CHAPTER 5

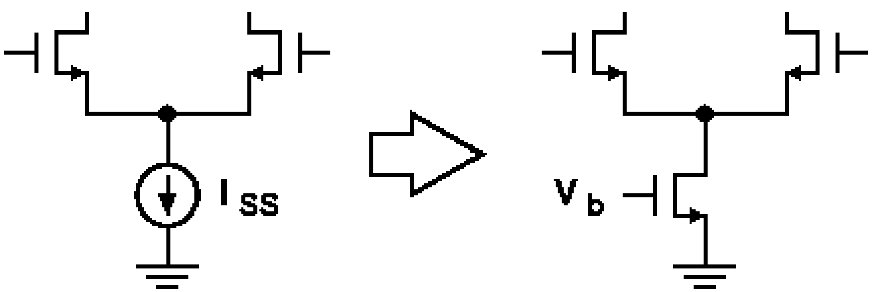
# Current Mirror

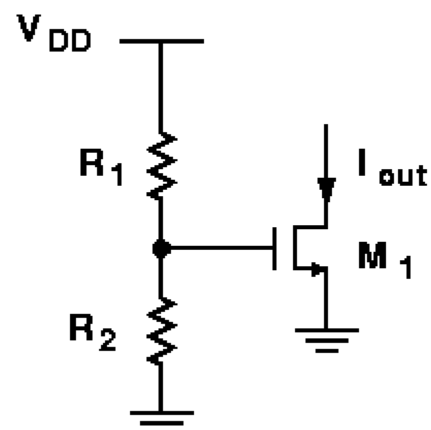
# Outline

1. **Basic Current Mirrors**
2. Cascode Current Mirrors
3. Active Current Mirrors

# Current Source Issues

- Design issues
  - Voltage headroom.
  - Output impedance.
  - Supply, process, and temperature dependence.
  - Matching.



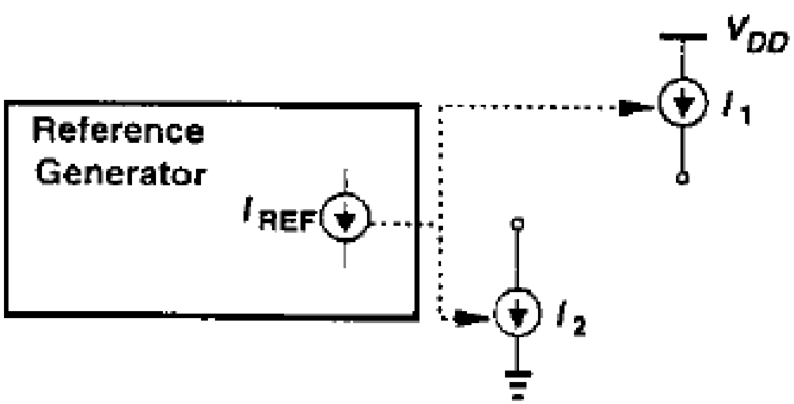



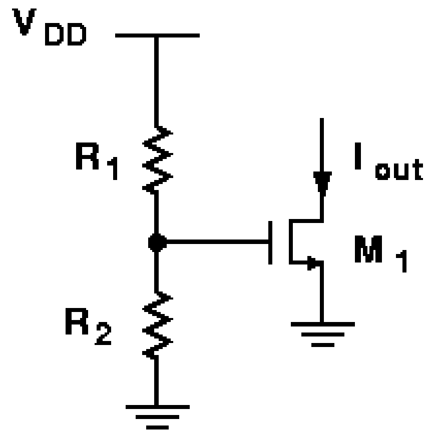

$$I_{out} \approx \frac{1}{2}\mu_n C_{ox}\frac{W}{L}\left(\frac{R_2}{R_1+R_2}V_{DD}-V_{TH}\right)^2$$

# Current Source with Constant $V_b$

- Depending on supply, process, and temperature.
- The threshold voltage may vary by 100 mV from wafer to wafer.
- Both $\mu_n$ and $V_{TH}$ exhibit temperature dependence.
- The issue becomes more severe as the device is biased with a smaller overdrive voltage. (200mV $V_{ov}$, 50mV $\Delta V_{TH}$ cause 44% error)
- If the gate-source voltage of a MOSFET is precisely defined, then its drain current is not.

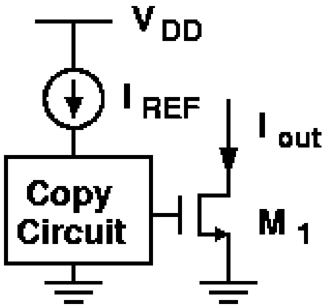
  → Copying currents from a reference.

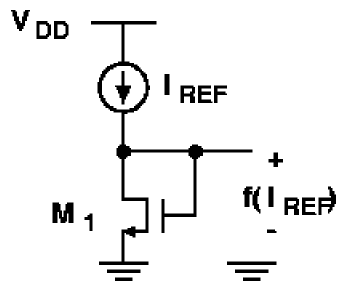


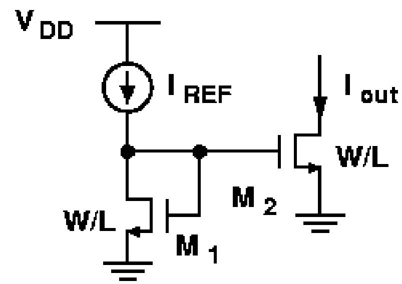



# Basic Current Mirror

- For $I_{out} = I_{REF}$




$$V_{GS} = f^{-1}(I_{REF})$$

$$f f^{-1}(I_{REF}) = I_{REF}$$

$$I_{REF} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_1 (V_{GS} - V_{TH})^2$$

$$I_{out} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_2 (V_{GS} - V_{TH})^2$$

$$\frac{I_{out}}{I_{REF}} = \frac{(W/L)_2}{(W/L)_1}$$

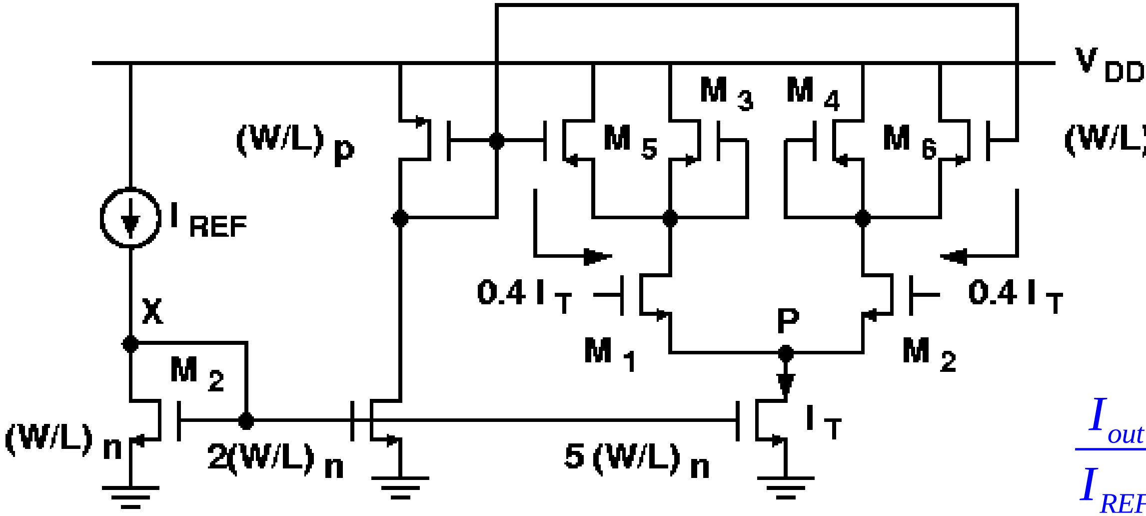
- It allows precise copying of the current with no dependence on process and temperature.

# Current Mirror: Sink & Source

- Current mirrors employ the same length for all of the transistors so as to minimize errors due to the side diffusion of the source and drain areas.

$$L_{eff} = L_{drawn} - 2L_D$$

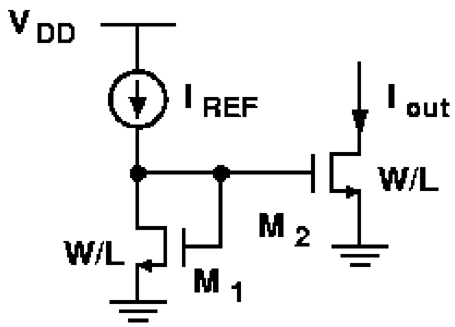
- Current ratio by only scaling the width of transistors.




$$\frac{I_{out}}{I_{REF}} = \frac{(W/L)_2}{(W/L)_1}, \quad L_1 = L_2$$

# Current Mirror with $r_o$

- Channel length modulation effect results in significant error in copying currents.




$$I_{D1} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_1 (V_{GS} - V_{TH})^2 (1 + \lambda \mathrm{V}_{\mathrm{DS1}}), \qquad I_{D2} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_2 (V_{GS} - V_{TH})^2 (1 + \lambda \mathrm{V}_{\mathrm{DS2}})$$

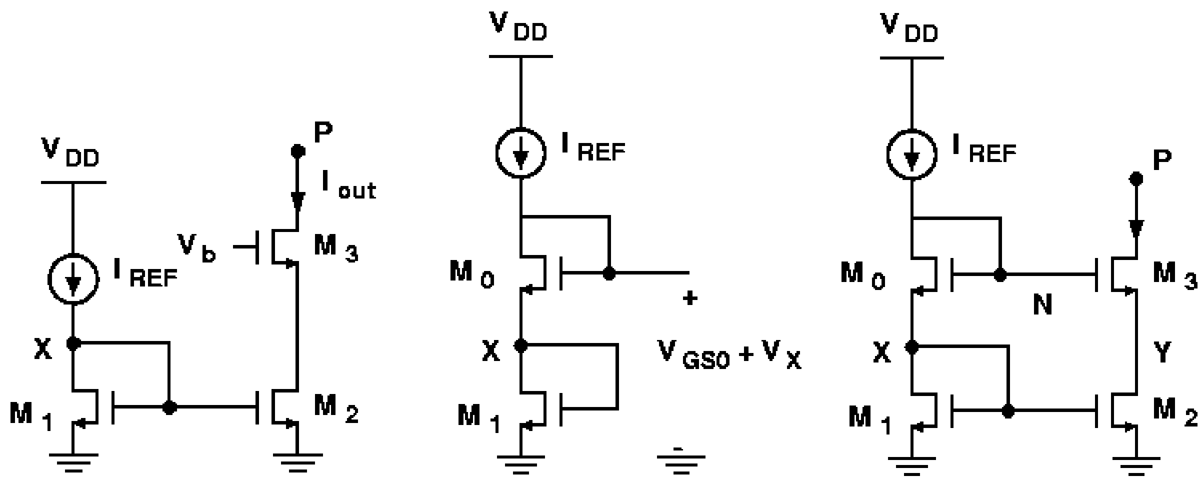
- As $\frac{I_{D2}}{I_{D1}} = \frac{(W/L)_2}{(W/L)_1}\frac{1+\lambda V_{DS2}}{1+\lambda V_{DS1}}$, for $I_{D1} = I_{D2}$, $V_{DS1}$ must be equal to $V_{DS2}$.

- Use cascode structure to improve the ratio accuracy of current mirror.

# Outline

1. Basic Current Mirrors
2. **Cascode Current Mirrors**
3. Active Current Mirrors

# Cascode Current Mirror




- $V_b$ is chosen such that $V_Y = V_X$.

$$V_b - V_{GS3} = V_X, \quad V_b = V_{GS3} + V_X, \quad V_N = V_{GS0} + V_X$$

$$\text{if} \quad \frac{(W/L)_3}{(W/L)_0} = \frac{(W/L)_2}{(W/L)_1}, \quad \text{then} \quad V_{GS0} = V_{GS3} \quad \text{and} \quad V_X = V_Y$$

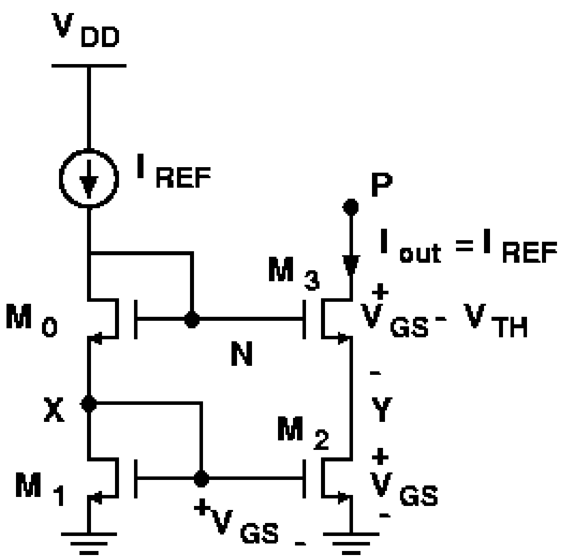
- Such accuracy is obtained at the cost of the voltage headroom consumed by $M_3$.

# Cascode Current Mirror

- The minimum allowable voltage at node P is equal to

$$V_N - V_{TH} = V_{GS1} + V_{GS0} - V_{TH}$$
$$= (V_{GS1} - V_{TH}) + (V_{GS0} - V_{TH}) + V_{TH}$$

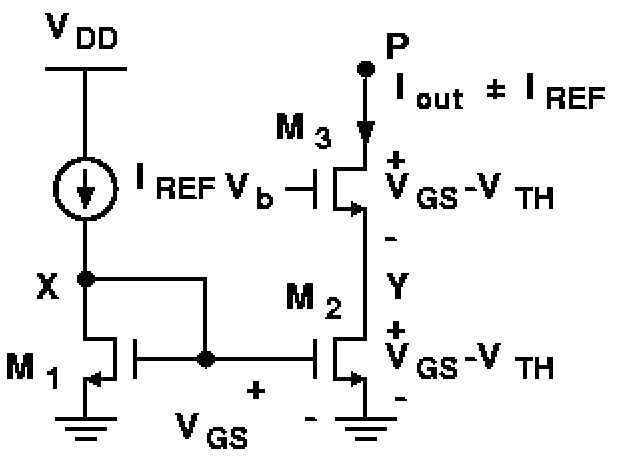
- The voltage of $V_N = V_{GS1} + V_{GS0}$




- For $M_2$ to be in saturation region, $V_b$ can be chosen as low as

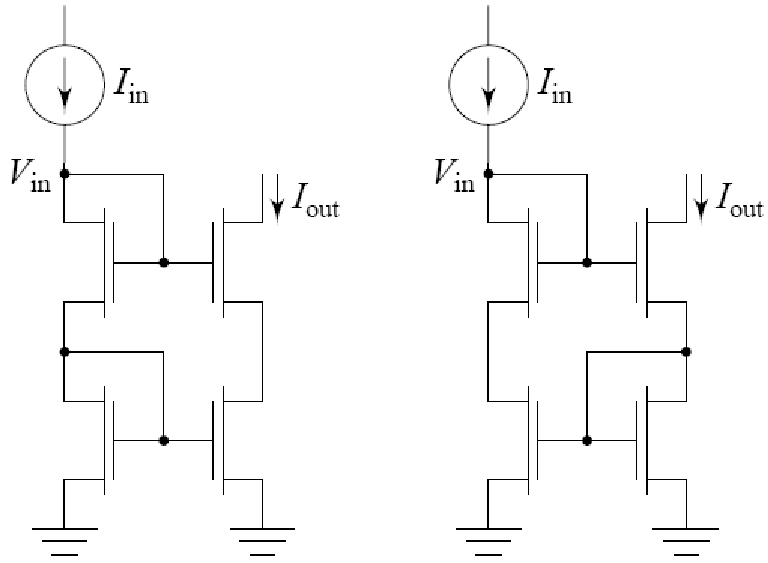
$$V_b = V_{GS3} + V_{DS2}$$

- But the output current does not accurately track $I_{REF}$.



# Cascode Current Mirror

- Each of these mirrors is self biasing, has a high output impedance, and provides a low systematic transfer error.
- Each requires an input voltage of two diode drops.
- Each has an output compliance voltage of a diode drop plus a saturation voltage.
- Neither is suitable for use with a low power supply voltage.

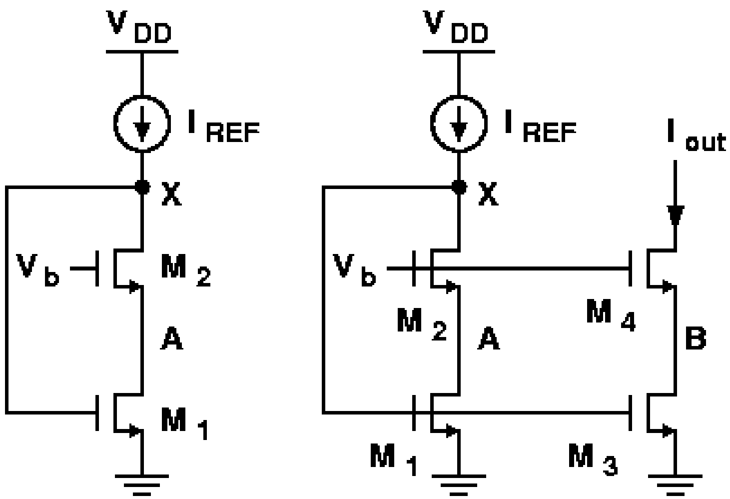



Stacked

Super Wilson

# Wide-Swing Cascode Current Mirror

- To eliminate the accuracy-headroom trade-off.




- For M2 to be saturated

$$V_b - V_{TH2} \le V_X (= V_{GS1})$$

- For M1 to be saturated

$$V_{GS1} - V_{TH1} \le V_A (= V_b - V_{GS2})$$

- Thus

$$V_{GS2} + (V_{GS1} - V_{TH1}) \le V_b \le V_{GS1} + V_{TH2}$$

- A solution exist if

$$V_{GS2} + (V_{GS1} - V_{TH1}) \le V_{GS1} + V_{TH2} \Rightarrow V_{GS2} - V_{TH2} \le V_{TH1}$$

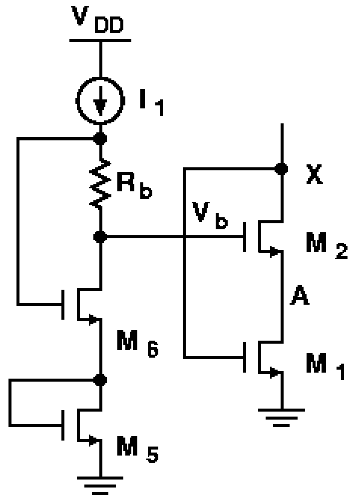
- Let

$$V_{GS2} = V_{GS4} \Rightarrow V_b = V_{GS2} + (V_{GS1} - V_{TH1}) = V_{GS4} + (V_{GS3} - V_{TH3})$$

# Wide-Swing Cascode Current Mirror

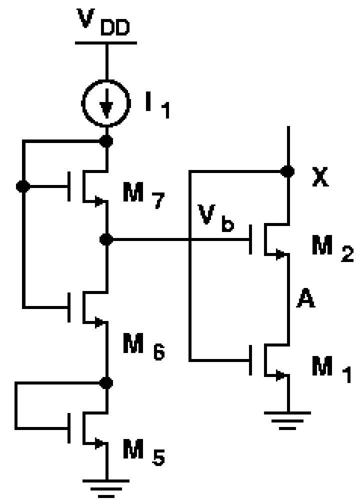
- Generation of biased voltage $V_b$
  - Let

$$V_{GS5} \approx V_{GS2}$$
$$V_{DS6} = V_{GS6} - I_1 R_b = V_{DS1}$$
$$\Rightarrow If \quad V_{GS6} = V_{GS1}$$
$$\Rightarrow I_1 R_b = V_{TH6} = V_{TH1}$$




  - Some inaccuracy arises because $M_5$ does not suffer from body effect whereas $M_2$ does.
  - $I_1 R_b$ is not well controlled.
- The diode connected M7 has a large W/L such that

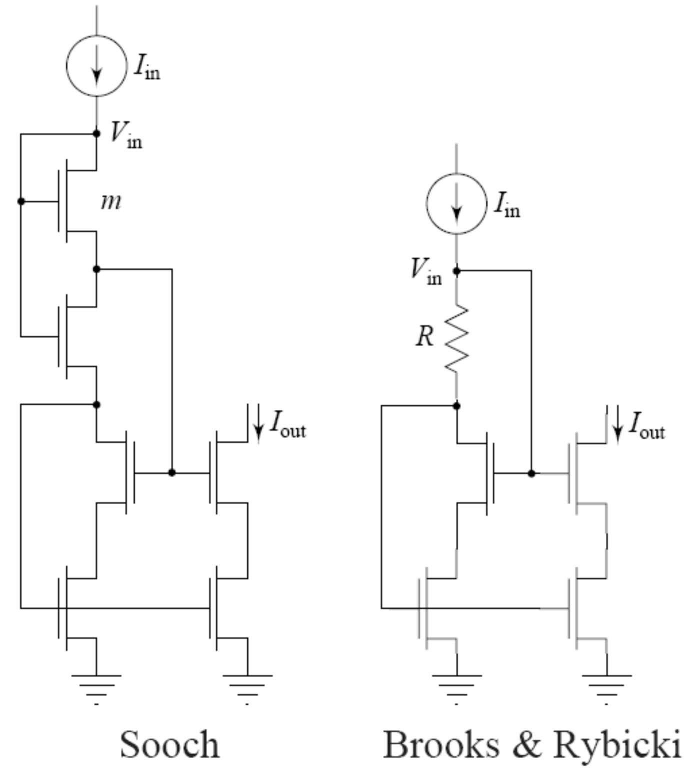
$$V_{GS7} \approx V_{TH7}$$
$$V_{DS6} \approx V_{GS6} - V_{TH7}$$
$$V_b = V_{GS5} + V_{GS6} - V_{TH7}$$




  - This circuit suffers from similar errors due to body effect.

# Wide-Swing Cascode Current Mirror

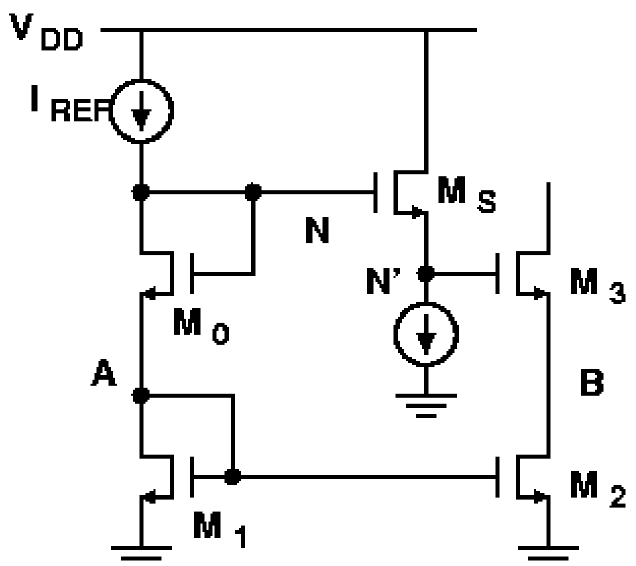
- All Self biasing, has a high output impedance, and provides a low systematic transfer error.
- Each has an output compliance voltage of two saturation voltages.
- The Sooch mirror requires an input voltage of two diode drops, which makes it unsuitable for low-voltage applications.
- The Brooks-Rybicki mirror requires an input voltage of a diode drop plus a saturation voltage, but requires a different value of *R for every* $I_{in}$.



# Wide-Swing Cascode + SF Level Shifter

- Shift the gate voltage of $M_3$ down with respect to $V_N$ by interposing a source follower.
- Let $M_S$'s $V_{GSs} = V_{TH3}$ ,

$$V_{N'} \approx V_N - V_{TH3}$$
$$V_B = V_{GS1} + V_{GS0} - V_{TH3} - V_{GS3} = V_{GS1} - V_{TH3}$$




- $M_S$ is biased at a very low current density,

$$V_{GSs} - V_{THs} \approx \sqrt{\frac{2I}{\mu_n C_{ox} W / L}}$$

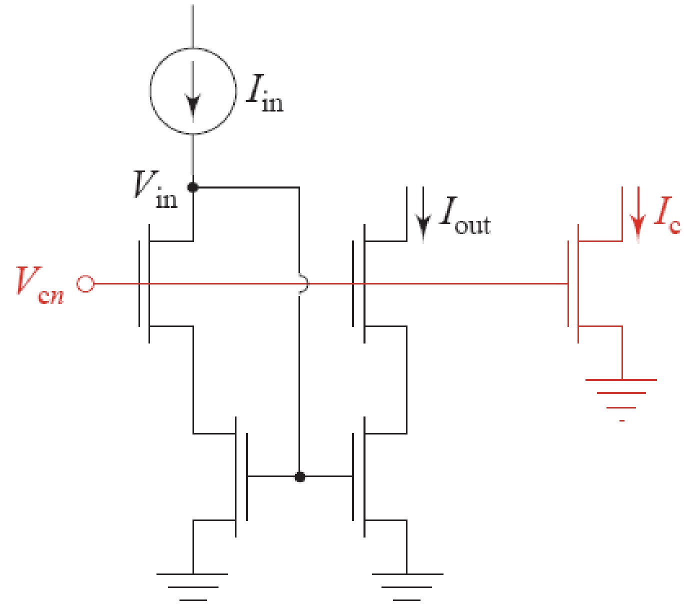
- $M_2$ is at the edge of the saturation region.
- Substantial current mismatch is introduced for

$$V_{DS2} \neq V_{DS1}$$

- If the body effect of $M_0$, $M_S$, and $M_3$ is considered, it is difficult to guarantee that M2 operates in saturation.

# Wide-Swing Cascode Current Mirror

- To facilitate low-voltage operation, we can remove the cascode bias-voltage generation from the input branch.
- The output compliance voltage remains twos saturation voltages.
- The input voltage becomes a diode drop, comparable to that of a simple mirror.
- *The optimal value of $V_{cn}$* depends on $I_{in}$, *which sometimes requires us to* generate $V_{cn}$ *adaptively.*

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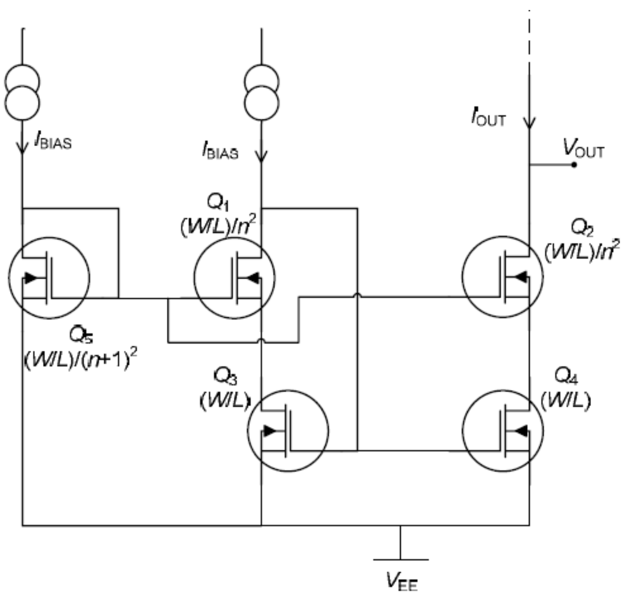
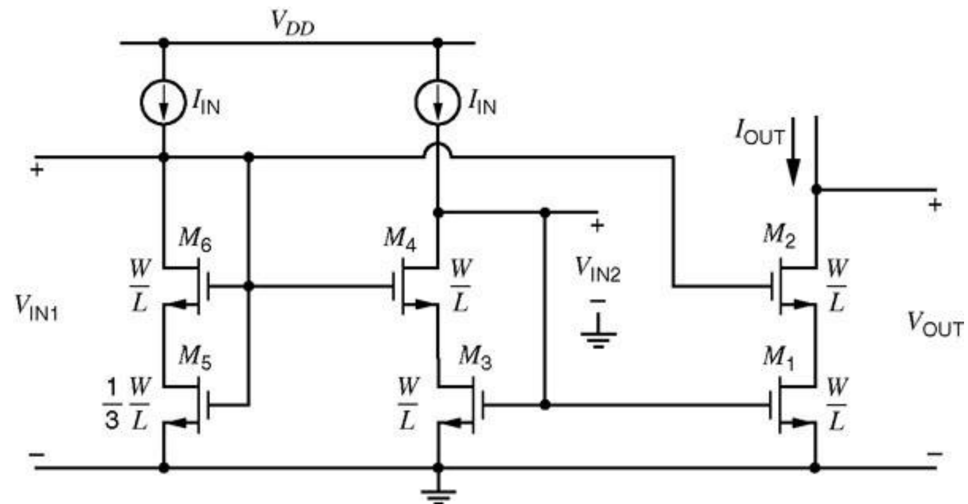
# Wide-Swing Cascode Current Mirror

- $V_{OUT} = V_{DS2} + V_{DS4} = V_{OD2} + V_{OD4}$ *and* $V_{OD4} = nV_{OD2}$
- $V_{OUT\,min} = V_{OD2} + nV_{OD2} = (n+1)V_{OD}$ , Often $n = 1$; $V_{OUT\,min} = 2(V_{GS2} - V_t)$



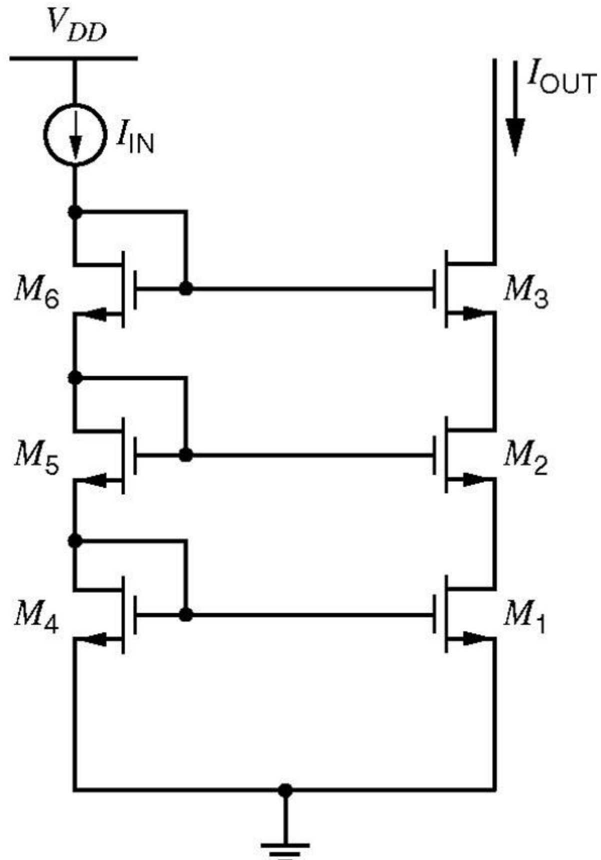




$$V_{IN1} = V_{DS5} + V_{DS6} = V_t + 2V_{OV}$$

$$V_{IN2} = V_{GS3} = V_t + V_{OV}$$

# Double-Cascode Current Mirror

- Higher output impedance, more current ratio accuracy
- Smaller output swing



# Outline

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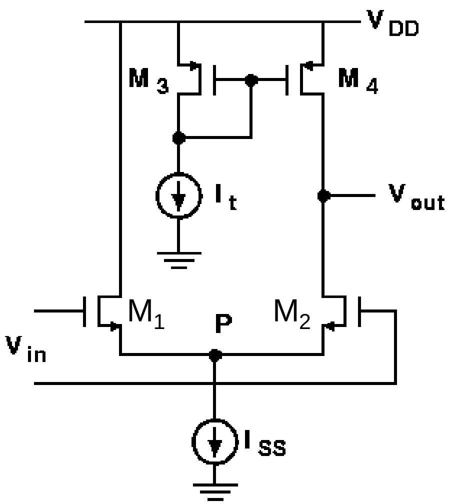
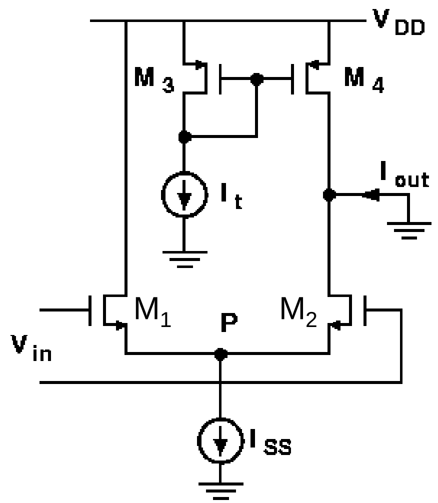
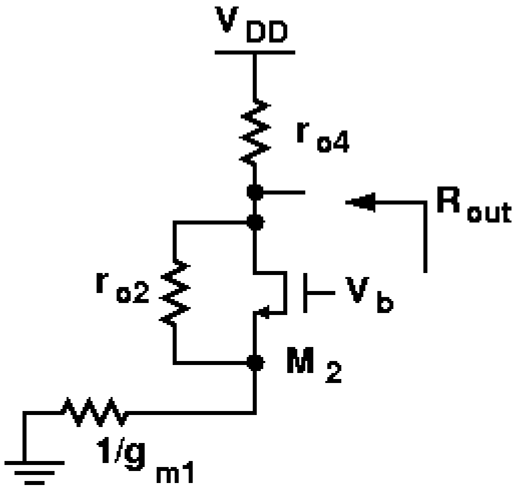
3. **Active Current Mirrors**

# Active Current Mirror

- Current mirror can also process signals




$$|A_V| = G_m R_{out} \quad G_m = \frac{I_{out}}{V_{in}} = \frac{g_{m1} V_{in}/2}{V_{in}} = \frac{g_{m1}}{2}$$

- The output impedance looking into the drain of $M_2$ is

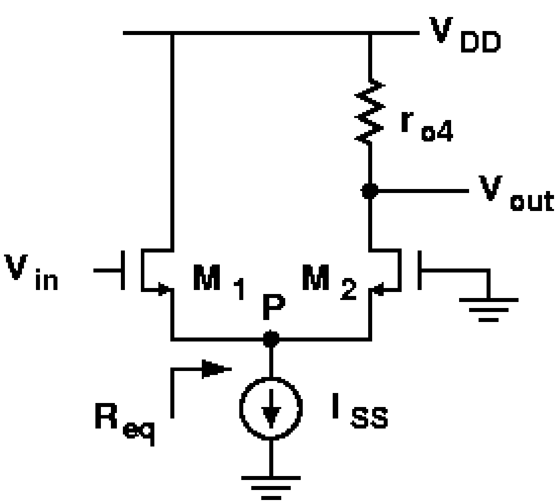
$$(1+g_{m2} r_{O2})(1/g_{m1,2}) + r_{O2} = 2r_{O2} + 1/g_{m1} \approx 2r_{O2}$$

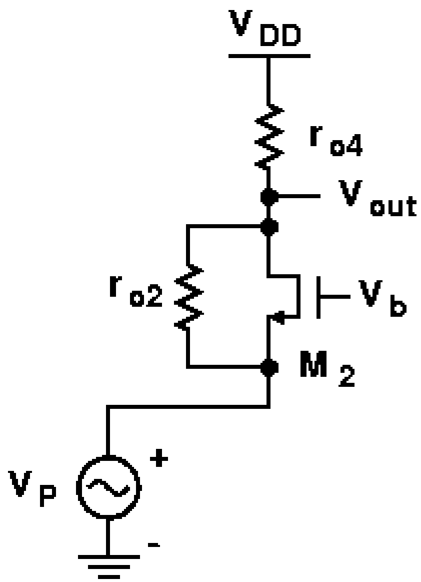
- Thus,

$$R_{out} \approx (2r_{O2}) \| r_{O4} \Rightarrow |A_v| \approx \frac{g_{m1}}{2}\left[(2r_{O2}) \| r_{O4}\right] \text{ If } r_{O4} \to \infty \Rightarrow |A_v| \approx g_{m1} r_{O2}$$

# Active Current Mirror

- *An Alternative Solution*




$$\frac{V_{out}}{V_{in}} = \frac{V_{out}}{V_p}\frac{V_p}{V_{in}} \qquad \frac{V_p}{V_{in}} = \frac{R_{eq}}{R_{eq} + \frac{1}{g_{m1}}}$$

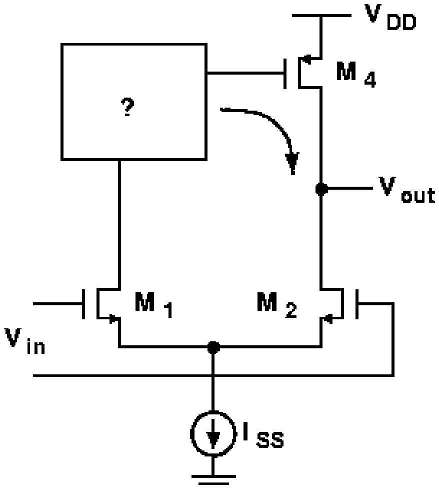
$$R_{eq} \approx \frac{1}{g_{m2}} + \frac{r_{O4}}{g_{m2} r_{O2}} = \frac{1}{g_{m2}}\left(1 + \frac{r_{O4}}{r_{O2}}\right)$$

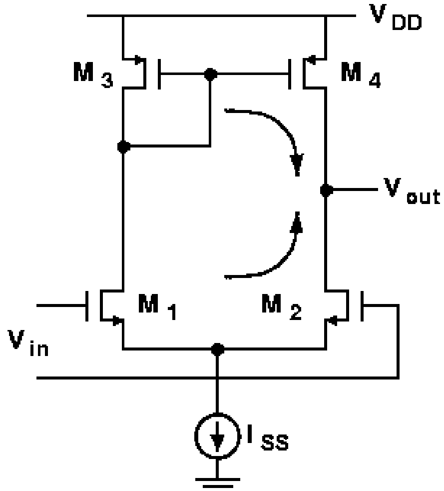
$$\frac{V_P}{V_{in}} = \frac{\frac{1}{g_{m2}}\left(1 + \frac{r_{O4}}{r_{O2}}\right)}{\frac{1}{g_{m1}} + \frac{1}{g_{m2}}\left(1 + \frac{r_{O4}}{r_{O2}}\right)} = \frac{1 + \frac{r_{O4}}{r_{O2}}}{2 + \frac{r_{O4}}{r_{O2}}}$$

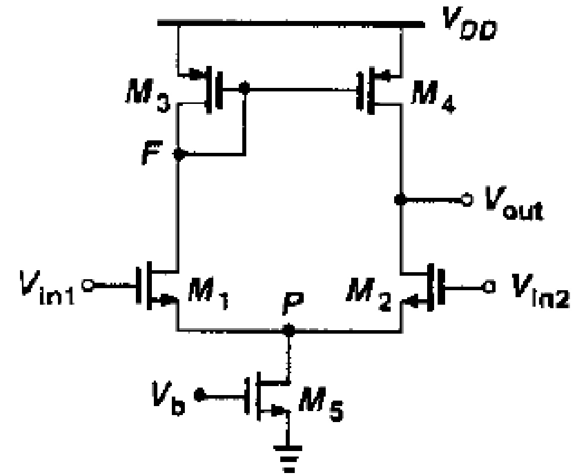
$$\frac{V_{out}}{V_{in}} = \frac{1 + \frac{r_{O4}}{r_{O2}}}{2 + \frac{r_{O4}}{r_{O2}}} \cdot \frac{g_{m2} r_{O2}}{1 + \frac{r_{O2}}{r_{O4}}} = \frac{g_{m2} r_{O2} r_{O4}}{2 r_{O2} + r_{O4}} = \frac{g_{m2}}{2}\left[\left(2 r_{O2}\right) \| r_{O4}\right]$$

# Differential to Single-Ended Amplifier

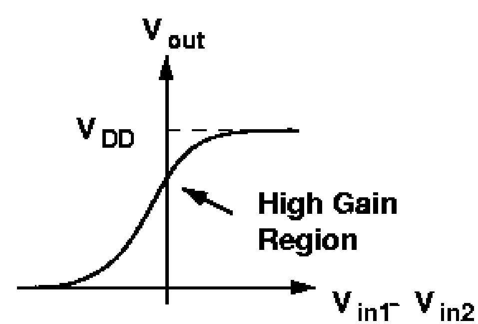
- Current combination utilizing current mirror.



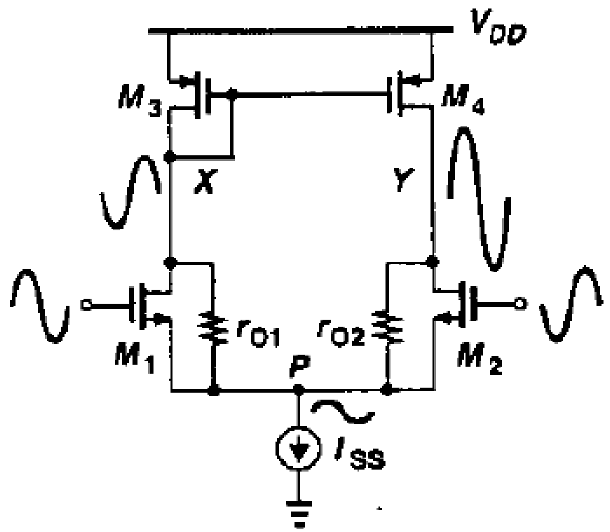




- If $V_{in1}$ is much more negative than $V_{in2}$, $M_1$ is off and so are $M_3$ and $M_4$. Both $M_2$ and $M_5$ operate in deep triode region.
- For a small $|V_{in1} - V_{in2}|$, $M_1 – M_4$ are saturated => high gain
- The minimum input voltage level of $V_{in2} = V_{GS1,2}+V_{DS5,min}$
- With perfect symmetry, $V_{out} = V_F = V_{DD} - |V_{GS3}|$ .
- But $V_{out}$ can vary a lot if device mismatches occur.

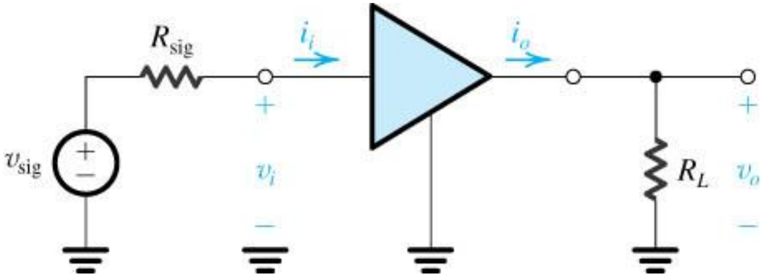


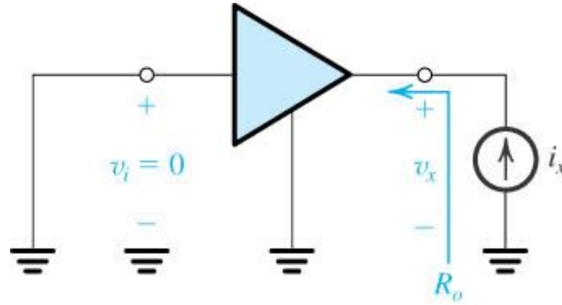
# Small-Signal Analysis

- Node "P" is not a virtual ground since amplitude of $V_X \neq V_Y$




- Find $G_m$ and $R_{out}$, $|A_v| = G_m R_{out}$,




*Short-circuit Transconductance*

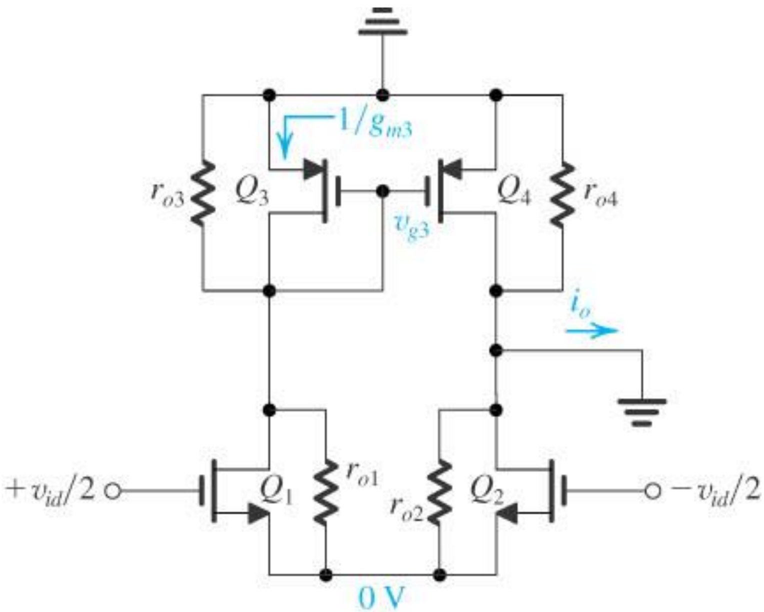
$$G_m \equiv \left.\frac{i_o}{v_i}\right|_{R_L=0}$$

