Lecture 15: High Gain Op Amps

- **Announcements**:
  - Midterm will be on the date specified in your syllabus: Thursday, March 21, 3:30-5 p.m. in 390 Hearst Mining Building
  - No lecture the day of the midterm
  - HW#7 due this coming Friday
  - HW#8 will be available Thursday and due Tuesday next week (I know, but this will help you on the midterm)
- **Lecture Topics**:
  - High Gain Op Amps
  - Slew Rate
- -------------------------------------
- **Last Time**:
- First pass on feedback

Observations:

1. Closed loop DC gain $= \frac{A_o}{1+\beta A_o} = \frac{A_o}{1+T_o} \approx \frac{A_o}{T_o}$ $[T_o \gg 1]$

   i.e., the closed loop gain is reduced from the open loop gain by $1+T_o$ → show this on graph
2. Alternatively, closed loop DC gain $\approx \frac{A_o}{\beta A_o} = \frac{1}{\beta}$ $[T_o \gg 1]$
3. ω_{-3dB} has increased from $\omega_b \rightarrow \omega_b(1+A_o\beta) = \omega_b(1+T_o)$
4. Gain-BW Product $= \frac{A_o}{1+\beta A_o}\omega_b(1+\beta A_o) = A_o\omega_b = \omega_T$

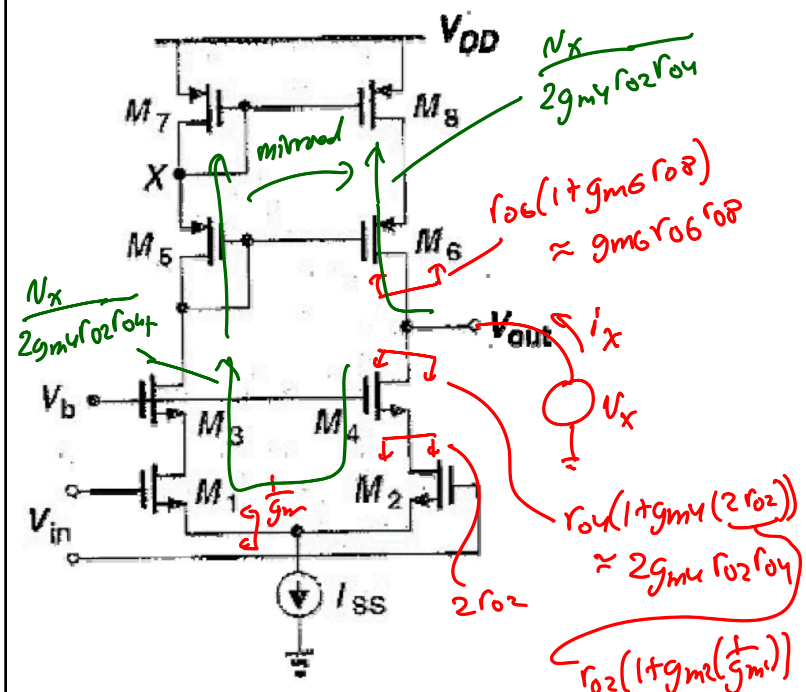
   ∴ the Gain-BW product remains the same for the open & closed loop FB cases!

High Gain Op Amps

How can we increase gain?

