# BIPOLAR TRANSISTORS

CHAPTER 2

## 2.1 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.[1] 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 in which 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.

There are two major species of transistors: in this chapter we will learn about bipolar junction transistors (BJTs), which historically came first with their Nobel Prize-winning invention in 1947 at Bell Laboratories. The next chapter deals with "field-effect" transistors (FETs), the now-dominant species in digital electronics. To give the coarsest comparison, BJTs excel in accuracy and low noise, whereas FETs excel in low power, high impedance, and high-current switching; there is, of course, much more to this complex subject.

Our treatment of bipolar 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 instead build up a very simple introductory transistor model and immediately work out some circuits with it. Its limitations will soon become apparent; then we will expand the model to include the respected Ebers–Moll conventions. With the Ebers–Moll equations and a simple three-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,

[1] It is even possible to achieve modest voltage gain in a circuit comprising only resistors and capacitors. To explore this idea, surprising even to seasoned engineers, look at Appendix J on SPICE.

and $V_{EE}$ is the (negative) supply voltage associated with the emitter.[2]

Why transistor circuits are difficult

For those learning electronics for the first time, this chapter will be difficult. Here's why: all the circuits in the last chapter dealt with *two-terminal devices*, whether linear (resistors, capacitors, inductors) or nonlinear (diodes). So there was only one voltage (the voltage between the terminals) and only one current (the current flowing through the device) to think about. Transistors, by contrast, are *three-terminal devices*, which means there are two voltages and two currents to juggle.[3]

### 2.1.1 First transistor model: current amplifier

Let's begin. A bipolar transistor is a three-terminal device (Figure 2.1), in which a small current applied to the base controls a much larger current flowing between the collector and emitter. It is available in two flavors (*npn* and *pnp*), with properties that meet the following rules for *npn* transistors (for *pnp* simply reverse all polarities):

1. **Polarity** The collector must be more positive than the emitter.
2. **Junctions** The base–emitter and base–collector circuits behave like diodes (Figure 2.2) in which a small current applied to the base controls a much larger current flowing between the collector and emitter. Normally the base–emitter diode is conducting, whereas the base–collector diode is reverse-biased, i.e., the applied voltage is in the opposite direction to easy current flow.
3. **Maximum ratings** 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 the listing in Table 2.1 on page 74, Table 2.1 on page 106, and Table 8.1 on pages 501–502 There are also other limits, such as power dissipation ($I_C V_{CE}$), temperature, and $V_{BE}$, that you must keep in mind.
4. **Current amplifier** When rules 1–3 are obeyed, $I_C$ is roughly proportional to $I_B$ and can be written as

$$I_C = h_{FE} I_B = \beta I_B, \tag{2.1}$$

where $\beta$, the current gain (sometimes called[4] $h_{FE}$), is typically about 100. Both $I_B$ 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."

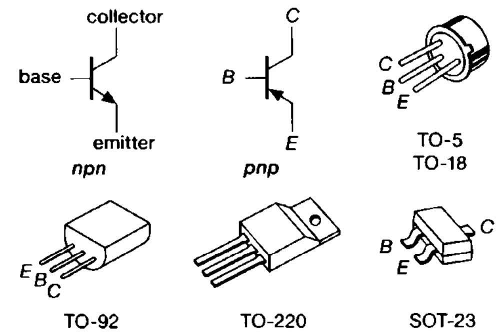


**Figure 2.1.** Transistor symbols and small transistor package drawings (not to scale). A selection of common transistor packages are shown in Figure 2.3.

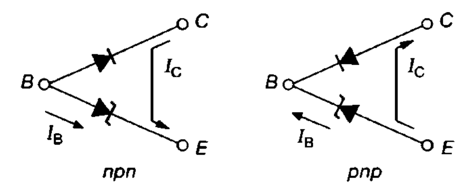


**Figure 2.2.** An ohmmeter's view of a transistor's terminals.

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

An important warning: the current gain $\beta$ 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 on the collector current, collector-to-emitter voltage, and temperature. *A circuit that depends on a particular value for beta is a bad circuit.*

Note particularly the effect of rule 2. This means you can't go sticking sticking an arbitrary 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 V (forward diode drop). This rule also implies that an operating transistor has $V_B \approx V_E + 0.6\,\text{V}$ ($V_B = V_E + V_{BE}$). 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,

[2] In practice, circuit designers use $V_{CC}$ to designate the positive supply and $V_{EE}$ the negative supply, even though logically they should be interchanged for *pnp* transistors (where all polarities are reversed).

