Logic Circuit Design
NAND-1

20171009

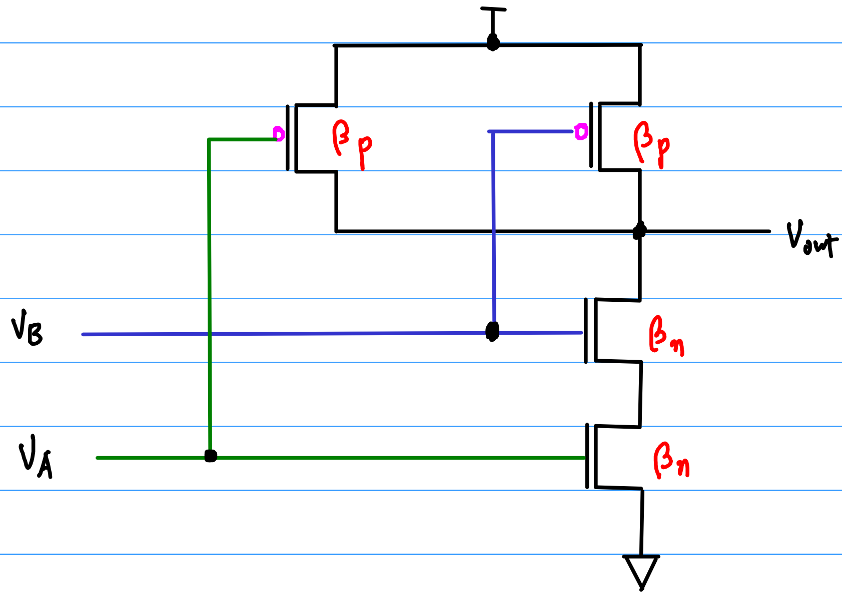
References

Some Figures from the following sites

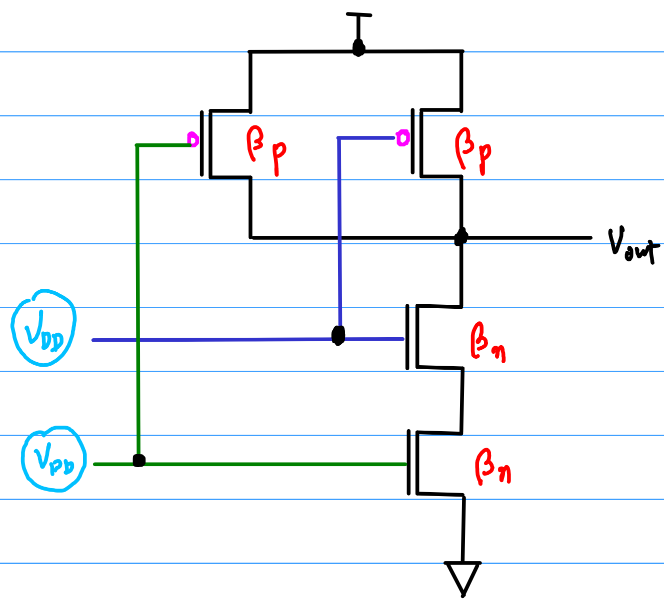
[1] http://pages.hmc.edu/harris/cmosvlsi/4e/index.html
Weste & Harris Book Site

