C. Waves

We have seen that sound consists of vibrations or oscillations. Scientists study traveling vibrations under a general category called waves, a topic we investigate further in this chapter. We are already familiar with several periodic wave characteristics such as amplitude, frequency, and waveform. So we have been studying waves already. Here, we will sharpen our skills by probing deeper into what a wave is. A definition can be given as: **a wave is a traveling disturbance.**

Fig. C-1a below illustrates a very simple traveling disturbance. Our assistant has shaken a hand up and down at the left end of a rope to make a single crest. This "crest disturbance" is a pulse that travels to the brick wall. It is a wave; however, it is not periodic. The hand was shaken once. Notice that the rope moves up and down in the various locations along the rope as the pulse travels. The rope itself doesn't travel but the deformed moving shape does.

The rope is the medium that supports the waves. If there were no waves, the rope would appear at rest in equilibrium everywhere as a horizontal line. Since the rope medium moves up and down, i.e., transverse to the direction of motion as the disturbance passes, we say that the wave is *transverse*. What do you think happens when the pulse reaches the brick wall?

In Fig. C-1b we view a pulse on a slinky. Our assistant has pushed in and out quickly to start a compression wave. Note that the "slinky ringlets" move back and forth along the direction of propagation (parallel) as the pulse travels to the wall. The wave is said to be *longitudinal*.

Fig. C-1a. A Transverse Pulse Wave Traveling Down a Rope.

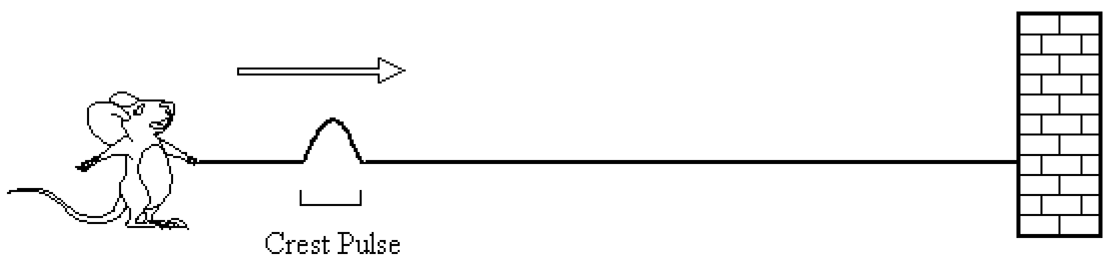


Fig. C-1b. A Longitudinal Pulse Wave Traveling Down a Slinky.

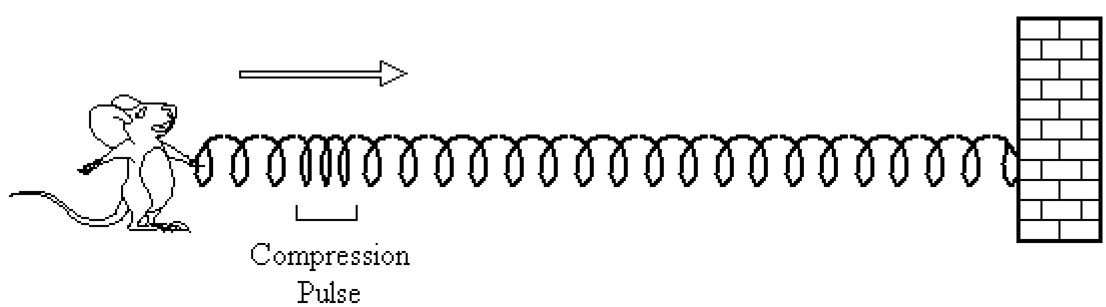
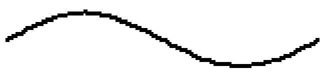
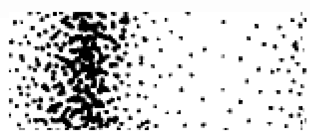


Fig. C-2 illustrates our rope wave, slinky wave, and a representation for a sound wave. The rope wave shows a crest and its counterpart, the trough. This is one complete wavelength for a simple periodic wave. You make a *crest* by pulling your hand up at the end of a rope; you make a *trough* by pulling down below the horizontal. Similarly, the slinky wave shows two sections, a compressed region and its opposite, a stretched region. You make a compressed region by pushing in at the end of a slinky; you make a stretched region by pulling out. A simple longitudinal wave then consists of a compressed region (analogous to the crest of a rope wave) and a stretched region (analogous to the trough of a rope wave). The rope wave is transverse and the slinky wave is longitudinal. The amplitude for the rope wave is the distance measured from the center equilibrium line up to the maximum point. For the slinky wave, we compare the density of "ringlets" (how many per cm for example) with the density for a normal slinky with no waves on it. In each case, the amplitude is a measure relative to the quiescent state of the medium.

