Wave Propagation

- **Wave motion:** Disturbance of particles in an elastic medium from equilibrium position \((x_0)\) can propagate through to particles that are coupled to the site of the disturbance, and then to particles that are coupled to those... etc.

- **Transverse Waves:**
  Particle motion is at right angles to direction of wave propagation.

- **Longitudinal Waves:**
  Particle motion is along the axis of wave propagation.

Animations courtesy of Dr. Dan Russell, Kettering University

http://paws.kettering.edu/~drussell/Demos/waves/wavemotion.html

Particles oscillate over only short distances, but pattern of motion propagates over long distance.

Sinusoidal oscillation of air molecule positions at any given point in space results in sinusoidal oscillation of pressure between pressure maxima and minima (rarefactions).
Longitudinal Sound Waves

- Sinusoidal oscillation in particle velocity also results--90° out of phase with pressure.
- Due to propagation sinusoidal pattern can also be seen in space.

Wavelength (\( \lambda \)) is the distance in space between successive maxima (or minima).
Wavelength and frequency

- **Speed of Sound (c):**
  Pressure wave propagates through air at 34,029 cm/sec

- Since distance traveled = velocity * elapsed time
  - if $T$ is the period of one sinusoidal oscillation, then:
    \[ \lambda = cT \]
  - And since $T = 1/f$:
    \[ \lambda = c/f \]
Superposition of waves

Waves traveling in opposite directions superpose when they coincide, then continue traveling.

Oscillations of the same frequency, and same amplitude form standing waves when they superpose.

- Don’t travel, only change in amplitude over time.
- Nodes: no change in position.
- Anti-nodes: maximal change in position.

Animation courtesy of Dr. Dan Russell, Kettering University
http://paws.kettering.edu/~drussell/Demos/superposition/superposition.html
Reflections

• Where there is a discontinuity in the medium, waves will be reflected.

• At a hard boundary, the displacement wave is reflected with the opposite polarity of velocity.
  • reflected and incident waves are constrained to always be anti-phase at boundary
  • node in the standing wave

• At a soft boundary, the wave is reflected with the same polarity.
  • reflected and incident waves are constrained to always be in-phase at boundary
  • anti-node in the standing wave

Animation courtesy of Dr. Dan Russell, Kettering University

http://www.walter-fendt.de/ph14e/stwaverfl.htm
http://paws.kettering.edu/~drussell/Demos/superposition/superposition.html
Standing Waves in a Tube

• In a tube with boundaries at both ends (either open or closed), only oscillations of certain wavelengths ($\lambda$) will produce sustained standing waves.

• This is because reflections cause there to be a node or anti-node of velocity (closed end) or an anti-node (open end) at each end.

• Only vibrations of the certain wavelengths will have the distance between nodes (or between node and anti-node), so as the match the condition (node or anti-node) at both ends.

http://www.walter-fendt.de/ph14e/stlwaves.htm
Tube closed at both ends

- Closed-end tube supports pressure anti-nodes or velocity nodes. Standing waves can be set up for a wavelength that has a pressure max (or min) at one end and a pressure max (or min) at the other.

- The distance between a pressure max and min is $\frac{1}{2} \lambda$, so if the length of the tube ($L$) = $\frac{1}{2} \lambda$, then a standing wave can be sustained. Put another way...

- When $\lambda = 2L$, the distance between pressure nodes (or anti-nodes) allows there to be one at both boundaries.
\[
L = \frac{\lambda}{2}
\]
\[
L = \frac{c}{2f}
\]
\[
f = \frac{c}{2L}
\]
\[
f = \frac{c}{L}
\]
\[
L = \frac{3\lambda}{2}
\]
\[
f = \frac{3c}{2L}
\]
\[
L = 2\lambda
\]
\[
f = \frac{2c}{L}
\]
\[
f = \frac{nc}{2L}
\]
\[
n = 1, 2, 3, 4...
\]

http://www.walter-fendt.de/ph14e/stlwaves.htm
Tube closed at one end

- Closed-end can support pressure anti-nodes, while open-end can support pressure nodes.
- Standing waves can be set up for a wavelength that has a pressure max at one end and a pressure zero (velocity max or min) at the other.
- The distance between a pressure max and zero is $1/4 \lambda$, so if the length of the tube ($L$) is $1/4 \lambda$, then the constraint of each end will be satisfied.
\[ L = \frac{\lambda}{4} \]

\[ L = c/4f \]

\[ f = c/4L \]

\[ L = 3\lambda/4 \quad f = 3c/4L \]

\[ L = 5\lambda/4 \quad f = 4c/4L \]

\[ L = 7\lambda/4 \quad f = 7c/4L \]

\[ f = \frac{nc}{4L} \quad n = 1, 3, 5, 7... \]

http://www.walter-fendt.de/ph14e/stlwaves.htm
Resonance frequencies (formants) in a given tube correspond to the frequencies that can set up standing waves.

For tube that is closed at one end, open at the other, the length of the tube has to be 1/4 of the wavelength (distance from pressure max or min to pressure zero) of the lowest frequency oscillation that can produce a standing wave.

\[ L = \frac{\lambda}{4} \]

\[ L = \frac{c}{4f} \]

\[ f = \frac{c}{4L} = \frac{34000}{4 \cdot 17} = 500 \]

Next higher resonances will occur when \( L = \frac{3\lambda}{4}, \frac{5\lambda}{4}, \frac{7\lambda}{4} \) and \( f \) will be:

\[ f = \frac{3c}{4L} \]

\[ f = \frac{5c}{4L} \]

\[ f = \frac{7c}{4L} \]

\[ f = \frac{nc}{4L} \]

\[ n = 1, 3, 5, 7... \]

\[ f = 500, 1500, 2500, 3500... \]
Resonance

• The vibration of the larynx (or our buzz) causes the air in the vocal to vibrate at a set frequencies that are integer multiples (harmonics) of the fundamental frequency.

• For frequencies that correspond to formants, the reflections will set up standing waves, with the energy at that frequency in the tube will be high.

• For other harmonics, reflections will cancel each other out, and the oscillatory energy in the vocal tract at these frequencies will be lower.

http://www.colorado.edu/physics/2000/microwaves/standing_wave2.html