ANNOUNCEMENTS

• Late Pre-Lab assignments will no longer be accepted!
• Review session: 3-5PM Friday (10/5) in 306 Soda (HP Auditorium)
• Midterm #1 (Thursday 10/11, 3:30PM-5:00PM) location:
  • 106 Stanley Hall: Students with last names starting with A-L
  • 306 Soda Hall: Students with last names starting with M-Z

OUTLINE

• Cascode Stage (cont’d)
  – supplementary remarks
• Current Mirrors

Reading: Chapter 9.2
Review: Cascode Stage $R_{out}$

- The impedance seen looking into the collector can be boosted significantly by using a BJT for emitter degeneration, with a relatively small reduction in headroom.

\[
R_{out} = [1 + g_m (r_{O2} \parallel r_{\pi1})]r_{O1} + r_{O2} \parallel r_{\pi1}
\]

\[
R_{out} \approx g_{m1}r_{O1} (r_{O2} \parallel r_{\pi1})
\]
Another View of a Cascode Stage

- Instead of considering a cascode as $Q_2$ degenerating $Q_1$, we can also think of it as $Q_1$ stacked on top of $Q_2$ (current source) to boost $Q_2$’s output impedance.

\[ R_{\text{out}} \approx g_m r_0 (r_{o2} \parallel r_{\pi1}) \]
Temperature and Supply-Voltage Dependence of Bias Current

- Circuits should be designed to operate properly over a range of supply voltages and temperatures.
- For the biasing scheme shown below, $I_1$ depends on the temperature as well as the supply voltage, since $V_T$ and $I_S$ depend on temperature.

$$I_1 = I_S e^{V_{BE}/V_T}$$

$$V_{BE} \approx \frac{R_2}{R_1 + R_2} V_{CC}$$
Concept of a Current Mirror

• Circuit designs to provide a supply- and temperature-independent current exist, but require many transistors to implement.
  → “golden current source”

• A current mirror is used to replicate the current from a “golden current source” to other locations.

[Diagram of a current mirror with symbols for reference current (IREF), power supply (Vcc), and copied current (I_copy)].
Current Mirror Circuitry

- Diode-connected $Q_{REF}$ produces an output voltage $V_X$ that forces $I_{copy1}$ to be equal to $I_{REF}$, if $Q_1$ is identical to $Q_{REF}$.

$V_X = V_T \ln \left( \frac{I_{copy1}}{I_{S,1}} \right) = V_T \ln \left( \frac{I_{REF}}{I_{S,REF}} \right)$

$I_{copy1} = \frac{I_{S,1}}{I_{S,REF}} I_{REF}$
Bad Current Mirror Example 1

If the collector and base of $Q_{REF}$ are not shorted together, there will not be a path for the base currents to flow, so that $I_{copy}$ is zero.
Bad Current Mirror Example 2

• Although it provides a path for base currents to flow, this biasing approach is no better than a resistive voltage divider.
Multiple Copies of $I_{REF}$

- Multiple copies of $I_{REF}$ can be generated at different locations by applying the current mirror concept to multiple transistors.

$$I_{copy,j} = \frac{I_{S,j}}{I_{S,REF}} I_{REF}$$
Current Scaling

- By scaling the emitter area of \( Q_j \) by a factor of \( n \) with respect to the emitter area of \( Q_{REF} \), \( I_{copy,j} \) is scaled by a factor of \( n \) with respect to \( I_{REF} \).
  - This is equivalent to placing \( n \) unit-sized transistors in parallel.

\[
I_{copy,j} = nI_{REF}
\]
Example: Scaled Currents

\[ \equiv 3 A_E \]

\[ \equiv 2 A_E \]
Fractional Scaling

• A fraction of $I_{\text{REF}}$ can be created in $Q_1$ by scaling up the emitter area of $Q_{\text{REF}}$.

$$I_{\text{REF}} = 3I_S \exp\left(\frac{V_X}{V_T}\right)$$

$$I_{\text{copy}} = I_S \exp\left(\frac{V_X}{V_T}\right)$$

$$I_{\text{copy}} = \frac{1}{3} I_{\text{REF}}$$
Example: Different Mirroring Ratios

- Using the concept of current scaling and fractional scaling, $I_{\text{copy1}} = 0.05\, \text{mA}$ and $I_{\text{copy2}} = 0.5\, \text{mA}$, derived from a single 0.2mA reference current source ($I_{\text{REF}}$).
Effect of Base Currents

\[ I_{C,REF} = \frac{I_{copy}}{n} \]

\[ I_{REF} = I_{C,REF} + \frac{I_{copy}}{n\beta} + \frac{I_{copy}}{\beta} \]

\[ I_{copy} = \frac{nI_{REF}}{1 + \frac{1}{\beta}(n+1)} \]
Improved Mirroring Accuracy

- Use $Q_F$ (rather than $I_{REF}$) to supply the base currents of $Q_{REF}$ and $Q_1$, reduce the mirroring error by a factor of $\beta$.

$$I_{REF} = I_{B,F} + I_{C,REF}$$

$$I_{C,REF} = \frac{I_{copy}}{n}$$

$$I_{C,F} \approx I_{E,F} = \frac{I_{copy}}{n\beta} + \frac{I_{copy}}{\beta}$$

$$I_{B,F} \approx \frac{I_{copy}}{\beta^2} \left( \frac{1}{n} + 1 \right)$$

$$I_{copy} = \frac{nI_{REF}}{1 + \frac{1}{\beta^2}(n+1)}$$
Different Mirroring Ratio Accuracy

\[ I_{REF} = I_{B,F} + 4I_{C,REF} \]

\[ I_{C,F} \approx \frac{I_{\text{copy1}}}{\beta} + \frac{I_{\text{copy2}}}{\beta} + 4 \frac{I_{C,REF}}{\beta} \]

\[ I_{B,F} \approx \frac{15I_{\text{copy1}}}{\beta^2} \]

\[ I_{\text{copy1}} = \frac{I_{REF}}{4 + \frac{15}{\beta^2}} \]

\[ I_{\text{copy2}} = \frac{10I_{REF}}{4 + \frac{15}{\beta^2}} \]
PNP Current Mirror

- A PNP BJT current mirror can be used as a current-source load for an NPN BJT amplifier stage.
Generation of $I_{\text{REF}}$ for a PNP-BJT Current Mirror

- Neglecting base currents, the currents flowing through $Q_M$ and $Q_{\text{REF}2}$ are the same.
Current Mirror with Discrete BJTs

- If $Q_{\text{REF}}$ and $Q_1$ are discrete NPN BJTs, $I_{\text{REF}}$ and $I_{\text{copy1}}$ can differ dramatically, due to $I_S$ mismatch.