BIPOLAR JUNCTION TRANSISTORS

LAB 7: INTRODUCTION TO TRANSISTOR AMPLIFERS AND MAKING AN AUDIO AMPLIFIER

DEFINITIONS

h_{fe} **or** β – transistor current gain intrinsic to the transistor itself.
V_E, V_B, V_C – voltages at the emitter, base, and collector, respectively.

BIPOLAR JUNCTION TRANSISTORS - GENERAL USE

An electrical signal can be amplified using a device that allows a small current or voltage to control the flow of a much larger current from a dc power source. Transistors are the basic devices providing control of this kind. There are two general types of transistors, bipolar and field-effect. The difference between these two types is that for bipolar devices an input current controls the large current flow through the device, while for field-effect transistors an input voltage provides the current control. In this experiment we will build a two-stage amplifier using two bipolar transistors.

In many practical applications it is better to use an op-amp as a source of gain rather than to build an amplifier from discrete transistors. A good understanding of transistor fundamentals is nevertheless essential because op-amps are built from transistors. We will learn about digital circuits in Lab 9, which are also made from transistors. In addition to the importance of transistors as components of op-amps, digital circuits, and an enormous variety of other integrated circuits, single transistors (usually called "discrete" transistors) are used in many applications. They are important as interface devices between integrated circuits and sensors, indicators, and other devices used to communicate with the outside world. High-performance amplifiers operating from DC through microwave frequencies use discrete transistor "front-ends" to achieve the lowest possible noise. Discrete transistors are generally much faster than op-amps. The device we will use this week has a gain-bandwidth product of 300 MHz.

The three terminals of a bipolar transistor are called the emitter, base, and collector (Figure 1). A small current into the base controls a large current flow from the collector to the emitter. The current at the base is typically about 1% of the collector-emitter current. This means that the transistor acts as a current amplifier with a typical current gain (h_{fe} or β) of ~100. Moreover, the large collector current flow is almost independent of the voltage across the transistor from collector to emitter. This makes it possible to obtain a large amplification of voltage by having the collector current flow through a resistor.
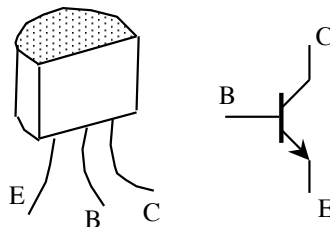

Figure 1: Diagram of a NPN bipolar junction transistor (left) and schematic symbol (right).

CURRENT AMPLIFIER MODEL OF A BIPOLAR TRANSISTOR

From the simplest point of view a bipolar transistor is a current amplifier. The current flowing from collector to emitter is equal to the base current multiplied by a factor. An npn transistor like the 2N3904 operates with the collector voltage at least a few tenths of a volt above the emitter, and with a current flowing *into* the base (There are also pnp transistors with opposite polarity voltages and currents). The base-emitter junction then acts like a forward-biased diode with a 0.6 V drop:

$V_B \approx V_E + 0.6V$.

Under these conditions, the collector current is proportional to the base current:

$I_C = h_{fe} I_B$.

The constant of proportionality ('current gain') is called h_{fe} because it is one of the "h-parameters," a set of numbers that give a complete description of the small-signal properties of a transistor. It is important to keep in mind that h_{fe} is not really a constant. It depends on collector current (see H&H Fig. 2.78), and it varies by 50% or more from device to device. If you want to know the emitter current rather than the collector current you can find it by current conservation:

$I_E = I_B + I_C = (1/h_{fe} + 1) I_C$.

The difference between I_C and I_E is almost never important since h_{fe} is normally in the range 100 – 1000. Another way to say this is that the base current is very small compared to the collector and emitter currents.

