CHAPTER 5

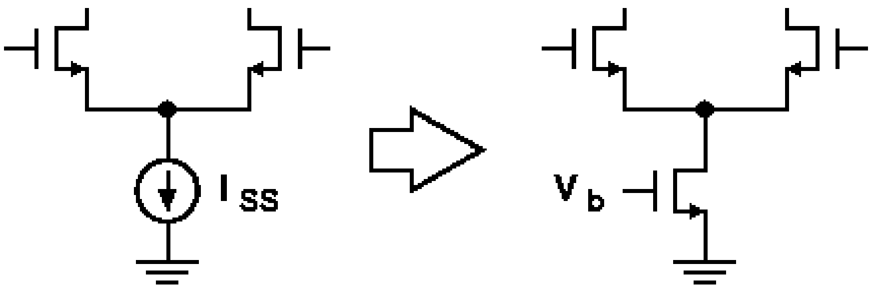
Current Mirror

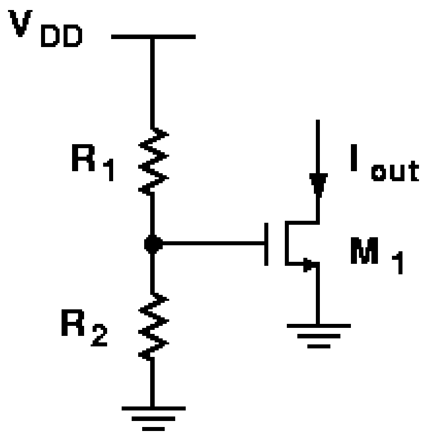
Outline

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.



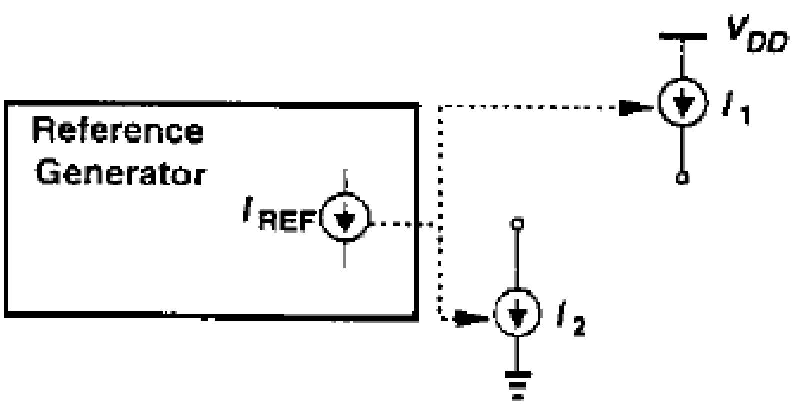


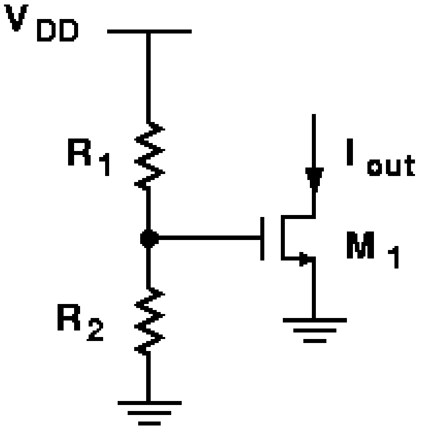
$$I_{out} \approx \frac{1}{2}\mu_n C_{ox}\frac{W}{L}\left(\frac{R_2}{R_1+R_2}V_{DD}-V_{TH}\right)^2$$

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 μ_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 ΔV_{TH} cause 44% error)
- If the gate-source voltage of a MOSFET is precisely defined, then its drain current is not.

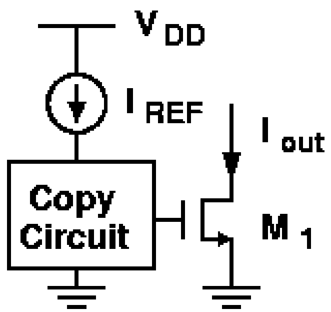
→ Copying currents from a reference.

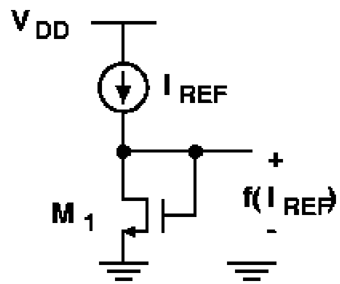


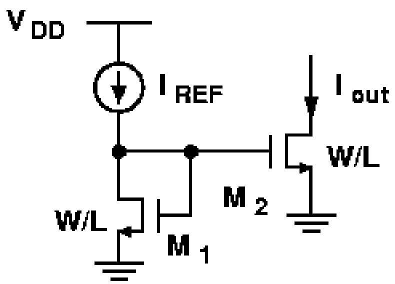


Basic Current Mirror

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







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

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

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

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

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

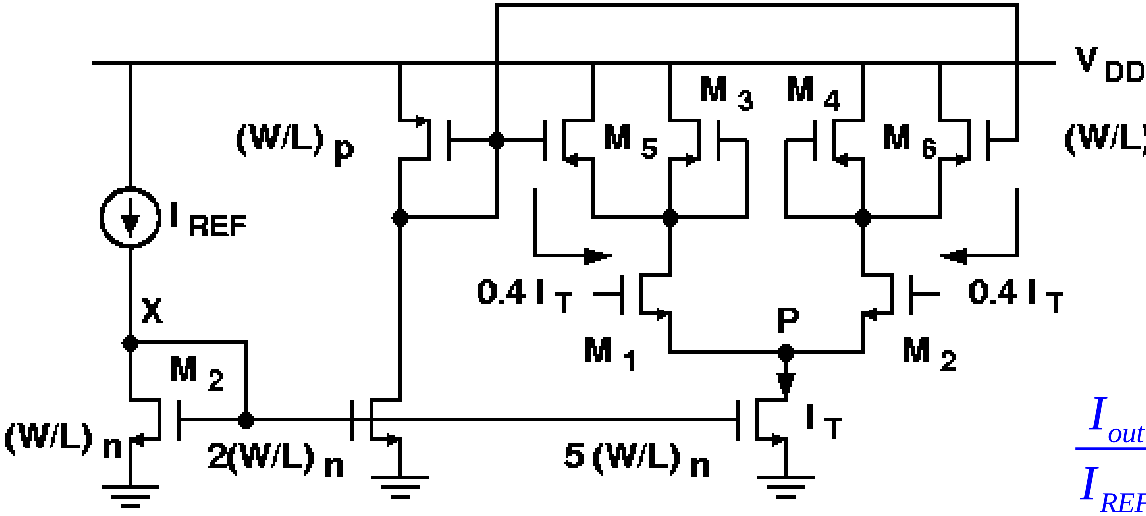
- It allows precise copying of the current with no dependence on process and temperature.

