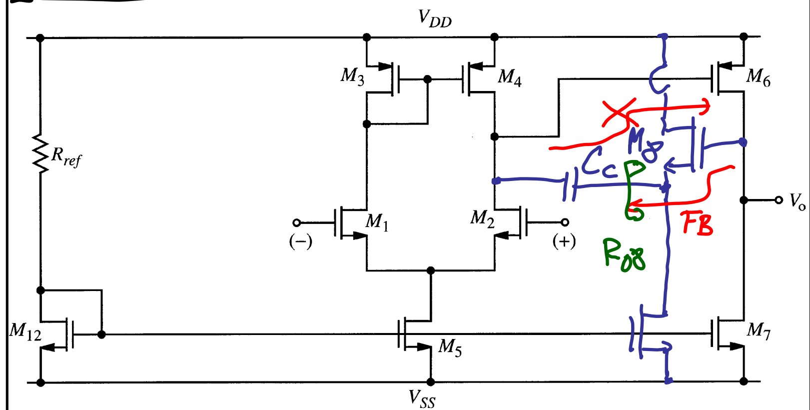
Lecture 23: MOS R & Slew Rate (revisited)

- Announcements:
- HW#9 due tomorrow at 8 a.m.
- HW#10 online soon
- Lab#3 (Design Project) in progress
- Design Project Checkpoint:
  - Due today at 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
- I'll be traveling this coming Thursday
  - Lecture by videotape
- Lecture Topics:
  - Nulling the RHP Zero (actual implementation)
  - Lab#3 Procedure
  - Slew Rate (revisited)
- ------------------------------------
- Last Time: Nulling the RHP Zero

over

Actual Implementation of Buffer-Based Cancellation

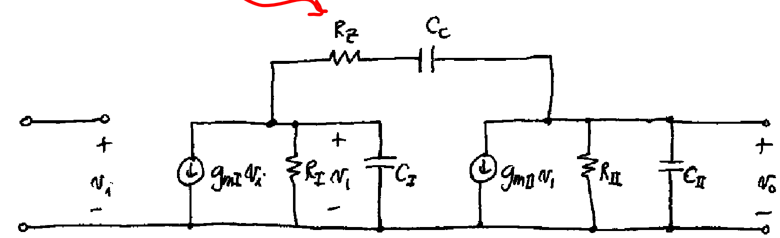


$R_{o8} = \frac{1}{g_{m8}} = \frac{1}{\sqrt{2\mu_n C_{ox}(W/L)_8 I_{D8}}}$ → want this sufficiently small to drive $|p_3|\uparrow$

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:

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

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

Same as before

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

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

Note: The position of the zero depends 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!

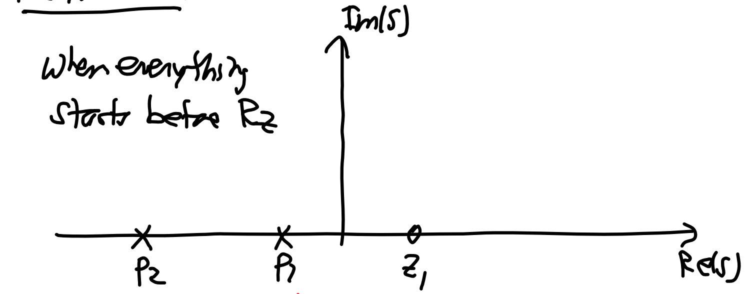
This is great! → can convert the RHP zero to a LHP one!

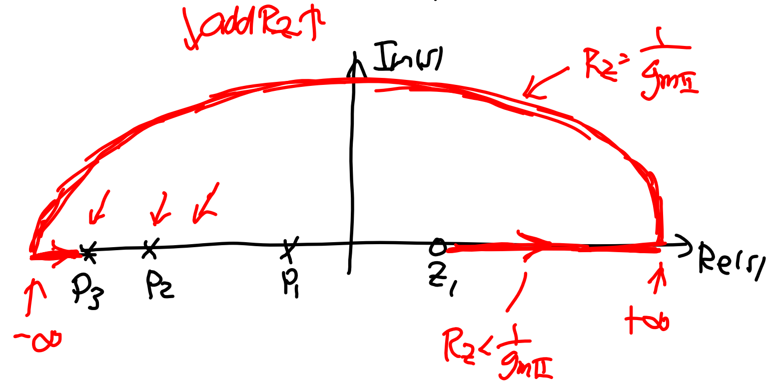
can even stick the zero on top of a pole to eliminate it!

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

↑ if $z_1 = p_1$

The Root Locus:





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 $C_{II} \gg C_I$ (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:

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

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

After this: ① p_3 gone; p_1 & p_2 left

② Now, can place ω_{u1f} @ $|p_2|$ and really set PM = 45° → don't have to worry about phase influence of p_3!

