وَمَا أُوتِيتُم مِّنَ الْعِلْمِ إِلَّا قَلِيلًا

Analog IC Design

Lecture 19
Common-Mode Feedback (CMFB)

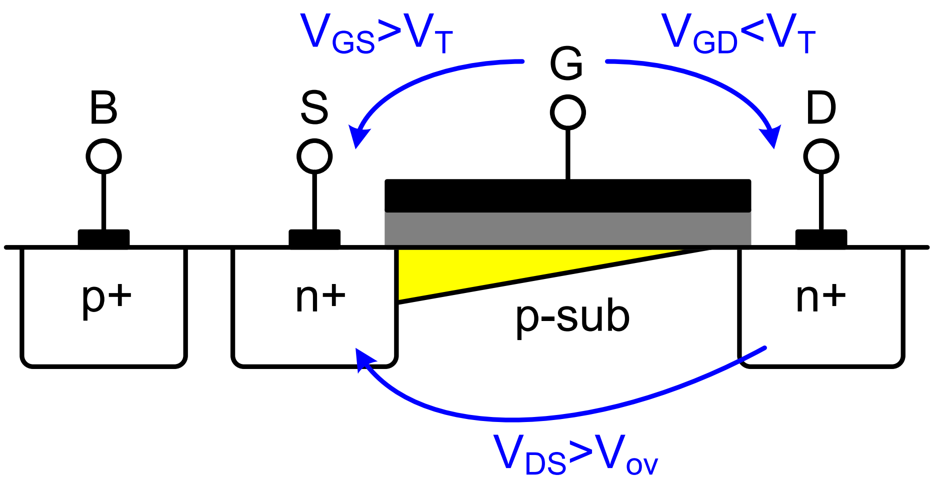
Dr. Hesham A. Omran

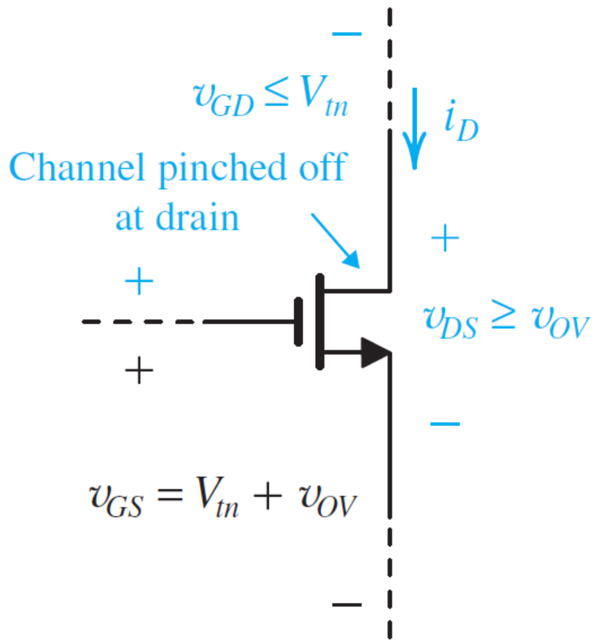
Integrated Circuits Lab (ICL)
Electronics and Communications Eng. Dept.
Faculty of Engineering
Ain Shams University

MOSFET in Saturation

- The channel is pinched off if the difference between the gate and drain voltages is not sufficient to create an inversion layer

$$I_D = \frac{\mu_n C_{ox}}{2} \frac{W}{L} \cdot V_{ov}^2 (1 + \lambda V_{DS})$$





[Sedra/Smith, 2015]

Regions of Operation Summary

OFF (Subthreshold)

$V_{GS} < V_T$

ON

$V_{GS} > V_T$

Triode

$V_{DS} < V_{ov}$

Or

$V_{GD} > V_T$

$$I_D = \mu C_{ox} \frac{W}{L} \left(V_{ov} V_{DS} - \frac{V_{DS}^2}{2} \right)$$

Pinch-Off (Saturation)

$V_{DS} \geq V_{ov}$

Or

$V_{GD} \leq V_T$

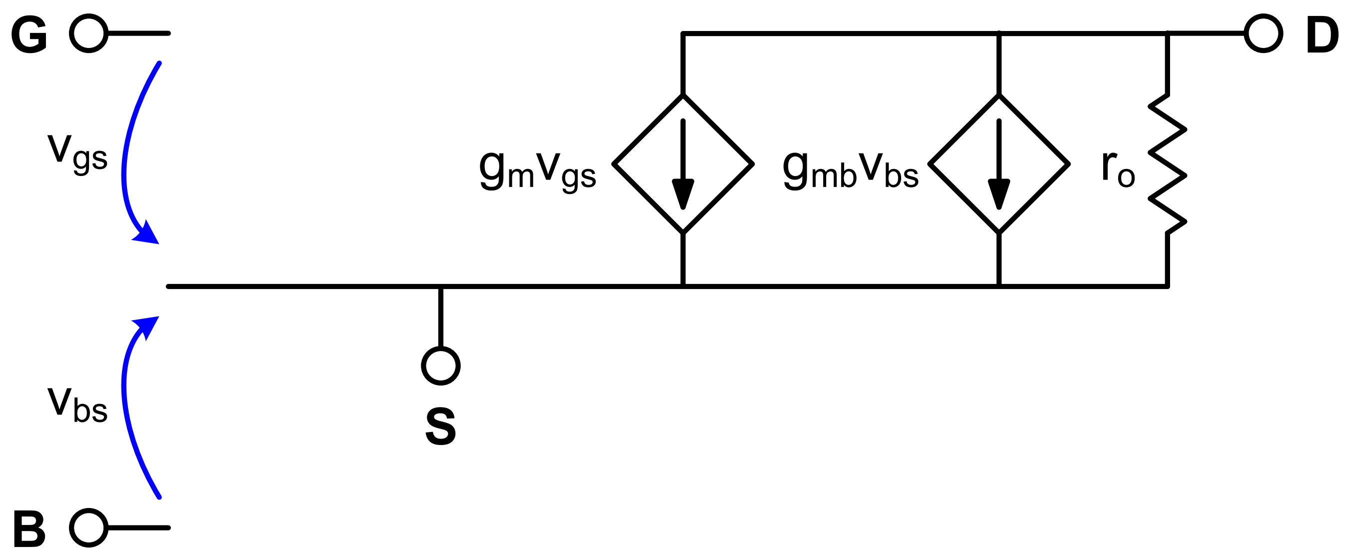
$$I_D = \frac{\mu C_{ox}}{2} \frac{W}{L} V_{ov}^2 (1 + \lambda V_{DS})$$

Low-Frequency Small-Signal Model

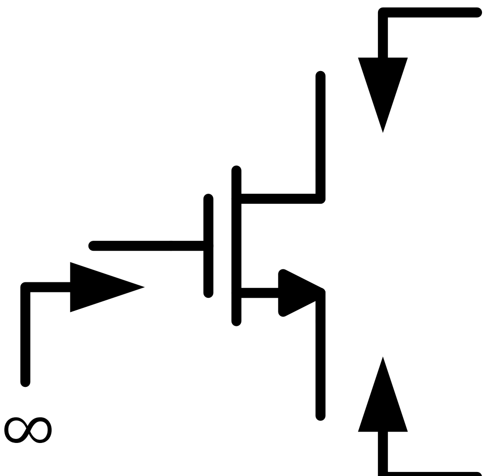
$$g_m = \frac{\partial I_D}{\partial V_{GS}} = \mu C_{ox}\frac{W}{L}V_{ov} = \sqrt{\mu C_{ox}\frac{W}{L}\cdot 2I_D} = \frac{2I_D}{V_{ov}}$$

$$g_{mb} = \eta g_m, \qquad \eta \approx 0.1 - 0.25$$

$$r_o = \frac{1}{\frac{\partial I_D}{\partial V_{DS}}} = \frac{1}{\lambda I_D}, \qquad \lambda \propto \frac{1}{L}$$



Rin/out Shortcuts Summary



$r_o[1 + (g_m + g_{mb})R_S]$

H.I.N.

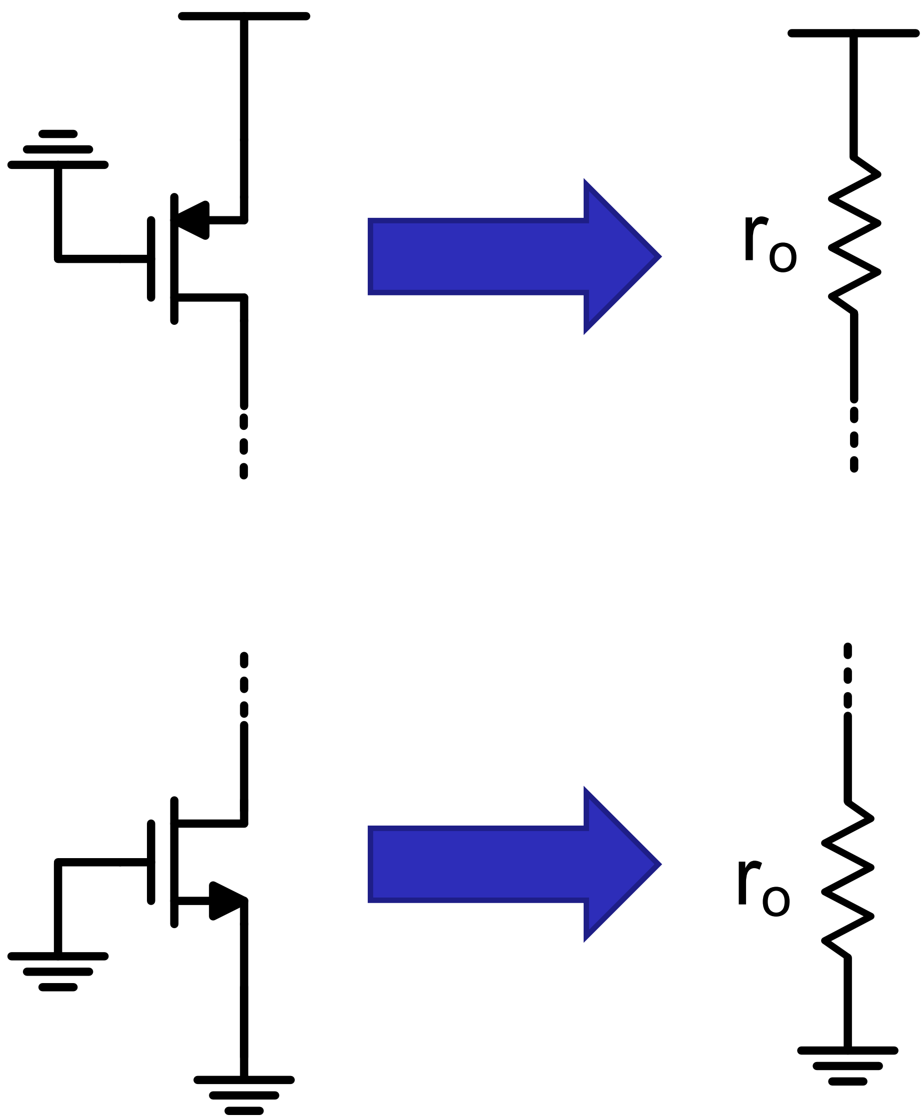
∞

At low frequencies **ONLY**

$$\frac{1}{g_m + g_{mb}}\left(1 + \frac{R_D}{r_o}\right)$$

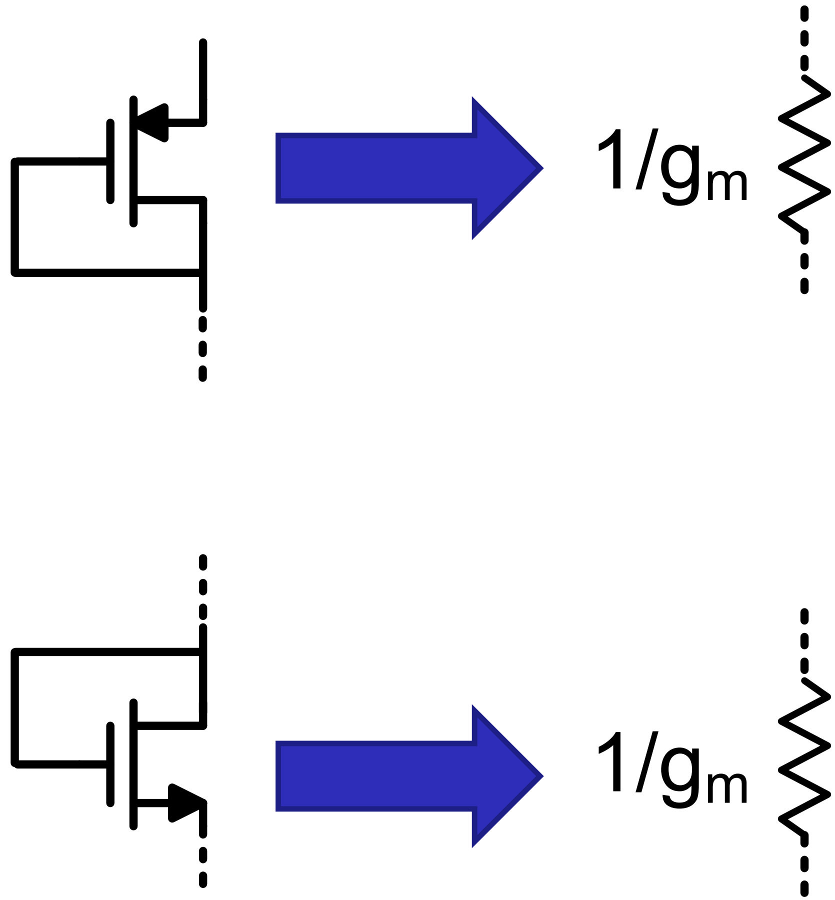
L.I.N.

