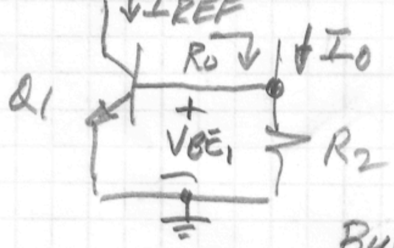
• V_{BE} Bias current source

• Let's develop this from the beginning. The obvious approach is to place a V_{BE} across a Resistor:

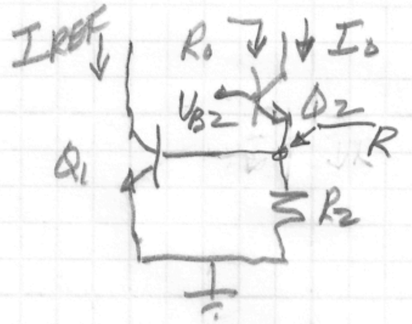


• Neglecting base current,

$$\boxed{I_o = \frac{V_{BE_1}}{R_2}}$$; note: no direct V_{CC} dependence.

But, this circuit has serious problems. Among several, I_o is a poor current source because $R_o = r_{\pi 2} \,//\, R_2$ is not large.

• Fix this problem by adding Q_2 as shown:



With $\beta = \infty$, $I_{C2} = I_{E2} = \frac{V_{BE1}}{R_2} = I_o$

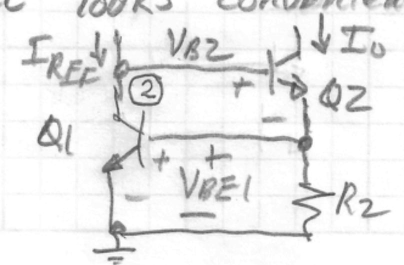
This circuit is better in two ways:

(i) We can use transistors to do something with I_o (e.g., mirrors)

(ii) Much higher $R_o = \left[1 + \frac{(g_{m2} + g_{o2})R}{1 + g_\pi R}\right] r_{o2}$

$$\simeq \frac{g_{m2} r_{o2} R}{1 + g_\pi R} \quad \text{where } R = R_2 \,//\, r_{\pi_1}$$

• But, now we need to find a convenient bias point, V_{B2}, for the base voltage of Q_2. Grab a point that looks convenient:



i) DC voltage at ② not established until base of Q_2 connected.

ii) Source of base current for Q_2

Thus, $V_2 = V_{BE1} + V_{BE2} \simeq 1.4V$

- Now, let's find $S_{V_{CC}}^{I_O}$: (neglect base currents)

$$I_{ref} = \frac{V_{CC} - 2V_{BE(ON)}}{R_1} \simeq \frac{V_{CC}}{R_1} \; ; \; \therefore \frac{\partial I_{ref}}{\partial V_{CC}} = \frac{1}{R_1}$$

$$I_O = \frac{V_{BE1}}{R_2} = \frac{V_T}{R_2} \ln \frac{I_{ref}}{I_{S1}} = \frac{V_T}{R_2} \left(\ln I_{ref} - \ln I_{S1} \right)$$

$$\frac{\partial I_O}{\partial V_{CC}} = \frac{V_T}{R_2} \left[\frac{1}{I_{ref}} \frac{\partial I_{ref}}{\partial V_{CC}} - \frac{1}{I_{S1}} \frac{\partial I_{S1}}{\partial V_{CC}} \right]$$

$$S_{V_{CC}}^{I_O} = \frac{V_{CC}}{I_O} \frac{\partial I_O}{\partial V_{CC}} = \frac{V_T}{I_O R_2} \left[\frac{V_{CC}}{I_{ref}} \frac{\partial I_{ref}}{\partial V_{CC}} - \frac{V_{CC}}{I_{S1}} \frac{\partial I_{S1}}{\partial V_{CC}} \right]$$

