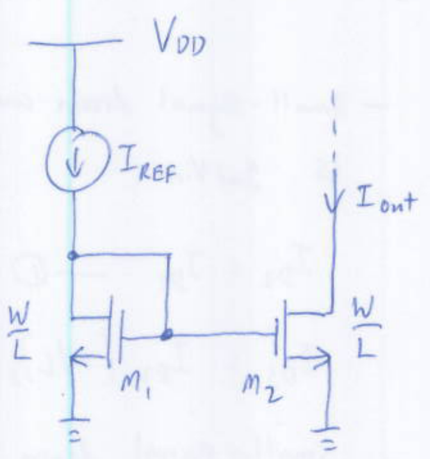


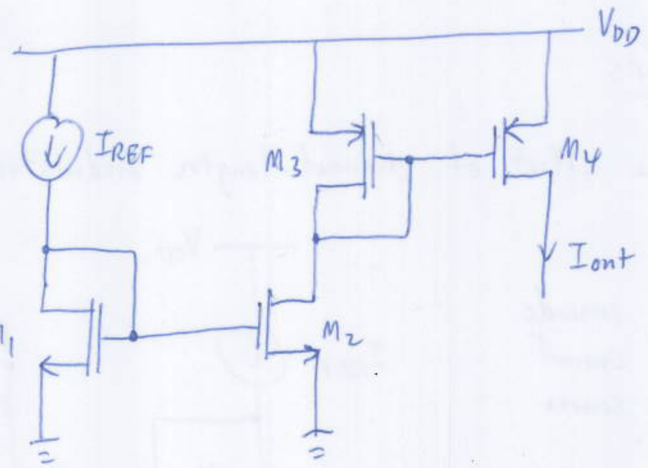
$$I_{REF} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_1 (V_{GS}-V_{TH})^2 \quad — ①$$

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

② ÷ ①

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

E.g. Find the drain current of M_4 if all of the transistors are in saturation.



Solution

$$I_{D2} = I_{REF}\left[(W/L)_2/(W/L)_1\right] \quad — ①$$

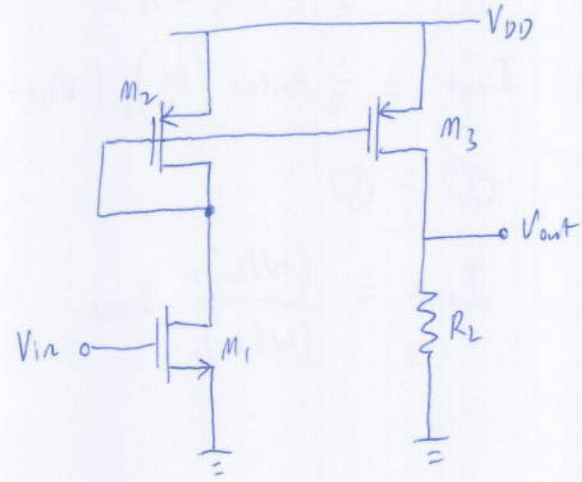
$$|I_{D3}| = |I_{D2}| \quad — ②$$

$$I_{D4} = I_{D3}\left[(W/L)_4/(W/L)_3\right] \quad — ③$$

Thus, $|I_{D4}| = \alpha\beta I_{REF}$ where $\alpha = (W/L)_2/(W/L)_1$

$\beta = (W/L)_4/(W/L)_3$

E.g. Calculate the small-signal voltage gain of the circuit below



- small-signal drain current of M_1 is $g_{m1} V_{in}$.

$$I_{D2} = I_{D1} \quad \text{— (1)}$$

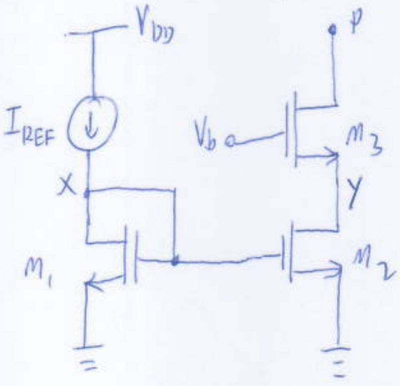
$$I_{D3} = I_{D2} (W/L)_3 / (W/L)_2 \quad \text{— (2)}$$

