Lecture 24

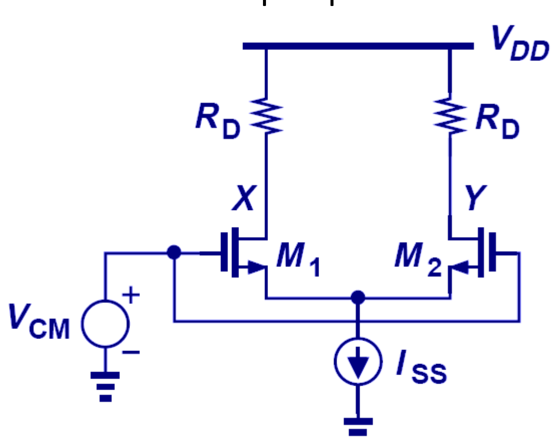
OUTLINE

- MOSFET Differential Amplifiers

- Reading: Chapter 10.3-10.6

Common-Mode (CM) Response

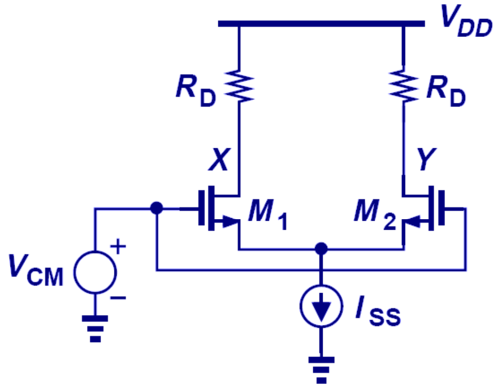
- Similarly to its BJT counterpart, a MOSFET differential pair produces zero differential output



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

Equilibrium Overdrive Voltage

- The ***equilibrium overdrive voltage*** is defined as V_{GS}-V_{TH} when M_1 and M_2 each carry a current of $I_{SS}/2$.



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

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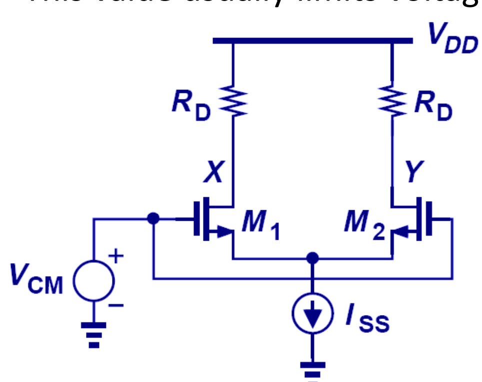
Minimum CM Output Voltage

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



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

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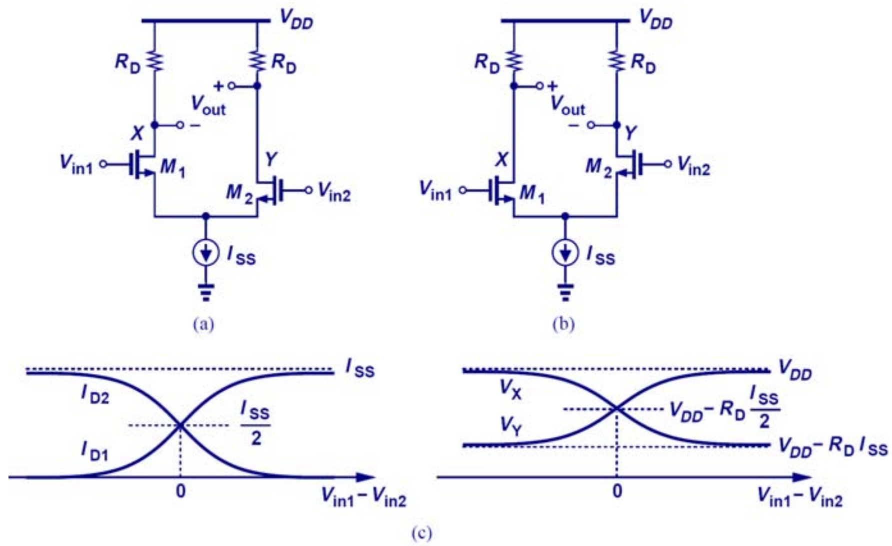
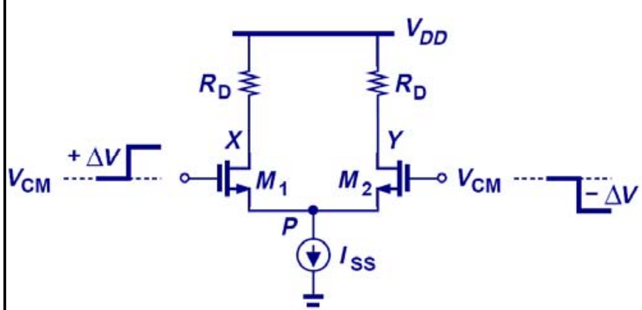
Differential Response