[3] You might think that there would be three voltages and three currents; but it's slightly less complicated than that, because there are only two independent voltages and two independent currents, thanks to Kirchhoff's voltage and current laws.

[4] As the "*h*-parameter" transistor model has fallen out of popularity, you tend often to see $\beta$ (instead of $h_{FE}$) as the symbol for current gain.

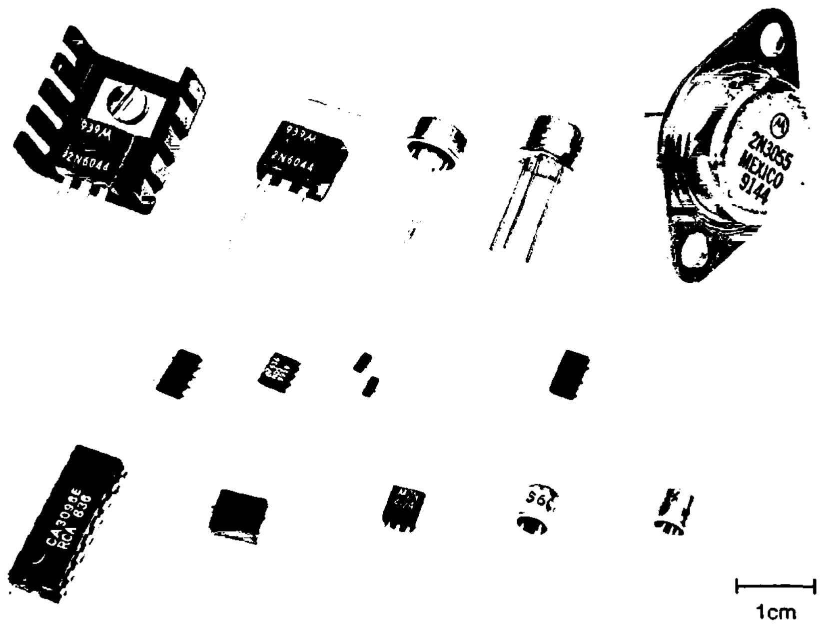


**Figure 2.3.** Most of the common packages are shown here, for which we give the traditional designations. Top row (power), left to right: TO-220 (with and without heatsink), TO-39, TO-5, TO-3. Middle row (surface mount): SM-8 (dual), SO-8 (dual), SOT-23, ceramic SOE, SOT-223. Bottom row: DIP-16 (quad), DIP-4, TO-92, TO-18, TO-18 (dual).

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, in which the current rises very rapidly with applied voltage.

Table 2.1 on the following page includes a selection of commonly used bipolar transistors, with the corresponding curves of current gain[5] in Figure 2.4, and a selection of transistors intended for power applications is listed in Table 2.2 on page 106. A more complete listing can be found in Table 8.1 on pages 501–502 and Figure 8.39 in Chapter 8.

## 2.2 Some basic transistor circuits

### 2.2.1 Transistor switch

Look at the circuit in Figure 2.5. 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.

When the switch is closed, the base rises to 0.6 V (base–emitter diode is in forward conduction). The drop across the base resistor is 9.4 V, so the base current is 9.4 mA. Blind application of Rule 4 gives $I_C = 940\,\text{mA}$ (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 100 mA the lamp has 10 V 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 0.05–0.2 V, see Chapter 2*x*.) and stays there. In this case, the lamp goes on, with its rated 10 V across it.

Overdriving the base (we used 9.4 mA when 1.0 mA 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

[5] In addition to listing typical betas ($h_{FE}$) and maximum allowed collector-to-emitter voltages ($V_{CEO}$), Table 2.1 includes the cutoff frequency ($f_T$, at which the beta has decreased to 1) and the feedback capacitance ($C_{cb}$). These are important when dealing with fast signals or high frequencies; we'll see them in §2.4.5 and Chapter 2*x*.

