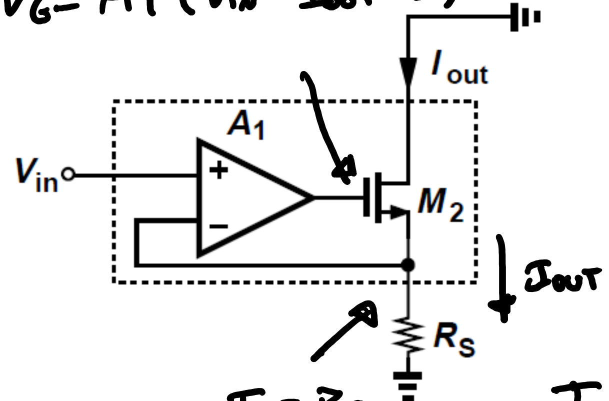
Lecture #18, Feb 18th, 2022

- We will bounce between chapters 8 (Feedback) and 9 (Op Amp design).
- Homework #3 Assigned.
- Project 2 will be assigned immediately.
- Monday we'll start Feedback
- Today
  - Regulated Cascode
  - Common-Mode Feedback.

Gain Boosting Techniques: Effective Gm

$V_G = A_1 (V_{IN} - I_{OUT} R_S)$



$$V_{GS} = A_1 (V_{IN} - I_{OUT} R_S) - I_{OUT} R_S$$

$$I_{OUT} = g_m \cdot V_{GS}$$

$$I_{OUT} = g_m \left[A_1 (V_{IN} - I_{OUT} R_S) - I_{OUT} R_S \right]$$

$$= g_m \cdot A_1 \cdot V_{IN} - g_m A_1 I_{OUT} R_S - g_m I_{OUT} R_S$$

$$I_{OUT} (1 + g_m A_1 R_S + g_m R_S) = g_m \cdot A_1 \cdot V_{IN}$$

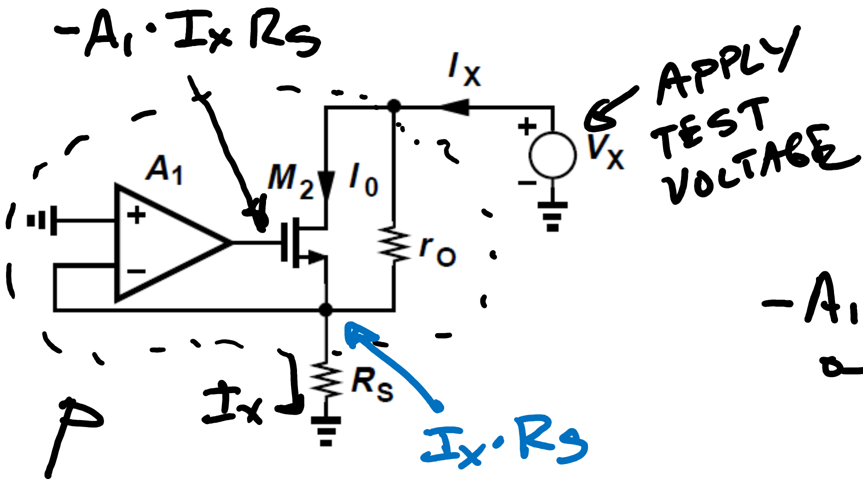
FOR $1 \ll A_1$

$$G_m = \frac{I_{OUT}}{V_{IN}} = \frac{g_m \cdot A_1}{(1 + g_m R_S (1 + A_1))}$$

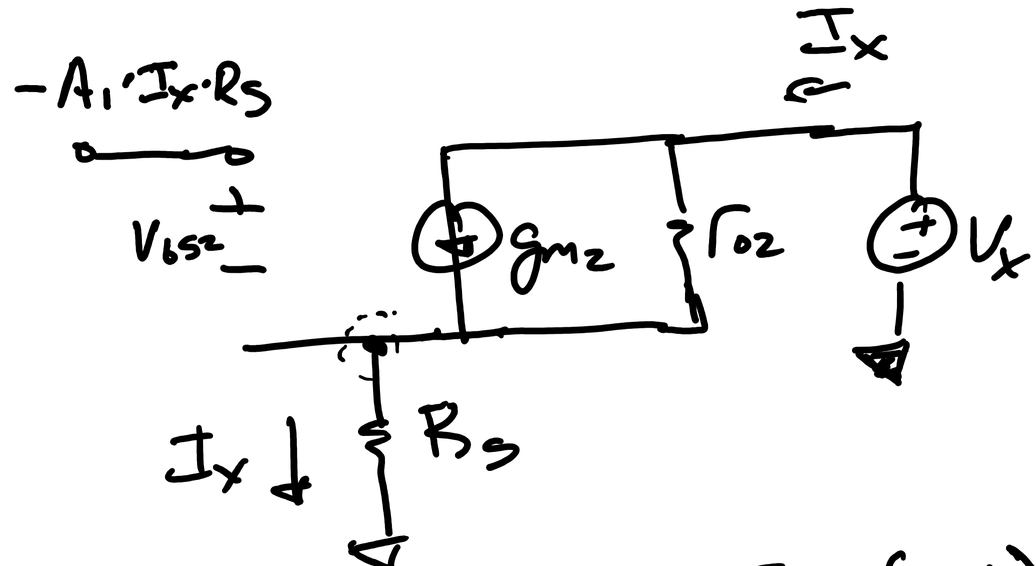
$G_m \simeq \dfrac{1}{R_S}$,

SAME RESULT w/o A_1.

Output Resistance of Gain Boosting Stage



TREAT AS A SUPER NODE



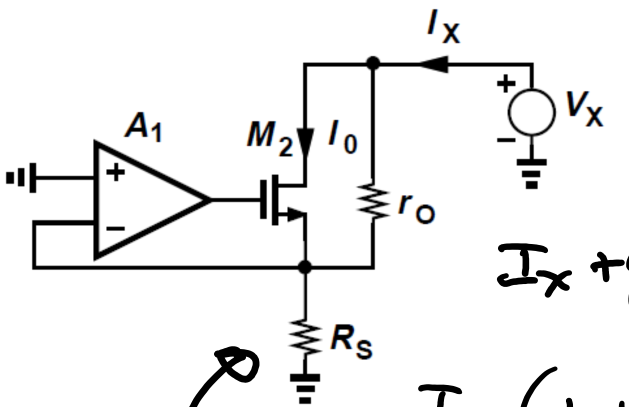
$$V_{GS} = -A_1 \cdot I_x R_S - I_x \cdot R_S = -I_x R_S (1 + A_1)$$

KCL @ SOURCE

$$I_x - g_{m2} V_{GS} - (V_x - V_S) g_{o2} = 0 \qquad V_S = I_x R_S$$

$$I_x + g_{m2} I_x R_S (1 + A_1) - V_x g_{o2} + I_x R_S g_{o2} = 0$$

Output Resistance of Gain-Boosted Stage



REPLACE w/ DEVICE.