EMITTER FOLLOWER AND COMMON EMITTER AMPLIFIERS

We will begin by constructing a common emitter amplifier, which operates on the principle of a current amplifier. A major fault of a single-stage common emitter amplifier is its high output impedance. (Remember why this is a problem? Think voltage divider and Ohm's Law.) This problem can be addressed by adding an emitter follower as a second stage. In the emitter follower circuit, the control signal is again applied at the base, but the output is taken from the emitter. The emitter voltage precisely follows the base voltage, but more current is available from the emitter. The common-emitter stage and the emitter follower stage are the most common bipolar transistor circuit configurations.
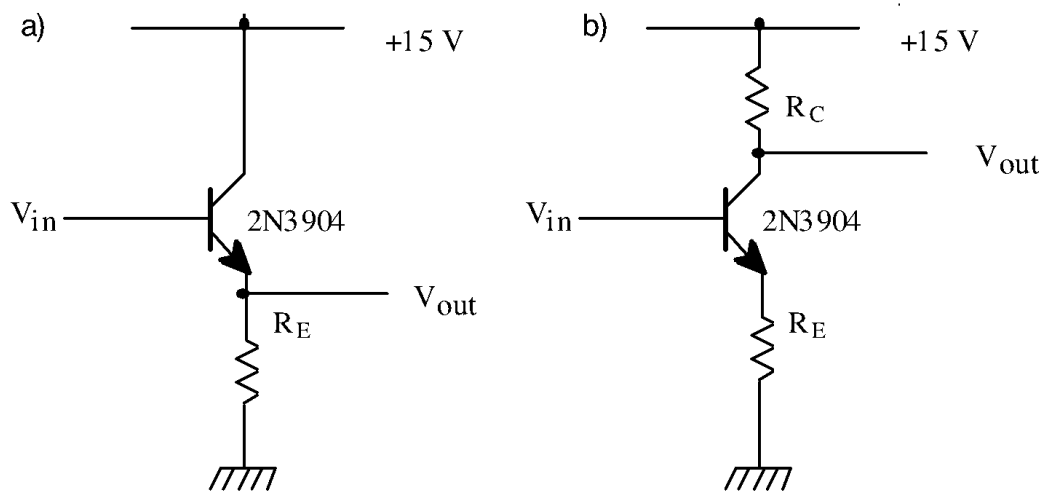
Figure 2 Two basic transistor amplifiers. (a) Emitter Follower and (b) Common emitter.

In the emitter-follower stage of Figure 2a, the output (emitter) voltage is always 0.6V (one diode drop) below the input (base) voltage. A small signal of amplitude δV at the input will therefore give a signal δV at the output, i.e. the output just "follows" the input. As we will see later, the advantage of this circuit that it has high input impedance and low output impedance.

In the common-emitter stage of Figure 2b, a small signal of amplitude δV at the input will again give a signal δV at the emitter. This will cause a varying current of amplitude $\delta V / R_E$ to flow from the emitter to ground, and hence also through R_C. This current generates a V_{out} of $-R_C(\delta V / R_E)$. Thus the common emitter stage has a small-signal voltage gain of:

$$G = \frac{-R_C}{R_E}$$

Note: this Gain is about the *change* in voltage, which is a bit different than the earlier "Gains" you were working with.

BIASING A TRANSISTOR AMPLIFIER

Although we usually want to amplify a small ac signal, it is nonetheless very important to set up the proper "quiescent point" or bias voltages, the dc voltages present when the signal is zero. The first step is to fix the dc voltage of the base with a voltage divider (R_1 and R_2 in Figure 3). The emitter voltage will then be 0.6 V less than the base voltage. With the emitter voltage known, the current flowing from the emitter is determined by the emitter resistor: $I_E = V_E/R_E$. For an emitter follower, the collector is usually tied to the positive supply voltage V_{ps}. The only difference between biasing the emitter follower and biasing the common emitter circuit is that the common emitter circuit always has a collector resistor. The collector resistor does not change the base or emitter voltage, but the drop across the collector resistor does determine the collector voltage: $V_C = V_{ps} - I_C R_C$.