Fig. C-2. Three Types of Waves.

	Wave	Disturbance	Amplitude
	Rope	Crests Troughs	Displacement (centimeters)
	Slinky	Compressed Regions Stretched Regions	Density (ringlets per cm)
	Sound	Compressions Rarefactions	Pressure (atm)

The third example in Fig. C-2 represents a sound wave. Sound waves are similar to slinky waves. The layers of air are compressed in some regions, where the molecules get closer together. Air layers are less dense in other regions. These less dense regions are called *rarefactions*. The amplitude of a wave is always measured from equilibrium.

The equilibrium density for air is that density when there are no sound waves. We can use this value or alternatively the equilibrium pressure. Then the *compressions* are regions of higher pressure and the *rarefactions* are regions of lower pressure. A unit of pressure is the atmosphere (atm). At sea level under normal conditions, the pressure of still air is 1 atm. We will not need to worry about units for amplitudes of sound waves in this text. Since sound is similar to the slinky case, we state the following important observation: **sound is a longitudinal wave.**

The easiest wave to sketch is the transverse wave (see the rope wave in Fig. C-2). Slinky waves are hard to draw. Layers of air molecules are just too cumbersome to mess with. So we sketch the transverse picture to represent all three types of waves. In Fig. C-2, the three waves are lined up. The crest of the transverse wave coincides with a compressed region in the slinky wave and compression in the sound wave. The trough coincides with the stretched slinky and rarefaction. So the crest in a transverse picture can mean compression (higher pressure) and the trough indicate rarefaction (lower pressure).

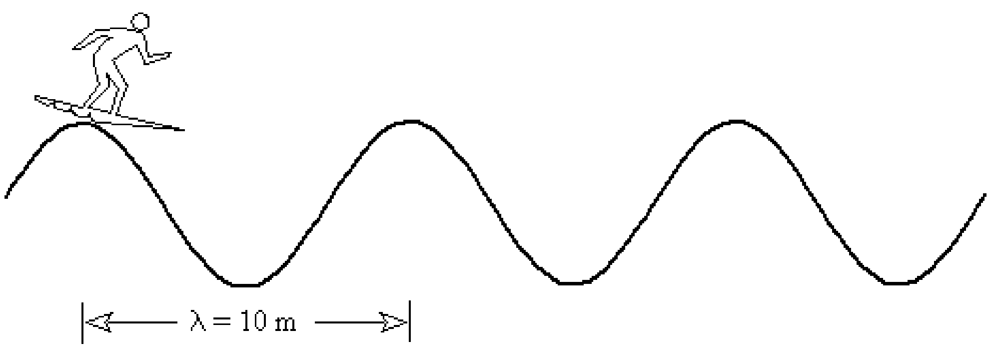
This representation is more meaningful than you may realize. Push your hand in and out like you are driving a slinky. You can imagine your hand to be the membrane of a speaker generating sound waves. In either case, you are making longitudinal waves. Now someone comes along, tapes a piece of chalk to your moving hand, picks you up, orients you properly so that the chalk touches a blackboard, and carries you across the room as your hand writes on the board. You will trace out a transverse picture of your longitudinal wave. This is just what the oscilloscope (mentioned earlier) does for us. So we will use the transverse drawings to represent our longitudinal sound waves.

Before we discuss basic properties of waves in general such as reflection, let's look at the general relationship between frequency and wavelength in more detail. We already know that high frequencies have short wavelengths and vice versa. Now we will learn that the frequency and wavelength are related to the speed of the wave (also called the velocity). Suppose you are riding on a periodic wave (see Fig. C-3 below). For a specific example, say that the wavelength is 10 m and that these pass by a stationary observer on the shore at a frequency f = 5 Hz (5 go by per second). This is some wave! (But not a real water wave.) Then, the rider moves 5 x 10 = 50 m/s. We see that the speed of a wave is equal to the wavelength multiplied by the frequency.

wave speed = wavelength x frequency

$$v = \lambda f$$

Fig. C-3. A 5-Hz Wave with Wavelength 10 m Moving to the Right.