- small-signal drain current of M_3 is $g_{m1} V_{in} (W/L)_3 / (W/L)_2$

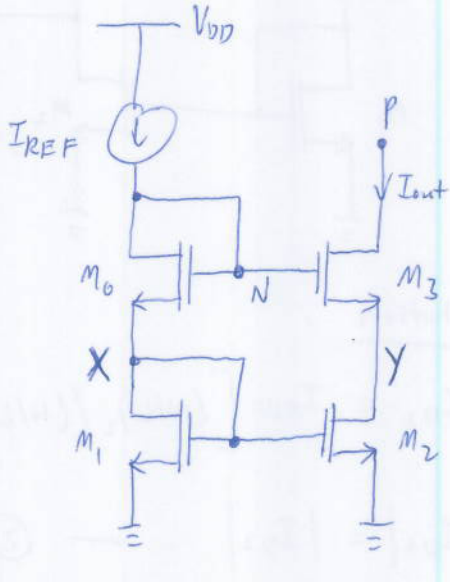
$$\text{Voltage gain} = g_{m1} R_L (W/L)_3 / (W/L)_2$$

Cascode current mirrors

→ can suppress the effect of channel-length modulation.



cascode current source



cascode current mirror

We want $V_X = V_Y$,

$$V_b - V_{GS3} = V_X$$

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

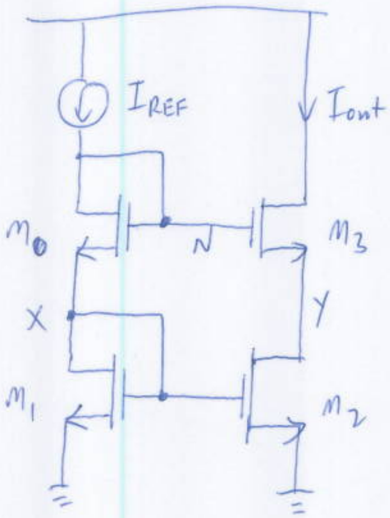
$$V_N = V_{GS0} + V_X = V_{GS3} + V_Y$$

If $(W/L)_3 / (W/L)_0 = (W/L)_2 / (W/L)_1$,

$V_{GS3} = V_{GS0}$ and $V_X = V_Y$

This result holds even if M_0 and M_3 suffer from body effect.

(E.g.) If I_{REF} requires 0.5V to operate as a current source, what is its maximum value?



M_2 and M_3 properly ratioed with respect to M_1 and M_0, we have

$$V_Y = V_X \approx \sqrt{2I_{REF}/[\mu_n C_{ox}(W/L)_1]} + V_{TH1}.$$

To find max value of I_{REF}, we note that

$$V_N = V_{GS0} + V_{GS1}$$

$$= \sqrt{\frac{2I_{REF}}{\mu_n C_{ox}}}\left[\sqrt{\left(\frac{L}{W}\right)_0} + \sqrt{\left(\frac{L}{W}\right)_1}\right] + V_{TH0} + V_{TH1}.$$

Thus,

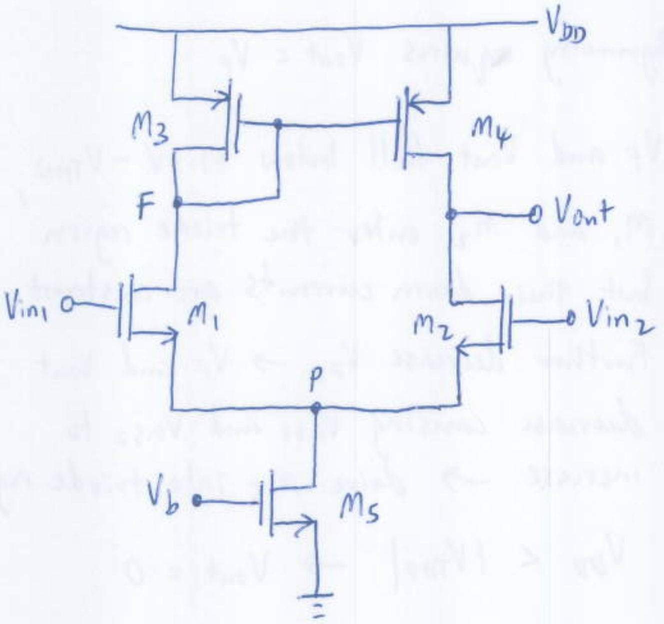
$$V_{DD} - \sqrt{\frac{2I_{REF}}{\mu_n C_{ox}}}\left[\sqrt{\left(\frac{L}{W}\right)_0} + \sqrt{\left(\frac{L}{W}\right)_1}\right] - V_{TH0} - V_{TH1} = 0.5V$$

