Chapter 9

Waves

Chapter 9 is finished, but is not in camera-ready format. Specifically, all of the diagrams are missing. But here are some excerpts from the text, with omissions indicated by .....

This chapter does not give a "complete" explanation of waves. Instead, its goal is to help you understand a few key principles that will make it easier for you to learn the details from your textbook and teacher. First read Section 9.1. At the end of it are suggestions for using the rest of Chapter 9.

9.1 Basic Principles of Wave Motion

Imagine that you are on a small island in the middle of a lake on a windless day. The water surface is totally flat. Somewhere to the left of you a partly submerged object begins to move up and down in regular rhythm. This disturbance produces *waves* that move outward, away from the object, along the surface of the water.

Three snapshot-photos of this wave are shown below. You stand at "x" and take a photo when a *wave crest* (high point) is directly in front of you, another when the first *wave trough* (low point) reaches you, and a third when the next crest (marked "•" to help you follow its progress) is in front of you. The camera has a stopwatch that shows the time when each photo is taken: at t = 0, .25 s and .50 s.

The distance from crest to crest (or trough to trough) is the *wavelength* "λ". During the .50 s between the first & third pictures, • moves a distance of λ. The wave *velocity* "**v**" is easy to calculate: $v = \Delta x / \Delta t = (1.50\,m)/(.50\,s) = 3.00$ m/s. To find the wave *frequency* "**f**", just count the number of full wave-cycles that pass you during one second; one wave passes during the first .50 s and another will pass during the next .50 s, so f = 2 cycles per second. Or you can... .....

[pictures will be here, and they include "p" which is a location in the water]

..... [snip] ..... Notice that p moves up and down, oscillating about its equilibrium position, but doesn't move sideways. This is a distinctive characteristic of waves:

A wave transfers disturbance (and energy) from one place to another without a transfer of matter.

To convince yourself that this is true, think about what happens when you shake one end of a string up and down to produce waves that travel sideways (just like in the water-wave pictures above). Individual parts of the string move up & down, but they don't move sideways even though the string-waves are moving sideways.

Problem 9-# explains why a water wave can carry a surfboard forward.

Transverse and Longitudinal Waves

The pictures below show two ways to make waves on a "slinky spring". You can shake one end up and down to make a *transverse wave* with spring-oscillations (◊) that are perpendicular to the direction of wave motion (→). Or you can shake the end back and forth to make a *longitudinal wave* with *compressions* [where coils are temporarily close together] and *expansions* [where coils are temporarily far apart] traveling along the spring. The longitudinal spring oscillations (↔) are along the same direction as the wave motion (→).

The crest of a transverse wave occurs when **displacement** (how far the spring has moved from its equilibrium position) is a maximum. The crest of a longitudinal wave occurs when the spring's **compression** is a maximum.

{ note: In the most common type of longitudinal wave, a sound wave moving through air, compression occurs at locations where air pressure is temporarily higher than usual (because air molecules are closer together than usual) and expansion occurs at temporary low-pressure locations. } ..... [snip] .....

Wave Mediums

With one exception — light waves — all waves must travel through a *medium.* Each part of a medium is "connected" to neighboring parts, so a wave-disturbance at point A disturbs its neighbor at B, then B disturbs C, and so on, as the wave-disturbance moves through the medium. .....

CHOICES

You can read the rest of Chapter 9 in any order. Here is a summary of each section:
9.2 shows how the reflection and addition of waves leads to formation of standing waves and music.
9.3 compares "relative velocity" for bullets, sound waves, and light waves.
9.4 discusses the Doppler Effect for sound waves.
9.5 compares amplitude, power, intensity & intensity level [decibels], and shows (clearly, so you can easily understand) how to solve problems that involve logarithms.

Optional: **9.93** discusses the physics of music (scales, chords, harmony), the physical and cultural differences between music and noise, three kinds of musical improvisation, and how to make bamboo flutes. **9.94** explains the equations for traveling waves {"$y = y_{max} \sin(kx + \omega t)$",...} and standing waves, plus motion graphs for waves.

LIGHT WAVES are discussed in Chapters 14-17.

9.2 Standing Waves and Music

The pictures below show how a "standing wave" is produced by the interaction of two waves that travel in opposite directions on a string. ..... [snip] .....

When two waves are *in phase* so they are both crests (as in Pictures #1 and #5) or both troughs (as in #3), *constructive interference* occurs and the resultant wave has maximum displacement. When waves are *totally out of phase* (as in Pictures #2 and #4), *destructive interference* occurs and the resultant wave displacement is a minimum. Between these extremes, waves are "partially out of phase" and *partially destructive interference* occurs.