The relationship $v = \lambda f$ incorporates our observation that higher frequencies mean shorter wavelengths. The speed v for the wave depends on the medium. For sound at room temperature, this is 340 m/s. Suppose we have a rope wave where the speed is 100 m/s. Then, a low frequency of 5 Hz means a wavelength of 20 m since 20 x 5 = 100.

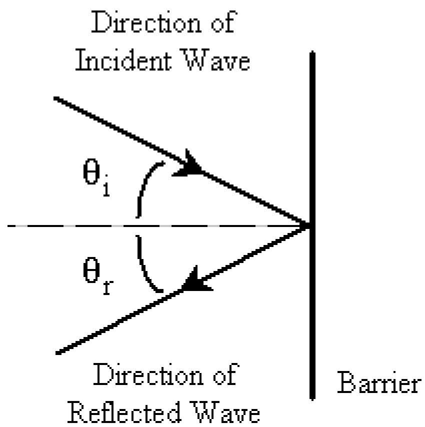
If we increase the frequency to 10 Hz, then the wavelength shortens to 10 m since 10 x 10 = 100. Raising the frequency to 25 Hz, the wavelength becomes even shorter, 4 m (since 4 x 25 = 100). Think of an analogy with money where 100 stands for a dollar. You can get a dollar with 20 nickels or 10 dimes or 4 quarters. Can you think of other combinations? Note that as you increase the value of each coin, the number of coins decreases because the total amount of money is fixed at a dollar. This is analogous to our fixed wave speed. Again, what does this imply in terms of wavelength and frequency?

Reflection

Waves exhibit the property of reflection. A reflection occurs when a wave bounces off an obstacle. The directions of the incident and reflected waves have a simple relationship. Fig. C-4 illustrates the *law of reflection*. We do not show the waves in Fig. C-4, just the direction of the waves. The waves bounce off the barrier so the angles of incidence and reflection are equal. These angles are measured relative to a center reference line called the *normal*. The law of reflection is demonstrated readily with a flashlight, i.e., using light. You can easily achieve a concentrated beam of with your flashlight. You use a mirror for the reflecting barrier.

The law of reflection also describes bouncing a ball off a side of a pool table. Finally, if we neglect gravity or go on the space shuttle, throwing a ball along the direction of incidence in Fig. C-4 will result in the ball leaving along the direction of reflection, after its collision with the wall.

Fig. C-4. Law of Reflection.