[2] Introduction to VLSI Circuits and Systems, Uyemura

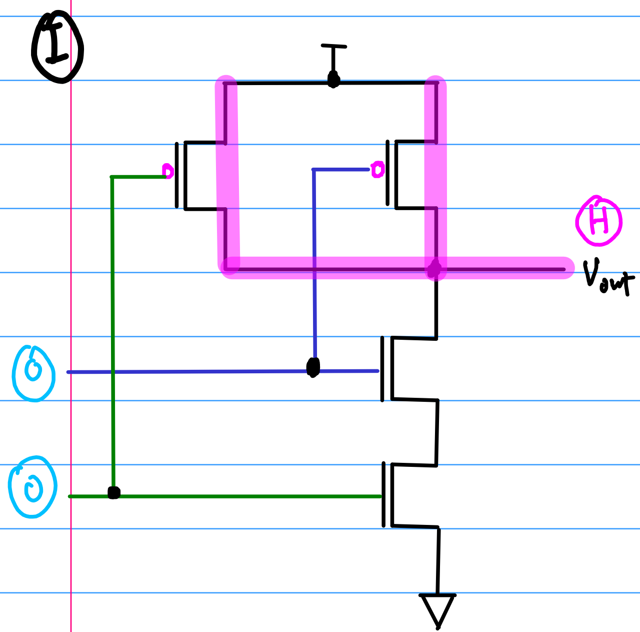
[2] en.wikipedia.org

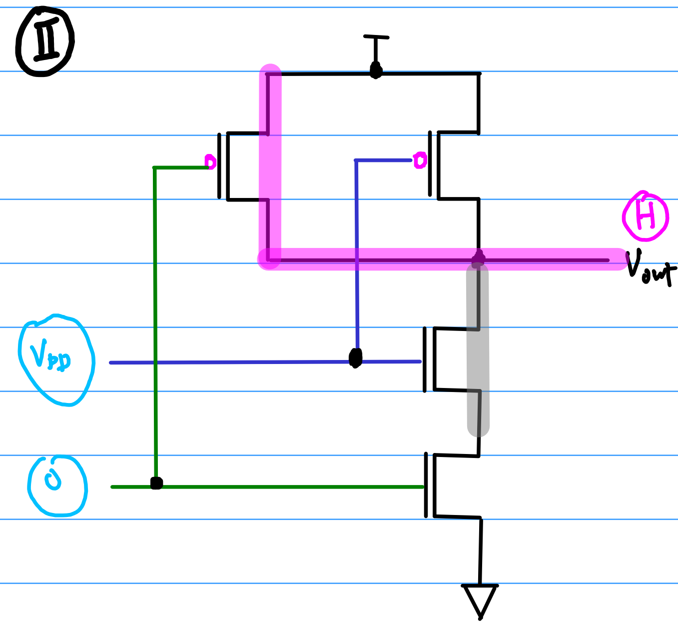


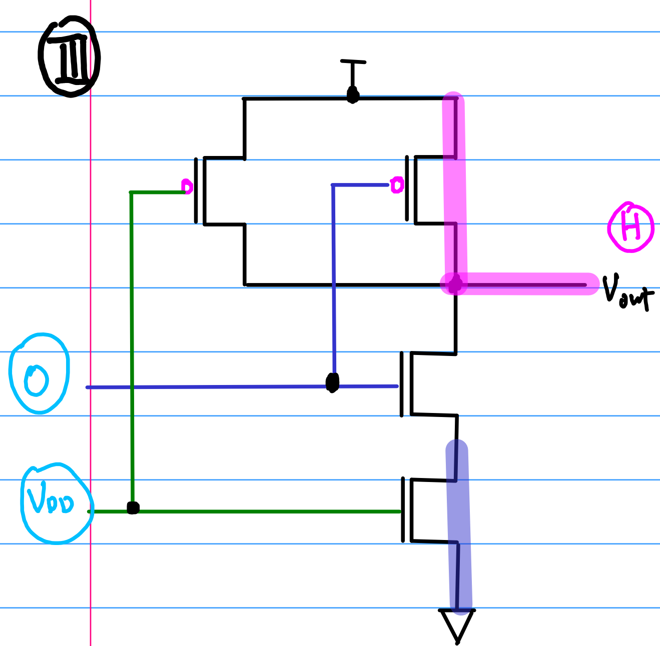
βp
βp
Vout
VB
βn
VA
βn

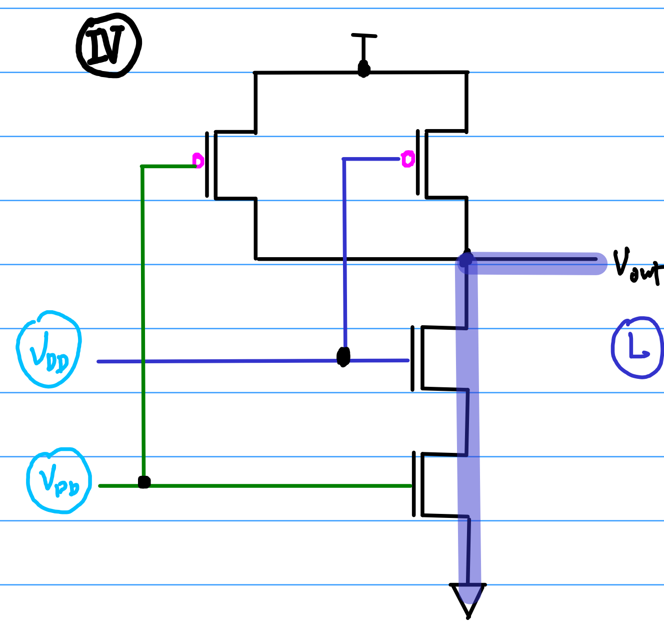


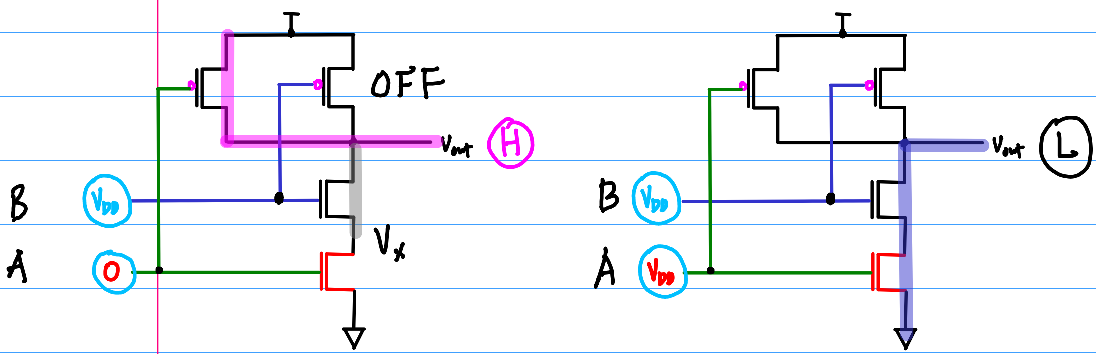
βp
βp
Vout
VDD
βn
VDD
βn

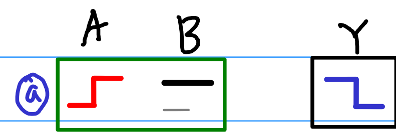

I
H
Vout
0
0


II
H
Vout
VDD
0


III
H
Vout