$$I_x + g_{m2} I_x R_S (1+A_1) - V_x g_{o2} + I_x R_S g_{o2} = 0$$

$$I_x \left(1 + g_{m2} \cdot R_S (1+A_1) + R_S g_{o2}\right) = V_x g_{o2}$$

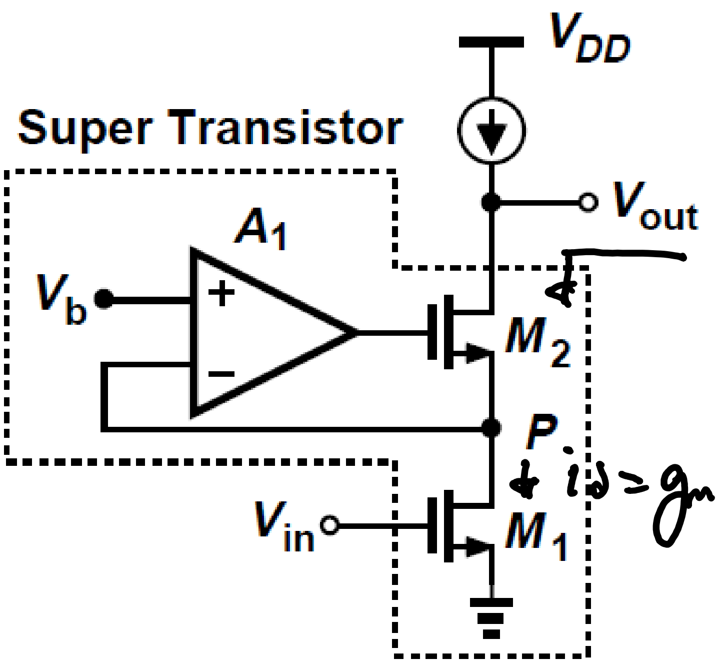
$$\frac{V_x}{I_x} = \frac{\left(1 + g_{m2} R_S (1+A_1) + R_S / r_{o2}\right)}{1/r_{o2}}$$

$$= r_{o2} + g_{m2} R_S r_{o2} (1+A_1) + R_S$$

$$r_{o2},\ R_S \ll g_{m2} R_S r_{o2} (1+A_1)$$

$$R_o \approx g_{m2} R_S r_{o2} (1+A_1) \approx g_{m2} R_S r_{o2} A_1$$

Gain-boosting with Active/Regulated Cascode



$i_d \approx g_{m1} v_{in}$

was R_S

$$R_o \approx g_{m2} (r_{o1}) r_{o2} \cdot A_1$$

$$G_m \approx g_{m1}$$

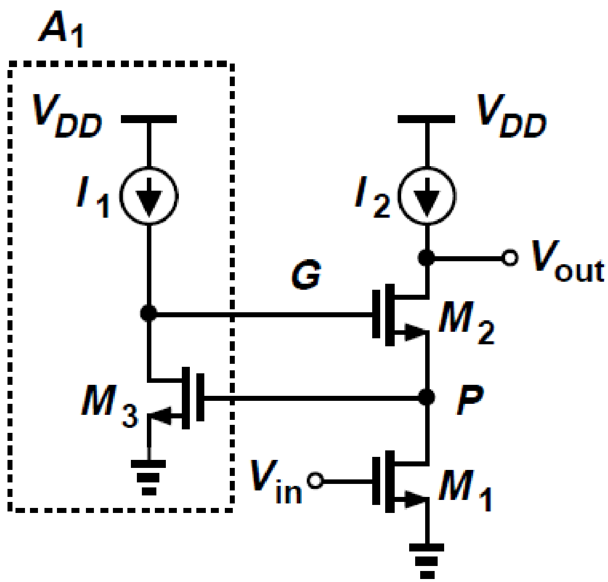
$$A_v \approx -g_{m1} \cdot (g_{m2}) (r_{o1}) r_{o2} \cdot A_1$$

$$\approx -g_m^2 r_{on}^2 \cdot A_1$$

$$10\text{s} < A_1 < \sim 100{,}000\text{s}$$

- POTENTIALLY BLAST THE R_o & A_v!

Example Implementations



POPULAR IMPLEMENTATION.