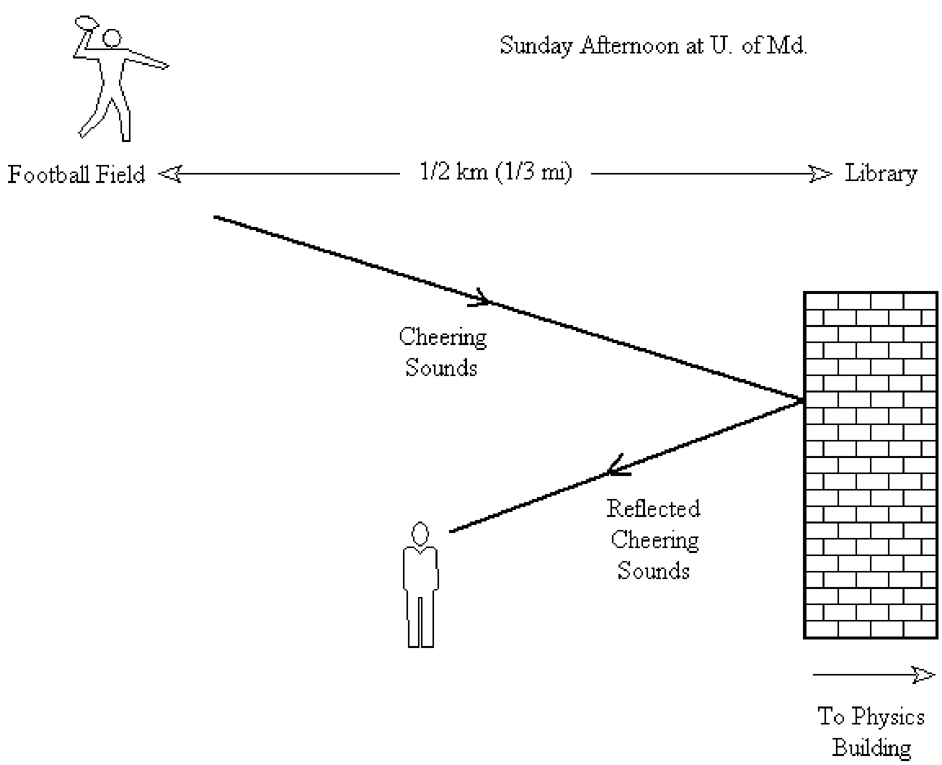


The angle of incidence equals the angle of reflection: $\boldsymbol{\theta_i = \theta_r}$.

Every time you hear an echo, you experience the reflections of sound. One fine Sunday afternoon, the author heard a dramatic reflection outdoors at the *University of Maryland*. He was walking from Graduate Housing to the Physics Building in the early afternoon to do physics. Most people were at the football game. He heard cheers and shouts as he walked through the parking lots. As he approached the *Undergraduate Library*, which is situated across the street from the *Physics Building*, he heard the cheers coming from in front of him. This was an eerie experience as the library was in that direction (see Fig. C-5 below), not a cheering crowd.

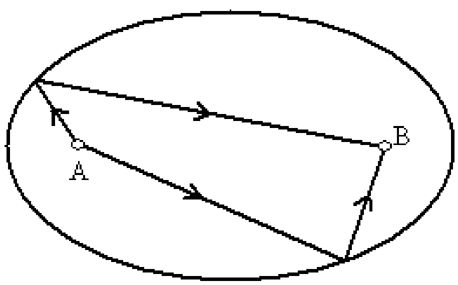
It was especially strange because other buildings between the football field and the observer (not shown below) prevented any direct sounds from the field to reach him. Therefore, the usual echo effect did not occur. One just heard the "reflected beams" and was tricked into interpreting them as the real thing. After a moment's "reflection," the author figured out what was going on.

Fig. C-5. Sound Reflecting From Tall Brick Building.



Another example of reflected sound is found in the *whispering chamber*. This room has an elliptical shape (see Fig. C-6 below). A person at position A can have a conversation with a person at position B even though the distance between these points may be great. In fact, the speaker at A can speak gently or whisper. The sound waves bounce off the walls in such a way that they focus after reflection at point B. Two such rays are shown in Fig. C-6. Imagine numerous rays emanating from A, hitting the wall at various places, yet all reaching B! Other observers throughout the room may get a few rays but the observer at B gets reinforcement from all the reflections of waves starting at A and vice versa.

Fig. C-6. Sound Reflecting In a Whispering Chamber.



There is a *whispering chamber* in the *Capitol Building* in Washington, DC. Other examples can sometimes be found in wall structures outdoors. Can you locate the one on the *UNCA* campus?

Museums sometimes have a demonstration where there are two large dishes. You speak at a designated point in front of one of these and your friend far away at a corresponding point near a second dish can hear you. Dishes for sending waves far to another dish need to be parabolic in shape, a shape similar to the ends (left and right) of the elliptical walls in Fig. C-6.

There is also the story of a church in Europe with the *whispering chamber* effect. By some architectural coincidence, a confessional was placed near one focal point, while the other focal point was somewhere down the aisle. The person at the right spot in line for confession was able to hear the sins being confessed at the moment (so the story goes).

Refraction

Sound travels at different speeds through air with different temperatures. Sound travels faster in warmer air than it does in cooler air. Table C-1 below lists some air temperatures and the corresponding speeds of sound at those temperatures. Can you see a relationship between speed and temperature? The general relationship is that the speed of sound increases as temperature increases.

Analyze the data and see if you can determine by how much the speed increases in m/s (meters per second) for every 10 degrees on the Celsius or centigrade scale. Scientists get excited when they discover such relationships in data. They are fascinated by the recurring order and beauty found in nature. Their delight in such order and beauty is similar to the appreciation of balance and grace in a Rembrandt painting or the experience of harmony and elegance in a Mozart sonata.

The nice rule incorporated in the data of Table C-1 is valid over the temperatures that we usually find in our environment. Things get complicated if the air becomes extremely hot or cold.

Table C-1. Sound Speed and Temperature.

