EE223 Analog Integrated Circuits
Fall 2018

Lecture 19: OTA

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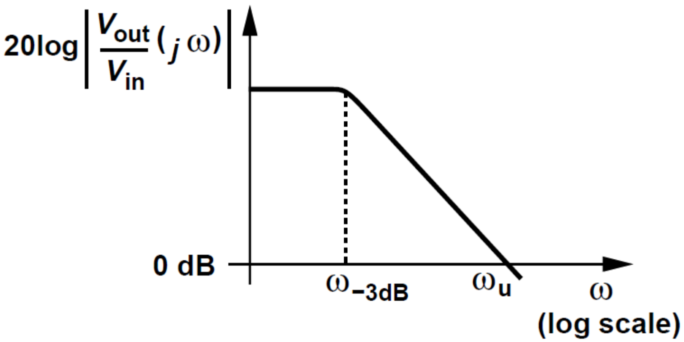
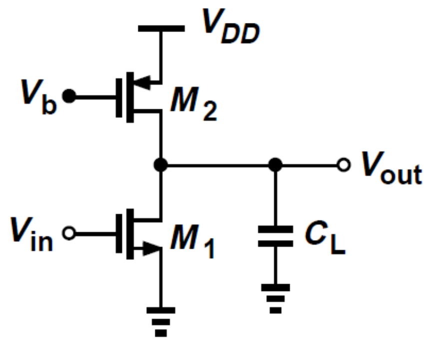
ENG-259

Amplifier Gain-Bandwidth Trade-Offs



- We wish to maximize both the gain and the bandwidth of amplifiers.
- we are interested in both the 3-dB bandwidth, ω_{-3dB} , and the "unity-gain" bandwidth, ω_u.

One Pole Circuit



$$A_V(s) = \frac{V_{out}}{V_{in}} = \frac{A_0}{1 + \frac{s}{\omega_p}}$$

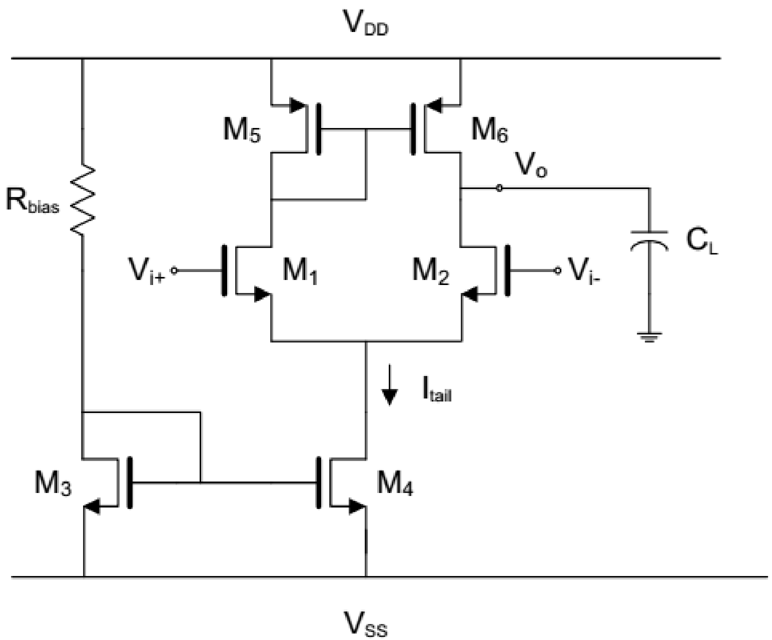
- Gain Bandwidth product

$$\begin{aligned} \mathrm{GBW} &= A_0\omega_p \\ &= g_{m1}(r_{O1}||r_{O2}) \frac{1}{2\pi(r_{O1}||r_{O2})C_L} \\ &= \frac{g_{m1}}{2\pi C_L} \end{aligned}$$