$A_1 \approx \underbrace{g_{m3} \cdot r_{o3}}$

INTRINSIC GAIN OF M3

$A_v \simeq -g_{m1}^2 r_o^2 \cdot A_1$

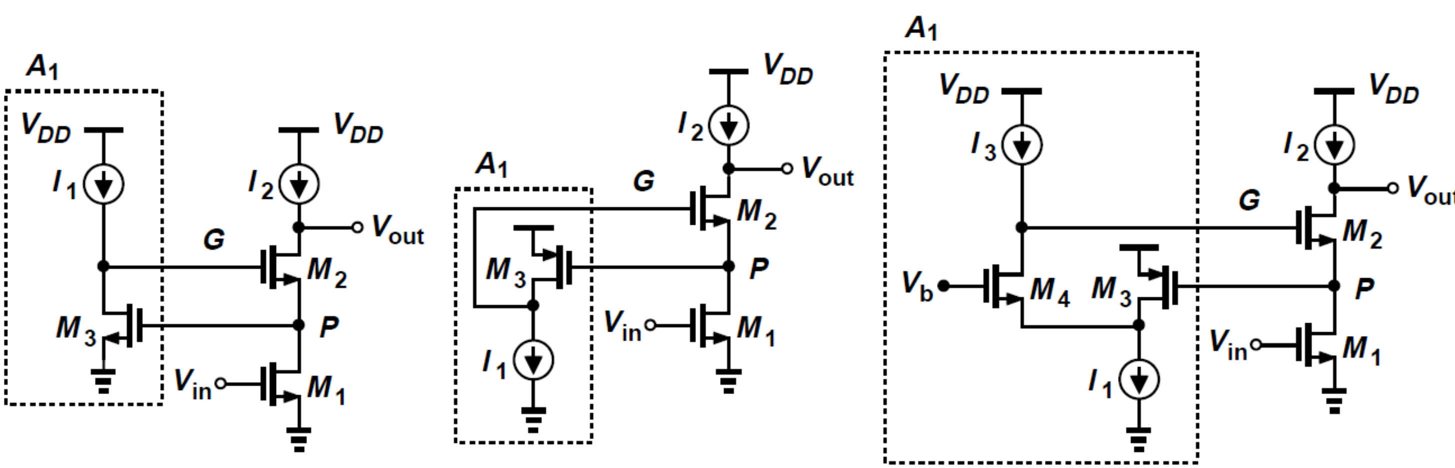
$= -g_m^3 r_o^3$

Gain Boosting Circuit Implementation

- **Simplest a common-source stage**

$$|V_{out}/V_{in}| \approx g_{m1}r_{O1}g_{m2}r_{O2}(g_{m3}r_{O3} + 1)$$

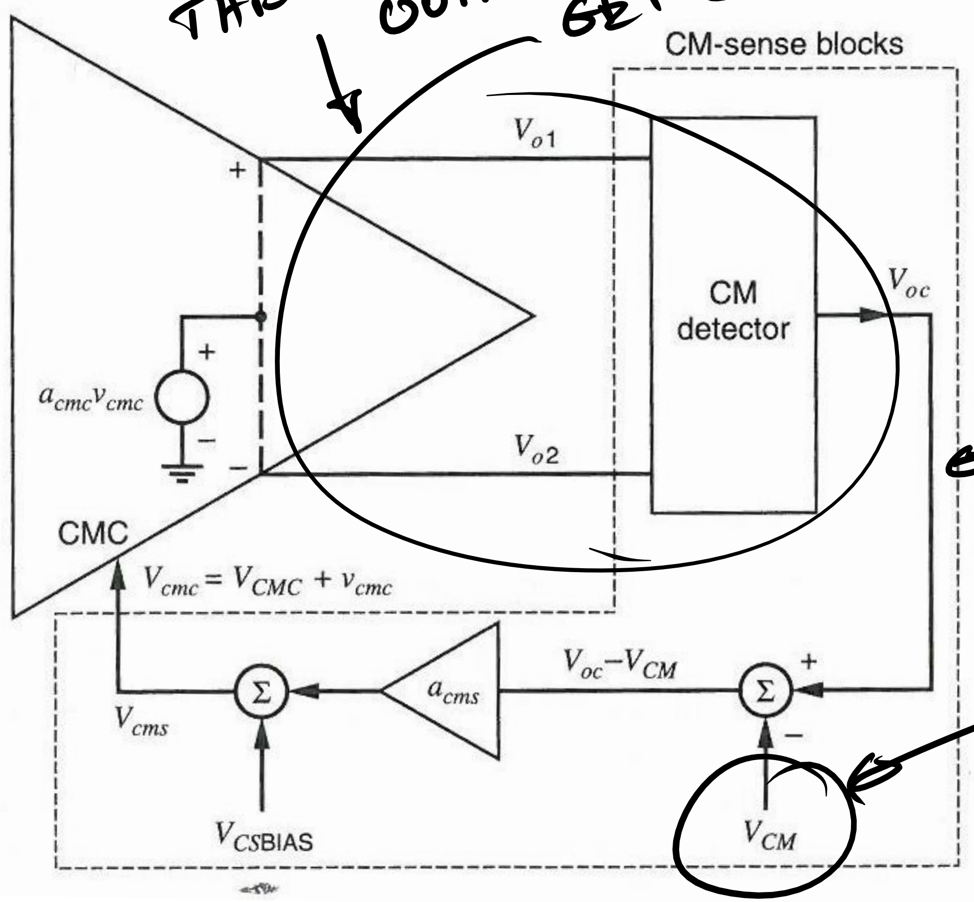
- **Avoid headroom limitation, PMOS common-source stage is better, but M3 could go in triode**
- **Folded-cascode inserts one more stage**



(a) (b) (c)

Common-Mode Feedback

AVERAGE THE DIFFERENTIAL OUTPUT VOLTAGE TO GET CM.

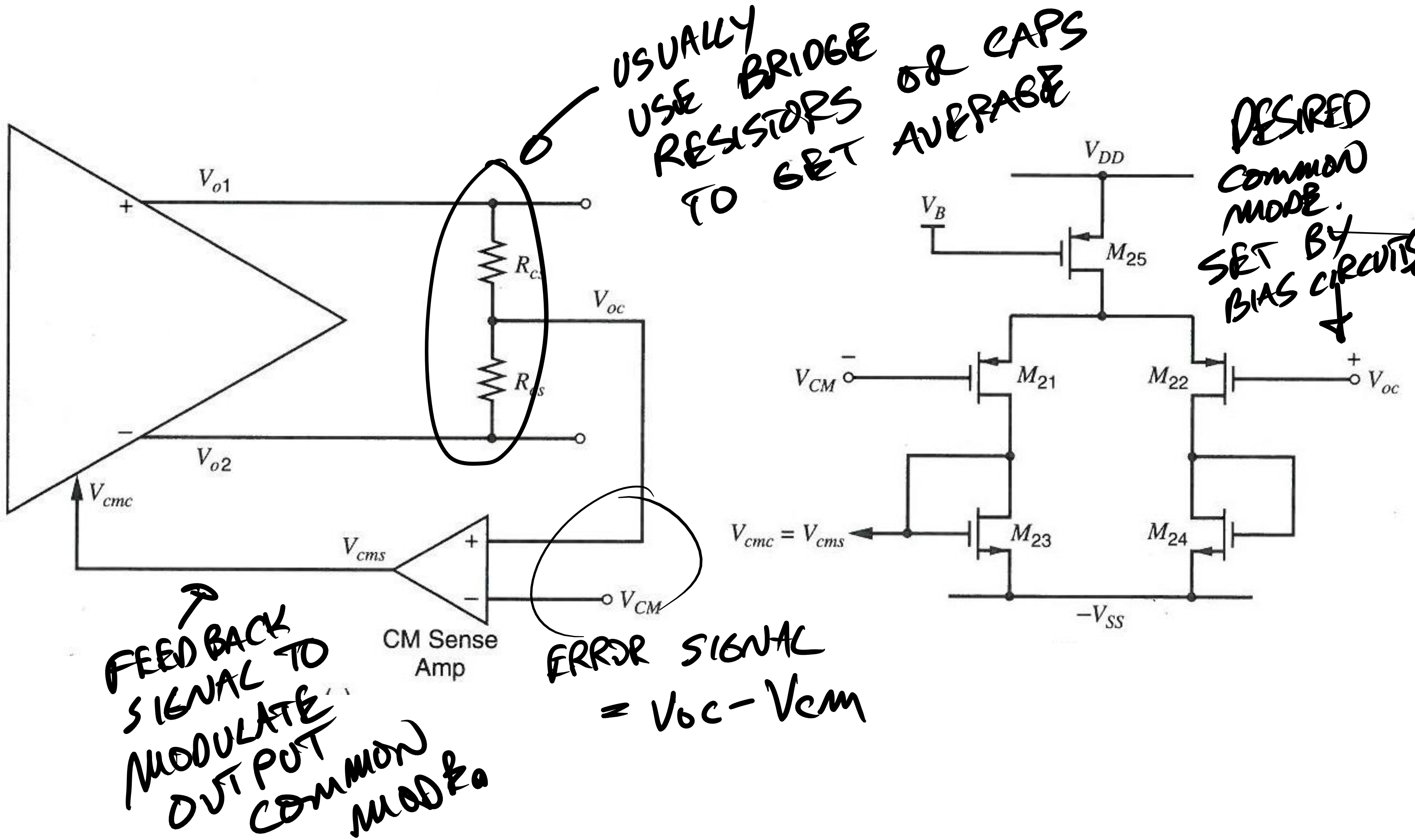


• IN DIFFERENTIAL AMPS, NEED TO SET OUTPUT COMMON MODE VOLTAGE.

