6.301 Solid-State Circuits

Recitation 13: Current Sources and Current Mirrors
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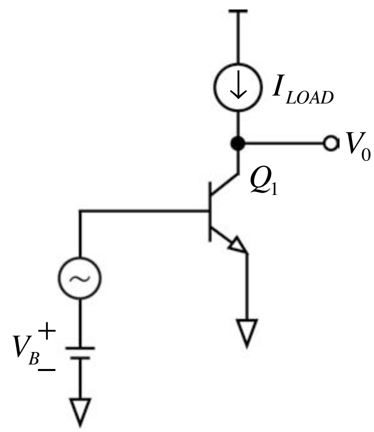
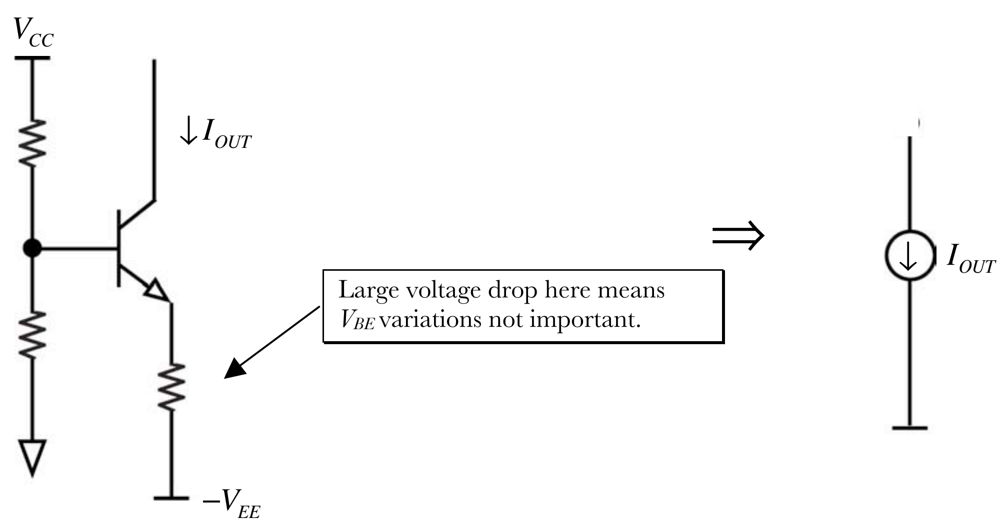
Many times in complex analog systems, it is useful to have a current source. Consider our "active loading" concept from the last recitation:



Remember we speculated that if we could make the collector current of Q_1 match I_{LOAD}, this might be a way to get a very high gain stage. Infinite gain, even, were it not for base width modulation.

Now we know that transistors themselves make very good <u>dependent</u> current sources. This suggests their use as good independent current sources, provided that we fix the base-emitter voltage in some sensible way.

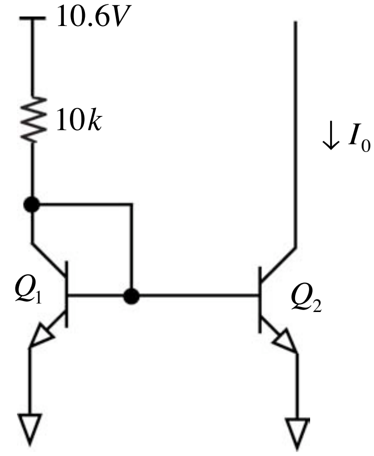
One sensible way that we looked at as follows:



This is a fine idea when you have a lot of voltage headroom. Today we're going to look at alternatives, though, that often prove to be more useful.

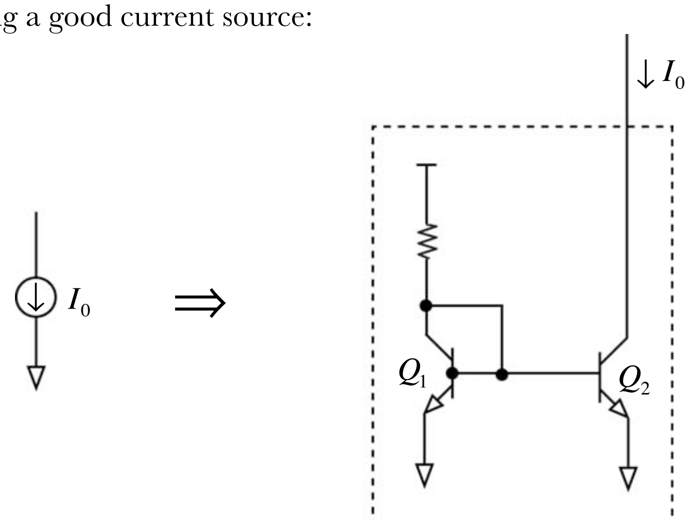
CLASS EXERCISE

Compute I_0 for the following circuit:

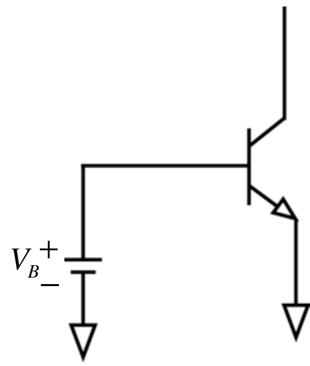


(Workspace)

And just like that, we discover the current mirror. It's a basic analog building block, and is one way that we have for building a good current source:



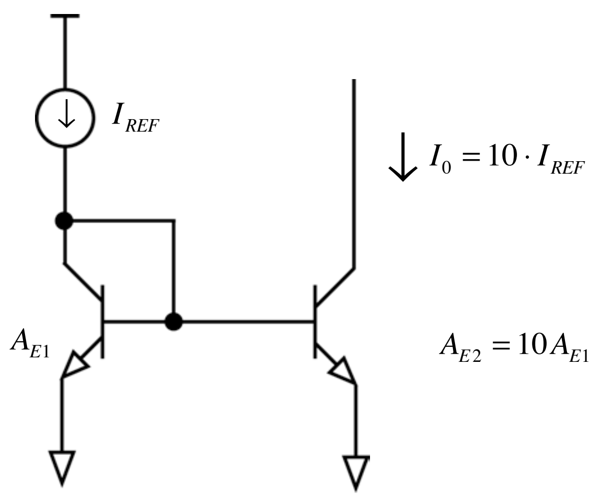
Notice how this technique solves a thorny problem for using transistors as a current source. We've always avoided doing things like:



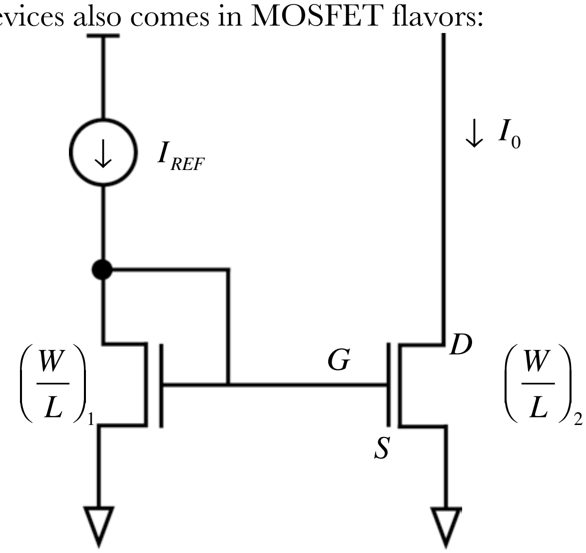
$$I_0 = I_s e^{\frac{qV_B}{k_T}}$$

Because of the uncertainty in I_S. But if Q_1 and Q_2 are <u>matched</u>, we don't care what the exact value of I_S is. We establish a reference current using the power supply and Q_1, and use the nonlinearity of the $I_1 - V_{BE1}$ relationship to "undo" the nonlinearity of the $V_{BE2} - I_2$ relationship. In other words, I_{C1} gets mirrored into the collector of I_{C2}.

Remember that $I_S = A_E \cdot \left(\frac{qD_n n_i^2}{W_B N_B} \right)$, where A_E is the emitter area. Accordingly, we can get some variety in our current mirrors by sizing the transistors differently:



This idea of using matched devices also comes in MOSFET flavors:

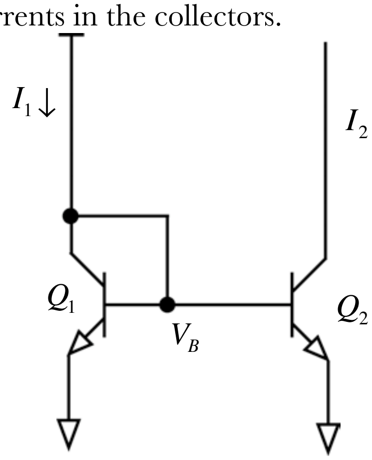


$$I_D = \frac{\mu_n C_{ox}}{2}\left(\frac{W}{L}\right)(V_{GS} - V_{TH})^2$$

$$I_0 = I_{REF} \cdot \frac{\left(\frac{W}{L}\right)_2}{\left(\frac{W}{L}\right)_1}$$

Matching

Now we agreed that if the devices in a bipolar current mirror are matched, we have close to identical currents in the collectors.



$$I_{C1} = I_{S1} \exp\left(\frac{qV_B}{k_T}\right)$$

$$I_{C2} = I_{S2} \exp\left(\frac{qV_B}{k_T}\right)$$

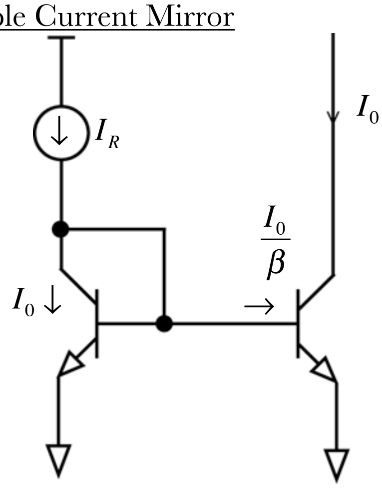
We can conclude that for matching, we have:

$$I_{C1} - I_{C2} = \left(I_{S1} - I_{S2}\right)\exp\left(\frac{qV_B}{kT}\right)$$

$$\frac{\Delta I_C}{I_C} = \frac{\Delta I_S}{I_S}$$

Some common current mirrors:

Simple Current Mirror



$$KCL: \quad I_R = I_0 + \frac{2I_0}{\beta} = I_0\left(1+\frac{2}{\beta}\right) = I_0\left(\frac{\beta+2}{\beta}\right)$$

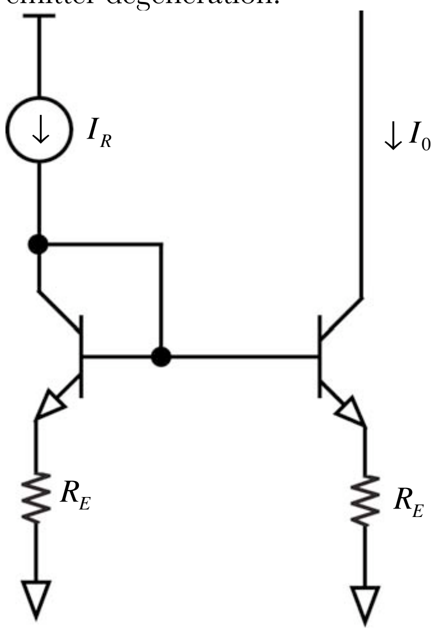
$$I_0 = I_R\left(\frac{\beta}{\beta+2}\right)$$

We calculate the error according to $I_0 = \frac{I_R}{1+\frac{2}{\beta}}$

$$Error = \frac{2}{\beta}$$

$$R_0 = r_0 \quad [Output\ impedance]$$

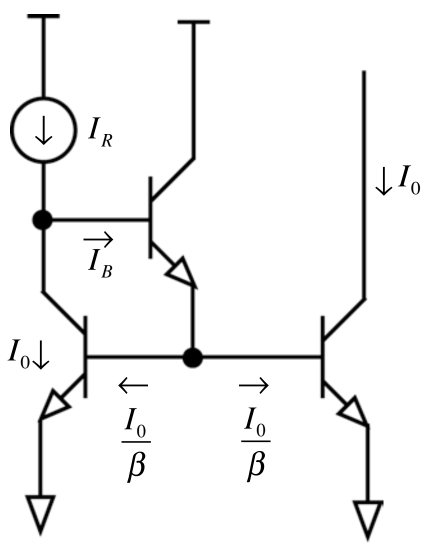
Can prevent thermal runaway, boost output impedance, and reduce sensitivity to matching by using emitter degeneration:



$$Error = \frac{2}{\beta}$$

$$R_0 \approx r_\pi \| R_E + \left(1 + g_m \left(r_\pi \| R_E\right)\right) r_0$$

<u>Buffered Current Mirror</u>



$$I_B = \frac{2I_0}{(\beta+1)\beta}$$

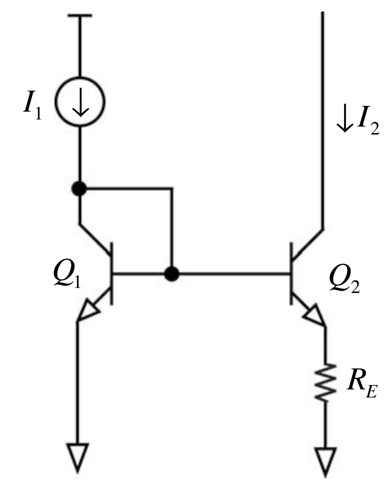
$$I_R = I_0 + \frac{2I_0}{\beta(\beta+1)}$$

$$I_0 = \frac{I_R}{1 + \frac{2}{\beta(\beta+1)}}$$

$$Error = \frac{2}{\beta(\beta+1)} \approx \frac{2}{\beta^2}$$

$$R_0 = r_0$$

<u>Widlar Current Mirror</u> (How to get very small output currents)



$$KVL : V_{BE1} = V_{BE2} + I_2 R_E$$

$$V_T \ln\left(\frac{I_1}{I_S}\right) = V_T \ln\left(\frac{I_2}{I_S}\right) + I_2 R_E$$

$$V_T \ln\left(\frac{I_1}{I_2}\right) = I_2 R_E$$

So if, for instance, we wanted $I_1 = 1mA \quad and \quad I_2 = 1\mu A$:

$$V_T \ln\left(\frac{10^{-3}A}{10^{-6}A}\right) = V_T \ln(1000) = 180mV$$

$$I_2 R_E = 180mV$$

$$R_E = \frac{180mV}{1\mu A} = 180k\Omega$$

The output impedance of this mirror is

$$r_0 \approx r_{\pi 2} \| r_E + \left(1 + g_{m2}\left(r_{\pi 2} \| R_E\right)\right) r_{02}$$

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