Week 4: Transistors cont’d – Ebers-Moll, differential amplifiers, toward an op-amp from discrete components
Let’s begin by revisiting the emitter amplifier (here with blocking cap and DC-offset)

Recall property 4 of transistors, from last week: $I_C = \beta I_B$

... but this breaks down when we ask too much of our transistor...

This brings us to a slightly modified (and more accurate) representation of the BJT: the Ebers-Moll model. Provided properties 1-3 are satisfied ($V_C > V_E$; $V_{be} > 0.6$; $I_C$, $I_B$ & $V_{CE}$ below limit values):

$\begin{align*}
I_C &= I_S \left( e^{\frac{q V_{BE}}{kT}} - 1 \right) \\
V_T &= kT/2q = 25 \text{ mV} @ \text{Room Temp.}
\end{align*}$

Where $I_S$ is the $T$-dependent saturation current of the transistor.

Introduction of blocking cap enhances gain and introduces non-linear response of the amplifier.

Points for discussion on Piazza:

1. What is the input impedance for this amplifier, and why?
2. What is $f_{3dB}$ for the emitter leg configuration including a 15μF capacitor?
How does Ebers-Moll alter our four properties of transistors?

Ebers-Moll implies the following four important quantities (see AoE § 2.10):

1. We must now view our transistor as a \textit{trans-conductance device}: it can drive currents in proportion to $V_{BE}$. With E-M, this implies a diode curve. From E-M relation, we can calculate the required increase in $V_{BE}$ to generate a 10-fold increase in $I_C$: $I_C = I_C^0 e^{\Delta V/25}$. At room temperature. This corresponds to an increase of 10x per ~60mV increase of $V_{BE}$.

2. Small-signal impedance into the emitter implies a `little-$r_e$’ – this resistance can be calculated by taking the derivative of $V_{BE}$ with respect to $I_C$: $r_e = \frac{V_T}{I_C} = 25mV/IC$ ohms. Here, $r_e$ acts like a series resistor with the emitter leg.

3. $V_{BE}$ has a negative temperature coefficient (it decreases as $T$ increases).

4. The Early effect: $V_{BE}$ depends on $V_{CE}$ as: $\Delta V_{BE} = -\alpha \Delta V_{CE}$, where $\alpha$ is typically 1e-4.

Points for discussion on Piazza:
Why does $V_{BE}$ have a negative Temp. coefficient?
(Hint: it has to do with how $I_S$ behaves)
An inelegant segue: The dreaded *common-mode*: how to handle a signal that is susceptible to ambient electrical noise?

Suppose you have a transducer attached to a sample:

And there is ambient electrical noise.

Note that both leads, + and −, carry this noise!

- You can easily see this from the 50 Hz signal carried on power lines.

\[ ΔT = \frac{1}{50} \]

Often, your signal will look like this:

While expecting this:
Let’s reject the common-mode with differential amplifiers:

In order to reject swings of $V$ that occur on both the `+` and `−` lines of our signal – the so-called `common mode.' Differential amplifiers are ideally suited to this purpose, as they only amplify differences between the signal leads. Let’s take a look:

- Evaluate gain for $− = +$ (common-mode)
  
  @ point A, $V_A$ increases/decreases in proportion to input.
  
  $G_{cm} = \frac{R_c}{(R_E + 2R_1)}$

- Evaluate gain for $Δ− = −Δ+$(normal-mode):
  
  @ point A, $V$ is fixed (consider symmetry of circuit).
  
  $G_{nn} = \frac{-R_c}{2R_E}$
Differential amplifier continued:

Let us now evaluate the **relative gain of CM & NM**, the "CMRR" (common-mode rejection ratio):

\[
CMRR = \frac{G_{NM}}{G_{CM}} = \frac{\frac{R_c}{2R_e}}{\frac{R_e+2R_1}{R_c}} = \frac{R_e+2R_1}{2R_e} \approx \frac{R_1}{R_e} \quad (\text{if } R_1 \gg R_e)
\]

Points for discussion on Piazza:

1. Verify the gain of the common-mode with this amplifier construction
2. Verify the gain of the normal-mode with this amplifier construction
Enhancing CMRR: current-source biasing

Note that for a given $R_E$, whatever load is attached to the collector will pull $I_C$ through it:

$$I_C = \frac{V_b - 0.6}{R_E}.$$  

The circuit is thus a current source.

Recognizing that point A in our differential amplifier is a quiescent point, what happens if we replace $R_1$ with a current source? Let’s review our CMRR:

$$\text{CMRR} = \frac{R_1}{R_E} \ldots \text{but what is } R_1 \text{ for the current source?}$$

**Hint:** For $\Delta V$, how does $\Delta I$ change?

In any case, $R_1$ for the current source is large.

- For a p-channel transistor set & a JFET current source, CMRR can exceed $10^5$!

![Circuit Diagram]
Building an open-loop op-amp from discretes

Here, we’ll use discrete components to build an open-loop op-amp from discrete transistors & passives. Note that the layout prescribes the pins used on the CA 3096 IC, which includes 5 transistors on-board (3 npn & 2 pnp). These can offset T-related modifications to transistor response, as all transistors are the same temperature.