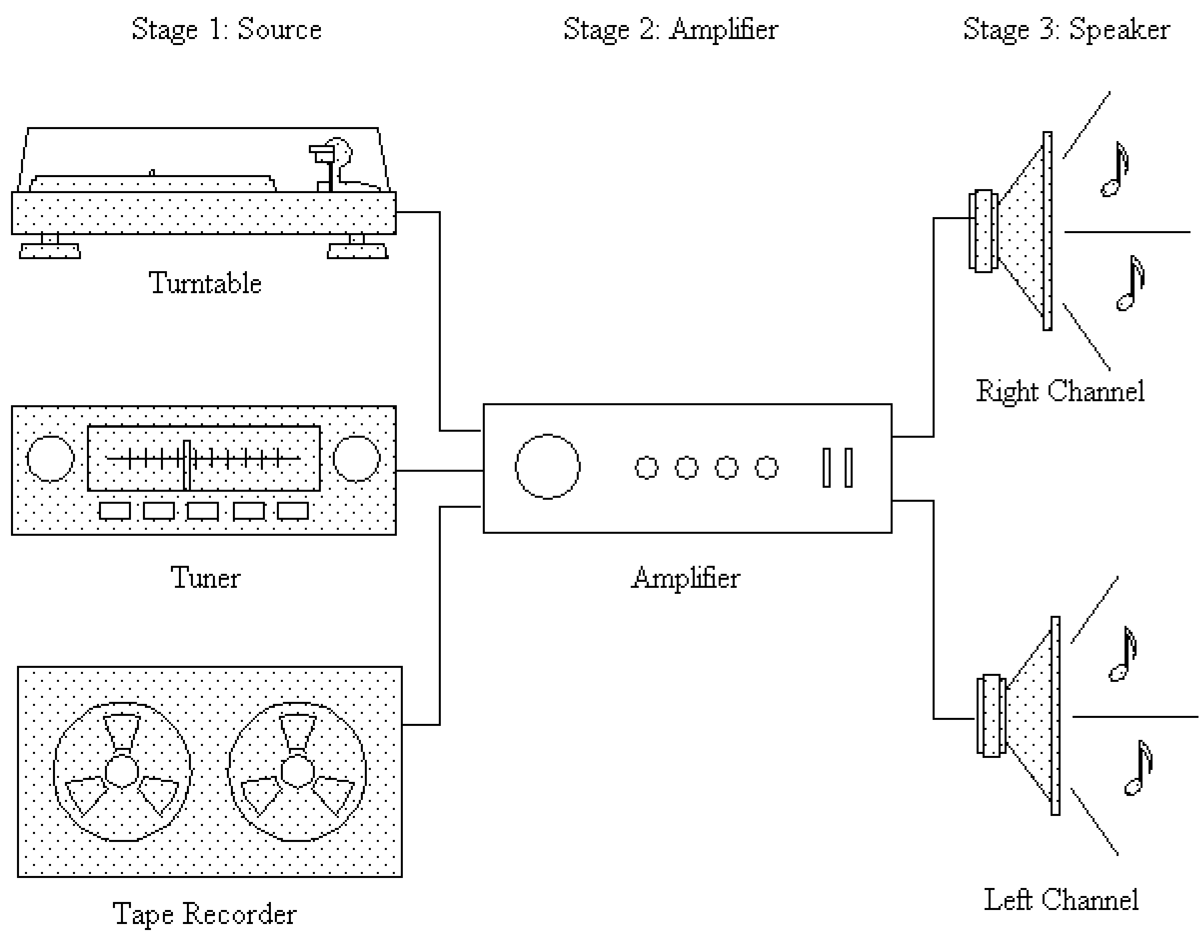
N. Analog Electronics II and Digital Electronics

Fig. N-1 illustrates the three basic stages of sound reproduction as it was realized in the stereo high-fidelity systems of the 1960s. The sources are the turntable (record player), tuner, and tape recorder (reel-to-reel). The amplifier is the common second stage. The third stage is the speaker, one for each channel. The hi-fi buff would have a collection of hundreds of LPs and dozens of tapes. The tapes would be recorded and played at 7.5 ips for high-fidelity. In order to get the *Rachmaninoff Third Piano Concerto* on one side of a tape, you need 40 minutes. A tape speed of 7.5 inches per second calls for a tape length of 7.5 x 60 = 450 inches for one minute. This is 450/12 = 37.5 feet, almost 40 feet for a minute of music. So you need about 1600 ft of tape. No problem. Tapes were sold on 7-inch diameter reels with 1800 feet and other lengths. You could get 2400-ft and even 3600-ft reels. How many minutes of music can you tape on one side of a 3600-ft reel at 7.5 ips?

We have already studied record players, tape decks, and speakers. In this chapter we investigate the amplifier and tuner. By the 1970s it was standard practice to purchase the tuner with the amplifier combined in one unit. Such a unit is called a *receiver*.

Fig. N-1. Hi-Fi System, 1960s.

