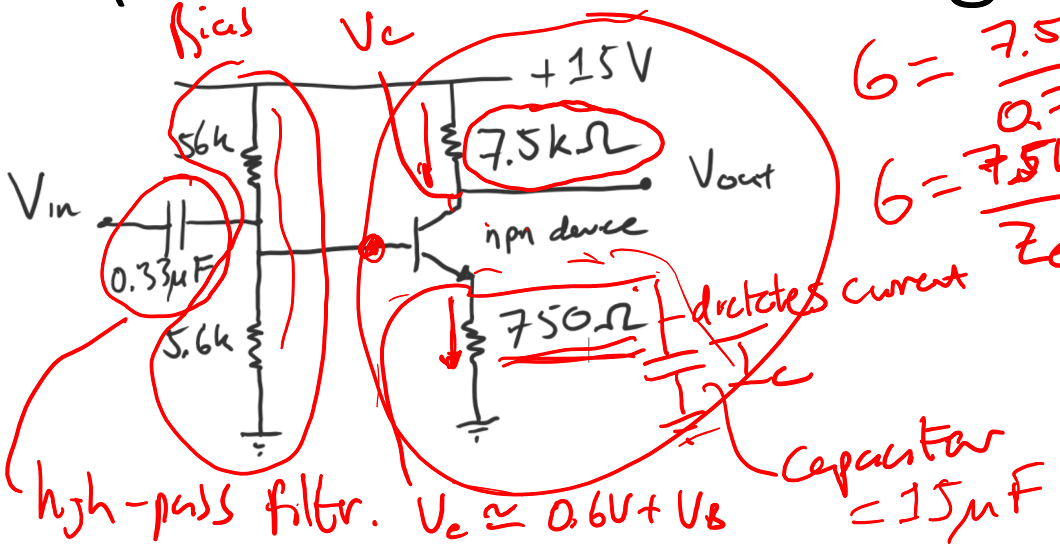
Week 4: Transistors cont’d – Ebers-Moll, differential amplifiers, toward an op-amp from discrete components

Let's begin by revisiting the emitter amplifier (here with blocking cap and DC-offset)

$G = \frac{7.5k}{0.75k}$ @ D.C.

$G = \frac{7.5k}{Z_e}$ @ A.C. : can become v. large!



Recall property 4 of transistors, from last week: $I_C = \beta IB$ 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 (Vc > Ve; Vbe > 0.6; I_C, I_B & V_{CE} below limit values):

$$I_C = IS\left(e^{\frac{q\,VBE}{kT}} - 1\right)$$

1. I_s 2. V_{BE} 3.

Where I_S is the *T*-dependent saturation current of the transistor. Note that $kT/q = V_T = 25$ mV @ Room temp.

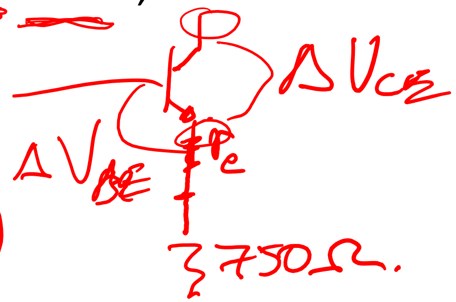
Introduction of blocking cap *enhances gain* and introduces non-linear response of the amplifier

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?