If we have capacitors or inductors in parallel (or in place) of the resistors R_C and R_E, then we would use the ac impedances.
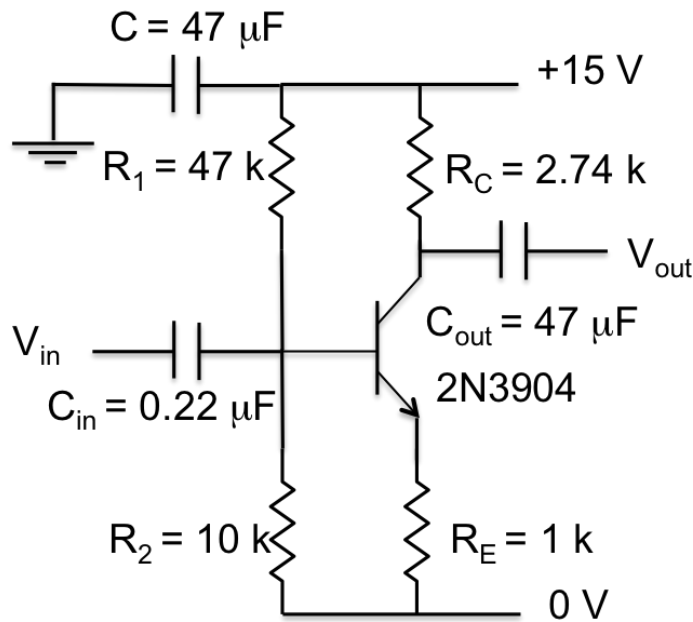
3

Figure 3. Common-emitter amplifier with biasing resistors in place.

Even with proper biasing of the transistor, the output voltage has a range that is less than 0–15V. Let's determine the maximum and minimum output voltages. Since V_{out} = 15 V – $I_C R_C$, the maximum voltage will occur when I_C=0 and the minimum voltage when I_C is a maximum.

Maximum voltage: This occurs when the transistor is turned off and no current is flowing. As there is no current flowing through R_C, there is no voltage drop across it. Thus V_{out} = V_{max} = 15 V.

Minimum Voltage: This occurs when the transistor is fully on. The maximum current is flowing and there is very little voltage drop across the transistor. The voltage is:
$$V_{out} = V_{min} = 15\ V - R_C\ I_C\ (max)$$
I_C(max) can be found by considering the voltage drop from the power supply to ground when there is no voltage drop across the transistor: $15V - R_C\ I_C - R_E\ I_E = 0$.

This simple model does not include the ~ 0.1 V drop across the transistor itself even when it is fully on.

INPUT AND OUTPUT IMPEDANCES

The input impedance is the same for both emitter followers and common emitter stages. The input impedance looking into the base is
$$r_{in} = R_E\ h_{fe}$$
In this expression R_E is whatever impedance is connected to the emitter. For a common emitter stage, R_E would usually just be the emitter resistor, but for an emitter follower R_E might be the emitter resistor in parallel with the input impedance of the next stage. **If you want the input impedance of the whole circuit, rather than just that looking into the base, you will have to consider r_{in} in parallel with the base bias resistors.**

The output impedance of a common emitter stage (Fig. 2b) alone is just equal to the collector resistor R_C.

$$r_{out} = R_C \text{ (common emitter stage)}$$

The output impedance looking into the emitter of an emitter follower (e.g. Fig. 2a) is given by

$$r_{out} = \frac{R_B}{h_{fe}+1} \text{ (emitter follower stage)}$$

R_B stands for whatever impedance is connected to the base. Usually this impedance is in parallel with whatever impedance is connected to the emitter (R_E).

EBERS-MOLL MODEL OF A BIPOLAR TRANSISTOR

A slightly more complete model of the bipolar transistor is required to understand what happens when the emitter resistor is very small. Instead of using the current amplifier model, one can take the view that the collector current I_C is controlled by the base-emitter voltage V_{BE}. For our purposes, the Ebers-Moll model modifies our current amplifier model of the transistor in only one important way. For small variations about the quiescent point, the transistor now acts as if it has a small internal resistor, r_e, in series with the emitter. The magnitude of the intrinsic emitter resistance, r_e, depends on the collector current I_C.

$$r_e = 25\Omega \left(\frac{1 \, mA}{I_C}\right)$$

The presence of the intrinsic emitter resistance, r_e, modifies the above equations as follows.

$$r_{in} = (R_e + r_e)h_{fe}$$

$$r_{out} = \frac{R_B}{h_{fe}+1} + r_e \text{ (emitter follower stage)}$$

The most important of these results is the modified gain:

$$G = \frac{-R_C}{R_E + r_e}$$

which shows that the common emitter gain is not infinite when the external emitter resistor goes to zero.

