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# TRANSISTOR CIRCUITS

by Thomas M. Adams

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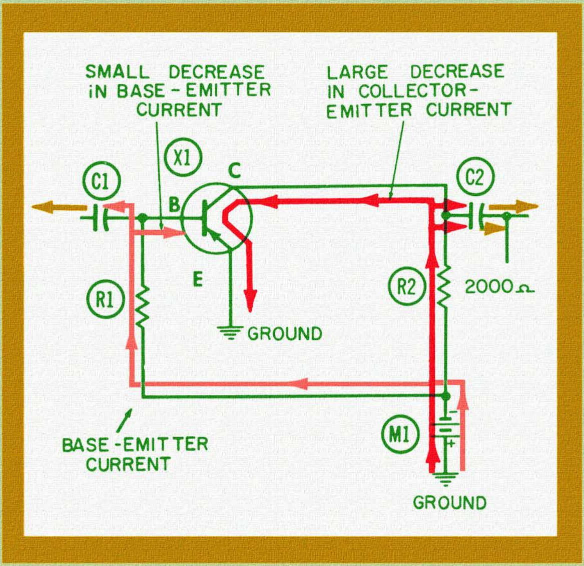

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# Basic Electronics Series
# TRANSISTOR CIRCUITS

**By Thomas M. Adams**
**Captain, United States Navy**

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# PREFACE

Even though the transistor is only slightly more than a decade old—just coming into its teens, so to speak—there is already a wealth of literature available on its circuits and applications. However, most of this literature requires considerable prior knowledge on the part of the technician or student in order to be understood.

The basic concept of this book is that if the reader can visualize the flow of *electron* currents within a transistor circuit, he can comprehend the operation of that circuit. This same technique was used in the three previous volumes of this "Basic Electronics" series devoted to vacuum-tube circuit actions. The diagrams in this book, as in the others, illustrate circuit actions rather than merely circuit connections. The configurations are fairly standard and widely used. Enough of them are presented so that the reader can apply the same analytical techniques to any transistor circuit he may encounter.

The discussions and explanations of what happens inside transistors are oriented almost exclusively around causes and effects of external actions. In other words, in analyzing circuit operation, the emphasis is on *electron* currents rather than on *hole* currents (which move in the opposite direction from electrons).

The concept of hole currents in solid-state physics is valuable to designers and physicists. However, the results of hole current *within* a transistor can be analyzed in terms of *external* electron currents. Therefore, the concept of electron-current flow—which in the past has served admirably in helping readers understand vacuum-tube circuit actions—continues to be the best available tool for analyzing and understanding transistor circuit operation.

This book is devoted almost entirely to helping the reader understand circuit actions. Since an understanding of these actions is essential in the education of both technicians and graduate engineering students, the text is considered neither too advanced for high-school or technical-institute use, nor too elementary for college level.

The author is indebted to the many educators in the Washington area (named in the Preface to *Oscillator Circuits*) for taking the time to review some of the early drawings for this series, and for making many helpful suggestions. Additionally, another debt of gratitude is owed my wife, who has been patience personified during the production of these volumes.

THOMAS M. ADAMS

February, 1962

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# Chapter 1

# TRANSISTOR PHYSICS SIMPLIFIED

Before delving into the action within a semiconductor, and the operation of circuits employing transistors, it will be necessary to review some basic definitions, and the physical principles which support them. The well-known electron-drift process within electrical conductors is a logical starting point.

## THE ELECTRON-DRIFT PROCESS

Fig. 1-1 shows a simplified germanium atom. It consists of a positively charged nucleus and four planetary electrons revolving in orbit around it. Each electron carries a negative charge of electricity, so that they together will just neutralize the positive charge of the nucleus, making the entire atom electrically neutral.

(This atomic picture is simplified, in that the germanium atom has a total of 32 planetary electrons in orbit, and the central nucleus has a resulting positive charge of 32 units. Twenty-eight of these electrons are so tightly bound to the nucleus, however, that they are completely unavailable for purposes of being dislodged to form an electron current. These 28 electrons are not shown in Fig. 1-1.)

The electrons shown in the illustration are in the *valence* band, or ring, of the atom. Germanium is normally a good insulator and a poor conductor. This means that only with great difficulty can one of the planetary electrons be dislodged from its orbit by the normal electron drift process. In a good conductor, on the other hand, electron drift occurs quite easily. When an electric field (electric potential, or a voltage) such as from a battery is applied across the terminals of a good conductor, electrons will be driven through the conductor, from the negative to the positive end. This flow of electron is called electric current, and it consists of a long series of "domino" actions between the free electrons in the material (including planetary electrons which can easily be set free). An individual electron, moving into the conductor very quickly, finds itself approaching a head-on collision with another electron, perhaps one in orbit around

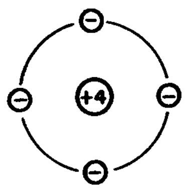



**Fig. 1-1. Simplified drawing of a germanium atom, showing the four orbiting electrons.**

an atomic nucleus. Since electrons carry a negative charge, they mutually repel each other, and no electron collision occurs. Instead, this orbiting electron will be "knocked out" of its orbit, not by collision, but by the electrical repulsion from the approaching electron. Once set free in this manner, the released electron will assume the velocity and direction of the approaching electron. The approaching electron then finds itself slowed down and in the vicinity of a positively charged atomic nucleus; as a result, it "falls into" the recently vacated orbit. Thus, one complete sequence of electron drift action has taken place—an electron has been repelled from its orbit around a nucleus, and replaced by another electron.

## ACCEPTOR ATOMS AND P-TYPE SEMICONDUCTORS

Germanium, the insulator, becomes germanium, the semiconductor, with the addition of selected impurities. Two very common impurities are boron and arsenic. Fig. 1-2 shows the

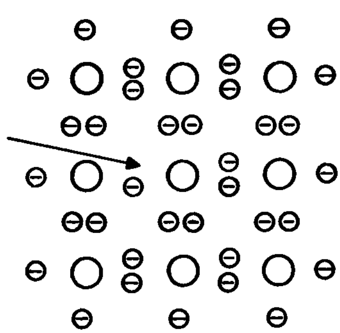


**Fig. 1-2. A boron atom tied to four germanium atoms.**

atomic realignment that occurs when a small portion of boron is added to germanium. An atom of boron has a total of three planetary electrons in its valence band. One atom of boron will "lock" itself very firmly in place with four adjoining germanium atoms. When this happens, the resulting combination needs or wants one additional electron to complete itself, and will take ("accept") it from a nearby germanium atom. This action gives it the title of an acceptor atom. Before it takes this extra electron from its neighbor, the impurity atom is electrically neutral—neither positive nor negative. After it takes this electron, the acceptor becomes permanently negatively charged.

### The Concept of "Positive Holes"

The adjacent germanium atom becomes positively charged after relinquishing one electron. This positively charged atom becomes what is known as a "hole," or the carrier of a positive electrical charge; and the material is called a P-type semiconductor. The hole is indicated by the arrow in Fig. 1-2.

If we consider only this one positive atom and the negatively charged acceptor which "stole" its electron, we might well ask why the stolen electron does not return to its original orbit. How can both positive and negative charges exist side by side without immediately neutralizing themselves? The answer can be found in the physics of atomic structure which is beyond the scope of this book. We must be content with the picture of the acceptor atom, taking and holding tightly the extra electron which gives it an over-all negative charge.

For every atom of impurity, there is eventually created one negatively charged acceptor atom and its positive counterpart, the germanium hole, which is deficient by one electron. Even though the germanium atom by itself will not participate in the electron drift process (it is a poor conductor), the germanium "hole" becomes a fairly good conductor of electricity. It is said that holes move freely through a semiconductor, but this statement requires some elaboration. The positively charged atoms do not move through the semiconductor. By capturing planetary electrons from nearby atomic orbits, the "hole" can be given the appearance of moving fairly rapidly through a series of germanium atoms. In reality, each such atom in turn loses an electron and becomes a hole, then in turn captures an electron from the next atom, causing it to become a hole, and so on.

Thus, the positive charge seems to move in the direction of applied *positive* voltage—meaning *away* from a plus voltage and *toward* a minus voltage such as the negative terminal of a battery This process of hole-current movement resembles conventional electron drift, but with the important difference that the electron drift process presupposes extra electrons traveling through the atomic structure and, in effect, "pushing" planetary electrons out of their orbits. "Hole" current seems to travel in the opposite direction through a semiconductor, by "pulling" planetary electrons out of orbit.

### "Mobility" of Charge Carriers

Electron charge is concentrated at a single point, whereas the positive charge of a hole seems to be distributed somewhat—if not over the entire volume of the atom, then at least over a portion of it or a portion of the orbit. This would seem to indicate that the "pulling" of electrons from orbit might be more difficult than the normal process of pushing them from orbit. That this is the case may be verified from the "mobility" of electrons and holes in germanium.

The mobility of an electric charge is a measure of the relative ease or difficulty with which the charge can be moved by an applied electric field (voltage). It is usually expressed as the "drift velocity" of the charge in centimeters per second. The mobility of free electrons in a germanium semiconductor, when the applied electric field has a strength of one volt per centimeter, is about 3,600 centimeters per second.

The mobility of positive "holes" through a germanium semiconductor for the same applied electric field of one volt per centimeter, is about 1,700 centimeters per second. Thus, the drift velocity of free electrons through a germanium semiconductor is more than twice as great as the drift velocity of holes.

## DONOR ATOMS AND N-TYPE SEMICONDUCTORS

Fig. 1-3 shows the atomic structure that results when an impurity atom such as arsenic is added to the germanium. Arsenic is chosen as an impurity because it has five planetary electrons orbiting about the nucleus. The arsenic atom will "lock" in place with four germanium atoms; and one of the five valence electrons will be released, or "donated," after this combination occurs. This action gives the resulting atom the name "donor atom." The extra electron is indicated by the arrow in Fig. 1-3. Before giving up one electron, the atom has a neutral electric charge; and afterward, it becomes a positively charged "donor" atom.

Like the negatively charged acceptor atom discussed previously, the donor atom holds on very tightly to its new electrical condition, and does not recapture the electron it released. Consequently, both the positive atom and the negative electron can

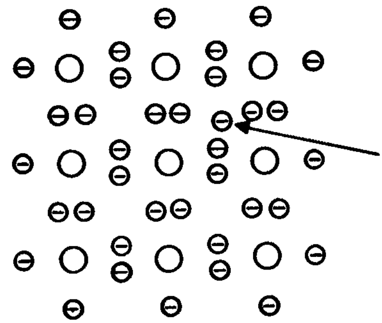


**Fig. 1-3. An arsenic atom tied to four germanium atoms.**

exist side by side in the same portion of the semiconductor without recombining. Although the total charge of this semiconductor will be zero (since the number of electrons released equals the number of positively charged donor atoms), the semiconductor becomes known as an N-type because of the availability of negative carriers (electrons). The positively charged donor atoms do not act as current carriers, and are not "holes."

We have now created the two basic types of semiconductors. The N-type has an excess of free electrons available for carrying current: whereas the P-type has a series of positively charged germanium atoms, called holes, also available for letting electron current flow through the semiconductor.

## IMPURITY CONTENT OF SEMICONDUCTORS

Very small portions of an impurity are required to convert the insulator germanium to a semiconductor germanium—about one part impurity to a million parts germanium. This is due to the conductivity of the material, which varies directly with the density of current carriers (free electrons and holes) contained therein. The number of current carriers in a particular sample will equal the number of impurity atoms.

## THE JUNCTION DIODE

When an N-type semiconductor is bonded to a P-type semiconductor, a junction diode is formed. Fig. 1-4 shows the junction diode under three voltage conditions.

The natural tendency for the electrical charges in the junction diode, when no external voltage is applied (Fig. 1-4A), is for excess electrons in the N-material to cross the junction (moving to the left in Fig. 1-4A) and recombine with the positive holes in the P-region. A small amount of such recombining does occur, but it is prevented from happening on a wholesale basis. As soon as a few electrons have left the N-region, it will no longer be electrically neutral, but will have a slightly positive charge. Likewise as soon as the P-region has acquired a few excess electrons, it will no longer be electrically neutral, but will possess a slightly negative charge. This charge redistribution is shown in Fig. 1-4A.

The current carriers in both semiconductors are repelled from the area of the junction. The area close to the junction is variously known as a depletion zone (because it is depleted of current carriers) or as a transition region. The particular charge distribution is referred to as a potential hill across the junction, a potential barrier, a dipole charge layer, a space charge layer, differing energy levels, among others.

In Fig. 1-4B a negative voltage is shown being applied to the P-type material and a positive voltage to the N-type. This condition, known as reverse bias, is not conducive to current flow through the junction. Electrons will try to flow from the P- to the N- material, but will encounter high opposition or resistance in their attempt to flow in the opposite direction. The reverse bias *adds* to the potential barrier set up by the junction when no bias is present.

Fig. 1-4C shows conditions across the junction when forward bias is applied. This term implies that the normal tendency of electron current to flow from N-type to P-type will be aided or encouraged by the applied voltage, and that a substantial electron current will cross the junction and flow through the external circuit.

The foregoing two paragraphs reveal the possibility of using semiconductors as a rectifying device for converting an applied alternating current to a unidirectional current. The rectifying *principle* finds wide application in both rectifier power supplies and detection or demodulation circuits.

## THE JUNCTION TRANSISTOR

We are now ready to assemble three semiconductors in such a fashion that they become a transistor. Fig. 1-5 shows a P-type, an N-type, and another P-type semiconductor bonded together to constitute a PNP transistor. The charge distribution, when no external voltage is applied, is as indicated. The so-called charge dipole layer forms at each junction, so that both edges of the center semiconductor are slightly positive. This positive charge is composed of the fixed donor atoms, which do not move and hence do not participate in the electron drift process. The free electrons in the N- material are seen to be bunched near the center. They are held in position by the fixed negative acceptor atoms on the two adjoining faces of the P-type semiconductors, the repelling electric field of which extends through the positive concentrations of donor atoms on either edge of the N- material to the center.

This charge dipole layer at each junction could be shown as being produced by a small simulated battery across each junction, resulting in the existing polarities. It is important to understand that, even under this static or equilibrium condition of no external voltage applied, there actually are small voltages (or electric fields) existing across each junction in a transistor.

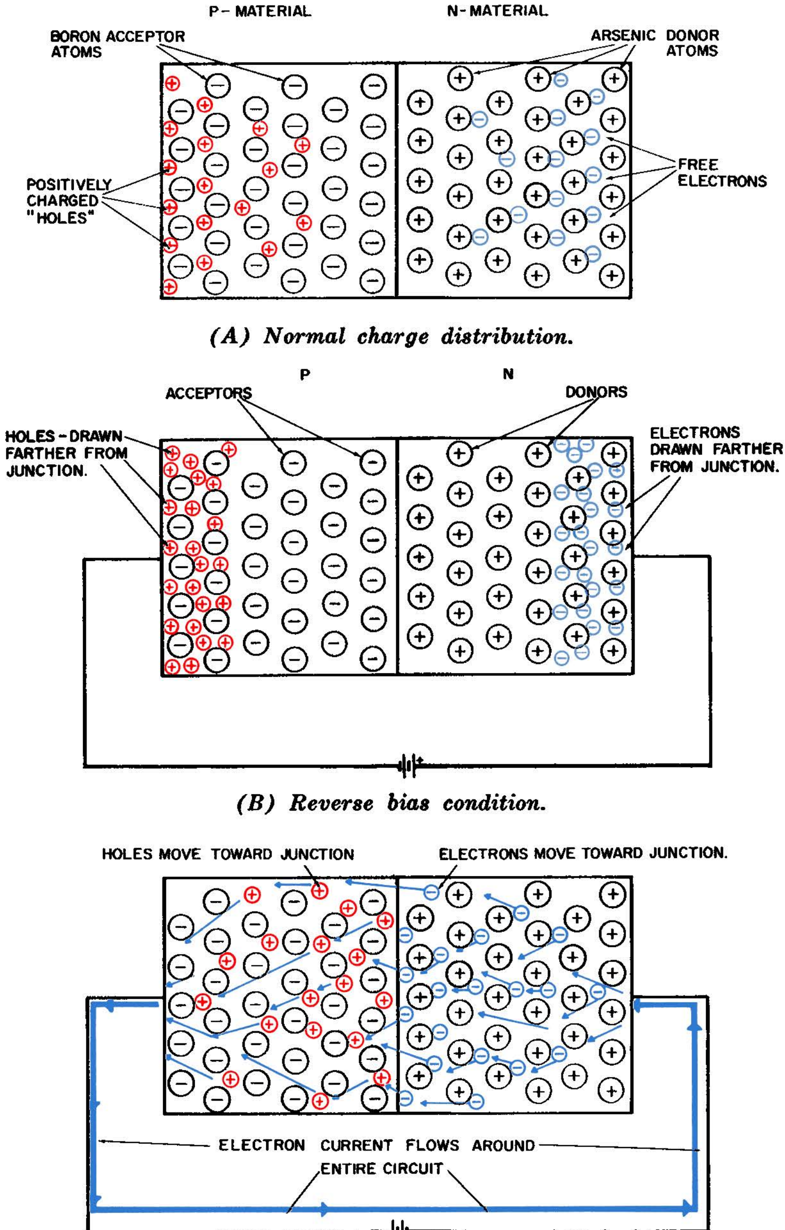
A *graphical* representation of this charge distribution is given immediately below the *symbolic* representation in Fig. 1-5. This charge distribution is also called an electric field—or more simply, a voltage. The fixed positive and negative atoms are omitted from this diagram. However, they would be distributed around each junction, just as they are around the single junction of Fig. 1-4A.

The graphical picture (Fig. 1-5B) tells us the same story as the symbolic picture in Fig. 1-5A—namely, that within the base, but adjacent to each junction, there is a positive electric field due to the relative scarcity of free electrons. In the center of the base, however, there is a negative electric field due to the presence of excess free electrons. Within the emitter and collector, but immediately adjacent to each junction, there is a negative electric field due to the relative absence of positively charged "holes." As we move away from each junction, this electric field changes from negative to positive—due now to the presence of an excess of positive holes.

Because the collector is usually manufactured with a much lower conductivity factor than the emitter, considerably *fewer* free charge carrier (positive holes) will be milling around within it. The conductivity of a semiconductor is directly proportional to the density, or concentration, of these charge carriers. Frequently, the emitter material will have a hundred times greater conductivity than the collector material.

In Fig. 1-5A, the lower charge density indicated in the collector reduces the electric field across the base-collector junction, as shown graphically in Fig. 1-5B. And the smaller this electric field or voltage is, the easier will it be to breach the natural tendencies of the junction and get electron current to flow *from the* P-material of the collector into the N-material of the base.

As explained more fully in connection with Figs. 1-8, 1-9, and 1-10, this is accomplished by using a "signal" current (or




*(A) Normal charge distribution.*

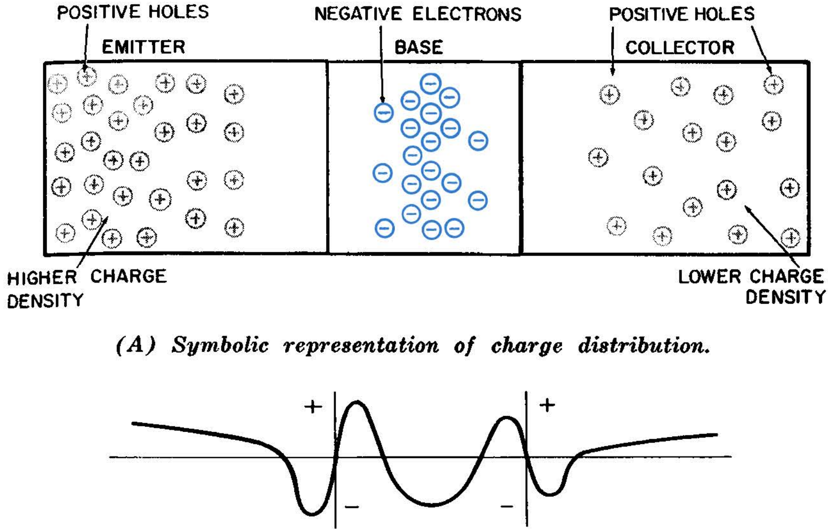


*(B) Reverse bias condition.*



*(C) Forward bias condition.*

**Fig. 1-4. The P-N junction under various bias conditions.**




*(A) Symbolic representation of charge distribution.*

*(B) Graphical representation of charge distribution.*

**Fig. 1-5. The PNP junction transistor with no external applied voltage.**

voltage) to vary the electron concentration within the base and thereby vary the strength of the small electric field across the base-collector junction. In this manner, it is possible to regulate the quantity of electrons flowing (as a result of the collector bias voltage) into the collector and through the transistor.

The transistor becomes a useful circuit device when external leads are attached to each semiconductor, and the leads brought to appropriate voltages and circuitry. The transistor can be compared, in some respects, to the triode vacuum tube. As explained in earlier books of this "Basic Electronics" series, the cathode of a triode *emits* electrons into the tube. The control grid, by virtue of the voltage applied to it, then *regulates,* or *controls,* the flow of these electrons through the tube; and the plate *receives* them after they have completed their journey.

## TRANSISTOR SYMBOLISM

The *symbolic* representations of the basic types of transistors, PNP and NPN, are shown in Fig. 1-6 and 1-7. In each illustration the left-hand semiconductor is labeled the base, the bottom right-hand one the emitter, and the upper right-hand semiconductor the collector. Since the function of the emitter is to *emit* current through the base to the collector, it is usually compared to the cathode of a tube. By virtue of the biasing conditions (current and voltage) applied between base and emitter, it is possible to control, or regulate, the flow of emitted current to the collector; consequently, the base of a transistor performs the same function as the grid of a tube. The collector *receives,* or *collects,* the current emitted by the emitter and, in that sense, corresponds to the plate of a tube.

## ELECTRON-FLOW DIRECTIONS IN TRANSISTOR CIRCUITS

Fig. 1-6 indicates an arrow pointing into the base from the emitter, a symbol which immediately identifies this as a PNP type transistor. The arrow indicates the direction in which the *positive* units of current—in other words, holes—flow. As we shall see in a later example of circuitry, electron flow through a PNP transistor is *into* the collector from the external circuit, then into the base, from there *into* the emitter, and out the emitter to the external circuit again.

Fig. 1-7 indicates an arrow pointing into the emitter from the base, a symbol which immediately identifies any transistor as an NPN type. The arrow again corresponds to the more or less theoretical direction of flow of the *positive* units of current—holes again. In NPN circuitry, it is universally accepted that the *electron* flow is *into* the emitter from the external circuit, then into the base, from there into the collector, and out the collector to the external circuit. Thus, the direction of the electron flow is the same through the NPN transistor and the vacuum tube—*from* emitter (or cathode) *to* collector (or plate). Hence, the analogy between a transistor and a vacuum tube is more precise for an NPN type.

The electron-flow directions through the two types of transistors are indicated in color in Figs. 1-6 and 1-7. The main electron stream (collector current) is shown in red; the base current, which usually carries the applied signal and a biasing current, is in green.

### Forward Biasing of Emitters

Fig. 1-8 shows the PNP transistor of Fig. 1-5 when biasing voltages are applied to the emitter and collector. The voltage applied to the emitter (left-hand semiconductor) is positive. Its polarity is such that electrons are drawn *from* the base *into* the emitter. Since this is the *normal* direction of electron flow through an NP junction, the emitter is said to be "forward biased" with respect to the base.

## Reverse Biasing of Collectors

The voltage applied to the collector (right-hand semiconductor) is negative. Its polarity is such that electrons are driven *from* the collector *into* the base. Since this is the reverse of the normal direction of electron flow through a PN junction, the collector is said to be "reverse-biased" with respect to the base.

One fact should be especially noted. The two external voltage sources (batteries in this example) are connected so that they would drive electron current in a counterclockwise direction from the negative terminal of the "reverse bias" voltage and into the collector. From there the electron flow is through the base and emitter, to the positive terminal of the "forward bias" battery, then continues through the rest of the external circuit and returns to the positive terminal of the reverse-bias voltage source. In other words, these two voltage sources are not opposing each other. Rather, they are in series with each other and of like polarity—meaning both are trying to drive electrons in the same direction, or counterclockwise through collector, base, and emitter in that order.

## Electrons in Base

In Figs. 1-5, 1-8, 1-9, and 1-10, we are concerned with free electrons from several sources. Since an understanding of each source is essential to an understanding of transistor action, each electron group has been shown in a different color.

Fig. 1-5 shows the free electrons of the base material in blue. These are bunched along the center line of the base, whereas the positive holes in the adjoining P-type semiconductors, (in gray) are bunched along the outer edges. The fixed negative acceptor atoms in the P-material, and the fixed positive donor atoms in the N-material, have been omitted in this diagram, and also in Figs. 1-8 through 1-10.

Fig. 1-8 deals with the free electrons which exist within the N-type material; they are shown in blue, as in Fig. 1-5. It is the concentration, or density, of these free electrons that determines the *normal* conductivity of the base.

Also shown (in red) are the free electrons driven from right to left through the transistor by the two biasing voltages. When there is no signal voltage applied between base and emitter (as in Fig. 1-8), this current assumes a normal, or "equilibrium," value. It is the main electron stream through the transistor, and corresponds to the plate current in vacuum-tube circuits.

Finally, we have an equilibrium value of electron current (green) flowing from base to emitter. When electrons from this

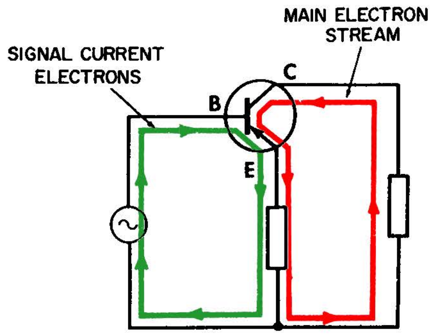



Fig. 1-6. The PNP transistor, with external circuitry.

current are within the base, they increase the electron density in the base, and consequently, the conductivity of the base. The volume of the main electron stream from collector to emitter (red) is regulated by the conductivity of the base. Therefore, in Fig. 1-9, when the base is "biased" so that additional electrons are driven into it, the volume of current flowing across it from collector to emitter is drastically increased. The attempt has been made in this figure to show the concentration of blue electrons in the base as relatively unchanged from Fig. 1-8. There are slightly more green electrons in the base than were shown in Fig. 1-8.

However, because of this slight increase in electron concentration in the base, a considerably larger main collector-to-emitter current flows. These electrons, shown in red, now flow in some profusion from right to left through the three sections of the transistor.

When the polarity of the signal voltage is reversed (Fig. 1-10), the base-to-emitter current is restricted to a low value. This accounts for the low number of electrons (green) in the base. The resulting decrease in conductivity of the base substantially reduces the main electron stream (red) through the transistor.

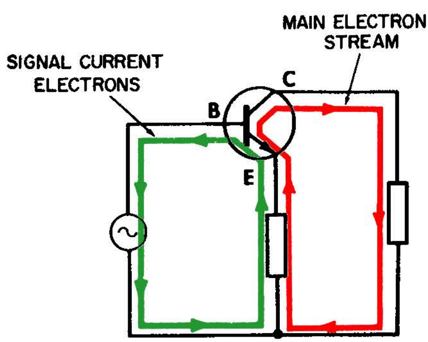



Fig. 1-7. The NPN transistor, with external circuitry.

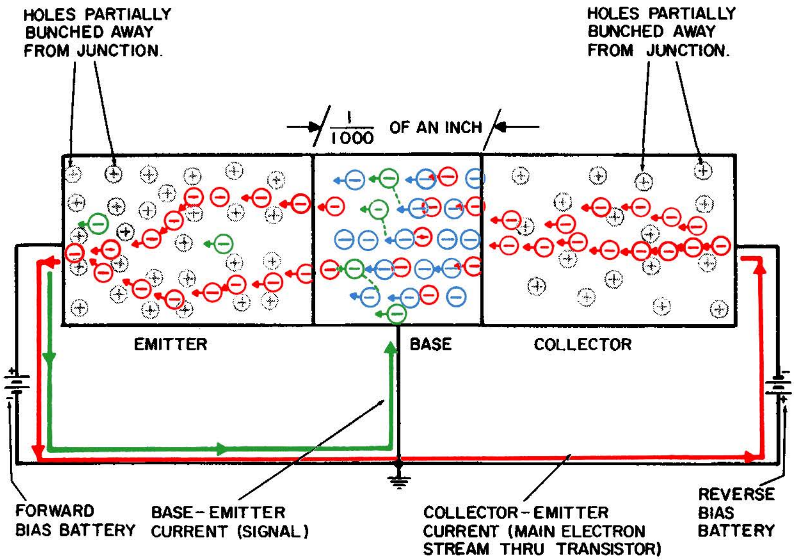



**Fig. 1-8. The common-base PNP transistor circuit—no signal current.**

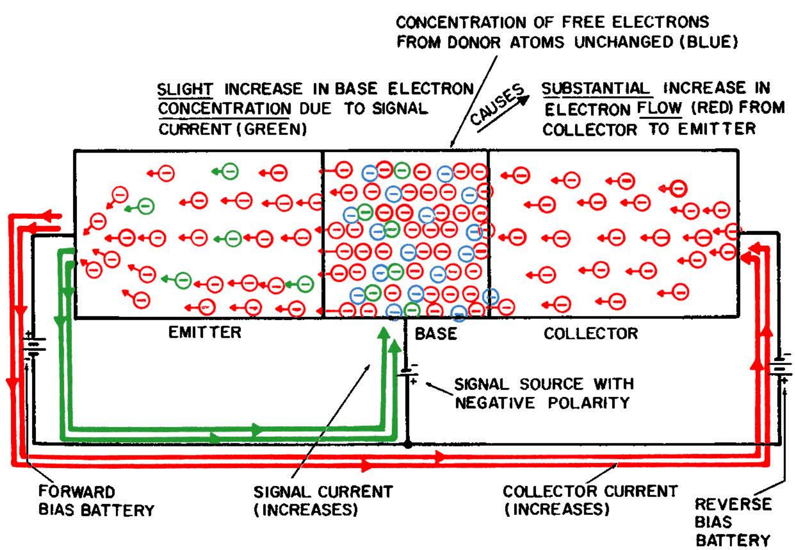



**Fig. 1-9. The common-base PNP transistor circuit—negative half-cycle of operation.**

It is desirable now to consider the transistor in operation in a sample circuit. This requires us to assign representative values to the applied voltages and to the two resistances in the emitter and collector circuits, and also to provide a means for changing the bias conditions between emitter and base. (In a vacuum-tube circuit, this latter function is known as "driving" the grid.)

## TRANSISTORS AS CURRENT AMPLIFIERS

Transistors are referred to as "current-operated" devices, because the driving signal applied between base and emitter is usually referred to as a "current" rather than a voltage. Tubes, on the other hand, are considered to be "voltage-operated" devices, because it is the instantaneous value of voltage at the tube grid that determines the amount of electron current which can pass through the tube.

