Lecture 10: Supply & Temperature Indep. Biasing

- **Announcements**:
  - HW#4 due tomorrow at 8 a.m.
  - HW#5 online soon
  - Lab#1 reports are due on Oct. 5
    - Submit them in your lab section
  - Lab#2 is online
    - This is a hardware lab
    - You must show up to lab for Lab#2
  - Videos online in the lecture chart
- **Lecture Topics**:
  - Supply & Temperature Independent Biasing
  - Output Swing
  - Dynamic Range
- ---------------------------------
- **Last Time**: Started supply independent biasing

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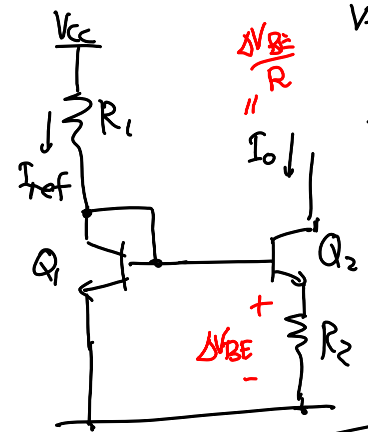
Widlar Current Source (Any better?)



$$V_T \ln\frac{I_{ref}}{I_o} = I_o R_2$$

$$V_T(\ln I_{ref} - \ln I_o) = I_o R_2$$

Differentiate w.r.t. V_{cc}:

$$V_T\left(\frac{1}{I_{ref}}\frac{\partial I_{ref}}{\partial V_{cc}} - \frac{1}{I_o}\frac{\partial I_o}{\partial V_{cc}}\right) = R_2\frac{\partial I_o}{\partial V_{cc}}$$

rearrange

$$\frac{\partial I_o}{\partial V_{cc}} = \frac{\frac{V_T}{I_{ref}}\frac{\partial I_{ref}}{\partial V_{cc}}}{\left(R_2 + \frac{V_T}{I_o}\right)}$$

$$\therefore S^{I_o}_{V_{cc}} = \frac{V_{cc}}{I_o}\frac{\partial I_o}{\partial V_{cc}} = \frac{V_T\left(\frac{V_{cc}}{I_{ref}}\frac{\partial I_{ref}}{\partial V_{cc}}\right)}{I_oR_2 + V_T}$$

$S^{I_{ref}}_{V_{cc}}$

$$\Rightarrow \boxed{S^{I_o}_{V_{cc}} = \left(\frac{1}{1+\frac{I_oR_2}{V_T}}\right) S^{I_{ref}}_{V_{cc}}}$$

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Since $I_{ref} = \frac{V_{CC}-V_{BE(on)}}{R_1} \simeq \frac{V_{CC}}{R_1} \Rightarrow S_{V_{CC}}^{I_{ref}} \approx 1$

$$\therefore \boxed{S_{V_{CC}}^{I_o} = \frac{1}{1+\frac{I_o R_2}{V_T}}}$$

For $I_{ref} = 1mA$, $I_o = 10\mu A$, $R_2 = 11.9k\Omega$, then

10% Δ in V_{CC} → 1.39% Δ in I_o

(better than a simple current source)

How can we do better? → use another voltage reference!

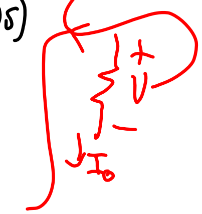
✓ ① $V_{BE(on)}$ → base emitter junction voltage

② V_Z → Zener diode

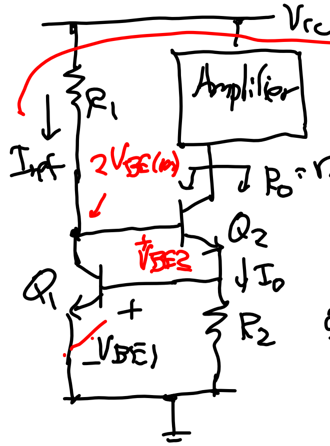
✓ ③ V_t → threshold voltage (MOS)

