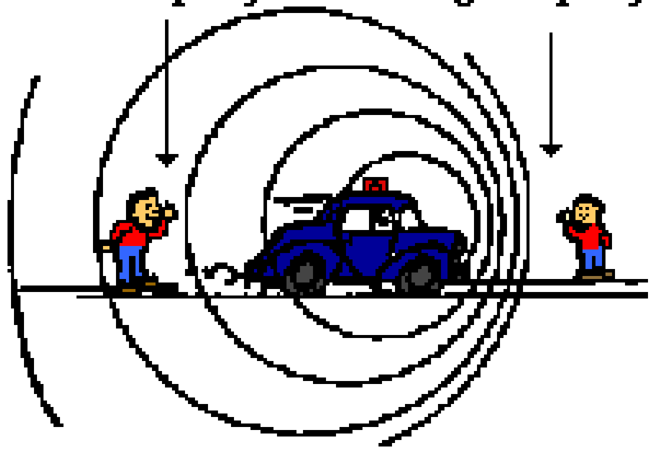
Pipe waves Example

- Organ pipe A, with both ends open, has a fundamental frequency of 300Hz. The third harmonic of organ pipe B, with one end open, has the same frequency as the second harmonic of pipe A. How long are pipes A & B?

Doppler Effect. Qualitative.

- The Doppler effect occurs when there is relative motion between the source and detector of waves
  - The detected frequency may be either increased or decreased as a result
  - All velocities are measured relative to velocity of air (i.e., wind speed) – medium, through which waves propagate
- Doppler effect applies to ALL waves, including light. Heavily used in astronomy to measure speeds of, say, stars.

Left observer counts fewer wavefronts, i.e. ***wavelength dilates***



The Doppler Effect for a moving sound source

Right observer counts more wavefronts, i.e. ***wavelength shrinks***

Doppler Effect. Quantitative.

- Detector moving, source not

$$f' = f\frac{v \pm v_D}{v}$$

- Source moving, detector not

$$f' = \frac{v}{\lambda'} = \frac{v}{(vT \pm v_S T)} = f\frac{v}{v \pm v_S}$$

- Source & detector moving

$$\boxed{f' = f\frac{v \pm v_D}{v \pm v_S}}$$

- Remembering which sign to use
  - frequency should increase whenever source and/or detector move toward one another; decrease otherwise

Doppler Examples: Some Notes

- Note 1: The Doppler effect and the beats that result when a source wave is added to a reflected wave are often used together in devices
- Note 2: When a device emits waves that bounce off a moving object, the Doppler effect occurs <u>twice</u>
  - First, when the moving object "hears" the waves, which are Doppler-shifted by virtue of the motion of the object (the "detector")
  - Second, when the <u>moving</u> object reflects (re-emits) the wave, it is Doppler-shifted again—now the moving object has become the source

