Lecture 23: Practical Compensation

- **Announcements**:
- Design Project Checkpoint:
  - Due Monday, April 23, 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
- **Lecture Topics**:
  - RHP Zero
  - Nulling the RHP Zero
- ------------------------------------
- **Last Time**:

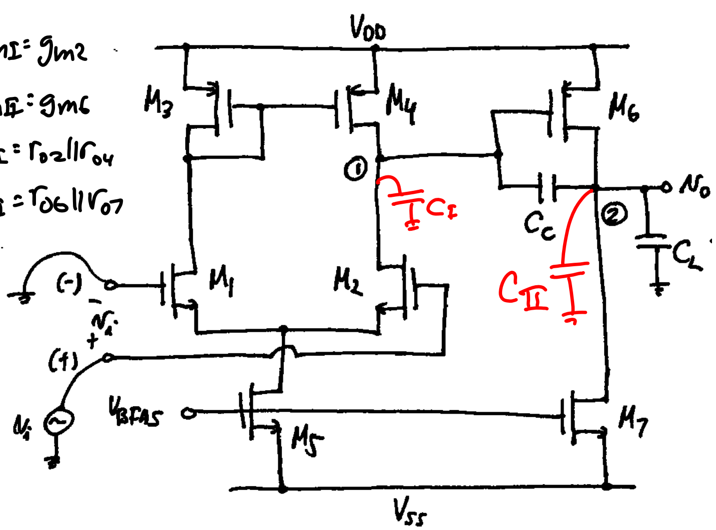
$\boxed{\text{CMOS 2-Stage Op Amp Compensation}}$ (Summary)

$g_{mI} = g_{m2}$

$g_{mII} = g_{m6}$

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

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



From our previous analysis:

$$p_1 = -\frac{1}{g_{mII} R_I R_{II} C_c} \qquad [C_c \gg C_I \text{ or } C_{II}] \qquad [C_L \gg C_I]$$

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

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

Remarks.

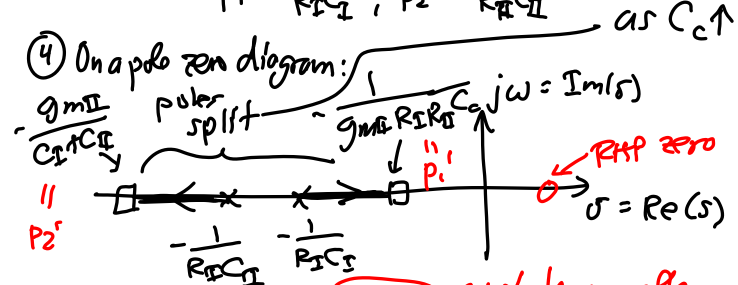
① Note that as $C_c \uparrow \rightarrow p_1 \downarrow \rightarrow 0$

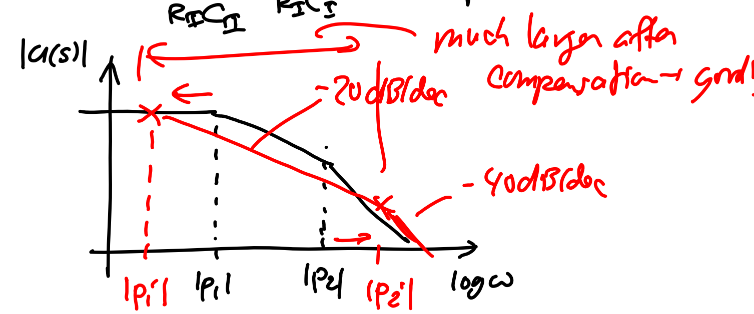
② As $C_c \uparrow \rightarrow p_2 \uparrow \rightarrow p_2 = \frac{g_{mII}}{C_I + C_{II}}$

