Lecture 21: CMOS Op Amp Compensation

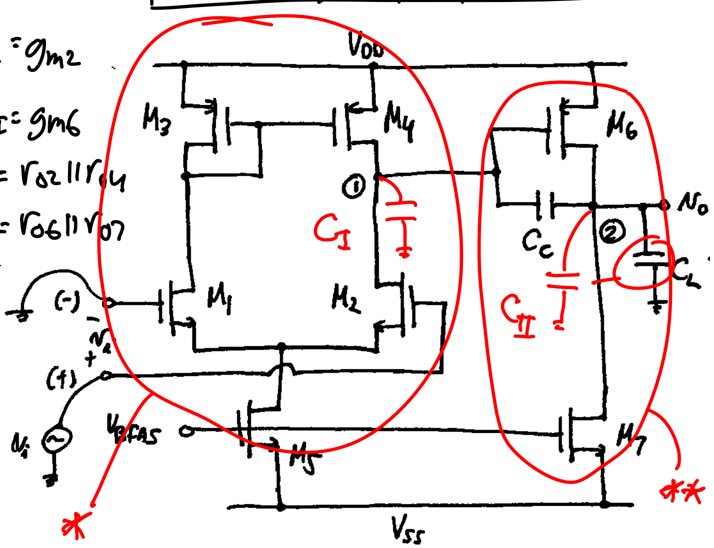
- Announcements:
- Design Project Checkpoint:
  - Due Tuesday, Nov. 19, 11:59 p.m.
  - Send to your TA a spice file for your op amp design that simulates correctly, i.e., that reaches a stable bias point where all transistors are saturated (except MOS R's)
  - It doesn't need to meet the project specs, but it should simulate correctly
- HW#9 due tomorrow at 8 a.m.
- HW#10 online soon
- Lecture Topics:
  - Practical CMOS Op Amp Compensation
  - Review of Pole-Zero Plots
  - Nulling the RHP Zero
- ------------------------------------
- Last Time: $\boxed{\text{CMOS 2-Stage Op Amp Compensation}}$

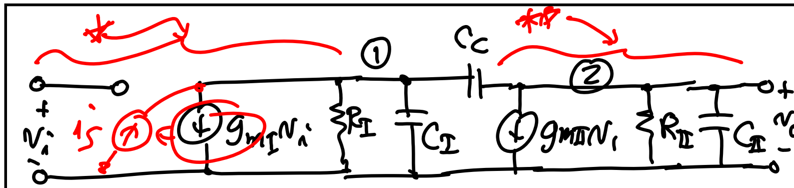
$g_{mI} = g_{m2}$

$g_{mII} = g_{m6}$

$R_I = r_{o2} \| r_{o4}$

$R_{II} = r_{o6} \| r_{o7}$





KCL①: $i_s = \frac{v_1}{R_I} + sC_I v_1 + (v_1 - v_o)sC_c$

KCL②: $g_{mII} v_1 + \frac{v_o}{R_{II}} + sC_{II} v_o + (v_o - v_1)sC_c = 0$

$$\frac{v_o}{i_s} = \frac{\overbrace{(g_{mII} - sC_c)R_I R_{II}}^{N(s)}}{\underbrace{1 + s[(C_{II}+C_c)R_{II} + (C_I+C_c)R_I + g_{mII}R_I R_{II} C_c] + s^2 R_I R_{II}(C_I C_{II} + C_c C_I + C_c C_{II})}_{D(s)}}$$

$\frac{v_o}{i_s}(s) = \frac{N(s)}{D(s)} \to$ This Xfer fcn has 2 poles & one zero.

The zero: $N(s) = 0 \to \boxed{z = \frac{g_{mII}}{C_c}} \leftarrow$ (+) & real
$z = s$
↑ RHP in the complex plane

The Poles:

$D(s) = \left(1 - \frac{s}{p_1}\right)\left(1 - \frac{s}{p_2}\right) = 1 - s\left(\frac{1}{p_1} + \frac{1}{p_2}\right) + \frac{s^2}{p_1 p_2}$ neg.

