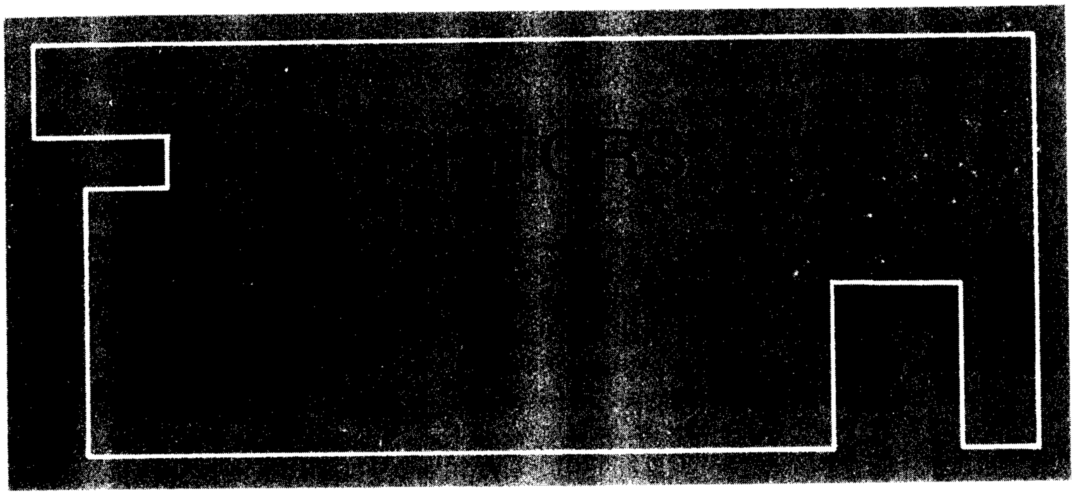
From *The Art of Electronics* (Second Edition)
by Horowitz + Hill.



INTRODUCTION

The transistor is our most important example of an "active" component, a device that can amplify, producing an output signal with more power in it than the input signal. The additional power comes from an external source of power (the power supply, to be exact). Note that voltage amplification isn't what matters, since, for example, a step-up transformer, a "passive" component just like a resistor or capacitor, has voltage gain but no power gain. Devices with power gain are distinguishable by their ability to make oscillators, by feeding some output signal back into the input.

It is interesting to note that the property of power amplification seemed very important to the inventors of the transistor. Almost the first thing they did to convince themselves that they had really invented something was to power a loudspeaker from a transistor, observing that the output signal sounded louder than the input signal.

The transistor is the essential ingredient of every electronic circuit, from the simplest amplifier or oscillator to the most elaborate digital computer. Integrated circuits (ICs), which have largely replaced circuits constructed from discrete transistors, are themselves merely arrays of transistors and other components built from a single chip of semiconductor material.

A good understanding of transistors is very important, even if most of your circuits are made from ICs, because you need to understand the input and output properties of the IC in order to connect it to the rest of your circuit and to the outside world. In addition, the transistor is the single most powerful resource for interfacing, whether between ICs and other circuitry or between one subcircuit and another. Finally, there are frequent (some might say too frequent) situations where the right IC just doesn't exist, and you have to rely on discrete transistor circuitry to do the job. As you will see, transistors have an excitement all their own. Learning how they work can be great fun.

Our treatment of transistors is going to be quite different from that of many other books. It is common practice to use the *h*-parameter model and equivalent circuit. In our opinion that is unnecessarily complicated and unintuitive. Not only does circuit behavior tend to be revealed to you as something that drops out of elaborate equations, rather than deriving from a clear understanding in your own mind as to how the circuit functions; you also have the tendency to lose sight of which parameters of transistor behavior you can count on and, more important, which ones can vary over large ranges.

In this chapter we will build up instead a very simple introductory transistor model and immediately work out some circuits with it. Soon its limitations will become apparent; then we will expand the model to include the respected Ebers-Moll conventions. With the Ebers-Moll equations and a simple 3-terminal model, you will have a good understanding of transistors; you won't need to do a lot of calculations, and your designs will be first-rate. In particular, they will be largely independent of the poorly controlled transistor parameters such as current gain.