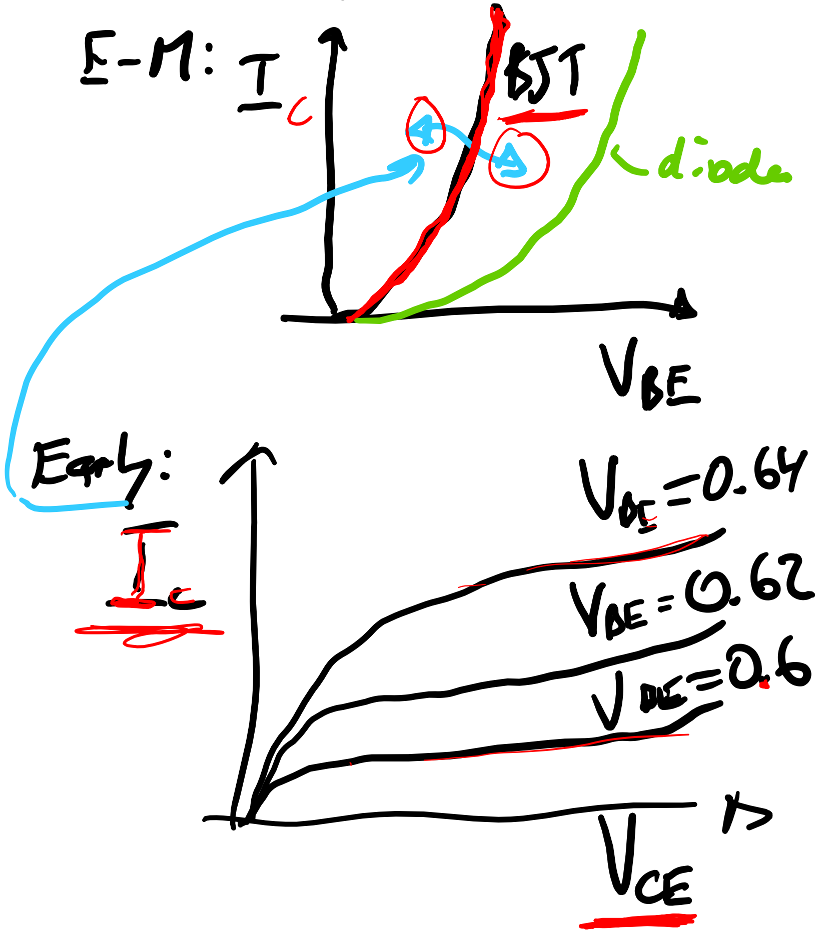
Ebers-Moll implies the following four important quantities (see AoE § 2.10):

1. We must now view our transistor as a *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: $I_C = IC_0\, e^{\Delta V/25}$ mV At room temperature. This corresponds to an increase of 10x per ~60mV increase of V_{BE}. ($V_T \approx 25$ mV)
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: $\Delta V_{BE} = -\alpha\, \Delta VCE$, where α is typically 1e-4.



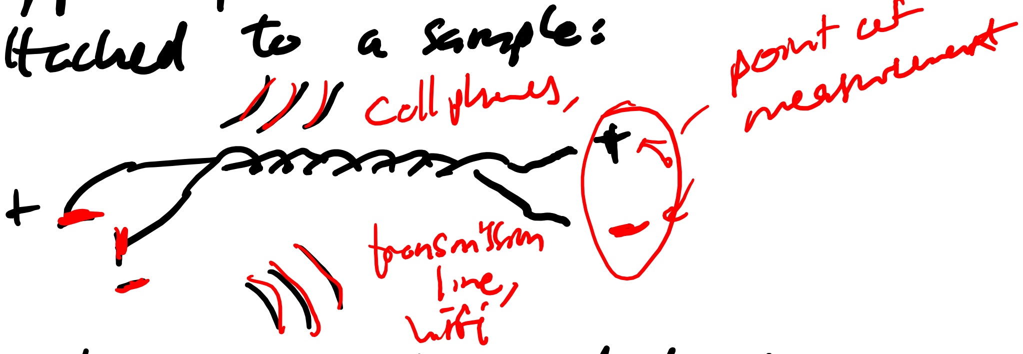
Points for discussion on Piazza:
Why does V_{BE} have a negative Temp. coefficient?
(Hint: it has to do with how I_S behaves)

A graphical summary of Ebers-Moll and the Early Effect:



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:

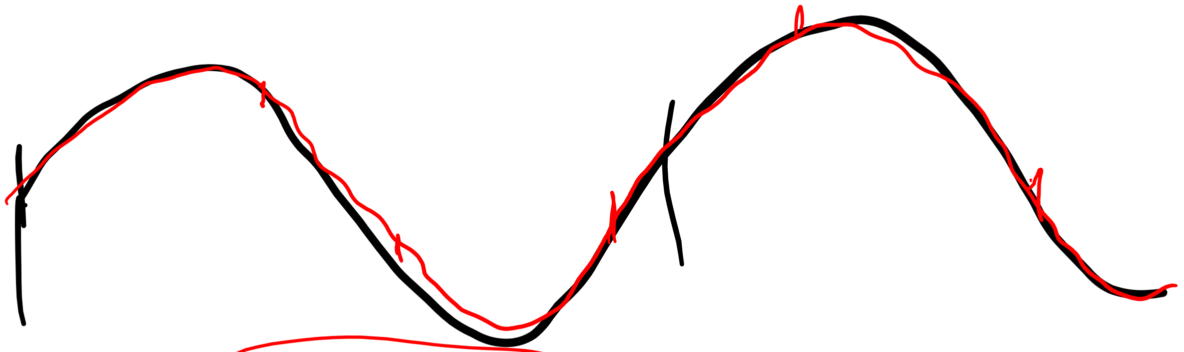


And there is ambient electrical noise:

Note that both leads, + & -, carry this noise!

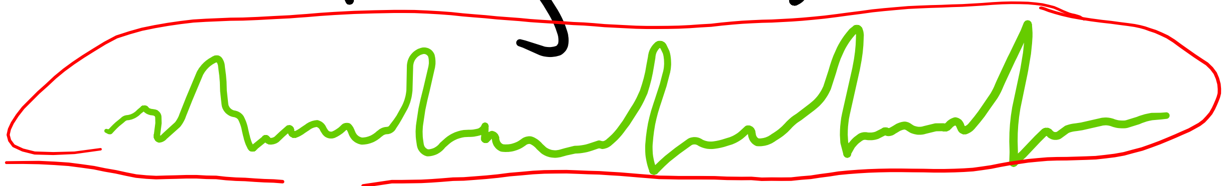
- you can easily see this from the 50 Hz signal carried on power lines.

Often, your signal will look like this:



$$\Delta T = \frac{1}{50}$$

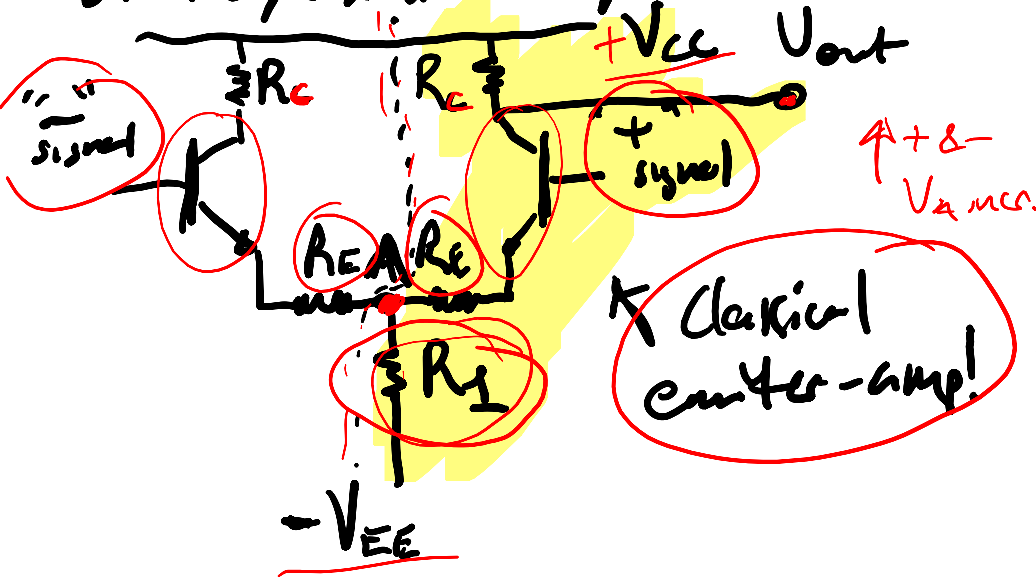
While expecting this:



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:

Start w/ Emitter Amps:



A is a "quiescent point"

How does this reject common-mode?