Active Load (Source OFF)



Diode Connected (Source Absorption)

- Always in saturation
- Bulk effect: $g_m \rightarrow g_m + g_{mb}$



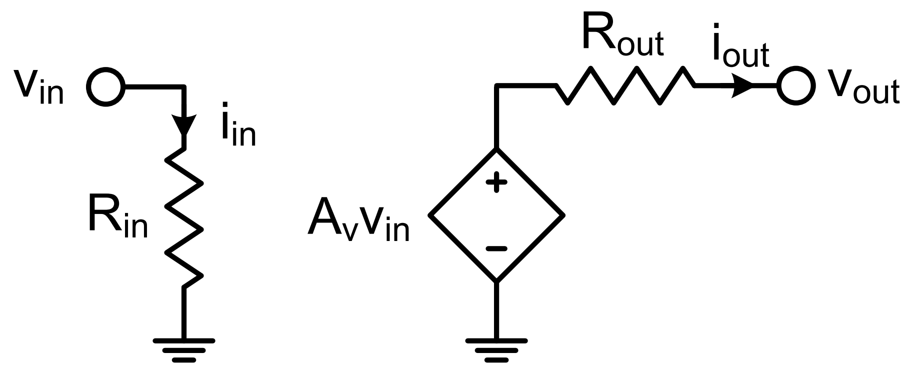
Why GmRout?

$$R_{out} = \frac{v_x}{i_x} @ v_{in} = 0$$

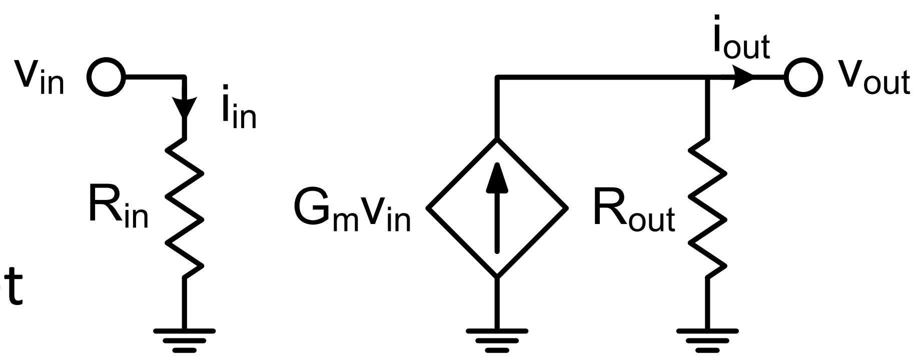
$$G_m = \frac{i_{out,sc}}{v_{in}}$$

$$A_v = G_m R_{out}$$

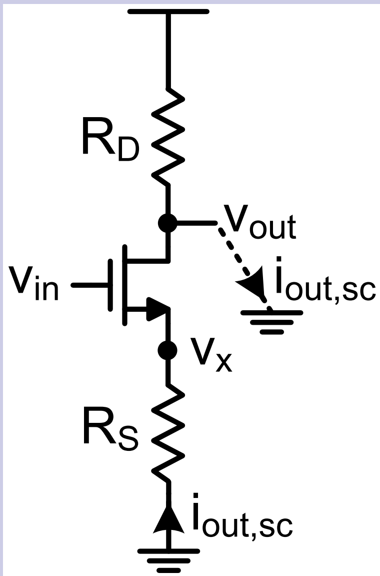
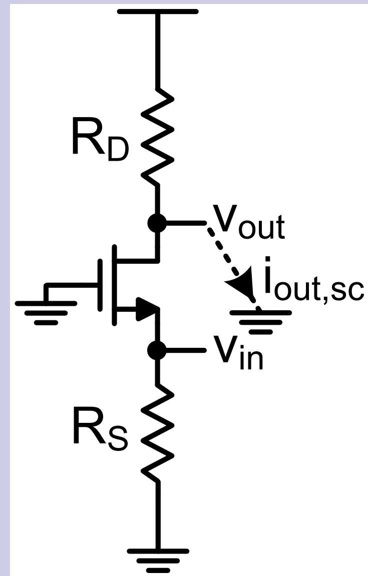
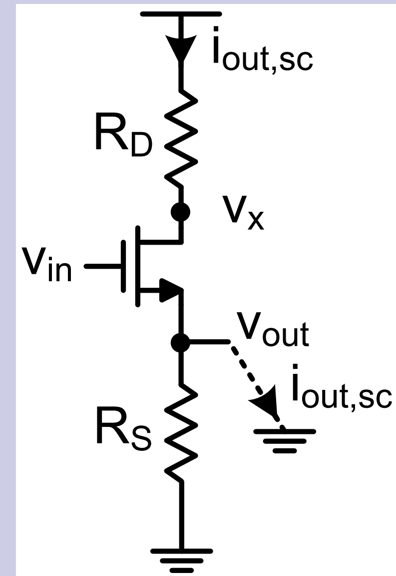
$$A_i = G_m R_{in}$$



- Divide and conquer
  - Rout simplified: vin=0
  - Gm simplified: vout=0
  - We already need Rin/out
  - We can quickly and easily get Rin/out from the shortcuts



Summary of Basic Topologies

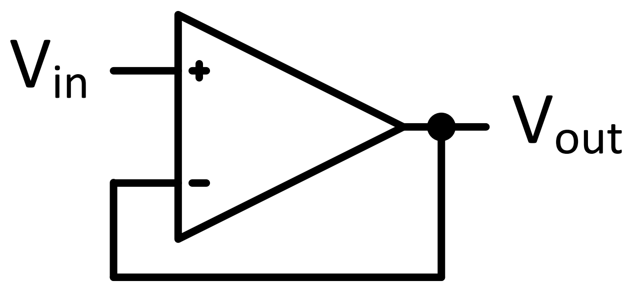
	CS	CG	CD (SF)
			
	Voltage & current amplifier	Current buffer	Voltage buffer
Rin	∞	$R_S // \frac{1}{g_m + g_{mb}}\left(1 + \frac{R_D}{r_o}\right)$	∞
Rout	$R_D // r_o[1 + (g_m + g_{mb})R_S]$	$R_D // r_o$	$R_S // \frac{1}{g_m + g_{mb}}\left(1 + \frac{R_D}{r_o}\right)$
Gm	$\frac{-g_m}{1 + (g_m + g_{mb})R_S}$	$g_m + g_{mb}$	$\frac{g_m}{1 + R_D / r_o}$

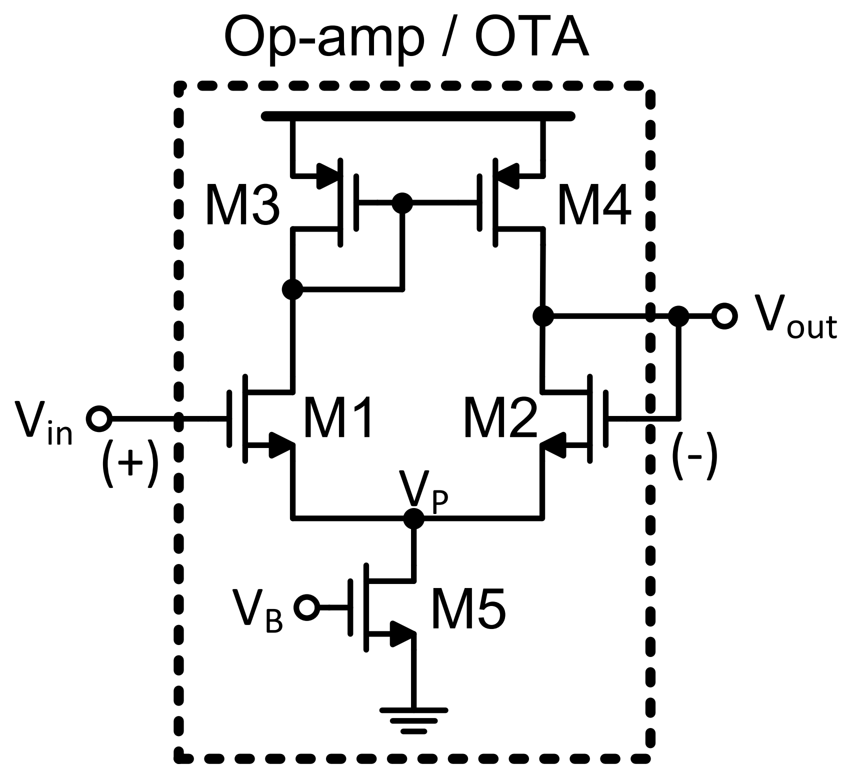
Differential Amplifier

	Pseudo Diff Amp	Diff Pair (w/ ideal CS)	Diff Pair (w/ R_{SS})
A_{vd}	$-g_m R_D$	$-g_m R_D$	$-g_m R_D$
A_{vCM}	$-g_m R_D$	0	$\dfrac{-g_m R_D}{1+2(g_m+g_{mb})R_{SS}}$
A_{vd}/A_{vCM}	1	∞	$2(g_m+g_{mb})R_{SS} \gg 1$

What is an OTA / Op-Amp?

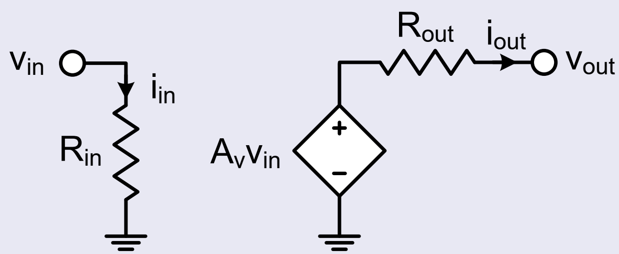
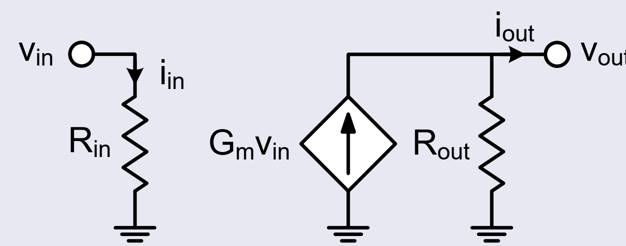
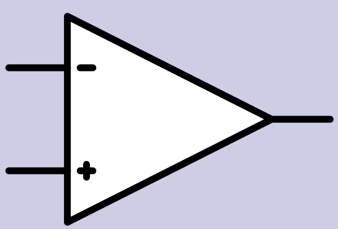
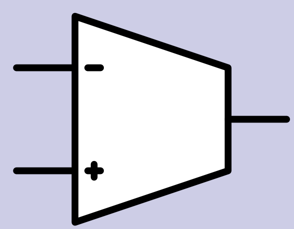
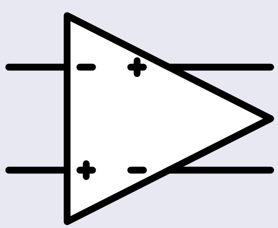
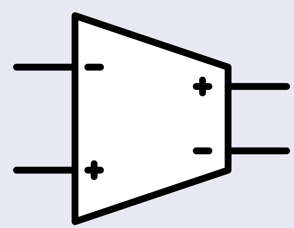
- An op-amp is simply a high gain differential amplifier
- The gain can be increased by using cascodes and multi-stage amplifiers





Op-Amp vs OTA

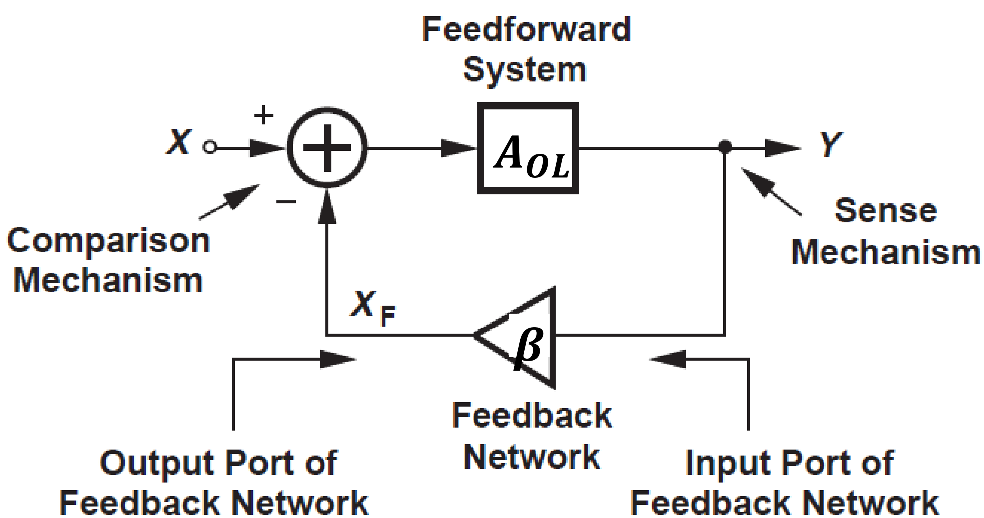
- ❑ An OTA is an op-amp without an output stage (buffer)
- ❑ Some designers just use op-amp name and symbol for both