Some important engineering notation should be mentioned. Voltage at a transistor terminal (relative to ground) is indicated by a single subscript (C, B, or E): V_C is the collector voltage, for instance. Voltage between two terminals is indicated by a double subscript: V_{BE} is the base-to-emitter voltage drop, for instance. If the same letter is repeated, that means a power-supply voltage: V_{CC} is the (positive) power-supply voltage associated with the collector, and V_{EE} is the (negative) supply voltage associated with the emitter.

2.01 First transistor model: current amplifier

Let's begin. A transistor is a 3-terminal device (Fig. 2.1) available in 2 flavors (*npn* and *pnp*), with properties that meet the following rules for *npn* transistors (for *pnp* simply reverse all polarities):

1. The collector must be more positive than the emitter.

2. The base-emitter and base-collector circuits behave like diodes (Fig. 2.2). Normally the base-emitter diode is conducting and the base-collector diode is reverse-biased, i.e., the applied voltage is in the opposite direction to easy current flow.

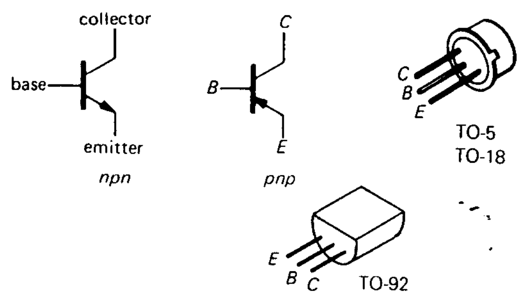


Figure 2.1. Transistor symbols, and small transistor packages.

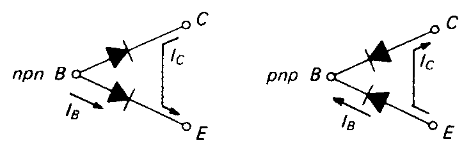


Figure 2.2. An ohmmeter's view of a transistor's terminals.

3. Any given transistor has maximum values of I_C, I_B, and V_{CE} that cannot be exceeded without costing the exceeder the price of a new transistor (for typical values, see Table 2.1). There are also other limits, such as power dissipation ($I_C V_{CE}$), temperature, V_{BE}, etc., that you must keep in mind.

4. When rules 1–3 are obeyed, I_C is roughly proportional to I_B and can be written as

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

where h_{FE}, the current gain (also called beta), is typically about 100. Both I_C and I_E flow to the emitter. Note: The collector current is not due to forward conduction of the base-collector diode;

that diode is reverse-biased. Just think of it as "transistor action."

Property 4 gives the transistor its usefulness: A small current flowing into the base controls a much larger current flowing into the collector.

Warning: h_{FE} is not a "good" transistor parameter; for instance, its value can vary from 50 to 250 for different specimens of a given transistor type. It also depends upon the collector current, collector-to-emitter voltage, and temperature. *A circuit that depends on a particular value for h_{FE} is a bad circuit.*

Note particularly the effect of property 2. This means you can't go sticking a voltage across the base-emitter terminals, because an enormous current will flow if the base is more positive than the emitter by more than about 0.6 to 0.8 volt (forward diode drop). This rule also implies that an operating transistor has $V_B \approx V_E + 0.6$ volt ($V_B = V_E + V_{BE}$). Again, polarities are normally given for *npn* transistors; reverse them for *pnp*.

Let us emphasize again that you should not try to think of the collector current as diode conduction. It isn't, because the collector-base diode normally has voltages applied across it in the reverse direction. Furthermore, collector current varies very little with collector voltage (it behaves like a not-too-great current source), unlike forward diode conduction, where the current rises very rapidly with applied voltage.

SOME BASIC TRANSISTOR CIRCUITS

2.02 Transistor switch

Look at the circuit in Figure 2.3. This application, in which a small control current enables a much larger current to flow in another circuit, is called a transistor switch. From the preceding rules it is easy to understand. When the mechanical switch is open, there is no base current. So, from rule 4, there is no collector current. The lamp is off.

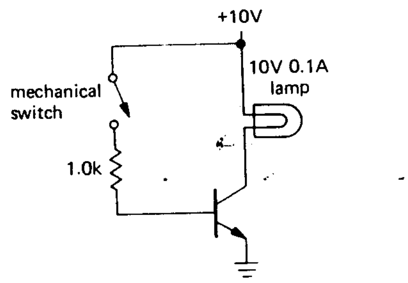


Figure 2.3. Transistor switch example.