Transistors, on the other hand, are referred to as "current amplifiers" because a small change in the bias current flowing between emitter and base will cause a much greater change in the amount of current flowing between emitter and collector. The necessary small change in bias current is usually provided by a very weak signal current (on the order of micro-amperes). Obviously, such a signal current will have a companion signal voltage, since one cannot reasonably exist without the other. Convenience and custom, however, have established the signal current as the prime agent in changing the instantaneous bias conditions of the transistor and thus regulating the flow of emitter-to-collector current.

Fig. 1-9 shows the same PNP transistor of Fig. 1-8, but with an additional current source in the line leading to the base. This current source is shown as a small battery in order to establish the desired direction of electron flow from its negative terminal into the base, and then into and out of the emitter. From here the electrons travel into the positive terminal of the "forward-bias" battery (after passing through any resistor included in the emitter circuit), and finally out of the negative terminal and back to the positive terminal of the added battery.

A little reflection will confirm that the emitter-voltage source (battery) and the additional voltage source (shown as a battery) in the base circuit have polarities which drive the electron current in the same direction (counterclockwise), whereas the polarities of the base and collector voltage sources are such that these two voltages *oppose* each other. The negative voltage applied at the base *tends* to drive the electron current *clockwise* through the collector circuit, but is prevented from doing so by the much larger negative voltage applied to the collector; the latter would like to drive the electron current counterclockwise into the base and the emitter.

### Signal Current Action

We are now almost down to the water's edge in understanding how a transistor can "amplify" a current, and thus give both voltage and power gain. When this tiny additional electron current is made to flow into the base and emitter, it manages somehow to open the flood gates and let a much larger electron current flow from collector to emitter.

Should the polarity of this signal voltage be reversed, an opposite effect will occur and the electron current flowing from collector to emitter will be reduced considerably. This is depicted in Fig. 1-10, where the new biasing voltage added in the base circuit has a positive rather than negative polarity; consequently, it *tends* to draw electrons out of the base, rather than push new ones in. The consequent reduction in quantity of electrons flowing from collector to emitter is shown pictorially.

Current amplification is considered to have occurred in Figs. 1-8 and 1-9 because the resulting fluctuations in collector-to-emitter current are much larger than the fluctuations in the signal current applied to the base. (The ratio between the two may easily be as high as 50 to 1.)

## THE CHARACTERISTIC CURVE

A typical characteristic curve for a PNP transistor is given in Fig. 1-11. The horizontal scale is graduated in volts applied to the collector, and the vertical scale is graduated in milliamperes of collector current. The third variable, the amount of current flowing in the base, is shown by the lines running upward to the right. For any given values of collector voltage and base current, we can locate a single point on the base-current line and, projecting horizontally, find the amount of collector (to emitter) current flowing through the transistor.

The circuit of Fig. 1-12 is known as a "common-emitter" or "grounded-emitter" configuration. It differs somewhat from the examples shown in Figs. 1-8 through 1-10, which were common-base configurations that required two separate biasing voltage sources (the forward-bias and reverse-bias batteries). A common-emitter configuration such as the one in Fig. 1-12 has the special advantage that a single voltage source serves very adequately for both biasing functions.

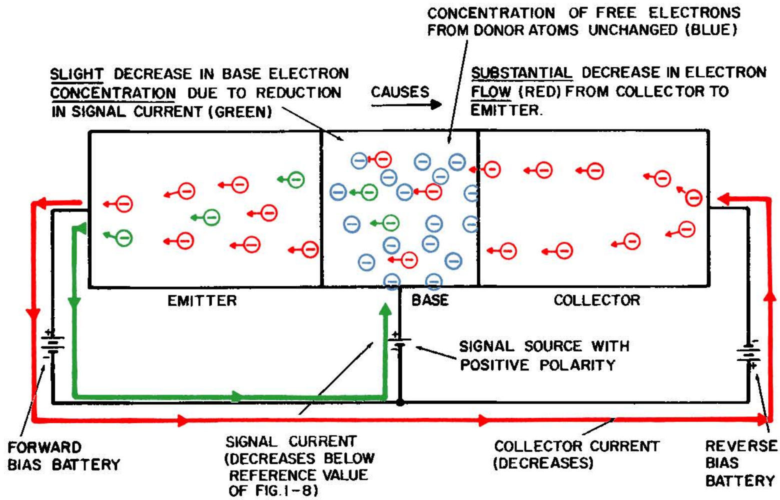



**Fig. 1-10. The common-base PNP transistor circuit—positive half-cycle of operation.**

The common-emitter circuit corresponds most closely to the conventional vacuum-tube circuit, wherein the cathode of the tube is either grounded directly or is connected to ground through a low-value resistor which provides cathode biasing. Circuit diagrams for the common-emitter configuration are normally drawn with the transistor in the "vertical" position—that is, with the collector at the top, the base in the middle, and the emitter at the bottom. The signal is applied to the base from the left side of the diagram, and is "coupled" away to the next stage on the right side.

Note the convenience of this analogy to conventional vacuum-tube circuitry, where the tube plate is shown at the top of a tube diagram, the grid in the middle, and the cathode at the bottom. This convention of displaying a transistor vertically, with the collector at the top, should ease your mental transition from tube circuits to transistor circuits. That is to say, those who have learned to *visualize* the various electron currents moving around a tube circuit should have a minimum of difficulty in visualizing the comparable electron currents at work in a transistor circuit.

## USE OF A "LOAD LINE"

Fig. 1-12 shows the PNP transistor with typical values of applied voltage at emitter and collector, and typical values of resistance in the emitter and collector circuit. Using these values of voltage and resistance, you can work a sample problem on the characteristic curve of Fig. 1-11. First, it is necessary to construct what is known as a "load line" on the characteristic curve. This can be done by determining two important points—corresponding to zero collector current and to zero collector voltage—and drawing a line between them.

The first point is evident from a consideration of Ohm's law, which states that the voltage developed across a resistor is proportional to the current flowing through that resistor. If no current flows through the load resistor, R2, then there is no voltage drop across it. Thus, its two ends must be at the same voltage, which is the value of collector supply voltage $E_C$. In this example, a value of 4 volts has been chosen, so this is also the voltage at the junction of base and collector when zero collector current is flowing. This value determines the location of the point corresponding to the zero collector current in Fig. 1-11.

Ohm's law can again help us locate the second point. If the collector voltage is truly zero, then the voltage "dropped," or used up by the collector current in flowing through R2, must equal the collector supply voltage. Since, by Ohm's law:

$$\text{Current (in amperes)} = \frac{\text{Voltage (in volts)}}{\text{Resistance (in ohms)}}$$

we can calculate:

$$\begin{aligned} \text{I (collector current)} &= \frac{E_C}{R2} \\ &= \frac{4}{2{,}000} \\ &= 2 \text{ milliamperes} \end{aligned}$$

This determines the point corresponding to zero collector voltage. The line between the two points is the so-called "load line"; at any given instant, it relates the exact voltage at the collector to the exact amount of current flowing through the collector (toward the emitter).

There will always be a small resistance to electron flow through the transistor; consequently, a small "voltage drop" must exist across the transistor. Since this resistance is no more than 10 or 20 ohms at the most, it is negligible in comparison with load resistance (which in this example is assumed to be 2,000 ohms) and may be ignored in a qualitative example like that chosen here.

## Operating Point

The next step in using the characteristic curve is to determine the operating point on the load line. This is the point corresponding to no applied signal in the base circuit. Common sense dictates that it should be somewhere near the middle of the load line, so that signal fluctuations in a positive direction will *decrease* the collector-to-emitter current by the same amount that a signal fluctuation in the negative direction will increase this current.

We can arbitrarily choose the point where the 20-microampere base-current line intersects the load line. Also, let us assume that the signal current to be amplified has a peak-to-peak swing of 20 microamperes, and that it is applied in the external circuit between the base and emitter. Any one of several standard coupling methods could be used. The method chosen is capacitive coupling, and the new signal will be driven in and out of the base circuit through capacitor C1.

The special virtue of the load line is that it at all moments will relate the three important variables of collector current, collector voltage, and base current. Thus, when the base current increases to −30 microamperes, the collector current *increases* to −1.6 milliamperes and the collector voltage decreases to −0.9 volt. (This is comparable to vacuum-tube circuitry, where an increase in plate current through a resistive load reduces the plate voltage.)

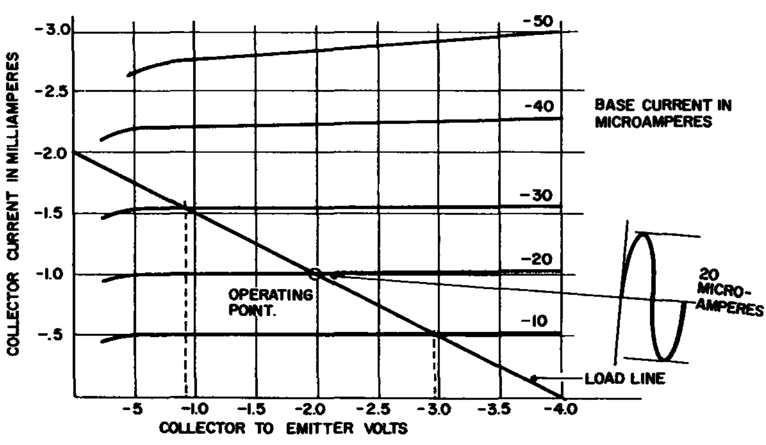



**Fig. 1-11. Characteristic curve for a PNP transistor in a common-emitter configuration.**

Alternatively, when the signal current reduces the total base current to $-10$ microamperes, the collector voltage increases to $-2.95$ volts while the collector current is decreasing to $-0.55$ milliampere.

## THE BETA FACTOR

Current amplification is said to have occurred in the previous example because we started with a signal amplitude of 20 microamperes in the base-emitter circuit and came out with a variation of 1.05 milliamperes in the collector current. The ratio between these two current swings is:

$$\frac{1.05 \times 10^{-3}}{20 \times 10^{-6}} = 52.5$$

Or, slightly over 50-to-1.

Such a high ratio is not uncommon among transistors. It is an important figure of merit known as the "transport factor" and symbolized by the Greek letter $\beta$. For this reason it is sometimes called the "beta factor" of a transistor.

To understand *why* a small signal current can subject the collector current to these wide variations, we must further study Fig. 1-5. Obviously, the explanation is not going to be as simple, nor as straightforward, as for vacuum tubes! In Fig. 1-5, note especially how the two junctions will assume certain charge distributions. Within the base section (which is N-type material), the negative free electrons will be repelled slightly from each of the interfaces. Thus, the outer edges of the base are slightly positive and its interior is slightly negative.

Likewise, the so-called free "holes" of positive charge in each of the P-sections (emitter and collector) will be slightly repelled from the interfaces. Both interface areas in the P-material are therefore slightly negative. The free electrons in the base region would like to cross both junctions and combine with the positive holes. Referring to Figs. 1-8 and 1-9 you can see that, with the emitter "forward biased," some of these actions are now going on. But it is important to note that the unusual charge distribution at the interfaces has only been reduced in strength, not wiped out entirely. Free electrons are crossing the junction from base to emitter—*in spite of the fact* that fixed negative charges at the junction edge in the emitter are still exerting an electric repulsion field on them, trying to keep them out. According to the characteristic curve of Fig. 1-11, when the normal base current of $-20$ microamperes is flowing, the collector current has a value of $-1.02$ milliamperes.

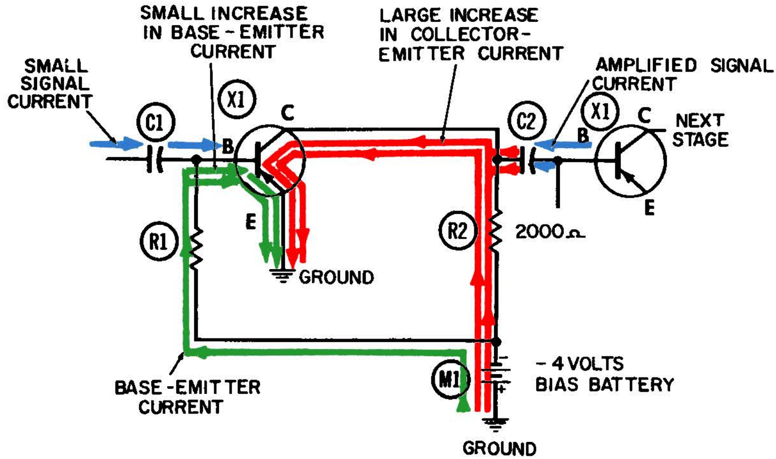



**Fig. 1-12. A common-emitter PNP transistor circuit—negative half-cycle.**

## THE ALPHA FACTOR

Electrons from both the base and collector currents will flow through the emitter. Thus, the total emitter current will be the sum of these two, or 1.04 milliamperes—only slightly larger than the collector current. The ratio between collector and emitter currents, known as the alpha gain, is another important figure of merit for transistors. In a junction transistor it cannot be greater than unity, but is normally very close to it. In this example:

$$\text{Alpha} = \frac{1.02}{1.04}$$

or, about 98%.

In Fig. 1-9, a small external voltage is applied to the base with such a polarity that it drives additional electrons into the base and through it to the emitter. This corresponds roughly to what happens when the base current is increased from −20 to −30 microamperes.

## BASE CONDUCTIVITY

What happens within the base itself under these conditions? For one thing, the concentration, or density, of the negative current carriers (electrons) is increased, and the conductivity of any semiconductor varies directly with the density of current carriers in the material. Thus, the base becomes a much better

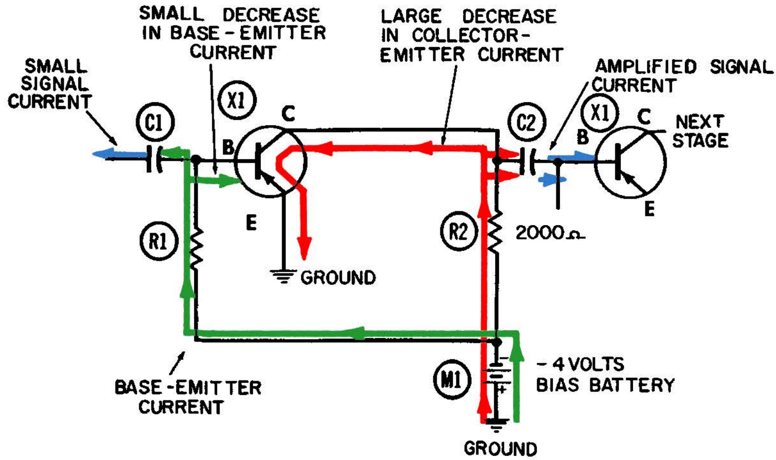



**Fig. 1-13. A common-emitter PNP transistor circuit—positive half-cycle.**

conductor when more electrons are driven in. Conversely, when fewer base-current electrons flow (as in Fig. 1-10), the conductivity of the base is reduced.

Hence, the base acts as a variable resistor situated between emitter and collector, and having two power sources—the reverse bias and the forward bias.

How is it possible for such a small bias current to actuate this variable resistor? Fig. 1-9 shows the momentary increase in electron density in the base. Thus, the positive carriers (the so-called "holes") in the emitter are repelled less strongly by the "dipole charge layer" at the junction, and will therefore move closer to it. We can assume that this shorter distance between the holes in the emitter and the free electrons in the base greatly expedites the electron drift process.

The "dipole charge layer" between base and collector will also have been diminished in strength, and consequently in width, so that the positive holes in the collector can draw closer to the excess of free electrons in the base. This will also tend to improve the conditions conducive to current flow—the interchange of free electrons from orbit to orbit of positively charged atoms which so closely resembles the electron drift process.

## BASE WIDTH

One additional fact of great importance is the width of the base itself. This is normally less than a thousandth of an inch, so that the two sections of P-type material are separated by only this minute distance. Thus, any increase in electron flow between base and emitter will increase the electron density in the base. In turn, more electron current will flow out of the collector, toward the emitter. It is almost as if the increased electron density in the base had created, between the collector and emitter, a series of "electron bridges" across which relatively large quantities of electrons can flow. Of course, this flow is in conformity with the special requirements of the electron drift process.

When the polarity of the applied signal voltage is such that it *reduces* the amount of electron current flowing from base to emitter, (as depicted in Fig. 1-10), the opposite effect can be created. There are fewer intrinsic electrons within the volume of the base; this in turn decreases the conductivity of the base, since conductivity varies directly with the density of current carriers in the material. Even if there were no other contributory effect to consider, the main electron stream through the transistor would still be substantially reduced, by virtue of having to flow through the higher base resistance.

## SIZE OF AN ELECTRON

Even though the base is limited to a width of about a thousandth of an inch, it is worthwhile to consider how much "maneuvering room" is provided for the electrons within. The electron has a diameter of less than $10^{-12}$ centimeter. This means that if electrons could be arrayed end to end, a line one centimeter long would contain *more than one trillion* of them. Thus, a base width of a thousandth of an inch can still accommodate about two and a half billion electrons laid end to end.

This should give some idea of how drastically the number of electrons shown in Figs. 1-8, 1-9, 1-10 and others has been reduced and oversimplified in order to make a pictorial representation that can even be comprehended.

Figs. 1-8, 1-9, and 1-10 suggest a series of possible electron paths through the base of the transistor under three conditions of applied signal current. Fig. 1-8 assumes the condition of normal bias—i.e., zero signal applied to the base, and a forward bias such that an "equilibrium" electron current of −20 microamperes is driven from base to emitter. This permits an "equilibrium" electron current of 1.05 milliamperes through the collector. Note the bunching of free electrons towards the vertical center line of the base, and also that an electron drift process is occurring throughout the three elements of the transistor. From the negative terminal of the reverse-bias battery, the electrons move from right to left into the P-type collector, jumping from hole to hole, then across the first junction and into the base. Here they impart their energy to other free electrons. The latter in turn cross the second junction into the emitter, jumping from hole to hole until they emerge into the external circuit and enter the positive terminal of the forward-bias battery.

Fig. 1-9 shows the same transistor when the signal current from base to emitter is increased from −20 to −30 microamperes. Being composed entirely of free electrons, this larger signal current increases the electron density in the base and also reduces the width of the "dipole charge layer" at the two junction interfaces. Simultaneously, the electron current from collector to emitter is vastly increased. This can be due to the greater ease of the electrons in crossing the existing "electron bridges" in the base, to the opening of new bridges, or a combination of both. If the beta factor of the transistor is 50, then for each additional signal-current electron that passes through the base, a total of about fifty additional electrons will be made to flow across the base from collector to emitter.

Fig. 1-10 shows the same transistor when the signal current from base to emitter is reduced from −20 to −10 microamperes. Now the width of the charged layer at the two junctions will be increased. This restricts rather than encourages the electron drift process across the two junctions, although it still goes on at a reduced rate (−.55 milliampere). The smaller electron current can be due to fewer electron bridges through the base, to the increased difficulty in getting across the existing bridges, or a combination of both.

It is easy, from these analogies, to see how a greater width and consequently greater volume for the base would require more signal current in order to increase the base conductivity by increasing its electron density. It is obvious that a wider base would mean longer electron paths or "bridges" through the base, and that to open up new ones (or improve the conductivity of existing ones) would require many more new electrons driven by the signal current. Consequently, the beta factor—or ratio between a change in collector current for a corresponding change in signal current—would be much lower, and the transistor would not be as good an amplifying device.

## MEANING OF NEGATIVE CURRENT VALUES

Those of you who are new to transistors and their circuits should not become confused by the fact that the base and collector currents are both shown as being "negative" in the characteristic curve of Fig. 1-11. Whether a particular current is negative or positive depends on whether it is made up of negative electrons, or of positive charges such as "holes." It also depends on which direction the current is flowing in a circuit.

These matters have already been settled for us—the term "current" in transistor work is normally taken to mean "conventional" current, which is composed of positively charged particles such as "holes." Additionally, the "normal" direction of "conventional" current flow through any PNP transistor is from emitter to base to collector. However, in the NPN transistor, the polarity of the two biasing batteries would be reversed; the direction of *electron* flow would be from emitter to base to collector. Obviously, positively charged particles such as holes will flow in the opposite direction—from collector to base to emitter.

The flow direction of positive hole current through the NPN transistor has been chosen as conventional, or normal, perhaps because the flow directions of electron and hole currents through the NPN transistor correspond to the respective flow directions of electron and conventional or "positive" currents through vacuum tubes. Thus, a characteristic curve for an NPN transistor shows positive values for collector voltage (corresponding to positive plate voltage in a vacuum tube), and also positive values for base current and collector current. Therefore, in making any qualitative analysis of transistor-circuit operation, it is necessary to differentiate between the direction of electron current and that of positive, or hole, current.

## THE COMMON-EMITTER CIRCUIT

Fig. 1-12 shows a sample circuit using the same PNP transistor whose characteristic curve appears in Fig. 1-11. This particular transistor, the 2N105, is designed for use at audio frequencies when the currents and powers involved are low. Additional circuit components required are:

R1—Base resistor.
R2—Load resistor.
C1—Input capacitor.
C2—output capacitor.
M1—Bias battery (−4 volts).

There are three electron currents which should be visualized in order to understand the operation of this circuit, which could serve as a low-power amplifier in the audio-frequency range. These currents are:

1. Signal current (blue).
2. Base-emitter biasing current (green).
3. Collector-emitter current (red).

The signal current corresponds in many respects to the grid driving current in vacuum-tube operation. This signal current is driven by a signal voltage applied to input capacitor C1. In the so-called negative half-cycle depicted in Fig. 1-12, a negative signal applied at the input point drives a small electron current onto the left plate of capacitor C1. This in turn drives an electron current *of equal size* off the right plate of C1.

Some important facts of transistor operation can be relearned from Figs. 1-12 and 1-13. One is that a *small increase* in the number of electrons flowing from base to emitter encourages a *large increase* in the number of electrons which will flow from collector to emitter. This condition is depicted in Fig. 1-12. During the half-cycle which we have termed "negative," the signal voltage is driving electron current *onto* the left plate of capacitor C1. Normal capacitor action requires that an equal number of electrons be driven *away* from the right plate of this capacitor, and these electrons are shown as being added to the base-emitter current.

The increased base-emitter current causes a substantial increase in the collector-emitter current. The latter current, shown in red, is the main electron stream through the transistor.

This increased electron current flows through load resistor R1 and causes an increase in the voltage "drop" across it, in accordance with Ohm's law. Thus, the voltage at the *top* of the resistor (the output point of the circuit) will become *less* negative during this half-cycle. This has the effect of drawing electrons *onto* the right plate of capacitor C2, as shown in Fig. 1-12.

The flow directions of the original signal current flowing into C1, and the amplified signal current flowing beyond C2 tell us that a phase reversal occurs as the signal passes through this transistor circuit. This is comparable to our experience with vacuum tubes in a grounded-cathode configuration.

Fig. 1-13 is a "positive" half-cycle of the same circuit. The "positive" connotation is arbitrarily chosen to mean that half-cycle during which *less and less* electron current is flowing into the base. The signal voltage applied to capacitor C1 acts as a sort of "pumping" action—alternately drawing off some of the electrons coming up through R1 (on the positive half-cycles), and delivering them to the base (on negative half-cycles). In this way, the total current entering the base can easily be varied between −10 and −30 microamperes.

The main current stream from collector to emitter has been shown in red in these two diagrams. In Fig. 1-13, when the driving current decreases the total current entering the base, the collector-to-emitter current stream is decreased in the same proportion. Using values previously calculated from the characteristic curve, the collector current during this second half-cycle drops to its minimum value of −.55 milliampere, and during the preceding half-cycle it reached its maximum value of −1.6 milliamperes.

The output point of this circuit is connected directly to the collector and, as we have seen, the voltage at this point fluctuates between the extremes of −.75 volt (at the peak of the first half-cycle) to −2.90 volts (at the peak of the second half-cycle). Thus, we have a voltage swing exceeding 2 volts peak-to-peak at the collector.

Both the collector current and the base current are pulsating direct currents. This tells us they are unidirectional (flow in one direction only). Both currents are driven by the same bias battery of 4 volts. The path of the collector current begins at the negative terminal of this battery. Electrons are driven upward through load resistance R2, then to the left and downward through the collector, base, and emitter to ground. From the ground point, the collector current has the necessary free access to the positive terminal of the battery. As is the case with the plate current in a vacuum tube, a closed path must exist through the power supply (battery) and the regulating device (transistor).

The path of the base current also begins at the negative terminal of the battery. Electrons are driven upward through base resistor R1 and through the base and emitter to ground. From here the base current can return freely to the positive (grounded) terminal of the battery. This closed path must also exist; and it is somewhat comparable to the grid return path provided in every vacuum-tube circuit.

One feature that makes the common-emitter configuration particularly attractive is that forward and reverse biasing can both be provided from a single voltage source. The important consideration in any transistor circuit is to assure that the voltage source or sources are wired so that their polarities will drive electrons in the proper direction throughout the circuit. Regardless of whether the transistor is a PNP or an NPN, the collector current and base current must flow in the same direction through the emitter.

The second consideration is that a *negative* voltage must be provided in order to drive these currents in the PNP transistor, whereas those in the NPN require a positive voltage.

A word of caution: this circuit arrangement, including component values and the applied voltage value of 4 volts, has been chosen for one reason only—to clarify some of the important fundamentals of transistor operation in a sample circuit. They might not prove to be the best component values for low-frequency audio amplification in a particular circuit. Also, even though the 2N105 transistor works equally well in a higher voltage range, that portion of its characteristic curve which applies in this range has been omitted from Fig. 1-11.

## Chapter 2

# THE THREE BASIC CONFIGURATIONS

A transistor may be connected into a circuit in one of three ways, or configurations—namely, the common base, common emitter, and common collector. Of the three, the common-emitter configuration is by far the most versatile and widely used. However, since the other two configurations have overriding advantages for special applications (such as impedance matching), it is essential that you be able to recognize each of the three circuit configurations when you encounter them.

In the conventional three-terminal transistor, a signal is normally applied *to* one of the three elements (base, emitter, and collector), and the resulting signal extracted *from* one of the two remaining elements. Another way of saying exactly the same thing is that an input signal is applied between two terminals of the transistor and extracted from two terminals, one of which is different and one of which is common to both input and output circuit. The terminal which is common to both input and output circuit will prove, in actual practice, either to be connected directly to ground (grounded, in other words), or to be separated from ground by some fixed voltage source only, such as a battery or power supply. A review of the many circuit diagrams used in this series will confirm that, in the vast majority, the input-signal voltage is developed across some type of impedance between the input terminal and ground. Also, the output-signal voltage is developed across another impedance between the output terminal and ground. ("Ground" in each instance is the point of neutral, or reference, voltage.) Every circuit must have a reference voltage against which all other voltages in the circuit—whether positive or negative, or alternating, pulsating, or direct—can be compared. The most convenient such voltage is that of the earth, or ground, which is normally taken to be zero volts.

It is frequently easier to identify the input and output terminals of a transistor circuit than the terminal common to both circuits. However, the common terminal can be identified by the process of elimination. Once the common terminal has been recognized, it is usually a simple matter to satisfy one's self that it is grounded either directly or through a fixed voltage source.

## VOLTAGE, CURRENT, AND POWER GAIN

When the "configuration" of a circuit has been established, it is usually desirable to know what gains in voltage, current, and power the circuit can be expected to deliver. These values of gain are tabulated in Table 2-1, along with the input and output impedances for each type of circuit, since both voltage gain and power gain are directly related to the input and output impedances.

**Table 2-1. Typical Gain and Impedance Values.**

| | Type of Circuit | | |
|---|---|---|---|
| | **Common Base** | **Common Emitter** | **Common Collector** |
| Current gain | Less than unity | Medium—about 50 | Medium—about 50 |
| Voltage gain | More than 100 | Several hundred | Less than unity |
| Power gain | Medium | High | Low |
| Input impedance | Very low | Low | Very high |
| Output Impedance | Very high | Medium | Very low |

## THE COMMON-EMITTER CIRCUIT

Figs. 2-1 and 2-2 depict two successive half-cycles in the operation of a typical phase-inverter circuit which uses two PNP transistors, the first in a common-emitter and the second in a common-base configuration. This circuit (and the common collector configuration discussed later) will substantiate the characteristics listed in Table 2-1. Before discussing these characteristics, it is desirable that each circuit operation be understood; and this requires a detailed discussion of the electron currents which flow in each circuit.

### Identification of Currents

The following electron currents are flowing continuously in the two-stage phase-inverter circuit of Figs. 2-1 and 2-2.

1. Input driving current for transistor X1 (dotted green).

2. Voltage-divider and biasing current (solid green).
3. Base-emitter current for transistor X1 (frequently referred to as base current) (also in solid green).
4. Collector-emitter current for transistor X1 (frequently referred to as collector current) (red).
5. Base-emitter current (base current) for transistor X2. (dotted blue).
6. Collector-emitter current (collector current) for transistor X2 (solid blue).

### Circuit Operation

The input driving current (dotted green) flows up and down through resistor R1 at the basic frequency, which is being amplified. During the half-cycle depicted in Fig. 2-1, this current is being drawn *upward* through R1. This tells us the applied input voltage is positive during this half-cycle. The positive component of applied voltage must be subtracted from the negative voltage created at the junction of R2 and R1 by the flow of the voltage-divider and biasing current (solid green). This current originates at the negative terminal of battery M1 and flows through R3, R2, and R1 (in that order) in order to reach ground and be able to re-enter the positive battery terminal, which is also grounded. Each point along this path is at a lower negative voltage than any preceding point. In other words, the voltage at the junction of R3 and R2 is less negative than the battery voltage, but more negative than the voltage at the junction of R1 and R2. Likewise, the voltage at the junction of R1 and R2 is less negative than the voltage at the junction of R2 and R3, but it is still negative with respect to ground.

The voltage at the base of X1 is the instantaneous sum of the negative voltage created by the voltage-divider action, and of the input voltage across R1. The latter is positive during the first half-cycle shown in Fig. 2-1, and negative during the second half-cycle of Fig. 2-2. This instantaneous voltage is one of the two important biasing voltages of any transistor, the other being the voltage at the emitter of X1. This is a negative voltage, the result of four separate electron currents flowing downward through R4 and every one varying somewhat during a single cycle of operation. Consequently, an exact computation of emitter voltage at any instant is a difficult process. However, in the PNP transistor the voltage at the emitter of X1 must always be more positive than the base in order for any electron current to flow from base to emitter. This base-emitter current is known as the "biasing current." Another way of saying this is that the base must be more negative than the emitter in order for biasing current to flow. During a positive half-cycle, the base is made less negative, and this restricts the flow of base-emitter biasing current.