**Table 2.1 Representative Bipolar Transistors**

| Part # npn TO-92 | npn SOT-23 | pnp TO-92 | pnp SOT-23 | $V_{CEO}$ (V) | $I_C$ (max) (mA) | $h_{FE}$ (typ) | @ mA | gain curve | $C_{cb}$[a] (pF) | $f_T$[a] (MHz) | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2N3904 | MMBT3904 | 2N3906 | MMBT3906 | 40 | 150 | 200 | 10 | 6 | 2.5 | 300 | jellybean |
| 2N4401 | MMBT4401 | 2N4403 | MMBT4403 | 40 | 500 | 150 | 150 | 7 | 7 | 300 | '2222 and '2907 dies |
| BC337 | BC817 | BC327 | BC807 | 45 | 500 | 350 | 40 | 5 | 10 | 150 | jellybean |
| 2N5089 | MMBT5089 | 2N5087 | MMBT5087 | 30 | 50 | 500 | 1 | 3 | 1.8 | 350 | high beta |
| BC547C | BC847C | BC557C | BC857C | 45 | 100 | 500 | 10 | 4 | 5 | 150 | jellybean[b] |
| MPSA14 | MMBTA14 | MPSA64 | MMBTA64 | 30 | 300 | 10000 | 50 | - | 7 | 125 | Darlington |
| ZTX618 | FMMT618 | ZTX718 | FMMT718 | 20 | 2500 | 320 | 3A | 3a | - | 120 | high $I_C$, small pkg |
| PN2369 | MMBT2369 | 2N5771 | MMBT5771 | 15 | 150 | 100 | 10 | 10 | 3 | 500 | fast switch, gold doped |
| 2N5550 | MMBT5550 | 2N5401 | MMBT5401 | 150 | 100 | 100 | 10 | 5a | 2.5 | 100 | SOT-223 available |
| MPSA42 | MMBTA42 | MPSA92 | MMBTA92 | 300 | 30 | 75 | 10 | 9 | 1.5 | 50 | HV small signal |
| MPS5179 | BFS17 | MPSH81 | MMBTH81 | 15 | 25 | 90 | 20 | 8 | 0.9 | 900 | RF amplifier |
| — | BFR93[c] | — | BFT93[c] | 12 | 50 | 50 | 15 | 10 | 0.5 | 4000 | RF amp |
| TIP142 | — | TIP147 | — | 100 | 10A | >1000 | 5A | - | high | low | TO-220, Darlington |

Notes: (a) see Chapter 2x for graphs of $C_{cb}$ and $f_T$. (b) lower beta versions have an -A or -B suffix; low-noise versions are BC850 (*npn*) and BC860 (*pnp*). (c) also BFR25A and BFT25A. (d) see Figure 2.4.

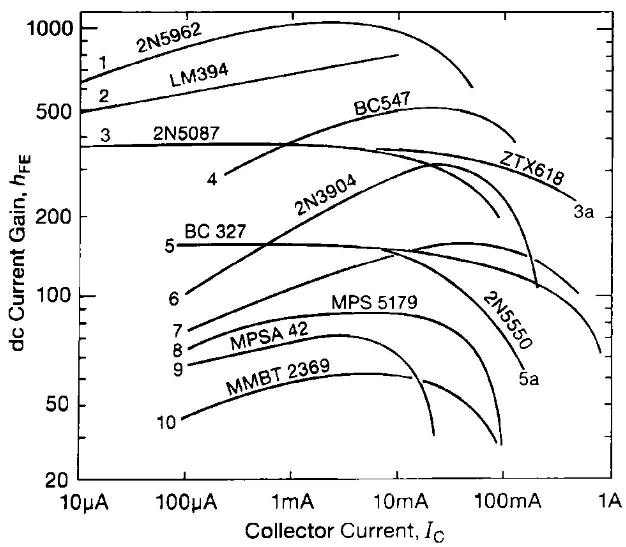


**Figure 2.4.** Curves of typical transistor current gain, $\beta$, for a selection of transistors from Table 2.1. These curves are taken from manufacturers' literature. You can expect production spreads of +100%, −50% from the "typical" values graphed. See also Figure 8.39 for measured beta plots for 44 types of "low-noise" transistors.

a transistor into full saturation. 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 0.06 mA from the base circuit.

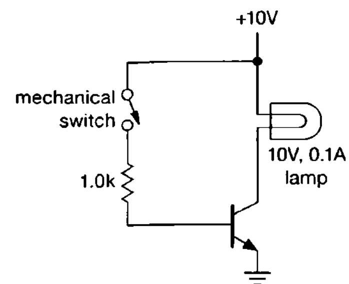


**Figure 2.5.** Transistor switch example.

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).[6]
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

[6] A small "speed-up" capacitor – typically just a few picofarads – is often connected across the base resistor to improve high-speed performance.

across the load, as shown in Figure 2.6.[7] 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 §1.6.7).