0
VDD


IV
Vout
L
VDD
VDD

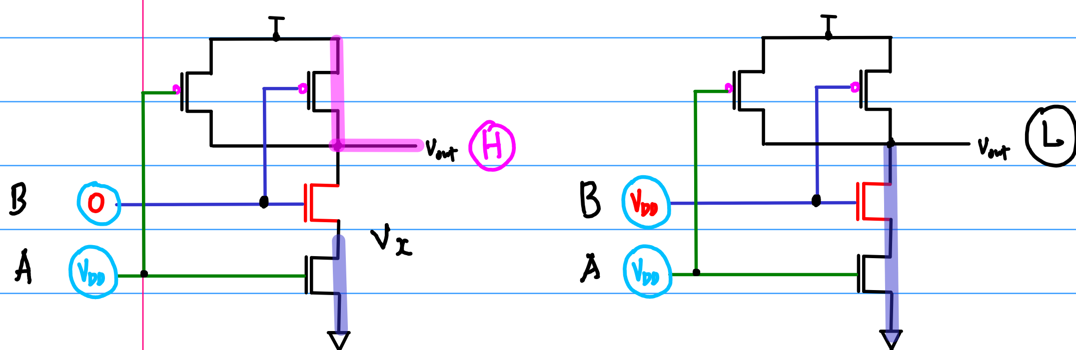


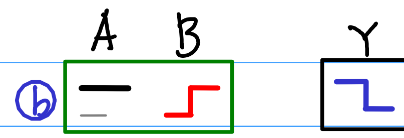


Weak PUN

nMB : resistor

nMA : ~~Body Effect~~

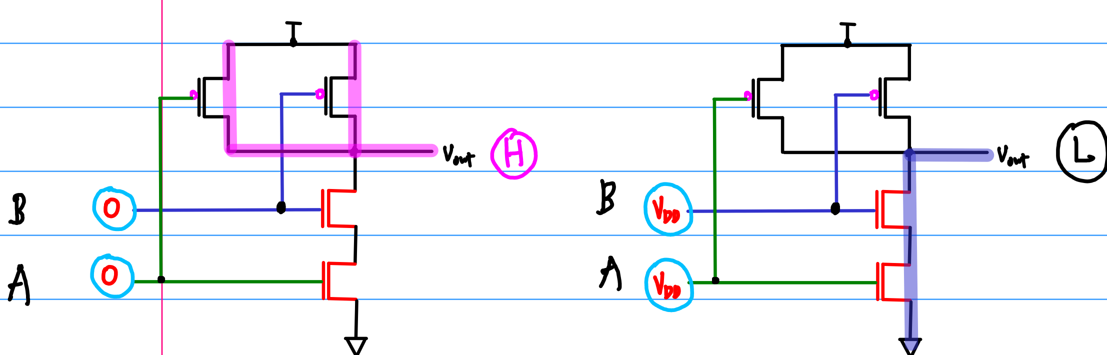


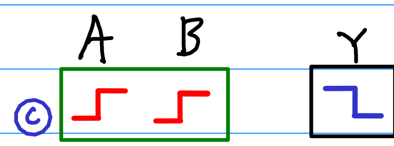


Weak PUN

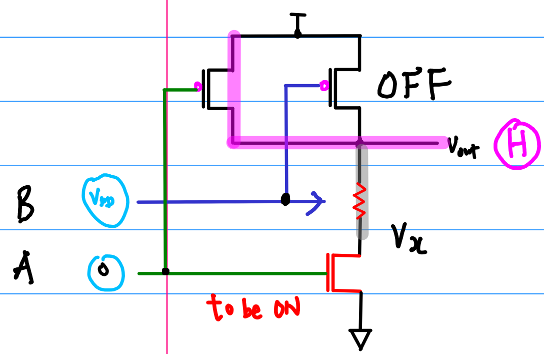
nMB : Body Effect

nMA ; resistor





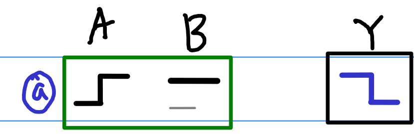
Strong PUN



{ small R
large C (load)