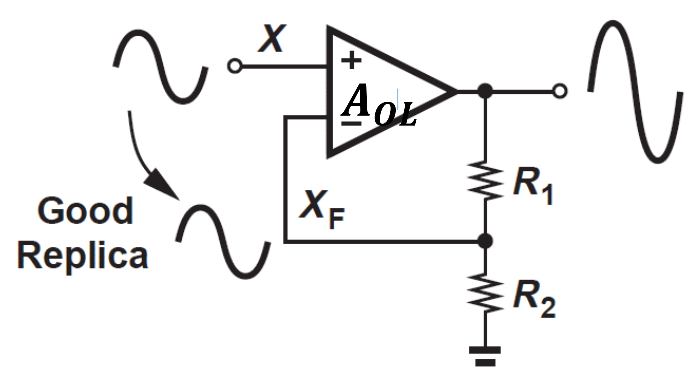
	Op-amp	OTA
Rout	**LOW**	**HIGH**
Model		
Diff input, SE output		
Fully diff		

Negative Feedback

- A_{OL} = Open loop (OL) gain $\gg 1$
- $A_{CL} = \frac{Y}{X}$ = Closed loop (CL) gain
- Error signal = $X - X_F$

$$Y = A_{OL}(X - X_F) = A_{OL}(X - \beta Y)$$
$$A_{CL} = \frac{Y}{X} = \frac{A_{OL}}{1 + \beta \cdot A_{OL}} \approx \frac{1}{\beta}$$

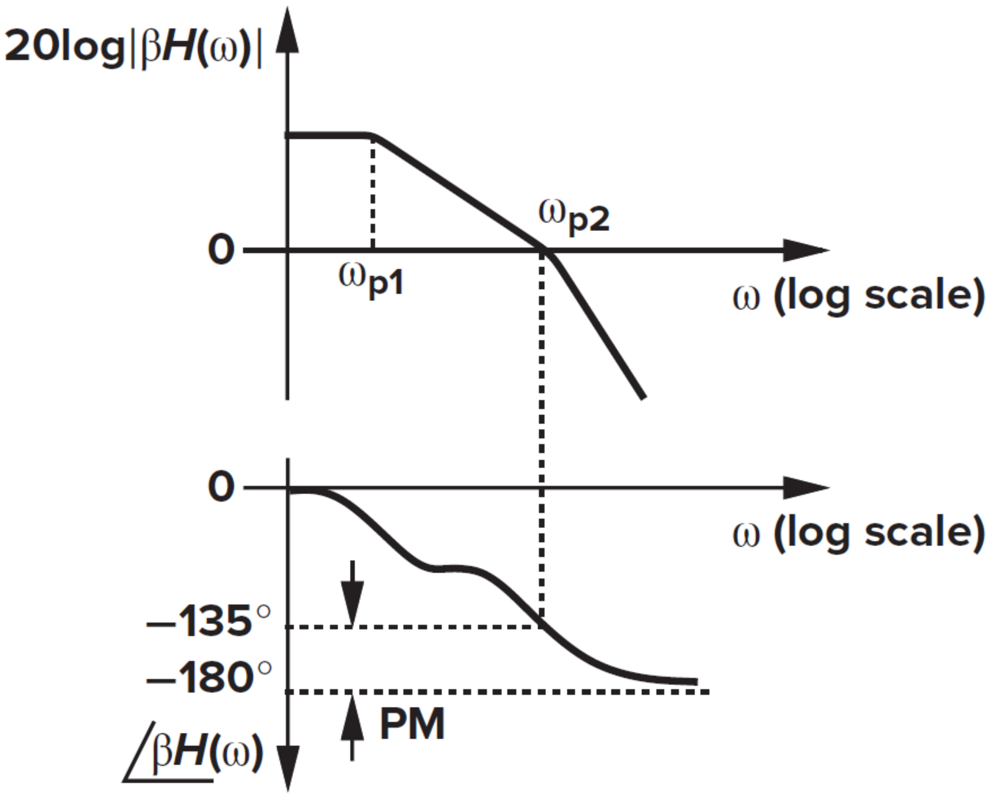


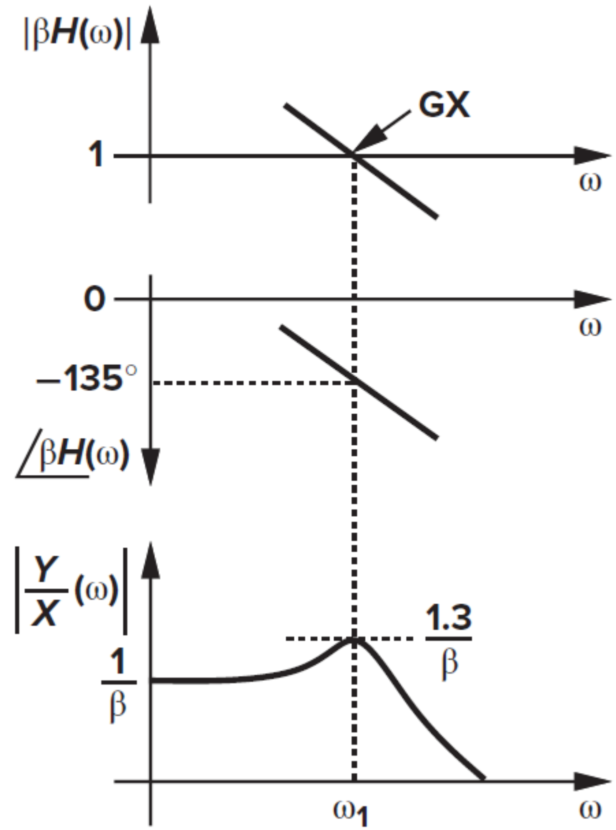


[Razavi, 2014]

Stability: Phase Margin

- If $\omega_{p2} = \omega_u$: PM = 45° → typically inadequate (peaking/ringing)
- The ultimate ω_u cannot exceed ω_{p2} → $\omega_{p1} < \omega_u < \omega_{p2}$
  - For $\omega < \omega_u$ the Bode plot is similar to a 1st order system





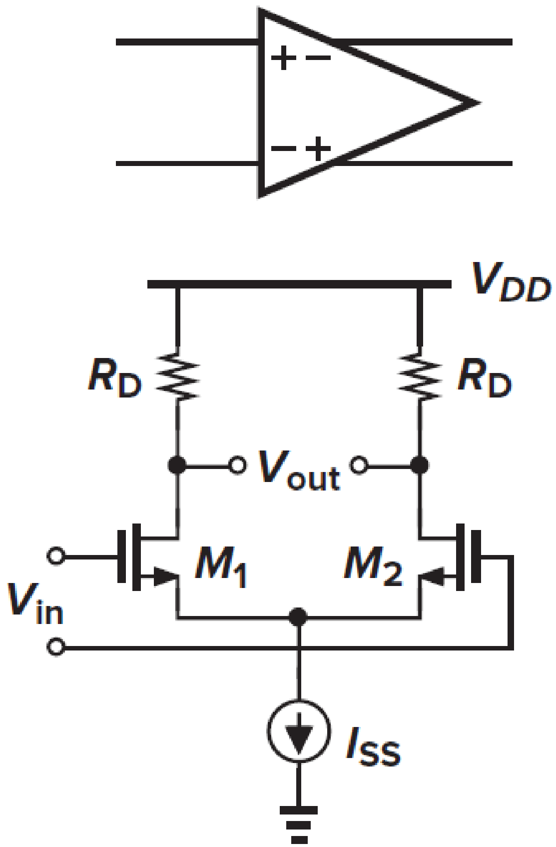
[Razavi, 2017]

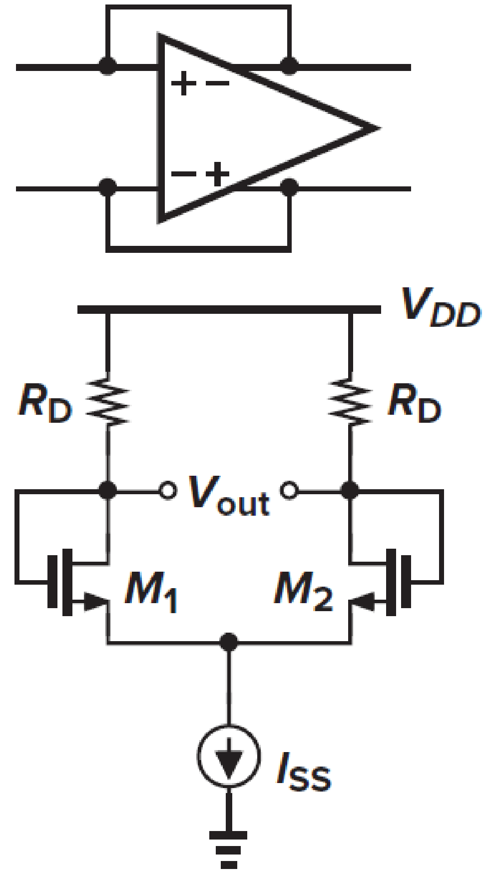
Why Fully Differential Circuits

- Fully differential vs diff input SE output
  - Larger output swing
  - No mirror poles (higher speed)
  - Better CMRR
  - Better linearity (lower distortion)
- But common-mode feedback (CMFB) circuit is required…

Well Defined Input/Output CM Level

- The input and output common-mode levels are fairly well defined
- VCM = VDD – ISS*RD/2

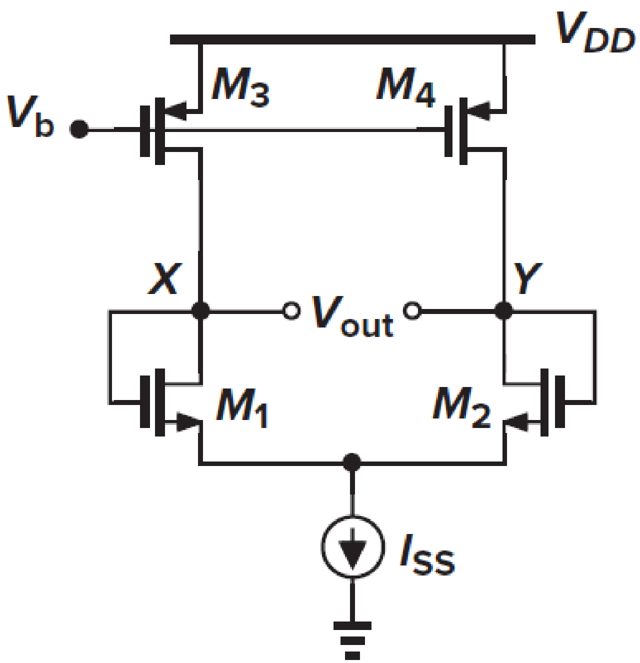


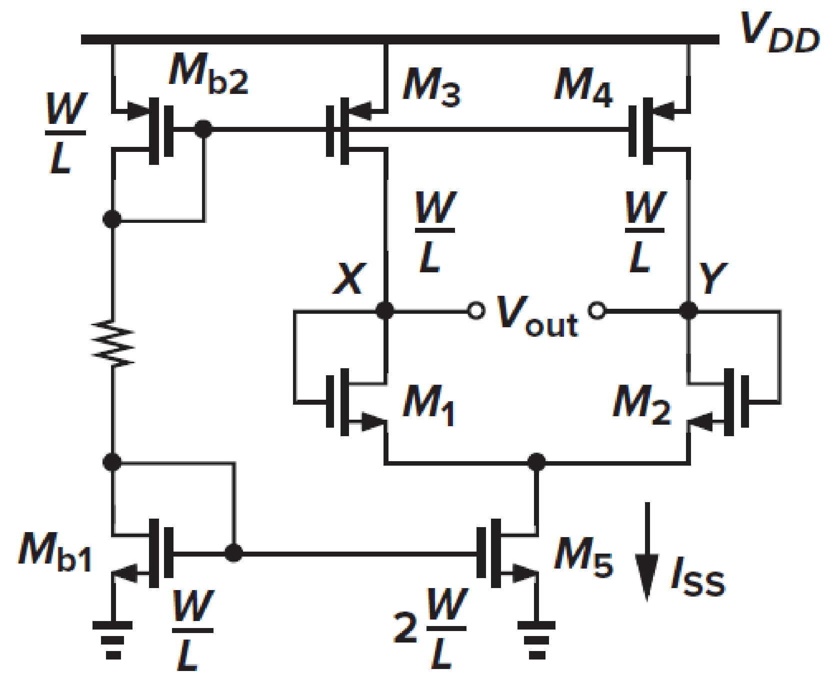


[Razavi, 2017]

ILL-Defined Input/Output CM Level

- Mismatches ALWAYS create a finite error between ID3,4 and ISS/2
- If ID3,4 > ISS/2: VX and VY must rise (M3 and M4 enter triode) so that ID3,4 fall to ISS/2
- If ID3,4 < ISS/2: VX and VY must drop (M5 enters triode) region so that ISS falls to 2*ID3,4

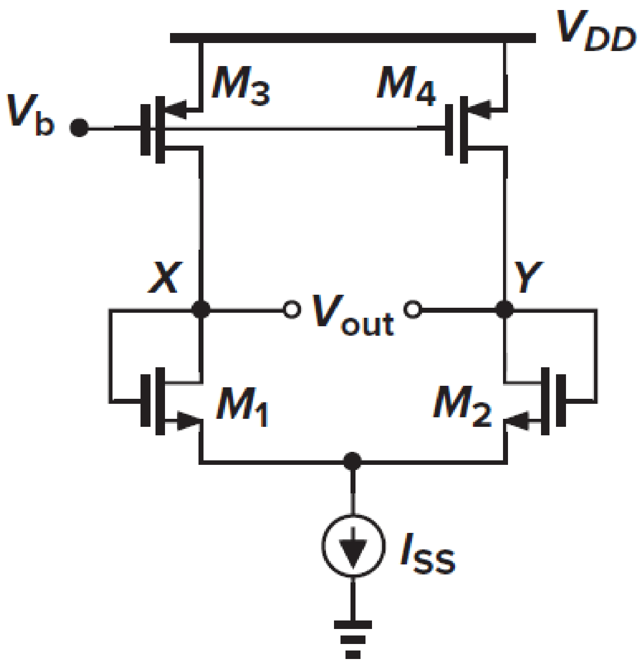


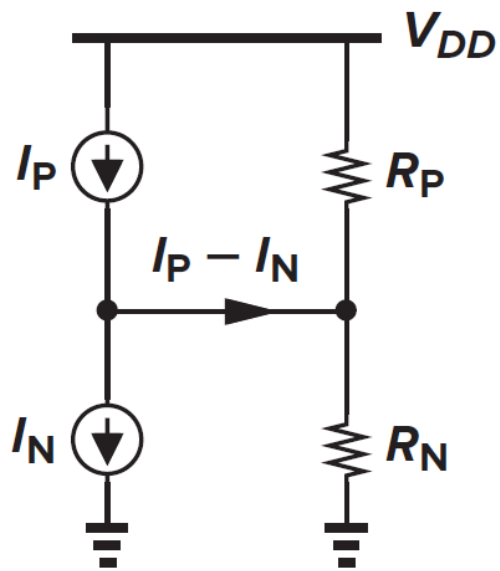


[Razavi, 2017]

ILL-Defined Input/Output CM Level

- This is a fundamental problem in high-gain amplifiers
- Vb can be adjusted in simulations but not in a real circuit
- Why don't we suffer from this problem in SE output OTA?

