

Lecture 20-21: Choosing Cc

- **Announcements**:
- This lecture will be 2 hours (2nd lecture to make up for missing Tuesday)
- Next lecture will also be 2 hours
- HW#9 due tomorrow
- HW#10 online soon
- Design Project Checkpoint:
  - Due Monday, April 22, 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**:
  - Review of Pole-Zero Plots
  - Choosing Cc
  - CMOS Op Amp Compensation
- ------------------------------------
- **Last Time**:

Two Ways to Compensate:

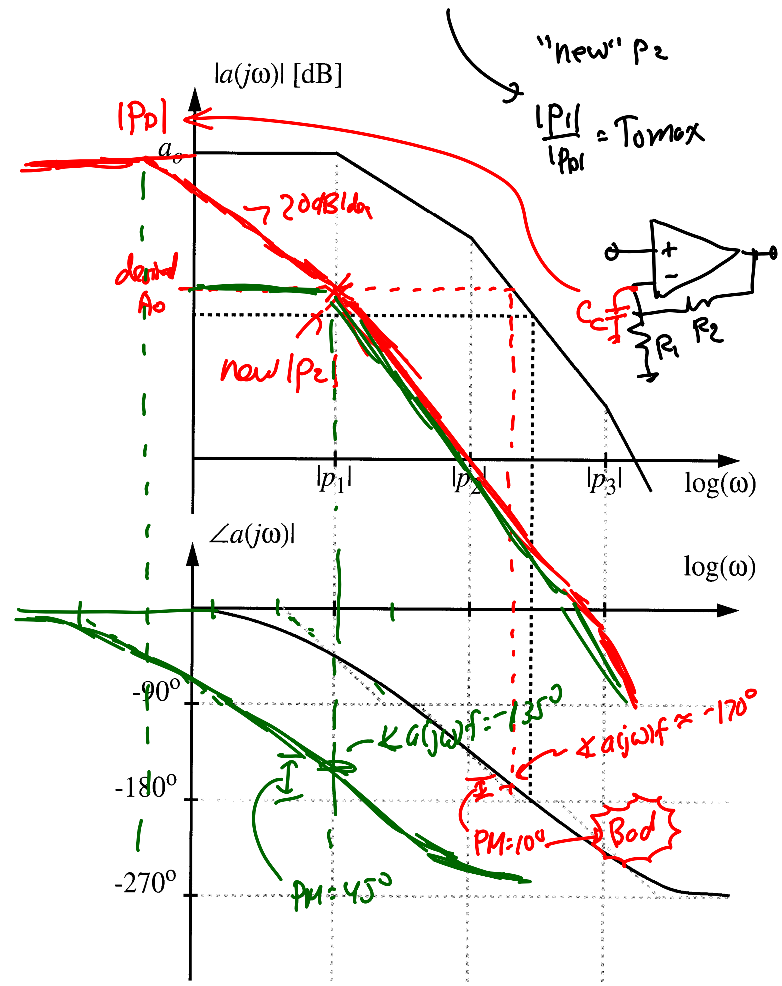
① Narrowbanding

② Pole Splitting

$\boxed{\text{Narrowbanding}}$

dominant ≡ "D"

→ introduce a pole p_D so that there is sufficient separation between p_D & p_1 ← which becomes the "new" p_2



Remarks on Narrowbanding

① Assumption: p_1, p_2, p_3 don't move when p_D is introduced (often not true, but their movement isn't that big)

② Summarize: choose p_D such that $|T(j\omega)| = 0\,dB = 1$ @ p_1 (which becomes the "new 2nd most dominant pole")
↳ this gives PM = 45° (for $|p_2| \gg |p_1|$ & $|p_3| \gg |p_2|$)

③ Why do this? Wouldn't it be much better to just move the original $|p_1|$ (i.e., pole-split)
↳ Do it when you have no other choice, e.g., when you have a packaged op amp & have access only to a few terminals, not the optimum compensation node.