Temperature	Sound Speed (m/s)	Fahrenheit Value
Freezing (0°C)	331	32°F
Cold (10°C)	337	50°F
Room (20°C)	343	68°F
Hot (30°C)	349	86°F

The speed of sound's dependency on air temperature has interesting effects. In order to easily illustrate this, we need to learn how to sketch wave crests. Fig. C-7 shows a sine wave with a sketch of the wave crests below it. Remember that the sine wave can also describe longitudinal waves. The vertical lines can represent the crests of a water wave or the high-pressure regions of a sound wave (the compressions).

Fig. C-7. Sine Wave and Wave Crests.

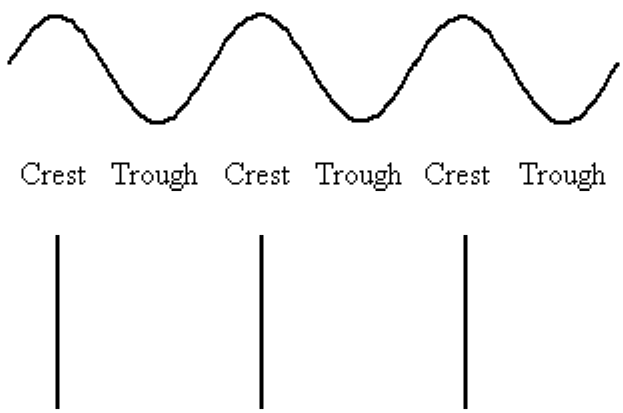


Fig. C-8 below illustrates crests emanating from a point source. Think of a stone dropped into water. Circular waves move outward. Fig. C-8 is a snapshot in time showing the circular crests at a given moment. The center source can also represent a sound source. Then the outgoing waves are spherical in three dimensions. However, you have the basic idea in the two-dimensional picture.

Fig. C-8. Crests From Center Point Source.

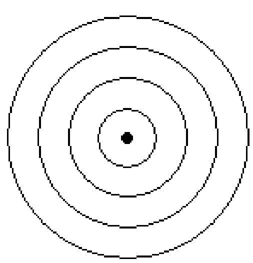
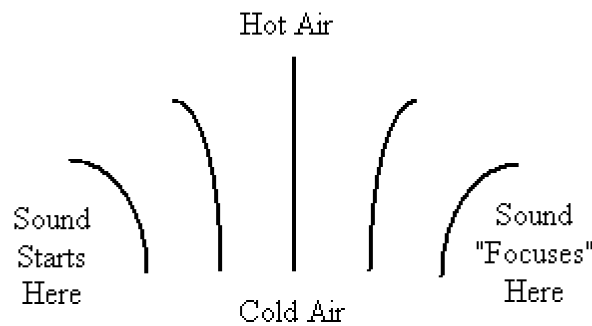


Fig. C-9 depicts a source of sound at the left of the figure. Only part of the outgoing circular (really spherical) wave is shown, the part heading toward the right. These circular crests get distorted since the air temperature is not the same everywhere. In our example, the air is cooler at the ground and warmer above. The crest travels faster in warm air so the top parts of the crests get ahead of the lower parts. This causes the wave crests to straighten out (see center crest) and then curve the other way. The waves in a sense "focus" at a point to the right. This converging is the opposite of spreading out and the sound is reinforced at the far right. The second half is kind of like running a movie backwards. In summary, sound waves first spread out, then recollect. This phenomenon is called *refraction*.

Fig. C-9. Sound Crests and Refraction.



Tops of Crests Move Faster.

An observer at the far right is in a better position to hear the source than an observer in the middle. This will occur when hot air is above cold air. In the daytime, heat from the sun makes the ground hot. The air near the ground is hotter than the air above. Have you ever walked in your bare feet on an n asphalt driveway at noon in the summer? At night, the ground cools as the hot air rises with no additional sunlight streaming down. This cool ground with warm air above is now the opposite of what we had in the day. It is called a *temperature inversion*. This temperature inversion allows sound to be heard better farther away. It's not that sound "carries" at night; the bending waves do the trick.

