From Last Time...

Wave Properties

- **Amplitude** is the maximum displacement of string above the equilibrium position.
- **Wavelength**, \( \lambda \), is the distance between two successive points that behave identically.
- **Period**: required to complete one cycle.
- **Frequency** = \( 1/\text{Period} \) = rate at which cycles are completed.
- **Velocity** = Wavelength/Period, \( v = \lambda / \text{T} \), or \( v = \lambda f \).

Question

A sound wave is traveling through air when it encounters a large helium-filled balloon. The sound velocity inside the balloon is greater than in the air. Compare the wavelength of the sound wave inside and outside the balloon.

A. \( \lambda_{\text{inside}} = \lambda_{\text{outside}} \)
B. \( \lambda_{\text{inside}} > \lambda_{\text{outside}} \)
C. \( \lambda_{\text{inside}} < \lambda_{\text{outside}} \)

The frequency inside the balloon is the same as outside. Use \( \lambda = v / f \) to find that the wavelength is less.

Types of waves

- **Transverse**
  - Waves on a rope
- **Longitudinal (compressional)**
  - Sound waves
- **Other examples of waves**
  - Seismic waves
  - Water waves

Seismic waves

Waves in the earth generated by earthquake

- **P** (primary) wave: compressional
  \( v_P \approx 6 \text{ km/s} \)

- **S** (secondary) waves: transverse
  \( v_S \approx 3.5 \text{ km/s} \)

Locating an earthquake

Time difference between P arrival time and S arrival time due to difference in velocities.

- P travel time = distance / P-velocity
- S travel time = distance / S-velocity

Arrival time diff. = distance / S-vel - distance / P-vel

\[
\Delta t = \frac{d}{v_S} - \frac{d}{v_P} = \left( \frac{1}{v_S} - \frac{1}{v_P} \right)d \approx 0.119 \text{ s/km}
\]

Multiply arrival time difference in seconds by 8.4 to get distance to epicenter in kilometers.

Detecting with seismometer

- P (transverse) wave travels faster than S (compressional) wave, so it registers first on seismometer.
**Seismic Rayleigh wave (R-wave)**

- Rayleigh wave: another wave from earthquakes
  - Particle motion roughly circular.
  - Amplitude decreases with depth.
  - A ‘surface wave’.

*This is same as a water wave!*

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**Water waves**

- Water waves occur on the surface. They are a kind of transverse wave.

**Surface water waves**

- Surface water waves produced by wind.
- The wave travels with constant speed, but the water circles!

**Water’s Motion**

- Circling strongest at surface
- Weak ~ 1/2 wavelength deep

**Wavelength of water wave**

- The longer the wavelength of the wave
  - the faster it travels
  - the deeper it goes
  - the more energy it contains for a given amplitude

Tsunamis are very long wavelength, very deep, very high energy waves
**Tsunamis**

- Generate by some disturbance
  - Landslide
  - Undersea earthquake
- Generates long-wavelength propagating water wave

**Tsunami is a wave**

- December 26, 2004 tsunami was generated from the 9.0 Richter scale Sumatra earthquake
- Like all waves, tsunami transported energy but not mass.
  - The water that impacted the beaches in Sri Lanka, for example, did not 'come from' Sumatra;
  - Just the energy 'came from' Sumatra.
- Wavelength, period, and velocity:
  - velocity = wavelength \times frequency
- Frequency = 1 / period:
  - period of 40 minutes gives frequency of about 0.0004Hz (cycles per second).
  - The wavelength of a tsunami in deep water is about 500km
  - From this we can compute the tsunami velocity to be about 200m/s or 450 miles an hour - about as fast as a jet airplane!

**Sound waves again**

- Sound is a compressional wave
- The crest is a local compression of the air, the trough a local rarefraction.
- Can be produced by objects transferring their vibratory motion to the air
  - Tuning fork
  - Speaker
  - Musical instrument

**Sensing sound**

- Middle ear transmits sound to cochlea, which discriminates loudness and pitch

**Discriminating pitch**

- Your ear detects sound
  - A mechanosensitive hair bundle in the cochlea of the ear. Each hair bundle is made up of 30-300 stereocilia (tiny hairs).
  - Different locations host bundles that send different pitch signals.
Pitch