1. Cascode
2. Cascode Amplifiers

Telescopic Op Amp w/ Single-Ended Output



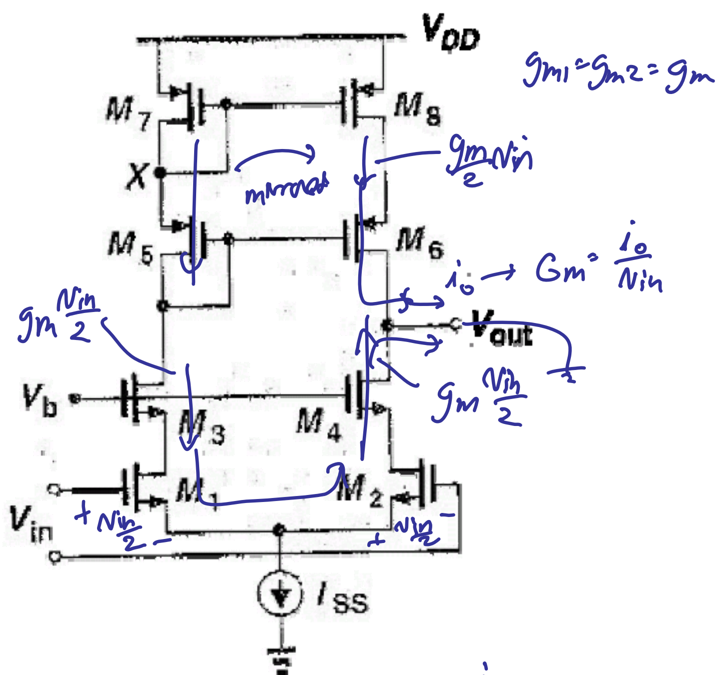
Get R_o:

$$i_x = \frac{v_x}{g_{m6}r_{o6}r_{o8}} + \frac{v_x}{2g_{m4}r_{o2}r_{o4}} + \frac{v_x}{2g_{m4}r_{o2}r_{o4}}$$

$$\frac{i_x}{v_x} = \frac{1}{g_{m6}r_{o6}r_{o8}} + \frac{1}{g_{m4}r_{o2}r_{o4}}$$

$R_o = \frac{v_x}{i_x} = (g_{m6} r_{o6} r_{o8}) \| (g_{m4} r_{o2} r_{o4})$

$R_o = (g_{mp} r_{op}^2) \| (g_{mn} r_{on}^2)$



$g_{m1} = g_{m2} = g_m$

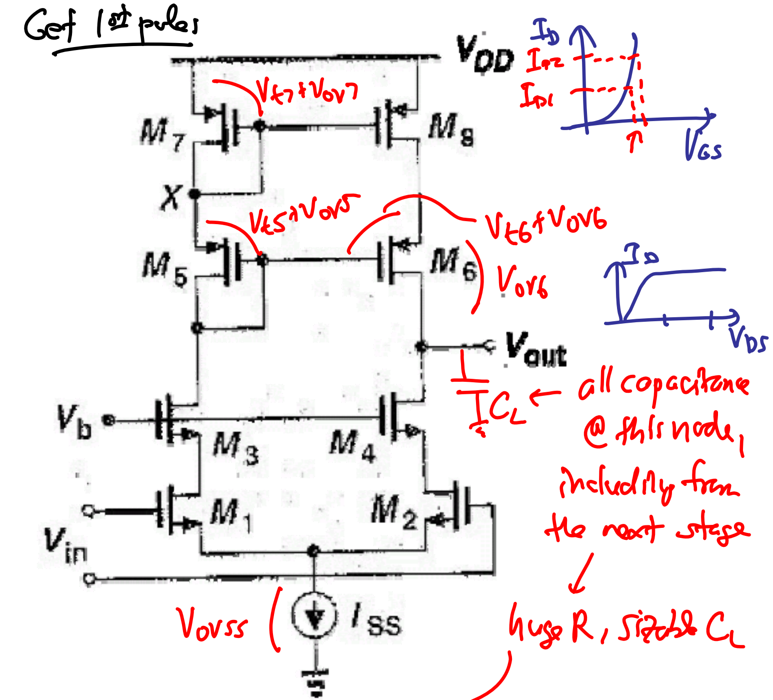
$i_o = \frac{g_m}{2} v_{in} + \frac{g_m}{2} v_{in} \to G_m = \frac{i_o}{v_{in}} = g_m$

$\therefore$ Gain $= a_v = g_{mn} \left[(g_{mn} r_{on}^2) \| (g_{mp} r_{op}^2) \right]$

huge R! huge R!

Gain → BIG!