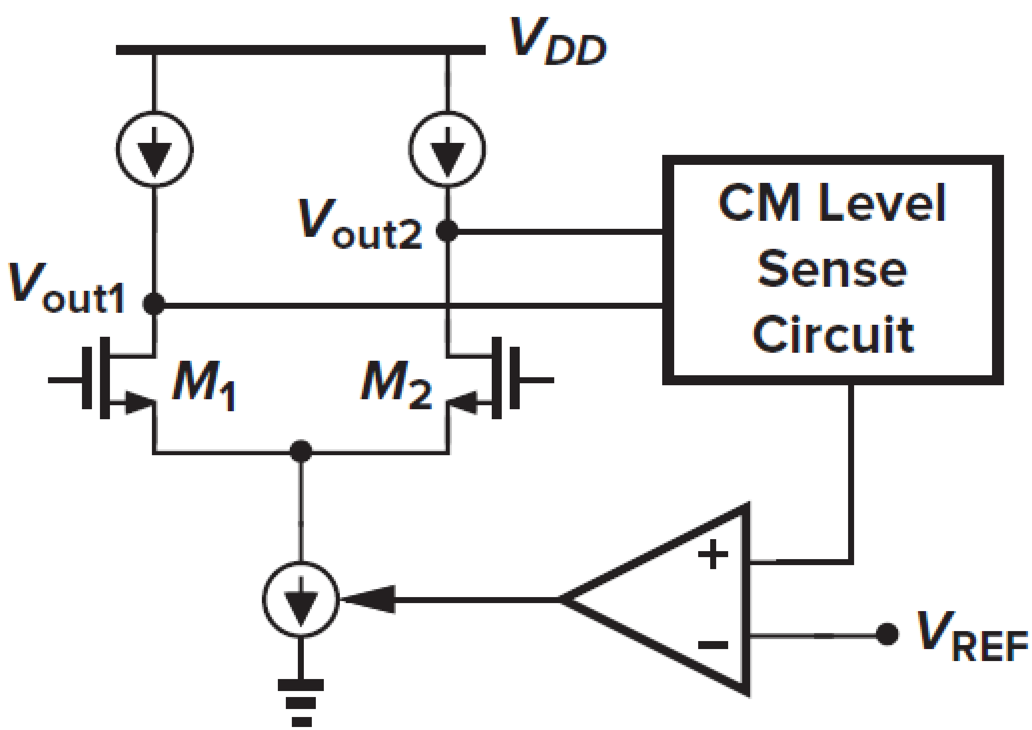




[Razavi, 2017]

Common-Mode Feedback (CMFB)

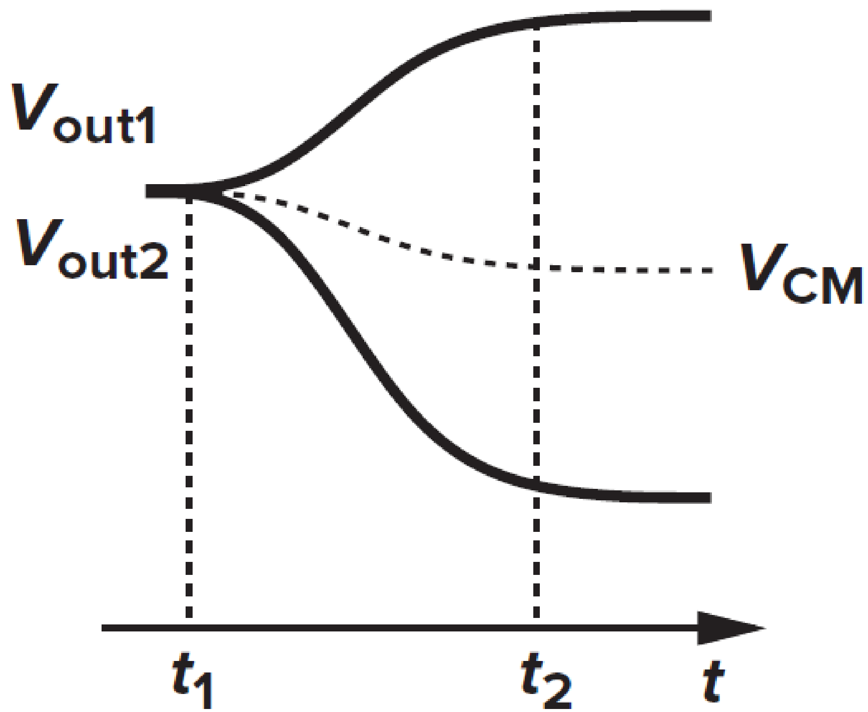
- Negative FB system
  1. Sense CM level
  2. Compare it to a reference
  3. Return the error to the bias circuit



[Razavi, 2017]

CMFB

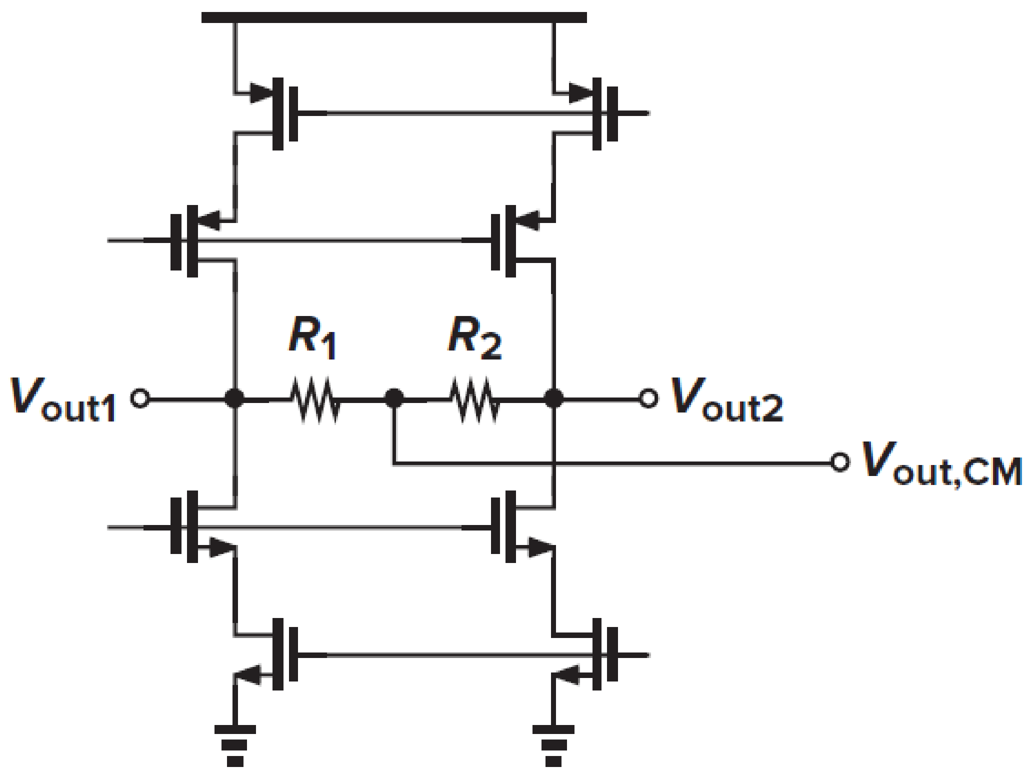
- CM level must be independent of the differential signal
  - CM sensing must not depend on the differential signal



[Razavi, 2017]

CM Sensing: Resistive Sensing

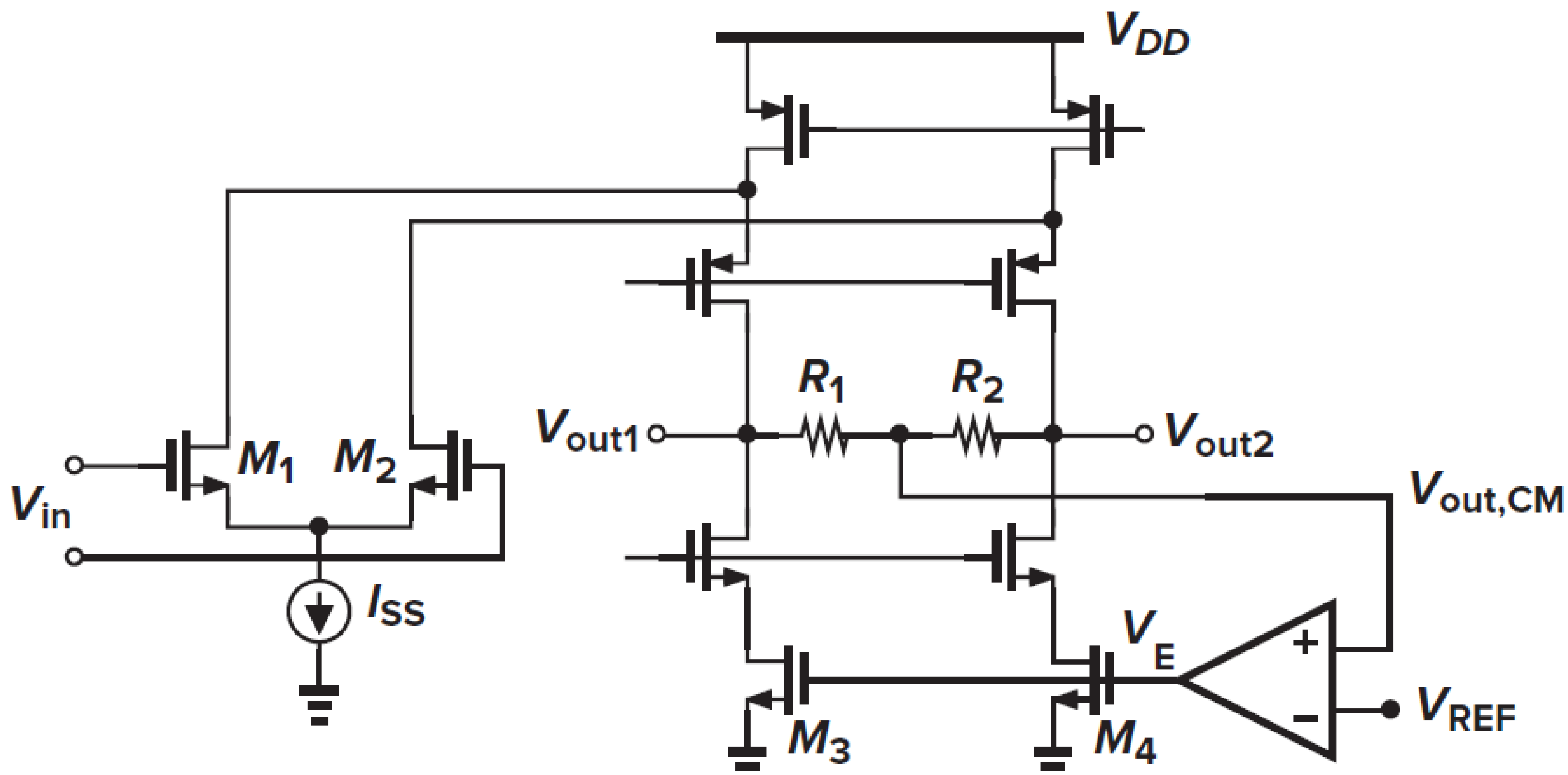
- Small R will degrade the gain
- Large R occupies large area and has large parasitic capacitors
  - May degrade the CMFB loop stability!