When the switch is closed, the base rises to 0.6 volt (base-emitter diode is in forward conduction). The drop across the base resistor is 9.4 volts, so the base current is 9.4mA. Blind application of rule 4 gives I_C = 940mA (for a typical beta of 100). That is wrong. Why? Because rule 4 holds only if rule 1 is obeyed; at a collector current of 100mA the lamp has 10 volts across it. To get a higher current you would have to pull the collector below ground. A transistor can't do this, and the result is what's called saturation – the collector goes as close to ground as it can (typical saturation voltages are about 0.05–0.2V, see Appendix G) and stays there. In this case, the lamp goes on, with its rated 10 volts across it.

Overdriving the base (we used 9.4mA when 1.0mA would have barely sufficed) makes the circuit conservative; in this particular case it is a good idea, since a lamp draws more current when cold (the resistance of a lamp when cold is 5 to 10 times lower than its resistance at operating current). Also transistor beta drops at low collector-to-base voltages, so some extra base current is necessary to bring a transistor into full saturation (see Appendix G). Incidentally, in a real circuit you would probably put a resistor from base to ground (perhaps 10k in this case) to make sure the base is at ground with the switch open. It wouldn't affect the "on" operation, because it would sink only 0.06mA from the base circuit.

There are certain cautions to be observed when designing transistor switches: *1.* Choose the base resistor conservatively to get plenty of excess base current, especially when driving lamps, because of the reduced beta at low V_{CE}. This is also a good idea for high-speed switching, because of capacitive effects and reduced beta at very high frequencies (many megahertz). A small "speedup" capacitor is often connected across the base resistor to improve high-speed performance.
2. If the load swings below ground for some reason (e.g., it is driven from ac, or it is inductive), use a diode in series with the collector (or a diode in the reverse direction to ground) to prevent collector-base conduction on negative swings.
3. For inductive loads, protect the transistor with a diode across the load, as shown in Figure 2.4. Without the diode the inductor will swing the collector to a large positive voltage when the switch is opened, most likely exceeding the collector-emitter breakdown voltage, as the inductor tries to maintain its "on" current from V_{CC} to the collector (see the discussion of inductors in Section 1.31).

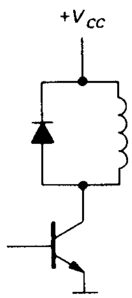


Figure 2.4. Always use a suppression diode when switching an inductive load.

Transistor switches enable you to switch very rapidly, typically in a small fraction of a microsecond. Also, you can switch many different circuits with a single control signal. One further advantage is the possibility of remote *cold switching,* in which only dc control voltages snake around through cables to reach front-panel switches, rather than the electronically inferior approach of having the signals themselves traveling through cables and switches (if you run lots of signals through cables, you're likely to get capacitive pickup as well as some signal degradation).

"Transistor man"

Figure 2.5 presents a cartoon that will help you understand some limits of transistor

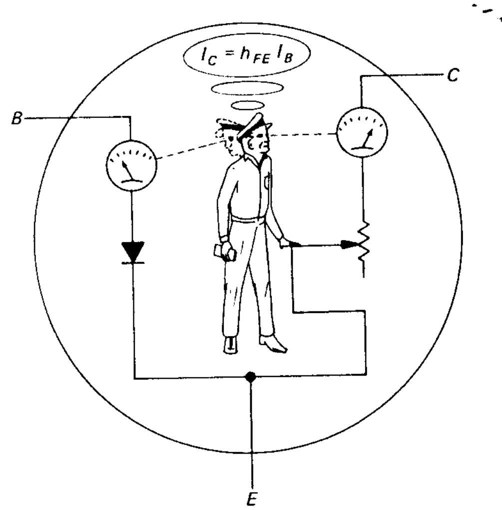


Figure 2.5. "Transistor man" observes the base current, and adjusts the output rheostat in an attempt to maintain the output current h_{FE} times larger.

behavior. The little man's perpetual task in life is to try to keep $I_C = h_{FE}I_B$; however, he is only allowed to turn the knob on the variable resistor. Thus he can go from a short circuit (saturation) to an open circuit (transistor in the "off" state), or anything in between, but he isn't allowed to use batteries, current sources, etc. One warning is in order here: Don't think that the collector of a transistor looks like a resistor. It doesn't. Rather, it looks approximately like a poor-quality constant-current sink (the value of current depending on the signal applied to the base), primarily because of this little man's efforts.

