Physics 623
Transistor Characteristics and Single Transistor Amplifier

February 10, 2023

1 Prelab Worksheet

Note: Work out the exercises on this sheet before the lab. It must be turned in when you arrive for the lab and will be graded. If you have any problems with these exercises, please [see, call, email] the instructor well in advance of the lab.

A. Read sections 2.1.1, 2.2.1A, and 2.2.7 in H&H. We'll need the first two transistor rules, which can be summarized as follows:

Golden Rules for Transistors
1) If the transistor is not "cut off" (i.e., if $I_C \quad 0$), then $V_{BE} \approx 0.6$ V.
2) If the transistor is not "saturated" (i.e., if $V_{CE} \quad 0$ – really $\quad\approx 0.2$ V), then $I_C = \beta I_B$. (usually $\beta \gg 1$)

B. Figure out the operating ("Q") point of the circuit in the lab writeup. Get the data sheet for the 2N1480 transistor from the course webpage. Outline of procedure for doing this:

1. Assume that the "If's" in the rules are satisfied. You should check this at the end.

2. For the first cut, assume that β is very large, and therefore, from 2nd rule, $I_B = I_C/\beta \approx 0$.

3. With no current into the base, the bias circuit of R_1 and R_2 is a simple unloaded voltage divider, so you can find VB (single subscripts on V's mean with respect to ground).

4. Use V_B and rule 1) to find V_E.

5. V_E is the voltage across R_E, so you can find the current through it, which is I_E.

6. Kierkoff's laws (just conservation of charge), require that the current into the collector plus the current into the base equals the current out of the emitter. Since $I_B \approx 0$, $I_C = I_E$.

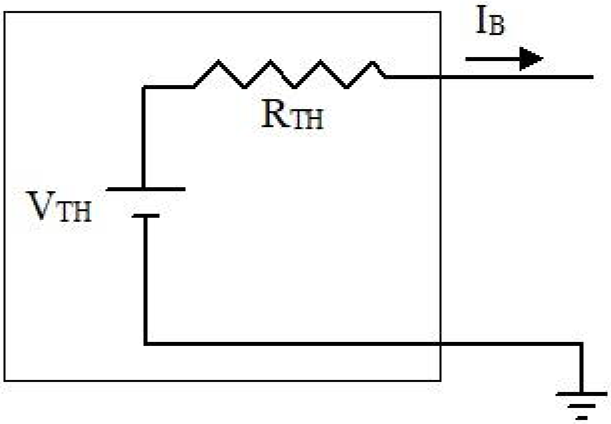
7. Use I_C to find the voltage drop across R_C. Subtract this from V_{CC} (the power supply voltage at the top of R_C) to get V_C (with respect to ground).

8. The difference $V_C - V_E \equiv$ VCE. Calculate this and check the "If" in rule 2.

C. Now calculate the 1st-order correction for finite β:

1. Use your first-cut value for I_C to calculate I_B for $\beta = 30$. ($I_B = I_C/\beta$, from rule 2.)

2. Make a Thevenin equivalent circuit of the bias divider:



V_{Th} = ________________

R_{Th} = ________________

3. Find V_B. ($V_B = V_{Th} – I_B R_{Th}$, from Ohm's law.)

4. Repeat 4 and 5 from part B to get V_E and I_E.

5. $I_C = I_E - I_B$ from conservation of charge.

6. Again, find V_C as in B7.

7. You could use the new I_C to find a new I_B and iterate, or (horrors!) write down the equations and solve simultaneously to get an exact V_C. In practice, **neither of these is normally necessary!**

D. Read Appendix F in the text on load lines.

E. Figure out what the "Voltage Gain" (A_V) of the circuit is: $A_V \equiv \Delta V_C/\Delta V_{In}$. In this circuit, $\Delta V_{In} = \Delta V_B$. Remember that ohm's law is linear, and with linear equations, you can solve for just the changes from your operating point.

2 Lab Instructions

2.1 Purpose

- To measure and understand the common emitter transistor characteristic curves.
- To use the base current gain (β), and load line analysis to predict and experimentally to verify the DC operating point (often called the "Q point") for your transistor in the common emitter configuration.
- To predict, using the transresistance model, the AC properties of your amplifier circuit and to verify them experimentally.
- To distinguish between current and voltage driven base signals.
- To understand the effect of emitter resistor by-pass (degenerative feedback) through a transresistance analysis.

2.2 Procedure

1. **Characteristic Curves** (common emitter)

   The first step in this experiment is to measure and record the common emitter characteristic curves for a silicon NPN 2N1480 transistor. These are diffused junction transistors with a fairly small base current gain.

