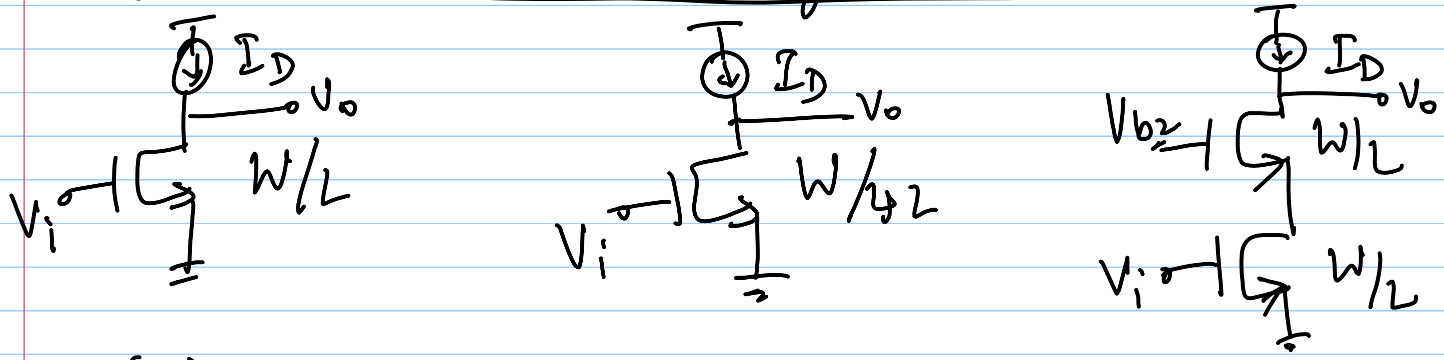
10/1/12

Lec 5

Compare with length increase:



(a) original

(b) $4 \times L$

(c) cascode

$$V_{DSAT_b} = 2 \times V_{DSAT_a}$$
$$V_{DSAT_c} = 2 \times V_{DSAT_a}$$
} equal voltage constraints

$$|a_{v_a}| = g_m r_{DS} = \sqrt{2 \mu C_{ox} \frac{W}{L} I_D} \cdot \frac{1}{\lambda_a I_D}$$

$$\lambda \propto \frac{1}{L} \Rightarrow \lambda_b = \frac{1}{4} \lambda_a$$

$$g_{m_b} = \frac{1}{2} g_{m_a} \; ; \; r_{ds_b} = 4\, r_{ds_a}$$

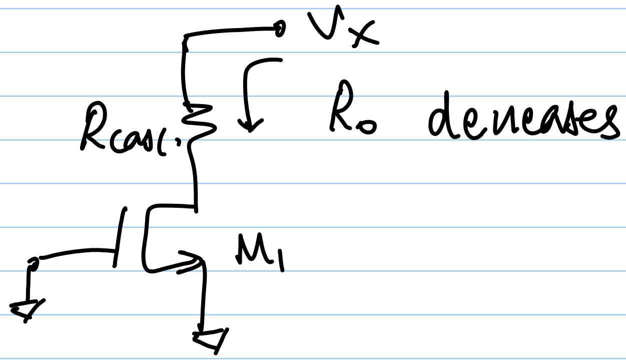
$$|a_{v_b}| = 2 \times |a_{v_a}|$$

$$|a_{v_c}| = (g_m r_{ds}) \times |a_{v_a}|$$

* noise of b is also worse (more later)

