

PRACTICAL ELECTRONICS

for

INVENTORS

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Table 4.1 provides an overview of some of the most popular transistors. Note that the term *normally* used in this chart refers to conditions where the control lead (e.g., base, gate) is shorted (is at the same potential) with one of its channel leads (e.g., emitter, source). Also, the terms *on* and *off* used in this chart are not to be taken too literally; the amount of current flow through a device is usually a variable quantity, set by the magnitude of the control voltage. The transistors described in this chart will be discussed in greater detail later on in this chapter.

4.3.2 Bipolar Transistors

Bipolar transistors are three-terminal devices that act as electrically controlled switches or as amplifier controls. These devices come in either *npn* or *pnp* configurations, as shown in Fig. 4.20. An *npn* bipolar transistor uses a small input current and positive voltage at its base (relative to its emitter) to control a much larger collector-to-emitter current. Conversely, a *pnp* transistor uses a small output base current and negative base voltage (relative its emitter) to control a larger emitter-to-collector current.

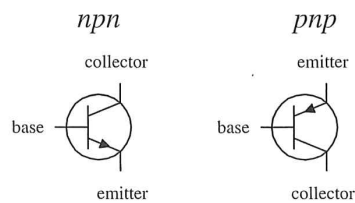


FIGURE 4.20

Bipolar transistors are incredibly useful devices. Their ability to control current flow by means of applied control signals makes them essential elements in electrically controlled switching circuits, current-regulator circuits, voltage-regulator circuits, amplifier circuits, oscillator circuits, and memory circuits.

How Bipolar Transistors Work

Here is a simple model of how an *npn* bipolar transistor works. (For a *pnp* bipolar transistor, all ingredients, polarities, and currents are reversed.)

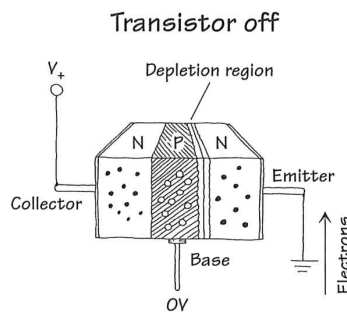


FIGURE 4.21

An *npn* bipolar transistor is made by sandwiching a thin slice of *p* semiconductor between two *n*-type semiconductors. When no voltage is applied at the transistor's base, electrons in the emitter are prevented from passing to the collector side because of the *pn* junction. (Remember that for electrons to flow across a *pn* junction, a biasing voltage is needed to give the electrons enough energy to "escape" the atomic forces holding them to the *n* side.) Notice that if a negative voltage is applied to the base, things get even worse—the *pn* junction between the base and emitter becomes reverse-biased. As a result, a depletion region forms and prevents current flow.

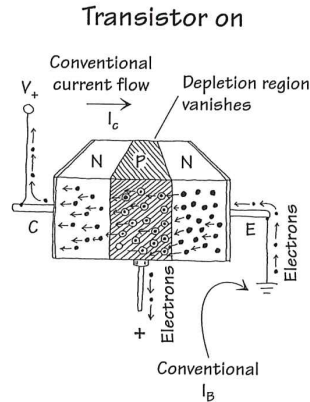


FIGURE 4.21 (Continued)

If a positive voltage (of at least 0.6V) is applied to the base of an *npn* transistor, the *pn* junction between the base and emitter is forward-biased. During forward bias, escaping electrons are drawn to the positive base. Some electrons exit through the base, but—this is the trick—because the *p*-type base is so thin, the onslaught of electrons that leave the emitter get close enough to the collector side that they begin jumping into the collector. Increasing the base voltage increases this jumping effect and hence increases the emitter-to-collector electron flow. Remember that conventional currents are moving in the opposite direction to the electron flow. Thus, in terms of conventional currents, a positive voltage and input current applied at the base cause a “positive” current *I* to flow from the collector to the emitter.

Theory

Figure 4.22 shows a typical characteristic curve for a bipolar transistor. This characteristic curve describes the effects the base current I_B and the emitter-to-collector voltage V_{EC} have on the emitter/collector currents I_E and I_C . (As you will see in a second, I_C is practically equal to I_E .)

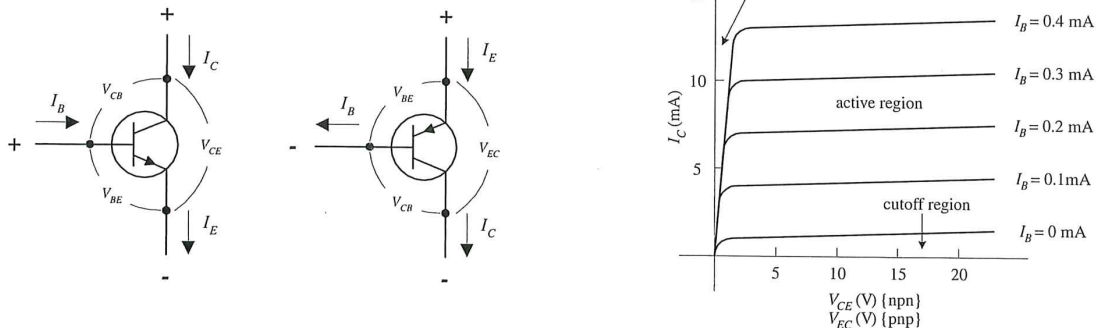


FIGURE 4.22

Some important terms used to describe a transistor's operation include saturation region, cutoff region, active mode/region, bias, and quiescent point (Q-point). *Saturation region* refers to a region of operation where maximum collector current flows and the transistor acts much like a closed switch from collector to emitter. *Cutoff region* refers to the region of operation near the voltage axis of the collector characteristics graph, where the transistor acts like an open switch—only a very small leakage current flows in this mode of operation. *Active mode/region* describes transistor operation in the region to the right of saturation and above cutoff, where a near-linear relationship exists between terminal currents (I_B , I_C , I_E). *Bias* refers to the specific dc terminal voltages and current of the transistor to set a desired point of active-mode operation, called the *quiescent point*, or *Q-point*.

SOME IMPORTANT RULES

Rule 1 For an *npn* transistor, the voltage at the collector V_C must be greater than the voltage at the emitter V_E by at least a few tenths of a volt; otherwise, current will not flow through the collector-emitter junction, no matter what the applied voltage is at the base. For *pnp* transistors, the emitter voltage must be greater than the collector voltage by a similar amount.

Rule 2 For an *npn* transistor, there is a voltage drop from the base to the emitter of 0.6 V. For a *pnp* transistor, there is a 0.6-V rise from base to emitter. In terms of operation, this means that the base voltage V_B of an *npn* transistor must be at least 0.6 V greater than the emitter voltage V_E ; otherwise, the transistor will pass an emitter-to-collector current. For a *pnp* transistor, V_B must be at least 0.6 V less than V_E ; otherwise, it will not pass a collector-to-emitter current.

The Formulas

The fundamental formula used to describe the behavior of a bipolar transistor (at least within the active region) is

$$I_C = h_{FE} I_B = \beta I_B$$

where I_B is the base current, I_C is the collector current, and h_{FE} (also referred to as β) is the *current gain*. Every transistor has its own unique h_{FE} . The h_{FE} of a transistor is often taken to be a constant, typically around 10 to 500, but it may change slightly with temperature and with changes in collector-to-emitter voltage. (A transistor's h_{FE} is given in transistor spec tables.) A simple explanation of what the current-gain formula tells you is this: If you take a bipolar transistor with, say, an h_{FE} of 100 and then feed (*npn*) or sink (*pnp*) a 1-mA current into (*npn*) or out of (*pnp*) its base, a collector current of 100 mA will result. Now, it is important to note that the current-gain formula applies only if rules 1 and 2 are met, i.e., assuming the transistor is within the active region. Also, there is a limit to how much current can flow through a transistor's terminals and a limit to the size of voltage that can be applied across them. I will discuss these limits later in the chapter (Fig. 4.23).