{ small voltage drop
slow change

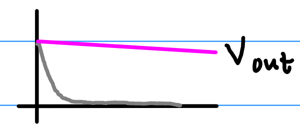
small effect on VTC

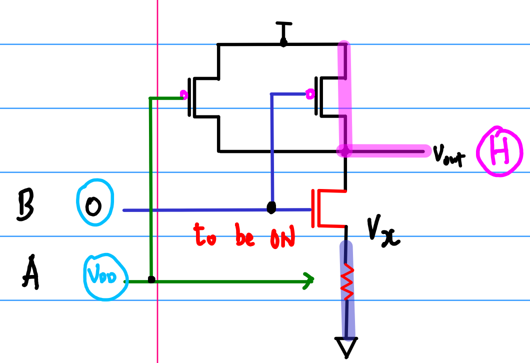


Weak PUN

nMB : resistor

nMA : ~~Body Effect~~





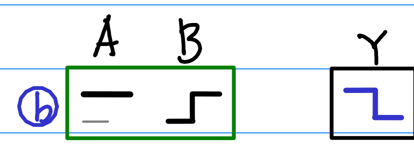
{ small R
small C (load)

{ large voltage drop
immediate change

increase V_T

→ hard to turn ON nMB

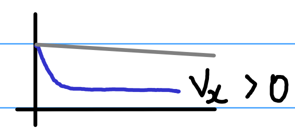
→ VTC shifted to the right

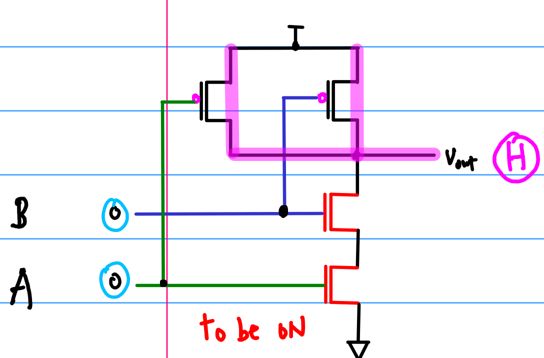


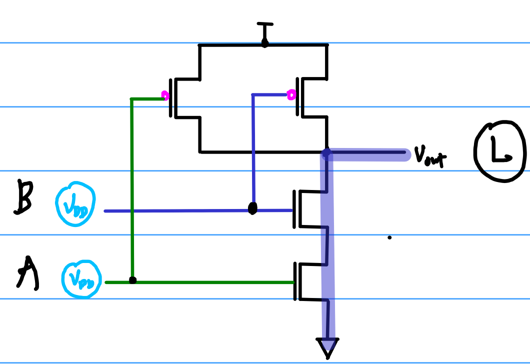
Weak PUN

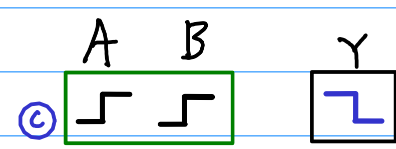
nMB : Body Effect

nMA : resistor







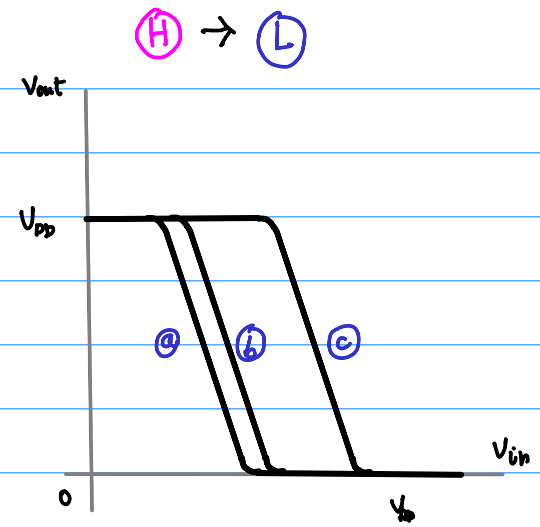


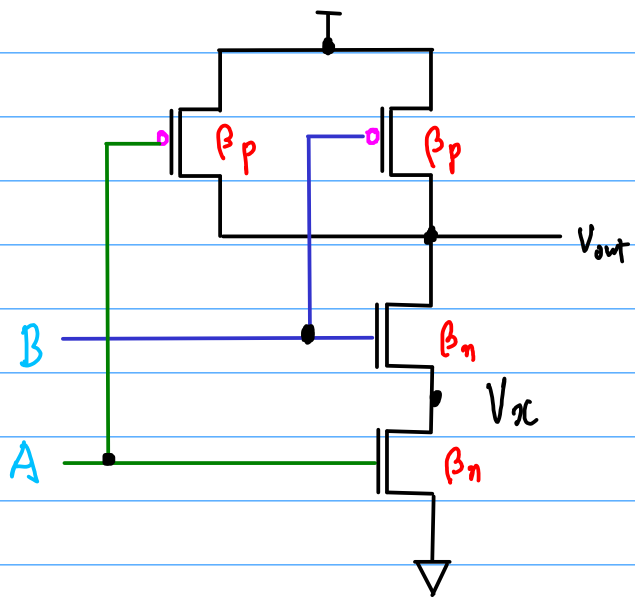
Strong PUN

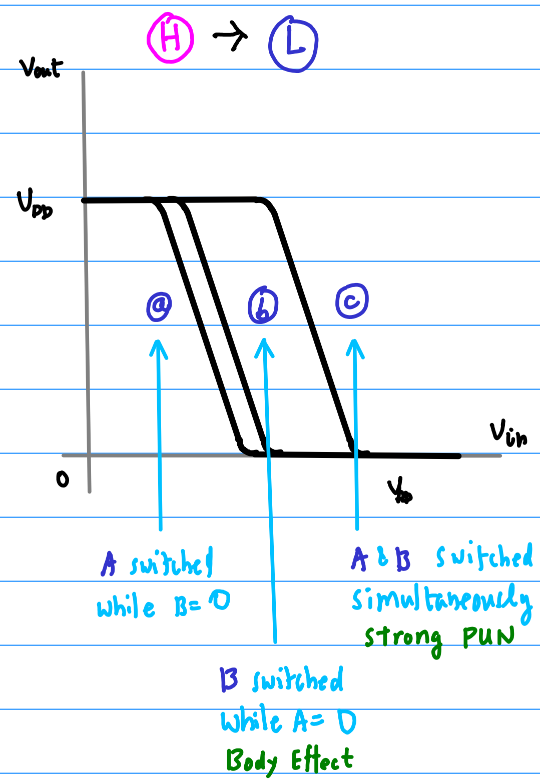
→ hard to turn ON nMA & nMB

→ VTC shifted to the right

	V_A	V_B	V_{out}
ⓒ	0	0	V_{DD}
ⓐ	0	V_{DD}	V_{DD}
ⓑ	V_{DD}	0	V_{DD}
	V_{DD}	V_{DD}	0







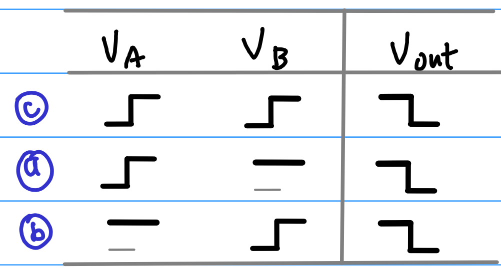
A : gate input of the bottom nMOS

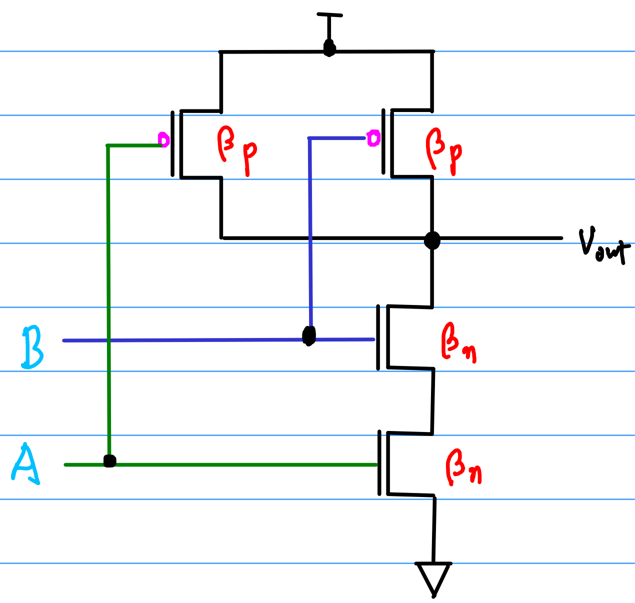
B : gate input of the top nMOS

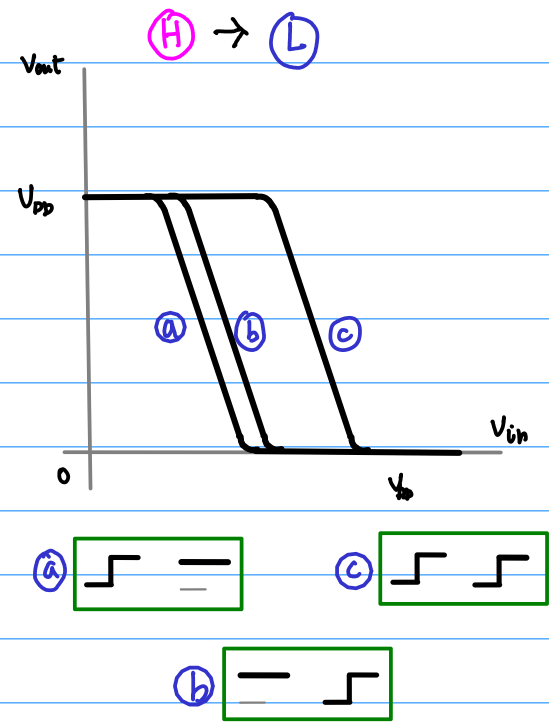
Strong PUN }
Body Effect } difficult to turn on nMOS