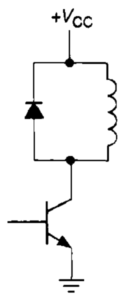


Figure 2.6. Always use a suppression diode when switching an inductive load.

You might ask why we are bothering with a transistor, and all its complexity, when we could just use that mechanical switch alone to control the lamp or other load. There are several good reasons: (a) a transistor switch can be driven *electrically* from some other circuit, for example a computer output bit; (b) transistor switches enable you to switch very rapidly, typically in a small fraction of a microsecond; (c) you can switch many different circuits with a single control signal; (d) mechanical switches suffer from wear, and their contacts "bounce" when the switch is activated, often making and breaking the circuit a few dozen times in the first few milliseconds after activation; and (e) with transistor switches you can take advantage 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).

### A. "Transistor man"

The cartoon in Figure 2.7 may help you understand some limits of transistor behavior. The little man's perpetual task in life is to try to keep $I_C = \beta I_B$; 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.

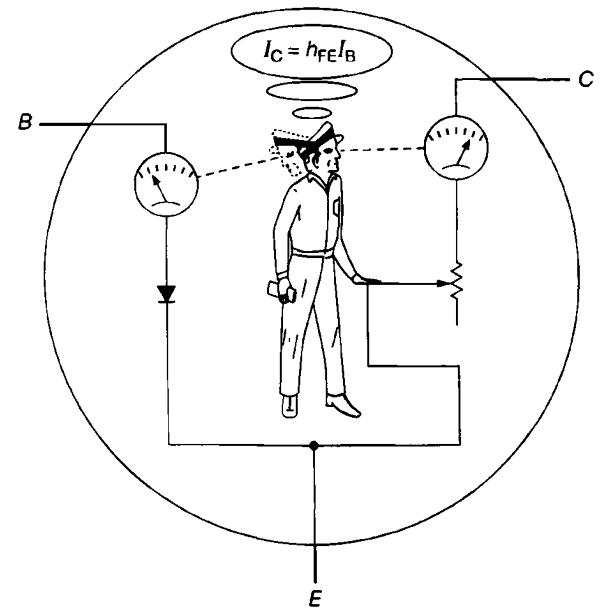


Figure 2.7. "Transistor man" observes the base current, and adjusts the output rheostat in an attempt to maintain the output current $\beta$ times larger.

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 the discussion of transistor saturation in Chapter 2x for more details.

### 2.2.2 Switching circuit examples

The transistor switch is an example of a *nonlinear* circuit: the output is not proportional to the input;[8] instead it goes to one of two possible states (cut off, or saturated). Such two-state circuits are extremely common[9] and form the basis of digital electronics. But to the authors the subject of

[7] Or, for faster turn-off, with a resistor, an $RC$ network, or zener clamp; see §1.6.7.

[8] A mathematician would define linearity by saying that the response to the sum of two inputs is the sum of the individual responses; this necessarily implies proportionality.

[9] If you took a census, asking the transistors of the world what they are doing, at least 95% would tell you they are switches.

*linear* circuits (such as amplifiers, current sources, and integrators) offers the most interesting challenges and the potential for great circuit creativity. We will move on to linear circuits in a moment, but this is a good time to enjoy a few circuit examples with transistors acting as switches – we like to give a feeling for the richness of electronics by showing real-world examples as soon as possible.

### A. LED driver

Light-emitting diode indicators – LEDs – have replaced the incandescent lamps of yesteryear for all electronic indicator and readout applications; they're cheap, they come in lots of colors, and they last just about forever. Electrically they are similar to the ordinary silicon signal diodes we met in Chapter 1, but with a larger forward voltage drop (generally in the range of 1.5–3.5 V, rather than approximately[10] 0.6 V); that is, as you slowly increase the voltage across an LED's terminals, you find that they start conducting current at, say, 1.5 V, and the current increases rapidly as you apply somewhat more voltage (Figure 2.8). They light up, too! Typical "high-efficiency" indicator LEDs look pretty good at a few milliamps, and they'll knock your eye out at 10–20 mA.