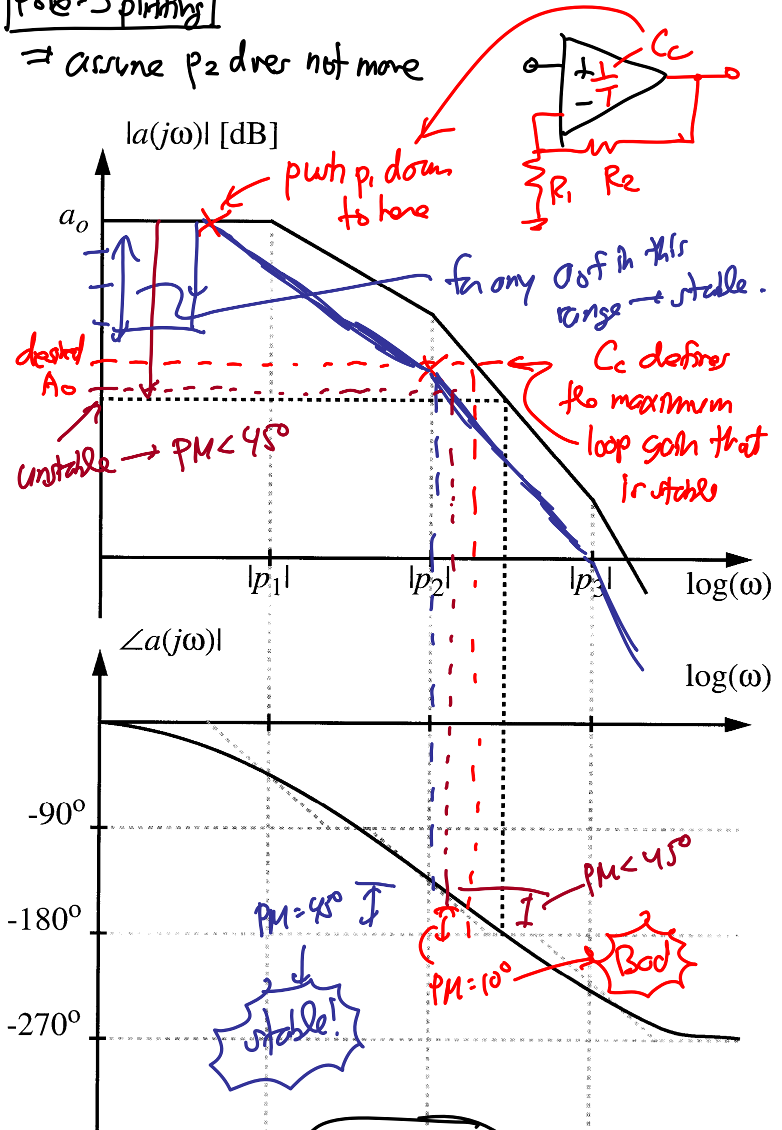
④ $$\boxed{|p_D| = \frac{|p_1|}{T_{o\,max}}}$$ ← maximum expected/needed loop gain

Problem:
① often, $|p_D| \ll |p_1|$ ∴ f_{-3dB} BW of the op amp will be very small
② $\omega_{closed\,loop} = |p_1|$ which isn't that large

Solution: Pole-Splitting
↳ move $|p_1|$ down & either keep $|p_2|$ still
↳ or move $|p_2|$ up simultaneously
↳ after doing this:
① $\omega_{-3dB} = |p_1'|$ ② $\omega_{closed\,loop} = |p_2'|$