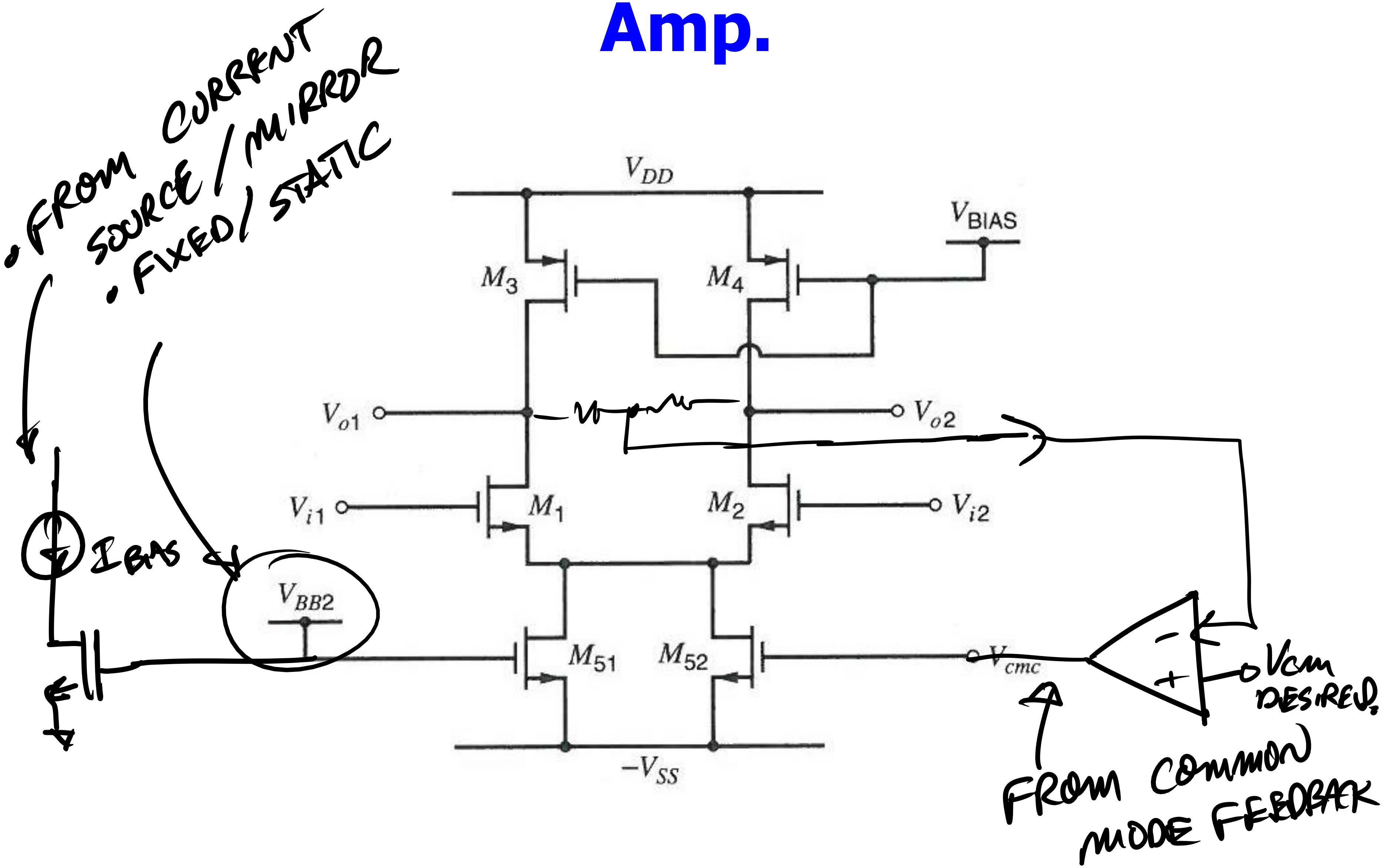
MEASURED COMMON MODE VOLTAGE.

COMPARE TO THE DESIRED COMMON MODE VOLTAGE.

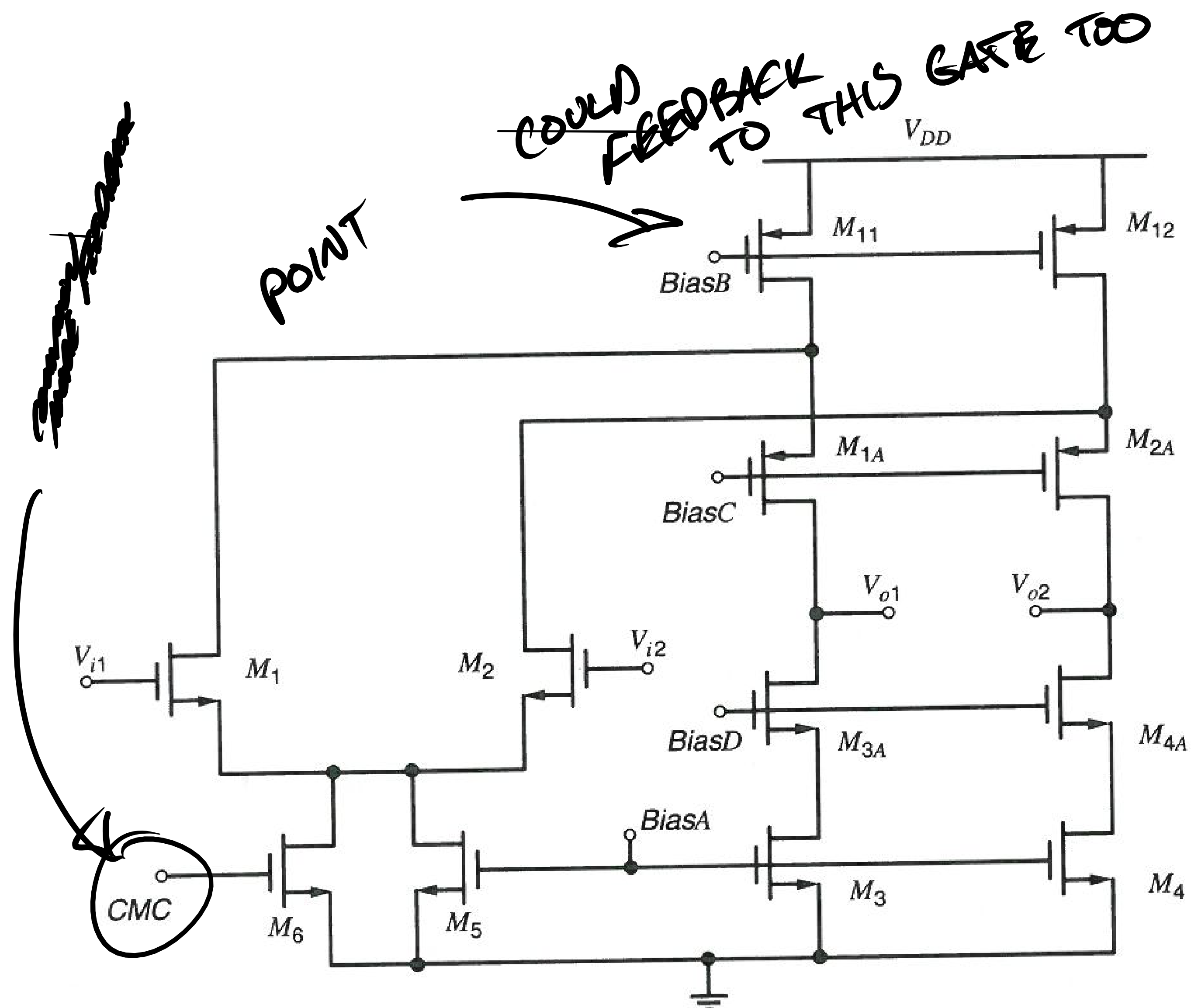
Methods to Measure and Compare Common-Mode Voltage



Feeding back the Common Signal to the Amp.

