Lab 8: Differential Amplifier

U.C. Davis Physics 116A

Reference: Bobrow, pp. 650-659

INTRODUCTION

In this lab, you will build and analyze a differential amplifier, or "differential pair". It has this name because this circuit amplifies the difference between two input voltages.

This two-transistor configuration is at the heart of the operational amplifier or "op amp" which we have already encountered in the ideal form in our circuit analysis. Most real-world lab amplifiers use op amps or some sort of differential amplification scheme.

1. PRELAB (!)

Before coming to lab, do the DC calculations for the differential amplifier, shown in figure 1. Assume $v_1 = v_2 = 0\text{V}$, the emitter currents are the same in the two transistors, and both transistors are in the active region. Also assume $I_C \approx I_E$. Use the following values for the resistors:

$$R_C = R_B = R' = 4.7\text{k}\Omega - 10\text{k}\Omega$$

(pick a single value for the R's above),

$$R_E = 100\Omega.$$

Calculate the voltages at points A, B, C, D, E, and F.

For your lab report, show your calculations.

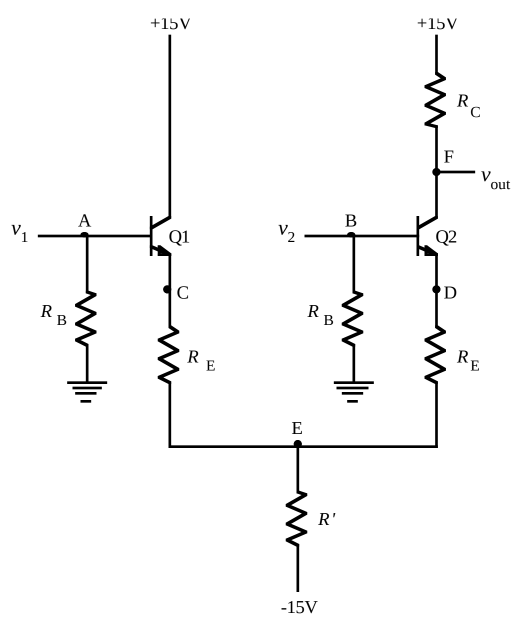

Figure 1: A differential amplifier.

2. DC ANALYSIS

Construct the circuit of figure 1, for which you have already calculated the voltages at the lettered nodes. Leaving v_1 and v_2 unconnected, measure the voltages at the lettered nodes and compare to your calculated values. Put this in your report.

3. AC ANALYSIS

Now use the function generator to supply the AC input voltages for v_1 and v_2. Use three separate configurations: one with v_1 receiving input and v_2 grounded, one the opposite of this (v_2 receiving input and v_1 grounded), and one with both v_1 and v_2 connected together receiving input. The first two configurations are "differential modes" and the latter is "common mode". For each of these configurations, measure the small signal gain. For each measurement, try to use an output signal that is several volts peak-to-peak and is centered on 7.5 volts. Compare these measured gains to the values calculated in class (if they have been calculated in class).

Also for each of these three configurations, note the phase of the output with respect to the input. Which configurations invert (180 degree phase shift) and which do not? The v_1 input is called the "noninverting input" and v_2 is called the "inverting input". Do these names agree with what you observe?

For your lab report, include the calculated and measured gains and phase shifts, a brief discussion comparing them (in the standard error-analysis way), and a brief discussion on the naming of the inputs.

4. QUALITY OF OUTPUT

Measure the output signal rise time. To do this, put a high frequency square wave on the noninverting input and ground the inverting input. Adjust the input voltage so the output is a fairly large amplitude. ("Large amplitude" means close to the power supply limits.) For your report, sketch the output and identify and measure the rise time.

Ideally, an amplifier will be *linear*. That is, it will very accurately obey

$$v_{\text{out}} = A_v v_{\text{in}} + V_{\text{offset}}.$$

(Compare to the equation for a line, $y = m x + b$ from linear algebra.) Real amplifiers approach linearity only for a limited range of output voltages.

Find the range of output voltages for which this amplifier is reasonably linear. To do this, put a large amplitude, medium frequency triangle wave on one of the inputs and ground the other. The output waveform will be very straight where the amplifier is linear and will appear curved where it is nonlinear. For your report, sketch a sample output waveform showing linear and nonlinear regions and mark the approximate voltage range where the output is linear.

Last, increase the gain of the amplifier and see if this affects its linearity. To do this, short out the emitter resistors. Measure the gain (in noninverting differential mode only) of this new circuit and repeat the linearity check described above. R_{E} provides negative feedback which should improve linearity and reduce gain. Is this what you observe? For your lab report, include the new measured gain, a new sketch of the output indicating nonlinearities, and a brief discussion of how R_{E} affects linearity and gain.

Physics 116A: Differential Amplifier: Analysis of Operation

David E. Pellett
UC Davis Physics Department
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The differential amplifier shown in Fig. 1 is useful because:

- it operates without input capacitors (DC amplifier);
- it provides voltage gain for *differential* signals on the inputs, $V_d \equiv V_1 - V_2$, while attenuating interfering *common-mode* signals, $V_c \equiv (V_1 + V_2)/2$;
- it provides the inverting and non-inverting inputs needed for operational amplifiers.

With slight variations, the circuit can also be made with pnp BJTs or FETs. A current source can replace R' and V_{EE} for better common mode signal rejection.