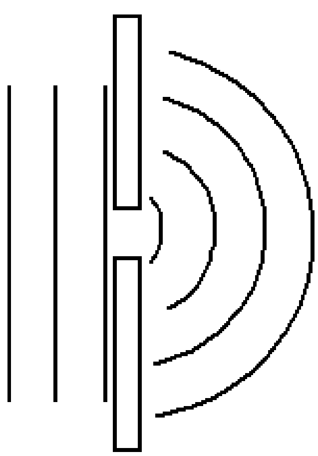
The author often heard music from the *Grove Park Inn* at his former home on Howland Road about half a mile away (little less than 1 km). He thought there was a party around the block until he realized it was refraction of sound due to the temperature inversion at night. UNCA's first chancellor, Chancellor Highsmith, told the author (around 1980) that he heard it also from the Chancellor's Residence on Macon Avenue.

Diffraction

Diffraction refers to the bending of waves near openings, corners, and obstacles. This is another type of bending of waves in addition to refraction.

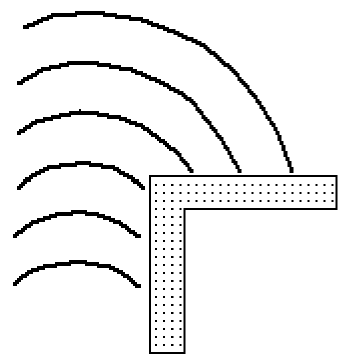
D1. Openings. An easy way to understand diffraction is to think of water waves heading toward an opening between two barges (see Fig. C-10a). The crests of the water waves are linear as they approach the opening. Then circular waves spread out on the other side of the opening. Do sound waves spread out like this through open doorways? Can you hear someone call you from within a classroom if you are down the hall?

Fig. C-10a. Diffraction Through Opening.



D2. Corners. Waves also diffract around corners. Can you call a friend who has just walked around the corner of a building? Does the sound reach your friend? A general guide for diffraction is that waves will diffract, i.e., bend around openings, corners, or obstacles, provided that the encountered structures are comparable in size to the wavelength of the waves (distance between crests).

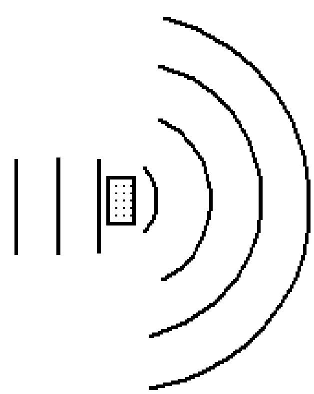
Fig. C-10b. Diffraction Around Corner.



D3. Obstacles. Waves also diffract around obstacles. Have you ever tried talking to someone on the other side of a tree? Can they hear you? Can you turn around and still maintain a conversation with someone behind you at home? Do the sound waves wrap around your head and get to the other person?

In light of what was said in 2 above about the conditions for diffraction, why do you think light doesn't bend around trees?

Fig. C-10c. Diffraction Around Obstacle.



Interference

Two waves combine when they meet. You simply add the amplitudes. Fig. C-11 considers square waves so that addition is easy. In Fig. C-11a the waves reinforce because the crests of the two waves match and likewise the troughs. The waves are *in phase*. The *interference* is *constructive*. In Fig. C-11b the interference is *destructive* as crest meets trough and vice versa. The waves are *out of phase*.

Fig. C-11a. Constructive Interference (Two Identical Waves In Phase).

