Chapter 15: Traveling Waves and Sound

Section 15.1: The Wave Model

Waves and Wave Fronts

- Oscillation + propagation: combination of two separate and distinct motions
- Oscillation: periodic motion with respect to some fixed reference (vibration)
- Propagation: linear translational motion through space
- You can have one without the other, but when they occur simultaneously, it's a wave

Mechanical Waves

- Still oscillation + propagation
- Propagation is through some material medium (matter)
- What actually propagates is energy, not mass—this is very important!
- Wave speed measures speed of propagation

Electromagnetic and Matter Waves

- Matter waves require a physical medium through which to propagate
- Electromagnetic waves do not require a medium
- Either way, it's still energy that is propagating

Two Kinds of Waves

- Transverse: Oscillation is perpendicular to propagation
  Electromagnetic waves are transverse
- Longitudinal: Oscillation is parallel to propagation
  Sound waves are longitudinal
- Fluid medium: Sound waves are exclusively longitudinal
- Solid medium: S ound waves may have both a longitudinal and transverse component

S-Waves and P-Waves

- Seismic waves have both longitudinal and transverse components
- Longitudinal component: P-wave
- Transverse component: S-wave

Section 15.2: Traveling Waves

Waves on a String

- This shows clearly that the medium oscillates, but does not propagate
- The molecules of the string remain fixed in position with respect to each other
- The energy propagates from molecule to molecule

Sound Waves

- Something (has to be a real thing) starts vibrating
- Energy is propagated through the medium (this is 3-dimensional!)
- Sound through air is longitudinal: pressure wave

Compressions and Rarefactions

- Region of slightly increased density = compression
- Region of slightly decreased density = rarefaction
- Region of average (equilibrium) density = node

Wave Speed is a Property of the Medium

- In a matter wave, the propagation speed reflects how quickly energy can be passed from atom-to-atom (or molecule-to-molecule)
- Conduction is the only way to propagate a wave through matter

Speed of a Wave on a String

- Total mass, total length do not affect wave speed
- Linear density: Mass per unit length $\mu = m/L$
- Newton #2 to the rescue: For a given force, the more mass you have, the less acceleration
- Greater μ means you have to move more mass with the same amount of force (whatever is causing the oscillation)

Speed of Sound Through a Gas

- Speed depends on temperature: higher temperature means faster speed
- Speed depends on molecular weight: at a given temperature, the less massive the molecule, the faster the speed
- Surprisingly, wave speed does not depend on the density or pressure

Speed of Sound in Air

- Warm air is faster than cold air
  $v = [331 + 0.6\ T(°C)]$ m/s
- Humid air is faster than dry air
  Water molecules less massive than N_2 or O_2 molecules
- Low frequency waves propagate better than high frequency waves
  Higher f waves interact more with air and water molecules, lose energy faster

Speeds Through Other Media

- Solids tend to be fastest
- Strong cohesive bonding between atoms, crystal structure, and elasticity

Speed of Light

- 3×10^8 m/s through vacuum is the fastest
- Any material medium slows light down
- Air is slightly slower, but go ahead and use c in problem solving

Section 15.3: Graphical and Mathematical Descriptions of Waves

Quick! Draw Me a Wave!

- Crest: Maximum positive displacement from equilibrium
- Trough: Maximum negative displacement from equilibrium
- Node: Point at which the displacement from equilibrium is zero
- Amplitude A: Magnitude of maximum displacement from equilibrium
- Wavelength λ: Repeat distance (separation of points on the waveform that are in phase, i.e. two crests)
- Period T: Total time to complete one full cycle of oscillation (seconds)
- Frequency f: Number of waves per unit of time (cycles of oscillation per second)

Now Describe It Mathematically

- Position as a function of time: $y(t) = A \cos[(2\pi/T)t]$ (this is the oscillation!)
- Position as a function of distance: $y(x) = A \cos[(2\pi/\lambda)x]$ (this is the propagation)
- Combine into a single function: $y(x, t) = A \cos[2\pi(x/\lambda - t/T)]$

Wave Speed: The Fundamental relationship for Sinusoidal Waves

- Wave speed: $v = \lambda f$

Change the Frequency, Change the Wavelength

- And vice-versa
- Through a given medium (set of conditions), the speed is fixed
- Change the frequency: wavelength changes automatically; speed does not in- or de-crease

Section 15.4: Sound and Light Waves

Sound Waves

- Longitudinal pressure waves with compressions and rarefactions
- Compression: Localized area of greater density; molecules closer together
- Rarefaction: Localized area of decreased density; molecules farther apart
- Node: No displacement from equilibrium; molecules at equilibrium spacing

Audible Frequencies

- Lowest audible frequency: About 20 Hz
- Highest audible frequency: About 20kHz
- Note that this is spread over 3 orders of magnitude

Inaudible Frequencies

- Infrasonic: Frequency too low to be heard
- Ultrasonic: Frequency too high to be heard
- Upper limit: About 1 GHz
  Why? At this point, you will start reaching the elastic limit of the material and trying to make it vibrate at a greater frequency will start breaking bonds: high frequency sound shatters glass

Wavelength (Frequency) and Resolution

- If you are using sound waves as a sensor, the limit of your ability to 'see' is the wavelength (frequency)
- You can't see details smaller than the wavelength (frequency)
- Bats use echolocation at ultrasonic frequencies 20kHz–200kHz
- Ultrasound imaging uses frequencies 1MHz–20MHz

Electromagnetic Waves

- An e·m wave is created when you oscillate a charged particle
- Visible light is the range of frequencies we happen to be able to see
- The rest of the e·m spectrum (radio, IR, UV, x-Ray, γ-Ray) same thing, different frequency

Section 15.5: Energy and Intensity

Wave Amplitude in a 2-D Medium

- Greater amplitude means greater energy (think about a mass bobbing on a spring: $U = \frac{1}{2}kx^2$)
- Amplitude is greatest at the source, decreases with distance (surprise…not really)
- Think about the vibration of individual molecules; as r increases, the ring of matter around the source increases
- But you have the same total amount of energy, and you have to vibrate more molecules

New and Improved! Now In Three Dimensions!