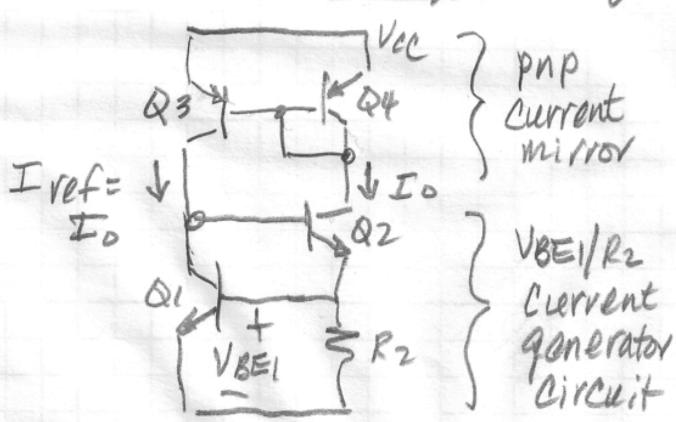
$$= \frac{V_T}{I_O R_2} \left[\underbrace{S_{V_{CC}}^{I_{ref}}}_{1} - \underbrace{S_{V_{CC}}^{I_{S1}}}_{0} \right] \simeq \frac{V_T}{V_{BE1(ON)}} \longleftarrow$$

Note: $S_{V_{CC}}^{I_O}$ is small ($\simeq 0.035$) but how to make it smaller (ideally, $=0$)?

Observation: Non-zero $S_{V_{CC}}^{I_O}$ comes fro $S_{V_{CC}}^{I_{ref}} = 1$.

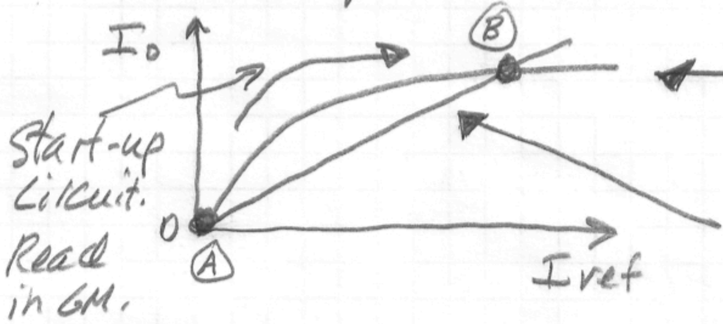
Solution: Find another current to Replace $I_{REF} \simeq V_{CC}/R_1$ that is much less sensitive to V_{CC} variations; i.e., We want a new I_{REF} with $S_{V_{CC}}^{I_{REF}} \simeq 0$.
We have that current already, I_O.

- Use self-biasing technique:



- Solutions:
  - i) Graphical
  - ii) Analytical

- Consider a graphical solution:

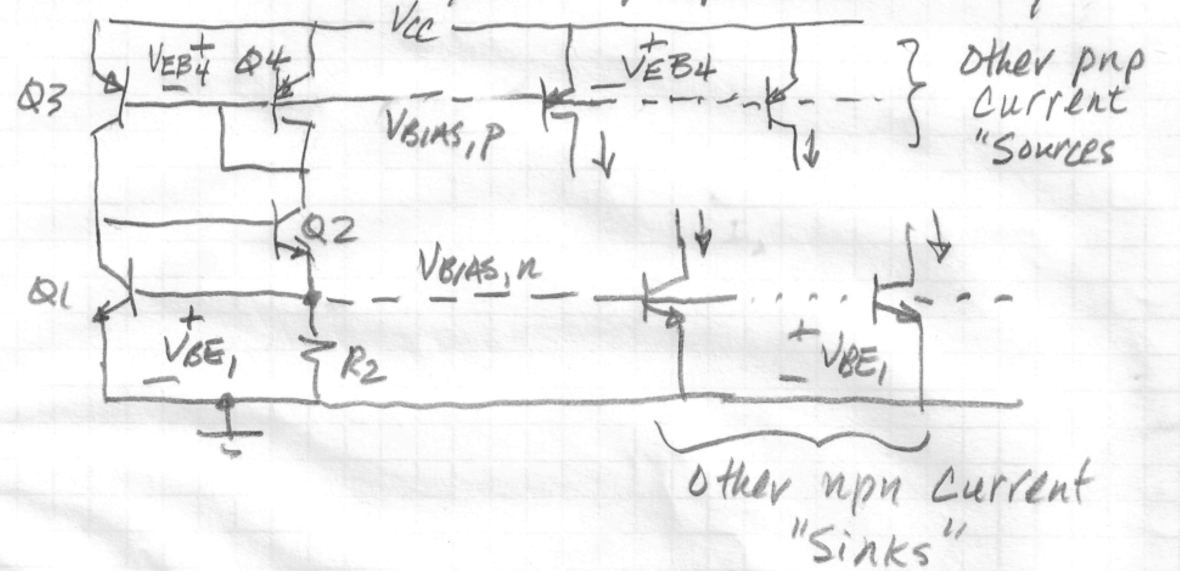


- Bottom half of circuit: V_{BE} generator:
$$I_0 \simeq \frac{V_{BE1}}{R_2} = \frac{V_t \ln \frac{I_{ref}}{I_{S1}}}{R_2}$$
- Top half of circuit: pnp current mirror
$$I_0 = I_{ref}$$

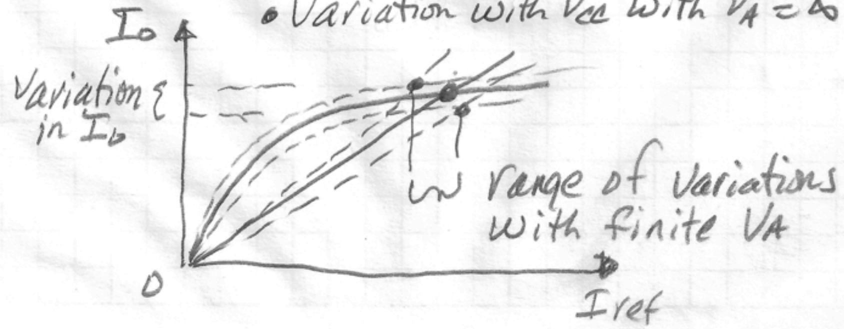
- Two possible stable solutions:

(A) Zero current solution. In a practical circuit, avoid (A) by including a start-up circuit. Once current is flowing, circuit operation moves to (B) as desired. $S_{V_{CC}}^{I_0} = 0$ ignoring V_A effects.

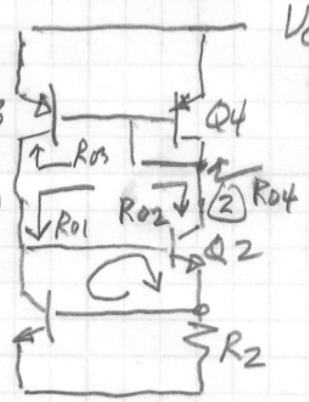
We now have a general purpose current generator:



- Variation with V_{CC} with $V_A = \infty$



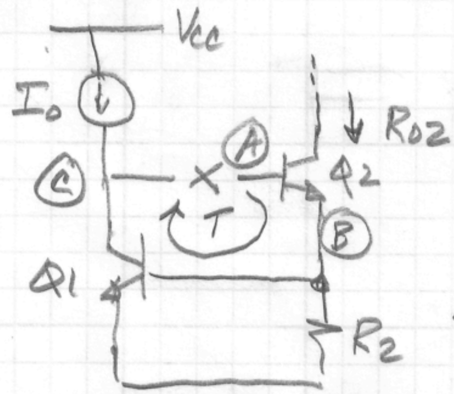
- Let's gain some insight using simple negative feedback



Suppose V_{cc} is perturbed by an amount, ΔV_{cc}. How much are the voltage perturbations at nodes ① and ②? Use small-signal voltage divider analysis:

<u>at node ②</u>: $\Delta V_2 = \dfrac{R_{O2}}{R_{O2} + R_{O4}} \Delta V_{cc}$.

