Electronics

Radio

Television

Radar

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HOW VACUUM TUBES AND TRANSISTORS WORK ASSIGNMENT 15

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The basic idea of the thermionic vacuum tube has probably been the most important single invention in the development of the radio, television, and electronics arts. The development which is second in importance is the transistor. Without these elements the high power, high quality radio transmission and reception to which we are accustomed today would not be possible. Television reception would still be a mere dream, and electronics would be beyond the vision of the most fantastic dreamer.

Vacuum tubes and transistors are used in almost every circuit in radio transmitters and receivers. They are used in transmitters for amplifying the weak audio frequency signals set up in the microphone circuit; and for generating and modulating the radio frequency carrier current that produces the radio waves which radiate from the transmitting antenna. In radio receivers, vacuum tubes and transistors are employed for greatly amplifying the weak signal voltages generated in the receiving antenna, and for detecting or removing the audio-frequency signal from the carrier signal. They amplify the audio signal obtained from the detection process in order to make loudspeaker operation possible. They are also used for converting the a-c voltages supplied by the power lines to d-c voltages for operation of the transmitter and receiver.

Hundreds of new applications are being found daily for vacuum tubes and transistors, and their associated circuits in all branches of industry, in defense, in the space program, in commerce, and in the home. As we shall see when studying some of these uses in later assignments, they are being employed for such functions as amplification, rectification, detection of current or voltage impulses, operation of counting and sorting devices, computing, alarms and signal systems, controlling large amounts of energy and machinery, and even for cooking hot dogs. There is seemingly an endless variety of uses for vacuum tubes and transistors, and every person who plans to associate himself with the electronics industry must be on intimate terms with the fundamental theories upon which vacuum tubes and transistors operate.

Transistors are replacing vacuum tubes in many types of newly developed electronics equipment, but there are still many hundreds of millions of vacuum tubes in use in existing equipment. Also, there are many instances where vacuum tubes are being employed in newly designed equipment. Thus, the study of vacuum tubes in this training program is of vital importance and will be presented hand-in-hand with the study of transistors.

VACUUM TUBES

Of the two components to be considered in this assignment—vacuum tubes and transistors—the vacuum tubes were developed first. Let us, therefore, turn our attention first to vacuum tubes, and then to transistors.

Figure 1 illustrates a large number of different types of vacuum tubes. The small tubes in this illustration are receiving tubes, and the larger tubes are transmitting tubes. The large tubes with the long cylindrical metal ends are water cooled transmitting tubes and those with the radiator fins are air cooled.

The Edison Effect

Over eighty years ago (in 1883) Thomas A. Edison, while at work on the development of his incandescent lamp, was troubled by frequent failure of his lamps which were caused by burn outs of the carbon filaments. The experimental lamps on which he was working used batteries to supply the current to heat the filament, and his investigations disclosed that nearly all of these burn outs occurred at the positive end of the filaments. He then constructed a special lamp in which he placed a small metal plate, in addition to the filament. The metal plate was insulated from the filament and was connected by a wire through the glass to an outside terminal. An illustration of such a lamp is shown in Figure 2(A). He found that when he connected this plate to the positive end of the filament battery and connected a very sensitive current indicating meter in series with it, as shown in Figure 2(B), that a small current flow was indicated by the meter. However, when the plate and meter were connected to the negative side of the filament battery, as shown in Figure 2(C), no current flowed. Furthermore, Edison's investigations showed that this current flow was always from the plate, through the meter and back to the filament, and never did the current flow in the opposite direction. Also, the current flow stopped just as soon as the lamp's filament was allowed to become cold.

Here then, was a real mystery, for at that time nothing was known about the emission of electrons. A current was apparently flowing inside the tube, from the filament, through the vacuum to the plate. This action is now known as the "Edison Effect". Edison was too busy with the development of his lamp to spend much time continuing this investigation, but he made a record of it. The explanation for the Edison Effect remained a mystery until 1899, when J. J. Thompson showed that this phenomenon was due to electrons being given off by the filament when it was heated.

Electron Emission from Solids

To better understand this giving off of electrons by a filament when it is heated, let us briefly review the nature of matter. Suppose we were to take any piece of matter—a pound of butter, a piece of paper, a block of wood, a grain of salt—and divide it up into two pieces. We could then take one of these pieces and divide it into two more pieces, divide up one of these pieces, and so on. For a long time, it was thought that this process could be continued indefinitely, but it is now known that this is not true. If we were to divide a grain of salt in this manner, we would finally get a very small piece of salt, and we could not further divide this piece and still have a piece which would look, taste, and act like salt. This would be the smallest particle of salt which could exist, and we would call it a **molecule** of salt. If we were to divide this, we would find that we no longer have salt, but would instead have **atoms** of sodium and chlorine—the elements which, when properly combined, form salt. These atoms of sodium and chlorine are the smallest particles of these elements which can exist, and if we were to analyze one of these atoms we would find that it is made of particles of electricity known as electrons and protons. We have already learned that these **electrons have a negative charge** and these **protons have a positive charge,** and that **the atom has a nucleus which contains all of the protons.** Around this nucleus revolve the electrons associated with the atom. These electrons are revolving at various distances or levels, and they are constantly changing levels at a rate proportional to the temperature of the atom. Though the total number of electrons in any atom remains the same at all times, they are constantly changing places, and the higher the temperature, the faster they rush back and forth.

In Edison's lamp, and in most vacuum tubes, the filament is heated by passing a current through it, and the electrons in the filament move around at a faster and faster rate. At low temperatures, these electrons are kept within the surface of the filament by the attraction of their nucleus and by another property known as the cohesion of the surface of the metal. As the temperature of the wire filament is raised, the electrons travel faster and faster. Finally at some temperature, the electrons are traveling at such a high rate of speed that some of them break through the surface of the metal and are carried on into the space surrounding it. At still higher temperatures, more electrons leave the wire and soon there are a number of electrons in the space around it.

The emission of electrons from a heated body may be compared to the evaporation of water. If we raise the temperature of a pan full of water by heating it, the agitation of its molecules increases and when the temperature commonly known as the "boiling point" is reached, the molecules have gained enough energy to enable them to break through the surface tension of the water and shoot out into the atmosphere in the form of tiny particles of water vapor. Of course, this action is not exactly like that of electron emission, for in this case, molecules of water, each containing several atoms and many electrons, are boiled off; in the case of electron emission, only the electrons are emitted.

If we will recall the laws of electrostatic charges we will remember that unlike electric charges attract each other, while like charges repel each other. If any electrode in the tube (such as a plate) has a positive potential with respect to the electron-emitting filament it will attract these electrons which are being emitted.

This explains why Edison noted that a current would flow in the external circuit, from the plate back to the filament battery, when the circuit was returned to the positive end of the filament battery as shown in Figure 2(B). In this circuit, the plate is more positive than the greater portion of the filament, so it attracts the electrons which are being emitted from the filament. Also, since like charges repel, no electrons were attracted to the plate when it was returned to the negative end of the filament battery as shown in Figure 2(C), due to the fact that the plate is negative in respect to the greater portion of the filament in this circuit.

With this knowledge of electron emission, it is easy to see why the current flow is always from the filament to the plate, and through the external circuit from the plate, back to the filament, as Edison discovered. It is due to the fact that electrons are emitted, or given off, by the filament and are attracted to the plate due to a positive charge on the plate. Current cannot flow from the plate to the filament inside the tube because the plate does not (under normal conditions) emit electrons, and therefore electrons cannot move (current flow) from the plate to filament.

It should be understood that the heated filament gives off electrons because it is **hot** and not because electricity is passing through it. It could be heated in any manner, but electricity is the most convenient method. Some experimental vacuum tubes have been made, wherein the emitter was heated by a gas flame. The emission of electrons by applying heat to the body is called thermionic **emission** and tubes employing this principle are called **thermionic vacuum tubes.** The body which emits the electrons is generally called the **filament,** or **cathode.** The element which is inserted in the tube in addition to the filament, for the purpose of attracting the emitted electrons, is called the **plate** or **anode.**

In battery-operated vacuum tubes, the electric current used to heat the electron emitter flows through the filament wire which, when heated to a dull red, gives off electrons. In most applications of vacuum tubes when a-c current is used to heat the emitter, it is preferable not to have the heating current flow through the body which emits the electrons. Figure 3 illustrates the construction of the **indirectly heated cathode.** In this case, a separate heating device is placed in mechanical (but not electrical) contact with the electron emitter. The a-c current flows through this resistance wire, called the **heater,** causing it to become hot. Heat from the **heater** is conducted to the cathode, raising its temperature to the point where it emits electrons. The **heater** is used merely to heat up the cathode (electron emitter), and performs **no other function.**

Space Charge

When the cathode is heated, either directly as in the battery type of tube or indirectly as in the a-c type of tube, electrons break through the surface and shoot into the space surrounding the cathode. Their velocity is soon used up however, and if there is no positively charged plate nearby, they will fall back to the cathode Thus, millions and millions of electrons break through the surface of the emitter into space and then fall back. This is continuously happening if the filament is hot and so a constant cloud of electrons is present around the filament. It is a continuous state of motion; although the total number of electrons will remain about the same for any one temperature. This motion is the motion of millions of electrons rushing from the emitter to this cloud of electrons and millions of electrons falling back to the filament. This cloud of electrons is called the **space charge** and, being made up of electrons, is negative. The space charge thus tends to repel more electrons which are being emitted and a balance is reached at any one filament temperature.