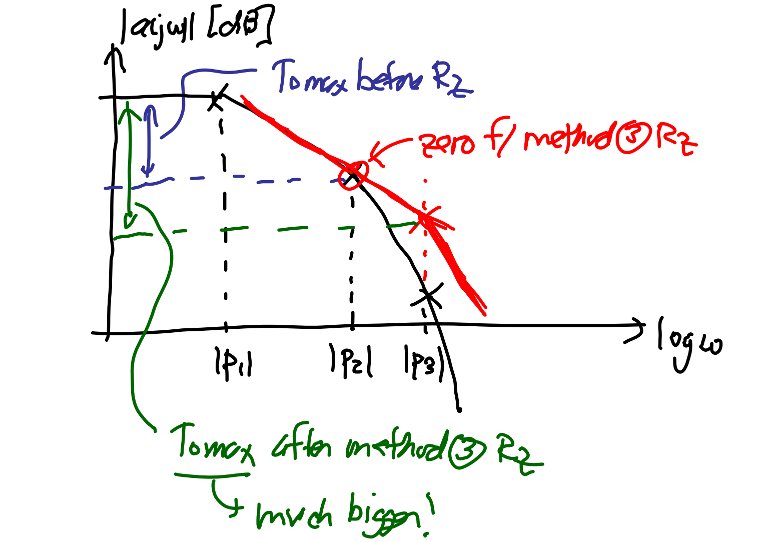
But can still do better

③ Eliminate p_2 by placing z_1 on top of it:

⇒ p_3 becomes the "new" p_2! (higher freq., higher T_{omax})

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

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



W/ 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°

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

For PM=60°:

$$C_c = \frac{1.73\, g_{mI}}{\omega_{p3}|A_o|} \longrightarrow C_c = \sqrt{\frac{1.73\, g_{mI}}{g_{mII}} \frac{C_I C_{II}}{A_o}}$$

$[C_I << C_{II}]$ — For PM=60°

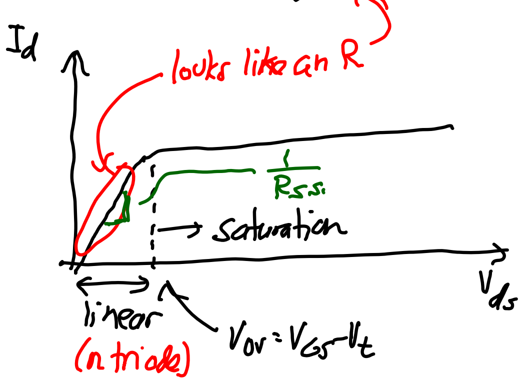
Remark. If settling time is important, then approach ③ may not be the best approach. The reason is that if the zero is not exactly equal to the pole, the a "doublet" ensues, which actually can hurt the settling time.

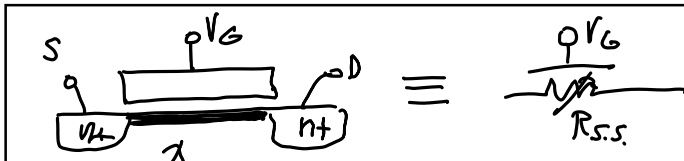
Discussed in a handout to be posted on the course website. → also, discussed in Razavi, problem 10.19.

$\boxed{\text{Actual Implementation}}$

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

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





uniform inversion charge → just like n+ material
↘ control effective def R by Δ'ing the gate voltage V_G

In the linear region:

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

$$\downarrow$$

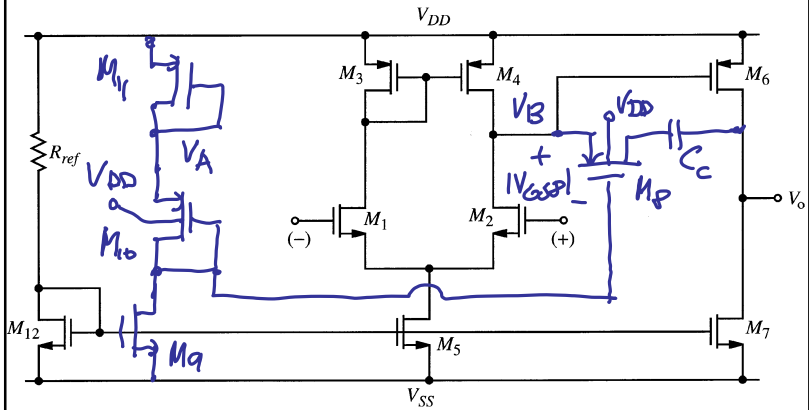
$$\frac{\partial i_d}{\partial V_{ds}} = \mu_n C_{ox} \frac{W}{L}(V_{gs} - V_t - V_{ds})$$

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

variable resistor controllable by V_{GS}!