- Note the negative feedback loop that now exists relative to what we found in the middle of page 71. With V_{B2} = constant bias voltage, $R_o = \left[1 + \dfrac{(g_{m2} + g_{o2})R}{1 + g_\pi R}\right] r_{o2}$



Break feedback loop at point x (very high impedance to right but much less to left).

i) Estimate by inspection

Loop gain $= T = \underbrace{\dfrac{V_{Ⓑ}}{V_{Ⓐ}}}_{\substack{\simeq 1 \\ \text{Emitter} \\ \text{follower}}} \cdot \underbrace{\dfrac{V_c}{V_{Ⓑ}}}_{\substack{= \frac{g_{m1}}{g_{o1}} \\ \text{Common} \\ \text{Emitter stage.}}}$

ii) Determine R_{O2} with loop broken:

But this is just R_o as found before.

iii) This is series negative feedback:

$R_{O2} \simeq (1+T) R_o \simeq T R_o = \dfrac{g_{m1}}{g_{o1}} R_o$ ← Very high resistance

---

Apply same approach at ① except now <u>shunt</u> feedback:

R_C (open-loop) $= R_{O1} \Rightarrow \dfrac{r_{o1}}{(1+T)} \simeq \dfrac{r_{o1}}{g_{m1} r_{o1}} \simeq \dfrac{1}{g_{m1}}$ ← very low resistance

Thus, $\Delta V_2 \simeq \dfrac{R_{O2}}{R_{O2}+R_{O4}}\Delta V_{cc}$ note: $R_{O4} = \dfrac{1}{g_{m4}+g_{o4}} \simeq \dfrac{1}{g_{m4}}$ (Diode-connected Device)

$$\simeq \frac{g_{m1} r_{o1} R_O \,\Delta V_{cc}}{g_{m1} r_{o1} R_O + \frac{1}{g_{m4}}} \simeq \frac{g_{m1} g_{m4} r_{o1} R_O}{1+g_{m1} g_{m4} r_{o1} R_O} \underline{\underline{\simeq \Delta V_{cc}}}$$

and $\Delta V_1 = \dfrac{R_{O1}}{R_{O1}+R_{O3}}$

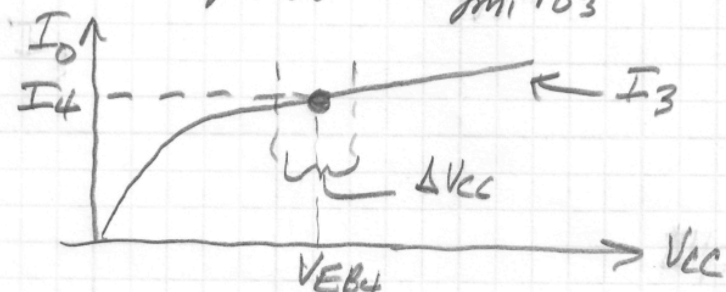
$$\simeq \frac{\frac{1}{g_{m1}}}{\frac{1}{g_{m1}}+r_{o3}} = \frac{1}{1+g_{m1} r_{o3}} \simeq \frac{\Delta V_{cc}}{g_{m1} r_{o3}}$$

(Small voltage change at ①.)