Electron Emission Due to Light

It has been found that a similar electronic emission occurs when light rays of certain frequencies, colors, or wave lengths are made to fall upon certain materials. This is known as the **photo-emissive effect**; the emission of electrons by this method is known as **photo-electric emission.** The photo-electric cell or tube employed in sound motion picture equipment, and in many commercial counting, sorting, and controlling devices, operates on this principle.

There are many materials which exhibit the photo-electric emission property, among these are zinc, sodium, lithium, cesium, rubidium, germanium, silicon, and selenium. Of these, the two most widely used ones in modern photocells are silicon and selenium. In our study of electronics we shall find many instances when photo-electric devices are used.

Electron Emission by Bombardment

Electrons may also be forced out of a body by the impact of other electrons projected against its surface. This action is known as **secondary emission.** At the voltages employed in ordinary vacuum tubes, the electrons moving from the cathode to the plate have sufficient velocity to knock other electrons off the plate. The electrons knocked off the plate are called **secondary electrons.**

When the velocity with which the electrons strike the metal plate increases beyond a certain critical value, one primary electron can knock out more than one secondary electron from the plate. This is the principle upon which the "electron multiplier" used in the television camera tube operates, as we shall learn later.

Emission Due to Electric Field

The basic law of electricity states that unlike charges attract, and it is possible to produce electron emission by utilizing this fact. If two plates are separated in a vacuum, and the potential difference between the two plates is increased, a point will be reached where electrons will be literally "jerked" out of the negative plate by the attraction of the positive plate. These electrons then travel through the vacuum to the positive plate. These electrons are said to have been "emitted" by the negative plate, although we see that they were not "given off" (this is what emit means), but were "taken away" from the negative plate by the positive plate. This principle has been employed in certain types of rectifier tubes where it is desirable to operate the tube with the cathode un-heated.

Let us summarize the emission of electrons.

There are four principle means of producing electron emission. These are:

1. Thermionic emission.
2. Photo-electric emission.
3. Emission by bombardment.
4. Emission due to the electric field.

The greater majority of vacuum tubes employ the principle of thermionic emission. The other methods of emission are used in certain specific applications.

The Reason for the Vacuum

Perhaps you have wondered why electron tubes have a vacuum in them. A vacuum, of course, is merely a space in which all air is removed. The primary reason for the removal of air from a tube is so that the filament or cathode will not "burn out". If an electric light bulb is turned on, and a small hole is drilled in the glass bulb, the filament will burn out in a fraction of a second. This is due to the chemical combination of the oxygen in the air and the hot metal of the filament. To prevent this chemical combination from occurring, the air is pumped out of a light bulb. Under these conditions, the filament will operate for many months. The same principle applies to the vacuum tube. As much of the air is removed as is possible, so that the filament will not burn out. Another reason for removing the air is, that if there are a great number of air molecules present in the space between the cathode and the plate, they will be struck by the emitted electrons as they move through this area and this will interfere with the normal operation of the tube. In most receiving tubes, after all the air that can be removed cheaply by pumping has been eliminated, a chemical compound is ignited inside the tube. This chemical compound, called a **getter**, removes the remaining traces of air.

In some special applications, certain inert gasses, such as mercury vapor, argon, etc., are placed in the tube after the air has been removed. These gasses do not combine chemically with the filament as oxygen does, and therefore do not cause the filament to burn out. These tubes are used chiefly for rectification and will be discussed later.

The Fleming Valve

In 1896, Dr. J. A. Fleming investigated the "Edison Effect", and his work led to a useful application of the two-electrode vacuum tube. (Electrode is the name given each separate electrical part in a vacuum tube.) The two-electrode vacuum tube has a filament, or cathode, and a plate. The schematic symbol for a two-element vacuum tube is shown in Figure

4(A). The two-element tube developed by Fleming was referred to as the "Fleming Valve", and the term valve is still used in Europe to designate what we here in America refer to as a vacuum tube or electronic tube. The term valve is roughly descriptive of the real operation of the tube.

In his experiment, Fleming connected the two-electrode tube in a circuit as shown in Figure 4(B).

We see that this circuit is very similar to Edison's circuit, except another battery has been added. Also a variable resistor R, has been added. The purpose of the resistor R is to control the current flowing through the filament, and thereby control the filament temperature. The battery used to supply the filament current is called the "A" battery and the battery in the plate circuit is called the "B" battery. When the "B" battery was connected as shown in Figure 4(B), it was found that the current flowing from the plate, through the meter and battery, and back to the filament was much greater than that experienced in the "Edison Effect" when no "B" battery was used. Also, no current flowed in this external circuit when the polarity of the "B" battery was reversed so that the plate was connected to the negative end. In all modern vacuum tube circuits, the B+ is connected to the plate. So that there will be a complete path for current to flow from the plate back to the filament, the negative end of the "B" battery may be connected either to the negative end of the "A" battery or to the positive end of the "A" battery. Very little difference results from either connection. In some battery operated receivers, the A+ and B— terminals are connected together; in others the A— and B— go together.

When the plate has a positive potential, a steady stream of electrons will be attracted from the heated filament to the plate and will then continue their journey around the circuit from the plate to the "B" battery, through the "B" battery from the + to the — terminal, up through the filament leg, and back to the filament. We thus have a circulation of electrons from filament to plate and back through the "B" battery to the filament again; just as many returning every second as there are being emitted every second, and no electrons are lost or gained. Notice that this path for electron flow is independent of the path of the current used to heat the filament, and that the only function of the "A" battery is to heat the emitter sufficiently to cause it to give off electrons. It is evident that the mystery in the effect which Edison noticed in his lamp was really due to the fact that while it was then supposed that the space between the filament and the plate was absolutely empty, actually it was filled with moving electrons emitted by the hot filament, and constituting the flow of electric current which was indicated on his meter.

The two-element tube, or **diode** as it is generally called, which we have been describing can be used to regulate the flow of current, but can not be used to amplify or "build-up" a voltage to a large value. The diode can be used to regulate the flow of current, since it allows current to flow in one direction only. It has been emphasized several times that this flow of current from the heated filament to the plate, from the plate through the external circuit, to the filament, occurs only when the plate is made more positive than the filament. For this reason, the diode may be used to convert an alternating current into a pulsating direct current. If a-c is applied to such a tube, the tube will allow current to flow in only one direction, and therefore the current will no longer be an alternating current but will be a pulsating direct current. This process is called **rectification**, and will be discussed in detail later. The diode tube is used in many radio receivers as the **detector** and in many receivers (except battery sets), as the rectifier tube to change the a-c from the power line to d-c.

We have by no means completed our study of the diode tube, but let us leave it at this point and find how a vacuum tube may be made to amplify or "build-up" an a-c voltage.

The Triode Vacuum Tube

The development of the diode vacuum tube by Dr. Fleming was the forerunner of the **triode** or three-electrode vacuum tube which was invented by Dr. Lee DeForest in 1906. He called it the "audion", because he found that when he used his newly invented tube, he could hear the signal in his headphones much louder.

The introduction of this third element made possible audio frequency amplification, radio frequency amplification, and the generation and modulation of high frequency currents. There is no doubt that without the invention of the triode, radio, television, and electronics could never have even approached the state of perfection they enjoy today.

Basically, the triode is the same as the diode; but has in addition a third electrode or "grid" in the form of a metallic mesh (or usually a coil of very fine wire with widely spaced turns) placed between the filament and the plate. A side view of the elements in a triode is shown in Figure 5. Figure 5(A) shows the filament, 5(B) shows the grid, and 5(C) shows the plate. These elements are arranged as shown in Figure 5(D) which shows what would be seen if you were looking down on the top of the tube. The filament is surrounded by the grid, and the grid is surrounded by the thin metal plate. In this way, the electrons emitted from all sides of the filament wire are attracted by the plate and must pass through the open spaces in the grid wire. The schematic symbol for the triode is shown in Figure 5(E).

Now let us see how the grid is going to affect the electron flow between the filament and the plate. This is illustrated in Figure 6. In Figure 6(A), we see a triode tube with the filament, or "A", battery connected in the normal fashion, and with a "B" battery connected so as to make the plate positive in respect to the filament. The grid is not connected to anything. In this case, there will be a certain amount of current flowing inside the tube from the filament to the plate, through the external circuit from the plate back to the filament, just as we had in a diode when the plate was positive. This current is commonly called the **plate** current. The amount of plate current flowing is indicated by the meter in the plate circuit. The position of the arrow in the meter symbol will be used to indicate the amount of plate current. In this case, the meter indicates about ½ scale current. Notice that in Figure 6(A), there are still quite a few electrons left surrounding the filament, forming what we have called the **space** charge.