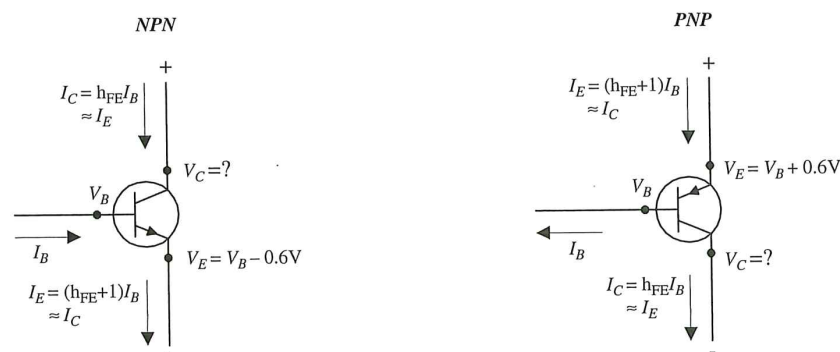


FIGURE 4.23

Now, if you apply the law of conservation of current (follow the arrows in Fig. 4.23), you get the following useful expression relating the emitter, collector, and base currents:

$$I_E = I_C + I_B$$

If you combine this equation with the current-gain equation, you can come up with an equation relating the emitter and base currents:

$$I_E = (h_{FE} + 1)I_B$$

As you can see, this equation is almost identical to the current-gain equation ($I_C = h_{FE}I_B$), with the exception of the +1 term. In practice, the +1 is insignificant as long as h_{FE} is large (which is almost always the case). This means that you can make the following approximation:

$$I_E \approx I_C$$

Finally, the second equation below is simply rule 2 expressed in mathematical form:

$$V_{BE} = V_B - V_E = +0.6 \text{ V (npn)}$$

$$V_{BE} = V_B - V_E = -0.6 \text{ V (pnp)}$$

Figure 4.23 shows how all the terminal currents and voltages are related. In the figure, notice that the collector voltage has a question mark next to it. As it turns out, the value of V_C cannot be determined directly by applying the formulas. Instead, V_C 's value depends on the network that is connected to it. For example, if you consider the setup shown in Fig. 4.24, you must find the voltage drop across the resistor in order to find the collector voltage. By applying Ohm's law and using the current-gain relation, you can calculate V_C . The results are shown in the figure.

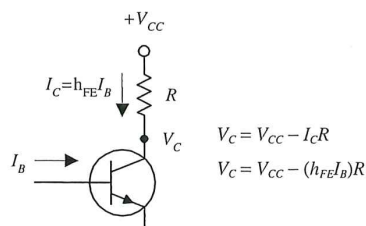


FIGURE 4.24

It is important to note that the equations here are idealistic in form. In reality, these equations may result in "unreal" answers. For instance, they tend to "screw up" when the currents and voltages are not within the bounds provided by the characteristic curves. If you apply the equations blindly, without considering the operating characteristics, you could end up with some wild results that are physically impossible.

One final note with regard to bipolar transistor theory involves what is called *transresistance* r_{tr} . Transresistance represents a small resistance that is inherently present within the emitter junction region of a transistor. Two things that determine the transresistance of a transistor are temperature and emitter current flow. The following equation provides a rough approximation of the r_{tr} :

$$r_{tr} \approx \frac{0.026 \text{ V}}{I_E}$$

In many cases, r_{tr} is insignificantly small (usually well below 1000Ω) and does not pose a major threat to the overall operation of a circuit. However, in certain types of circuits, treating r_{tr} as being insignificant will not do. In fact, its presence may be the major factor determining the overall behavior of a circuit. We will take a closer look at transresistance later on in this chapter.

Here are a couple of problems that should help explain how the equations work. The first example deals with an *nnp* transistor; the second deals with a *pnnp* transistor.

EXAMPLE 1 Given $V_{CC} = +20 \text{ V}$, $V_B = 5.6 \text{ V}$, $R_1 = 4.7 \text{ k}\Omega$, $R_2 = 3.3 \text{ k}\Omega$, and $h_{FE} = 100$, find V_E , I_E , I_B , I_C , and V_C .

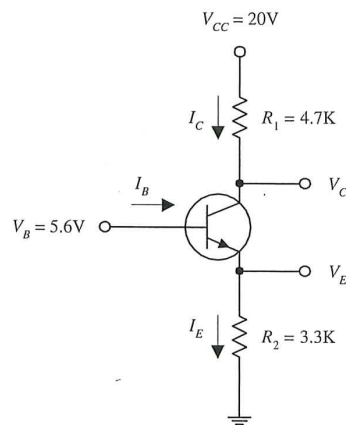


FIGURE 4.25

$$V_E = V_B - 0.6 \text{ V}$$

$$V_E = 5.6 \text{ V} - 0.6 \text{ V} = 5.0 \text{ V}$$

$$I_E = \frac{V_E - 0 \text{ V}}{R_2} = \frac{5.0 \text{ V}}{3300 \Omega} = 1.5 \text{ mA}$$

$$I_B = \frac{I_E}{(1 + h_{FE})} = \frac{1.5 \text{ mA}}{(1 + 100)} = 0.015 \text{ mA}$$

$$I_C = I_E - I_B \approx I_E = 1.5 \text{ mA}$$

$$V_C = V_{CC} - I_C R_1$$

$$V_C = 20 \text{ V} - (1.5 \text{ mA})(4700 \Omega)$$

$$V_C = 13 \text{ V}$$

EXAMPLE 2 Given $V_{CC} = +10 \text{ V}$, $V_B = 8.2 \text{ V}$, $R_1 = 560 \Omega$, $R_2 = 2.8 \text{ k}\Omega$, and $h_{FE} = 100$, find V_E , I_E , I_B , I_C , and V_C .

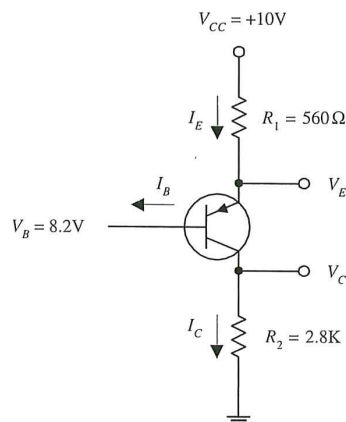


FIGURE 4.26

$$V_E = V_B + 0.6 \text{ V}$$

$$V_E = 8.2 \text{ V} + 0.6 \text{ V} = 8.8 \text{ V}$$

$$I_E = \frac{V_{CC} - V_E}{R_1} = \frac{10 \text{ V} - 8.8 \text{ V}}{560 \Omega} = 2.1 \text{ mA}$$

$$I_B = \frac{I_E}{(1 + h_{FE})} = \frac{2.1 \text{ mA}}{(1 + 100)} = 0.02 \text{ mA}$$