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.

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

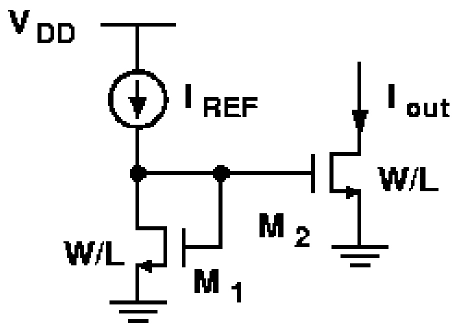
- Current ratio by only scaling the width of transistors.



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

Current Mirror with r_o

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



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

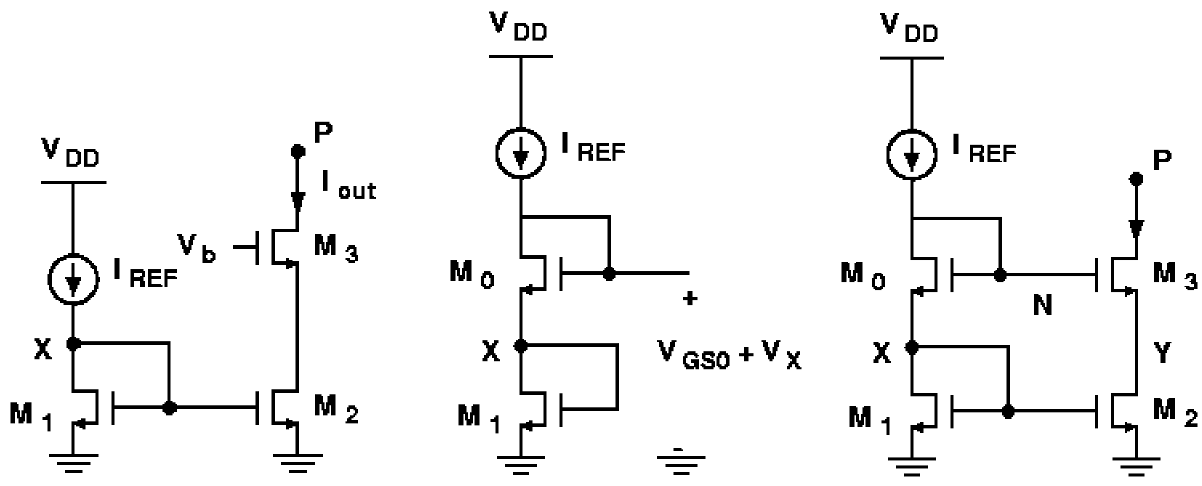
- As $\frac{I_{D2}}{I_{D1}} = \frac{(W/L)_2}{(W/L)_1}\frac{1+\lambda V_{DS2}}{1+\lambda V_{DS1}}$, for $I_{D1} = I_{D2}$, V_{DS1} must be equal to V_{DS2}.

- 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 $V_Y = V_X$.

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

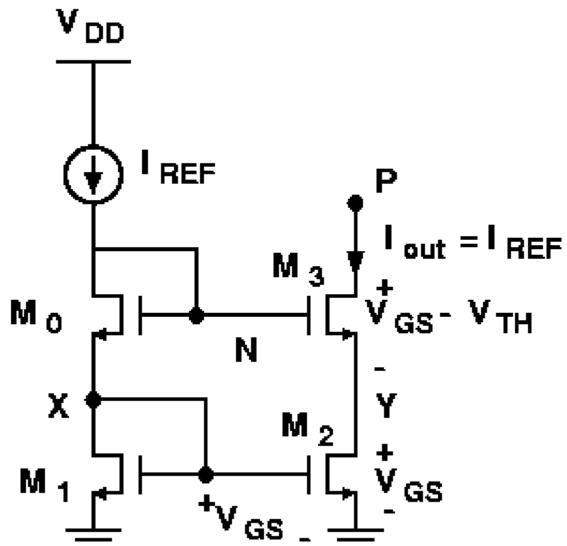
$$\text{if} \quad \frac{(W/L)_3}{(W/L)_0} = \frac{(W/L)_2}{(W/L)_1}, \quad \text{then} \quad V_{GS0} = V_{GS3} \quad \text{and} \quad V_X = V_Y$$

- 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

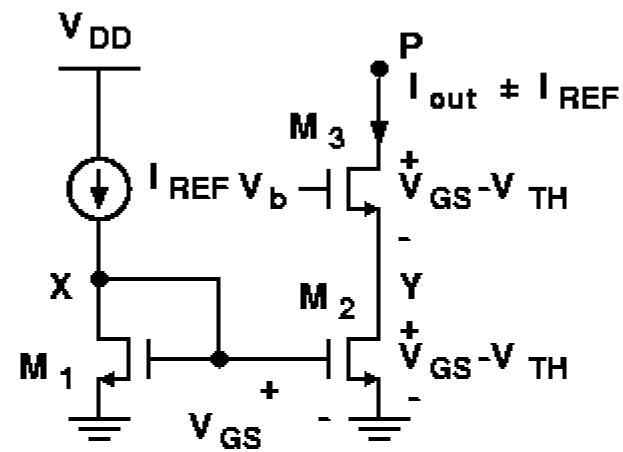
$$V_N - V_{TH} = V_{GS1} + V_{GS0} - V_{TH}$$
$$= \left(V_{GS1} - V_{TH}\right) + \left(V_{GS0} - V_{TH}\right) + V_{TH}$$