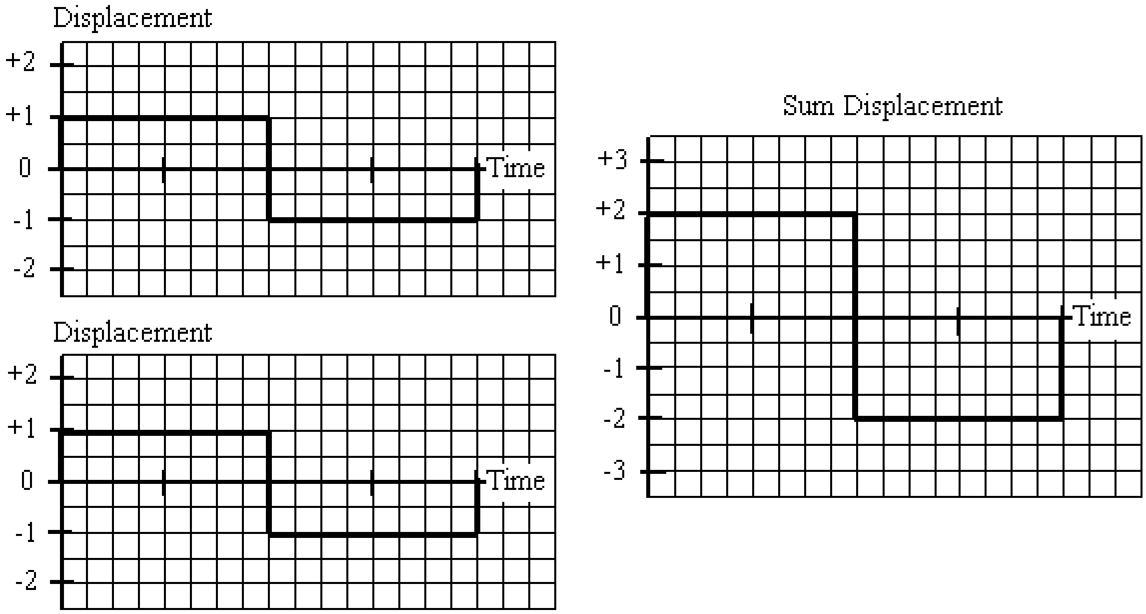
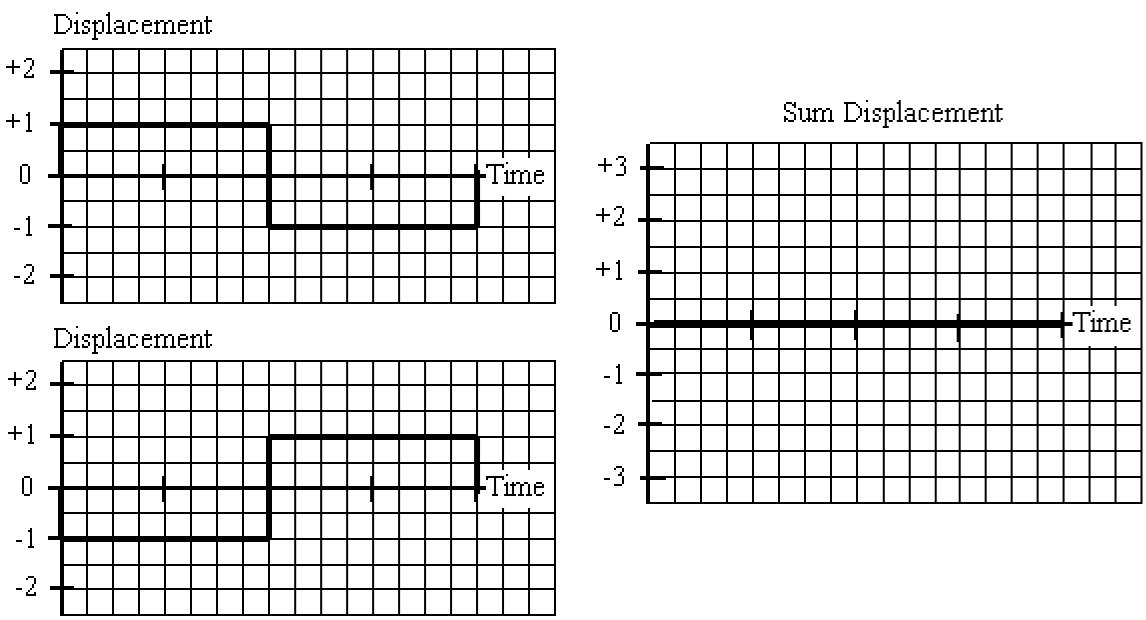


Fig. C-11b. Destructive Interference (Two Identical Waves Out of Phase).