$$I_C = I_E - I_B \approx I_E = 2.1 \text{ mA}$$

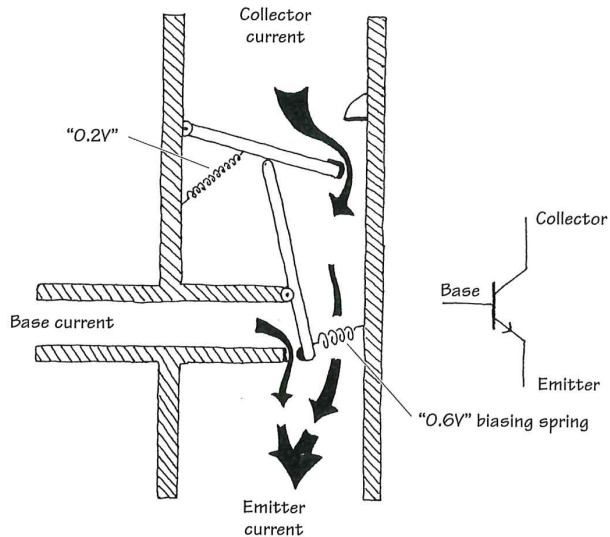
$$V_C = 0 \text{ V} + I_C R_2$$

$$V_C = 0 \text{ V} + (2.1 \text{ mA})(2800 \Omega)$$

$$V_C = 5.9 \text{ V}$$

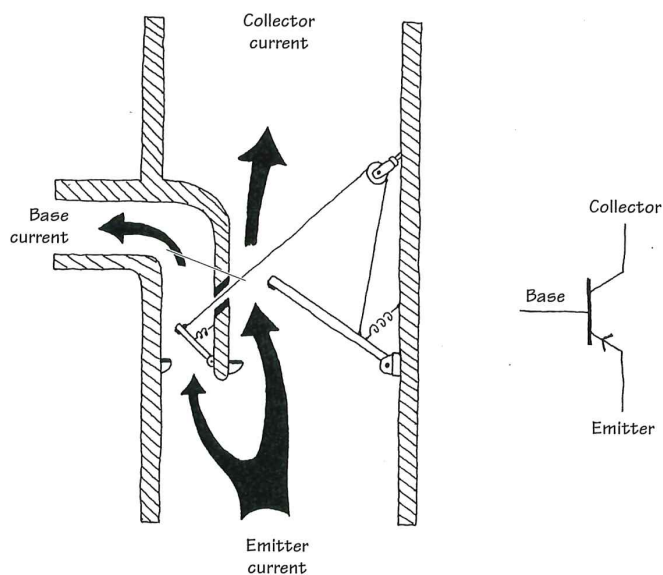
Bipolar Transistor Water Analogy

NPN WATER ANALOGY



The base of the *npn* water transistor represents the smaller tube entering the main device from the left side. The collector is represented by the upper portion of the vertical tube, while the emitter is represented by the lower portion of the vertical tube. When no pressure or current is applied through the "base" tube (analogous to an *npn* transistor's base being open circuited), the lower lever arm remains vertical while the top of this arm holds the upper main door shut. This state is analogous to a real bipolar *npn* transistor off state. In the water analogy, when a small current and pressure are applied to the base tube, the vertical lever is pushed by the entering current and swings counterclockwise. When this lever arm swings, the upper main door is permitted to swing open a certain amount that is dependent on the amount of swing of the lever arm. In this state, water can make its way from the collector tube to the emitter tube, provided there is enough pressure to overcome the force of the spring holding the door shut. This spring force is analogous to the 0.6V biasing voltage needed to allow current through the collector-emitter channel. Notice that in this analogy, the small base water current combines with the collector current.

PNP WATER ANALOGY

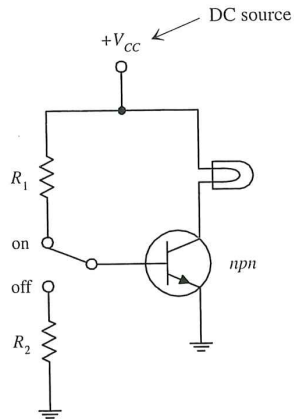


The main feature to note here is the need for a lower pressure at the base for the *pn*p water transistor to turn on. By allowing current to flow out the base tube, the lever moves, allowing the emitter-collector door to open. The degree of openness varies with the amount of swing in the lever arm, which corresponds to the amount of current escaping through the base tube. Again, note the 0.6V biasing spring.

FIGURE 4.27

Basic Operation

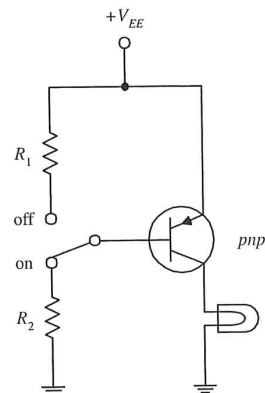
TRANSISTOR SWITCH



Here, an *npn* transistor is used to control current flow through a light bulb. When the switch is thrown to the on position, the transistor is properly biased, and the collector-to-emitter channel opens, allowing current to flow from V_{CC} through the light bulb and into ground. The amount of current entering the base is determined by

$$I_B = \frac{V_E + 0.6V}{R_1} = \frac{0V + 0.6V}{R_1}$$

To find the collector current, you can use the current-gain relation ($I_C = h_{FE}I_B$), provided that there is not too large a voltage drop across the light bulb (it shouldn't cause V_C to drop below $0.6V + V_E$). When the switch is thrown to the off position, the base is set to ground, and the transistor turns off, cutting current flow to the light bulb. R_2 should be large (e.g., 10 k Ω) so that very little current flows to ground.



In the *pnp* circuit, everything is reversed; current must leave the base in order for a collector current to flow.

FIGURE 4.28

CURRENT SOURCE

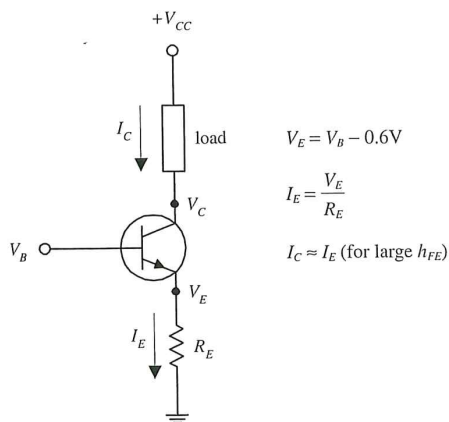


FIGURE 4.29

The circuit here shows how an *npn* transistor can be used to make a simple current source. By applying a small input voltage and current at the transistor's base, a larger collector/load current can be controlled. The collector/load current is related to the base voltage by

$$I_C = I_{load} = \frac{V_B - 0.6V}{R_E}$$

The derivation of this equation is shown with the figure.

CURRENT BIASING METHODS

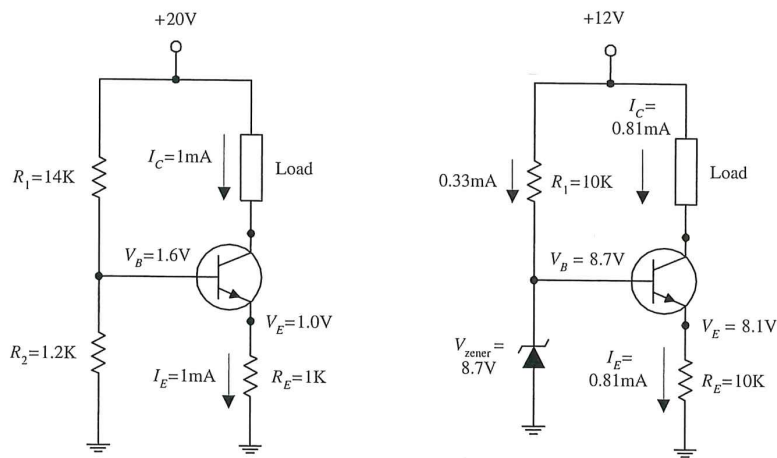


FIGURE 4.30

Two common methods for biasing a current source are to use either a voltage-divider circuit (shown in the leftmost circuit) or a zener diode regulator (shown in the rightmost circuit). In the voltage-divider circuit, the base voltage is set by R_1 and R_2 and is equal to

$$V_B = \frac{R_2}{R_1 + R_2} V_{CC}$$

In the zener diode circuit, the base voltage is set by the zener diode's breakdown voltage such that

$$V_B = V_{\text{zener}}$$

EMITTER FOLLOWER

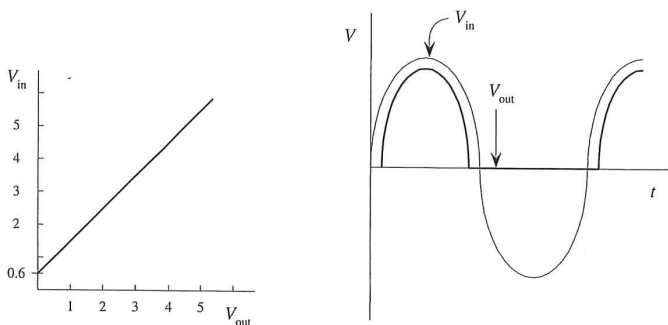
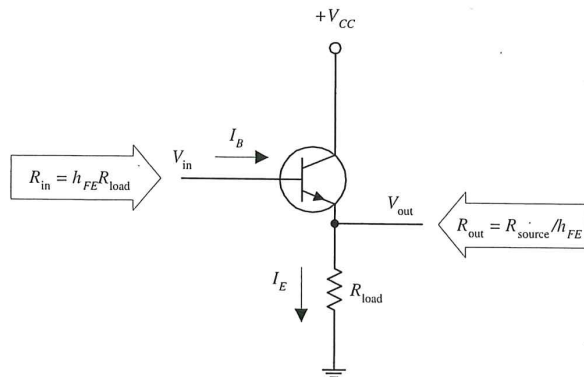