Transistor action is such that a slight reduction in base-emitter biasing current generates a much larger reduction in the other electron stream flowing through the transistor—namely, the collector-emitter current, shown here in red. This phenomenon accounts for the decreases in the two currents indicated in Fig. 2-1.

During a negative half-cycle, the base voltage is made *more negative*. This drives more base-emitter biasing current through the transistor, and thus a much larger collector-emitter current is generated. This phenomenon accounts for the increases in the two currents indicated in Fig. 2-2.

With this somewhat elementary understanding of current and voltage actions around the transistor, we are in a position to explain the meanings of the various characteristics listed in Table 2-1 for the common-emitter configuration—namely, current, voltage, and power gain, and input and output impedance.

$$\text{Current gain} = \frac{\text{Change in collector current}}{\text{Change in base current}}$$

Values of 50 or even 100 are not uncommon for common-emitter configurations. The current gain of a common-emitter circuit is closely related to the beta factor of the transistor discussed in Chapter 1. However, the amount of current gain achieved in any particular circuit will depend not only on the beta factor, but also on the values of resistors external to the transistors.

$$\text{Voltage gain} = \frac{\text{Change in collector voltage}}{\text{Change in base voltage}}$$

During static operation of the circuit of Fig. 2-1, when no input signal voltage is applied (meaning zero driving current is flowing), the difference between emitter and base voltages is normally only a fraction of a volt. Consequently, changing the base voltage by a small fraction of a volt will cause a substantial change in the amount of collector-emitter current. Since this current must flow through a large load resistor, R3, it develops a large voltage drop across this resistor. This voltage drop is always directly proportional to the amount of collector current, in accordance with the Ohm's-law relationship between voltage and current.

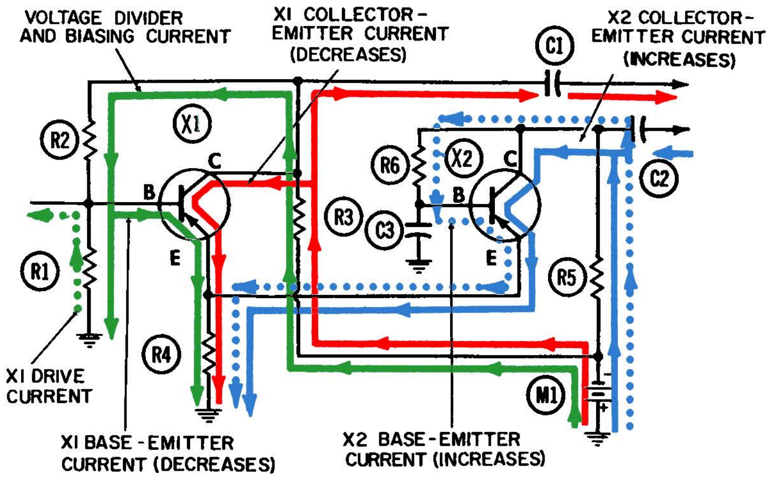



**Fig. 2-1. Operation of a two-stage phase inverter using common-emitter and common-base configurations—positive half-cycle.**

Because the lower end of resistor R3 is tied to a point of fixed voltage (the negative battery terminal), the voltage at the top of R3 will become more negative when the collector current decreases (Fig. 2-1), and less negative when it increases (Fig. 2-2). Since the upper end of R3 is connected

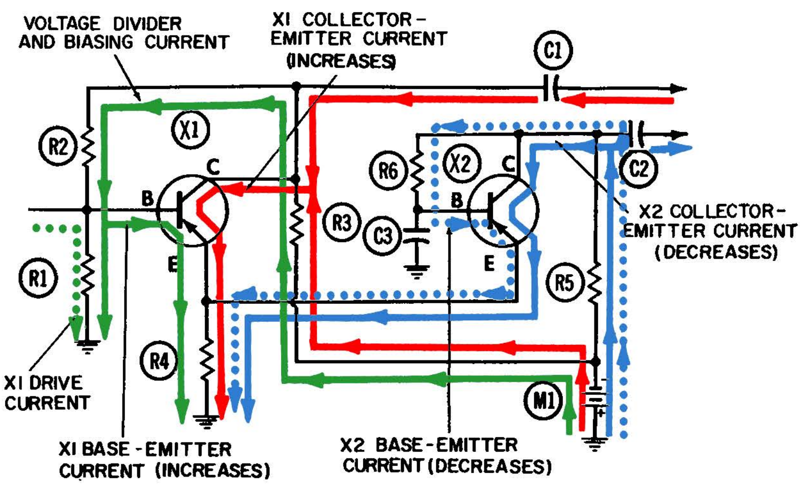



**Fig. 2-2. Operation of a two-stage phase inverter using common-emitter and common-base configurations—negative half-cycle.**

directly to the collector terminal of the transistor, large changes in voltage are occurring at the collector as a result of very small changes in voltage applied to the base. Thus it is easy to visualize how a large voltage gain is achieved in the common-emitter configuration, as indicated in Table 2-1.

$$\text{Power gain} = \text{Voltage gain} \times \text{current gain}$$

$$\text{Also, power gain} = \frac{\text{Power delivered at load}}{\text{Power delivered to input}}$$

Since we have already satisfied ourselves that high voltage and current gains are both available from the typical junction transistor in a common-emitter configuration, the product of these two gains will obviously give a high power gain. Another way of looking at power gain is provided by the second formula. This leads naturally to a consideration of the two other important characteristics of any transistor circuit—namely, input impedance and output impedance.

Impedance, in the broadest sense, represents *opposition to electron flow*. It can always be expressed as a ratio between any applied voltage and the resulting current flow. This ratio stems directly from Ohm's law, which states that:

$$E = I \times R$$

where,

E is the voltage applied across a component in volts,
I is the resulting flow of electron current through the component, in amperes,
R is the resistance or impedance of the component, in ohms.

The input impedance of transistor X1 in Fig. 2-1 is the resistance between the input point (the base) and the ground connection below emitter resistor R4. The internal resistance in the "forward" direction, between base and emitter of the PNP transistor, is only 20 to 40 ohms. Resistor R4 is in series with this junction resistor, but emitter resistors are normally held down to a few hundred ohms, or at most one or two thousand ohms. Additionally, R4 is shunted by the emitter-base resistance of X2 and the other components connected to the base of X2. As a result, the input impedance at the base of X1 is low. This means that only a small voltage change is required at the base to cause a significant change in the base current. Input impedance might thus be defined as the change in input voltage required to produce a change in input current.

The output impedance of transistor X1 in Fig. 2-1 is the total resistance between the output point (collector) and the ground connection below emitter resistor R4. The bulk of this resistance is made up of the collector-to-base junction resistance within the transistor. This is the so-called "reverse" direction—meaning the electron flow from collector to base is opposite, or against, the normal flow direction for a PN junction. Consequently, the impedance to electron flow from collector to base (this is actually the direction in which collector-emitter current *does* flow within the transistor) is as high as one or two megohms. We can look at the output impedance as a ratio between a change in collector voltage and the resulting change in collector current. Because collectors are biased in the reverse direction, so that batteries such as M1 are trying to drive electrons against the normal flow direction of the collector-to-base junction, a relatively large change in collector voltage will have only an insignificant effect on the amount of collector-emitter current.

Large changes in the collector-emitter current can be generated by changes in the base-emitter biasing current. These changes in collector-emitter current will *cause* substantial voltage changes at the collector, by virtue of the voltage drop which this current develops across R3. However, it does not necessarily follow that these changes in collector-emitter current can be brought about by changing the collector voltage by the same amount. In this respect, the collector terminal is analogous to the plate of a pentode vacuum tube. The plate voltage of a pentode has almost no control over the amount of plate current which flows; likewise the intrinsic value of collector voltage has almost no control over the amount of collector current. Just as the amount of grid-bias voltage regulates electron flow through the pentode, so does the amount of biasing current regulate the collector current through the transistor. Because of these considerations, the output impedance of a common-emitter configuration is very high.

## THE COMMON-BASE CIRCUIT

Transistor X2 is connected in a common-base configuration (i.e., the base is common to both the input and output circuits). X2 like X1, is also a PNP transistor, which tells us the direction of electron flow through the transistor is *from* the base and collector, *into* the emitter. The arrows indicate the flow direction of the two transistor currents through X2; the collector-emitter current is in solid blue, and the base-emitter current in dotted blue.

To understand the biasing conditions which regulate the currents flowing through X2, let us refresh our memories on the two important conditions which control the flow of transistor currents. These conditions are the voltages at the emitter and base, and of course the difference between these two voltages.

The base-emitter current of X2 begins at the negative terminal of battery M1, flows through resistors R5 and R6, and then through the very small "forward" resistance of the base-to-emitter junction. From there it continues through resistor R4 to ground, where it has a free return access to the grounded positive terminal of M1. This is in every sense a voltage-divider action, and every point along the current path is at a lesser negative voltage than any preceding point.

We have already seen that during the positive half-cycles of Fig. 2-1, there is a decrease in both the base-emitter and collector-emitter currents through transistor X1. Since both currents flow through resistor R4, toward the ground connection at its lower terminal, any decrease in them will result in a smaller voltage drop across R4. This *smaller negative voltage,* at the upper terminal of R4, is applied directly to the emitter of X2. A smaller negative voltage at this emitter will *increase* the base-emitter biasing current through X2. This increase, and the inevitable increase in collector-emitter current, have been indicated in Fig. 2-1.

During the negative half-cycle shown in Fig. 2-2, both currents flowing through transistor X1 are increased, for reasons previously discussed. Since both must flow downward through R4, a greater voltage drop is generated across this resistor, and the upper terminal becomes more negative during this half-cycle. This more negative voltage is applied to the emittter of X2; hence, as with any PNP transistor, *less* base-emitter biasing current will flow through X2 and automatically reduce the collector-emitter current. These decreases have been indicated in Fig. 2-2.

With this preliminary understanding of voltage and current conditions around transistor X2, let us consider the common-base characteristics listed in Table 2-1. The most important one is the current gain. In the common-base configuration, current gain is similar to the alpha factor of the transistor—it can approach but cannot exceed unity. It can be expressed by this ratio:

$$\text{Current gain} = \frac{\text{Change in collector current}}{\text{Change in emitter current}}$$

Since the base and collector currents of any transistor must also flow through its emitter, the emitter current will always be somewhat greater than the collector current. Also, to achieve any particular change in the quantity of collector current requires a slightly greater change in the emitter current. The emitter is the input point in this type of circuit, and changes in the collector current can only be effected by larger changes in the emitter current. Consequently, the current gain in the common-base configuration, as expressed in the above formula, will always be a fraction less than unity—although in the average transistor, it will usually exceed .95 and will frequently be as high as .98.

$$\text{Voltage gain} = \frac{\text{Change in collector voltage}}{\text{Change in emitter voltage}}$$

Also,

$$\text{Voltage gain} = \text{Current gain} \times \text{resistance gain}$$

In the first formula, the voltage gain in reality is a comparison of output versus input voltages, since the voltage output is taken from the transistor collector, whereas the input is applied to the emitter. You have already seen that extremely small voltage differences between base and emitter voltages will cause significant changes in the amounts of the two currents through the transistor. In the common-base configuration, a small change in emitter voltage is either achieved or accompanied by a change in the base-emitter current flowing through the low-resistance input circuit. Simultaneously, a similar change occurs in the collector current flowing through the collector load resistance in the output circuit. Since this load resistance is usually many times larger than the resistance of the input circuit (through which the base-emitter current must flow), a large change in the voltage at the collector (collector voltage) will occur as a result of a small change in emitter voltage. This is what is meant by voltage gain.

The second formula for voltage gain is based on the Ohm's-law relationship between current, voltage, and resistance. "Resistance gain" has nothing to do with the intrinsic properties of a transistor, but just a convenient way to express the ratio between the resistances of the output circuit and input circuit, respectively. "Current gain" has already been defined as the ratio between output current and input current. Since input current must flow through the small input resistance, and since output current must flow through the large output resistance, the product of current gain and the so-called resistance gain will give the same voltage gain as the first formula.

Because current gain is less than unity in the common-base configuration, the voltage gain achieved by the above formula will be slightly less than the resistance gain.

Table 2-1 tells us that the input impedance of the common-base configured circuit is very low. Input impedance of any circuit can be expressed as a ratio between a given change in applied voltage (in this case, the emitter-voltage) and the resulting change in input current (in this case, the emitter current). We know that the two important biasing voltages of any transistor are those at the base and emitter, and that normally they differ by less than a volt. A small change in either voltage will cause a small change in the base-emitter biasing current, and lead to a much larger change in the collector-emitter current. Thus a small change in the applied voltage at the emitter will eventually produce a *large* change in the collector-emitter current, and the emitter current is composed largely of the collector-emitter current. Therefore, a small change in input voltage leads to a large change in input current (emitter current). This is the definition of a low-impedance circuit.

The output impedance of the common-base circuit is very high. The output impedance is the ratio between any change in applied voltage at the output point (the collector) and the resulting change in output (collector-emitter) current. Because of the "reverse-bias" nature of the collector-base junction, the collector voltage normally has very little control over the collector current. In the common-base circuit of Fig. 2-1, this lack of control is compounded by the fact that any change in collector current (brought about by a change in collector voltage) is largely nullified when the collector current flows downward through resistor R4, thereby developing a change in the important emitter biasing voltage which counter-acts the original change in the collector voltage. Perhaps an example will make this action clear.

Fig. 2-1 shows a half-cycle of operation during which the collector-emitter current of transistor X2 has been increased. Let us forget momentarily about the normal operating conditions responsible for this increase in collector-emitter current, and imagine for a moment that it was brought about by a large increase in the negative voltage applied to the collector (a difficult feat in any transistor!). As this increased collector current flows downward through emitter resistor R4, it develops a larger negative voltage at the upper terminal of R4, and also at the emitter of X2. In a PNP transistor, when the emitter voltage is made more negative (or less positive), less base-emitter biasing current flows and, in turn, less collector-emitter current. This is a form of degeneration. There are many examples of degeneration in tube and transistor circuits, and they all seem to be characteristized by the following two conditions:

1. An increase in electron-current flow through the tube or transistor will change the biasing conditions of the device in such a direction as to reduce the current through the device.

2. A decrease in electron-current flow through the device (usually on an alternate half-cycle) will change the biasing conditions in such a direction as to increase the current flow through the device.

"Phase inversion" of the input signal applied to the base of X1 has been accomplished by the complete circuit, because when the voltage at the collector of X1 becomes *more* negative, (as it did in Fig. 2-1), the voltage at the collector of X2 becomes *less* negative. Relating these important voltage changes to the electron currents which must actually flow in order to couple the voltage changes to the respective output circuits, we see electrons flowing *into* capacitor C1 in Fig. 2-1 and driving other electrons beyond C1, into the external circuit. This action "delivers" a negative voltage to that external circuit. Likewise, we see electrons being drawn out of capacitor C2. This action withdraws other electrons from the external circuit beyond C2 and, by so doing, "delivers" a positive voltage to that external circuit.

In Fig. 2-2 a half-cycle later, the increased collector current through X1 causes a smaller negative voltage to exist at the top of load resistor R3. Some portion of this increased current demand is supplied directly from C1, as electrons are withdrawn from its left plate. This action withdraws other electrons from the external circuit beyond C1, and thereby constitutes a positive voltage to the external circuit. The decreased collector current through X2 (and through R5) causes the voltage at the upper terminal of R5 to become *more* negative. This is symbolized by a flow of electrons onto the left plate of C2, and this action drives other electrons into the external circuit, beyond C2. The external circuit recognized the inflow of electrons as a negative voltage.

## THE COMMON-COLLECTOR CIRCUIT

Figs. 2-3 and 2-4 show two successive half-cycles in the operation of a typical common-collector circuit. The common-collector configuration has limited application and for this reason is not widely used. In this example it provides a high-impedance input circuit, in order to "match" this impedance with some equally high-impedance circuit which is providing the input voltage and current (doing the driving, in other words). The common-collector circuit also provides a low-impedance output. The primary purpose for including this type of circuit at this point in the book is to convey some measure of qualitative understanding of the characteristics listed in Table 2-1 for the common-collector circuit. Before these characteristics can be understood, all the currents which flow in the circuit, and the resulting voltages and their changes, should be clear in your mind.

## Identification of Components

This circuit includes the following components:

R1—Input resistor.
R2—Voltage-divider and biasing resistor.
R3—Voltage-divider, biasing, and input resistor.
R4—Emitter output resistor.
C1—Input coupling capacitor.
X1—PNP transistor.
M1—Battery or other DC power source.

## Circuit Operation

This circuit may quickly be recognized as a common-collector configuration by the process of elimination. The input signal is obviously applied to the base (or more accurately, between the base and ground). The output signal is obviously taken from the emitter (or between the emitter and ground). This leaves the collector, which is automatically "common" to both circuits. In the diagrams of Figs. 2-3 and 2-4, the collector technically is not grounded, but rather is connected to ground through the fixed voltage or power source M1. Power supplies, in practice, are usually bypassed by suitable filter capacitors, so that even at the lowest frequency of operation, signal-frequency currents will be bypassed around the power supply to ground. This filtering process is known as decoupling and is discussed at greater length in other volumes of this series. The presence of such a capacitor effectively places the collector at "ground" voltage to signal frequencies and thus enables us to say that it is a grounded-collector (or the more accurate common-collector) circuit.

Four electron currents are at work in this circuit. They are:

1. Input driving current, usually called the "signal" (blue).
2. Voltage-divider and biasing current (solid green).
3. Base-emitter biasing current (dotted green).
4. Collector-emitter current (red).

Let us momentarily ignore the presence of the signal current in Fig. 2-3, and consider only the currents which would flow during "static" conditions. First is the voltage-divider current, in solid green. It will flow continuously from the negative terminal of battery M1 and downward, through resistors R2 and R3, to ground. This current flow places a certain negative voltage at the junction of R2 and R3. Since the transistor base is connected directly to this point, this voltage constitutes the "base-biasing" voltage, and starts the initial flow of base-emitter current through the transistor. The base-emitter current is shown in dotted green; it also originates at the negative terminal of battery M1. Base-emitter current is known as "biasing" current because it regulates the flow of the much larger collector-emitter current (in red) through the transistor. When these two currents are established at their equilibrium values, they develop a voltage across resistor R4 because they must flow downward through R4 on their way to ground. This voltage, which is negative at the upper terminal, becomes the emitter "biasing" voltage. It must be less negative than the base voltage in a PNP transistor in order for any base-emitter biasing current to flow. The difference in the voltages at base and emitter normally is only a fraction of a volt, and only the tiniest change is required in either voltage to change the amount of base-emitter biasing current and consequently to bring about the much larger change in collector-emitter current.

The function of the applied signal voltage is to provide these necessary small changes in the voltage at the base. In the negative half-cycle of Fig. 2-3, the signal current is being driven *downward* through resistors R1 and R3. The small component of negative voltage developed at the top of R3 by the signal current must be added to the fixed negative voltage created at that point by the voltage-divider current. The result is *more* negative voltage at the base and in turn, an *increase* in both the base-emitter biasing current and collector-emitter current. These increases have been indicated in Fig. 2-3.

During the positive half-cycle of Fig. 2-4, the impressed signal voltage becomes positive and the signal current is drawn *upward* through resistors R1 and R3. This creates a small component of *positive* voltage at the upper terminal of R3, and a *less negative* voltage at the base. In a PNP transistor, the lower base voltage *decreases* the flow of both currents through the transistor, as indicated in Fig. 2-4.

The current gain of a transistor in the common-collector configuration approaches the beta value (10 to 100) of the transistor itself. Since only a small change in the base-emitter biasing current is necessary to achieve a much larger change in the collector-emitter current, the current gain is high.

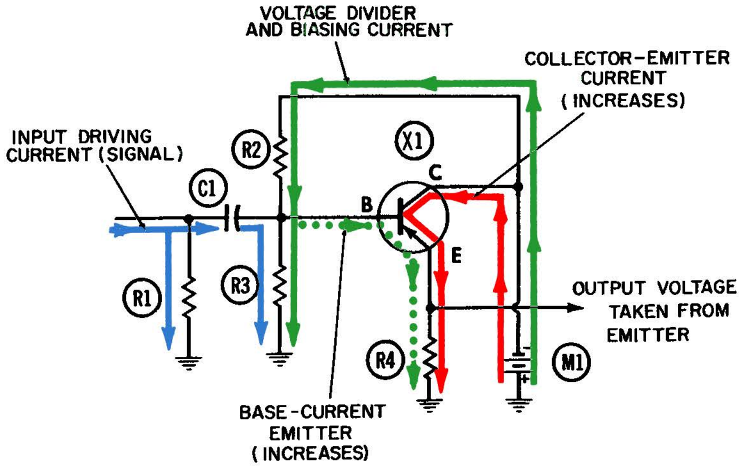



**Fig. 2-3. Operation of the common-collector configuration—negative half-cycle.**

The voltage gain is a comparison, or ratio, between the voltage change applied to the input and the resulting voltage change developed at the output. This gain cannot exceed unity in the common-collector configuration because the input and output voltages are also the two important biasing voltages for the transistor. It was previously stated that the voltages at the base and emitter are the biasing voltages, and that their

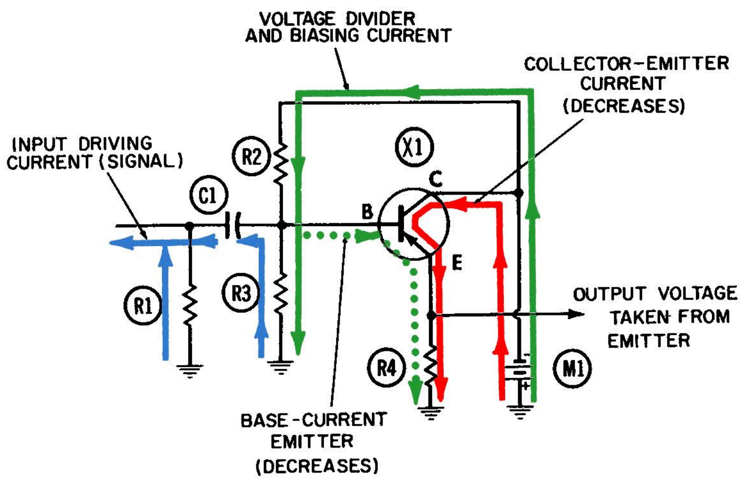



**Fig. 2-4. Operation of the common-collector configuration—positive half-cycle.**

difference is normally less than a volt. Also, it was stated that a very small change in either voltage will change the amount of the two currents flowing through the transistor.

Let us consider the example in Fig. 2-3, where the applied signal current flowing downward through R3 is of such a quantity that it develops −0.1 volt at the base. This bias is added to the negative voltage already there as a result of the voltage-divider current. A more negative base in a PNP transistor causes additional base-emitter biasing current and, in turn, additional collector-emitter current, to flow. Both of these increased currents must flow downward through emitter resistor R4; and in doing so, they increase the negative voltage already at the emitter.

If this increase in voltage at the emitter were to exceed −0.1 volt, then the *difference* between base and emitter voltage would be a smaller negative voltage than it was before the signal was applied. Consequently, instead of increasing as it should, the base-emitter biasing current would now tend to decrease, and so would the collector-emitter current.

To sum this action up, the voltage change at the emitter is the output voltage, and the voltage change at the base is the input voltage. The output-voltage change cannot exceed the input-voltage change without completely nullifying the latter. Therefore, the voltage gain of a common-collector configuration will always be less than unity.

Even though no voltage gain is available, this is not true for power gain in the common-collector configuration. Power gain is current gain multiplied by voltage gain, and even though voltage gain is slightly less than one, current gain may be high, as previously stated.

Table 2-1 indicates that the input impedance of a common-collector configuration is very high. This is due to the difficulty in effecting any significant change in base-emitter biasing current by making changes in the base voltage. We have already seen that this is true, because the collector current flows through the emitter resistor and acts to nullify any change in the base voltage. Impedance can always be thought of as a ratio between some voltage and an associated current. Input impedance is a ratio between the amount of change needed in the input voltage (base voltage) to change the input current (the base current, which is also the base-emitter biasing current). Because of the "self-compensating" nature of the circuit, it is extremely difficult to effect any change whatsoever in the biasing current. For this reason, the input impedance of the common-collector configuration is very high.

On the other hand, the output impedance of the common-collector is very low. The output impedance is a measure of the relative ease or difficulty with which the output current (collector-emitter current) can be changed by varying the output voltage (emitter voltage). Since the emitter voltage is one of the two important biasing voltages of any transistor, a change of only a volt or two at the emitter will cause a large change in the amount of base-emitter biasing current, and an even larger change in the amount of collector-emitter current.

## Chapter 3

# OSCILLATOR CIRCUITS

An oscillator is a nonrotating device which generates a signal at a frequency determined by the circuit constants. In this chapter the operation of the Hartley and Colpitts RF oscillators, which generate sinusoidal waveforms, and the multivibrator, which generates a nonsinusoidal waveform, will be discussed.

## THE HARTLEY OSCILLATOR

Figs. 3-1 and 3-2 show two alternate half-cycles in the operation of a transistorized version of the Hartley oscillator. This oscillator is widely used in commercial electronic equipment as well as in such household equipment as television and radio receivers.

### Identification of Components

The circuit components and their functions are listed below. The manner in which these functions are accomplished—in other words, *how the circuit operates*—will be discussed later in the chapter.

R1—Base-biasing and voltage-divider resistor.
R2—Voltage-divider resistor.
R3—Emitter stabilizing resistor.
R4—Collector load resistor.
C1—Feedback coupling capacitor.
C2—Emitter filter capacitor.
C3—Output coupling and blocking capacitor.
C4—Oscillating tank capacitor.
T1—Oscillating tank inductor and output inductor.
X1—PNP transistor.
M1—Battery power supply.

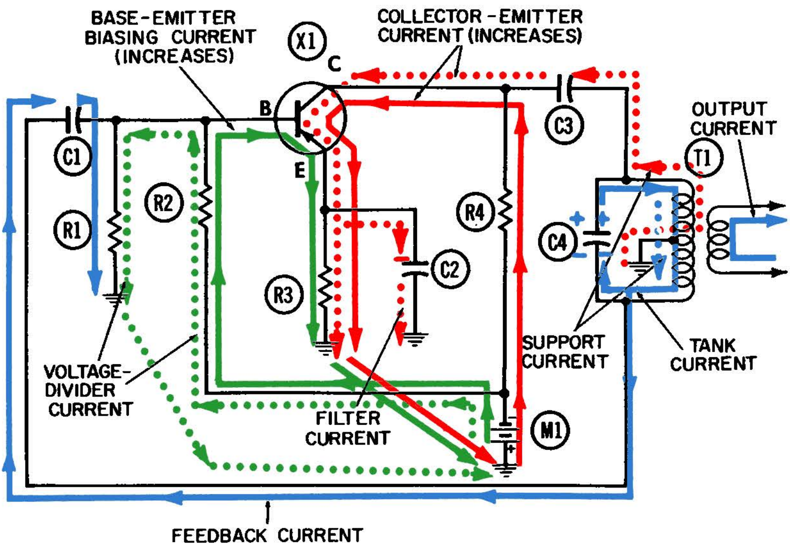



**Fig. 3-1. Operation of the Hartley oscillator—negative half-cycle.**

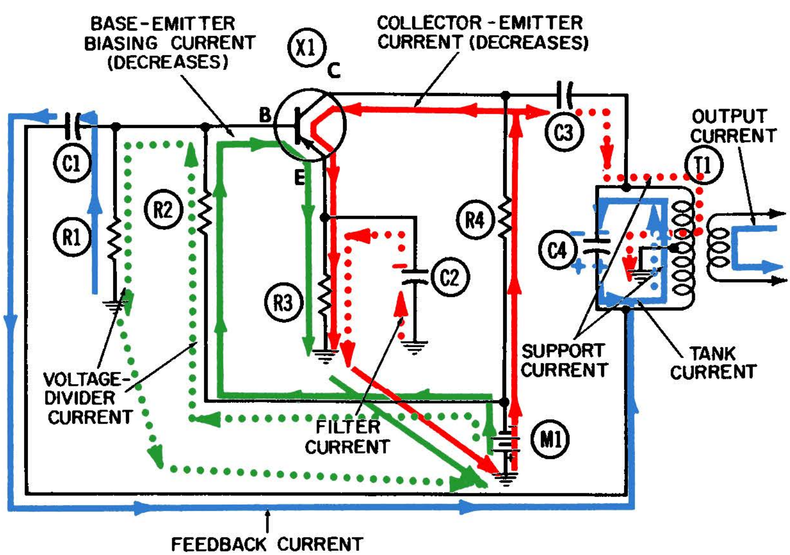



**Fig. 3-2. Operation of the Hartley oscillator—positive half-cycle.**

## Identification of Currents

The following electron currents are at work in this circuit, and it is necessary that their movements be understood before the operation of the circuit as a whole can be comprehended.

1. Voltage-divider current, used for base biasing (dotted green).
2. Base-emitter biasing current (solid green).
3. Collector-emitter current (in both solid and dotted red).
4. Oscillating tank current (solid blue).
5. Feedback current (also in solid blue).
6. Replenishment current for support of the oscillation (dotted blue).
7. Output current in transformer secondary (also in solid blue).

## Circuit Operation — Static Conditions

Fig. 3-1 has been labeled the negative half-cycle of operation, because during this half-cycle the feedback current flows *downward* through R1 and creates a more negative voltage at the upper end of this resistor. This voltage is applied directly to the base of the transistor as part of the base-biasing voltage.

Conversely, Fig. 3-2 is labeled the positive half-cycle, because the feedback current flows *upward* through R1, creating a less negative voltage at the upper end of this resistor.

A single battery, M1, provides electron current for both main current paths through any three-element transistor. These current paths are from base to emitter, and from collector to emitter. The complete path of the base-emitter current, in solid green, includes a trip upward through battery M1 and out through its negative terminal, then to the left, and upward through R2 to the base of the transistor. From the base, the current goes to the emitter *within* the transistor, and then downward through stabilizing resistor R3 to the common ground point. From here it has free access to re-enter the positive terminal of the battery.

This base-emitter current is frequently referred to as the "biasing" current of a transistor, because a small change in its amount will normally cause a much larger change in the amount of collector-emitter current flowing through the transistor.

The base-emitter current normally is not much more than a few microamperes, and it is regulated by the difference in the voltages at the base and emitter. This voltage difference is frequently no more than a tenth of a volt. The origins of these element voltages will be discussed as the other currents are described.

The complete path of the voltage-divider current (in dotted green) is from the negative terminal of battery M1, upward through resistor R2 and downward through R1 to common ground, where it has a ready return access to the positive terminal of the battery. Normally, R1 will be considerably smaller than R2 in value, so that most of the battery voltage will be "dropped" across R2. The voltage measured at the top of R1 is the biasing voltage, which is applied to the base of the transistor.