The everyday meaning of "interference" implies "opposition". But in physics, interference [which could called combination, addition, or superposition] can produce a wave that is either larger (through cooperation) or smaller (through conflict). .....

A Musical Standing Wave

When a guitar string is plucked, waves of many different frequencies travel in both directions (← and →) until they reach the ends of the string and are "reflected" backward. Continuing reflection makes waves constantly run back & forth in both directions. Most wave frequencies interfere destructively and quickly fade away, but at some *resonant frequencies* the → and ← waves interfere constructively, as described above, to produce standing waves.

Many different standing waves occur on a string simultaneously. Four of these standing-wave *modes of vibration* are shown below; each picture shows one mode at its instant of maximum displacement. In any mode, the string's endpoints must be nodes. Why? If the string is held firmly against the guitar at the endpoints, the string cannot move up & down at these points, thus producing "endpoint nodes". .....

MUSIC: Somewhat amazingly, many modes of vibration (with n = 1, 2, 3, 4, 5,...) exist simultaneously on a vibrating guitar string.

When a string vibrates it alternately compresses & expands the air around itself, thus producing longitudinal sound waves that move outward from the string. Each string-vibration mode (standing wave) produces *sound* (traveling waves in the air) of equal frequency: frequency of string-vibration = frequency of sound-wave.

A large tuba (or a note at the left end of a piano) produces sound waves with long wavelength, low frequency, and "low pitch". A small trumpet (or note at the left end of a piano) produces sound with short wavelength, high frequency and "high pitch". The *pitch* of a sound wave is determined mainly by its frequency.

Each vibration mode of a string has a characteristic frequency. By combining formulas from earlier in Chapter 9 { $f\lambda = v$, $\lambda = 2L/n$, $v = \sqrt{F_T/(m/L)}$ } we can derive a formula for the frequency of string-vibration:

$$f = (n / 2L)\sqrt{F_T/(m/L)}$$

This equation shows that the frequency of a musical note produced by a string is affected by four factors: n, L, F_T and m/L. Let's look at each of these factor.

n: If the fundamental n = 1 mode has a frequency of 200 Hz, the overtones (with n = 2, 3,...) are 400 Hz, 600 Hz, ... Our ears hear all of these frequencies but the "pitch" we perceive is determined by the fundamental frequency of 200 Hz.

Overtones don't affect pitch, but they do help give each instrument (guitar, piano, trombone, saxophone, singer,...) its distinctive "character". In physics, the *quality* of a tone refers to its mix of harmonics: the loudness of overtones (first, second,...) compared with the fundamental. We can tell the difference between a guitar and saxophone, even when they play notes with the same pitch, partly because their tone quality is different. { As commonly occurs, a nontechnical definition of "tone quality" as a measure of the "artistic excellence of a tone" is not the same as the physics definition. }

L: Frequency is proportional to 1/L. When a musician presses a string against the guitar neck to shorten the length "L" of freely vibrating string, the fundamental wavelength ($\lambda = 2L/n = 2L/1$) decreases, and the frequency and pitch increase.

OCTAVES: If L is cut in half, frequency doubles and we perceive the new pitch to be an *octave* higher than the original pitch. For example, middle-C on a piano is 264 Hz, so other "C notes" appear in higher octaves at 528 Hz, 1056 Hz, ..., and also in lower octaves at 132 Hz, 66 Hz, ...

F_T : When F_T increases, so does pitch. A guitar player, by twisting the tuning peg of a string, can change the string's tension (F_T) and pitch.

m / L : If m/L increases, pitch decreases. A guitar uses thick strings (with large m/L) for low pitches and thin strings (with small m/L) for high pitches, because this makes it easier to produce a wide range of pitches and still have reasonable string lengths and tensions.

PHYSICS and PHYSIOLOGY: When you listen to a jazz band that has guitar, bass, piano, trumpet, saxophone, singer and drums, your ears instantly convert sound-waves into electrical signals that are processed by an amazingly powerful and flexible computer — your brain. There is a huge amount of information, with many notes (plus overtones) played in constantly changing rhythm, but your ear-and-brain are so well designed that you can make sense of it as "music" with rhythm, melody, harmony and lyrics. You can even focus your attention on a single instrument, selecting its sound waves from all of the other vibrations that are occurring simultaneously.

Section 9.93 discusses music (harmony, improvisation,...) in more detail. ..... [snip] .....

STANDING WAVES IN A PIPE are formed in the same way as standing waves on a string. Read your textbook to find out why there are nodes at the closed end of a pipe, and antinodes at the open end. ..... [snip] .....