Another thing to keep in mind is that, at any given time, a transistor may be (a) cut off (no collector current), (b) in the active region (some collector current, and collector voltage more than a few tenths of a volt above the emitter), or (c) in saturation (collector within a few tenths of a volt of the emitter). See Appendix G on transistor saturation for more details.

2.03 Emitter follower

Figure 2.6 shows an example of an *emitter follower*. It is called that because the output terminal is the emitter, which follows the input (the base), less one diode drop:

$V_E \approx V_B - 0.6$ volt

The output is a replica of the input, but 0.6 to 0.7 volt less positive. For this circuit, V_{in} must stay at +0.6 volt or more, or else the output will sit at ground. By returning the emitter resistor to a negative supply voltage, you can permit negative voltage swings as well. Note that there is no collector resistor in an emitter follower.

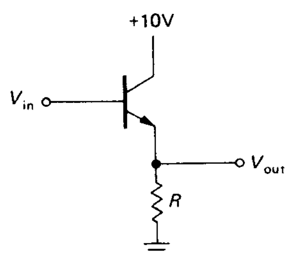


Figure 2.6. Emitter follower.

At first glance this circuit may appear useless, until you realize that the input impedance is much larger than the output impedance, as will be demonstrated shortly. This means that the circuit requires less power from the signal source to drive a given load than would be the case if the signal source were to drive the load directly. Or a signal of some internal impedance (in the Thévenin sense) can now drive a load of comparable or even lower impedance without loss of amplitude (from the usual voltage-divider effect). In other words, an emitter follower has current gain, even though it has no voltage gain. It has power gain. Voltage gain isn't everything!

Impedances of sources and loads

This last point is very important and is worth some more discussion before we calculate in detail the beneficial effects of emitter followers. In electronic circuits, you're always hooking the output of something to the input of something else, as suggested in Figure 2.7. The signal source might be the output of an amplifier stage (with Thévenin equivalent series impedance $\mathbf{Z}_{out}$), driving the next stage or perhaps a load (of some input impedance $\mathbf{Z}_{in}$). In general, the loading effect of the following stage causes a reduction of signal, as we discussed earlier in Section 1.05. For this reason it is usually best to keep $Z_{out} \ll Z_{in}$ (a factor of 10 is a comfortable rule of thumb).

In some situations it is OK to forgo this general goal of making the source stiff compared with the load. In particular, if the load is always connected (e.g., within a circuit) and if it presents a known and constant $\mathbf{Z}_{in}$, it is not too serious if it "loads" the source. However, it is always nicer if signal levels don't change when a load is connected. Also, if $\mathbf{Z}_{in}$ varies with signal level, then having a stiff source ($Z_{out} \ll Z_{in}$) assures linearity, where otherwise the level-dependent voltage divider would cause distortion.

Finally, there are two situations where $Z_{out} \ll Z_{in}$ is actually the wrong thing to

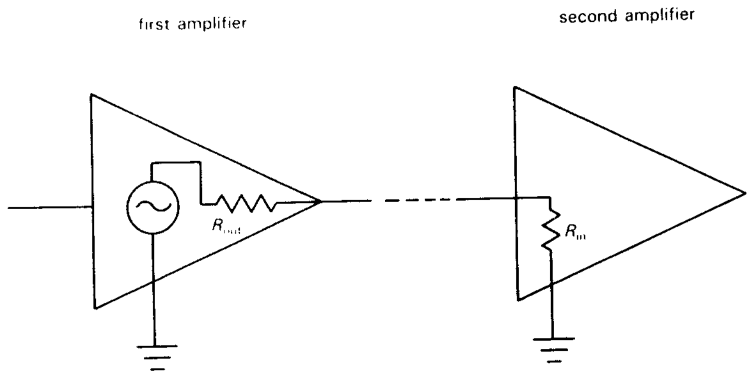


Figure 2.7. Illustrating circuit "loading" as a voltage divider.

do: In radiofrequency circuits we usually *match* impedances ($Z_{out} = Z_{in}$), for reasons we'll describe in Chapter 14. A second exception applies if the signal being coupled is a *current* rather than a voltage. In that case the situation is reversed, and one strives to make $Z_{in} \ll Z_{out}$ ($Z_{out} = \infty$, for a current source).

Input and output impedances of emitter followers

As you have just seen, the emitter follower is useful for changing impedances of signals or loads. To put it bluntly, that's the whole point of an emitter follower.

