# E. Modulation


*Ovenbird, Courtesy Photographer Dr. Dan Sudia*


*WOXL* Van and Oldies

*Photo by Prof. Ruiz, December 23, 2002*

We now turn to modulation. The idea is simple, yet its use in acoustics gives us an enriching variety of sounds. *Modulation* simply means change. We know from experience that too much of any one thing can get boring. We like variety. Experts warn that if a teacher is lecturing in the same fashion for more than 12 minutes, then the class is gone - bored. You must move around, change pace, or do something different.

Musicians will often change how loudly and softly they play. Musical lines are shaped into phrases much like sentences. They rise and fall with "inflection." Composers change keys in a composition - such changes are actually called modulations. In everyday life, people change the clothes they wear. Most people vary the food they eat from night to night. Can you think of other examples of change?

We have seen that sound has three basic physical characteristics, which also have perceptual counterparts. These are amplitude (loudness), frequency (pitch), and timbre (waveform). This chapter is divided into three sections where we investigate modulation of each of these fundamental wave features.

**Amplitude Modulation**

The easiest wave characteristic to consider first is the amplitude. This physical feature corresponds essentially to the perception of loudness. Remember that the amplitude is a measure of the wave disturbance relative to equilibrium. If there is no wave, i.e., no sound, then the air is at its normal equilibrium pressure everywhere.

We represent equilibrium by drawing a horizontal line. This straight line indicates zero disturbance. The medium is at equilibrium everywhere. It's like a quiet lake. The water surface is flat. It is still and there are no waves.

A simple sine-wave disturbance about equilibrium consists of crests (above the equilibrium line) and troughs (below the equilibrium line). A sketch of such a wave is given in Fig. E-1.

The definition of amplitude is a measure from equilibrium to the maximum height of a crest. Note that all the crests in Fig. E-1 have the same height. Therefore, the amplitude of the sine wave in Fig. E-1 is constant. The wave does not increase in loudness but stays at a steady volume.

The wavelength (distance between crests) is also constant. Therefore, the frequency is constant too. So we hear the same pitch. Of course, the timbre is the same since from cycle to cycle we have the same repeated waveform. The timbre or waveform for the wave in Fig. E-1 is a sine wave, the simplest of all periodic waves.

Fig. E-1. A Simple Sine Wave Before Modulation.

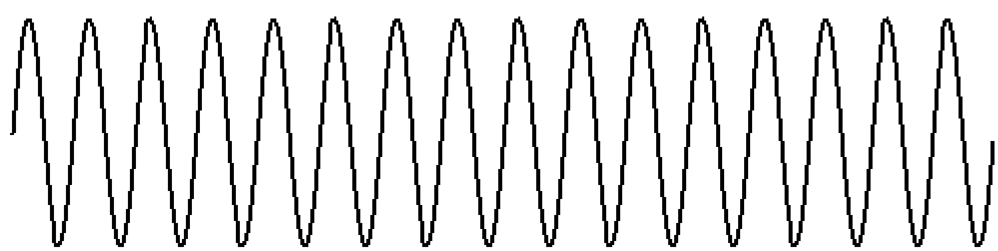


Fig. E-2b is an amplitude-modulated sine wave. It results from taking the sine wave in Fig. E-1 and varying the amplitude according to the sketch in Fig. E-2a. Imagine sliding the sine wave of Fig. E-2a down so that it fits snugly on top of the amplitude-modulated wave of Fig. E-2b. Fig. E-2a tells us how the amplitude is changing.

We note two things here. First, the amplitude of Fig. E-2a changes smoothly, but it is a new sine wave. Second, this sine wave has a frequency, which we call the *modulating frequency,* that is much lower than the frequency of the basic wave (Fig. E-1). Compare the wavelength of Fig. E-2a with the wavelength of Fig. E-1 to confirm this.

Fig. E-2a. Amplitude Change for Amplitude-Modulated Sine Wave in Fig. E-2b.

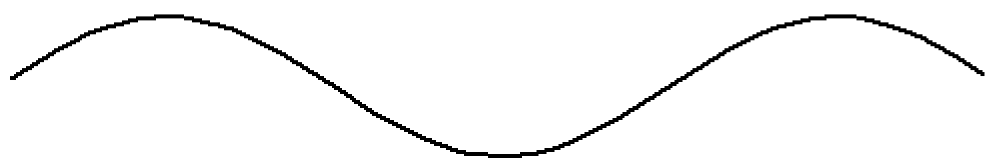
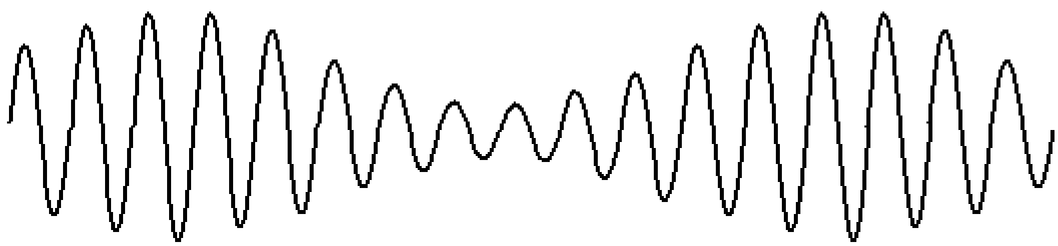


Fig. E-2b. Amplitude-Modulated Sine Wave.



Therefore, the waves of Fig. E-1, Fig. E-2a, and Fig. E-2b are related. The basic wave found in Fig. E-1 is called the carrier wave or simply the *carrier*. It is the wave that experiences a change imposed on it. The wave in Fig. E-2a is called the modulator wave or simply the *modulator*. It describes how the changes are made. When this modulator is applied to the amplitude, the amplitude changes in step with it. The result is the amplitude-modulated wave, Fig. E-2b.