- Unity Gain Bandwidth

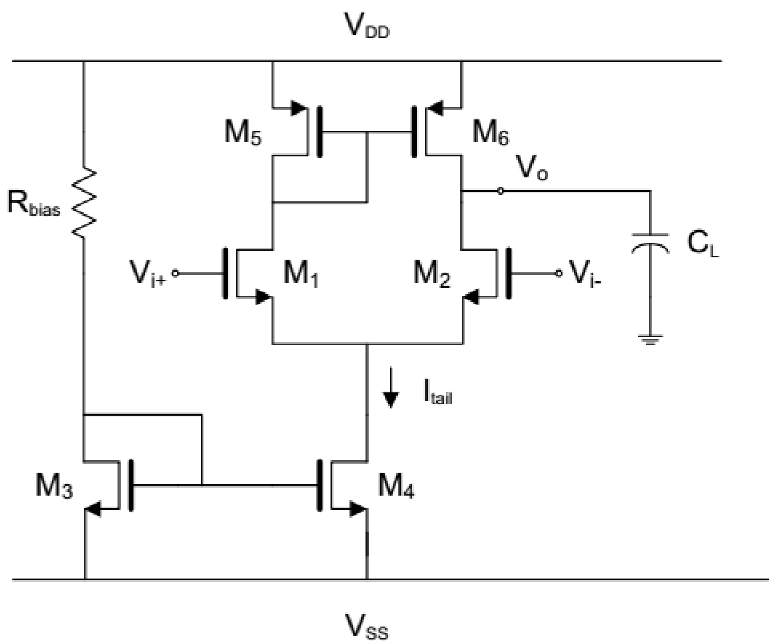
$$\frac{A_0}{\sqrt{1+(\frac{\omega_u}{\omega_p})^2}} = 1 \longrightarrow \omega_u = \sqrt{A_0^2 - 1}\omega_p \approx A_0\omega_p$$

Operational Transconductance Amplifiers (OTA)



- Important Parameters
  - Differential Gain
  - Gain-Bandwidth Product
  - Common-Mode Input Range
  - Common-Mode Gain
  - Common-Mode Rejection Ratio (CMRR)
  - Power-Supply Rejection Ratio (PSRR)
  - Slew Rate

OTA Differential Gain



$$\text{Let } V_{i+} = \frac{v_{id}}{2} \text{ and } V_{i-} = -\frac{v_{id}}{2}$$

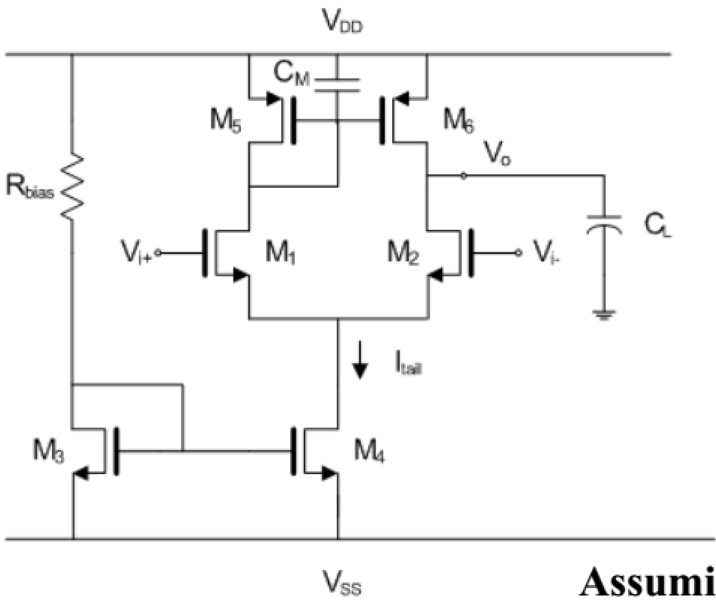
$$v_o = -g_{m2} r_{out}\left(-\frac{v_{id}}{2}\right) - \frac{g_{m1}}{g_{m5}}\left(-g_{m6} r_{out}\right)\left(\frac{v_{id}}{2}\right)$$

$$\text{By design } g_{m1} = g_{m2} \text{ and } g_{m5} = g_{m6}$$

$$v_o = g_{m1} r_{out} v_{id}$$

$$\boxed{A_{DM} = \frac{v_o}{v_{id}} = g_{m1} r_{out} = \frac{g_{m1}}{g_{o6} + g_{o2}}}$$