FIGURE 4.31

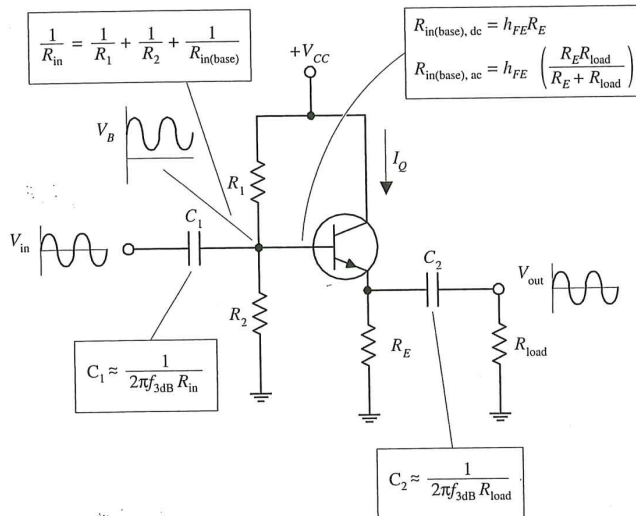
The network shown here is called an *emitter follower*. In this circuit, the output voltage (tapped at the emitter) is almost a mirror image of the input (output "follows" input), with the exception of a 0.6 V drop in the output relative to the input (caused by base-emitter *pn* junction). Also, whenever $V_B \leq V_E + 0.6 \text{ V}$ (during negative swings in input), the transistor will turn off (the *pn* junction is reversed-biased). This effect results in clipping of the output (see graph). At first glance, it may appear that the emitter follower is useless—it has no voltage gain. However, if you look at the circuit more closely, you will see that it has a much larger input impedance than an output impedance, or more precisely, it has a much larger output current (I_E) relative to an input current (I_B). In other words, the emitter follower has current gain, a feature that is just as important in applications as voltage gain. This means that this circuit requires less power from the signal source (applied to V_{in}) to drive a load than would otherwise be required if the load were to be powered directly by the source. By manipulating the transistor gain equation and using Ohm's law, the input resistance and output resistance are:

$$R_{in} = h_{FE} R_{load}$$

$$R_{out} = \frac{R_{source}}{h_{FE}}$$

EMITTER-FOLLOWER (COMMON-COLLECTOR) AMPLIFIER

The circuit shown here is called a *common-collector amplifier*, which has current gain but no voltage gain. It makes use of the emitter-follower arrangement but is modified to avoid clipping during negative input swings. The voltage divider (R_1 and R_2) is used to give the input signal (after passing through the capacitor) a positive dc level or operating point (known as the *quiescent point*). Both the input and output capacitors are included so that an ac input-output signal can be added without disturbing the dc operating point. The capacitors, as you will see, also act as filtering elements.



To design a common-collector amplifier used to power a 3-k Ω load, which has a supply voltage $V_{CC} = +10$ V, a transistor h_{FE} of 100, and a desired f_{3dB} point of 100 Hz, you

1. Choose a quiescent current $I_Q = I_C$. For this problem, pick $I_Q = 1$ mA.
2. Next, select $V_E = \frac{1}{2}V_{CC}$ to allow for the largest possible symmetric output swing without clipping, which in this case, is 5 V. To set $V_E = 5$ V and still get $I_Q = 1$ mA, make use of R_E , whose value you find by applying Ohm's law:

$$R_E = \frac{\frac{1}{2}V_{CC}}{I_Q} = \frac{5 \text{ V}}{1 \text{ mA}} = 5 \text{ k}\Omega$$

3. Next, set the $V_B = V_{EE} + 0.6$ V for quiescent conditions (to match up V_{EE} so as to avoid clipping). To set the base voltage, use the voltage divider (R_1 and R_2). The ratio between R_1 and R_2 is determined by rearranging the voltage-divider relation and substituting into it $V_B = V_{EE} + 0.6$ V:

$$\frac{R_2}{R_1} = \frac{V_B}{V_{CC} - V_B} = \frac{V_E + 0.6 \text{ V}}{V_{CC} - (V_E + 0.6 \text{ V})}$$

Fortunately, you can make an approximation and simply let $R_1 = R_2$. This approximation "forgets" the 0.6-V drop but usually isn't too dramatic. The actual sizes of R_2 and R_1 should be such that their parallel resistance is less than or equal to one-tenth the dc (quiescent) input resistance at the base (this prevents the voltage divider's output voltage from lowering under loading conditions):

$$\frac{R_1 R_2}{R_1 + R_2} \leq \frac{1}{10} R_{in(base),dc}$$

$$\frac{R}{2} \leq \frac{1}{10} R_{in(base),dc} \quad (\text{using the approximation } R = R_1 = R_2)$$

Here, $R_{in(base),dc} = h_{FE} R_E$, or specially, $R_{in(base),dc} = 100(5 \text{ k}) = 500 \text{ k}$. Using the approximation above, R_1 and R_2 are calculated to be 100 k each. (Here you did not have to worry about the ac coupler load; it did not influence the voltage divider because you assumed quiescent setup conditions; C_2 acts as an open circuit, hence "eliminating" the presence of the load.)

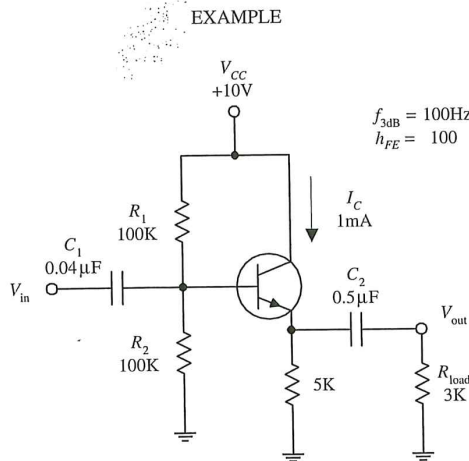


FIGURE 4.32

4. Next, choose the ac coupling capacitors so as to block out dc levels and other undesired frequencies. C_1 forms a high-pass filter with R_{in} (see diagram). To find R_{in} , treat the voltage divider and $R_{in(base),ac}$ as being in parallel:

$$\frac{1}{R_{in}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_{in(base),ac}}$$

Notice that $R_{in(base),ac}$ is used, not $R_{in(base),dc}$. This is so because you can no longer treat the load as being absent when fluctuating signals are applied to the input; the capacitor begins to pass a displacement current. This means that you must take R_E and R_{load} in parallel and multiply by h_{FE} to find $R_{in(base),ac}$:

$$R_{in(base),ac} = h_{FE} \left(\frac{R_E R_{load}}{R_E + R_{load}} \right) = 100 \left[\frac{5 \text{ k}\Omega (3 \text{ k}\Omega)}{5 \text{ k}\Omega + 3 \text{ k}\Omega} \right] = 190 \text{ k}\Omega$$

Now you can find R_{in} :

$$\frac{1}{R_{in}} = \frac{1}{100 \text{ k}\Omega} + \frac{1}{100 \text{ k}\Omega} + \frac{1}{190 \text{ k}\Omega}$$

$$R_{in} = 40 \text{ k}\Omega$$

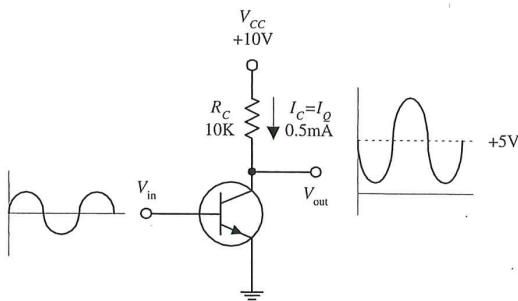
Once you have found R_{in} , choose C_1 to set the f_{3dB} point (C_1 and R_{in} form a high-pass filter.) The f_{3dB} point is found by using the following formula:

$$C_1 = \frac{1}{2\pi f_{3dB} R_{in}} = \frac{1}{2\pi(100 \text{ Hz})(40 \text{ k}\Omega)} = 0.04 \text{ }\mu\text{F}$$