Actual Implementation

$V_{DS8} = 0V \Rightarrow R_8 = \dfrac{1}{\mu_p C_{ox}(W/L)_8 \underbrace{(|V_{GS8}| - |V_{t8}|)}_{|V_{ov8}|}}$



Design:

Need $V_A = V_B \rightarrow |V_{GS11}| = |V_{GS6}|$, know $|V_{t11}| = |V_{t6}|$

$$\sqrt{\frac{2I_{D1}}{\mu_p C_{ox}(\frac{W}{L})_{11}}} = \sqrt{\frac{2I_{D6}}{\mu_p C_{ox}(\frac{W}{L})_6}}$$

$$\boxed{\left(\frac{W}{L}\right)_{11} = \left(\frac{W}{L}\right)_6 \frac{I_{D11}}{I_{D6}} = \left(\frac{W}{L}\right)_6 \frac{I_{D10}}{I_{D6}}}$$

Also, need $|V_{GS10}| = |V_{GS8}|$.

Because $V_A = V_B \rightarrow V_{S10} = V_{S8} \rightarrow |V_{t10}| = |V_{t8}|$

$\therefore |V_{ov10}| = |V_{ov8}| = \sqrt{\dfrac{2I_{D10}}{\mu_p C_{ox}(W/L)_{10}}}$

Thus:

$$R_8 = \frac{1}{\mu_p C_{ox}(\frac{W}{L})_8 \sqrt{\frac{2I_{D10}}{\mu_p C_{ox}(\frac{W}{L})_{10}}}} = \frac{\sqrt{\mu_p C_{ox}(W/L)_{10}}}{\mu_p C_{ox}(\frac{W}{L})_8 \sqrt{2I_{D10}}}$$

Case: Eliminate p_2 by placing z on top it.

$$R_z = \frac{C_c + C_L}{g_{m6} C_c} = \frac{\sqrt{\mu_p C_{ox}(W/L)_{10}}}{\mu_p C_{ox}(\frac{W}{L})_8 \sqrt{2I_{D10}}}$$

$g_{m6} = \sqrt{2\mu_p C_{ox}(W/L)_6 I_{D6}}$

$$\left(\frac{W}{L}\right)_8 = \sqrt{\left(\frac{W}{L}\right)_6 \left(\frac{W}{L}\right)_{10} \frac{I_{D6}}{I_{D10}}} \cdot \left(\frac{C_L}{C_c + C_L}\right)$$

Case: Move $z_1 \rightarrow \infty$.

$$R_z = \frac{1}{g_{m6}} \rightarrow \left(\frac{W}{L}\right)_8 = \sqrt{\left(\frac{W}{L}\right)_6 \left(\frac{W}{L}\right)_{10} \frac{I_{D6}}{I_{D10}}}$$

Project Design → Lab#3

Ad Hoc Procedure:

① Write down all equations for all needed specs.
then, study the dependencies, e.g.,

$$a_o = \text{gain} = f(I_D, \lambda, \ldots) \sim \frac{1}{\sqrt{I_D}}$$

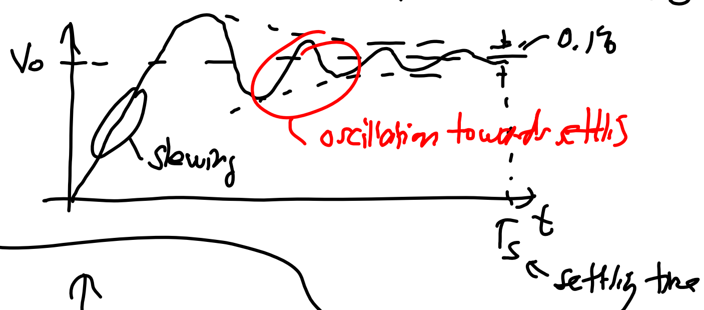
② Choose C_c

$$\omega_u = \text{unity gain freq.} = \frac{g_{mI}}{C_c} \sim \sqrt{I_D}$$

$$|p_2| \cong + \frac{g_{mII}}{C_L} \rightarrow \text{For PM} = 60^\circ: \ \omega_u = \frac{|p_2|}{\sqrt{3}}$$

③ Choose I_D's → SR

④ Determine $\frac{W}{L}$'s (governed by swing & input range)