- Key point: look at accuracy of pnp current mirror versus ΔV_{cc} perturbations:

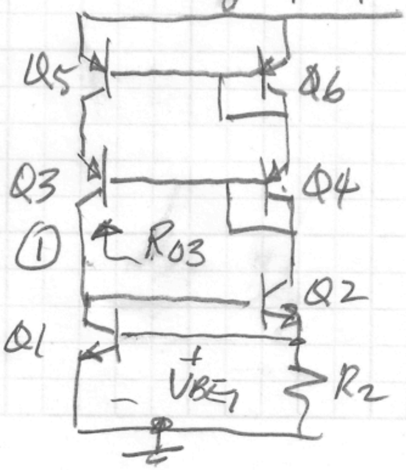
$\Delta V_{EC4} = \Delta V_{cc} - \Delta V_2 = \underline{\underline{0}}$

$\Delta V_{EC3} = \Delta V_{cc} - \dfrac{\Delta V_{cc}}{g_{m1} r_{o3}} = \dfrac{(g_{m1} r_{o3} - 1)}{g_{m1} r_{o3}}\Delta V_{cc} \simeq \underline{\underline{\Delta V_{cc}}}$



Some change in $I_4 = I_{ref}$ due to Early effect.

- Improve using pnp cascode current mirror



- $R_{O3} \gg r_{o3}$ so $\Delta V_1 \simeq 0$
- But $R_{O3} \simeq g_{m3} r_{o3} r_{o5}$

So $\Delta I_{ref} = \dfrac{\Delta V_{cc}}{g_{m3} r_{o3} r_{o5}}$

is very small so

$$\frac{\partial I_{ref}}{\partial V_{cc}} \simeq 0!$$

$\int_{V_{CC}}^{I_O} \simeq 0$!!! What about temperature sensitivity?

- Define Fractional Temperature coefficient:

$$TC_F = \frac{1}{I_O}\frac{\partial I_O}{\partial T} \quad \text{where } I_O = \frac{V_{BE1}}{R_2}$$

$$= \frac{R_2}{V_{BE1}}\frac{\partial}{\partial T}\left(\frac{V_{BE1}}{R_2}\right) = \frac{R_2}{V_{BE1}}\left(\frac{1}{R_2}\frac{\partial V_{BE1}}{\partial T} - \frac{V_{BE1}}{R_2^2}\frac{\partial R_2}{\partial T}\right)$$

$$\therefore \boxed{TC_F = \underbrace{\frac{1}{V_{BE1}}\frac{\partial V_{BE1}}{\partial T}}_{TCF|_{V_{BE1}}} - \underbrace{\frac{1}{R_2}\frac{\partial R_2}{\partial T}}_{TCF|_{R_2}}}$$

Can we cancel?

- Typical TC_F Values:
  - Diffused R's ~ 1000 – 1500 ppm/°C (parts per million)
    (Note: 1000 ppm $= \frac{1000}{1{,}000{,}000} = 0.1\%$)
  - Polysilicon R's ~ 500 ppm/°C
  - V_{BE} ~ −3300 ppm/°C

- So, back to our V_{BE1}/R_2 reference!

$$TCF = TCF|_{V_{BE1}} - TC_F|_{r_2}$$

$$\simeq -3300\ \text{ppm/°C} - 1000\ \text{ppm/°C} = \underline{-4300\ \text{ppm/°C}}$$

(i) Commercial Temperature Range = 0–70°C

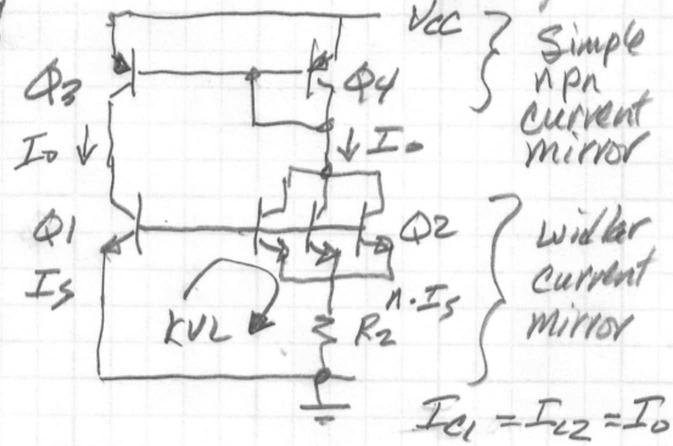
$\Longrightarrow$ ~ 30% Variation in I_O