- 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

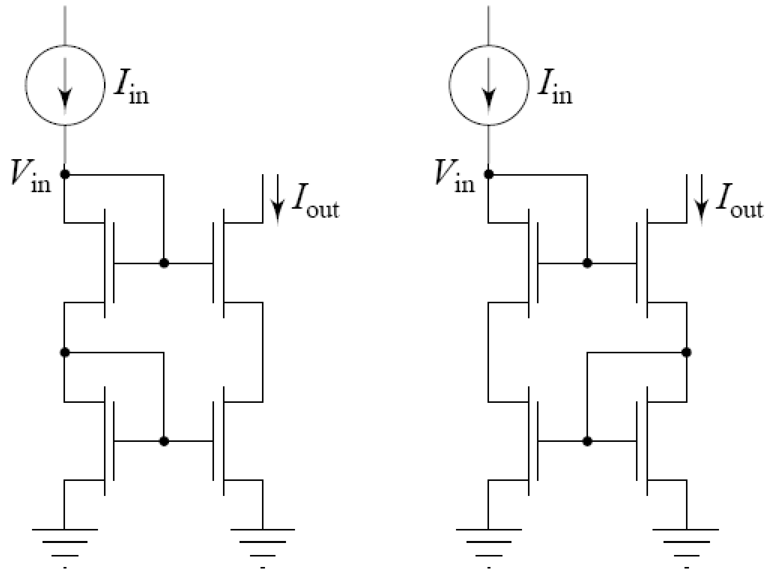
$$V_b = V_{GS3} + V_{DS2}$$



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

Cascode Current Mirror

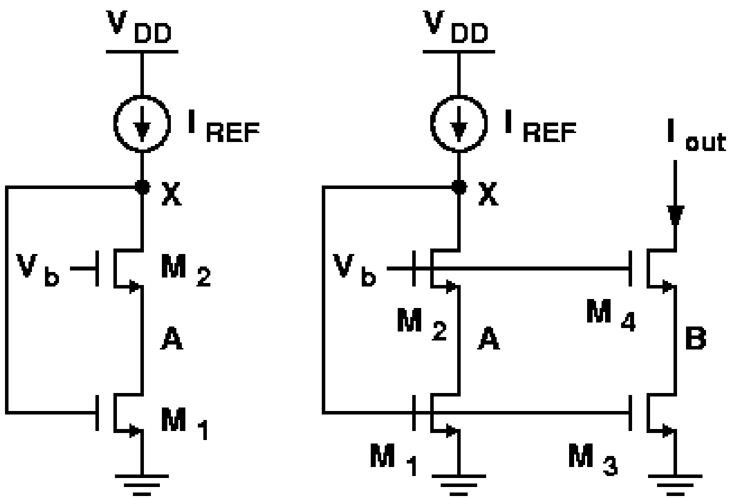
- Each of these mirrors is self biasing, has a high output impedance, and provides a low systematic transfer error.
- Each requires an input voltage of two diode drops.
- Each has an output compliance voltage of a diode drop plus a saturation voltage.
- Neither is suitable for use with a low power supply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

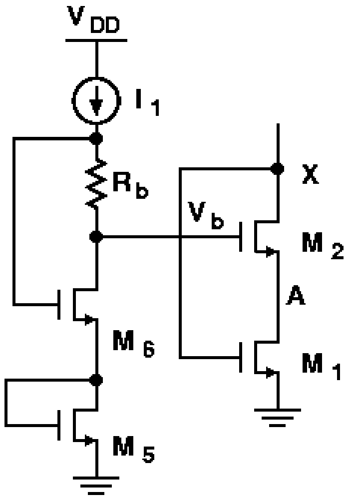
$$V_{GS2} + (V_{GS1} - V_{TH1}) \le V_{GS1} + V_{TH2} \Rightarrow V_{GS2} - V_{TH2} \le V_{TH1}$$

- Let

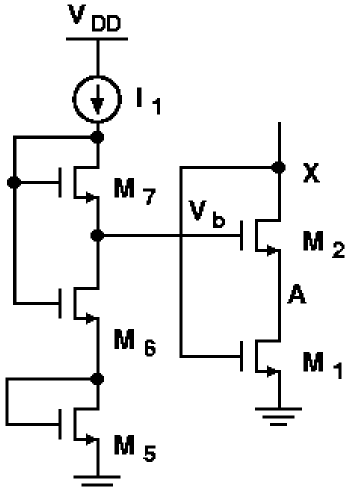
$$V_{GS2} = V_{GS4} \Rightarrow V_b = V_{GS2} + (V_{GS1} - V_{TH1}) = V_{GS4} + (V_{GS3} - V_{TH3})$$

Wide-Swing Cascode Current Mirror

- Generation of biased voltage V_b
  - Let
$$V_{GS5} \approx V_{GS2}$$
$$V_{DS6} = V_{GS6} - I_1 R_b = V_{DS1}$$
$$\Rightarrow If \quad V_{GS6} = V_{GS1}$$
$$\Rightarrow I_1 R_b = V_{TH6} = V_{TH1}$$



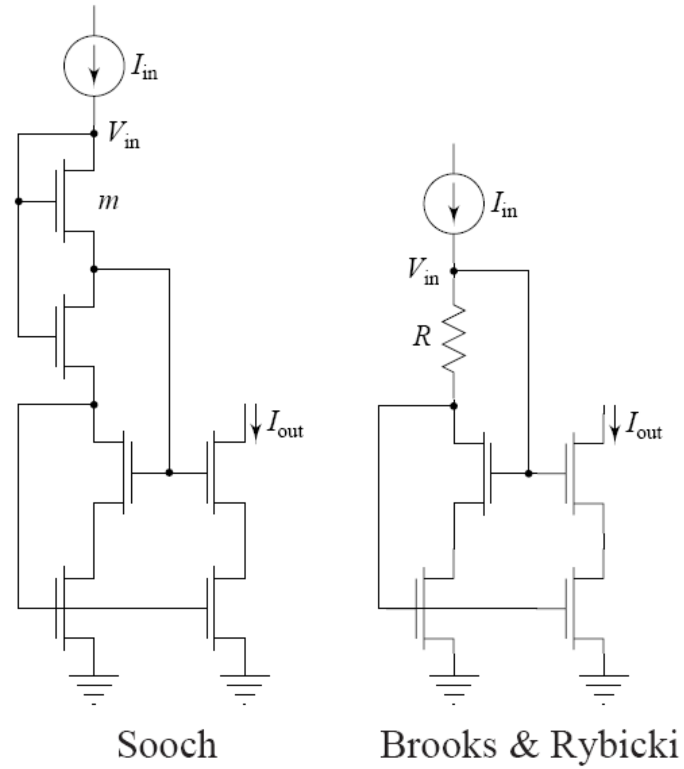
  - Some inaccuracy arises because M_5 does not suffer from body effect whereas M_2 does.
  - $I_1 R_b$ is not well controlled.
- The diode connected M7 has a large W/L such that
$$V_{GS7} \approx V_{TH7}$$
$$V_{DS6} \approx V_{GS6} - V_{TH7}$$
$$V_b = V_{GS5} + V_{GS6} - V_{TH7}$$



