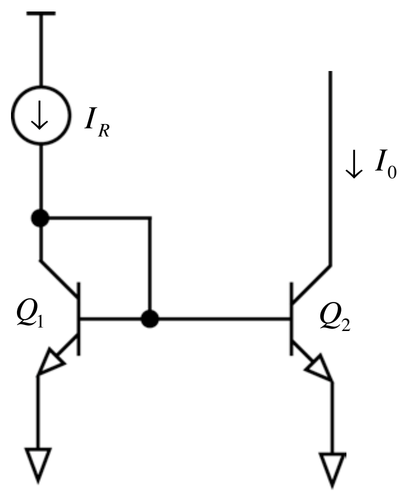
6.301 Solid-State Circuits

Recitation 14: Op-Amps and Assorted Other Topics
Prof. Joel L. Dawson

First, let's take a moment to further explore device matching for current mirrors:



and ask what happens when Q_1 and Q_2 operate at different temperatures. It turns out that grinding through the math doesn't yield a great deal of insight:

$$\frac{I_1}{I_2} = \frac{I_{S1}\exp\left[\frac{qV_{BE}}{kT_1}\right]}{I_{S2}\exp\left[\frac{qV_{BE}}{kT_2}\right]} = \frac{I_{S1}}{I_{S2}}\exp\left[\frac{qV_{BE}}{k}\left(\frac{1}{T_1}-\frac{1}{T_2}\right)\right]$$

We must consider, too that the saturation currents I_S are temperature-dependent as well. It turns out that I_S can be written

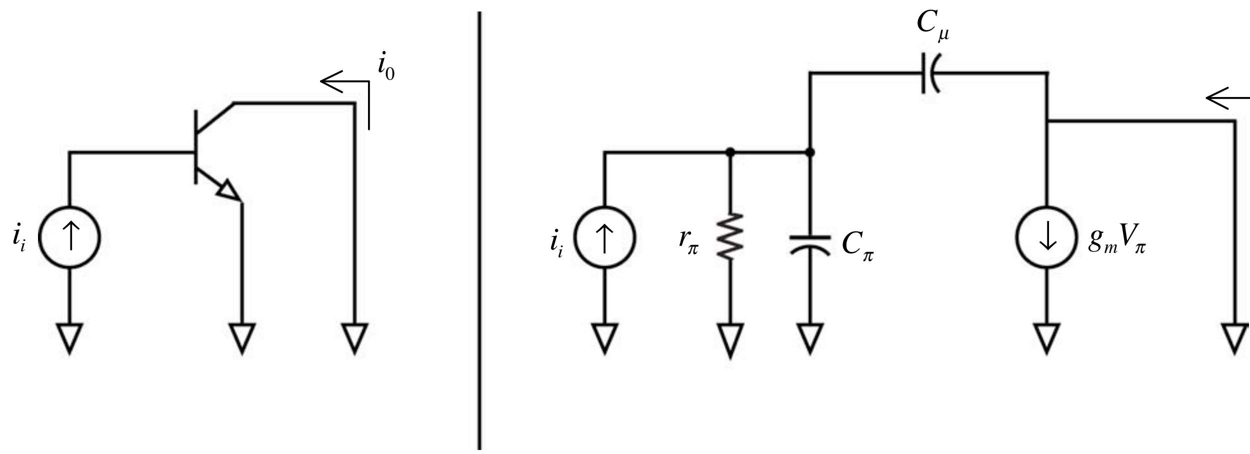
$$I_S = \frac{T^{\gamma}}{E}\exp\left(-\frac{qV_{G0}}{kT}\right)$$

Where E, γ are constants and V_{G0} is the bandgap voltage. All I can say here is that if Q_1 and Q_2 are at different temperatures, $I_1 \neq I_2$. End of story.

Next, let's take a moment to consider carefully a (true) statement that Prof. Roberge has made in class in previous semesters. I can't quote him exactly, but he said something like:

"When transistors are run at low collector currents, they tend to have low f_T s."

