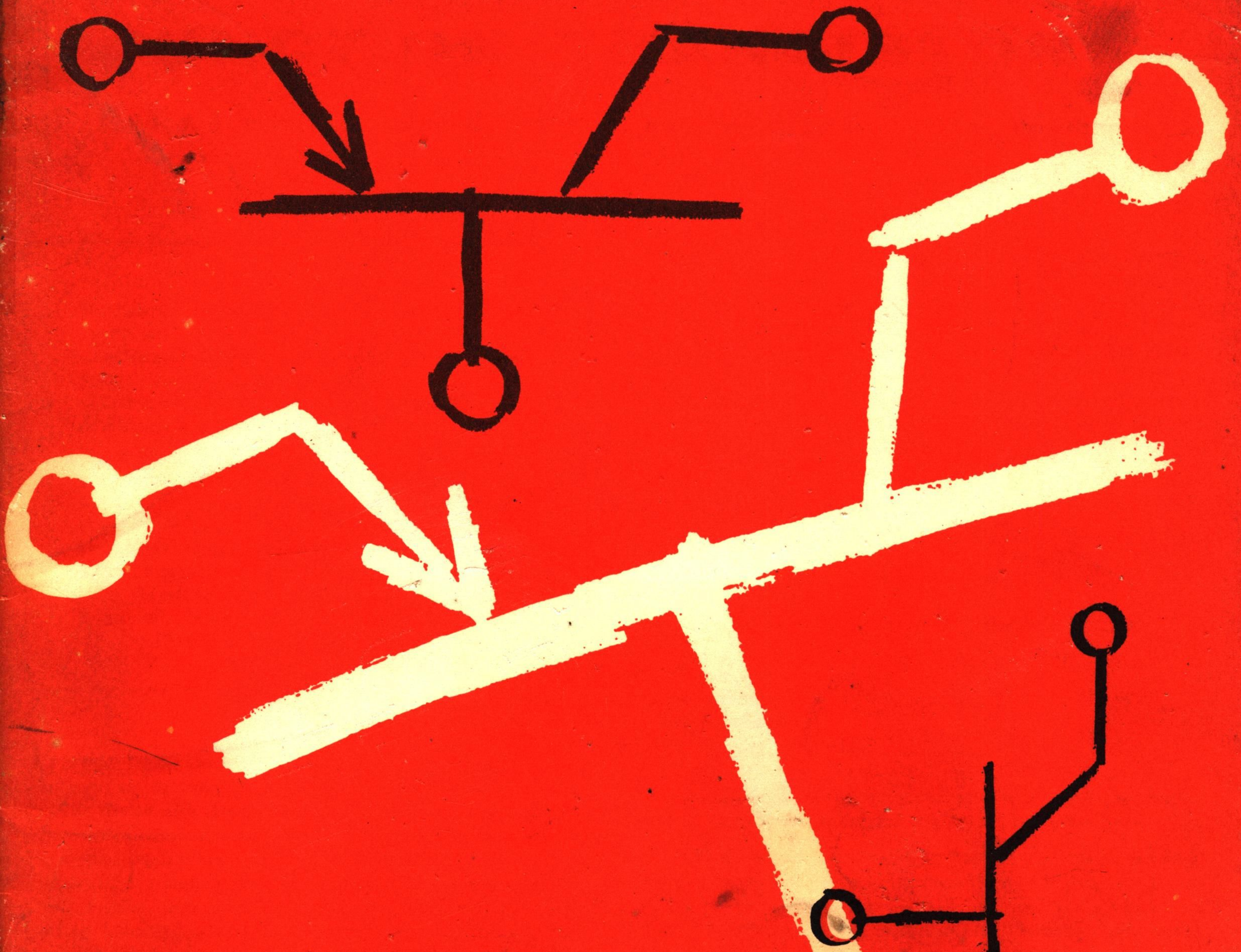

INTRODUCTION TO

JUNCTION TRANSISTORS

"SIMPLIFIED APPROACH TO CIRCUIT DESIGN"

by R. N. HURST

RADIO CORPORATION OF AMERICA

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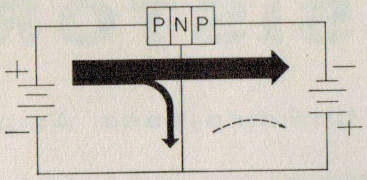
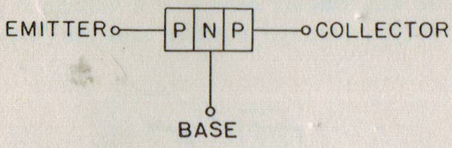
pletely through both junctions, except for a small current which would flow as shown in this sketch:



(5)

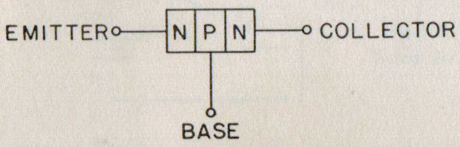
This unexpected behavior, which is observed only if the center region is thin, is the basis for transistor action.

Since the left-hand P-region emits current into the transistor, it is called the *emitter*. The middle region (the N-region here) through which the emitter current passes is called the *base*. The right-hand P-region, which collects the current emitted by the emitter, is called the *collector*.



(6)

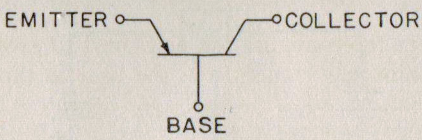
A transistor constructed in this manner (as a "sandwich" of N-type "meat" and P-type "bread") is called a *PNP Transistor*. By reversing the "meat" and the "bread," another arrangement is possible:



(7)

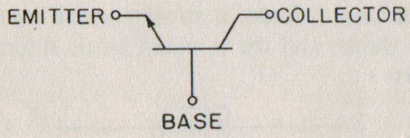
This arrangement is called an *NPN Transistor*. The major difference between the two is that the various voltages applied to a PNP transistor must be reversed for an NPN transistor.

In schematic diagrams, a PNP transistor is symbolized in this way:



(8)

and an NPN transistor this way:



(9)

It will be noticed that both NPN and PNP transistors exhibit left-to-right symmetry; that is, the emitter and collector of a given transistor are both made of the same material, and apparently connected to the base in the same way. It is reasonable to ask whether it makes any difference which of the outer regions is the emitter and which the collector. In some transistors, called *symmetrical* transistors, it makes no difference. In most transistors, however, the emitter and collector regions are manufactured differently. It is this difference which determines the proper naming of these regions. Regardless of this difference, a typical small transistor may usually be made to operate in a very limited manner with emitter and collector leads interchanged.

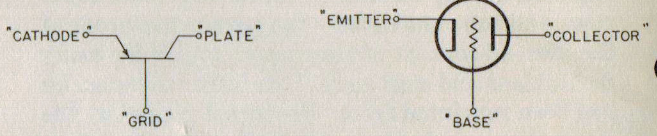
Transistor vs Vacuum Tube

The transistor, being an amplifying device, bears a resemblance to a vacuum tube in that the three "elements" of a transistor correspond (approximately) to the three elements of a triode tube:

Transistor	*Vacuum Tube*
Emitter	Cathode
Base	Grid
Collector	Plate

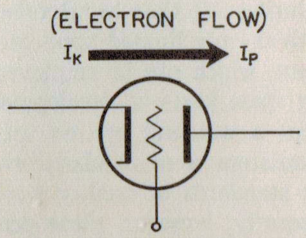
(10)

This correspondence between transistor and vacuum tube can be used to produce the following equivalent symbols:



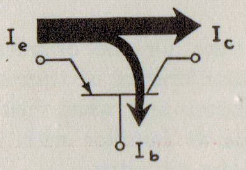
(11)

One should not infer, however, that these equivalences are anything but approximate. For example, consider the difference between a grid and a base. A grid, in normal negative-biased operation, draws no current. The total cathode current flows in the plate circuit:



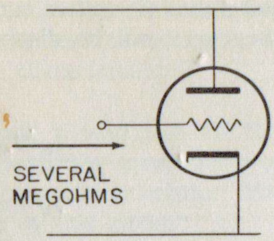
(12)

It was stated above, however, that the emitter current in a transistor divides between the collector and the base, so that the base has an appreciable current flowing in it:



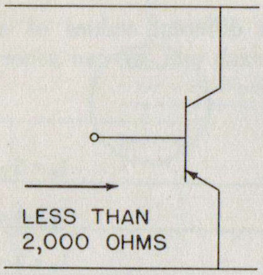
(13)

Since the current that flows (for a given voltage) is an indication of the impedance of a circuit, the fact that the base draws current while a grid does not leads to the conclusion that the impedance seen looking into a base would be very much smaller than the impedance seen looking into a grid. The conclusion is correct; a typical vacuum tube, it is well known, has a grid impedance of several megohms,



(14)

while a typical transistor may have a base impedance less than 2000 ohms:



(15)

Definition of Alpha and Beta

Although sufficient current flows in the base circuit to make the base appear as a low impedance, this base current represents only a small portion of the emitter current—approximately two percent in a typical transistor. The remaining 98 percent appears in the collector circuit. This current division is used to define an important transistor parameter called *alpha.* If 98 percent of the emitter current of a certain transistor flows in its collector, the transistor has an alpha of 0.98. Mathematically, it is stated:

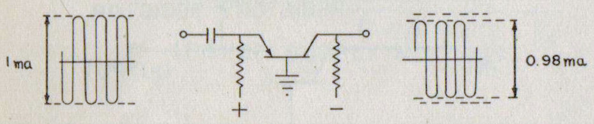
$$\alpha_{DC} = \frac{I_c}{I_e} \qquad (16)$$

Since I_c (dc collector current) and I_e (dc emitter current) are bias currents, their ratio is called *dc alpha,* hence the dc subscript. The more frequent use of the word alpha refers to a ratio of signal currents (where i_c and i_e are signal currents in the collector and emitter, respectively):

$$\alpha_{AC} = \frac{i_c}{i_e} \qquad (17)$$

The word alpha as used herein always refers to the ratio of signal currents, unless there is a statement to the contrary. It is interesting to note, in passing, that both definitions give almost the same value for alpha.

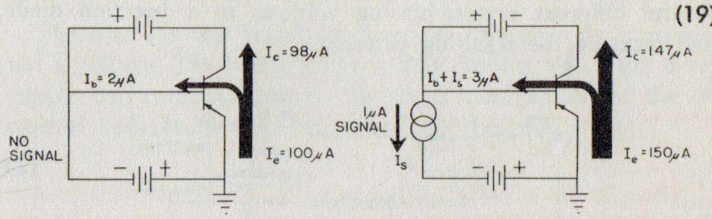
Since the collector current is always a little less than the emitter current, alpha will always be a little less than one. Therefore, a transistor will offer loss instead of gain for a *current* signal impressed on the emitter and observed at the collector:



(18)

Nonetheless, useful arrangements can be made using this circuit, even though it does not give us a *current* gain. Some of the ways of using this configuration, which is called the *grounded-base configuration,* are discussed later in this article.

How, then, is current gain obtained? It is obtained by controlling the base current (two percent in the foregoing example) by applying a signal to the base. The base current, when controlled by a small fluctuating (signal) current, causes a corresponding fluctuation in the much larger emitter current, thereby causing the same fluctuation in the collector current:



(19)

Since the small signal-current introduced in the base circuit causes a larger signal-current to appear in the collector circuit, we say that a *current gain* has taken place.

The current gain obtained here is clearly the ratio between the collector current and the base current. This current ratio is another important transistor parameter, and is called *beta.* Mathematically, it is stated:

$$\beta_{DC} = \frac{I_c}{I_B} \qquad (20)$$

This ratio is called *dc beta,* for reasons similar to those given for dc alpha. More frequently, the word beta refers to a ratio of *signal* currents:

$$\beta_{AC} = \frac{i_c}{i_B} \qquad (21)$$

This definition of beta is the one which is used in this article unless there is a statement to the contrary.

In sketch 19, a signal current of 1 μA in the base caused a change of 49 μA (147 μA —98 μA) in the collector current. The beta of this transistor would be:

$$\beta = \frac{49}{1} = 49 \qquad (22)$$

This is a fairly typical value.

Note that in the configuration employed to give current gain, the ground point was moved from the base to the emitter. This circuit is therefore called the *grounded-emitter configuration,* or *common-emitter*[2] *configuration.* It is roughly equivalent to the grounded-cathode configuration of a vacuum tube, but the analogy should be employed with caution. For example, it has already been pointed out that the impedance, looking into the base, is typically 2000 ohms, instead of the high impedance usual for a vacuum-tube grid.

Note also that signals and biases in transistors are described as currents, not as voltages, as is common in vacuum tubes. The gain (beta) which roughly corresponds to mu in a vacuum tube, is a *current* ratio, whereas mu is a *voltage* ratio. It is usually much more convenient, for transistor work, to describe the circuits in terms of currents, rather than in terms of voltages.

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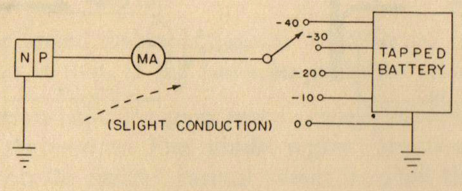
[2] In these articles, the prefix "common-" will be used in preference to "grounded-," since it is more general. For example, it is not unusual to have a common-emitter amplifier in which the emitter is not connected to ground.

Characteristic Curves of Transistors

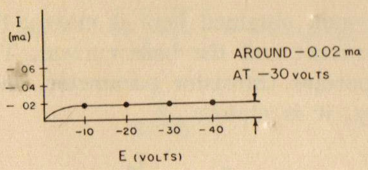
In the introduction to this subject, the transistor was presented as an extension of an ordinary junction diode. This same approach can be used to derive the characteristic curves of a typical transistor, which show very clearly the behavior that can be expected.

If we set up a laboratory experiment in which we apply several different reverse-biasing voltages to a junction diode, and measure the resulting currents,



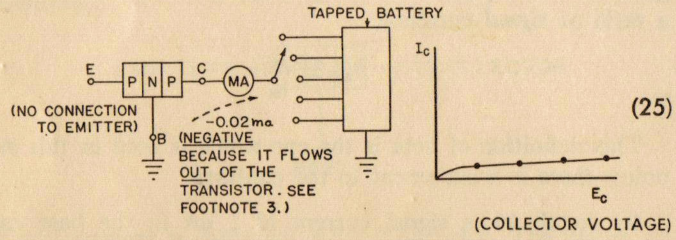
(23)

we can plot from the resulting data a curve showing the reverse-bias characteristic of a junction diode:



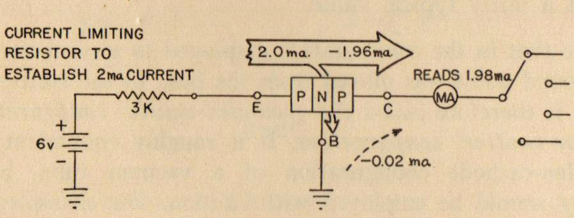
(24)

Simply extending this reverse-biased diode (to make it into a transistor) will not change the curve,



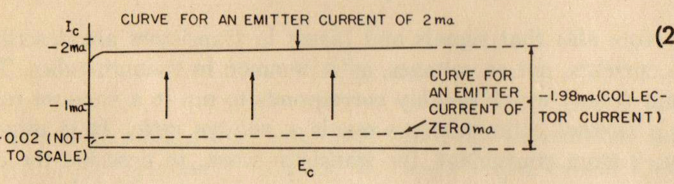
(25)

but forward-biasing the *new* junction (which is the way we establish transistor action) will cause a definite change in the curve, since the forward-bias current will flow through both junctions and appear in the circuit containing the milliammeter:



(26)

This additional current will displace the entire curve upward:



(27)

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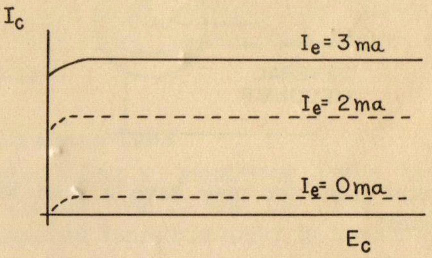
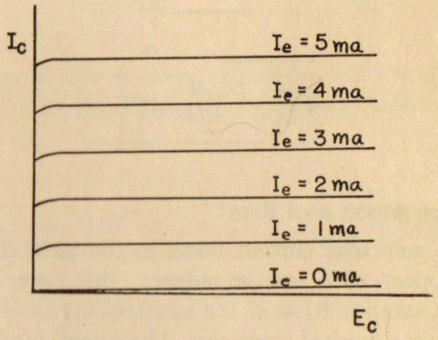
[3] Conventional network theory states, arbitrarily, that current flowing *into* a network is positive; current flowing *out*, negative. This convention is followed in these articles. It is also used in transistor data sheets.

If we choose a different value of emitter current—say 3.0 ma instead of 2.0 ma—the curve will be displaced upward even farther:



(28)

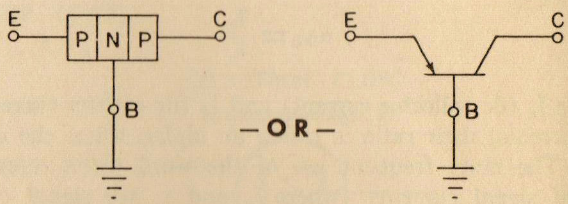
By selecting several different values of emitter current and showing a curve for each one, we can generate an entire family of curves:



(29)

This family is typical of the curves found in data sheets.

You will note that these curves are drawn for a transistor operating with its base grounded:

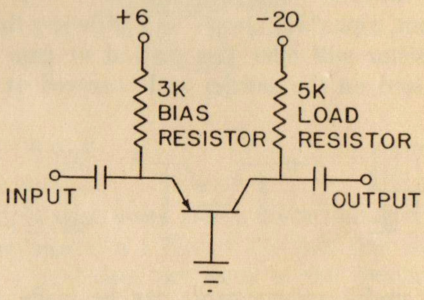


(30)

Therefore, these curves are called *common-base curves,* and an amplifier built using a transistor connected in this manner is called a *common-base amplifier*. These curves can be used to show the behavior of a common-base amplifier.

Transistor Amplifier

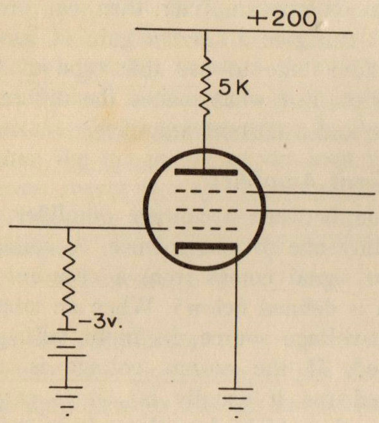
Let us suppose that a piece of broadcast equipment contains this common-base transistor amplifier (using a PNP transistor):



(31)

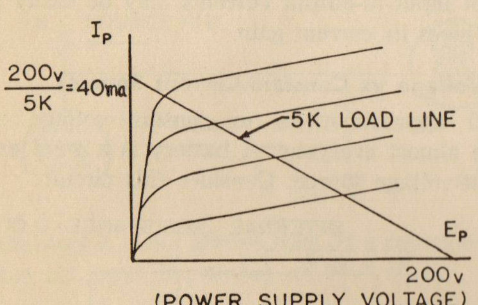
We wish to know how this amplifier is operating—what the bias is, how much collector current flows, how much power is dissipated in the collector, and how much gain it will offer. All these facts may be ascertained by a simple construction on the common-base characteristics.