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

Wide-Swing Cascode Current Mirror

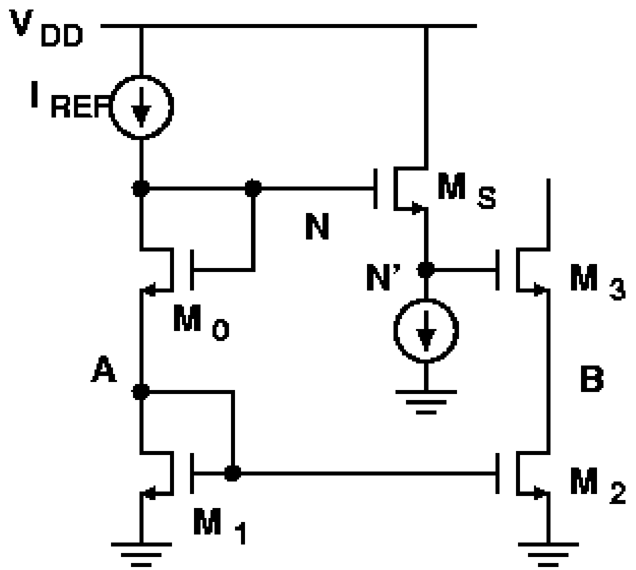
- All Self biasing, has a high output impedance, and provides a low systematic transfer error.
- Each has an output compliance voltage of two saturation voltages.
- The Sooch mirror requires an input voltage of two diode drops, which makes it unsuitable for low-voltage applications.
- The Brooks-Rybicki 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,

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

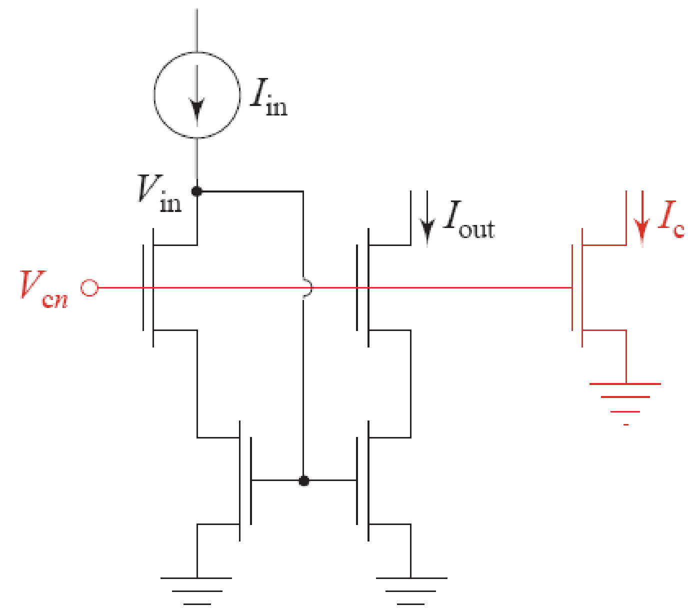
- M_2 is at the edge of the saturation region.
- Substantial current mismatch is introduced for

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

- 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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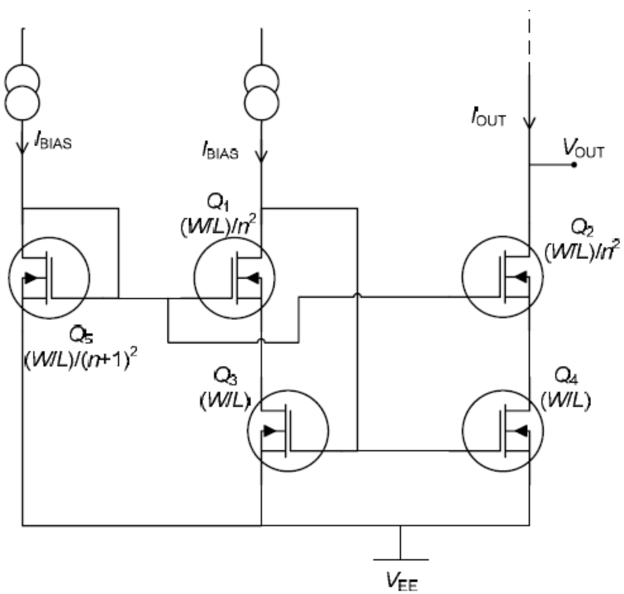
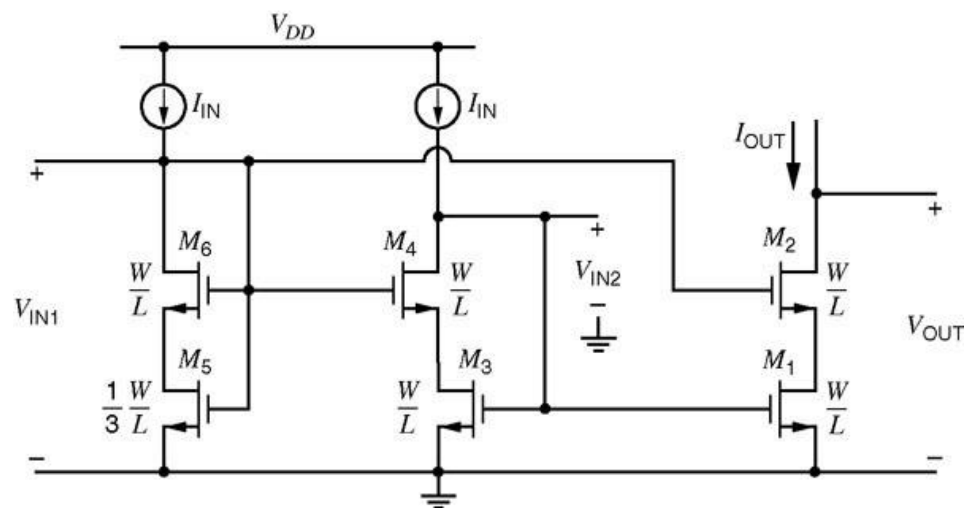
Wide-Swing Cascode Current Mirror