[Razavi, 2017]

CMFB Techniques

- Resistive sensing
- The feedback network forces the CM level of Vout1 and Vout2 to approach VREF
- The feedback can also be applied to the PMOS current sources



[Razavi, 2017]

CMFB Techniques

- Resistive sensing
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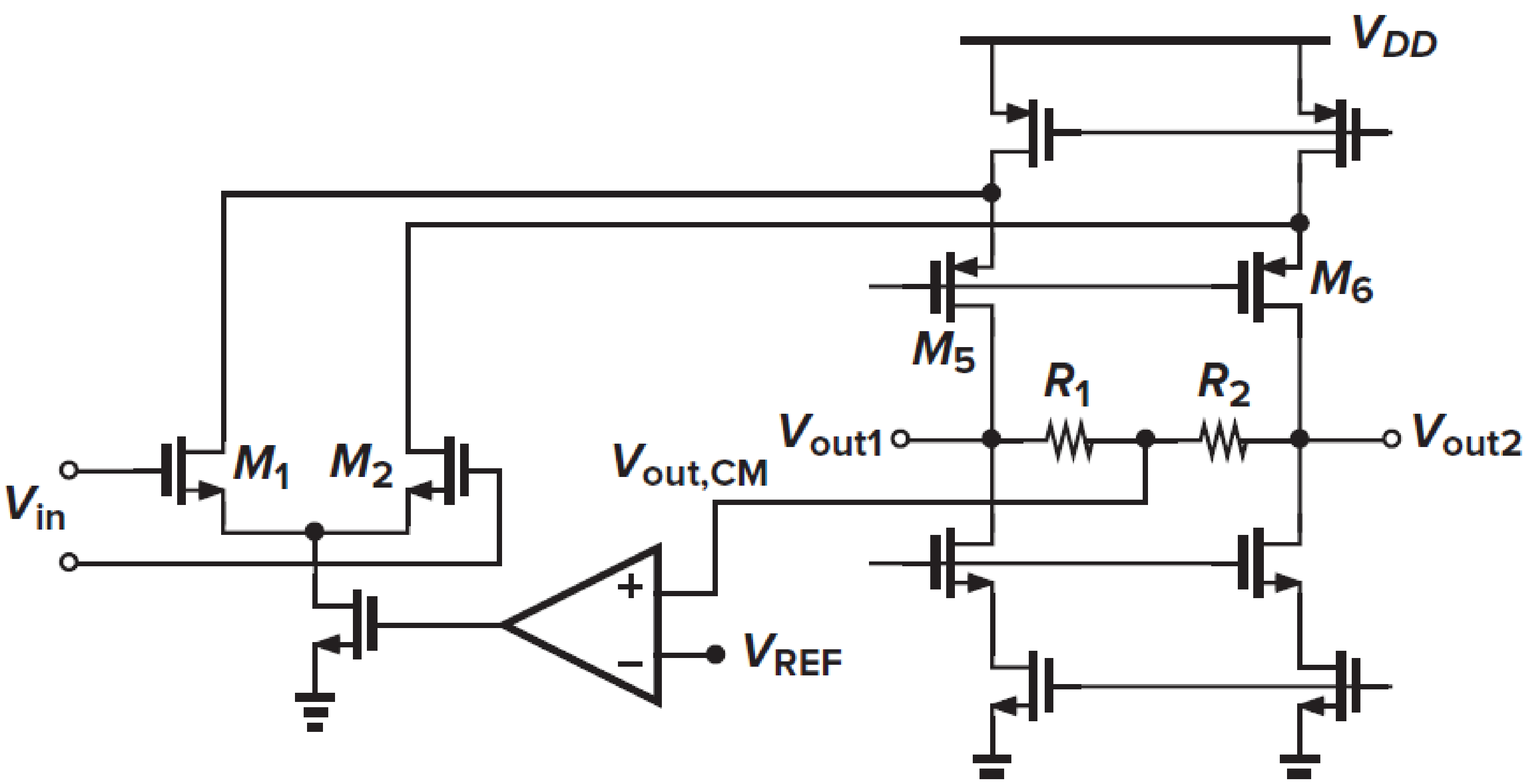
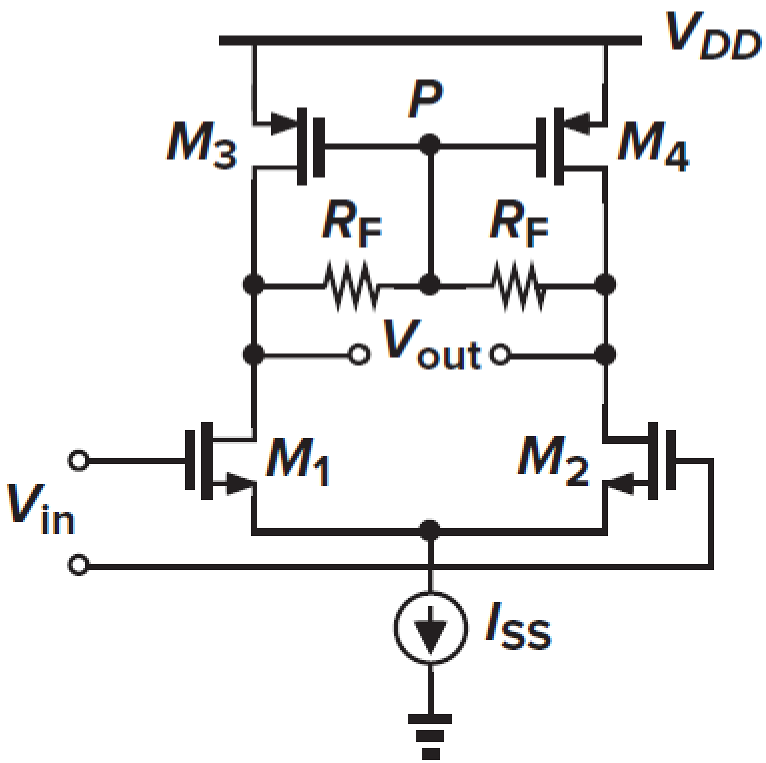
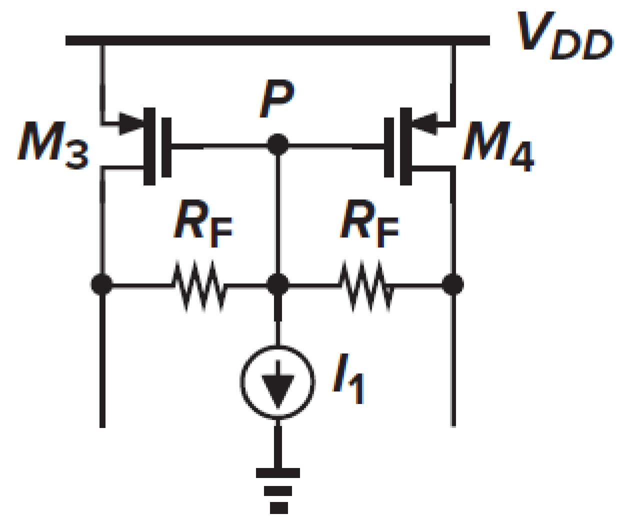


[Razavi, 2017]

CMFB Techniques

- For CM level M3 and M4 behave as diode connected devices
- Maximum swing obtained by setting $\frac{I_1}{2} R_F = V_{TH}$

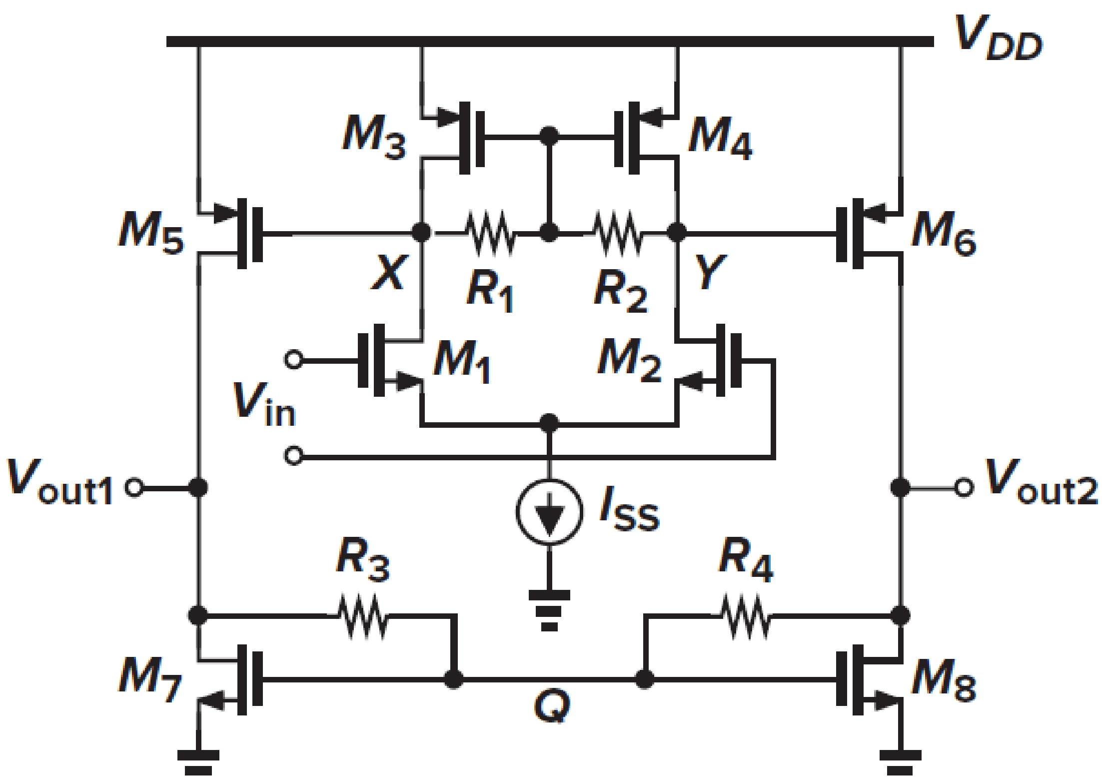




[Razavi, 2017]

CMFB Techniques

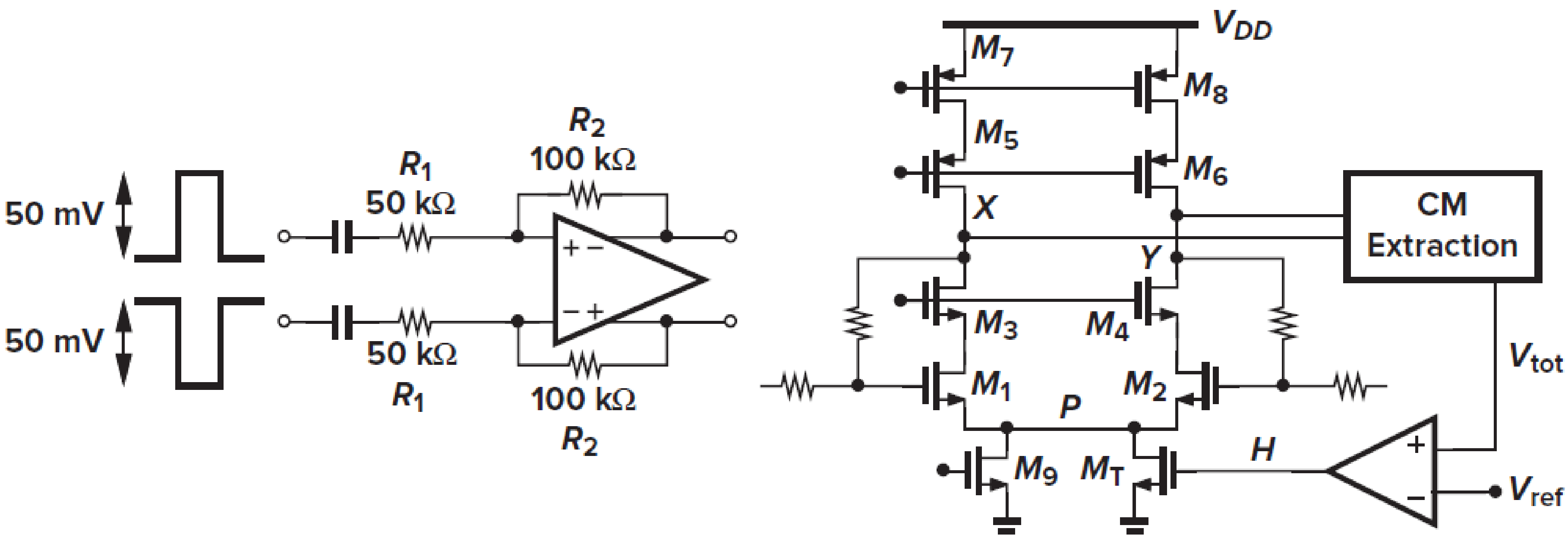
- Two stage OTA: Two separate CMFB loops for the first and second stages



[Razavi, 2017]