An easy way to keep all of the above straight is to image a simple flute playing a constant tone from your CD player. We can assume that the flute produces a sine wave. You hear the same pitch and loudness as the flute continues with the same note. Fig. E-1 can represent the flute tone. This is the carrier wave. Then you take your hand and turn the volume control up and down in a natural way (sine wave). Your hand motion is described by the sine wave in Fig. E-2a. This is the modulator wave. Note that since your hand can't wiggle back and forth very fast, this modulator wave has a long wavelength and therefore low frequency. The frequency is so low that you never hear sound when you wiggle your hand back and forth. The result you hear is the flute tone with pulsations in loudness. After all, you are changing (modulating) the amplitude. The resulting wave is described by Fig. E-2b. Musicians call this pulsating tone *tremolo*.

In AM Radio broadcasting, a radio wave is sent to your home. A radio wave is not a sound wave; it is a wave involving electric and magnetic interactions. The frequency of these waves is very high, like millions of cycles per second. The frequency of a station's transmitted AM radio waves is obtained from the number the radio announcer constantly reminds you to tune in to. For example, *WISE 1310* broadcasts at 1310 kHz (kilohertz).

The lower-frequency sound information is coded in the amplitude variation of this radio wave. In this analogy, Fig. E-1 represents the radio wave, Fig. E-2a represents a sound frequency such as a whistling tone. As the radio travels through space, there is no sound. The sound information is transmitted as the amplitude variation. It is said that the radio wave carries the sound information. That's why we call the basic wave the carrier.

Radio carrier waves can travel in the vacuum of outer space. They are a very special kind of waves called electromagnetic waves. Electromagnetic waves do not need a medium in which to travel. Light is also an electromagnetic wave.

The sound information is extracted by your AM radio. Your radio gets the audio information from the variations in the amplitude. You have probably guessed by now what AM stands for - *amplitude modulation*.

Think carefully about our two analogies. In the first case, your hand-wave frequency modulates a sound wave. In the second application, a sound-wave frequency modulates a radio wave. The modulator effect on a carrier's amplitude can be understood by multiplying waves.

We have seen how to add waves. We will review wave addition and then take up wave multiplication. Fig. E-3a reviews wave addition. Think of the addition in 4 stages. For the 1st stage or quarter, both the top wave and bottom wave in Fig. E-3a have displacements of 1. Therefore, the total displacement for that region is $1 + 1 = 2$. Then we combine $-1$ with $+1$ for the 2nd quarter to obtain $-1 + 1 = 0$.

For the 3rd and 4th quarters the lower wave is 0. We can just sketch the top wave for the sum here. Adding nothing leaves the wave alone. Note that the amplitude of the top wave in Fig. E-3a is 1. The displacement of the wave changes as we go through ups and downs (crests and troughs). But the definition of the amplitude calls for a measure from the equilibrium to the highest point. If the amplitude (maximum displacement) changes from cycle to cycle, we then have amplitude change or modulation.

For multiplication, we multiply the appropriate pairs of numbers instead of adding. For the first and second quarters, the upper wave is untouched since the lower wave has a value of 1 in this region. Refer to Fig. E-3b. Multiplying by 1 doesn't change anything.

However, the situation is quite different for the third and fourth quarters where the lower wave has a value of 0. Multiplying by zero gives zero. The upper wave is wiped out in this latter region. The lower wave acts like a gate. It allows the upper wave to survive when the lower wave has a value of 1 (gate is open).

Then, when the lower wave has a value of 0 (gate is closed), there is no surviving wave. This effect is called *gating*. It's important in music synthesizers. When you press a key, you get something; when you release the key, the tone is destroyed.

Fig. E-3a. Wave Addition.