We might assume some typical values as follows:

$$\begin{aligned} \text{Let } R1 &= 1{,}000 \text{ ohms} \\ R2 &= 5{,}000 \text{ ohms} \\ M1 &= \quad -6 \text{ volts} \end{aligned}$$

Then, the voltage-divider current could be calculated from Ohm's law as follows:

$$\begin{aligned} I &= \frac{E}{R} \\ &= \frac{-6V}{5000 + 1000} \\ &= -1 \text{ milliampere} \end{aligned}$$

The voltage across R1 would then be:

$$\begin{aligned} E_1 &= IR_1 \\ &= .001 \times 1000 \\ &= 1 \text{ volt} \end{aligned}$$

and would have a *negative* value at the top of R1. The voltage across R2 would be:

$$\begin{aligned} E_2 &= IR_2 \\ &= .001 \times 5{,}000 \\ &= 5 \text{ volts} \end{aligned}$$

The complete path of the collector-emitter current (in solid red, and usually referred to as the collector current) is from the negative terminal of battery M1, then upward through collector load resistor R4, through the transistor from collector to emitter, and downward through emitter stabilizing or swamping resistor R3 to the common-ground connection. From here it is free to return to the grounded positive terminal of the battery.

The directions in which the two transistor currents flow are of course dictated by the nature of the transistor itself. The one used in this circuit is a PNP, as indicated by the emitter arrow pointing *toward* the base. This is a universal symbol, and the two electron currents always flow into the emitter in the direction *opposite* to that in which the arrow is pointing. The battery must necessarily be connected so that its polarity will support the electron-flow directions dictated by the construction of the transistor itself. With this or any PNP transistor, both the base and collector must be connected to a *negative* biasing voltage.

The base-emitter, collector-emitter, and voltage-divider currents described in the foregoing are "static" currents, in the sense that they flow continuously, whether an oscillation exists in the tank circuit or not. If no oscillation or feedback currents existed, these three currents would all be "pure" DC, with no fluctuations in value. However, if the circuit is properly connected, an oscillating current will spring into existence in the tuned tank circuit as soon as power is applied from the battery. Through the mechanics of the feedback connection, the collector current through the transistor will be increased or decreased in such a fashion that it will in turn support or replenish the oscillation of electrons in the tank current. The circuit is then said to be operating under "dynamic" conditions, during which all the additional currents for accomplishing the oscillation and replenishing it come into existence along with the currents for accomplishing the feedback or filtering action at the emitter and for delivering an output current to the next stage. Additionally, the two currents through the transistor become pulsating rather than pure DC. Let us examine the interrelationships between these currents.

## Operation Under Dynamic Conditions

As soon as power is applied to the transistor circuit, a small amount of electron current (solid green) will begin flowing through the transistor, from base to emitter, and immediately cause a much larger current to flow from collector to emitter. The latter current, in both solid and dotted red, initially is drawn both through load resistor R4 and also from the left plate of coupling capacitor C3.

Capacitor action is always such that when a certain number of electrons are drawn *away* from one plate, an equal number will be drawn onto the opposite plate from the external circuit. That is what happens here; the current being drawn onto the right plate of capacitor C3 is shown in dotted red lines. Its complete path is from ground, into the center tap and through the upper half of the transformer primary to the coupling capacitor.

As this current is drawn through part of the transformer, what is known as autotransformer action occurs throughout the entire primary winding. In any inductor, the fundamental electrical action is such that the inductor opposes any change in the amount of current flowing through it. Another way of saying this is that an inductor will try to keep at a constant value the current flowing through it.

We can visualize this fundamental inductor action by looking at the current being drawn upward through the upper half of the winding. During the first half-cycle depicted by Fig. 3-1, this current is flowing upward at an *increasing* rate. In so doing, it *induces* a second current (in dotted blue) to flow downward through the entire primary winding, also at an increasing rate. Because of its downward flow during the first half-cycle, the induced current delivers electrons to the lower plate of tank capacitor C4 and builds up a negative charge, or voltage, there.

This negative voltage drives electron current through the feedback line to the left plate of coupling capacitor C1, and this action in turn drives an equal amount of electron current *downward,* through biasing-and-driving resistor R1. This makes the voltage at the top of R1 more negative and, in effect, increases the "forward bias" at the base of the transistor, thereby driving *more* electron current from the base through the emitter than would normally flow under static conditions.

Action within the transistor will always be such that a small increase in the base-emitter current is accompanied by a large increase in collector-emitter current. Notice the cumulative nature of all the dynamic conditions described so far during the first half-cycle of Fig. 3-1: The initial surge of electron current (both solid and dotted red) into the collector caused autotransformer action within the primary winding, and the latter action placed a negative voltage on the lower plate of tank capacitor C4. The resulting feedback current through resistor R1 developed a voltage across it of such polarity as to *increase* the base-emitter current and to further increase the current entering the collector terminal.

Two independent circuit actions now occur and prevent these cumulative increases in both currents from continuing indefinitely. As the collector-emitter current increases, the voltage it develops across emitter resistor R3 will also increase. (This voltage will be negative at the top of R3.)

As the negative voltage at the top of R3 increases due to this increased collector current, the voltage-bias conditions between the base and emitter are affected adversely. In any PNP transistor, the voltage at the base must always be slightly *more* negative than the voltage at the emitter, in order for electron current to flow from base to emitter. Thus, the rise in collector current eventually *reduces* the base-emitter current which, in turn, reduces the amount of collector-emitter current flowing through the transistor.

This particular set of cumulative actions eventually reduces the collector-emitter current, bringing us to the conditions shown in Fig. 3-2. This is the logical moment to discuss the second independent action, which operates to keep the collector-emitter current from increasing indefinitely. This is the action of the tuned tank circuit, consisting of capacitor C4 and the primary winding of transformer T1. This tank is tuned to be resonant at the desired frequency of oscillation; and once the lower plate of C4 has been charged to its initial negative voltage, an oscillation of electrons between inductor and capacitor will automatically begin. During the second half-cycle shown in Fig. 3-2, the electrons initially stored on the lower plate of C4 will flow upward through the primary winding of transformer T1, until at the end of this half-cycle practically all of them will have been delivered to the upper plate of C4, placing a negative voltage on it and a positive voltage (a deficiency of electrons) on the lower plate.

This positive voltage on the lower plate of C4 reverses the flow direction of the feedback current, shown in solid blue. Electrons are now drawn from the left plate of C1 along the feedback line, toward the tuned tank. This in turn draws electron current *upward* through resistor R1 and creates a small *positive* voltage at its upper terminal. The small positive voltage partially neutralizes the permanent negative voltage which exists at this point because of the flow through R2 and R1 of the voltage-divider current shown in dotted green. The algebraic or instantaneous sum of these two voltages across R1—one a fixed negative voltage and the other a voltage which is constantly changing from negative to positive and back again—constitutes the complete biasing voltage present at the base of the transistor.

The voltage at the bottom of the tank circuit reaches its most positive value at the same moment the base-emitter current reaches its minimum value, and the collector-emitter current will in turn be reduced to its minimum value. This reduction is indicated in Fig. 3-2 by the absence of a dotted red line passing through the transistor. Electron current flowing upward through the load resistor R4 will be temporarily diverted onto the left plate of capacitor C3 during this second half-cycle, since it is unable to enter the collector terminal. This action accounts for the reversal in flow direction of the support current shown in dotted red. It now flows *away* from the right plate of capacitor C3 and downward, through the upper half of the transformer primary winding, to ground.

This replenishment current again supports the oscillation of the tank current during this half-cycle, by inducing in the entire primary winding a current which will again be in phase with the tank current. This induced current (dotted blue in Fig. 3-2) flows upward through the inductor. Being in phase with the tank current, it is therefore able to replenish the inevitable losses which occur in any oscillation, and thus permit the oscillation to continue indefinitely.

There are three main sources of loss which exist for this particular tank-circuit oscillation. The resistive wire losses within the inductor winding are inherent in any tank circuit. They cause a small percentage of electrons to drop out of oscillation during each half-cycle, so that the number which reach one capacitor plate at the end of any particular half-cycle is never quite as large as the number which left the other capacitor plate at the beginning of the half-cycle.

The electron current, which we call the feedback current and which is driven up and down through the biasing resistor R1 represents another source of loss to the tank-circuit oscillation. Consequently, it is always desirable to keep this feedback current as small as possible. This might be accomplished by making resistor R1 as large as possible. However, the overriding considerations in the choice of resistor values for both R1 and R2 are first, the amount of base-emitter current which the transistor requires for normal operation, and secondly, the amount of normal biasing voltage which should be provided to the base.

The third source of loss to the tank circuit is the support of the output current flowing in the secondary winding of transformer T1. This output current, shown in solid blue, flows up and down at the radio frequency generated in the tank circuit.

## THE COLPITTS OSCILLATOR

Figs. 3-3 and 3-4 show two successive half-cycles in the operation of a transistorized Colpitts oscillator. The circuit components and their functions are:

R1—Voltage divider or biasing resistor.
R2—Voltage divider or biasing resistor.
R3—Emitter stabilizing resistor.
R4—Collector load resistor.
C1—Filtering or bypass capacitor.
C2—Output coupling and blocking capacitor.
C3 and C4—Voltage-dividing capacitors in tuned tank circuit.
T1—Radio-frequency transformer.
X1—NPN transistor.
M1—Battery power supply.

## Identification of Currents

The following electron currents are at work in this typical oscillator circuit, and a thorough understanding of their movements is essential to an understanding of circuit operation, as well as to an ability to troubleshoot and repair the circuit or to modify its design or adapt it to various applications:

1. Voltage-divider current (dotted green).
2. Base-emitter current (solid green).
3. Collector-emitter current (solid red).
4. Oscillator tank current (solid blue).
5. Feedback current to the emitter (also in solid blue).
6. Output current in transformer secondary (also in solid blue).
7. Support current which supports the tank oscillation (dotted red).
8. Base-emitter filter current (solid green).

The first three are static currents, or DC, and they will flow whenever power is applied to the circuit, whether an oscillation exists in the tuned tank circuit or not. The remaining currents are directly associated with the oscillating tank currents, and are consequently known as "dynamic" currents.

## Details of Operation

The transistor base is brought to its desired bias voltage by voltage divider R1-R2 across battery M1. The voltage-divider current (dotted green) flows continuously in a clockwise direction around a closed circuit consisting of R1, R2 and M1. This clockwise flow is of course dictated by the polarity of the battery, since electrons must always leave a battery at its negative terminal and re-enter it at the positive terminal. Normally, R2 will be somewhat larger in resistance than R1, so that most of the battery or applied voltage is "dropped" across

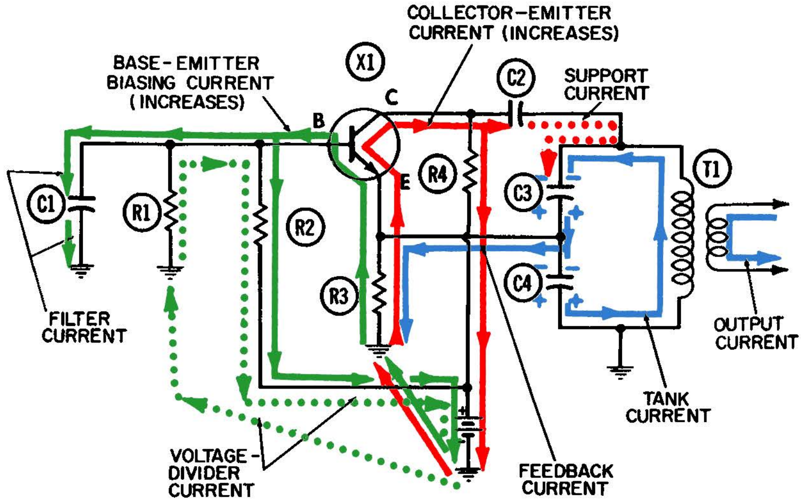



**Fig. 3-3. Operation of the Colpitt's oscillator—negative half-cycle.**

R2. The voltage at the junction of these two resistors is also the voltage applied to the transistor base.

The base-emitter current (in solid green in both circuit diagrams) flows around the closed path that begins at the negative terminal of the power supply (which in this circuit

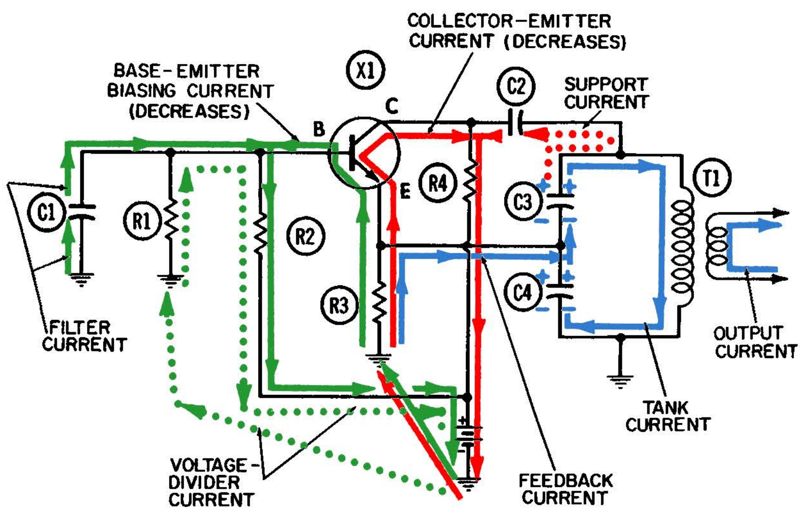



**Fig. 3-4. Operation of the Colpitt's oscillator—positive half-cycle.**

is connected to ground). This current flows upward through stabilizing resistor R3 and through the transistor, from emitter to base, then downward through resistor R2, and to the right where it re-enters the battery at its positive terminal.

The closed loop around which this base-emitter current flows obviously includes the three circuit elements consisting of R2, R3, and M1. But it also includes the semiconductor junction between the base and the emitter *within* the transistor. The external voltages applied to these two elements really determine how much of this base-emitter current can flow through the transistor and, consequently, around the entire loop. Normally, the base-emitter current will range from perhaps 100 microamperes, down to only a few microamperes.

The third of the three static currents in this circuit is the collector-emitter current, which flows continuously around its own closed loop in a clockwise direction. This current flow (shown in solid red) begins at the negative terminal of the battery. From here, the path is through ground to the lower end of emitter resistor R3 and upward through it to the emitter. The electrons enter the transistor at the emitter and exit at the collector, then flow downward through collector load resistor R4 and enter the positive terminal of the battery.

The fact that an NPN transistor is used here determines the directions of both of the currents which actually flow through the transistor. The emitter arrow points *away* from the base in an NPN transistor, and you will recall that the electron currents through a transistor *always* flow *against* the direction of the emitter arrow.

The amount of collector-emitter electron current which flows around the closed loop discussed previously is determined almost entirely by conditions within the transistor, rather than by the particular voltage value applied to the collector. The overriding condition within the transistor is the amount of base-emitter current flowing. The fluctuations in this small current control the fluctuations in the much larger collector-emitter current. This phenomenon will be discussed in considerably more detail later.

## Operation Under Dynamic Conditions

The manner in which an oscillation is set up in the tank circuit can be visualized by referring to Fig. 3-3, which is labeled the negative half-cycle of operation. As soon as power is applied to the circuit, the base-emitter current (in solid green) will flow through the transistor in the direction shown. As explained in connection with Figs. 1-8 and 1-9 of Chapter 1, the quantity of electrons *within* the base at any instant directly affects and controls the quantity of electrons which can flow through the base between emitter and collector—in other words, the amount of collector-emitter current which can flow.

The initial surge of collector-emitter current delivers electrons to the upper terminal of load resistor R4, and also onto the left plate of coupling capacitor C2. By normal capacitor action, these electrons cannot enter one side of a capacitor unless an equal number are driven away from the opposite side. The electrons which are driven away (dotted red) flow down into the tuned tank and set up the oscillation of electrons shown in solid blue. Once any voltage or current unbalance is applied to a resonant tank circuit, electrons will be set in oscillation between the tank capacitor(s) and tank inductor. This oscillation, even if unsupported, will continue for many cycles—depending on the strength of the initial disturbance and on the *Q*, or quality, of the tank circuit.

Fig. 3-4 shows a second half-cycle of this tank-circuit oscillation occurring. Electrons now flow downward through the transformer primary, which acts as the necessary inductor for the tank circuit. As a result of this flow, electrons are removed from the upper plate of capacitor C3 and eventually delivered to the lower plate of C4. The current flows downward throughout this entire second, or positive, half-cycle, with maximum voltage (indicated by minus signs on the lower plate of C4 and plus signs on the upper plate of C3) occurring across the tank at the end of the half-cycle.

## How Feedback is Accomplished

Feedback is accomplished in this oscillator by connecting the emitter to the point between C3 and C4. These two tank capacitors constitute a capacitive voltage divider. The two voltages across them are in series, and they add to equal the total voltage existing across the tank circuit at any instant. The portion of the total tank voltage across C4 is applied directly to the emitter as the feedback voltage. It is perhaps easier to visualize this feedback voltage if you also visualize the feedback current which must flow in conjunction with it. This current (in solid blue), flows to the left and *downward* through emitter resistor R3 during the negative half-cycle of Fig. 3-3, adding a small amount of negative voltage to the positive voltage already existing at the emitter. The latter is produced by the upward flow of the base-emitter and collector-emitter currents through resistor R3. Thus, the effect of the feedback voltage, during the negative half-cycle of Fig. 3-3, is to slightly reduce the positive voltage at the emitter and thereby *increase* the amount of base-emitter current.

This small increase in base-emitter current causes a much larger increase in the collector-emitter current. The extra collector current delivers more electrons onto the left plate of coupling capacitor C2, and in turn adds electrons (dotted red) to those being driven down into the tuned tank circuit. Since the electrons in dotted red arrive at the tank circuit in the appropriate phase (meaning at the appropriate time) to support or reinforce the oscillation of electrons within the tank, the feedback is said to be "regenerative."

In Fig. 3-4 the total voltage across the tuned tank circuit is positive, as indicated by plus signs on the upper plates of tank capacitors C3 and C4. The fraction of the total tank voltage across C4 now draws electrons upward through emitter resistor R3, and also adds a small increment of positive voltage to the positive voltage already existing at the top of R3. Since the top of R3 is connected directly to the emitter, the positive voltage already at the emitter increases slightly and thereby reduces the base-emitter current.

Transistor action will always be such that a small decrease in base-emitter current will cause a much greater decrease in collector-emitter current. When the collector current decreases, the support current between capacitor C2 and the tank circuit now reverses direction and flows upward, away from the tank and toward capacitor C2. Again, this flow direction supports the oscillation in the tuned tank. Thus, we see that both the increases and decreases in collector current deliver reinforcing impulses to the oscillation in the tuned tank.

Since emitter resistor R3 is not bypassed by a filter capacitor, degeneration will occur as a result of the changes in collector current. Degeneration is synonymous with loss of amplification. To see how it occurs, we need to consider the voltage changes produced at the top of R3 by the variations in collector-emitter current flowing through it.

Three electron currents flow independently through resistor R3—the base-emitter, collector-emitter, and feedback currents. The effects of the feedback current on the collector-emitter current have already been discussed, and need not be reconsidered here. Although the base-emitter current changes in value from half-cycle to half-cycle, the amount—in comparison with the changes in collector-emitter current—is insignificant. Consequently, voltage changes generated by these current changes across R3 are so negligible that they may be disregarded.

This brings us to the collector-emitter current (frequently referred to in many books as the collector current). At the start of the negative half-cycle of Fig. 3-3, the collector current will have been reduced to its minimum; and as a result of its flow through R3, a small component of positive voltage will exist at the top of R3. At the end of this half-cycle, a much larger collector current will be flowing, and hence a much larger positive voltage will exist at the top of R3 and also at the emitter.

This larger positive voltage, at the emitter of an NPN transistor, has an adverse effect on the bias conditions existing between base and emitter. The end result is to *reduce* the base-emitter current. This is contrary to the effect of the feedback current and voltage, which at the end of the same negative half-cycle will *increase* the base-emitter current.

The feedback voltage developed across resistor R3 is in reality the signal, or driving, voltage for the whole transistor circuit. Whenever a feedback voltage and the resulting transistor current are out of phase with each other, then degeneration is said to be occurring.

Degeneration also occurs during the positive half-cycle of Fig. 3-4. At the end of this half-cycle, the feedback voltage across R3 is positive, reducing the two currents through the transistor and R3. The latter flows upward through R3, reducing the positive voltage across this resistor and thus partially counteracting the increase in positive voltage caused by the feedback. This is degeneration; and as stated before, its effect is to lower the amplification from that which the circuit would normally deliver.

Resistor R2 and the battery are bypassed (or filtered) by capacitor C1, so that degeneration does not occur in this part of the circuit. The fluctuations in base-emitter current through R2 would normally change the voltage at the base of the transistor, and these voltage changes would affect the amount of base-emitter current. As an example, the increase in base-emitter current indicated in Fig. 3-3 would normally cause a greater voltage drop across R2 which would *lower* the positive voltage at the top of R2. Since this voltage is applied directly to the base of the transistor, less base-emitter current would flow.

This would be degeneration, which is avoided by having filter capacitor C1 in the circuit. It, along with R2, constitutes a conventional long time-constant circuit. In Fig. 3-3, excess electrons flowing through the transistor from emitter to base (the base-emitter current) will accumulate on the upper plate of capacitor C1 and drive an equal number away from the lower plate. This is the filtering current and is shown in solid green. On the positive half-cycle of Fig. 3-4, when the base-emitter current is reduced, the excess electrons driven onto the upper plate of C1 will now drain off, through resistor R2, to the positive terminal of the power supply or battery.

As long as this filtering is permitted, the base-emitter current will be fairly pure or constant direct current during its passage through R2 and the battery. For the remainder of its journey through resistor R3 and the transistor, it is pulsating DC. Since the base-emitter current through R2 is pure DC, the voltage it develops across R2 will be constant, and the voltage applied to the base will be steady from one half-cycle to the next.

Normal transformer action between the primary and secondary windings of T1 induces an output current in the secondary, as shown in solid blue in Figs. 3-3 and 3-4. This output current normally is used to develop the driving voltage for succeeding amplifier stages.

## THE FREE-RUNNING MULTIVIBRATOR

Figs. 3-5 and 3-6 show two successive half-cycles in the operating of a typical transistorized multivibrator circuit. The title "free-running" is applied to any multivibrator which oscillates continuously. Such a multivibrator is said to be "bistable"—as opposed to a one-shot, or "monostable," multivibrator where each cycle of oscillation must be initiated by a separate trigger pulse.

### Identification of Components

This circuit is composed of the following components:

R1—Voltage-divider and collector load resistor for X1.
R2—Voltage-divider and filter resistor.
R3—Voltage-divider and base biasing resistor for X2.
R4—Voltage-divider and collector load resistor for X2.
R5—Voltage-divider and filter resistor.
R6—Voltage-divider and base-biasing resistor for X1.
R7—Emitter stabilizing resistor for both transistors.
C1—Coupling capacitor between X1 collector and X2 base.
C2—Coupling capacitor between X2 collector and X1 base.
C3—Emitter bypass capacitor for both transistors.
X1—PNP transistor.
X2—PNP transistor.
M1—12-volt battery power supply.

### Identification of Currents

At least ten electron currents flow in this circuit. Once their movements and significance are thoroughly understood, their associated voltages likewise become easy to understand. These ten electron currents are:

1. Voltage-divider current, which provides "bias" voltages for the collector of transistor X1 and the base of X2 (solid red).
2. Collector-emitter current for transistor X1 (dotted red).
3. Base-emitter current for transistor X2 (also in dotted red).
4. Voltage-divider current, which provides "bias" voltage to the collector of transistor X2 and the base of X1 (solid green).
5. Collector-emitter current for transistor X2 (dotted green).
6. Base-emitter current for transistor X1 (also in dotted green).
7. The instantaneous pulsation of current, which flows at the *beginning* of the first half-cycle and cuts off all current flow through transistor X2 (solid blue).
8. The instantaneous pulsation of current which flows at the *beginning* of the second half-cycle and cuts off all current flow through transistor X1 (dotted blue).
9. The long time-constant discharge current flowing between capacitor C1 and resistor R2 (also in dotted blue).
10. The long time-constant discharge current flowing between capacitor C2 and resistor R5 (also in solid blue).

### Details of Operation

As soon as power is applied to this circuit, the two voltage-divider currents shown in solid red and solid green, respectively, will begin to flow. The flow directions of both currents are as shown in Figs. 3-5 and 3-6. The path of the first current (in solid red) is upward from the negative terminal of battery M1, through resistors R1, R2, and R3 to the common ground connection. The path of the second current (in solid green) is upward from the battery, and through resistors R4, R5, and R6 to ground.

These electron flow directions tell us that the voltage at the left end of resistor R2 (collector voltage of X1) must be more negative than the voltage at the right end of R2, because electrons inevitably flow from more negative to less negative areas.

Fig. 3-7 shows the relationships between the two collector and two base voltages. At the beginning of the first half-cycle, transistor X1 starts to conduct electrons from collector to emitter. This collector-emitter current (dotted red in Fig. 3-5) follows the expected path for a PNP transistor. This is upward from the negative terminal of M1, through resistor R1, into the collector and out the emitter of X1, then down through common emitter stabilizing resistor R7 to ground. Here it has ready return access to the positive terminal of battery, which is connected to ground.

The fact that two currents are now flowing side by side upward through R1 causes a greater voltage drop across R1 than before. Since the voltage at the battery end of R1 is fixed at −12 volts, the voltage at the top of R1 must become *less* negative. As a rough example, the voltage at the collector of X1 (line 1 of Fig. 3-7) is shown increasing abruptly from −8 to —4 volts.

As soon as this voltage begins to change (at the start of the first half-cycle), the voltage at the base of transistor X2 also begins to go in the positive direction because of coupling capacitor C1. This action quickly cuts off the flow of base-emitter current through transistor X2, because in a PNP transistor the base must be less negative than the emitter in order for this current to flow. And since the base-emitter current is the "biasing" current which causes or permits the other current to flow between collector and emitter, both currents through transistor X2 are cut off immediately at the first half-cycle.

Now only one current will be flowing upward through resistor R4 instead of two. As a result, the smaller voltage drop across R4 causes the negative voltage at the upper terminal of R4 to become *more* negative.

This increase in negative voltage at the collector of X2 is passed to the base of X1 via coupling capacitor C2. A more negative base voltage on any PNP transistor acts to *increase* the base-emitter biasing current, and also the collector-emitter current. The rise in collector-emitter current through X1 further raises the voltage at the collector of X1, making the collector voltage still less negative and in turn contributing further to the positive voltage at the base of X2.

All the events described in the foregoing are cumulative and occur at the very beginning of the first half-cycle, so that as transistor X1 goes from zero to full conduction, X2 goes from full conduction to zero, or "cutoff."

At the start of the second half-cycle, the opposite sequence will occur—X1, which is conducting, will end up cut off, and X2 will go into full conduction. This sequence is initiated by the discharge action which has been occurring between capacitor C1 and resistor R2 throughout the entire first half-cycle.

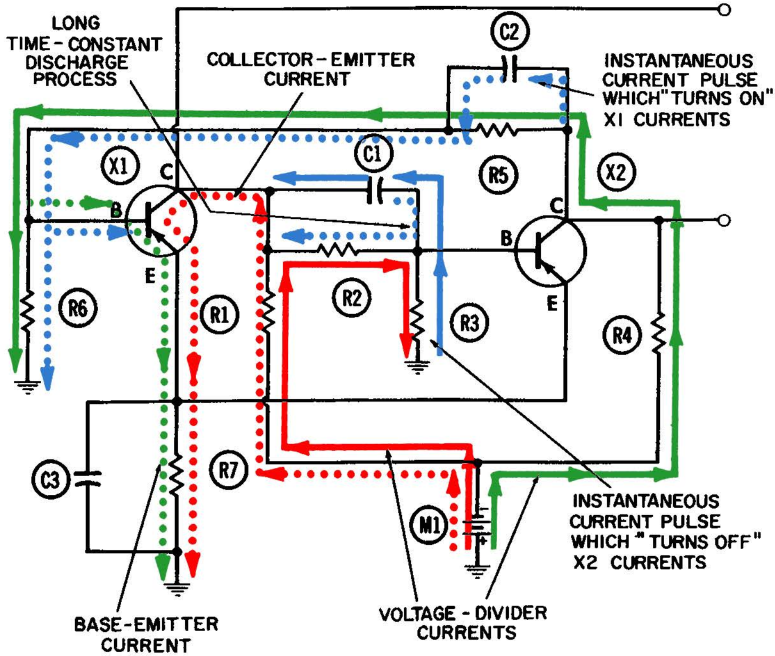



**Fig. 3-5. Operataion of the free-running multivibrator—first half-cycle.**

Line 2 of Fig. 3-7 shows the voltage at the base of transistor X2 throughout the entire cycle. This waveform, during the first half-cycle, resembles an "exponential" discharge or charging curve and is actually the result of several actions to be described later. There is one significant fact about any free-running multivibrator, whether it uses vacuum tubes or transistors as the switching devices: when one begins to conduct electrons, it changes the bias voltage on the other and thereby cuts it off. The latter will remain cut off until an RC discharge action can take place. After the discharge has been completed, the device which was cut off will begin to conduct again, initiating a new half-cycle. The duration of each half-cycle is therefore regulated by the values of resistors and capacitors being discharged.

It is evident from Figs. 3-5 and 3-6 that transistor X1 conducts its two currents during the first half-cycle only, and that transistor X2 conducts its two currents during the second half-cycle only. The base-emitter current for X1 (dotted green in Fig. 3-5) may be considered an offshoot of the voltage-divider current (solid green) which flows continuously through divider resistors R4, R5, and R6. The base-emitter current,

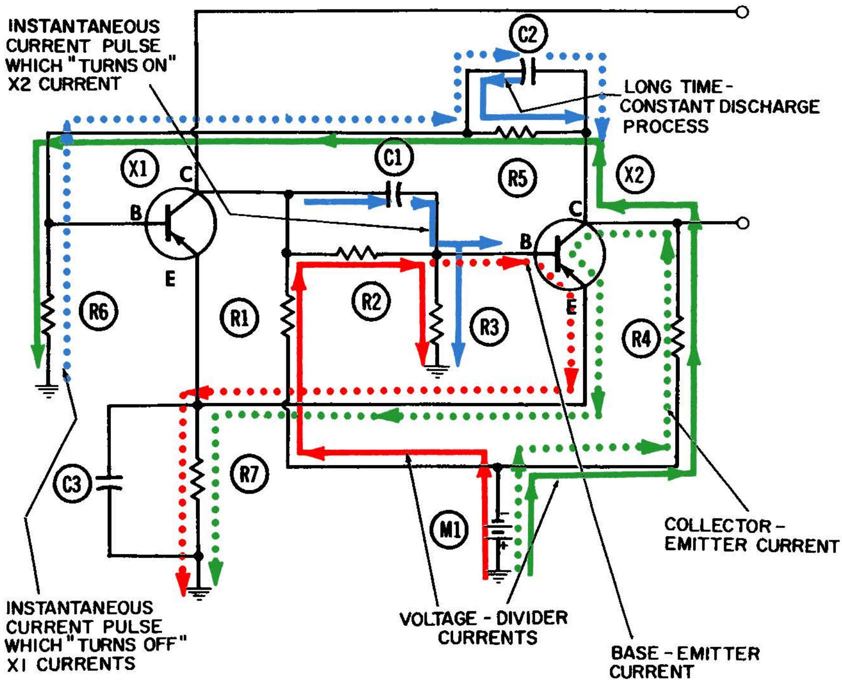



**Fig. 3-6. Operation of the free-running multivibrator—second half-cycle.**

which is the "biasing" current for X1, enters the base and exits from the emitter (normal flow direction for the PNP transistor). It then flows downward, through stabilizing resistor R7, to ground. From here it can re-enter the grounded positive terminal of battery M1. This current will flow only when the base of X1 is more negative than the emitter.