CMFB Loop Stability

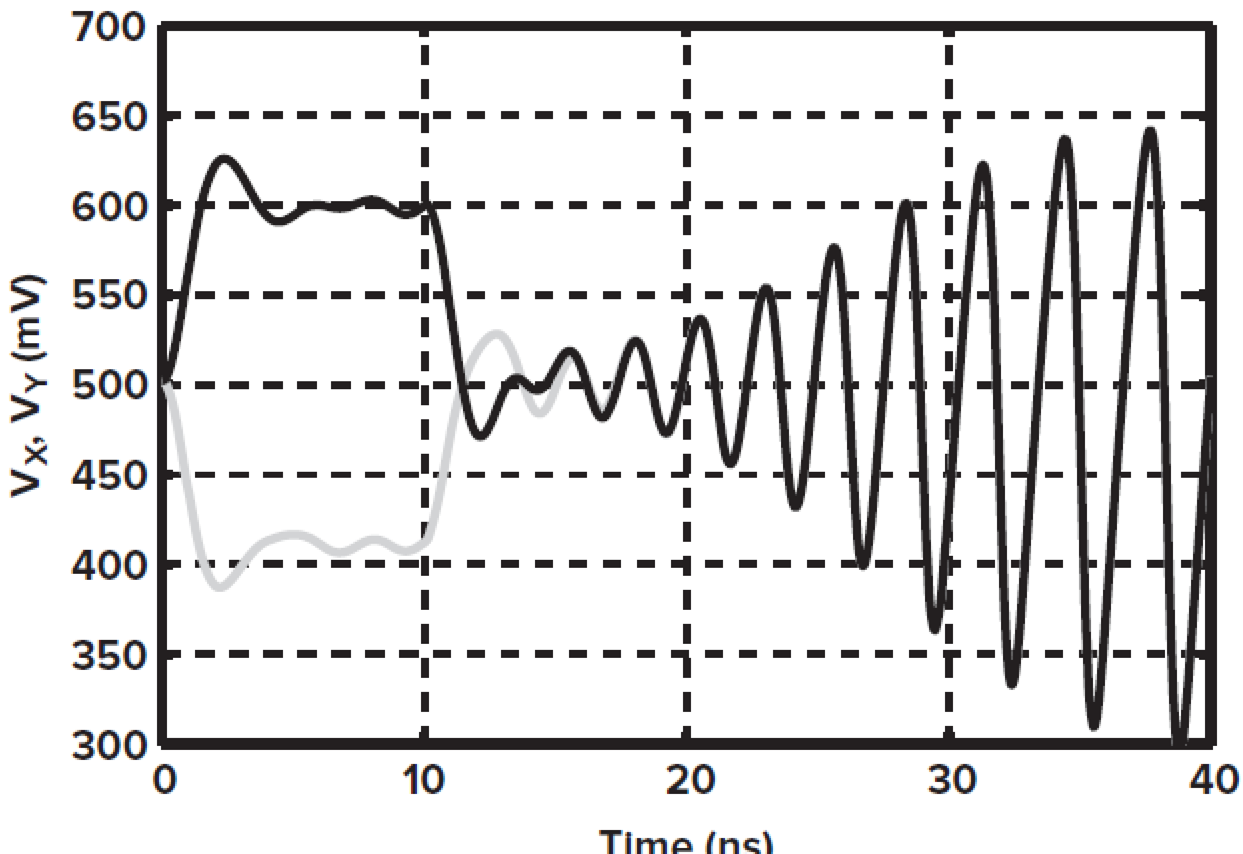
- Simulating CMFB loop stability
  - Place the OTA in a closed-loop feedback system
  - Apply differential pulses (transient analysis)
    - ➢ Large signal effects are captured



[Razavi, 2017]

CMFB Loop Stability

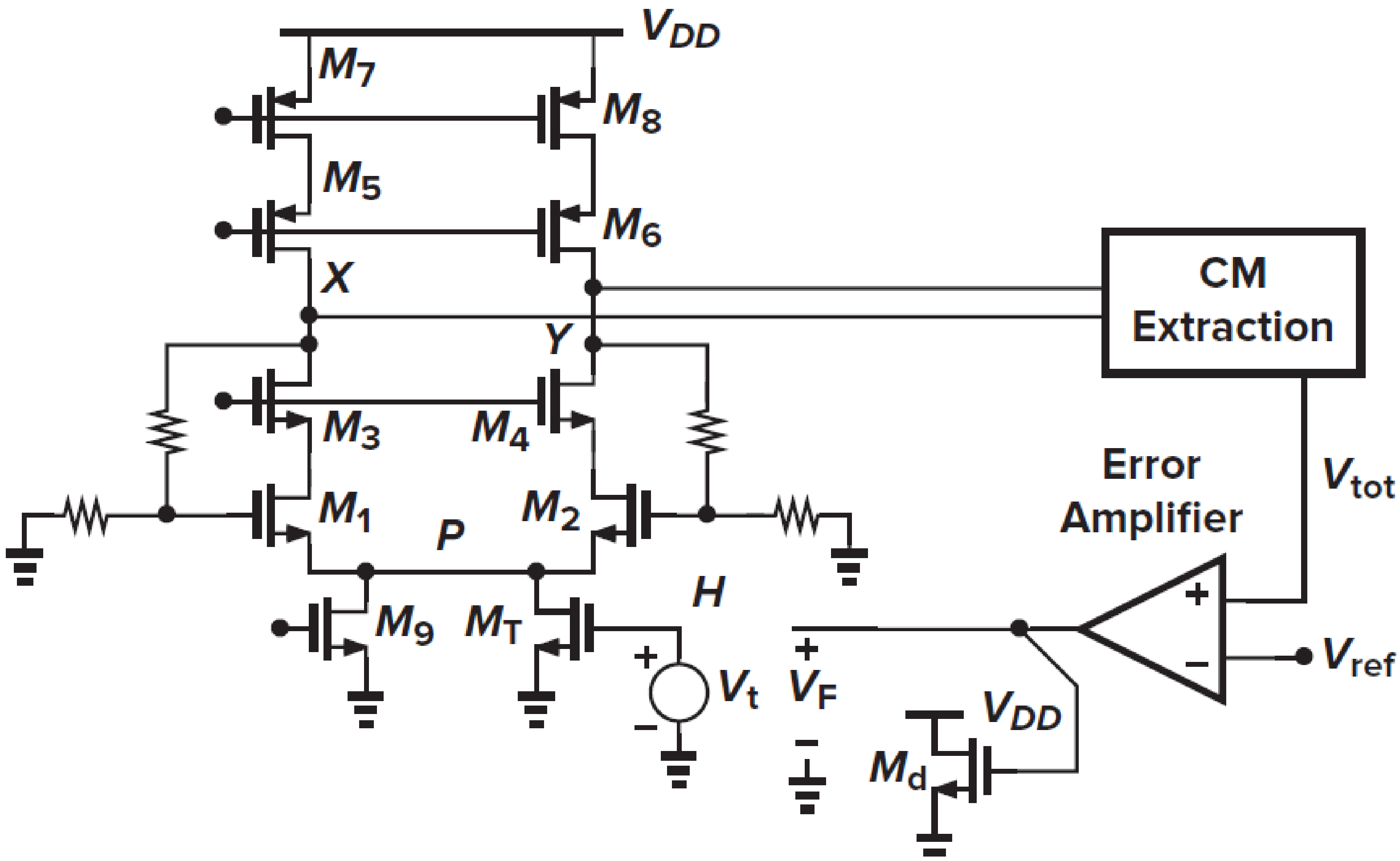
- The CMFB loop is unstable!
  - Requires compensation



[Razavi, 2017]

CMFB Loop Stability

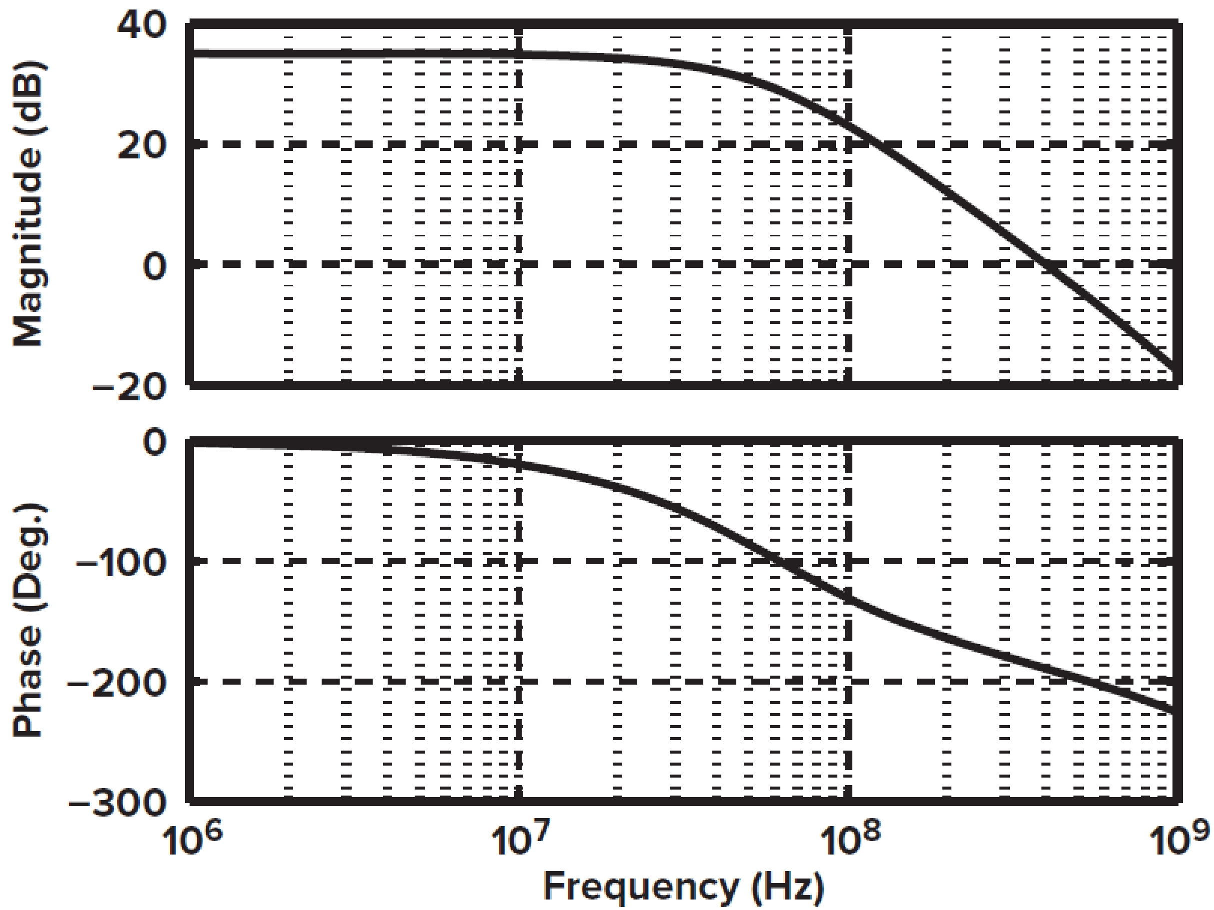
- ❑ Hand analysis: Break the loop to analyze the CMFB loop gain
- ❑ Simulation: Use STB analysis (loading and bilateral effects)



[Razavi, 2017]

CMFB Loop Stability

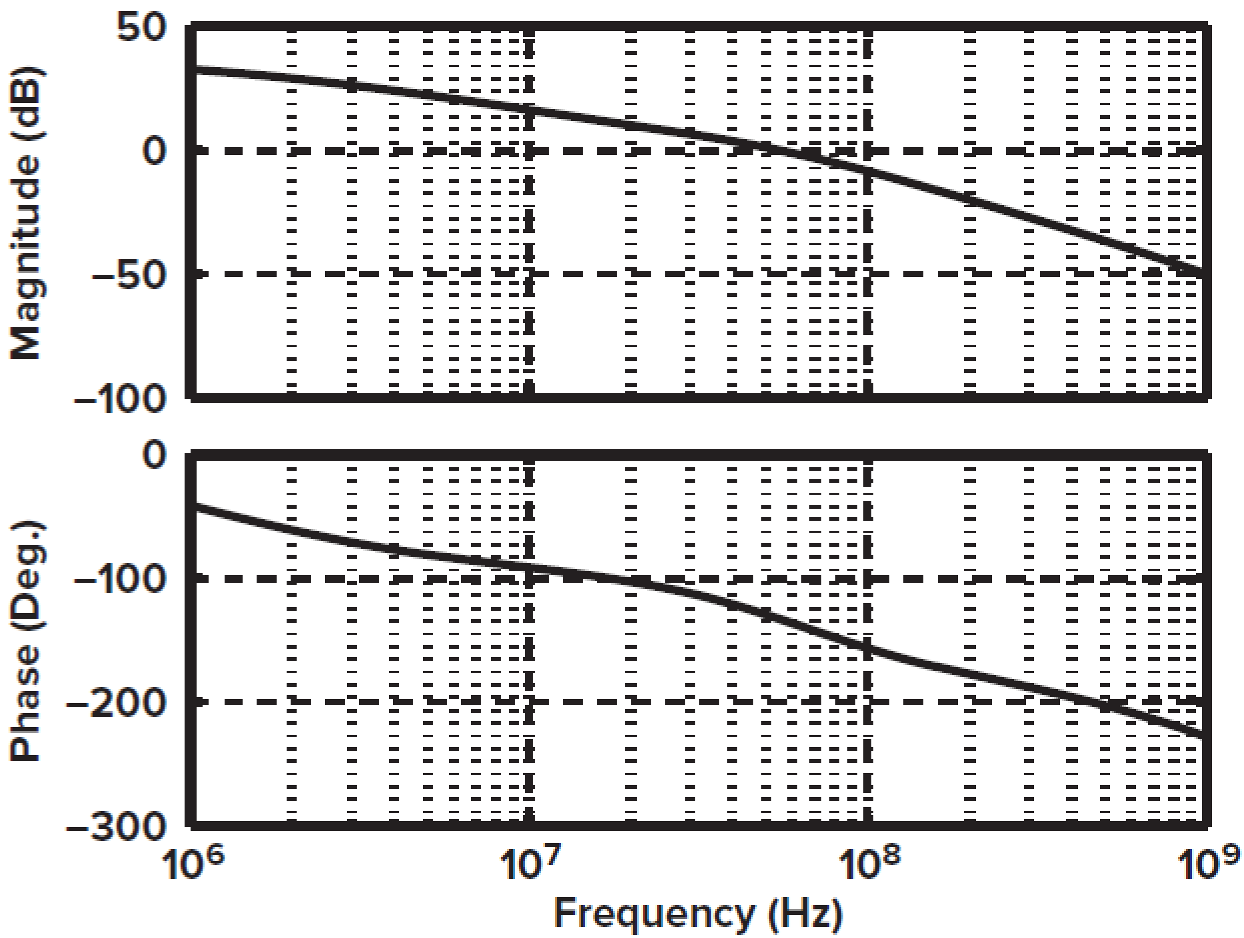
- PM = -10°
- Note the CMFB loop does not require very high gain



[Razavi, 2017]