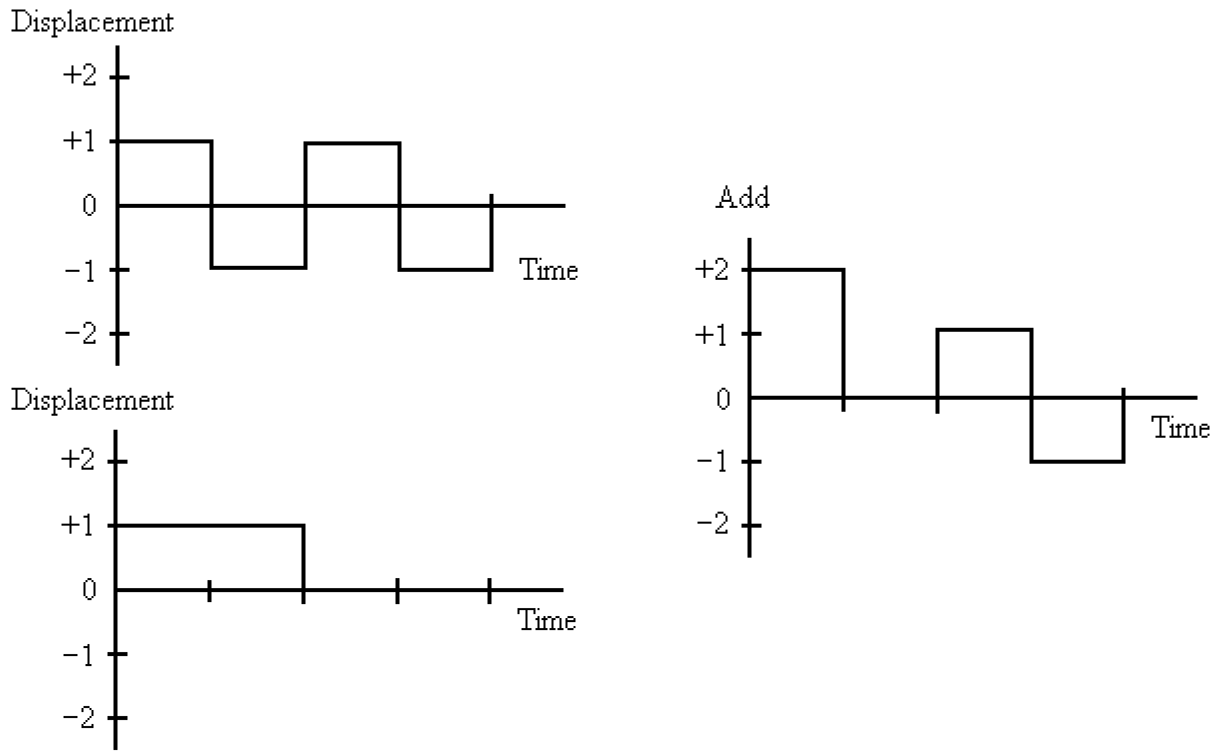
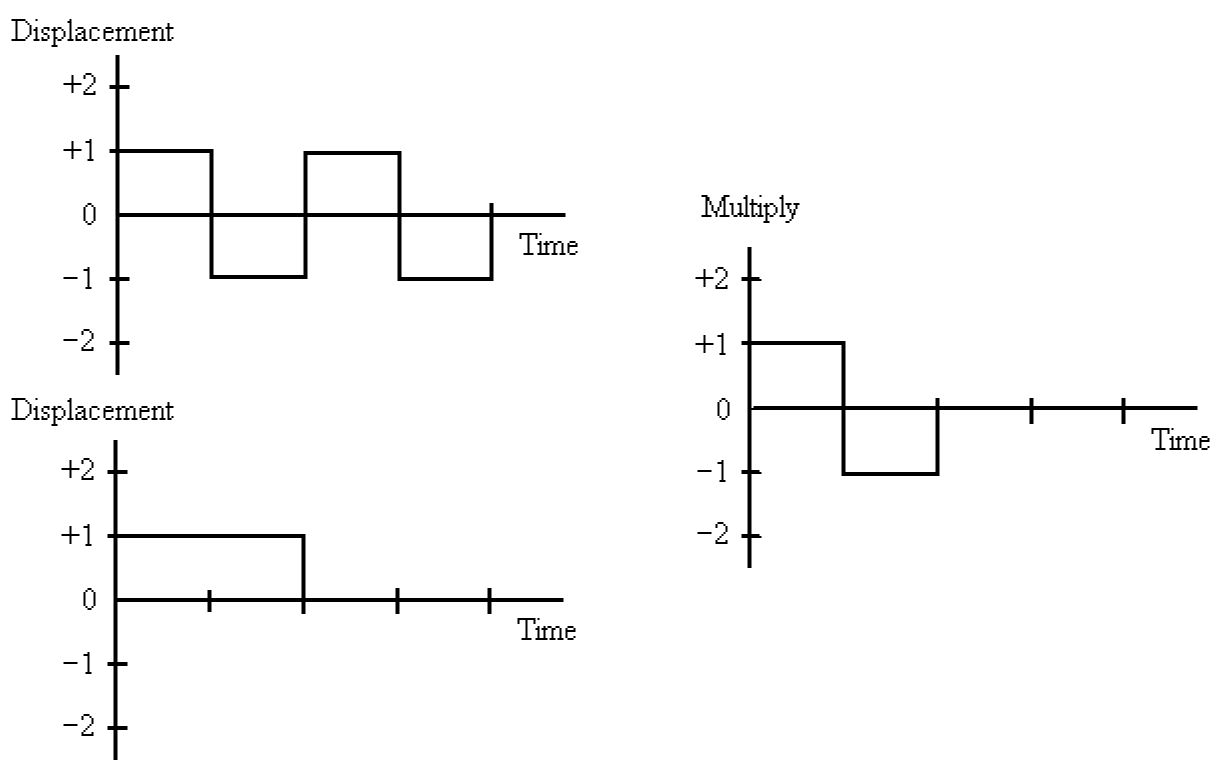



Fig. E-3b. Wave Multiplication.



We will now relate wave multiplication to amplitude modulation. We will use the pulse train wave as the carrier and a triangle wave as the modulator. See Fig. E-4 below. Don't be concerned that the reference line is at the far bottom here. In the analysis of waves, the reference can be freely chosen to simplify the way of looking at the problem. You might say we introduce an offset, i.e., offset the horizontal line at our leisure.

In the electronic production of waves, this is referred to as a voltage offset. Physicists play the same game analyzing falling objects. Sometimes, the ground is called the zero point for height. If a ball falls to a table, then the table is taken to be the zero point.

Fig. E-4a. Pulse-Train Carrier and Triangle Modulator.

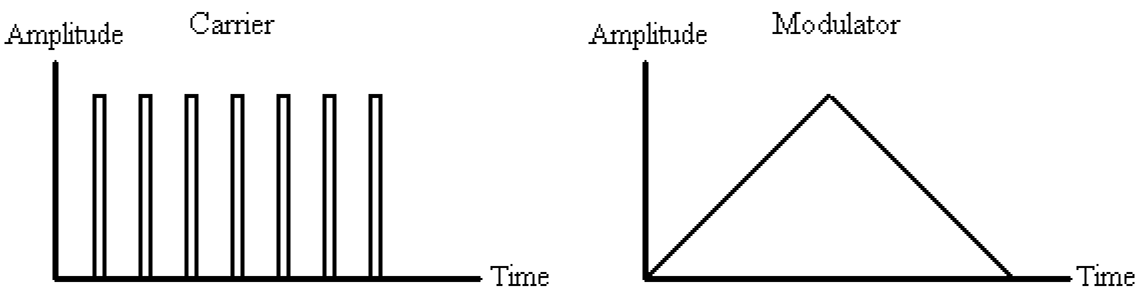
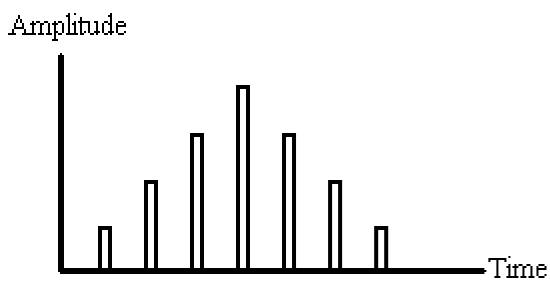



Fig. E-4b. Result When the Modulator Modulates the Amplitude of the Carrier (see above).