Let's calculate the input and output impedances of the emitter follower. In the preceding circuit we will consider R to be the load (in practice it sometimes is the load; otherwise the load is in parallel with R, but with R dominating the parallel resistance anyway). Make a voltage change ΔV_B at the base; the corresponding change at the emitter is $\Delta V_E = \Delta V_B$. Then the change in emitter current is

$$\Delta I_E = \Delta V_B / R$$

so

$$\Delta I_B = \frac{1}{h_{fe}+1}\Delta I_E = \frac{\Delta V_B}{R(h_{fe}+1)}$$

(using $I_E = I_C + I_B$). The input resistance is $\Delta V_B / \Delta I_B$. Therefore

$$r_{in} = (h_{fe}+1)R$$

The transistor beta (h_{fe}) is typically about 100, so a low-impedance load looks like a much higher impedance at the base; it is easier to drive.

In the preceding calculation, as in Chapter 1, we have used lower-case symbols such as h_{fe} to signify small-signal (incremental) quantities. Frequently one concentrates on the *changes* in voltages (or currents) in a circuit, rather than the steady (dc) values of those voltages (or currents). This is most common when these "small-signal" variations represent a possible signal, as in an audio amplifier, riding on a steady dc "bias" (see Section 2.05). The distinction between dc current gain (h_{FE}) and small-signal current gain (h_{fe}) isn't always made clear, and the term beta is used for both. That's alright, since $h_{fe} \approx h_{FE}$ (except at very high frequencies), and you never assume you know them accurately, anyway.

Although we used resistances in the preceding derivation, we could generalize to complex impedances by allowing ΔV_B, ΔI_B, etc., to become complex numbers. We would find that the same transformation rule applies for impedances: $Z_{in} = (h_{fe} + 1)Z_{load}$.

We could do a similar calculation to find that the output impedance Z_{out} of an emitter follower (the impedance looking into the emitter) driven from a source of internal impedance Z_{source} is given by

$$Z_{out} = \frac{Z_{source}}{h_{fe} + 1}$$

Strictly speaking, the output impedance of the circuit should also include the parallel resistance of R, but in practice Z_{out} (the impedance looking into the emitter) dominates.

EXERCISE 2.1

Show that the preceding relationship is correct. Hint: Hold the source voltage fixed, and find the change in output current for a given change in output voltage. Remember that the source voltage is connected to the base through a series resistor.

Because of these nice properties, emitter followers find application in many situations, e.g., making low-impedance signal sources within a circuit (or at outputs), making stiff voltage references from higher-impedance references (formed from voltage dividers, say), and generally isolating signal sources from the loading effects of subsequent stages.

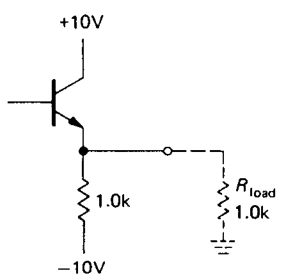


Figure 2.8. An *npn* emitter follower can source plenty of current through the transistor, but can sink limited current only through its emitter resistor.

EXERCISE 2.2

Use a follower with base driven from a voltage divider to provide a stiff source of +5 volts from an available regulated +15 volt supply. Load current (max) = 25mA. Choose your resistor values so that the output voltage doesn't drop more than 5% under full load.

Important points about followers

1. Notice (Section 2.01, rule 4) that in an emitter follower the *npn* transistor can only "source" current. For instance, in the loaded circuit shown in Figure 2.8 the output can swing to within a transistor saturation voltage drop of V_{CC} (about +9.9V), but it cannot go more negative than −5 volts. That is because on the extreme negative swing, the transistor can do no more than turn off, which it does at −4.4 volts input (−5V output). Further negative swing at the input results in backbiasing of the base-emitter junction, but no further change in output. The output, for a 10 volt amplitude sine-wave input, looks as shown in Figure 2.9.

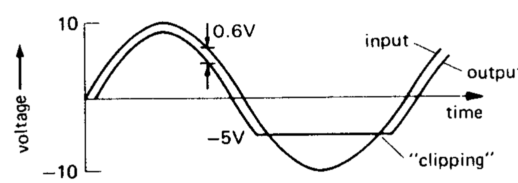


Figure 2.9. Illustrating the asymmetrical current drive capability of the *npn* emitter follower.

