Lecture 9: Supply & Temperature Independent Biasing

- Announcements:
  - Lab#1's due next week in your lab section (on Friday, Feb. 29)
  - Lab#2 will be online this week
    - This is a hardware lab, so you will need to use the lab to make measurements
    - You are all being added to the access list for 353 Cory
  - Those taking 240A will soon get additional HW assignments to supplement the regular ones

- Lecture Topics:
  - Widlar Current Source
  - Supply & Temperature Independent Biasing
  - Output Swing (Headroom)
  - High Swing Current Sources

Last Time:
- Reviewed current sources using prepared lecture material
- Now finish this (with Widlar current sources)

To reduce the error term, use a

\[
\text{Buffered Voltage-Generator}
\]

\[
\text{Add a buffer, Xistor, to attenuate low currents from Xistor current sources.}
\]

\[
I_{\text{ref}} = I_{c1} + I_{\text{B}1A}
\]

\[
I_{\text{B}1A} = \frac{I_{B2} + \cdots + I_{Bn}}{\beta + 1} = \frac{n I_{c1}}{\beta (\beta + 1)}
\]

\[
\left(\text{Assuming identical Xistors}\right)
\]

\[
I_{\text{ref}} = I_{c1} \left(1 + \frac{n}{\beta (\beta + 1)}\right)
\]

\[
\Rightarrow I_1 \approx I_{\text{ee}} \approx \frac{I_{\text{ref}}}{1 + \frac{n}{\beta (\beta + 1)}} \approx I_{\text{ref}} \left(1 - \frac{n}{\beta} \right)
\]

Note: Now,

\[
I_{\text{ref}} = \frac{V_{cc} - 2 \text{VBE(on)}}{R_{\text{ref}}}
\]

Problem: For power savings reasons, often times very small bias currents are needed, on the order of 5uA. This might force you to use an R_{\text{ref}} in the above bipolar V_{BE} generator.
Supply & Temperature Independent Biasing

- \( V_{BE1} = V_{BE2} + V_R + \frac{1}{2} I_c R_c = V_{BE1} + I_c R_c \)
- \( I_{CE2} = V_{BE1} - V_{BE2} = V_t \ln \frac{I_c}{I_o} - V_t \ln \frac{I_c}{I_o} \)
- \( I_{CE2} = V_t \ln \frac{I_c}{I_o} \) (Assuming \( Q_1 = Q_2 \) are matched)

Rule of Thumb:
- \( V_t = I_{CE} = \frac{1}{2} I_o \)
- \( 108 \text{mV} \)
- \( 42 \text{mV} \)
- \( 60 \text{mV} \)
- \( 120 \text{mV} \)

Example:
- \( I_c = 5 \mu A, V_c = 3 \text{V} \)
- \( I_{CE} = \frac{1}{2} \times 5 \mu A = 2.5 \mu A \)
- \( R_c = 200 \text{k} \Omega \) (That's way too big!)
- \( V_{BE2} = 120 \text{mV} \rightarrow R_c = \frac{120 \text{mV}}{5 \mu A} = 24 \text{k} \Omega \)
- \( I_{REF} = 500 \mu A \rightarrow R_c = \frac{20 \text{V}}{500 \mu A} = 40 \text{k} \Omega \)

More reasonable than 600 \text{k} \Omega before.

- If want smaller, scale by more instead.
- Another advantage of the Widlar: larger \( R_c \) :: more ideal current source:
  \( R_o = V_o(1 + 600 \times R_o) \)
Supply & Temperature Independent Biasing

- Why is it necessary?
- For battery-operated systems, battery voltages vary over time
  - Amplifier gains change
  - Power consumption changes
  - Frequency of oscillators changes
  - In summary: long-term stability degrades
  - Large uncertainty in biasing translates to overdesign that wastes power
- Same issues as above when temperature varies with time
- Short-term supply variations
  - In mixed signal circuits, i.e., both analog and digital together, digital switching generates noise on the supply lines
  - Noise can couple to analog circuits, reducing their dynamic range

\[
\text{Definition: Sensitivity of } Y \text{ to } X
\]
\[
S_{Y} = \frac{\Delta Y}{\Delta X} \cdot \frac{X}{Y} \cdot \frac{\Delta Y}{\Delta X} = \frac{X \Delta Y}{Y \Delta X}
\]

For supply independence, we want \( S_{V_{cc}} = 0 \).

