- **Announcements**:
  - Make-up lecture tonight, 7 p.m., in 247 Cory
- **Today**:
  - RHP Zero Issues for Compensation
  - Slew Rate Design

Last Time –

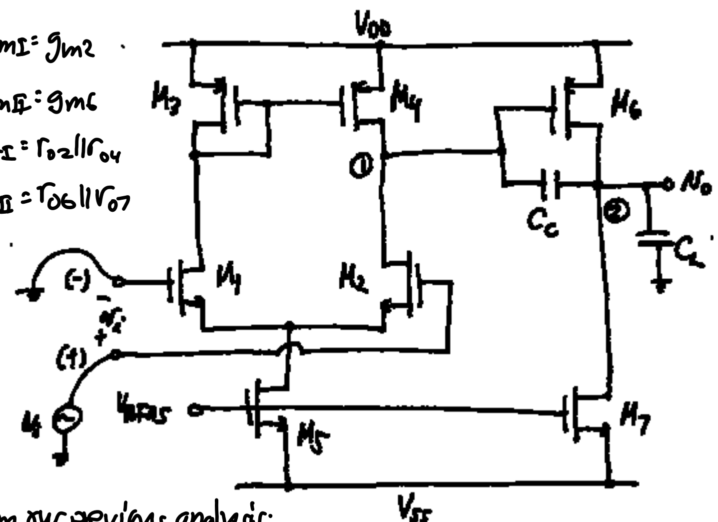
$\boxed{\text{CMOS 2-Stage Op Amp Compensation}}$

$g_{mI} = g_{m2}$

$g_{mII} = g_{m6}$

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

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



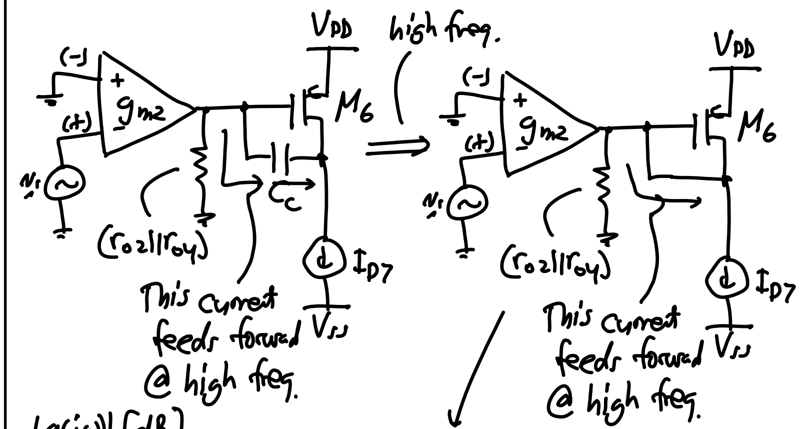
From our previous analysis:

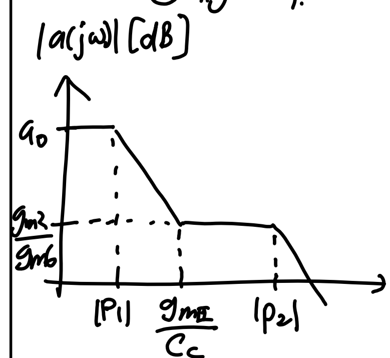
$$p_1 = -\frac{1}{g_{mII} R_I R_{II} C_c} \qquad [C_c \gg C_I \text{ or } C_{II}] \qquad [C_L \gg C_I]$$

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

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

Where does the RHP zero come from?





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

Negative! Should be (+)!

Thus, will get instability!

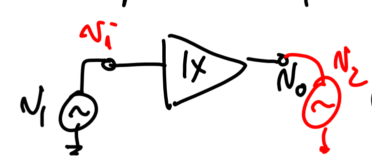
Observation:

The Miller effect (for compensation) requires the FB path

BUT: the feedforward path (that causes the zero) isn't needed!

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

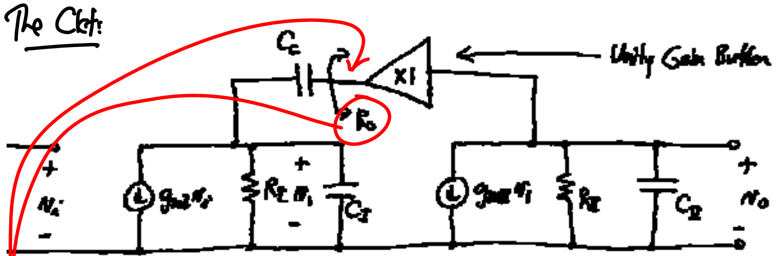
Stick in a unity gain buffer in series w/ the C_c



$\frac{v_1}{v_2}$ = small ∴ <1

$\frac{v_o}{v_1}$ = finite gain > 1

The Ckt:



Apply KCL:

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

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

$[C_c \gg C_I]$

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

Series combination of C_I & C_c.

Comes from this node

$$z_2 \cong -\frac{1}{R_o C_c} \leftarrow \text{LHP zero! (Good!)}$$

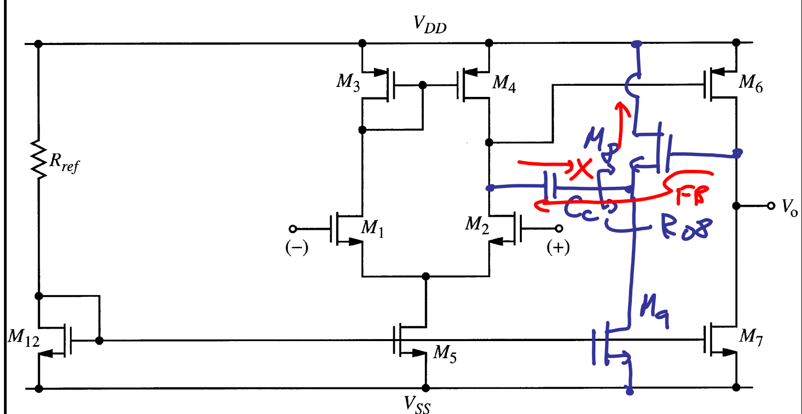
Remarks:

① An additional pole $p_3 \cong -\frac{1}{R_o C_I}$ 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 @ $\omega_{u\ell g}$, 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)

$\boxed{\text{Actual Implementation of Butte-Band Zero Cancellation}}$

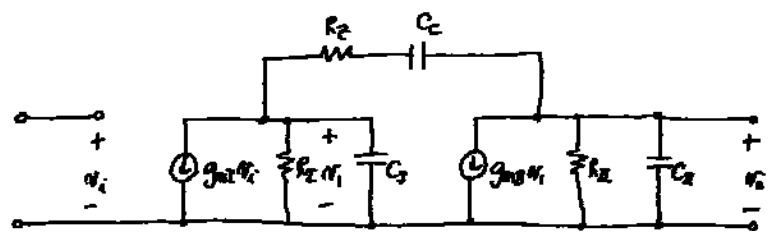


$$R_{o8} \cong \frac{1}{g_{m8}} = \frac{1}{\sqrt{2\mu_n C_{ox}(\frac{W}{L})_8 I_{D8}}}$$
→ want this sufficiently small to drive $|p_3| \uparrow$

must use large enough I_{D8}
↳ Problem: power dissipation!

↳ Solution: a better technique!

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



Doing KCL:

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

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

Same as before

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

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

Note: The position of the zero depends upon 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 great! → can convert the zero to a LHP one!

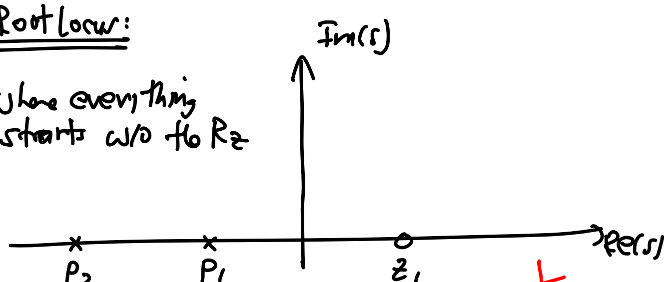
→ can even stick it right on top of a pole!

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

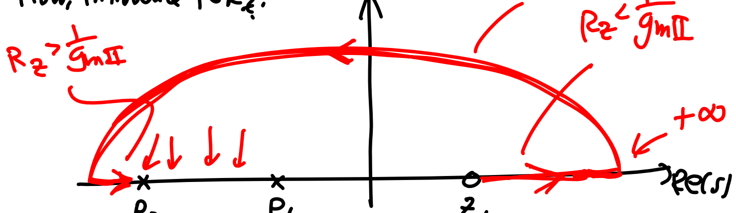
If $z_1 = p_1$ →

The Root Locus:

where everything starts w/o the R_Z



Now, introduce the R_Z:



Zero Placement Strategies:

① Eliminate z_1 → move it to ∞:

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

After doing this: $p_3 \cong -\dfrac{g_{mII}}{C_I}$, $p_2 \cong -\dfrac{g_{mII}}{C_{II}}$

Usually, $C_{II} \gg C_I$ (load cap.), 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:

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

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

After this:

① p_3 gone, p_1 & p_2 left

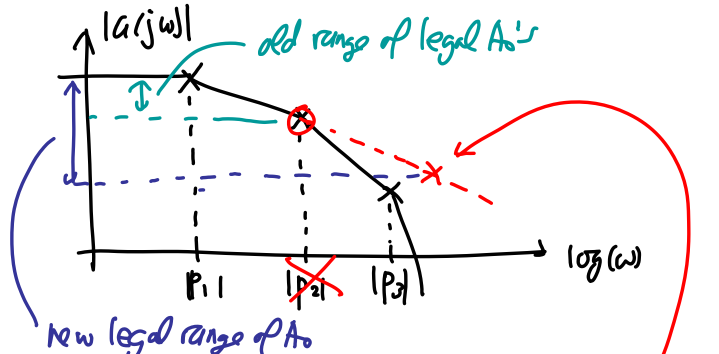
② Now, can place $\omega_{u\ell g}$ @ p_2 and really get PM = 45° (w/o worrying about the influence of p_3)

But can still do better than this... → next

③ Eliminate p_2 by placing z_1 on top of it:

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

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



With this choice of R_Z:

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

$$\boxed{p_3 = -\frac{g_{mII} C_c}{C_I (C_c + C_{II})}}$$ ← This becomes the new p_2!

For PM=45°:

$$C_c = \frac{g_{mI}}{|p_3| A_o} = \frac{g_{mI}}{g_{mII}} \frac{C_I (C_c + C_{II})}{C_c A_o}$$

the "new" $|p_2|$

solve for C_c

For PM=45°:

$$\boxed{C_c \simeq \sqrt{\frac{g_{mI}}{g_{mII}} \frac{C_I C_{II}}{A_o}}}$$

For PM=60°:

$$C_c = \frac{1.73\, g_{mI}}{|p_3| A_o} \rightarrow \boxed{C_c \simeq \sqrt{\frac{1.73\, g_{mI}}{g_{mII}} \frac{C_I C_{II}}{A_o}}}$$

$[C_I \ll C_{II}]$

For PM=60°.

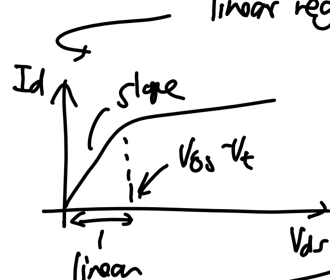
Remark. If settling time is important, then approach ③ may not be the best approach. The reason is that if the zero is not exactly equal to the pole, the a "doublet" ensues, which actually can hurt the settling time.

Discussed in a handout to be posted on the course website. → also, discussed in Razavi, problem 10.19.

Actual Implementation

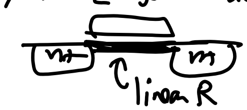
⇒ resistor are too big! → ∴ implement using a much smaller MOS resistor!

MOS Resistor: just an MOS Xistor operated in the linear region



$$I_d = \mu_n C_{ox} \frac{W}{L}\left[(V_{gs} - V_t)V_{ds} - \frac{1}{2}V_{ds}^2\right]$$

$$\frac{\partial I_d}{\partial V_{ds}} = \mu_n C_{ox} \frac{W}{L}(V_{gs} - V_t - V_{ds})$$



$$\boxed{R_{s.s.} = \left[\frac{dI_d}{dV_{ds}}\right]^{-1}_{V_{gs}=V_{GS},\, V_{ds}=V_{DS}} = \frac{1}{\mu_n C_{ox} \frac{W}{L}(V_{GS} - V_t - V_{DS})} = \frac{1}{g_{ds}}}$$

a variable resistor controllable by V_{GS}!