OTA Gain and Bandwidth



$$A_{DM} = \frac{g_{m1}}{g_{o6} + g_{o2}}$$

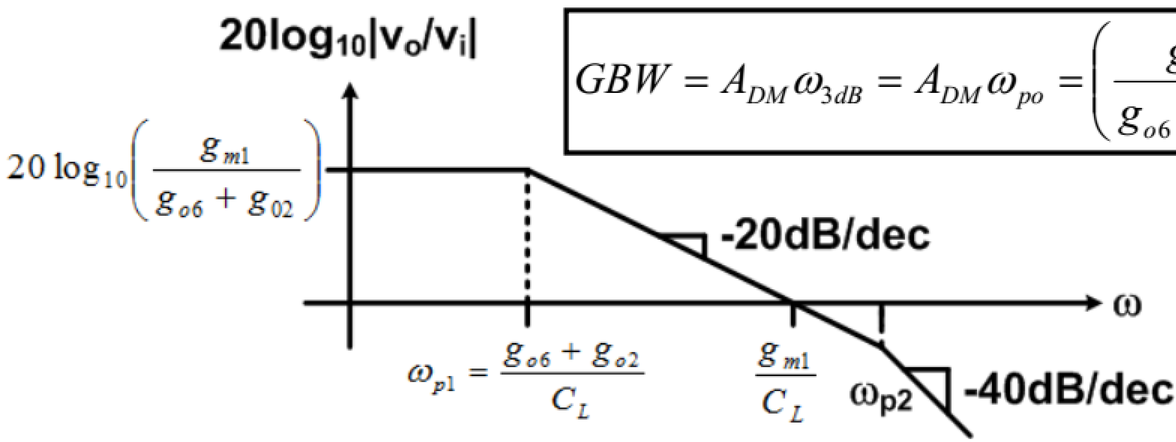
The circuit will have 2 poles

ω_{po} at the output node and ω_{pm} at the "mirror" node

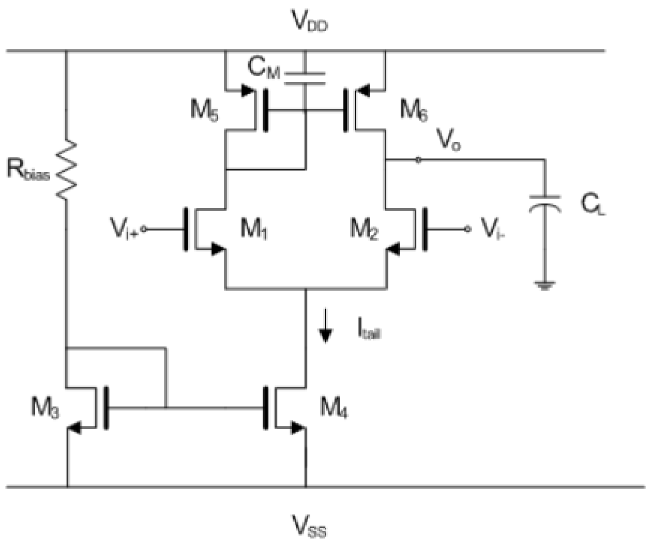
$$\omega_{po} \approx \frac{g_{o6} + g_{o2}}{C_L}, \qquad \omega_{pm} \approx \frac{g_{m5}}{C_M}$$

Assuming the poles are widely spaced and ω_{po} dominates

$$\boxed{GBW = A_{DM}\omega_{3dB} = A_{DM}\omega_{po} = \left(\frac{g_{m1}}{g_{o6} + g_{o2}}\right)\left(\frac{g_{o6} + g_{o2}}{C_L}\right) = \frac{g_{m1}}{C_L}}$$



OTA Common-Mode Input Range



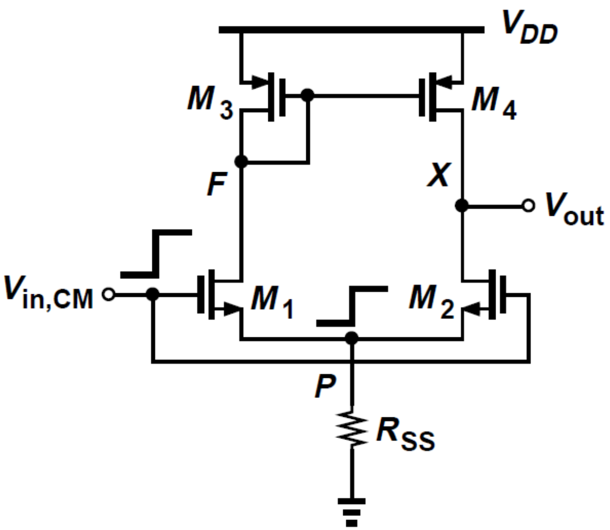
- Common-mode input range set by transistor saturation conditions
  - Low-end set by tail current source saturation