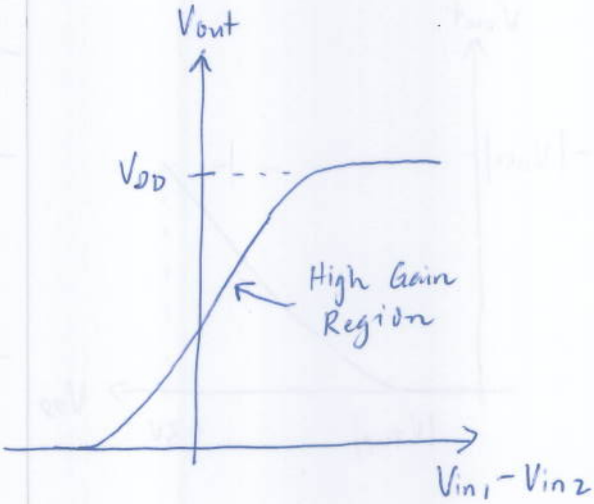
and hence,

$$I_{REF,max} = \frac{\mu_n C_{ox}}{2} \frac{(V_{DD} - 0.5V - V_{TH0} - V_{TH1})^2}{(\sqrt{(L/W)_0} + \sqrt{(L/W)_1})^2}$$

Active Current Mirrors

Differential pair with active current mirror



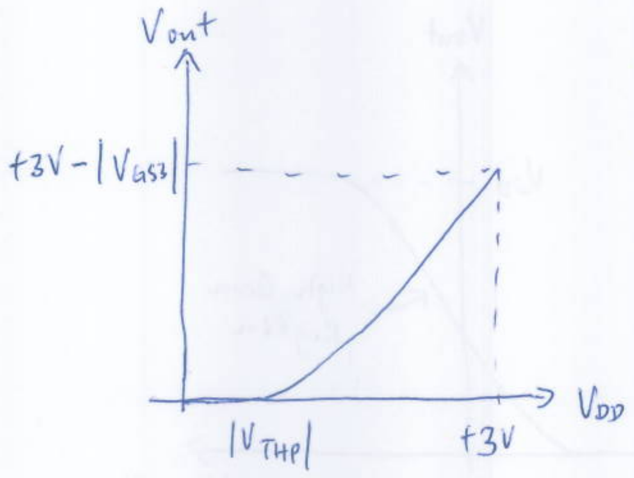


- If V_{in1} much more negative than V_{in2}, M_1, M_3 and M_4 are off
- No current can flow from V_{DD} $\rightarrow$ M_2 and M_5 operate in deep triode region, carrying zero current.

  $\rightarrow$ $V_{out} = 0$

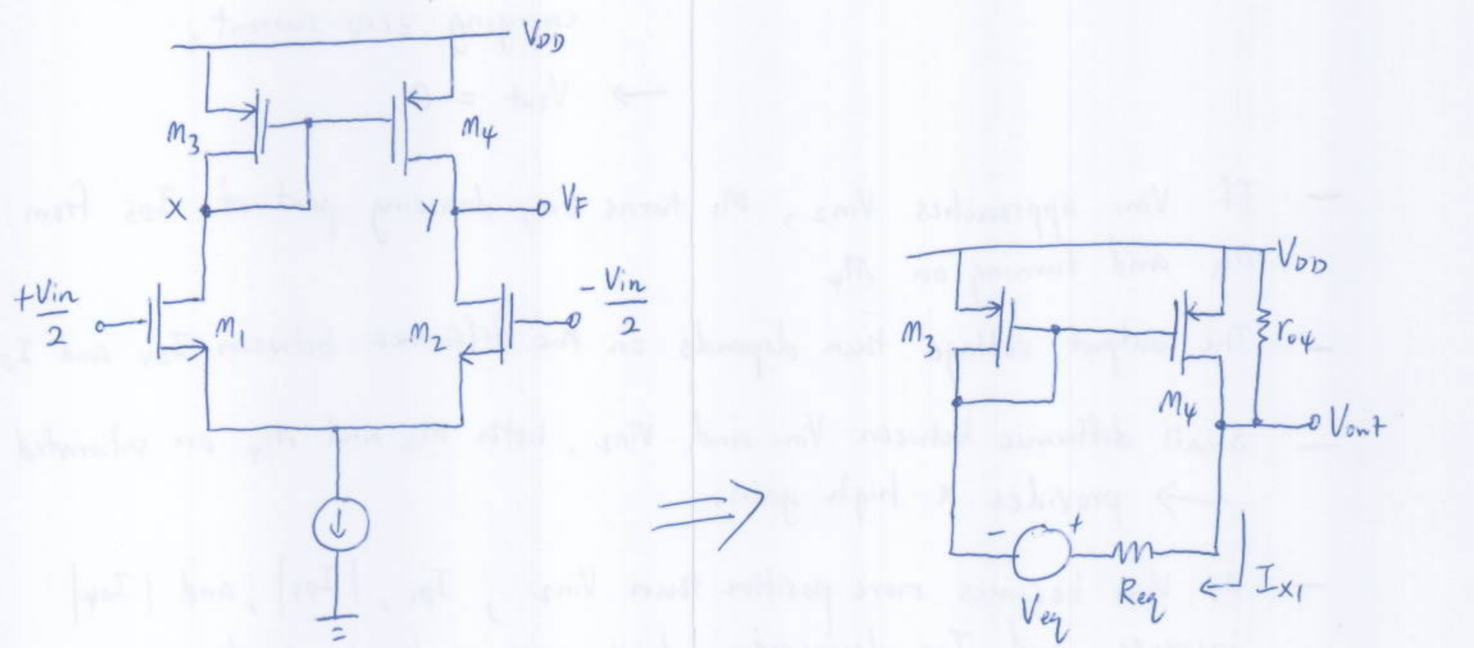
- If V_{in1} approaches V_{in2}, M_1 turns on, drawing part of I_{D5} from M_3 and turning on M_4
- The output voltage then depends on the difference between I_{D4} and I_{D2}
- Small difference between V_{in1} and V_{in2}, both M_2 and M_4 are saturated $\rightarrow$ provides a high gain.
- As V_{in1} becomes more positive than V_{in2}, I_{D1}, $|I_{D3}|$, and $|I_{D4}|$ increase and I_{D2} decreases, driving M_4 into the triode region.
- If $V_{in1} - V_{in2}$ is sufficiently large, M_2 turns off, M_4 operates in deep triode region with zero current, and $V_{out} = V_{DD}$
- Note that if $V_{in1} > V_F + V_{TH}$, then M_1 enters the triode region.

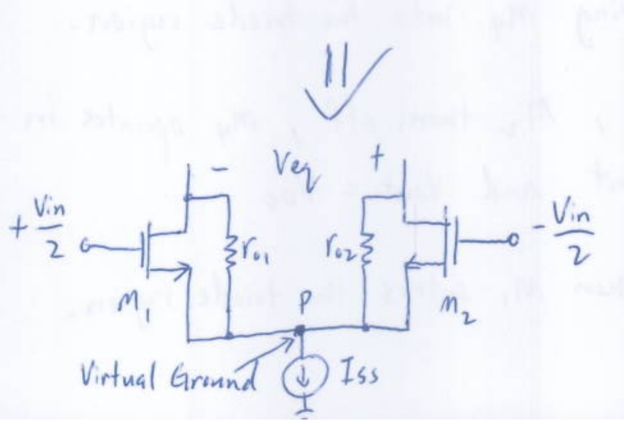
E.g. Based on previous figures, if $V_{in1} = V_{in2} = +1.5V$, sketch the output voltage of the circuit as V_{DD} varies from 3V to zero. Assume that for $V_{DD} = 3V$ all of the devices are saturated.



- Symmetry requires $V_{out} = V_F$
- V_F and V_{out} fall below $+1.5V - V_{THN}$, M_1 and M_2 enter the triode region but their drain currents are constant.
- Further decrease $V_{DD} \rightarrow V_F$ and V_{out} decrease causing V_{GS1} and V_{GS2} to increase $\rightarrow$ drive M_5 into triode region
- $V_{DD} < |V_{THP}| \rightarrow V_{out} = 0$.

Using Thevenin Equivalent to find small signal gain





Current through R_{eq},

$$I_{x1} = \frac{V_{out} - V_{eq}}{R_{eq} + R_{M3}}$$

$$= \frac{V_{out} - g_{m1,2}\, r_{o1,2}\, V_{in}}{2r_{o1,2} + \frac{1}{g_{m3}} \,//\, r_{o3}}$$

$I_{1/g_{m3}}$

The fraction of this current is mirrored into M_4 with unity gain,

$$2\,\frac{V_{out} - g_{m1,2}\, r_{o1,2}\, V_{in}}{2r_{o1,2} + \frac{1}{g_{m3}} \,//\, r_{o3}} \cdot \frac{r_{o3}}{r_{o3} + \frac{1}{g_{m3}}} = -\frac{V_{out}}{r_{o4}}$$

Assuming $2r_{o1,2} \gg \frac{1}{g_{m3,4}} \,//\, r_{o3,4}$, the voltage gain is

$$\frac{V_{out}}{V_{in}} = \frac{g_{m1,2}\, r_{o3,4}\, r_{o1,2}}{r_{o1,2} + r_{o3,4}} = g_{m1,2}\left(r_{o1,2} \,//\, r_{o3,4}\right)$$