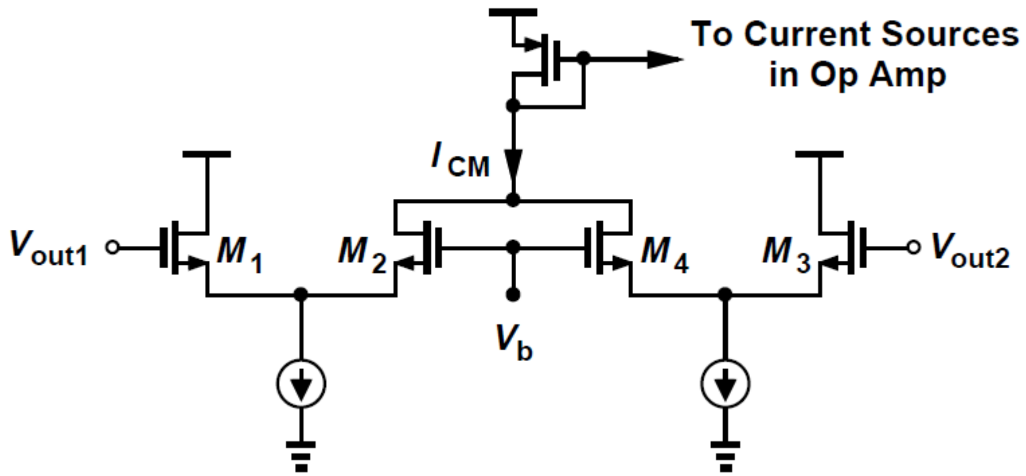


Folded Cascode and Common-Mode Feedback



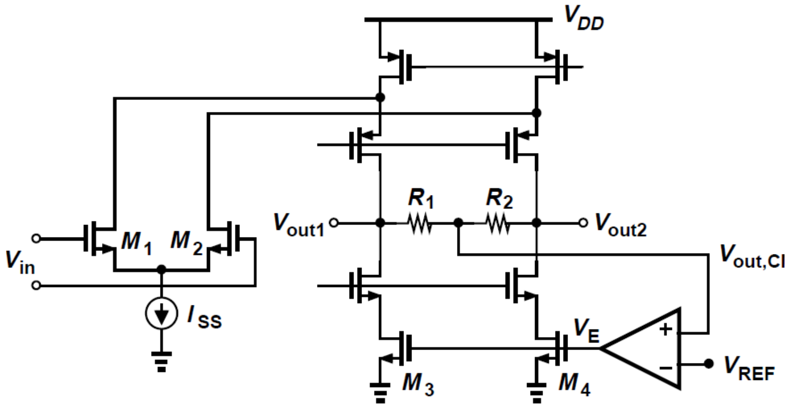
CM Sensing Techniques

- **Differential pair sensing**
  - $I_{CM} \propto V_{out1} + V_{out2}$ **by small signal analysis**
  - **Under Large swings situation, sensing is not valid due to large non-linearity.**