Another way to view the problem is to say that the emitter follower has low small-signal output impedance. Its large-signal output impedance is much larger (as large as R_E). The output impedance changes over from its small-signal value to its large-signal value at the point where the transistor goes out of the active region (in this case at an output voltage of -5V). To put this point another way, a low value of small-signal output impedance doesn't necessarily mean that the circuit can generate large signal swings into a low-resistance load. Low small-signal output impedance doesn't imply large output current capability.

Possible solutions to this problem involve either decreasing the value of the emitter resistor (with greater power dissipation in resistor and transistor), using a *pnp* transistor (if all signals are negative only), or using a "push-pull" configuration, in which two complementary transistors (one *npn*, one *pnp*), are used (Section 2.15). This sort of problem can also come up when the load of an emitter follower contains voltage or current sources of its own. This happens most often with regulated power supplies (the output is usually an emitter follower) driving a circuit that has other power supplies.

2. Always remember that the base-emitter reverse breakdown voltage for silicon transistors is small, quite often as little as 6 volts. Input swings large enough to take the transistor out of conduction can easily result in breakdown (with consequent degradation of h_{FE}) unless a protective diode is added (Fig. 2.10).

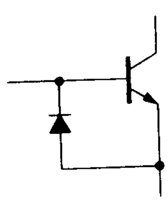


Figure 2.10. A diode prevents base-emitter reverse voltage breakdown.

3. The voltage gain of an emitter follower is actually slightly less than 1.0, because the base-emitter voltage drop is not really constant, but depends slightly on collector current. You will see how to handle that later in the chapter, when we have the Ebers-Moll equation.

2.04 Emitter followers as voltage regulators

The simplest regulated supply of voltage is simply a zener (Fig. 2.11). Some current must flow through the zener, so you choose

$$\frac{V_{in} - V_{out}}{R} > I_{out}\,(\max)$$

Because V_{in} isn't regulated, you use the lowest value of V_{in} that might occur for this formula. This is called worst-case design. In practice, you would also worry about component tolerances, line-voltage limits, etc., designing to accommodate the worst possible combination that would ever occur.

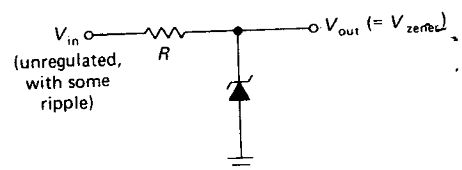


Figure 2.11. Simple zener voltage regulator.

The zener must be able to dissipate

$$P_{zener} = \left(\frac{V_{in} - V_{out}}{R} - I_{out}\right) V_{zener}$$

Again, for worst-case design, you would use V_{in} (max), R_{min}, and I_{out} (min).

EXERCISE 2.3

Design a +10 volt regulated supply for load currents from 0 to 100mA; the input voltage is +20 to +25 volts. Allow at least 10mA zener current under all (worst-case) conditions. What power rating must the zener have?

This simple zener-regulated supply is sometimes used for noncritical circuits, or circuits using little supply current. However, it has limited usefulness, for several reasons:

1. V_{out} isn't adjustable, or settable to a precise value.

2. Zener diodes give only moderate ripple rejection and regulation against changes of

input or load, owing to their finite dynamic impedance.

3. For widely varying load currents a high-power zener is often necessary to handle the dissipation at low load current.

By using an emitter follower to isolate the zener, you get the improved circuit shown in Figure 2.12. Now the situation is much better. Zener current can be made relatively independent of load current, since the transistor base current is small, and far lower zener power dissipation is possible (reduced by as much as $1/h_{FE}$). The collector resistor R_C can be added to protect the transistor from momentary output short circuits by limiting the current, even though it is not essential to the emitter follower function. Choose R_C so that the voltage drop across it is less than the drop across R for the highest normal load current.

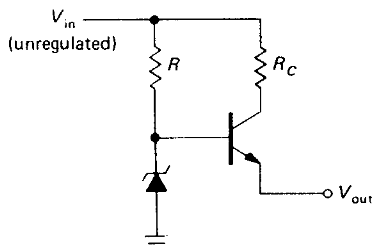


Figure 2.12. Zener regulator with follower, for increased output current. R_C protects the transistor by limiting maximum output current.