✓ ④ $V_T = \frac{kT}{q}$ → thermal voltage

✓ ⑤ E_g → bandgap



V_{BE}-Referenced Biasing



$I_{ref} = \frac{V_{CC}-2V_{BE(on)}}{R_1}$ → $S_{V_{CC}}^{I_{ref}} = 1$

$R_o = r_{o2}(1+g_{m2}R_2)$

$$I_o = \frac{V_{BE1}}{R_2} = \frac{V_T}{R_2}\ln\frac{I_{ref}}{I_{S1}}$$

$$\frac{\partial I_o}{\partial V_{CC}} = \frac{V_T}{R_2}\left(\frac{1}{I_{ref}}\frac{\partial I_{ref}}{\partial V_{CC}} - \frac{1}{I_{S1}}\frac{\partial I_{S1}}{\partial V_{CC}}\right)$$

$$S_{V_{CC}}^{I_o} = \frac{V_{CC}}{I_o}\frac{\partial I_o}{\partial V_{CC}} = \frac{V_{CC}}{\ln(I_{ref}/I_{S1})}\left(\overbrace{\frac{1}{I_{ref}}\frac{\partial I_{ref}}{\partial V_{CC}}}^{=\frac{1}{V_{CC}}} - \frac{1}{I_{S1}}\frac{\partial I_{S1}}{\partial V_{CC}}\right)$$

Problem: I_{ref} still depends on V_{CC} → $S_{V_{CC}}^{I_{ref}} = 1 = \frac{V_{CC}}{I_{ref}}\frac{\partial I_{ref}}{\partial V_{CC}}$

$$S_{V_{CC}}^{I_o} = \frac{1}{\ln(I_{ref}/I_{S1})}\left[1 - \underbrace{\frac{V_{CC}}{I_o}\frac{\partial I_{S1}}{\partial V_{CC}}}_{=0}\right] = \frac{1}{\ln(I_{ref}/I_{S1})}$$

If we can eliminate this '1', then $S_{V_{CC}}^{I_o} = 0$

Need to eliminate the dependence of I_{ref} on V_{CC}!

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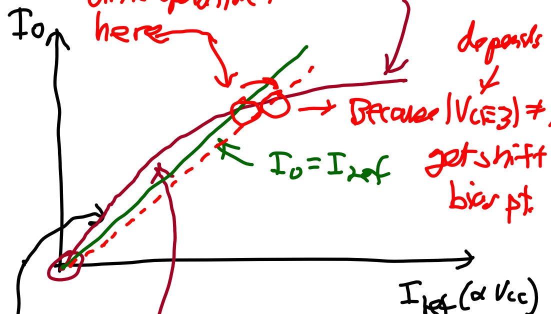
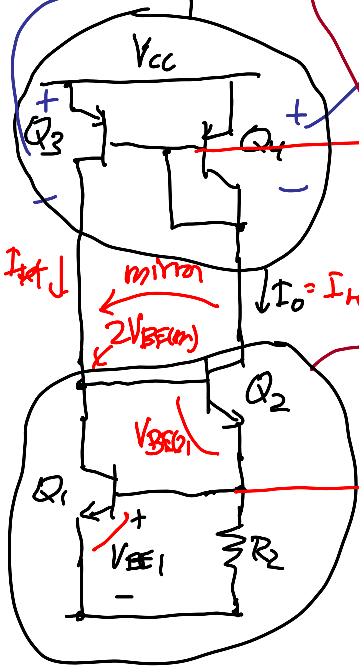
Solution: Derive I_{ref} independently of V_{CC}
↳ use self-biasing!

Graphically:



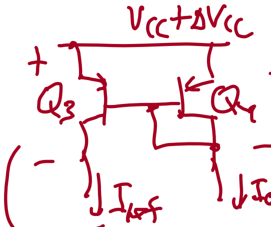
$|V_{CE3}| = V_{CC} - 2V_{BE(on)} + \Delta V_{CC}$ → $I_O \neq I_{ref}$ (but it's close)

$|V_{CE4}| = |V_{BE4}|$



$S_{V_{CC}}^{I_{ref}} \to S_{V_{CC}}^{I_O} \approx 0$

Pretty Darn Good!