USEFUL READINGS
1. FC chapters 5 (bipolar junction transistors) & 6 (common emitter amplifier)
2. A data sheet for the 2N3904 transistor is posted on our course web site.
3. Horowitz and Hill, Chapter 2. The most important sections are 2.01–2.03, 2.05, the first page of 2.06, 2.07, 2.09–2.12, and the part of 2.13 on page 84 and 85. Have a look at Table 2.1 and Figure 2.78 for a summary of the specifications of some real devices.

LAB PREP ACTIVITIES

Answer the following questions using Mathematica or by hand in your lab book. **Bring an electronic copy of your notebook to lab, preferably on your own laptop.**

Question 1	**Biasing the transistor**
	   a. Calculate the quiescent voltages (the DC voltages with no signal present) V_B, V_E, and V_C and the currents I_E and I_C for the common emitter circuit in Figure 3. You may assume that h_{fe} is so large that the base current is negligible.
	   b. How much power is dissipated in the transistor itself? Is the power safely below P_{max}? See 2N3904 data sheet posted on our web site.
	   c. What is the purpose of the input and output capacitors, C_{in} and C_{out}?

Question 2	**Transistor amplifier – single stage (common emitter)**
	   a. What is the maximum h_{fe} value at 10 mA collector current? See 2N3904 data sheet posted on our web site. (You may use this value for calculations below.)
	   b. What is the ac voltage gain of the circuit in Figure 3 for 15 kHz sine waves?
	   c. What are the maximum and minimum possible output voltages?
	   d. For the single stage in Figure 3, what are the input and output impedances r_{in} and r_{out} at 15kHz? Note that the input impedance of the common emitter with the bias resistor network is the input resistance of the common emitter *in parallel* with both R_1 and R_2. That is, r_{in} (total) = r_{in} (common emitter) $\|$ R_1 $\|$ R_2.
	   e. Calculate the fraction of the original amplitude obtained when a 560 Ω load is connected to the output via a coupling capacitor (C_{out} in Fig. 3) to ground. *HINT: the 560 Ω resistor will be in series with the output impedance of the circuit to ground. Even at only 15 kHz, the output capacitor acts as a wire for the ac impedance. It serves to block only the DC voltage.*

Question 3	**Transistor amplifier – dual stage (common emitter + emitter follower)**
	   a. What is the ac voltage gain of the entire dual-stage amplifier (common emitter + emitter follower) circuit in Figure 4 for 15 kHz sine waves?
	   b. For the entire dual stage amplifier in Figure 4, what is the output impedance r_{out} at 15kHz? *HINT: The impedance at the base of the emitter follower is the collector resistor of the common emitter.*
	   f. Calculate the fraction of the original amplitude obtained when a 560 Ω load is connected to the output via a coupling capacitor (C_{out} in Fig. 4). *HINT: the 560 Ω resistor will be in series with the output impedance of the circuit to ground. Even at only 15 kHz, the output capacitor acts as a wire for the ac impedance. It serves to block only the DC voltage.*

Question 4	**Audio Amplifier**
	   a. What is the output impedance of your phone (or partner's phone)? See Figure 5.
	   b. A standard non-amplified speaker has an input impedance of 8 Ω. If your phone had an output voltage at 1 V unloaded, what would the loaded voltage be if you hooked it up to the 8 Ω speaker? *HINT: Think voltage divider.*
	   c. Now, instead you can use the common emitter to amplify the signal from your phone first. If your common emitter amplifier has an unloaded output voltage of 2.7 V (assuming a gain of 2.7), what is the output voltage if you connect an 8 Ω speaker to the amplifier? *HINT: Think voltage divider with the output impedance of the common emitter.*
	   d. Finally, consider using the two-stage amplifier shown in figure 4 to drive the speaker. If the emitter follower amplifier output stage has an unloaded output voltage of 2.7 V (assuming a gain of 2.7), what is the output voltage if you connect an 8 Ω speaker to the amplifier? *HINT: Think voltage divider with the output impedance of the emitter follower.*

Question 5	**Lab activities**
	    a. Read through all of the lab steps and identify the step (or sub-step) that you think will be the most challenging.
	    b. List at least one question you have about the lab activity.

