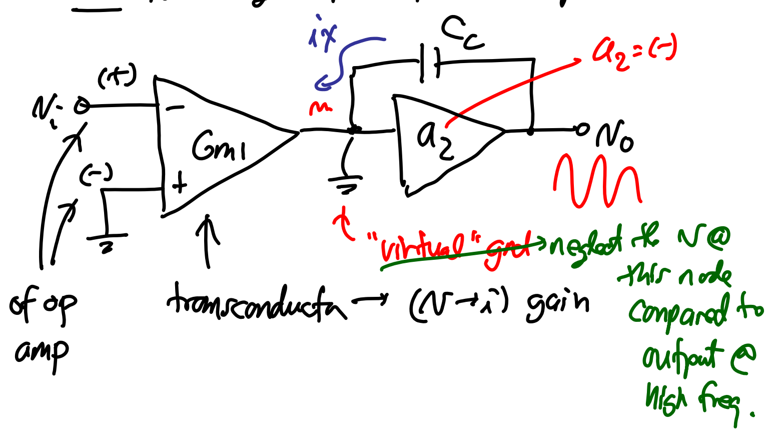
Lecture 22: CMOS Op Amp Compensation

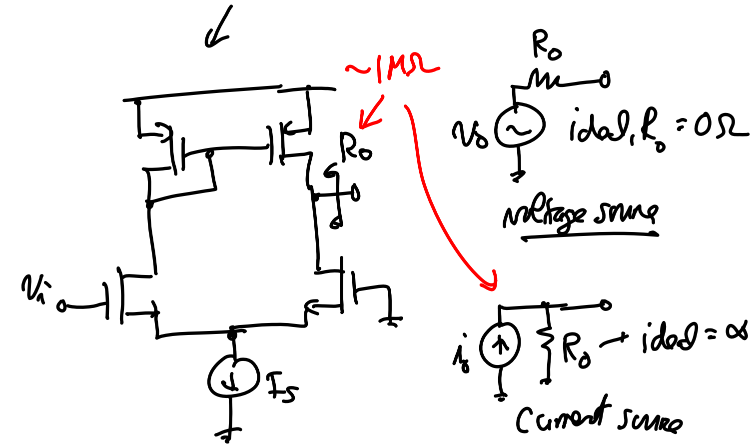
- Announcements:
  - HW#9 due today
  - HW#10 online: shorter than usual, since you also have your project (Lab#3) to work on
- Lecture Topics:
  - Choosing Cc (cont.)
  - CMOS 2-Stage Op Amp Poles & Zeros
  - RHP Zero
  - Nulling the RHP Zero
- ------------------------------------
- Last Time:

$\boxed{\text{Choosing } C_c}$ (assume no RHP zeroes & $|p_3| >> |p_2|$)

$\Rightarrow$ assume $\frac{1}{sC_c} <<$ surrounding impedance @ high freq.

① Case: Two-Stage Amplifier, Miller compensation

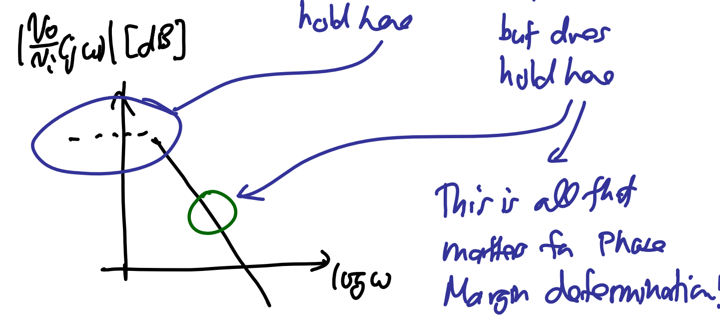




$$v_o = \frac{i_x}{sC_c}, \quad i_x = G_{m1} v_i \quad \Rightarrow \quad v_o = \frac{G_{m1}}{sC_c} v_i \rightarrow \frac{v_o}{v_i}(s) = \frac{G_{m1}}{sC_c}$$

does not hold here

but does hold here



This is all that matters for Phase Margin determination!