Doppler Examples: Qualitative

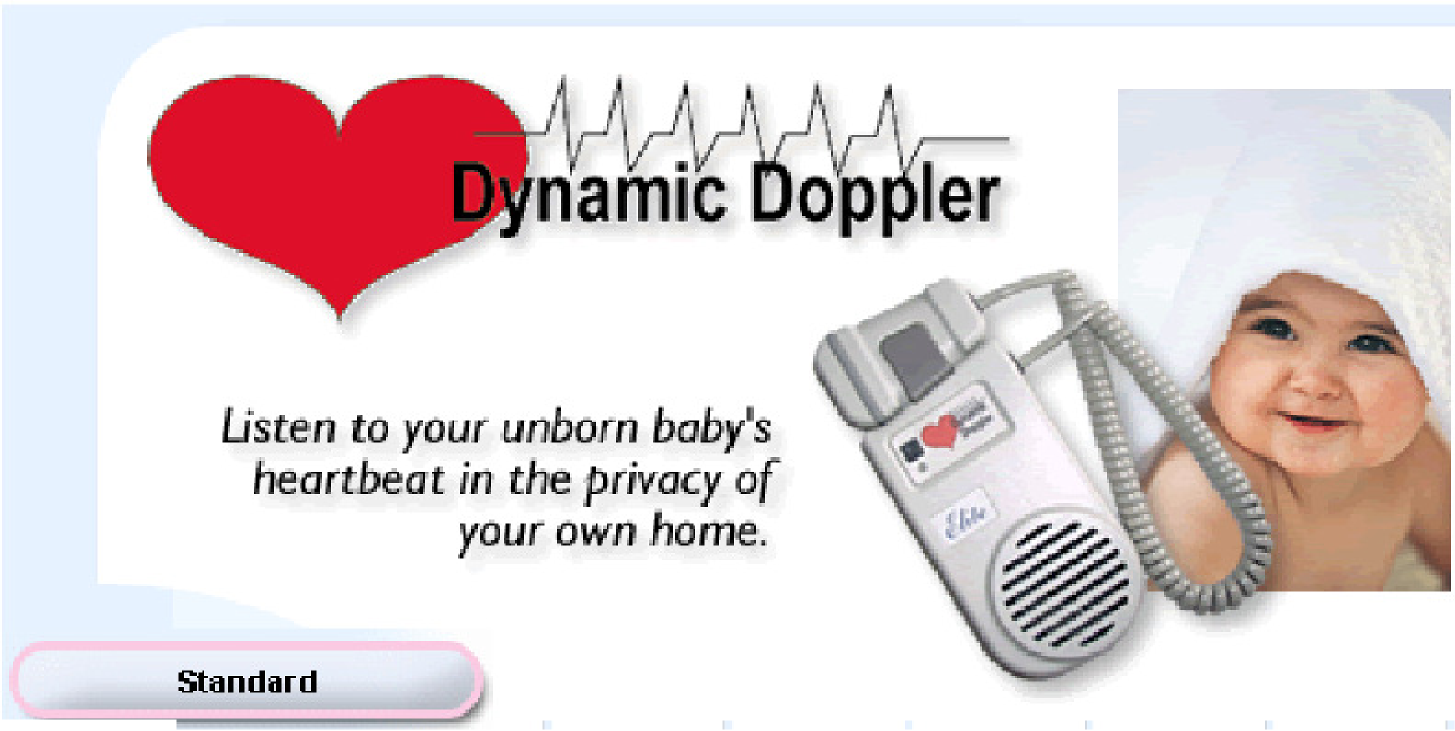
- Police radar
  - K-band broadcast at 30 GHz (30×10^9Hz)
  - Doppler-shifted waves reflect, off your car as you move towards the police car
  - Radar unit then measures the beat frequency arising from the original 30 GHz signal mixed with the reflected ($30+\delta$) GHz signal
    - at 65mph, beat frequency is about 5,800Hz
    - at 75mph, beat frequency is about 6,700Hz

www.speedtrap.org

  - Questions to ask yourself (not the officer):
    - how well is 30 GHz calibrated?
    - how well can beat frequency be measured?
    - what happens if the police car is also moving?
    - if you wire up a K-band broadcaster at ($30+\delta$) GHz, with δ suitably small, can you defeat the system?
      - warning: some radars run in the X band, at 10.6 GHz

Doppler Examples: Qualitative

- Rate of blood flow
  - reflect ultrasound off red-blood cells in an artery
  - reflected ultrasound is Doppler shifted



Doppler Example: Quantitative

- An acoustic burglar alarm consists of a source emitting waves of frequency 28kHz. What is the beat frequency between the source waves and the waves reflected from an intruder walking at an average speed of 0.95m/s directly away from the alarm?
  - use $f' = f\,(v - v_D)/(v + v_S)$
  - beat freq. = $f - f' = f(1 - (v - v_D)/(v + v_S))$
  - with $v = 343\text{m/s}$, $v_D = v_S = 0.95$, $f - f' = 155\text{Hz}$

- Important to note: there were two Doppler shifts in this problem!
  - burglar receives waves, Doppler shifted
  - burglar re-broadcasts the Doppler shifted waves, with another Doppler shifting!

What we learned

- Intensity of sound
  - $I = P_s/(4\pi r^2)$
- Pipes w/ ends
  - Draw 'em
- Interference of waves

  $\phi/2\pi = \Delta L/\lambda$
- Intensity of sound
  - $f' = f\ (v \pm v_D)/(v \pm v_S)$

Next Time

- Thermodynamics
- Zeroth Law of Thermodynamics
- Temperature
- Thermal expansion
- Heat