Start by drawing a load line on the characteristics. This construction is exactly the same as the corresponding construction on vacuum-tube characteristics. You will remember that a typical pentode in this circuit;



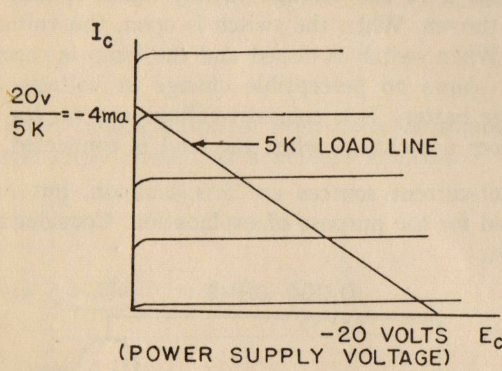
(32)

will have a load line connecting the 200-volt point and the 40-ma point, (the 40-ma point is obtained by dividing 200 volts by 5,000 ohms):



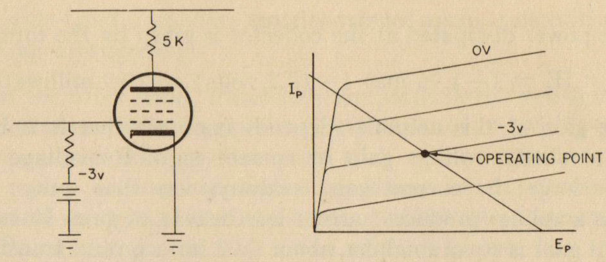
(33)

In an exactly similar manner, the load line for the common-base amplifier will be a straight line connecting the —20-volt point and the —4-ma point:



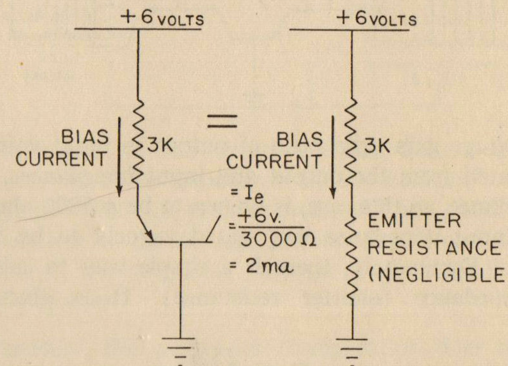
(34)

Just as for vacuum tubes, the operating point of the transistor amplifier must lie somewhere on its load line. For the pentode, the operating point lies at the intersection of the load line and the curve representing the particular bias chosen by the design engineer:



(35)

The bias for this transistor amplifier, however, is a *current*, not a voltage. The bias current is that current which the 6-volt supply can cause to flow in the series combination of the 3K resistor and the forward-biased emitter[4] junction:

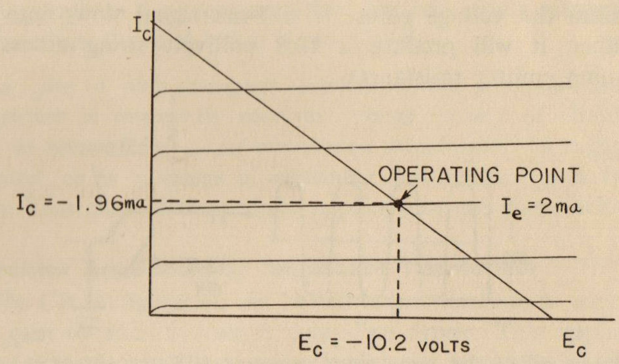


(36)

Since the emitter resistance is usually very small (less than 50 ohms), its resistance may be neglected in computing the bias current. The current is therefore:

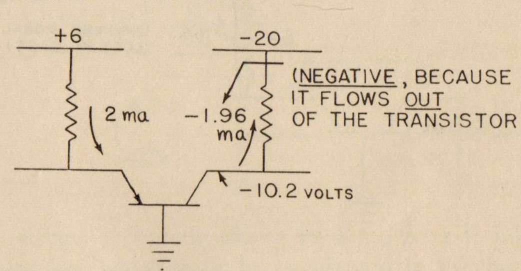
$$I_e = \frac{6 \text{ volts}}{3{,}000 \text{ ohms}} = 2 \text{ ma} \qquad (37)$$

which will put the operating point at the intersection of the load line and the 2-ma curve:



(38)

This transistor amplifier therefore operates with a bias current of 2 ma, a collector current of —1.96 ma, and a voltage at the collector of —10.2 volts:



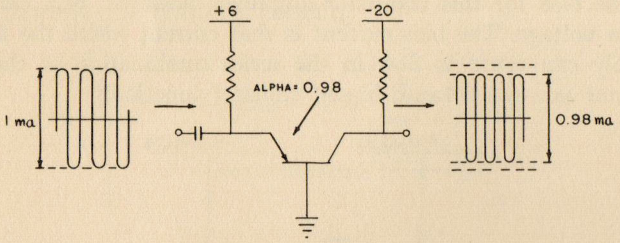
(39)

[4] The comparison of *grid* bias and *emitter* bias could confuse the reader into thinking the *grid* and *emitter* are equivalent. They are not; the comparison is used merely because the graphical constructions are similar. The *grid* corresponds to the *base*.

The power dissipated at the collector is given by the formula:

$$P = IE = (-1.96 \text{ ma}) \; (-10.2 \text{ volts}) = 19.9 \text{ milliwatts}$$

The gain of this amplifier depends upon whether it is being used to obtain voltage gain or current gain. Its voltage gain can be large; its current gain is always less than unity; that is, this amplifier produces current loss instead of gain. Its actual current gain is equal to alpha, about 0.98 for a typical transistor:



(40)

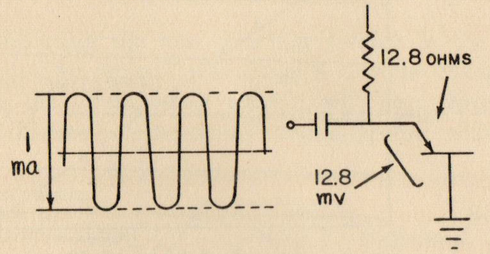
The *voltage* gain (the ratio of output to input voltages) can be calculated from the output and input impedances. The output impedance, in this case, is known to be a 5000-ohm resistor, but the input impedance was stated vaguely to be "less than 50 ohms." Fortunately, there is a simple way to calculate the input impedance (emitter resistance). It is given by the formula[5]:

$$R_e = \frac{25.6}{I_e} \qquad (41)$$

In this formula R_e is the emitter resistance in ohms, and I_e is the emitter current in milliamperes. For the transistor amplifier in this example, the emitter is biased with 2 ma. so the emitter resistance is:

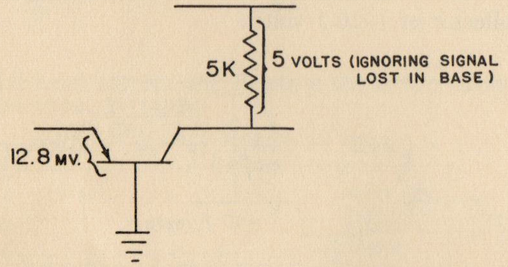
$$R_e = \frac{25.6}{2 \text{ ma}} = 12.8 \text{ ohms} \qquad (42)$$

Now, knowing both input and output impedances, we can calculate the voltage gains. If a 1-ma signal flows into this amplifier, it will produce a 12.8 millivolt swing across the 12.8-ohm emitter resistance:



(43)

Almost all of the 1-ma signal current (98 percent of it) flows in the 5000-ohm load resistor, producing a 5-volt drop across it:



(44)

[5] This expression is derived from basic semiconductor physics. It can be shown that $R_e = (kT/e)/I_e$, where k is boltzman's constant, T is the absolute temperature, and e is the charge on an electron. Inserting proper values gives a value of 25.6 for kT/e, at 25 degrees C. This is a theoretical value subject to appreciable variation in practical transistors.

The voltage gain in this case is:

$$G_V = \frac{5 \text{ v}}{12.8 \text{ mv}} = \frac{5}{0.0128} = 391 \qquad (45)$$

The same answer can be obtained by taking the ratio of the output and input resistances:

$$G_V = \frac{5{,}000 \text{ ohms}}{12.8 \text{ ohms}} = 391 \qquad (46)$$

The same common-base amplifier, then, can provide a *voltage* gain of 391, but can give a *current* gain of less than 1. It is clearly to our advantage to use this type of amplifier as a voltage-gain device. But what makes the difference between a voltage amplifier and a current amplifier?

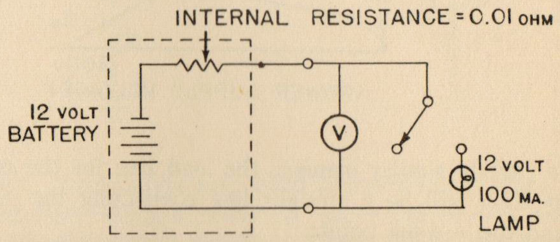
Voltage vs Current Amplifier

The distinction between a voltage amplifier and a current amplifier is mainly one of convenience. A voltage amplifier is one whose input signal comes from a *constant-voltage source* (note, this term is defined below). When an amplifier is driven from a constant-voltage source, its input voltage is known or easily determined. If the output voltage is also known or easily determined (as it usually is), it is easy to take the output-to-input ratio, which gives the voltage gain. Under these circumstances, it is *convenient* to consider the amplifier as a *voltage* amplifier.

Similarly, if an amplifier's signal source is a *constant-current source* it is *convenient* to consider it as a *current amplifier,* for the ratio of input-to-output currents may be easily determined. This ratio gives its current gain.

Constant-Voltage vs Constant-Current Sources

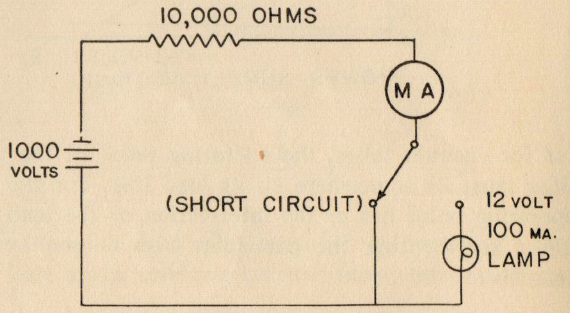
Practical approximations to constant-voltage sources are familiar to almost everyone. A battery is a good example of a dc constant-voltage source. Consider this circuit:



(47)

Note that a 12-volt storage battery lights a lamp when the switch is thrown. When the switch is open, the voltmeter reads 12 volts. When switch is closed and the lamp is connected, the voltmeter shows no perceptible change in voltage. Therefore, the storage battery is a constant-voltage source, for its output voltage does not change when the load is connected.

Constant-current sources are less common, but one can be synthesized for the purpose of explanation. Consider the following circuit:



(48)

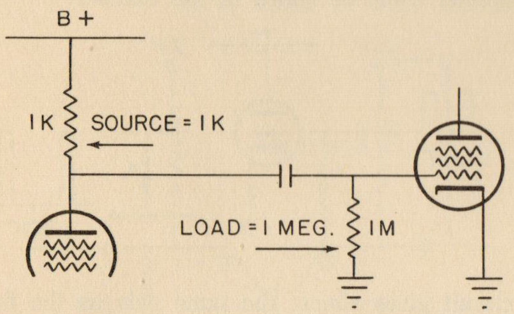
Note that a 1000-volt battery supplies current to a lamp when the switch is thrown.

When the switch is in the short-circuit position, the milliameter indicates that 100 ma flows in the circuit. When the lamp is lit, the milliameter shows no perceptible change in the 100-ma current. We therefore say that the battery-plus-resistor combination is a constant-current source, for its output current does not change when the short circuit is replaced by the load.

One can easily see that these "constant" sources are only *approximately* constant. How nearly constant they remain depends upon the relationship between their internal impedances and their respective load impedances. In practical cases, a source is called a *constant-voltage source* when its internal impedance is much less than the impedance of the load it feeds. Likewise a *constant-current source* is a source whose internal impedance is much *greater* than the impedance of the load it feeds. Inspect the two dc examples above, to verify these statements. (The 12-volt lamp has an impedance of 120 ohms.)

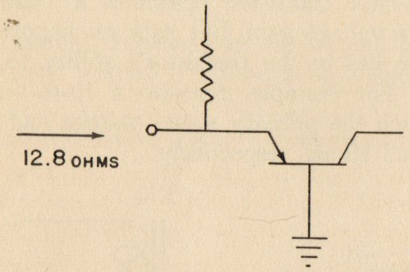
Voltage vs Current Amplifiers

Through vacuum-tube experience, it has become the custom to think of *all* amplifiers as voltage amplifiers, since the grid of a vacuum tube makes almost any source look like a low-impedance (constant-voltage) source, by comparison:



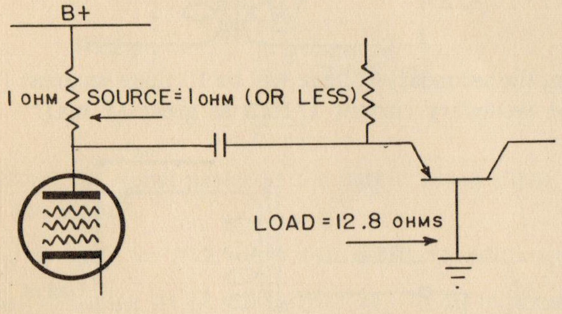
(49)

With transistors it is not always thus. If a common-base (CB) amplifier has an input impedance of 12.8 ohms;



(50)

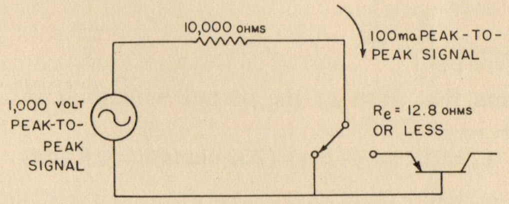
it must be fed from a source of even *lower* impedance in order to be conveniently classed as a voltage amplifier:



(51)

This is not always practical. Transformers may be used to obtain such low impedances in narrow-band or tuned amplifiers, but wide-band amplifiers usually cannot make practical use of such an arrangement.

On the other hand, transistors are particularly well-suited for operation as current amplifiers. A transistor—especially in the common-base configuration—has such a low-impedance input that many sources are higher-impedance in comparison, and therefore are treated as current sources. Consider, as an example, the dc current source used as an example above, but with an ac signal in place of the battery:



(52)

The impedance of the source—10,000 ohms—is certainly much greater than the impedance of the emitter.[6] A constant signal-current of 100 ma, peak-to-peak, will flow, without regard for the position of the switch. Driven thus from a constant-current source, the transistor may most easily be regarded as a current amplifier.

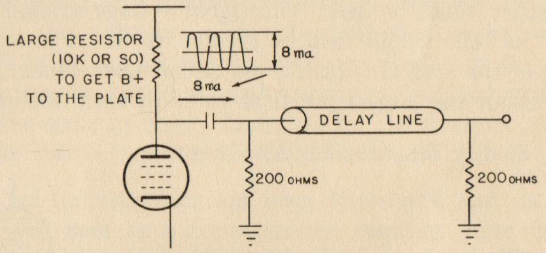
Unfortunately, this particular configuration does not give a useful current gain. With a 100-ma signal flowing into the emitter, only a 98-ma signal will flow from the collector (if alpha = 0.98). The common-base amplifier actually gives a current *loss* instead of a current gain.

The behavior of a common-base amplifier may be summarized thus: If a very low-impedance source is available, it will operate as a voltage amplifier, giving large voltage gains. Such sources are rather uncommon, however, particularly for wide-band amplifiers. If a moderately-high-impedance source is available, it will operate as a current amplifier, but will give a current gain of less than one, and hence is not useful.

In spite of such stringent restrictions, the common-base configuration is frequently used in a large variety of circuits. It will be seen acting as an impedance transformer, as a capacity isolator, or as a means of obtaining non-inverted gain from a tube. Examples of these three applications are given below.

Transistor Application as Impedance Transformer

The CB configuration can be put to practical use in improving the gain obtainable from a delay-line driver. This application is an example of its use as an impedance transforming device. Consider the following circuit:

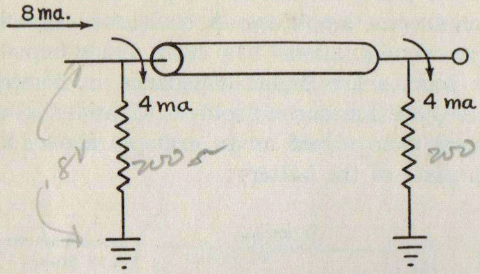


(53)

In this circuit a pentode drives an 8-ma peak-to-peak signal into a delay line which *must* be terminated in its characteristic

6 The emitter resistance of 12.8 ohms was calculated for a bias current of 2 ma. To operate linearity with a signal swing of 100 ma, bias current would have to be at least 50 ma, which would give, by (41), $R_e = 0.51$ ohms.

impedance of 200 ohms. The 8 ma will divide equally between the input termination and the output termination:

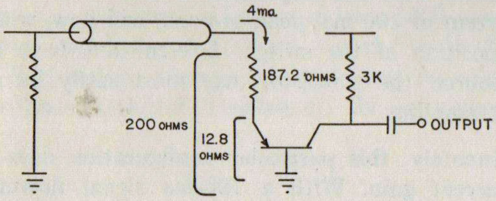


(54)

The 4 ma that flows at the output will result in an output signal of:

$$e_o = iR = (4 \text{ ma})\ (200 \text{ ohms}) = 0.8 \text{ volts} \qquad (55)$$

A considerable improvement in the output level can be made by inserting a transistor in this manner:



(56)

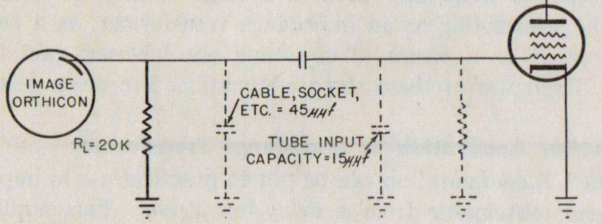
(Means of biasing are ignored to keep the picture uncluttered). In this case, the 4-ma signal flows through the transistor and appears (except for the two percent lost in the base, which we ignore here) in the collector circuit. The voltage output from this circuit is:

$$e_o = iR = (4 \text{ ma})\ (3{,}000 \text{ ohms}) = 12 \text{ volts} \qquad (57)$$

This is an *effective* gain of 15 over the first circuit.

Transistor Application as Capacity Isolator

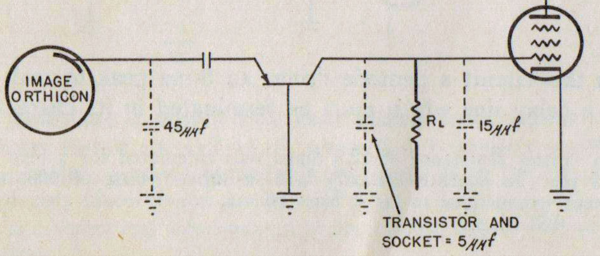
A common-base amplifier as a capacity isolator, can also give an effective gain. Consider the following circuit:



(58)

In this circuit a total of 60 $\mu\mu$f of stray capacity shunts R_L, the 20K load resistor. If the stray capacitance were less, a larger load resistor could be used. The signal voltage available at the grid of the tube would then be greater, in direct proportion to the size of the load resistor. As the circuit now stands, however, 20K is about the largest practical value of load resistor.

Now, modify the circuit in this manner:

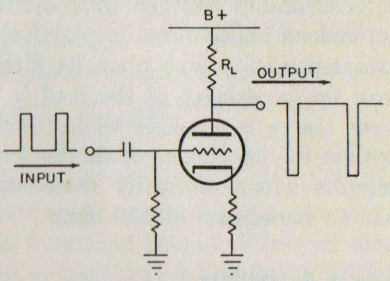


(59)

Note that only $15 + 5 = 20$ $\mu\mu$f appears across the load resistor. Since this is only $^1/_3$ of the 60 $\mu\mu$f of the first circuit, R_L can be 3 times as big, or 60K. The result is an *effective* gain of three.

