From Last Time... 
Wave Properties

- **Interference:** waves can superimpose constructively or destructively
- Two speakers can be quieter than one!
- Doppler effect
  - Frequency shift (up or down) from moving source.

Doppler Effect for a moving source

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

Question

A police car is moving toward you at constant speed. You would hear

A. A constant pitch
B. A pitch increasing in frequency
C. A pitch decreasing in frequency
D. A pitch moving up and down in frequency

Shock Waves and Sonic Booms

- 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

Sonic Boom

- Source of sound approaching the listener is equal to or faster than the speed of sound
  - Each successive wave is superimposed on the previous one
  - Shock wave results as air compression in crest gets very large

Breaking the sound barrier

- No sound received till after the source passes the listener - then a sonic boom followed by normal sound from the source
- Conical bow wave from condensed water vapor at high pressure shock wave front.
Breaking the ‘sound’ barrier in a canoe!

If the canoe moves faster than the water wave velocity, shock wave also builds up where all the crests line up.

For water wave velocity - 1 m/s, so Mach 2 is 2 m/s = 4.5 mph !!

Resonance

- So far have been talking about waves traveling in media that extend in all directions.
- In a finite object, the boundaries cause reflections.
- The reflected wave interferes with rest of wave, causing destructive or constructive interference.
- For destructive interference, the wave tends to die away.
- But for constructive interference, the wave builds up.
- Which one happens depends on wavelength.

Resonance on string

- First three vibrational modes of string fixed at both ends
- A normal pluck excites primarily the first vibrational mode.
- Node: region of no string displacement
- Antinode: region of maximum string displacement.

Reflection of waves

- Whenever a traveling wave reaches a boundary, some or all of the wave is reflected
- Like a particle, it bounces back. But...
- When it is reflected from a fixed end, the wave is inverted
- Now think about a series of pulses, up and down, incident on the wall.

Closed tube resonance

- Air compression reflects from end as air expansion
- So at end must be no pressure change at all
- This is a node.

Half-closed tube

I blow into a soda bottle. The wave configuration at the top and bottom can be described as

A. Node at top, node and bottom
B. Anti-node at top anti-node and bottom
C. Anti-node at top, node at bottom
D. Node at top, anti-node at bottom
Closed tube resonance

- First resonance: $\lambda/4 = L$
- Second resonance: $3\lambda/4 = L$
- Third resonance: $5\lambda/4 = L$

Bottle resonance

What is the fundamental frequency if the bottle ‘length’ is 10 cm? (speed of sound = 340 m/s)

- A. 340 Hz
- B. 34 Hz
- C. 680 Hz
- D. 850 Hz
- E. 1700 Hz

Open at both ends

- Tube open at both ends:
  - Both ends are antinodes
- Shortest wavelength:
  - 1/2 wavelength fits in tube
- Next shortest wavelength
  - 3/2 wavelength fits in tube
- $L = n(\lambda/2)$

Air column in typical wind instrument

- Half wave “fits” in to column and creates fundamental
- If all holes are covered, this recorder is “long”
- If first few are open, the effective length is shorter
- Wind instruments play different notes by changing their length
Plucking or bowing can be used to start a string oscillating

- Bowing a string transfers energy gradually
  - Rhythmic excitation at the right frequency causes sympathetic vibration
  - Bowing always excites string at the right frequency
  - The longer the string’s resonance lasts, the more effective the gradual energy transfer
- Plucking a string transfers energy instantly
  - Excited modes depend on where you pluck

http://capa6.phy.ohiou.edu/psc/105x4d/plucker.html

Most objects resonate

- But even complicated objects have some natural frequency of oscillation
- Pendulum
- Wine glass
- Musical instruments
- Natural frequency has to do with size and materials properties of object.

The different length wood blocks ‘resonate’ at different wavelengths, producing different frequency sound waves.
- Striking the block with a mallet produces waves of many different wavelengths in the block. Reflections from the ends interfere destructively for all but the natural frequencies.

Wine glass resonances

Stroboscopic movie of fundamental vibration mode of a wineglass.

Holographic interferometry showing contour map of vibration for different modes. Points of maximum motion appear as bull’s eyes.

Ben Franklin

‘Of all my inventions, the glass armonica has given me the greatest personal satisfaction.’ - Ben Franklin

The glass armonica was one of the most celebrated instruments of the 18th century. Composers such as Beethoven, Mozart, and Donizetti would write music for the armonica.

- Mozart wrote two pieces for the armonica, including ‘Adagio and Rondo 617,’ and Beethoven wrote a melodrama with a narrator accompanied by armonica.
- Armonica performers complained that the instrument was upsetting them emotionally. They said that the vibrations were entering their fingertips and causing mental anguish.
- Maybe lead poisoning from lead in the glass hemispheres of the instrument.
Driving at resonance

- Can tune a speaker to the fundamental resonant frequency of the wine glass (here 1210 Hz).
- More and more energy poured into glass - the glass vibrates with larger and larger amplitude.
- The glass shatters as the vibration amplitude becomes too large.

Tacoma Narrows Bridge

- Even a non-resonant drive can transfer energy.
- Driven by 40 mph wind