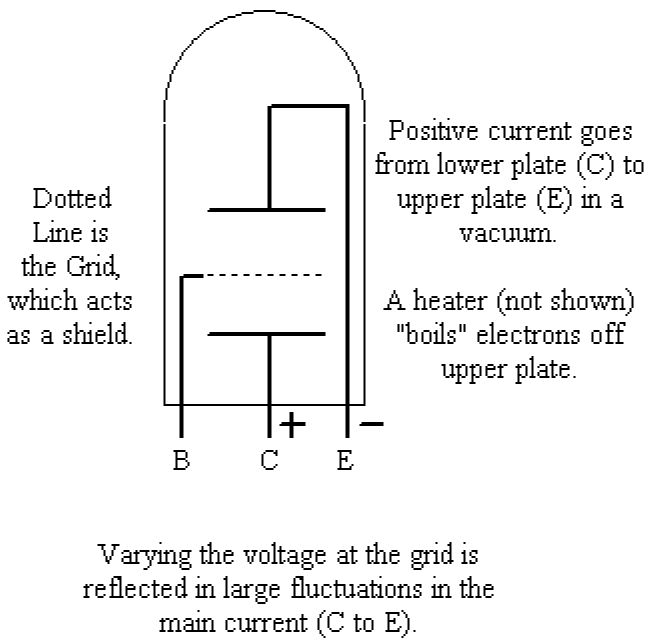


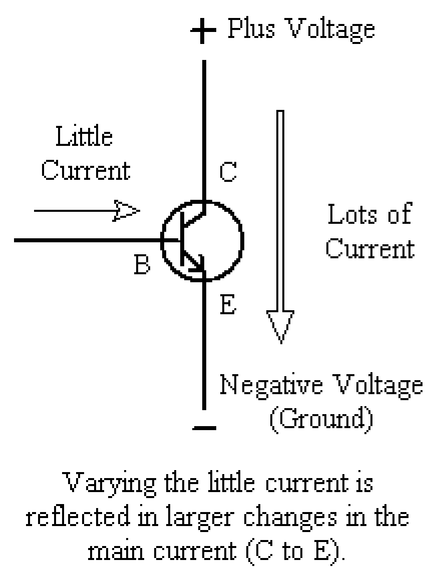
Amplifiers

We mentioned in the last chapter that we are not going to study the inner structure of the transistor, which is the semiconductor technology of solid-state physics. However, in this section we will present the old *vacuum tube* which played the role of a transistor. The transistor was discovered at *Bell Labs* in 1948. Later in the early 1970s, the integrated circuit (IC) could fit many transistors in smaller form on one chip. Today, we can have millions of tiny transistors in a chip we can hold in our hand. Such innovations made possible the desktop computer of the 1980s and beyond. All of these developments are not possible with vacuum tubes.

We can gain insight into the function played by a transistor by looking at its earlier counterpart, the *triode* vacuum tube. The triode was invented in 1907. Fig. N-2 below compares a triode to a transistor. Our aim is to understand how each functions as an amplifier.

Fig. N-2. Comparison of Triode Vacuum Tube (Left) and Transistor (Right).





There is a vacuum inside the tube in Fig. N-2. A heater (not shown) is used to boil electrons off the negative plate (connected to E), which plate is called the *cathode*. Electrons are also called *cathode rays*. Your TV has a cathode-ray tube that boils electrons off so they can be guided to the screen and light up phosphors. A current flows, by our convention, from C to E (opposite direction). This is a large current. Making the grid negative, discourages electrons to come toward it on their way to C. The grid can be thought of as a shield. Minor fluctuations in charge at B are then reflected in large changes in the main current from C to E. The triode amplifies the changes fed in at B.

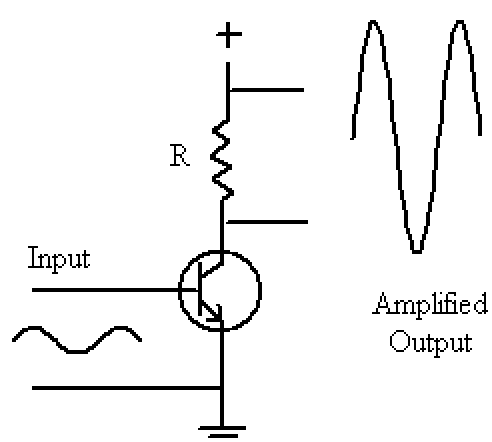
The transistor does essentially the same thing. A little current fed into the base B, activates the transistor so the pathway is now clear for lots of current to flow from C to E. Increase the little current, and you see a corresponding enhanced change in the main current. Think of the base as a stream that feeds into a structure that opens the dam to a river. A mechanical advantage is supplied by a fulcrum-counterweight structure (remember the record player) so that when the little stream pushes "a small trap door" open, the mechanism raises the flood gates for the river to flow. The plus and negative in our transistor diagram corresponds to differences in elevation. Plus means high elevation and negative means lower elevation, or *ground* in electronics terminology.

The river always wants to flow downstream but it can't because the main gate prevents it. Unless these gates are opened by the action of the little stream, nothing happens. If the little stream pushes the "trap door" only half way, then, the large volumes of the river water flow but at half strength. If the "back trap door" (the base B) is pushed in all the way, then the entire river current flows. Now play with the "back door" pushing it in and pulling it back rapidly. These small fluctuations are reflected in the larger changes of the river flow. The river current oscillates in step with the base stream oscillations. This is our amplifier action.

A small changing electrical signal fed into the base of the transistor or the triode produces a corresponding larger changing main current from the collector to the emitter. This larger varying current "to the tune" of our base-input signal is our amplified signal. The transistor is far superior to the vacuum tube. Transistors do not boil off electrons from a plate and therefore do not need heaters. Transistors are smaller. Therefore, devices made with transistors are smaller and cooler than those made with vacuum-tube technology.