C_2 forms a high-pass filter with the load. It is chosen by using

$$C_2 = \frac{1}{2\pi f_{3dB} R_{load}} = \frac{1}{2\pi(100 \text{ Hz})(3 \text{ k}\Omega)} = 0.5 \text{ }\mu\text{F}$$

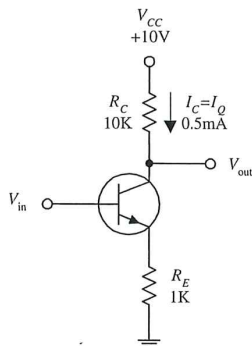
COMMON-EMITTER CONFIGURATION



The transistor configuration here is referred to as the *common-emitter configuration*. Unlike the emitter follower, the common emitter has voltage gain. To figure out how this circuit works, first set $V_C = \frac{1}{2}V_{CC}$ to allow for maximum swing without clipping. Like the emitter follower, again pick a quiescent current I_Q to start with. To set $V_C = \frac{1}{2}V_{CC}$ with a desired I_Q , use R_C , which is found by Ohm's law:

$$R_C = \frac{V_{CC} - V_C}{I_C} = \frac{V_{CC} - \frac{1}{2}V_{CC}}{I_Q} = \frac{\frac{1}{2}V_{CC}}{I_Q}$$

INCLUDING R_E FOR TEMPERATURE STABILITY



For example, if V_{CC} is 10V and I_Q is 0.5 mA, R_C is then 10 k. The gain of this circuit is found by realizing that $\Delta V_E = \Delta V_B$ (where Δ represents a small fluctuation). The emitter current is found using Ohm's law:

$$\Delta I_E = \frac{\Delta V_E}{R_E} = \frac{\Delta V_B}{R_E} \approx \Delta I_C$$

Using $V_C = V_{CC} - I_C R_C$ and the last expression, you get

$$\Delta V_C = -\Delta I_C R_C = -\frac{\Delta V_B}{R_E} R_C$$

Since V_C is V_{out} and V_B is V_{in} , the gain is

$$\text{Gain} = \frac{V_{out}}{V_{in}} = \frac{\Delta V_C}{\Delta V_B} = -\frac{R_C}{R_E}$$

But what about R_E ? According to the circuit, there's no emitter resistor. If you use the gain formula, it would appear that $R_E = 0 \Omega$, making the gain infinite. However, as mentioned earlier, bipolar transistors have a trans-resistance (small internal resistance) in the emitter region, which is approximated by using

$$r_{tr} \approx \frac{0.026 \text{ V}}{I_E}$$

Applying this formula to the example, taking $I_Q = 0.5 \text{ mA} = I_C \approx I_E$, the R_E term in the gain equation, or r_{tr} equals 52 Ω . This means the gain is actually equal to

$$\text{Gain} = -\frac{R_C}{R_E} = -\frac{R_C}{r_{tr}} = -\frac{10 \text{ k}\Omega}{52 \Omega} = -192$$

Notice that the gain is negative (output is inverted). This results in the fact that as V_{in} increases, I_C increases, while V_C (V_{out}) decreases (Ohm's law). Now, there is one problem with this circuit. The r_{tr} term happens to be very unstable, which in effect makes the gain unstable. The instability stems from r_{tr} dependence on temperature. As the temperature rises, V_E

ACHIEVING HIGH-GAIN WITH TEMPERATURE STABILITY

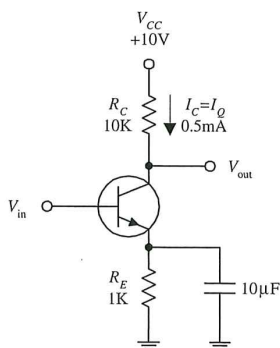


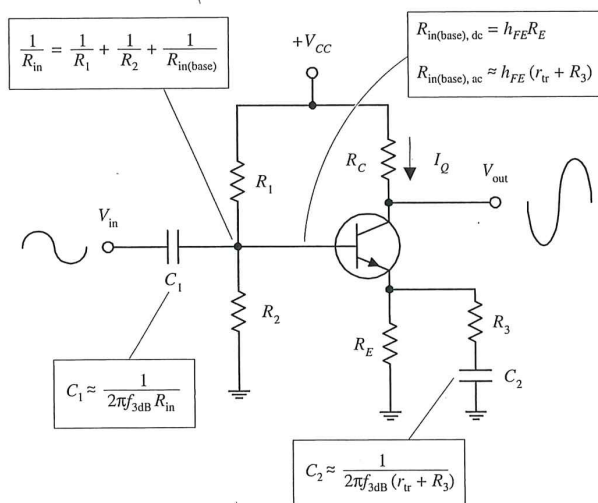
FIGURE 4.33

and I_C increase, V_{BE} decreases, but V_B remains fixed. This means that the biasing-voltage range narrows, which in effect turns the transistor's "valve" off. To eliminate this pinch, an emitter resistor is placed from emitter to ground (see second circuit). Treating R_E and r_{tr} as series resistors, the gain becomes

$$\text{Gain} = \frac{R_C}{R_E + r_{tr}}$$

By adding R_E , variations in the denominator are reduced, and therefore, the variations in gain are reduced as well. In practice, R_E should be chosen to place V_E around 1 V (for temperature stability and maximum swing in output). Using Ohm's law (and applying it to the example), choose $R_E = V_E/I_E = V_E/I_Q = 1\text{ V}/1\text{ mA} = 1\text{ k}\Omega$. One drawback that arises when R_E is added to the circuit is a reduction in gain. However, there is a trick you can use to eliminate this reduction in voltage gain and at the same time maintain the temperature stability. If you bypass R_E with a capacitor (see third circuit), you can make R_E "disappear" when high-frequency input signals are applied. (Recall that a capacitor behaves like an infinitely large resistor to dc signals but becomes less "resistive," or reactive to ac signals.) In terms of the gain equation, the R_E term goes to zero because the capacitor diverts current away from it toward ground. The only resistance left in the gain equation is r_{tr} .

COMMON-EMITTER AMPLIFIER



EXAMPLE

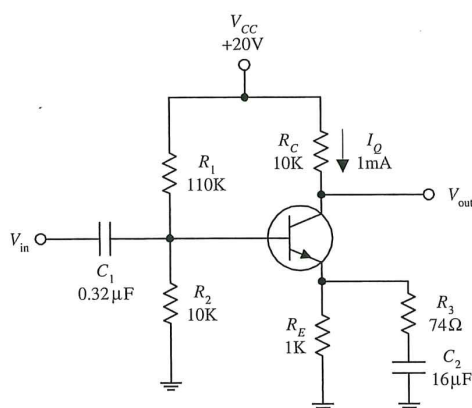


FIGURE 4.34

After plugging $R_1 = 11.5R_2$ into this expression and using $R_{in(base), dc} = h_{FE}R_E$, you find that $R_2 = 10\text{ k}\Omega$, which in turn means $R_1 = 115\text{ k}\Omega$ (let's say, $110\text{ k}\Omega$ is close enough for R_1).

The circuit shown here is known as a *common-emitter amplifier*. Unlike the common-collector amplifier, the common-emitter amplifier provides voltage gain. This amplifier makes use of the common-emitter arrangement and is modified to allow for ac coupling. To understand how the amplifier works, let's go through the following example.