   (a) Your lab instructor will illustrate the basic principles of operation of the curve tracer. The curve tracer will be used to measure the characteristics of your transistor and to make hard copies for your notebook.

   (b) Be sure to record the appropriate scale readings for your transistor for later analysis. Note also the wide variation between your transistor and those of your neighbors. In the Appendix we give the specifications for this transistor as listed by the manufacturer.

   (c) Compare your measured $\beta = I_C/I_B$ to the range given on the spec sheet. Except for Q-point calculations, the generally more useful quantity is the small signal parameter $h_{fe} = dI_C/dI_B$. The difference in value is usually not important.

2. **The "Q point" (or DC quiescent point)**

   So far we have been concerned only with the properties of the transistor itself. In practical amplifier applications, it is desirable to design a circuit whose properties are predictable, i.e. which don't depend strongly on your accidental choice of a specific transistor. In Fig. 1 we show a very common configuration of base and emitter biasing for the common emitter amplifier configuration. This circuit is reasonably stable against variations in transistor properties (for $\beta = h_{fe}$ ranging from 14 to 40, the Q point stays within 20% of $V_{CE} \simeq 6.5\ V$).

3. Before you connect your circuit, predict what the DC operating point (Q point) will be. This may be done in the following way:

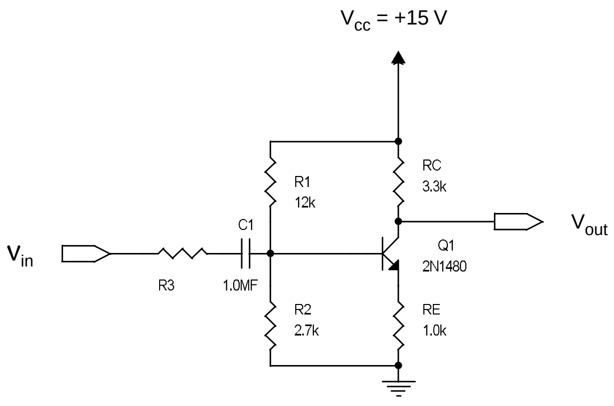


Figure 1: Basic Single Transistor Amplifier

(a) Construct the Thevenin equivalent circuit for the base bias circuit.

(b) The base-emitter voltage drop for a forward-biased Si transistor is 0.6 V. Therefore $V_E = V_B - 0.6$ V.

(c) The emitter current I_E, will be $I_E = \frac{V_E}{R_E}$ from Ohm's law. The base current $I_B = \frac{I_E}{\beta}$. You could load your Thevenin equivalent of the base bias circuit with the current I_B, calculate a new V_B and solve these equations simultaneously to get the exact operating point, but this is seldom necessary. If the bias network design is good (meaning not too sensitive to β, a single iteration will yield a very accurate approximation to the operating point.

(d) Using Ohm's law, calculate I_E, and, thus I_C, since they are about the same.

(e) From the equation for the collector-emitter circuit:

$$V_{CC} = I_C R_C + V_{CE} + I_E R_E$$

calculate V_{CE}. You have now determined the DC operating point (the Q point). The equation for the load line can be written (assuming $I_C = I_E$),

$$I_C = \frac{(V_{CC} - V_{CE})}{(R_E + R_C)}$$

4. Draw the load line on your characteristic curves and mark your calculated Q point.

5. Next connect the circuit as shown schematically in Fig. 1. Be sure to check the transistor pin-out diagram at the end of the transistor data sheet. (**Transistors** are normally drawn as if you were **looking at the transistor leads from the lead side** while integrated circuits are normally drawn as if you were looking at the pins from

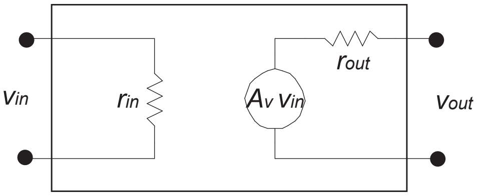


Figure 2: Equivalent Circuit for a Voltage Amplifier. This circuit *defines* A_V, r_{in}, and r_{out}.