Small-Signal Response

- For small input voltages (+ΔV and -ΔV), the g_m values are ~equal, so the increase in I_{D1} and decrease in I_{D2} are ~equal in magnitude. Thus, the voltage at node P is constant and can be considered as AC ground.



$$I_{D1} = \frac{I_{EE}}{2} + \Delta I$$

$$I_{D2} = \frac{I_{EE}}{2} - \Delta I$$

$$\Delta I_{D1} = g_m \left(\Delta V - \Delta V_P \right)$$

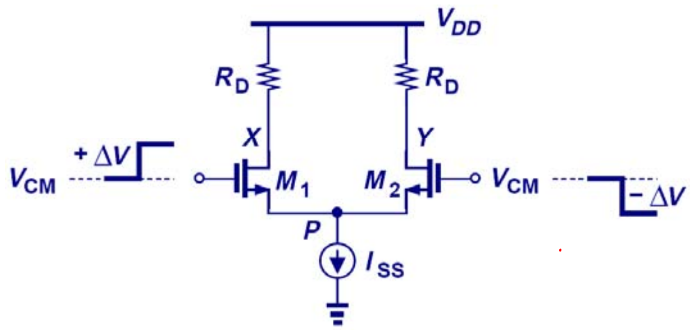
$$\Delta I_{D2} = g_m \left(-\Delta V - \Delta V_P \right)$$

$$\Delta I_{D1} = -\Delta I_{D2}$$

$$\Rightarrow \boxed{\Delta V_P = 0}$$

Small-Signal Differential Gain

- Since the output signal changes by $-2g_m \Delta V R_D$ when the input signal changes by $2\Delta V$, the small-signal voltage gain is $-g_m R_D$.
- Note that the voltage gain is the same as for a CS stage, but that the power dissipation is doubled.



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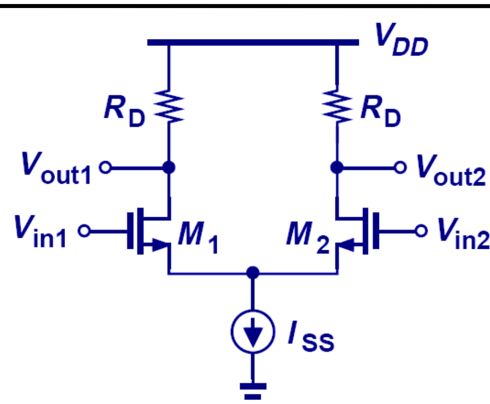
Large-Signal Analysis



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

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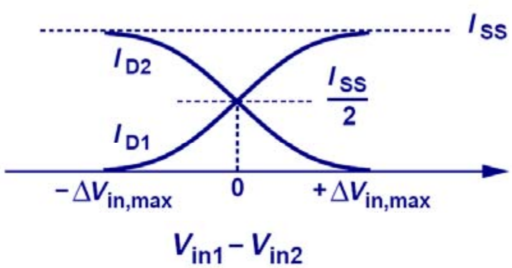
Maximum Differential Input Voltage

- 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***.



If all current flows through M_2:

$$V_{GS2} = V_{TH} + \sqrt{\frac{2I_{SS}}{\mu_n C_{ox} \frac{W}{L}}}$$

$$I_{D1} = 0 \quad \Rightarrow \quad V_{GS1} = V_{TH}$$

$$\left|V_{in1} - V_{in2}\right|_{max} = \sqrt{\frac{2I_{SS}}{\mu_n C_{ox} \frac{W}{L}}}$$

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

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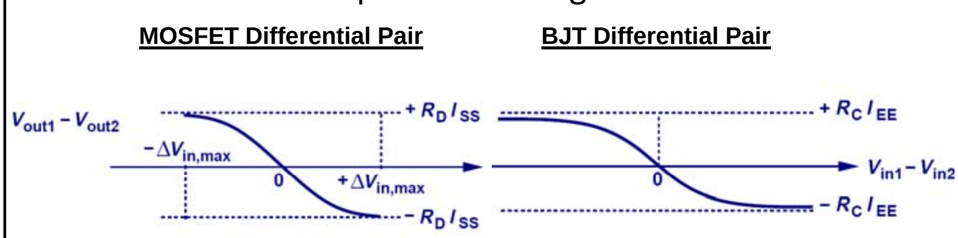
MOSFET *vs.* BJT Differential Pairs

