Lecture 22: RHP Zero

- Announcements:
- HW#9 due next Wednesday at 8 a.m.
- Lab#3 (Design Project) in progress
- Design Project Checkpoint:
  - Due Tuesday, Nov. 17, 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 (or linear if an MOS resistor)
  - It doesn't need to meet the project specs, but it should simulate correctly
- Thursday (next week) I'll be traveling
  - Lecture by videotape
- Handout on "RHP Zero" online
- Lecture Topics:
  - CMOS Op Amp Compensation
  - Nulling the RHP Zero
- ---------------------------------------
- Last Time: Choosing Cc

over

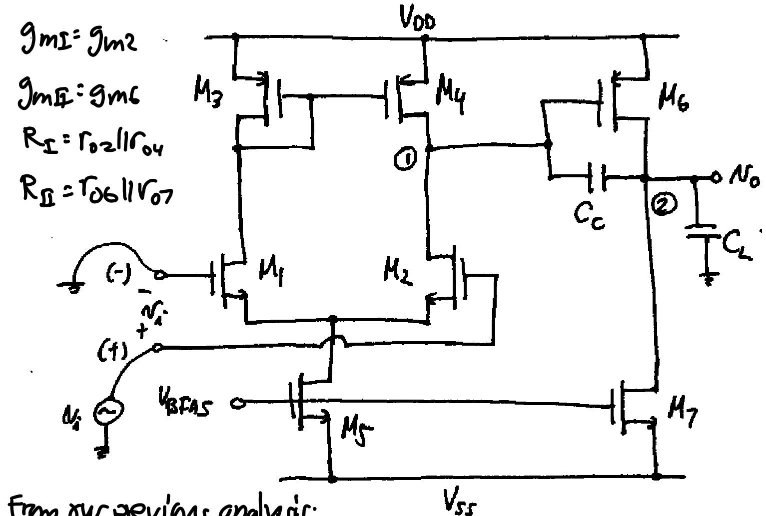
CMOS 2-Stage Op Amp Compensation (Summary)

$g_{mI} = g_{m2}$

$g_{mII} = g_{m6}$

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

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



From our previous analysis:

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

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

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

$$z = +\frac{g_{mII}}{C_c}$$ ← RHP zero (this will cause problems)

Remarks:

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

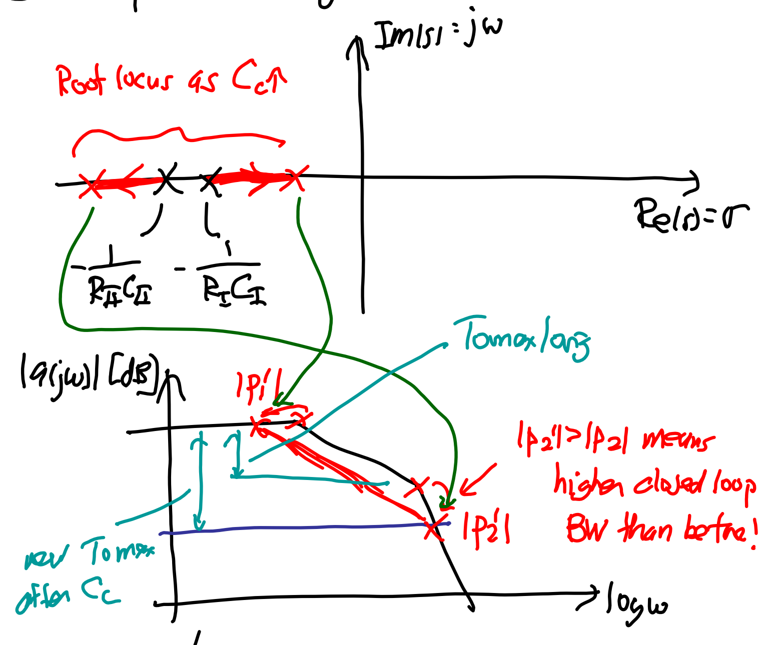
② As $C_c\uparrow \rightarrow |p_2|\uparrow \rightarrow |p_2| = \frac{g_{mII}}{C_I + C_{II}}$