CMFB Loop Stability

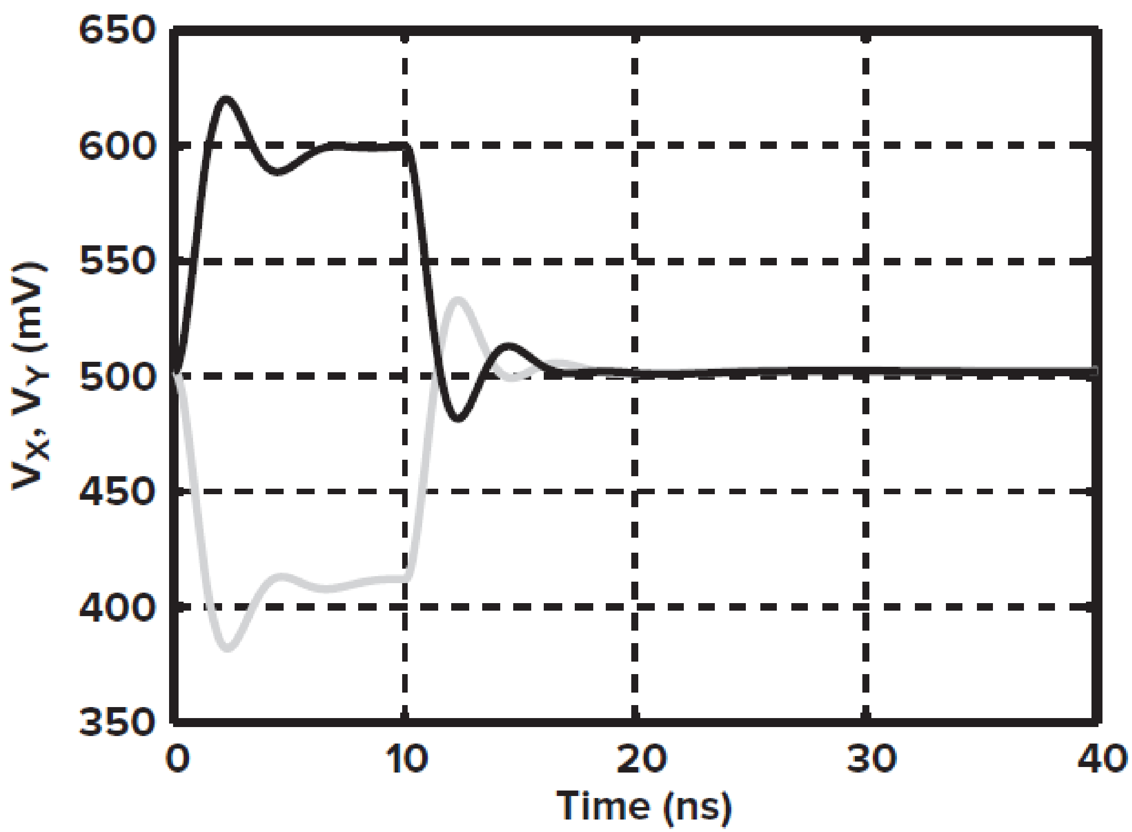
- Add 3pF to the error amplifier output → PM = 50°



[Razavi, 2017]

CMFB Loop Stability

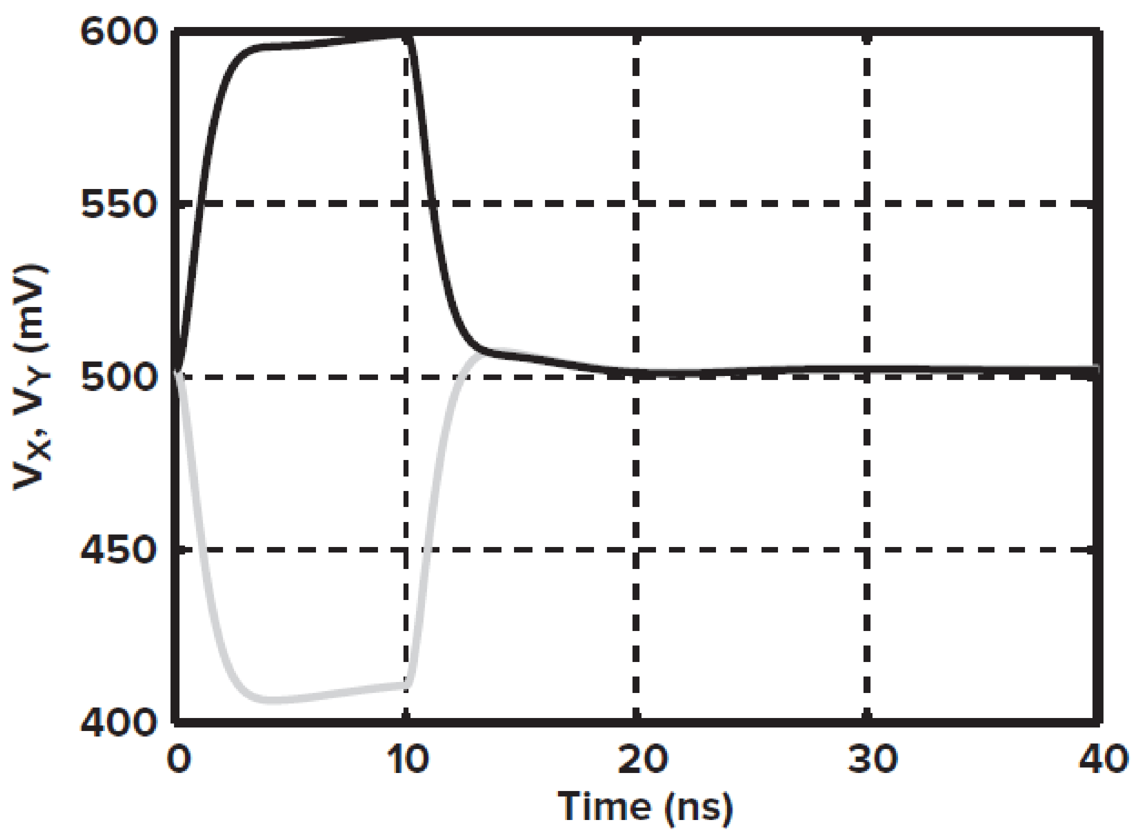
- Transient analysis repeated → CMFB loop is stable
- But there is differential ringing?



[Razavi, 2017]

CMFB Loop Stability

- The feedback resistance and the OTA input cap add a pole
- Fixed by adding small cap parallel with the large feedback resistance (usually required when using large feedback res)

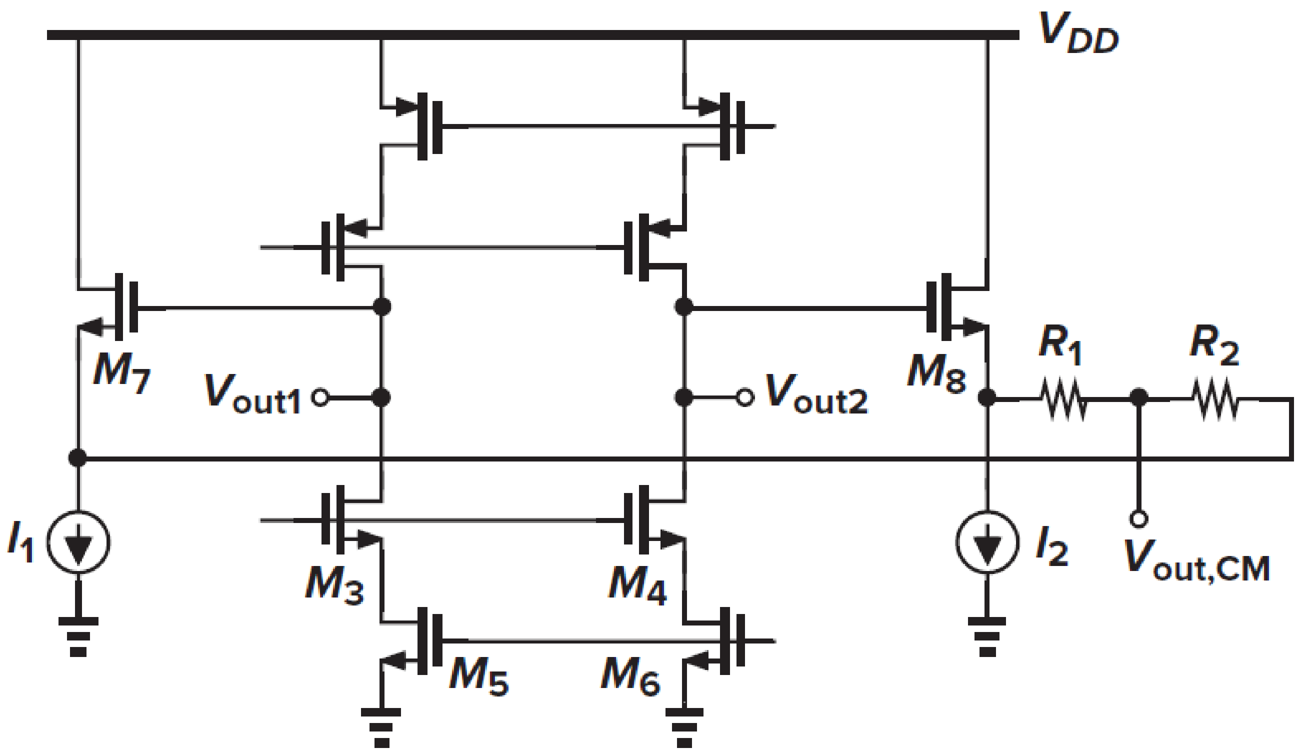


[Razavi, 2017]

Thank you!

CM Sensing: Source Followers

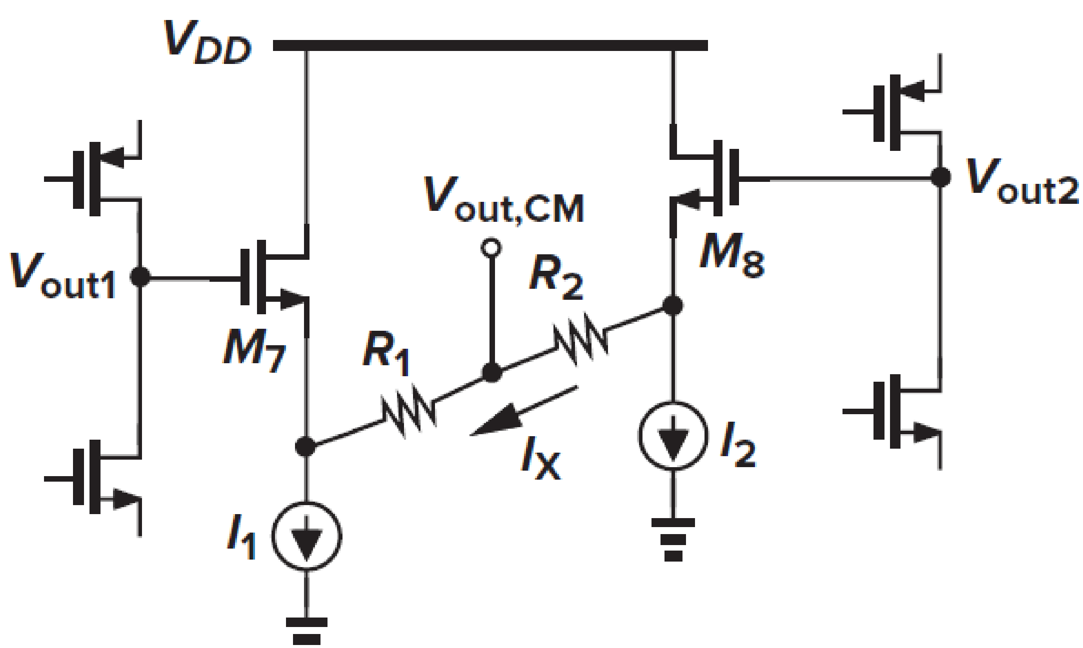
- Voltage shift can be taken into account in the comparison step



[Razavi, 2017]