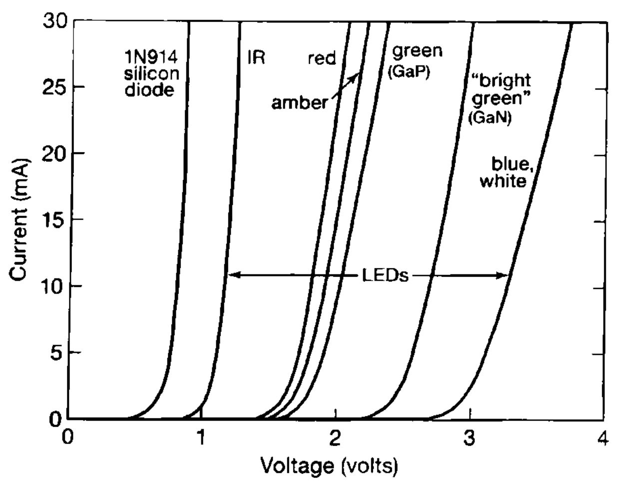


**Figure 2.8.** Like silicon diodes, LEDs have rapidly increasing current versus applied voltage, but with larger forward voltage drops.

We'll show a variety of techniques for driving LEDs in Chapter 12; but we can drive them already, with what we know. The first thing to realize is that we can't just switch a voltage across them, as in Figure 2.5, because of their steep $I$ versus $V$ behavior; for example, applying 5 V across an LED is guaranteed to blow it out. We need instead to treat it gently, coaxing it to draw the right current.

Let's assume that we want the LED to light in response to a digital signal line when it goes to a HIGH value of +3.3 V (from its normal resting voltage near ground). Let's assume also that the digital line can provide up to 1 mA of current, if needed. The procedure goes like this: first, choose an LED operating current that will provide adequate brightness, say 5 mA (you might want to try a few samples, to make sure you like the color, brightness, and viewing angle). Then use an *npn* transistor as a switch (Figure 2.9), choosing the collector resistor to provide the chosen LED current, realizing that the voltage drop across the resistor is the supply voltage minus the LED forward drop at its operating current. Finally, choose the base resistor to ensure saturation, assuming a conservatively low transistor beta ($\beta \geq 25$ is pretty safe for a typical small-signal transistor like the popular 2N3904).

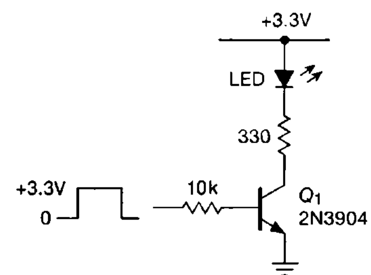


**Figure 2.9.** Driving an LED from a "logic-level" input signal, using an *npn* saturated switch and series current-limiting resistor.

Note that the transistor is acting as a saturated switch, with the collector resistor setting the operating current. As we'll see shortly, you can devise circuits that provide an accurate *current* output, largely independent of what the load does. Such a "current source" can also be used to drive LEDs. But our circuit is simple, and effective. There are other variations: we'll see in the next chapter that a MOSFET-type[11] transistor is often a better choice. And in Chapters 10–12 we'll see ways to drive LEDs and other optoelectronic devices directly from digital integrated circuits, without external discrete transistors.

**Exercise 2.1.** What is the LED current, approximately, in the circuit of Figure 2.9? What minimum beta is required for $Q_1$?

### B. Variations on a theme

For these switch examples, one side of the load is connected to a positive supply voltage, and the other side is

[10] The larger drop is due to the use of different semiconductor materials such as GaAsP, GaAlAs, and GaN, with their larger bandgaps.

[11] metal-oxide semiconductor field-effect transistor.

switched to ground by the *npn* transistor switch. What if you want instead to ground one side of the load and switch the "high side" to a positive voltage?

It's easy enough – but you've got to use the other polarity of transistor (*pnp*), with its emitter at the positive rail, and its collector tied to the load's high side, as in Figure 2.10A. The transistor is cut off when the base is held at the emitter voltage (here +15 V), and switched into saturation by bringing the base toward the collector (i.e., toward ground). When the input is brought to ground, there's about 4 mA of base current through the 3.3 kΩ base resistor, sufficient for switching loads up to about 200 mA ($\beta > 50$).