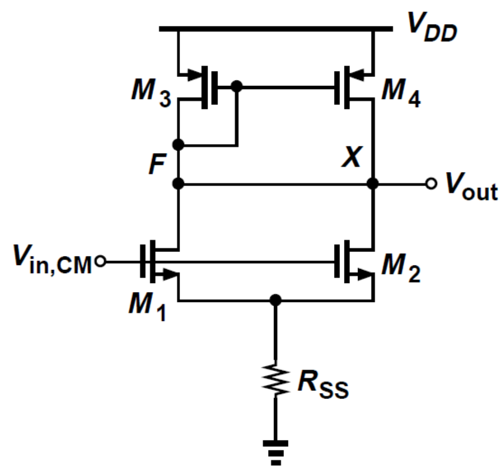
$$V_{icm} \geq V_{SS} + V_{DSAT4} + V_{GS1} = V_{SS} + \sqrt{\frac{2I_{tail}}{\mu_n C_{ox} \frac{W}{L}_4}} + \sqrt{\frac{I_{tail}}{\mu_n C_{ox} \frac{W}{L}_1}} + V_{Tn1}$$

Vicmin = Vgs1 + Vdsat4

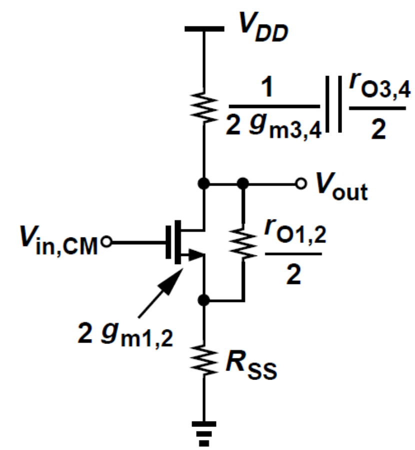
Vicmax – Vgs1 = Vdd – Vgs5 – Vdsat1

Common Mode Properties





(a)



(b)

$$A_{CM} = \frac{\Delta V_{out}}{\Delta V_{in,CM}}.$$

$$A_{CM} \approx \frac{-\dfrac{1}{2g_{m3,4}} \Big\| \dfrac{r_{O3,4}}{2}}{\dfrac{1}{2g_{m1,2}} + R_{SS}}$$

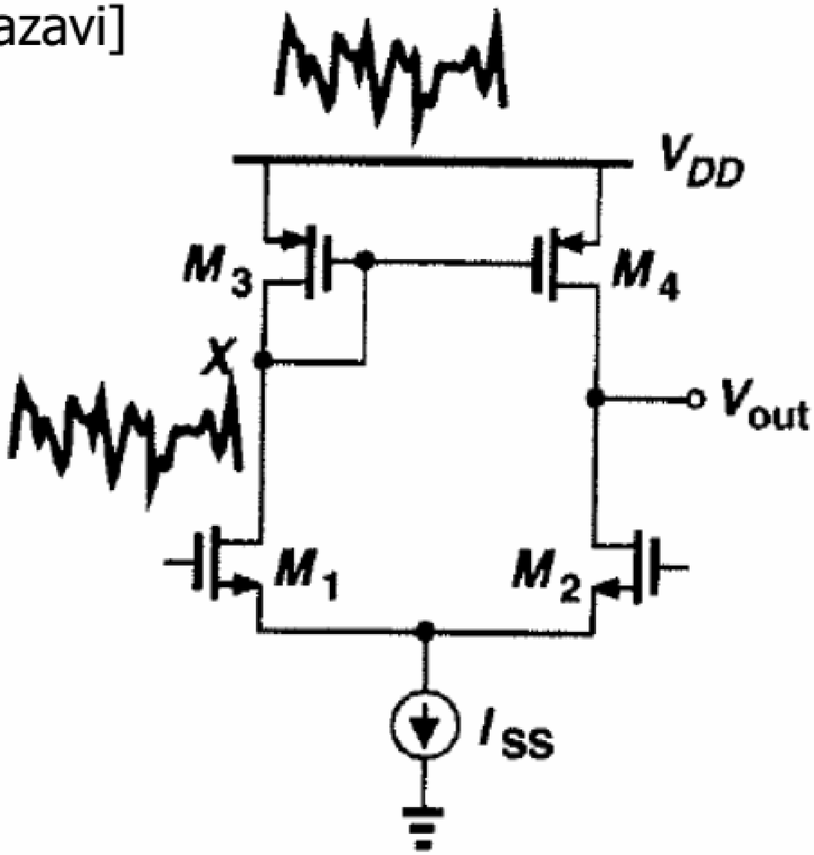
$$= \frac{-1}{1+2g_{m1,2}R_{SS}} \frac{g_{m1,2}}{g_{m3,4}}$$