What does this mean? Well, f_T concerns the result of the following experiment:



We ask ourselves, what is the frequency at which the current gain $\left|\frac{i_0}{i_i}\right|$ falls to unity? That frequency is called the "f_T" of transistor, and is given by the expression

$$f_T = \frac{1}{2\pi} \frac{g_m}{C_\pi + C_\mu}$$

People quote this number as a general indication of how "fast" a transistor is. Generally speaking, it will be easier to design a high-bandwidth amplifier using a transistor with a higher, rather than lower f_T . Note that since the output is short-circuited, the Miller effect never comes into play. This causes C_π and C_μ to be treated equally for the sake of f_T , but we know that for real voltage amplifiers C_μ can be more painful.

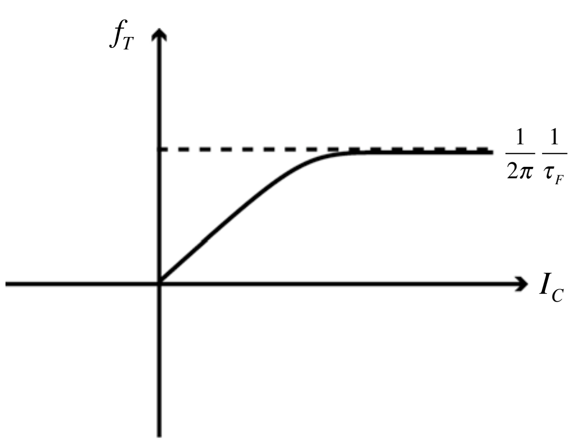
Looking at this expression, we can express parts of it in terms of the collector current I_C.

$$g_m = \frac{I_C}{V_T}$$

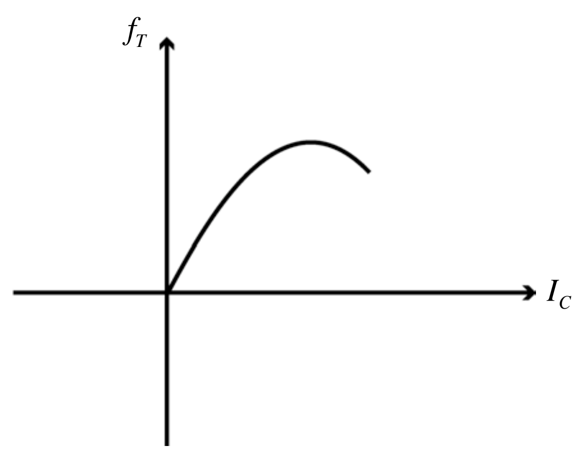
$$\begin{aligned} C_\pi &= g_m \tau_F + C_{je} \\ &= \frac{I_C}{V_T}\tau_F + C_{je} \end{aligned}$$

$$f_T = \frac{1}{2\pi} \frac{\frac{I_C}{V_T}}{\tau_F \frac{I_C}{V_T} + C_{je} + C_\mu}$$

We see that in the limit of $I_C \to 0$, $f_T \to 0$, while in the limit of $I_C \to \infty$, $f_T \to \frac{1}{2\pi}\frac{1}{\tau_F}$. Below is a sketch of f_T vs. I_C as predicted by this simple theory; next to it is a graph from a measured device.



Simple Theory



Reality
(β_F tends to decay at high currents.)

Now, at last on to the class exercise.