Figure 6(B) shows what happens when a battery is connected between the grid and the filament, so that the grid is made more positive than the filament. In this case the plate current meter is indicating a full scale reading which illustrates that the plate current has increased. This is true because the positive potential on the grid has caused electrons to flow from the filament to the plate in much greater numbers than in Figure 6(A). What happens is, that when the grid is made positive, the electrons from the filament rush toward it (it is much closer to the filament than the plate is). Since the grid is made of a mesh of very fine wires, most of the electrons miss the grid wires and travel right on through the grid to the plate (actually, a **few** electrons will strike the grid, and cause the grid to become hot. We shall see how this is overcome shortly). The important thing to notice in Figure 6(B) is **that when the grid is made positive, the plate current increases.**

Figure 6(C) shows what happens when the grid is made negative in respect to the filament. The battery which is connected between the grid and the filament, making the grid negative, is called the "C" battery by electronics men. When the grid is so connected, it **repels** the electrons and allows only a very few of the electrons from the filament to reach the plate. If the negative potential of the grid is of a high enough value, no electrons will be allowed to pass through and go to the plate.

Notice that when the **grid is made negative the plate current decreases,** as shown by the plate current meter.

These figures clearly illustrate the fact that in a triode tube, the **grid voltage controls the plate current.** For this reason, this grid is usually called the **control grid.** It was for this purpose (that of controlling plate current) that the grid was added to the tube by Dr. De Forest.

In Figure 7(A), we have the circuit of a triode vacuum tube with the grid connected to a 5 volt battery, making the grid 5 volts negative in respect to the filament. The plate meter indicates that there is a certain amount of plate current flowing. In Figure 7(B), the 5 volt "C" battery has been replaced with a 3 volt "C" battery. The plate current meter indicates that there is an increase in the amount of plate current flowing. Notice that the plate current **increases** when the grid is made **less negative.** The grid is still negative, but the potential is not as great as in Figure 7(A). In ordinary vacuum tube circuits, the grid is operated at a small negative voltage of about —3 volts or —5 volts. Then the grid voltage is varied, more negatively, and less negatively, about this negative voltage point. The negative voltage applied to the grid of a tube is called the **bias** voltage, and often referred to as the **grid bias** or **grid bias voltage.** The grid is operated at this small negative potential, so that none of the electrons from the filament will flow to the grid, but will continue on to the plate. Notice that the plate current increases when the grid is made less negative (more positive). The grid did not have to be made positive to increase the plate current. All that is necessary is to change the grid voltage in a positive direction (—5 to —3).

How a Triode Amplifies

Up to this point, we have seen how the grid voltage controlled the plate current, but let us now see how the grid enables a tube to amplify, or produce a larger signal. Before delving into this subject, let us consider the circuit shown in Figure 8(A). This circuit consists of a source of emf, a milliammeter, and a load resistor of 10,000 ohms. Let us suppose that the current delivered to this load resistor is pulsating direct current. For example, it flows in one direction only, as shown in the figure, but varies in magnitude from time to time. Let us further assume that the variations in the amount of current are as shown in the graph of Figure 8(B). At an instant of time, which we shall call T_1, the current delivered to the load resistor is 2 mA; at an instant of time later, which we call T_2, the current is 1 mA. At T_3, the current is again 2 mA, at T_4, it is 3 mA, and at T_5, it is 2 mA again.

Since this current is flowing through a resistor of known value, we can apply Ohm's Law and determine the voltage across the load resistor at any instant. For example, at time T_1, the current through the 10,000 ohm resistor is 2 mA. Applying Ohm's Law:

$$E = IR$$
$$= .002 \times 10{,}000$$
$$E = 20 \text{ volts.}$$

At time T_2, the voltage is:

$$E = IR$$
$$= .001 \times 10{,}000$$
$$E = 10 \text{ volts.}$$

Likewise, the voltage at T_3 can be found to be 20 volts, at T_4 to be 30 volts, and at T_5 to be 20 volts.

Figure 8(C) is a graph of the voltage across the load resistor. The vertical axis is marked off in volts, and the horizontal axis in time as in Figure 8(B).

These figures illustrate one important point. This is, **that when a pulsa-**

ting direct current flows through a fixed resistor, there will be a pulsating voltage across this resistor.

Figure 9 shows a vacuum tube circuit which is very similar to the circuit shown in Figure 8(A). The source has been replaced with a vacuum tube and its associated batteries. We have already demonstrated in Figure 6, and in Figure 7, that if we change the potential between the grid and filament of a tube (labeled INPUT in Figure 9), we can cause the plate current to change. This changing (or pulsating) plate current flows in only one direction, from the plate, through the meter, load resistor, and "B" battery to the filament. By varying the grid voltage, the plate current can be varied in magnitude. Thus, we see that the vacuum tube and associated circuit delivers a pulsating direct current just as the source in Figure 8.

In a vacuum tube, only a small change in **grid voltage** is required to produce a large change in **plate current**. In a typical vacuum tube, one-tenth volt change in grid voltage can cause a one milliampere change in plate current. For sake of clarification, let us assume that the plate current of the tube in Figure 9 is 2 mA when no voltage is applied between the grid and filament, and that when a voltage of .1 volt is connected to the grid in such a way as to make the grid negative, the plate current decreases to 1 mA. When .1 volt positive is applied to the grid, the plate current increases to 3 mA.By connecting the grid voltage in the proper polarity at the proper instant, we could cause the **plate current** to vary just as the pulsating current shown in Figure 8(B). In flowing through the 10,000 ohms load resistor, this would cause a pulsating voltage as shown in Figure 8(C) to be developed across the load resistor. Notice this point; the grid voltage was changed only from **0 to .1 volt negative, then to .1 volt positive,** but the voltage developed across the load resistor changed **10 volts negative** and then **10 volts positive.** This voltage change across the load resistor is 100 times as great as the voltage change in the grid circuit. The tube has **amplified** the changing signal applied to its grid. It has made it larger; in fact in this case, 100 times larger.

Figure 10 shows a complete circuit for an amplifier using a triode tube. The "C" battery supplies a steady d-c voltage to the grid of the tube and is so connected that the grid of the tube is negative. The input signal, to be amplified, is applied between the two terminals labeled **Input.** The input signal normally has a wave shape similar to the sine wave shown at the figure. The input signal adds to, and subtracts from, the d-c voltage applied to the grid of the tube. When the a-c signal is in its negative alternation, it adds to the d-c voltage applied to the grid, making it more negative. When the a-c signal is in its positive alternation, it subtracts from the negative voltage on the grid making it less negative. This causes the plate current to change or pulsate. The output signal which is **developed across the load resistor** is also shown in the figure. This output signal is an enlarged copy of the input signal. It has the same frequency; that is, it occurs in the same period of time, but its amplitude (or height) is much greater.

This type of circuit is called an amplifier circuit because the output signal is much stronger, or greater in magnitude, than the input signal. If the input signal in this case were the weak audio frequency signal from a microphone, the output signal would be a magnified reproduction of this. In a great number of cases, the amount of amplification obtained in a vacuum tube circuit, such as the one shown in Figure 10, is not great enough to build the weak input signal up to the desired strength. For this reason, several amplifiers will be operated in series, or **cascade.** In this type of operation, the output from one amplifier is fed to the input of the next. In the audio frequency section of a broadcast transmitter, there may be as many as 6 or 8 audio amplifiers operated in cascade to build up the weak signal from the microphone to the desired strength for the modulator stage.

There is one point in this amplifying process which may cause you some concern. This is the fact that there is more energy available in the plate circuit than in the grid circuit. It will be recalled that the fundamental law of matter is that **energy can be neither created nor destroyed.** It appears that the vacuum tube has created energy, since more is present in its plate circuit than in its grid circuit, but such is not the case. The energy is supplied by the "B" battery; the tube is merely serving to regulate this energy. This is easy to visualize, since the energy drained from the "B" battery will soon cause the battery to go dead, or become useless. The signal which is applied to the grid circuit of a tube never reaches the plate circuit. It merely controls the plate current, which produces the amplified signal across the load resistor. For a number of years triode tubes were used exclusively for amplification, and are still used for many applications. However, other types of tubes have been developed, which are superior to triodes for some uses.

Multi-Grid Tubes

The type of tube developed after the triode was the **tetrode**. This tube contains one more grid than the triode. This grid is called the screen grid, and is located between the control grid and the plate as shown in Figure 11(A). The schematic symbol for a tetrode is shown in Figure 11(B). This type tube has several advantages over the triode for some uses. Normally, the amount of amplification which may be obtained from this type tube is greater than from a triode.

A type of tube which was developed after the tetrode is the **pentode.** This tube has still another grid called the **suppressor grid**, which is located between the screen grid and the plate. Figure 12(A) shows the construction of the tube, and Figure 12(B) shows the schematic symbol for a pentode. Pentodes have been used very widely in all types of electronics equipment. We shall study why each of these tube types was developed after we have studied other circuit properties, such as capacitance and inductance, which enter into the reason for their development.

There are quite a few other types of tubes on the market. These are tubes with four grids, five grids, and even some with six grids. Sometimes, two, three, or even four of these "tubes" are made in one glass envelope, to save space and improve circuit efficiency.

The Constructional Features of Vacuum Tubes

Vacuum tubes are made in many forms with electrodes of various sizes, shapes and arrangements, each designed to give the tube certain special desired characteristics.

