6.071 Lab 3 - Transistors

April 8, 2002

1 Prelab, Week 1

Please read through the entire lab before attending the lab session. This lab builds on lab 2. We have taken every effort to explain how to do the relevant parts of lab 2 as quickly as possible. Nevertheless, if you did not complete lab 2, this lab will take significantly longer to finish, and you may need to come in outside of formal lab sessions.

1.1 Current Source

Calculate $I_{out}$ as a function of $V_{in}$ (the transfer function) for this circuit:

\[ \begin{array}{c}
V_{in} \\
\downarrow \\
V_{int} \\
\downarrow \\
R \\
\hline
\hline
\end{array} \quad \begin{array}{c}
I_{out} \\
\downarrow \\
\hline
\hline
\end{array} \]

Here, you can use the simple 0.6V model covered in lecture (Assume the transistor’s collector is at a high enough voltage for it to be in the linear region. Assume $V_{BE} = 0.6V$, $\beta = \infty$). In fact, you will probably not be able to find a closed form solution if you use the exact exponential model.

1.2 Gain Stage

Now, we’ll use this as a gain stage. Again, using the 0.6V model, give the $V_{out}$ as a function of $V_{in}$ for this circuit:
Again, assume that the resistor values are chosen so the collector is at a high enough voltage that the transistor is in the linear region. *You can reuse most of the work from the previous part.*

What happens to the gain as $R_1 \to 0$? Does this seems physically possible? What is the problem here (hint: compare to the “gain” in the previous part).

### 1.3 Buffer

We are trying to set a bias voltage across an unknown load $R_{load}$ in a circuit. We will try two configurations for this:

![Voltage Splitter](image1)

![Voltage Splitter with Buffer](image2)

Let $\beta = 200$, $V_{BE} = 0.6V$ and the resistor values be chosen such that, with no load, $V_{load} = 5V$.

With $R_{load} = 1k\Omega$, how much current will be going across the load? Where will this current come from? Qualitatively, how will this impact the voltage output by the voltage splitter?
With the buffer transistor, how much current will be going across the load? How much additional current will this pull out of the voltage splitter? In comparison, how will this impact the voltage splitter?
2 Prelab, Week 2

It is absolutely critical that you read the lab portion before going into lab. Without having read it, you will have a very hard time finishing lab.

2.1 Differential Pair

We will characterize the large-signal behavior of a differential pair. Again, assume the collectors are at a high enough voltage for the transistor to be in the linear region. Take this circuit:

\[ \begin{array}{c}
  \text{V}_{\text{in}1} & \text{V}_{\text{in}2} & \text{V}_{\text{int}} \\
  \text{I}_{\text{bias}} & & \\
  \text{I}_{\text{out}1} & \text{I}_{\text{out}2} \\
\end{array} \]

**Equilibrium behavior** Let \( \text{V}_{\text{in}1} = 0V \) and \( \text{V}_{\text{in}2} = 0V \). What is \( \text{V}_{\text{int}} \)? What are \( \text{I}_{\text{out}1} \) and \( \text{I}_{\text{out}2} \)? (Use the 0.6V model)

**Limit behavior** Let \( \text{V}_{\text{in}1} = 0V \) and \( \text{V}_{\text{in}2} = 5V \). What is \( \text{V}_{\text{int}} \)? What are \( \text{I}_{\text{out}1} \) and \( \text{I}_{\text{out}2} \)? (Use the 0.6V model)

**Gain** Now, we’ll calculate the gain around \( \text{V}_{\text{in}1} = \text{V}_{\text{in}2} \). Here, the simple 0.6V model would give us infinite gain, so we need to use either the small signal model or the exact exponential model.

Apply a small positive voltage to \( \text{V}_{\text{in}1} \) and an equal, but negative voltage to \( \text{V}_{\text{in}2} \). Argue that, by linearity, \( \text{V}_{\text{int}} \) will not change.

*If you know the small signal model:* Set up the the small signal model. The current should fall out pretty easily.

*If you don’t know the small signal model:* Take the transistor relationship: \( \text{I}_{\text{C}} = \text{I}_{\text{O}} e^{\frac{\text{V}_{\text{BB}}}{\text{V}_t}} \). Plug in the appropriate variables for \( \text{V}_B \) and \( \text{V}_E \), and take the derivative with respect to \( \text{V}_{\text{in}} \) to get \( \frac{d\text{V}_{\text{in}1}}{d\text{I}_{\text{out}1}} \).
3 Lab

3.1 Introducing the transistor

In this section, we’re going to characterize the properties of a transistor in the linear region. We will connect a voltage across the base-emitter junction, and measure the output current:

We’ll use the function generator to apply a voltage to the base-emitter junction. To measure the output current, we can either use the DMM in ammeter mode, or connect a resistor across the output. We’ll do the later. Since the base-emitter junction acts like a diode, it will blow up if we apply more than about 0.6V across it. To protect it, we’ll put in a 10K resistor in series with the base.

Connect the circuit. Plot the output current as a function of input voltage on the plot below:

*Hint: It may help to use your scope in X-Y mode. Measure $V_{BE}$ with one probe, and $V_C$ with the other. $(V_{DD} - V_C)/1K \Omega$ will give the output current.*

The output current can be approximated as $I_{out} = I_0 e^{\frac{V_{BE}}{Vth}}$. Estimate $I_{out}$ for your transistor (this will vary significantly from transistor to transistor).
3.2 A basic amplifier

In this section, we’ll build a basic transistor amplifier. First, we’ll build the voltage-controlled current source from the prelab:

Now, to measure the output current, we’ll stick a resistor from the output to ground:

Using the 0.6 model, what is the transfer function of this circuit \( \frac{V_{\text{out}}}{V_{\text{in}}} \), omitting any offset?