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

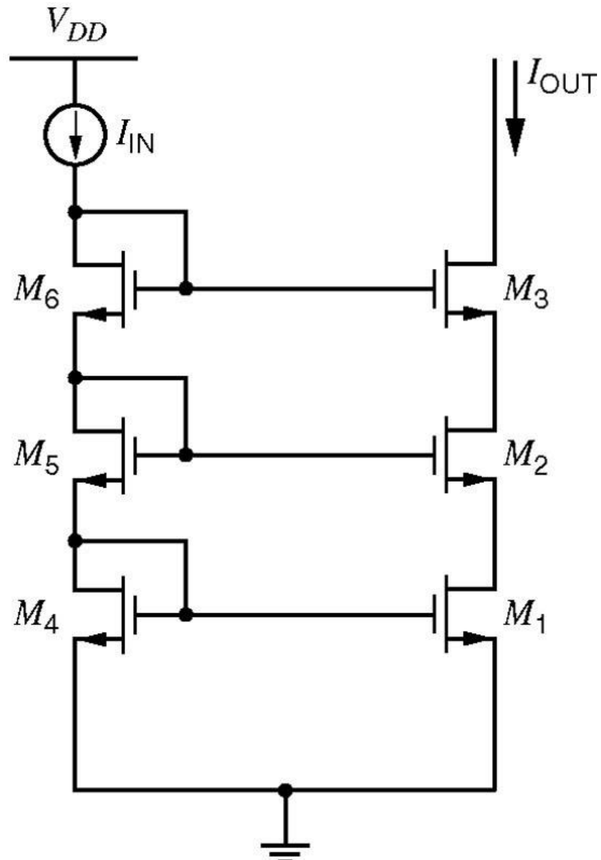




$$V_{IN1} = V_{DS5} + V_{DS6} = V_t + 2V_{OV}$$
$$V_{IN2} = V_{GS3} = V_t + V_{OV}$$

Double-Cascode Current Mirror

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



Outline

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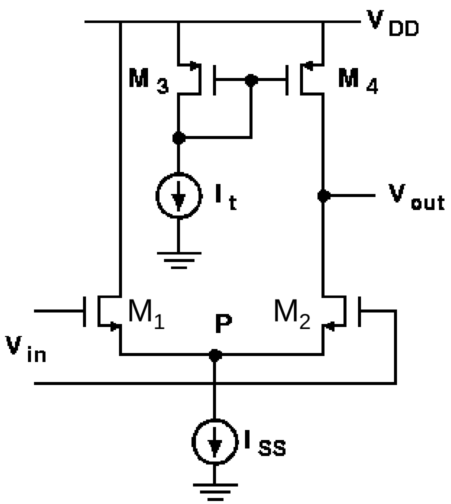
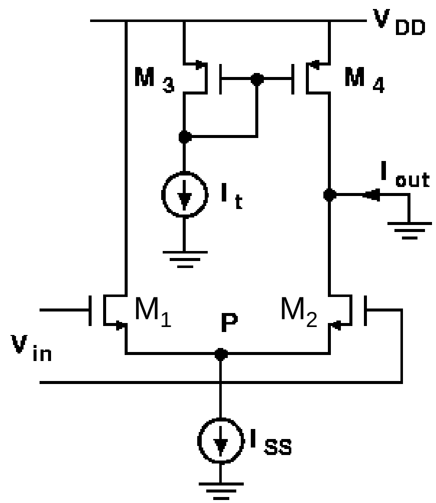
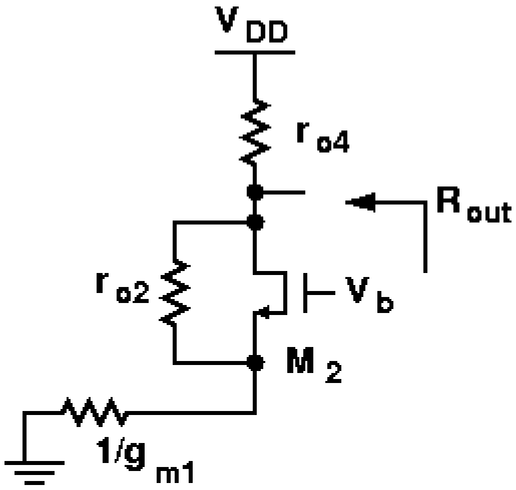
3. **Active Current Mirrors**

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

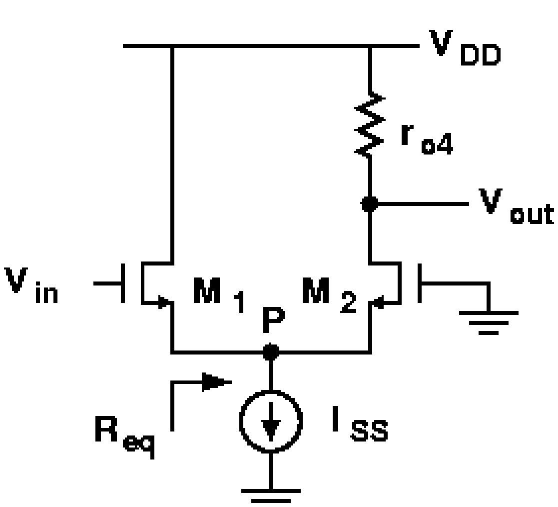
$$(1 + g_{m2} r_{O2})(1/g_{m1,2}) + r_{O2} = 2r_{O2} + 1/g_{m1} \approx 2r_{O2}$$