**Simple Current Source**

Neglecting base current:
\[
I_0 - I_{0f} = \frac{V_{cc} - V_{BIE}}{R}
\]
\[
I_0 \approx \frac{V_{cc} - V_{BIE}}{R}
\]

Thus,
\[
S_{R} = \frac{R \Delta I_0}{I_0 \Delta R} = \frac{p^2}{V_{cc} R^2} = S_{I_0} \Rightarrow S_{R} > -1
\]
\[
S_{V_{cc}} = \frac{V_{cc} \Delta I_0}{I_0 \Delta V_{cc}} = \frac{1}{R} = S_{V_{cc}} \Rightarrow S_{V_{cc}} > 1
\]

\[\therefore \text{ a 10\% change in } V_{cc} \text{ leads to 10\% change in } I_0! \quad (\text{terrible!})\]
Wider Current Source

\[ V_{CC} \quad \quad I_0 \quad \quad I_{ref} \quad \quad Q_1 \quad \quad Q_2 \quad \quad R_2 \]

\[ V_T \left( \frac{I_{ref}}{I_0} + \frac{1}{R_2} \frac{I_{ref}}{V_{CC}} \right) = R_2 \frac{I_{ref}}{V_{CC}} \]

\[ V_T \left( \frac{I_{ref}}{I_0} + \frac{1}{R_2} \frac{I_{ref}}{V_{CC}} \right) \]

\[ I_{ref} \frac{V_{CC}}{I_0} \frac{1}{R_2} \frac{I_{ref}}{V_{CC}} \]

\[ S_{V_{CC}} = \frac{I_0}{I_{ref}} \frac{V_{CC}}{R_2} \]

\[ \frac{I_{ref}}{I_0} = \frac{V_{CC}}{R_2} \]

\[ S_{V_{CC}} = \frac{I_0}{I_{ref}} \frac{V_{CC}}{R_2} \]

\[ S_{V_{CC}} = \frac{I_0}{I_{ref}} \frac{V_{CC}}{R_2} \]

\[ \frac{1}{V_T} \]
Solution: Derive $I_{ref}$ independently of $V_{cc}$.

Graphically:

$I_{0} = I_{ref}$

If must satisfy both curves, then the circuit must operate here:

$V_{ref}(\alpha V_{cc})$

Need to bootstrap out of this point:

$pnp$ current source

Vbase

Finale $R_{0}$ used make this finite.

This is pretty darn good: $S_{V_{cc}}^{I_{ref}} \rightarrow S_{V_{cc}}^{I_{0}} \approx 0$
• 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

Ex: Cell Phone
  - Power
  - constrained
  - Dynamic Range (DR)
  - for cell tower
  - may drop to you

Issue: Output Swing (Headroom)

\[ V_{SS} \leq V_{D} \leq V_{DD} \]

\[ V_{DD} - V_{OV2} \]

\[ V_{GG} - V_{GS} \]

\[ I_D \] vs. \( V_{DS} \) Characteristic:

\[ I_D = I_{S} \left( \frac{V_{GS} - V_{TS}}{R_o} \right) \]

\[ \text{slope: } \frac{I_D}{I_D} = \text{large} \]

\[ \text{slope: } \frac{I_D}{I_D} = \text{small} \]

\[ g_{m1} \cdot I_D \leq g_{m1} \]

\[ V_{GS} - U_T = V_{OV} \]