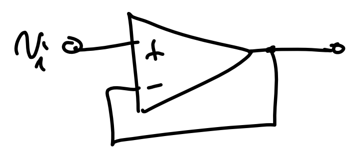
Pole-Splitting

⇒ assume p_2 does not move



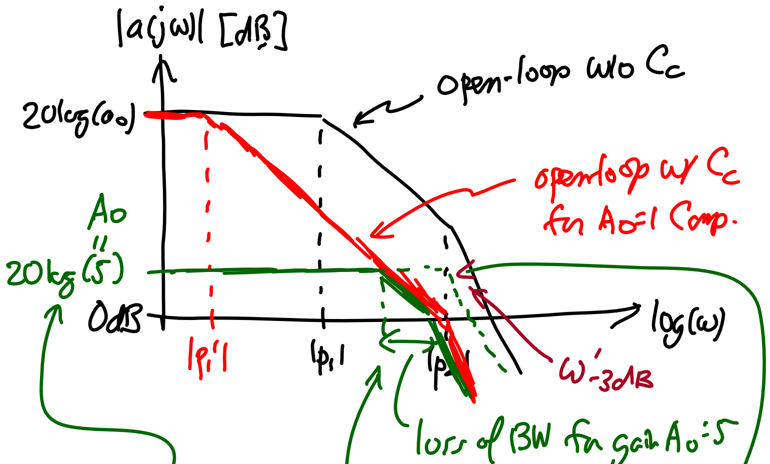
For pole-splitting: $$|p_1| = \frac{|p_2|}{T_{o\,max}}$$

Unity Gain Stable Op Amps → e.g., 741 op amp



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

monolithically compensated w/ an internal C_c to be stable when $A_o = 1$ (closed loop gain)

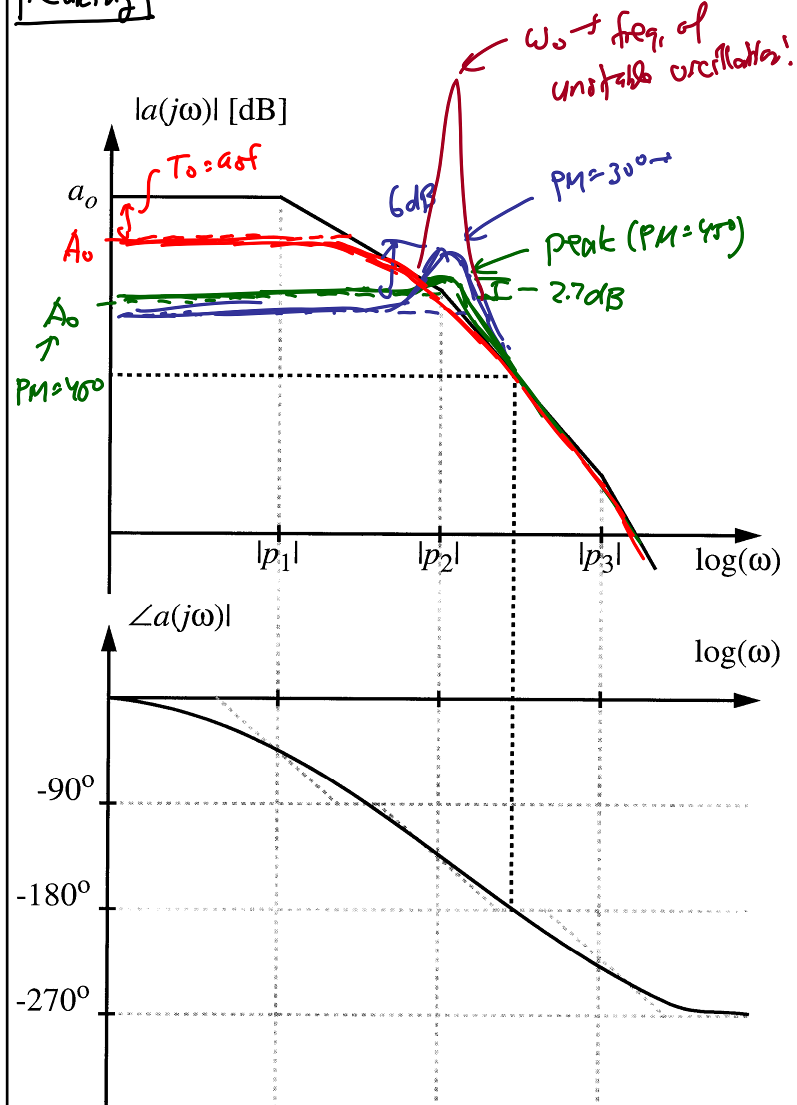


What if this were the lowest gain you needed?
↳ ω_{-3dB} would be this
↳ i.e., $A_o > 1$.