Fig. N-3 illustrates the use of the transistor as an amplifier. The small input signal is a sine wave. Note that we need two wires for a signal. The bottom wire is ground and the top wire is the live wire on which our small voltage fluctuations occur. The small input oscillations are magnified in the main current fluctuations in step with it. In order to tap into this amplified signal, we attach a resistor on top of the transistor in Fig. N-3. When the current rushes down in step with the input wave, we get a voltage across the resistor according to $V = IR$. The resistor experiences large voltage fluctuations due to the large currents. By "grabbing electronically" on to this resistor, we tap off the circuit our amplified voltage signal.

Fig. N-3. Transistor as Amplifier.



Tuners

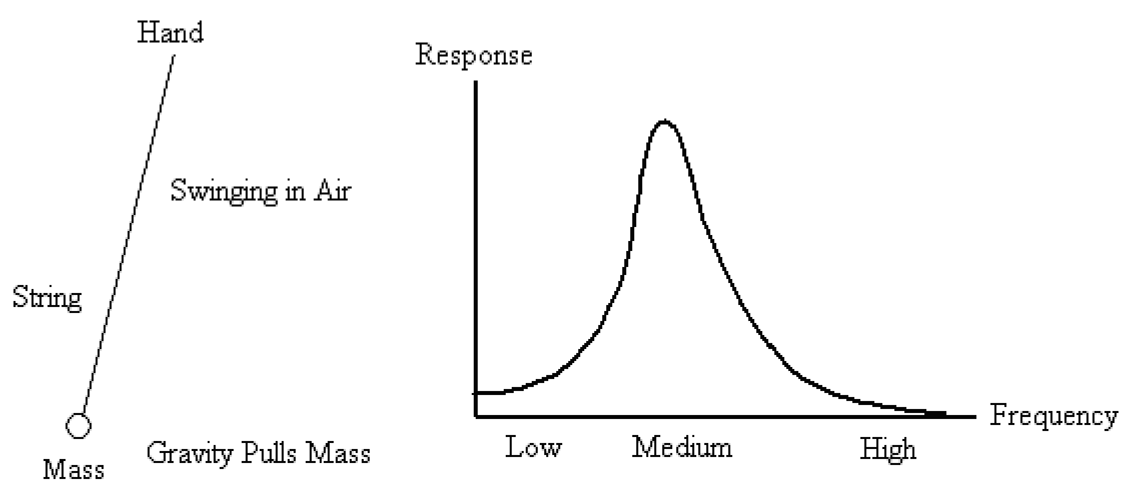
Tuners are radios without the amplifier and speakers. The circuit tunes in to receive a radio signal and decodes it. The tuner is another example of a source in our sound system. We have to amplify this weak source to get a strong output that can drive a speaker. We will focus on AM radio.

The AM tuner consists of two sections. First, the circuit that tunes in the radio wave and second, the part that decodes the signal. Remember, AM radio waves carry an encoded signal in the modulation of the amplitude.

The best way to understand the tuning circuit is by considering a mechanical analog, our old experiment shaking a ball on the end of a string (Fig. N-4). Let the shaking hand represent the incoming radio wave. Let the string represent an antenna. The signal we pick up is seen by the swinging ball. Refer to the resonance curve at the right in Fig. N-4. It's hard to get a response if the incoming frequency is too low or too high. However, for the middle frequency which we call the resonance frequency, we obtain the greatest response, i.e., amplitude for our swinging ball.

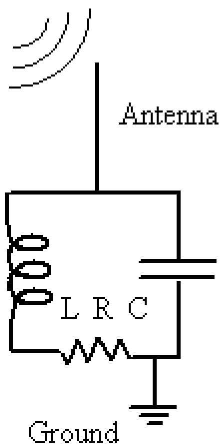
The ball always swings at the same frequency of the hand, but only for middle frequencies do we get a nice large sweep. We can say that the mechanical system is "tuned" to respond to the hand shaking at the resonance frequency. If the hand is shaking back and forth at a high frequency, this signal cannot get to the ball. But if we shorten the string, "tuning" our system to a different resonance frequency, we then can get a response. This is the mechanical analog of "tuning in" to get a specific radio station. Imagine many "invisible hands" trying to get the attention of the ball. Depending on the length of the string, one oscillating hand succeeds, the one shaking at the resonance frequency.

Fig. N-4. A Mechanical-Tuner Analogy.



Many signals in the air compete for the attention of your radio. However, the broadcasting frequency that succeeds is the resonance frequency you are tuned in to receive. The electrical analog to the mechanical resonance system is given in Fig. N-5. The incoming waves replace the moving hand. The incoming radio wave is an electromagnetic wave, a wave that electrons in an antenna can respond to.

Fig. N-5. Electrical Tuner Circuit.



L: Coil (Inductor), R: Resistor, C: Capacitor.

L acts as the mass (inertia), wants to keep the current going in same direction.
R is the resistance to the current (like the air in the mechanical case).
C is like gravity - too much charge on the plate wants to swing back.

The driving force (hand) is now the incoming radio signal. The antenna helps to "connect" this driving force to the circuit. The wire at the lower right is attached to a neutral body such as the Earth or chassis of a car.