pole-splitting

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

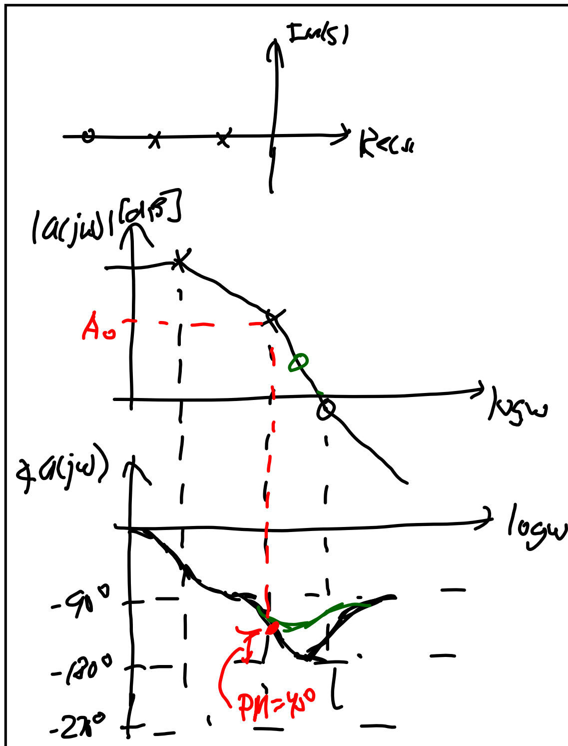
$$p_1 = -\frac{1}{R_I C_I}, \quad p_2 = -\frac{1}{R_{II} C_{II}}$$

④ On a pole-zero diagram:

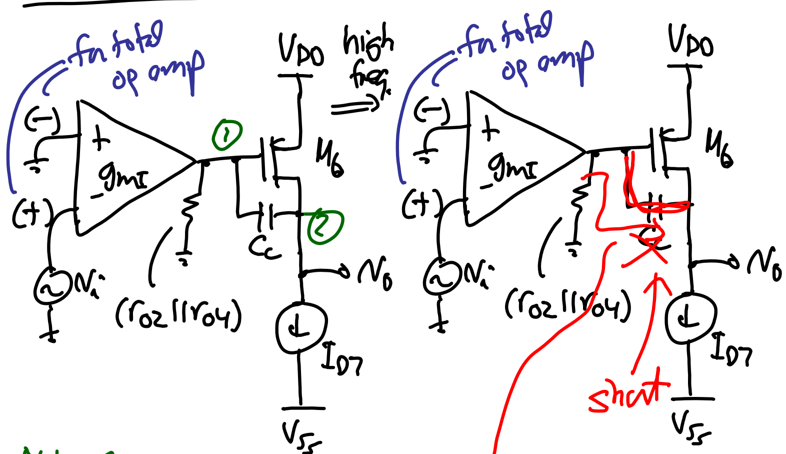


Great! → But what about the RHP zero?

- 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 high freq., get feed-forward path

At low freq.:

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

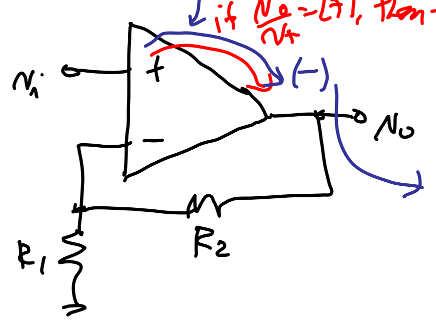
(-)

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

(-) (-)

$$\boxed{\frac{v_o}{v_i} = \frac{v_o}{v_+} = -\frac{g_{m1}}{g_{m6}} = (-)!}$$

if $\frac{v_o}{v_+} = (-)$, then this ckt. is neg. FB



total = pos. FB!

⇒ unstable!

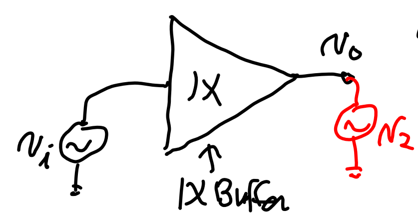
Observation.

Miller effect compensation requires neg. FB path.

↳ But: The feed-forward path (that creates the zero) is not needed!

Solution: ① Kill the feedforward path.

② Keep the feedback path.