COMMOM EMITTER AMPLIFIER

Step 1	**Quiescent State** a. Build the common emitter amplifier shown in Figure 3 (without the capacitors C_{in} and C_{out}) and check that the correct dc levels (quiescent voltages) are established. Measure the resistors before putting them in the circuit, and if they differ from the values used in your calculations, recalculate the predicted quiescent voltages. Draw the circuit schematic in your lab book and label all components. What are the dc levels V_B (at the transistor base), V_E (at the emitter) and V_C (at the collector)? Do they agree with your predictions?

Step 2	**Low frequency AC Gain**
	    a. Convert the previous circuit to an AC amplifier by adding the coupling capacitors C_{in} and C_{out}. Make sure to get the polarity correct (for C_{out}, consider ground on the right). The capacitors will transmit ac signals but block dc signals. This allows you to connect signals without disturbing the quiescent conditions.
	    b. When you switch on the power, you may see high frequency spontaneous oscillations. These must be suppressed before you can proceed. An additional bypass capacitor (~100nF) between +15V and ground close to the transistor may help. Also, reducing the length of your circuit wires can help.
	    c. Assemble a test set-up to observe the input and output of the amplifier with 15 kHz sine waves, using the 10x scope probe for the output. *HINT: You may need to add a 220 kΩ resistor to ground after C_{out} to keep the dc level at the scope input near ground as the large output capacitor can slowly charge up. You may also want to put the scope on ac coupling when you probe points with large dc offsets but switch it back to DC if you want to measure quiescent voltages.* Vary the input amplitude to determine the output amplitude at which clipping begins. You will want to stay below half of this clipping voltage to assure the amplifier is not distorting the output waveform.
	    d. Measure the gain of the amplifier for 15 kHz sine waves. Does your measurement agree with your prediction?

Step 3	**Output Impedance**
	    a. The common emitter amplifier often has a large output impedance. Connect a 560 Ω load from the output to ground. What fraction of the original output do you now see? Does this agree with your lab-prep predictions? If not, can you use your measurements of the output voltage before and after the resistor was in place to refine the model of your amplifier's output impedance?
	    b. Remove the load resistor and drive a speaker with the output of the amplifier. Explain how you hooked up the speaker. First drive the circuit with the function generator. Describe your measurements and observations. Do they agree with your model of the output impedance of the common emitter amplifier? *HINT:*

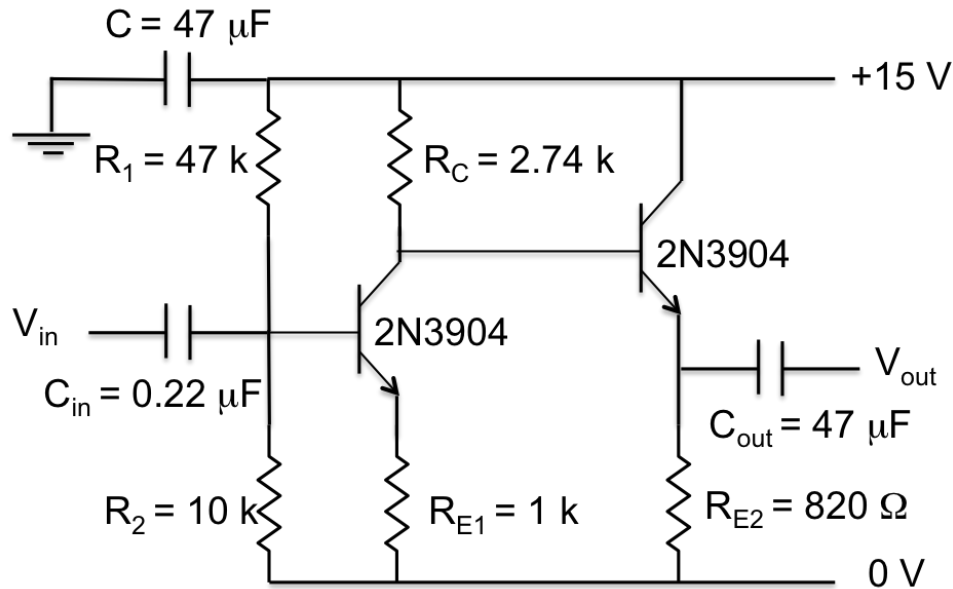|	
	Consider the maximum and minimum output voltages possible you calculated in the prelab. c. Now drive the circuit with an audio source. Describe your measurements and observations.