Vacuum tubes vary in filament rating, electron emitting characteristics, and the amount of amplification they are capable of producing. Their filaments may be designed to be operated from dry cells, storage batteries or alternating current, and the tubes can be constructed to handle from one or two milliwatts to several thousand watts of power. The filaments may be made from pure tungsten, thoriated tungsten, or a wire coated with the oxides of barium or calcium to increase the electron emission for a given temperature. Filaments may be made in the form of wires, or flat ribbons, and arranged in the form of a straight wire, an inverted V, a double V, etc. Or, as has been mentioned, in many tubes, the filament does not emit electrons at all, the electron emission being obtained from a separate cathode which is heated by the filament or heater.

All types of vacuum tubes (diodes, triodes, tetrodes, pentodes, etc.) are made with indirectly-heated cathodes. Figure 13 shows the schematic symbols used for these tubes.

The plates are usually plain, box shaped, or nearly cylindrical, with the grids corresponding. The relative spacing of grid, filament, and plate, as well as the fineness of the mesh in the grid, also depends on the tube type. While a very large number of types of tubes are manufactured, we will see that they all possess similar construction features.

Vacuum Tube Construction

In the manufacture of vacuum tubes, the metal parts are first assembled on the metal supports and spot-welded into place. In some tubes, additional bracing to prevent mechanical vibration of the elements is secured by a piece of mica holding the heater, grid and plate supports rigidly at the top. This reduces "microphonic" noises caused by variations of the distances between these elements by mechanical vibrations. The entire assembly is mounted on a glass stem through which the connecting wires are sealed, and from which a hollow tube extends at the bottom. This flare is then sealed to the outer glass or metal envelope, while the long glass tube is attached to the high-vacuum pumps which remove the air. While the exhaust pump is in operation, the tube is heated with gas flames, since this tends to drive out all the air and gas bubbles which may be entrapped in the pores of the glass wall and the metal parts. For the same reason, the filament is usually heated by an electric current at the same time. After the tube has been evacuated as much as possible by these methods, it is sealed off. The elements are then heated to a red heat to drive out any remaining gas by an external radio-frequency induction coil which drops over the envelope. The rapidly alternating powerful magnetic field of the coil induces powerful currents in the metal elements and their supports, which heats them to a red heat and thereby helps to remove the entrapped gases. This forces out the remaining gas molecules since they expand due to the heat, and at the same time, the "getter" material vaporizes and enters into chemical combination with these gases. Upon removal of the high frequency coil, the vaporized "getter" condenses on the comparatively cool glass walls where it forms the familiar silver film so noticeable in vacuum tubes.

Several materials are suitable for use as getters. Among the more common are: Aluminum, barium, magnesium, calcium, and cerium. Magnesium and barium are perhaps the two most widely used. A tiny metal cup containing the getter is mounted in an inverted position, usually below and to the side of the plate so that the getter will not be thrown against the metal elements in the tube when it is vaporized.

After the tube has been sealed off, it is cemented to the bakelite base (if one is used) and the lead-in wires are soldered to the tube prongs. These are made of hollow brass tubing, plated to prevent corrosion. The tube is then tested and aged by operating it at its heater voltage until the cathode emission becomes stable and constant.

Every possible effort is made to not only produce as perfect a vacuum as possible in modern vacuum tubes, but by means of the heating of the metal parts and the flashing of the getter, to eliminate even the small bubbles of gas and water vapor absorbed in the pores of the metal and glass parts. The life of a tube is largely dependent upon the degree of vacuum existing in it, varying from 100 hours for a poor vacuum to many thousand hours for a good vacuum.

The section concerning the construction of vacuum tubes has been included in this assignment, so that you will have a mental picture of just what is inside the glass or metal envelope of a vacuum tube. Quite possibly, an electronics technician may never be called upon to explain the internal construction of a vacuum tube, but it is believed that a better understanding of the operation of tubes in electronics equipment can be obtained if the way a vacuum tube is made is understood.

An Interesting Project

If possible, obtain a few "burned-out" tubes and study their mechanical construction. If you have no "burned-out" tubes, any local TV repair shop will be glad to give you a few. Remove the glass envelope carefully and examine the tube structure closely. Notice particularly the arrangement of the filament or cathode, the spacing between the grids, plates, etc. See if you can find the small cup which held the "getter". In some tubes, it is just a short length of wire. Notice also the manner in which the electrodes are held rigidly.

Disadvantages of Vacuum Tubes

Vacuum tubes have performed a wonderful job over the years enabling electronic engineers to develop circuits and equipment so that the electronics field has grown from the crude spark-gap transmitter era of World War I to the sophisticated radar era of World War II. In spite of the outstanding job performed by vacuum tubes, however, there are certain disadvantages associated with all vacuum tubes. Among these are: (1) relatively short operating lifetime (2,000 to 10,000 hours), (2) heating (cathode) power required, (3) relatively large physical size, (4) relatively fragile construction.

In view of the disadvantages associated with vacuum tubes, it was only natural that engineers and scientists doing basic research would be on the constant lookout for any phenomenon which might indicate the possibility of an "amplifying device" which would perform the same task as a vacuum tube, but which would eliminate many of the undesirable factors associated with the vacuum tube. In 1948, W. H. Brattain and J. Barden were doing research work in the Bell Telephone Laboratories. These two scientists, deeply engrossed in their studies of the surface properties of germanium, which they were using for some experimental rectifiers, noted that the conduction property of the rectifier could be controlled by an additional electrode attached to the surface of the unit (a phenomenon parallel to that observed by Dr. DeForest about 60 years ago when he added the grid to the then existing diode vacuum tube to form the triode). This discovery led to the development of the efficient transistors which are used very widely in many, many types of modern electronics equipment. Transistors are manufactured in many sizes, shapes, and ratings. Figure 14 illustrates a variety of transistors. The vacuum tube is included in the photograph to provide a size comparison.

Transistors operate on entirely different principles than vacuum tubes. Transistors are made of **solid material**—they contain no vacuum. For this reason,transistors and similar devices are often referred to as **solid-state devices.** All of these solid-state devices use semiconductor material; consequently, these devices are also often referred to as **semiconductor devices.**

Semiconductors

Earlier in the training program, it was pointed out that there are two large classifications of material—as far as electrical conductivity is concerned. These are conductors which pass current readily and insulators which offer an extremely high opposition to the flow of electric current. In fact, insulators offer such high resistance to the flow of a current that for all practical purposes it can be stated that they do not permit any current flow. In between these two—between the insulators and the conductors—lies a group of materials (mostly metals) which are not good insulators nor are they good conductors. These are the **semiconductors.** There are quite a few of these semiconductors but the two most important, as far as transistor work is concerned, are **germanium** and **silicon.** Practically all commercial transistors are manufactured using one or the other of these two semiconductor materials.

There are other ways in which semiconductors are different than conductors, one of which is that the resistivity of a semiconductor decreases with increasing temperature rather than increasing as is common with most metallic conductors. Another factor—and one which plays a very important part in the operation of transistors—is the fact that the electrical properties of the semiconductors depend to a very great extent upon the **amount of impurities** present in the semiconductor material. As a matter of fact, when one type of impurity is added to a semiconductor material, the material will exhibit one type of electrical property and if a different type of impurity is added, it can be made to exhibit the exact opposite type of electrical property. The two types of material which are produced are referred to as **N-type material** and **P-type material.** N-type material has an excess of free electrons compared to a crystal of the pure element (germanium or silicon) and P-type material has a deficiency of electrons in its crystalline structure compared to a crystal of the pure element. The deficiency of electrons in the crystalline construction of the atoms of P-type material produces an effect in the material just as though the material **actually had an excess of positive charges within it.** In transistor work, these mobile positive charges are referred to as **holes.**

Basic Transistor Construction

The P and N material can be sandwiched together in two ways to form two basic types of transistors. These two arrangements are illustrated in Figure 15. The P-N-P transistor is formed by sandwiching a thin layer of N-type material between two layers of P-type material as illustrated in Figure 15(A). The N-P-N transistor, illustrated in Figure 15(B), is formed by sandwiching a thin layer of P-material between two layers of N-material.

The basic transistor is a three-terminal device and is often referred to as a triode. The three terminals are called the **emitter,** the **base,** and the **collector,** as illustrated in Figure 15.

The schematic symbols for transistors are illustrated in Figure 16 with a symbol for the P-N-P transistor being shown in Figure 16(A) and the symbol for the N-P-N transistor in Figure 16(B). Note that the parts of the symbols for the base and the collector are the same in each of these symbols and the only difference is the direction in which the arrow points on the emitter terminal portion of the symbols. It is easy to remember which way the arrow points in these symbols. Just remember that in a P-N-P transistor, the arrow POINTS toward the base.

How a Transistor Amplifies

As we analyzed the manner in which a vacuum tube amplifies, we saw that such an arrangement was possible because a change in one circuit, the grid circuit, was able to produce a larger change in another circuit, the cathode-plate circuit. Similarly, a transistor is capable of amplification because a change in its input circuit, the base-emitter circuit, is capable of producing a larger change in its output circuit, the emitter-collector circuit. This is illustrated in

Figure 17. For simplicity, we will choose an N-P-N transistor and discuss at this time how amplification is obtained from that particular type of transistor.