The resonance frequency for the oscillating charges is determined by the circuit components L, R, and C. The movement back and forth of charges in response to the driving radio wave is analogous to the movement back and forth of the ball on the end of the string. If we pull the ball back and let it go on its own, it swings. If we force a lot of negative charges on one side of the capacitor, the charges will race through the circuit to the other side. But what keeps the ball going to overshoot the center position? The inertia of the mass of the ball.

Electrically, the coiled wire (the *coil*) does this. The reason is subtle. Consider the moment when the charges are flowing at full strength through the coil. Ampère's Law states that this current produces a magnetic field inside the coil. The charges begin to stop flowing through the coil when there aren't many left to flow. This decrease in current causes a decrease in the magnetic field produced by the current. The decrease in the magnetic field (a change) produces some electricity (Faraday's Law). This added electrical current gives the current "momentum" to keep going. So the charges overshoot the mark and charge the capacitor in the reverse way. Finally the current does stop.

The capacitor is then charged the opposite way. But now, the charges start moving again, this time the other way. The charges are moving to establish "equilibrium," i.e., no net charge on the capacitor. The whole process repeats in the reverse direction. They overshoot again and the capacitor is charged back the way it was before. After this, they start again, moving back the other way and so on. The charges "swishing" back and forth resemble our oscillating pendulum. The resistor in our circuit is analogous to the resistance of the air through which our pendulum swings.

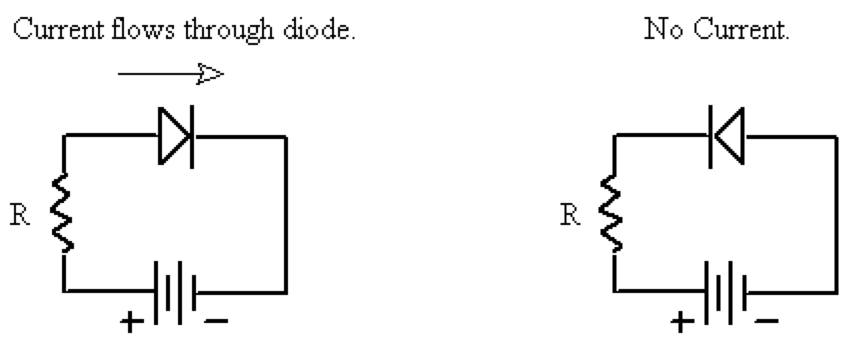
Let's continue discussing this subtle effect from different angles. When the charges start to flow, a magnetic field is produced (Ampère's Law). But going from no magnetic field to a magnetic field induces some current (Faraday's Law: changing magnetic field induces current). This electricity produced must oppose us. If not, we would be getting something for nothing. Before, when the magnetic field was decreasing, our current got a little kick (additional electricity) to keep the current alive for a little bit longer. Now, the magnetic field is increasing, so the electrical surge due to Faraday's Law wants to assist in keeping things the way they are - dead. Nature seems to work this way. It often opposes our desires.

If we want to decrease the magnetic field inside the coil by cutting back on the current, nature works against this by giving the current a little kick in the same direction the current is going. But this is the opposite of what we are trying to do. If we want to increase the magnetic field inside the coil by an increase in current, nature works against us by "kicking" in the opposite direction. In each case, nature is trying to preserve the status quo, against our wishes to change things. This opposition in the circuit is called *Lenz's Law*. It is analogous to Galileo's *Law of Inertia* (also Newton's First Law) which states that nature wants to keep objects doing whatever they are doing. If a mass is at rest, it wants to stay at rest. If it's moving, it wants to keep moving. You need a force like friction to stop a sliding box.

The electrical analog to the Law of Inertia is found in the behavior of the inductor (a coil). Current through a coil wants to keep doing whatever it's doing. So just as the mass of a pendulum overshoots equilibrium due to its inertia, the charges moving through an inductor overshoot and charge the capacitor in a reverse manner. Note that the coil is necessary because the coil allows for the interplay of Ampère's Law and Faraday's Law. This is deep physics!

The second part of the AM radio is the decoder of the amplitude modulation. The basic decoder is a *diode*. A diode is an electrical circuit element that lets current pass in only one direction. Fig. N-6 depicts a diode. Current passes through along the direction indicated by the triangle. Current trying to go the other way is blocked (right diagram in Fig. N-6).

Fig. N-6. Diode.



A diode lets current pass in one direction only.
The resistor R limits current to safe values.

