Pre-lab 7: Transistors

Transistors

The transistor is our first *active* device, a 3-terminal semiconductor device that controls the flow of current. You are not alone if, on a first introduction, these things make your head explode. The complication is that, unlike a 2-terminal device like a resistor or capacitor, there are now three voltage differences, and three currents, to keep track of. Happily, it's not that bad: Kirchhoff's Laws still apply, so the sum of the currents has to be zero, and ditto for the voltage drops going around the terminals; so there are "only" two independent voltage drops, and two currents. But still, you need to stay calm. In this task we will help you!

There are two types of transistors. A MOSFET is operated primarily as a switch, and we may see these later when we study digital electronics. We will mainly study bipolar junction transistors (BJT) which will be useful for "linear" circuits like amplifiers and current sources.

We'll see a few important BJT circuits, which we call "discrete" circuits because we make them from individual transistors and passive components. Later, we'll learn about the *operational amplifier* ("op-amp"), wonderful integrated circuits (containing a bunch of transistors that someone else designed) that make analog circuit design a cinch. Op-amps are the Swiss army knife of analog electronics. But for today let's explore the humble BJT.

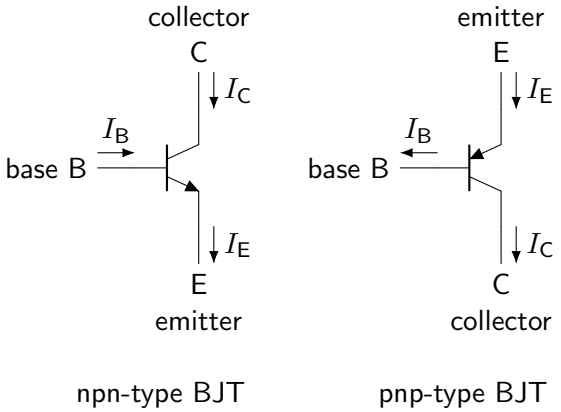


Figure 1: Circuit symbols for the two polarities of BJTs.

The first transistor to be discovered[1] were what's now called *bipolar junction transistors* (BJTs). The circuit symbols are shown in Figure 1 for both polarities, called *npn* and *pnp*.

The *base* (B) is the control terminal, which controls the current between *collector* and *emitter*. The npn and pnp varieties have the opposite polarities: if you have a circuit that works with an npn BJT, you can build a working pnp-BJT circuit by flipping the signs of all the voltages and letting the currents flow in the opposite directions.

We will stick with npn, at least for today.

Bringing the base (B) positive with respect to the emitter (E) brings the collector-emitter circuit into conduction. The base-emitter circuit is a semiconductor junction, in fact a diode, so there's base current

[1] Kinda by accident, the Bell Labs researchers were probing "surface states" and accidentally created a transistor.

I_B once V_{BE} becomes more positive than about 0.6 V. In the simplest BJT model (which is good enough for everything we'll be doing in this course), the resulting base current I_B allows a much larger collector current I_C to flow (assuming the external circuit wants to provide that current). The ratio I_C/I_B is called the "current gain," typically around 100, and is given the name beta (β, sometimes written h_{FE}).

$$\beta \equiv h_{FE} \equiv \frac{I_C}{I_B} \approx 100. \tag{1}$$

So we can think of the BJT as a *current amplifier*, where the base current flows through the base-emitter diode controls the much larger ($\times 100$) collector current. The only requirement is that the external circuit keeps the collector more positive than the emitter, i.e., $V_{CE} > 0$.

Emitter follower

Figure 2A shows one of the simplest BJT circuits, the emitter follower. An input signal drives the base of an npn BJT, with the collector held high (at +15 V), and a load resistor R_E is attached between the emitter and ground.