Now, measure the gain and offset of the circuit around \( V_{\text{in}} = 1V \). How does the gain compare to the calculated value?

Don’t disassemble your circuit. We will use it in the next part.

3.3 A buffer

We’re going to simulate a load by putting a resistor from the output to ground:

Measure and record how much the gain of the circuit changes from the previous part.
Now, we’ll put in a buffer on the output:

![Circuit Diagram]

Measure the gain again. Put a 10k load on the output. How much does the output change?
4 The differential pair

In this section, we study the differential pair from the prelab. For simplicity, we will connect one input to ground. We will also replace the current source with a resistor. Assuming both $V_{\text{in}}$ stays close to $0V$, the voltage across the resistor will be pretty constant around $15 - 0.6V$, and the current won’t change much from $\frac{15-0.6V}{15k\Omega}$:

![Circuit Diagram]

Build this circuit and plot $V_{\text{in}+}$ against $V_{\text{out}}$ for :

What is the maximum current down each side? What is the differential gain around $V_{\text{in}} = 0$? Compare these values to those calculated in the prelab. Keep this circuit on your kit for the next part.
5 AM Receiver Gain Stage

Now we have all of the components of the AM receiver. We will combine everything into the complete AM receiver. To help put the class on equal footing, we will review how to build the relevant parts from lab 2.

\[
\text{Antenna} \quad \text{Coil} \quad \text{Gain Stage} \quad \text{Tuning Filter} \quad \text{Peak Finder for Detection} \quad V_{\text{out}}
\]

\[
\begin{align*}
0.1 \mu F & \quad 10k \\
10k & \quad 15k \\
0.1 \mu F & \quad 10k
\end{align*}
\]

5.1 Tuned Element

As we saw, the gain of a differential pair goes as the collector resistor. We want a high gain around 455 KHz, and a low gain elsewhere. To achieve this, we build a tuned filter element.

We built the tuned element in lab 2, although several students ran out of time to test the center frequency, bandwidth, etc. To test the impedance of the tuned element, we put it in a voltage splitter with a large resistor:

\[
\begin{align*}
\text{Antenna} \\
\text{Gain Stage} \\
\text{~450k} \\
\text{1000pF} \quad 2.2k \\
\text{V}_{\text{out}}
\end{align*}
\]

We apply an AC voltage on the input, and change the frequency. The center frequency is where the output voltage $V_{\text{out}}$ peaks. Measure the low and high frequencies where the output voltage drops to $\frac{1}{\sqrt{2}}$. This difference between those frequencies gives you the bandwidth.

For the TAs version of this circuit, we found $C = 1000 \mu F$ and $R = 2.2k$ worked. If you cannot tune to 455 KHz, change the capacitance value (smaller capacitance $\rightarrow$ higher frequency). If you cannot achieve the desired bandwidth, change the resistance value (low resistance $\rightarrow$ lower bandwidth). For our purposes, slightly higher bandwidth is better than slightly lower.
5.2 Gain stage

For the gain stage, we will use the differential pair from the previous section.

We will couple the input through a large (0.1\(\mu\)F capacitor), so that the AC comes through, but DC does not. We will tie the DC to ground through a 10k\(\Omega\) resistor. This capacitors acts as a short circuit at 455KHz, and as an open circuit at DC.

For symmetry, we tie the negative input through the same type of network to ground. This isn't strictly necessary, but there may be a small DC drop across the 10k resistor on the left transistor. Putting in the same sort of transistor on the right keeps the diff pair operating closer to center.

Since we don’t need it, we will remove the first collector resistor. We replace the output collector resistor with our tuned element:

We chose a differential pair because it is very fast. Circuits are slow because of stray capacitances. In a differential pair, all of the major capacitances are to ground. There is no capacitance directly from the input to the output.

At this point, out circuit looks like:

![Gain Stage Diagram]

It may help to test the entire circuit before adding the antenna. If you wish to test it, connect the function generator through the capacitor to the gain stage. You will likely need to set the function generator to a very low input voltage. Sweep the function generator, and make sure the output spikes around 455KHz.

5.3 Antenna

In lab 2, we also placed a resistor in series with the antenna coil; in practice, we can omit this. The 10k resistor we use to couple the input to ground will gives us the bandwidth we need.

![Antenna Diagram]
To build the antenna circuit, place a capacitor in series with the antenna coil. A 100\textit{p}f capacitor should give a slightly higher value than 455KHz. Place a 12 – 100\textit{p}f trimmer cap (from your TA or from front desk) in parallel. The TA will have a transmitter set up in the middle of the lab. Tune the trimmer cap until the output across \(V_{out}\) peaks. When the trimmer cap is away from the tuned frequency, you will likely see no output.

If your output is too small, you can reduce the 15\textit{k} resistor to give a little bit more bias current.

Have your TA check off your receiver.

The course staff is looking into getting a more general purpose AM transmitter, as well as small amplified speakers you can connect to your receiver. Although it is unlikely we will have this available this year, if we do, and you’re interested, you can try plugging in one of the amplified speakers, and listening to music through the receiver.