$[p_2 \gg p_1] \rightarrow \approx 1 - \frac{s}{p_1} + \frac{s^2}{p_1 p_2}$ ← compare

↑ i.e., there is a dominant pole

Thus:

$$p_1 = -\frac{1}{(C_{II}+C_c)R_{II} + (C_I+C_c)R_I + \underline{g_{mII}R_IR_{II}C_c}}$$

Miller multiplied term >> others

as $C_c\uparrow \to |p_1|\downarrow$ (pole-splitting)

$$\boxed{p_1 \simeq -\frac{1}{g_{mII}R_IR_{II}C_c}}$$

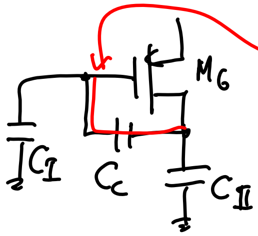
For the 2nd Pole:

$$p_1p_2 = \frac{1}{R_IR_{II}(C_IC_{II}+C_cC_I+C_cC_{II})}$$

$$p_2 = -\frac{g_{mII}C_c}{C_IC_{II}+C_cC_I+C_cC_{II}} \xrightarrow{C_c\to\infty} \boxed{p_2 \simeq -\frac{g_{mII}}{C_I+C_{II}}}$$

as $C_c\uparrow \to |p_2|\uparrow$

$\boxed{\omega_2 \text{ by Inspection}}$



When C_c = big, @ high freq. (around ω_2), it becomes a short

→ M6 becomes "diode-connected"

$$\omega_2 = \frac{1}{\tau} = \frac{1}{\left(\frac{1}{g_{m6}}\right)(C_I+C_{II})} = \frac{g_{mII}}{C_I+C_{II}}\ \checkmark$$

$g_{m6} = g_{mII}$

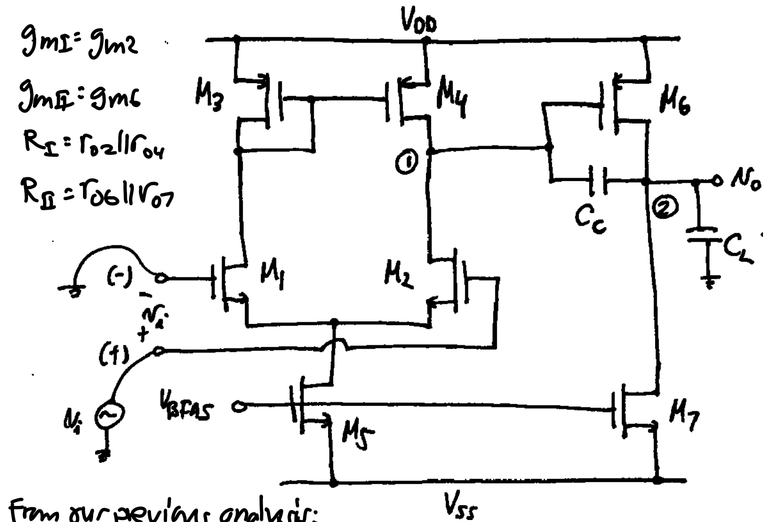
$\boxed{\text{CMOS 2-Stage Op Amp Compensation}}$ (Summary)

$g_{mI} = g_{m2}$

$g_{mII} = g_{m6}$

$R_I = r_{o2}\|r_{o4}$

$R_{II} = r_{o6}\|r_{o7}$



From our previous analysis:

$$p_1 = -\frac{1}{g_{mII}R_IR_{II}C_c}$$

$[C_c \gg C_I \text{ or } C_{II}]$ $[C_L \gg C_I]$

$$p_2 = -\frac{g_{mII}C_c}{C_IC_{II}+C_c(C_I+C_{II})} \approx -\frac{g_{mII}}{C_I+C_{II}} \approx -\frac{g_{m6}}{C_L}$$

$$z = +\frac{g_{mI}}{C_c} \leftarrow \text{RHP zero (this will cause problems)}$$

Remarks.