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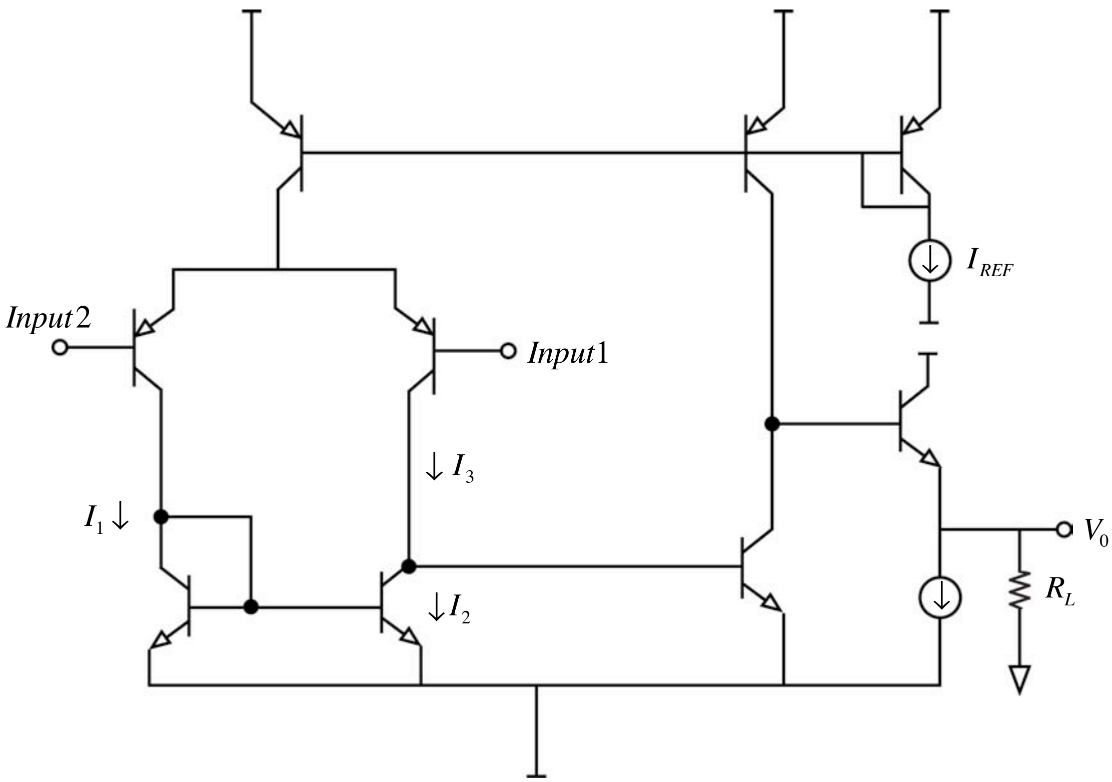
CLASS EXERCISE

Consider the simple op-amp shown below. Which is the inverting input, and which is the non-inverting input?

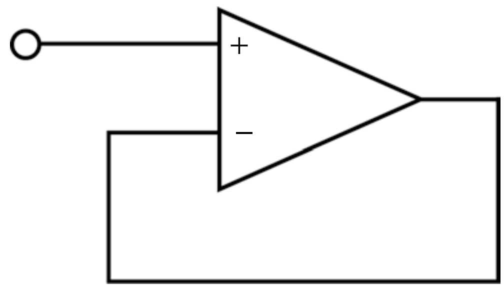


This is a seemingly simple exercise, but tracing things through helps you begin to understand how these things are put together.

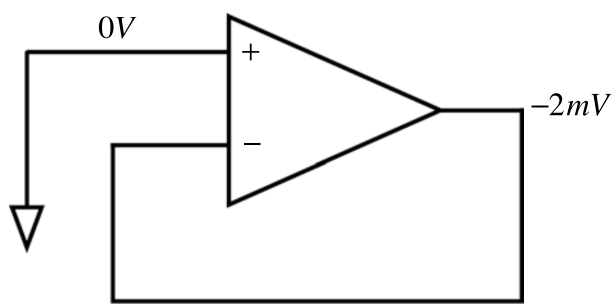
Now, notice that the input stage is loaded with a current mirror. We know, based on our knowledge of the "simple" current mirror, that I_1 and I_2 are related by

$$I_2 = \frac{I_1}{1+\frac{2}{\beta}}$$

If the two inputs are the same (the differential input voltage is zero), $I_1 = I_3$. This means that $I_3 \neq I_2$ …which means trouble? Fortunately not. This is one of those cases where the designer relies on the op-amp being in a feedback connection. Take, for example, a follower:

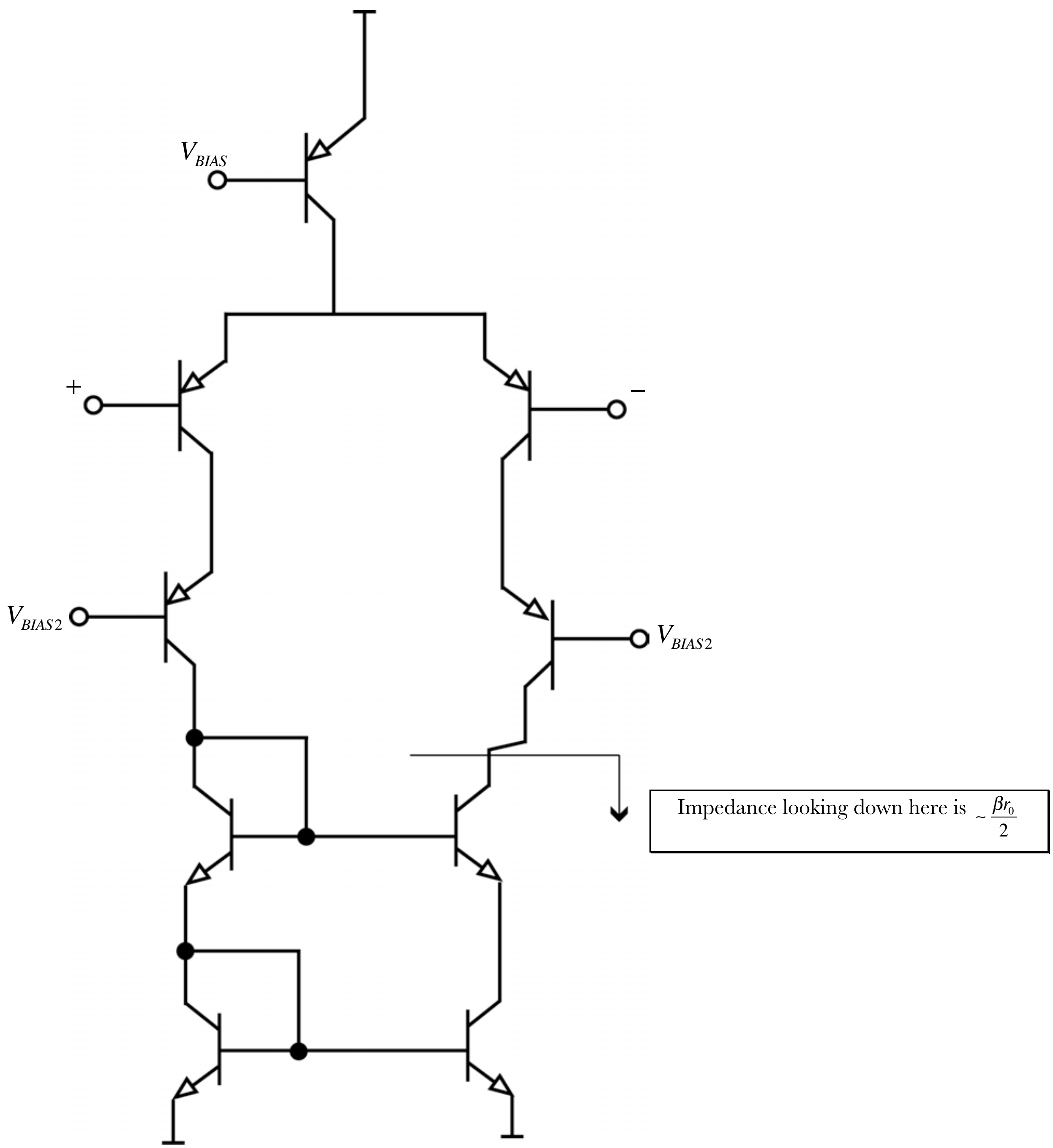


In the op-amp on the last page, we expect $I_2 < I_3$ for zero differential input. Connected as above, though, this would drive the output, and therefore the inverting input, low. When the inverting input is drawn low, it causes I_2 to increase. The system quickly equilibrates to $I_2 \approx I_3$, and if we measure the voltages we might measure something like:



Particularly in ICs it is not uncommon to implement an entire op-amp in a single stage. There are many tricks for getting a lot of gain. It is sometimes useful to use cascoding to establish very high-impedance nodes.

Input stage that could be used for very high gain:



This concept is more commonly used with MOSFETS, especially in situations when you expect to drive a purely capacitive load.

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