In Figure 17(A) we see an N-P-N transistor with the base connected directly to the emitter so that there is zero voltage in this circuit. The battery connected in series with the meter in the collector-emitter circuit would generally have a voltage of 9 or perhaps 12 volts. With the base-emitter circuit at zero voltage, as illustrated in that figure, there is a very low value of current which flows from the emitter to the collector and through the meter to the battery. This current is so low that for all practical purposes, in this discussion, we can consider it to be zero.

Now, let us examine the circuit of Figure 17(B). Here a battery is connected between the base and the emitter so that the base is positive and the emitter is negative. The voltage chosen for this example is .2 volt. Under these conditions, it will be noted, as indicated by the arrow in the meter, that the emitter-collector current has increased, thus it can be seen that the base-emitter voltage affects the emitter-collector current. To see what occurs when this voltage is changed, analyze Figure 17(C). This figure is identical to Figure 17(B) except the bias voltage (voltage connected between base and emitter) has been reduced from .2 to .1 volt. Under these conditions, it can be seen that the emitter-collector current decreases as indicated by the meter pointer. Similarly, in Figure 17(D) we have increased the bias voltage to .3 volts and the meter pointer indicates that the emitter-collector current has increased to a value greater than it was in Figure 17(B) when we had .2 volt bias.

Figure 17, therefore, illustrates that changing the base-emitter voltage will cause a change in emitter-collector current. Now, compare the similarity of this action with that of a vacuum tube illustrated in Figures 6 and 7. It should be apparent that a close parallel exists. In the vacuum tube the grid-filament voltage controls the filament-plate current and in a transistor, the base-emitter voltage controls the emitter-collector current.

Some of the advantages of the transistor should also be apparent from comparing Figure 17 with Figure 7. Figure 7 shows that the filament or cathode of a tube requires heating power; whereas, Figure 17 illustrates that this is not true in the case of a transistor. Another fact which these two figures reveal is that lower voltages are usually employed in connection with transistors than vacuum tubes. Notice the difference in the value of bias voltages used in the circuits. Similarly, the plate voltage in the vacuum tube circuit would generally range from 90 volts to perhaps 300 volts in normal installation; whereas, as mentioned, the collector battery voltage in Figure 17 would generally be found in a range from 9 to 12 volts.

Now look at Figure 18. This is the circuit for a complete transistor amplifier using an N-P-N transistor. The input signal, to be amplified, is applied between the two terminals labeled **input**. The .2 volt battery shown supplies the steady d-c voltage for the base-emitter circuit and is connected so that the base is positive with respect to the emitter. A typical input signal

—a sine wave—is shown at Figure 18(A) and this input signal adds to and subtracts from the d-c voltage applied to the base-emitter circuit. When the a-c input signal is in its positive alternation, it adds to the d-c voltage applied to the base making the base more positive with respect to the emitter. This causes an increase in the emitter-collector current which flows through the load resistor R_L. On the negative alternation of the input signal, the applied a-c voltage subtracts from the bias voltage thereby making the base less positive with respect to the emitter, reducing the emitter-collector current. This reduces the voltage drop across the load resistor R_L. As the sine-wave input signal gradually changes so does the output signal across R_L as illustrated in Figure 18(C). Thus the output signal is an enlarged copy of the input signal. It has the same frequency; that is, it occurs in the same period of time; but its amplitude, or height, is much greater. **It has, therefore, been amplified.**

Just as in the case of vacuum-tube amplifiers, it will be found that in many cases one transistor amplifier will not produce enough amplification to build up a weak input signal to the desired strength. Thus, it will often be found that several transistor amplifiers will be operated in series, or cascade, and the output signal from one amplifier is fed to the input of the next.

As Figures 15 and 16 illustrated, there are two fundamental types of transistors which are made by arranging the N and P types of materials in the two different arrangements. We have considered to this point an N-P-N transistor in an amplifying circuit, and Figure 19 illustrates a similar circuit employing a P-N-P transistor. It will be noted that the circuit arrangement is quite similar to that of Figure 18(B) with the exception that the battery polarities are reversed. When one considers the opposite way in which the P and the N materials are arranged in the two basic types of transistors as illustrated in Figure 15, it becomes logical that the battery voltages would be reversed in the case of a P-N-P transistor as compared to that of the N-P-N. This is always the case. The two types of transistors work equally well and many varieties of each type have been manufactured. However, the P-N-P transistors are somewhat easier to manufacture and for this reason more P-N-P transistors will be found than N-P-N.

Summary

One of the fundamental operations in electronics work is amplification. This is the name given the process wherein the output signal is made to be a larger, or increased, version of the input signal. Vacuum tube circuits and transistor circuits are capable of producing amplification.

Transistors have several advantages over vacuum tubes, among which are: (1) Long operating lifetime, (2) small physical size, (3) no heating (cathode) power required, (4) extreme ruggedness, and (5) operation at low voltages. In view of these advantages, transistors are replacing vacuum tubes in a large percentage of the newly designed circuits. In spite of this, however, it appears that it will be many, many years before transistors will have completely replaced vacuum tubes and it is therefore necessary for an electronics

technician to understand, thoroughly, the operation of both vacuum tubes and transistors.

VACUUM TUBES

The filament or cathode emits electrons because it is hot.
The cloud of the electrons, which surrounds the cathode, is called the space charge.
Emitted electrons will go from the filament to the plate if the plate is positive.
Current **cannot** flow in the tube from the plate to the filament.
The control grid controls the amount of plate current which will flow from the filament to the plate.
The negative d-c voltage which is usually applied between the grid and cathode is called the grid bias.
If the grid voltage is made more negative, less plate current flows.
If the grid voltage is made less negative, more plate current flows.
Most tubes operated from a-c use indirectly heated cathodes.

TRANSISTORS

There are two basic types of transistors, P-N-P, and N-P-N.
The three terminals in a transistor are called the emitter, base, and collector.
Transistors operate with lower applied voltages than vacuum tubes.
In the N-P-N transistor, the base is biased positively with respect to the emitter and the collector is also positive with respect to the emitter.
The base-emitter voltage controls the emitter-collector current.
The polarity of the d-c voltages supplied to a P-N-P transistor are opposite to those required by an N-P-N transistor.

General

The information presented in this assignment on vacuum tube amplifiers and transistor amplifiers is for the purpose of giving you a basic understanding of amplification and how it is accomplished through the use of these two circuit components—tubes and transistors. Only the basic principles have been discussed but this should be sufficient at this time to give you a general understanding of the subject. In future assignments, both of these circuit components—transistors and tubes—will be discussed in detail, and amplifiers employing these two circuit components will be analyzed carefully. In other words, this assignment should serve as your first step to a complete understanding of amplification and in the future assignments dealing with these subjects you'll be "marching along" toward your thorough understanding of them, which is essential on the part of an electronics technician.

Test Questions

Use the enclosed answer sheet for your answers to this assignment.

The questions on this test are of the multiple choice type. In each case four answers will be given, one of which is the correct answer, except in cases where two answers will be required, as indicated. To indicate your choice of the correct answer, **mark out** the letter opposite the question number on the answer sheet which corresponds to the correct answer. This is illustrated by the following example:

1. How many grids are there in a diode vacuum tube?

(A) 1	(C) 0
(B) 2	(D) 3

The correct answer is (C) 0. If this were an actual test question on this examination, to indicate that (C) is the correct answer, you would mark out (C) opposite the number 1 on the answer sheet, thus: 1. (A) (B) (~~C~~) (D).

Submit your answers to this assignment immediately after you finish them. This will give you the greatest possible benefit from our personal grading service.

1. The two most important semiconductors, as far as transistors are concerned are:
   (A) Lead and lead oxide.
   (B) Zinc and sodium.
   (C) Germanium and silicon.
   (D) Copper and silver.

2. In the symbol for a PNP transistor (check two answers):
   (A) The arrowhead is on the portion of the symbol representing the collector.
   (B) The arrowhead is on the portion of the symbol representing the emitter.
   (C) The arrow points toward the base.
   (D) The arrow points away from the base.

3. In the vacuum tube the element which emits electrons is called:
   (A) The plate
   (B) The screen grid.
   (C) The cathode or filament.
   (D) The grid.

4. Assume that a triode vacuum tube is operating with —4 volts applied between the grid and the filament, and the plate current is 2 milliamperes.
   If the grid voltage is changed to —5 volts:
   (A) the plate current will become less than 2 mA.
   (B) the plate current will remain unchanged.
   (C) the plate current will become more than 2 mA.
   (D) the plate current will reverse its direction of travel, going from the plate to the cathode.

5. If a sine wave with a maximum value of .2 volts is applied to a transistor amplifier which can amplify 50 times, what will be the maximum value of the output wave?
   (A) 50 volts.
   (B) 100 volts.
   (C) 25 volts.
   (D) 10 volts.

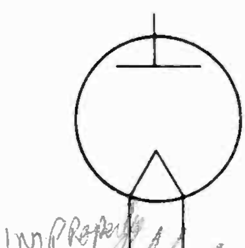
6. The ordinary vacuum tube such as used in the amplifiers of electronics equipment, or in radio or television receivers, operates upon the principle of:
   (A) electron emission due to light.
   (B) electron emission due to bombardment.
   (C) electron emission due to electric field.
   (D) thermionic emission.

7. In an amplifier using an NPN transistor, the battery voltages are arranged so that: (check two)
   (A) the collector is more positive than the emitter.
   (B) the collector is more negative than the emitter.
   (C) the base is more positive than the emitter.
   (D) the base is more negative than the emitter.