The base-emitter current of X2 (dotted red in Fig. 3-6) may be looked on as an offshoot of the other voltage-divider current which flows continuously through R1, R2, and R3. The former enters the base of X1 and exits from the emitter, then flows down through R7 to ground. Like its companion current in the other transistor, the base-emitter current through X2 can flow only when the base of X2 is more negative than the emitter. This mandatory set of conditions is implied by the descriptive term "forward bias."

## The Instantaneous Current Pulses

Figs. 3-5 and 3-6 show two currents which are best described as instantaneous pulses of current. It is necessary to understand the movements of both in order to understand how each transistor is turned on or cut off. Let us consider the actions which occur at the start of the first half-cycle. You have already seen how the X1 collector voltage becomes *less* negative when collector current begins its flow. The extra electrons necessary to make up this increased current cannot be drawn immediately through resistor R1, but must be taken from the left plate of coupling capacitor C1. This can occur only if an equal number of electrons are drawn onto the right plate. These electrons must be drawn upward through resistor R3; there is no other circuit component through which they can possibly come.

In flowing upward through R3, this electron current (in solid blue) inevitably is associated with a voltage which is positive at the top of R3, because electrons flow away from negative-voltage areas and toward positive-voltage areas. This electron flow is of course opposite to the continuously downward flow of the voltage-divider current (in solid red). Thus, during the first half-cycle, two currents are flowing in opposite directions through the same resistor, R3, and developing two components of voltage which are opposite in polarity across it. The voltage at the base of X2, at any instant, is the algebraic sum of these two voltages. At the start of the first half-cycle, the positive voltage clearly predominates. This can only mean that the instantaneous current pulse which is shown in solid blue, and which is equal to the *change* in collector current being drawn into X1, is *much larger* than the voltage-divider current flowing downward through R3.

The discharging action between capacitor C1 and resistor R2 is a difficult one to visualize. It begins at the start of the first half-cycle and continues throughout the half-cycle. The electron current that actually does the discharging has been shown in dotted blue, to differentiate it from the instantaneous current, in solid blue, moving to the left along the capacitive path represented by C2. The path of this discharge current is from the right plate, through resistor R2, to the left plate of C2.

It can be looked upon as an equalizing current, which must flow to correct or redistribute the unbalance of electric charge between the two plates of capacitor C2. It flows at what is called an *exponential* rate, a term derived from higher mathematics and beyond the scope of this book. For our purposes, it describes a discharge process which begins at a high rate and continues at a decreasing rate to zero. Theoretically, no quantity can ever be decreased to zero by this system, because, during each unit of time a certain percentage of the quantity that existed at the beginning of the unit of time will be discharged. Hence, some fraction of the original quantity, however small, will always exist. Practically, five time periods are sufficient for charge redistribution to occur between a capacitor and resistor.

An exponential discharge curve is shown in the first half-cycle of Line 2, Fig. 3-7. This portion of the curve actually represents the intrinsic voltage at the base of X1. However, it also *resembles* the quantity of discharge current flowing between C1 and R2 during the same half-cycle—namely, a large current to start with, and decreasing exponentially throughout the entire half-cycle.

By momentarily considering this RC combination isolated from all other circuit components, it will be fairly simple to visualize the discharge action. When the left plate of C1 is made more positive than the right plate, electrons will flow, or "discharge," through resistor R2 in the direction shown in Fig. 3-5. This discharge will continue until there is no longer any charge unbalance between the plates, meaning there is no voltage across the capacitor. However, this RC combination is *not* isolated from the rest of the circuit. Instead, across resistor R2, there is a permanent, or fixed, voltage difference caused by the flow of voltage-divider current (in solid red). This permanent voltage difference also exists across the capacitor plates, making the left plate more negative than the right.

This permanent voltage across C1 is momentarily upset or modified by the sudden change in collector voltage at the start of the first half-cycle. The collector voltage moves abruptly in the positive direction by an amount assumed to be 4 volts, or from −8 to −4 volts. If the voltage on the right plate of C1, as well as at the base of transistor X2, was assumed to be −1 volt before, it must now increase in the positive direction by the same 4 volts, to a new instantaneous value of +3 volts. This positive peak value of the X2 base voltage (Line 2, Fig. 3-7) will cut off both currents through X2, and they will remain cut off until the base can again be made more negative than the emitter (which does not occur until the end of the first half-cycle).

To sum these actions up, the *total* current through resistor R2 always flows from left to right. The instant before the first half-cycle begins, the total current consists exclusively of the voltage-divider current (in solid red). The amount is determined by the Ohm's-law relationship between the combined series resistances of R2 and R3 and the −8 volts at the collector of X1.

The instant before the first half-cycle ends, and while X1 is still conducting, the total current through R2 again consists exclusively of the voltage-divider current shown in solid red.

Its amount has changed, however, because the voltage at the collector of X1 has dropped from −8 to −4 volts. This would indicate that the voltage-divider current has been reduced by exactly one-half.

This change in amount of current *during* the first half-cycle might be looked on as an exponential *reduction* in the current flowing from left to right. Such a reduction must occur because, the instant before the first half-cycle starts, the voltage difference across R4 is 7 volts (−8 volts at the left end and −1

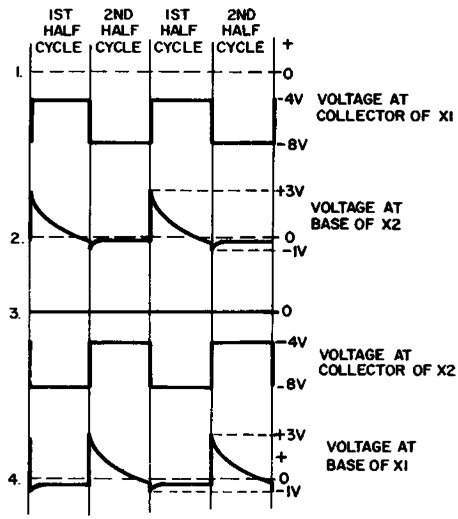



**Fig. 3-7. Voltage waveforms in the free-running multivibrator.**

volt at the right end), whereas the instant before this half-cycle ends, this voltage difference is only 3 volts (−4 volts at the left end and −1 volt at the right end, after the capacitor discharge).

## The Second Half Cycle

How current conduction is initiated through X2 at the start of the second half-cycle has already been discussed. The expected series of cumulative actions occurs almost instantaneously. As the collector voltage of X2 begins to rise from −8 to −4 volts, it raises the base voltage at X1 in the positive direction, cutting off both currents through X1. In turn, the X1 collector voltage is driven from −4 to −8 volts. This tends to drive the base of X2 even more negative, and quickly leads to full electron conduction through X2.

The base voltages cannot be driven as far negative as they can be positive. This is due to the "forward bias" condition of each transistor. As soon as the base of any PNP transistor becomes more negative than the emitter, electrons flow very freely from base to emitter. The reason is that the diode junction, N to P, has very little resistance in the so-called "forward" direction. Another way of saying this is that the forward-biased junction "short-circuits" the base resistors. This does not occur when the base-emitter junctions are reverse-biased. In Fig. 3-6, for example, the instantaneous current (in solid blue) flows downward exclusively through R3 as long as the base is less negative than the emitter. The moment the base becomes more negative, this current pulse is largely diverted through the much lower resistance path represented by the diode junction and resistor R7.

In Fig. 3-5, the instantaneous pulse current (in dotted blue) flows exclusively through R6 until the diode junction between base and emitter becomes forward-biased and offers a much lower resistance path.

Resistor R7 serves to prevent thermal runaway of either transistor. Both transistor currents must flow downward through R7 to ground, and this continuing current flow keeps both emitters at a small negative voltage. Thermal runaway is an undesirable, cumulative condition whereby an overheated transistor begins to conduct larger quantities of both currents, and the increased conduction further aggravates the overheated condition. With an emitter stabilizing resistor such as R7 in the circuit, any runaway current condition is quickly checked by the resulting increase in negative voltage at both emitters because an increase in negative voltage at a PNP emitter will reduce or cut off the currents through the transistor. Thus, a stabilizing resistor automatically prevents thermal runaway.

Relatively little has been said about the instantaneous pulse current, (in dotted blue) which flows through C2 and R6 and "turns off" the currents through X1; nor about the long time constant discharge current (in solid blue) which flows between C2 and R5 and eventually turns the transistor currents back on again. The movements of these currents are associated with the voltages shown in Lines 3 and 4 of Fig. 3-7. Observe that the square wave of voltage generated at the collector of X2 is exactly a half-cycle out of phase with the collector voltage of X1. Also, the exponential voltage waveforms at the two bases are exactly a half-cycle out of phase with each other.

Because of the similarity in physical action between the pulse currents and the exponential discharge currents for the two transistors, there is no need to discuss this set of currents—their action is the same as for the set already discussed.

# Chapter 4

# AMPLIFIER CIRCUITS

An amplifier receives a signal and "boosts" it to a higher level for application to another amplifier or to an output device. The operation of four types of amplifier circuits is discussed in this chapter. All are audio amplifiers; however the same basic principles apply to RF amplifiers except, of course, the component values are different and transformer coupling is usually employed.

## CLASS-A AUDIO AMPLIFIER

Figs. 4-1 and 4-2 show two successive half-cycles in the operation of a typical audio-amplifier circuit which utilizes transformer coupling to the next stage. The circuit is classified as a Class-A amplifier because the collector-emitter current flows continuously during the entire cycle.

### Identification of Components

The following components perform necessary functions in this amplifier circuit:

R1—Voltage divider and biasing resistor.
R2—Voltage divider and biasing resistor.
R3—Emitter stabilizing resistor.
C1—Input coupling and blocking capacitor.
C2—Emitter bypass or filter capacitor.
T1—Audio-frequency output transformer.
X1—NPN transistor.
M1—Battery or other DC source.

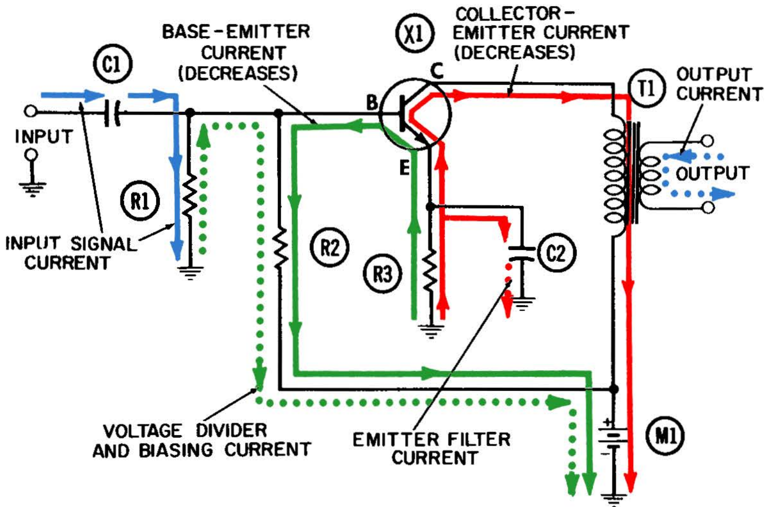



**Fig. 4-1. Operation of the Class-A amplifier—negative half-cycle.**

## Identification of Currents

A total of six different electron currents perform the various essential functions in this circuit. The currents are:

1. Voltage-divider current (dotted green).
2. Base-emitter current (solid green).
3. Collector-emitter current (frequently referred to as the collector current; solid red).
4. Input signal current (solid blue).
5. Output signal current (dotted blue).
6. Emitter filter current (dotted red).

The first three are static currents, which begin to flow as soon as power is applied to the circuit. In the absence of an applied signal voltage or current, these three static currents will be essentially pure DC. When a signal voltage is applied to the circuit to be amplified, the base-emitter and collector-emitter currents will become pulsating DC.

As soon as a signal voltage is applied, the circuit is then operating under dynamic conditions, and the latter three currents will come into existence.

## Details of Operation

The current through resistors R1 and R2 (shown in dotted green) flows clockwise into the positive terminal of battery M1

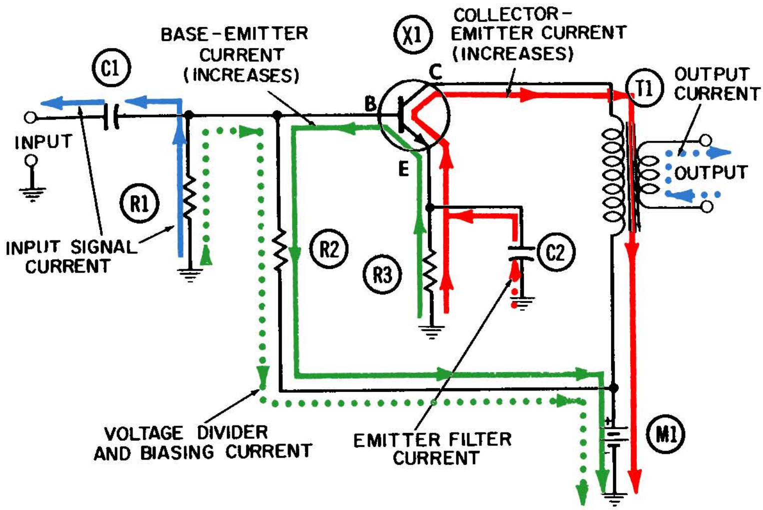



**Fig. 4-2. Operation of the Class-A amplifier—positive half-cycle.**

and out the negative terminal, returning to the lower terminal of R1. The use of two or more resistors across a fixed voltage source is a very common means of obtaining some fraction of the total voltage available. It is a particularly valuable technique in transistor circuits, which require only 1 or 2 volts for biasing the base with respect to the emitter, and another voltage perhaps three to five times as large—*but always of the same polarity*—for biasing the collector with respect to the emitter.

These requirements can of course be met by two separate voltage sources or batteries, but it is usually desirable to have as few batteries as possible in any circuit. Since the current drain on batteries in transistor circuits is normally very small, the power losses incurred by a voltage-divider current such as this one are well compensated for by the elimination of a separate battery for providing low-voltage bias between base and emitter.

The base-emitter current flowing through a transistor connected like this one will normally be only 10 or 20 microamperes. This current (in solid green) flows upward from ground through resistor R3 and through the NPN transistor, from emitter to base. It then goes to the right, down through resistor R2, and enters the positive terminal of M1. The current then flows through the battery and out its negative terminal, to common ground.

The collector-emitter current flows in a clockwise direction through the closed loop which starts at ground, then upward through resistor R3, through the transistor from emitter to collector, downward through the primary winding of transformer T1, and into the positive terminal of battery M1. Like the two other static currents, this one must also flow *through* the battery, from the positive to the negative terminal (ground).

This circuit does not function as an amplifier until a signal voltage is applied to its input circuit. Its purpose is to amplify, or increase the strength of, this signal voltage. Let us consider now how this important function is accomplished. An alternating signal voltage at an audio frequency will be applied to input capacitor C1. The result is that a signal current (shown in solid blue) will be made to flow, at the same frequency, up and down through input driving resistor R1. Fig. 4-1 has been labeled the negative half-cycle, because this input signal current flows *downward* through R1 and develops a small component of negative voltage across this resistor. This negative component must be subtracted from the positive voltage developed across this same resistor by the voltage-divider current. The net result, during the negative half-cycle shown in Fig. 4-1 is a reduction in the positive voltage applied to the base of the transistor. Since this is an NPN, less electron current flows from emitter to base.

Probably the most important single truth in the internal physics of the transistor action is that a *slight* increase (or decrease) in the emitter-to-base (or base-to-emitter) current will produce a much larger increase (or decrease) in the emitter-to-collector (or collector-to-emitter) current. This is the central fact that enables the transistor to be used as an amplifier.

In Fig. 4-1, the voltage to be amplified is negative and therefore drives a signal current (solid blue) *downward* through R1, making the top of this resistor negative. As a result of this negative biasing action at the base, the main electron stream through the transistor (the collector-emitter current) is reduced to its minimum value. This *decrease* in current flowing downward through the primary of output transformer T1 causes the current to flow in the same direction in the secondary winding. This is normal transformer action at work, and it accounts for the output current (in dotted blue) flowing downward in the secondary in Fig. 4-1.

In Fig. 4-2, the phase of the input signal voltage is reversed. Being positive, it now draws the signal-current electrons *upward* through resistor R1, adding to the positive voltage already created there by the upward flow of voltage-divider current (in dotted green). The higher positive voltage increases the flow of both transistor currents; and as more collector current flows downward through the primary, more output current flows upward in the secondary.

The transformer action is probably the most difficult of the five basic electronic actions to visualize. When an alternating current is driven through either winding, it becomes the primary winding, and the current through it can be labeled the primary current. The primary current will cause a secondary current to flow in the other winding. The phase relationship between the two currents will always be governed by the following considerations:

1. When the primary current is *increasing* in the downward direction, the secondary current must be *decreasing* in the downward direction, or increasing in the upward direction.
2. When the primary current is *decreasing* in the downward direction, the secondary current must be *increasing* in the downward direction, or decreasing in the upward direction.

Obviously, two similar rules can be written to account for increases or decreases in the primary current when flowing upward.

The quantity relationship between primary and secondary currents is regulated by the turns ratio of the transformer. Expressed as a formula:

$$\frac{N_1}{N_2} = \frac{I_2}{I_1} = \frac{E_1}{E_2}$$

where,

$N_1$ is the number of turns of wire in the primary,
$N_2$ is the number of turns of wire in the secondary,
$I_1$ is the quantity of primary current,
$I_2$ is the quantity of secondary current,
$E_1$ is the voltage impressed across the primary winding,
$E_2$ is the voltage induced across the secondary winding.

In order for the circuit as a whole to function as a voltage amplifier, the alternating instantaneous voltage $E_1$ across the primary winding must be greater than the instantaneous voltage developed across R1 by the input-signal current.

The classification of this circuit as a Class-A amplifier tells us that the collector-emitter current is never completely cut off during the entire cycle; some current flows continuously through the primary of T1.

Degeneration, or loss of signal strength, is prevented in this circuit by the presence of filter capacitor C2 across emitter resistor R3. C2 keeps the pulsations in collector-emitter current from developing voltage pulsations across R3. During the positive half-cycle of Fig. 4-2, the biasing conditions are such that they encourage or demand more collector-emitter current through the transistor. These extra electrons are drawn from the upper plate of capacitor C2, rather than through resistor R3. An equal number of electrons (the filter current, in dotted red) are drawn onto the lower plate of C2 from ground.

The opposite action occurs during the negative half-cycle of Fig. 4-1. Now biasing conditions are such that they discourage or restrict the flow of electrons which make up the collector-emitter current. The electrons flowing upward through R3 are momentarily shunted aside and flow onto the upper plate of capacitor C2, driving an equal number of filter-current electrons downward from the lower plate of C2 to ground.

Thus, C2 is carrying out its normal capacitor action of "passing" an alternating current from one plate to another without permitting any continuous flow in a single direction (DC). The values of R3 and C2 must be so chosen that the resistance of R3 is much greater than the capacitive reactance (opposition to alternating current flow) of C2. The reactance of any capacitor varies *inversely* with the frequency of the current being passed, in accordance with the standard formula:

$$X_C = \frac{1}{2\pi f C}$$

where,

$X_C$ is the reactance in ohms,
f is the frequency in cycles per second,
C is the capacitance in farads.

When this gross inequality between resistance (of $R_3$) and reactance (of $C_2$) has been met, then the combination of the two components automatically forms a "long time-constant" circuit. The *product* of the resistance in ohms and the capacitance in farads equals the time constant of the circuit, in accordance with the formula:

$$T = R \times C$$

where,

T is the time constant in seconds,
R is the resistance in ohms,
C is the capacitance in farads.

Any combination where the time constant, T, is at least five times longer than the time required *for a single cycle* of the current being passed to complete itself is defined as a long time-constant circuit. The time for a single cycle of any current is related to the frequency of that current by the simple relationship:

$$T = \frac{1}{f}$$

where,

T is the time duration of a single cycle,
f is the frequency in cycles per second.

The voltage which accumulates on the upper plate of capacitor C2 may be likened to a deep pool of positive ions, out of which electrons are drawn during the positive half-cycle of Fig. 4-2, and to which electrons are added during the negative half-cycle of Fig. 4-1. The true significance of a "long time-constant" RC circuit is that not enough electrons are withdrawn or added to appreciably change the voltage represented by this ion pool. Another way of saying this is that so few electrons are withdrawn during a positive half-cycle, in comparison with the number of positive ions already stored there, that no measurable increase in positive voltage occurs. Likewise, the number of negative electrons added to this ion pool during a negative half-cycle is so small, in comparison with the number of positive ions already stored there, that no measurable decrease in positive voltage occurs.

There is a simple arithmetical relationship between the quantity of electrons (or ions) stored on a capacitor plate, the size of the capacitor, and the resulting voltage across the capacitor. Known as Coulomb's law, it is written as follows:

$$Q = C \times E$$

where,

Q is the quantity of charge in Coulombs (one coulomb is equal to $6.25 \times 10^{18}$ negative electrons or positive ions),
C is the size of the capacitor in farads,
E is the resulting voltage in volts.

## DIRECT-COUPLED AMPLIFIER

Figs. 4-3 and 4-4 show two successive half-cycles in the operation of a direct-coupled (DC) amplifier using transistors. Direct coupling is advantageous in that the inherent losses in capacitive or transformer coupling, at low and high frequencies, respectively, are avoided.

The principle known as complementary symmetry is used in this circuit. Here the collector of an NPN transistor, X1, has been coupled directly to the base of a PNP transistor, X1. The significance of the biasing-voltage polarities and current-flow directions in the two types of transistors will be discussed later in the chapter.

### Identification of Components

This circuit is composed of the following components:
R1—Input driving and voltage-dividing resistor.
R2—Voltage-dividing resistor.
R3—Emitter stabilizing resistor.
R4—Collector load resistor.
R5—Emitter stabilizing resistor.
R6—Collector load resistor.
C1—Input capacitor for coupling signal from preceding stage.
C2—Emitter bypass capacitor.
C3—Emitter bypass capacitor.
X1—NPN transistor.
X2—PNP transistor.
M1—Battery or other DC power supply.

### Identification of Currents

There are at least eight significant electron currents at work in this circuit. Their movements and interrelationships must be understood by anyone aspiring to know how this circuit operates. These currents are:

1. Input dividing current (dotted blue).
2. Voltage-divider current (dotted green).
3. Base-emitter current for transistor X1 (solid green).
4. Collector-emitter current for transistor X1 (solid red).
5. Base-emitter current for transistor X2 (solid blue).
6. Collector-emitter current for transistor X2 (dotted red).
7. Emitter filter current for transistor X1 (also in solid red).
8. Emitter filter current for transistor X2 (also in dotted red).

### Details of Operation

Fig. 4-3 has been labeled a negative half-cycle of operation, because the input driving signal flows *downward* through resistor R1, making the voltage at the base of transistor X1 *more negative* during this half-cycle. Fig. 4-4 has been labeled a positive half-cycle because now the input driving signal flows *upward* through R1, making the base of X1 more positive. The instantaneous voltages which this input-signal current develops at the top of R1 must be added to or subtracted from the more permanent positive voltage developed there by the voltage-divider current (in dotted green).

This voltage-divider current flows through the closed path from ground, upward through R1, across and down through R2, and then into the positive terminal of power supply M1. From here, it flows through the battery and out the negative terminal to the common-ground connection. The purpose of this current (and consequently, of the voltage divider itself) is to develop a particular value of positive voltage at the junction of R1 and R2. This becomes the biasing voltage for the base of transistor X1. The term "biasing voltage" requires some explanation. Transistors are normally considered "current-controlled" devices, and the base-emitter current is usually referred to as the "biasing current." However, no biasing current will flow unless certain values of voltage are applied to the base and emitter. It is quite proper to refer to these values as "biasing voltages," because they determine the amount of biasing current which will flow between base and emitter.

The actual biasing current flowing from emitter to base has been shown in solid green. Its electrons flow upward from ground, through emitter stabilizing resistor R3, into the transistor (flowing against the direction of the emitter arrow, of course), then out of the base and downward through resistor R2 to the positive terminal of battery M1. When no signal is applied to input capacitor C1 to be amplified, this biasing current is a pure DC. In the negative half-cycle of Fig. 4-3, the negative voltage which the downward-flowing signal current develops at the top of R1 will *reduce* the biasing current through transistor X1. The lower biasing current will in turn reduce the collector current (in solid red).

The complete path of this emitter-collector current begins at ground, below resistor R3. The current flows upward, through R3, into the emitter and out the collector of X1, and down through load resistor R4 to the positive terminal of the battery. This electron current then returns to common ground by flowing through the battery and out its negative terminal.

At that moment when the signal current in the negative half-cycle of Fig. 4-3 is flowing downward through R1, at its maximum rate, the biasing and collector currents will have their minimum values. The reduction in collector current causes the voltage at the collector to become *more positive.* The reason is this voltage will always be equal to the power-supply voltage (positive in this case) *minus* the voltage drop occasioned across R4 by the flow of collector-emitter current through it. As this current decreases, so does the resulting voltage drop across R4, and the voltage at the collector will rise toward the full value of power-supply voltage.

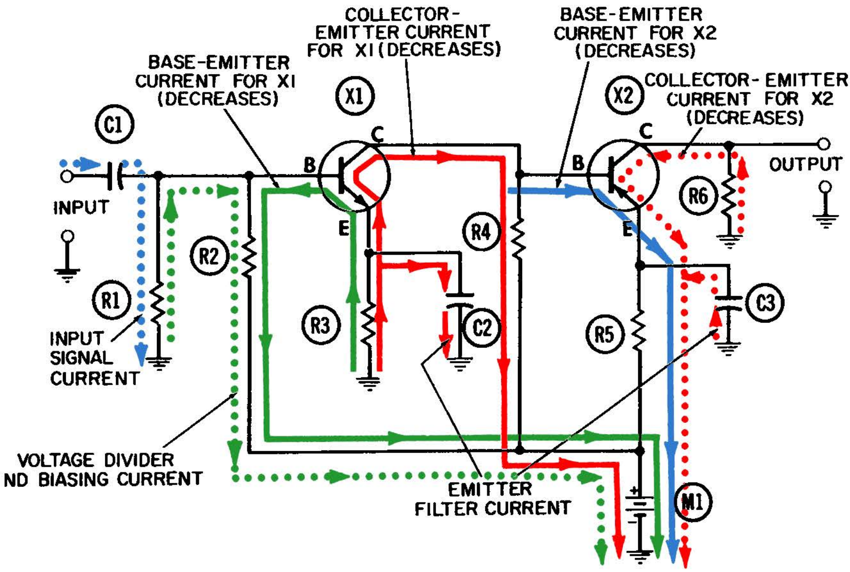



**Fig. 4-3. Operation of the direct-coupled amplifier—negative half-cycle.**

The exception to the foregoing would be where the collector-emitter current is cut off entirely. Then the voltage difference between the two terminals of R4 (the voltage drop across R4) would be zero, and the collector voltage would necessarily be the same as the power-supply voltage.

Since the collector of X1 is coupled or connected directly to the base of X2, the voltages at these two elements must always be identical. Let us now consider the biasing conditions at the elements of X2, so that we may then predict what will happen to the currents through X2 during this negative half-cycle.

Since X2, is a PNP transistor, electron currents will flow into its collector and out its emitter—instead of from emitter to collector as in NPN transistor X1.

The important biasing voltages for X2 (or any other transistor) are the instantaneous voltages at the base and emitter. You have already seen that the voltage at the base of X2 is determined at all times by the voltage at the collector of X1. The voltage at the emitter of X2 is jointly determined by the power-supply voltage of M1 and by the voltage drop across emitter resistor R5 as the collector-emitter current flows through R5. The complete path of this collector current (in dotted red) begins at ground, below resistor R6. It flows upward through R6 into the collector and out the emitter of the transistor, then down through R5 to the

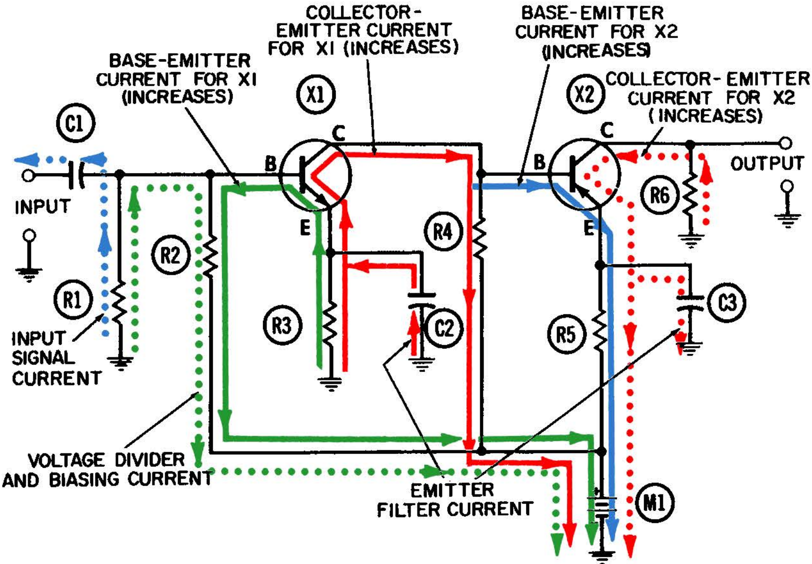



**Fig. 4-4. Operation of the direct-coupled amplifier—positive half-cycle.**

positive terminal of power supply M1. Its journey is completed to common ground by flowing through the battery and out its negative terminal.