$$\begin{aligned} CMRR &= \left|\frac{A_{DM}}{A_{CM}}\right| \\ &= g_{m1,2}(r_{O1,2}\|r_{O3,4})\frac{g_{m3,4}(1+2g_{m1,2}R_{SS})}{g_{m1,2}} \\ &= (1+2g_{m1,2}R_{SS})g_{m3,4}(r_{O1,2}\|r_{O3,4}). \end{aligned}$$

- Increase R_{ss} to increase CMRR

OTA Power Supply Rejection Ratio (PSRR)

[Razavi]



$$PSRR^{+} = 20 \cdot \log_{10}\left(\left|\frac{A_{dm}}{v_o / v_{DD}}\right|\right)$$

$$PSRR^{-} = 20 \cdot \log_{10}\left(\left|\frac{A_{dm}}{v_o / v_{SS}}\right|\right)$$

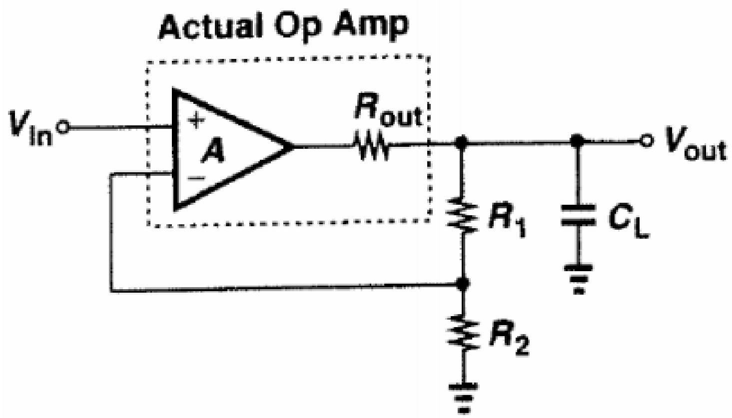
$$A_{dm} = \frac{g_{m1}}{g_{o2} + g_{o4}}$$