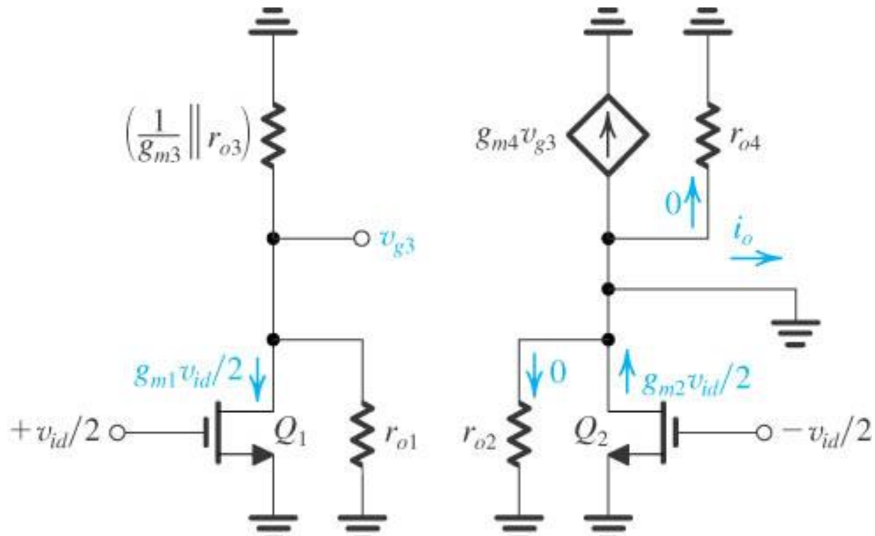
*Output resistance of amplifier proper*

$$R_o \equiv \left.\frac{v_x}{i_x}\right|_{v_i=0}$$

# Transconductance $G_m$

- The impedance from Q1 drain to ground is small, it makes source node as virtual ground.




$$R_{Q_1-Drain}=\frac{1}{g_{m3}}\parallel r_{o3}\parallel r_{o1}$$

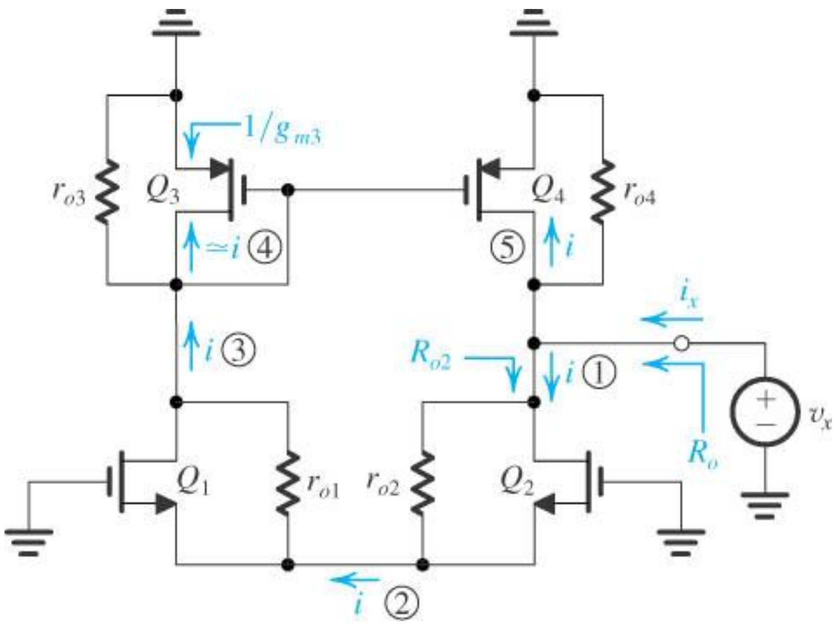
$$v_{g3}=-g_{m1}\left(\frac{v_{id}}{2}\right)\left(\frac{1}{g_{m3}}\parallel r_{o3}\parallel r_{o1}\right)\approx-\left(\frac{g_{m1}}{g_{m3}}\right)\left(\frac{v_{id}}{2}\right)$$

$$i_o=-g_{m4}v_{g3}+g_{m2}(v_{id}/2)$$

$$i_o=g_{m1}\left(\frac{g_{m4}}{g_{m3}}\right)\left(\frac{v_{id}}{2}\right)+g_{m2}\left(\frac{v_{id}}{2}\right)$$

$$g_{m3}=g_{m4},\ g_{m1}=g_{m2}=g_m,\ i_o=g_m v_{id},\ G_m=g_m$$

# Determining the Output Resistance $R_o$




$$R_{o2} = r_{o2} + (1 + g_{m2} r_{o2})(1/g_{m1}) \approx 2r_{O2}$$

$$For \quad g_{m1} = g_{m2} = g_m , \qquad g_{m2} r_{O2} >> 1$$

$$\Rightarrow \quad R_{o2} \cong 2r_{O2}$$

$$i_x = \frac{v_x}{R_{o2}} + \frac{v_x}{r_{o4}}$$

$$R_o = R_{o2} \parallel r_{o4} \cong \frac{1}{2} r_o$$

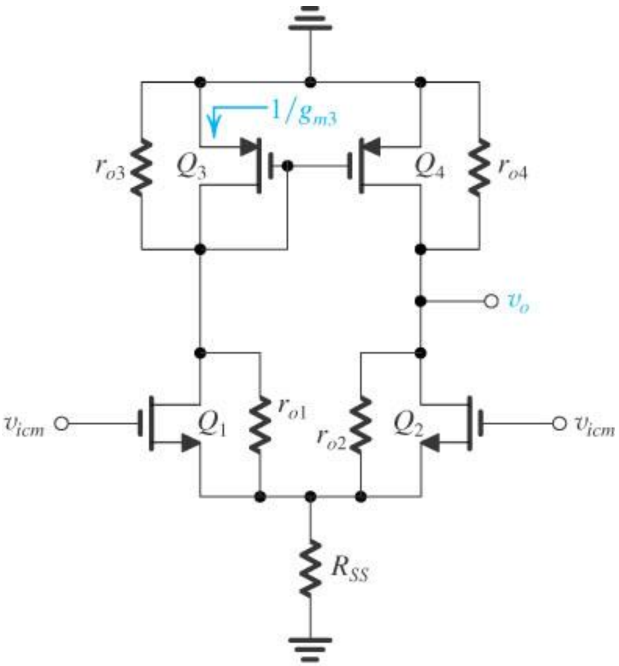
- $G_m = g_{m1.2} \cong g_m, R_{out} = R_o \cong \frac{1}{2} r_o$
- $|A_v| = G_m R_{out} = g_m \left[ (2r_{O2}) \parallel r_{O4} \right] \cong \frac{1}{2} g_m r_o$

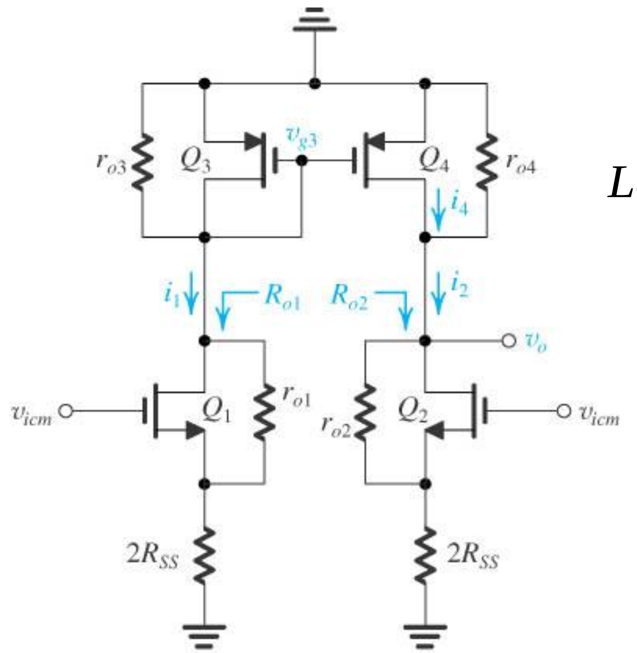
compared to p.21

$$A_v = \frac{g_{m2}}{2} \left[ (2r_{O2}) \parallel r_{O4} \right],$$

6dB improved

# Common-Mode Gain and CMRR




$$i_1 = i_2 \cong \frac{v_{icm}}{2R_{SS}}$$

$$Let \quad r_{o1} = r_{o2} = r_o \quad g_{m1} = g_{m2} = g_m$$

$$R_{o1} = R_{o2} = r_o + 2R_{SS} + 2g_m r_O R_{SS}$$

$$v_{g3} = -i_1\left(\frac{1}{g_{m3}} \parallel r_{O3}\right)$$

$$i_4 = -g_{m4} v_{g3} = i_1 g_{m4}\left(\frac{1}{g_{m3}} \parallel r_{O3}\right)$$

$$v_O = (i_4 - i_2) r_{O4} = \left[i_1 g_{m4}\left(\frac{1}{g_{m3}} \parallel r_{O3}\right) - i_2\right] r_{O4}$$