An awkwardness of this circuit is the need to hold the input at +15 V to turn off the switch; it would be much better to use a lower control voltage, for example, +3 V and ground, commonly available in digital logic that we'll be seeing in Chapters 10–15. Figure 2.10B shows how to do that: *npn* switch $Q_2$ accepts the "logic-level" input of 0 V or +3 V, pulling its collector load to ground accordingly. When $Q_2$ is cut off, $R_3$ holds $Q_3$ off; when $Q_2$ is saturated (by a +3 V input), $R_2$ sinks base current from $Q_3$ to bring it into saturation.

The "divider" formed by $R_2R_3$ may be confusing: $R_3$'s job is to keep $Q_3$ off when $Q_2$ is off; and when $Q_2$ pulls its collector low, most of its collector current comes from $Q_3$'s base (because only ~0.6 mA of the 4.4 mA collector current comes from $R_3$ – make sure you understand why). That is, $R_3$ does not have much effect on $Q_3$'s saturation. Another way to say it is that the divider would sit at about +11.6 V (rather than +14.4 V), were it not for $Q_3$'s base–emitter diode, which consequently gets most of $Q_2$'s collector current. In any case, the value of $R_3$ is not critical and could be made larger; the tradeoff is slower turn-off of $Q_3$, owing to capacitive effects.[12]

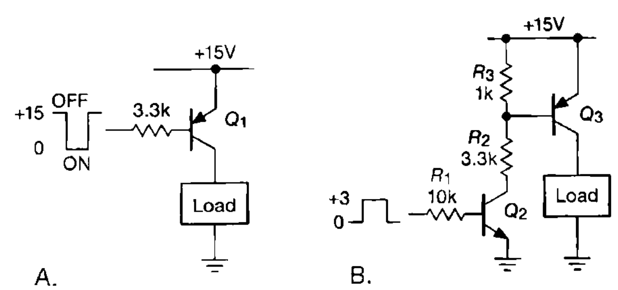


**Figure 2.10.** Switching the high side of a load returned to ground.

### C. Pulse generator – I

By including a simple $RC$, you can make a circuit that gives a pulse output from a step input; the time constant $\tau = RC$ determines the pulse width. Figure 2.11 shows one way. $Q_2$ is normally held in saturation by $R_3$, so its output is close to ground; note that $R_3$ is chosen small enough to ensure $Q_2$'s saturation. With the circuit's input at ground, $Q_1$ is cut off, with its collector at +5 V. The capacitor $C_1$ is therefore charged, with +5 V on its left terminal and approximately +0.6 V on its right terminal; i.e., it has about 4.4 V across it. The circuit is waiting for something to happen.

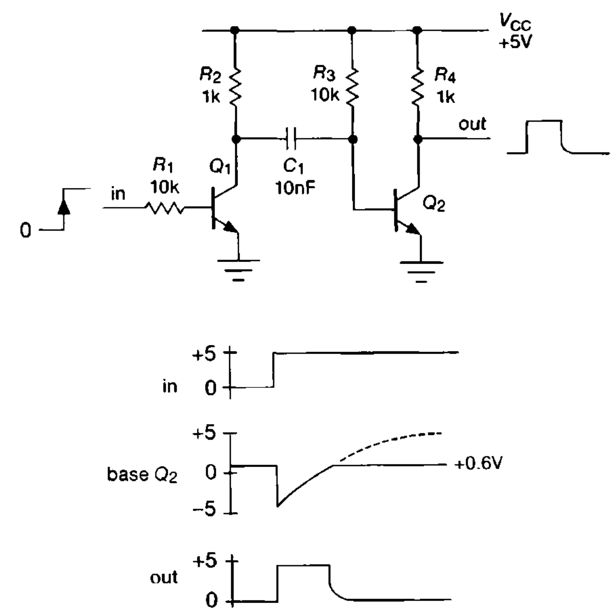


**Figure 2.11.** Generating a short pulse from a step input waveform.

A +5 V positive input step brings $Q_1$ into saturation (note the values of $R_1$ and $R_2$), forcing its collector to ground; because of the voltage across $C_1$, this brings the base of $Q_2$ momentarily negative, to about −4.4 V.[13] $Q_2$ is then cutoff, no current flows through $R_4$, and so its output jumps to +5 V; this is the beginning of the output pulse. Now for the $RC$: $C_1$ can't hold $Q_2$'s base below ground forever, because current is flowing down through $R_3$, trying to pull it up. So the right-hand side of the capacitor charges toward +5 V, with a time constant $\tau = R_3C_1$, here equal to 100 μs. The output pulse width is set by this time constant

[12] But don't make it too small: $Q_3$ would not switch at all if $R_3$ were reduced to 100 Ω (why?). We were surprised to see this basic error in an instrument, the rest of which displayed circuit design of the highest sophistication.