Get 1st poles



C_L ← all capacitance @ this node, including from the next stage

huge R, sizable C_L

→ Contributes dominant pole: $\omega_H = \frac{1}{R_o C_L}$

Problems/Issues:

① Limited output swing:

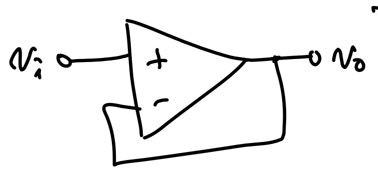
$V_{omax} = V_{DD} - |V_{t7}| - |V_{ov7}| - |V_{t5}| - |V_{ov5}| + |V_{t6}| + |V_{ov6}| - |V_{ov6}|$

$V_{omin} = V_{ovss} + V_{ov2} + V_{ov4}$

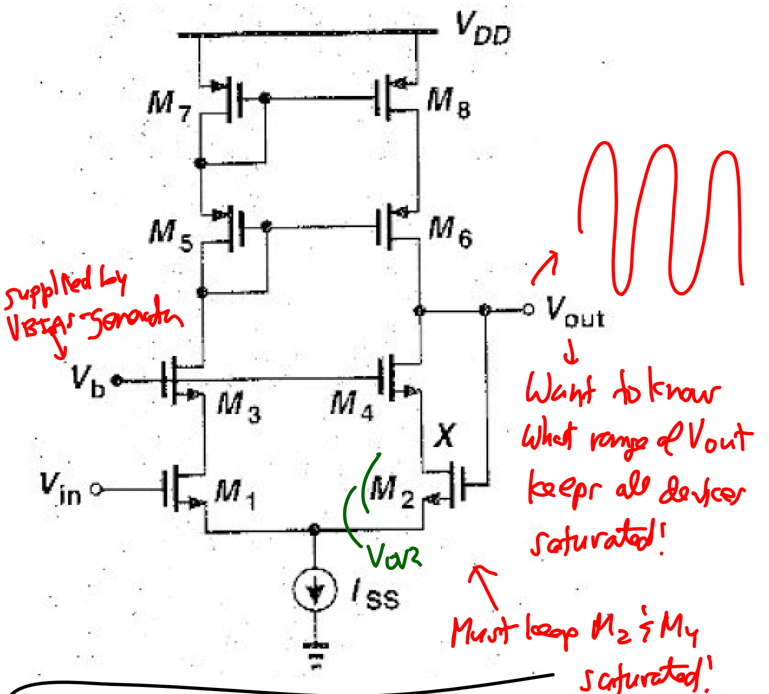
$V_{oswing} = V_{omax} - V_{omin}$

Problem: Not enough swing! (too many transistors stacked)

Problem ②: Difficult to tie input to output!



unity gain buffer (very useful!)

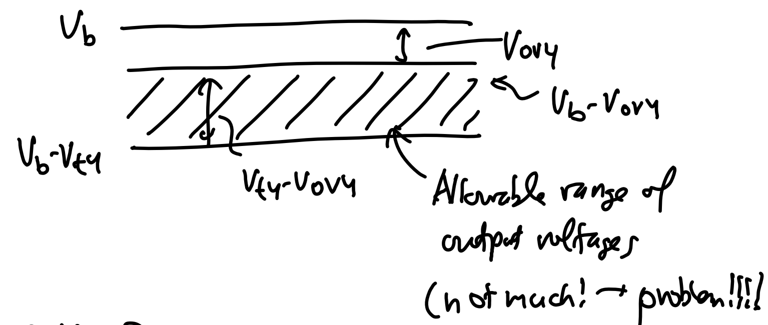


M_4: Need $V_{out} \geq V_b - V_{GS4} + V_{OV4} = V_b - V_{t4} - V_{OV4} + V_{OV4}$

$\therefore V_{out} \geq V_b - V_{t4}$

M_2: Need $V_{out} \leq V_X - V_{OV2} + V_{t2} + V_{OV2}$

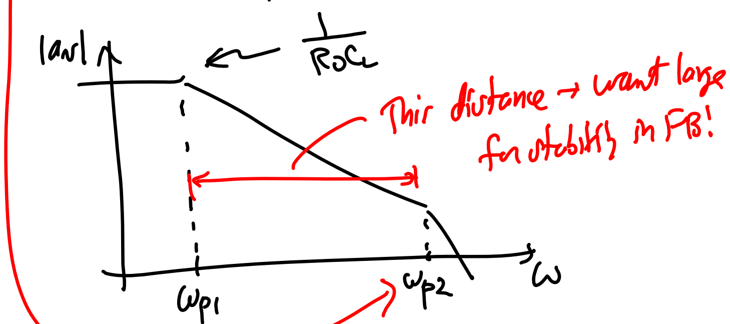
$V_{out} \leq V_b - V_{t4} - V_{OV4} + V_{t2} \approx V_b - V_{OV4}$ ($V_{t2} \approx V_{t4}$)