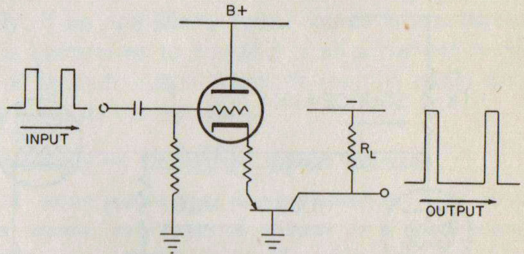
Transistor Application for Preserving Signal Polarity

A common-base amplifier can also be used to preserve the polarity of a signal, whenever necessary. If a tube giving a gain of ten is required to amplify a pulse, the following circuit might be employed if an output signal of inverted polarity could be used:



(60)

However, if a noninverted pulse is required, the above circuit cannot be used. (A noninverted pulse can be obtained at the cathode, but not at the required level.) To obtain a noninverted pulse of the required amplitude, a common-base transistor amplifier could be added in this manner:

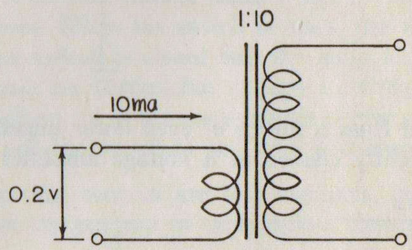


(61)

This circuit gives almost the same gain as the first circuit, and does not invert the signal.

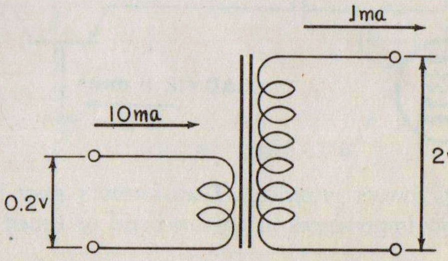
Power Gain

A common-base transistor resembles a transformer in its ability to give voltage gain, but with an important difference. The difference lies in the transistor's ability to give a *power gain* as well. For example, consider a 10-to-1 step-up transformer in which the primary signal voltage and signal current are 0.2 volt and 10 ma, respectively:



(62)

Then, the secondary voltage will be 10 times as great (2 volts) and the secondary current 1/10th as great (1 ma):



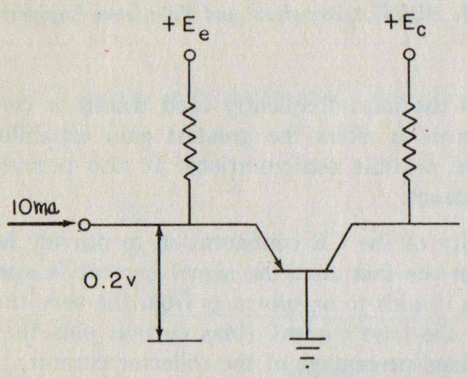
(63)

The power at the output, (neglecting losses) is the same as the power at the input:

$$P_{in} = E_{in}\ I_{in} = (0.2 \text{ volts})\ (10 \text{ ma}) = 2 \text{ milliwatts} \quad (64)$$

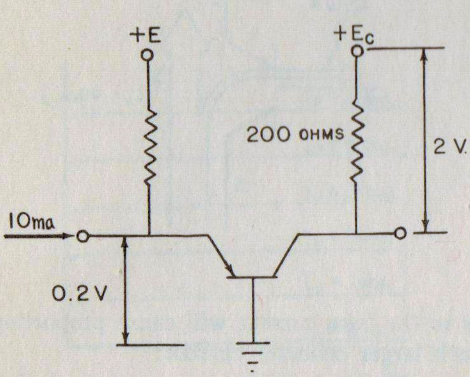
$$P_{out} = E_{out}\ I_{out} = (2 \text{ volts})\ (1 \text{ ma}) = 2 \text{ milliwatts}$$

Now, compare a transistor with similar input conditions as the 10-to-1 step-up transformer:



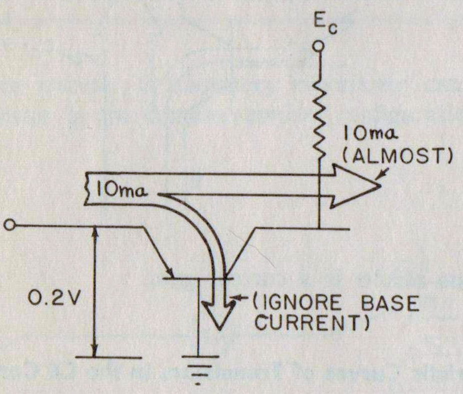
(65)

The transistor can be given a collector load which will give the same signal voltage gain as the 10-to-1 step-up transformer:



(66)

The signal current, however, at the output is not reduced proportionally, but instead is virtually the same as the input current:



(67)

Therefore, the signal power at the output is ten times greater than at the input:

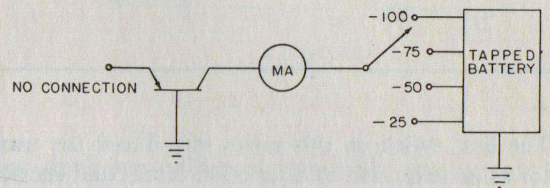
$$P_{in} = e_{in}\ i_{in} = (0.2 \text{ volts})\ (10 \text{ ma}) = 2 \text{ milliwatts}$$

$$P_{out} = e_{out}\ i_{out} = (2 \text{ volts})\ (10 \text{ ma}) = 20 \text{ milliwatts} \quad (68)$$

This power gain is a better indication of a transistor's gain capabilities than is *voltage* gain or *current* gain. Voltage or current gain can be obtained from an ordinary transformer; power gain cannot.

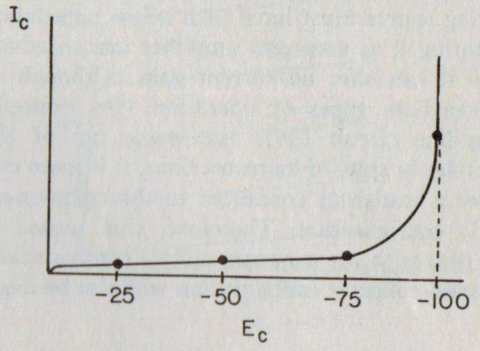
Maximum Voltages and Currents

The maximum collector voltage that can be applied to a transistor is limited by a phenomenon called *breakdown*. Consider this example in which the collector voltage is increased beyond a certain limit:



(69)

Then the collector junction will begin to pass an abnormally large current:



(70)

The voltage at which the curve breaks sharply upward is called the *breakdown voltage*. In this region, a transistor does not behave normally. To insure proper transistor action, the operating point must be well removed from the breakdown region.

A transistor will not *necessarily* be destroyed by breakdown. If a transistor rated at 200 milliwatts breaks down from overvoltage and, while in the breakdown region, dissipates 500 milliwatts, it will very likely be destroyed or at least damaged. On the other hand, a transistor may go into breakdown without being damaged at all if the circuit includes a series resistance to limit the maximum power to a safe value.

Breakdown defines the maximum allowable voltage. However, the maximum *current*, which bears no relation to the breakdown voltage, is not so well defined. At higher and higher currents, progressively smaller portions of the emitter current appear in the collector, with the result that alpha, which is around 0.98 at small currents, may become 0.6 or 0.5 or even less. The practical limit on high currents is reached when alpha falls below some arbitrary limit, set by the designer to fit the particular requirements of the circuit at hand.

Thus far the transistor has been introduced and its characteristics and uses as a common-base amplifier have been described. It has been pointed out that there are many restrictions on the common-base configuration which limit its usefulness. The next part in this series will describe a configuration which is not so limited—the common-emitter configuration. It will be shown how a common-emitter amplifier can provide both voltage gain *and* current gain, simultaneously, but at the expense of an inherently narrower bandwidth.

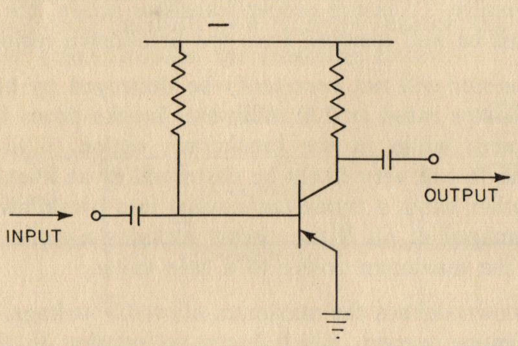
INTRODUCTION TO JUNCTION TRANSISTORS

PART II — The Common-Emitter Amplifier and the Common-Collector Amplifier

by R. N. HURST,* *Broadcast and Television Engineering*

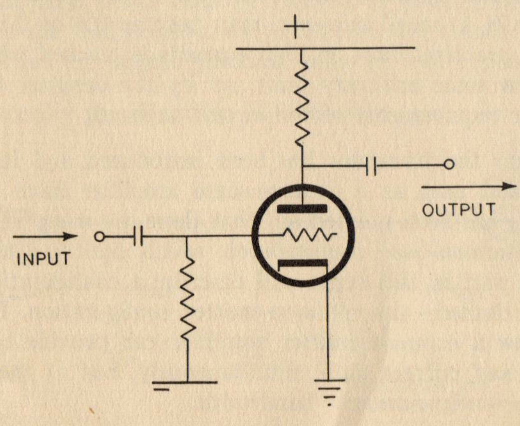
> The first article in this series introduced the transistor as an extension of a junction diode, and showed the characteristics and behavior of a common-base amplifier, which can give large voltage gains, but always gives a current gain less than one. Operating it as a voltage amplifier is very difficult, since the driving source must have such a low impedance, and operating it as a current amplifier has no advantage, since it can offer no current gain. Although certain intermediate types of operation (for example, the delay-line circuit [56]) can make use of the CB amplifier in spite of its restrictions, it is more common to see a transistor connected in the common-emitter (CE) configuration. Therefore, this second article will deal with the common-emitter configuration. The common-collector configuration will also be discussed.

The common-emitter configuration



(71)

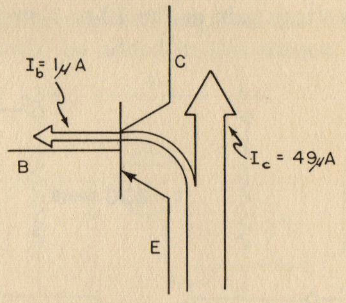
corresponds roughly to the grounded cathode configuration of a vacuum tube:



(72)

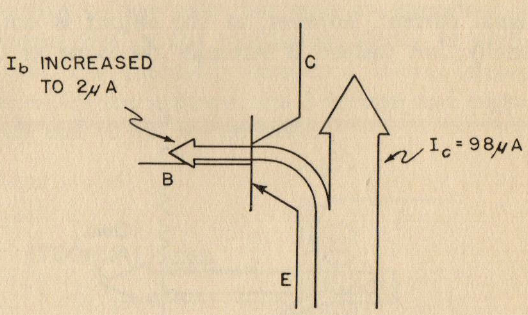
It is one of the most frequently used transistor configurations, chiefly because it offers the greatest gain capabilities of any of the three possible configurations. It also provides a higher input impedance.

The ability of the CE configuration to provide large current gains lies in the fact that the signal current is applied to the base, where it adds to or subtracts from the very tiny base current. Since the base current (bias current plus the signal current) is a fixed percentage of the collector current,



(73)

variations in the base current will cause proportional variations in the much larger collector current:



(74)

This action results in a current gain.

Characteristic Curves of Transistors in the CE Configuration

In studying the CB configuration, a laboratory experiment was described (23, 24, 25) in which the transistor was connected to a tapped battery, in this manner;

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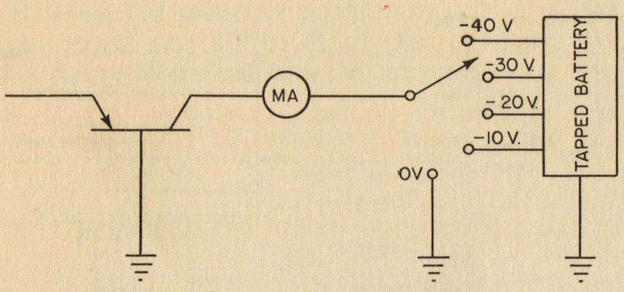
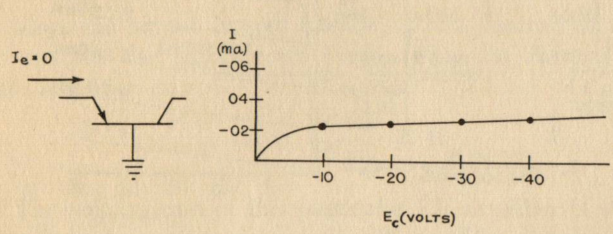
* This series of articles is abstracted from a group of transistor lectures given jointly by the author and Mr. A. C. Luther. The author wishes to acknowledge the fact that many of Mr. Luther's valuable contributions to the lectures have been retained in these articles.



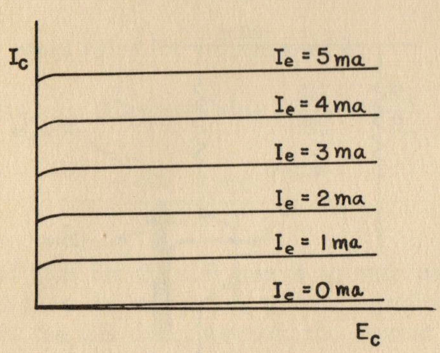
(75)

and the E_c vs I_c curves were determined; first for zero emitter current:



(76)

and then for several different values of emitter current:

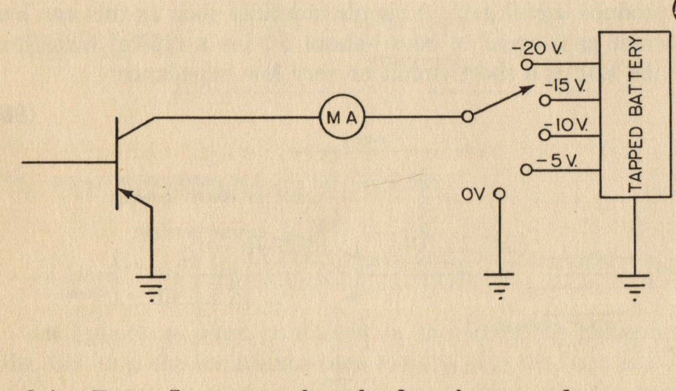


(77)

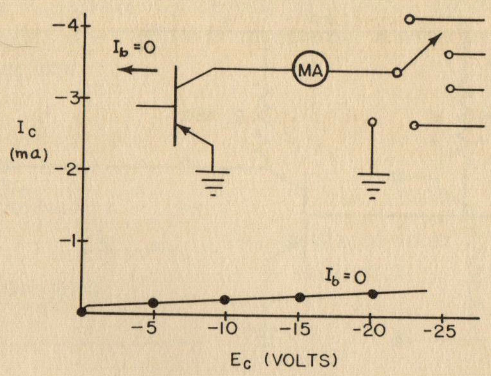
thereby generating the E_c vs I_c curves for the common-base configuration. With these curves the operation of a CB amplifier was analyzed.

In a similar manner, a laboratory experiment can be set up with a transistor in the common-*emitter* configuration:

(78)

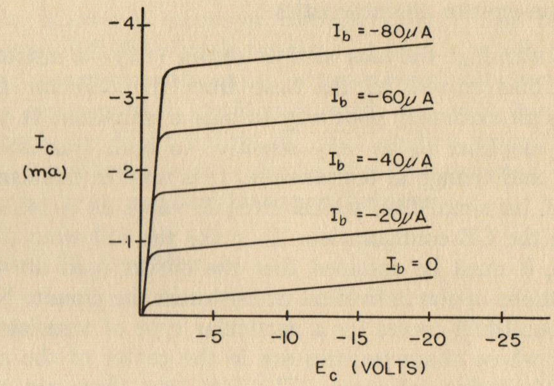


and its E_c vs I_c curves plotted; first for zero *base* current:



(79)

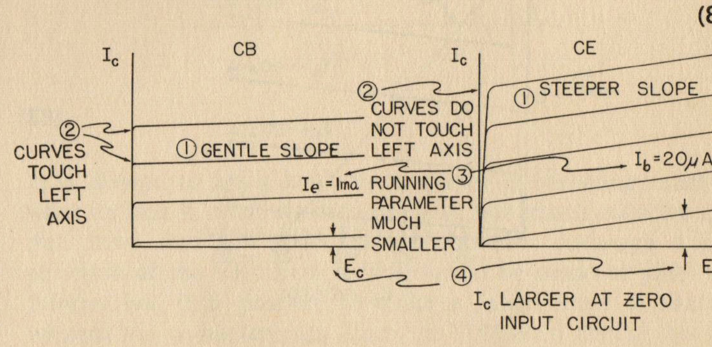
and then for several different values of base current:



(80)

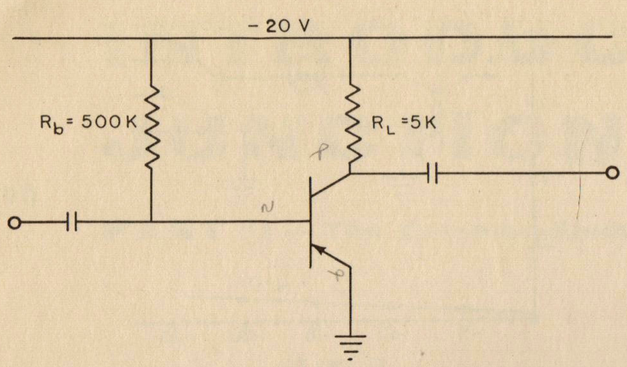
It will be observed that these curves differ from the CB curves in several respects. First, the curves have a steeper slope (1); second, the curves do not run all the way over to the left-hand axis (2); third, the running parameter, I_b, is a very small current, as compared to the collector current (3); and fourth, the collector current for zero input (base) current is much greater than the corresponding curve for the CB configuration (zero emitter current) (4). These differences are indicated in this figure:

(81)



The significance of these differences will become apparent in the following discussion.

Let it be supposed that a piece of equipment contains this amplifier:

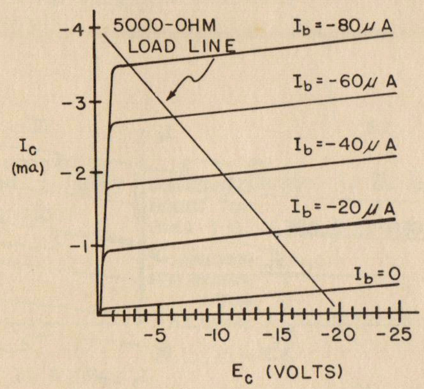


(82)

It is desired to know how this amplifier is operating—what the bias is, how much collector current flows, how much power is dissipated in the collector, and how much gain it will offer. All these facts may be ascertained by a simple construction on the common-emitter characteristics.