- Pitch is related mainly, although not completely, to the frequency of the sound
- Pitch is not a physical property of the sound
- Frequency is the stimulus and pitch is the response
  - It is a psychological reaction that allows humans to place the sound on a scale

Frequency Response Curves

- Bottom curve is the threshold of hearing
  - Threshold of hearing is strongly dependent on frequency
  - Easiest frequency to hear is about 3000 Hz
- When the sound is loud (top curve, threshold of pain) all frequencies can be heard equally well

Timbre

- In music, the characteristic sound of any instrument is referred to as the quality of sound, or the timbre of the sound
- Not all sound is a pure tone.
- The quality depends on the mixture of ‘harmonics’ in the sound.
- This is a mixture of other frequencies with the original.
- Can completely describe the sound by only including ‘overtones’

Quality of Sound - Tuning Fork

- Tuning fork produces only the fundamental frequency

Quality of Sound - Flute

- The same note played on a flute sounds differently
- Not a pure tone

Quality of Sound - Clarinet

- The fifth harmonic is very strong
- The first and fourth harmonics are very similar, with the third being close to them
Combining waves

- Two traveling waves can meet and pass through each other without being destroyed or even altered.
- Waves obey the Superposition Principle:
  - If two or more traveling waves are moving through a medium, the resulting wave is found by adding together the displacements of the individual waves point by point.
  - Constructive interference: waves reinforce.
  - Destructive interference: waves tend to cancel.

Constructive Interference in a String

- Two pulses are traveling in opposite directions.
- The net displacement when they overlap is the sum of the displacements of the pulses.
- Note that the pulses are unchanged after the interference.

Constructive Interference

- Two waves, a and b, have the same frequency, amplitude, and start point.
  - Are in phase.
- The combined wave, c, has the same frequency and a greater amplitude.

Destructive Interference in a String

- Two pulses are traveling in opposite directions.
- The net displacement when they overlap the displacements of the pulses subtract.
- Note that the pulses are unchanged after the interference.

Destructive interference in a continuous wave

- Two waves, a and b, have the same amplitude and frequency.
- They are 1/2 wavelength out of phase.
- When they combine, the waveforms cancel.

Interference of sound waves

- Interference arises when waves change their ‘phase relationship’.
- Can vary phase relationship of two waves by changing physical location of speaker.

- In-phase
- 1/2 λ, phase diff
**Example**

- Speed of sound ~ 340 m/s
- So $f=340$ Hz gives $\lambda = \frac{v}{f} = 1$ meter
- Change of 1/2 wavelength is 1/2 meter.

- Or can change phase relationship by changing relative distance from source.

**Interference**

- Water drop is a source of circular waves (two-dimensions here)
- When the waves overlap, they superimpose.
- In some areas they cancel, in others they reinforce.
- This is called interference

**Spherical Waves**

- A spherical wave propagates radially outward from the oscillating sphere
- The energy propagates equally in all directions

**Representations of Waves**

- Wave fronts are the concentric arcs
  - The distance between successive wave fronts is the wavelength
- Rays are the radial lines pointing out from the source and perpendicular to the wave fronts

**Interference engineering**

- Off-axis sound canceled by interference on the vertical axis.
- Horizontal plane unaffected
- Total sound intensity drops off more slowly

**Line array works by interference**

- Off-axis sound canceled by interference on the vertical axis.
- Horizontal plane unaffected
- Total sound intensity drops off more slowly
**Doppler Effect**

- A Doppler effect is experienced whenever there is relative motion between a source of waves and an observer.
  - When the source and the observer are moving toward each other, the observer hears a higher frequency.
  - When the source and the observer are moving away from each other, the observer hears a lower frequency.
- Although the Doppler Effect is commonly experienced with sound waves, it is a phenomena common to all waves.

**Doppler Effect, Case 1**

- An observer is moving toward a stationary source.
- Due to his movement, the observer detects an additional number of wave fronts.
- The frequency heard is increased.

**Doppler Effect, Case 2**

- An observer is moving away from a stationary source.
- The observer detects fewer wave fronts per second.
- The frequency appears lower.

**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**

- What happens if the 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.
  - If the speed is exceeded, no sound received till after the source passes the listener - then a sonic boom, followed by normal sound from the source.
  - Conical bow wave.
  - Much like triangular bow wave behind a duck swimming in a pond.
Breaking the sound barrier