To design a common-emitter amplifier with a voltage gain of -100 , an f_{3dB} point of 100 Hz, and a quiescent current $I_Q = 1\text{ mA}$, where $h_{FE} = 100$ and $V_{CC} = 20\text{ V}$:

1. Choose R_C to center V_{out} (or V_C) to $\frac{1}{2}V_{CC}$ to allow for maximum symmetrical swings in the output. In this example, this means V_C should be set to 10 V. Using Ohm's law, you find R_C :

$$R_C = \frac{V_C - V_{CE}}{I_C} = \frac{0.5V_{CC} - V_{CE}}{I_Q} = \frac{10\text{ V}}{1\text{ mA}} = 10\text{ k}\Omega$$

2. Next we select R_E to set $V_E = 1\text{ V}$ for temperature stability. Using Ohm's law, and taking $I_Q = I_E = 1\text{ mA}$, we get $R_E = V_E/I_E = 1\text{ V}/1\text{ mA} = 1\text{ k}\Omega$.
3. Now, choose R_1 and R_2 to set the voltage divider to establish the quiescent base voltage of $V_B = V_E + 0.6\text{ V}$, or 1.6 V. To find the proper ratio between R_1 and R_2 , use the voltage divider (rearranged a bit):

$$\frac{R_2}{R_1} = \frac{V_B}{V_{CC} - V_B} = \frac{1.6\text{ V}}{20\text{ V} - 1.6\text{ V}} = \frac{1}{11.5}$$

This means $R_1 = 11.5R_2$. The size of these resistors is found using the similar procedure you used for the common-collector amplifier; their parallel resistance should be less than or equal to $\frac{1}{10}R_{in(base), dc}$.

$$\frac{R_1 R_2}{R_1 + R_2} \leq \frac{1}{10} R_{in(base), dc}$$

4. Next, choose R_3 for the desired gain, where

$$\text{Gain} = -\frac{R_C}{R_E \parallel (r_{tr} + R_3)} = -100$$

(The double line means to take R_E and $(r_{tr} + R_3)$ in parallel.) To find r_{tr} , use $r_{tr} = 0.026 \text{ V}/I_E = 0.026 \text{ V}/I_C = 0.026 \text{ V}/1 \text{ mA} = 26 \Omega$. Now you can simplify the gain expression by assuming R_E "disappears" when ac signals are applied. This means the gain can be simplified to

$$\text{Gain} = -\frac{R_C}{r_{tr} + R_3} = -\frac{10 \text{ k}}{26 \Omega + R_3} = -100$$

Solving this equation for R_3 , you get $R_3 = 74 \Omega$.

5. Next, choose C_1 for filtering purposes such that $C_1 = \frac{1}{2\pi f_{3\text{dB}} R_{in}}$. Here, R_{in} is the combined parallel resistance of the voltage-divider resistors, and $R_{in(\text{base}),ac}$ looking in from the left into the voltage divider:

$$\frac{1}{R_{in}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{h_{FE}(r_{tr} + R_3)} = \frac{1}{110 \text{ k}\Omega} + \frac{1}{10 \text{ k}\Omega} + \frac{1}{100(26 \Omega + 74 \Omega)}$$

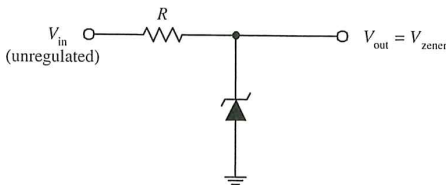
Solving this equation, you get $R_{in} = 5 \text{ k}$. This means

$$C_1 = \frac{1}{2\pi(100 \text{ Hz})(5 \text{ k}\Omega)} = 0.32 \mu\text{F}$$

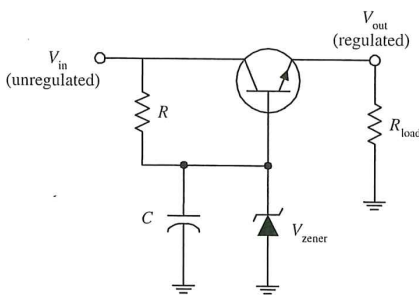
6. To choose C_2 , treat C_2 and $r_{tr} + R_3$ as a high-pass filter (again, treat R_E as being negligible during ac conditions). C_2 is given by

$$C_2 = \frac{1}{2\pi f_{3\text{dB}}(r_{tr} + R_3)} = \frac{1}{2\pi(100 \text{ Hz})(26 \Omega + 74 \Omega)} = 16 \mu\text{F}$$

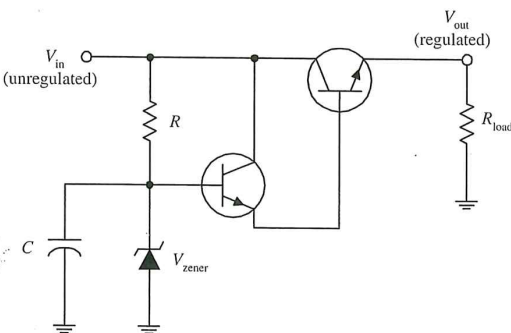
VOLTAGE REGULATOR



The zener diode circuit here can be used to make a simple voltage regulator. However, in many applications, the simple regulator has problems; V_{out} isn't adjustable to a precise value, and the zener diode provides only moderate protection against ripple voltages. Also, the simple zener diode regulator does not work particularly well when the load impedance varies. Accommodating large load variations requires a zener diode with a large power rating—which can be costly.



The second circuit in the figure, unlike the first circuit, does a better job of regulating; it provides regulation with load variations and provides high-current output and somewhat better stability. This circuit closely resembles the preceding circuit, except that the zener diode is connected to the base of an *npn* transistor and is used to regulate the collector-to-emitter current. The transistor is configured in the emitter-follower configuration. This means that the emitter will follow the base (except there is the 0.6-V drop). Using a zener diode to regulate the base voltage results in a regulated emitter voltage. According to the transistor rules, the current required by the base is only $1/h_{FE}$ times the emitter-to-collector current. Therefore, a low-power zener diode can regulate the base voltage of a transistor that can pass a considerable amount of



current. The capacitor is added to reduce the noise from the zener diode and also forms an RC filter with the resistor that is used to reduce ripple voltages.

In some instances, the preceding zener diode circuit may not be able to supply enough base current. One way to fix this problem is to add a second transistor, as shown in the third circuit. The extra transistor (the one whose base is connected to the zener diode) acts to amplify current sent to the base of the upper transistor.

FIGURE 4.35

DARLINGTON PAIR

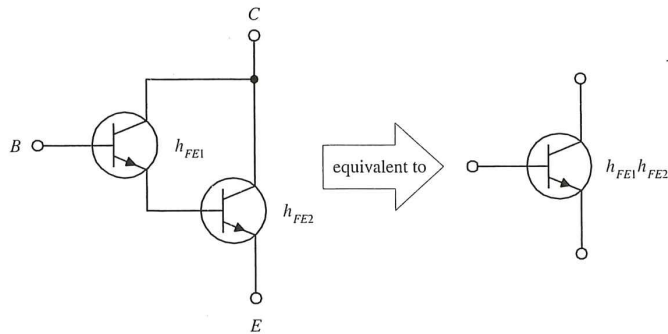
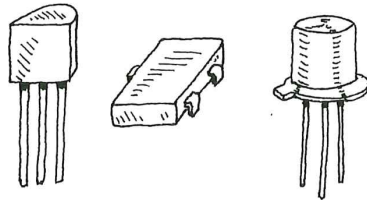


FIGURE 4.36

By attaching two transistors together as shown here, a larger current-handling, larger h_{FE} equivalent transistor circuit is formed. The combination is referred to as a *Darlington pair*. The equivalent h_{FE} for the pair is equal to the product of the individual transistor's h_{FE} values ($h_{FE} = h_{FE1}h_{FE2}$). Darlington pairs are used for large current applications and as input stages for amplifiers, where big input impedances are required. Unlike single transistors, however, Darlington pairs have slower response times (it takes longer for the top transistor to turn the lower transistor on and off) and have twice the base-to-emitter voltage drop (1.2V instead of 0.6V) as compared with single transistors. Darlington pairs can be purchased in single packages.

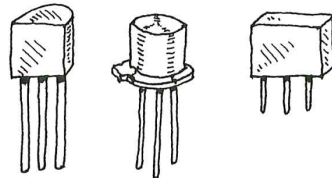
Types of Bipolar Transistors

SMALL SIGNAL



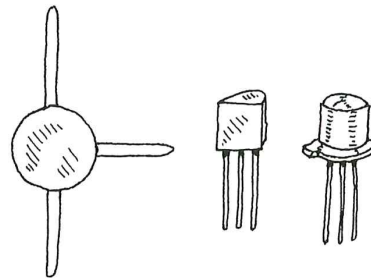
This type of transistor is used to amplify low-level signals but also can be used as a switch. Typical h_{FE} values range from 10 to 500, with maximum I_C ratings from about 80 to 600 mA. They come in both *npn* and *pnp* forms. Maximum operating frequencies range from about 1 to 300 MHz.