It is too tedious to multiply the carrier and modulator in Fig. E-4a point by point to arrive at the amplitude modulation in Fig. E-4b. Rather, let's reason it out. The triangle wave starts out at zero. This means the carrier is knocked out at the beginning since zero times anything is zero. Now look at the middle of the above triangle. The triangle is high. Consider this top point to be 1, 100% full strength. The effect on the carrier is to leave the carrier alone here: one times the carrier equals the carrier. Between the beginning and this high point, the modulator gradually increases. So we sketch the carrier's crests gradually increasing from the beginning to this point (see Fig. E-4b). The reverse happens for the decreasing side.

Consider a "cookie-cutter" analogy. Take the modulator shape in your mind and place it over the carrier. Imagine the carrier to have crests of "dough." Then slice the "dough peaks" with the modulator "cookie cutter." You have modulated the amplitude.

The previous modulation can be demonstrated by playing a tape of a pulse-train wave with your tape deck. Imagine a somewhat harsh tone with a fixed pitch. You then manipulate the volume control, i.e., modify the loudness. You gradually turn the volume up from the zero level to some maximum, then turn the volume off.

However, you are not turning the knob in the most natural wave (the sine wave or sinusoidal motion). Your turning is described by the triangle wave.

Try moving your hand across a sheet of paper with a pencil in it. Begin moving your hand up and down in a "triangular" sort of way. See if you can do it. Remember to keep the sweep speed across the paper a constant rate. Your sweeping hand will trace out the wave the way the oscilloscope draws pictures of waves.

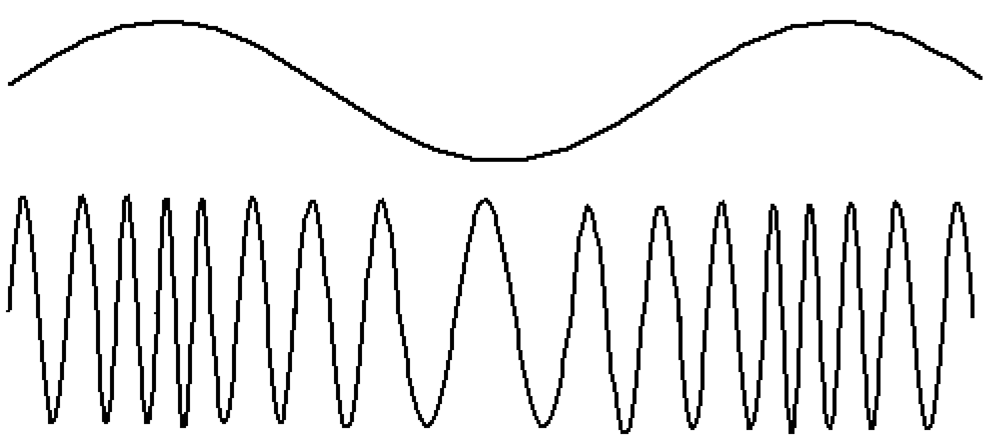
When the oscilloscope gets to the far right in its sweep, it starts over. Its electronics is designed so that it can retrace its steps for a nice periodic tone. The retrace gives us a steady picture on the screen. However, when the input wave is very low in frequency, like a typical modulator frequency, you can often see a bright dot wiggling across the screen. For faster frequencies, the retrace gives a complete picture due to the lit screen glowing for a split second and our persistence of vision. Persistence of vision is our retention of the previous image seen for a fraction of a second. It's what makes movies possible.

**Frequency Modulation**

We will now apply the same modulator used in Fig. E-2a, but not to change the amplitude of the sine wave in Fig. E-1, but to change its frequency. The resulting frequency modulation is given in Fig. E-5. There isn't a simple way to get this modulated picture by some arithmetic manipulation. We simply sketch the result.

When the modulator wave is high in its value (crest), this means increase the frequency, i.e., shorten the wavelength. Before (with amplitude modulation) we increased the amplitude, now we increase the frequency. When the modulator dips to a trough, we decrease the frequency, i.e., lengthen the wavelength. So we can also call this wavelength modulation. FM radio encodes its information this way. FM stands for *frequency modulation*. With FM radio, the carrier is once again a radio wave.

Fig. E-5. Modulator (Upper Wave) Modulating Frequency to Get FM Wave.



We continue our application in the area of radio broadcasting. The modulator wave in Fig. E-5 can represent the sound wave we are to broadcast. The radio station is playing a tape with a perfect sine wave. It can be the sine wave of a whistling constant tone. Whistlers can produce good sine waves. The information is encoded by varying the frequency of the carrier radio wave.

The carrier waves for frequency modulation are greater than those used for amplitude modulation. For example, our classical station, *WCQS*, broadcasts at 88.1 million hertz. The metric prefix for million is Mega, so we can write this as 88.1 MHz (Megahertz). Our earlier example for an AM station was *WISE* at 1310 kHz, which is 1,310,000 Hz or 1.31 MHz.

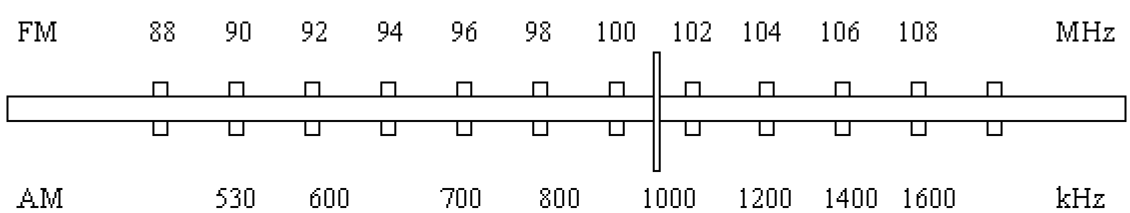
The frequency 88.1 MHz is reserved for *WCQS*. Also, some frequencies a little less and a little greater are also reserved because the 88.1-MHz radio wave will be frequency modulated. This band of frequencies is called that station's *bandwidth*. The center is 88.1 MHz. Another example of an FM station is *Kiss Country* at 99.9 MHz (*WKSF*). If country is not your style, try its neighbor *Mix 96.5* (*WOXL*) at 96.5 MHz on the radio spectrum for a mixture of music.