$|V_{CE4}| = |V_{BE4(on)}|$ ← stays still

$I_O = I_S \exp\left(\frac{|V_{BE4}|}{V_T}\right)\left(1 + \cancel{\frac{|V_{CE4}|}{V_A}}\right)$ $\Delta V_{CE4} = 0$

$|V_{CE3}| = V_{CC} - 2V_{BE(on)} + \Delta V_{CC}$ → $\Delta V_{CE3} = \Delta V_{CC}$

$I_{ref} = I_S \exp\left(\frac{|V_{BE3}|}{V_T}\right)\left(1 + \frac{|V_{CE3}|}{V_A}\right)$

$\therefore I_{ref} = f(V_{CC}) \neq I_O$

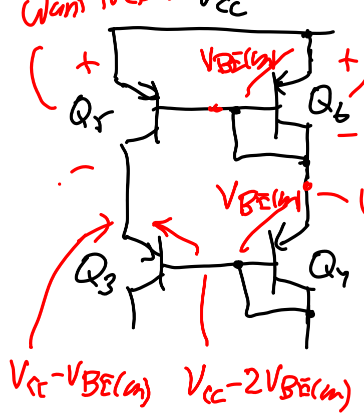
$\therefore S_{V_{CC}}^{I_O} \neq 0$, but it's close

Can we do better?

Want $|V_{CE5}|$ = clamped $\neq f(V_{CC})$ — clamped at one $V_{BE(on)}$ below V_{CC}

$|V_{CE6}|$ = clamped ← just like

These set current



$I_O = I_{ref}$

$\therefore$ w/ $|V_{CE5}|$ & $|V_{CE6}|$ clamped → $S_{V_{CC}}^{I_O} = 0$

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Determine Temperature Dependence of the V_{BE}-Ref

Define. Fractional Temperature Coefficient

$$TC_f = \frac{1}{I_o}\frac{\partial I_o}{\partial T} \quad [\text{ppm}/K]$$

T ← temperature

ppm: parts per million (same as 10^{-6})

For $I_o = \frac{V_{BE}}{R}$:

$$TC_f = \frac{1}{I_o}\frac{\partial I_o}{\partial T} = \frac{R}{V_{BE}}\left(\frac{1}{R}\frac{\partial V_{BE}}{\partial T} - \frac{V_{BE}}{R^2}\frac{\partial R}{\partial T}\right)$$

$$\therefore\ TC_f = \underbrace{\frac{1}{V_{BE}}\frac{\partial V_{BE}}{\partial T}}_{TC_f|_{V_{BE}}} - \underbrace{\frac{1}{R}\frac{\partial R}{\partial T}}_{TC_f|_R}$$

Some Typical TC_f's:

Diffused R's ~ 1000 – 1500 ppm/°C

poly Si R's ~ 500 ppm/°C

V_{BE} ~ –3300 ppm/°C

- $TC_f \sim -3300 - 1000$
  $= -4300$ ppm/°C ~ 0.43%/°C
- 0 → 70°C : ~ 25% I_o variation

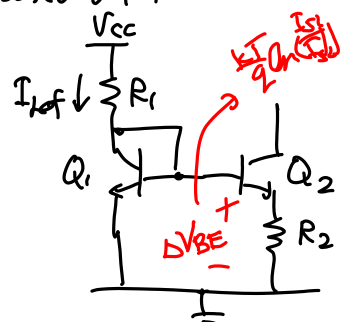
  –55 → 125°C : ~60–70% I_o variation

  ⇓

  <u>Not</u> so good!

$\frac{kT}{q}$-Referenced Bias Ckt.

Based on the Widlar current source:



Here, $I_{ref} \neq I_o$.