[13] A caution here: this circuit should not be run from a supply voltage greater than +7 V, because the negative pulse can drive $Q_2$'s base into reverse breakdown. This is a common oversight, even among experienced circuit designers.

and is proportional to $\tau$. To figure out the pulse width accurately you have to look in detail at the circuit operation. In this case it's easy enough to see that the output transistor $Q_2$ will turn on again, terminating the output pulse, when the rising voltage on the right-hand side of the transistor reaches the $\approx$0.6 V $V_{BE}$ drop required for turn-on. Try this problem to test your understanding.

**Exercise 2.2.** Show that the output pulse width for the circuit of Figure 2.11 is approximately $T_{pulse}=0.63R_3C_1=63\mu s$. A good starting point is to notice that $C_1$ is charging exponentially from $-4.4$ V toward +5 V, with the time constant as above.

### D. Pulse generator – II

Let's play with this circuit a bit. It works fine as described, but note that it requires that the input remain high throughout the duration of the output pulse, at least. It would be nice to eliminate that restriction, and the circuit in Figure 2.12 shows how. To the original circuit we've added a third transistor switch $Q_3$, whose job is to hold the collector of $Q_1$ at ground once the output pulse begins, regardless of what the input signal does. Now any positive input pulse – whether longer or shorter than the desired output pulse width – produces the same output pulse width; look at the waveforms in the figure. Note that we've chosen $R_5$ relatively large to minimize output loading while still ensuring full saturation of $Q_3$.

**Exercise 2.3.** Elaborate on this last statement: what is the output voltage during the pulse, slightly reduced owing to the loading effect of $R_5$? What is the minimum required beta of $Q_3$ to guarantee its saturation during the output pulse?

### E. Pulse generator – III

For our final act, let's fix a deficiency of these circuits, namely a tendency for the output pulse to turn off somewhat slowly. That happens because $Q_2$'s base voltage, with its leisurely 100 $\mu$s *RC* time constant, rises smoothly (and relatively slowly) through the turn-on voltage threshold of $\approx$0.6 V. Note, by the way, that this problem does not occur at the turn-*on* of the output pulse, because at that transition $Q_2$'s base voltage drops abruptly down to approximately $-4.4$ V, owing to the sharp input step waveform, which is further sharpened by the switching action of $Q_1$.

The cure here is to add at the output a clever circuit known as a *Schmitt trigger*, shown in its transistor implementation[14] in Figure 2.13A. It works like this: imagine a time within the positive output pulse of the previous circuits, so the input to this new Schmitt circuit is high (near

[14] We'll see other ways of making a Schmitt trigger, using op-amps or comparators, in Chapter 4.

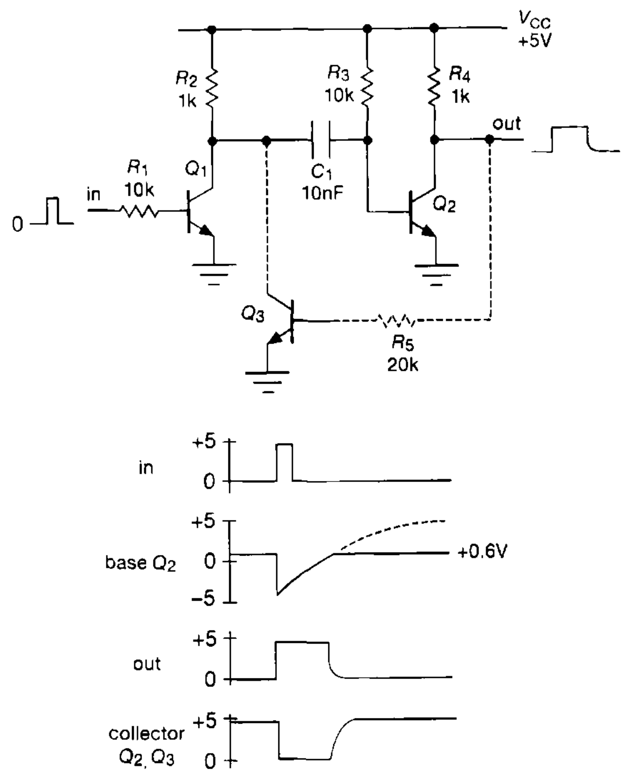


Figure 2.12. Generating a short pulse from a step or pulse input.