We stress that sound waves are not broadcasted. Radio waves are sent to your home. The sound information is encoded in the frequency modulation. The station's radio wave undergoes variations in frequency at the rate of the audio frequency it's carrying. For example, a 400-Hz sound wave is encoded by WCQS by varying the frequency of the 88.1 MHz carrier at the rate of 400 Hz. Your FM radio extracts this information using an FM radio circuit.

Why do you think FM radio reception is better than AM? Which part of the carrier is more susceptible to distortion or deterioration - the amplitude or frequency? Remember that the valuable information is encoded in the amplitude for AM broadcast and the frequency for FM broadcast. HINT: When you comb your hair in your car during a dry winter morning, static readily affects the amplitude.

A sketch of the front panel of an AM-FM Radio is given in Fig. E-6. Note that the FM numbers are given in MHz while the AM numbers are in kHz. Also note that the numbers are not equally spaced on the AM scale. That's because the same dial control is used for both and the spacing reflects the numbers dictated by the AM circuit. Did you ever notice this? Then again, you might have a digital radio and never deal with turning a tuning knob.

Fig. E-6. FM and AM Radio.



You can actually do a frequency-modulation yourself. On a synthesizer, you vary the control that alters the frequency. This is the pitch-bend control. First, press a key to play one note and keep the key held down. Then vary the pitch-blend control just a little at some periodic rate. Your frequency will increase slightly and then decrease in a periodic fashion.

If you do not have a synthesizer, you can sing a tone and try varying the frequency with your voice. Musicians call this *vibrato*. It sounds like a quiver.

We will shortly see a variety of examples of frequency modulation from everyday life. We now give the picture for a triangle wave modulating the frequency of a pulse train. In Fig. E-4 we encountered the result when a triangle wave modulates the amplitude of a pulse train. Fig. E-7 provides us with the same carrier and modulator as Fig. E-4. However, now the modulator works on the frequency rather than the amplitude. Employ the same reasoning as we used in understanding Fig. E-5. Higher frequency is evident by shorter wavelength. When the modulator wave has a high value, look for shorter wavelengths in the carrier.

Fig. E-7a. Pulse-Train Carrier and Triangle Modulator.

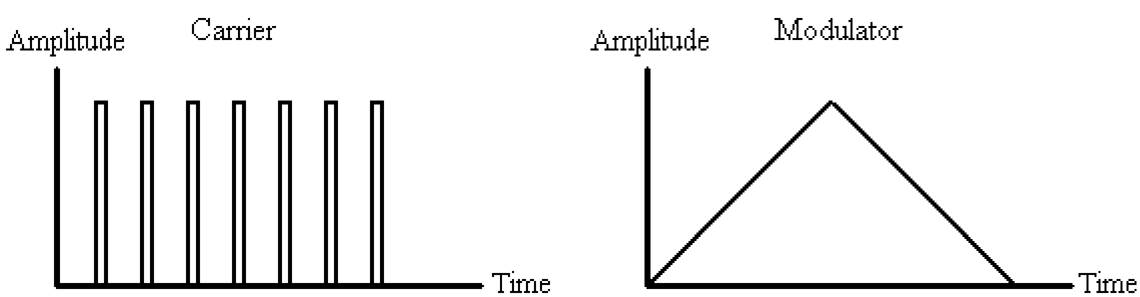



Fig. E-7b. Result When the Modulator Modulates the Frequency of the Carrier (see above).

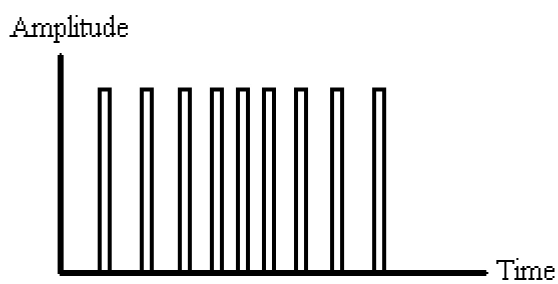
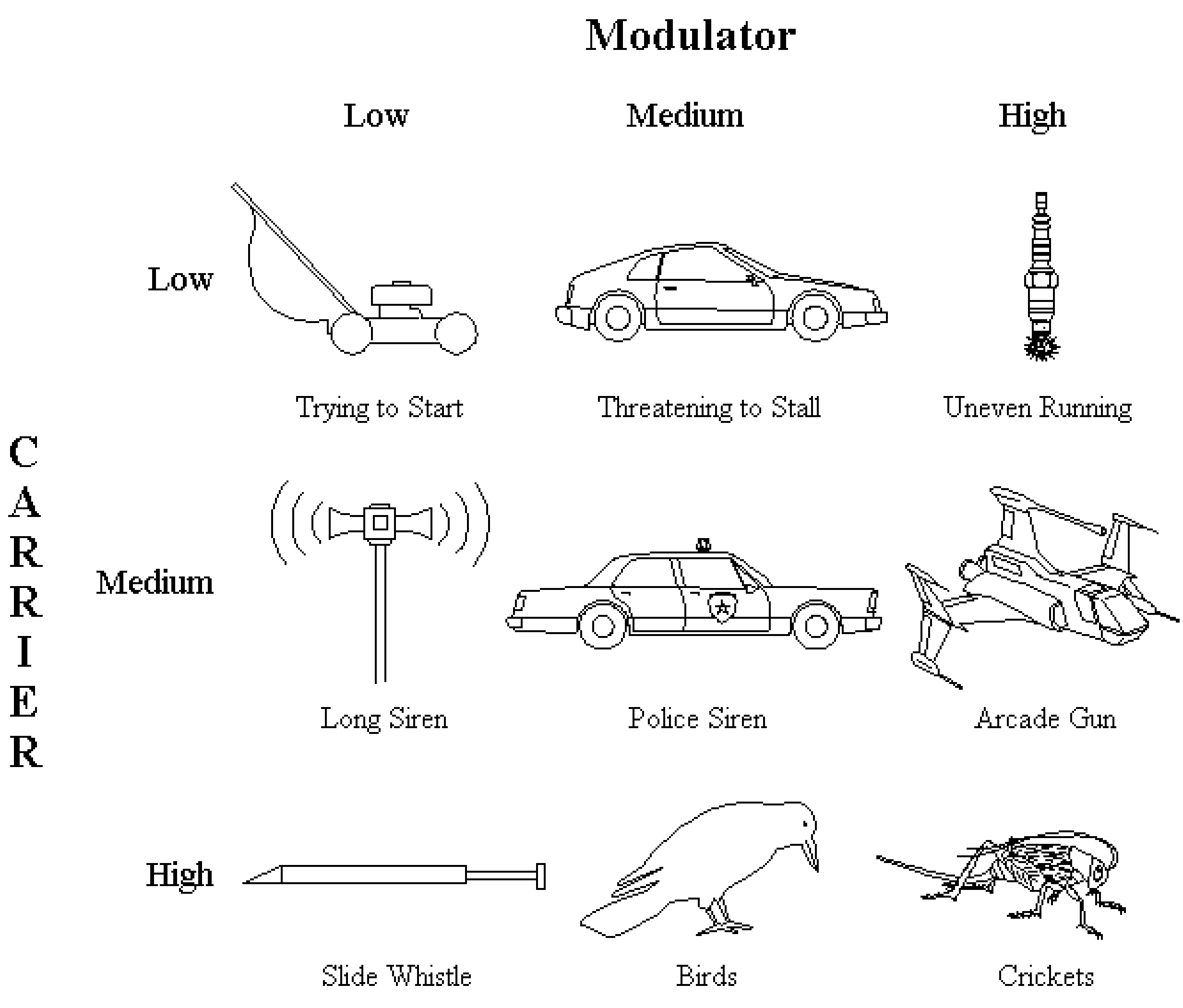