The voltage which this current flow develops across emitter resistor R5 must be subtracted from the battery voltage to determine the exact voltage at the emitter (the emitter biasing voltage). It and the voltage at the base (the base biasing voltage previously discussed) regulate the amount of biasing current flowing from base to emitter. As with all transistors, the amount of biasing current through the transistor exercises direct control over the amount of collector-emitter current. This brings us back to a consideration of how much voltage this collector current will develop across R5 while flowing through it; this voltage affects the emitter biasing voltage, etc.

The complete path of the emitter-base current (in solid blue) truly begins at ground, below transistor X1. It flows through resistor R3 and transistor X1 as part of the collector current (in solid red). At the collector of X1 the emitter-base current separates from the main collector current and assumes its individual identity, flowing directly into the base of transistor X1 and out its emitter, then downward through resistor R5 to the positive terminal of battery M1. From here it can return to ground by flowing through the battery.

During the negative half-cycle shown in Fig 4-3 (collector current through X1 reduced by the biasing conditions at X1), the positive collector voltage is increased and so is the positive voltage at the base of X2. The latter action *reduces* the base-emitter current (biasing current) through X2. It may be difficult to visualize why a more positive base voltage for X2 reduces its base-emitter current. If so, consider again the exception for transistor X1, when we assumed that no collector current at all was flowing through X1. This no-current condition raised the voltage at the collector of X1 until it equaled the power-supply voltage. The base of X2 would necessarily assume the same voltage value. Obviously, no current would then flow between the base and the positive terminal of the battery, since the two points would be at the same voltage. (No electron current can flow between two points unless a difference in voltage exists between them. Electrons will always flow from the more negative point (point of greater electrons) to the more positive point (point of fewer electrons) to make up for the deficiency there.)

During the positive half-cycle depicted in Fig. 4-4, the following changes in voltage polarities and current quantities occur:

1. The signal current (dotted blue) flows upward through R1, making the voltage at the base of X1 more positive.
2. The base-emitter biasing current (solid green) through X1 increases.
3. The emitter-collector current (solid red) through X1 also increases.
4. The positive voltage at the collector of X1 decreases and lowers the positive voltage at the base of X2.
5. The base-emitter biasing current (solid blue) through X2 increases.
6. The collector-emitter current (solid blue) through X2 also increases.

## Comparison of Output and Input Voltages

The output voltage for this amplifier circuit is taken from the collector of X2. It will vary from a low to a high positive value, depending on the amount of collector current. During the negative half-cycle shown in Fig. 4-3, the collector current is reduced to its minimum value; therefore, the voltage it develops at the top of load resistor R6 will have its lowest positive value, too. This collector voltage will be positive, because the collector current always flows upward through R6, and electron current always flows from a less positive to a more positive point.

During the positive half-cycle of Fig. 4-4, the collector current reaches its maximum value; consequently, the instantaneous output voltage at the top of R6 will have its maximum positive value. The magnitude of the difference in the two collector voltages is the peak-to-peak value of the amplified voltage. With the circuit shown here, this peak-to-peak output might easily reach 12 or 15 volts, even though the input signal voltage developed across resistor R1 by the signal current will normally have a peak to peak value of only a small fraction of a volt. Therefore, we can say that the input-signal voltage has been substantially "amplified."

The output voltage will be "in phase" with the input-signal voltage. This means that in the negative half-cycle of Fig. 4-3 (input voltage negative at the top of resistor R1), the output voltage at the top of resistor R6 will have its least positive value. Conversely, when the input voltage is positive (as in Fig. 4-4), the output voltage will have its highest positive value.

## Filter Currents

The emitter resistors, R3, and R5, are bypassed to ground by C2 and C3. These two filter capacitors prevent loss of signal voltage due to degeneration. (Degeneration was described at some length in the previous amplifier discussion.) Without going into extensive detail about the various causative factors, the significant and observable effects that occur in capacitor C2 and resistor R3 can be tabulated:

1. The currents through transistor X1 flow upward through R3 therefore the voltage at the top of R3 has to be positive. The upper plate of capacitor C2 will always assume the same voltage, which can be likened to a pool of positive ions.
2. The combination of R3 and C2 forms a "long time-constant" circuit. Consequently, the pool of positive ions on the upper plate is so everwhelmingly large, in comparison with the number of electrons drawn out of it and into the transistor during the positive half-cycles, that the positive voltage on the plate does not increase during these half-cycles.
3. This pool of positive ions is also overwhelmingly large, in comparison with the number of electrons which flow onto the upper plate of C2 from the top of resistor R3 during the negative half-cycles. Therefore, the positive voltage on this plate does not decrease during these negative half-cycles.

4. When the collector current decreases during the negative half-cycles (Fig. 4-3) electrons flow onto the upper plate of C2, driving the filter current *downward* from the lower plate of C2 to ground.
5. When the collector current increases (Fig. 4-4), electrons are drawn from the upper plate of C2. A like number of electrons are drawn *upward* from ground onto the lower plate of C2.

When all of these actions are permitted to occur, the emitter resistor is said to be bypassed or filtered, and degeneration has been avoided. Otherwise, the following would occur:

1. On negative half-cycles, the positive voltage at the emitter would fall as the collector current through R3 is reduced. The base-emitter and collector-emitter currents would tend to *increase* and thus nullify part of the original decrease in collector current.
2. Degeneration during positive half-cycles would be characterized by a rise in the positive voltage at the emitter as the collector current increases. Now the base-emitter and collector-emitter curents would tend to decrease and thus nullify part of the original increase in collector current.

The filtering action occurring across capacitor C3 is identical in nature but opposite in phase to that just described for C2. A decrease in collector current through X2 during negative half-cycles causes filter current to flow out of ground and onto the bottom plate of C3. An increase in collector current through X2 during positive half-cycles would drive this filter current back into ground.

### Complementary Symmetry

The term "complementary symmetry" refers to the fact that currents flow in opposite directions in an NPN and a PNP transistor. Also, it refers to the fact that to increase conduction in an NPN transistor, the signal applied to its base must be positive; whereas in the PNP transistor, the signal applied to its base must be negative.

The principle of complementary symmetry will be utilized later in this chapter in a push-pull circuit.

## RC-COUPLED AMPLIFIER WITH NEGATIVE FEEDBACK

Figs. 4-5 and 4-6 show two successive half-cycles in the operation of a two-transistor audio amplifier which employs RC coupling and a negative-feedback network. The important advantage of negative feedback is a reduction in distortion. Other advantages are reduction in the variation in gain provided by different transistors, and an apparent increase in input impedance of the circuit using the feedback. The inevitable disadvantage of negative feedback is some loss in gain—however, this is a small price to pay for the many advantages obtained through its use.

## Identification of Components

The following circuit components perform the functions indicated. The manner in which these functions are accomplished will be elaborated on when the individual electron currents are discussed.

R1—Input driving resistor.
R2—Emitter stabilizing resistor for X1.
R3—Collector load resistor for X1.
R4—Voltage-dividing and biasing resistor.
R5—Voltage-dividing and biasing resistor.
R6—Input driving resistor for X2.
R7—Emitter stabilizing resistor for X2.
R8—Collector load resistor for X2.
R9—Feedback resistor.
C1—Input coupling capacitor.
C2—Interstage coupling capacitor.
C3—Output coupling capacitor.
C4—Feedback capacitor.
C5—Emitter filter capacitor.
C6—Voltage-divider filter capacitor.
X1 and X2—PNP transistors.
M1—Battery power supply.

## Identification of Currents

This circuit has at least ten separate electron currents at work during normal operation. To understand how such a circuit works, you must be able to visualize each current—what makes it flow and what this flow in turn accomplishes, what its complete flow path is, etc. Once the currents are understood and visualized, the significance of their various functions will be perfectly clear.

1. Input driving current (solid blue).
2. Voltage-divider current (dotted green).
3. Base-emitter current through each transistor (solid green).

4. Collector-emitter current through X1 (solid red).
5. Driving current for transistor X2 (also in solid blue).
6. Collector-emitter current for X2 (dotted red).
7. Feedback current (dotted blue).
8. Emitter filter current for X2 (also in dotted red).
9. Output current (also in dotted blue).
10. Filter currents across part of voltage divider (also in dotted blue).

## Details of Operation

As long as no signal is applied to the input capacitor, the driving current shown in solid blue will not exist, and the rest of the circuit will be operating under a static condition. Let us consider first the five currents which flow during such a static condition—namely, the voltage-divider current, and the two currents through each transistor.

The voltage-divider current (in dotted green) flows continuously in a clockwise path, upward through resistors R5 and R4 and downward through battery M1 from its positive to its negative terminal. The flow of this current through R5 develops a positive voltage at the top of R5, and this voltage is applied directly to the base of each transistor through another set of resistors. Consequently, the positive voltage at the top of R5 can be labeled the "base biasing voltage." Since the full battery voltage (22.5 volts) exists across both of the resistors in series, the amount across R5 can be determined by a simple proportional relationship involving the sizes of R5 and R4 and the battery voltage. The formula is:

$$E_{R5} = \frac{R_5}{R_4 + R_5} \times E_{M1}$$

where,

$E_{R5}$ is the voltage developed across R5 by the voltage-divider currents, in volts,
$R_5$ is the resistance of R5 in ohms,
$R_4$ is the resistance of R4 in ohms,
$E_{M1}$ is the voltage of the battery in volts.

The base-emitter current through X1 (solid red) will flow initially in an amount determined by the voltage at the base and emitter. This current flow through emitter resistor R2 develops a small positive voltage at the top of R2, and it may be labeled the "emitter biasing voltage." Flowing downward through resistor R1, this current develops a small component of negative voltage at the top of R1, and this component reduces somewhat the positive voltage applied to the base from the voltage divider. The complete path of this electron current is upward from ground through resistor R2, through the transistor from emitter to base, and downward through R1 to the junction of R4 and R5. Then it goes *upward,* through R4, to the positive terminal of battery M1, where the chemical action of the battery makes it flow out the negative terminal and back to ground. The reason this electron current flows upward rather than downward at the junction of R4 and R5 is the attraction of the positive terminal of the battery. This is the highest positive voltage in the loop made by the current, and consequently the point toward which all electron currents will be drawn.

Since transistors are "current-operated" devices, the flow of an electron current from emitter to base will change the current flow from emitter to collector. (The emitter-to-base current is called the biasing current.) The upward flow of collector current through resistor R2 will develop an additional component of positive voltage at the top of R2. This voltage further modifies the emitter biasing voltage, and consequently affects the total amount of biasing current which will flow through the transistor from emitter to base.

The complete path of the collector current begins at ground, below R2, and flows upward through R2 into the emitter and out the collector. Then it goes downward through the collector load resistor R3, into the positive terminal of battery M1, and returns to ground from the negative terminal.

Within transistor X2, an initial flow of electron current from emitter to base is set in motion by application of the base biasing voltage obtained from the junction of R4 and R5 as a result of the voltage-divider current action previously discussed. Its complete path, shown in solid green is upward from ground through R7, into the emitter and out the base, downward through R6, then upward through R4 to the positive terminal of battery M1. As soon as this initial current begins to flow, it will alter both the emitter and the base voltage. The voltage at the top of R7 will become more positive, and the voltage at the top of R6 will become more negative. Both voltage changes are of such polarity that they *restrict or oppose* the flow of the base-emitter current.

Transistors are very sensitive to temperature changes—a rise in temperature causes *more* current to flow between emitter and base. In turn, more emitter-collector current flows, the transistor becomes still hotter and the current further increases. Such runaway condition will eventually destroy the transistor. The presence of emitter stabilizing resistors such as R2 and R7 prevents this from happening. Since all the current for X2 must

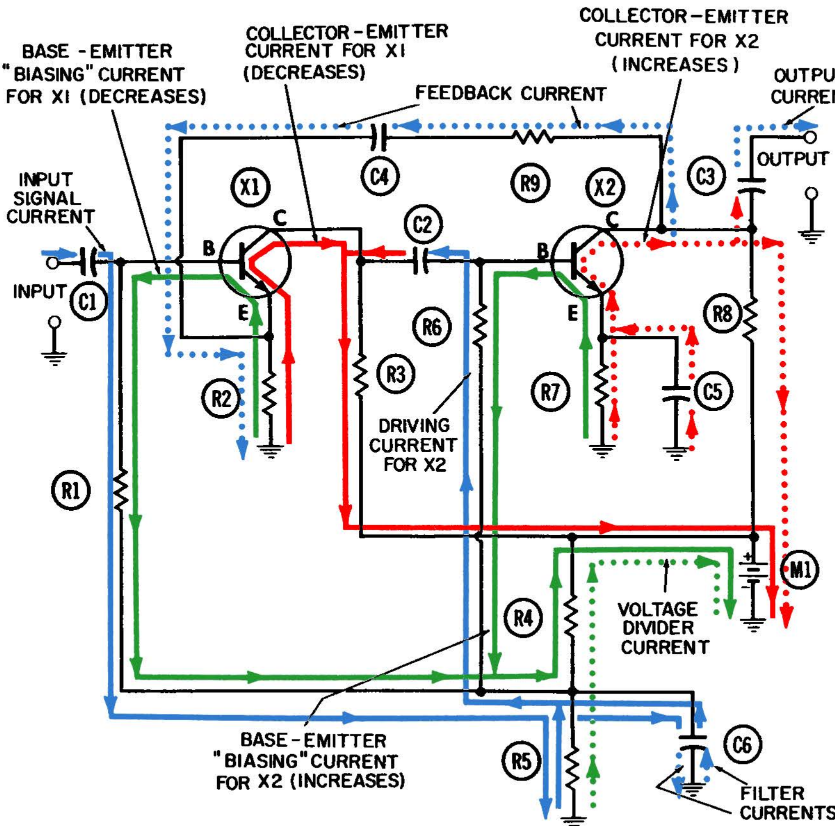



**Fig. 4-5. Operation of the resistance-capacitance coupled amplifier with negative feedback—negative half-cycle.**

first flow upward through R7, these current increases will rapidly make the voltage at the top of R7 so positive that it will tend to restrict or oppose the flow of these currents. (Remember that the voltage applied to an emitter is one of the two important biasing voltages of a transistor.)

The emitter-collector current for X2 (in dotted red) flows upward from ground, through R7, into the emitter and out the collector. Then it heads downward through load resistor R8 and into the positive terminal of the battery.

In summary, it can be verified that all four of the currents which flow through the two transistors are drawn from ground and through their respective paths by the positive voltage of the power supply or battery.

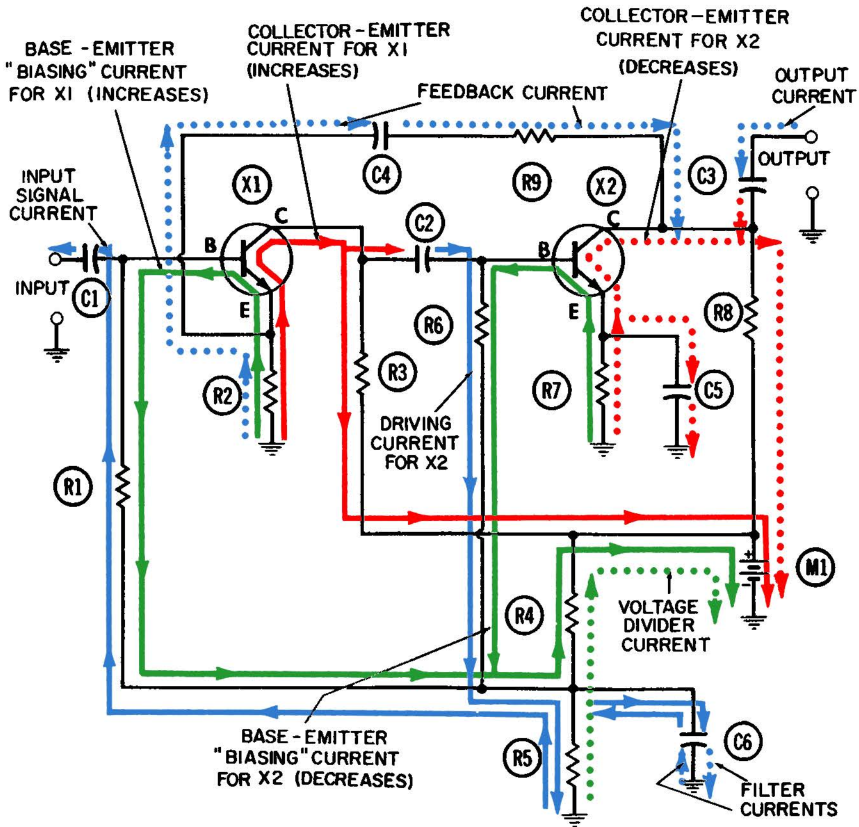



**Fig. 4-6. Operation of the resistance-capacitance coupled amplifier with negative feedback—positive half-cycle.**

## Operation Under Dynamic Conditions

The application of a signal voltage to input capacitor C1 brings six more electron currents into existence, and all of them will be true alternating currents—meaning that they will periodically reverse their directions of flow along their respective paths in accordance with the frequency of the applied signal. Additionally, the presence of an input signal will modify the four currents flowing through the two transistors, so that they will become pulsating rather than pure direct currents.

When an alternating voltage to be amplified is applied to input capacitor C1 the voltage begins to drive an electron current up and down through resistors R1 and R5. Fig. 4-5 has been labeled the negative half-cycle because the input voltage is negative during this period. This negative voltage causes the input driving current (in solid blue) to flow *downward* through R1 and R5 to ground. The component of negative voltage now developed at the top of R1 must be subtracted from the positive voltage already applied there by the voltage-divider action at the junction of R4 and R5. Since the upper terminal of R1 is connected directly to the base of transistor X1, this over-all decrease in positive voltage at the base during the negative half-cycle will *oppose* and thereby restrict the flow of emitter-base current ( in solid green).

Any such reduction in the emitter-base biasing current will cause a much larger reduction in the emitter-collector current through the transistor. The latter may be looked upon as the main electron stream through the transistor. A reduction in this current, as it flows through load resistor R3, causes the positive voltage at the top of R3 (and consequently at the collector) to rise. To satisfy yourself that a reduction in collector current causes a rise in collector voltage, suppose the collector current were cut off entirely. Under this condition, there could be no voltage drop whatsoever across R3, so both of its terminals would necessarily assume the full positive voltage of the battery or power supply.

When the collector voltage rises during the negative half-cycles, electrons will be drawn toward this point from any external circuit connected to it. This accounts for the upward movement of the driving current (in solid blue) through biasing and driving resistor R6. The component of positive voltage now created at the top of R6 adds to the positive biasing voltage already existing at the base of X2 as a result of the voltage-divider current through R5 and R4.

The resulting increase in positive voltage at the base of X2 acts to encourage, or increase, the flow of emitter-base biasing current through X2 (in solid green). In turn, the emitter-collector current also increases and, in so doing, creates a larger voltage drop across load resistor R8. The amount of this voltage drop must of course be subtracted from the power-supply voltage to determine the instantaneous value of collector voltage. Thus, you can see that as the collector current rises, the positive collector voltage drops in value.

This drop in collector voltage is simultaneously "passed" to the output circuit through capacitor C3 and, via the feedback network, back to the emitter of transistor X1. Physically this is accomplished by electrons being driven *into* each external circuit, as shown in Fig. 4-5. This occurs because excess electrons are momentarily pouring out of the collector but cannot immediately flow downward through load resistor R8; therefore they choose any alternate path available.

Consequently, during this negative half-cycle a feedback current (in dotted blue) flows to the left, through resistor R9, and into feedback capacitor C4. An equal number of electrons are driven away from the left plate of C4 and downward through emitter resistor R2. The downward movement through R2 places a small component of negative voltage at the emitter of X1, which must be subtracted from the positive voltage normally existing there as a result of the two transistor currents flowing upward through R2. Any reduction in the positive voltage at this point (previously identified as the "emitter biasing voltage") will increase the electron current flowing from emitter to base through the transistor (the "biasing" current of the transistor).

Since the negative portion of the signal had originally *reduced* the biasing current through transistor X1, this feedback action must be classified as negative because it opposes the signal action and thereby lowers the total gain available from the transistor.

Recall earlier that when the negative portion of the signal was applied to the base, less collector current flowed. As a result, an entirely independent negative-feedback action occurs simultaneously across emitter resistor R2. The decrease in both the emitter and collector currents flowing upward through R2 lowers the voltage drop across R2 and also reduces the positive voltage at the emitter (the emitter biasing voltage). This change in the bias conditions of the transistor will tend to *increase* the biasing current flowing from emitter to base. Thus the biasing current is acting in opposition to the negative signal at the base because, during this same negative half-cycle, the signal is trying to *reduce* the flow of this current through the transistor.

The common name for this particular negative feedback is degeneration. One drawback is that it reduces the gain available from the transistor.

## Actions During Positive Half-Cycle

During the positive half-cycle shown in Fig. 4-6, the following changes in current directions and voltage polarities occur:

1. The signal current (in solid blue) flows upward through R1, developing a component of positive voltage at the base. As a result, more emitter-base biasing current (in solid green) flows through the transistor.
2. The emitter-collector current (in solid red) is correspond-

ingly increased, causing a driving current (in solid blue) to flow *downward* through resistor R6. The latter develops a small component of negative voltage which alters the bias of transistor X2 in such a manner that *less* base-emitter biasing current now flows through the transistor.

3. In turn, the collector-emitter current through X2 also decreases, and as it falls, the positive voltage at the collector rises.
4. The higher positive voltage draws electrons toward the collector from any external circuit connected to it. This accounts for the reversal in flow of the output and feedback currents.
5. Since feedback current is drawn toward the collector, it must flow upward through emitter resistor R2. As it does, it creates a small component of positive voltage at the top of R2. Now the emitter biasing conditions of X1 are altered in such a manner that *less* base-emitter biasing current flows through X1. Since the positive portion of the applied signal is simultaneously trying to *increase* this biasing current, the feedback can again be identified as negative.
6. Negative feedback known as degeneration also occurs across resistor R2 during this half-cycle. The signal increases the two currents through transistor X1, but in flowing upward through R2, the now higher currents will increase the positive voltage at the emitter. In an NPN transistor, a more positive emitter will reduce the currents through the transistor.

## Filter Currents

Emitter resistor R7 for transistor X2 is bypassed with filter capacitor C5, so that degeneration does not occur across R7. The fluctuations from half-cycle to half-cycle in the current going into the emitter of X2 are in a sense "absorbed" by the filter capacitor. As a result, a constant current flows upward through R7 throughout the entire cycle. Likewise, the voltage it develops across R7 is constant rather than fluctuating. The capacitor is able to smooth out the current by delivering extra electrons to the emitter during the negative half-cycles and receiving extra electrons (from the current flowing up through R7) during the positive half-cycles. The filter current which flows between the lower plate of C5 and ground follows the movements of electron flow on and off the upper plate. For instance, extra electrons are drawn into the transistor from the upper plate of C5 during the negative half-cycles, so the filter current flows up from ground into the lower plate. During the positive half-cycles, the upper plate of C5 "recharges" by receiving additional electrons from R7, so the filter current flows down from the lower plate of C5 to ground.

Resistor R5 in the voltage-divider circuit is also bypassed with a filter capacitor, C6. This is necessary because the driving currents for the two transistors (both in solid blue) flow through R5 in opposite directions. Without this capacitor, the voltage each current would develop across R5 would oppose the other voltage. Two separate filter currents flow side by side between the lower plate of capacitor C6 and ground. While the driving current through resistor R1 draws a filter current downward from C6 during negative half-cycles, the driving current through R6 is drawing its own filter current upward from ground into C6.

## Summary

There are two electron currents which flow through the average transistor and the amount of each is closely regulated by the voltage at the base and emitter terminals. These are the biasing or controlling current, which flows from base to emitter (or emitter to base in NPN transistors); and the main electron stream (called collector-emitter current, or more commonly, the collector current), which flows from emitter to collector in NPN transistors.

The amount of biasing current which flows from emitter to base is regulated by the instantaneous voltages at the emitter and base. The voltage at the collector, like the voltage at the plate of a pentode amplifier, has an almost insignificant effect on the amount of collector current which flows.

The voltage at the base of transistor X1 is the algebraic sum of three voltages (one fixed and two variable). The fixed voltage is that developed across R5 by the voltage-divider current. The variable voltages are the ones developed across R1—one by the downward flow of base-emitter current, and the other by the signal current.

The instantaneous voltage at the emitter of transistor X1 is the algebraic sum of three voltages, all variable. Two of them are pulsating direct currents and are the two transistor currents—namely, the emitter-base and emitter-collector. The one which is alternating is the feedback current (shown in dotted blue) that flows up and down through resistor R2.

The instantaneous voltage at the base of transistor X2 is the algebraic sum of three independent voltages. The one fixed voltage is developed across resistor R5 by the voltage-divider current. One of the two variable voltages is developed across driving resistor R6 by the amplified signal current, which actually flows in two directions through the resistor. The second variable voltage is developed across this same resistor by the emitter-base biasing current (in solid green)—a pulsating direct current which flows downward through R6.

The voltage at the emitter of X2 is the sum of two fixed voltages; therefore, it can probably be described as a "pure" direct voltage. The two fixed voltages which contribute to it are those developed across emitter resistor R7 by the base-emitter and collector-emitter current through the transistor. Both currents pulsate through the transistor; but thanks to the filtering action of capacitor C5, they are "pure" DC when flowing through R7.

## COMPLEMENTARY SYMMETRY PUSH-PULL AMPLIFIER

Figs. 4-7, 4-8, and 4-9 show three different conditions in the operation of a push-pull amplifier using the complementary symmetry of an NPN and a PNP transistor. This feature permits using the push-pull connection to drive a speaker without the necessity of an output transformer. Both are classed as power transistors, because of the relatively large collector current each must deliver for driving the speaker.

Fig. 4-7 shows the currents which flow in this circuit under static conditions only (while no signal voltage is being amplified).

Fig. 4-8 has been labeled a negative half-cycle, because the signal current (in solid blue) flows in such directions through driving resistors R1 and R4 that it makes the bases of the two transistors negative. (The bases are their input points.)

Fig. 4-9 has been labeled the positive half-cycle, because the signal current causes positive voltages to exist at the two bases.

### Identification of Components

The following components perform the indicated functions in this circuit:

R1—Voltage-divider and biasing resistor.
R2—Voltage-divider and biasing resistor.
R3—Emitter stabilizing resistor.
R4—Voltage-divider and biasing resistor.
R5—Voltage-divider and biasing resistor.
R6—Emitter stabilizing resistor.
C1—Input capacitor.
C2—Input capacitor.

C3—Emitter bypass capacitor.
C4—Emitter bypass capacitor.
L1—Voice coil of the speaker.
X1—NPN power transistor.
X2—PNP power transistor.
M1—Battery or power supply.
M2—Battery or power supply.

### Identification of Currents

During the static period depicted by Fig. 4-7, no signal currents are flowing in this circuit; but the following electron currents, all pure DC, will flow:

1. Voltage-divider and biasing currents for both transistors (dotted green).
2. Base-emitter current through both transistors (solid green).
3. Collector-emitter current through both transistors, (solid red).

During the period of dynamic operation depicted by Figs. 4-8 and 4-9, the following additional electron currents will come into existence:

4. Input signal current (solid blue).
5. Fluctuations in the two base-emitter currents (also in solid green).
6. Fluctuations in the currents through the two voltage-divider circuits (also in dotted green).
7. Fluctuations in the two collector-emitter currents (also in solid red).
8. Current through the speaker voice coil (dotted red)
9. Two emitter filter currents (dotted red).

### Details of Operation

Being fairly straightforward the three electron currents shown in Fig. 4-7 for the static period of operation can be easily explained. The voltage-divider current (dotted green) flows continuously counterclockwise, upward through the two battery power supplies and to the left through resistor R2. Next it heads downward through resistors R1 and R4, then to the right through resistor R5, where it re-enters the positive terminal of the battery M2.

Electron current will flow around the base-emitter closed-loop circuitry of any transistor, in accordance with the voltage-biasing conditions at the base and emitter. Transistor X1, an NPN, has an initial negative voltage applied to its emitter from the negative terminal of battery M1. Because of the voltage-divider current action at the junction of resistors R1 and R2, however, a less negative voltage is applied to its base.

The voltage polarities around the circuit loop consisting of M1, R2, and R1 may be estimated qualitatively by recognizing that the voltage at the right terminal of resistor R2 will have the same voltage as the battery M1 (−22.5 volts). The voltage at the left terminal of R2 (this is the voltage applied directly to the base of X1) must be somewhat lower than this value (meaning somewhat less negative) because the voltage-divider current flows to the left through this resistor. Recall that the terminal from which electron current leaves a resistor is *always* more positive (or less negative) than the terminal at which it enters the resistor.

Since the junction of resistors R1 and R4 is connected directly to ground, the voltage at this point must always be zero. The

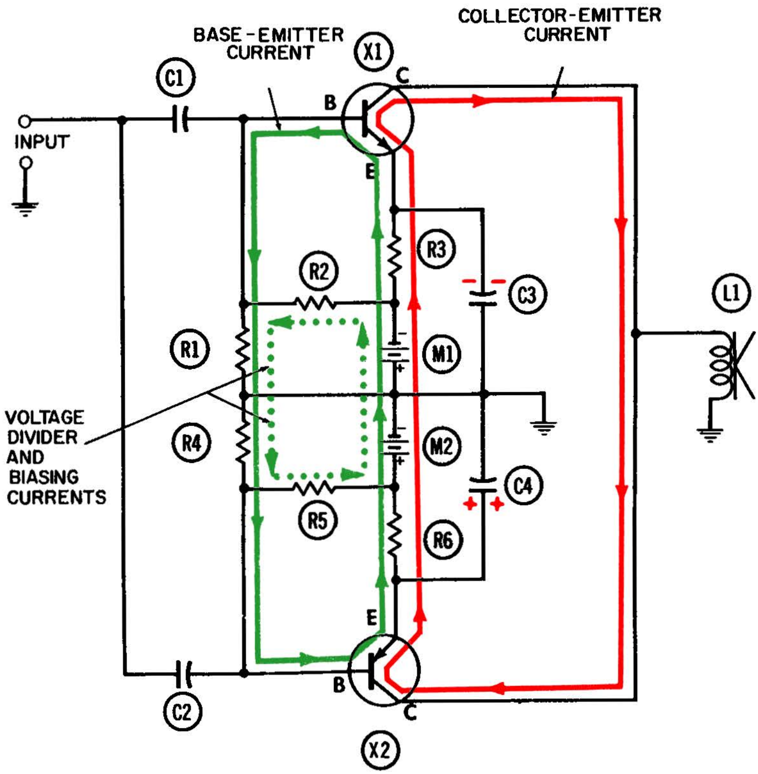



**Fig. 4-7. Current conditions in the complementary symmetry push-pull amplifier—static operation with no signal currents.**

junction of the two batteries is also grounded. As the voltage-divider current continues around this closed loop, it moves into a region of progressively higher positive voltages. The junction of R4 and R5 is positive with respect to ground, and the right terminal of R5 will always be at the full +22.5 volts of the battery.