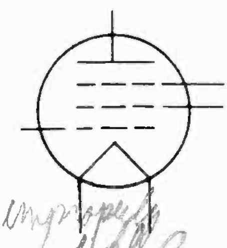
8. In a vacuum tube the element to which the emitted electrons travel is called:
   (A) the grid.
   (B) the cathode or filament.
   (C) the plate.
   (D) the getter.

9. In a vacuum tube amplifier the voltages are arranged so that: (check two)
   (A) the plate is more positive than the cathode.
   (B) the plate is more negative than the cathode.
   (C) the grid is more positive than the cathode.
   (D) the grid is more negative than the cathode.

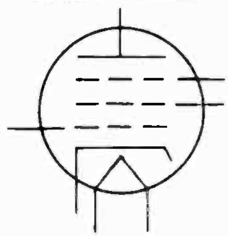
10. Which **two** of the following symbols are <u>improperly</u> labeled?



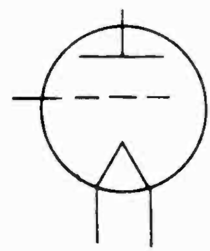
(A) Diode with indirectly heated cathode



(B) Tetrode with filament



(C) Pentode with indirectly heated cathode



(D) Triode with filament

VACUUM TUBES

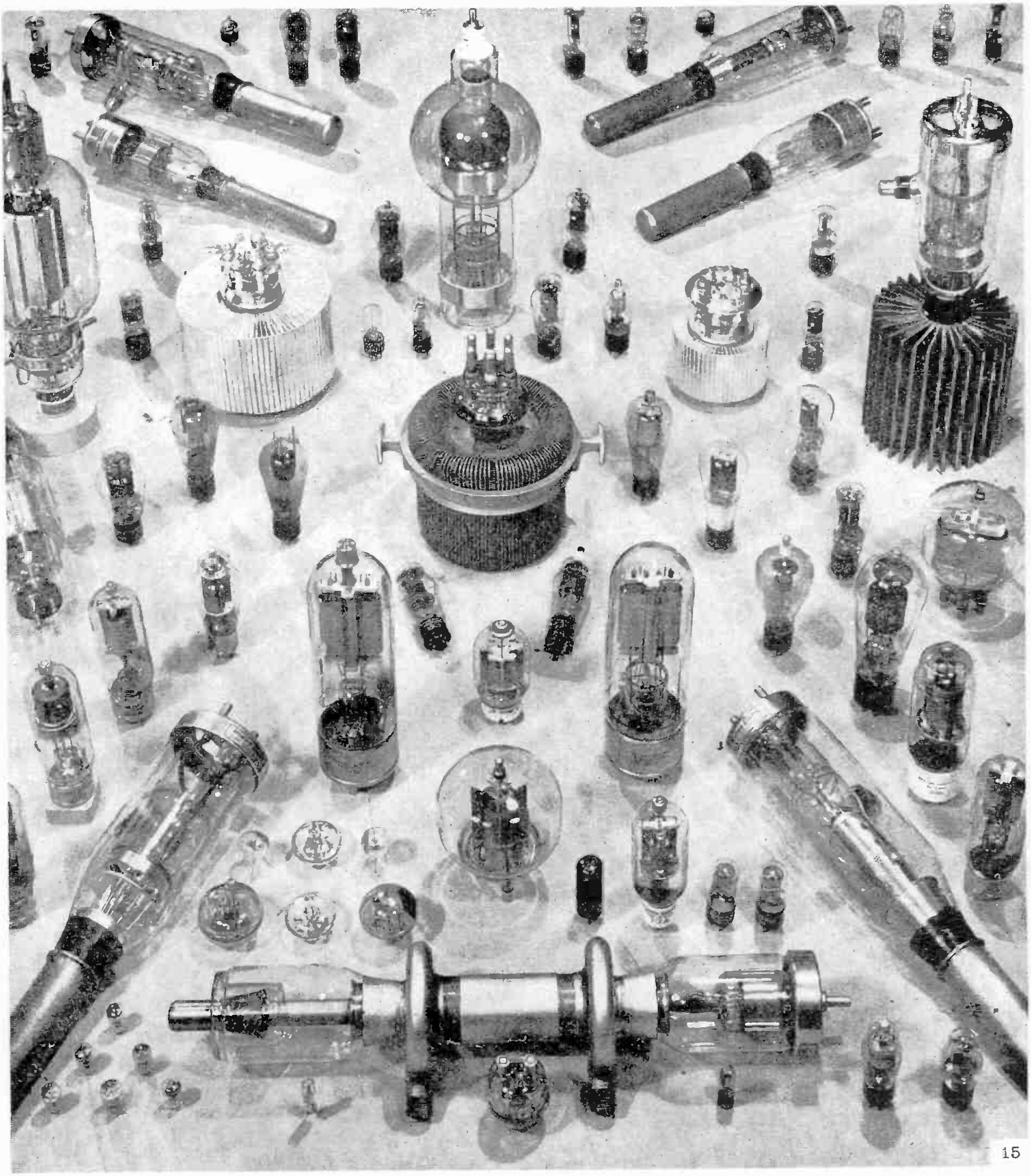


FIGURE I

THE EDISON EFFECT