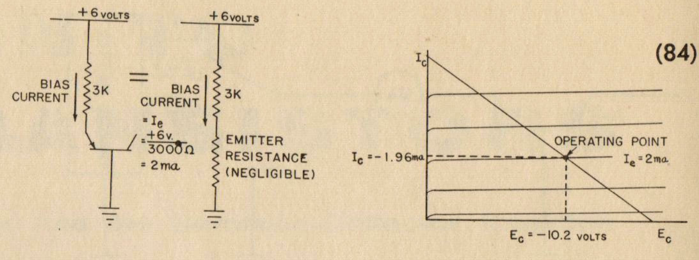
First, a warning: the bias method shown (82)—a resistor R_b supplying bias current to the base from the collector power supply—is an extremely poor way to bias a transistor. It would cause the amplifier to be very sensitive to both transistor replacement and change in temperature. It is used in this example because of its simplicity, which gives it value as a means of explaining the CE configuration. To make the following discussion valid, it must be assumed that the curves used are exact representations of the individual transistor in the circuit. Normally, the published curves for a particular type of transistor are for a unit whose characteristics are in the center of the allowable manufacturing tolerances. The fact that there are rather wide tolerances on transistors is one of the factors which makes necessary the use of more elaborate biasing techniques in practical circuits.

Analysis of this common-emitter amplifier follows basically the same pattern as the analysis of the common-base amplifier (34). The analysis is begun by drawing the load line on the common-emitter characteristics:



(83)

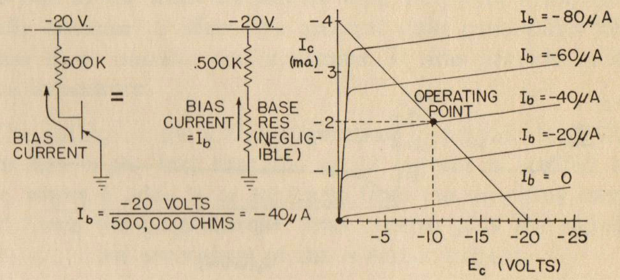
Just as for the common-base circuit, this amplifier's operating point must lie somewhere on its load line. For the common-base amplifier, it was shown (38) that the operating point lies at the intersection of the load line and the particular bias-current chosen:



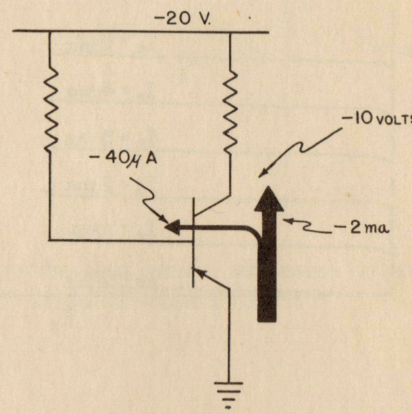
(84)

The operating point of this common-emitter amplifier may be found in a similar manner:

(85)



This common-emitter amplifier therefore operates with a bias current of 40 μA, a collector current of —2 ma, and a collector voltage of —10 volts:



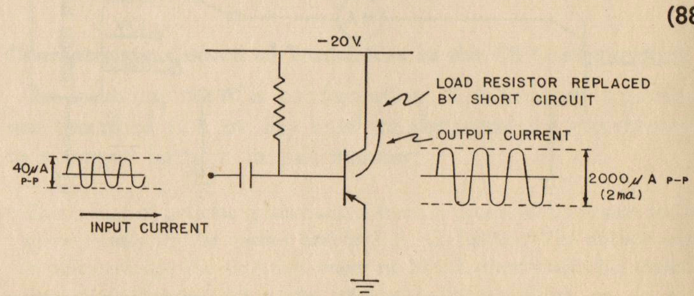
(86)

The power dissipated at the collector is:

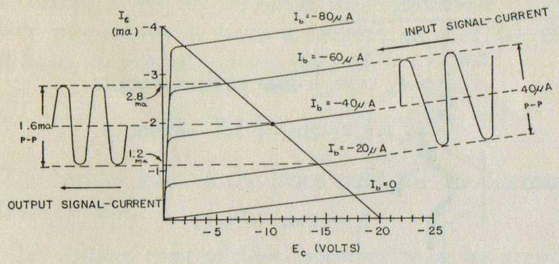
$$P = IE = (-2 \text{ ma})\ (-10 \text{ volts}) = 20 \text{ milliwatts} \quad (87)$$

The gain of this amplifier depends upon whether it is being used to produce voltage gain or current gain. In either case, it can produce useful gain. A simple amplifier such as this one has a current gain equal to beta—about 50 for a typical transistor —if the load is a short circuit or very low impedance:

(88)



However, this particular amplifier has a load of 5000 ohms, so its current gain will be slightly less than beta. The actual value can be determined from the characteristics in this way:



(89)

Since the output current is only 1.6 ma (instead of 2 ma, as it was for the short-circuit load) (88), the current gain of this amplifier is:

$$G_c = \frac{1.6 \text{ ma}}{40\ \mu\text{A}} = 40 \qquad (90)$$

The voltage gain of this particular CE amplifier is somewhat less than the voltage gain of the CB amplifier already analyzed (46). It was shown, in that analysis, that the voltage gain is given approximately by the expression:

$$Gv_{CB} = \frac{R_L}{R_e} = \frac{5{,}000}{12.8} = 391 \qquad (91)$$

A more nearly exact value for voltage gain is:

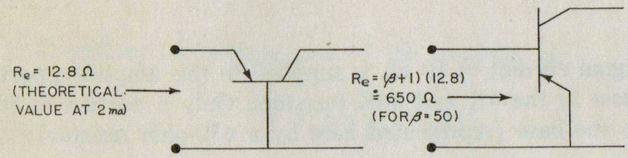
$$Gv_{CB} = (\text{Current Gain}) \times \frac{R_L}{R_e} = \alpha \frac{R_L}{R_e}$$

$$= \frac{(0.98)\ (5{,}000)}{12.8} = 382 \qquad (92)$$

but the current gain for the CB case is so near unity that it can be omitted from the expression, without introducing appreciable error. In the CE case, however, the current gain is so large that it must be included in the expression:

$$Gv_{CE} = G_C \frac{R_L}{R_b} \qquad (93)$$

Note also that in the expression for CE voltage gain the input impedance is given as R_b, the base resistance, in place of R_e, the emitter resistance. The base resistance is larger than the emitter resistance by a factor of $\beta + 1$:



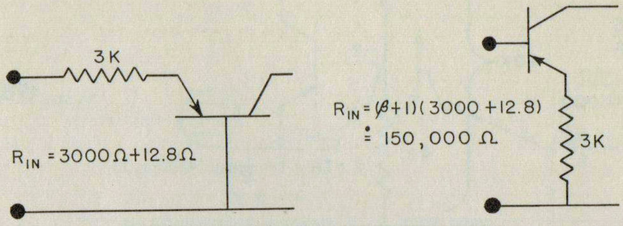
(94)

Therefore, the voltage gain is given by:

$$Gv_{CE} = \frac{G_C R_L}{(\beta + 1) R_e} = \frac{(40)\ (5{,}000)}{(51)\ (12.8)} = 306 \qquad (95)$$

An important point contained in the foregoing paragraph is the fact that the impedance seen looking into the base is $\beta + 1$ times larger than that impedance seen looking into the emitter.

This base impedance can become very large—approaching that of a vacuum tube's grid—if an external resistor is included in the emitter lead:



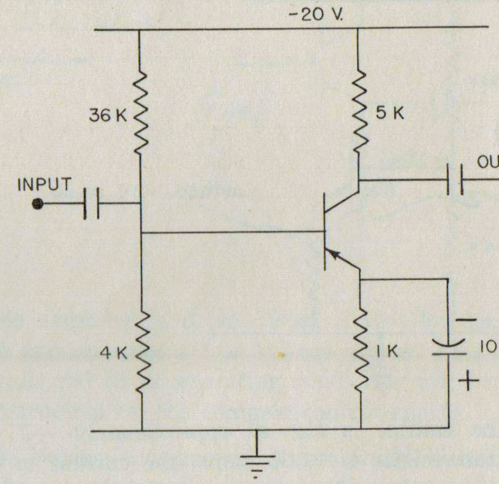
(96)

This external impedance, however, behaves like an unbypassed cathode resistor in a tube circuit—it gives higher input impedance (and greater stability as well) at the expense of gain.

The CE circuit analyzed thus far is admittedly an impractical circuit. Biasing a transistor through a large base resistor (in this case, 500,000 ohms) results in a circuit which may work well at room temperatures but becomes completely inoperative at higher temperatures. Or, it may work well with one transistor but work poorly or not at all with another transistor of the same type. Therefore, it is also necessary to analyze a CE amplifier using more practical biasing techniques.

Practical CE Amplifier

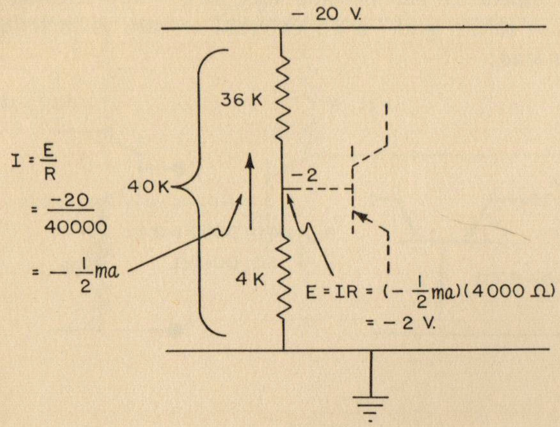
Let us suppose that a piece of broadcast equipment contains this circuit:



(97)

It is desired to know how this amplifier is operating; that is, what its bias is, what its dissipation is, how much collector current flows, and how much gain it provides. Although a construction of the CE characteristics could be made to yield this information, it is possible to make a fairly accurate analysis without the characteristics, since the 1000-ohm emitter resistor stabilizes the circuit and thereby makes its d-c behavior fairly independent of the transistor's characteristics.

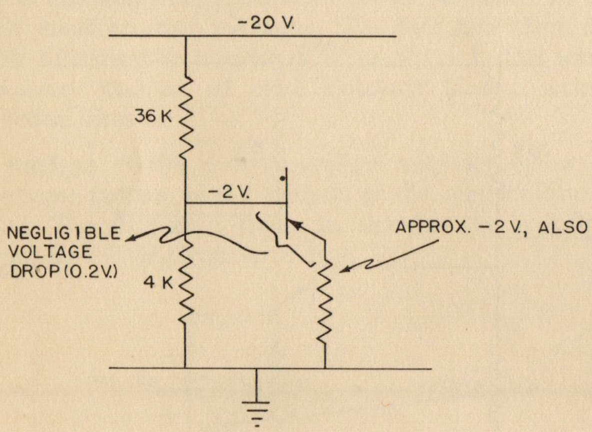
The analysis is begun by observing that, with the transistor out of the circuit, a potential of —2 volts appears at the junction of the 36K resistor and the 4K resistor which form the bias network. This figure shows the calculations:



(98)

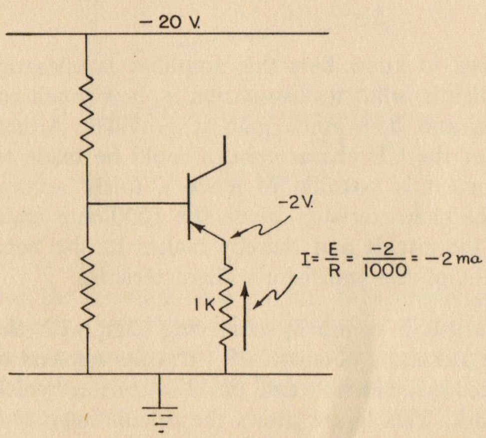
When the transistor is connected, the base current, which flows *out* of the (PNP) transistor, joins the ½-ma current in the bias network and slightly alters this —2 volt potential. However, the base current is assumed to be much smaller than the bias-network current and may therefore be safely ignored in an approximate analysis such as this one. (This assumption is usually correct in the analysis of well-designed circuits. If it should happen to be incorrect, one of the succeeding steps will reveal the error.)

Therefore, even with the transistor in the circuit, the potential at the base is —2 volts. Since the emitter and base taken together form a forward-biased diode, the voltage drop from emitter to base is very small—about 0.2 volt; a negligible amount in this analysis:



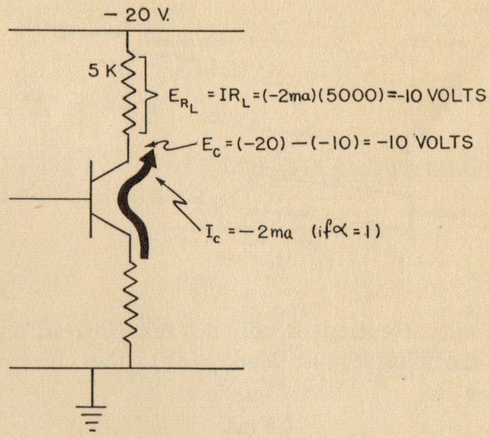
(99)

Therefore, the emitter is also at approximately —2 volts. Since the emitter resistor is 1,000 ohms, the current to cause this 2-volt drop must be —2 ma.



(100)

Assuming that $\alpha = 1$ (instead of 0.98) for this approximation, the current flowing from the collector is also —2 ma, and the potential at the collector is therefore —10 volts:



(101)

Since the emitter is at —2 volts, the voltage across the transistor is only —8 volts; therefore the power dissipation is:

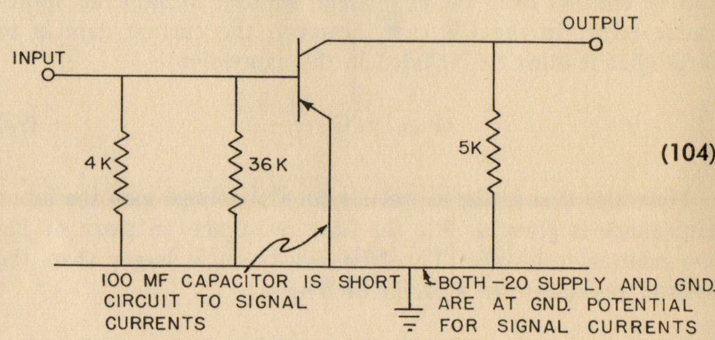
$$P_c = IE = (-2 \text{ ma})\ (-8 \text{ v}) = 16 \text{ milliwatts} \qquad (102)$$

Also, with the knowledge that $I_c = -2$ ma, (and assuming that $\beta_{DC} = 50$), the base current can be calculated:

$$I_b = \frac{I_C}{\beta_{DC}} = \frac{-2 \text{ ma}}{50} = -40\ \mu A \qquad (103)$$

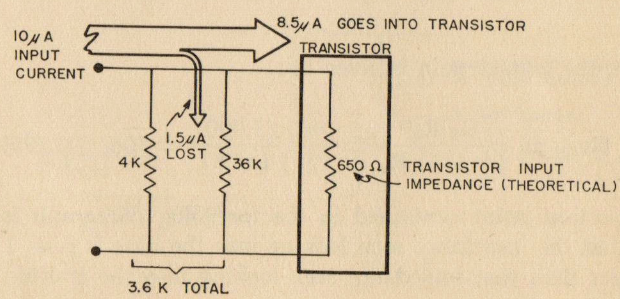
The earlier assumption that the base current was much smaller than the ½-ma bias-network current is thereby substantiated.

In computing the gain of this amplifier, the circuit may be redrawn in the following manner, which shows the circuit as it appears to the signal current:



(104)

If a signal current of 10 μA is supplied to this amplifier, part of it is lost in the 4K and 36K resistors. Only a portion of it goes into the base (represented here by a 650-ohm resistor):



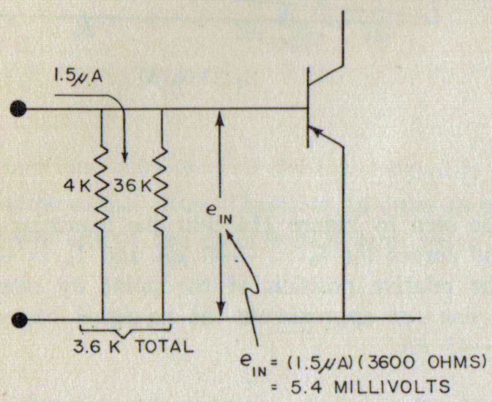
(105)

Since 15 percent of the input signal is lost before it ever gets into the base, the overall current gain of this amplifier is 15 percent lower than the gain of the simple amplifier already analyzed (90). (That amplifier lost a negligible amount of signal current in its 500,000-ohm biasing resistor.) Since that amplifier was shown to have a current gain of 40, this amplifier will have an overall current gain of:

$$G_c = 40 - (0.15)\ (40) = 34 \qquad (106)$$

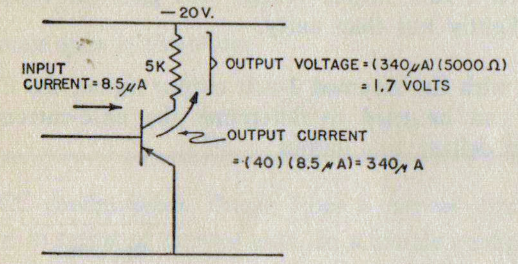
The loss of gain is the price paid for the increased stability of this circuit.

The voltage gain of this amplifier may be approximated by observing that the 1.5 μA lost in the bias network causes a voltage swing of 5.4 millivolts to appear across the two resistors:



(107)

At the same time, 8.5 μA is being amplified by the transistor so that $(8.5) \times (40) = 340\ \mu$A appears as a current swing in the load resistor, and an output of 1.7 volts appears across the load resistor:



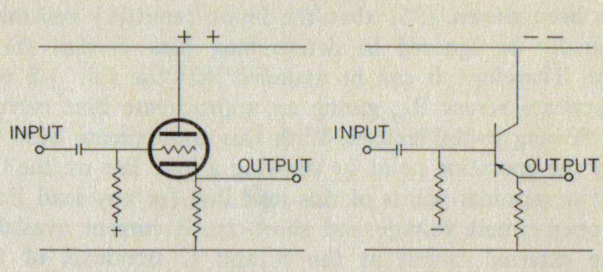
(108)

Therefore, the voltage gain of the amplifier is:

$$G_V = \frac{1.7\ \text{v}}{5.4\ \text{mv}} = 315 \qquad (109)$$

The Common-Collector Configuration

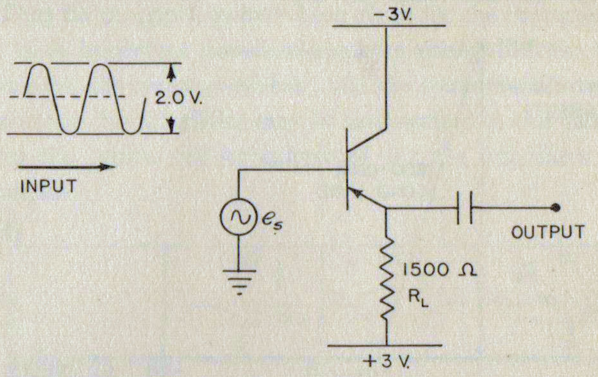
So far, the common-base and common-emitter amplifiers have been considered and their curves and characteristics briefly indicated. The CB amplifier is capable of large voltage gain but less-then-unity current gain. The CE amplifier can provide both voltage *and* current gain. The final configuration, the *common-collector* (CC), is the opposite of the CB configuration in that it can produce a large current gain but less-than-unity voltage gain. In that respect, it resembles its vacuum-tube counterpart, the cathode follower. Indeed, it is often called the emitter-follower configuration. Good reason for this name can be seen in the following figure:



(110)

In this article, however, the name *common-collector* and the abbreviation CC will be employed, except where clarity may be served by the other name.