EXERCISE 2.4

Design a +10 volt supply with the same specifications as in Exercise 2.3. Use a zener and emitter follower. Calculate worst-case dissipation in transistor and zener. What is the percentage change in zener current from the no-load condition to full load? Compare with your previous circuit.

A nice variation of this circuit aims to eliminate the effect of ripple current (through R) on the zener voltage by supplying the zener current from a current source, which is the subject of Section 2.06. An alternative method uses a low-pass filter in the zener bias circuit (Fig. 2.13). R is chosen to provide sufficient zener current. Then C is chosen large enough so that $RC \gg 1/f_{\text{ripple}}$. (In a variation of this circuit, the upper resistor is replaced by a diode.)

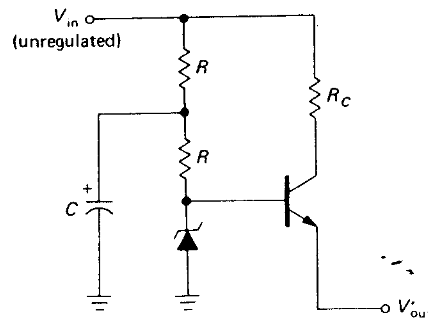


Figure 2.13. Reducing ripple in the zener regulator.

Later you will see better voltage regulators, ones in which you can vary the output easily and continuously, using feedback. They are also better voltage sources, with output impedances measured in milliohms, temperature coefficients of a few parts per million per degree centigrade, etc.

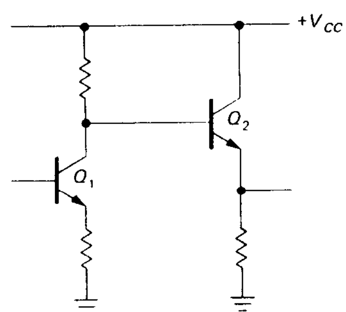


Figure 2.14

2.05 Emitter follower biasing

When an emitter follower is driven from a preceding stage in a circuit, it is usually OK to connect its base directly to the previous stage's output, as shown in Figure 2.14.

Because the signal on Q_1's collector is always within the range of the power supplies, Q_2's base will be between V_{CC} and ground, and therefore Q_2 is in the active region (neither cut off nor saturated), with its base-emitter diode in conduction and its collector at least a few tenths of a volt more positive than its emitter. Sometimes, though, the input to a follower may not be so conveniently situated with respect to the supply voltages. A typical example is a capacitively coupled (or ac-coupled) signal from some external source (e.g., an audio signal input to a high-fidelity amplifier). In that case the signal's average voltage is zero, and direct coupling to an emitter follower will give an output like that in Figure 2.15.

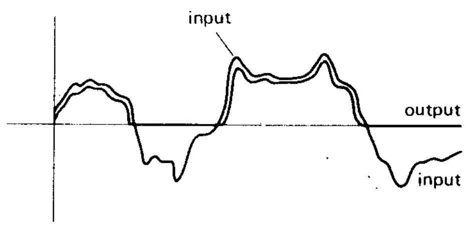


Figure 2.15. A transistor amplifier powered from a single positive supply cannot generate negative voltage swings at the transistor output terminal.

It is necessary to *bias* the follower (in fact, any transistor amplifier) so that collector current flows during the entire signal swing. In this case a voltage divider is the simplest way (Fig. 2.16). R_1 and R_2 are chosen to put the base halfway between ground and V_{CC} with no input signal, i.e., R_1 and R_2 are approximately equal. The process of selecting the operating voltages in a circuit, in the absence of applied signals, is known as setting the *quiescent point*. In this case, as in most cases, the quiescent point is chosen to allow maximum symmetrical signal swing of the output waveform without *clipping* (flattening of the top or bottom of the waveform). What values should R_1 and R_2 have? Applying our general principle (Section 1.05), we make the impedance of the dc bias source (the impedance looking into the voltage divider) small compared with the load it drives (the dc impedance looking into the base of the follower). In this case,

$$R_1 \| R_2 \ll h_{FE} R_E$$

This is approximately equivalent to saying that the current flowing in the voltage divider should be large compared with the current drawn by the base.