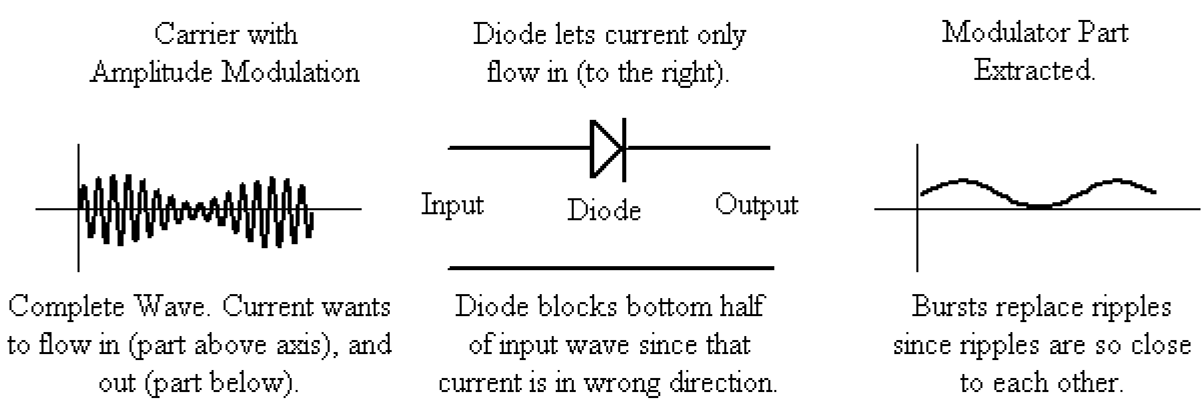
Fig. N-7 shows how a diode can be used as a decoder for amplitude modulation. The incoming wave is oscillating to and fro. It wants to quickly push current into the diode and then pull current back in the opposite direction. The diode passes the "to" part and blocks the "fro." Current can only pass through a diode in one direction. Therefore, the output is just the top part of the input wave, that part representing pushing current into the diode. The part representing the pulling of current back (below the horizontal axis) is blocked.

Since the carrier wavelength is so short (ripples) compared to the modulation of the amplitude (long wavy contour of amplitude), we sketch the output with these ripples merged. The result is the wavy contour of the amplitude. But do you remember why the carrier wavelength is so short and the modulation wavelength long?

The carrier wave is a radio wave. For an AM radio station, a typical frequency is 1310 kHz (*WISE*). This is 1.3 MHz, i.e., about 1 million times a second. The amplitude varies at an audio frequency. Take a sine wave of 100 Hz (a bass tone). That is only 1 hundred times a second. Let's compare 100 with 1,000,000. Well, one million is 10,000 times more! That means the radio carrier wave wiggles back and forth 10,000 times before the amplitude undergoes one crest and trough! So our picture at the left in Fig. N-7 is exaggerated. Fig. N-7 shows about 16 ripples for our carrier wave as it goes through about one cycle and a half of amplitude variation. There should be thousands of ripples instead.

The output wave is a result of the current that went through the diode in the correct direction. This is the upper part of the input wave. We can consider the output as bursts of current since the carrier waves (ripples) are closely packed (thousands) and all the current now is in the same direction. These bursts occur at the modulator frequency. This is our sound wave, i.e., the wave at 100 Hz. We have decoded (demodulated) the AM radio signal. We send this to an amplifier and then to a speaker to hear it.

Fig. N-7. Diode Used as Demodulator.

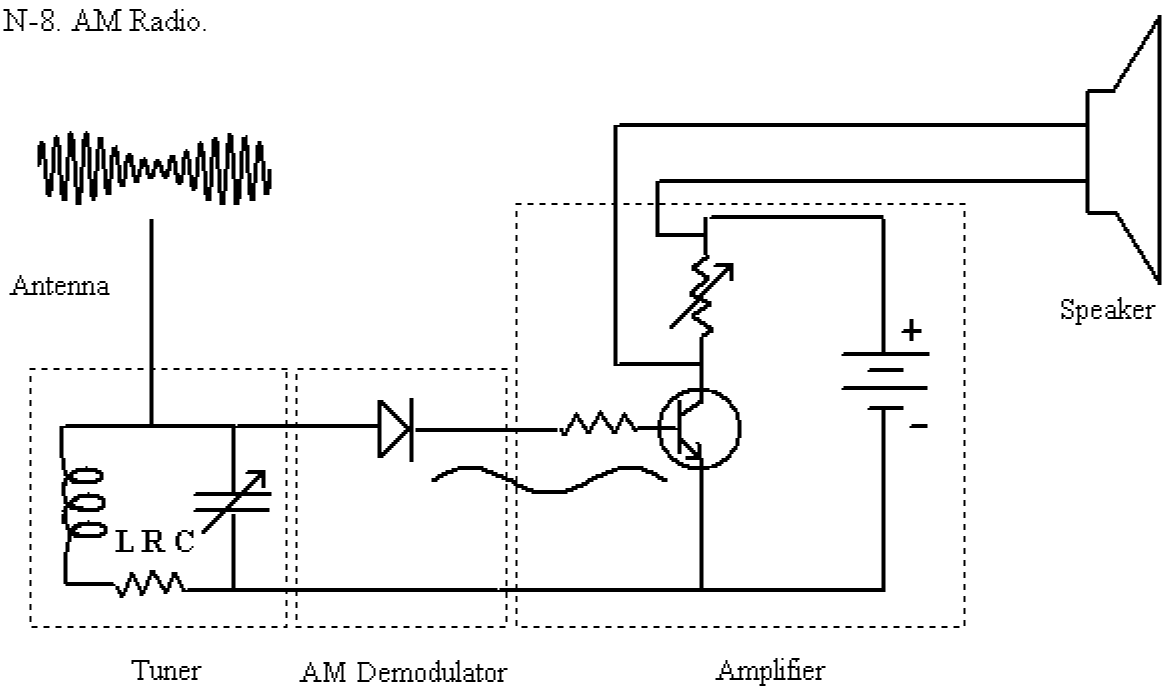


Now we are ready to put all of this together: the tuner, the demodulator, the amplifier, and the speaker. The result is Fig. N-8, one big impressive diagram. Focus your attention on each component. These have already been discussed. If you are confused, localize the difficulty. Then review that section in the text in order to understand that particular part. Note that the amplifier circuit includes a variable resistor so you can control the volume of the output signal. The capacitor likewise has a variable control. You also know the inside structure of a speaker from an earlier chapter. So you really understand quite a bit about the circuit in Fig. N-8. The ground wire (see Fig. N-5) is not shown in Fig. N-8. Sketch it in.