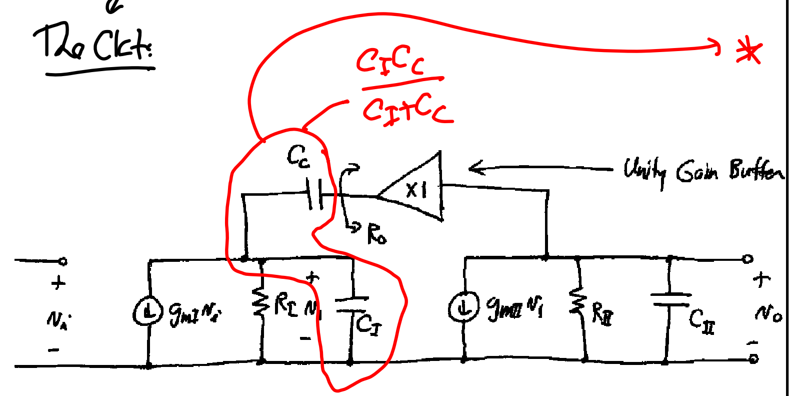
$\frac{v_o}{v_i} = 1$

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

∴ buffer is directional!

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

The Ckt:



Apply KCL:

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

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

$[C_c >> C_I]$

$$* \; p_3 \cong -\frac{1}{R_o \underbrace{\left(C_I C_c/(C_I + C_c)\right)}_{\text{series comb. of } C_I \,\&\, C_c}} \cong -\frac{1}{R_o C_I}$$

$$z \cong -\frac{1}{R_o C_c}$$ ← LHP zero! → Good!

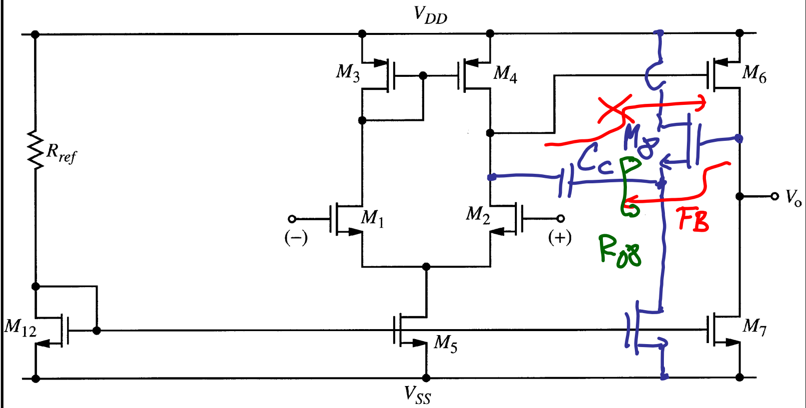
Remarks.

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↑)

Actual Implementation of Buffer-Based Cancellation

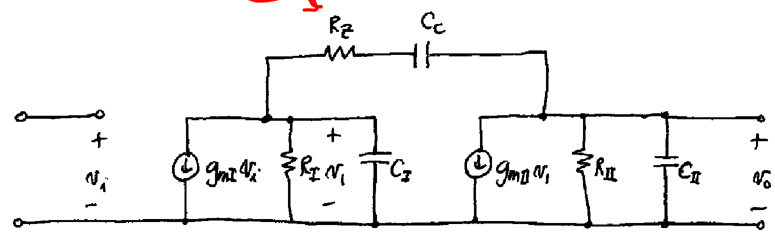


$R_{o8} = \frac{1}{g_{m8}} = \frac{1}{\sqrt{2\mu_n C_{ox}(W/L)_8 I_{D8}}}$ → want this sufficiently small to drive $|p_3|$↑

increase I_{D8} or increase $(W/L)_8$

Problem { ↓ more power ✗ ↓ more area → cost! ✗

Solution: $\boxed{\text{Nulling Resistor in Series w/ } C_c}$



Doing KCL:

$$\left.\begin{aligned} p_1 &\approx -\frac{1}{g_{mII} R_S R_{II} C_c} \\ p_2 &\approx -\frac{-g_{mII} C_c}{C_I C_{II} + C_c(C_I + C_{II})} \cong -\frac{g_{mII}}{C_{II}} \end{aligned}\right\} \text{Same as before}$$

$$p_3 = -\frac{1}{R_Z C_I} \leftarrow \text{pole due to } R_Z$$

$$z = \frac{1}{C_c\left(\frac{1}{g_{mII}} - R_Z\right)} \leftarrow \text{relocated zero (function of } R_Z)$$

Note: The position of the zero depends upon the value of "nulling resistor" R_Z.