CM Sensing: Source Followers

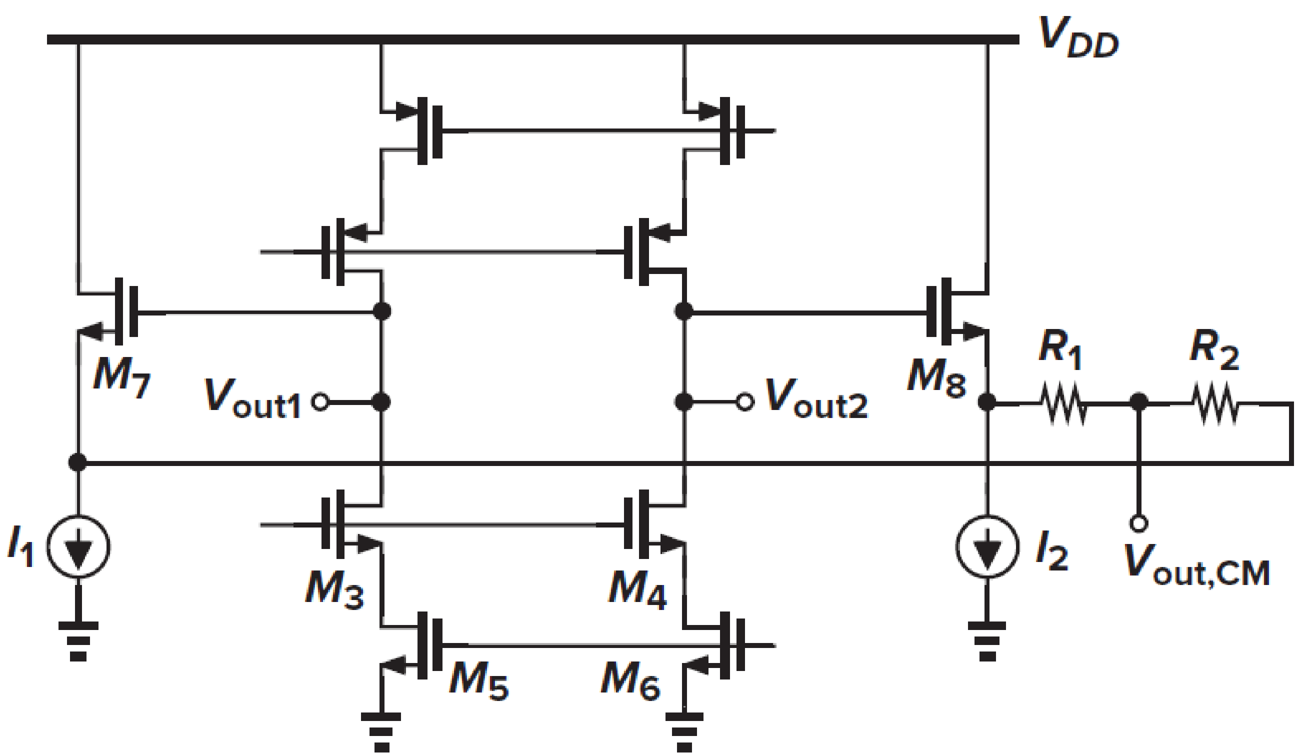
- R1 and R2 or I1 and I2 must be large enough to ensure that M7 or M8 is not "starved" when a large differential swing appears at the output
- If Vout2 >> Vout1
  - I1 must sink both IX ≈ (Vout2 − Vout1)/(R1 + R2) and ID7.
  - If R1 + R2 or I1 is not sufficiently large: ID7 drops to zero



[Razavi, 2017]

CM Sensing: Source Followers

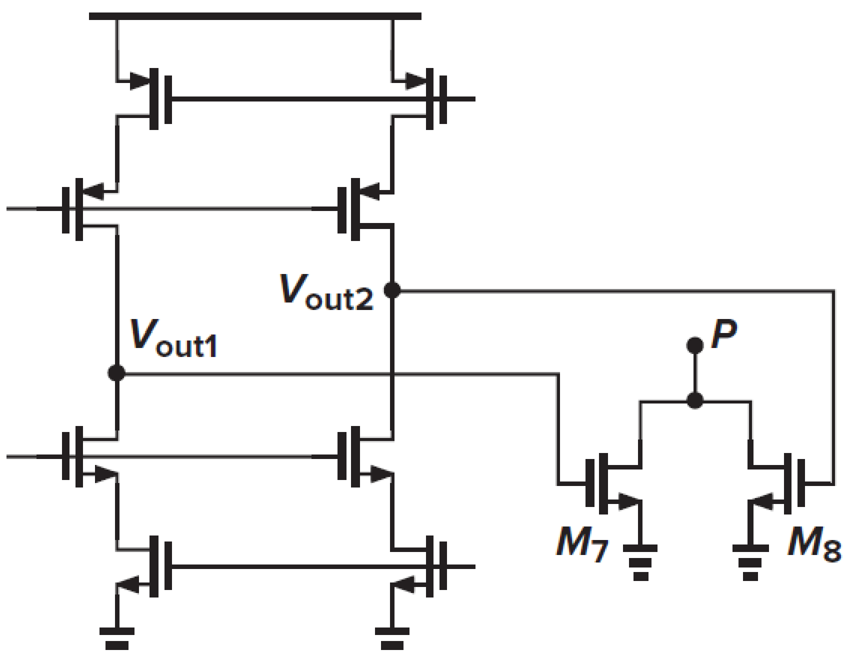
- Output swing is reduced
  - Without CMFB: $V_{out,min} = V_{ov3} + V_{ov5}$
  - With CMFB: $V_{out,min} = V_{TH} + V_{ov7} + V_{I1}$



[Razavi, 2017]

CM Sensing: Deep Triode

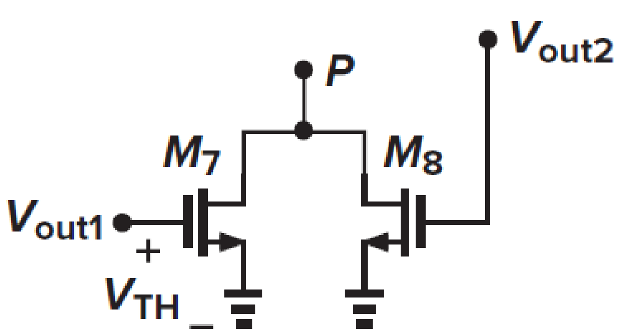
$$
\begin{aligned}
R_{tot} &= R_{on7} \| R_{on8} \\
&= \frac{1}{\mu_n C_{ox} \frac{W}{L}(V_{out1} - V_{TH})} \Bigg\| \frac{1}{\mu_n C_{ox} \frac{W}{L}(V_{out2} - V_{TH})} \\
&= \frac{1}{\mu_n C_{ox} \frac{W}{L}(V_{out2} + V_{out1} - 2V_{TH})}
\end{aligned}
$$



[Razavi, 2017]

CM Sensing: Deep Triode

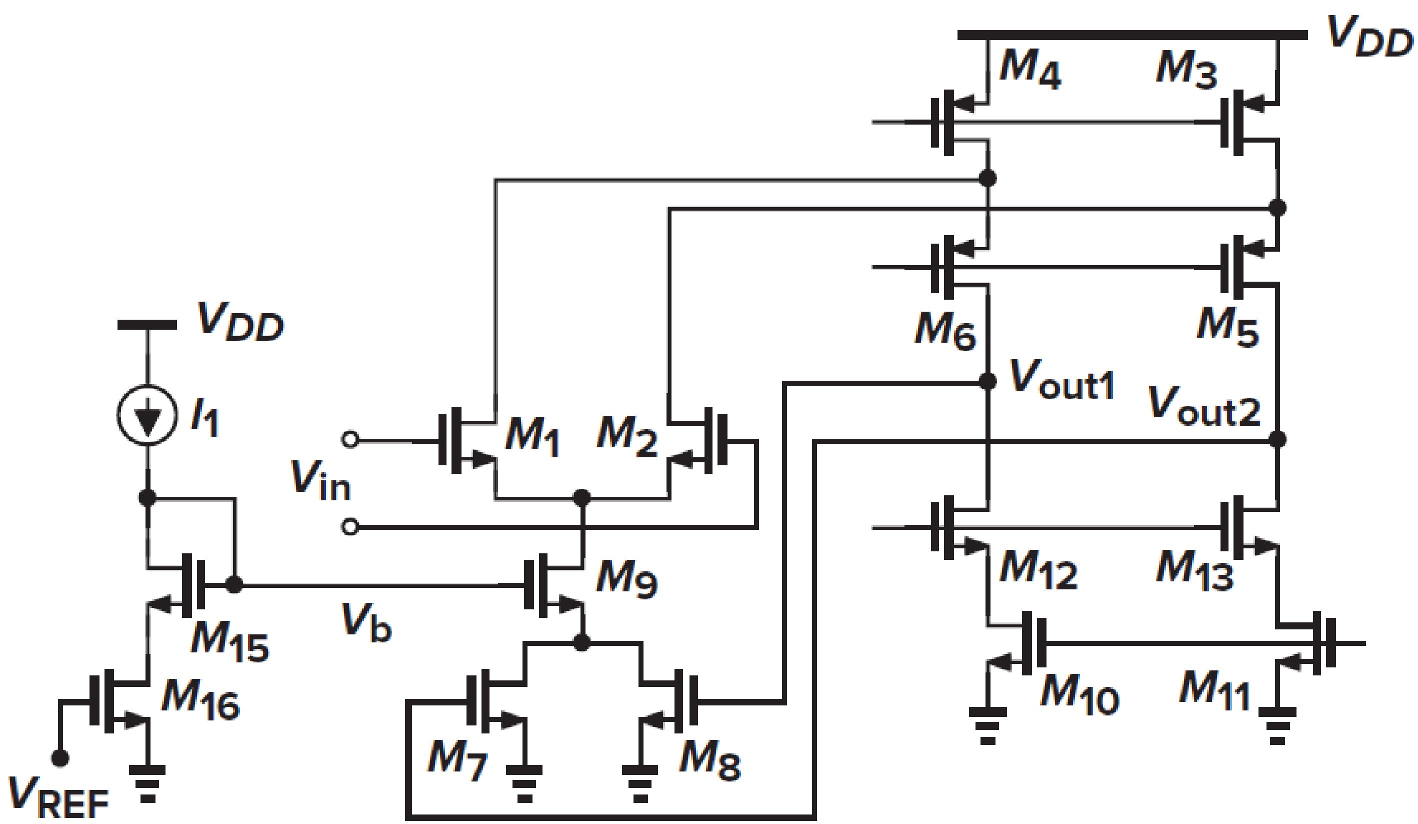
- If the assumption of deep triode is invalid, R_{tot} will be function of the individual values of V_{out1} and V_{out2}
  - If V_{out1} approaches V_{TH} (V_{ov} is very small) M7 will enter sat
  - CM sensing becomes nonlinear and dependent on the individual values of V_{out1} and V_{out2}



[Razavi, 2017]

CMFB Techniques

- Sensing by deep triode devices
- $(W/L)_{15} = (W/L)_9$ and $(W/L)_{16} = (W/L)_7 + (W/L)_8$
- $I_{D9} = I_{D15}$ if $V_{out,CM} = V_{REF}$



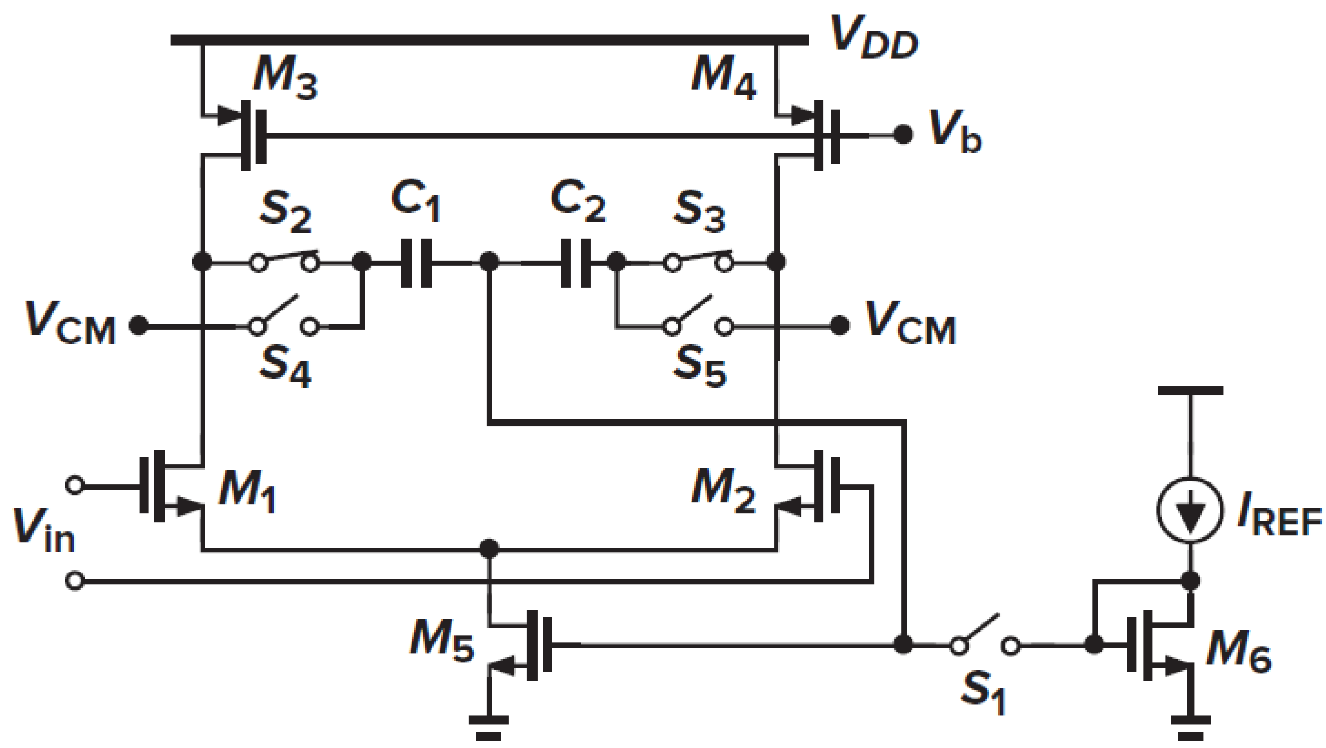
[Razavi, 2017]

Continuous Time vs Discrete Time CMFB

- Resistive sensing → Low voltage gain
- Source followers or deep triode → Limited linear range
- All the previous techniques are continuous-time CMFB circuits
- Designing continuous-time (CT) CMFB circuits that are both linear and operate with low power-supply voltages is not an easy task
  - Actually it is an area of continuing research!
- Another technique that is currently very popular is using switched-capacitor circuits
  - But the circuit must be refreshed periodically
  - Suitable for discrete time switched-capacitor circuits
    - Discrete time (DT) CMFB

Switched Capacitor CMFB

- Reset phase: S1, S4, and S5 close
  - Capacitor charged to $V_{CM} - V_{GS6}$
- Amplification phase: S2 and S3 close
  - $V_{outCM} = V_C + V_{GS5} = V_{CM} - V_{GS6} + V_{GS5} \approx V_{CM}$



[Razavi, 2017]