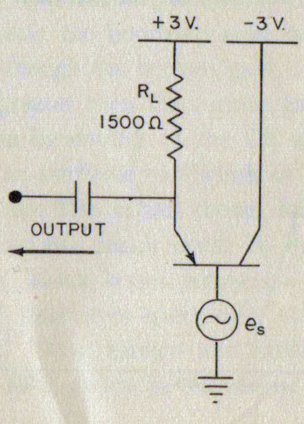
The discussion of common-collector amplifiers could run parallel to the discussions of the other configurations, starting with a derivation of the CC characteristic curves, and using these curves to analyze a typical amplifier. In this case, however, such an approach is not practical, because CC curves are rarely given in data sheets. Any analysis based on CC curves could not be duplicated in a practical situation, without first deriving a set of CC curves from the data sheet's CE curves. Fortunately, an approximate analysis can be performed using CE curves directly. This is demonstrated in the following analysis of this CC amplifier:



(111)

This amplifier is driven from a very-low-impedance source which approximates a true voltage source. This amplifier's voltage gain and its dc operating conditions will be determined by a construction on the common-*emitter* curves.

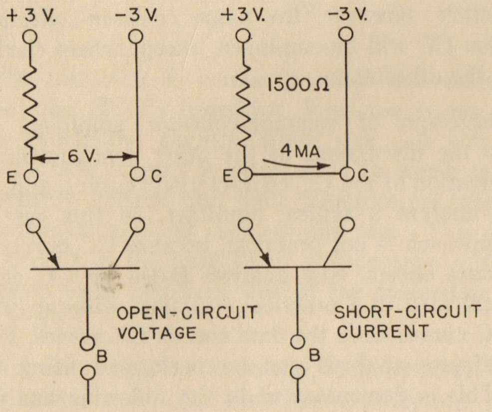
The biasing arrangement is practically identical to the common-base biasing-method already discussed (36). To show this similarity, the circuit can be redrawn in this manner:



(112)

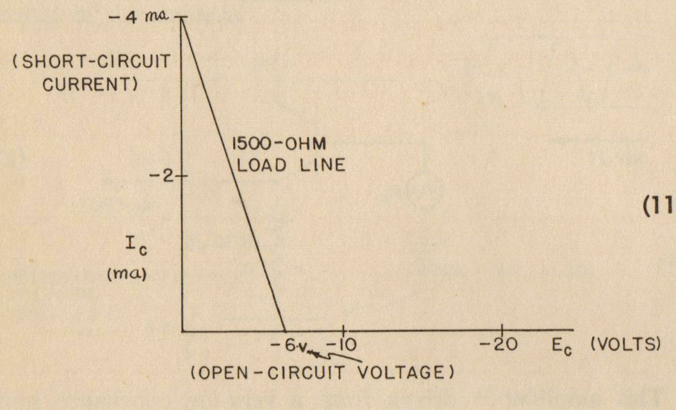
Remembering that e_s, the signal source, is practically a short circuit to the bias currents, it can be seen that the biasing arrangement bears a strong resemblance to common-base biasing.

It has been shown (36) that the input (emitter) resistance could usually be ignored in determining bias current for a CB stage. Therefore, it can be assumed that the full +3 volt supply appears across R_L, giving an approximate bias current of 2 ma flowing in the emitter. With this approximate bias, we may find the operating point by drawing a load line on the CE curves. The terminal points of this load line (or any load line) are the open-circuit voltage and short-circuit current available from the external circuit at the E and C terminals of the transistor:



(113)

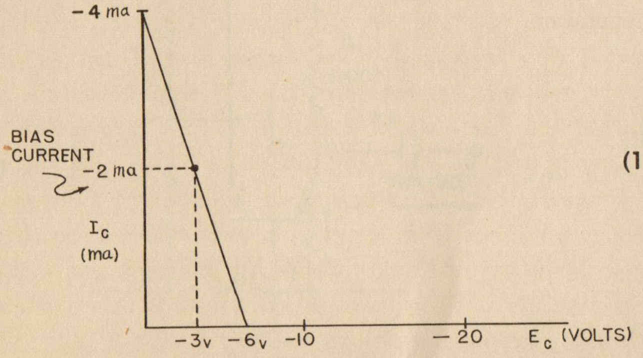
so that the load line looks like this:



(114)

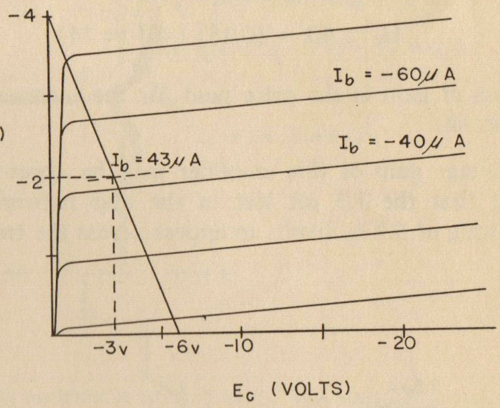
Actually, drawing a straight line between the two end points determined in the above manner is not entirely accurate because the current scale of the graph is I_c, whereas it is really I_e which flows through R_L. However, the error involved is small since I_c and I_e are nearly equal.

An approximate operating point may then be found by entering the approximate bias current on the load line of Fig. 114, as follows:



(115)

The actual CE characteristics have not been drawn on the foregoing graph purposely to show that the transistor characteristics have nothing to do with the approximate determination of the operating point. However, these characteristics must be included in order to calculate gain:

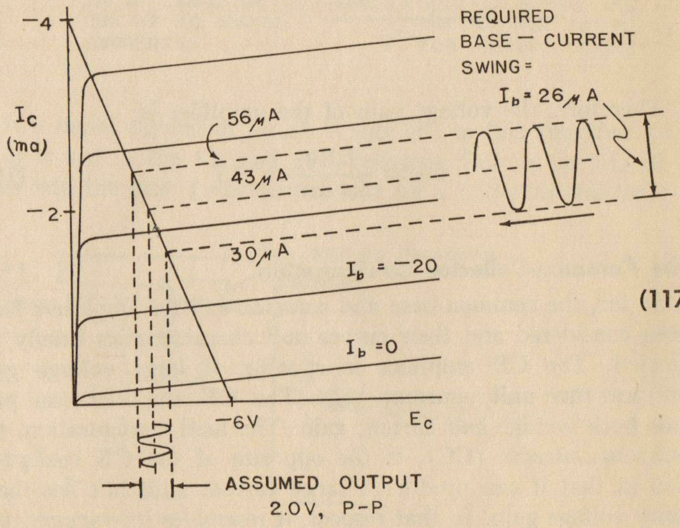


(116)

It can be seen in Figure 116 that the operating point lies between the curves for $I_b = -40\ \mu A$ and $I_b = -60\ \mu A$. Judging the relative position of the point by simple visual inspection, one can approximate the no-signal base-current to be about —43 μA.

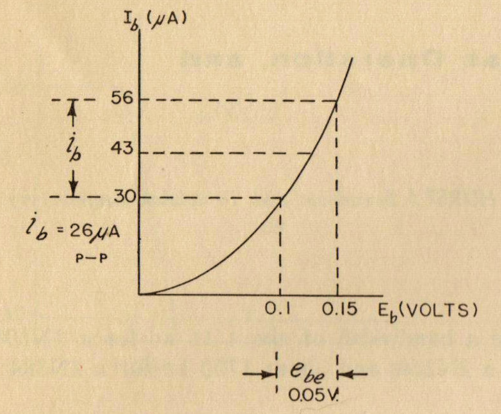
To simplify the analysis at this point, a rather surprising assumption is made. It is now assumed that the voltage gain is unity; that is, it is assumed that the full 2-volt input signal appears at the output. Working backwards from this assumed output voltage, one can then proceed to show that *more* than 2 volts of signal is required at the input to produce a 2-volt output. The relationship between this new input voltage and the assumed 2-volt output voltage will give the actual gain, which is slightly less than unity.

Starting with the assumed 2-volt output signal, the CE characteristics can be used to determine the base-current swing required to deliver this output:



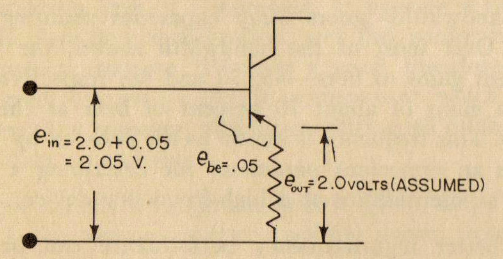
(117)

The data sheet for this transistor is then consulted to find the curve giving the relationship between base current and base-to-emitter voltage. This curve is usually given for transistors designed to handle fairly large signal swings. Using this curve:



(118)

it can be seen that 0.05 volts of the input signal is lost in the base-to-emitter voltage drop. Therefore, in order to produce the assumed 2-volt output, the input voltage must swing 2.05 volts:

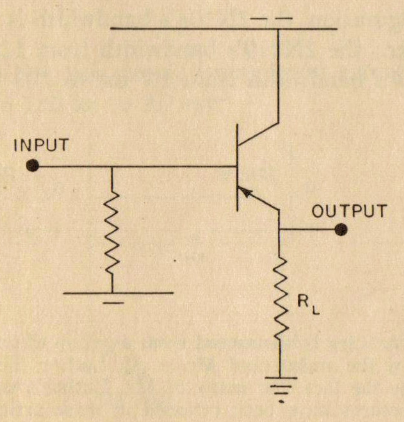


(119)

The voltage gain is therefore:

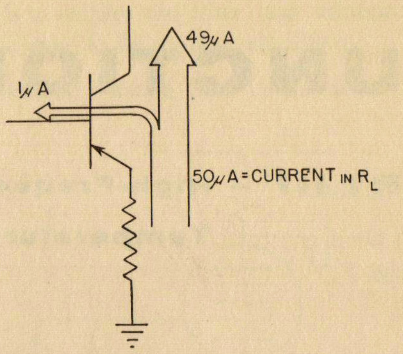
$$G_V = \frac{e_{out}}{e_{in}} = \frac{2.0}{2.05} = 0.976 \qquad (120)$$

The CC configuration, driven from a *current* source, can be described in terms of *current* gain. In a simple configuration, in which negligible signal current is lost in the biasing arrangement:



(121)

a transistor with a beta of 49 will give a current gain of 50:



(122)

which, in general terms, is a current gain of $\beta + 1$.

The input impedance of a CC amplifier is very large. This may be seen from the fact that, in the example, a 2-volt signal causes only 26 μA to flow into the amplifier. This gives an input impedance of:

$$R_{in} = \frac{e_{in}}{i_{in}} = \frac{2.0}{26 \times 10^{-6}} = 77{,}000 \text{ ohms} \qquad (123)$$

which agrees closely with the value of input impedance calculated by multiplying R_L, (1500 ohms), by $\beta + 1$.

Thus far descriptions have been given for the characteristics of the three important transistor-amplifier configurations: the common-base, the common-emitter, and the common-collector. Their important characteristics may be summarized in this table which gives the typical values calculated for the amplifiers used as examples:

	CB (IN, OUT)	CE (IN, OUT)	CC (IN, OUT)
CURRENT GAIN	0.98	49	50
VOLTAGE GAIN	382	306	0.976
INPUT R	12.8Ω	650Ω	77,000Ω
FREQ. RESPONSE	1MC	20KC	20KC - 1 MC DEPENDING ON SOURCE AND LOAD

The last row of information, frequency response, indicates the price paid to obtain the improved gain capabilities of the CE configuration. Although the current gain of the CE amplifier is about 50 times greater than the current gain of the CB amplifier, the available bandwidth of the CE amplifier is about 50 times *less* than the available bandwidth of a CB amplifier using the same transistor. The values chosen for the table represent the frequency response which could be expected from typical audio transistors. Much better frequency response can be obtained by using transistors specifically designed for high-frequency operation. These matters and others will be considered in the next, and final, article in this series.

INTRODUCTION TO JUNCTION TRANSISTORS

PART III — High-Frequency Operation, Pulse Operation, and Temperature Considerations

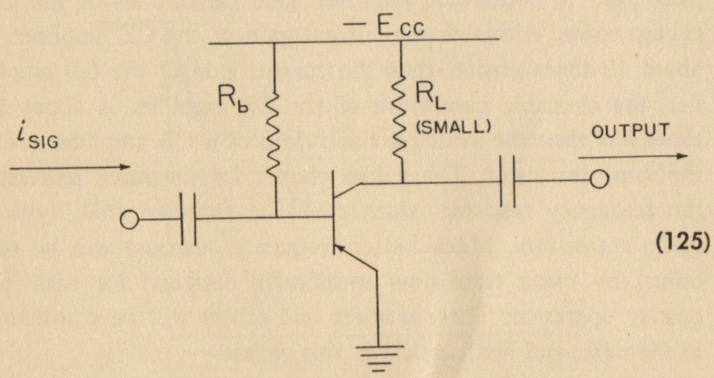
by R. N. HURST,† *Broadcast and Television Engineering*

Previous articles in this series have presented the three basic transistor configurations—the common-emitter, the common-base, and the common-collector—and have briefly described their characteristics. In all these descriptions, it was assumed that the signal frequencies were in the audio region, the signal amplitudes small, and the ambient temperature around 70 F. If any or all of these assumptions are not true, the transistor's behavior cannot be predicted from the simplified descriptions of the first two articles. This article will extend those descriptions to show transistor behavior at high frequencies, at high temperatures, and in highly non-linear operation.

Present-day transistors are not capable of providing high-frequency operation and wide bandwidths with the same ease that vacuum tubes can provide such performance. However, proper choice of transistor, transistor configuration and associated circuitry can result in very good video amplifiers and tuned high-frequency amplifiers, with performance equal to that of conventional tube circuits. The circuits and configurations necessary to obtain these results will now be considered.

High Frequency Operation

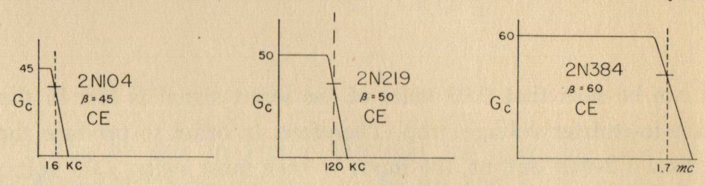
The high-frequency performance of a transistor circuit is strongly influenced by the type of transistor employed. A given circuit will provide widely different high-frequency responses with different transistors. For example, a simple current-driven CE amplifier:



(125)

will provide a bandwidth of about 16 kc for a 2N104; about 120 kc for a 2N219, and about 1700 kc for a 2N384:

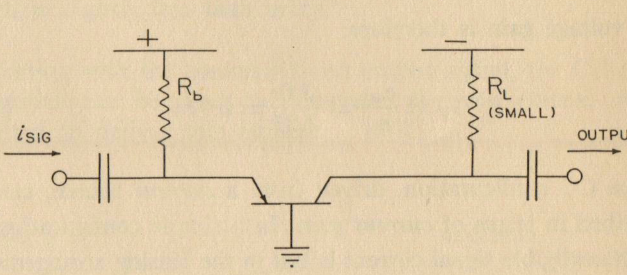
(126)



(These bandwidths ignore stray capacities shunting the load resistor.) Over most of the bandwidth shown, the transistors give current gains of beta—45, 50 and 60, respectively—which fall off to gains of about 70 percent of beta at the specified frequency. This frequency is known as the *beta cut-off frequency*, f_β, and is an important parameter for describing a particular transistor's potentialities as a high-frequency device.

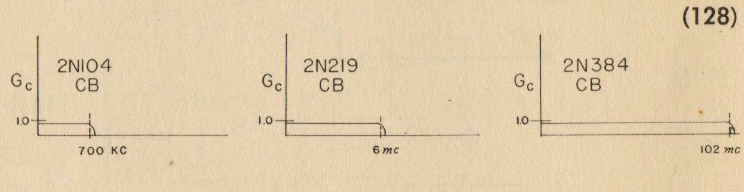
Much better high-frequency performance can be obtained from a transistor in the common-base configuration:

(127)



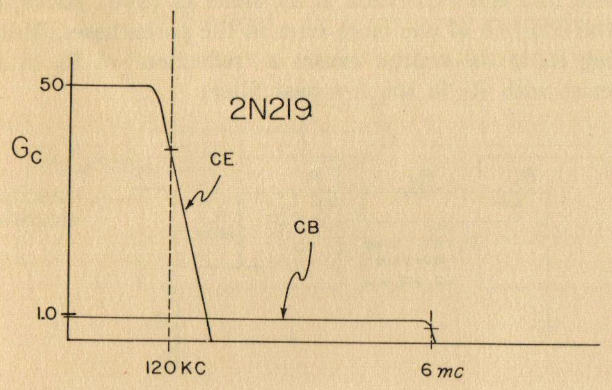
In this configuration, the 2N104's bandwidth is extended from 16 kc to 700 kc; the 2N219's bandwidth from 120 kc to 6 mc; and the 2N384's bandwidth from 1.7 mc to 102 mc:

(128)



† This series of articles is abstracted from a group of transistor lectures given jointly by the author and Mr. A. C. Luther. The author wishes to acknowledge the fact that many of Mr. Luther's valuable contributions to the lectures have been retained in these articles.

Although these are impressive bandwidths, note that in each case, the current gain has dropped from beta (around 50) to alpha (less than 1). That is, going from CE operation to CB operation extends the bandwidth by a factor of beta, but at the same time reduces the current gain by the same factor:



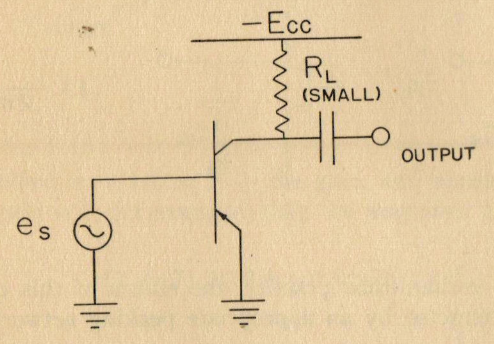
(129)

In the common-base case, the frequency at which the current gain is down 70 percent (6 mc for the 2N219) is called the *alpha cut-off frequency*, f_a. It is the frequency most commonly given in transistor data sheets, and is related to f_β by the expression:

$$f_a = \beta f_\beta \qquad (130)$$

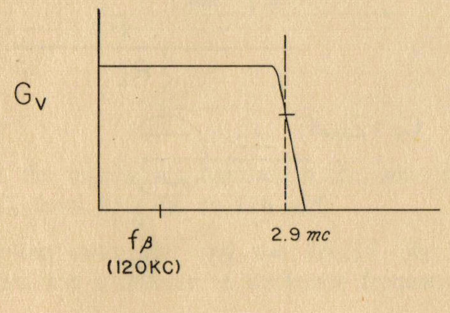
For maximum gain, it is necessary to operate a transistor in the common-emitter configuration; yet this configuration gives poor frequency response. There is a need, therefore, to arrive at some configuration or circuit arrangement which will yield better frequency response without sacrificing all of the common-emitter's gain capabilities.