If $R_Z < \frac{1}{g_{mII}}$ then z is in the RHP

If $R_Z > \frac{1}{g_{mII}}$ then " " " LHP!

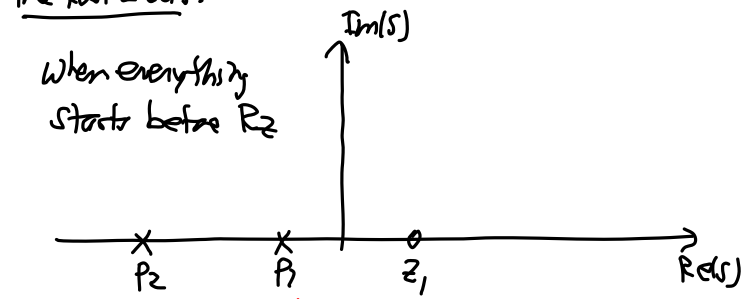
This is great! → can convert the RHP zero to a LHP one!

can even stick the zero on top of a pole to eliminate it!

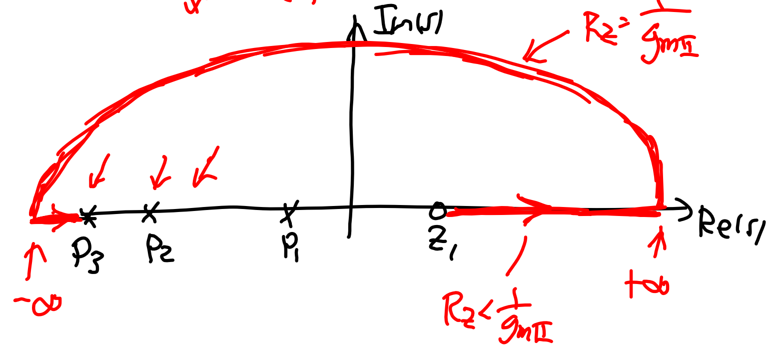
$$H(s) = \cdots \frac{\cancel{(s - z_1)}}{\cancel{(s - p_1)}}$$

if $z_1 = p_1$

The Root Locus:



add R_Z ↑



Zero Placement Strategies

① Eliminate z_1 → move it to ∞:

$$z_1 = \frac{1}{C_c\left(\frac{1}{g_{mII}} - R_Z\right)} \to \infty \text{ when } \boxed{R_Z = \frac{1}{g_{mII}}}$$

After doing this:

$$\left.\begin{aligned} p_3 &\cong -\frac{g_{mII}}{C_I} \\ p_2 &\cong -\frac{g_{mII}}{C_{II}} \end{aligned}\right\}$$

Load Cap.

Usually $C_{II} \gg C_I$ so these poles are far apart... but be careful

This is good, but we can do better:

② Eliminate p_3 by placing z_1 on top of it:

$$z_1 = p_3 \Rightarrow \frac{1}{C_c\left(\frac{1}{g_{mII}} - R_z\right)} = -\frac{1}{R_z C_I}$$

$$\boxed{R_z = \frac{1}{g_{mII}\left(1 - \frac{C_I}{C_c}\right)}}$$

After this: ① p_3 gone; p_1 & p_2 left

② Now, can place ω_u @ $|p_2|$ and really set PM = 45° → don't have to worry about phase influence of p_3!

But can still do better

③ Eliminate p_2 by placing z_1 on top of it:

⇒ p_3 becomes the "new" p_2! (higher freq., higher $T_{o\max}$)

$$z_1 = p_2 \Rightarrow \frac{1}{C_c\left(\frac{1}{g_{mII}} - R_z\right)} = -\frac{g_{mII}}{C_{II}}$$

$$\boxed{R_z = \left(\frac{C_c + C_{II}}{C_c}\right)\left(\frac{1}{g_{mII}}\right) = \frac{1}{g_{mII}}\left(1 + \frac{C_{II}}{C_c}\right)}$$