Table E-1 below gives a variety of sounds from everyday life. These sounds can be approximated by frequency modulation. The carrier wave is in the audible range. Low means bass, pitches near the bottom of the piano, medium is around the middle of the piano, and high is near the top. The carrier should be a square wave for the best results overall. It gives the carrier some richness, yet not too much.

Modulator frequencies are very low, below the threshold of hearing. Use your vibrating hand as a guide. Shaking at a low frequency is about 1 Hz (once per second). A medium modulator is a quiver at about 4 Hz. A high modulator is changing at a greater frequency, perhaps as high as 10 Hz or more. This is a rough guide in interpreting Table E-1.

Table E-1. Frequency Modulation in Everyday Life.



Consider a low modulator changing the frequency of a low carrier (Table E-1). The example in the table for these conditions is trying to start a lawn mower. As you pull on the cord, the engine starts to increase its rotational speed. But often it doesn't start and begins to slow down. You keep pulling the cord every second or two (the low modulator) and the engine increases and decreases its turning rate in the slow realm (low carrier frequency) until it starts.

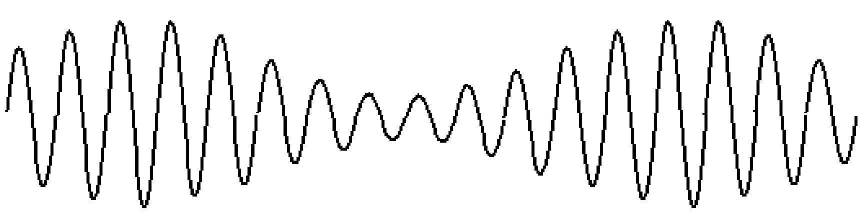
For the case of a medium carrier, we use a running car about to stall. The engine is turning slowly, in the low-carrier audio spectrum, but higher than the lawn mower. Low carrier simply means low audible frequencies. There is variation in the engine speed as it slows down threatening to stall, then speeds up. Imagine this variation (medium modulator) happening at a rate faster than your repeated pulling on the lawn mower cord. But remember that the medium modulator has a frequency of still only about 4 or 5 Hz.

On the other hand, the low carrier frequency is much higher than this. Audible frequencies are higher than the modulator frequencies in Table E-1. Finally, consider the uneven running of an engine (still at a low carrier value of rotations per minute, i.e., rpm), however, with more rapid variations (higher modulating frequency).

The next group of three (going across from left to right) in Table E-1 is the middle group with a medium carrier frequency. The first example is the long siren. It takes awhile (low modulator frequency) to sweep through different frequencies of the siren carrier wave (medium or mid-range carrier frequency). Once the author was freaked out as a child in Camden, NJ when he suddenly heard at night a slowly-varying siren from the desolate Philadelphia shipyard nearby. Increasing the rate of change for our siren brings us to the police siren. The changes are more rapid (medium modulator) and the carrier is once again in a middle frequency range, like our other siren (which makes it easier to hear). Changing a medium carrier very rapidly mimics the sounds in arcade or video games.

The final group of three at the bottom of Table E-1 takes us to high carrier frequencies. These are high pitches. The slide whistle is an example of changing a fairly high-pitched tone slowly. The change occurs as the player slowly moves the sliding part of the whistle in and out. If the variation is more rapid, we obtain sounds that approximate singing birds. We may have to start with a carrier even higher in frequency than the slide whistle. Our table is approximate and it is understood that you may have to search for the best frequencies in each case. If we vary the high carrier really fast (high modulator), the sound resembles crickets.

Some of the sounds in Table E-1 are very effective when demonstrated electronically using a square wave for the carrier. The actual waveform for the modulator is not that critical. However, a triangle wave works well. The triangle modulator makes nice sliding-whistle tones and sirens. A factor that we didn't mention is the extent of the sweep. When we change a 500-Hz carrier wave once a second, do we sweep up to 505 Hz or 600 Hz every second? If we sweep very little, staying close to the original carrier frequency, the resulting sound is more of a quiver (vibrato). If we sweep a fair amount, we have our siren sounds.



**Timbral Modulation**

The final basic characteristic to change is the timbre. The pulse train is an excellent waveform to work with. A simple way to vary the waveform is to increase the width of the pulses. In other words, change it into a square wave and back, in some periodic fashion. Note that this is only one way to vary the waveform. It is simple conceptually and electronically. This particular type of timbral modulation is called *pulse-width modulation*. See Fig. 8 below.