① Note that as $C_c\uparrow \to |p_1|\downarrow$

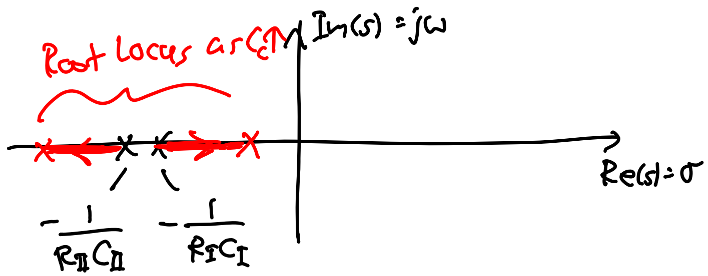
② As $C_c\uparrow \to |p_2|\uparrow \to |p_2| = \frac{g_{mII}}{C_I+C_{II}}$

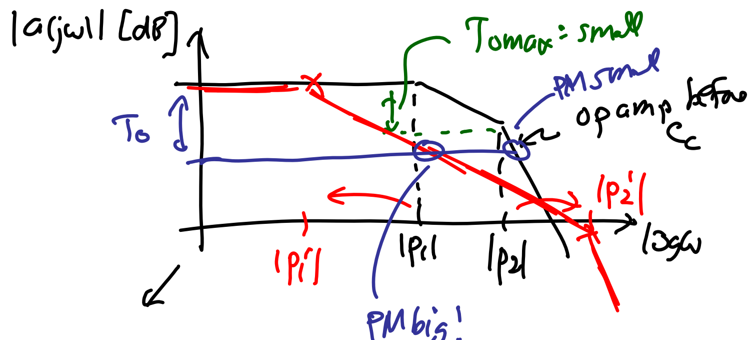
} pole-splitting

③ With $C_c = 0$ (i.e., before compensation)

$$p_1 = -\frac{1}{R_IC_I} \qquad p = -\frac{1}{R_{II}C_{II}}$$

(4) On a pole/zero diagram



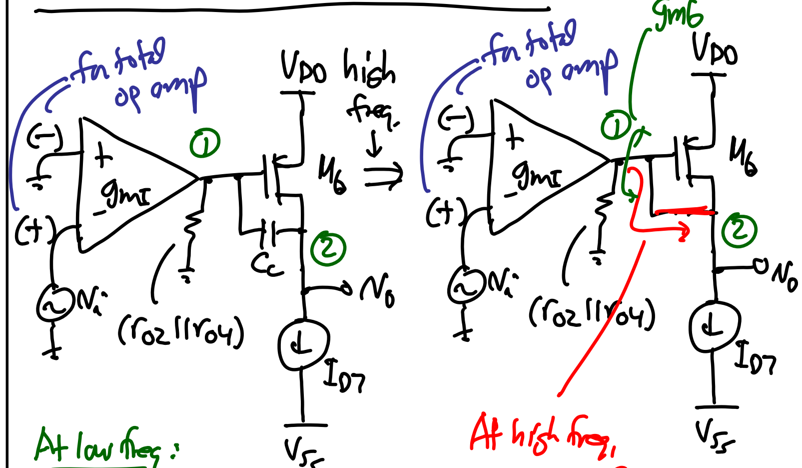


Great!

But what about the RHP zero?

- Now, go through the handouts:
  - Review of Pole/Zero Plots
  - RHP Zero
- These give a general picture of how a RHP zero can hurt stability (but a LHP plane zero can really help)

Where Does the RHP Zero come from?