Could have done this if compensate for the needed
$A_o = 5 \rightarrow \omega'_{-3dB} > \omega_{3dB}$

Higher BW if compensate for A_o, rather than for unity gain.

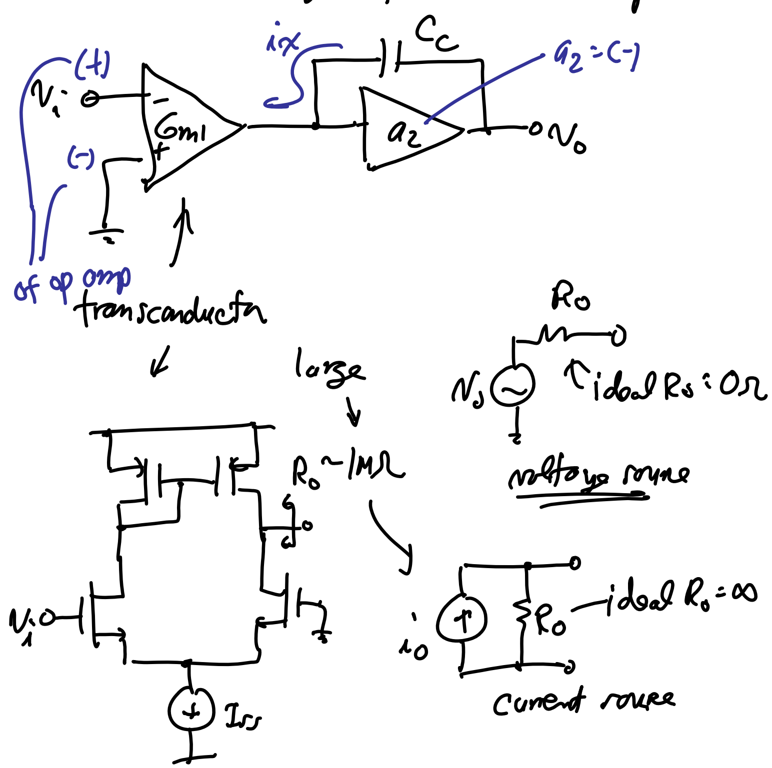
Peaking

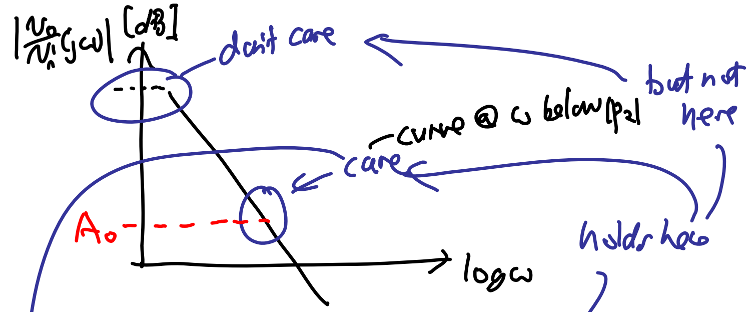


$\boxed{\text{Choosing } C_c}$ (assume no RHP zeros & $|p_3| >> |p_2|$)

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

① Case ①: Two-Stage Amplifier, Miller Compensation





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

Only care about behavior here, because this is where phase margin is determined!