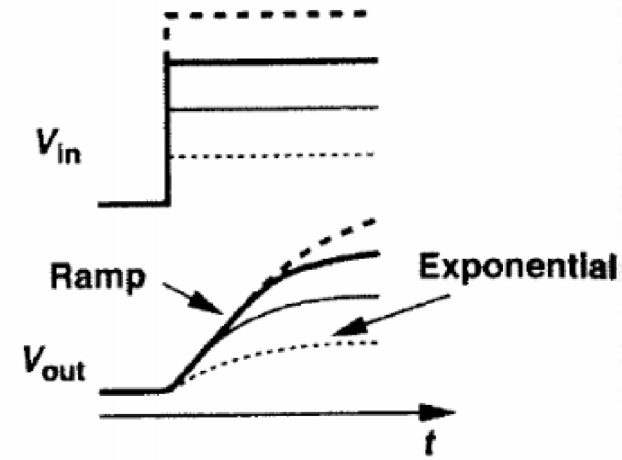
$$A_{vdd} \approx 1$$

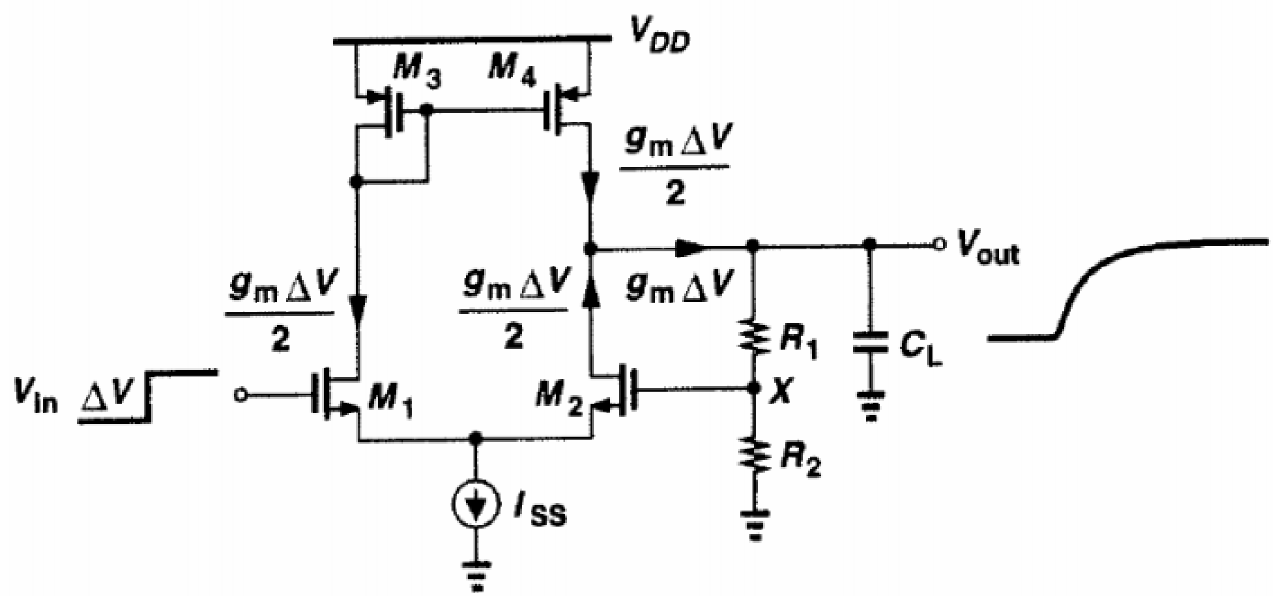
$$PSRR^{+} \approx \frac{g_{m1}}{g_{o2} + g_{o4}}$$

OTA Slew Rate

[Razavi]