When the triangular modulator has a maximum value, we now interpret this to mean the widest pulse widths. Think of the pulse train as an array of buildings. A large modulator value means that we have a wide building at that point. Note that all the buildings have the same height (amplitude) and are equally spaced (wavelength, frequency). It's the widths of the buildings that change. The lower values of the modulator indicate narrower buildings or pulse widths. We decide to let a zero modulator value signify a minimum pulse width rather than no pulse width. Our spirit is qualitative; and remember, there is freedom in choosing the zero-reference point.

Fig. E-8a. Pulse-Train Carrier and Triangle Modulator.

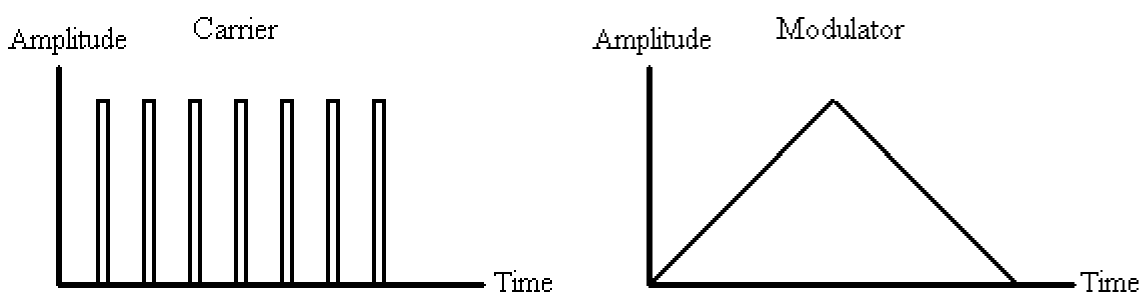
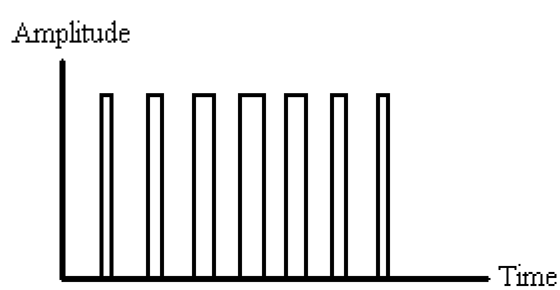



Fig. E-8b. Result When the Modulator Modulates the Pulse Width of the Carrier (see above).




Timbral modulation is heard when the quality of the sound changes in an intrinsic way, not the loudness or pitch, but the very nature of the sound. This occurs dramatically when a trumpet player moves a mute in and out at the bell end while holding a note. Try singing vowel sounds at the same loudness and pitch. As you change each vowel, you change the timbre.

Pulse-width modulation sounds like buzzing bees. We will try to understand why. Similar bees produce similar sounds. We can assume the bees are identical so the waves are identical in amplitude, frequency, and waveform. But different parts of these identical waves reach our ears at any given time. Perhaps a crest (compression) reaches an ear from the 15th bee, while the point 60% of the way up the crest reaches the same ear from the 20th bee, and so on.

This brings us back to the concept of phase. Remember that when two crests overlap, we say the waves are in phase. When a crest meets a trough from another wave, we say the waves are out of phase. The relationship among the waves of our many bees is complicated. There is no simple phase relation. The phases are all mixed. There are all possible cases in between in-phase and out-of-phase. This sound of mixed phases from similar sources has a distinct quality. It's called the *chorus effect*. The bees are singing together like a choir.

The rapid changes of the pulse width in our pulse-width modulation is a crude approximation to superimposing many low-intensity square waves on top of each other. The random shifting phases are approximated to some extent by the shifting width of the pulse wave. Therefore, the pulse-width modulation sounds like a buzzing choir of bees.

The distinct sound of the chorus effect is very different from the sound of a single source. We can pick out a solo instrument such as a violin if it plays something different from the rest of the violins. Therefore, you can usually hear the soloist in a violin concerto against the background of many violins playing in unison. Of course, the conductor keeps the violin section from overpowering the single soloist. Nevertheless, the chorus effect is relevant and likewise plays an important role. The mixed phases of the violins playing in unison are heard as a different sound than a solo melodic line.

The common example of the chorus effect is people singing in unison. They can also recite in unison. A less common example of the chorus effect is the group sounds of cicadas (sih-KAY-duhs).

Fig. E-9. Cicada.

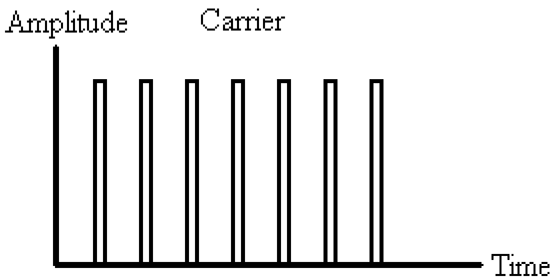
Courtesy www.artsjournal.com

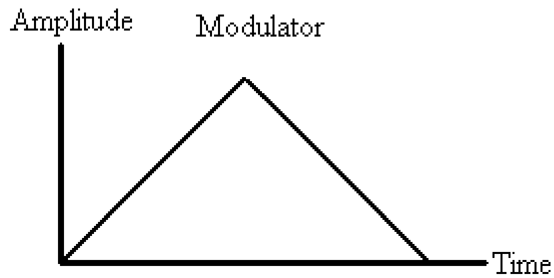
Hordes of cicadas are not around every year. A common type of cicada (see Fig. E-9) returns every 17 years. They live underground sucking nourishment from roots until they are mature. They then come out in the thousands. Males make sounds to attract females. You can turn down a side street and often be surprised at the tremendous cicada chorus effect when you run across hordes of them in trees. This lasts for only a few weeks. The adults die after mating and the new generation waits underground for the next cycle of 17 years.

A group made a riot of sound in Asheville in 1991. The party of the next generation of cicadas was held in 2008. However there is more than one type of cicada. Some return at different time intervals.