DUAL STAGE AMPLIFIER

Figure 4: Dual stage amplifier.

Step 4	**Quiescent State** a. Ordinarily, the quiescent base voltage is determined by a bias circuit (as was done for the common emitter stage). In the present case, the collector voltage V_C of the previous circuit already has a value suitable for biasing the follower, so a direct dc connection can be made between the two circuits. Add the emitter follower to your circuit to build the dual stage amplifier shown in Figure 4. Do not connect the 560 Ω load to the output yet. b. Predict and then measure the DC voltage values on the emitter follower's base, emitter, and collector. Do the measurements agree with your predictions? Correct for/Reconcile any errors before proceeding.
Step 5	**Low frequency AC Gain** a. Measure the voltage gain of the entire amplifier. Drive the complete system with the function generator. Measure the ac amplitudes at the input of the common emitter and emitter follower, and at the output. What is the gain of your emitter follower? Do these measurements agree with your predictions? *HINT: You may need to add a 220 kΩ resistor to ground after C_{out} to keep the dc level at the scope input near ground as the large output capacitor can slowly charge up. You may also want to put the scope on ac coupling when you probe points with large dc offsets but switch it back to DC if you want to measure quiescent voltages.*

Step 6	**Output Impedance**
	a. The emitter follower amplifier should have a low output impedance. Connect a 560 Ω load from the output to ground. What fraction of the original output do you now see? Does this agree with your lab-prep predictions? If not, can you use your measurements of the output voltage before and after the resistor was in place to refine the model of your amplifier's output impedance?
	b. Remove the load resistor and drive a speaker with the output of the amplifier. Explain how you hooked up the speaker. You can drive your amplifier with either an audio souce or the function generator. Describe your measurements and observations. Do they agree with your model of the output impedance of the dual stage amplifier?

Product	Output Impedance
Apple iPhone 4	0.97
Apple iPad I	1.39
Apple iPad2	0.89
Apple iPhone 4S	1.90
Samsung Nexus S	13.63
Samsung Galaxy Note 3G	3.44
Samsung Galaxy Note LTE	10.14
LG Optimus 2X	8.12
MOTOROLA QRTY (A853)	42.09
SONY ERICSSON XPERIA arc	13.44
Samsung Galaxy Tab 7.0	25.73
Samsung Galaxy S2 HD LTE U_PLUS	10.36
LG OPTIMUS LTE	7.69
Sky Vega Racer	10.16
SAMSUNG Slate 7	53.15
MOTOROLA ATRIX	42.42
htc EVO 4G+	22.88
Apple iPod 5.5G	5.29
Samsung Galaxy Player3.6 YP-GS1	1.98
Apple iPod touch 4G	3.74
SAMSUNG Galaxy Player YP-GB1	1.26
Apple iPad3	0.78
SKY Vega Racer2(LG U-Plus)	1.44
SAMSUNG Galaxy S3 (SKT 3G)	3.45
SAMSUNG Galaxy S3 (KT LTE)	3.96
Apple iPhone 5	**3.27**

Figure 5: Common cell phone output impedances.