$$\left|\frac{v_o}{v_i}(j\omega)\right| = \frac{G_{m1}}{\omega C_c}$$ $\Rightarrow$ this should equal A_o @ the freq. ω corresponding to the target phase margin

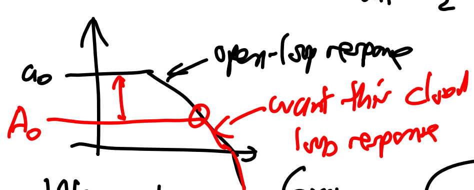
For PM = 45°:

$\omega_{ult} = \omega$ @ $|a(j\omega)f| = 1$

"ult" = "unity loop transmission"

$|a(j\omega)f| = 1$

For PM = 45° → $\omega_{ult} = \omega_2$ ← freq. of the 2nd pole in the $a(j\omega)$ transfer fcn.



$\left|\frac{v_o}{v_i}(j\omega_2)\right| = A_o = \frac{G_{m1}}{\omega_2 C_c} \rightarrow \boxed{C_c = \frac{G_{m1}}{\omega_2 A_o}}$

Closed-loop gain

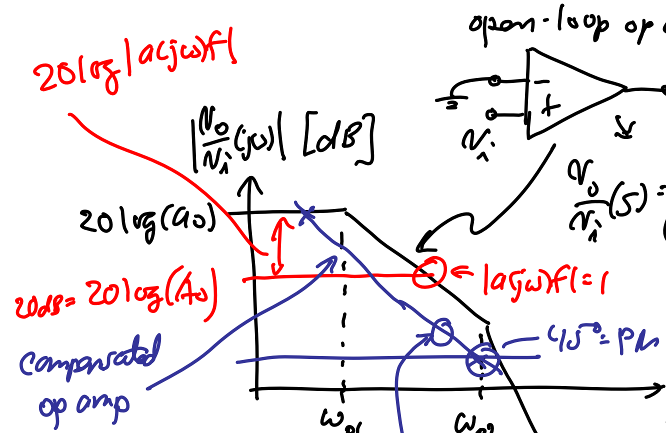
For PM = 45°
(provided $|p_3| \gg |p_2|$)

For PM = 60°:

$\omega_{ult} = \frac{\omega_2}{1.73} \rightarrow \left|\frac{v_o}{v_i}\left(j\frac{\omega_2}{1.73}\right)\right| = A_o = \frac{G_{m1}}{\left(\frac{\omega_2}{1.73}\right)C_c}$

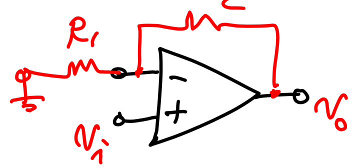
$\boxed{C_c = \frac{1.73\, G_{m1}}{\omega_2 A_o}}$ ← For PM = 60°.

Review: To make sure everyone understands



$\frac{v_o}{v_i}(s) = \frac{a_o}{\left(1+\frac{s}{\omega_{p1}}\right)\left(1+\frac{s}{\omega_{p2}}\right)}$

PM = 60° → $\omega = \frac{\omega_{p2}}{1.73} = \frac{\omega_{p2}}{\sqrt{3}}$



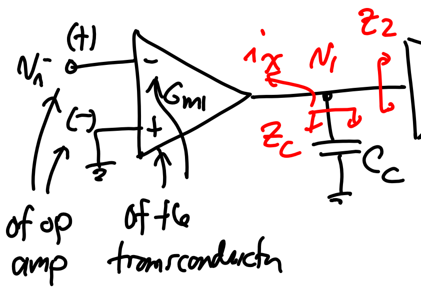
$\rightarrow \frac{v_o}{v_i}(s) = \frac{A_o}{1+\frac{s}{\omega_{cl}}}$

$A_o = \frac{a_o}{1+a_o f} \simeq \frac{1}{f} \rightarrow \therefore A_o \simeq 1 + \frac{R_2}{R_1}$

$f = \frac{R_1}{R_1+R_2}$

Got at least 50% thumbs up!