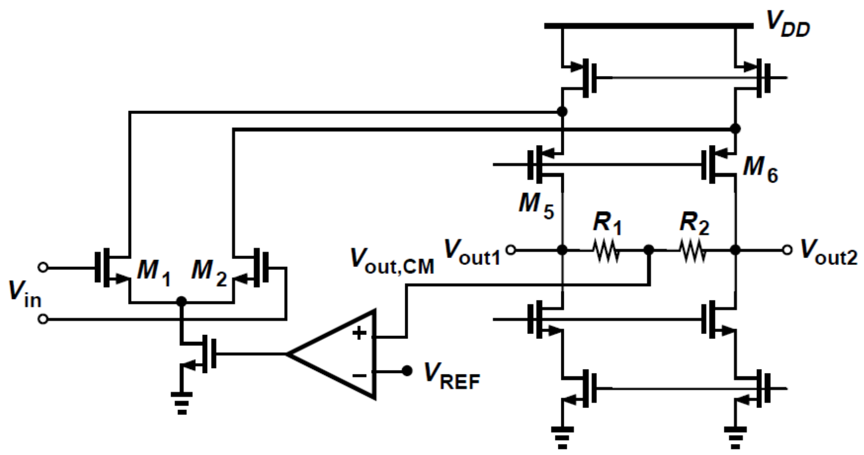


CM Feedback Techniques

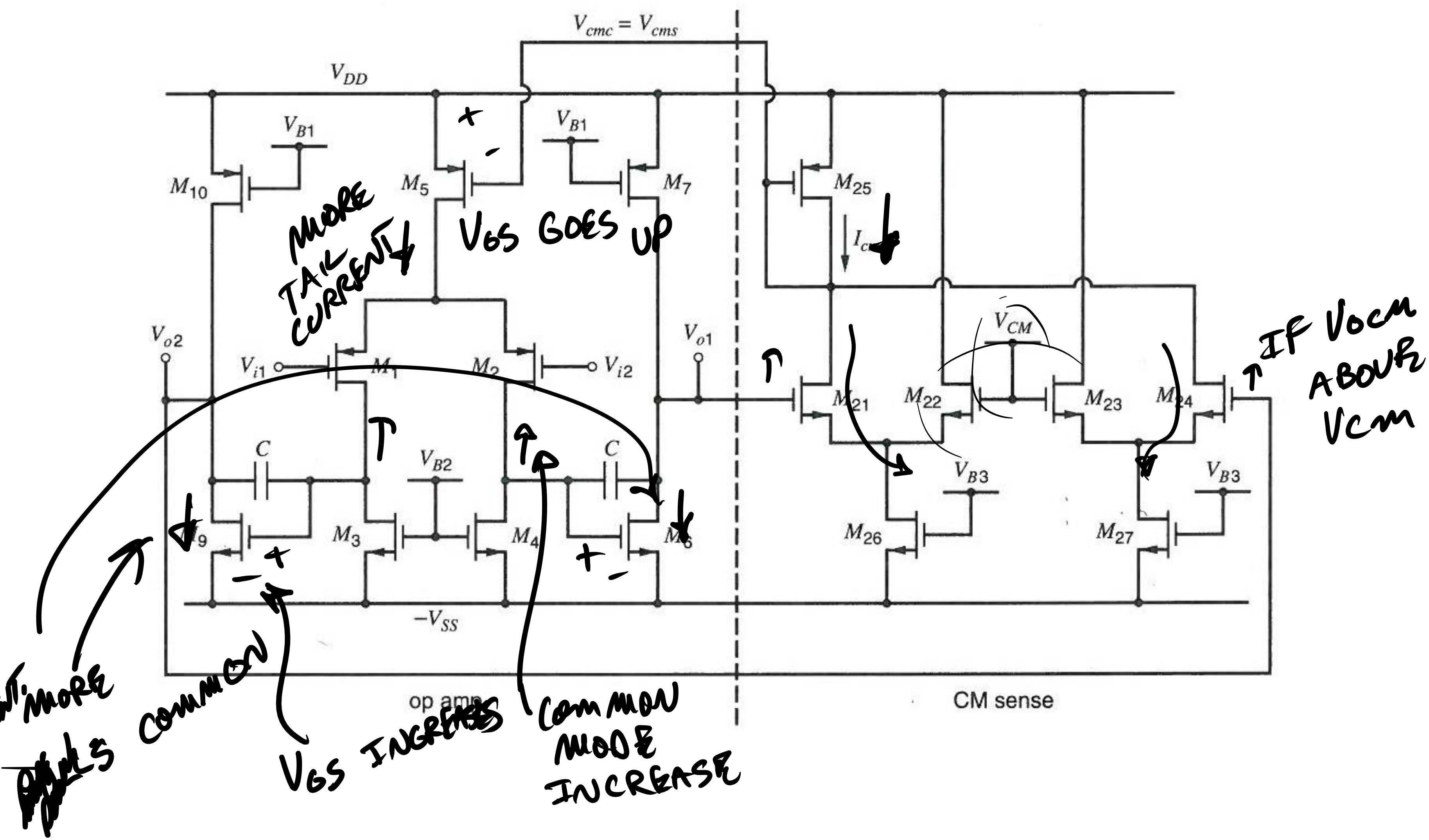
- **Control cascade current source**



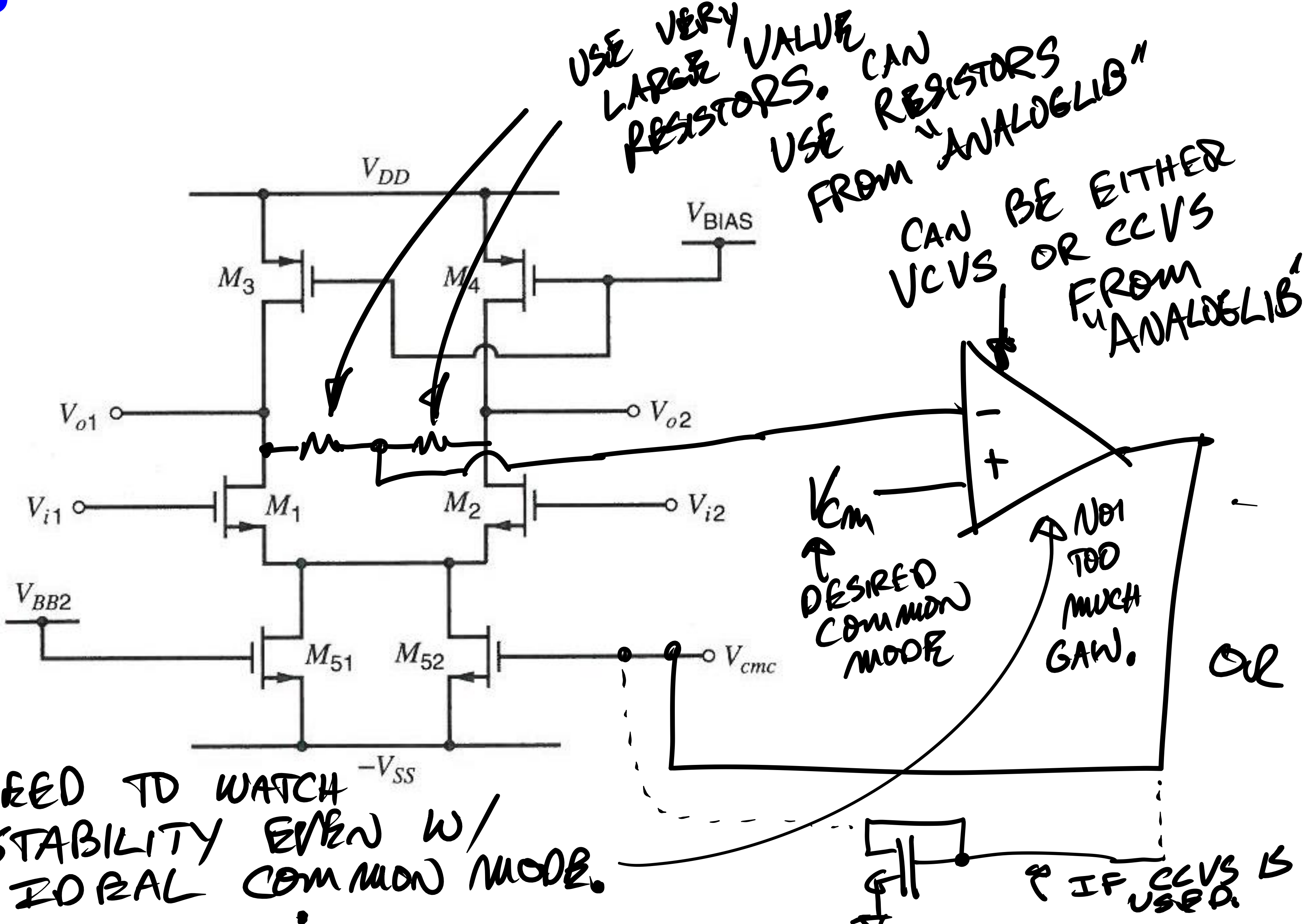
- **Control tail current source**



Detection w/o Bridge R or C



Project: Ideal Common-Mode Feedback



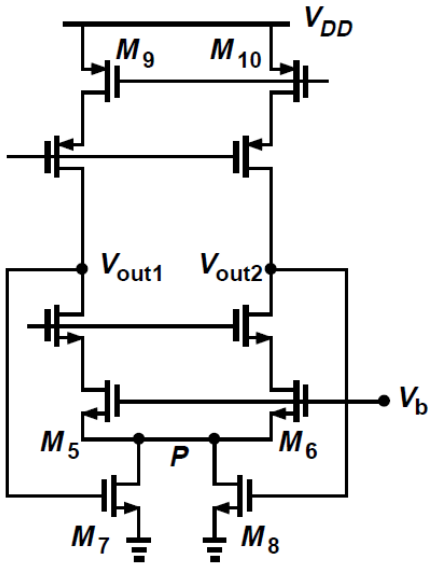
• NEED TO WATCH STABILITY EVEN W/ IDEAL COMMON MODE.

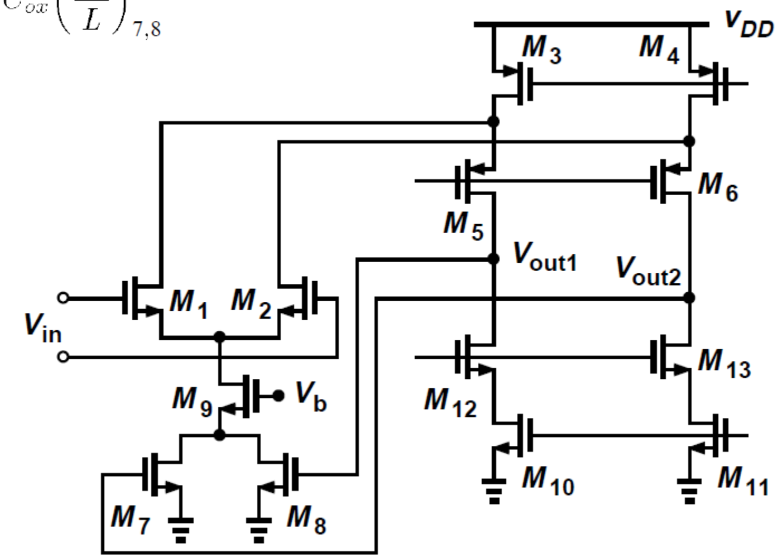
CM Feedback Techniques

- **Deep triode sensing feedback**
  - **Limited headroom**
  - **Large C**
  - **Device variation**

- **Deep triode folded-cascade sensing feedback**

$$V_{out1} + V_{out2} = \frac{2I_D}{\mu_n C_{ox}\left(\frac{W}{L}\right)_{7,8}} \frac{1}{V_b - V_{GS5}} + 2V_{TH}$$



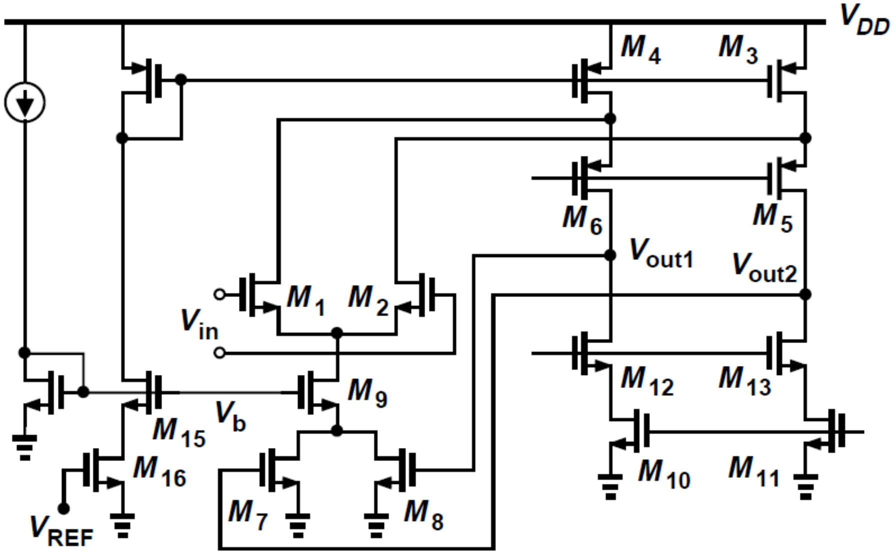


CM Feedback Techniques

- **Modification of deep triode sensing feedback**

$$(W/L)_{15} = (W/L)_9 \qquad (W/L)_{16} = (W/L)_7 + (W/L)_8$$

- **The output level is relatively independent of device parameters and lowers sensitivity of Vb**