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

For PM = 45°:

ω_{ult} = ω @ $|a(j\omega)f| = 1$

"ult" = "unity loop transmission"

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

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

desired closed-loop gain

For PM = 45°

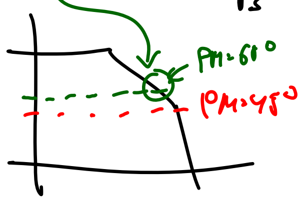
(provided $|p_3| >> |p_2|$)

(also $|p_2| >> |p_1|$)

For PM = 60°:

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

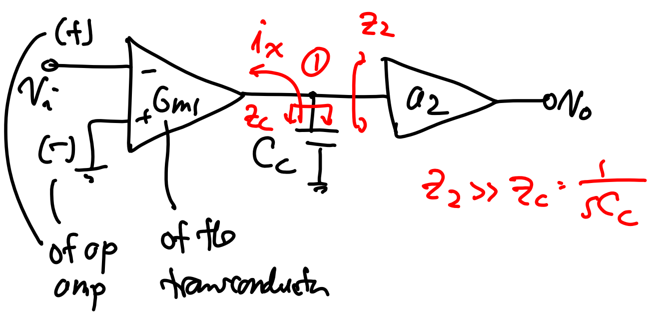
$\sqrt{3}$



$$\boxed{C_c = \frac{1.73\, G_{m1}}{\omega_2 A_o}}$$

For PM = 60°

② Case: Two-Stage Amplifier, Shunt C_c Compensation



$$z_2 >> z_c = \frac{1}{sC_c}$$

$$\left.\begin{aligned} v_1 &= -\frac{G_{m1} v_i}{sC_c} \\ v_o &= a_2 v_1 \end{aligned}\right\} \quad v_o = -\frac{G_{m1} a_2}{sC_c} v_i$$

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

(−)

Closed-loop gain A_o must again intersect this curve @ the right ω_{ult} for the needed PM

For PM = 45°:

$$\left|\frac{v_o}{v_i}(j\omega_{ult})\right| = A_o = \frac{G_{m1} a_2}{\omega_2 C_c} \rightarrow \boxed{C_c = \frac{G_{m1} a_2}{\omega_2 A_o}}$$

[For PM = 45°, $\omega_{ult} = \omega_2$]

For PM = 45°.

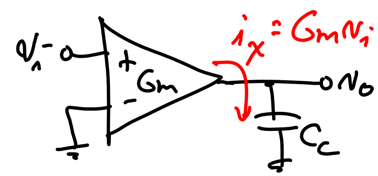
For PM = 60°:

$$\boxed{C_c = \frac{1.73\, G_{m1} a_2}{\omega_2 A_o}}$$

For PM = 60°.

Case ③: Single-Stage Amplifier, Shunt C_c Compensation

e.g., telescopic cascode op amp



$$\left.\begin{aligned} v_o &= \frac{i_x}{sC_c} \\ i_x &= G_m v_i \end{aligned}\right\} \quad \frac{v_o}{v_i}(s) = \frac{G_{m1}}{sC_c} \leftarrow \text{Same as case ①!}$$

(Miller comp.)

Thus:

$$\boxed{C_c = \frac{G_{m1}}{\omega_2 A_o}} \leftarrow PM = 45^\circ \qquad \boxed{C_c = \frac{1.73\,G_{m1}}{\omega_2 A_o}} \leftarrow PM = 60^\circ$$