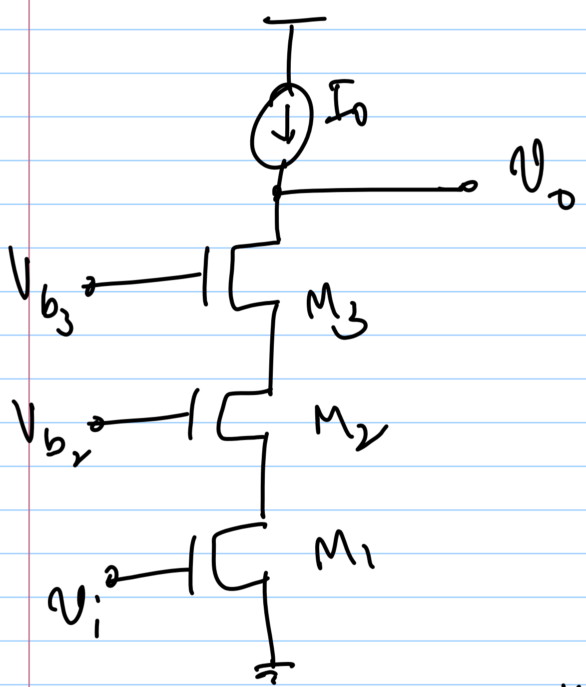
* Note: Cascode works well only if devices are in sat.

If cascode device is in non-sat:



as $V_x \downarrow$, eventually M_1 also enters triode

<u>Triple Cascode:</u>



* $$\frac{v_o}{v_i} = -(g_m r_{ds})_1 \cdot (g_m r_{ds})_2 \cdot (g_m r_{ds})_3$$

$$|a_v| \sim (g_m r_{ds})^3$$

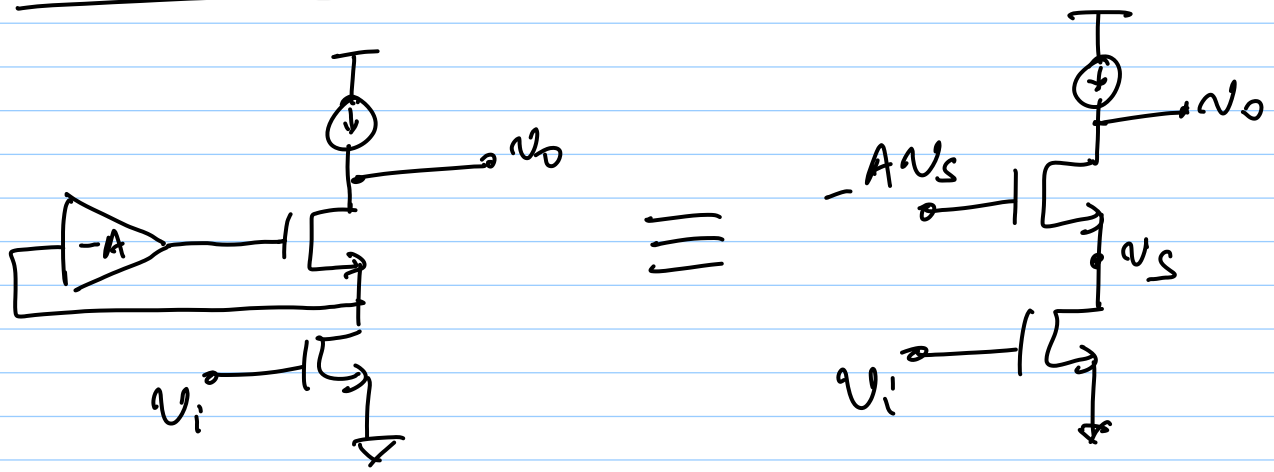
* Voltage swings are limited

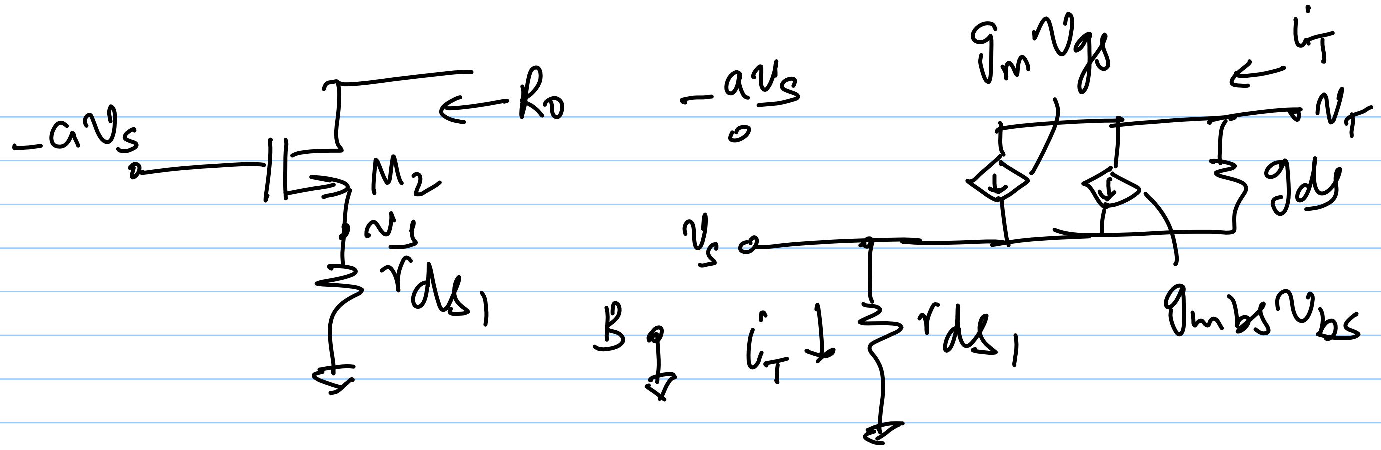
⇒ not used @ $V_{DD} < 3V$, typically

Can you do better than cascode (with headroom constraint)?

$\Rightarrow$ improve $-ve$ f.b. further

Active cascode





$$v_s = i_T / g_{ds_1}$$

$$i_T = g_{m_2}(-av_s - v_s) + g_{mbs_2}(0 - v_s)$$

$$+ g_{ds_2}(v_T - v_s)$$

$$i_T \left\{ 1 + (a+1)\frac{g_{m_2}}{g_{ds_1}} + \frac{g_{mbs_2}}{g_{ds_1}} + \frac{g_{ds_2}}{g_{ds_1}} \right\}$$

$$= g_{ds_2} \cdot v_T$$

$$R_o = \frac{v_T}{i_T} = \frac{1}{g_{ds_2}} \left[\cancel{1} + \frac{(a+\cancel{1})g_{m_2} + \cancel{g_{mbs_2}} + \cancel{g_{ds_2}}}{g_{ds_1}} \right]$$

$$\simeq a \cdot g_{m_2} r_{ds_2} \cdot r_{ds_1}$$

even higher than regular cascode!

$$a_v = -g_{m_1} R_o$$

$$= \boxed{-g_{m_1} r_{ds_1} \cdot g_{m_2} r_{ds_2} \cdot a}$$

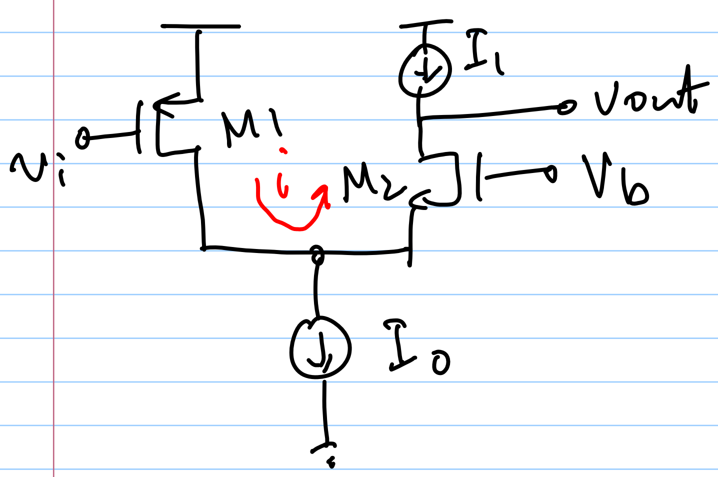
very high gain ckt!