A simple circuit arrangement which gives better frequency response is the common-emitter amplifier driven from a voltage (low-impedance) source:



(131)

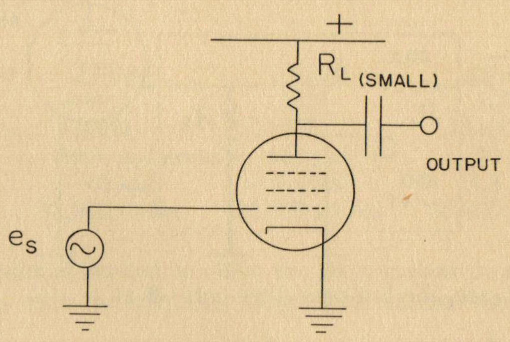
For the 2N219, this circuit arrangement extends the frequency response from 120 kc to 2.9 mc:



(132)

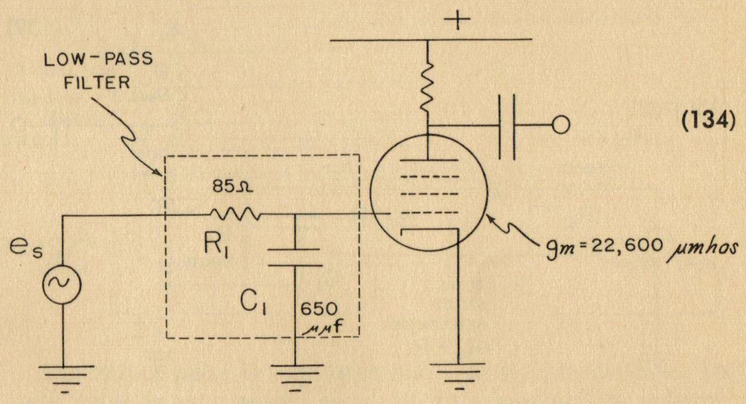
At this point, it is interesting to compare this CE amplifier with a vacuum tube amplifier. We may do so easily, since the CE emplifier is a voltage amplifier, and vacuum tubes are also normally considered to be voltage amplifiers.

A typical pentode vacuum tube in the same circuit



(133)

would have a bandwidth several times greater than the transistor bandwidth, but its gain would be only one-half to one-third as great. It would be possible to make a tube circuit which would behave almost like a 2N219, but to do so would require a pentode with a high transconductance—more than 22,000 μmhos —and would also require the use of a low-pass filter in the grid circuit, to simulate the poor frequency response of the transistor:



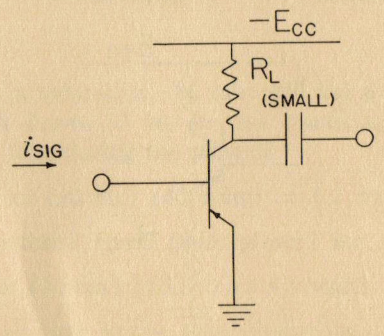
(134)

The 70 percent response point of the low-pass filter is at a frequency

$$f = \frac{1}{2\pi \ R_1 C_1} = \frac{1}{2\pi \ (85\Omega) \ (650 \ \mu\mu f)} = 2.9 \text{ mc} \qquad (135)$$

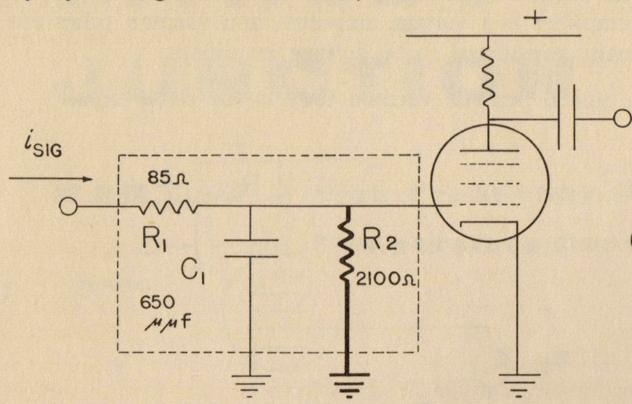
which is the cut-off frequency shown in figure 132.

It is possible to extend this comparison circuit to the case of the current-driven amplifier



(136)

merely by adding another resistor, R_2:



(137)

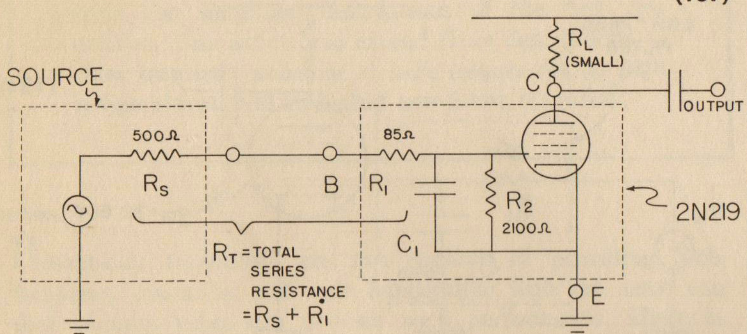
In this case, the low-pass filter cuts off at

$$f_\beta = \frac{1}{2\pi\ R_2\ C_1} = \frac{1}{2\pi\ (2100\Omega)\ (650\ \mu\mu f)} = 120\ \text{kc} \qquad (138)$$

which is the frequency given above as f_B for the 2N219.

In practical cases, transistors are not driven from perfect voltage sources (zero internal impedance) or from perfect current sources (infinite internal impedance), but from sources of some definite impedance. For example, a possible source for a 2N219 could have an internal impedance of 500 ohms:

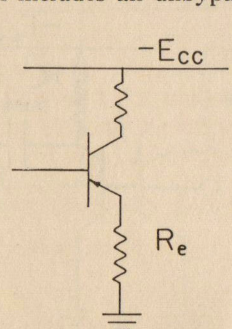
(139)



In this case, it can be shown that the original f_β bandwidth is improved by a factor of 4.6:

$$\begin{aligned} f' &= f_\beta\left(1 + \frac{R_2}{R_T}\right) \\ &= 120\ \text{kc}\left(1 + \frac{2100}{500 + 85}\right) \\ &= 120\ \text{kc}\ (4.6) \\ &= 550\ \text{kc} \end{aligned} \qquad (140)$$

Another simple circuit which extends bandwidth considerably is the circuit which includes an unbypassed emitter resistor:

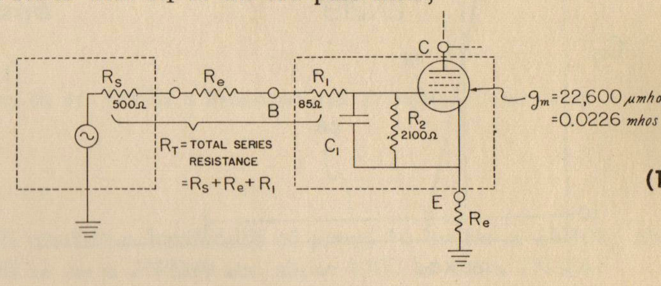


(141)

In this case, the beta cut-off frequency is extended by an even larger factor, as shown in this expression:

$$f' = f_\beta\left(1 + \frac{R_2}{R_T} + g_m\ R_e\ \frac{R_2}{R_T}\right) \qquad (142)$$

Note that this expression is the same as (140) above, except for the addition of one more term in the parentheses. Moreover, adding R_e in the emitter causes a "reflection" of R_e to appear in series with R_1 in the low-pass filter;

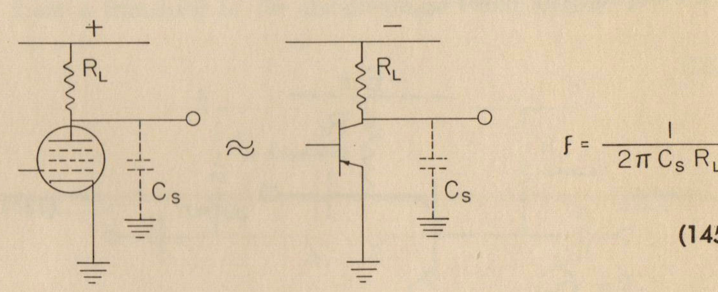


(143)

which means that a resistance equal to R_e must now be included in R_T, the total series resistance. If the value of R_e is, for example, 300 ohms, the new bandwidth is:

$$\begin{aligned} f' &= 120\ \text{kc}\left(1 + \frac{2100}{500 + 300 + 85} + (0.0226)\ (300)\ \frac{2100}{500 + 300 + 85}\right) \\ &= 120\ \text{kc}\ (1 + 2.36 + 16.0) \\ &= 2.33\ \text{mc} \end{aligned} \qquad (144)$$

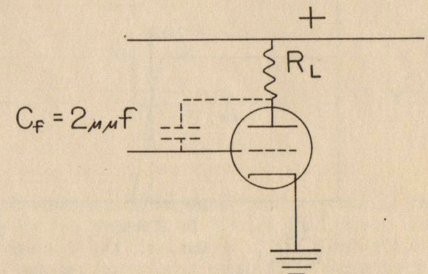
In all the foregoing discussion, the load resistor, R_L, was clearly tagged "small", in order to avoid, temporarily, the additional complications which arise when the load resistor is not small. The first complication is familiar to anyone who has used a vacuum tube in a wideband amplifier—stray capacity across R_L enters as an important bandwidth-limiting factor:



(145)

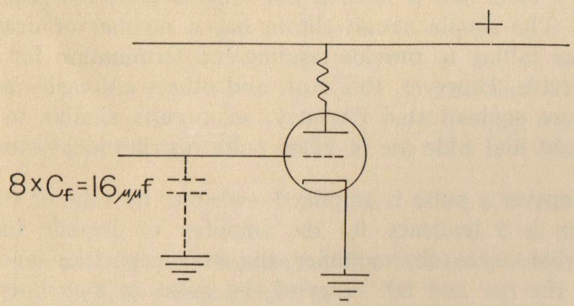
Just as in vacuum-tube practice, the effects of this capacity may be counteracted by an appropriate peaking network.

The other complication is also familiar to vacuum-tube users—the so-called "Miller Effect". In a vacuum tube, a small feedback capacity—typically about 2 $\mu\mu$f—appears between grid and plate:



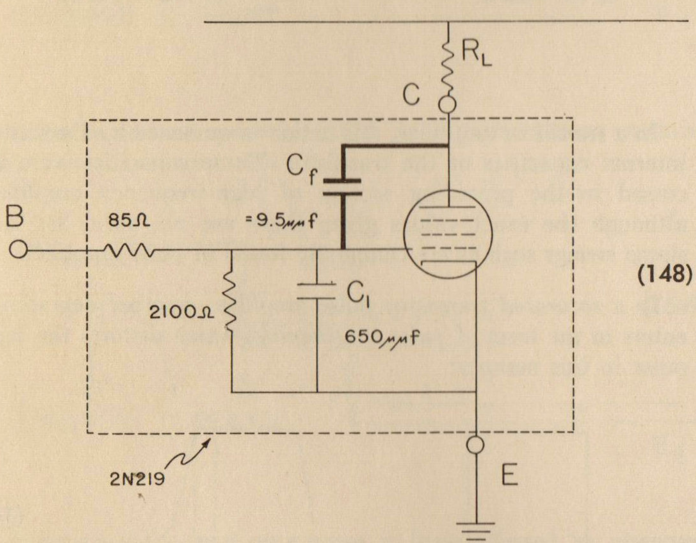
(146)

If the load resistor R_L is large enough to give this tube a gain of 7, for example, the small capacity C_f is multiplied by 1 + the gain, and appears as an 8-times larger capacitor shunting the input:



(147)

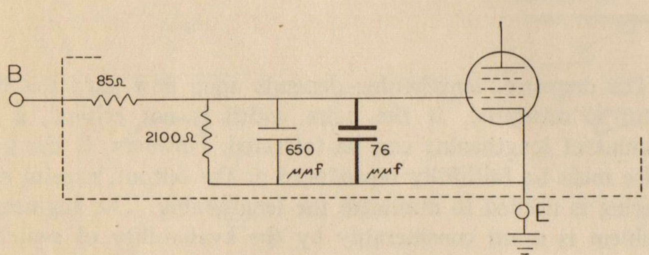
In transistors, a similar effect takes place. If the load resistor is large enough to give a useful gain, then a feedback capacity C_f which appears in this manner;



(148)

is magnified by a factor 1 + the gain, and appears across C_1. If the gain is 7, for example, then the magnified capacity is

$$(1 + 7) \times 9.5\ \mu\mu f = 76.0\ \mu\mu f \quad (149)$$



which affects the transistor's bandwidth the same as would an increase of C_1 from 650 $\mu\mu f$ to 726 $\mu\mu f$.

The preceding examples used the 2N219. By present-day standards, this is a transistor of moderate frequency response, designed principally to be used as the mixer in transistorized broadcast-band receivers. The examples may be converted to show the behavior of a 2N104 or a 2N384 by substituting the appropriate values in this table:

(150)

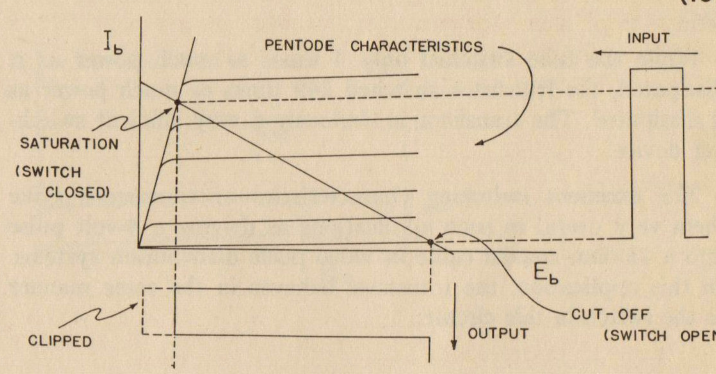
Equivalent Circuit Parameter	*2N104*	*2N219*	*2N384*
R_1	290Ω	85Ω	50Ω
R_2	1380Ω	2100Ω	1040Ω
C_1	6900 $\mu\mu f$	650 $\mu\mu f$	90 $\mu\mu f$
C_f	40 $\mu\mu f$	9.5 $\mu\mu f$	1.3 $\mu\mu f$
g_m	32,000 μmhos	22,600 μmhos	56,800 μmhos

The reader is invited to make the substitutions to extend his familiarity with the frequency response of various transistors.

Pulse Operation

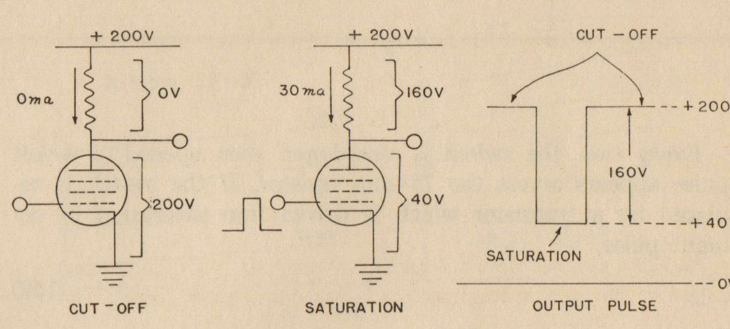
When a pulse is to be amplified, linearity is not a requirement of the amplifier. Consequently, the tube or transistor which is used as a pulse amplifier can be used as a switch, by driving it from cut-off to saturation:

(151)



The output pulse is very large under these circumstances. Its peak value is very nearly equal to the power supply voltage:

(152)



Note that even in saturation, the tube still has a 40-volt drop across it. Since it draws 30 ma in this condition, the power dissipated by the tube during the pulse is

$$P_p = IE = (30\text{ ma})\ (40\text{ volts}) = 1.2\text{ watts} \quad (153)$$

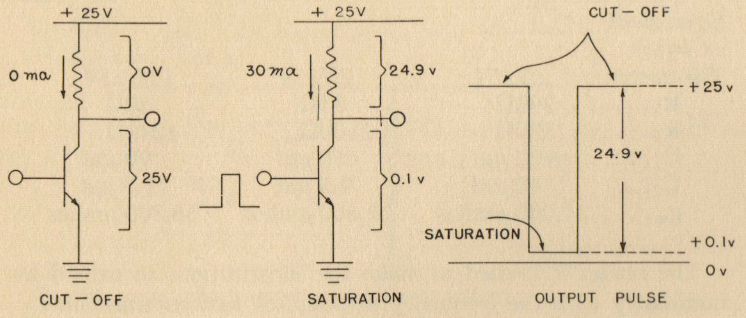
and the power switched (peak pulse power) is:

$$P_s = (30\text{ ma})\ (160\text{ v}) = 4.8\text{ watts} \quad (154)$$

which is 4 times as large as the tube dissipation.

A transistor can be used in much the same manner, but with two major differences: the ouput voltage is limited to (typically) 25 volts, and the drop across the saturated transistor is typically 0.1 volt:

(155)



In this case, the transistor dissipates (during the pulse) only

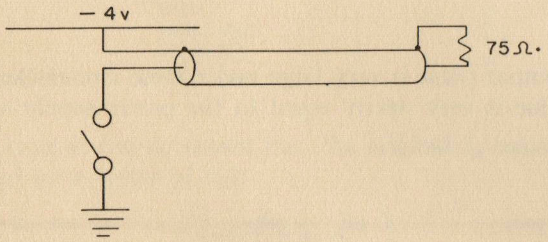
$$P_c = IE = (30\text{ ma})\ (0.1\text{ v}) = 3.0\text{ milliwatt} \qquad (156)$$

while the peak pulse power (power switched) is

$$P_s = IE = (30\text{ ma})\ (24.9\text{ v}) = 747.0\text{ mw} \qquad (157)$$

While the tube switched only 4 times as much power as it dissipated, the transistor switched 249 times as much power as it dissipated. The transistor is obviously a very efficient switching device.

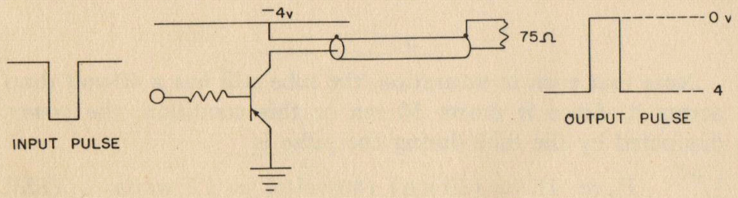
The excellent switching characteristics of transistors make them very useful in such applications as driving a 4-volt pulse into a 75-ohm coaxial cable in video pulse distribution systems. In this application, the transistor behaves in the same manner as the switch in this circuit:



(158)

Every time the switch is closed and then opened, a 4-volt pulse appears across the 75-ohm resistor. If the switch is replaced by a transistor which is driven into saturation by an input pulse,

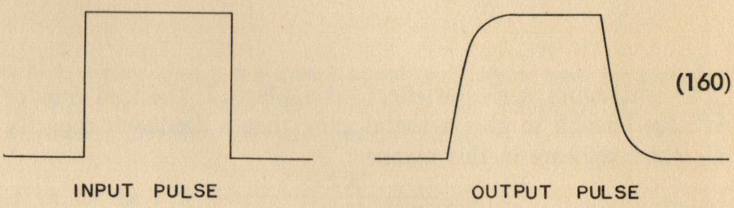
(159)



the transistor will open and close like a switch, alternately disconnecting and connecting the battery and the coaxial cable, and thereby causing a pulse to appear across the 75-ohm terminating resistor.

One of the most attractive features of this circuit is that the transistor's excellent switching efficiency makes it possible to drive 4 volts into a 75-ohm line with a tiny, low-power transistor. The simple circuit shown has a number of drawbacks, such as failing to provide sending-end termination for the coaxial cable. However, this fault and others are easily remedied by more sophisticated circuitry, so circuits similar to it will no doubt find wide use in video pulse distribution systems.

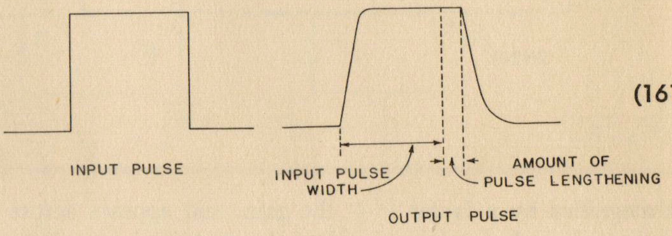
Whenever a pulse is amplified—whether by tube or transistor—there is a tendency for the amplifier to degrade the pulse somewhat. In a tube amplifier, the stray capacities tend to degrade the rise and fall times of the pulse, in a manner shown exaggeratedly here:



(160)

In a transistor amplifier, this action is worsened by the various internal capacities of the transistor. These capacities were discussed in the preceding section of high-frequency amplifiers, although the exact values given there are not valid for large signal swings such as are commonly found in pulse amplifiers.