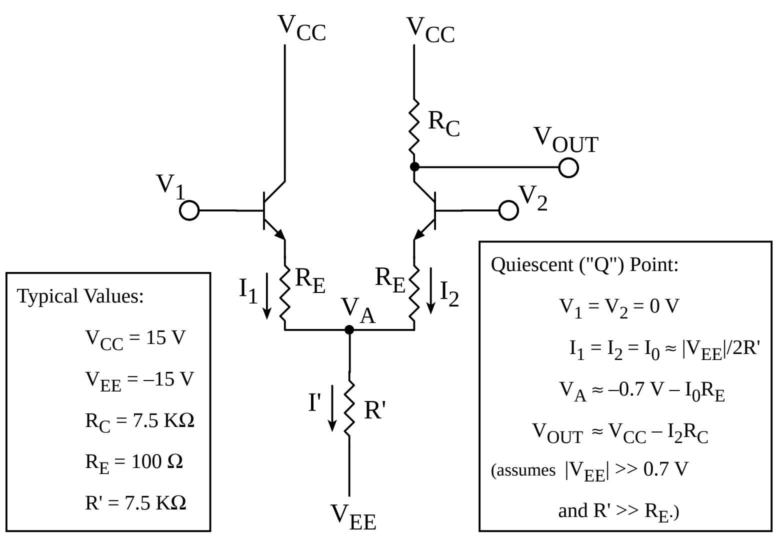

Figure 1: Differential amplifier circuit diagram with representative component values and Q point parameters for npn BJTs.

The differential amplifier operation can be understood qualitatively as follows. V_{EE} and R' form an approximate constant current source, $I' \approx |V_{EE}|/R'$, with

$$I_1 + I_2 = I'.$$

When both inputs are at 0 V, the current splits equally in the two branches.

If V_1 is raised slightly while holding $V_2 = 0$, KVL going from input 1 to input 2 (ground) by way of point A tells us:

$$V_1 - 0.7\text{ V} - I_1 R_E + I_2 R_E + 0.7\text{ V} = 0.$$

This reduces to

$$I_1 = I_2 + V_1/R_E.$$

I_1 is now greater than I_2, so I_2 must have decreased since the total, I', is approximately constant. Reducing I_2 lowers the voltage drop across R_C, so V_{out} increases. V_1 is the non-inverting input.

In the same way, raising V_2 slightly with V_1 grounded increases I_2. This now increases the voltage drop across R_C and lowers V_{out}. V_2 is the inverting input.

A more complete analysis can be done using the small signal AC model for the circuit, shown in Fig. 2.

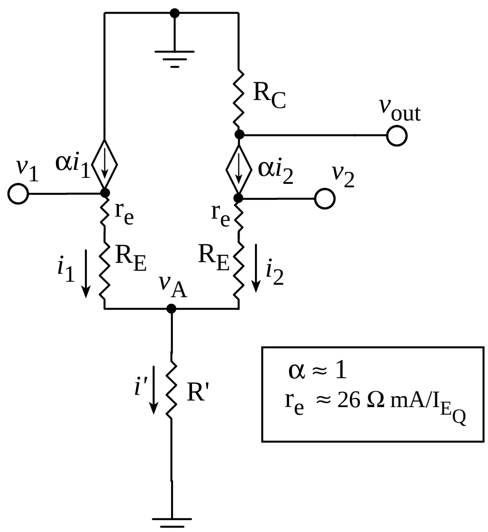

Figure 2: Small signal AC model for the differential amplifier.

Here, all voltages and currents have been replaced by the *deviations* from their values at the quiescient point. For example, $i_1 = I_1 - I_0$. The transistors have been replaced by simple active region models.

1. *Differential mode* gain:

   Define $v_d \equiv v_1 - v_2$. The differential mode gain is

   $$A_{vd} \equiv v_{out}/v_d.$$

   Apply the following input voltages to the amplifier: $v_1 = v_d/2$ and $v_2 = -v_d/2$. Use KVL:

   $$v_1 = i_1(r_e + R_E) + (i_1 + i_2)R' = v_d/2,$$
   $$v_2 = i_2(r_e + R_E) + (i_1 + i_2)R' = -v_d/2.$$

   Adding the equations and collecting terms results in $i_2 = -i_1$, which also leads to $v_A = (i_1 + i_2)R' = 0$. Therefore,

   $$i_2 = v_2/(r_e + R_E) = -v_d/2(r_e + R_E).$$

$v_{out} = -R_C i_2$, so $v_{out} = -R_C(-v_d)/2(r_e + R_E)$. We can now solve for the differential mode gain:

$$A_{vd} \equiv v_{out}/v_d = R_C/2(r_e + R_E).$$

2. *Common mode* gain:

   Define $v_c \equiv \frac{1}{2}(v_1 + v_2)$. The common mode gain is

$$A_{vc} \equiv v_{out}/v_c.$$

   Apply $v_1 = v_2 = v_c$ and use KVL to find i_2 in terms of $v_c = v_2$:

$$v_c = i_2(r_e + R_E) + 2i_2R',$$

$$i_2 = v_c/(r_e + R_E + 2R').$$

   Since $v_{out} = -i_2 R_C$,

$$A_{vc} \equiv v_{out}/v_c = -R_C/(r_e + R_E + 2R').$$