② Case: Two Stage Amplifier, Shunt C_c Compensation



$Z_2 >> Z_c = \frac{1}{sC_c}$

$$\left.\begin{array}{l} v_1 = -\frac{G_{m1} v_i'}{sC_c} \\ v_o = a_2 v_1 \end{array}\right\} v_o = -\frac{G_{m1} a_2}{sC_c} v_i'$$

$a_2 = (-)$

$$\therefore \frac{v_o}{v_i'}(s) = \underbrace{-}_{(+)}\frac{G_{m1} a_2}{sC_c}$$

} Closed loop gain A_o must again intersect this curve @ the right ω_{ulf} for a given PM

For PM=45°:

$$\left|\frac{v_o}{v_i'}(j\omega_{ulf})\right| = A_o = \frac{G_{m1} a_2}{\omega_{ulf} C_c}$$

(For PM=45°: $\omega_{ulf} = \omega_2$)

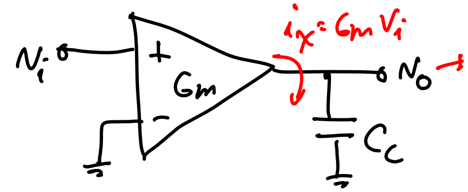
$$\boxed{C_c = \frac{G_{m1} a_2}{\omega_2 A_o}}$$ ← For PM=45°.

For PM=60°:

$$\boxed{C_c = \frac{1.73\, G_{m1} a_2}{\omega_2 A_o}}$$ ← For PM=60°.

Case ③: Single-Stage Amplifier, Shunt C_c Compensation

e.g., telescopic cascode op amp



$$\left.\begin{array}{l} v_o = \frac{i_x}{sC_c} \\ i_x = G_{m1} v_i \end{array}\right\}$$

$$\frac{v_o}{v_i'}(s) = \frac{G_{m1}}{sC_c} \leftarrow \text{same as case ①!}$$

Thus

$$\boxed{C_c = \frac{G_{m1}}{\omega_2 A_o}} \leftarrow PM = 45°$$

$$\boxed{C_c = \frac{1.73\, G_{m1}}{\omega_2 A_o}} \leftarrow PM = 60°$$

This is the final ω_2 after C_c is inserted.