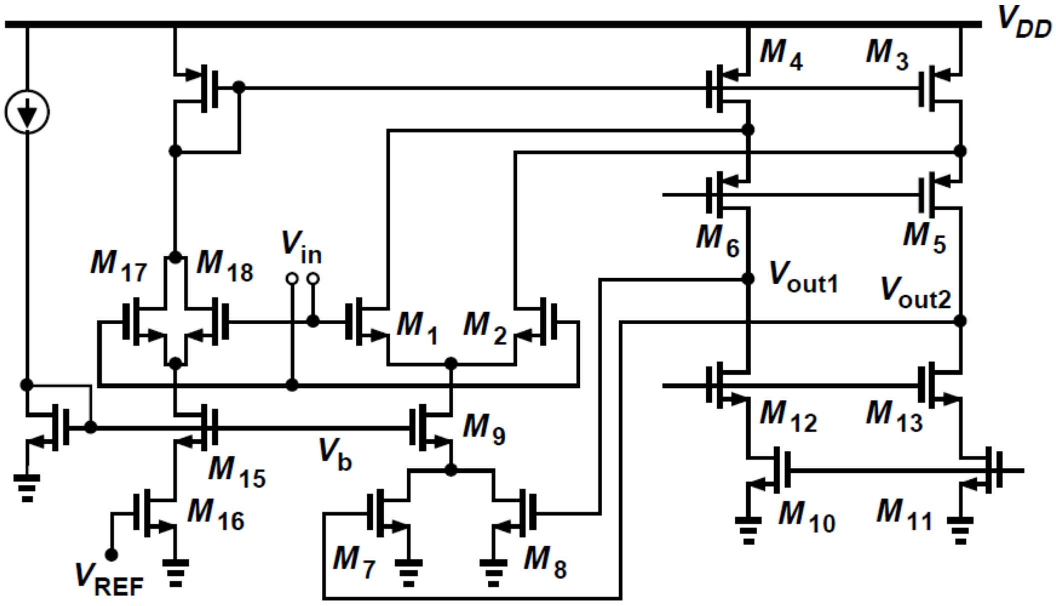


CM Feedback Techniques

- **Modification of deep triode sensing feedback**

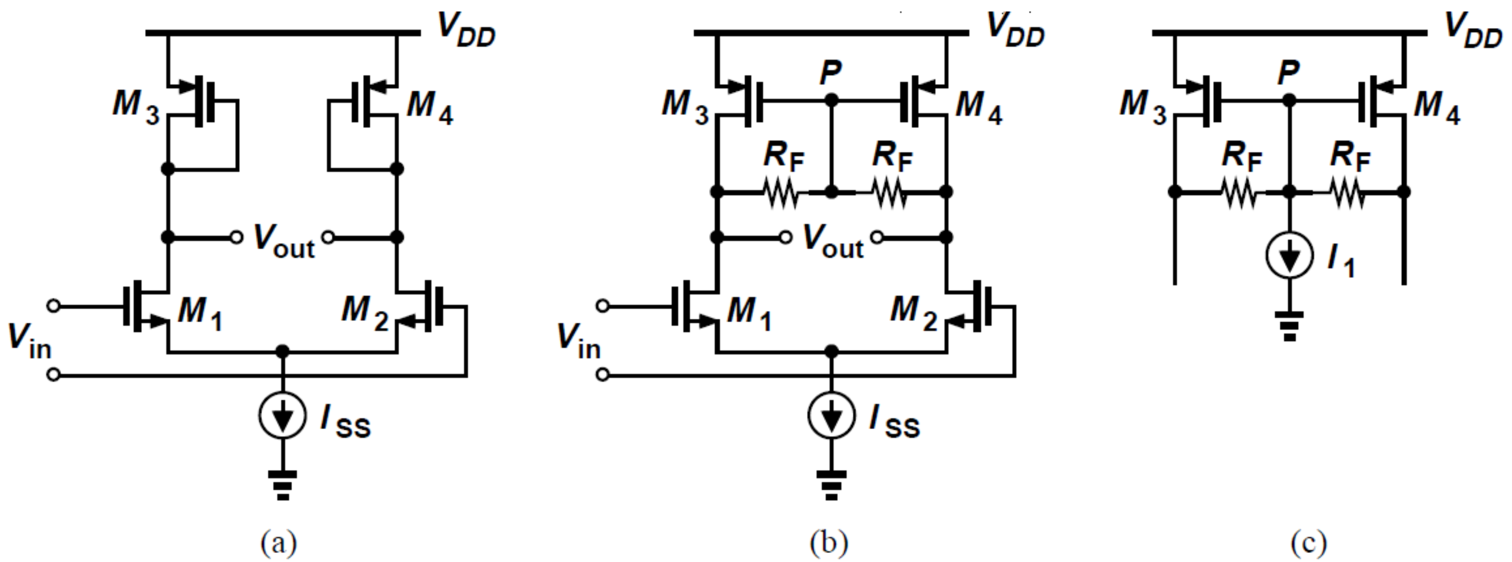
$$(W/L)_{15} = (W/L)_9 \qquad (W/L)_{16} = (W/L)_7 + (W/L)_8$$

- **M17, M18 reproduces the drain of M15 a voltage equal to the source voltage of M1 and M2**



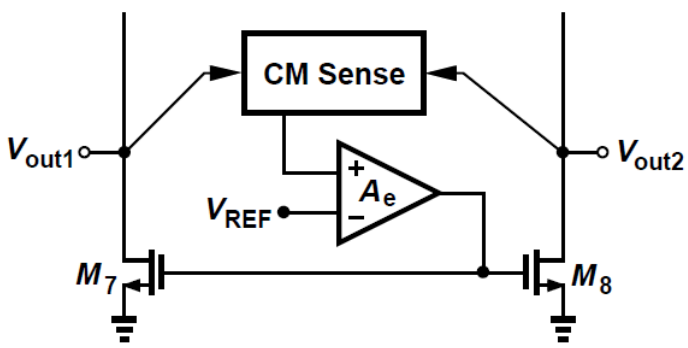
CM Feedback Techniques

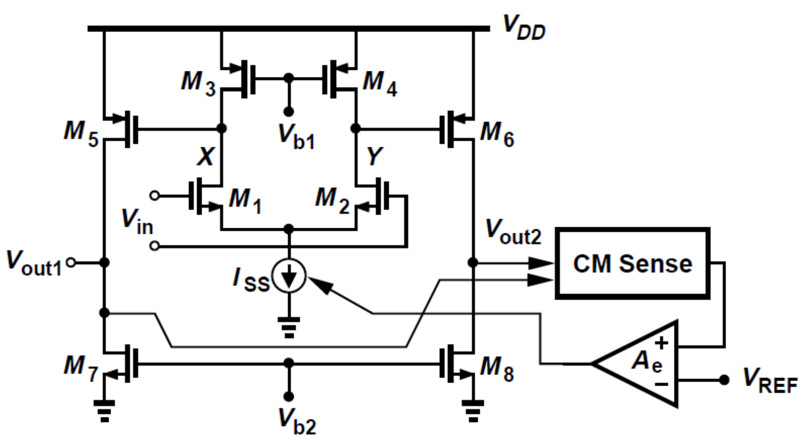
- **Another type of CM feedback topology**
- **Diode-connected loads' output CM level is well-defined**
- **Differential small signal gain** $g_{m1,2}(r_{O1,2}||r_{O3,4}||R_F)$
- **Common-mode work as a diode-connected** $R_F \gg r_{O1,2}||r_{O3,4}$
- **Low supply voltage design** $I_1 R_F/2 = |V_{TH3,4}|$