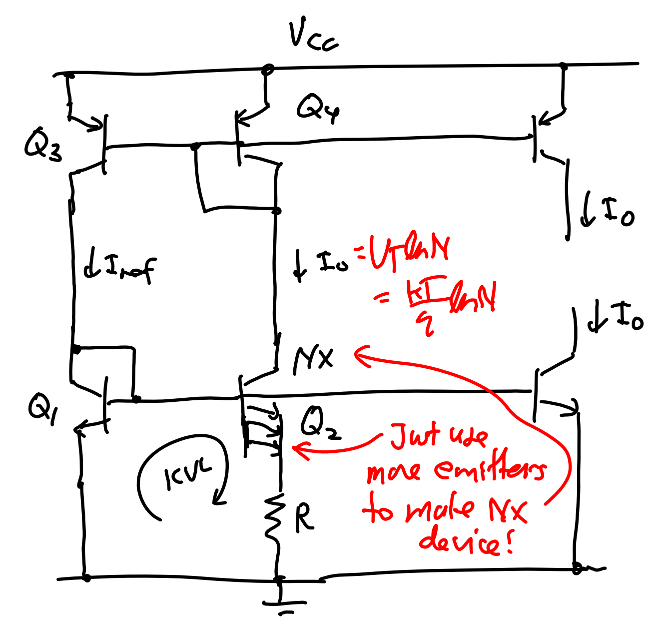
⇓

so sensitive to V_{cc} variations

⇓

But can fix this by setting $I_{ref} = I_o$.

Use self-biasing:

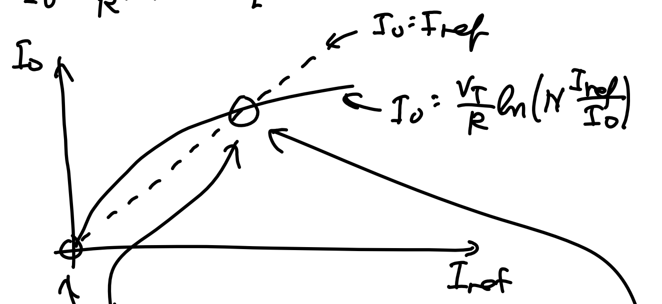


Assuming $I_{S2} = N I_{S1}$:

KVL: $I_o R = V_{BE1} - V_{BE2} = V_T \ln N$

~~at least w.r.t. V_{CC}~~

$$I_o = \frac{V_T}{R}\ln N = \frac{kT}{q}(\text{const.})$$



Two possible operating pts.

⇒ use startup ckt to guarantee this one

(where we have very small $S^{I_o}_{V_{CC}}$)

$\frac{kT}{q}$-Reference Temperature Dependence

$$TC_f = \frac{1}{I_o}\frac{\partial I_o}{\partial T} = \cancel{\ln N}\left(\frac{1}{R}\frac{\partial V_T}{\partial T} - \frac{V_T}{R^2}\frac{\partial R}{\partial T}\right)\frac{R}{\cancel{V_T \ln N}}$$

$$\therefore\ TC_f = \frac{1}{V_T}\frac{\partial V_T}{\partial T} - \frac{1}{R}\frac{\partial R}{\partial T}$$

$$= \underbrace{TC_f|_{V_T}}_{3300\,ppm/^\circ C} - \underbrace{TC_f|_R}_{1800\,ppm/^\circ C} \sim 1500\,ppm/^\circ C$$

→ Better than V_{BE}-Ref, but still not zero...

How can get ↗ ?

Bandgap Reference

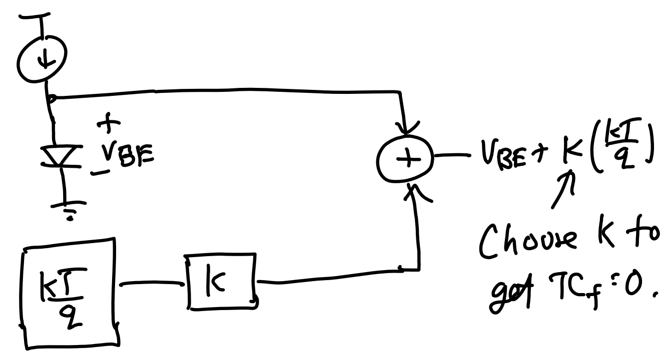
Basic Idea:

$V_{BE} \longrightarrow$ neg. TC_f

$\frac{kT}{q} \longrightarrow$ pos. TC_f

→ Add together to cancel ⇒ get net $TC_f = 0$!