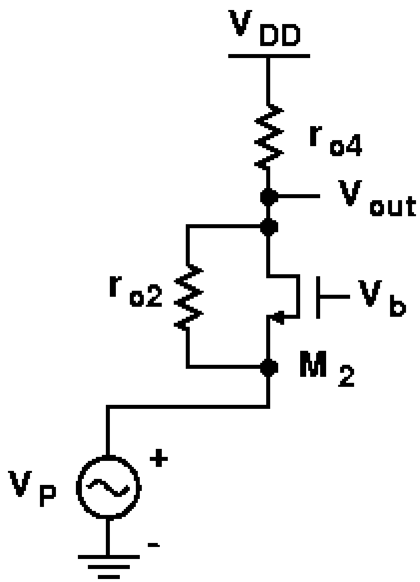
- Thus,

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

Active Current Mirror

- *An Alternative Solution*





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

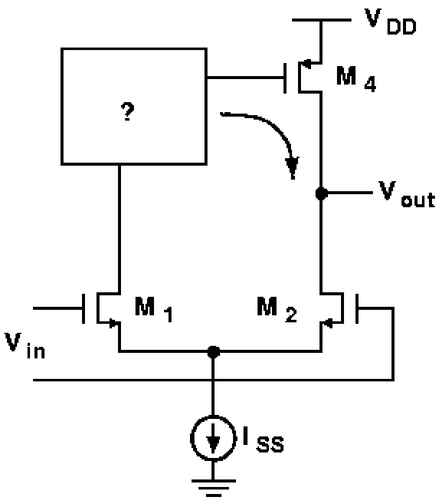
$$R_{eq} \approx \frac{1}{g_{m2}} + \frac{r_{O4}}{g_{m2} r_{O2}} = \frac{1}{g_{m2}}\left(1 + \frac{r_{O4}}{r_{O2}}\right)$$

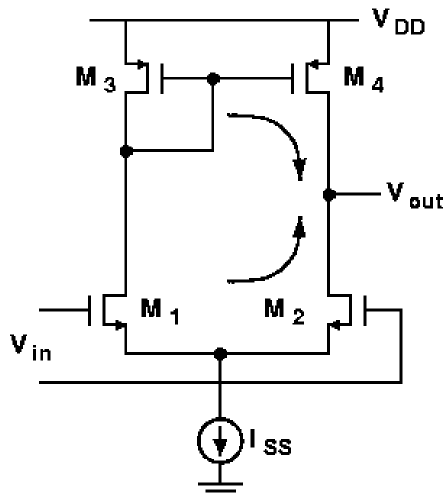
$$\frac{V_P}{V_{in}} = \frac{\frac{1}{g_{m2}}\left(1+\frac{r_{O4}}{r_{O2}}\right)}{\frac{1}{g_{m1}} + \frac{1}{g_{m2}}\left(1+\frac{r_{O4}}{r_{O2}}\right)} = \frac{1+\frac{r_{O4}}{r_{O2}}}{2+\frac{r_{O4}}{r_{O2}}}$$

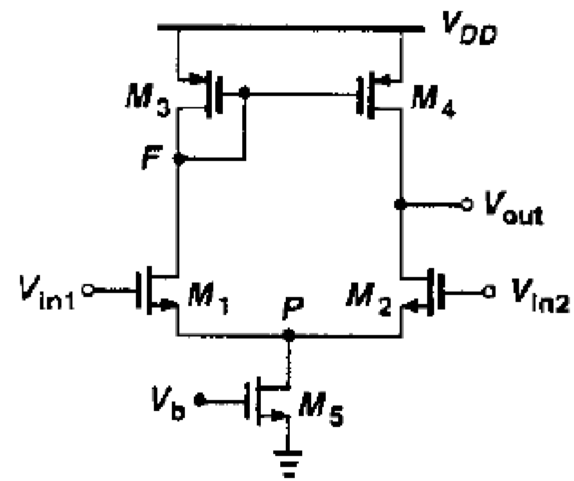
$$\frac{V_{out}}{V_{in}} = \frac{1+\frac{r_{O4}}{r_{O2}}}{2+\frac{r_{O4}}{r_{O2}}} \cdot \frac{g_{m2} r_{O2}}{1+\frac{r_{O2}}{r_{O4}}} = \frac{g_{m2} r_{O2} r_{O4}}{2r_{O2} + r_{O4}} = \frac{g_{m2}}{2}\left[\left(2r_{O2}\right) \| r_{O4}\right]$$

Differential to Single-Ended Amplifier

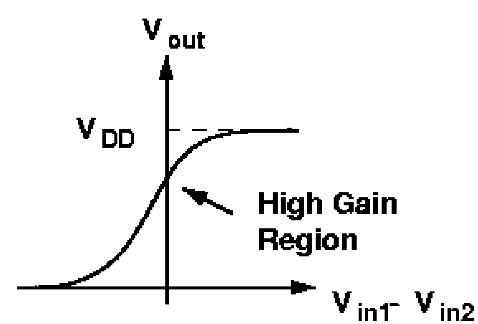
- Current combination utilizing current mirror.





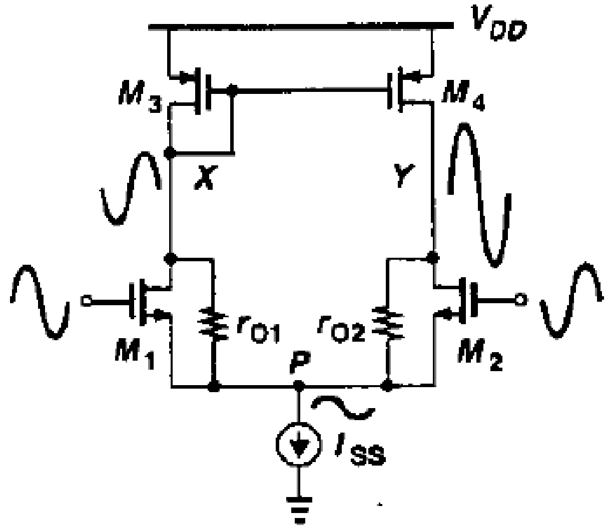


- If V_{in1} is much more negative than V_{in2}, M_1 is off and so are M_3 and M_4. Both M_2 and M_5 operate in deep triode region.
- For a small $|V_{in1} - V_{in2}|$, $M_1 – M_4$ are saturated => high gain
- The minimum input voltage level of $V_{in2} = V_{GS1,2}+V_{DS5,min}$
- With perfect symmetry,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