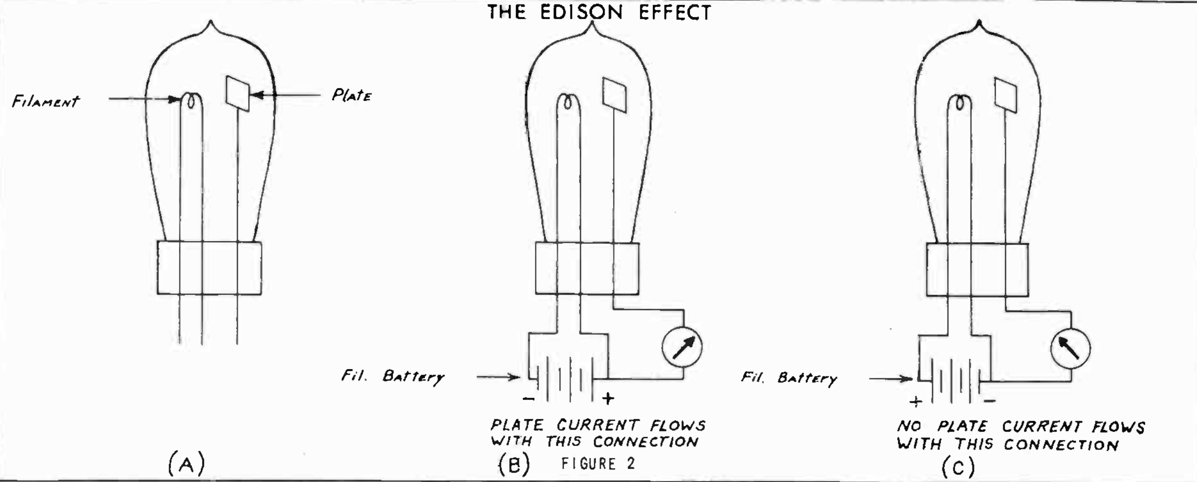


FIGURE 2

CONSTRUCTION OF INDIRECTLY HEATED CATHODE

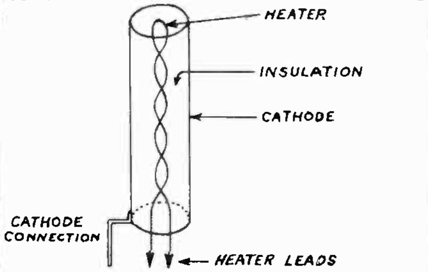


FIGURE 3

THE TWO-ELEMENT VACUUM TUBE

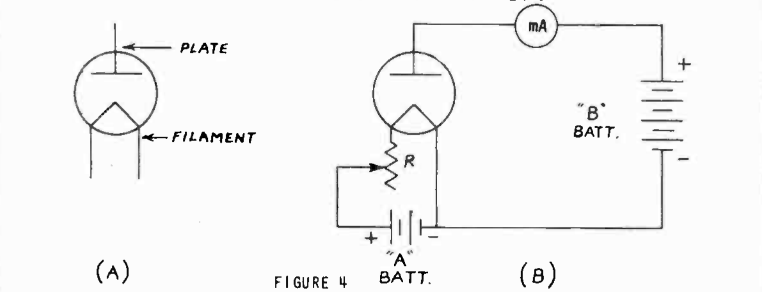


FIGURE 4

THE TRIODE TUBE

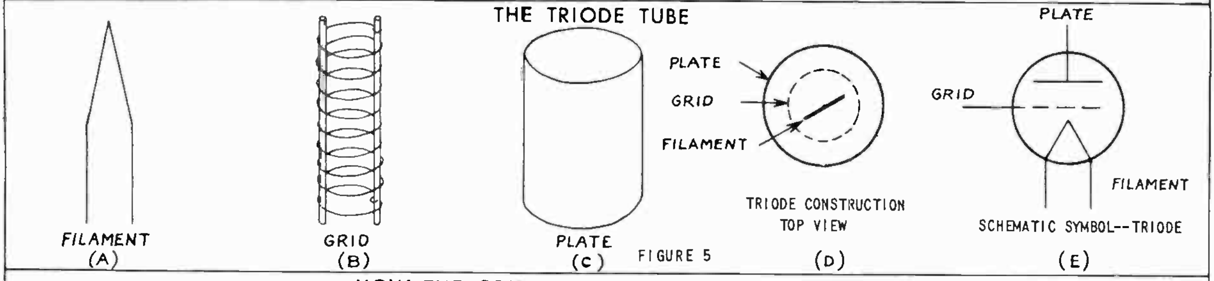


FIGURE 5

HOW THE GRID CONTROLS PLATE CURRENT

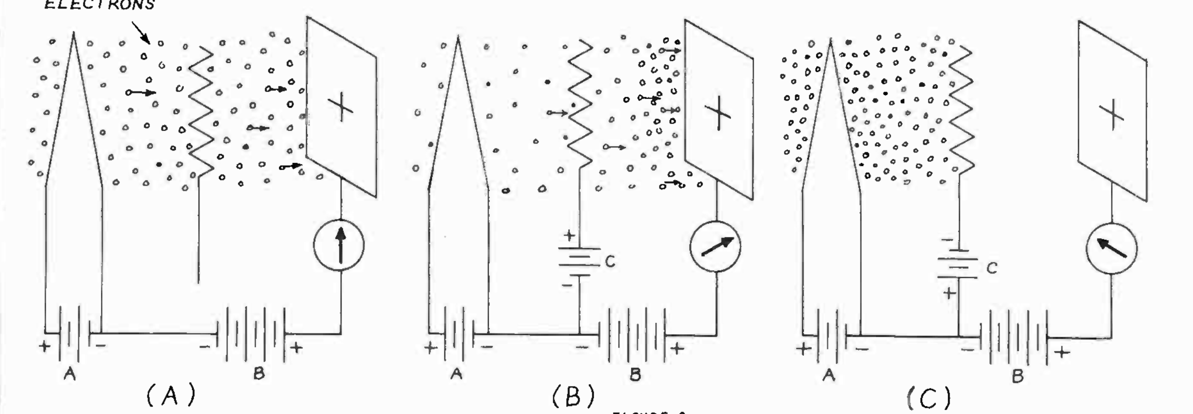


FIGURE 6

CHANGING THE GRID VOLTAGE CHANGES THE PLATE CURRENT

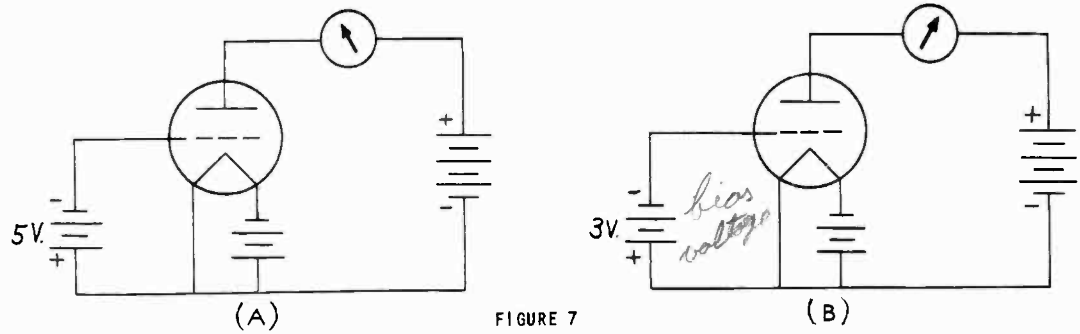


FIGURE 7

AN EXPLANATORY CIRCUIT

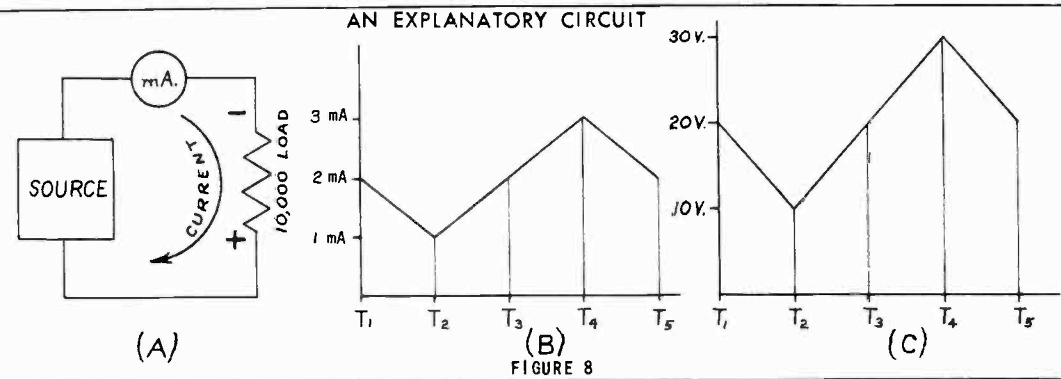


FIGURE 8

A BASIC AMPLIFIER

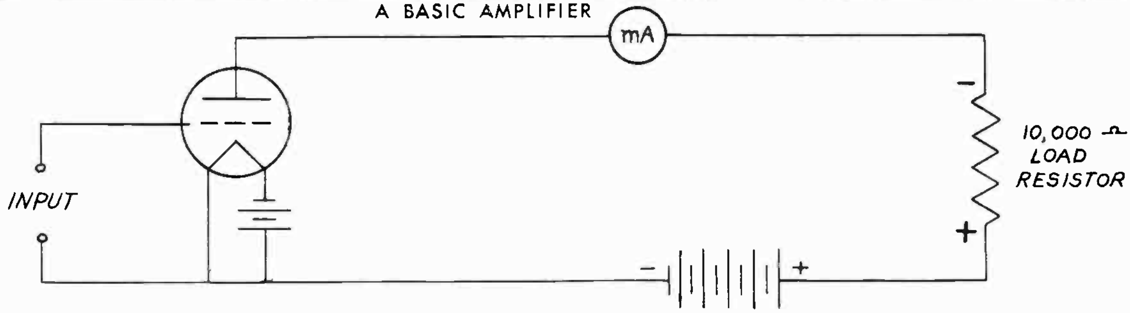


FIGURE 9

A COMPLETE AMPLIFIER CIRCUIT

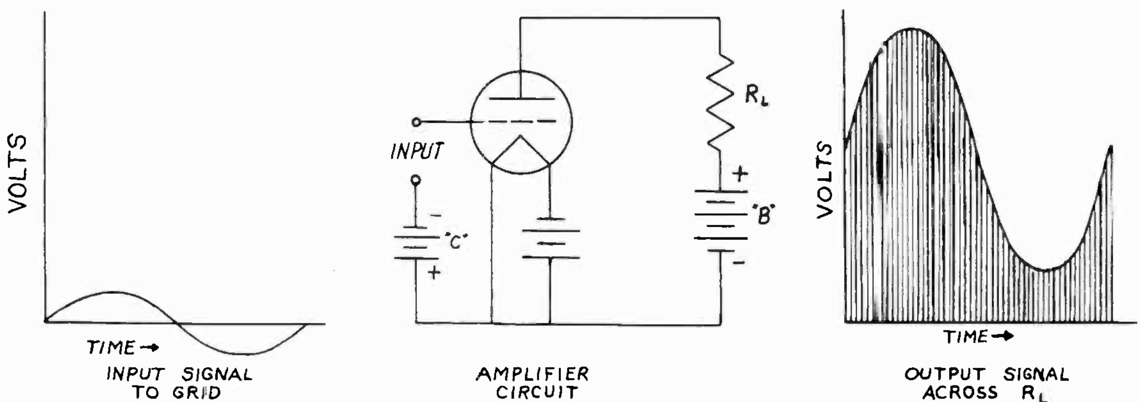
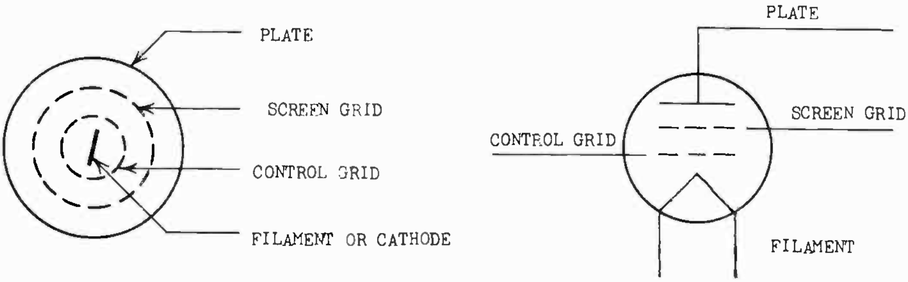


FIGURE 10

THE TETRODE TUBE

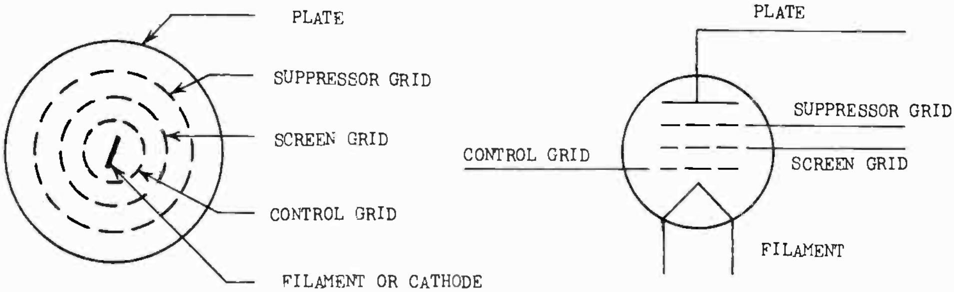


TETRODE CONSTRUCTION
TOP VIEW
(A)