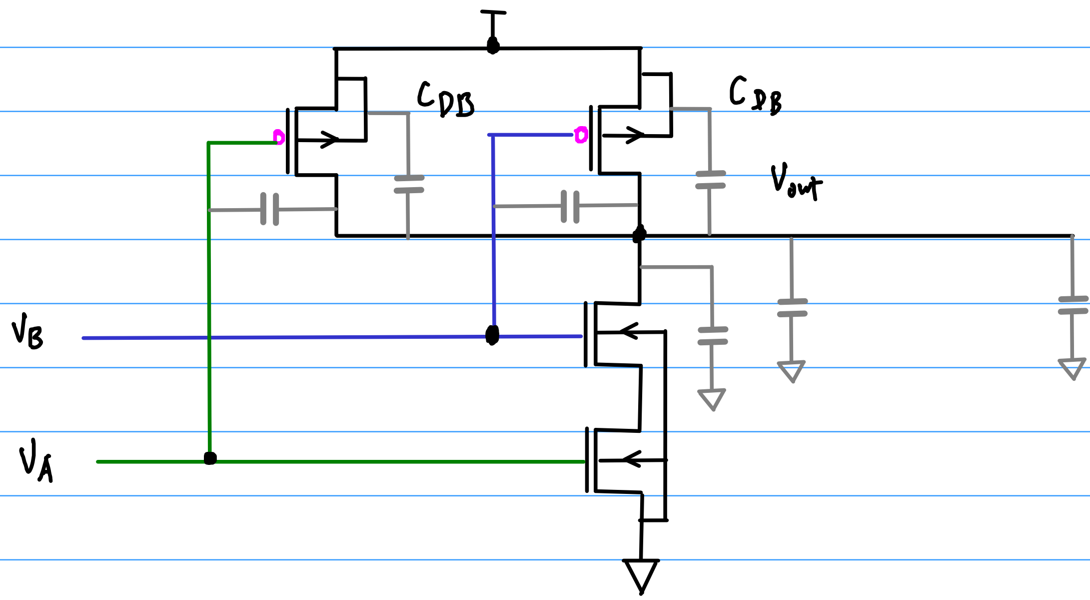
VTC shifted the right

	V_A	V_B	V_{out}
ⓒ	0	0	V_{DD}
ⓐ	0	V_{DD}	V_{DD}
ⓑ	V_{DD}	0	V_{DD}
	V_{DD}	V_{DD}	0

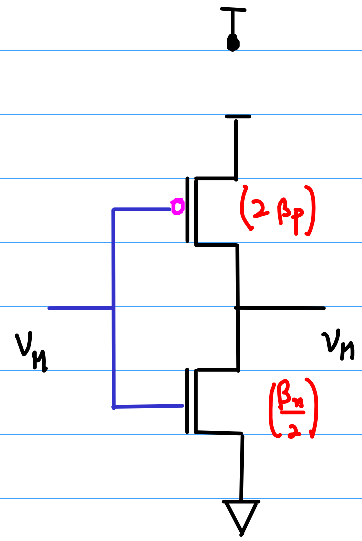




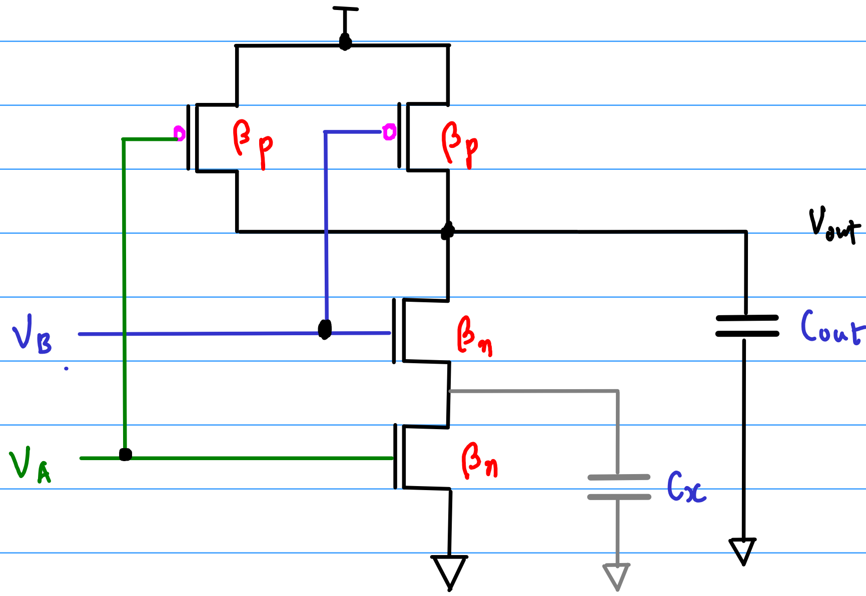




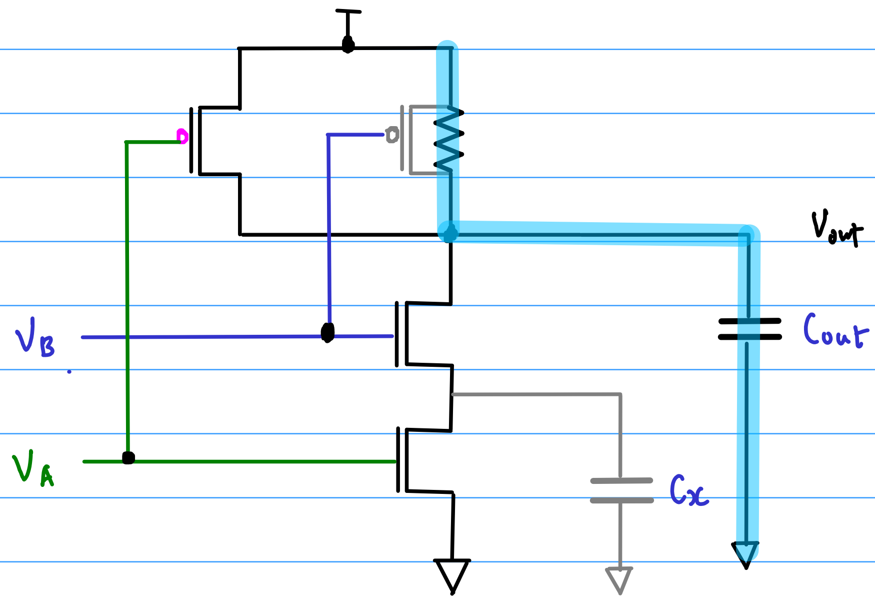
CDB
CDB
Vout
VB
VA



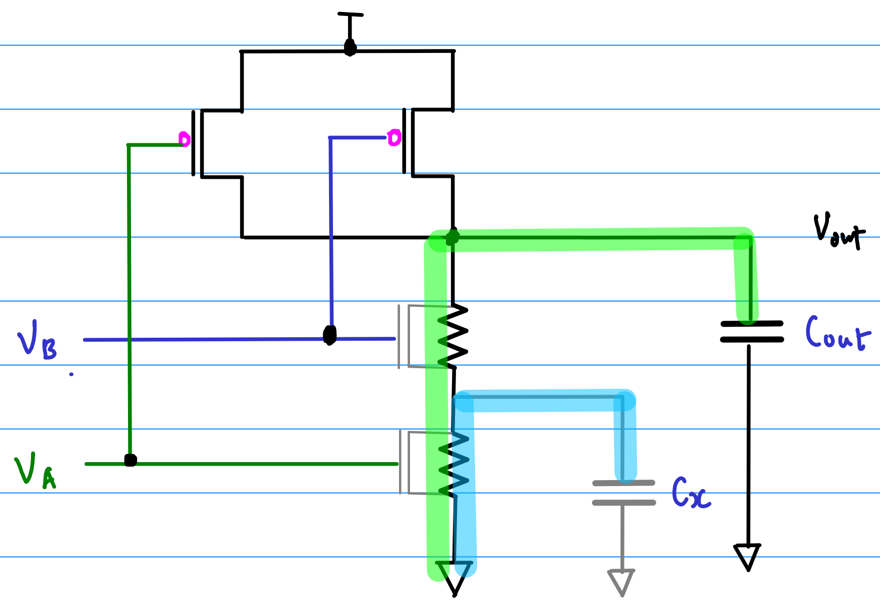
$(2\beta_p)$
V_{in}
V_{in}
$\left(\frac{\beta_n}{2}\right)$