In the old days (the 1950s) it was common to buy a tuner, consisting of the tuner section and the demodulator. You would really be buying two circuits since your tuner would be able to pick up AM and FM radio waves. This consisted of one of your source components. Remember, the source component is stage one in sound reproduction. The amplifier is stage two. That would be your second component. Then you would buy speakers for the third stage.

Manufacturers began combining the tuners with the amplifiers. These combo units are called receivers. Today, it is very common to buy a receiver. You get the radio and amplifier. This assumes the higher-end product where components are specialized. Of course, you can buy a radio which includes everything, tuner, amplifier, and speaker(s). The author had a 6-transistor pocket AM radio as a kid in 1963, complete with everything. The 6 transistors allowed for stages of amplification. The little radio used a 9-volt battery and could pick up Houston or Cincinnati from Philadelphia at night as AM radio waves bounced off the upper atmosphere (the *ionosphere*, which is higher at night).

Fig. N-8. AM Radio.

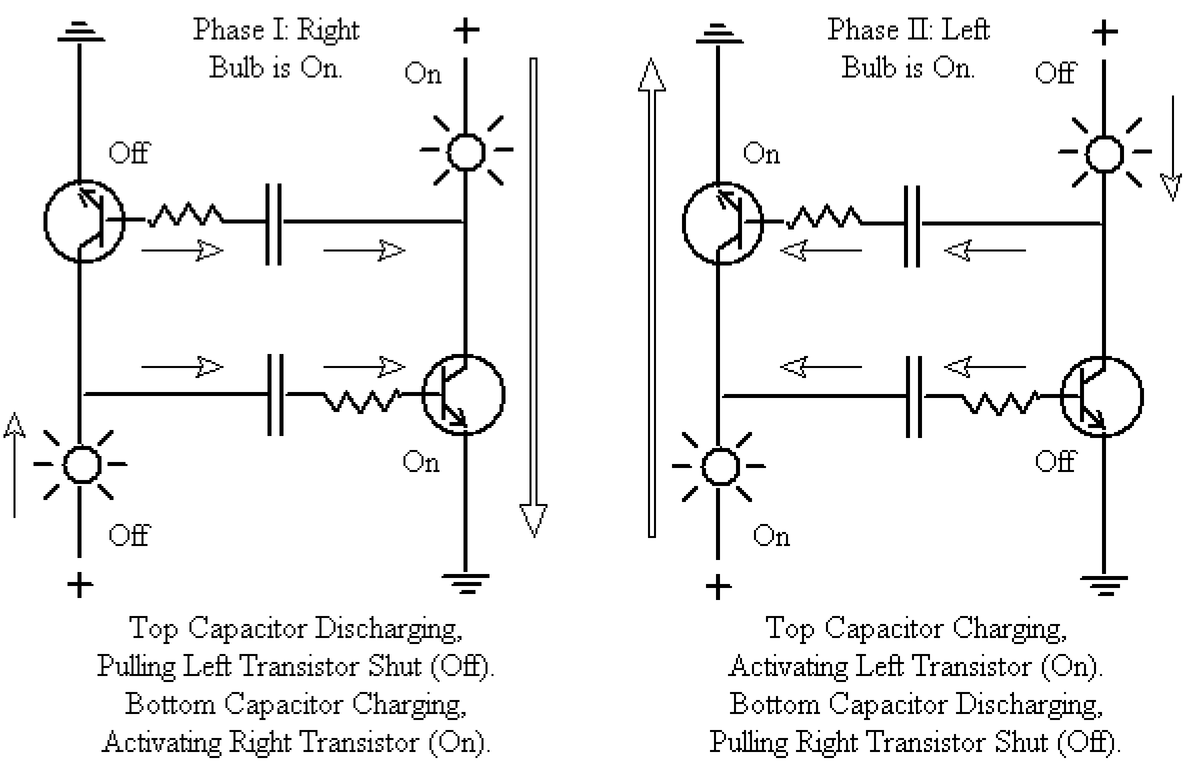


Oscillators (Optional Section)

Oscillator circuits are important for both radio frequencies and audio frequencies. An oscillator is used to produce the carrier waves in radio broadcasting. Oscillators are also used at audio frequencies to produce tones in music synthesizers. In the spirit of this text, the simplest possible oscillator circuit is given in Fig. N-9. Try to get an overall understanding for what the circuit does. Shift your eyes back and forth between the diagrams below. The current changes direction. The bulbs take turns going on and off. Only one is on at a time.

The battery for the circuit is not shown directly. The plus and minus (ground) symbols indicate where to connect to the battery terminals. In the left diagram, the bottom capacitor is charging. The current going through the left bulb is too weak to light it up. The top capacitor is discharging, "sucking" current from the left transistor (pulling the "trap door" the wrong way a little). The left transistor is off. When the lower capacitor is fully charged, the reverse (right diagram) takes place. The left bulb goes on; the right bulb goes off. This circuit is called the *astable multivibrator*. We can replace the bulbs with resistors. Then tap off one of these resistors and we have our oscillator. The particular resistor-capacitor combination chosen for the charging circuits determines the frequency of the oscillator.