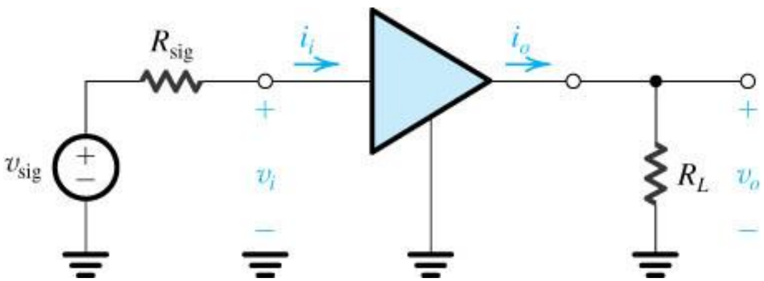


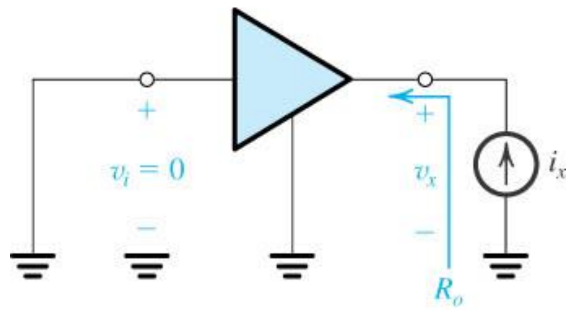
Small-Signal Analysis

- 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

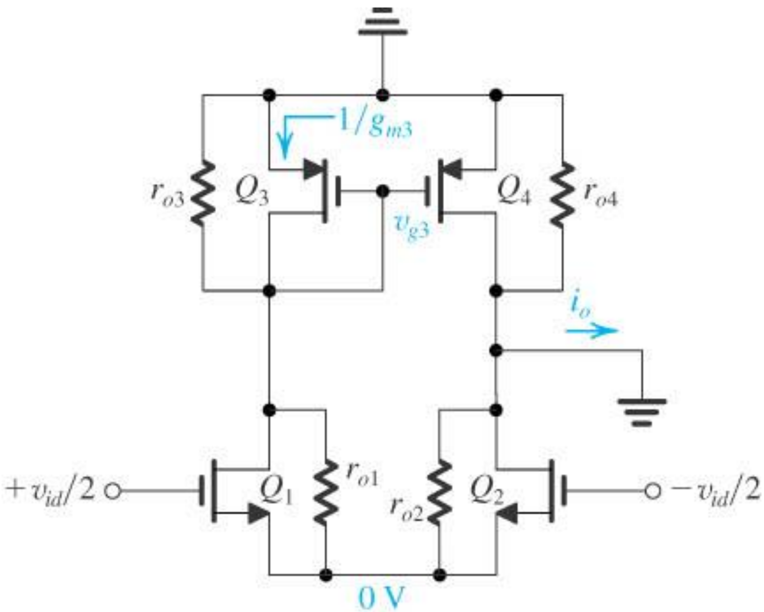
$$G_m \equiv \left. \frac{i_o}{v_i} \right|_{R_L=0}$$