Musical Improvisation: Each musician listens to the music, sorts through the information to find out what the other musicians are doing, and simultaneously decides what notes she (or he) wants to add to the musical mix. During improvisation these decisions can be based on memory and habit patterns, or structure that has been pre-planned by the group, or conscious analysis and creative imagination.

9.3 Relative Velocity for Waves of Sound & Light

The picture below shows a train moving rightward at 60 m/s. In the middle of the train is a column with (from top to bottom) a bulb that emits light waves toward the left & right, loudspeakers that emit sound waves toward the left & right, and guns that shoot bullets at 240 m/s toward the left & right. {Weather report: 15° C, no wind. When temperature is 15° C, the speed of sound in air is 340 m/s.}

There are four observers. The speeds of leftward-moving things (light, sound, bullet) are measured by observers on the ground and on the train. Speeds toward the right are also reported by a train-observer and a ground-observer.

Study these speeds and try to find the logical "rules" that govern the observed speed of light waves, sound waves, and bullets. .....[pictures will be here].....

The bullet speeds are just what the common sense *relative motion principles* of Section 2.10 lead you to expect. The train-observers move along with the gun so they see the bullets leave the gun at 240 m/s. For ground-observers the train's rightward motion subtracts 60 m/s or adds 60 m/s to make the observed speeds 180 m/s leftward and 300 m/s rightward, respectively.

Sound waves travel at 340 m/s with respect to the air. Observers standing on the ground are at rest with respect to the air, so they measure 340 m/s. One observer on the train moves away from air that carries the leftward-moving wave, ←340 60→, so he observes the wave moving away at 400 m/s. The other train-observer "chases" a wave toward the right, →60 340→, so he sees the wave move away at only 280 m/s. { Imagine that the sound waves are 340 m/s trains, moving either ← or →, that you observe from your 60 m/s train. } Do you see how sound speed differs from bullet speed?

For light waves the speed-rule is simple but strange: every observer measures the same speed, independent of the source-velocity or observer-velocity.

Compare the behavior of bullets, sound and light. The speed of each thing follows its own logical rule, but each rule is different. A bullet, sound wave, and light wave move at a specific speed with respect to the gun, air, and observer, respectively.

With the exception of light, all waves travel because they interact with a medium (air, water, string, ...) so, as you might expect, each type of wave has a certain speed with respect to the medium in which it travels. Light behaves in a surprising way, unlike either bullets or normal waves!

By working out the logical implications of two constancies (with light-speed and physical laws both constant), Einstein formulated the theory of *relativity* that is discussed in Chapter 16. One implication, which is verified by experiments, is that particles don't behave in Section 2.11's common sense way when they travel extremely fast, at speeds close to the speed of light.

There is another difference between waves and particles. Waves always have a certain speed. For example, sound waves travel through 15° C air at 340 m/s, and light waves travel through air at around 299,709,080 m/s. But a bullet-particle can travel at many different speeds — at 240 m/s, or 20 m/s, or 500 m/s, or...

Sound speed depends on temperature and on the medium (air, water, steel, ...) in which the sound wave travels. Your textbook may give a formula like " $v = \sqrt{\text{elastic modulus/density}}$ " for the speed of sound in a solid or liquid.

Sound cannot travel through a *vacuum* (empty space), but light travels through vacuum at 299,792,458 m/s. As explained in Section 14.2, when light travels through a non-vacuum medium (like air, water or glass) it slows down slightly. If the limitations of "significant figures" are ignored, the speed of light through "standard air" can be calculated as 299,709,080 m/s. Very fast. }

9.4 The Doppler Effect

You have probably noticed that when sound is emitted by a moving source (a train whistle, fire truck siren, car horn or engine, ...) the tone's pitch drops sharply as the moving source passes you. This change in frequency is a result of the wave-speed principles that are summarized in Section 9.3.

The following formula can be used when the air is still, with no "wind": ..... [snip] .....

9.5 amplitude, power and intensity
The Decibel Scale for sound intensity

Amplitude, power, and intensity all measure how "big" a wave is, so they are often confused by students. But each term has a different meaning. Let's compare these terms, so you will understand and remember what each of them means. ..... [snip] .....

the INVERSE SQUARE relationship of intensity. If a tiny source produces waves that radiate equally in every direction, all waves that are emitted at a certain time will, at a later time, be on the surface of an imaginary sphere, because waves have moved the same distance in every direction. The wave's energy is spread evenly over this sphere, whose surface area is $4\pi r^2$.

Ratio logic: If you are three times as far from the source as another observer, you are on a sphere that has 3 times the radius and (because A is proportional to r^2) 9 times the area, compared with the smaller sphere. But if no energy is absorbed, the total power passing through each sphere is the same; it is the power produced by the source. The intensity you measure is 1/9 as large because the same amount of energy is spread over an area that is 9 times as large. ..... [snip] .....

