What is a wave?

- A wave is a disturbance that transfers energy progressively from one point to another.
- Though the medium through which the wave travels may experience local oscillations, particles in the medium do not travel with the wave.
- Example: When a wave pulse travels from left to right on a string, the string is displaced up and down, but the string itself does not experience any net motion.

Superposition of Waves

- When two (or more) waves travel through the same medium at the same time they pass through each other without being disturbed.
- Click image for animation:

Constructive and Destructive Interference

- Consider the phase of the waves being added.
- The sum of waves in the same medium leads to:
  1. constructive interference: the two waves are in phase and their sum leads to an increase of amplitude
  2. destructive interference: the two waves are out of phase and the sum leads to a decrease in the overall amplitude.
- Click image for animation:
Reflections at Boundaries

- So how do we get two waves in the same medium?
- When a wave is confined to a medium (such as on a string), when it reaches a boundary it will reflect.
- At a fixed end the displacement wave is inverted.
- Click image for animation:

- At a free end the displacement wave is not inverted.
- Click image for animation:

Standing Waves

- Reflection causes destructive and constructive interference of traveling waves, leading to standing waves.
- Click image for animation:

- Standing wave: pattern of alternating nodes and antinodes.
- Click image for animation:

- The fundamental mode of oscillation, is determined by the shortest node-antinode pattern.

Standing Waves and Boundaries

- Standing waves created from a fixed boundary:
  Click image for animation:

- Standing waves created from a free boundary:
  Click image for animation:

Guitar String

- The guitar string is fixed at both ends—therefore it has a node at both ends.

- For a string of length $L$ and each harmonic number $n$,
  - the wavelength is $\lambda_n = \frac{2}{n}L$.
  - the frequency is $f_n = n \frac{v}{2L} = nf_1$ (where $v$ is the speed of sound).
Open-Open Tube

- Displacement waves in a tube open at both ends:

![Standing displacement waves in an open tube.](Image)

- Though opposite-phase to displacement on a string, the harmonics follow the same relationship:
  - wavelength: \( \lambda_n = \frac{2L}{n} \)
  - frequency: \( f_n = n \frac{v}{2L} = n f_1 \)
- Pressure waves are opposite phase to displacement waves (they look like displacement on a guitar string).

Closed-Open Tube

- Displacement waves in a tube closed at one end:

![Standing waves for displacement in a closed-open tube.](Image)

- The wavelength of the first harmonic is \( \lambda_1 = 4L \).
- Adding an antinode/node creates the next standing wave pattern with wavelength \( \lambda_3 = \frac{4L}{3} \)
- Since \( \lambda_3 \) is \( \frac{1}{3} \)rd the length of \( \lambda_1 \), the frequency is 3 times the fundamental and it is the “third” harmonic.
- Notice the second harmonic is missing!

Odd harmonics in a closed tube

- The closed tube has only odd harmonics:
  \( n = 1, 3, 5, ... \)

![Standing waves for pressure in a closed tube.](Image)

- For odd \( n \), the harmonics of the closed tube have the following properties:
  - wavelength: \( \lambda = \frac{4L}{n} \)
  - frequency: \( f_n = n \frac{v}{4L} \)