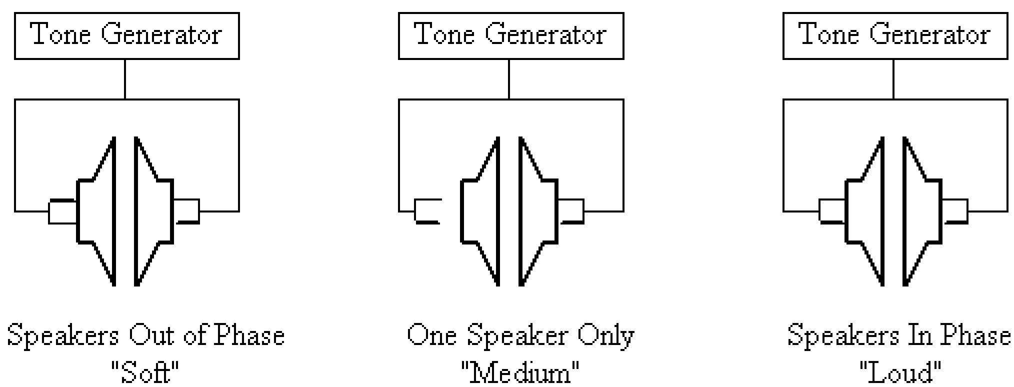


Sketch a sine wave on a piece of paper and see if you can sketch underneath your sine wave another similar wave aligned so that the crests and troughs work together. Now do another sketch for the case where the waves work against each other and cancel.

Fig. C-12 illustrates an arrangement to study interference. We have two speakers. We let them face each other to get them close to each other. We send a simple tone to each speaker to keep the input easy to compare. We do not use stereo but send the same signal to each speaker.

We experiment with switching the polarity of one of the speaker connections. The speaker wire contains two wires, insulated but bundled together in the wire leaving the source. With the polarity reversed for one speaker, one speaker membrane pushes out to produce compression while the other pulls in to make a rarefaction. The waves then work against each other as compression competes with a rarefaction. The sound level drops. In fact, it is softer than one speaker alone (middle case illustrated in Fig. C-12). Of course the loudest sound occurs when the speakers send out compressions together (case at far right of Fig. C-12).

Fig. C-12. Interference with Speakers.



Instructions usually warn you not to cross one of your speaker hook-up wires. These speaker wires attach your amplifier to your speakers. They assume that you sit equidistant from each speaker so that a compression leaving one will arrive at you directly when a rarefaction does so from the other speaker, if wired incorrectly. Here are some questions to think about.

1. If your speakers are wired incorrectly, would you be better off in an open field (assuming electricity is available) or in a house with walls? Think of reflection.

2. If speakers are wired incorrectly, are you better off listening to stereo or an old monaural recording?

3. What happens if you reverse the polarity of both speakers?

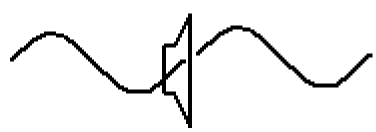
There is an interesting demonstration that illustrates both diffraction and interference. Consider a speaker by itself. Then consider a speaker inserted into a hole of a flat board. The latter speaker is said to have a baffle. You could also insert the speaker into a wall to get a similar effect.

A speaker membrane sends out waves both to the front and to the rear. When the membrane pushes out, compression is sent out toward the front. At the same time, a rarefaction is sent out the rear. The waves leaving the front are out of phase with the waves leaving the rear. Refer to the sine waves in Fig. C-13. Without the baffle, a portion of the front and rear waves diffract. That is, part of the rear wave diffracts and gets to the front and vice versa. Suppose you were talking to two friends, one in front of you and one behind you. Both would hear you. The person in the rear would hear part of the forward wave that diffracts around your head. But since you do not talk out of the back of your head at the same time, you don't need to worry about a second wave interfering.

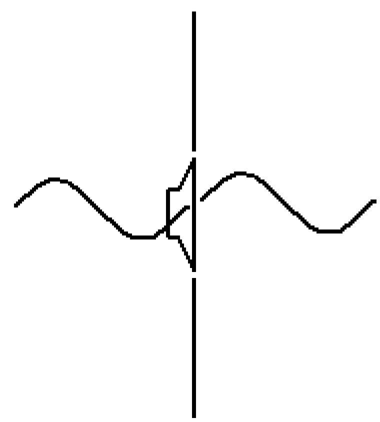
The problem with the speaker is that unlike you, the speaker produces waves out the front and rear simultaneously due to its simple membrane structure. And these are out of phase! When they diffract and mix, they interfere destructively. The sound is weakened.

The baffle (see right diagram in Fig. C-13) prevents the waves from diffracting. Therefore the waves cannot mix. There is no destructive interference and the sound is louder. The speaker can now produce the sound it is capable of without working against itself. The emitted sound is improved in both the forward and rear directions.

Fig. C-13. Speaker With and Without Baffle.



Waves Leaving Front and Rear Can Diffract and Interfere.



Waves Leaving Front and Rear Cannot Diffract and Interfere.

--- End of Chapter C ---