Problem ③:

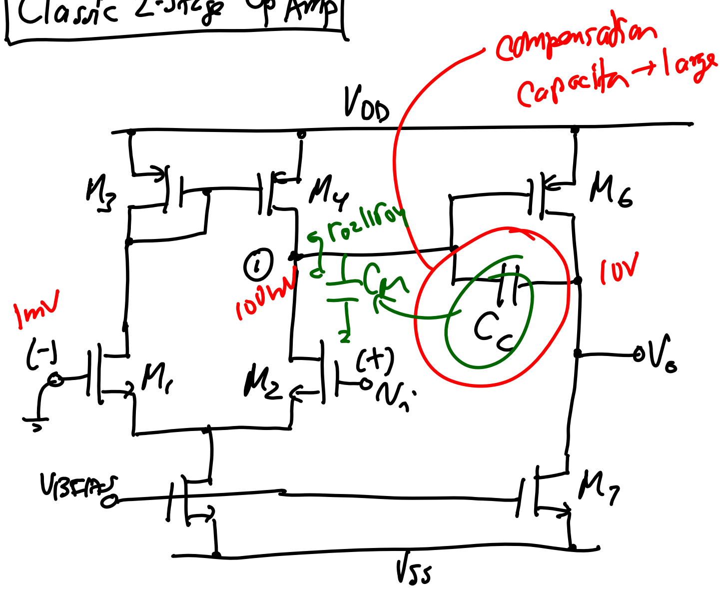
Low freq. non-dominant pole associated w/ "mirror" node → will hurt stability in a FB ckt! (we'll cover this later)

Soln: fully-differential, fully-cascoded op amp



Another Soln: 2-stage op amp

Classic 2-Stage Op Amp



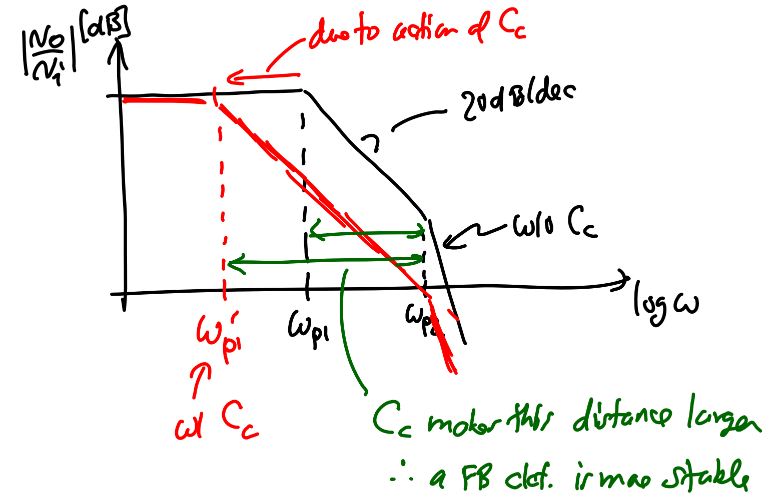
Gain:

1st Stage: $a_{v1} = \frac{v_{①}}{v_i} = -g_{m2}(r_{o2} \| r_{o4})$

2nd Stage: $a_{v2} = \frac{v_o}{v_{①}} = -g_{m6}(r_{o6} \| r_{o7})$

$$a_v = a_{v1} a_{v2} = g_{m2}(r_{o2} \| r_{o4}) \, g_{m6}(r_{o6} \| r_{o7})$$

Freq. Response:



Dominant Pole:

$$\omega_{p1} = \omega_H = \frac{1}{(r_{o2} \| r_{o4})\underbrace{(1 + g_{m6}(r_{o6} \| r_{o7}))}_{\text{Miller Effect}} C_c}$$

Output Swing:

$$V_{o\,swing} = V_{DD} - V_{SS} - |V_{ov6}| - V_{ov7}$$