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



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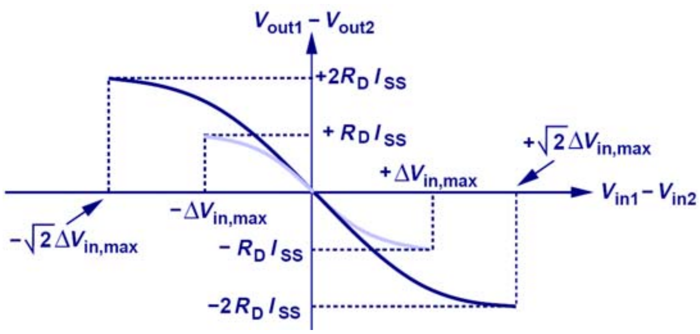
Effect of Doubling the Tail Current

- If I_{SS} is doubled, the equilibrium overdrive voltage for each transistor increases by $\sqrt{2}$, thus $\Delta V_{in,max}$ increases by $\sqrt{2}$ as well. Moreover, the differential output swing will double.



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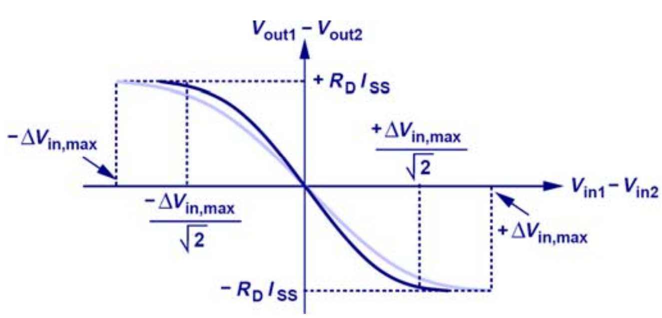
Effect of Doubling *W/L*

- If *W/L* is doubled, the equilibrium overdrive voltage is lowered by $\sqrt{2}$, thus $\Delta V_{in,max}$ will be lowered by $\sqrt{2}$ as well. The differential output swing will be unchanged.



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Small-Signal Analysis

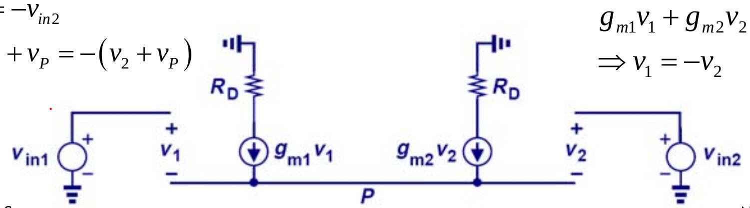
- When the input differential signal is small compared to $4I_{SS}/\mu_n C_{ox}(W/L)$, the output differential current is ~ linearly proportional to it:

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

- We can use the small-signal model to prove that the change in tail node voltage (v_P) is zero:

$$v_{in1}=-v_{in2}$$
$$\Rightarrow v_1+v_P=-(v_2+v_P)$$

$$g_{m1}v_1+g_{m2}v_2=0$$
$$\Rightarrow v_1=-v_2$$



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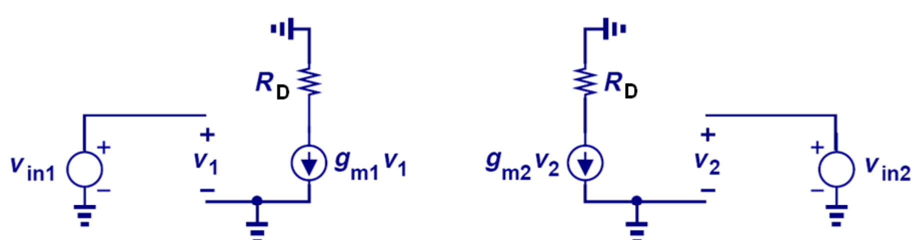
Virtual Ground and Half Circuit

- Since the voltage at node *P* does not change for small input signals, the half circuit can be used to calculate the voltage gain.



$$v_P=0$$
$$A_v=-g_m R_D$$

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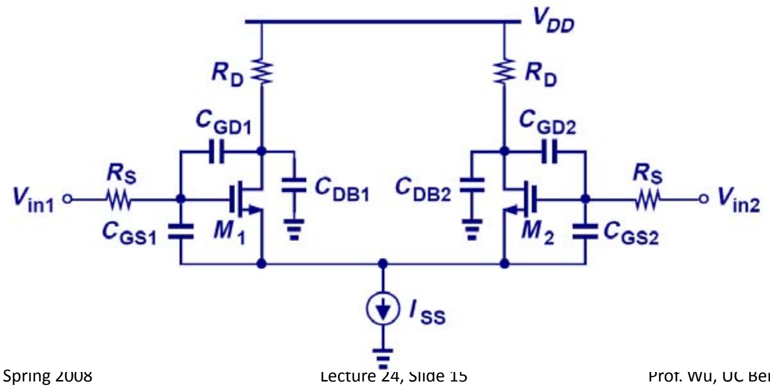
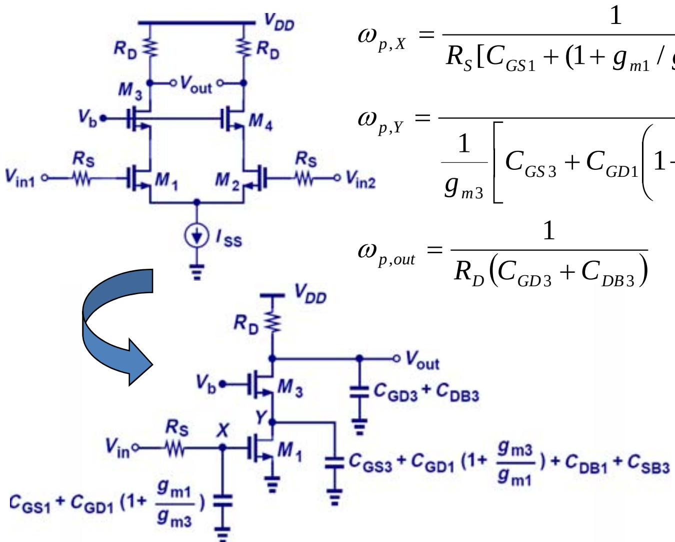
MOSFET Diff. Pair Frequency Response

- Since the MOSFET differential pair can be analyzed using its half-circuit, its transfer function, I/O impedances, locations of poles/zeros are the same as that of the half circuit's.



Example



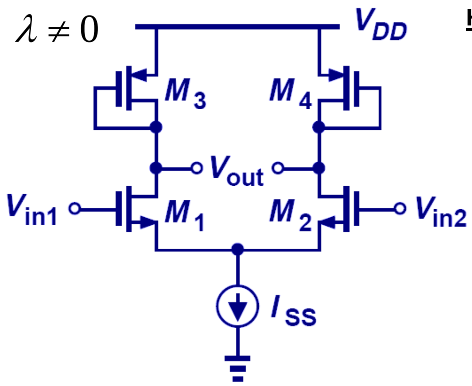
$$\omega_{p,X} = \frac{1}{R_S[C_{GS1} + (1 + g_{m1}/g_{m3})C_{GD1}]}$$

$$\omega_{p,Y} = \frac{1}{\frac{1}{g_{m3}}\left[C_{GS3} + C_{GD1}\left(1 + \frac{g_{m3}}{g_{m1}}\right) + C_{DB1} + C_{SB3}\right]}$$

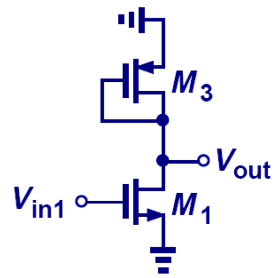
$$\omega_{p,out} = \frac{1}{R_D\left(C_{GD3} + C_{DB3}\right)}$$

Half Circuit Example 1

$\lambda \neq 0$



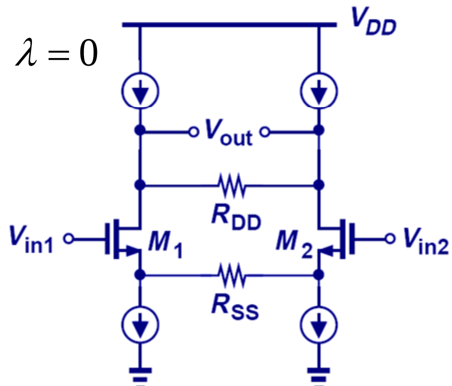
Half circuit for small-signal analysis



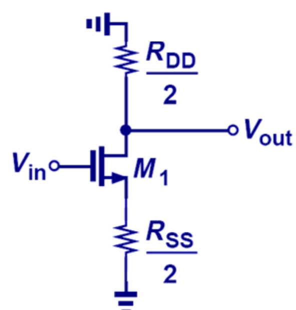
$$A_v = -g_{m1}\left(\frac{1}{g_{m3}} \| r_{O3} \| r_{O1}\right)$$

Half Circuit Example 2

$\lambda = 0$

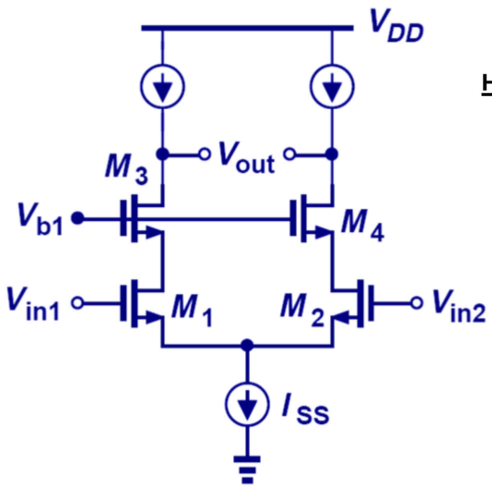


Half circuit for small-signal analysis

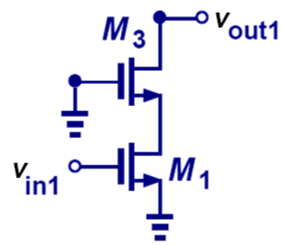


$$A_v = -\frac{R_{DD}/2}{(1/g_m) + (R_{SS}/2)}$$

MOSFET Cascode Differential Pair



Half circuit for small-signal analysis



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

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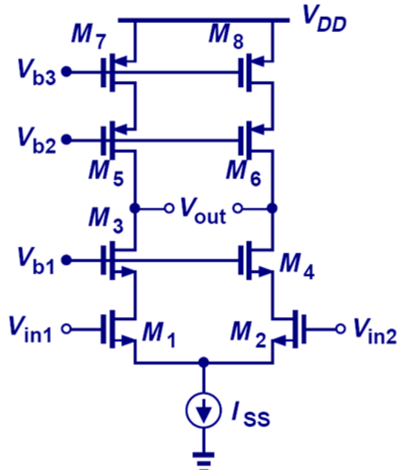
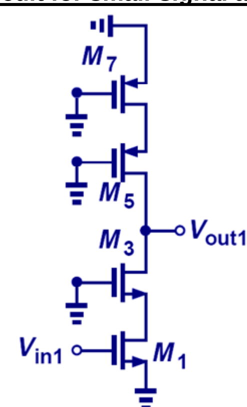
MOSFET Telescopic Cascode Amplifier



Half circuit for small-signal analysis



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

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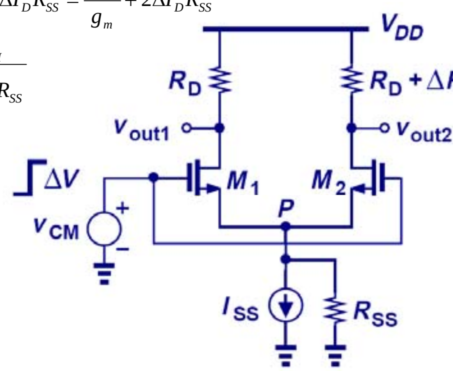
CM to DM Conversion Gain, $A_{CM\text{-}DM}$

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

$$\Delta V_{CM} = \Delta V_{GS} + 2\Delta I_D R_{SS} = \frac{\Delta I_D}{g_m} + 2\Delta I_D R_{SS}$$

$$\Rightarrow \Delta I_D = \frac{\Delta V_{CM}}{\frac{1}{g_m} + 2R_{SS}}$$



$$\Delta V_{out1} = -\Delta I_D R_D$$
$$\Delta V_{out2} = -\Delta I_D (R_D + \Delta R_D)$$
$$\Delta V_{out} = \Delta V_{out1} - \Delta V_{out2} = -\Delta I_D \Delta R_D$$