- Now imagine the molecules vibrating all around the source (a sphere instead of a circle)
- Again, bigger r means less energy, but now it's shared by molecules covering an area (instead of a line)
- The distance dependence is now an inverse square rule!

Wave Power and Intensity

- Intensity = power distribution
- Power: energy/time (rate at which energy is propagated)
- Distribution: over an area (think of pressure: force/area)
- units: Watts/m^2

Inverse Square Relationships

- $I = P/A = P/(4\pi r^2)$
- I proportional to $1/r^2$
- Intensity falls off rapidly with distance
  Double the distance, ¼ the intensity
  Triple the distance, $^1/_9$ the intensity

Reflected Pulses: Upside Down or Right-Side Up?

- Reflection: Wave strikes a boundary and bounces off; what orientation?
- Depends on the obstacle the wave hits, and how much of the energy it transmits

So Which Is It? Compare the Impedance

- Impedance Z: Quantify how much energy a medium will reflect (vs absorb)
- Z of a medium is a measure of the difficulty a wave has in distorting the medium
- Depends on both the medium's elastic and inertial properties

Section 15.6: Loudness of Sound

Loudness

- Loudness is how we perceive the intensity of sound
- Threshold of hearing: $I_o = 10^{-12}$ W/m^2
- Threshold of pain: $I_p = 1$ W/m^2
- To be heard: sound must have frequency in the audible range and intensity greater than I_o

Loudness is Not Linear

- Audible range of intensities covers 12 orders of magnitude
- Doubling the intensity does not double the loudness:
  6×10^{-4} W/m^2 is not twice as loud as 3×10^{-4} W/m^2
- To double the loudness, you have to increase intensity by an order of magnitude:
  6×10^{-4} W/m^2 is twice as loud as $6\text{x}10^{-5}$ W/m^2

Sound Intensity Level

- Not the same as sound intensity
- Intensity is an absolute measurement
- Intensity level is a relative comparison: ratio I/I_o

The Bel

- Because audible intensities range over many orders of magnitude, mathematically convenient to use logarithmic scale
- If you just calculated ratio I/I_o, you would end up with huge numbers
  (Remember, Io puts an exponent of -12 in the denominator)
- Use logarithm: $\log(I/I_o)$ will give you a result between 0 and 12
  (Can't be any bigger because of that -12 exponent in the denominator)
- $I = I_o$: $\log(I/I_o) = \log(1) = 0$
- This is convenient, but too compressed. Need a finer scale.

The deciBel

- 1 bel = 10 decibels (dB)
- Decibel scale ranges from 0 to 120 dB
- $\beta = 10\log(I/I_o)$

The Scale is Not Linear

- 10 dB is not twice as loud as 5 dB
- A 3dB increase is a doubling of intensity
- A 10 dB increase is a factor of 10 increase in intensity (1 bel = 1 order of magnitude)
- A 20 dB increase is a factor of 100 increase in intensity (2 bel = 2 orders of magnitude)

Section 15.7: The Doppler Effect

Sound Waves From a Moving Source

- Observer notices an apparent change in the pitch of a sound
- But the actual frequency being generated by the source does not change
- The perceived frequency does not match actual frequency because of relative motion

How The Math Works Out

- Simple application of linear kinematics:
- Assume wave travels in a straight line at a constant speed
- Assume that whatever is moving (source or observer) also travels in a straight line at constant speed
- $f_o = [(v + v_o)/(v - v_s)]f_s$
- f_o: Frequency perceived by observer
- v_o: Speed of observer
- f_s: True frequency of the source
- v_s: Speed of source
- v: Speed of sound (or medium)

How To Apply the Sign Convention

- $v > 0$: Always use (+)
- $v_o > 0$: Observer moves toward source (+)
- $v_o < 0$: Observer moves away from source (–)
- $v_s > 0$: Source moves toward observer (+)
- $v_s < 0$: Source moves away from observer (–)

Effect of Approach

- Stationary observer, approaching source or
- Stationary source, approaching observer or
- Both observer and source in motion, net decrease in separation
- Does not matter how the relative motion is achieved
- Observer will perceive an increase in the frequency of the wave generated by the source

Effect of Receding

- Stationary observer, receding source or
- Stationary source, receding observer or
- Both observer and source in motion, net increase in separation
- Does not matter how the relative motion is achieved
- Observer will perceive an decrease in the frequency of the wave generated by the source

Frequency Shift on Reflection from a Moving Object

- $\Delta f = \pm 2f_s(v_o/v)$
- Huh? Why?
- Because this is how speed traps work!
- This is also how those Five Live Doppler Radars predict tornadoes!