SMALL SWITCHING



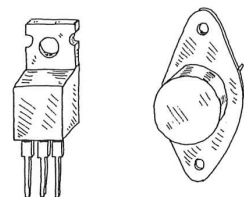
These transistors are used primarily as switches but also can be used as amplifiers. Typical h_{FE} values range from around 10 to 200, with maximum I_C ratings from around 10 to 1000 mA. They come in both *npn* and *pnp* forms. Maximum switching rates range between 10 and 2000 MHz.

HIGH FREQUENCY (RF)



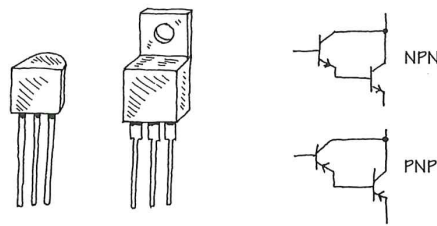
These transistors are used for small signals that run at high frequencies for high-speed switching applications. The base region is very thin, and the actual chip is very small. They are used in HF, VHF, UHF, CATV, and MATV amplifier and oscillator applications. They have a maximum frequency rating of around 2000 MHz and maximum I_C currents from 10 to 600 mA. They come in both *npn* and *pnp* forms.

POWER

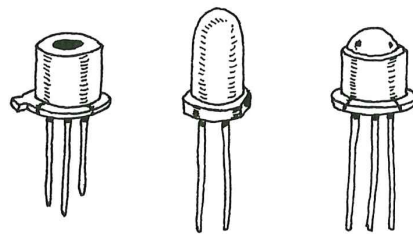


These transistors are used in high-power amplifiers and power supplies. The collector is connected to a metal base that acts as a heat sink. Typical power ratings range from around 10 to 300 W, with frequency ratings from about 1 to 100 MHz. Maximum I_C values range between 1 to 100 A. They come in *npn*, *pnp*, and Darlington (*npn* or *pnp*) forms.

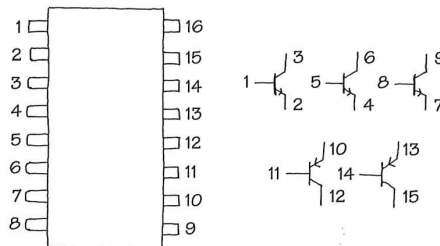
FIGURE 4.37

DARLINGTON PAIR

These are two transistors in one. They provide more stability at high current levels. The effective h_{FE} for the device is much larger than that of a single transistor, hence allowing for a larger current gain. They come in *nnp* (*D-nnp*) and *pnnp* (*D-pnp*) Darlington packages.

PHOTOTRANSISTOR

This transistor acts as a light-sensitive bipolar transistor (base is exposed to light). When light comes in contact with the base region, a base current results. Depending on the type of phototransistor, the light may act exclusively as a biasing agent (two-lead phototransistor) or may simply alter an already present base current (three-lead phototransistor). See Chap. 5 for more details.

TRANSISTOR ARRAY

This consists of a number of transistors combined into a single integrated package. For example, the transistor array shown here is made of three *nnp* transistors and two *pnp* transistors.

FIGURE 4.37 (Continued)

Important Things to Know about Bipolar Transistors

The current gain of a transistor (h_{FE}) is not a very good parameter to go by. It can vary from, say, 50 to 500 within same transistor group family and varies with changes in collector current, collector-to-emitter voltage, and temperature. Because h_{FE} is somewhat unpredictable, one should avoid building circuits that depend specifically on h_{FE} values.

All transistors have maximum collector-current ratings ($I_{C,max}$), maximum collector-to-base (BV_{CBO}), collector-to-emitter (BV_{CEO}), and emitter-to-base (V_{EB}) breakdown voltages, and maximum collector power dissipation (P_D) ratings. If these ratings are exceeded, the transistor may get zapped. One method to safeguard against BV_{EB} is to place a diode from the emitter to the base, as shown in Fig. 4.38a. The diode prevents emitter-to-base conduction whenever the emitter becomes more positive than the base (e.g., input at base swings negative while emitter is grounded). To avoid exceeding BV_{CBO} , a diode placed in series with the collector (Fig. 4.38b) can be used to prevent collector-base conduction from occurring when the base voltage becomes excessively larger than the collector voltage. To prevent exceeding BV_{CEO} , which may be an issue if the collector holds an inductive load, a diode placed in parallel with the

load (see Fig. 4.38c) will go into conduction before a collector-voltage spike, created by the inductive load, reaches the breakdown voltage.

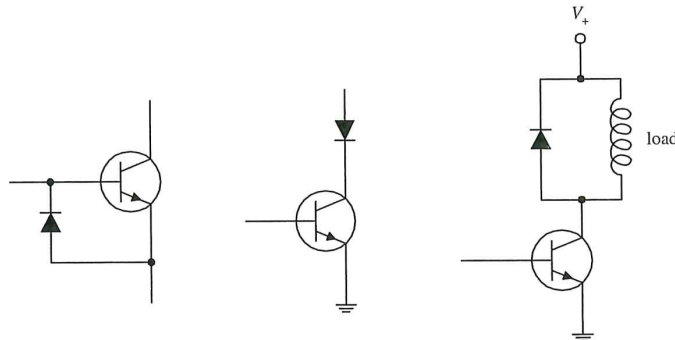


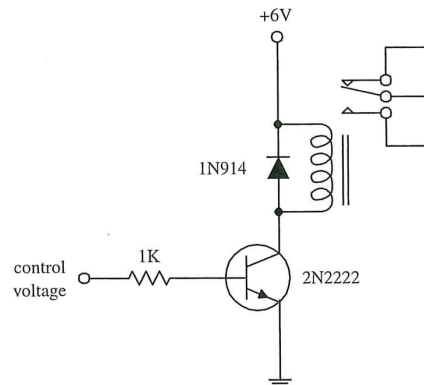
FIGURE 4.38

Pinouts for Bipolar Transistors

Bipolar transistors come in a variety of different package types. Some transistors come with plastic housings; others come with metal can-like housings. When attempting to isolate the leads that correspond to the base, emitter, and collector terminals, first check to see if the package that housed the transistor has a pinout diagram. If no pinout diagram is provided, a good cross-reference catalog (e.g., NTE Cross-Reference Catalog for Semiconductors) can be used. However, as is often the case, simple switching transistors that come in bulk cannot be “looked up”—they may not have a label. Also, these bulk suppliers often will throw together a bunch of transistors that all look alike but may have entirely different pinout designations and may include both *npn* and *npn* polarities. If you anticipate using transistors often, it may be in your best interest to purchase a digital multimeter that comes with a transistor tester. These multimeters are relatively inexpensive and are easy to use. Such a meter comes with a number of breadboard-like slots. To test a transistor, the pins of the transistor are placed into the slots. By simply pressing a button, the multimeter then tests the transistor and displays whether the device is an *npn* or *npn* transistor, provides you with the pinout designations (e.g., “ebc,” “cbe,” etc.), and will give you the transistor’s h_{FE} .

Applications

RELAY DRIVER



Here, an *npn* transistor is used to control a relay. When the transistor’s base receives a control voltage/current, the transistor will turn on, allowing current to flow through the relay coil and causing the relay to switch states. The diode is used to eliminate voltage spikes created by the relay’s coil. The relay must be chosen according to the proper voltage rating, etc.