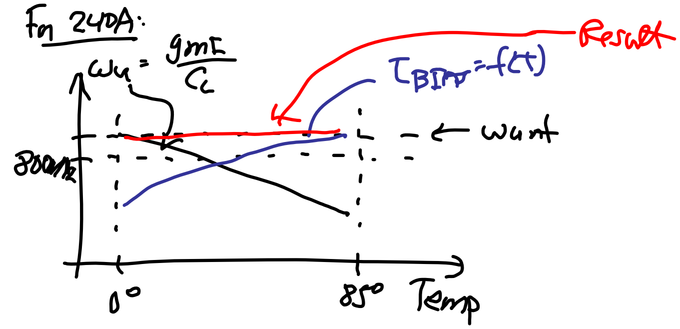


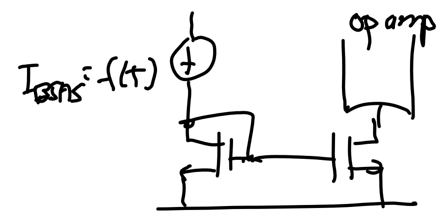
Rule of Thumb:

$$SR \cong \frac{V_o}{\frac{T_s}{10}} = \frac{10V_o}{T_s}$$

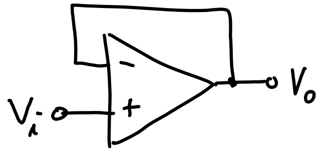
For 240A:

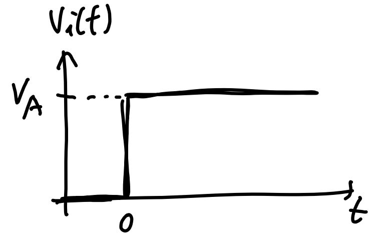
$$\omega_u = \frac{g_{mI}}{C_c}$$





Slew Rate (cf. before)





Using Laplace Xform Theory:

$$\frac{V_o}{V_i}(s) = \frac{1}{1+\frac{s}{\omega_1}} = \frac{1}{1+s\tau_1}$$

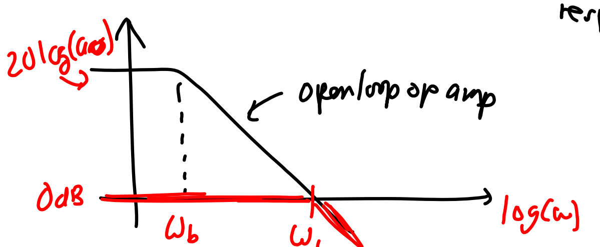
← single (dominant) pole

$$V_i(s) = \frac{V_A}{s}$$

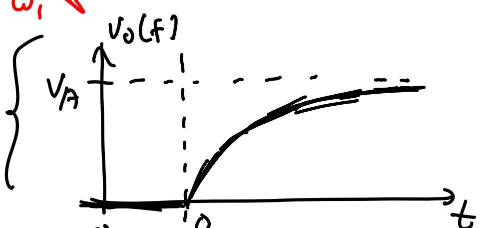
$$V_o(s) = \frac{V_A}{s(1+s\tau_1)} = \frac{V_A}{s} - \frac{V_A}{s+\frac{1}{\tau_1}}$$

⇕ Inverse Laplace Xform

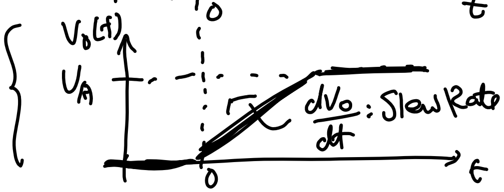
$$V_o(t) = V_A\left(1-e^{-t/\tau_1}\right)$$ ← expected response



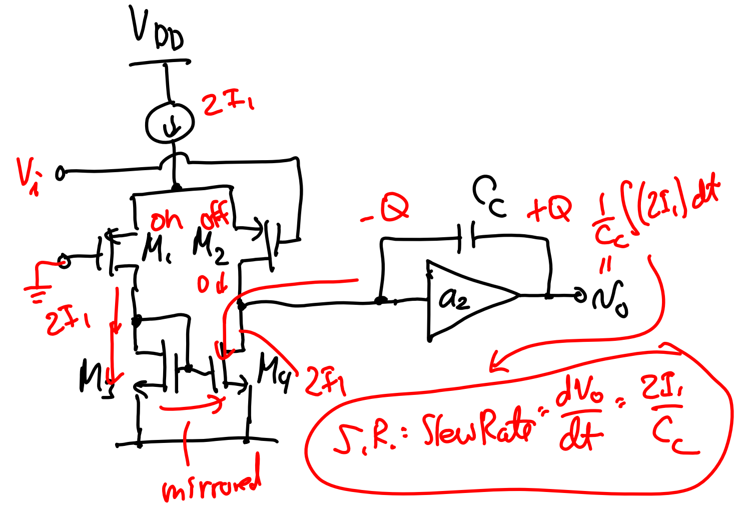
Expectation



What we really see from a real op amp



Reason: 1st or 2nd stage of op amp cannot source enough current to mimic the slope (or speed) of a fast rising input signal



$$S.R. = \text{Slew Rate} = \frac{dV_o}{dt} = \frac{2I_1}{C_c}$$

If apply a very fast (i.e., high frequency), large amplitude sinusoid: