Fundamentals of Microelectronics II

فصل ۱۰- تقویت کننده های تفاضلی

(قسمت دوم- زوج تفاضلی ماسفتی)

Mohammad Ali Mansouri- Birjandi

Majid Ghadrdan

Faculty of Electrical and Computer Engineering
University of Sistan and Baluchestan (USB)

mansouri@ece.usb.ac.ir ,
mamansouri@yahoo.com

Chapter 10 Differential Amplifiers

- 10.3 MOS Differential Pair
- 10.4 Cascode Differential Amplifiers
- 10.5 Common-Mode Rejection
- 10.6 Differential Pair with Active Load

یادآوری ۱–۱: تعریف سیگنال تفاضلی و مشترک

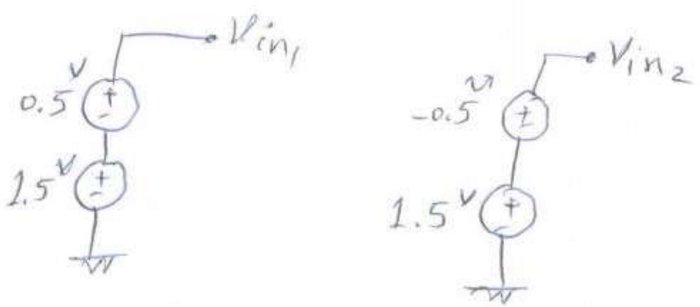
$$\begin{cases} V_{id} \triangleq V_{in_1} - V_{in_2} \\ V_{CM} \triangleq \frac{1}{2}\left(V_{in_1} + V_{in_2}\right) \end{cases}$$

$$\begin{cases} V_{in_1} = V_{CM} + \frac{1}{2} V_{id} \\ V_{in_2} = V_{CM} - \frac{1}{2} V_{id} \end{cases}$$

مثال:

$V_{in_1} = 2^V \quad , \quad V_{in_2} = 1^V$

$$\Rightarrow \begin{cases} V_{CM} = \frac{2+1}{2} = 1.5^V \\ V_{id} = 2 - 1 = 1^V \end{cases} \Longrightarrow$$



یادآوری ۱-۱: ادامه

$$V_{out} = A_d (V_{id}) + A_{cm} V_{cm}$$

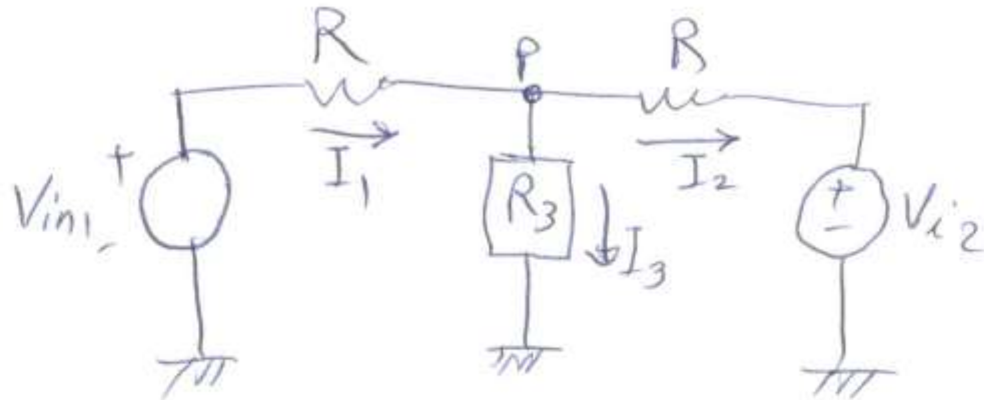
با استفاده از جمع آثار

$$\begin{cases} V_{id} \triangleq V_{in} = V_{in_1} - V_{in_2} \\ V_{cm} \triangleq \frac{1}{2}(V_{in_1} + V_{in_2}) \end{cases}$$

برای حالت ایده‌آل (تقارن کامل و ...) : $\boxed{A_{cM} = 0}$

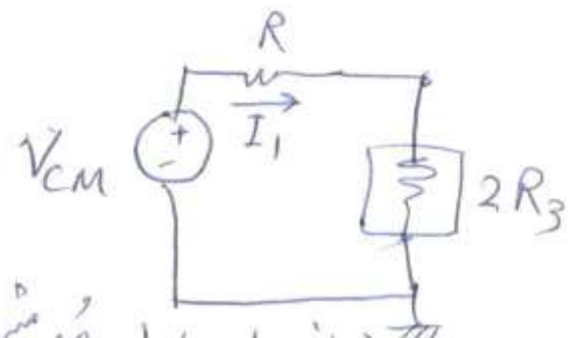
حذف مد مشترک در تقویت کننده تفاضلی

یادآوری ۲: نیم مدار حالت مشترک



اگر : $V_{in1} = V_{in2} = V_{CM}$

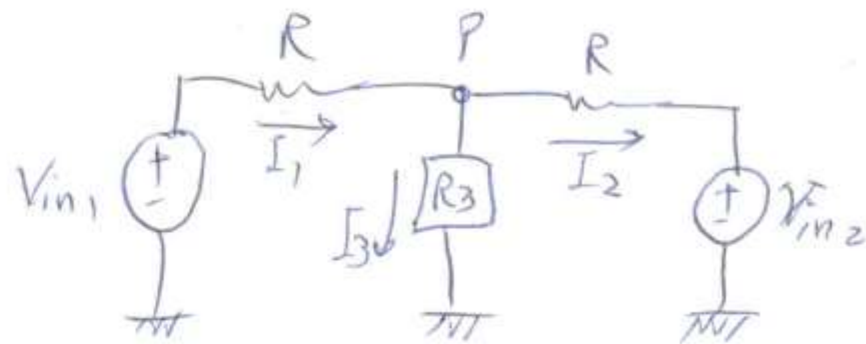
$$\Rightarrow \begin{cases} I_2 = -I_1 \\ I_3 = 2I_1 \end{cases} \Rightarrow$$



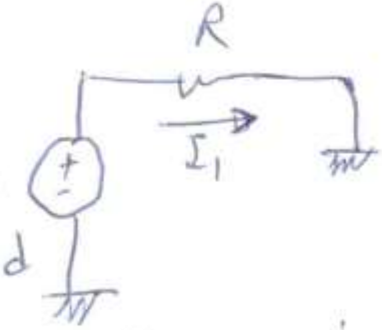
(نیم مدار معادل مُد مشترک)

دانشگاه سیستان و بلوچستان

یادآوری ۳: نیم مدار حالت تفاضلی



اگر: $\begin{cases} V_{in_2} = -V_{in_1} = -\frac{1}{2} V_{id} \\ V_{in_1} = \frac{1}{2} V_{id} \end{cases}$ $\Longrightarrow$ $V_{in_1} = \frac{1}{2} V_{id}$



$\Longrightarrow \begin{cases} I_2 = I_1 \\ I_3 = 0 \end{cases}$ و $\boxed{V_P = 0}$ زمین مجازی

نیم مدار معادل
(مد تفاضلی)

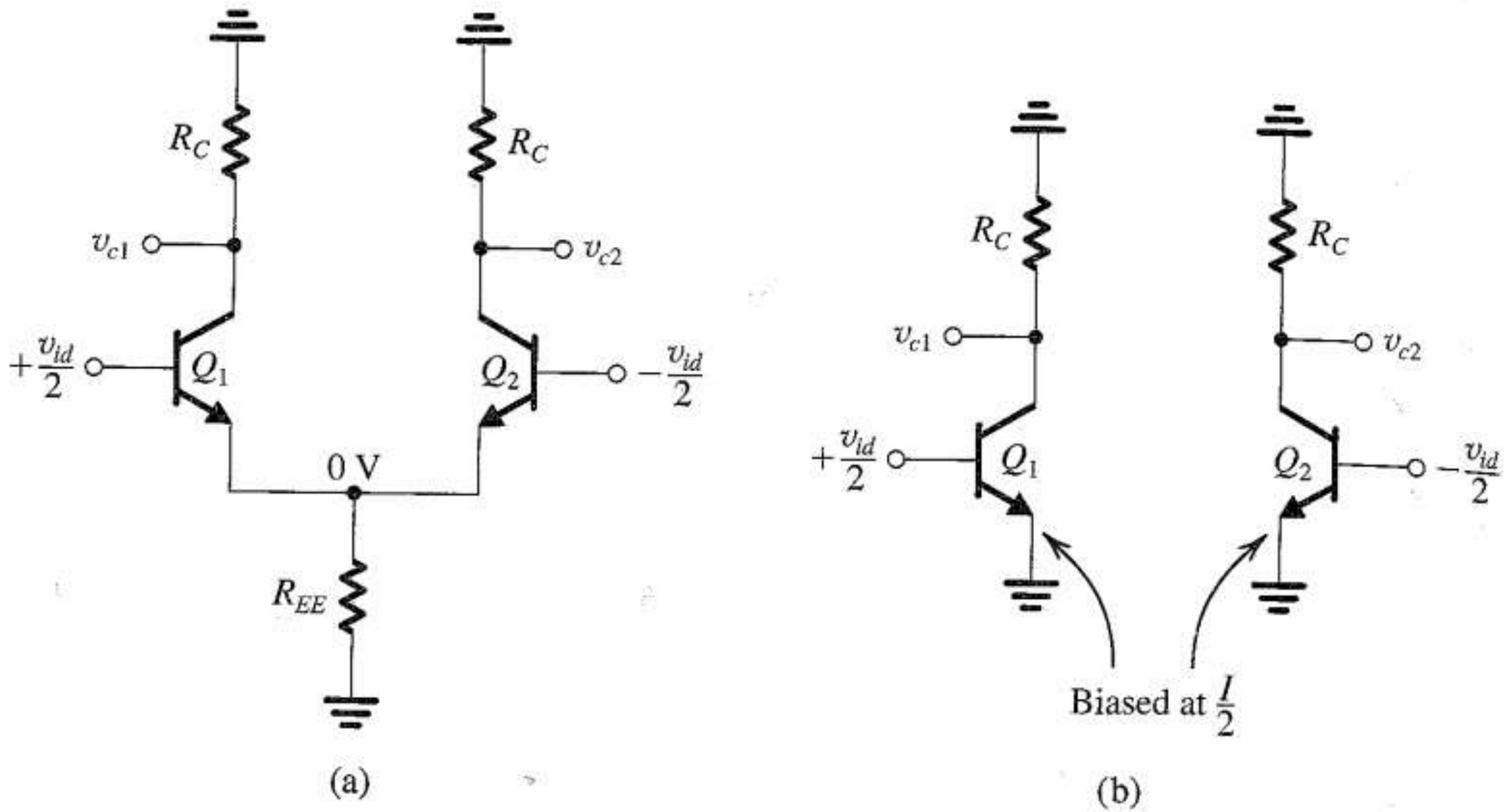
Differential Amplifiers

$$v_{icm} \equiv \frac{v_1 + v_2}{2}$$

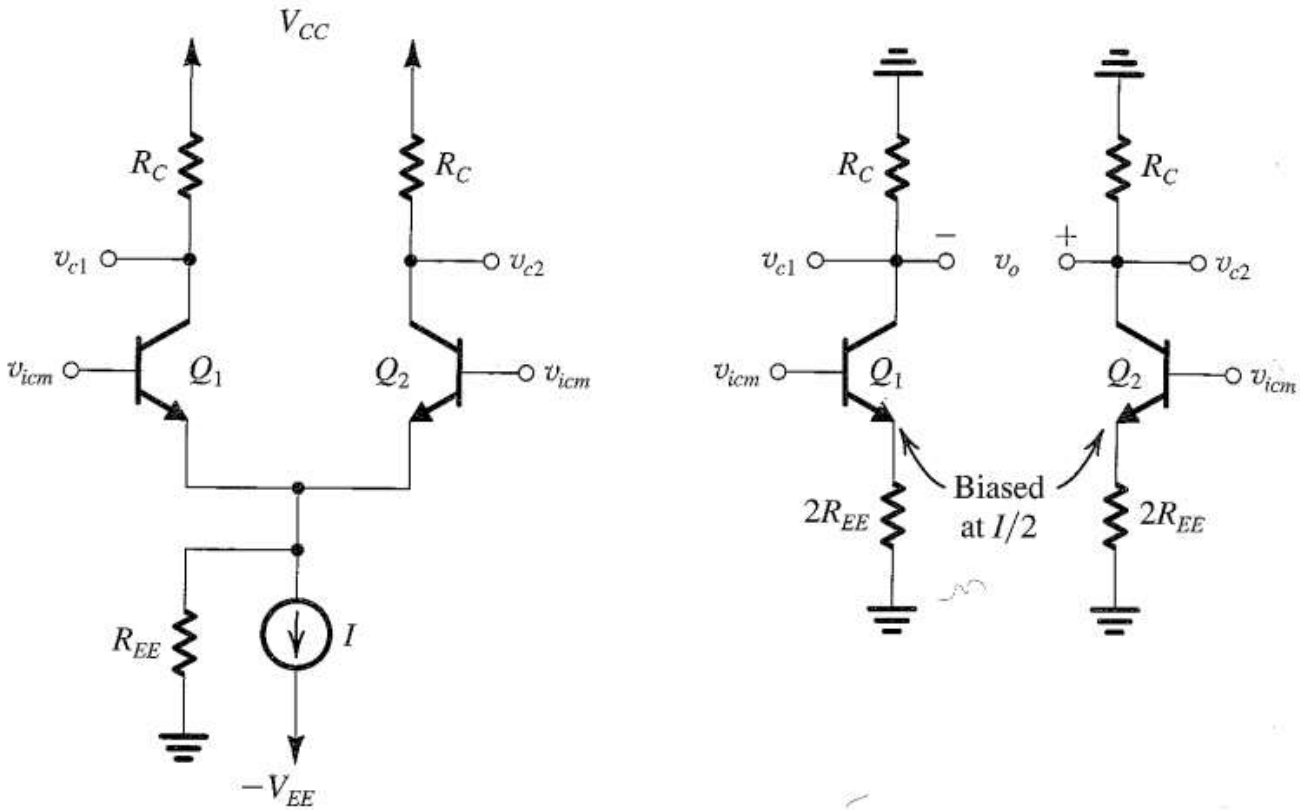
$$v_{id} \equiv v_1 - v_2$$

$$v_o = A_d(v_1 - v_2) + A_{cm}\left(\frac{v_1 + v_2}{2}\right)$$

Differential -Mode



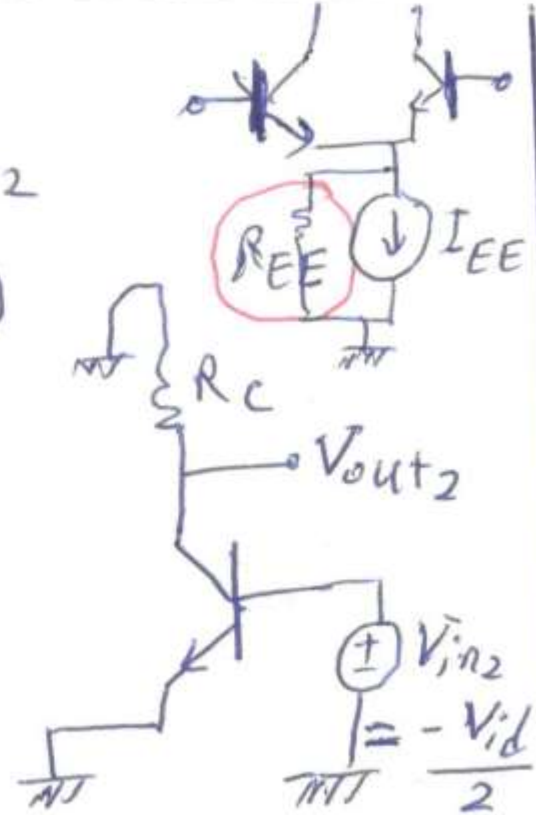
Common-Mode

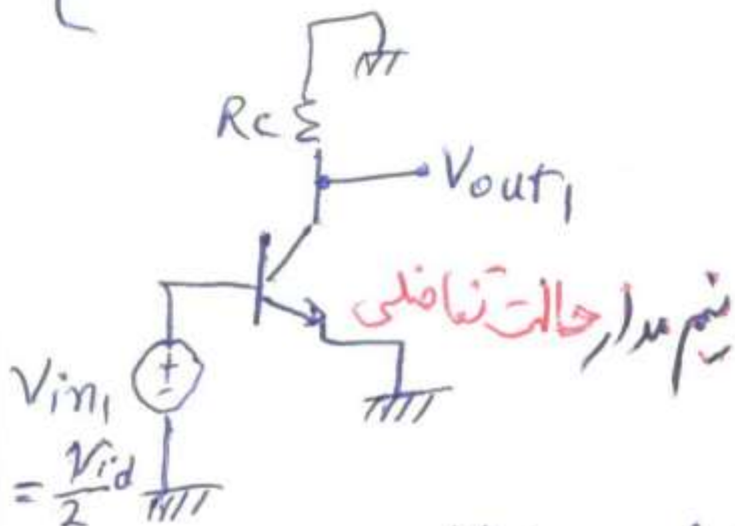


(a) (b)

یادآوری ۴: نیم مدار حالت تفاضلی

$$\begin{cases} V_{in} = V_{id} \triangleq V_{in_1} - V_{in_2} \\ V_{CM} \triangleq \frac{1}{2}\left(V_{in_1} + V_{in_2}\right) \end{cases}$$





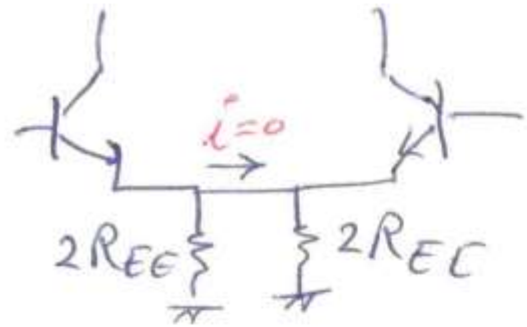
$$\begin{cases} V_{out_1} = -g_m R_C\left(\frac{V_{id}}{2}\right) = -\frac{1}{2} g_m R_C V_{id} \\ V_{out_2} = -V_{out_1} = +\frac{1}{2} g_m R_C V_{id} \end{cases}$$

$$V_{out} \triangleq V_{out_2} - V_{out_1} = g_m R_C V_{id}$$

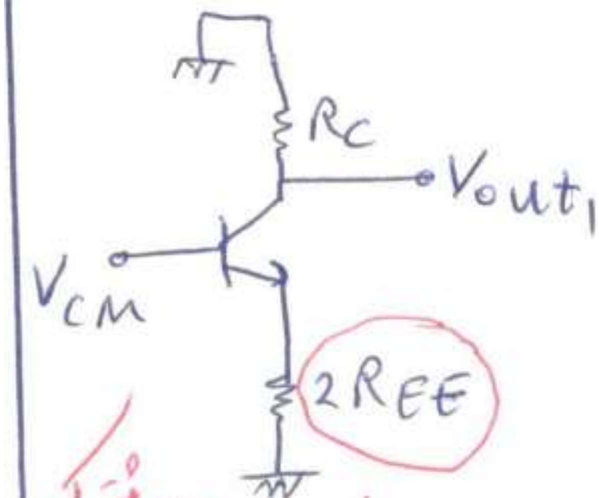
دانشگاه سیستان و بلوچستان

یادآوری ۵: نیم مدار حالت مشترک

برای حالت مشترک :



$V_{in_1} = V_{in_2} = V_{CM}$



نیم مدار حالت مشترک

$$V_{out_1} = V_{out_2} = = \frac{-R_C}{\frac{1}{g_m} + 2R_{EE}} \cdot V_{CM}$$

$$V_{out} \triangleq V_{out_2} - V_{out_1} = 0$$

در حالت مشترک

یادآوری ۶:

شرط سیگنال کوچک برای تقویت کننده تفاضلی BJT

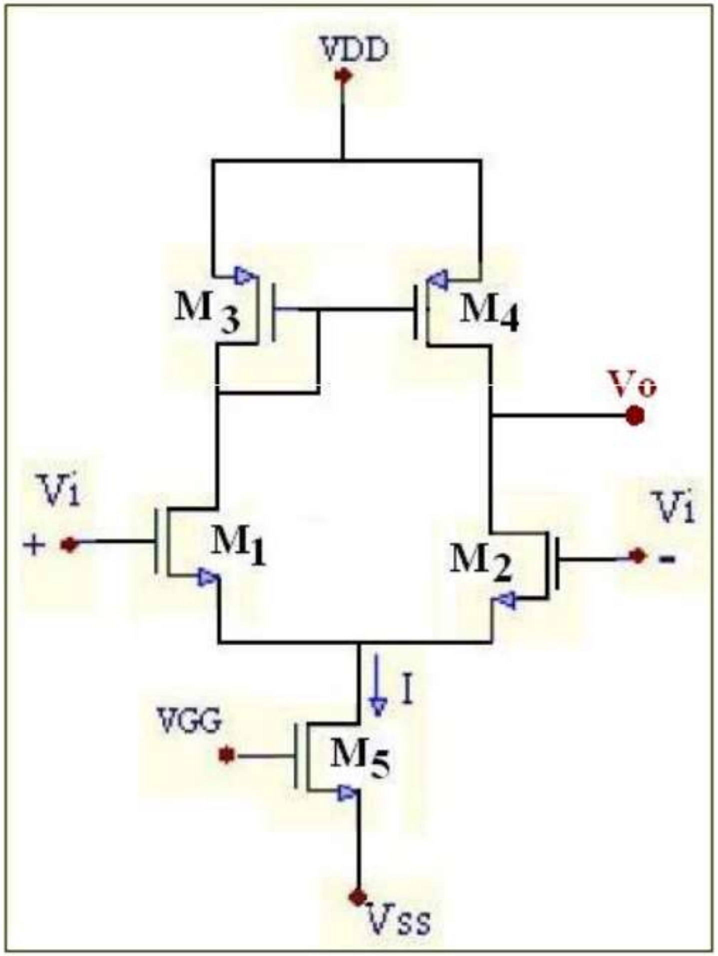
$$\left(\frac{1}{2}v_{id}\right) \ll V_T \Rightarrow \boxed{v_{id} \ll 2V_T}$$

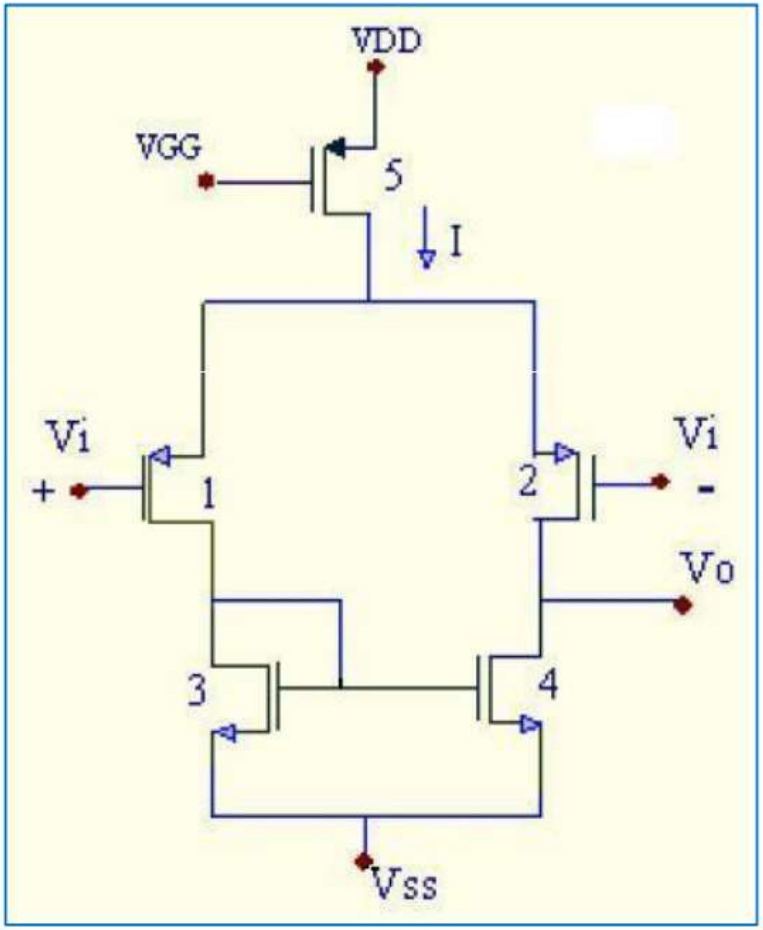
محدوده خطی برای BJT ها خیلی کوچک است.

* حداکثر مقدار ولتاژ حالت مشترک ورودی:

از روی مرز اشباع ترانزیستور بدست می آید.

MOS Differential Amplifier





MOS Differential Amplifier

بدلیل کمتر بودن موبلیتی الکترونها در PMOS، از نظر سرعت کار ترانزیستور، NMOS برتری دارد.

مزیت استفاده از PMOS در ورودی:
کمتر بودن سطح نویز این طبق نسبت به NMOS است.

MOS ها در زوج تفاضلی ورودی، از نظر بزرگ بودن S.R. نسبت به BJT ها یک مزیت است.
از نظر زیاد بودن ولتاژ آفست، برعکس است.

$K' = \mu . C_{ox} \quad K'_n \approx 17, \quad K'_p \approx 8 \quad (\mu A/v^2)$

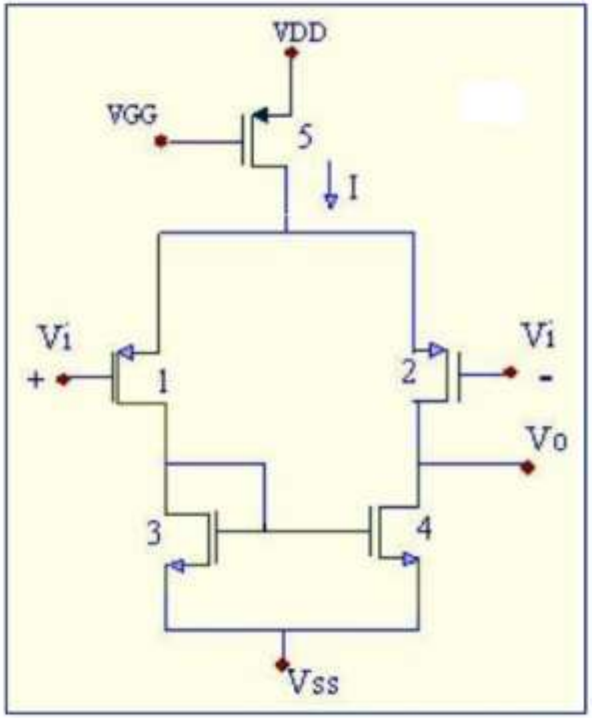
$$r_{out} = r_{ds2} \parallel r_{ds4}$$

$$A_V = \frac{V_O}{V_i} = g_{m1} . r_{out} = g_{m1}(r_{ds2} \parallel r_{ds4})$$

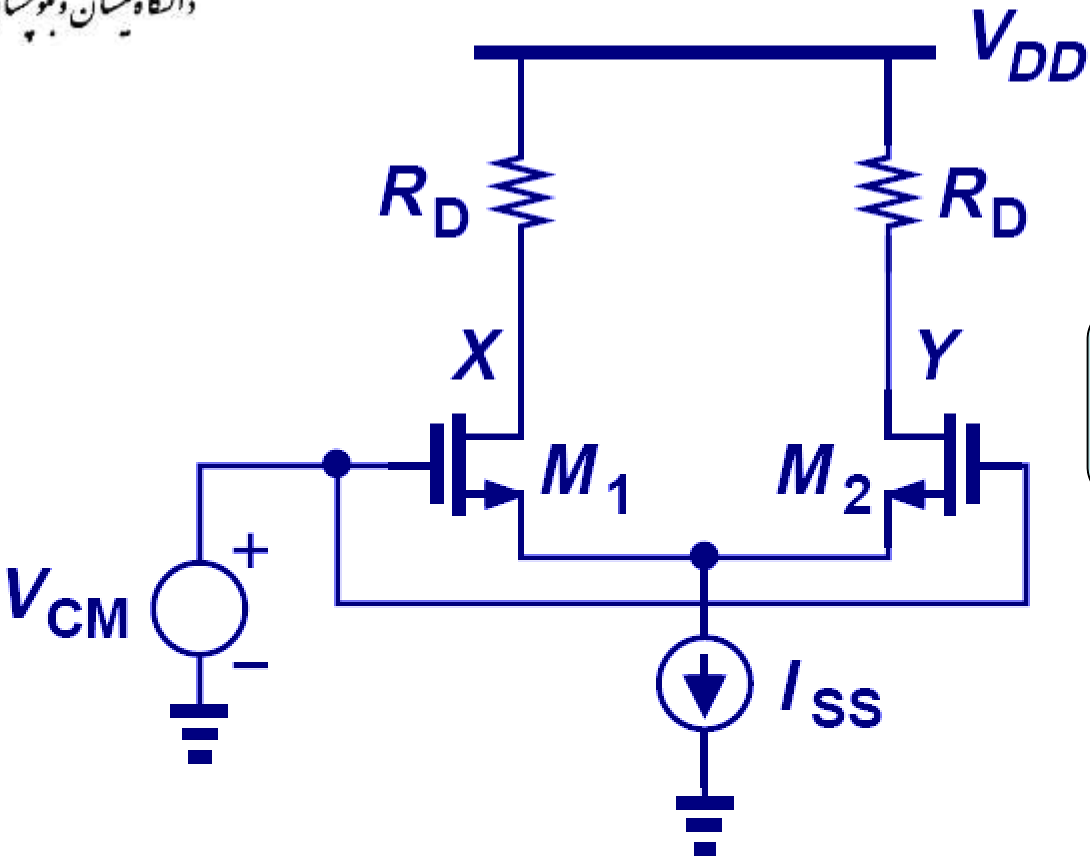
$$CMR = V_i(\max) - V_i(\min)$$

$$V_i(\max) = V_{DD} - V_{SD5}(sat) - |V_{T1}| - \sqrt{\frac{2I_{D1}}{\beta_1}}$$

$$V_i(\min) = V_{SS} + V_{T3} + \sqrt{\frac{2I_{D3}}{\beta_3}} - |V_{T1}|$$



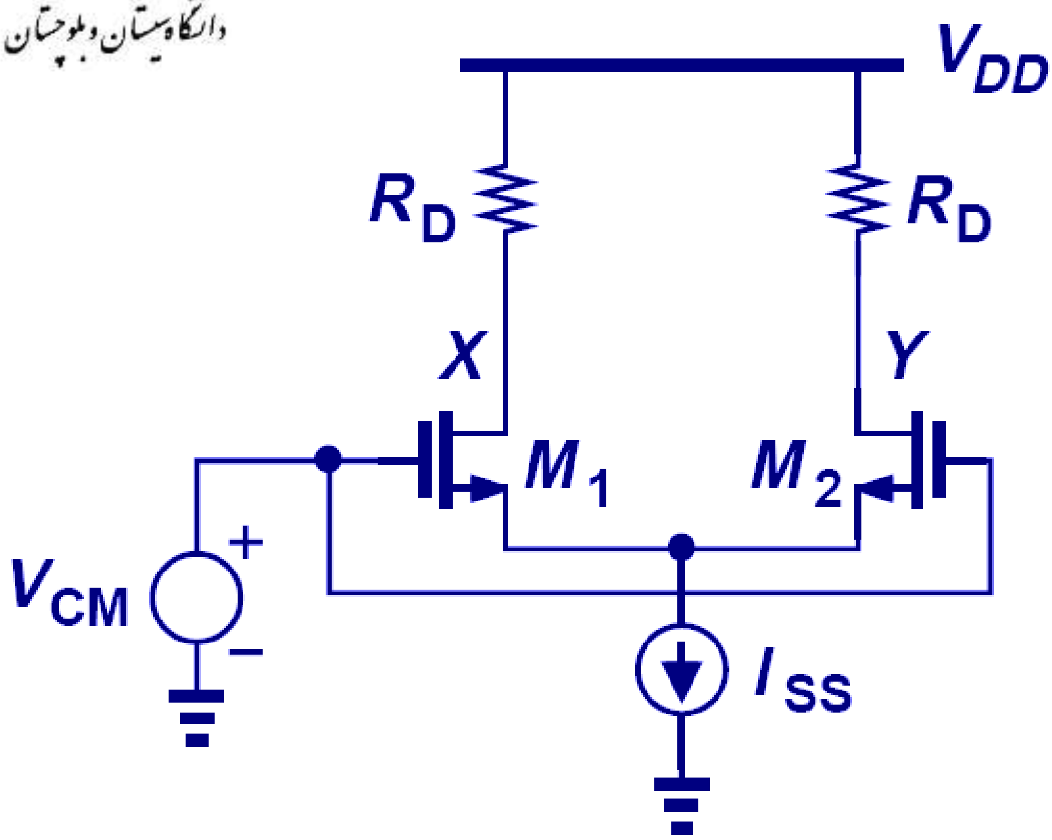
MOS Differential Pair's Common-Mode Response



$$V_X = V_Y = V_{DD} - R_D \frac{I_{SS}}{2}$$

- Similar to its bipolar counterpart, MOS differential pair produces zero differential output as V_{CM} changes.

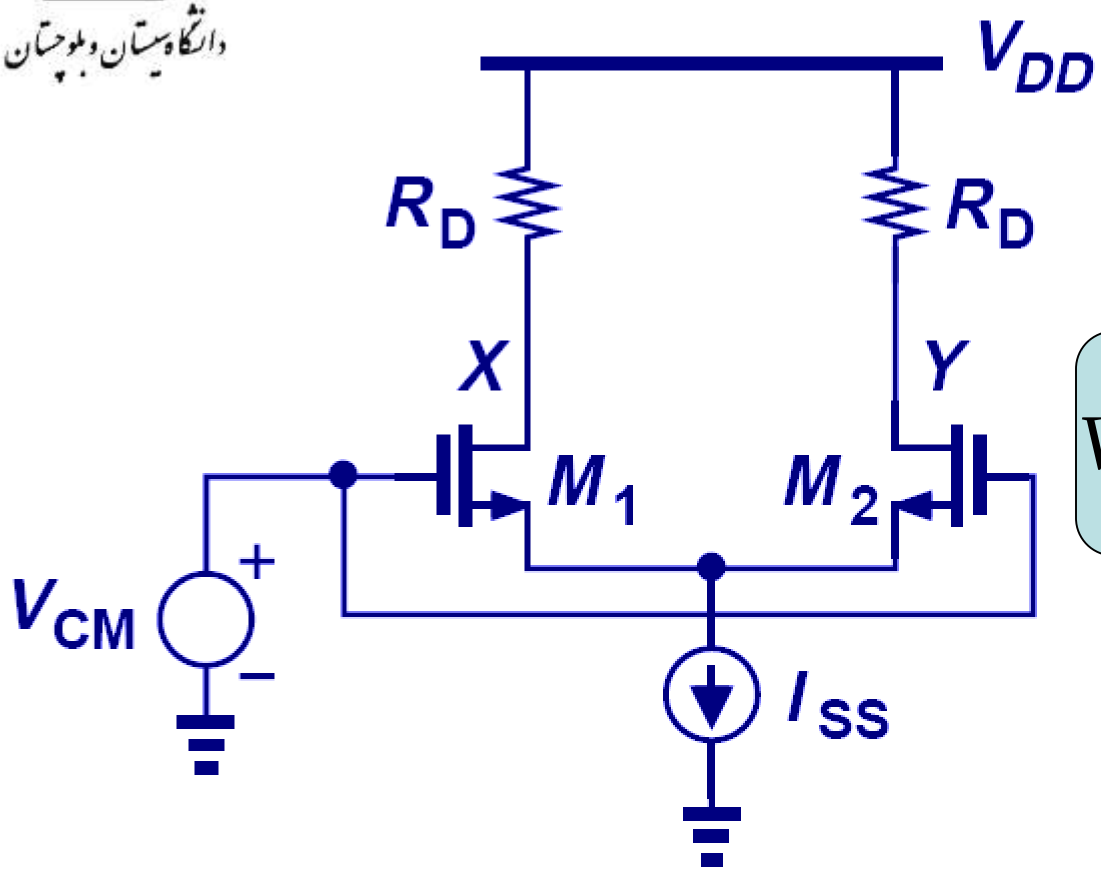
Equilibrium Overdrive Voltage



$$(V_{GS} - V_{TH})_{equil} = \sqrt{\frac{I_{SS}}{\mu_n C_{ox} \frac{W}{L}}}$$

- The equilibrium overdrive voltage is defined as the overdrive voltage seen by M_1 and M_2 when both of them carry a current of $I_{SS}/2$.

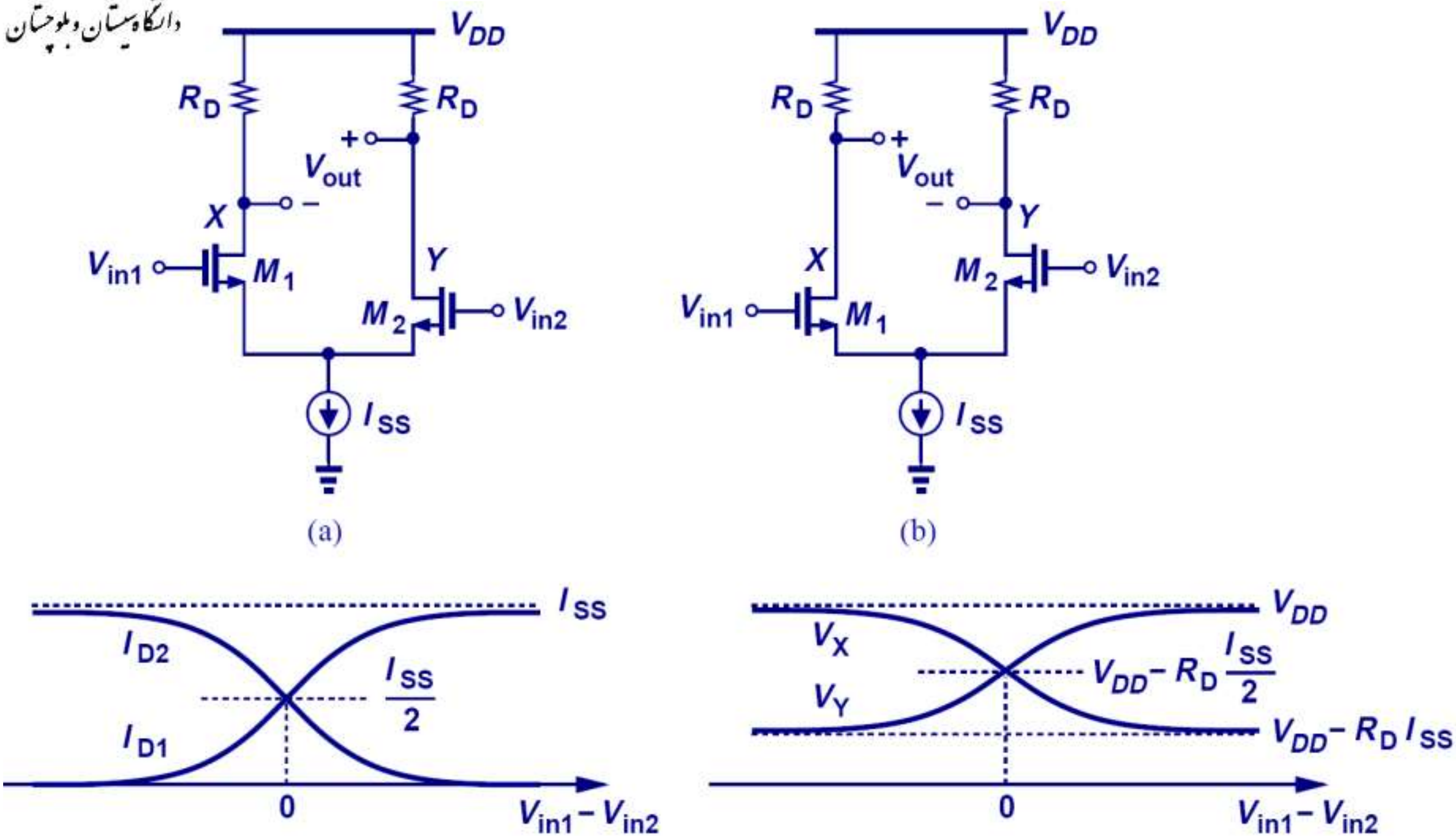
Minimum Common-mode Output Voltage



$$V_{DD} - R_D \frac{I_{SS}}{2} > V_{CM} - V_{TH}$$

- In order to maintain M_1 and M_2 in saturation, the common-mode output voltage cannot fall below the value above.
- This value usually limits voltage gain.

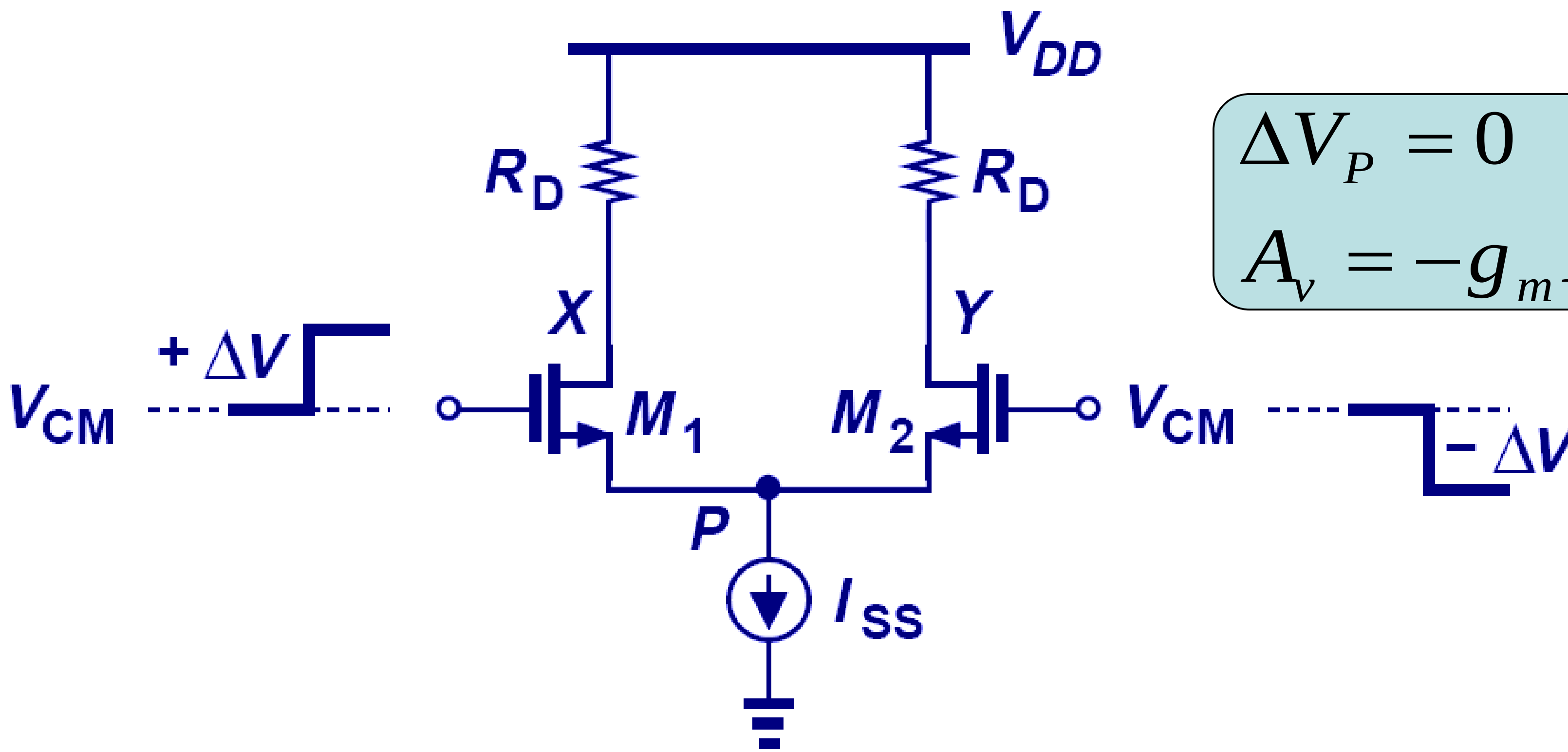
Differential Response



(a) (b)

(c)

Small-Signal Response

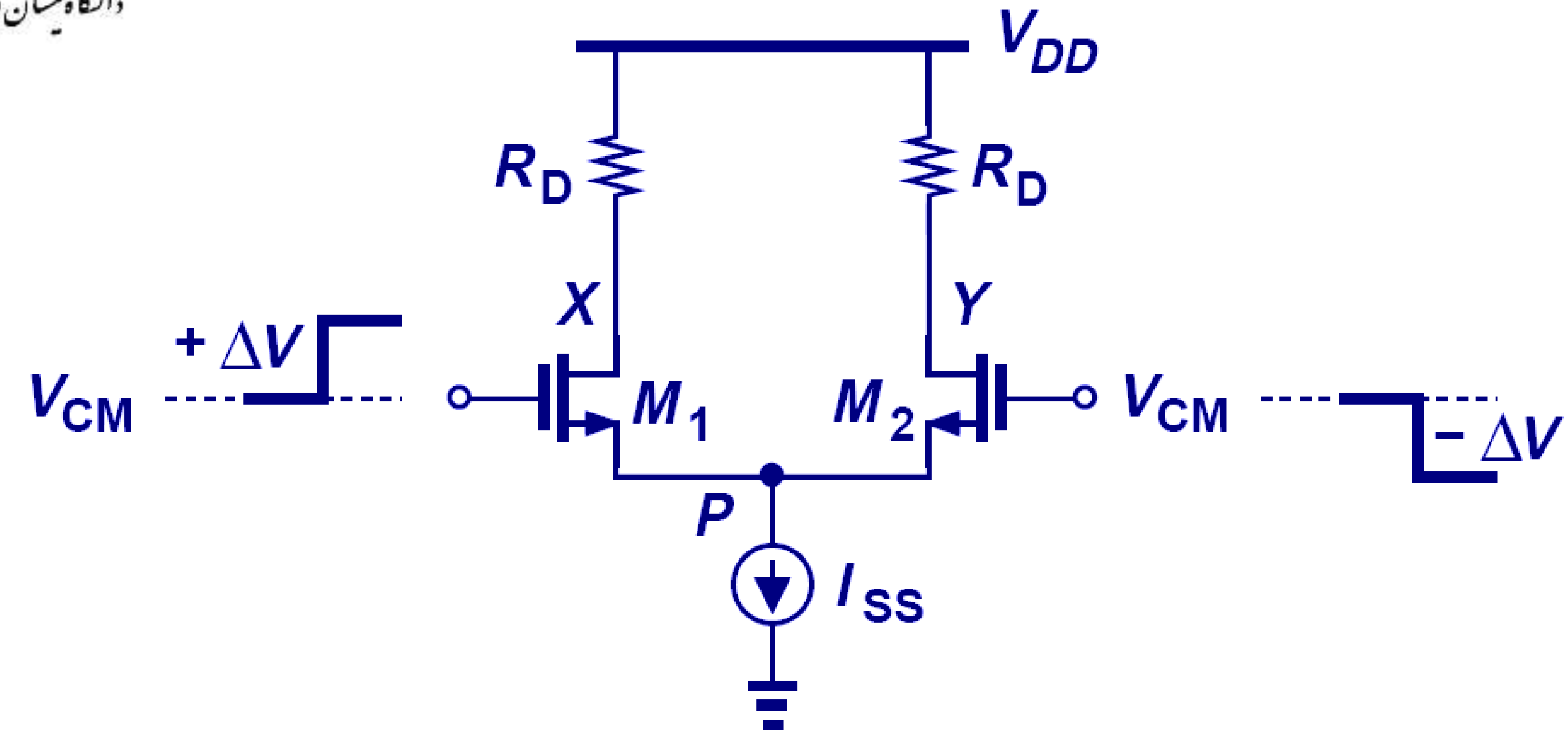


$$\Delta V_P = 0$$

$$A_v = -g_m R_D$$

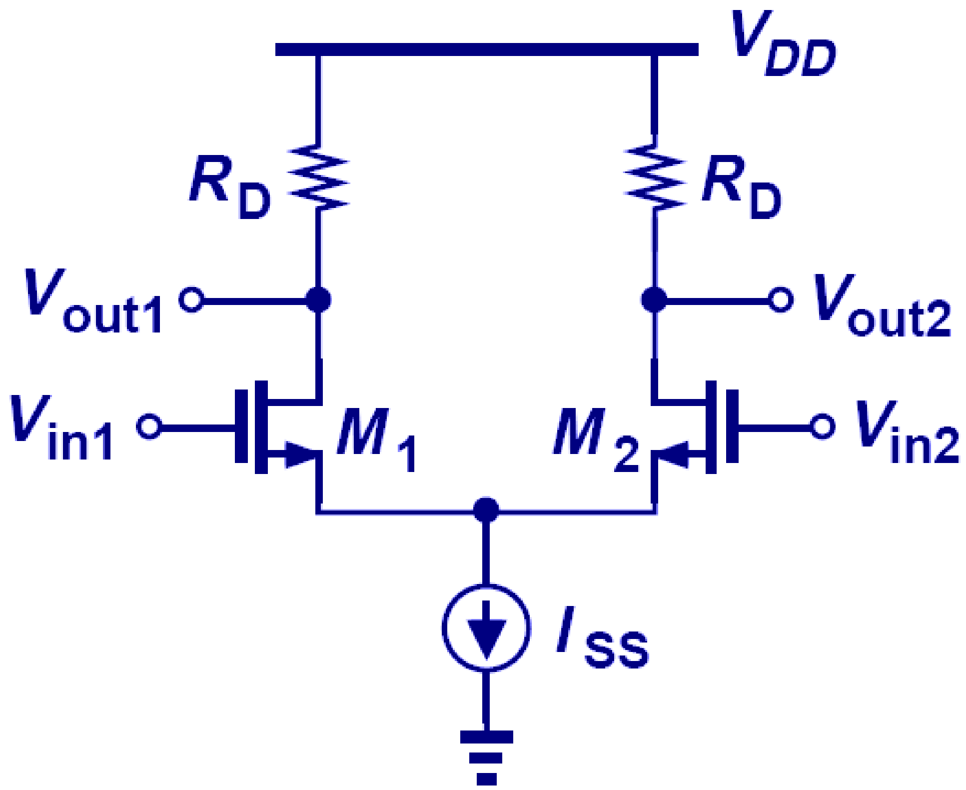
- Similar to its bipolar counterpart, the MOS differential pair exhibits the same virtual ground node and small signal gain.

Power and Gain Tradeoff



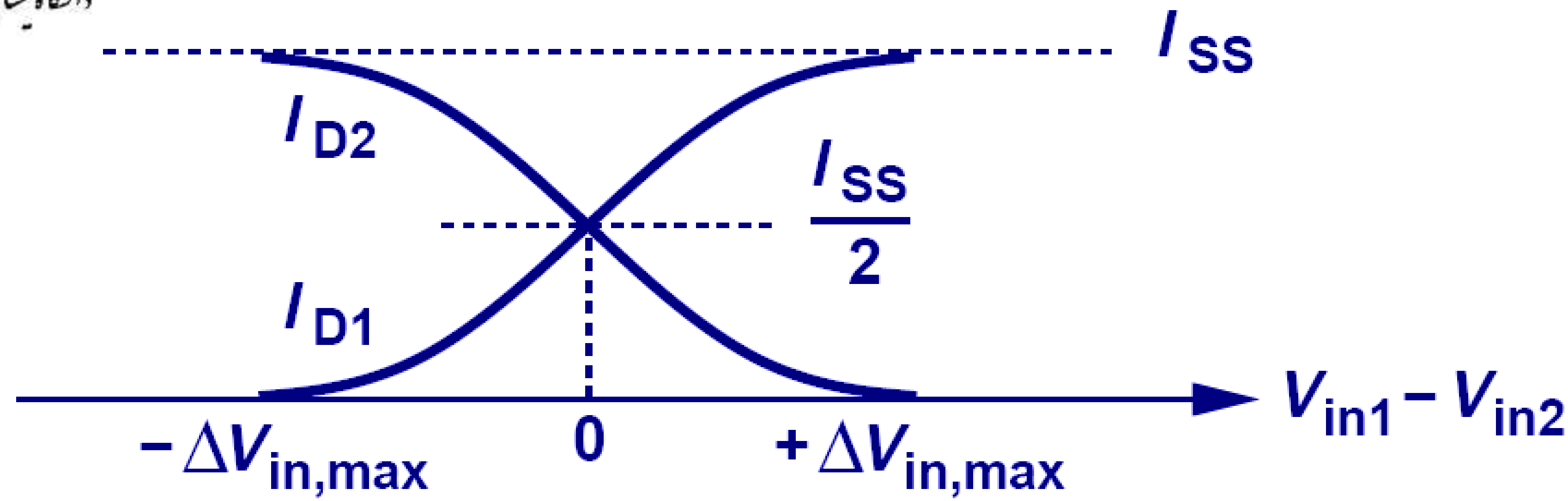
- **In order to obtain the source gain as a CS stage, a MOS differential pair must dissipate twice the amount of current. This power and gain tradeoff is also echoed in its bipolar counterpart.**

MOS Differential Pair's Large-Signal Response



$$I_{D1}-I_{D2}=\frac{1}{2}\mu_n C_{ox}\frac{W}{L}\left(V_{in1}-V_{in2}\right)\sqrt{\frac{4I_{SS}}{\mu_n C_{ox}\frac{W}{L}}-\left(V_{in1}-V_{in2}\right)^2}$$

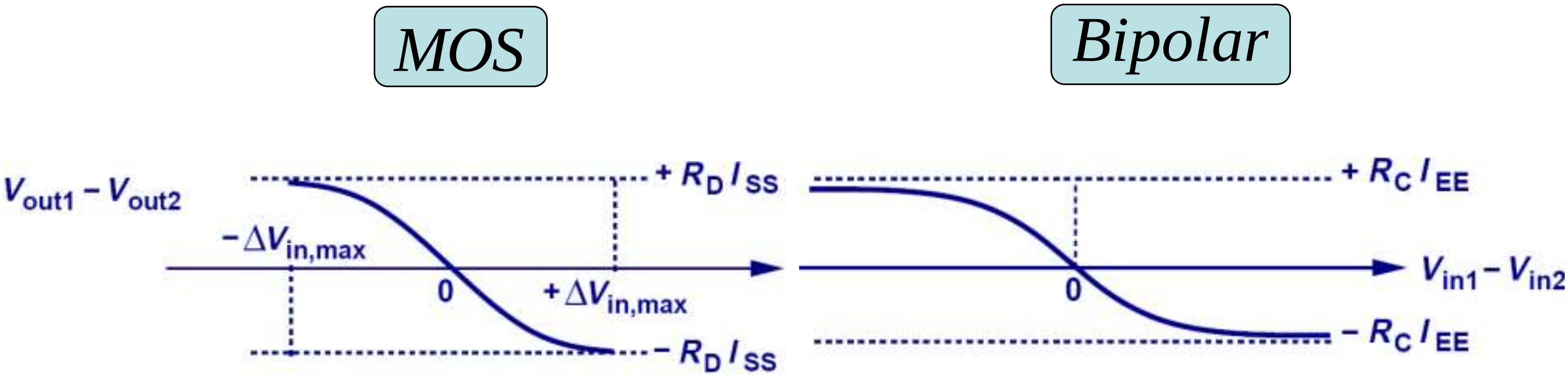
Maximum Differential Input Voltage



$$\left|V_{in1} - V_{in2}\right|_{\max} = \sqrt{2}\left(V_{GS} - V_{TH}\right)_{equil}$$

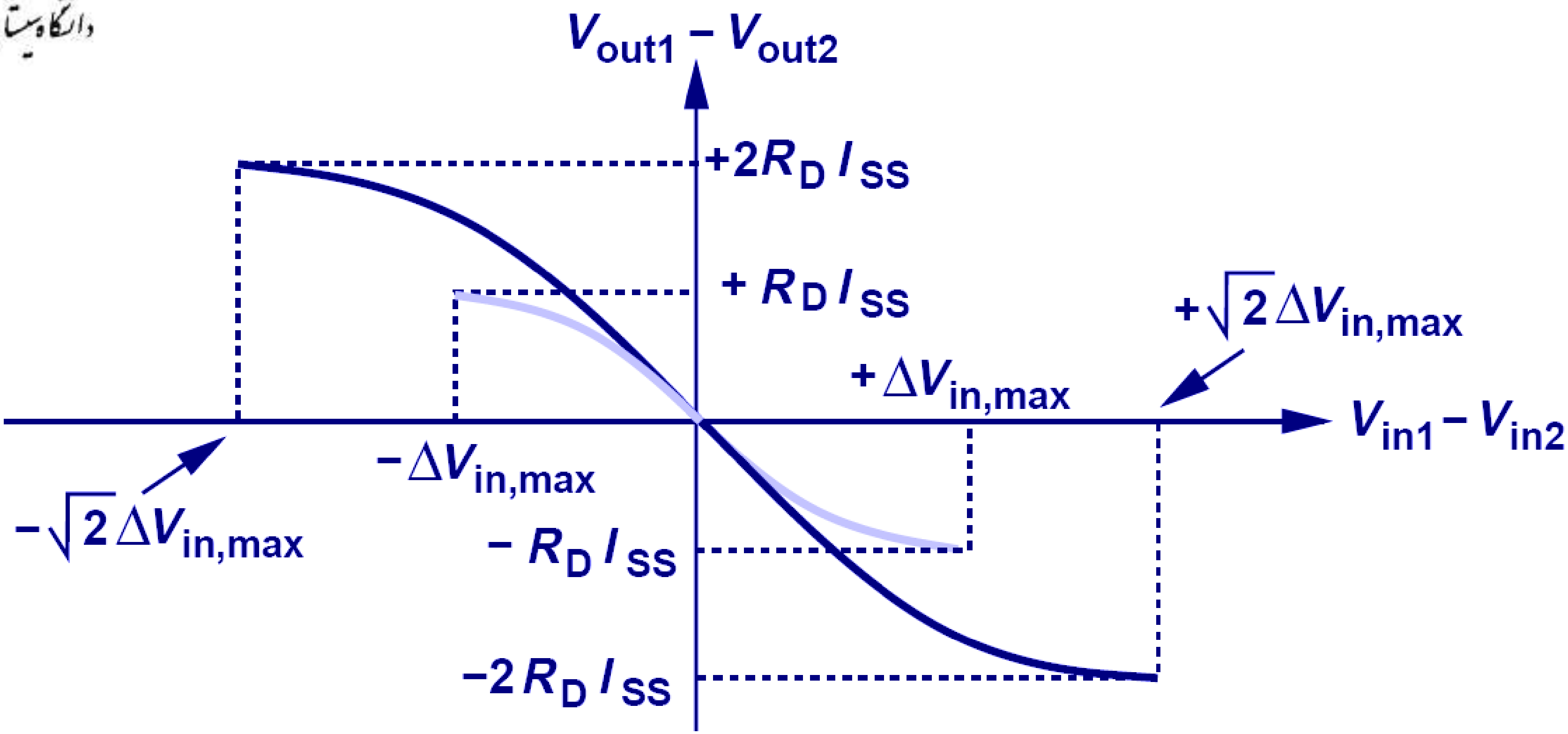
- **There exists a finite differential input voltage that completely steers the tail current from one transistor to the other. This value is known as the maximum differential input voltage.**

Contrast Between MOS and Bipolar Differential Pairs



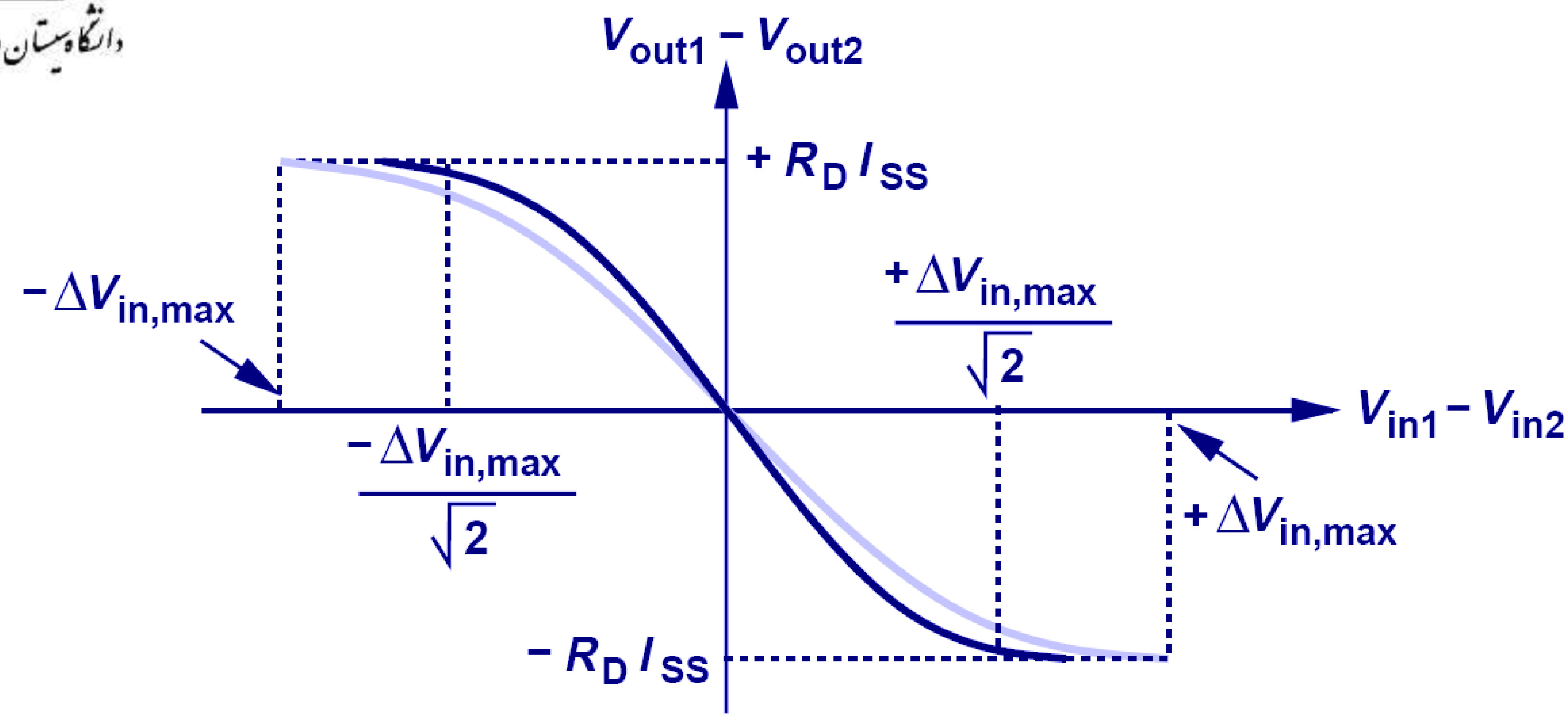
- In a MOS differential pair, there exists a finite differential input voltage to completely switch the current from one transistor to the other, whereas, in a bipolar pair that voltage is infinite.

The effects of Doubling the Tail Current



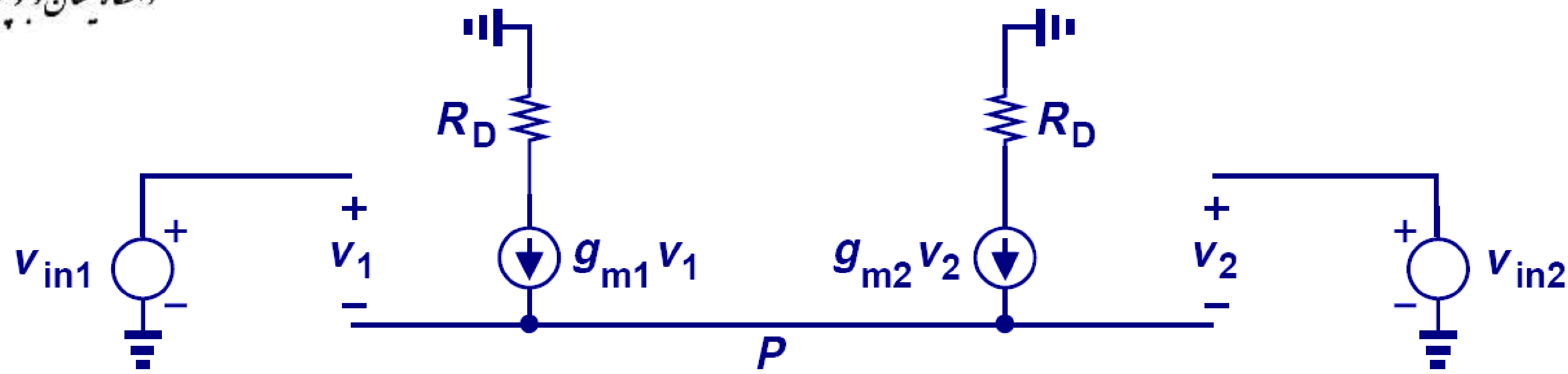
- Since I_{SS} is doubled and W/L is unchanged, the equilibrium overdrive voltage for each transistor must increase by $\sqrt{2}$ to accommodate this change, thus $\Delta V_{in,max}$ increases by $\sqrt{2}$ as well. Moreover, since I_{SS} is doubled, the differential output swing will double.

The effects of Doubling W/L



- **Since W/L is doubled and the tail current remains unchanged, the equilibrium overdrive voltage will be lowered by $\sqrt{2}$ to accommodate this change, thus $\Delta V_{in,max}$ will be lowered by $\sqrt{2}$ as well. Moreover, the differential output swing will remain unchanged since neither I_{SS} nor R_D has changed**

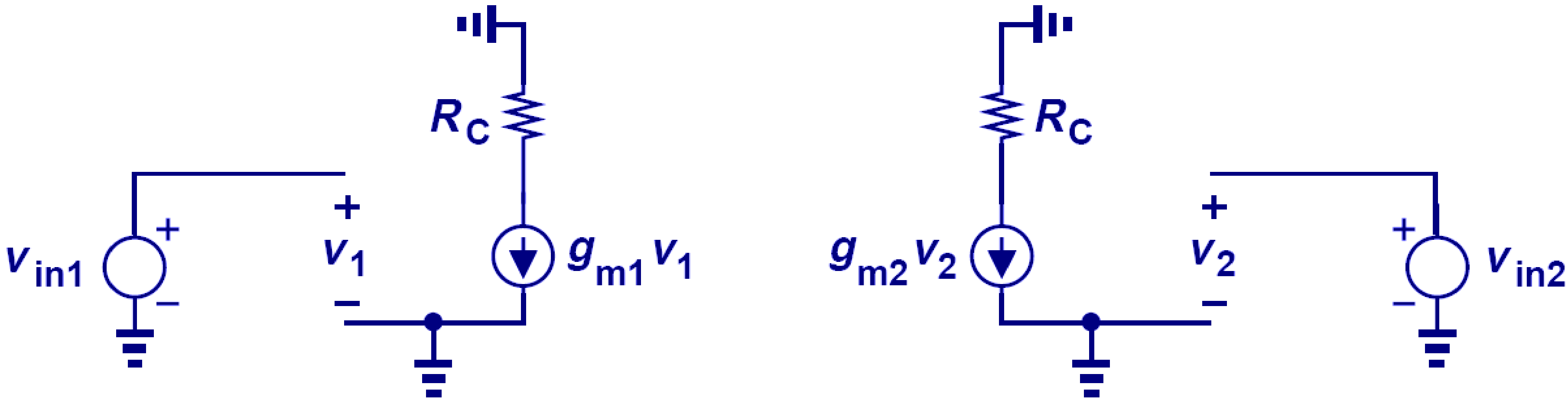
Small-Signal Analysis of MOS Differential Pair



$$I_{D1}-I_{D2}\approx\frac{1}{2}\mu_n C_{ox}\frac{W}{L}\left(V_{in1}-V_{in2}\right)\sqrt{\frac{4I_{SS}}{\mu_n C_{ox}\frac{W}{L}}}=\sqrt{\mu_n C_{ox}\frac{W}{L}I_{SS}}\left(V_{in1}-V_{in2}\right)$$

- **When the input differential signal is small compared to $4I_{SS}/\mu_n C_{ox}(W/L)$, the output differential current is linearly proportional to it, and small-signal model can be applied.**

Virtual Ground and Half Circuit

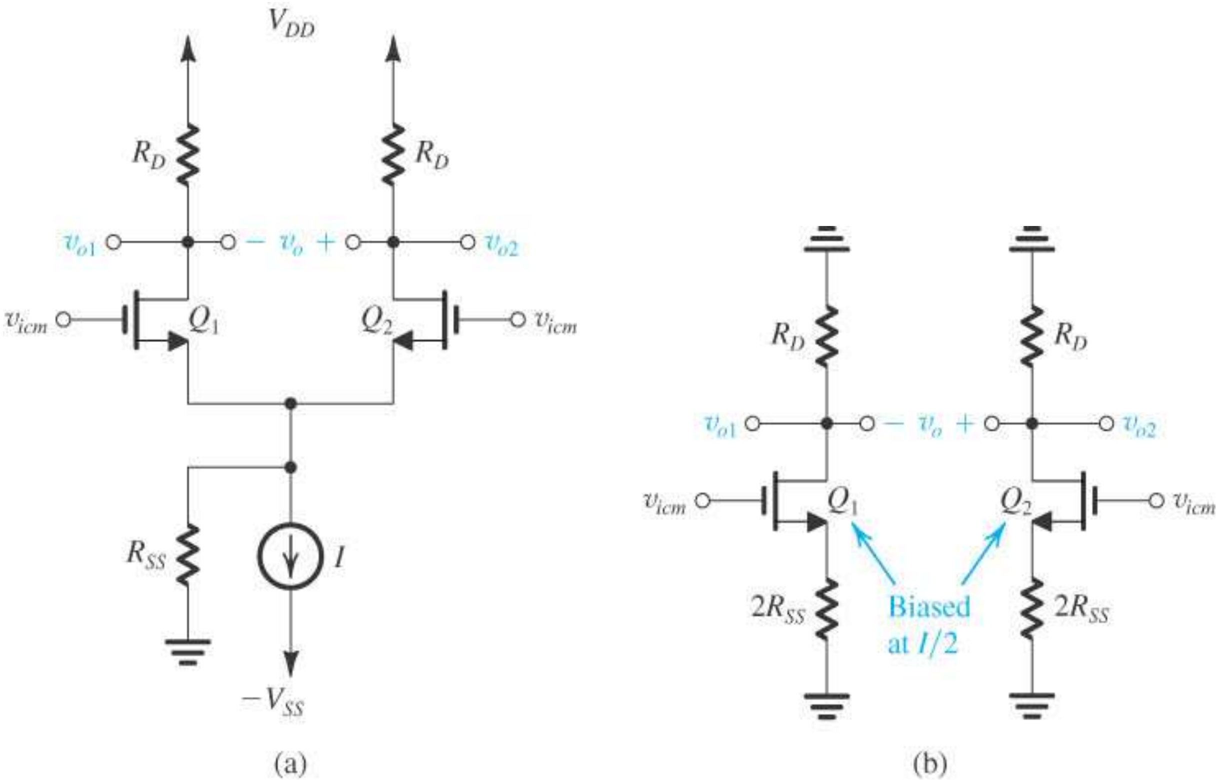


$$\Delta V_P = 0$$

$$A_v = -g_m R_C$$

- Applying the same analysis as the bipolar case, we will arrive at the same conclusion that node P will not move for small input signals and the concept of half circuit can be used to calculate the gain.

Common-mode input signal

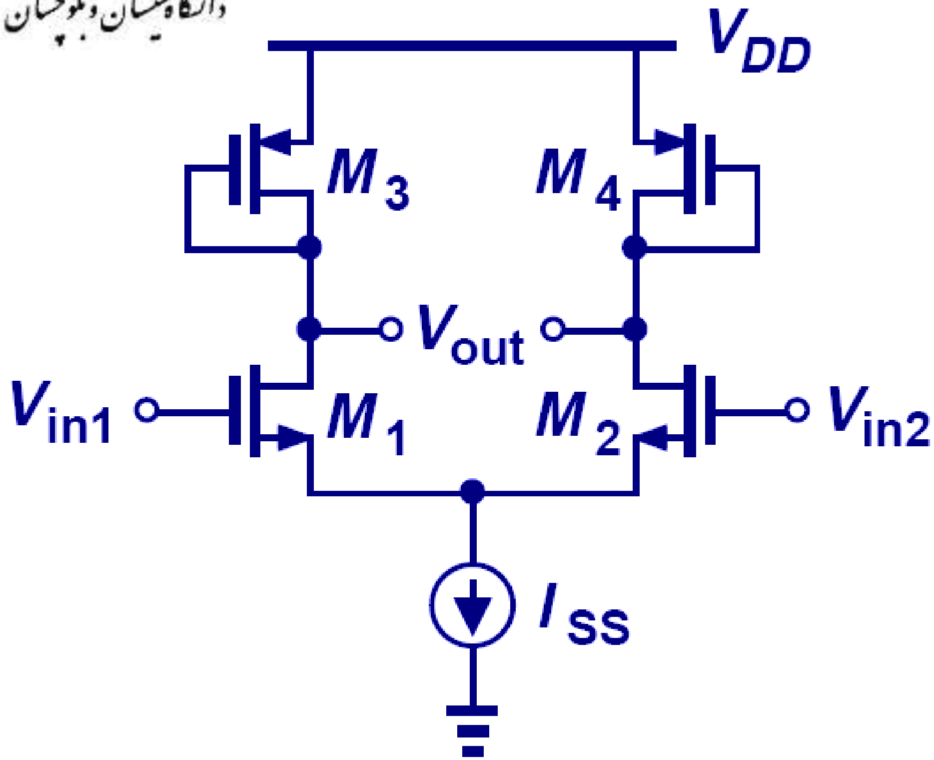


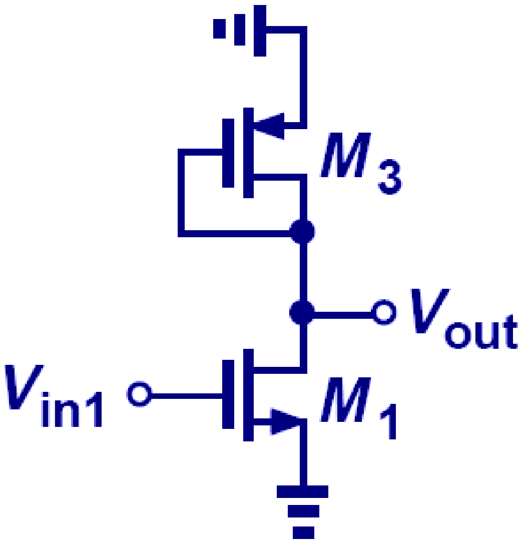
(a) The MOS differential amplifier with a common-mode input signal v_{ic}

(b) Equivalent circuit for determining the common-mode gain (with r_o ignored).

Each half of the circuit is known as the "**common-mode half-circuit**."

MOS Differential Pair Half Circuit Example I

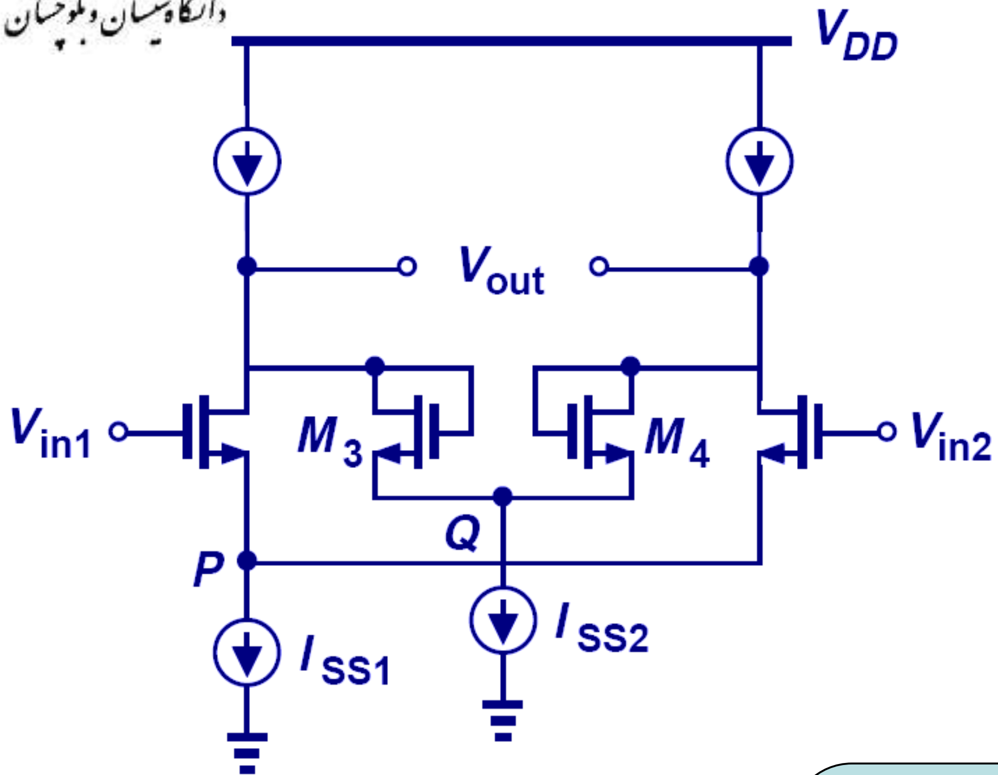


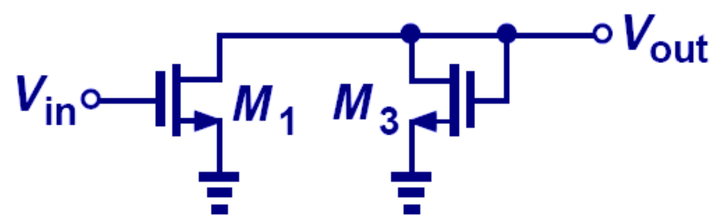


$$\lambda \neq 0$$

$$A_v = -g_{m1}\left(\frac{1}{g_{m3}} \| r_{O3} \| r_{O1}\right)$$

MOS Differential Pair Half Circuit Example II

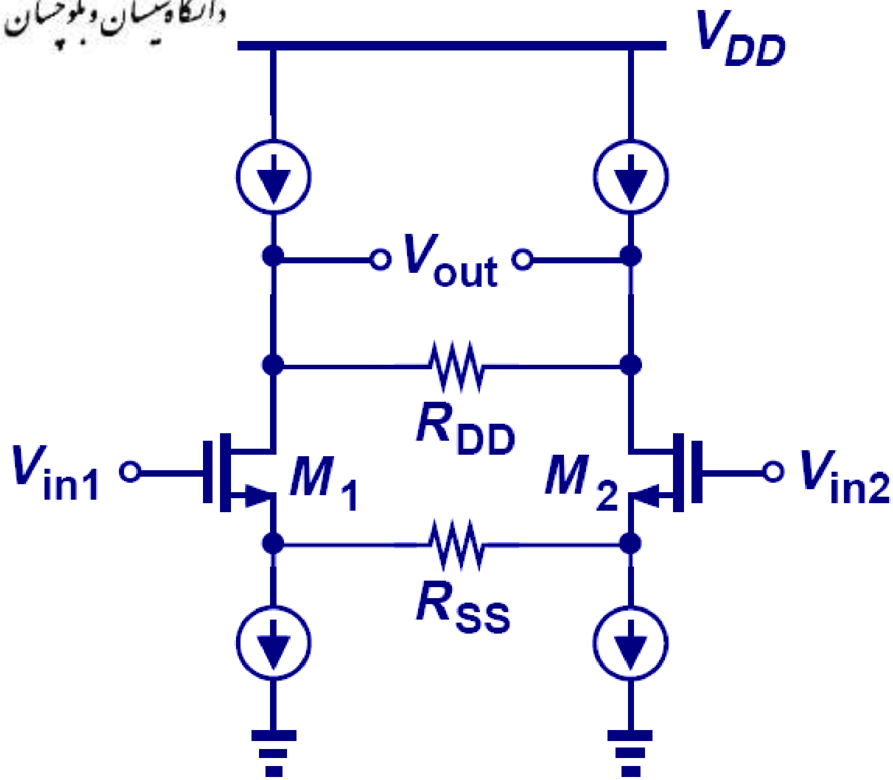


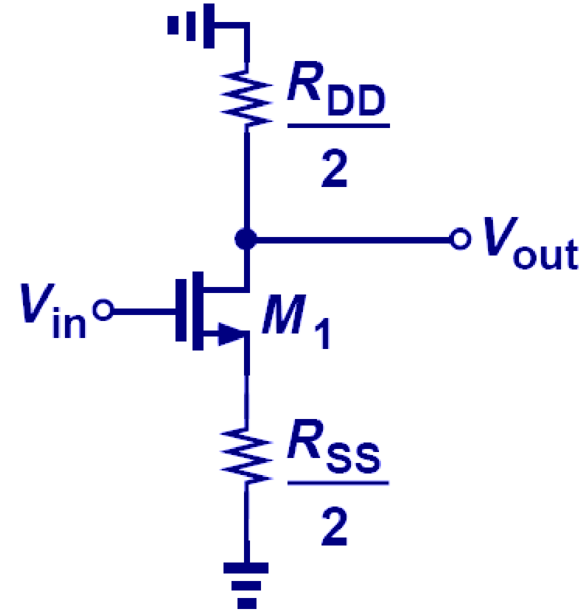


$$\lambda = 0$$

$$A_v = -\frac{g_{m1}}{g_{m3}}$$

MOS Differential Pair Half Circuit Example III

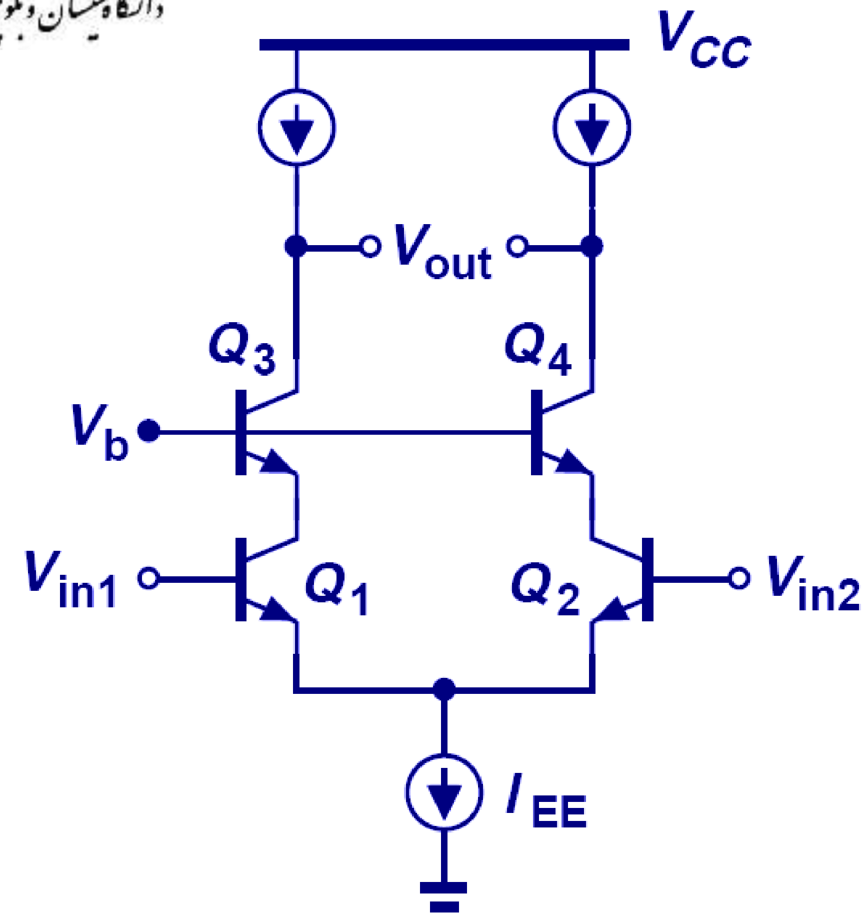


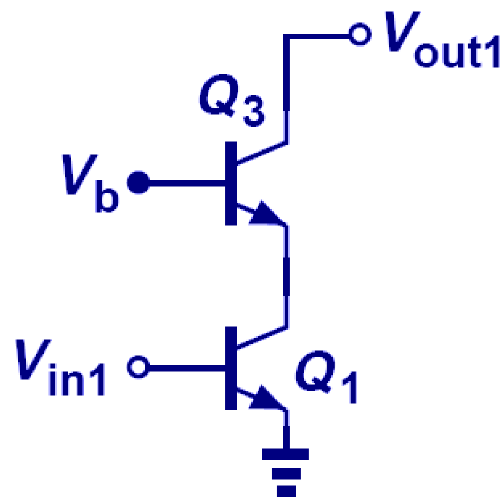


$$\lambda = 0$$

$$A_v = -\frac{R_{DD}/2}{R_{SS}/2 + 1/g_m}$$

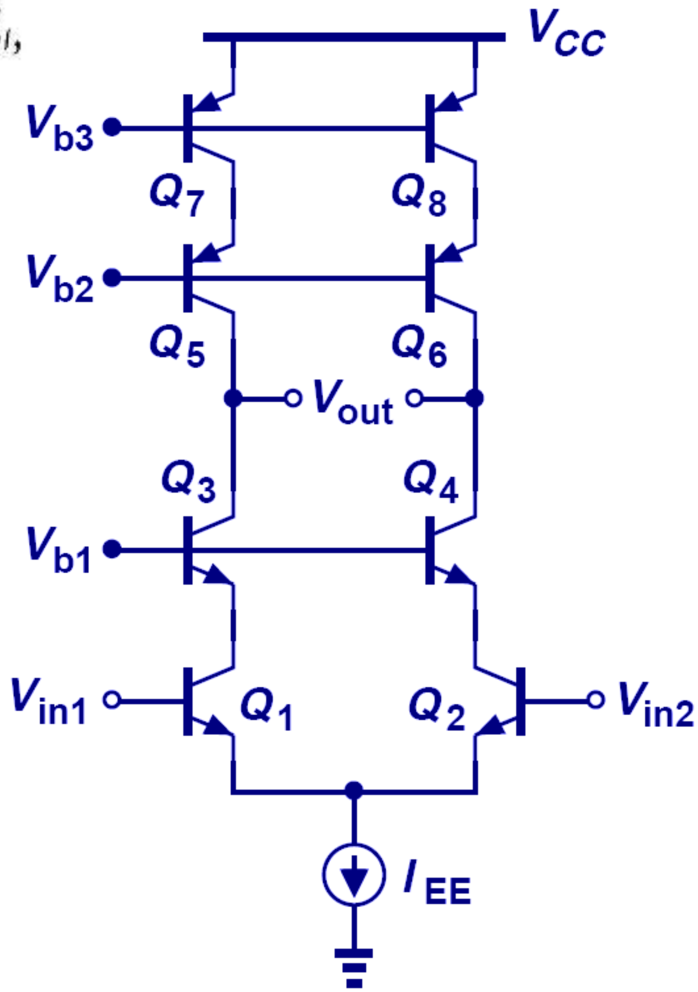
Bipolar Cascode Differential Pair

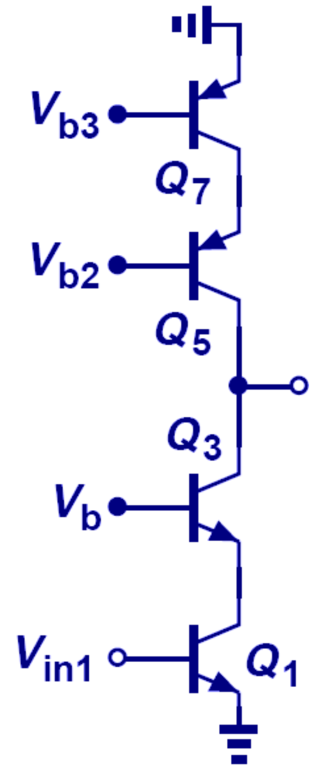




$$A_v = -g_{m1}\left[g_{m3}\left(r_{O1} \parallel r_{\pi 3}\right)r_{O3} + r_{O1}\right]$$

Bipolar Telescopic Cascode

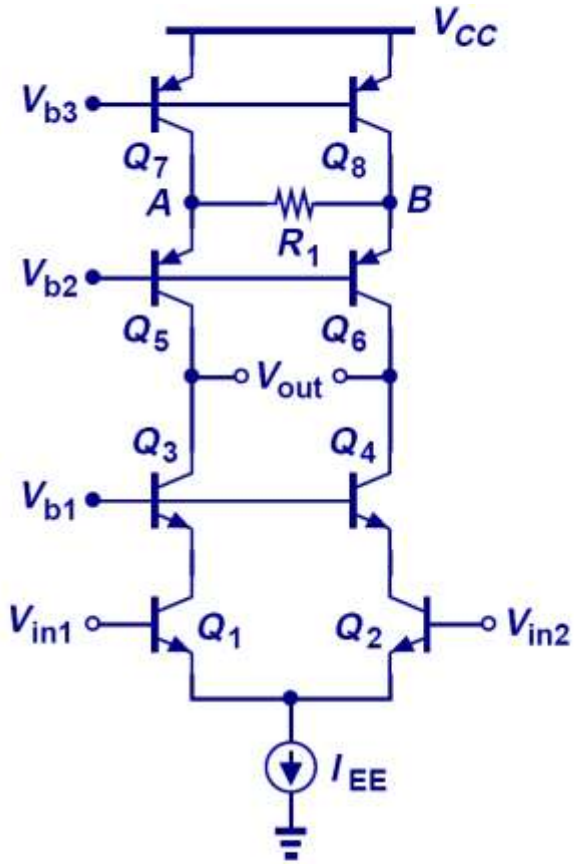


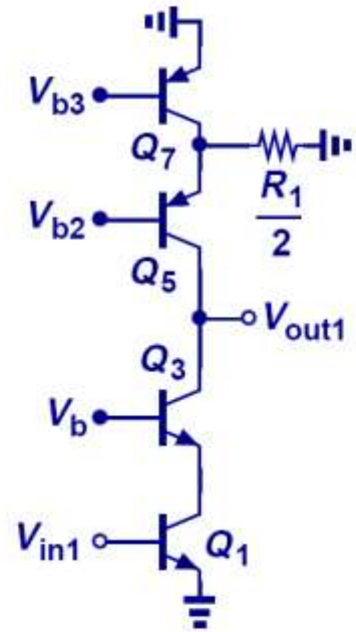


$$A_v \approx -g_{m1}\left[g_{m3} r_{O3}\left(r_{O1} \parallel r_{\pi 3}\right)\right] \parallel \left[g_{m5} r_{O5}\left(r_{O7} \parallel r_{\pi 5}\right)\right]$$

دانشگاه سیستان و بلوچستان

Example: Bipolar Telescopic Parasitic Resistance

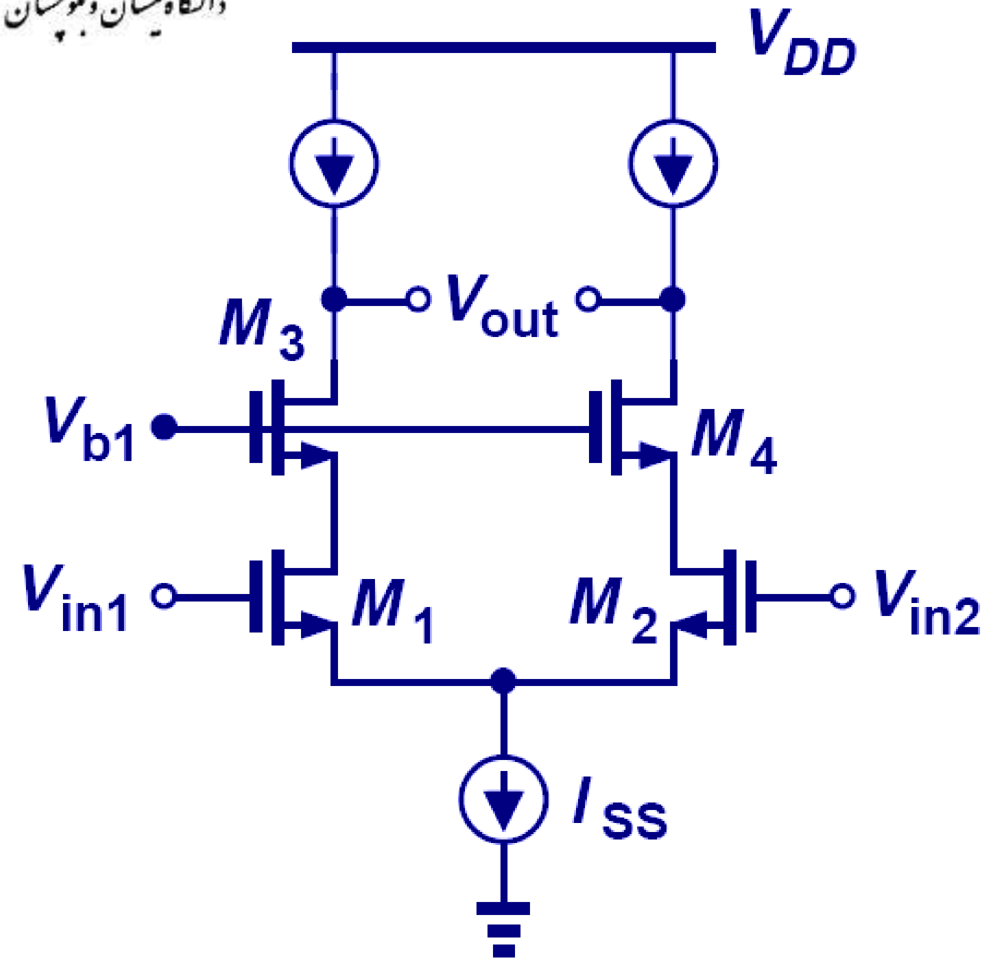


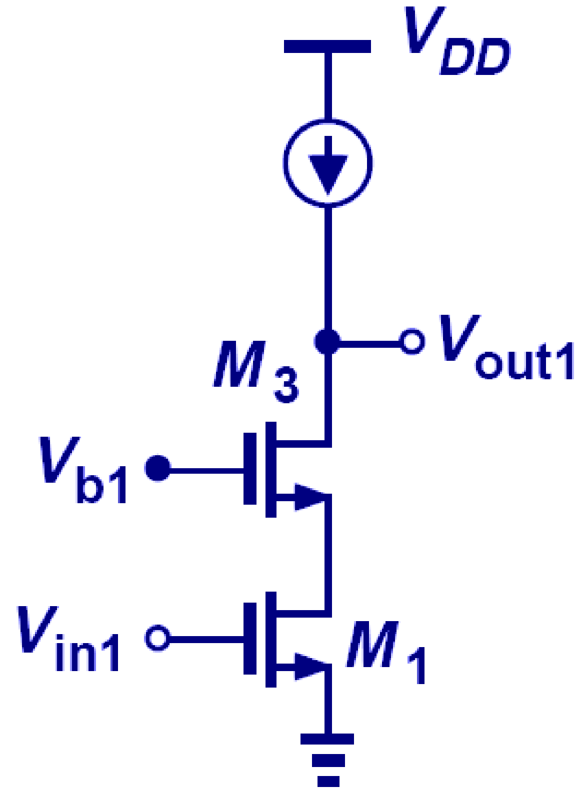


$$R_{op} = r_{O5}\left[1 + g_{m5}\left(r_{O7} \parallel r_{\pi 5} \parallel \frac{R_1}{2}\right)\right] + r_{O7} \parallel r_{\pi 5} \parallel \frac{R_1}{2}$$

$$A_v = -g_{m1}\left[g_{m3} r_{O3}(r_{O1} \parallel r_{\pi 3})\right] \parallel R_{op}$$

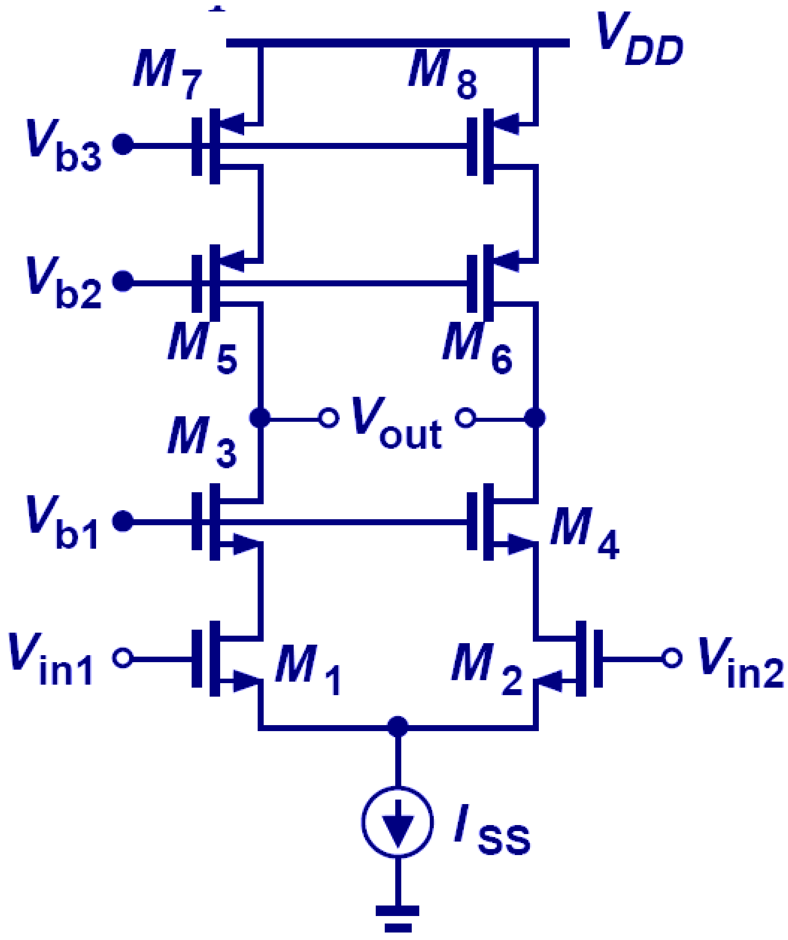
MOS Cascode Differential Pair

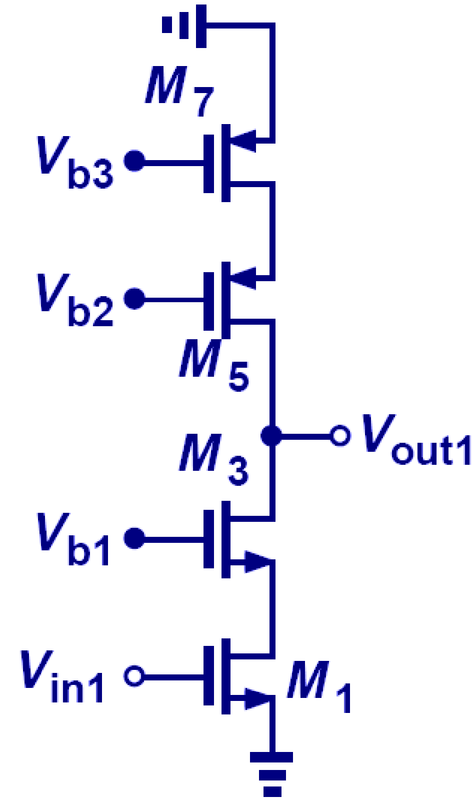




$$A_v \approx -g_{m1} r_{O3} g_{m3} r_{O1}$$

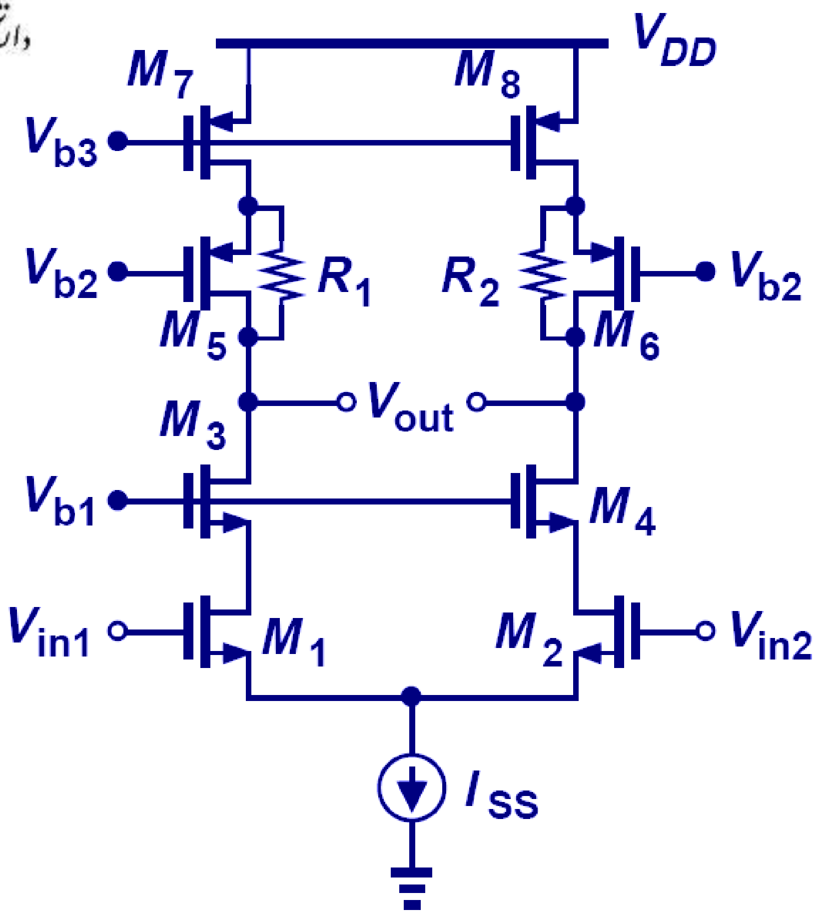
MOS Telescopic Cascode

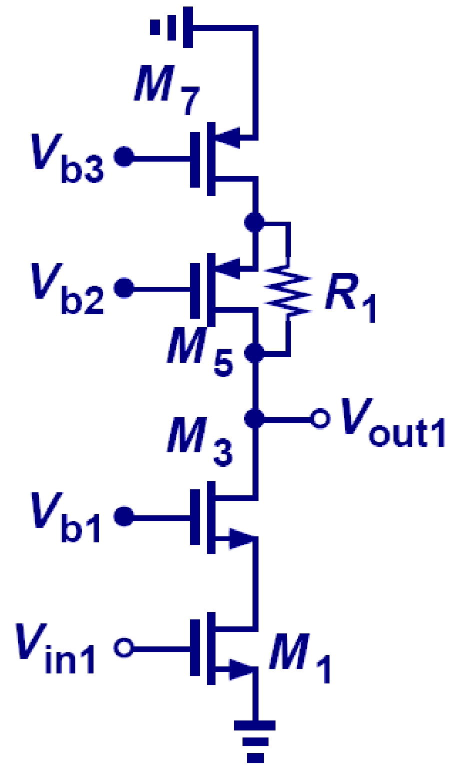




$$A_v \approx -g_{m1}\left[\left(g_{m3}r_{O3}r_{O1}\right) \| \left(g_{m5}r_{O5}r_{O7}\right)\right]$$

Example: MOS Telescopic Parasitic Resistance

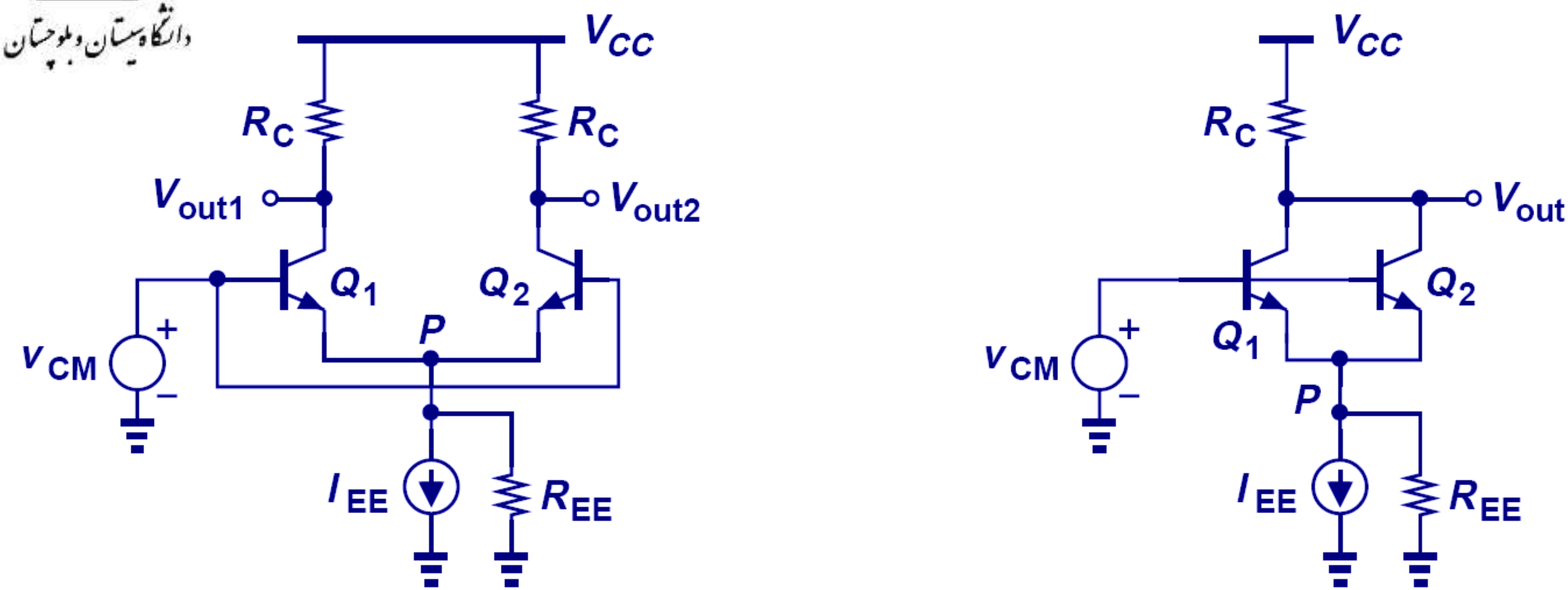




$$R_{op} = r_{O5} \parallel [R_1(1+g_{m5}r_{O7}) + r_{O7}]$$

$$A_v \approx -g_{m1}(R_{op} \parallel r_{O3}g_{m3}r_{O1})$$

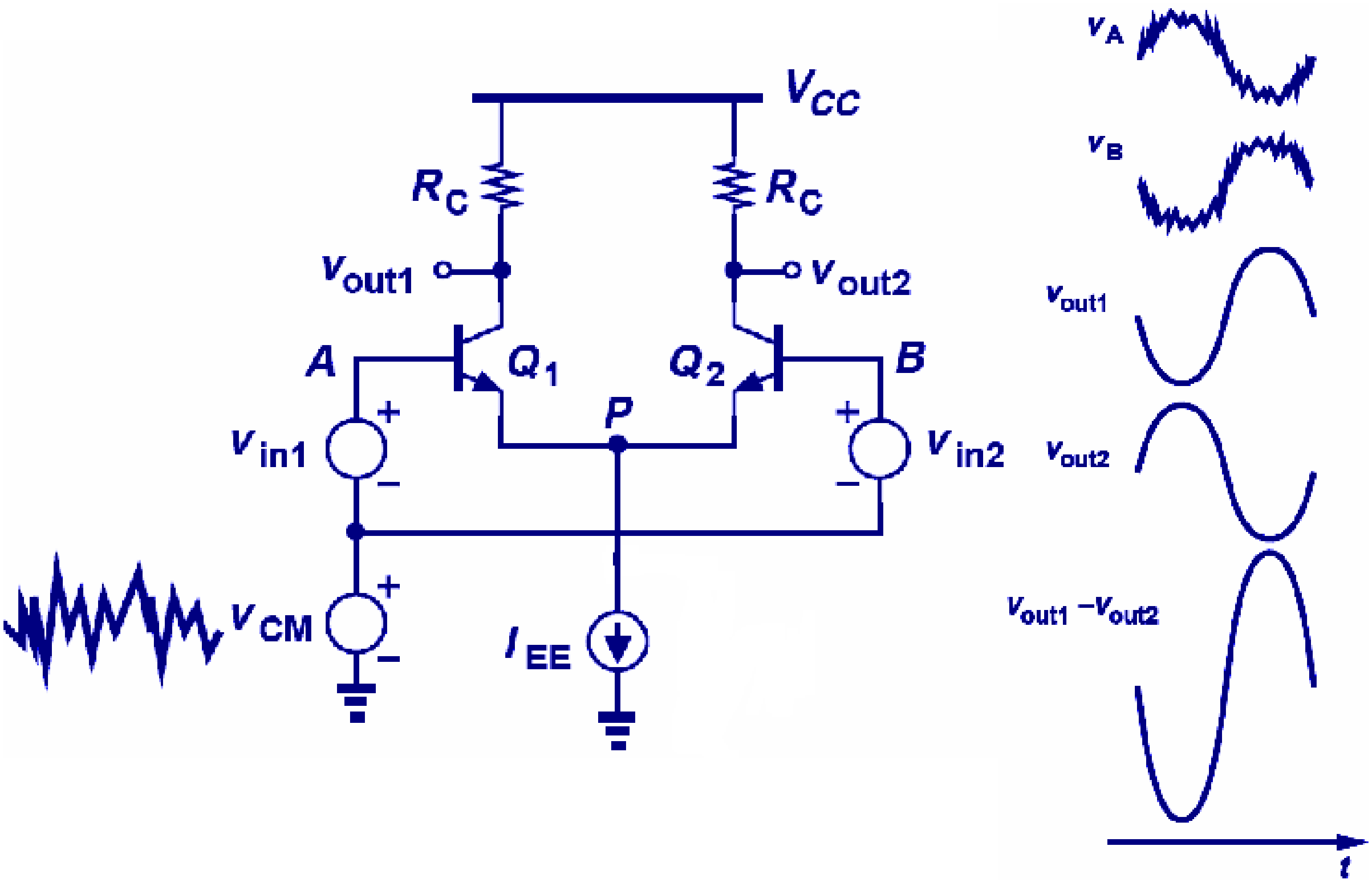
Effect of Finite Tail Impedance



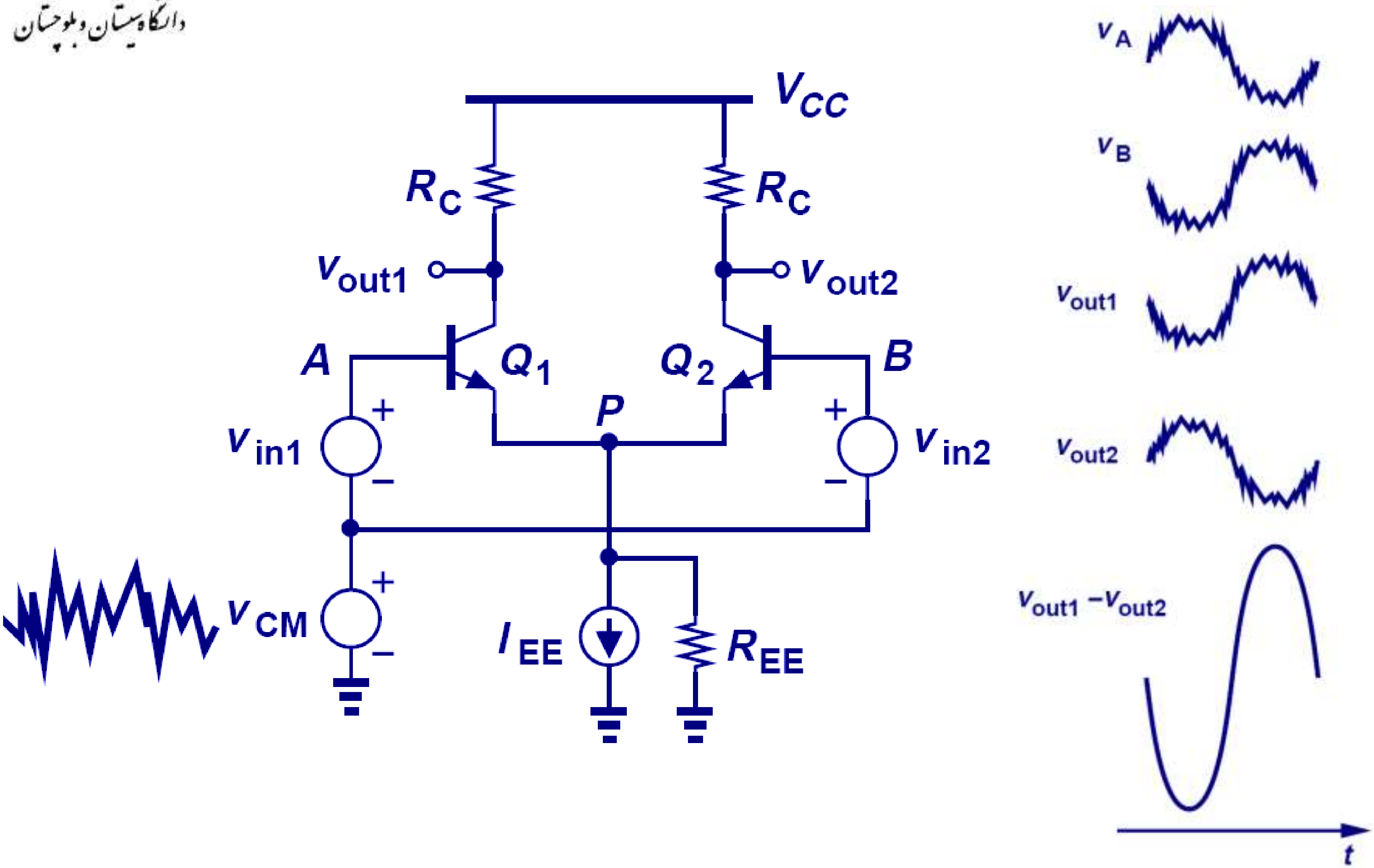
$$\frac{\Delta V_{out,CM}}{\Delta V_{in,CM}} = -\frac{R_C/2}{R_{EE}+1/2g_m}$$