Under no-signal conditions, the base-emitter current for both transistors (solid green) also flows continuously in a counterclockwise loop. Its path might be considered to begin at the ground point between the two batteries. From here it flows upward through M1 and resistor R3, into the emitter and out the base of X1. Heading downward through R1 and R4, it goes into the base and out the emitter of transistor X2, then through R6 and into the positive terminal of M2. Here, it flows through M2 back to the reference point or reference voltage which we call ground.

This base-emitter current of a transistor is usually called the "biasing" current, and it controls closely the amount of collector current (meaning collector-emitter current) which flows through the transistor. This phenomenon is the basis for the descriptive statement that transistors are "current-controlled" devices—in contrast to vacuum tubes, which are considered to be "voltage-controlled" devices.

The amount of this base-emitter biasing current is itself closely controlled and regulated by the voltage values at the base and emitter. Under no-signal conditions such as are depicted in Fig. 4-7, the voltage at the base of X1 is negative. In fact, it is the sum of (1) the negative voltage produced at the junction of R1 and R2 by the voltage divider current, and (2) the negative voltage caused at the upper end of resistor R1, by the base-emitter current flowing downward through R1.

The latter voltage may be more easily visualized by recognizing the current path which includes battery M1, resistor R3, the resistance of the junction between emitter and base within the transistor, and resistor R1 as another voltage divider. Starting at the negative terminal of battery M1, the voltage has its maximum negative value. Proceeding counterclockwise around this loop, the voltage at each point becomes progressively less negative until the ground point at the lower end of resistor R1 is reached, where the voltage is zero.

Under the assumption that the two transistors will conduct identical amounts of biasing current during this no-signal condition, the same amount of base-emitter current (in solid green) continues to flow through resistor R4, the resistance of the junction between base and emitter within transistor X1, resistor

R6, and battery M2. This loop constitutes another voltage divider, the voltage again becoming progressively more positive (i.e., less negative) as this electron current proceeds around the loop. Electrons move in the direction indicated because they flow inescapably *away* from more negative and *toward* more positive voltages.

Thus the "biasing" voltage at the base of transistor X2 is positive and is the sum of two separate components of positive voltage, both produced across resistor R4 by the two currents which flow downward through it.

The voltage at the emitter of transistor X1 is negative and is the sum of two separate components of negative voltage. These are produced at the upper terminal of resistor R3 by the two electron currents (the base-emitter current, in solid green; and the collector-emitter current, in solid red) flowing upward through R3.

The voltage at the emitter of transistor X2 is positive, and is the sum of two separate positive voltages. Both exist at the lower terminal of resistor R6 as a result of the same two electron currents—the base-emitter and collector-emitter currents which flow upward through it.

The path for the combined collector currents (under these no-signal conditions) might be considered to start at ground (the reference point) between the two batteries, and to flow upward through M1 and R3 into the emitter and out the collector of X1. Next it heads downward to the collector of X1, through X1 and out the emitter, then upward through R6 to the positive terminal of M2. This electron current is finally returned to ground by flowing through M2 to its negative terminal.

## Operation Under Dynamic Conditions

Once these three static currents have been visualized, you will be in a much better position to understand how this circuit operates when a signal is being amplified. Three additional currents come into existance. Also, the three currents previously discussed will now be changed from pure to pulsating DC. These pulsations represent the variations in the audio-frequency signal.

During the negative half-cycle depicted by Fig. 4-8, a signal voltage of negative polarity is applied to the left plates of capacitors C1 and C2. This negative voltage drives electron current (in solid blue) *onto* the left plates of these capacitors. In turn equal amounts of electron currents are driven away from the right plates. The current driven away from C1 flows downward through resistor R1 to ground and, in so doing, develops an instantaneous component of negative voltage at the upper terminal of R1. This component of negative voltage adds to the negative voltage already existing at that point as a result of the two currents which flow through R1. The *increase* in negative voltage at the base of X1 (or any other NPN transistor) will decrease the base-emitter biasing current flowing through the transistor. This, in turn, decreases the collector-emitter current through X1.

Unlike the collector current through transistor X1 the collector current through transistor X2 increases during negative half-cycles. The reasons why it does may be summarized briefly, as follows:

1. The input signal current (in solid blue) flows *upward* through resistor R4 to ground. The component of negative voltage it creates at the lower terminal of R4 must be subtracted from the positive voltage already existing at that point as a result of the two voltage-divider actions previously described. The net result is a reduction in the positive voltage at the base of transistor X1.
2. A reduction in positive voltage at the base of any PNP transistor will always increase the flow of biasing current. Therefore, more base-emitter current flows through transistor X1.
3. The increase in biasing current causes a companion increase in collector-emitter current, which is also the load current.

It should be obvious that this additional collector current for X2 cannot all be drawn through X1, since the collector current through X1 is decreasing during this negative half-cycle, as previously explained. Consequently, the extra collector current for X2 is drawn upward from ground and through the voice coil of the speaker. This current (in dotted red) will set up magnetic lines of force which will draw the speaker diaphram in one direction only, such as to the right in Fig. 4-8. The complete path of this current is through the voice coil, then into the collector and out the emitter of X2 upward through resistor R6 to the positive terminal of battery M2. Flowing through the battery to its negative terminal, the current re-enters the common ground, which provides a ready return access to the voice coil.

During the positive half-cycles depicted by Fig. 4-9, a similarly long series of events (which will be discussed later) increases the collector current through X1 and decreases the collector current through X2. This increase in collector current through X1 cannot be accepted by X2 during this same time period. Therefore, the current is driven through the speaker

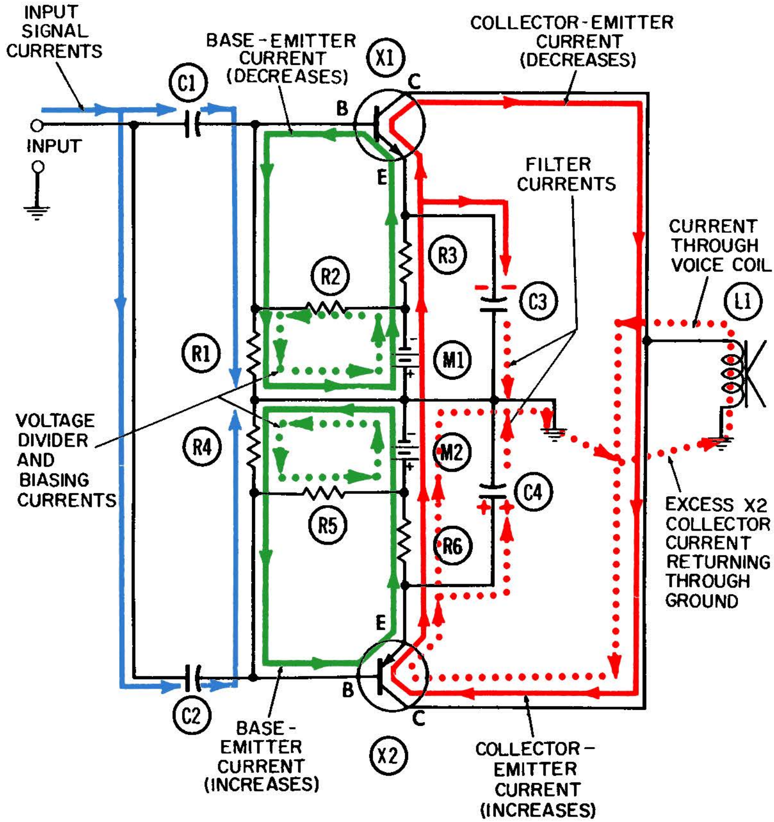



**Fig. 4-8. Operation of the complementary symmetry push-pull amplifier—negative half-cycle.**

voice coil and into the ground connection. Thus, current flows through the voice coil in one direction during negative half-cycles, and in the opposite direction during positive half-cycles. This causes the resultant magnetic lines of force in the voice coil to change direction every half-cycle. As a result, the permanent magnet (and speaker diaphram connected to it) will be alternately attracted to and repelled by the voice coil during each cycle. The back-and-forth movements of this diaphragm set up the air vibrations we know as sound waves.

To consider all the current and voltage changes which occur during a positive half-cycle of operation, we should start with the input signal. As long as its polarity is positive, electrons will be drawn onto the right plates of C1 and C2. As it flows upward through resistor R1 and downward through resistor R4, this electron current places small components of positive voltage at the upper terminal of R1 and the lower terminal of R4. These voltage components are added to the voltage already existing there as a result of the two voltage-divider actions previously discussed (the ones associated with the currents in solid and dotted green).

This signal current flow through the two resistors makes the normally negative voltage at the top of R1 less negative, and the normally positive voltage at the lower terminal of R4 more positive. As a result, the two currents flowing through transistor X1 (the base-emitter biasing current and the collector-emitter load current) increase, and the two flowing through transistor X2 decrease.

Thus, by application of a small audio-frequency signal at the input point of this circuit, it is possible to cause a fairly heavy flow of alternating current at the same frequency through the speaker voice coil. This circuit is classed as a power amplifier because much more audio-frequency power is delivered to the output (speaker) than is consumed in the input circuit (resistors R1 and R4). As an example, the speaker might be delivering one or more watts of audio power, whereas only a few milliwatts are being consumed in input resistors R1 and R4. Several important facts about transistors make this phenomenon possible:

1. In a transistor, a change of only a fraction of a volt in the voltage difference between base and emitter will cause a small change in the amount of biasing current and a much larger change in the amount of collector load current.
2. This fraction of a volt required can be developed at the transistor base by causing a current as small as a fraction of a milliampere to flow through an input resistor such as R1 or R4.

Moreover, the collector-emitter load current flowing through these power transistors may be hundreds of times greater than the signal current flowing up and down through input resistors R1 and R4.

Because of the voltage changes across these two resistors while the signal current is flowing, the amount of voltage-divider current (in dotted green) will be disturbed slightly. During the negative half-cycles (Fig. 4-8), the voltage at the junction of R1 and R2 is made more negative; consequently, the smaller voltage difference between the two terminals of resistor R2 will draw less current through R2 from the negative terminal of the battery.

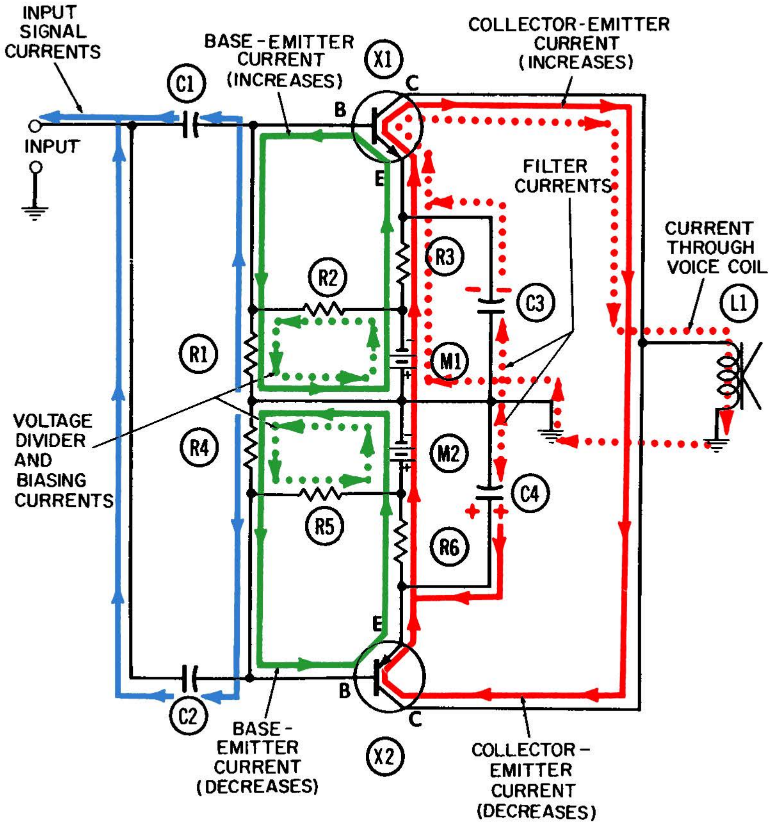



**Fig. 4-9. Operation of the complementary symmetry push-pull amplifier—positive half-cycle.**

During the positive half-cycles, this junction is made less negative and now the opposite is true—a larger voltage-divider current will be driven through R2 by the greater voltage difference across its terminals.

By similar reasoning, it can be shown that the voltage-divider current flowing through the lower network (consisting of R4, R5, and M2) also fluctuates with the applied signal voltage. Here, however, it *increases* during the negative and decreases during the positive half-cycles.

For this reason, the voltage-divider current (in dotted green) has been shown as two separate currents—flowing in two separate networks—while a signal is applied. Any difference in amount between these two currents will automatically be compensated for by a flow of electron current through the common ground connection between the junction of power sources M1 and M2, and the junction of resistors R1 and R4.

Likewise, any difference in amounts between the base-emitter currents through the two transistors will be compensated for by an appropriate flow of electron current (in solid green) through this same common ground connection. During the positive half-cycles (when more base-emitter current flows through X1 than through X2), this current will flow through ground from left to right—that is, from the junction of resistors R1 and R4, toward the junction between the two batteries. Conversely, it will flow through ground from right to left during the negative half-cycles, when the base-emitter current through X2 exceeds that through X1.

## Filter Currents

Emitter resistors R3 and R6 are bypassed by filter capacitors C3 and C4, respectively, to prevent loss of signal strength from that type of negative feedback known as degeneration. In order to forestall degeneration, the filter currents shown in dotted red must be able to flow freely between C3 and C4 to the nearest ground point. The voltage on the upper plate of C3 must always be identical to the one at the emitter of X1. Since this is a negative voltage, the accumulated charge on the upper plate of capacitor C3 can be conveniently represented as a "pool" of electrons. There will be a continual flow of electron current driven upward through resistor R3 by the negative terminal of battery M1. (This is the point of most negative voltage in the entire circuit.) If no collector current could escape into the transistor, the upper plate of capacitor C3 would soon acquire enough electrons that its voltage would equal the full negative battery voltage. At that time, the upward flow of electron current through R3 would cease. However, since transistor X1 is being operated under what are called Class-A conditions, some collector current flows throughout the entire cycle. Therefore the negative voltage on the upper plate of C3 will never attain the full negative voltage power source M1.

During the positive half-cycle such as in Fig. 4-9, the biasing conditions of transistor X1 cause an increase in the collector current. In turn, the electrons which make up this current are drawn quite easily from the electron pool on the upper plate of capacitor C3, and an equal number flows upward from ground to the lower plate. This is the essence of capacitor action . . . it is how capacitors will appear to "pass" an alternating current.

When the capacitor has sufficient size, or capacity, the quantity of extra electrons demanded by the transistor collector current during the positive half-cycles is such an infinitesimal percentage of the total number of electrons stored in the capacitor that the voltage does not change appreciably from half-cycle to half-cycle.

This is how a filter capacitor avoids the loss in signal strength known as degeneration. If emitter resistor R3 were not bypassed with a filter capacitor, then the increased collector current during the positive half-cycles would have to be drawn directly upward through R3. This would make the voltage difference, or "drop," across R3 larger, and would *lower* the negative voltage at the upper terminal of R3. Since the emitter of X1 is connected directly to this point, this lower negative voltage would constitute a change in the biasing conditions of the transistor, and would ultimately reduce the collector current flowing through the transistor. This would nullify at least part of the original increase in collector current, and would constitute a loss in the amount of amplification the circuit delivers. This is degeneration.

The voltage on the lower plate of capacitor C4 is always identical to the positive voltage at the emitter of transistor X1, since they are connected together. It is convenient to visualize a positive capacitor voltage as a pool of positive ions, out of which a continual flow of electrons will move upward and through resistor R6, toward the higher positive voltage of power source M2. If no collector-emitter current flowed through X2, the positive voltage on the lower plate of C4 would eventually equal the +22.5 volts of the battery at the lower terminal of M2. Instead, the continual inflow of collector-emitter current from X2 keeps it at a lower positive value.

Assuming capacitor C4 has sufficient size, or capacity, the quantity of excess electrons which flow onto its lower plate from the collector-emitter current during the negative half-cycles (Fig. 4-8) is such an infinitesimal percentage of the total number of positive ions already stored there that the voltage across capacitor C4 does not change appreciably from half-cycle to half-cycle.

If C4 were not in the circuit, or if for any reason the filter current between it and ground were prevented from flowing, then degeneration (loss of signal strength) would occur across R6. The increased collector-emitter current through X2 during negative half-cycles would flow directly through R6 and thereby increase the voltage drop across this resistor. The lower positive voltage now produced at its lower terminal and at the emitter would be a fundamental change in the biasing conditions of the transistor. The resultant decrease in collector-emitter current would nullify part of the original increase in this current and thereby lead to some loss in amplification.

# Chapter 5

# DETECTOR CIRCUITS

Like their triode vacuum-tube counterparts, transistors can be employed to detect, or demodulate, a modulated RF carrier signal and thereby develop an audio voltage. The first circuit discussed in this chapter is for a PNP transistorized detector. Crystal diodes are also employed as detectors in many transistor receivers. The second circuit discussed in this chapter is for an IF amplifier and diode detector, with AGC applied to the IF amplifier.

## PNP DETECTOR CIRCUIT

Figs. 5-1 and 5-2 show two successive audio half-cycles in the operation of a transistor detector. The necessary components of this circuit include:

R1—Voltage-divider resistor.
R2—Voltage-divider and base-bias resistor.
R3—Emitter stabilizing resistor.
R4—Collector load resistor.
C1—IF tank capacitor.
C2—IF filter capacitor.
C3—Emitter bypass capacitor.
C4—IF filter capacitor across load resistor R4.
C5—Output coupling and blocking capacitor.
T1—IF tank transformer.
X1—PNP transistor.
M1—Battery or other power supply.

### Identification of Currents

The following separate and distinct electron currents are at work in this circuit. The actions occurring in this or any circuit cannot be understood until the movements of these currents are clearly understood.

1. IF tank current (solid blue).
2. Base-emitter biasing current, a direct current which pulsates at the intermediate frequency (solid green).
3. Voltage-divider current (dotted green).
4. Two intermediate-frequency filter currents (dotted blue).
5. Collector-emitter current (solid red).
6. Audio filter current (dotted red).

**Details of Operation**

The intermediate-frequency input current (in solid blue) oscillates in the tank circuit consisting of C1 and the primary of transformer T1. This IF tank current induces a similar current in the secondary winding. With this secondary current there will always be associated the so-called secondary voltage, also known as "back electromotive-force" (back emf). Once during every cycle of this intermediate-frequency current, the upper terminal of the secondary winding will be driven to a peak of negative voltage. When this happens, the transistor will conduct the maximum base-emitter biasing current because, in the PNP transistor, electrons invariably flow *from* the base *to* the emitter against the direction of the emitter arrow). Hence, a more negative base voltage will naturally increase this flow.

Between each negative peak of induced voltage there will be an equal-sized peak of positive voltage. On these positive peaks, the transistor will conduct the minimum base-emitter current. Since this current always flows in the same direction through the transistor, the voltage alternations which were induced across the secondary winding of T1 are converted into current pulsations through the transistor.

The complete path of this base-emitter biasing current, which is shown in solid green and which pulsates at the intermediate frequency, begins at the negative terminal of battery M1. It flows to the left and upward through resistor R2 and the secondary winding of T1. Then it heads to the right into the base of the transistor and out the emitter and downward through resistor R3, to the common ground connection, where it has free access to re-enter the positive terminal of the battery.

In addition to the pulsations which occur at the basic intermediate frequency, this base-emitter current also varies in amount according to the modulation carried by the carrier signal. Fig. 5-3A shows a fairly conventional graphical representation of the so-called modulated carrier signal, or waveform. Many hundreds of even thousands of the carrier cycles will occur during one audio cycle, and their *strength* will periodically rise and fall in accordance with the modulation imposed on the carrier at the transmitter. These variations in carrier strength make up what is commonly known as the "modulation envelope." As is customary in waveform diagrams of this type, the modulation envelope has been indicated on Fig. 5-3A. This so-called "modulation envelope" in such diagrams is nothing more than a convenient graphical device which relates the relative strength of individual cycles of the carrier signal and, of course, points up the fact that the strength of these carrier cycles varies in accordance with the audio modulation imposed on the carrier at the transmitter.

Each pulsation of base-emitter current causes one cycle of IF filter current to flow through filter capacitor C2 to ground. During the negative peak portions of the secondary induced voltage across T1, maximum base-emitter current flows through the transistor X1. Inevitably some electron current is drawn from the upper plate of capacitor C2, and in turn the same quantity of electrons is drawn onto the lower plate. On the positive peak portion of secondary induced voltage, the base-emitter current is reduced to minimum. During these half-cycles of IF, the filter current flowing on either side of capacitor C2 heads downward again to ground.

The amount of base-emitter biasing current which flows through any transistor is determined by the two important biasing voltages, (at the base and emitter) and, of course, the difference between them. The voltage at the base of transistor X1 is determined primarily by the flow of voltage-divider current (in dotted green) upward through battery M1, to the left and upward through resistor R2, and downward through R1 to the common ground. From here, it has easy access back to the positive terminal of battery M1. The resulting voltage at the junction of resistors R1 and R2, being less negative than the power-supply voltage, will cause a flow of electron current across the junction between base and emitter. The amount of this so-called biasing current controls, or regulates, the flow of electron current from collector to base, within the transistor. (Once this current crosses the difficult "reverse" junction from collector to base, it flows fairly easily from base to emitter, and exits from the transistor at the emitter terminal.)

This second current through the transistor is usually called merely the collector current, and will be from 25 to 100 times larger than the biasing current (frequently referred to merely as the "base" current). The collector current, shown in solid

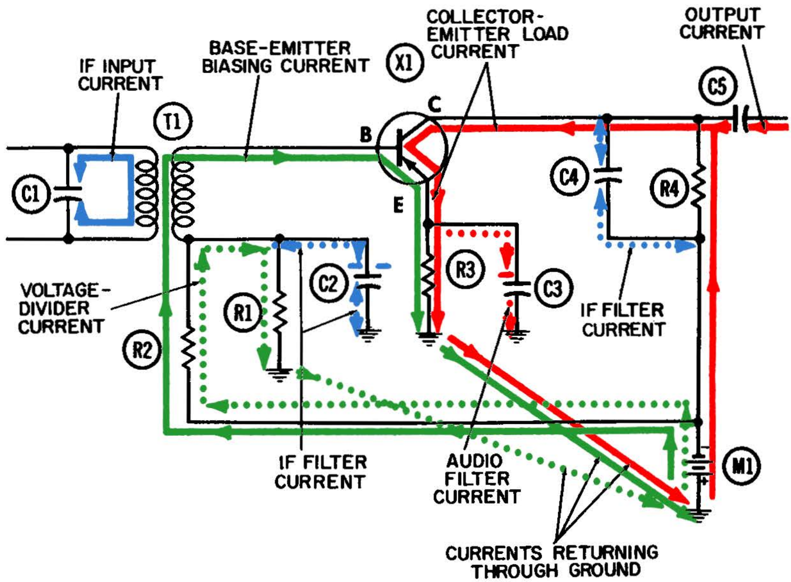



**Fig. 5-1. The transistorized detector circuit—conditions leading up to an audio modulation trough.**

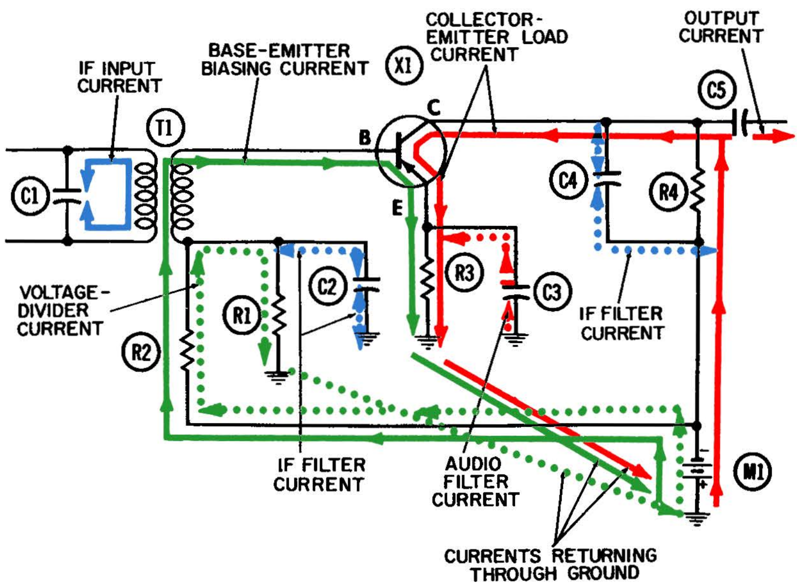



**Fig. 5-2. The transistorized detector circuit—conditions leading up to an audio modulation peak.**

red, begins at the negative terminal of battery M1. From here it flows upward through resistor R4, then downward through the transistor from collector to emitter, continuing downward through emitter resistor R3 to the common ground, where it can return to the positive terminal of the battery.

*(A) Modulated IF carrier.*

*(B) Base and emitter voltages.*

*(C) Collector current.*

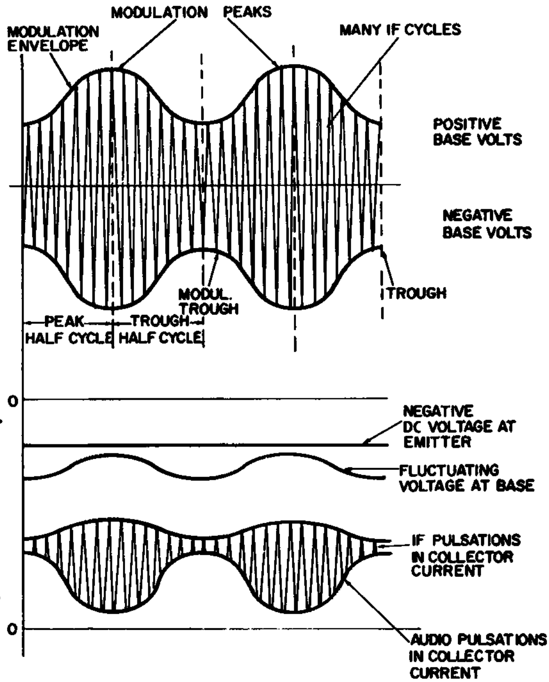



**Fig. 5-3. Waveform diagrams for the transistorized detector.**

In flowing downward through R3, the collector-emitter current will develop across R3 a voltage of negative polarity at the upper terminal and positive polarity at the lower terminal. The negative voltage polarity at the upper terminal of R3 becomes the second of the two important biasing voltages of the transistor.

Resistor R1 and capacitor C2 together constitute a "long-time constant" filter—one whose time constant is longer than the duration of a single intermediate-frequency cycle. Consequently, a negative voltage will appear on the upper plate of capacitor C2. This negative voltage, which remains unchanged between the individual IF cycles, has been indicated by the blue minus signs on C2. (A negative voltage stored on a capacitor plate can be most conveniently represented as a group or pool of electrons, the symbol for which is one or more minus signs.)

In Fig. 5-2, which represents a "Peak" half-cycle of audio voltage, the single minus sign on the upper plate of C2 indicates the negative base voltage which would correspond to a modulation peak. Fig. 5-3A tells us that during a modulation peak, the individual IF cycles have their maximum value, or strength. Each such cycle drives the transistor base to a negative voltage of such value that maximum base-emitter biasing current is permitted to flow through the transistor. This extra quantity of base-emitter biasing current must flow through resistor R2. In so doing, it lowers the negative voltage at the upper terminal of R2, because of the increased voltage drop across the resistor. The reduced negative voltage at the junction of R1 and R2 is also the voltage applied to the base. Thus, during the modulation peak of Fig. 5-2 a smaller negative biasing voltage is applied to the base of the transistor. As a result, the base-emitter biasing current which flows continuously through the transistor is reduced.

During the modulation trough of Fig. 5-1, the individual IF cycles reach smaller peak values and thereby reduce the base-emitter current during each cycle. Since this current must flow through resistor R2, the decreased voltage drop across R2 makes the voltage at the junction of R1 and R2 *more* negative. This is one of the two transistor biasing voltages, and it causes a general increase in the continuous flow of base-emitter current throughout the entire cycle.

The voltage which appears on the upper plate of capacitor C2 marks the first appearance of an audio voltage when a carrier signal is being modulated. It varies between two negative values, as indicated in Fig. 5-3B, and consequently regulates the flow of the two currents through the transistor so that they pulsate at an audio rate. The transistor currents also have pulsations, which occur at the intermediate frequency, as shown in Fig. 5-3C, and are filtered out by capacitors C2 and C4. These IF filtering currents have been shown in dotted blue.

Since the collector current varies, or pulsates, at the audio frequency being demodulated, an audio voltage is developed across collector load resistor R4. This audio voltage is coupled to the next amplifier stage by capacitor C5, which also serves to "block" the fixed negative voltage of battery M1 and thereby keep it from reaching the next stage. Fig. 5-1 depicts circuit conditions leading up to a modulation trough. Here the collector current is increasing, and this extra current is drawn from the left plate of C5. This action draws an equal amount of electron current onto the right plate from the external circuit beyond C5 which recognizes this surge of electrons as a positive voltage.

Under the conditions leading up to the modulation peak of Fig. 5-2, the collector current is decreasing. Thus, the excess electrons being driven through resistor R4 from battery M1 will flow onto the left plate of C5, driving an equal number off the right plate and through the external circuit. The external circuit beyond capacitor C5 recognizes this surge of electrons through it as a negative voltage.

The combination of emitter resistor R3 and filter capacitor C3 is deliberately chosen to have a longer time constant than the duration of one cycle of the lowest audio frequency being demodulated. Consequently, even though the collector-emitter current is pulsating as it comes through the transistor, it is prevented from flowing through R3 in pulsations and thereby developing an audio voltage across R3. Instead, the additional collector current which flows during the modulation trough is shunted momentarily onto the top plate of capacitor C3, and an equal quantity of electrons flows harmlessly from the lower plate into ground. This is one half-cycle of audio filter current. If there were no capacitor, this extra collector current would have to flow immediately through resistor R3, and, in so doing, would cause an additional component of negative voltage at the upper terminal of R3. Since this is one of the two important biasing voltages of the transistor, a more negative voltage at the emitter would restrict or reduce the flow of both currents through the transistor, just when they were trying to increase. This would be degeneration.

The decrease in collector current during the modulation peak of Fig. 5-2 would likewise cause a smaller voltage drop across R3 and, in turn, a less negative voltage at the emitter. As a result, both currents through the transistor would increase, just when they were supposed to decrease. This would be another half-cycle of degeneration. When a large enough filter capacitor is connected across R3, the excess electrons stored on its upper plate during the previous half-cycle will not be drawn off the top plate, and will flow down through R3 to ground, along with the regular flow of collector current. While this action is occurring, the filter current below C3 will be drawn upward from ground, toward the capacitor. This constitutes the second half-cycle of filter action.