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

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

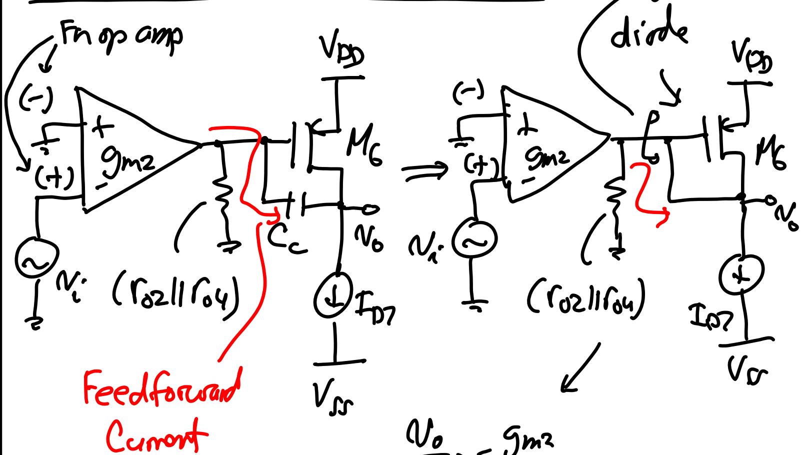
④ On a pole zero diagram:





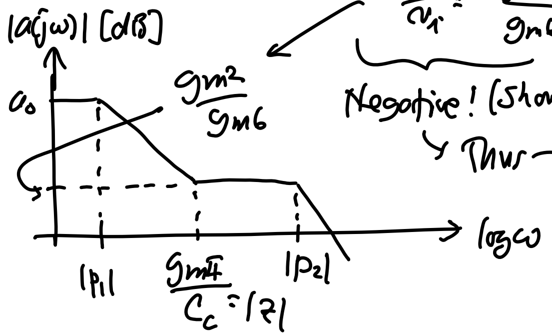
- Go through RHP zero handout: Lec12x

Where Does the RHP zero come from?



$$\frac{v_o}{v_i} = \underbrace{-\frac{g_{m2}}{g_{m6}}}$$

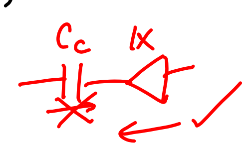
Negative! (should be (+))
→ Thus → instability!



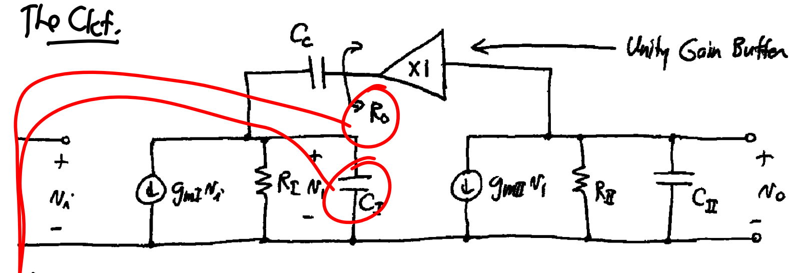
Observation:

The Miller effect (for compensation) requires the FB path around M_6 → BUT: the feedforward path (that causes the zero) isn't needed!

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



The Ckt.



Apply KCL:

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

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

$[C_c \gg C_I]$

$$p_3 \cong \frac{-1}{R_o[\underbrace{C_I C_c/(C_I+C_c)}]} \approx -\frac{1}{R_o C_I}$$

Series combination of C_I & C_c.

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

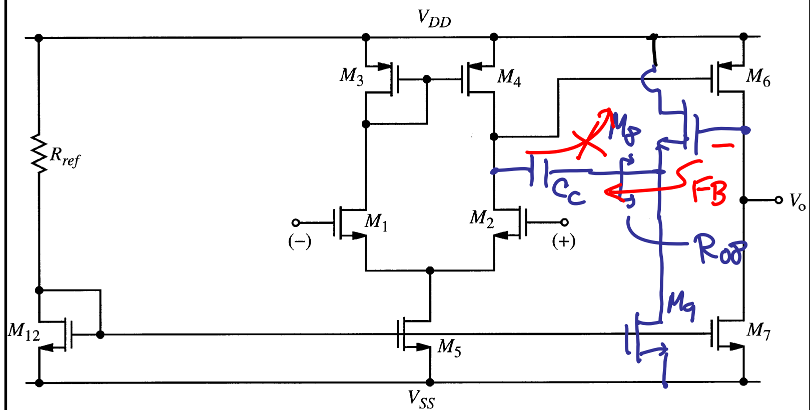
Remarks.