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

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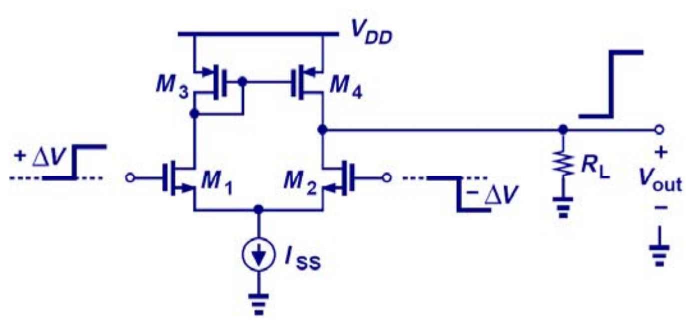
MOS Diff. Pair with Active Load

- Similarly to its BJT counterpart, a MOSFET differential pair can use an active load to enhance its single-ended output.



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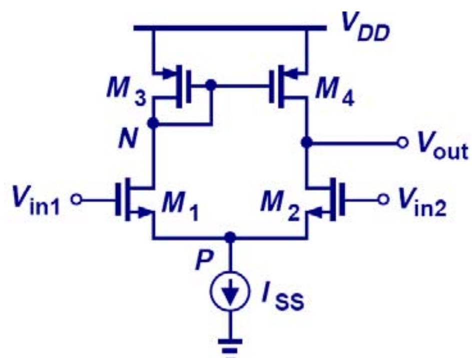
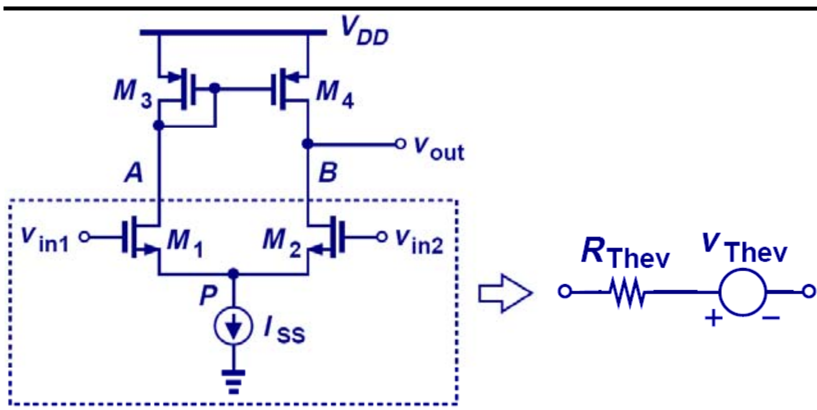
Asymmetric Differential Pair

- Because of the vast difference in magnitude of the resistances seen at the drains of M_1 and M_2, the voltage swings at these two nodes are different and therefore node P cannot be viewed as a virtual ground…

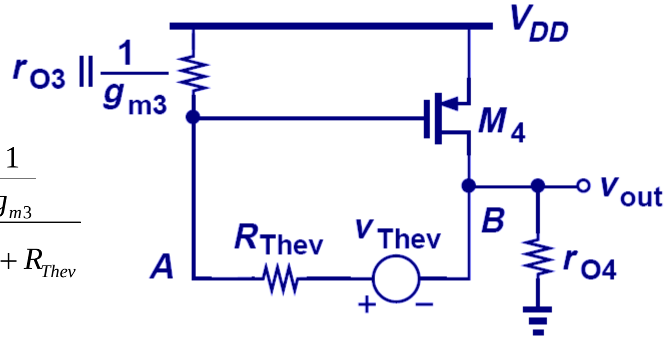


Thevenin Equivalent of the Input Pair



$$v_{Thev} = -g_{mN} r_{oN} (v_{in1} - v_{in2})$$
$$R_{Thev} = 2r_{oN}$$

Simplified Diff. Pair w/ Active Load



$$v_A = \left(v_{out} + v_{Thev}\right) \frac{\frac{1}{g_{m3}}}{\frac{1}{g_{m3}} + R_{Thev}}$$

$$\approx \frac{v_{out} + v_{Thev}}{g_{m3} \cdot 2r_{oN}}$$

$$\text{KCL at } v_{out}: \; g_{m4} v_A + \frac{v_{out}}{r_{o4}} + \frac{v_{out} + v_{Thev}}{\frac{1}{g_{m3}} + R_{Thev}} = 0$$

$$\frac{v_{out}}{v_{in1} - v_{in2}} = g_{mN}(r_{ON} \| r_{OP})$$