FIGURE 4.39

DIFFERENTIAL AMPLIFIER

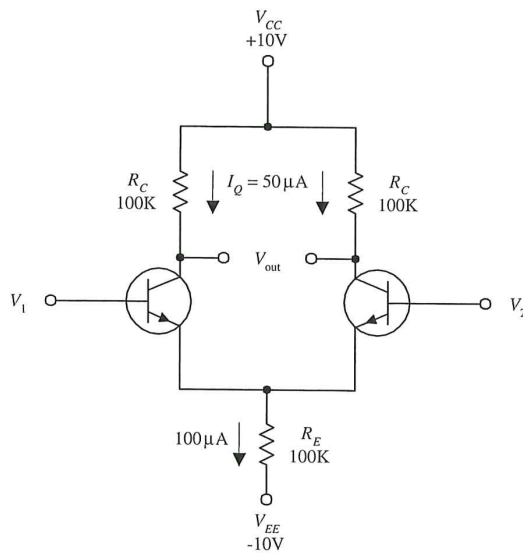


FIGURE 4.40

The differential amplifier shown here is a device that compares two separate input signals, takes the difference between them, and then amplifies this difference. To understand how the circuit works, treat both transistors as identical, and then notice that both transistors are set in the common-emitter configuration. Now, if you apply identical input signals to both V_1 and V_2 , identical currents flow through each transistor. This means that (by using $V_C = V_{CC} - I_C R_C$) both transistors' collector voltages are the same. Since the output terminals are simply the left and right transistors' collector voltages, the output voltage (potential difference) is zero. Now, assume the signals applied to the inputs are different, say V_1 is larger than V_2 . In this case, the current flow through the right transistor will be larger than the current flow through the left transistor. This means that right transistor's V_C will decrease relative to the left transistor's V_C . Because the transistors are set in the common-emitter configuration, the effect is amplified. The relationship between the input and output voltages is given by

$$V_{out} \approx \frac{R_C}{r_{tr}}(V_1 - V_2)$$

Rearranging this expression, you find that the gain is equal to R_C/r_{tr} .

Understanding what resistor values to choose can be explained by examining the circuit shown here. First, choose R_C to center V_C to $\frac{1}{2}V_{CC}$, or 5 V, to maximize the dynamic range. At the same time, you must choose a quiescent current (when no signals are applied), say, $I_Q = I_C = 50 \mu\text{A}$. By Ohm's law $R_C = 10 \text{ V} - 5 \text{ V} / 50 \mu\text{A} = 100 \text{ k}$. R_E is chosen to set the transistor's emitters (point A) as close to 0 V as possible. R_E is found by adding both the right and left branch's $50 \mu\text{A}$ and taking the sum to be the current flow through it, which is $100 \mu\text{A}$. Now, apply Ohm's law: $R_E = 0 \text{ V} - 10 \text{ V} / 100 \mu\text{A} = 100 \text{ k}\Omega$. Next, find the transresistance: $r_{tr} \approx 0.026 \text{ V} / I_E = 0.026 \text{ V} / 50 \mu\text{A} = 520 \Omega$. The gain then is equal to $100 \text{ k}\Omega / 520 \Omega = 192$.

In terms of applications, differential amplifiers can be used to extract a signal that has become weak and which has picked up considerable noise during transmission through a cable (differential amplifier is placed at the receiving end). Unlike a filter circuit, which can only extract a signal from noise if the noise frequency and signal frequency are different, a differential amplifier does not require this condition. The only requirement is that the noise be common in both wires.

When dealing with differential amplifiers, the term *common-mode rejection ratio* (CMRR) is frequently used to describe the quality of the amplifier. A good differential amplifier has a high CMRR (theoretically infinite). CMRR is the ratio of the voltage that must be applied at the two inputs in parallel (V_1 and V_2) to the difference voltage ($V_1 - V_2$) for the output to have the same magnitude.

COMPLEMENTARY-SYMMETRY AMPLIFIER

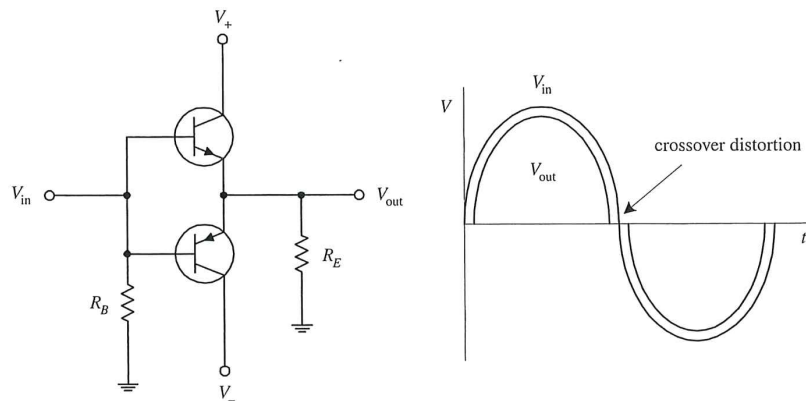


FIGURE 4.41

Recall that an *npn* emitter follower acts to clip the output during negative swings in the input (the transistor turns off when $V_B \leq V_E + 0.6\text{ V}$). Likewise, a *pn*p follower will clip the output during positive input swings. But now, if you combine an *npn* and *pn*p transistor, as shown in the circuit shown here, you get what is called a *push-pull follower*, or *complementary-symmetry amplifier*, an amplifier that provides current gain and that is capable of conducting during both positive and negative input swings. For $V_{in} = 0\text{ V}$, both transistors are biased to cutoff ($I_B = 0$). For $V_{in} > 0\text{ V}$, the upper transistor conducts and behaves like an emitter follower, while the lower transistor is cut off. For $V_{in} < 0\text{ V}$ the lower transistor conducts, while the upper transistor is cut off. In addition to being useful as a dc amplifier, this circuit also conserves power because the operating point for both transistors is near $I_C = 0$. However, at $I_C = 0$, the characteristics of h_{FE} and r_{tr} are not very constant, so the circuit is not very linear for small signals or for near-zero crossing points of large signals (crossover distortion occurs).

CURRENT MIRROR

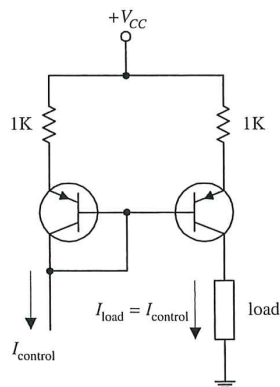


FIGURE 4.42

Here, two matched *pn*p transistors can be used to make what is called a *current mirror*. In this circuit, the load current is a "mirror image" of the control current that is sunk out of the leftmost transistor's collector. Since the same amount of biasing current leaves both transistors' bases, it follows that both transistors' collector-to-emitter currents should be the same. The control current can be set by, say, a resistor connected from the collector to a lower potential. Current mirrors can be made with *npn* transistors, too. However, you must flip this circuit upside down, replace the *pn*p transistors with *npn* transistors, reverse current directions, and swap the supply voltage with ground.

MULTIPLE CURRENT SOURCES

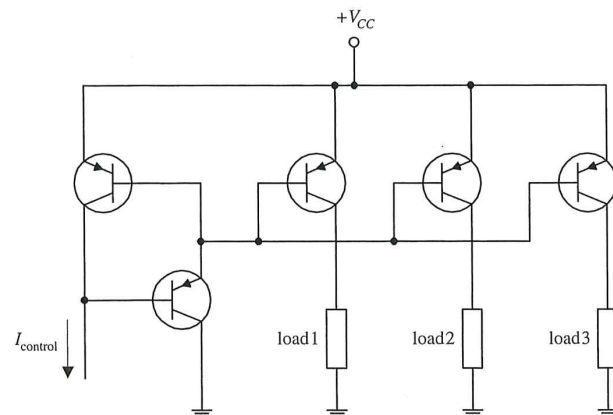


FIGURE 4.43

The circuit here is an expanded version of the previous circuit, which is used to supply a "mirror image" of control current to a number of different loads. (Again, you can design such a circuit with *npn* transistor, too, taking into consideration what was mentioned in the last example.) Note the addition of an extra transistor in the control side of the circuit. This transistor is included to help prevent one transistor that saturates (e.g., its load is removed) from stealing current from the common output base line and hence reducing the other output currents.

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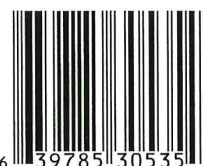
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