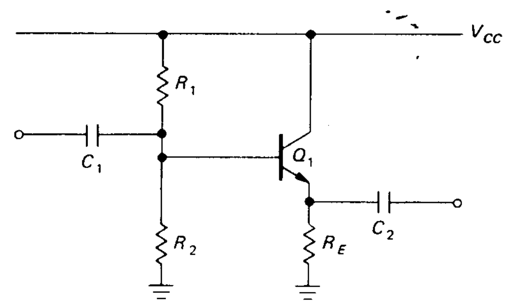


Figure 2.16. An ac-coupled emitter follower. Note base bias voltage divider.

Emitter follower design example

As an actual design example, let's make an emitter follower for audio signals (20Hz to 20kHz). V_{CC} is +15 volts, and quiescent current is to be 1mA.

Step 1. Choose V_E. For the largest possible symmetrical swing without clipping, $V_E = 0.5V_{CC}$, or +7.5 volts.

Step 2. Choose R_E. For a quiescent current of 1mA, R_E = 7.5k.

Step 3. Choose R_1 and R_2. V_B is V_E+ 0.6, or 8.1 volts. This determines the ratio of R_1 to R_2 as 1:1.17. The preceding loading criterion requires that the parallel resistance of R_1 and R_2 be about 75k or less (one-tenth of 7.5k times h_{FE}).

Suitable standard values are $R_1 = 130\text{k}$, $R_2 = 150\text{k}$.

Step 4. Choose C_1. C_1 forms a high-pass filter with the impedance it sees as a load, namely the impedance looking into the base in parallel with the impedance looking into the base voltage divider. If we assume that the load this circuit will drive is large compared with the emitter resistor, then the impedance looking into the base is $h_{FE}R_E$, about 750k. The divider looks like 70k. So the capacitor sees a load of about 63k, and it should have a value of at least $0.15\mu\text{F}$ so that the 3dB point will be below the lowest frequency of interest, 20Hz.

Step 5. Choose C_2. C_2 forms a high-pass filter in combination with the load impedance, which is unknown. However, it is safe to assume that the load impedance won't be smaller than R_E, which gives a value for C_2 of at least $1.0\mu\text{F}$ to put the 3dB point below 20Hz. Because there are now two cascaded high-pass filter sections, the capacitor values should be increased somewhat to prevent large attenuation (reduction of signal amplitude, in this case 6dB) at the lowest frequency of interest. $C_1 = 0.5\mu\text{F}$ and $C_2 = 3.3\mu\text{F}$ might be good choices.

Followers with split supplies

Because signals often are "near ground," it is convenient to use symmetrical positive and negative supplies. This simplifies biasing and eliminates coupling capacitors (Fig. 2.17).

Warning: You must always provide a dc path for base bias current, even if it goes only to ground. In the preceding circuit it is assumed that the signal source has a dc path to ground. If not (e.g., if the signal is capacitively coupled), you must provide a resistor to ground (Fig. 2.18). R_B could be about one-tenth of $h_{FE}R_E$, as before.

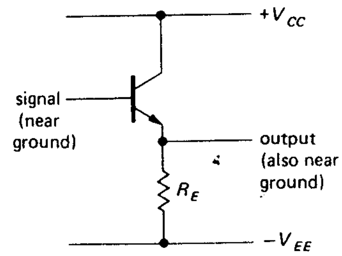


Figure 2.17. A dc-coupled emitter follower with split supply.

EXERCISE 2.5

Design an emitter follower with ±15 volt supplies to operate over the audio range (20Hz–20kHz). Use 5mA quiescent current and capacitive input coupling.

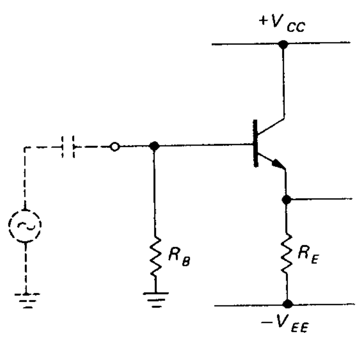


Figure 2.18

Bad biasing

Unfortunately, you sometimes see circuits like the disaster shown in Figure 2.19. R_B was chosen by assuming a particular value for h_{FE} (100), estimating the base current, and then hoping for a 7 volt drop across R_B. This is a bad design; h_{FE} is not a good parameter and will vary considerably. By using voltage biasing with a stiff voltage divider, as in the detailed example presented earlier, the quiescent point is insensitive to variations in transistor beta. For instance, in the previous design example the emitter voltage will increase by only 0.35 volt (5%) for a transistor with $h_{FE} = 200$ instead of the nominal