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_{ult}, 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 Zero Cancellation



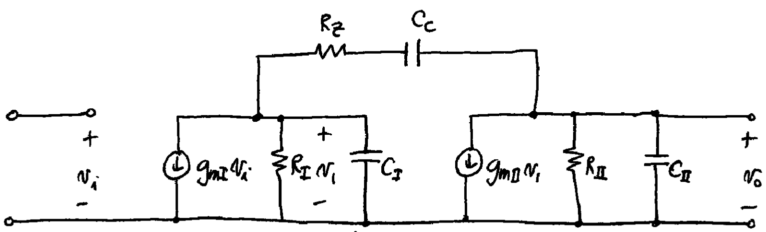
$R_{o8} \cong \frac{1}{g_{m8}} = \frac{1}{\sqrt{2\mu_n C_{ox}(W/L)_8 I_{D8}}}$ ← Want this sufficiently small to drive $|p_3|\uparrow$

① make $(W/L)_8$ big ✗ → area↑

② a use large enough I_{D8} ✗ → power↑

Solution: a better technique!

Nulling Resistor in Series w/ C_c



Doing KCL: $p_1 \cong -\frac{1}{g_{mII}R_I R_{II} C_c}$

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

} Same as before

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

$z_1 = \frac{1}{C_c\left(\frac{1}{g_{mII}} - R_Z\right)}$ ← relocated zero (function of R_Z)

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

- If $R_Z < \frac{1}{g_{mII}}$ then z_1 is in the RHP
- If $R_Z > \frac{1}{g_{mII}}$ then z_1 " " " LHP!

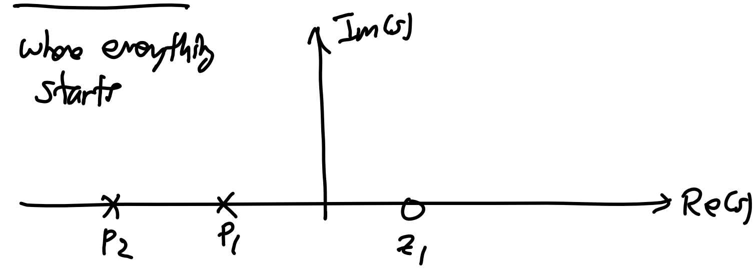
↳ This is good! → can convert the zero to a LHP zero!

↳ can even stick it on top of a pole → null it!

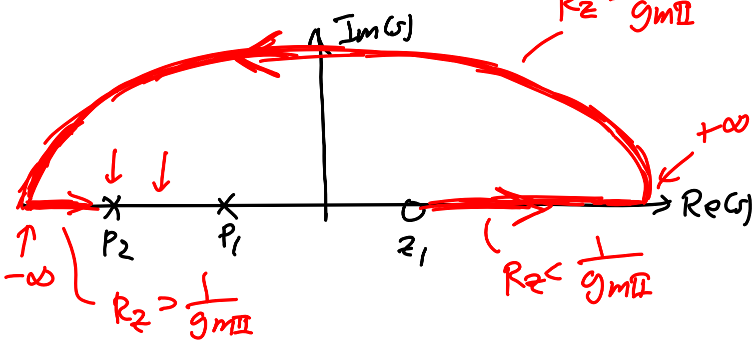
$H(s) = \frac{\cancel{(s-z_1)}}{\cancel{(s-p_1)}}$ If $z_1 = p_1$

The Root Locus:

where everything starts



Now, introduce 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: $p_3 \cong -\frac{g_{mII}}{C_I}$, $p_2 \cong -\frac{g_{mII}}{C_{II}}$ } usually, $C_{II} \gg C_I$, since $C_{II} = C_L$.

so these poles are often very far apart. (but be careful)

This is good... but we could do better...

② Eliminate p_3 by placing z_1 on top of it:

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

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

After this:

① p_3 gone; p_1 & p_2 left

② Now, can place $\omega_{u\ell t}$ @ p_2 and really get PM = 45° (w/o worrying about the influence of p_3)