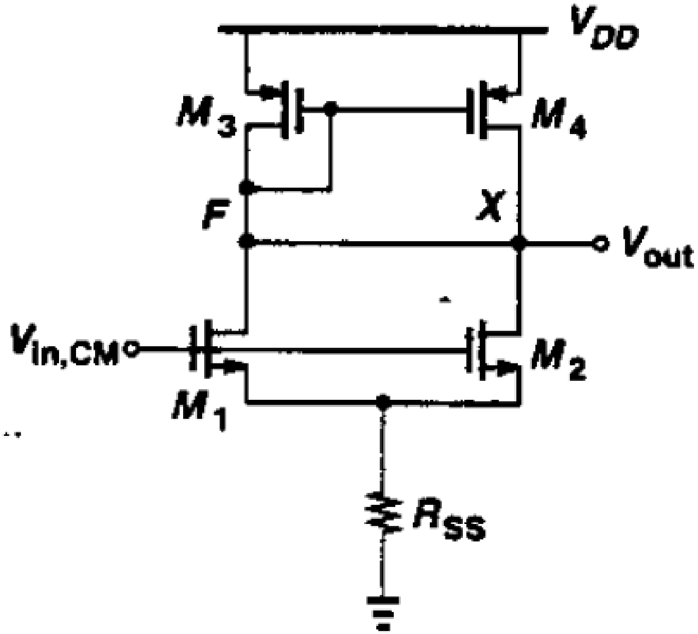
$$A_{cm} \equiv \frac{v_o}{v_{icm}} = -\frac{1}{2R_{SS}} \frac{r_{o4}}{1 + g_{m3} r_{o3}} \approx -\frac{1}{2g_{m3} R_{SS}}$$

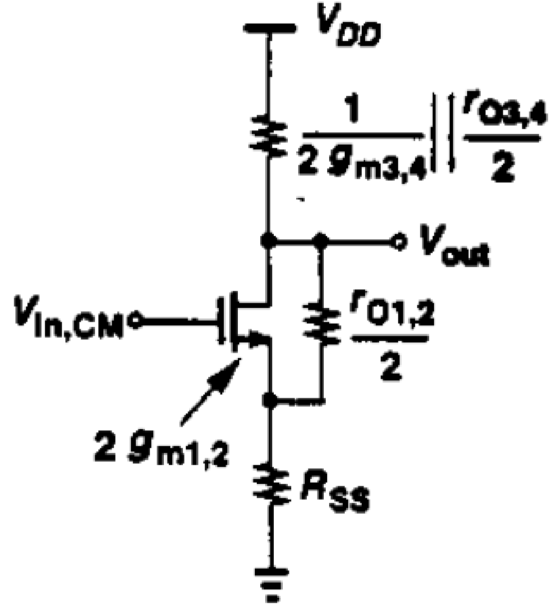
$$CMRR \equiv \frac{|A_d|}{|A_{cm}|} = [g_m (r_{O2} \parallel r_{O4})][2g_{m3} R_{SS}]$$

$$CMRR = (g_m r_o)(g_m R_{SS})$$

- The active-loaded MOS differential amplifier has a low $A_{cm}$ and a high CMRR.

# Common-Mode Gain Cont.

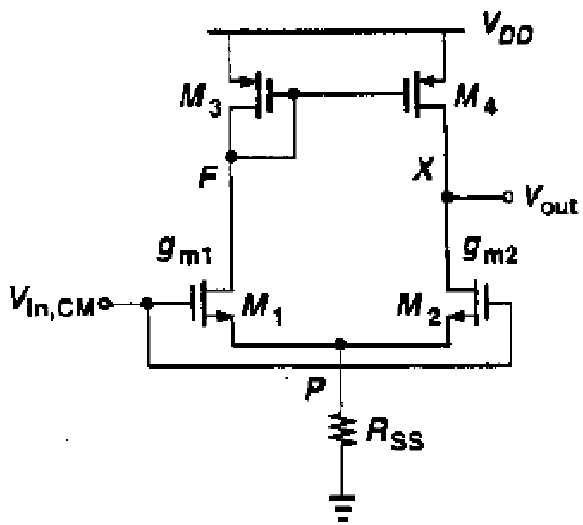


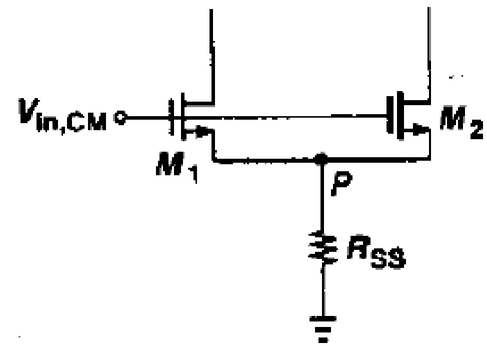




$$A_{CM} \approx \frac{-\frac{1}{2g_{m3,4}} \| \frac{r_{o3,4}}{2}}{\frac{1}{2g_{m1,2}} + R_{SS}} = \frac{-1}{1+2g_{m1,2}R_{SS}} \frac{g_{m1,2}}{g_{m3,4}}$$

# Differential Pair with $g_m$ Mismatch

- Voltage change at *P* can be obtained by considering $M_1$ and $M_2$ as a single transistor in a SF configuration.




$$\Delta V_P = \Delta V_{in,CM}\frac{R_{SS}}{R_{SS}+\dfrac{1}{g_{m1}+g_{m2}}}$$

$$\Delta I_{D1} = g_{m1}\left(\Delta V_{in,CM}-\Delta V_P\right)=\frac{\Delta V_{in,CM}}{R_{SS}+\dfrac{1}{g_{m1}+g_{m2}}}\frac{g_{m1}}{g_{m1}+g_{m2}},\quad \Delta I_{D2}= g_{m2}\left(\Delta V_{in,CM}-\Delta V_P\right)=\frac{\Delta V_{in,CM}}{R_{SS}+\dfrac{1}{g_{m1}+g_{m2}}}\frac{g_{m2}}{g_{m1}+g_{m2}}$$

$$\Delta I_{D4} = \Delta I_{D1}\left(\frac{1}{g_{m3}}\,||\,r_{O3}\right)g_{m4},\quad \Delta V_{out}=\left[\Delta I_{D4}-\Delta I_{D2}\right]r_{O4}=\left[\frac{g_{m1}\Delta V_{in,CM}}{1+\left(g_{m1}+g_{m2}\right)R_{SS}}\frac{r_{O3}}{r_{O3}+\dfrac{1}{g_{m3}}}-\frac{g_{m2}\Delta V_{in,CM}}{1+\left(g_{m1}+g_{m2}\right)R_{SS}}\right]r_{O4}$$

$$\Delta V_{out} = \frac{\Delta V_{in,CM}}{1+\left(g_{m1}+g_{m2}\right)R_{SS}}\frac{\left(g_{m1}-g_{m2}\right)r_{O3}-g_{m2}/g_{m3}}{r_{O3}+\dfrac{1}{g_{m3}}}r_{O4},\quad \frac{\Delta V_{out}}{\Delta V_{in,CM}}\approx\frac{\left(g_{m1}-g_{m2}\right)r_{O3}-g_{m2}/g_{m3}}{1+\left(g_{m1}+g_{m2}\right)R_{SS}}$$