CMFB in Two-Stage Op Amps

- **CMFB around second stage (not good)**
  - **May establish a current beyond nominal value**
- **CMFB from second stage to first stage**
  - **Global loop control of both stages**

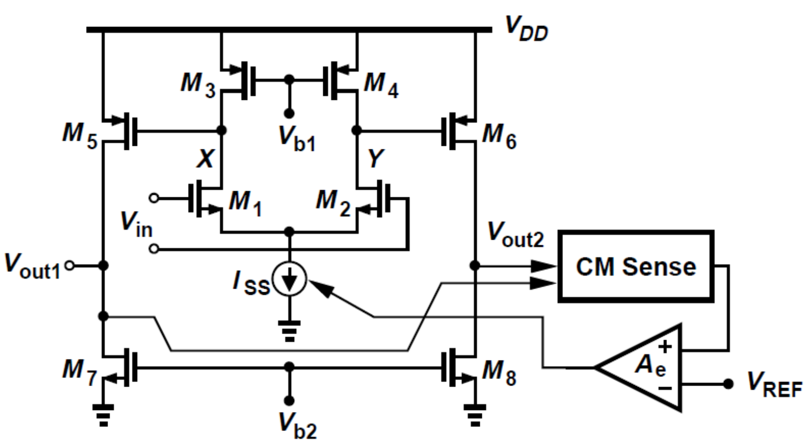


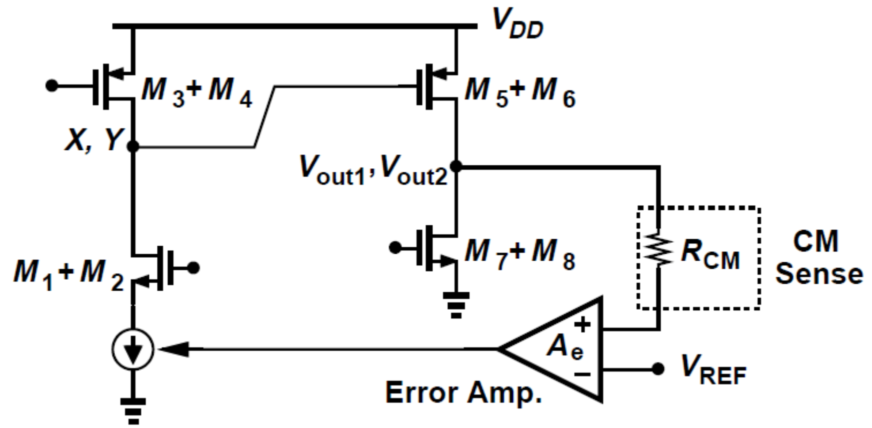


CMFB from Second to First Stage

- **CMFB from second stage to first stage limitation**

  - 3 or 4 poles, which makes it difficult for the loop stable

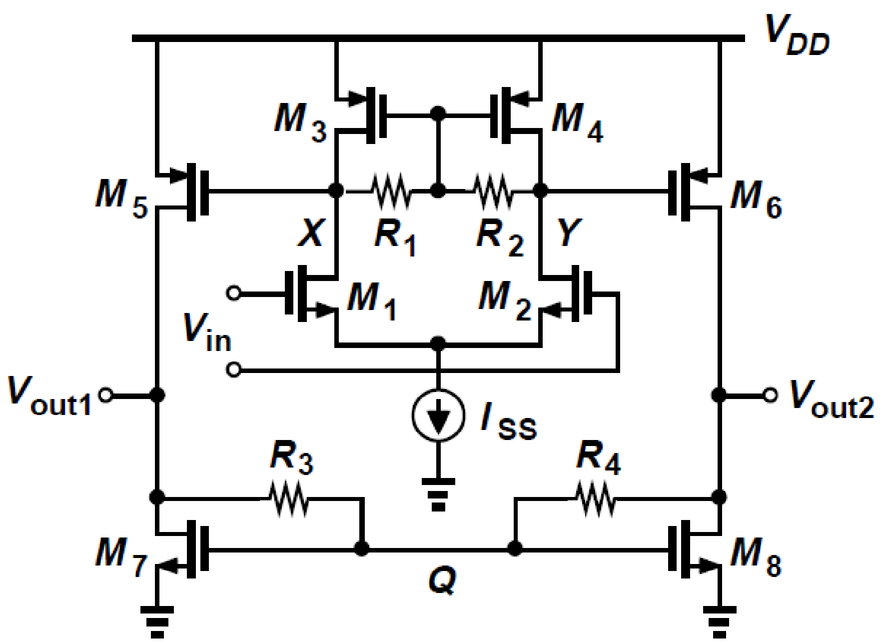




CMFB at both Stages

- All the drain currents are copied from Iss
- The differential voltage gain is equal to

$$g_{m1}(r_{O1}||r_{O3}||R_1)g_{m5}(r_{O5}||r_{O7}||R_3)$$

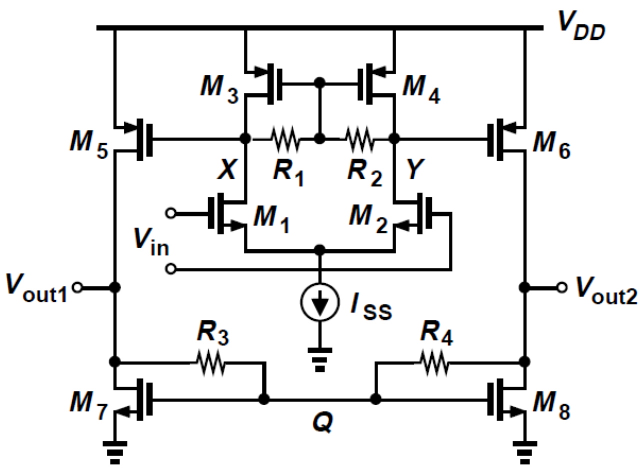


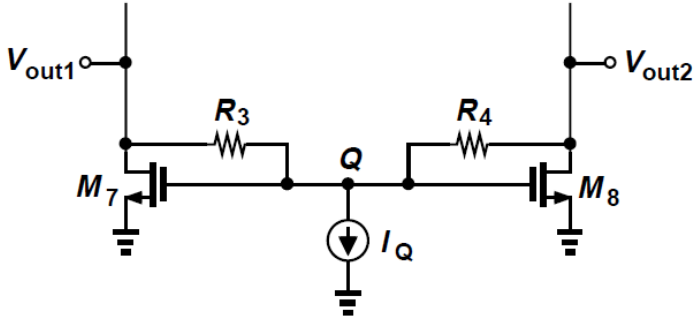
Example 9.21

For the below design explain why the output CM level is inevitably well below VDD/2 and hence the output swings are limited. Devise a solution.

Solution:

The output CM is equal to VG7,8, which is only slightly greater than one threshold. The issue can be resolved by drawing a small current from node Q. It can be upwards to desired output and the device is still in saturation.





CMFB for Cascode First Stage

- First stage use deep triode feedback loop to avoid loading.
- Achieving high gain while not precise