## AMPLIFIER WITH AGC DIODE

Figs. 5-4 and 5-5 show two successive half-cycles of a single radio-frequency cycle of operation for a fairly typical IF amplifier and detector circuit. The diode also provides automatic

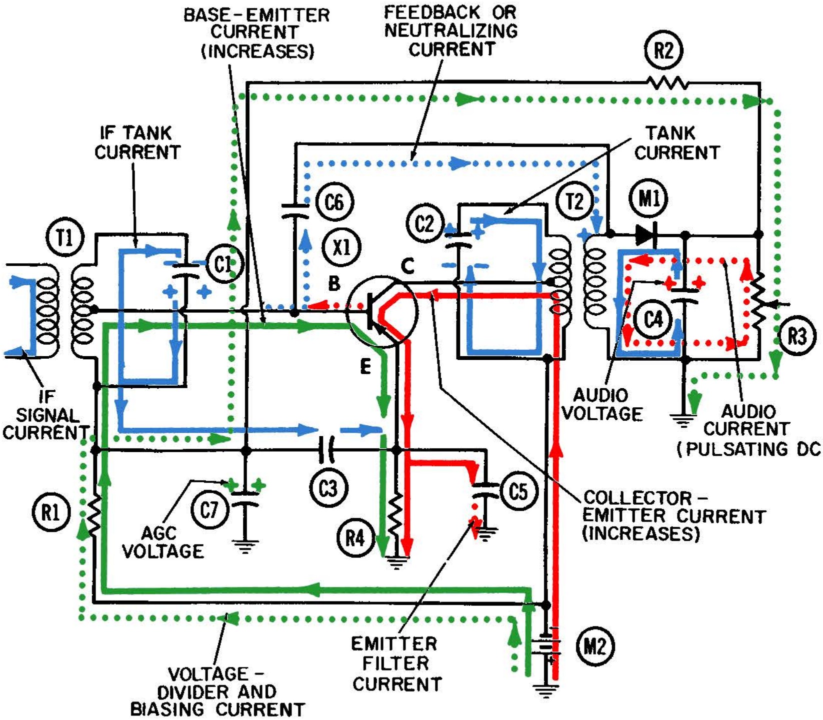



**Fig. 5-4. An IF amplifier with AGC diode—negative half-cycle during a period of normal signal strength.**

gain control (AGC), frequently called automatic volume control (AVC).

A fairly common intermediate frequency in broadcast receivers is 455 kilocycles per second. (In electronics terminology, "per second" is understood and so is omitted, and "kilocycles" is abbreviated to kc.) An intermediate frequency is normally much lower than the original carrier or radio frequency, and as such is somewhat easier to handle—meaning that the circuits which amplify it are less susceptible to losses from parasitic oscillations, radio-frequency interference (RFI), and other such disturbances. At the same time, a frequency as high as 455 kilocycles per second is high enough to be classed as a "radio frequency," so that tuned circuits of reasonable size can be put together which will resonate at the basic frequency, with many attendant advantages of signal strength gain, frequency selectivity, etc.

The components which make up this completed circuit are as follows:

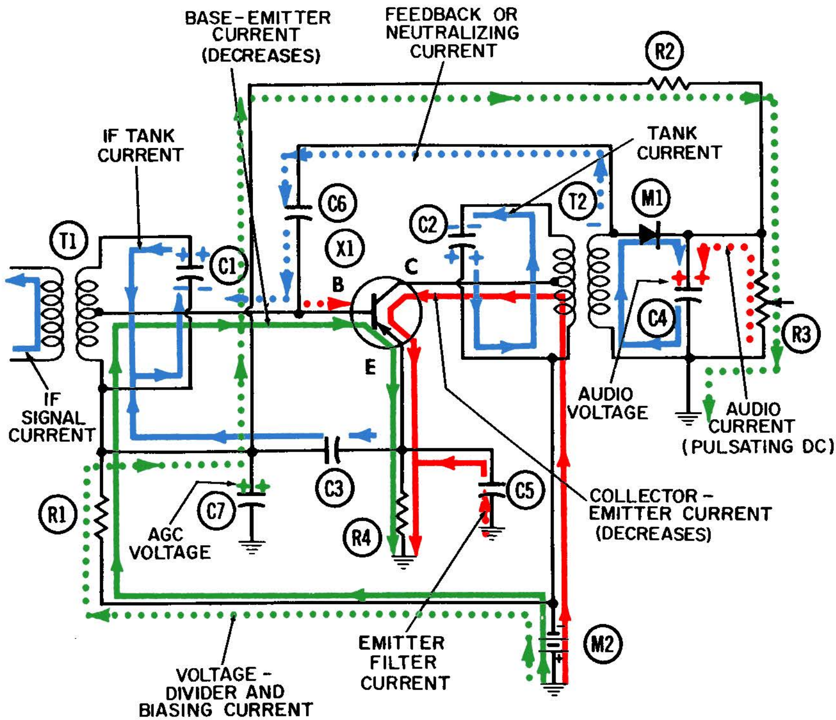



**Fig. 5-5. An IF amplifier with AGC diode—positive half-cycle during a period of normal signal strength.**

R1—Voltage-divider and biasing resistor.
R2—Voltage-divider and AGC resistor.
R3—Voltage-divider and audio-output resistor.
R4—Emitter stabilizing resistor.
C1—Input tank-circuit capacitor.
C2—Output tank-circuit capacitor.
C3—RF bypass capacitor.
C4—Audio-output capacitor.
C5—Emitter bypass capacitor.
C6—IF neutralizing capacitor.
C7—AGC capacitor.
T1—Input IF transformer.
T2—Output IF transformer.
X1—PNP transistor.
M1—Crystal diode.
M2—Battery or other DC power supply.

### Identification of Currents

There are a great many separate electron currents flowing in this circuit. Each current should be clearly identified in your mind before you can hope to understand the movements, and more important, the functions performed by these currents. First, there are the usual three currents which will flow in the average transistor circuit under "static" conditions, irrespective of whether a signal voltage or current is actually being amplified. These static currents are:

1. Voltage-divider current (dotted green).
2. Base-emitter current (solid green).
3. Collector-emitter current (solid red).

In addition to these static currents, several additional currents come into existence when a signal voltage or current is being amplified. These currents include:

4. Input signal current (solid blue).
5. IF tank current in both the input and output tank circuits (also in solid blue).
6. Output secondary current (also in solid blue).
7. IF neutralizing current (dotted blue).
8. Unidirectional diode current (dotted red).
9. Emitter filter current (also in dotted red).
10. AGC current (solid green in Figs. 5-6 through 5-9).

### Details of Operation

The movements of most of these currents can be understood from Figs. 5-4 and 5-5. In order that the actual generation of an audio frequency current and voltage can be visualized however, it is helpful to resort to additional circuit diagrams, of a type which will depict audio rather than intermediate-frequency half-cycles. Also, the generation of an automatic gain-control current and voltage can best be visualized by using extra diagrams to show how circuit conditions change as the signal strength does (signal fade or buildup). Figs. 5-6 through 5-9 depict these current and voltage changes. These extra diagrams are necessary because of the three widely separated frequencies that are always involved in the demodulation of an RF or IF carrier signal, and then in the development of a DC voltage which will be proportional to the strength of the original carrier signal. The latter may consequently be used to provide automatic control of the transistor gain and thus of the volume of the audio signal being delivered by the speaker.

These three frequencies are:

1. The carrier or intermediate frequency—in this case, 455,000 cycles per second.
2. The modulation frequency which is carried by the IF carrier and which, after demodulation, becomes the audio frequency from the speaker. A good average audio frequency in the "listening" range of frequencies is represented by the key of middle C, whose pitch is 256 cycles per second.
3. The frequency at which signal fades or buildups will occur because of anomalous propagation conditions. Fades and buildups occur independently of each other, so it is inaccurate to imply that such a thing as a single whole cycle of signal fade and signal buildup exists. It is more accurate to consider individual half-cycles, such as *either* a fade or a buildup, and to understand within what length of time such an event must occur. A signal fade or buildup may require several seconds or minutes to complete itself.

The time of one IF cycle of operation is always equal to the reciprocal of the frequency, in this case 1/455,000 second.

Thus, one half of one cycle will require slightly longer than one millionth of a second to complete itself. This is about the length of time required for the actions occurring in the tank circuits of Fig. 5-4. In the tank circuit consisting of the secondary winding of T1 and capacitor C1, the electrons which make up the tank current or circulating current have moved *upward* through T1 and are amassed on the upper plate of capacitor C1. Thus the voltage across the entire tank circuit has its maximum negative value at the end of this first half-cycle. The amount, or value, of this tank voltage exists to a lesser and lesser degree across portions of the secondary winding. Halfway down this coil, the instantaneous negative voltage at that point will be half of what it is at the top, and so on.

The base of the emitter is connected directly to a point that is quite far down on the secondary winding. This is done for impedance-matching purposes. The concept of impedance matching is a difficult one to visualize qualitatively. Impedance, like resistance, is a ratio between an existing voltage *and* the curent which this voltage will set in motion. The concept of impedance also represents the ratio of a *change* in an existing voltage across a circuit, to the *change* in current through this same circuit as a result of this voltage change.

A transistor connected in a common-emitter configuration such as this one, is said to have a very low input impedance.

This means that the ratio between a *change* in input voltage and the resulting change in current flow is low. In other words, only a small change in voltage will cause a substantial change in current. As always, in discussing and using the term "impedance," it is not merely helpful but actually mandatory that we understand exactly which voltage and which current we are talking about.

The input impedance of a transistor refers to the amount of change in voltage necessary between emitter and base in order to produce the desired change in base-emitter current through the transistor. The voltage difference between base and emitter is one of the fundamental biasing conditions of a transistor, and you have seen that this voltage difference is normally only a small fraction of a volt. For the desired fluctuations in base-emitter current to occur, it is only necessary to vary this existing base-emitter voltage difference by the tiniest fraction of a volt. Thus, a circuit in which a very small voltage change causes a substantial current change is a "low-impedance" circuit.

It will be helpful to remember the Ohm's-law relationship between resistance, voltage, and current whenever the impedance of a circuit is under discussion. Impedance, like resistance, is nothing more than a measure of opposition to the flow of electron current. For this reason, it can always be expressed mathematically as a ratio between voltage and current, just like resistance.

Transistors which are used in common-emitter configurations like this one are considered to have a high "output impedance." The output impedance of a transistor is again a means of expressing a ratio between a particular voltage and current. In an output circuit, we are interested in knowing what effect a change in collector voltage will have on the amount of collector-emitter current. Normally, it has relatively little effect. In this respect, the transistor is quite comparable to the pentode vacuum tube, where the plate voltage has only a small effect on the amount of plate current. As a result, the plate circuit of the pentode is considered to have a high output impedance.

For the transistor we can conclude, if we keep the Ohm's-law relationship in mind, that the output impedance is high by recognizing that an average change in the voltage at the collector will produce only a very small change in the amount of collector current. The important biasing conditions of a transistor are the voltages at the base and emitter. The difference between these two voltages exercises an overriding influence on the amount of the two currents which flow through a transistor.

Returning to the input circuit, it is necessary to use only a small portion of the voltage developed across the tank circuit consisting of capacitor C1 and the secondary winding of T1. This is why the inductor is tapped across only a small portion of its length. One might well ask why a tuned circuit is used, when the tank voltage it develops is much higher than is necessary or than can be used for amplification. The answer is that a tuned circuit provides the important feature of *selectivity*, or discrimination between signals of different frequencies. Depending on its values of inductance and capacitance, a highly tuned circuit will oscillate strongly at one particular frequency and will "reject" all others including those close to its own frequency of oscillation.

The selectivity of a tuned circuit varies in accordance with the $Q$ of the coil which is part of that circuit. $Q$ in this usage refers to "quality"—unlike in Coulomb's law, where $Q$ refers to the "quantity" of electric charge.

The $Q$ of a coil is the ratio between its reactance and resistance and is written arithmetically as:

$$Q = \frac{2\pi fL}{R}$$

where,

$Q$ is the coil "quality,"
f is the frequency of operation in cycles per second,
L is the coil inductance in henrys,
R is the coil resistance in ohms.

This relationship tells us that by increasing the inductance, L, in a coil without changing its resistance, R, we can greatly increase its $Q$ and thus improve the selectivity of the tuned circuit of which the coil is a part.

The "output impedance" of the transistor collector is also "matched" to an appropriate point on the primary winding of output transformer T2. The pulsations of collector current flowing upward through the lower portion of this primary winding will sustain an oscillation of tank-current electrons throughout the entire tank circuit. The exact phase relationships between these two currents have been discussed in greater detail in a preceding chapter on the Hartley oscillator. The cases are similar, because in a Hartley oscillator, current is drawn through a small portion of an inductor and, by autotransformer action, in turn supports an oscillation in the entire tank circuit.

The appropriate phase relations between the collector current, tank current, and tank voltage have been depicted in Figs. 5-4 and 5-5. In Fig. 5-4, while the collector-emitter current (in solid red) is increasing in the upward direction through the lower part of the primary winding of T2, it induces another current to flow at an ever-increasing rate in the downward direction through the entire primary winding. This induced current supports the tank current (in solid blue) and is essentially in phase with it. The tank current flows downward through the primary winding of T2 during the negative half-cycle of Fig. 5-4, and this accounts for the negative voltage shown on the lower plate of capacitor C2 at the end of this negative half-cycle.

During the positive half-cycle of Fig. 5-5, the collector current is still flowing upward through the lower portion of the primary winding of T2, but is now decreasing. Autotransformer action will now cause an induced current to flow in the same upward direction through the entire winding, but at an *increasing* rate. This induced current supports the main tank-circuit oscillation, which can be seen flowing upward through the winding in Fig. 5-5 and delivering electrons to the upper plate of capacitor C2. So, at the end of this positive half-cycle the upper plate of capacitor C2 exhibits a negative charge or voltage.

Probably the most important feature of a tuned tank circuit is that a relatively small amount of replenishment or support can set a sizable amount of electron current in oscillation and maintain it in oscillation. Thus, the current flow induced by the pulsations of collector current is intrinsically quite small in comparison with the amount of tank current which it maintains in oscillation.

This large tank current induces a current (solid blue) at the same frequency in the secondary winding of T2. Whenever alternating current flows through an inductor, an alternating voltage (known by such names as "induced emf," "counter emf," or "back emf") must exist across the inductor terminals. Its instantaneous polarity is always related directly to the direction in which its associated current flows, and also depends on whether this current is increasing or decreasing. (For a fuller discussion of the phase relationships existing between applied and induced voltages and current, refer to the introductory chapter of the book on oscillators in this "Basic Electronics" series.)

## The Principle of Neutralization

Neutralization is a technique used for coupling some of the energy from an output circuit of a tube or transistor back to its input circuit for the express purpose of preventing the circuit from breaking into self-sustained oscillations. It is a form of negative feedback between output and input, and is provided to counteract the effects of positive feedback which may be inherent in the tube or transistor. Let us examine the nature of this positive feedback which is inherent within transistors, and then see how capacitor C6 provides the desired negative feedback to neutralize the positive feedback.

The normal flow path for collector current in the PNP transistor is into the collector and out the emitter. In Fig. 5-4, you can see the increase in collector current following this path. However, there is inevitably some capacitance between the interior of a transistor and the external wires which lead up to it. Because of these inherent capacitances, the increase in collector current flowing through the base and toward the emitter in Fig. 5-4 will drive some electron current *away* from the base and into the external circuit leading up to the base. This current (in dotted red) flows in a direction that makes the transistor base *more* negative. This follows from the universal fact that when electron current is moving through a conductor, the terminal or point *from* which the electrons move is more negative than the point towards which they move.

In Fig. 5-5 the decrease in the collector current passing through the base again exerts a capacitive effect on the electrons within the wire leading up to the base, this time drawing them *toward* the base. Since these electrons are being drawn through the entire external circuit between base and ground, they develop a component of positive voltage at the base.

Both of these current actions in the circuit external to the base are classified as positive, or regenerative, feedback because they tend to reinforce the very conditions which caused them. During the negative half-cycle of Fig. 5-4, this component of negative voltage at the base further *increases* the two currents through the transistor. The resulting additional increase in collector current will make the component of negative voltage at the base still more negative, and so on. During the positive half-cycle of Fig. 5-5, the small component of positive voltage at the base *decreases* the two currents through the transistors. Because of the capacitive effect, the resulting additional decrease in collector current will make the component of positive voltage at the base still more positive.

These positive-feedback actions can be nullified or neutralized by causing another current to flow side by side in the external base circuit with this positive feedback current, but in the opposite direction. This is the neutralizing current, shown in dotted blue, and it can be obtained from the appropriate side of the secondary winding of T2. (A connection to the wrong end of the coil would give more positive feedback and probably lead to self-sustained oscillations.) In Fig. 5-4, the top of the secondary winding of T2 is assumed to be at a positive voltage as indicated by the blue + sign. This voltage is "coupled," via neutralizing capacitor C6, to the base of the transistor. Thus, a component of feedback current is drawn *toward* the transistor base at the same time the undesired feedback current is being driven *away* from the base.

In Fig. 5-5, when the top of the secondary winding of T2 is negative, electrons are driven to the left, through capacitor C6, and thus flow *away* from the base at the same time the unwanted feedback current is flowing *toward* it. In this fashion, neutralization automatically and continually compensates, during each cycle, for the positive feedback caused by inherent capacitances within the transistor.

## The Demodulation Process

Diode M1 in this circuit is a unidirectional device (one that permits current to flow in only one direction through it). Electrons can flow with relative ease *against* the direction of the arrow (to the left, in other words), but only with very great difficulty can they be made to flow in the opposite direction. This inherent property makes the diode a useful rectifying device for the demodulation of a modulated signal. When the top of the secondary winding of T2 has a positive voltage induced on it (such as during the half-cycle of Fig. 5-4), electrons (in dotted red) will flow up from ground, through resistor R3 and the diode. This current flow creates a positive voltage at the top of R3, as indicated by the red plus signs on capacitor C4.

During alternate half-cycles as in Fig. 5-5, the top of the secondary winding of T2 has a negative voltage induced on it, so

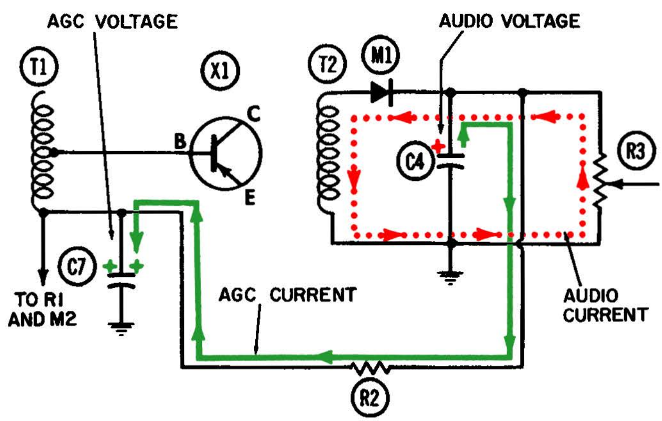



**Fig. 5-6. AGC portion of the circuit in Figs. 5-4 and 5-5—modulation trough during a period of weak signal strength.**

no current flows through diode M1 in either direction. The positive voltage on the upper plate of capacitor C4 persists throughout this positive half-cycle, because of the "integrating" action of the long time-constant RC combination consisting of R3 and C4. Any RC combination is a long time-constant combination to a particular frequency if the resistance in ohms multiplied by the capacitance in farads is more than five or six times greater than the time required for a single whole cycle of current movement to occur at the particular frequency. This is in accordance with the time-constant formula:

$$T = R \times C$$

where,

T is the time constant of the combination in seconds,
R is the resistance in ohms,
C is the capacitance in farads.

If an unmodulated carrier signal were being received, every RF cycle would have the same strength, and the voltage on the upper plate of C4 would be essentially DC. When a modulated signal is being received the strength of the individual RF cycles is not constant. Rather, it varies in accordance with modulation, and so does the voltage on C4. When a strong RF cycle is being received (this happens during a modulation peak), the induced voltage across the secondary winding of T2 will be higher. Thus, more electron current will be drawn upward through R3 and the diode. This means that a higher positive voltage will exist across R3 and on the upper plate of C4.

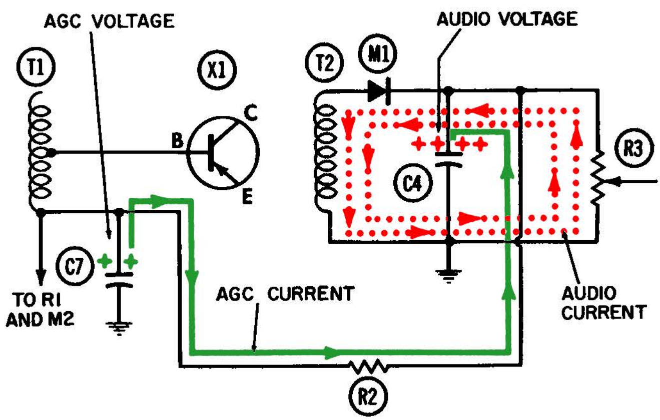



**Fig. 5-7. AGC portion of the circuit in Figs. 5-4 and 5-5—modulation peak during a period of weak signal strength.**

When a weak RF cycle is being received (this happens during a modulation trough), the induced voltage across the secondary winding of T2 will be lower. Now, less electron current will be drawn upward through R3, and a lower positive voltage will exist across R3 and on the upper plate of C4. Since the strength of the individual cycles of RF depends on the amount of modulation, the voltage produced at the top of resistor R3 is an audio-frequency voltage.

Figs. 5-6 and 5-7 show two successive half-cycles of the audio voltage as it appears for the first time, immediately after demodulation, in a typical receiver. Circuit components in these figures have been numbered to correspond to their counterparts in Figs. 5-4 and 5-5. The radio-frequency currents have not been shown in Figs. 5-6 and 5-7. These illustrations depict one entire audio cycle, consisting of a modulation trough followed by a modulation peak, while a weakened carrier signal is being received. The audio currents are shown in dotted red, the same as in Figs. 5-4 and 5-5. The AGC current (so labeled, and shown in solid green) flows in either direction along part of the same path used by the voltage-divider current (in dotted green in Figs. 5-4 and 5-5). During a modulation trough, when a low positive voltage exists on the upper plate of C4, the AGC current is drawn to the left, through resistor R2, by the higher positive voltage stored on the upper plate of C7.

During a modulation peak as in Fig. 5-7, this AGC current is drawn to the right, through resistor R2, by the higher positive voltage now stored on the upper plate of capacitor C4.

The intrinsic amount of positive voltage stored on the upper plate of AGC capacitor C7 does not change during a single audio cycle, even though electrons flow onto it during a modulation trough (Fig. 5-6) and out of it during a modulation peak (Fig. 5-7). The reason is that the combination of resistor R2 and capacitor C7 forms a long time-constant to the lowest audio frequency likely to be encountered. This means these components are large enough that their product is several times the period of a single low-frequency audio cycle. When these components are made large enough, the *amount* of electrons which flow through R2 on successive half-cycles will be insignificant, compared with the number of positive ions already stored on the upper plate of C7. Thus, by appropriate choice of the sizes of these two components, a DC voltage can be developed on the upper plate of C7 that does not vary with the modulation represented by the audio signal.

The voltage stored on an AGC capacitor such as C7 will always adjust itself to the average value of the trough and peak voltages on the upper plate of the audio-output capacitor—in this case, C4. This average value will remain the same unless the over-all strength of the RF carrier changes because of propagation anomalies, which cause what are known as signal fades or buildups. Figs. 5-8 and 5-9 depict two successive audio half-cycles during a period of excessive carrier-signal strength, or what is called a signal buildup. All the radio-frequency tank currents shown in solid blue in Figs. 5-4 and 5-5 will become proportionately stronger during such a period. As a result, more audio current will be drawn upward through R3 and diode M1 during both a modulation peak and a modulation trough. This is depicted by the additional dotted red lines in Figs. 5-8 and 5-9. This additional current flow increases the trough and peak voltages stored on C4 and so, increases their average value.

The voltage stored on capacitor C7 is "replenished" by the voltage stored on C4. During a signal buildup, when both the audio modulation trough voltage (Fig. 5-8) and the audio modulation peak voltage (Fig. 5-9) are increased, their average value is also increased. Consequently, the positive voltage on the upper plate of C7 must increase to this average value. This important action is accomplished by the AGC current shown in Figs. 5-6 through 5-9. During a period of normal or unchanging signal strength such as are shown in the two half-cycles of Figs. 5-4 and 5-5, an AGC current will flow, *at the audio frequency,* back and forth between capacitors C7 and C4, through resistor R2. The amount of current flowing to the left during each modulation trough *will be exactly equal* to the amount flowing to the right during the next modulation peak. Because of this, the positive voltage stored on C7 is maintained at the average value of the high and low positive voltages on C4.

When signal strength is increased by a signal buildup, both the high and low positive voltages will be increased in value. When this happens, the two half-cycles of AGC current flowing through resistor R2 will become "unbalanced." In other words, *more* electrons will flow away from C7 during the modulation peak of Fig. 5-9, and *fewer* electrons will flow into C7 during the modulation trough of Fig. 5-8. This condition of current unbalance will continue until the AGC voltage stored on C7 becomes sufficiently positive to just equal the average value of the trough and peak voltages on C4.

The circuit actions involved in achieving automatic gain control in a transistor circuit are fundamentally similar to those in vacuum-tube circuitry. These principles have been discussed with greater detail in the chapter on automatic volume control in the book about detector and rectifier circuits in this "Basic Electronics" series. Also, waveform diagrams appearing in that book may help to clarify the meaning and significance of terms such as modulation trough, modulation peak, signal fade, and signal buildup. The most important difference between AVC circuitry using tubes and transistors is that in tube circuitry a *negative* AVC voltage normally is developed whereas in the example of this chapter, the AVC voltage developed on capacitor C7 is positive instead.

## How AGC Voltage Controls Transistor Gain

In this type of circuit, the AGC voltage controls, or regulates, the transistor gain by exercising some control over the base-emitter current which flows through the transistor. Since this is a PNP transistor, any positive component of voltage applied to the base of the transistor will *decrease* the base-emitter current (called "biasing" current). Its quantity depends on the biasing conditions (meaning the biasing voltages) at the base and emitter. As was pointed out earlier in this chapter, a certain negative voltage is applied to the emitter of X1 (as a result of current flow through resistor R4), and a slightly higher negative voltage is applied to the base (as a result of voltage-divider action through R1, R2, and R3). The difference between these two applied voltages is one of the fundamental biasing conditions of the transistor (the most important one, in fact), and it controls the amount of electron current flowing from base to emitter (the base-emitter biasing current).

The existence of a permanent positive voltage on the upper plate of capacitor C7 will reduce the negative voltage created

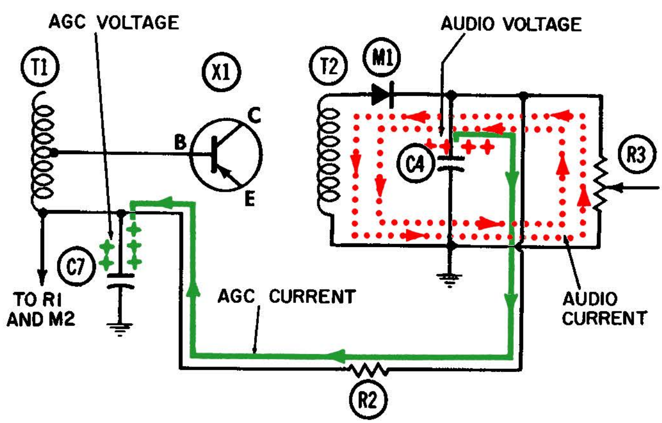



Fig. 5-8. AGC portion of the circuit in Figs. 5-4 and 5-5—modulating trough during a period of strong signal.

at the base of the transistor by the flow of voltage-divider current through R1, R2, and R3. The positive AGC voltage shown on C7 is not a composite value of all the voltages at the base of the transistor, but only the result of the AGC filter action occurring between R2 and C7. You have already seen that four other voltages exist at the base, each contributing in some small degree to the amount of base-emitter biasing current flowing. The AGC voltage makes a fifth one. These five voltages are:

1. The voltage resulting from voltage-divider current through resistors R1, R2, and R3. This is a fixed, or DC, voltage which is negative at the junction of R1 and R2, and consequently negative at the base.
2. The signal voltage, which is alternately positive and negative at the intermediate frequency, and which therefore lowers and raises the negative voltage at the base.
3. The voltage resulting from positive feedback caused within the transistor by capacitance between the internal elements (B, C, and E) and the external wiring of the transistor (IF).
4. The voltage due to negative feedback from output circuit to input circuit, through capacitor C6. (IF)
5. The AGC voltage on C7. Although essentially a DC voltage, it does vary if and when the signal strength of RF carrier varies.

The combination of resistor R2 and capacitor C7 is chosen so that their product will be a "long time-constant" when compared with the duration of a single low-frequency audio cycle. If the lowest audio frequency being amplified were 50 cycles per

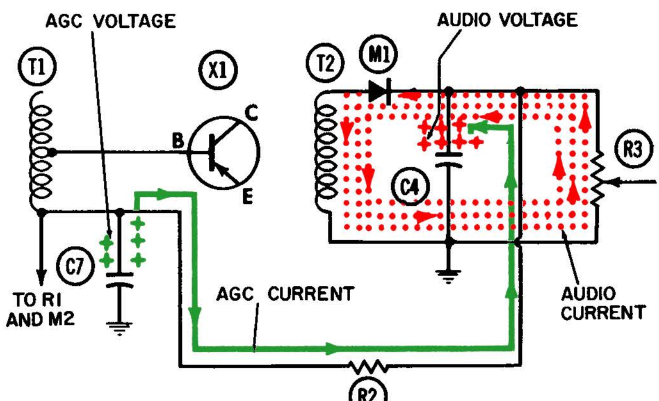



Fig. 5-9. AGC portion of the circuit in Figs. 5-4 and 5-5—modulation peak during a period of strong signal.

second, with a period of .02 second for each cycle, the R2-C7 combination would be a "long time-constant" combination to this frequency if their product were more than five times longer than this period—i.e., a tenth of a second or longer.

### The Audio-Output Voltage

An audio-output voltage is developed across resistor R3, by the pulsating DC which continuously flows upward through it. This current (in dotted red) also flows through M1, and as a result of the demodulation process previously described, its pulsations occur at the audio frequency. The arrow pointing into R3 indicates that this is a potentiometer, or variable resistor, with which any desired fraction of the total voltage may be tapped off for amplification by the next succeeding audio-amplifier stage. Potentiometer R3 thus constitutes a manual volume control for the receiver in which it is installed.

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