Vout
βp
βp
VB
βn
Cout
VA
βn
Cx



Vout
Cout
VB
VA
Cx

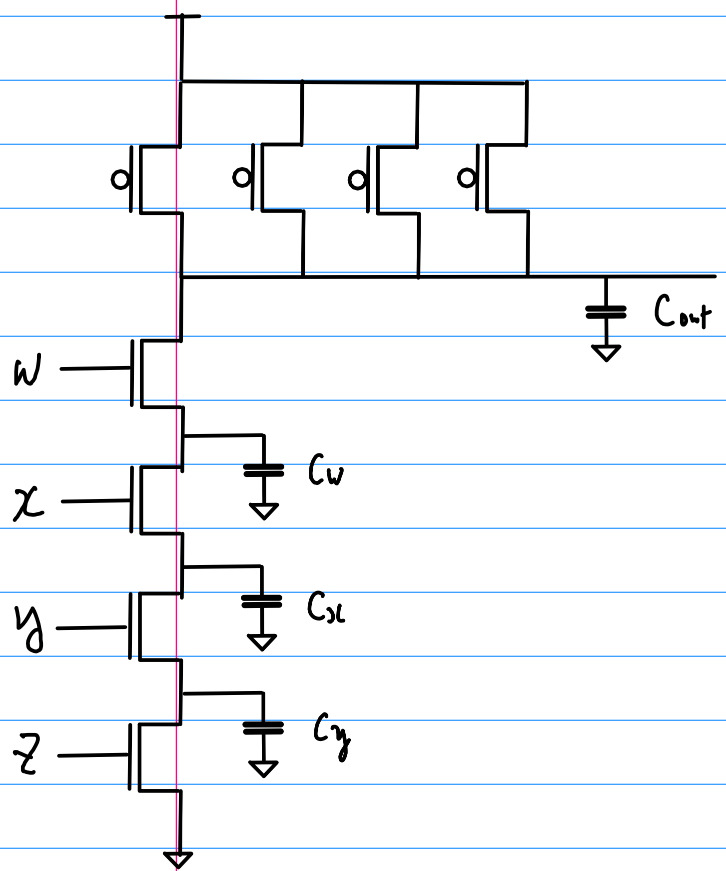


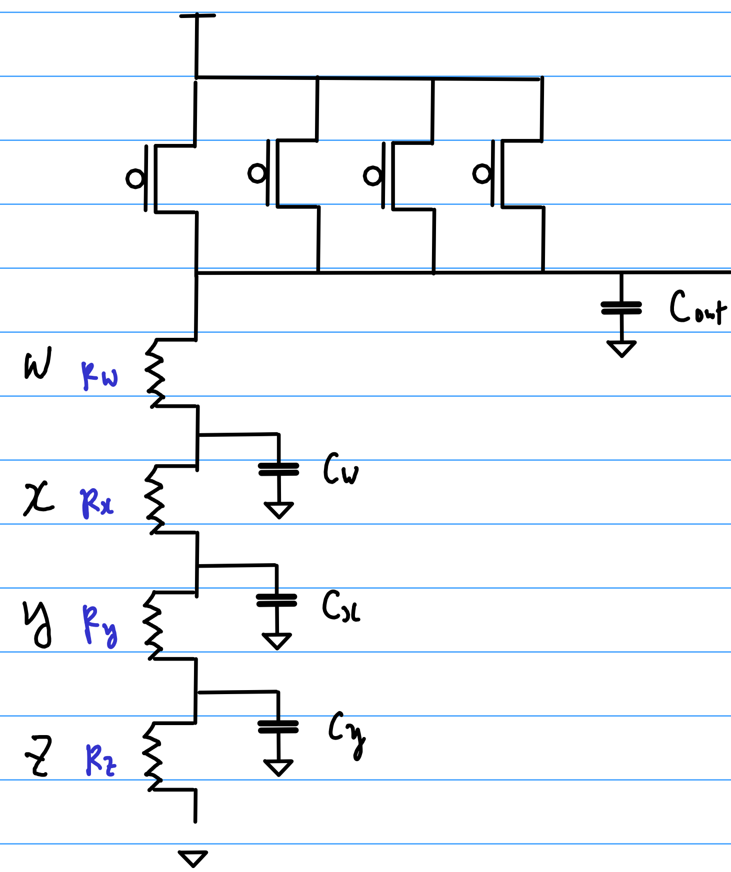
Vout
Cout
VB
VA
Cx

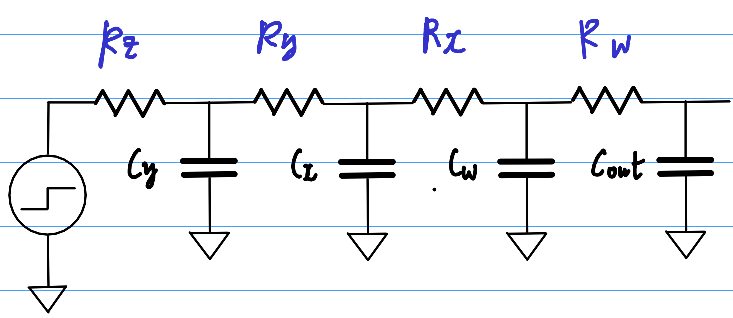
$$C_{out} = C_{FET} + C_L$$

$$C_{FET} = C_{Dn} + 2\,C_{Dp}$$

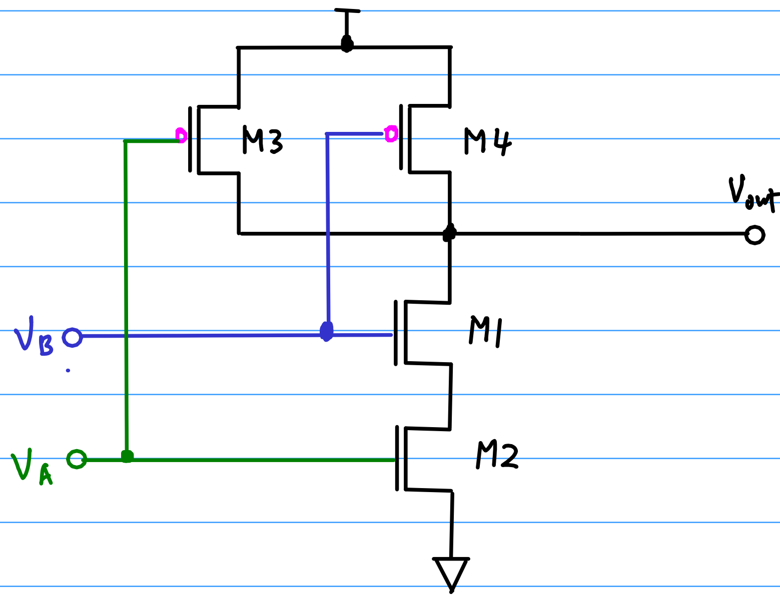
$$R_p = \frac{1}{\beta_p(V_{DD} - |V_{Tp}|)} \qquad R_n = \frac{1}{\beta_n(V_{DD} - V_{Tn})}$$







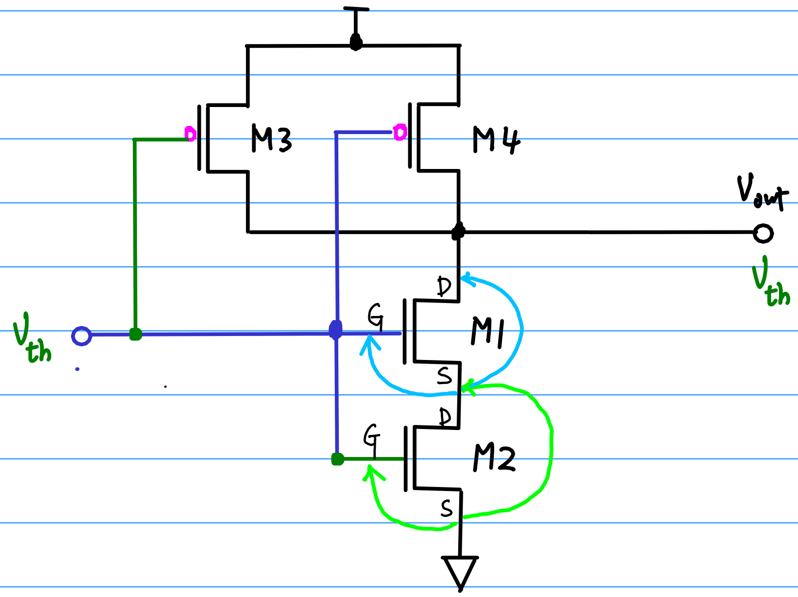
$$t_{pd} = C_y R_z + C_x(R_y + R_z) + C_w(R_x + R_y + R_z) + C_{out}(R_w + R_x + R_y + R_z)$$



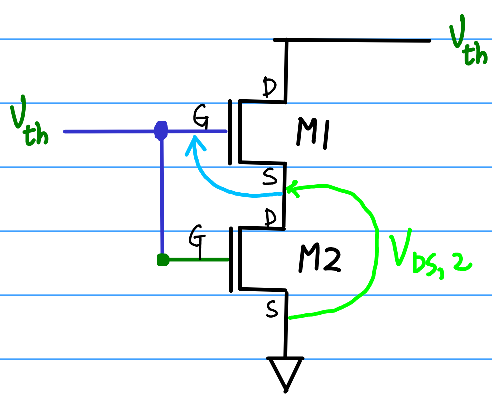
V_A	V_B	V_{out}
0	0	V_{DD}
V_{DD}	0	V_{DD}
0	V_{DD}	V_{DD}

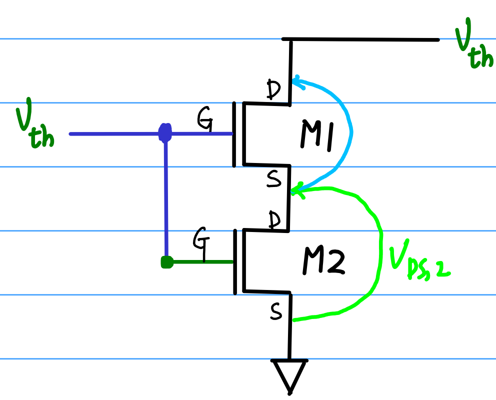
$\Rightarrow$

V_A	V_B	V_{out}
V_{th}	V_{th}	V_{th}
V_{DD}	V_{th}	V_{th}
V_{th}	V_{DD}	V_{th}



V_A	V_B	V_{out}
0	0	V_{DD}
↓	↓	↓
V_{th}	V_{th}	V_{th}



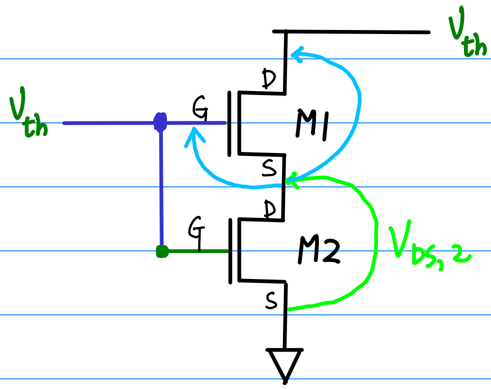


$$V_{GS,1} = V_{th} - V_{DS,2}$$

$$V_{th} = V_{DS,1} + V_{DS,2}$$

$$V_{th} - V_{DS,2} = V_{DS,1}$$

$\therefore$ $\boxed{V_{GS,1} = V_{DS,1}}$ M1 saturated.



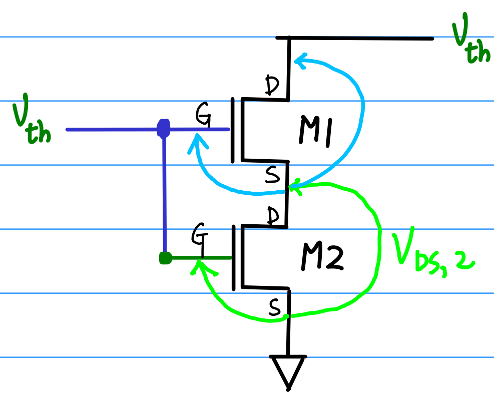
$$I_D = \frac{\beta_n}{2}\left(V_{GS,1} - V_{Ton}\right)^2$$

$$V_{GS,1} = V_{th} - V_{DS,2}$$

$$I_D = \frac{\beta_n}{2}\left(V_{th} - V_{DS,2} - V_{Ton}\right)^2$$

$$I_D = \frac{\beta_n}{2}\left(V_{th} - V_{Ton} - V_{DS,2}\right)^2$$

$\therefore$ $\boxed{V_{GS,1} = V_{DS,1}}$ M1 saturated.



$$V_{th} = V_{GS1} + V_{DS2}$$
$$= V_{GS2}$$

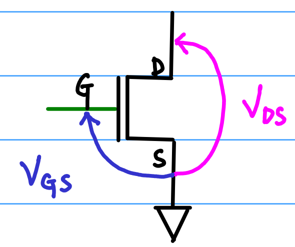
$$V_{GS1} < V_{GS2}$$

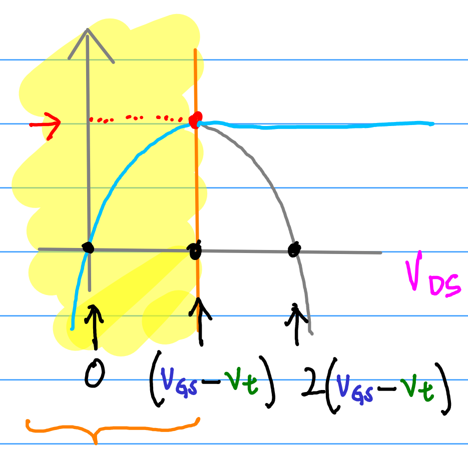
$$V_{GS2} - V_{DS2} = V_{GS1} > 0$$

$V_{GS,2} > V_{GS,1}$ Linear

$$I_{ds} = \begin{cases} 0 & V_{gs} < V_t & \text{cutoff} \\ \beta\left(V_{gs} - V_t - \frac{V_{ds}}{2}\right)V_{ds} & V_{ds} < V_{dsat} & \text{linear} \\ \frac{\beta}{2}\left(V_{gs} - V_t\right)^2 & V_{ds} > V_{dsat} & \text{saturation} \end{cases}$$

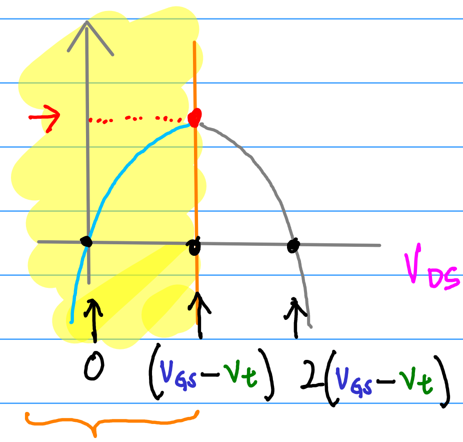
$$I_{ds} = f(V_{DS}) = \frac{\beta}{2}\left(2\left(V_{GS} - V_t\right) - V_{DS}\right) V_{DS}$$