- **If the tail current source is not ideal, then when a input CM voltage is applied, the currents in Q_1 and Q_2 and hence output CM voltage will change.**

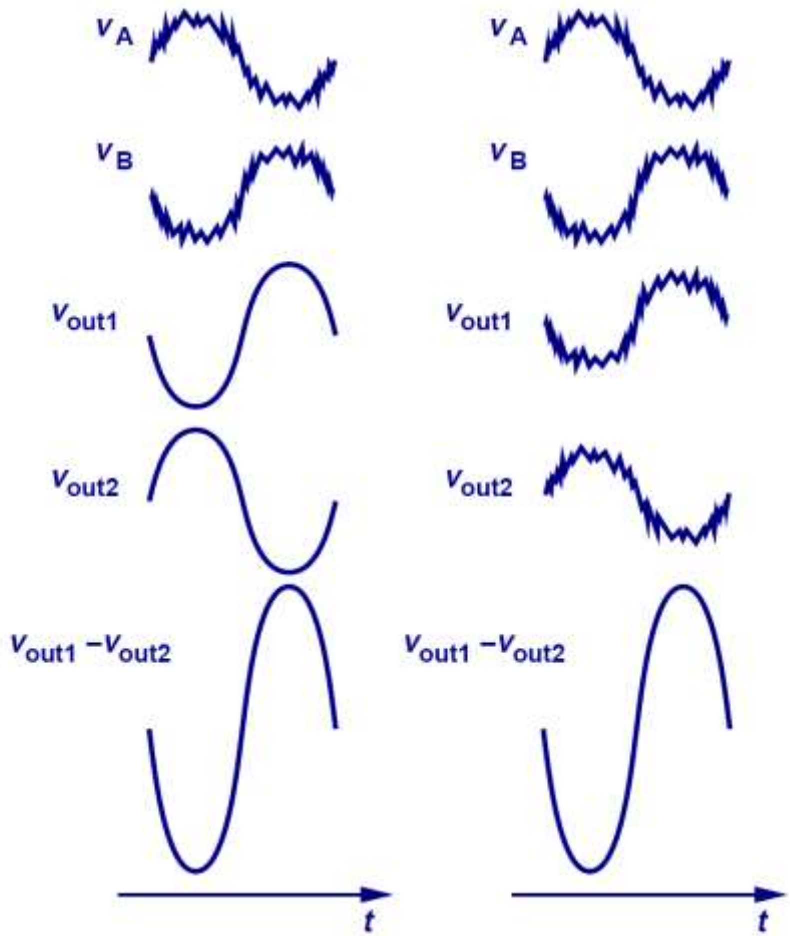
Input CM Noise with Ideal Tail Current



Input CM Noise with Non-ideal Tail Current

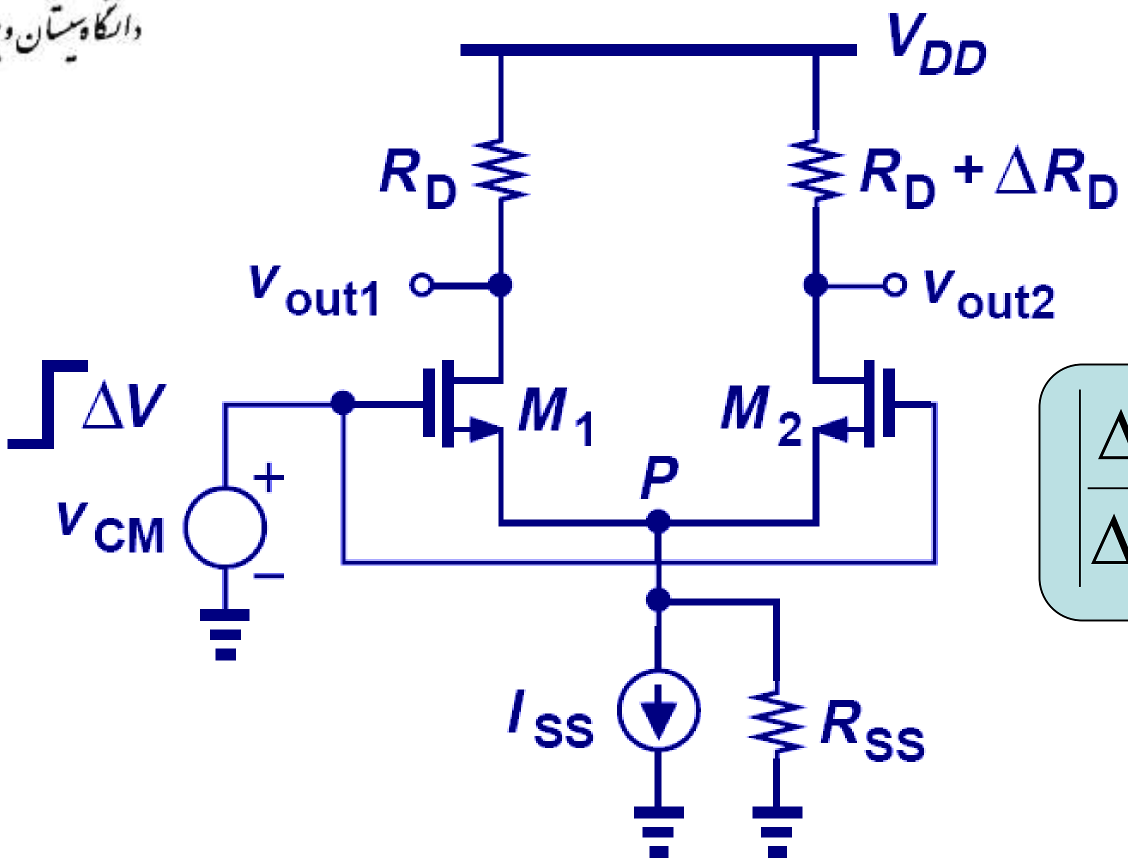


Comparison



- **As it can be seen, the differential output voltages for both cases are the same. So for small input CM noise, the differential pair is not affected.**

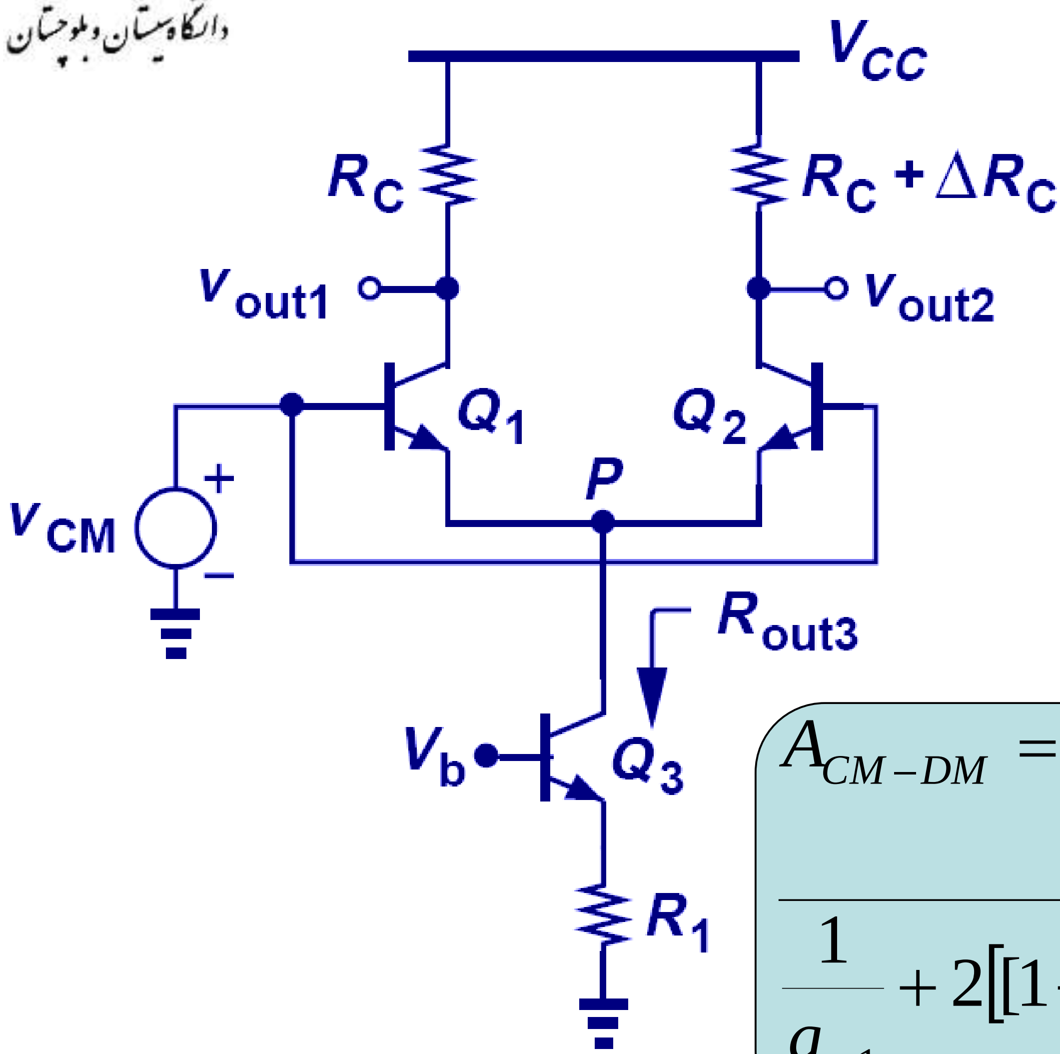
CM to DM Conversion, $A_{CM\text{-}DM}$



$$\left|\frac{\Delta V_{out}}{\Delta V_{CM}}\right| = \frac{\Delta R_D}{1/g_m + 2R_{EE}}$$

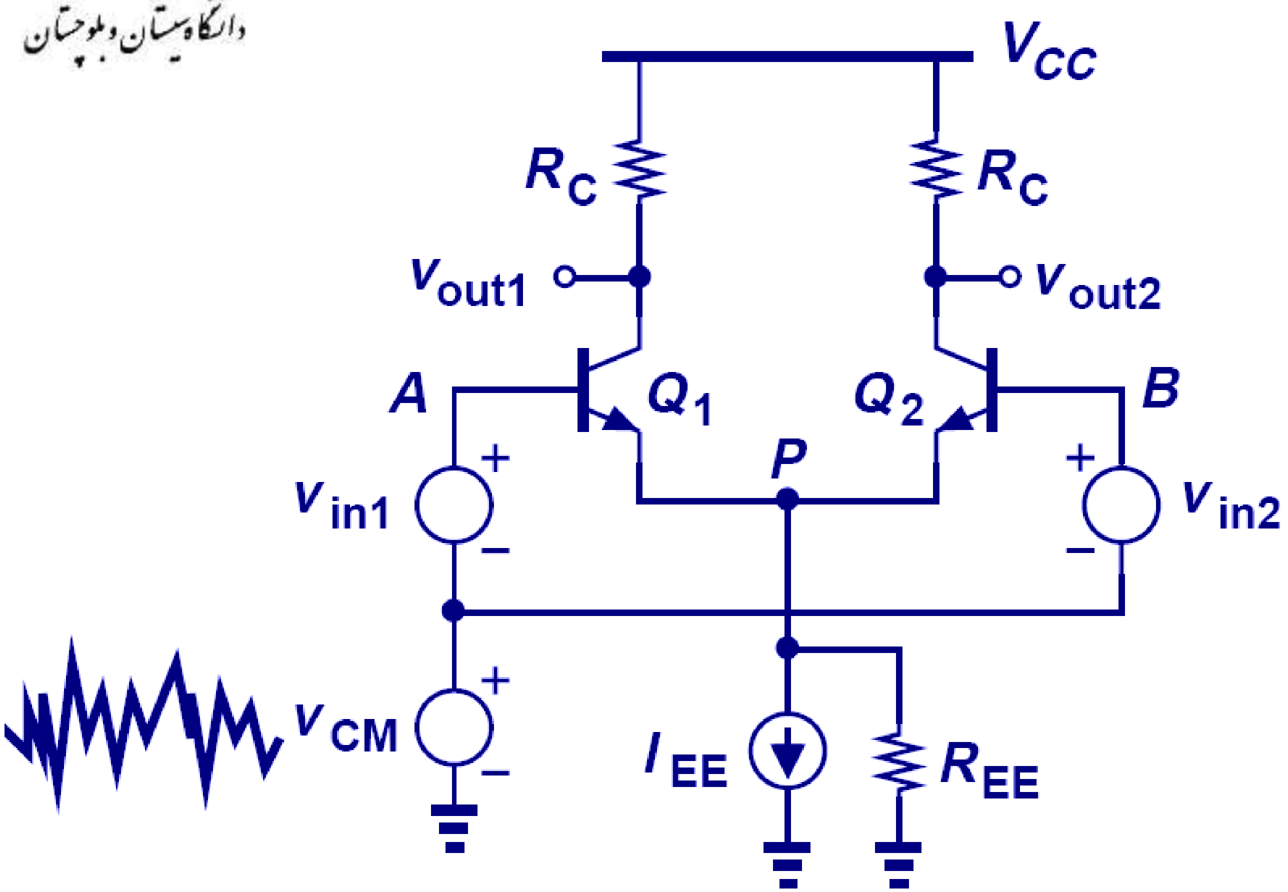
- **If finite tail impedance and asymmetry are both present, then the differential output signal will contain a portion of input common-mode signal.**

Example: A_{CM-DM}



$$A_{CM-DM} = \frac{\Delta R_C}{\frac{1}{g_{m1}} + 2[[1 + g_{m3}(R_1 \parallel r_{\pi 3})]r_{O3} + R_1 \parallel r_{\pi 3}]}$$

CMRR



$$CMRR = \frac{A_{DM}}{A_{CM-DM}}$$

- **CMRR defines the ratio of wanted amplified differential input signal to unwanted converted input common-mode noise that appears at the output.**