SCHEMATIC SYMBOL
TETRODE
(B)

FIGURE 11

THE PENTODE TUBE



PENTODE CONSTRUCTION
TOP VIEW
(A)

SCHEMATIC SYMBOL
PENTODE
(B)

FIGURE 12

SCHEMATIC SYMBOLS FOR TUBES WITH INDIRECTLY HEATED CATHODES

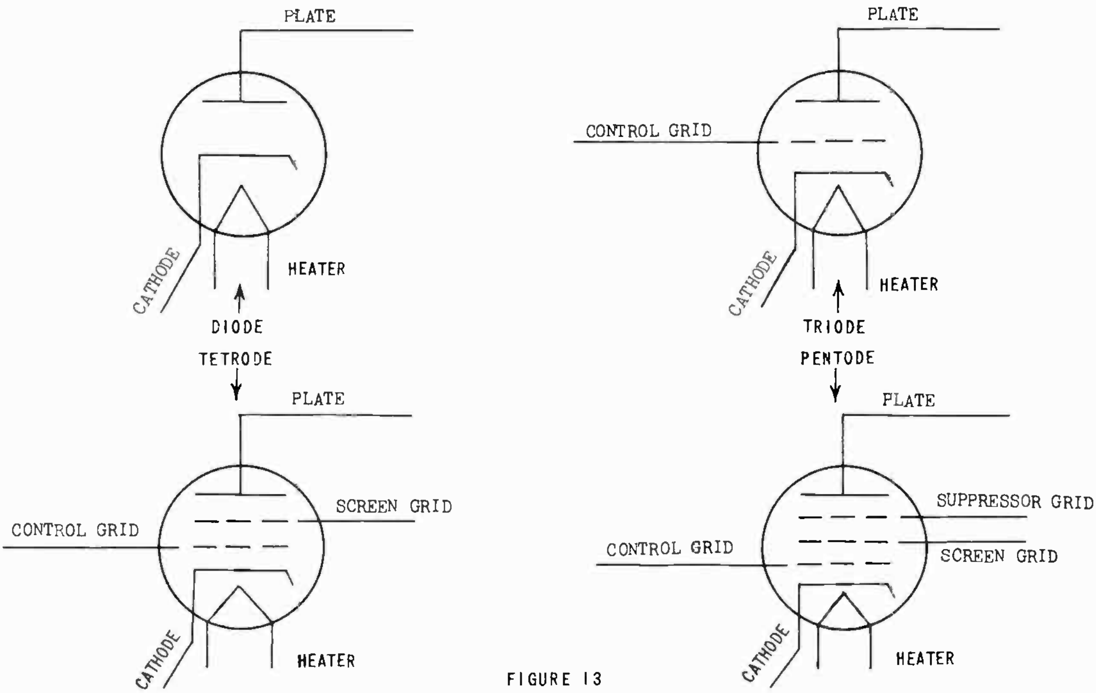


FIGURE 13

TYPICAL TRANSISTORS WITH ONE VACUUM TUBE FOR COMPARISON

FIGURE 14

SYMBOLIC CONSTRUCTION OF TRANSISTORS

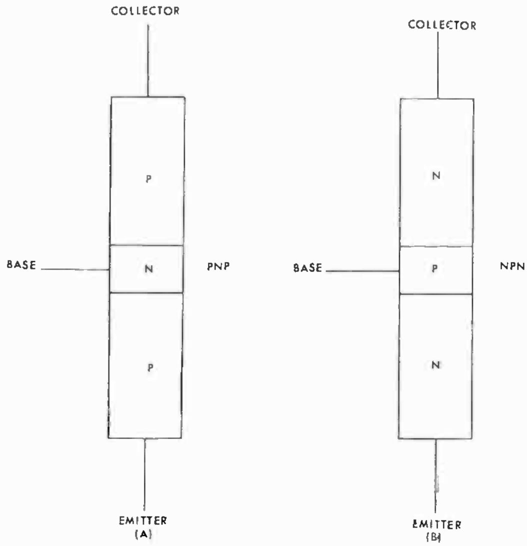


FIGURE 15

SCHEMATIC SYMBOLS FOR TRANSISTORS

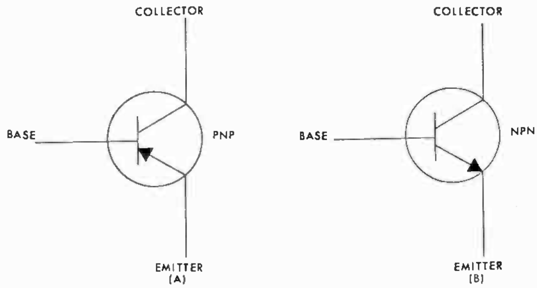


FIGURE I6

HOW THE BASE-EMITTER VOLTAGE CONTROLS THE EMITTER-COLLECTOR CURRENT IN A TRANSISTOR

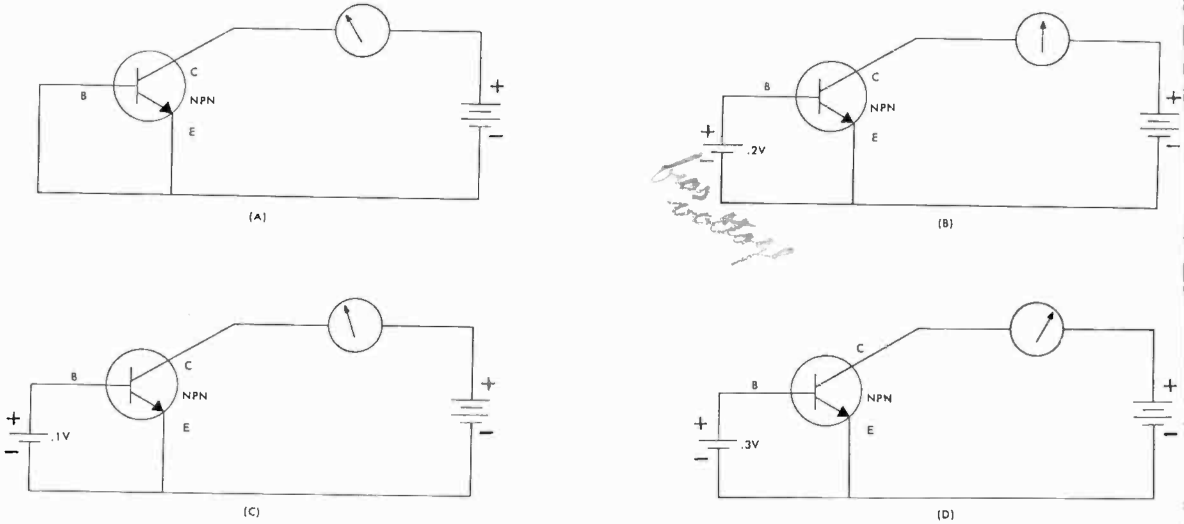


FIGURE I7

A COMPLETE AMPLIFIER CIRCUIT

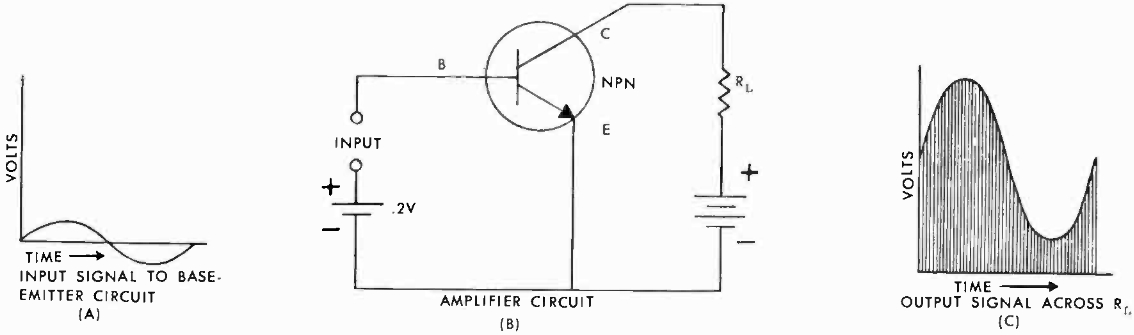


FIGURE 18

A TRANSISTOR AMPLIFIER USING A PNP TRANSISTOR

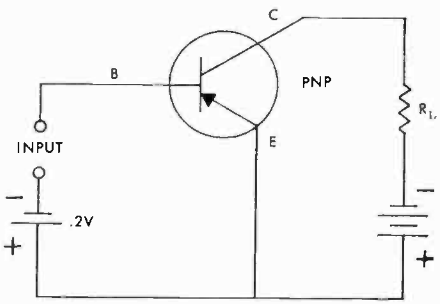


FIGURE 19