In a *saturated* transistor pulse amplifier, another degradation enters in the form of *pulse lengthening,* which distorts the input pulse in this manner:

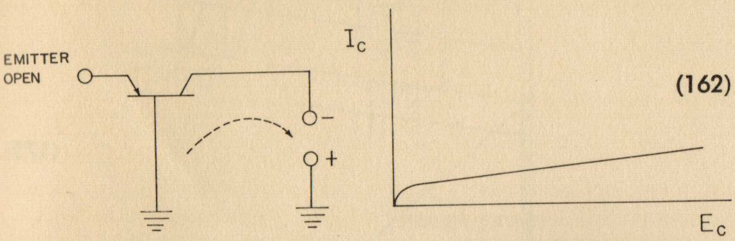


(161)

The degree of lengthening depends upon how hard the transistor is saturated. If the pulse width is not critical, a fair amount of lengthening can be tolerated. However, if the input pulse must be faithfully reproduced at the output, careful engineering is needed to minimize the lengthening. The engineering problem is eased considerably by the availability of switching transistors which are constructed to minimize this effect.

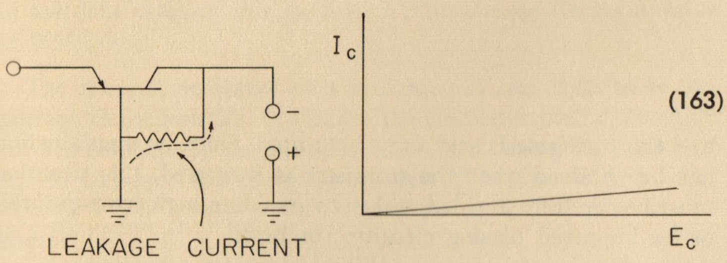
Temperature Effects

In the first article of this series, the transistor was introduced as an extension of a junction diode. It was shown that the reverse-biased collector junction passed a small current, just as would be expected of any junction diode:



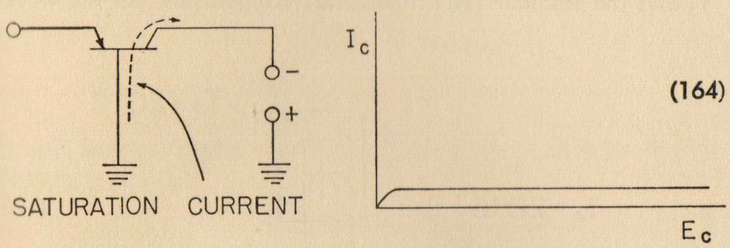
(162)

This current has two components. The first component results from simple resistive leakage paths,



(163)

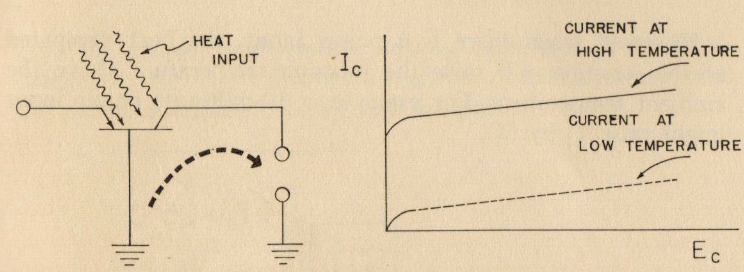
and the second component, called *saturation current,* results from a semiconductor action:



(164)

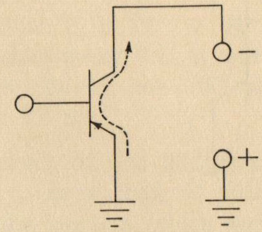
Although the saturation current is little affected by changes in collector voltage, it is extremely sensitive to changes in temperature. As junction temperature is increased, the saturation current increases:

(165)



The increase is very rapid; the current doubles about every 9 C. However, even at the highest operating temperatures, this relatively small current does not often cause trouble *as long as the base is grounded.*

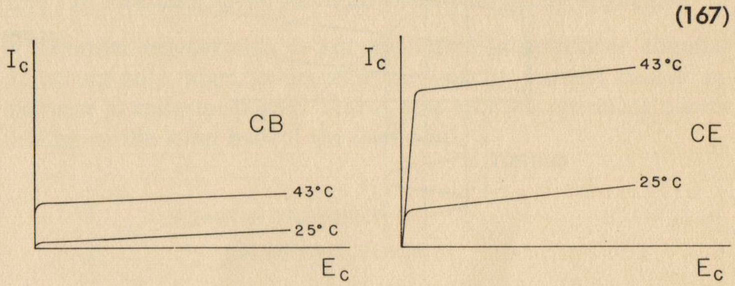
However, the transistor is often operated with the emitter grounded. In this configuration, the tiny reverse[1] current must pass through the base-emitter junction as well as the base-collector junction,



(166)

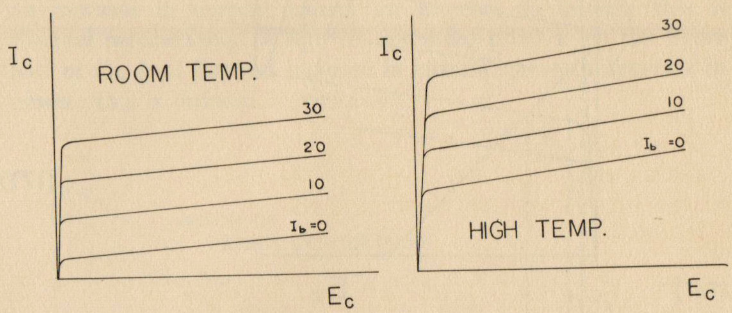
and in so doing, becomes amplified by the current-amplifying mechanism of the transistor. Consequently, the reverse current for the CE configuration is beta times greater than the reverse current for the CB configuration. With this larger current being doubled for every 9 C temperature rise, the high-temperature reverse current becomes a factor deserving serious consideration.

(167)



The family of curves is not distorted by the high-temperature reverse current, but merely displaced, intact, to another area of the graph:

(168)



This displacement can seriously disturb the functioning of an amplifier. Consider the effect that elevated temperatures would have on this simple CE amplifier:

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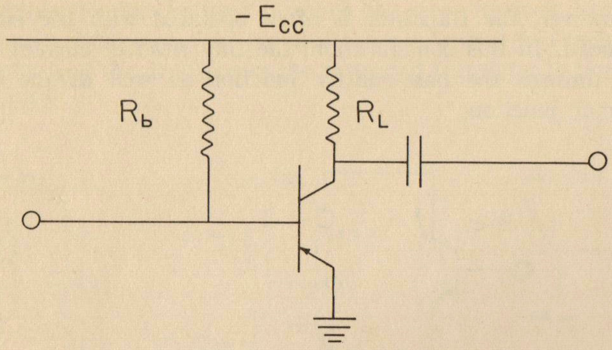
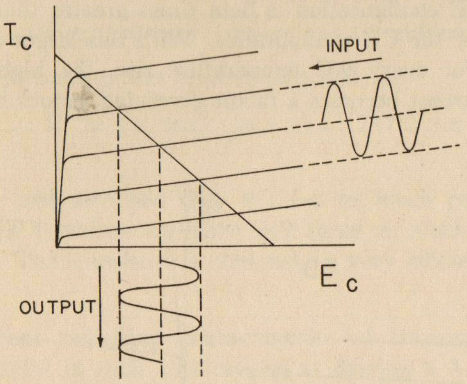
[1] Since the temperature problems are tied to only the saturation component of the total reverse current, the resistive (leakage) component will be ignored in this discussion, for the sake of simplification.



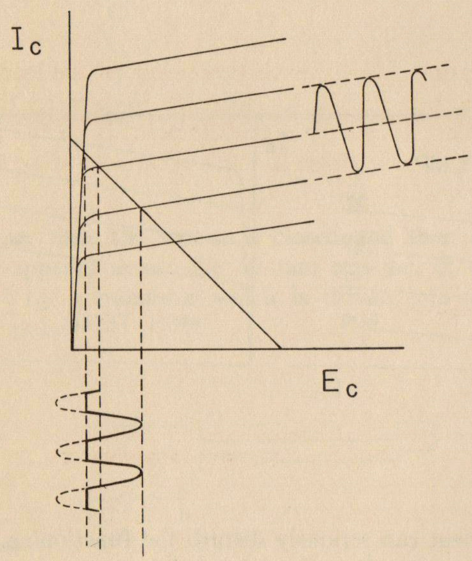
(169)

At normal operating temperatures, a sine wave input gives relatively distortion-free output:



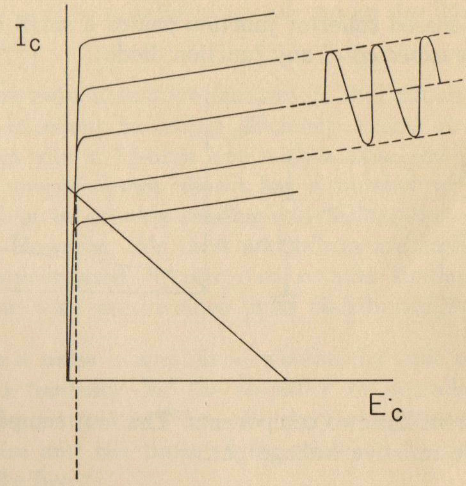
(170)

If the temperature is raised, however, the curves shift upward, and the amplifier begins to clip:



(171)

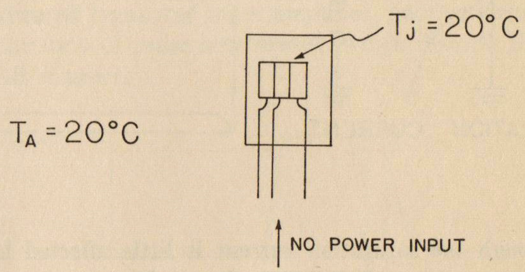
At a sufficiently high temperature, the signal is completely clipped,



(172)

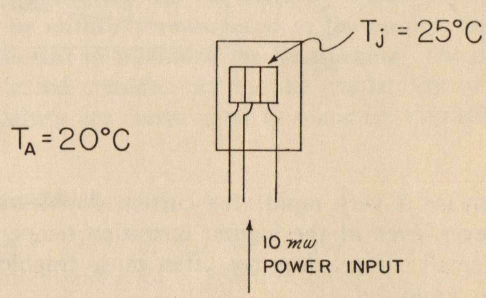
and the transistor is said to be saturated. Since no amplification can be obtained when the transistor is saturated, this situation must be carefully avoided, either by avoiding high temperatures, or by improved biasing circuitry, or both.

Note that the temperature referred to in all this discussion is *not* the temperature of the transistor's environment, but is rather the temperature of the collector junction itself. If the transistor is not drawing any current (as might be the case if it were in dead circuit or in storage) the junction temperature T_j and the ambient (environmental) temperature are the same:



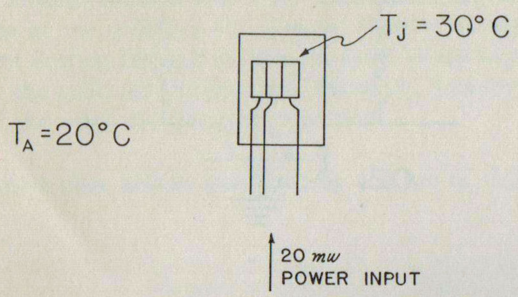
(173)

However, when there is a power input, the heat dissipated at the junction will raise the junction temperature above the ambient temperature. For example, a 10-milliwatt power input might raise T_j by 5C,



(174)

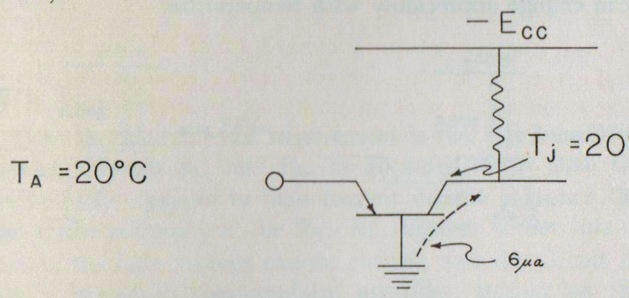
and a 20-milliwatt power input, by 10 C.



(175)

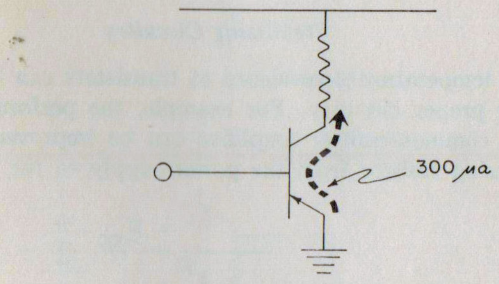
It is correct to deduce from these two cases that every 1 milliwatt of power input will cause a 0.5 C rise in junction temperature for this particular transistor. This characteristic of a transistor is called its *thermal resistance,* and would be listed in the data sheet of this particular transistor as having a value of 0.5°C/mw.

The thermal resistance of a transistor is one of its more important characteristics. It enables the transistor user to compute the temperature of the junction itself, and, using this value of T_j, to compute the temperature-induced reverse current. For example, if a transistor has a reverse current of 6μa in this circuit;



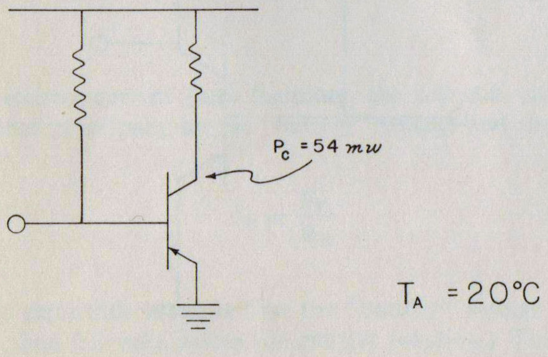
(176)

it will have a reverse current of $\beta \times 6\ \mu a = 300\ \mu a$ in this circuit:



(177)

If the simple single-resistor biasing technique is used (to exaggerate, for this example, the effects of temperature), and the circuit is adjusted for 54 mw dissipation,



(178)

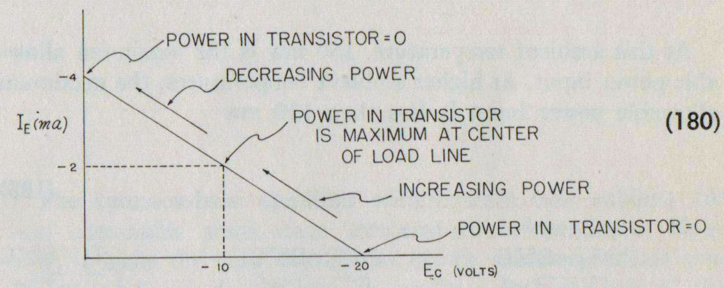
then a thermal resistance of 0.5 C/mw tells us that the junction temperature is higher than the ambient by

$$0.5°C/mw \times 54\ mw = 27°C; \quad (179)$$

and the actual T_j is $27° + 20° = 47°C$. Since the reverse current doubles every 9 C, it will be eight times larger in this 27° change, causing the 300 μa reverse current to become 2400 μa, or 2.4 ma.

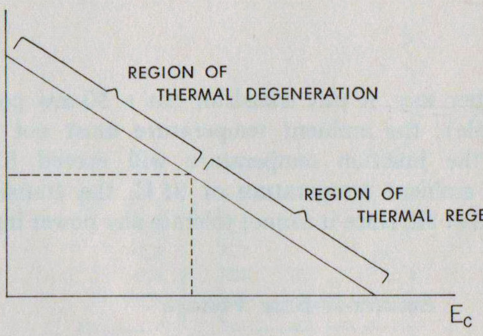
The presence of this additional 2.4 ma could increase the dissipation to more than 54 milliwatts, thereby causing more heating of the junction, which would result in even more reverse current, thereby causing even more heating, and so on. This mechanism, which is called *thermal regeneration,* can have a number of undesirable effects. In its milder forms, it can cause the operating point to be unduly sensitive to ambient-temperature changes. More serious cases can drive the operating point into the high-current region, with the consequent possibility of clipping and distorting the signal. The most serious result of thermal regeneration, however, is *thermal runaway,* which is a thermal regeneration resulting in the transistor's self-destruction. Proper design can prevent both of the serious effects, and can also make even the mild effect completely negligible.

Thermal regeneration is not inevitable in transistor circuits. It occurs only when an increase in collector current causes an increase in collector power. This is true only for operating points falling on the lower half of the load line:



(180)

When the operating point is on the lower half of the load line, an increase in current causes an increase in power; this is thermal regeneration. When the operating point is on the *upper* half of the load line, an increase in current causes a *decrease* in power; this is *thermal degeneration.*

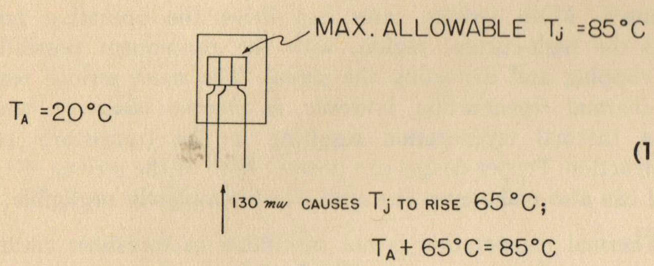


(181)

It might seem that transistor circuits should always be biased into the degenerative region as a safety precaution. However, this is usually not necessary. Proper circuit techniques make the regenerative region so stable that it is commonly used, particularly since it is the low-current region of the load line and therefore minimizes the current drawn by the equipment.

Maximum Power Dissipation

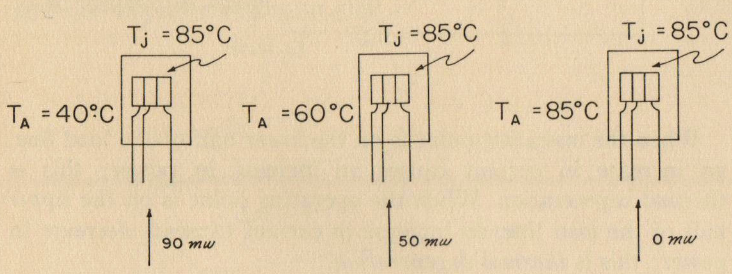
The thermal resistance given in a transistor's data sheet may be used to compute the maximum power dissipation allowable at a given ambient temperature. A typical small germanium transistor usually has a maximum allowable junction temperature of 85 C. If its thermal resistance is 0.5 C/mw, and the ambient temperature is 20 C, it can tolerate only enough power to raise the junction from 20 to 85 C, a change of 65 C. Since each milliwatt contributes 0.5 C, 130 mw will give a rise of 65 C:



(182)

At this ambient temperature, 130 mw is the maximum allowable power input. At higher ambient temperatures, the maximum allowable power input is less than 130 mw:

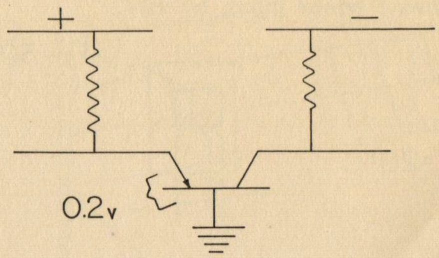
(183)



or, to put it another way, if this transistor has a 50-mw power input (for example), the ambient temperature must not rise above 60 C, or the junction temperature will exceed 85 C. Moreover, at an ambient temperature of 85 C, the transistor cannot be operated at all, since it cannot tolerate any power input.