The human ear is extremely sensitive. It can detect 0 dB sound that produces air pressure differences of 1 part per billion and eardrum movements less than the size of an atom. Yet it has the strength and resiliency to handle 120 dB sound that is 1000 billion times more intense than 0 dB. Unfortunately, your ears can be permanently damaged by high intensity sound.

Please be kind to your ears! It may not be obvious because damage is gradual, cumulative, and occurs at intensities below the level of actual pain, but your ears can be injured by loud sound: amplified music at a concert, at home, or with headphones, loud noise at work,... You know that staring at the sun can injure your eyes, so you don't do it. You should be just as smart about protecting your ears.

LOUDNESS. Intensity has a precise meaning; it can be defined by an equation and measured by a machine. But "loudness" is subjective; it is a sensation that is determined by the ear and mind of the listener.

As sound intensity increases, perceived loudness also increases, but not linearly. To be judged "twice as loud", sound intensity must be multiplied by approximately* 8 to 10 times, not (as you might expect) 2 times. For example, a 59 dB radio seems to be about twice as loud as a 50 dB radio, even though its intensity is 7.9 times greater. {* Loudness depends on many factors (wave frequency, listener sensitivity and psychology, cultural context,...) so there is no exact mathematical relationship between intensity and loudness.}

9.90 Memory-Improving Flash Cards

9.1	The SI units of f, λ and v are __ , __ , __ .	cycles per s, m per cycle (crest to crest), m/s
9.1	A traveling wave usually transfers __ , not __ .	"disturbance" and energy, matter
9.1	Oscillation and velocity are __ for __ waves. (2) For these waves, amplitude is maximum __ . (2)	⊥, transverse; same direction, longitudinal displacement change; compression change
9.1	All waves but __ move through __ because __ . Wave speed depends on neighborly __ and __ .	light, a medium, neighbors get disturbed interaction strength, response-quickness
9.2	A standing wave is produced by __ of __ .	superposition (addition), traveling waves
9.2	Wave interference is __ , __ or __ . when wave phase is __ , __ or __ .	constructive, destructive, partly destructive in phase, out of phase, partly out of phase

9.2	Standing-wave displacement varies with __ . At nodes & antinodes, string has __ movement.	time and position minimum (zero) & maximum transverse
9.2	Standing waves occur at __ frequencies when an __ fit between the __ at the string-ends.	resonant integral number of half-wavelengths, nodes
9.2	Each __ (which is a __ wave) produces __ (which is a __ wave) with the same __ .	string-vibration mode, standing sound, traveling longitudinal; frequency
9.2	This [picture missing] mode has n = _ , is called _ .	3, third harmonic or second overtone
9.2	Tone quality depends on a sound's __ .	mixture of harmonics (overtones)
9.2	Pitch depends on the __ of the __ mode of __ .	frequency, fundamental ($n = 1$), vibration
9.2	Pitch increases if __ increase or if __ decrease.	n or string-tension, L or m/L
9.2	For an octave that is higher or lower, f is __ .	doubled or halved
9.2	optional: Standing waves form on __ or in __ .	a string, a pipe (like a wind instrument)
9.2	optional: During beats, __ changes, __ doesn't.	loudness, frequency (and pitch)
9.3	Bullet speed is calculated using __ principles. Most waves (like sound) move at __ . Light waves travel at __ .	common sense *relative motion* (Section 2.11) constant speed with respect to wave-medium constant speed, observer (independent of v)
9.3	__ can have any speed, __ have definite speed.	particles (bullets), waves (sound, light),
9.4	Memory trick: __ , __ is on fraction-bottom.	PONS (+ observer − source), v_{sound}
9.4	v is + and f __ if source or observer __ . v is − and f __ if source or observer __ .	increases, move toward each other decreases, move away from each other
9.5	The SI units for power and intensity are __ .	J per s (≡ W), J/s per m^2 or J/m^2 per s
9.5	The decibel equation can be in __ format.	either logarithmic or exponential
9.5	You can solve decibel problems by __ or __ .	choose-substitute-solve, intuitive ratio logic
9.5	Ratio logic: __ is a __ for __ .	$10^{\beta/10}$, multiplying factor, intensity
9.5	Loudness (__) doubles if intensity (__) __ .	subjective, objective, ↑ by a factor of 8-10
9.5	Ear damage is __ and can occur at __ .	cumulative, intensities below the pain level

---

Eventually, Chapter 9 will be available in camera-ready format with diagrams.