At low freq.:

$$\frac{v_{②}}{v_{①}}=-g_{m6}(r_{o6}\|r_{o7})$$

$(-)$

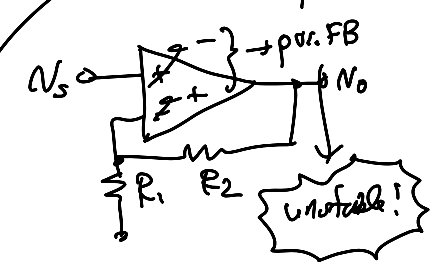
$$\text{total gain}=\frac{v_{①}}{v_i}\cdot\frac{v_{②}}{v_{①}}=(+)$$

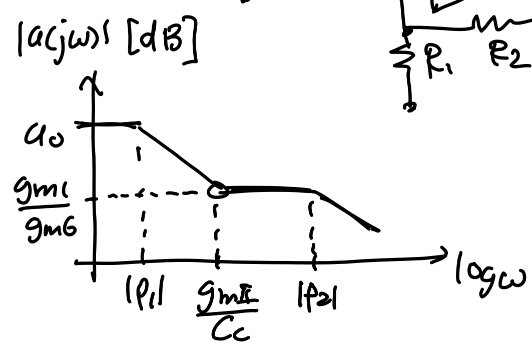
$(-)\quad(-)$

At high freq., got feed-forward path → creates the RHP zero

$$\frac{v_o}{v_i}=-\frac{g_{m1}}{g_{m6}}$$

total gain = $(-)$ → 180° phase shift!



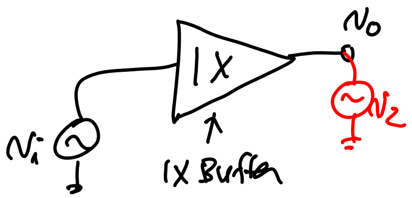


Observation.

Miller effect compensation requires FB path.

BUT: The feedforward path (that creates the zero) is not needed!

Solution: ① Kill the feedforward path
② Keep the feedback path



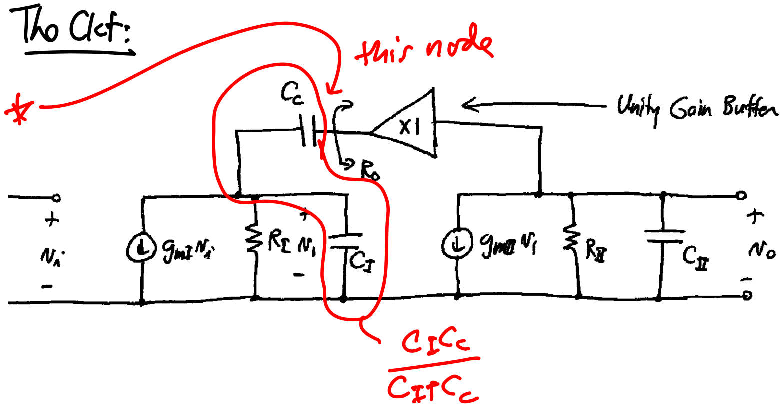
$\frac{v_o}{v_i} = 1$

$\frac{v_i}{v_2} \ll 1$

∴ buffer is directional!

Solution: Put a 1x buffer in series w/ C_c to prevent feedforward, but allow FB!

The Ckt:



Apply KCL:

$$p_1 \cong -\frac{1}{g_{mII} R_I R_{II} C_c} \quad \text{(same as before)}$$

$$p_2 \cong -\frac{g_{mII} C_c}{C_{II}(C_I + C_c)} \cong -\frac{g_{mII}}{C_{II}} \quad [C_c \gg C_I]$$

$$p_3 \cong -\frac{1}{R_o \underbrace{(C_I C_c / (C_I + C_c))}_{\text{series combination of } C_I \,\&\, C_c}} \cong -\frac{1}{R_o C_I}$$

comes from ✱

$$z \cong -\frac{1}{R_o C_c} \leftarrow \text{LHP zero!}$$

Good!

Remarks.

① An additional pole $p_3 = -\frac{1}{R_o C_I}$ has been created! But since R_o = small (for a buffer) and C_I = small, p_3 is at a very high freq. → contributes very little phase @ ω_{ulg}, where $|T(j\omega)| = 1$.

② A LHP zero now emerges, $z_I = -\frac{1}{R_o C_c}$.

This helps stability as discussed before. (by contributing (+) phase shift → PM↑)