Fig. N-9. Oscillator Circuit.



Digital Electronics

In digital electronics, the voltage can be in any of two states: on or off. We will consider 1 volt for on and 0 volts for off or simply 1 and 0. Digital electronics is the foundation of the digital computer. The computer only knows 1 or 0; however, zillions of these give the computer the ability to do anything imaginable. Below we introduce the logic of using 1s and 0s.

NOT (INVERTER)

The first example of a digital-logic component is the NOT or Inverter. Have you ever changed your mind about something or said to a friend "You look good. NOT!" You negate or invert your comment. We change Yes to No or vice versa. See Table N-10a.

Table N-0a. Inverter Logic

Before	**After**
No	Yes
Yes	No

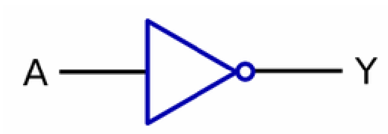
We will take 1 = Yes and 0 = No. You have some position on an issue, but after some reflection, you change your mind. Then the table is given as below. It is called a *Truth Table*. It lists all the cases. We refer to "Before" as the "Input" or "In" for short and "After" as the "Output" or simply "Out." Then we label "In" as A and "Out" as Y.

Table N-0b. Truth Table for Inverter Logic

A	**Y**
0	1
1	0

We would also like to have a visual representation of this logic in symbolic form. We are led us to our first digital-electronics symbol, also called a *Gate*.

Fig N-10. Inverter Gate Symbol



AND

Consider two qualities you must have in your date; otherwise, you do not date the person. Perhaps, you insist on a date that is attractive to you in some way and one that has polite manners. This is an example of an AND condition. We summarize this logic in the following truth table.

Table N-1a. AND Logic

Attractive in Some Way	**Polite Manners**	**Decision to Date**
No	No	No
No	Yes	No
Yes	No	No
Yes	Yes	Yes

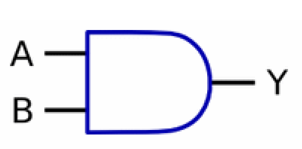
We generalize this logic by letting A = "Attractive in Some Way" and B = "Polite Manners." Then we take 1 = True and 0 = False. The Decision is the Output or Out.

Table N-1b. Truth Table for AND Logic

A	**B**	**Y**
0	0	0
0	1	0
1	0	0
1	1	1

The AND Gate symbol is given below.

Fig. N-11. AND Gate



OR

Consider two qualities, where only one is necessary for your decision to be true. Perhaps you are at your grandmom's house and she offers you lunch. Choice A = sandwich and Choice B = soup. But Grandmom says you can have both if you want. Then, the condition of eating lunch is satisfied by eating the sandwich, having the soup, or accepting both.

Table N-2a. OR Logic

Eat Sandwich?	Have Soup?	Did You Have Lunch?
No	No	No
No	Yes	Yes
Yes	No	Yes
Yes	Yes	Yes

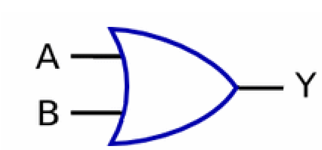
The corresponding generalized truth table is below.

Table N-2. Truth Table for OR Logic

A	B	Y
0	0	0
0	1	1
1	0	1
1	1	1

The OR Gate symbol is in Fig. N-12.

Fig. N-12. OR Gate



XOR

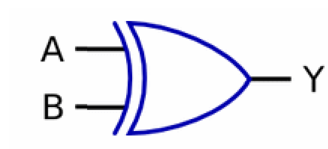
Now comes the "Exclusive OR." Grandmom says you can only have one for lunch: soup or sandwich. There is just not enough food to go around for everyone. In this case, the logic is summarized in Table N-3.

Table N-3. Truth Table for XOR Logic

A	B	Y
0	0	0
0	1	1
1	0	1
1	1	0

The XOR Gate is below. Remember the XOR by thinking both choices are "excluded: you can have one or the other, but not both.

Fig. N-13. XOR Gate



Can you think of other scenarios for the XOR?

NAND

Consider the NAND as the negation of the AND. You just flip the answers of the AND to their opposites. See Table N-4a.

Table N-4a. Truth Table for NAND Logic

A	B	Y
0	0	1
0	1	1
1	0	1
1	1	0

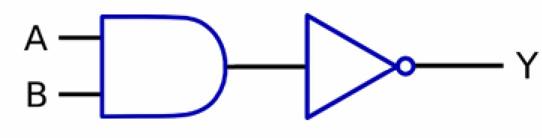
Below is another way of looking at your date requirements (see Table N-4b).

Table N-4b. NAND Logic

Attractive in Some Way	Polite Manners	Decision to Stay Home
No	No	Yes
No	Yes	Yes
Yes	No	Yes
Yes	Yes	No

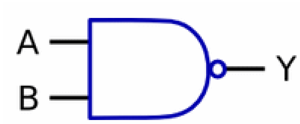
We can write the negative of the AND output with the inverter. See Fig. N14a.

Fig. N-14a. Constructing NAND Logic



The abbreviated form for Fig. N-14a is Fig. N-14b.