+5 V). That holds $Q_4$ in saturation, and so $Q_5$ is cut off, with the output at +5 V. The emitter current of $Q_4$ is about 5 mA, so the emitter voltage is approximately +100 mV; the base is a $V_{BE}$ higher, approximately +700 mV.

Now imagine the trailing edge of the input pulse waveform, whose voltage smoothly drops toward ground. As it drops below 700 mV, $Q_4$ begins to turn off, so its collector voltage rises. If this were a simple transistor switch (i.e., if $Q_5$ were absent) the collector would rise to +5 V; here, however, the collector resistor $R_7$ instead supplies current to $Q_5$, putting it in saturation. So $Q_5$'s collector drops nearly to ground.

At this simple level of analysis the circuit appears to be pretty useless, because its output is the same as its input! Let's look a little closer, though: as the input voltage drops through the 700 mV threshold and $Q_5$ turns on, the total emitter current rises to $\approx$10 mA (5 mA from $Q_5$'s collector current, and another $\approx$5 mA from its base current, both of which flow out the emitter). The drop across the emitter resistor is now 200 mV, which means that the input threshold has increased to about +800 mV. So the input voltage, which had just dropped below 700 mV, now finds itself well below the new threshold, causing the

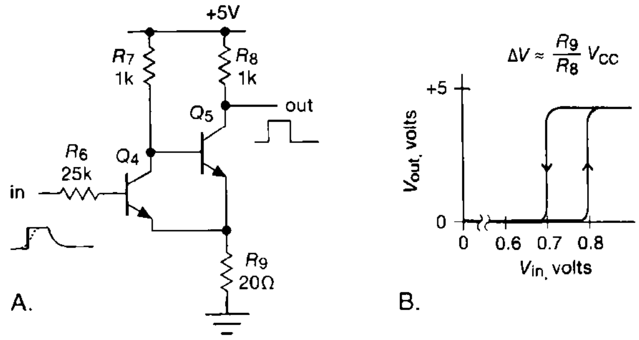


**Figure 2.13.** A "Schmitt trigger" produces an output with abrupt transitions, regardless of the speed of the input waveform.

output to switch abruptly. This "regenerative" action is how the Schmitt trigger turns a slowly moving waveform into an abrupt transition.

A similar action occurs as the input rises through this higher threshold; see Figure 2.13B, which illustrates how the output voltage changes as the input voltage passes through the two thresholds, an effect known as *hysteresis*. The Schmitt trigger produces rapid output transitions as the input passes through either threshold. We'll see Schmitt triggers again in Chapters 4 and 10.

There are many enjoyable applications of transistor switches, including "signal" applications like this (combined with more complex digital logic circuits), as well as "power switching" circuits in which transistors operating at high currents, high voltages, or both, are used to control hefty loads, perform power conversion, and so on. Transistor switches can also be used as substitutes for mechanical switches when we are dealing with continuous ("linear" or "analog") waveforms. We'll see examples of these in the next chapter, when we deal with FETs, which are ideally suited to such switching tasks, and again in Chapter 12, where we deal with the control of signals and external loads from logic-level signals.

We now move on to consider the first of several *linear* transistor circuits.

### 2.2.3 Emitter follower

Figure 2.14 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:

$$V_E \approx V_B - 0.6 \text{ volts}.$$

The output is a replica of the input, but 0.6 to 0.7 V less positive. For this circuit, $V_{in}$ must stay at +0.6 V 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.

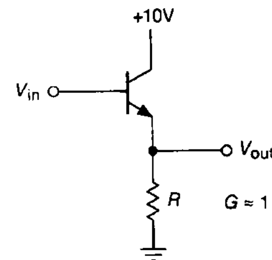


**Figure 2.14.** Emitter follower.

At first glance this circuit may appear quite thoroughly 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!

#### A. 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 2.15. 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 §1.2.5A. 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