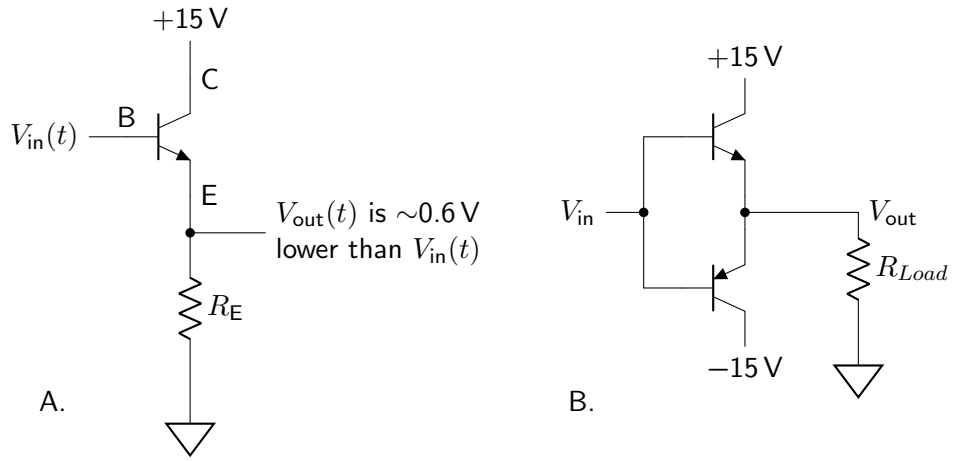


Figure 2: The emitter follower. A. single-ended. B. push-pull.

Since the base-emitter junction acts like a diode, the emitter "follows" the input waveform, offset by ~0.6V. Not interesting, you complain, just a plain ol' diode could do the same. But (and here's the important thing), the input current to the base is smaller (by a factor of 100) than the output current. Put another way, the input impedance presented by the BJT to the source signal is 100 times larger than the resistance of the load that the follower is driving. This is good news: input impedance is ideally large! We'll build one of these today in lab.

Figure 2B is a *push-pull* emitter follower, which uses a pair of BJTs, one npn (above) and one pnp (below). When V_{in} is positive, the npn BJT acts as an emitter follower. When V_{in} is negative, the npn BJT turns off, and the pnp BJT takes over. The advantage — and the weaknesses — of this circuit will be discussed when we build it in today's lab.

Pre-lab 7 Hand-in

Name: _____

Pre-lab 7.1 How are the voltage gain and current gain of the BJT related to its input and output impedance? Why is this useful?

If we make a small change in the base voltage V_B and base current I_B we will get a large change in the emitter current $I_E = \beta I_B$. Input impedance should be $Z_{in} = V_B/I_B = V_B/(I_E/\beta) = \beta V_B/I_E$. Since $V_B \sim V_E$ (difference of 0.6V) this relationship becomes $Z_{in} = \beta V_E/I_E = \beta R_E$. So, Z_{in} is large. We get a much larger input impedance than the load we are trying to drive! On the other hand, the output impedance is determined by looking backwards into the circuit. That gives us Z_{source} in parallel with Z_{load} with a small alteration: Z_{source} gets divided by β to account for the current gain of the BJT. So we have a very small output impedance. This is good because it means it is easy to drive our load.

Pre-lab 7.2 Consider the simple emitter-follower in 2A. Are there any limits on the output signal that this circuit can produce?

The output signal can only happen if current is sourced through the BJT from the collector to the emitter. If V_{out} is not positive, it will not source current. If V_B is larger than the supply, 15V, it will not source current. So our signal is limited between 0-15V.

Pre-lab 7.3 What could you do to the input signal to remove the limits or distortions you found in the last question? Try to come up with 2-3 different solutions.

1) Bias the input to make sure it does not drop below 0V. 2) Change the ground on the load to a negative voltage rail to expand the range. 3) Create an alternate path for negative input voltage (see push-pull follower).

From the last lab:

Pre-lab 7.4 Draw a clamp circuit to limit the output swing to approximately ± 1.2 V (two diode drops); use a 1 kΩ input resistor.

We've seen a simple clamp with two parallel diodes, which clamps the output to plus or minus one diode drop (± 0.6 V). We can add more diodes in series to create a clamp that conducts when the input voltage exceeds one diode drop per series diode, resulting in the circuit shown below.