Fig. N-14b. NAND Gate



NOR

Let's return to our visit to Grandmom's for lunch where she serves soup and sandwich. Suppose we ask the question "Did you fast at Grandmom's Luncheon?" The answers to this question are listed in Table N-5a.

Table N-5a. NOR Logic

Eat Sandwich?	Have Soup?	Did You Fast?
No	No	Yes
No	Yes	No
Yes	No	No
Yes	Yes	No

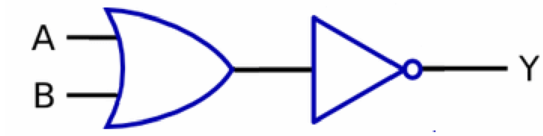
The general truth table is Table N-5.

Table N-5. Truth Table for NOR Logic

A	B	Y
0	0	1
0	1	0
1	0	0
1	1	0

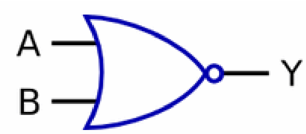
This table is the inverted version of the OR. Compare the output Y columns. You find that the NOR has the opposites compared to OR. We illustrate this in Fig. N-15a.

Fig. N-15a. Constructing NOR Logic



The abbreviated form for Fig. N-15a is Fig. N-15b.

Fig. N-15b. NOR Gate



You just place a little "bubble" on the end of the OR. Sometimes, NAND and NOR are referred to as a bubbled AND and bubbled OR respectively.

XNOR

Let's flip the outputs for the XOR. We then get the truth table in Table N-6.

Table N-6. Truth Table for XNOR Logic

A	B	Y
0	0	1
0	1	0
1	0	0
1	1	1

Can you think of an example where this logic would apply? You can have nothing or both. It's an all or nothing deal! How about maintaining balance on a plank where A = "Hold a Weight in Outstretched Left Arm" and B = "Hold a Weight in Outstretched Right Arm." When are you balanced?

My students taught me this next example. Let A = 1 mean A is in love with B and let B = 1 indicate that B loves A. Then the acceptable scenarios are the Platonic relation A = B = 0 or the love relation A = B = 1. The unrequited love cases have Y = 0. These relationships are undesirable.

You might ask why we don't write this one as NXOR with the N out if front? Well, we just don't. It would be too hard to pronounce it that way.
The corresponding digital circuit symbols are shown in Fig. N-16a and Fig. N-16b.

Fig. N-16a. XNOR Logic

Fig. 17. Summary of Digital Logic Gates

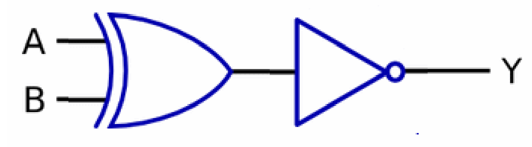
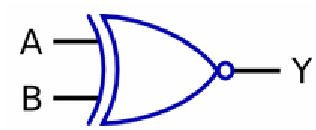
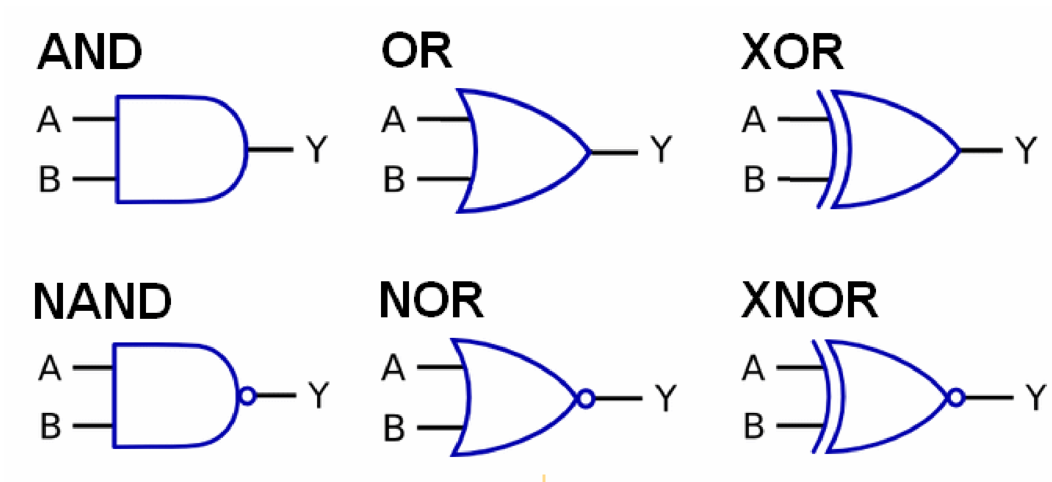


Fig N-16b. XNOR Gate



Check out the super summary below of all the gates (Fig. 17).



AND

A	B	OUT
0	0	0
0	1	0
1	0	0
1	1	1

OR

A	B	OUT
0	0	0
0	1	1
1	0	1
1	1	1

XOR

A	B	OUT
0	0	0
0	1	1
1	0	1
1	1	0

NAND

A	B	OUT
0	0	1
0	1	1
1	0	1
1	1	0

NOR

A	B	OUT
0	0	1
0	1	0
1	0	0
1	1	0

XNOR

A	B	OUT
0	0	1
0	1	0
1	0	0
1	1	1

--- End of Chapter N ---