0th Order Picture:



What should K be? (0th Order Picture)

⇒ get ballpark estimate

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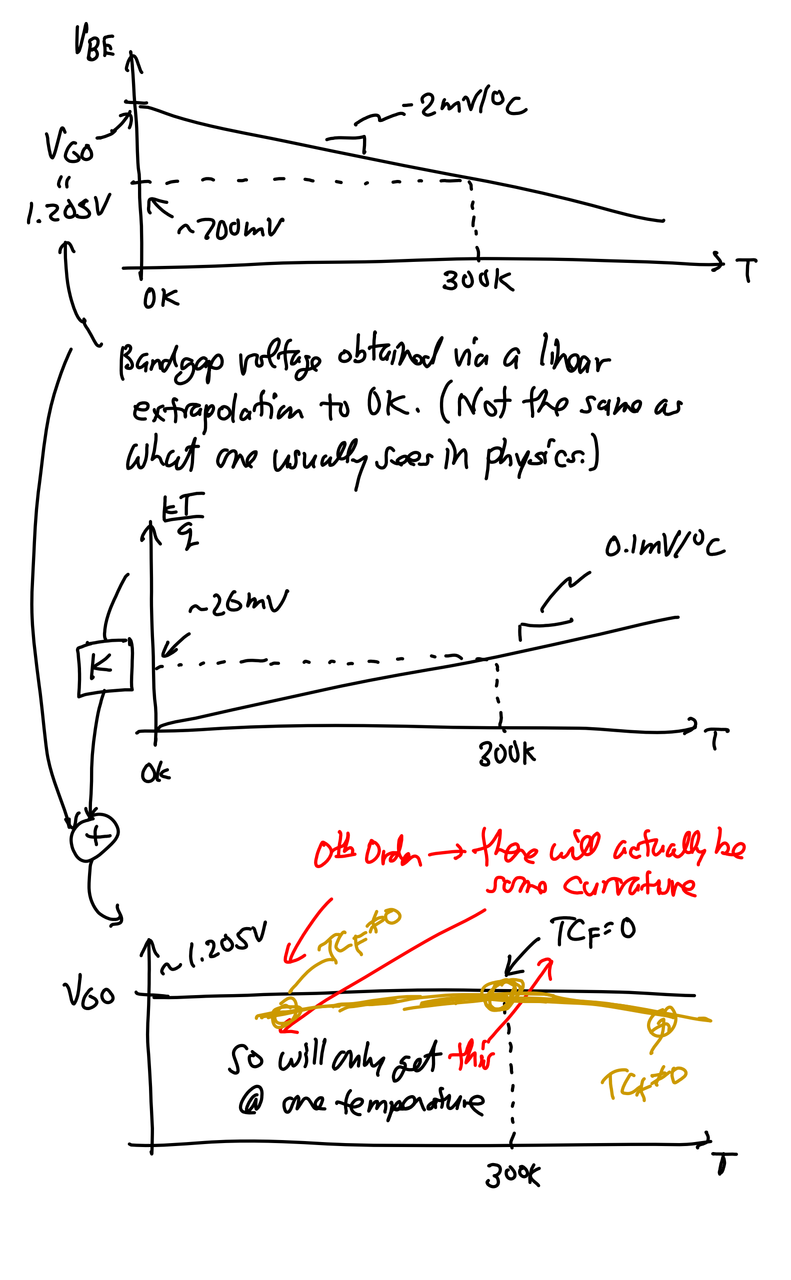

- **240A folks**: read Gray & Meyer
  - Sections 4.4.2 through 4.4.3
  - These cover supply and temperature independent biasing, including bandgap references
  - Can also read Razavi, Chpt. 11, on bandgap references

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