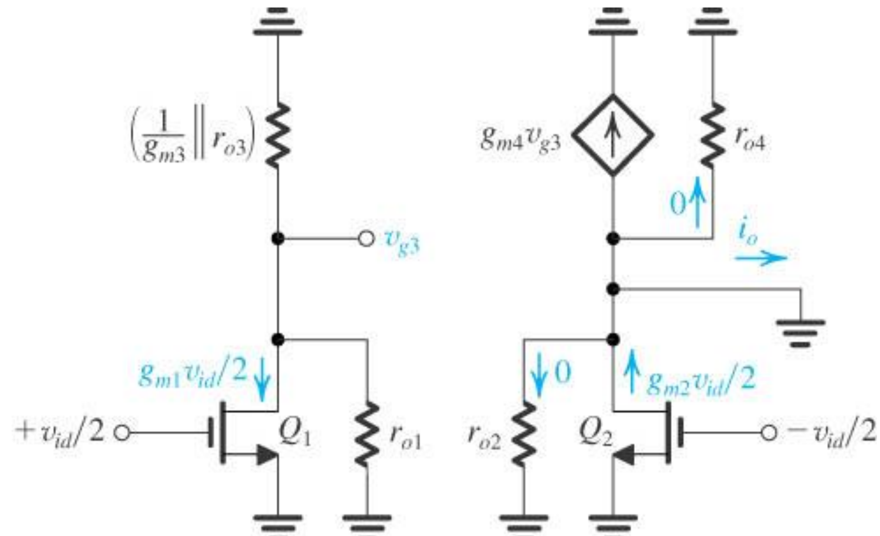
Output resistance of amplifier proper

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

Transconductance G_m

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





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

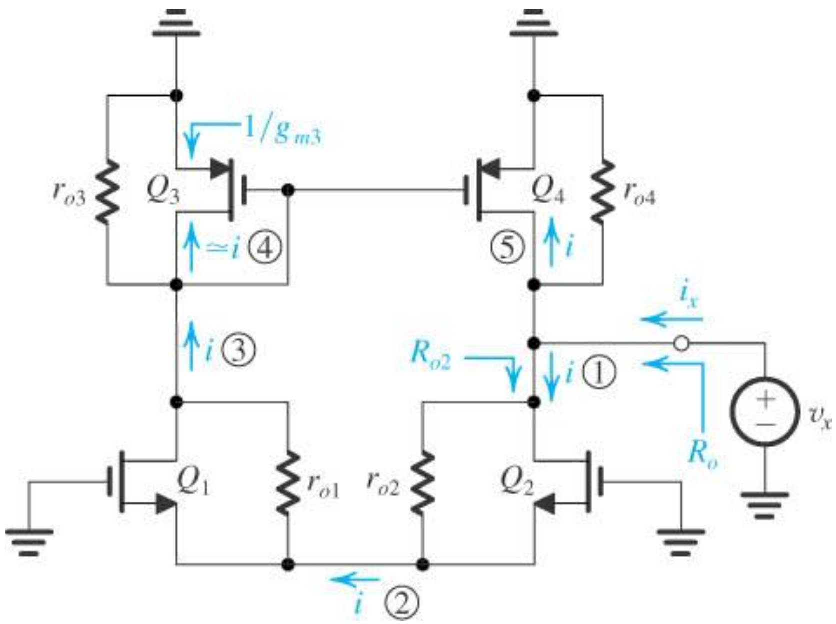
$$v_{g3} = -g_{m1}\left(\frac{v_{id}}{2}\right)\left(\frac{1}{g_{m3}} \| r_{o3} \| r_{o1}\right) \approx -\left(\frac{g_{m1}}{g_{m3}}\right)\left(\frac{v_{id}}{2}\right)$$

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

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

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

Determining the Output Resistance R_o



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

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

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

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

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

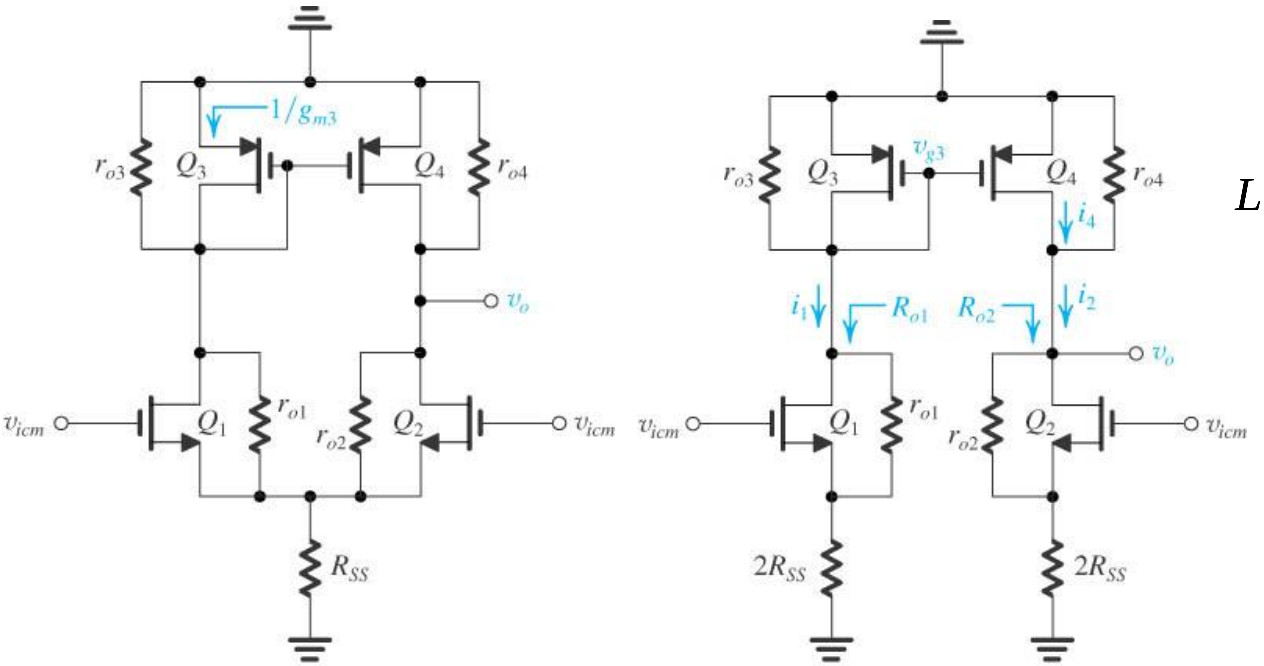
- $G_m = g_{m1.2} \cong g_m, R_{out} = R_o \cong \frac{1}{2} r_o$
- $|A_v| = G_m R_{out} = g_m \left[(2r_{O2}) \,||\, r_{O4} \right] \cong \frac{1}{2} g_m r_o$

compared to p.21

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

6dB improved

Common-Mode Gain and CMRR



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

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

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

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

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

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

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

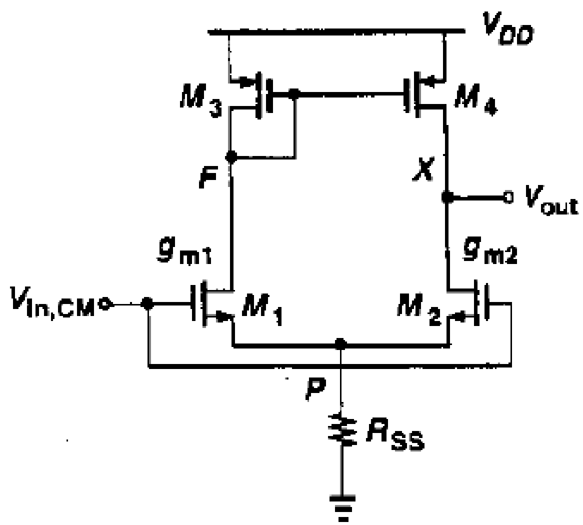
$$CMRR \equiv \frac{|A_d|}{|A_{cm}|} = [g_m(r_{O2} \parallel r_{O4})][2g_{m3}R_{SS}]$$

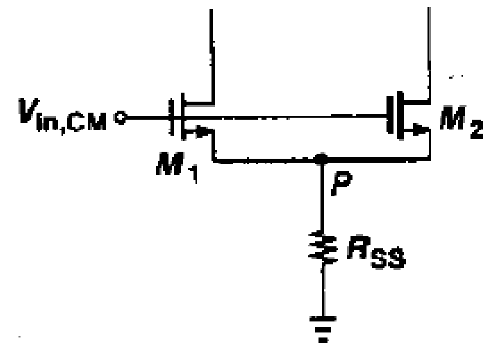
$$CMRR = (g_m r_o)(g_m R_{SS})$$

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

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.





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

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

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

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