- Evaluate gain for "–" = "+" (common-mode):
  @ point A, V_A increases/decreases in proportion to input.

$$\boxed{G_{cm} = \frac{R_c}{(R_E + 2R_1)}}$$

- Evaluate gain for Δ"–" = $-\Delta$"+" (normal-mode):
  @ point A, V is fixed (consider symmetry of circuit).

from symmetry of V

$$\boxed{G_{nm} = \frac{-R_c}{2R_E}}$$

Differential amplifier continued:

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

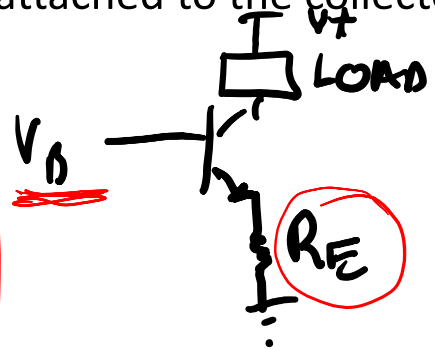
$$CMRR = \frac{G_{NM}}{G_{cm}} = \frac{R_c}{2R_E} \frac{(R_E + 2R_1)}{R_c} = \frac{R_E + 2R_1}{2R_E} \simeq \boxed{\frac{R_1}{R_E}} \quad (\text{if } R_1 \gg R_E)$$

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:



here, $I_C \cong \frac{V_B - 0.6}{R_E}$.

This circuit is thus a current source.

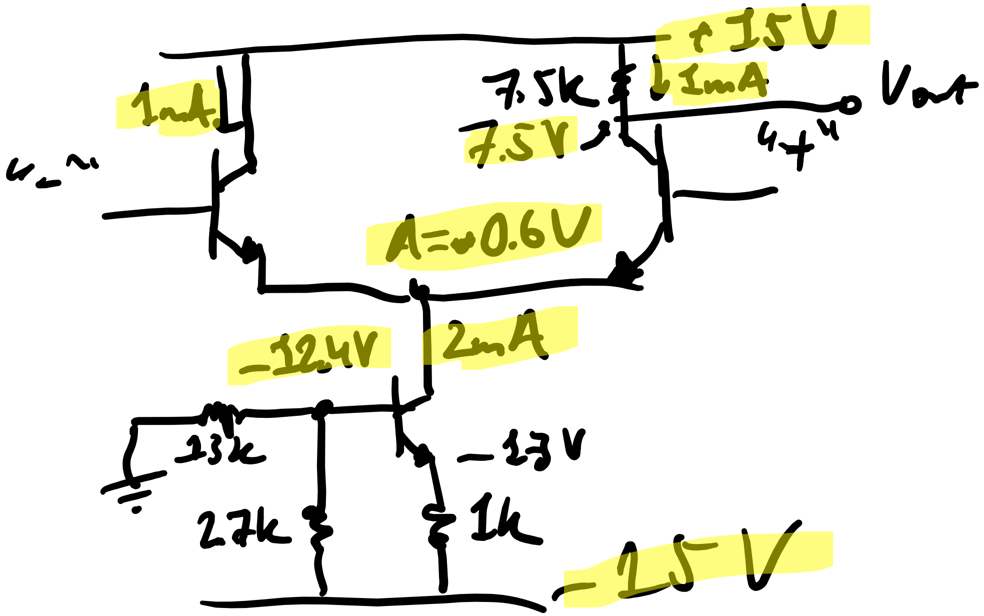
Recognizing that point A in our differential amplifier is a quiescent point, what happens if we replace R_1 with a current source? Let's review our CMRR:

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

hint: for ΔV, how does ΔI change?

In any case, R_{eff} for the current source is large.

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



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.