⇒ also called <u>"gain-boosted"</u> <u>cascode</u>

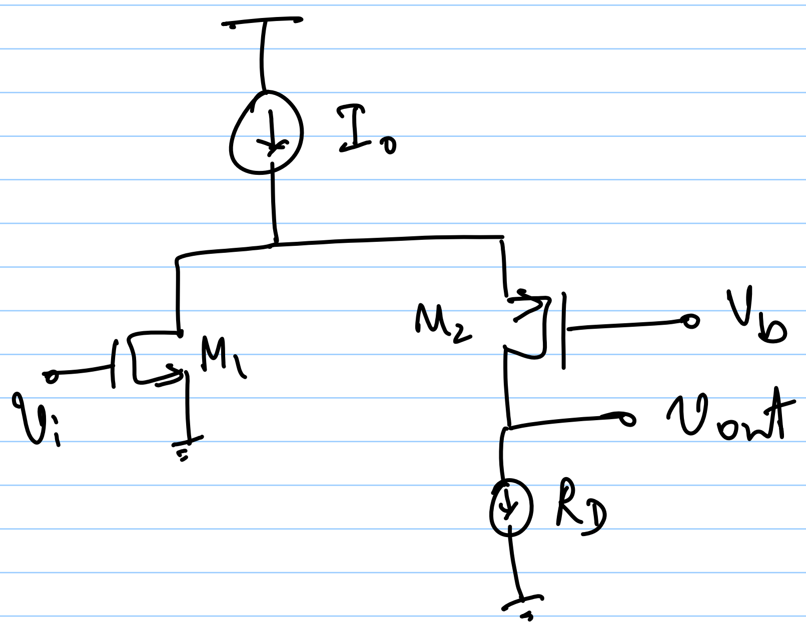
Folded Cascode

Normal cascode : input & cascode devices are same type.

Folded : NMOS − PMOS or PMOS − NMOS



* small signal current is folded up or down
* total bias current higher than normal cascode



$$R_{out} \simeq (g_{m_2} r_{ds_2}) \cdot r_{ds_1}$$

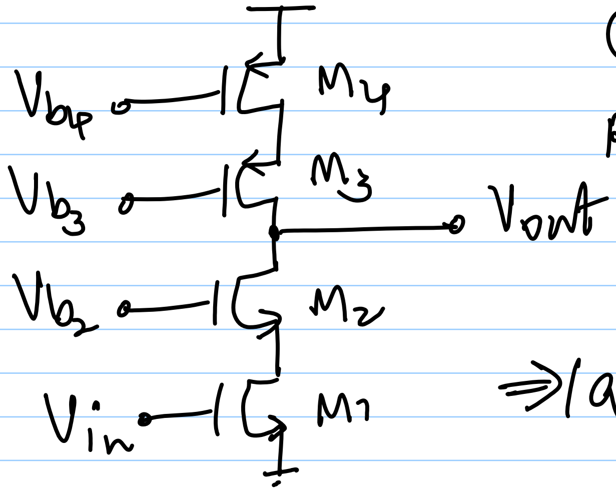
$$a_v \simeq -(g_{m_1} r_{ds_1})(g_{m_2} r_{ds_2})$$

{ same as traditional cascode }

Cascode Current source

high Rout ⇒ closer to ideal current source

→ more headroom required



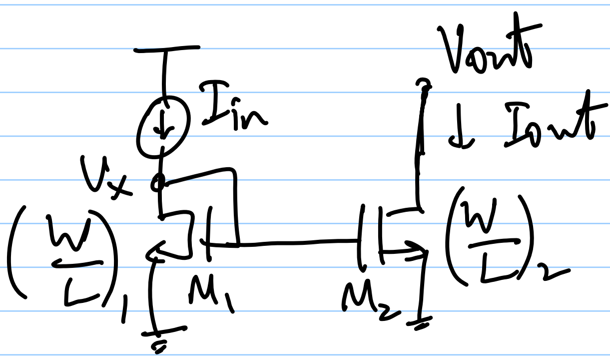
$G_m \simeq g_{m_1}$

$R_{out} = (g_{m_2} r_{ds_2}) r_{ds_1} \,||\, (g_{m_3} r_{ds_3}) r_{ds_4}$

$\Rightarrow |a_v| = g_{m_1} \cdot R_{out}$

Cascode Current Mirrors

Simple CM :



$V_{GS_1} = V_{GS_2} \; (= V_{DS_1})$

in general $V_{DS_1} \neq V_{DS_2}$

$$\frac{I_{out}}{I_{in}} = \frac{(W/L)_2}{(W/L)_1} \cdot \frac{1 + \lambda V_{DS_2}}{1 + \lambda V_{DS_1}}$$

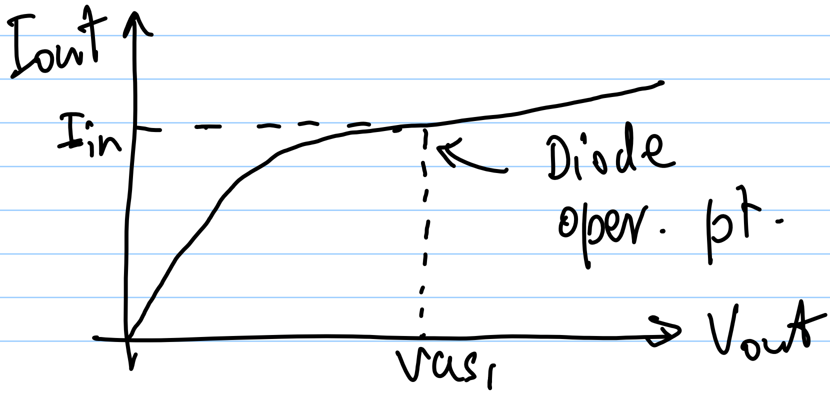
Choose $W_1 = W_2$ & $L_1 = L_2$

$$\frac{I_{out}}{I_{in}} = \frac{1+\lambda V_{out}}{1+\lambda V_X}$$

$$\approx (1+\lambda V_{out})(1-\lambda V_X)$$ for small λ (= large r_{ds})

$$\approx 1+\lambda(V_{out}-V_X)$$

$$= 1+\lambda(V_{out}-V_{GS_1})$$



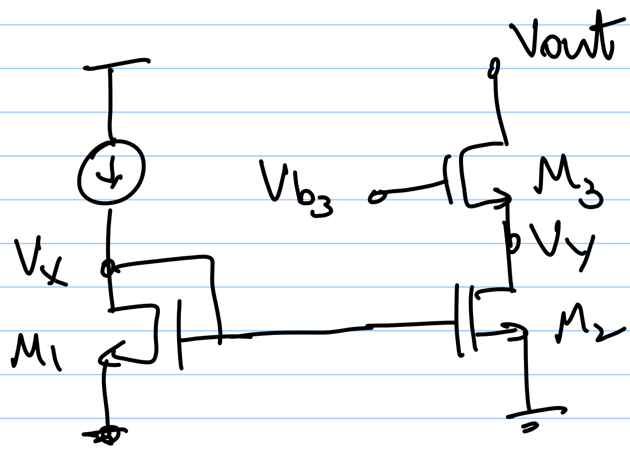
$$V_X = V_{GS_1} = V_{T_1} + V_{DSAT_1}$$

$$V_{out}(\text{min.}) = V_{DSAT_2}$$

$$R_X \approx 1/g_{m_1}$$ ← low R_{in}

$$R_{out} = r_{ds_2}$$ ← high R_{out}

Cascode : suppresses effect of CLM



DC balance:

choose V_b such that $V_y = V_x$

$\Rightarrow \dfrac{I_{D2}}{I_{D1}} \approx \dfrac{(W/L)_2}{(W/L)_1}$

* cascode device "shields" bottom device from Vout variations

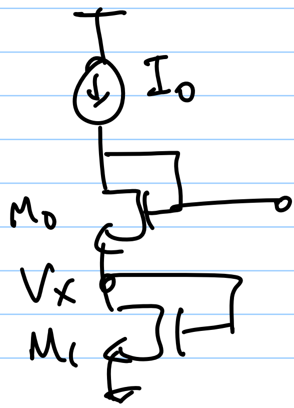
HW : p.t. $\Delta V_y = \Delta V_p / (g_{m3} + g_{mb3}) \cdot r_{DS3}$

Note: $L_1 = L_2$, but L_3 can be different

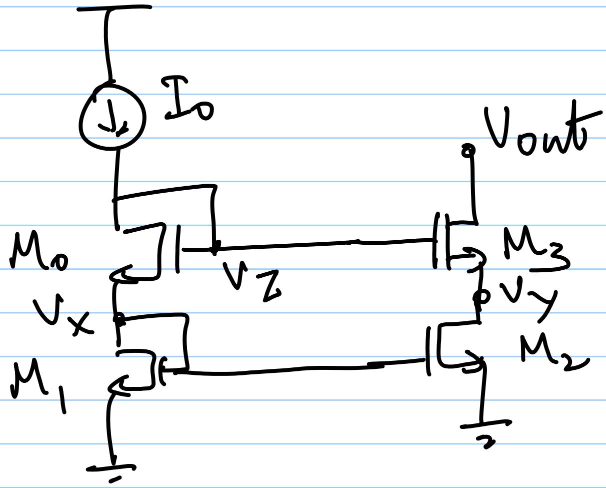
V_{b3}

$V_{b3} - V_{GS3} = V_Y = V_X$

$\Rightarrow V_{b3} = V_X + V_{GS3}$



$V = V_{GS0} + V_X \Rightarrow$ choose $V_{GS0} = V_{GS3}$



$V_{GS_0} + V_X = V_{GS_3} + V_Y$

$$\Rightarrow \frac{(W/L)_3}{(W/L)_0} = \frac{(W/L)_2}{(W/L)_1}$$

* Result holds even in presence of body effect for M_0 & M_3

$R_{in} = 1/g_{m_0} + 1/g_{m_1} \simeq 2/g_m$ (series)

$R_{out} = (g_{m_3} r_{ds_3}) r_{ds_4}$ (cascode)

headroom: (neglect body effect)

$V_{out_{min.}} = V_Z - V_T$

$= V_{GS_0} + V_{GS_1} - V_T$

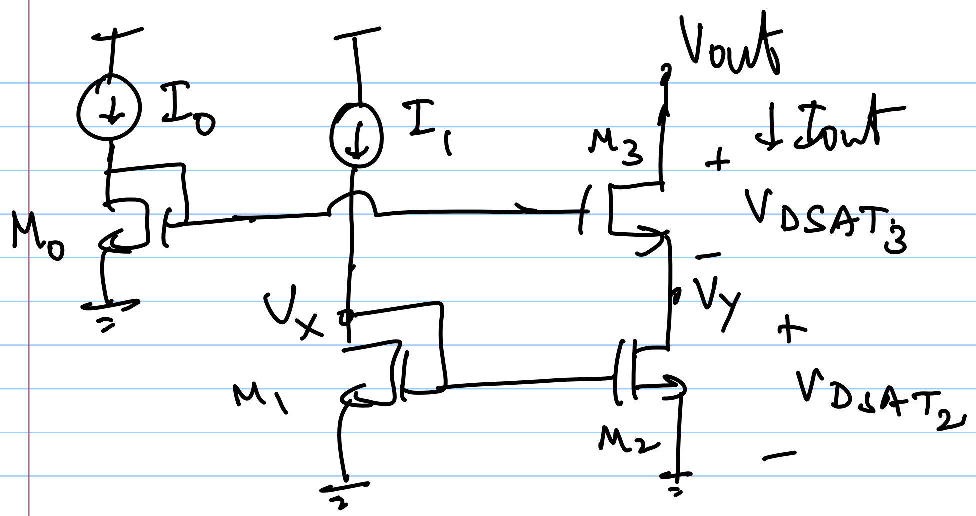
$= (V_{GS_0} - V_T) + (V_{GS_1} - V_T) + V_T$