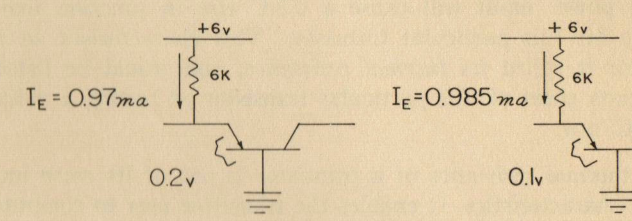
Emitter-to-Base Voltage

The reverse current is a temperature effect related to the reverse-biased collector junction. There is another temperature effect related to the forward-biased emitter junction. This junction, which at normal temperatures has a voltage drop of about 0.2 volts across it,



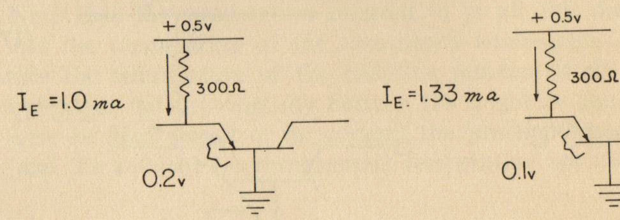
(184)

at higher temperatures has a smaller drop. This effect is of no consequence when the emitter is current-biased,



(185)

but as voltage-biased conditions are approached, the bias currents can change appreciably with temperature:

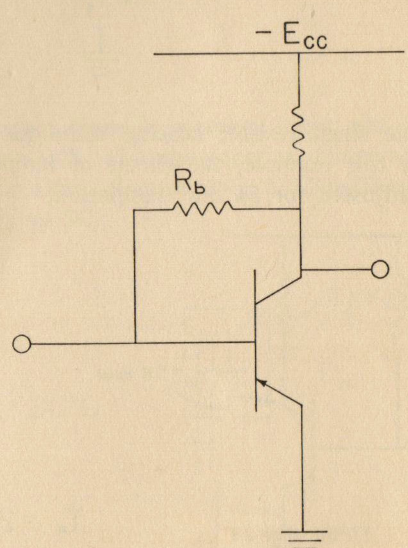


(186)

In general, voltage-bias of the emitter should be avoided, unless the circuit can accommodate the changes in operating currents without giving improper operation.

Stabilizing Circuitry

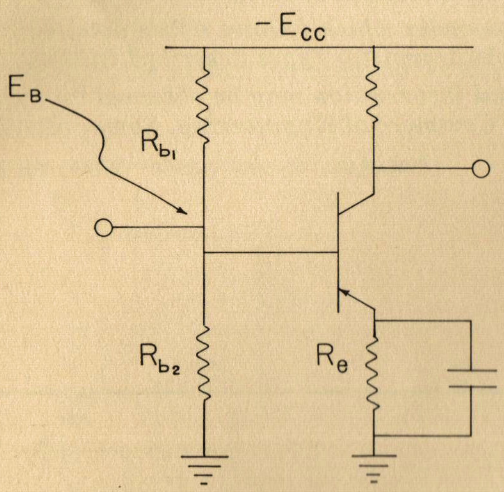
The temperature dependence of transistors can be minimized by the proper circuitry. For example, the performance of the simple common-emitter amplifier can be improved by moving the biasing resistor from the power supply to the collector:



(187)

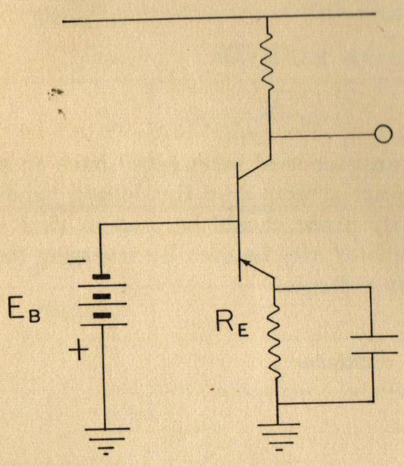
In this arrangement, any increase in collector current causes the voltage at the collector to decrease, thereby decreasing the bias current flowing through R_b into the base. When base current decreases, the collector current also decreases, thereby tending to restore the original operating condition.

A transistor may also be stabilized by the use of this circuit:



(188)

Here the fundamental requirement is that the bleeder current flowing through R_{b_1} and R_{b_2} be so much larger than the base current that changes in base current cannot influence the voltage at the midpoint of the R_{b_1}/R_{b_2} divider. Under this circumstance, the base voltage cannot change, and the circuit behaves like a biased-up common-base amplifier, insofar as the bias currents are concerned:



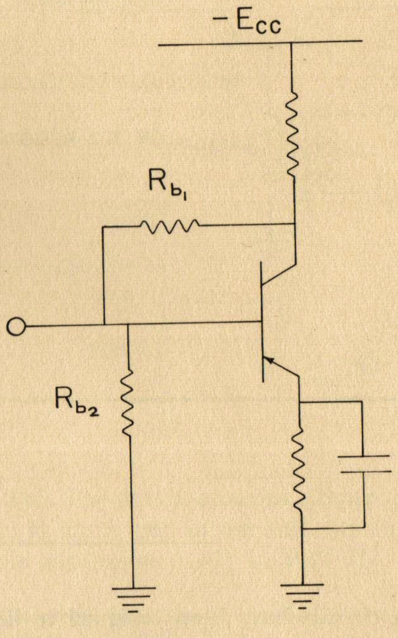
(189)

The emitter current (and therefore, the collector current) is determined principally by the "battery" voltage and the emitter resistor:

$$I_E = \frac{E_B}{R_E} \qquad (190)$$

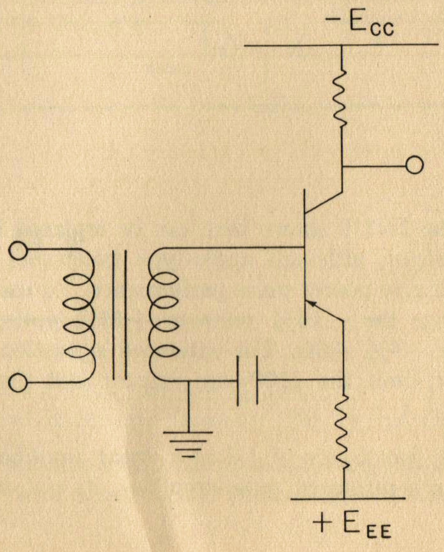
(This expression assumes that the "battery" voltage is much greater than 0.2 volts across the emitter junction.) The operating point is therefore almost independent of temperature, since neither E_B nor R_E is influenced by temperature.

The two foregoing circuits are sometimes found combined in a single circuit for increased stability:



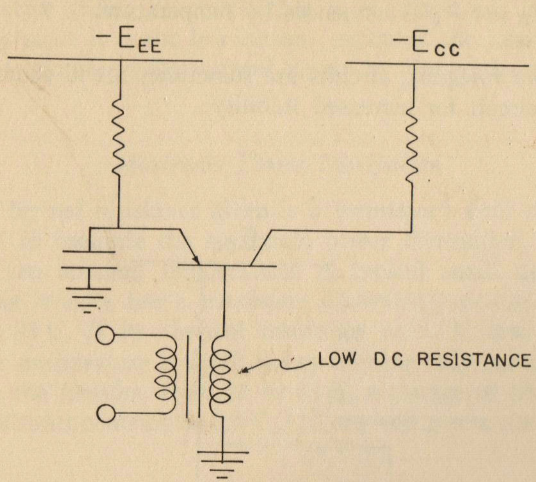
(191)

The common-base amplifier with current bias exhibits the best obtainable single-stage temperature independence. However, it lacks the gain capabilities of the common-emitter configuration. Some circuits can be arranged to make use of the good features of both the CE and CB configurations. This is accomplished by making the amplifier a CE configuration for signal currents:



(192)

and a CB configuration for bias currents:



(193)

Conclusion

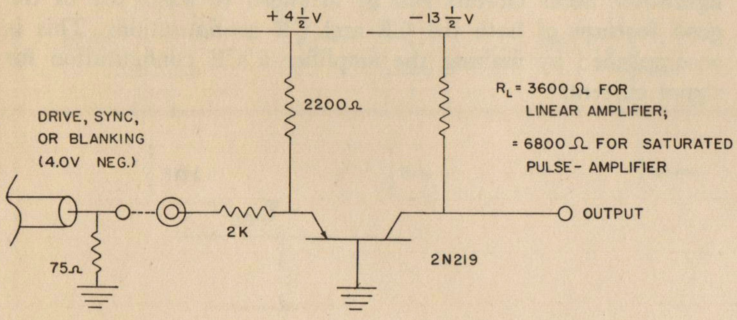
The information given in this series of three articles can be considered as nothing more than a narrow introduction to a broad subject. The material in these articles, properly assimilated, will facilitate a more detailed study of transistors, using one of the many excellent texts currently available (see the bibliography at the end of this article).

The appendix which follows offers detailed information on the transistor types described in these articles. Additional information may be obtained by writing to: RCA Commercial Engineering, Somerville, N. J.

APPENDIX

The following circuits have been designed to illustrate some of the principles of transistors. A 2N219, which is relatively inexpensive, will give very good results in any of the circuits except where noted otherwise. The potentials were chosen as those obtainable from two inexpensive batteries; the VS028 (4½ volts) and the VS304 (13½ volts).

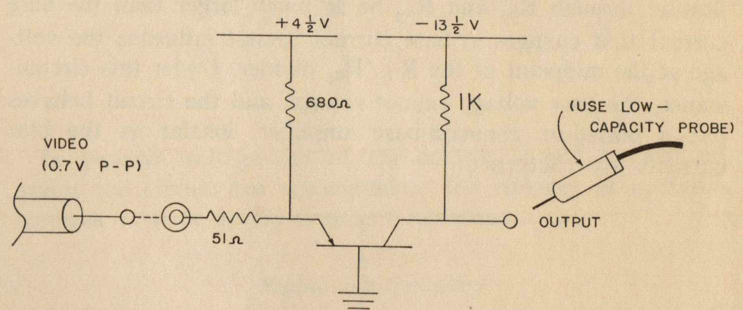
1. *A common-base amplifier*



Remarks: The 2N219 shown here can be replaced by almost any PNP transistor, although audio-type transistors (such as the 2N109) will give poorer pulse performance. To use an NPN transistor, change the —13½ volts to +13½ volts, and the +4½ volts to —4½ volts. For saturated operation with an NPN transistor, omit the 2200-ohm resistor and the 4½-volt bias supply.

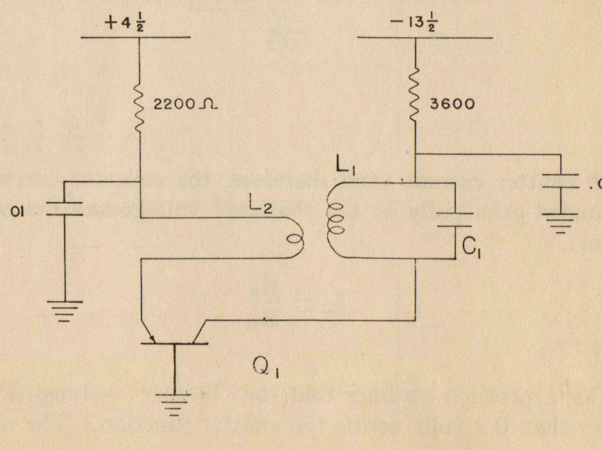
This amplifier has a gain of 1.8 as a linear amplifier ($G_v = 3600/2000$). As a saturated pulse-amplifier, its output is 13½ volts of pulse.

2. *A common-base video amplifier*



Remarks: The transistor used here should have an alpha cut-off frequency somewhat greater than the desired bandwidth. As shown, a low-capacity probe should be used to view the waveform. An NPN transistor may be used by reversing the polarity of the power supply voltages.

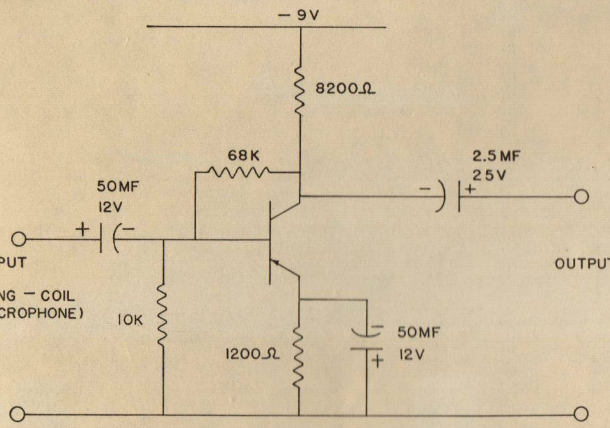
3. *A common-base oscillator*



Remarks: This simple oscillator will operate over a wide range of frequencies. For example, it will oscillate on the broadcast band if L_1 is a North Hills brown dot (105-200 mh), C_1 about 180 mmf, L_2 about 20 turns of #26 wire wound between the pies of L_1, and Q_1 a 2N219. The circuit should oscillate to at least 12 mc with the 2N219, with appropriate changes in the resonant tank L_1 - C_1 and in the feedback winding L_2. (L_2 should have about one-sixth the number of turns of L_1). With a 2N247, oscillations can be obtained to at least 60 mc, and with a 2N384, to at least 150 mc.

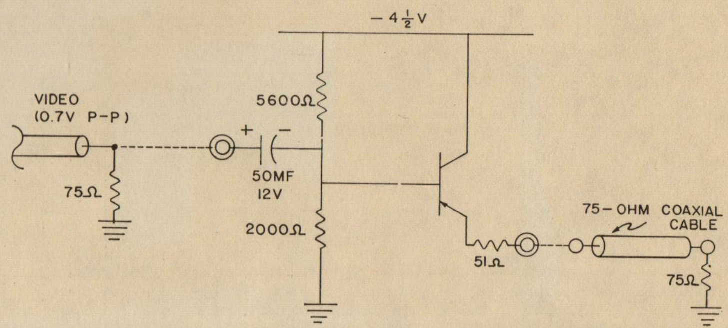
If the circuit does not oscillate, try reversing the leads from L_2.

4. *A common-emitter microphone preamplifier*[1]



Remarks: This circuit illustrates the temperature stabilization discussed on page 57 of Part III. The original circuit used a 2N109, but almost any PNP transistor should perform adequately. The circuit was designed to use an RCA 239S1 2⅛" speaker as a microphone. In such operation, one of the holes in the back of the speaker should be covered with cardboard having a 1/32" hole drilled in it. The remaining holes in the back of the speaker should be covered with felt, and the speaker mounted in a baffle or case.

5. *A common-collector line driver*



Remarks: This line-driver provides proper terminations for a 75-ohm line. It has a gain of one-half. Its bandwidth can be calculated from expression (142) in Part III.

[1] Circuit and speaker-modification information courtesy of RCA Semiconductor Division, Somerville, N. J.

	MAXIMUM RATINGS			CHARACTERISTICS			
	Collector-To-Base Volts	Collector Ma	Transistor Dissipation at 25°C	DC Collector Volts	DC Collector Ma	Current Transfer Ratio at 1 Kc	Alpha-Cutoff Frequency Mc
2N104	–30	–50	150	–6	–1	44	0.7
2N219	–16	–15	80	–9	–0.6	75	10
2N384	–30	–10	120	–12	–1.5	60	100

BIBLIOGRAPHY

The list which follows does not include many important transistor books, but will serve to guide the reader to these and other references:

1. Lo, Endres, Zawels, Walhauer, and Cheng, *Transistor Electronics.* Prentice-Hall, 1955.
2. *Transistors I.* RCA Laboratories, 1956.
3. Riddle and Ristenbatt, *Transistor Physics and Circuits.* Prentice-Hall, 1958.
4. Hurley, *Junction Transistor Electronics.* John Wiley & Sons, 1958.
5. Hunter (ed), *Handbook of Semiconductor Electronics.* McGraw-Hill, 1956.

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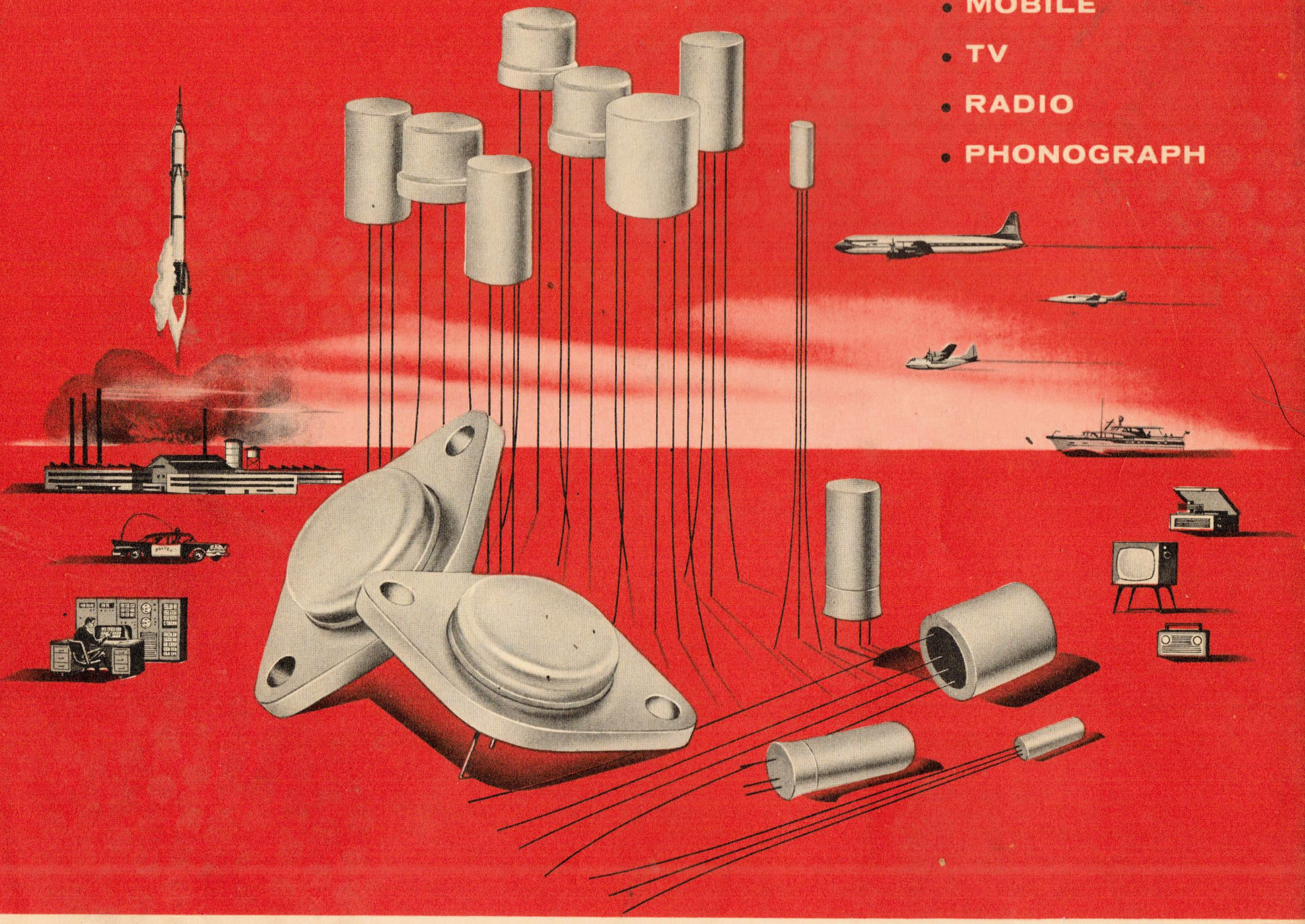

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