Lecture 15: High Gain Op Amps

- Announcements:
  - Midterm will be on the date specified in your syllabus: Thursday, March 21, 3:30-5 p.m. in 390 Hearst Mining Building
  - No lecture the day of the midterm
  - HW#7 due this coming Friday
  - HW#8 will be available Thursday and due Tuesday next week (I know, but this will help you on the midterm)

- Lecture Topics:
  - High Gain Op Amps
  - Slew Rate

- Last Time:
  - First pass on feedback

**Observations:**
1. Closed loop DC gain \( \frac{A_o}{1+\beta A_o} = \frac{A_o}{A_o + \frac{1}{A_o}} \approx \frac{A_o}{T_o} \)  
   i.e., the closed loop gain is reduced from the open loop gain by \( 1+T_o \) — show this on graph

2. Alternatively, 
   Closed loop DC gain \( \frac{A_o}{\beta A_o} = \frac{1}{\beta} \)  
   \( [T_o \gg 1] \)

3. \( \omega_{3dB} \) has increased from \( \omega_b \rightarrow \omega_b (1+\beta A_o) = \omega_b (1+T_o) \)

4. Gain-BW Product: \( \frac{A_o}{1+\beta A_o} \omega_b (1+\beta A_o) = A_o \omega_b = \omega_T \)  
   i.e., the Gain-BW product remains the same for the open \& closed loop FB cases!

- High Gain Op Amps

  How can we increase gain?
  1. Cascade
  2. Cascade Amplifier

- Telescopic Op Amp w/ Single-Ended Output

\[
\begin{align*}
V_{DD} & \quad 2 g_{m1} r_{o1} V_{in} \\
M_2 & \quad r_{o2} (1 + g_{m1} r_{o1} V_{in}) \\
M_3 & \quad 2 g_{m2} r_{o2} r_{o1} V_{in} \\
M_4 & \quad r_{o1} r_{o2} (1 + g_{m2} r_{o2} r_{o1} V_{in}) \\
M_5 & \quad 2 g_{m3} r_{o3} r_{o2} r_{o1} V_{in} \\
M_6 & \quad r_{o2} r_{o3} r_{o1} r_{o2} (1 + g_{m3} r_{o3} r_{o2} r_{o1} V_{in}) \\
M_7 & \quad 2 g_{m4} r_{o4} r_{o3} r_{o2} r_{o1} V_{in} \\
M_8 & \quad r_{o1} r_{o2} r_{o3} r_{o4} (1 + g_{m4} r_{o4} r_{o3} r_{o2} r_{o1} V_{in})
\end{align*}
\]
**Problem (Issues):**

1. **Limited output swing:**
   \[
   V_{\text{swing}} = \frac{V_{DD} - V_{GS1} - |V_{OL}| - |V_{OS}|}{2} + V_{GS1} + |V_{OL}| - |V_{OS}|
   \]

   \[
   V_{\text{min}} > V_{OS} + V_{OL} + V_{OS} + V_{OL}
   \]

   (Too many transistors stacked)

   \[
   \text{Gain} = \text{huge!}
   \]

   \[
   \text{Gain} \to \text{big!}
   \]
Problem 2: Difficult to get input to output.

\[ V_i \quad + \quad 0 \quad V_o \quad \text{(unity gain buffer, very useful!)} \]

\[ V_{DD} \quad M_7 \quad M_8 \]

\[ M_5 \quad M_6 \]

\[ V_{in} \quad - \quad V_{SS} \]

Want to know what range of \( V_{out} \) keep all devices saturated.

\[ M_2 \text{ must be } > M_4 \]

\[ V_{out} \geq V_b - V_{GS4} + V_{OV4} \]
\[ \Rightarrow V_{out} \geq V_b - V_{GS4} + V_{OV4} \]

\[ M_2 \text{ must be } > M_4 \text{ saturated.} \]

\[ M_4 \text{ need } V_{out} \geq V_b - V_{GS4} + V_{OV4} \]
\[ \Rightarrow V_{out} \geq V_b - V_{GS4} + V_{OV4} \]

\[ M_2 \text{ need } V_{out} \leq V_{X} - V_{GS2} + V_{OV2} \]
\[ V_{out} \leq V_{b} - V_{GS4} + V_{OV4} + V_{GS2} \]
\[ \approx V_{b} - V_{GS4} \]

Low freq. non-dominant pole associated with "mirror" node will hurt stability in a FB circuit.

\[ \text{Input} \quad \text{fully-differential, fully-balanced op amp} \]

\[ \frac{1}{R_{OC}} \]

This distance is the gain range for stability in FB.
Another Sbn: 2-stage op amp

Class 2-Stage Op Amp

Gain:
1st Stage: $a_{n1} = \frac{V_{i1}}{V_i} = -g_{m2} \left( \frac{r_{o2} l r_{04}}{} \right)$
2nd Stage: $a_{n2} = \frac{V_{o2}}{V_0} = -g_{m6} \left( \frac{r_{o6} l r_{07}}{} \right)$

$\alpha = a_{n1} a_{n2} = g_{m2} \left( \frac{r_{o2} l r_{04}}{} \right) g_{m6} \left( \frac{r_{o6} l r_{07}}{} \right)$

Freq. Response:

Due to action of $C_c$

2nd order

$w_p = \frac{1}{\sqrt{g_{m6} \left( \frac{r_{o6} l r_{07}}{} \right) C_c}}$

Cm makes this distance longer

A FB stage is now stable

Dominant Pole:

$w_p = w_h = \frac{1}{\left( \frac{r_{o2} l r_{04}}{} \right) \left( \frac{1}{g_{m6} \left( \frac{r_{o6} l r_{07}}{} \right) C_c} \right)}$

Miller Effect

Output Swing:

$V_{0 swing} = V_{DD} - V_{CE} - |V_{o4}| - |V_{o7}|$