$= V_{DSAT_0} + V_{DSAT_1} + V_T$

* headroom of V_T is "wasted"

* V_{b_3} can be chosen to be lower such that

$V_Y = V_{GS} - V_T$



* $V_y = V_{DSAT_2}$ — M_2 still is sat.
* $I_{out} \neq I_0$ because $V_x \neq V_y$ (DC imbalance)

$$V_{GS_0} - V_{GS_3} = V_{DS_2} = V_{DSAT_2}$$

$$(V_{T_0} + V_{DSAT_0}) - (V_{T_3} + V_{DSAT_3}) = V_{DSAT_2}$$

neglect body effect

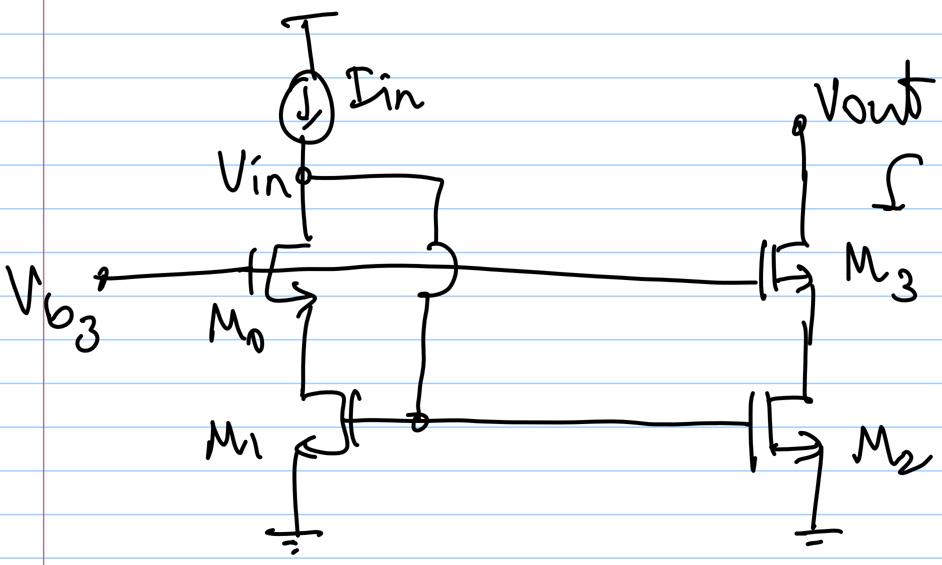
$$\Rightarrow V_{DSAT_0} = V_{DSAT_2} + V_{DSAT_3}$$

$$= 2 V_{DSAT_{2,3}} \text{ typically}$$

$$V_{DSAT_0} = \sqrt{\frac{2 I_0}{\mu_n C_{ox} (W/L)_0}}$$

$$I_0 = I_1 = I_{out} \Rightarrow \left(\frac{W}{L}\right)_0 = \frac{1}{4}\left(\frac{W}{L}\right)_{2,3}$$

"over the shoulder" cascode: (widely used)



$V_{in} = V_T + V_{DSAT_1}$

$R_{in} \simeq 1/g_{m_1}$

$R_{out} = (g_{m_3} r_{ds_3}) r_{ds_2}$

$V_{b_3} = V_T + 2 V_{DSAT}$

$V_{DS_1} = V_{DS_2} = V_{b_3} - V_{GS} = V_{DSAT}$