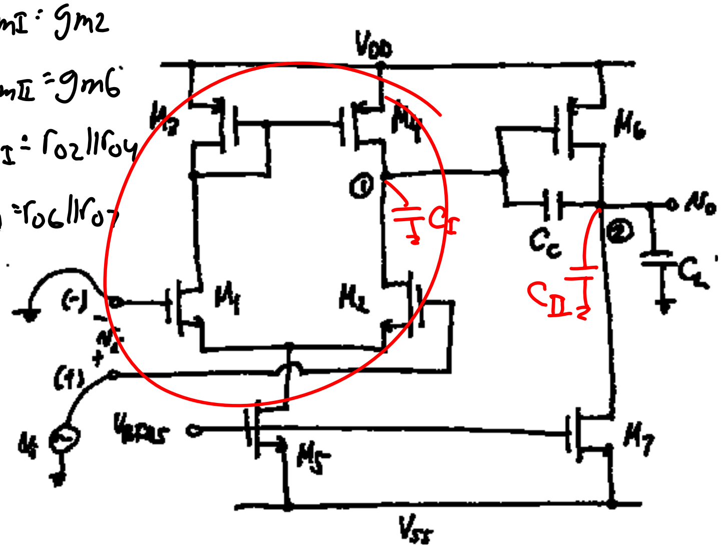
CMOS 2-Stage Op Amp Compensation

$g_{mI} = g_{m2}$

$g_{mII} = g_{m6}$

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

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

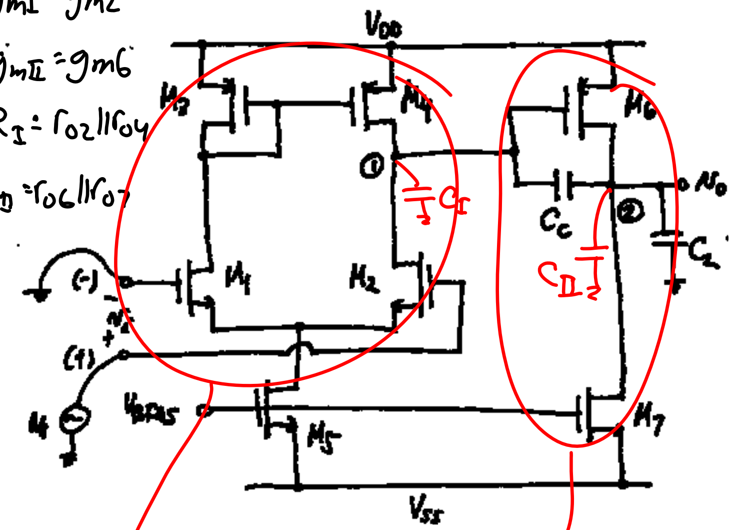


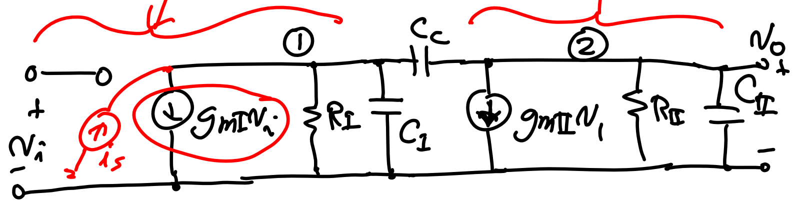
$g_{mI} = g_{m2}$

$g_{mII} = g_{m6}$

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

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





KCL①:

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

KCL②:

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

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

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

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

The poles:

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

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

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 $C_c \uparrow \rightarrow p_1 \downarrow$

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

for the 2nd pole:

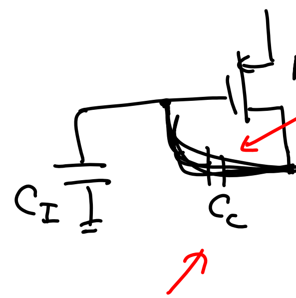
$p_1 p_2 = \frac{1}{R_I R_{II}(C_I C_{II} + C_c C_I + C_c C_{II})}$

$C_c \uparrow \rightarrow p_2 \uparrow$

$p_2 = -\frac{g_{mII} C_c}{C_I C_{II} + C_c C_I + C_c C_{II}} \xrightarrow{\text{As } C_c \uparrow} \cong p_2 = -\frac{g_{mII}}{C_I + C_{II}}$

ω_2 By Inspection

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



$\frac{1}{sC} = \frac{1}{j\omega C_c} \rightarrow 0$

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

$\omega_2 = |p_2|$