$$V_{DS} \leq V_{GS} - V_t$$

$$f(V_{DS}) = \frac{\beta}{2}\left[2(V_{GS}-V_t) - V_{DS}\right]V_{DS}$$

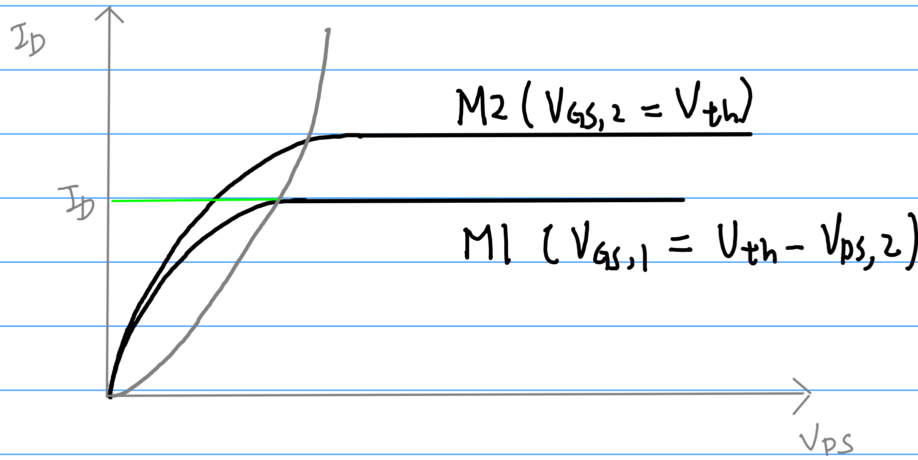


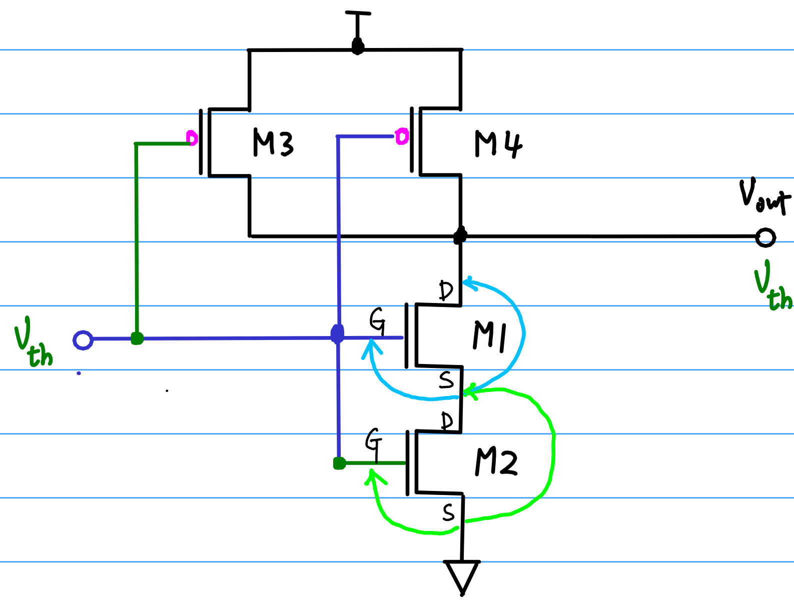
$$V_{DS} \leq V_{GS}-V_t$$

$$f(V_{GS}-V_t) = \frac{\beta}{2}\left(2(V_{GS}-V_t)-(V_{GS}-V_t)\right)(V_{GS}-V_t)$$

$$= \frac{\beta}{2}(V_{GS}-V_t)^2$$

$$I_{DS} = \frac{\beta}{2}(V_{GS}-V_t)^2$$: Saturated current





M1 SAT $\quad I_D = \frac{\beta_n}{2}(V_{th} - V_{Ton} - V_{DS,2})^2$

$V_{GS,2} > V_{GS,1}$ Linear

$$I_D = \frac{\beta_n}{2}\left(2(V_{th} - V_{Ton})V_{DS,2} - V_{DS,2}^2\right)$$

Simultaneous switching

$V_{GS,1} = V_{th} - V_{DS,2}$ $\quad\quad$ $V_{GS,2} = V_{th}$

$V_{th} = V_{DS,1} - V_{DS,2}$

$V_{GS,1} = V_{DS,1}$

$$I_D = \frac{\beta_n}{2}(V_{th} - V_{Ton} - V_{DS,2})^2$$

$$I_D = \frac{\beta_n}{2}(2(V_{th} - V_{Ton})V_{DS,2} - V_{DS,2}^2)$$

$$V_{DS,2} = (V_{th} - V_{Ton}) - \sqrt{\frac{2I_D}{\beta_n}}$$

$$V_{th} - V_{Ton} = (V_{DD} - V_{th})$$

$$V_{SG,3} = V_{SG,4} = (V_{DD} - V_{th})$$

$$V_{SD,3} = V_{SD,4} = (V_{DD} - V_{th})$$

$$I_D = I_{D,3} + I_{D,4} = \beta_p (V_{DD} - V_{th} - |V_{Top}|^2)$$

$$V_{th} = \frac{V_{Ton} + 2\sqrt{\frac{\beta_p}{\beta_n}}(V_{DD} - |V_{Top}|)}{1 + 2\sqrt{\frac{\beta_p}{\beta_n}}}$$

$$V_{th} = \frac{2V_{DD} - V_{To}}{1 + 2\sqrt{\frac{\beta_p}{\beta_n}}}$$

Single Input Switching

$$V_{GS,1} = V_{th} - V_{DS,2} \qquad V_{GS,2} = V_{DD}$$

$$I_D = \frac{\beta_n}{2}\left(V_{th} - V_{Ton} - V_{DS,2}\right)^2$$

$$= \frac{\beta_n}{2}\left[2\left(V_{DD} - V_{Ton}\right)V_{DS,2} - V_{DS,2}^2\right]$$

$$V_{DS,2} = \left(V_{th} - V_{Ton}\right) - \sqrt{\frac{2I_D}{\beta_n}}$$

$$\frac{4I_D}{\beta_n} = 2\left(V_{DD} - V_{Ton}\right)\left(V_{th} - V_{Ton}\right) + 2\sqrt{\frac{2I_D}{\beta_n}}\left(V_{th} - V_{DD}\right) - \left(V_{th} - V_{Ton}\right)^2$$

$$\sqrt{\frac{2I_D}{\beta_n}} = \sqrt{\frac{\beta_p}{\beta_n}}\left(V_{DD} - |V_{Ton}| - V_{th}\right)$$

$$\left[1 + 2\left(\sqrt{\frac{\beta_p}{\beta_n}} + \frac{\beta_p}{\beta_n}\right)\right]V_{th}^2$$
$$- \left\{\left[4\left(\frac{\beta_p}{\beta_n}\right) + 2 + 2\sqrt{\frac{\beta_p}{\beta_n}}\right]\left(V_{DD} - V_{T0}\right) + 2V_{T0} + 2V_{DD}\sqrt{\frac{\beta_p}{\beta_n}}\right\}V_{th}$$
$$+ 2\left[2\left(\frac{\beta_p}{\beta_n}\right)\left(V_{DD} - V_{T0}\right)^2 + 2\left(V_{T0} + \sqrt{\frac{\beta_p}{\beta_n}}\right)\left(V_{DD} - V_{T0}\right) + V_{T0}^2\right] = 0$$

$$V_{th} = \left(V_{DD} - 0.6V_{T0}\right) - \frac{1}{5}\sqrt{5V_{DD}^2 - 10V_{DD}V_{T0} + 4V_{T0}^2}$$