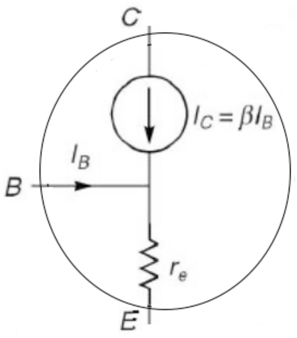


Figure 3: Small Signal Equivalent Circuit for NPN transistor. r_e (often called r_{tr}) represents the "dynamic impedance" (inverse local slope of the I-V curve) of the base-emitter diode.

above the circuit board, ie from the side away from the IC pins.) Measure V_{CE},V_E,V_B, and V_{BE} and compare with your calculated values. (They should agree within $\sim 10\%$).

6. **AC properties.** Three important parameters, defined by the coupled Thevenin equivalent circuits of the amplifier input and output shown in Fig. 2, determine the AC behavior of the amplifier. They are:

   (a) The input impedance (r_i),

   (b) The output impedance (r_o), and

   (c) The voltage gain ($A_v = v_o/v_i$).

   Before actually measuring these quantities, it is instructive to estimate them. Use the transresistance model, in which the transistor is replaced by an equivalent circuit containing a current generator $i_c = \beta \mathrm{i}_b$ in series with the base emitter resistor r_{tr} (called the transresistance). The equivalent circuit is shown in Fig. 3. By differentiating the basic diode equation (for a p-n junction) we find that the dynamic base emitter resistance or "transresistance" is inversely proportional to the current I_E.

$$r_{tr} = \frac{\partial V}{\partial I} = \frac{0.026\ \Omega \cdot \mathrm{A}}{I_E}.$$

Thus, the transresistance is:

$$r_{tr} = \left(\frac{0.026\ \Omega \cdot \mathrm{A}}{I_C} + 2\ \Omega \right)$$

where we have assumed $I_C \simeq I_E$ and the "2 ohm" is a rough average value for the ohmic resistance of the internal connection to the emitter junction. Note that an AC signal introduced on the base lead can pass to AC ground through three paths: R_1, R_2, and through the transistor. So, r_i (common emitter input impedance) is calculated as:

$$r_i = R_1 \parallel R_2 \parallel (r_b = \beta(r_{tr} + R_E))$$

(with "$\|$" meaning "in parallel" so you add reciprocals to get the reciprocal of the combination).

The common emitter AC voltage gain is then:

$$A_v = \frac{v_o}{v_i} = -\frac{i_c R_C}{i_c(r_{tr} + R_E)} = -\frac{R_C}{(r_{tr} + R_E)}.$$

In this approximation. the output impedance $r_o = R_C$.

7. **(a)** Now introduce a AC signal (a sine wave from the waveform generator) of frequency $f = 5\ KHz$ into the base through a coupling capacitor $C_c \geq 1.0\ \mu$F and measure r_i, A_v and r_o. To measure r_i , introduce a series resistor (R_3), and calculate r_i using the voltage divider equations.

   (b) Vary the magnitude of the input signal and note any distortion in the output signal which results.

   Interpret the distortion using the output characteristics and the load line.

   (c) Measure the frequency response (or band width) of your amplifier ($A_v(\omega)$) and try to identify the lower corner frequency in terms of the component values.

8. **Emitter Resistor Bypass ... Current and Voltage Drive.** To have a true common emitter configuration for an amplifier, the emitter resistor R_E, is bypassed by a large capacitor ($\sim$ 1 to 2 μF). The result is that the emitter is at AC ground, while at the same time preserving DC stability. In the previous measurements when R_E was not bypassed, much of the input signal was "fed back" onto the emitter, greatly reducing v_{be}, from its value when the emitter is at AC ground. This situation is an example of "degenerative (or negative) feedback" and has several results. One desirable effect is to enable the amplifier to linearly amplify for a larger range of input signals. Another is that the gain of the amplifier is determined mainly by the choice of circuit parameters R_C and R_E and not by variations in transistors. The price we pay for these advantages is a reduction in gain.

9. **(a)** Connect a 1 to 2 μF capacitor across R$_E$ and remeasure r_i, r_o and A$_v$. Again use the transresistance model to estimate the voltage gain and compare to your measurements. *Note: To avoid saturationg the transistor, the input signal must be reduced in magnitude by a factor* $\sim 20 - 50$, *which can be accomplished using the attenuator provided.*

   (b) Verify the reduction and connection at the input to the amplifier using the scope. Note the increased gain (and also the smaller bandwidth compared to the circuit incorporating feedback. The distortion is due to the fact that i_C depends exponentially on v_{BE}.

   (c) To produce a current signal for the input, introduce a 50k resistor in series with the function generator output to produce a high impedance (current) source.

   (d) Note that now v_o is undistorted while v_{be} is considerably distorted. Try to interpret this effect in your notebook.