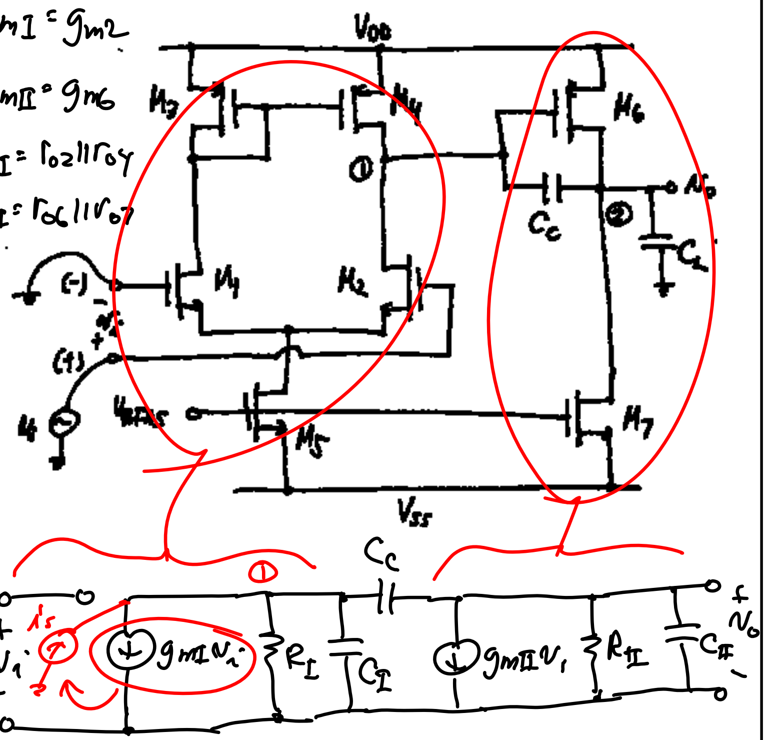
CMOS 2-Stage Op Amp Compensation

$g_{mI} = g_{m2}$

$g_{mII} = g_{m6}$

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

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



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

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

$$\frac{v_o}{i_s} = \frac{(g_{mII} - sC_c)R_I R_{II}}{\left\{1 + s\left[(C_{II}+C_c)R_{II} + (C_I + C_c)R_I + g_{mII}R_I R_{II} C_c\right] + s^2 R_I R_{II}(C_I C_{II} + C_c C_I + C_c C_{II})\right\}}$$

$\leftarrow N(s)$

$D(s) \nearrow$

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

The zero: $N(s) = 0 \rightarrow \boxed{z = \frac{g_{mII}}{C_c}}$ ← (+) and real

$z = s$

The poles:

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

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

i.e., there is a dominant pole

Thus:

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

As $C_c \uparrow \rightarrow p_1 \downarrow \rightarrow \approx -\frac{1}{g_{mII} R_I R_{II} C_c}$

For the 2nd pole:

$$p_1 p_2 = \frac{1}{R_I R_{II}(C_I C_{II} + C_c C_I + C_c C_{II})}$$

$$p_2 = -\frac{g_{mII} C_c}{C_I C_{II} + C_c C_I + C_c C_{II}}$$

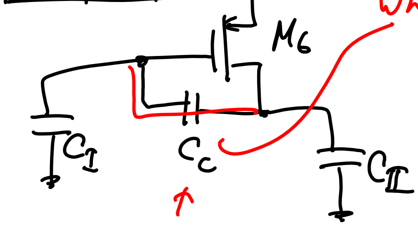
→ As $C_c \uparrow$

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

$C_c \uparrow \rightarrow p_2 \uparrow$

higher than before ∴

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



When $C_c \uparrow$, this becomes a short!
↳ M_6 becomes "diode-connected"!

$\frac{1}{sC_c} = \frac{1}{j\omega C_c}$

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

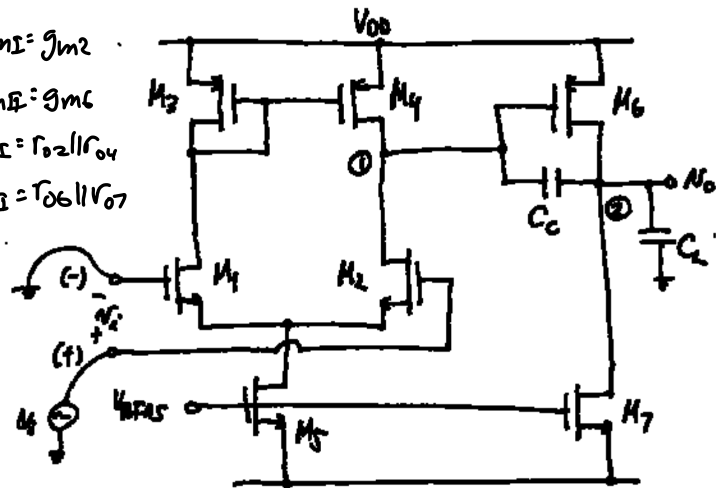
$\boxed{\text{CMOS 2-Stage Op Amp Compensation}}$ (Summary)

$g_{mI} = g_{m2}$

$g_{mII} = g_{m6}$

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

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



From our previous analysis:

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

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

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