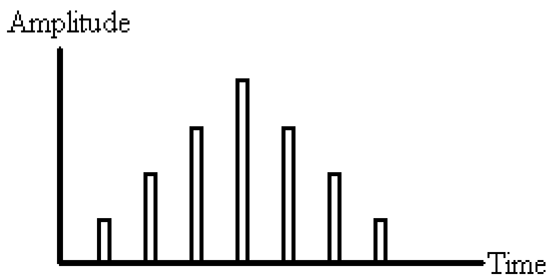
The three basic types of modulation encountered in this chapter are summarized below in Fig. E-10. You will recognize these as figures found earlier in the chapter. They are reproduced here for review and comparison.

Fig. E-10. Three Basic Types of Modulation.

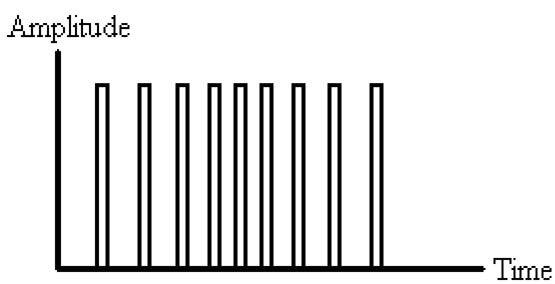


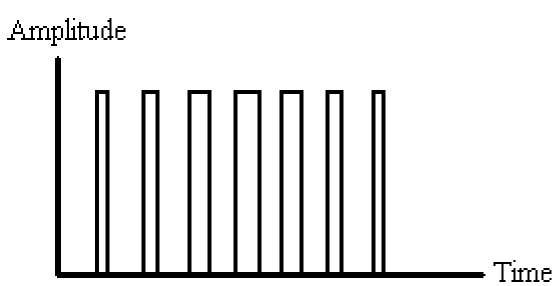

Case 1. Amplitude Modulation




Case 2. Frequency Modulation




Case 3. Timbral Modulation (Pulse-Width Modulation)



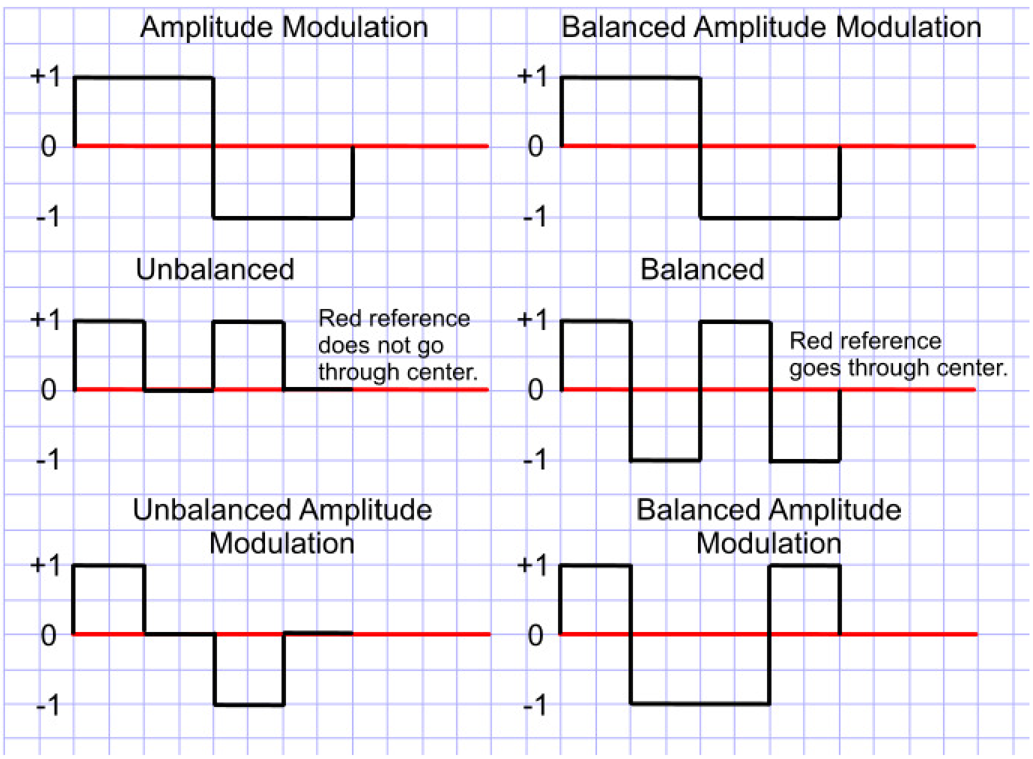

 

## Balanced Modulation

Earlier we mentioned that the vertical position of the wave could be freely chosen. We did that to simply our multiplications so that one wave would be at height 1 or height 0. You still have balanced modulation. However, if we are very careful to have the zero level go through the center of each wave, then we then have balanced amplitude modulation. We will illustrate that here.

Balanced modulation is amplitude modulation where the two waves have the zero-reference line running through the center of each wave. In Fig. E-11 balanced amplitude modulation, or simply balanced modulation, occurs in the right case. At the left, we have amplitude modulation, but the waves are not balanced. To be balanced, the red line at zero must go through the center of each wave.

Fig. E-11. Amplitude Modulation (Multiply in Each Case). Unbalanced (left), Balanced (right).




Here is a summary of the four possibilities for multiplication in balanced modulation. See Table. E-1. We can summarize these multiplications in Table E-2 where HIGH represents crest, a value of +1 and LOW is a trough, a value of -1.

Table. E-1. The Cases of Multiplication.

| | |
|---|---|
| crest meets crest: | (+1) (+1) = +1 |
| crest meets trough: | (+1) (-1) = -1 |
| trough meets crest: | (-1) (+1) = -1 |
| trough meets trough: | (-1) (-1) = +1 |

Table E-2. Input A and B with Output.

| A. Top Wave | B. Bottom Wave | Output Wave |
|---|---|---|
| HIGH | HIGH | HIGH |
| HIGH | LOW | LOW |
| LOW | HIGH | LOW |
| LOW | LOW | HIGH |

--- End of Chapter E ---