OTA Slew Rate

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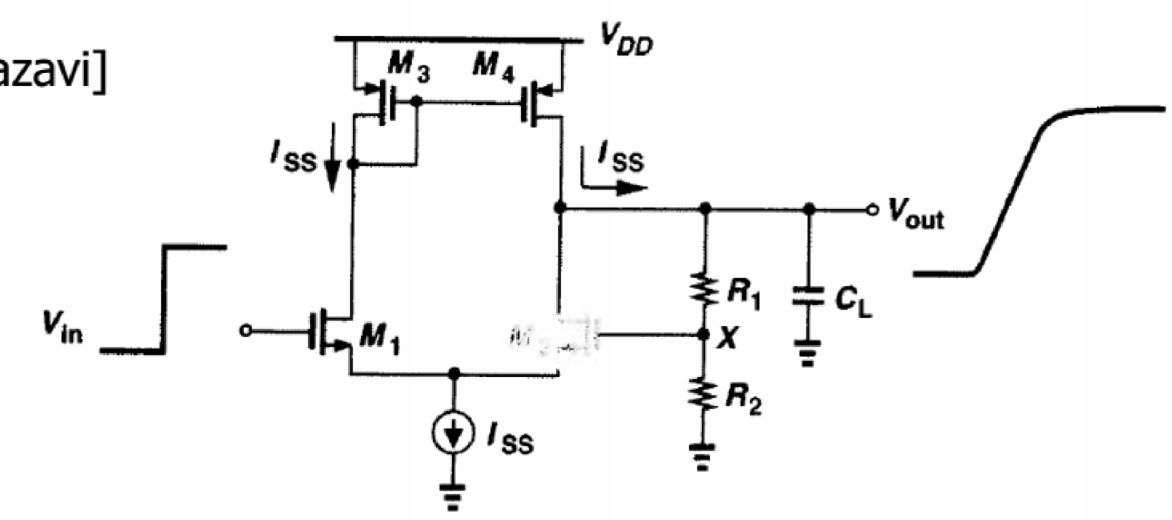
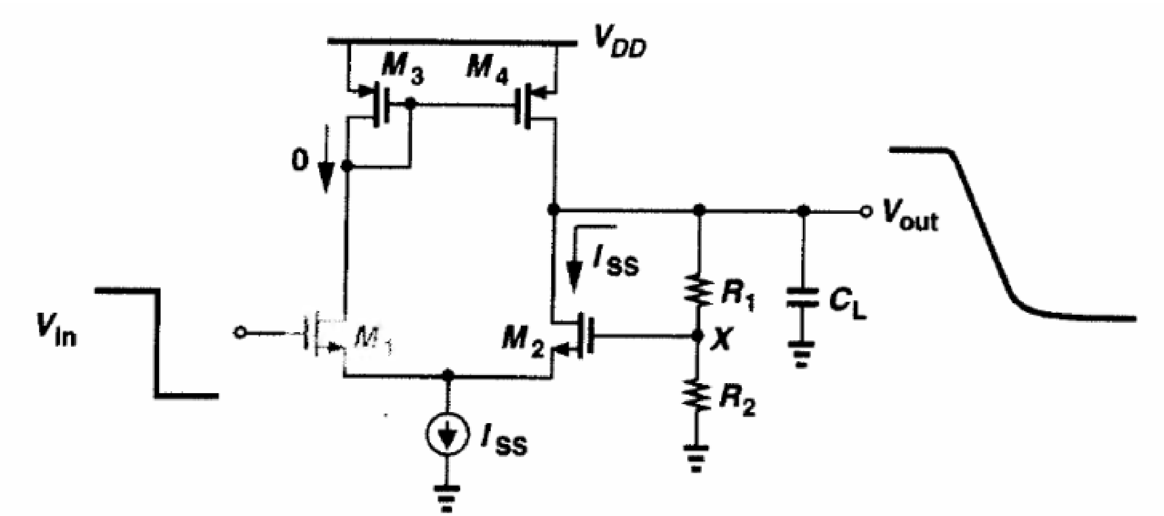
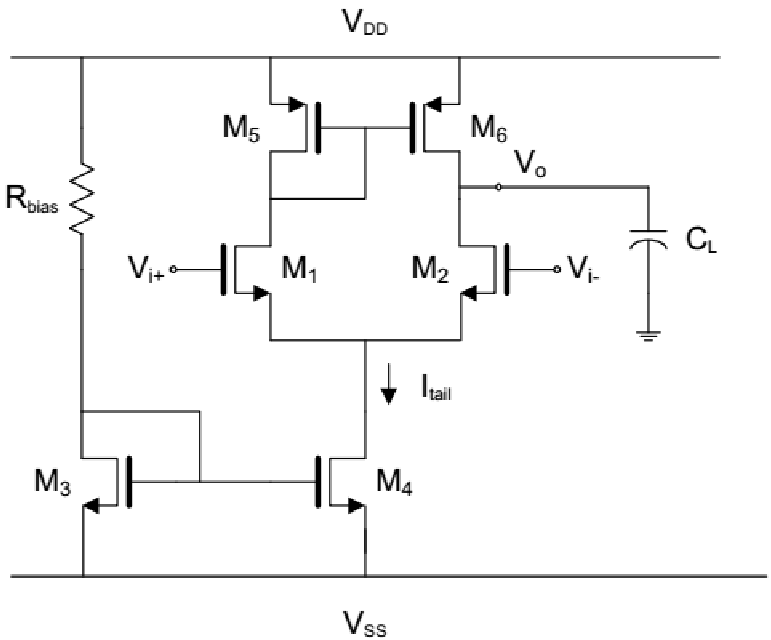




$$\text{Slew Rate} = \frac{I_{SS}}{C_L}$$

Simple OTA Summary



Transconductance $G_m = g_{m1} = \sqrt{KP_n \frac{W}{L}_1 I_{TAIL}}$

Output Conductance $g_{out} = g_{o2} + g_{o6} = \frac{I_{TAIL}}{2}\left(\lambda_n + \lambda_p\right)$

DC Gain $A_v = G_m R_{out} = \frac{g_{m1}}{g_{o2} + g_{o6}} = \frac{2\sqrt{\frac{KP_n}{I_{TAIL}} \frac{W}{L}_1}}{\lambda_n + \lambda_p}$

Dominant Pole $\omega_{\mathbf{p1}} = \frac{g_{o2} + g_{o6}}{C_L}$

Non-Dominant Pole $\omega_{p2} = \frac{g_{m6}}{C_M} \approx \frac{g_{mg}}{2C_{gs6}}$

Output Noise Current $i_{on}^2 = 2\left(\frac{8}{3}kT\right)\left(g_{m1} + g_{m6}\right)$

Input Noise Voltage $v_{in}^2 = 2\left(\frac{8}{3}kT\right)\left(\frac{1}{g_{m1}}\right)\left(1 + \frac{g_{m6}}{g_{m1}}\right)$

$GBW = \frac{G_m}{C_L} = \frac{\sqrt{KP_n \frac{W}{L}_1 I_{TAIL}}}{C_L}$

Slew Rate $SR = \frac{I_{tail}}{C_L}$