(ii) Military Temperature Range = −55 to 125 °C

$\Longrightarrow$ ~ 77% variation in I_O

- Consider a current generator with a positive TC_F:

$\frac{kT}{q}$ - based bias current generator (self-biased):



$I_{C1} = I_{C2} = I_0$ ➡

- KVL loop:

$$I_0 = \frac{V_{BE1} - V_{BE2}}{R_2}$$

$$\boxed{I_0 = \frac{\Delta V_{BE}}{R_2}}$$

$$I_0 = \frac{V_T}{R_2} \ln \frac{I_{S2}}{I_{S1}}$$

(Example) $= \frac{V_T}{R_2} \ln(N)$

(For $N=3$) $= \frac{1.10}{R_2} \frac{kT}{q}$

$\therefore$ kT/q reference

$$TC_F = \frac{1}{I_0} \frac{\partial I_0}{\partial T}$$

$$= \frac{R_2}{V_T \ln(N)} \frac{\partial}{\partial T}\left(\frac{V_T}{R_2} \ln(N)\right)$$

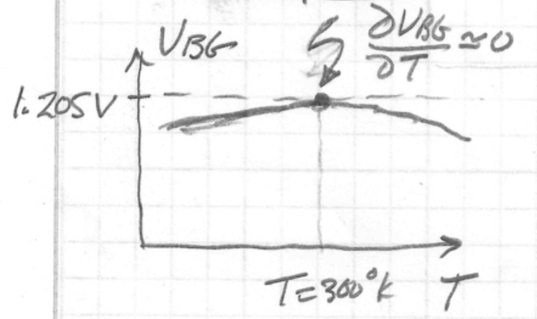
$$= \frac{R_2}{V_T \ln(N)} \cdot \ln(N) \left[\frac{1}{R_2} \frac{\partial V_T}{\partial T} - \frac{V_T}{R_2^2} \frac{\partial R_2}{\partial T}\right]$$

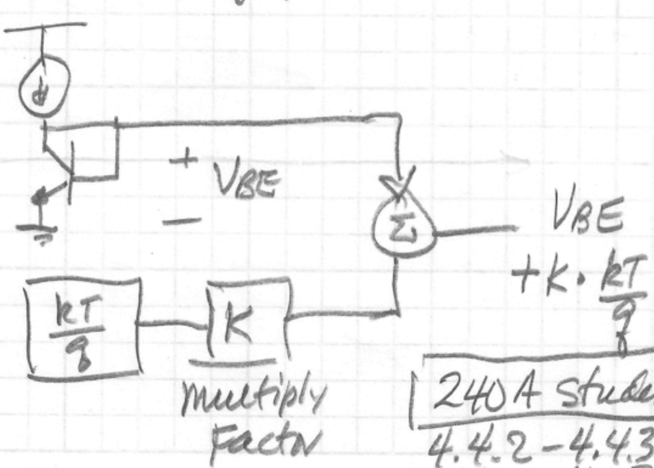
$$= \underbrace{\frac{1}{V_T} \frac{\partial V_T}{\partial T}}_{TC_F | V_T} - \underbrace{\frac{1}{R_2} \frac{\partial R_2}{\partial T}}_{TC_F | R_2} \simeq +3300\ \text{ppm}/^\circ C - 1000\ \text{ppm}/^\circ C = +2300\ \text{ppm}/^\circ C$$

- Better than $\frac{V_{BE1}}{R_2}$ reference but $\neq 0$

Solution: Silicon Bandgap Reference

Conceptual:





240A students: 4.4.2-4.4.3 GM Chap. 11 Razavi