CMOS Delay-7 (H.8)
Delay Model

20170127

.

References

Some Figures from the following sites

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

[2] en.wikipedia.org

β : Device Transconductance Parameter
k : Process Transconductance Parameter
μ : Electron / Hole Mobility

pMOS $\quad \beta_p = k'_p \left(\frac{W}{L}\right)_p \qquad k'_p = \mu_p C_{ox} \qquad C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}}$

nMOS $\quad \beta_n = k'_n \left(\frac{W}{L}\right)_n \qquad k'_n = \mu_n C_{ox} \qquad C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}}$

pMOS $\quad \beta_p = \mu_p \frac{\varepsilon_{ox}}{t_{ox}} \left(\frac{W}{L}\right)_p$

nMOS $\quad \beta_n = \mu_n \frac{\varepsilon_{ox}}{t_{ox}} \left(\frac{W}{L}\right)_n$

Saturation Current

$$I_{dp} = \frac{\beta_p}{2} \left(V_{GSn} - |V_{Tp}|\right)^2 \qquad V_{Tp} < 0$$

$$I_{dn} = \frac{\beta_n}{2} \left(V_{GSn} - V_{Tn}\right)^2 \qquad V_{Tn} > 0$$

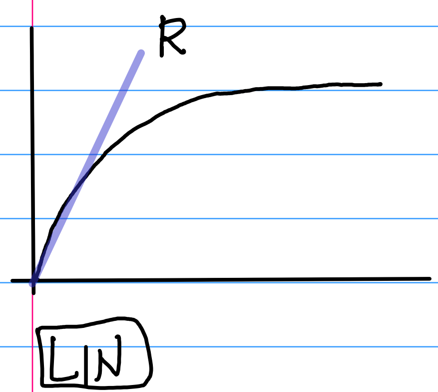
MODEL

$$\boxed{\frac{\beta_n}{\beta_p} \simeq \frac{k_n' \left(\frac{W}{L}\right)_n}{k_p' \left(\frac{W}{L}\right)_p}}$$

$$\frac{k_n'}{k_p'} = 2 \sim 3$$

$$\boxed{\frac{k_n'}{k_p'} = \frac{\mu_n}{\mu_p} = r}$$

$$\boxed{\frac{\beta_n}{\beta_p} = \frac{k'_n \left(\frac{W}{L}\right)_n}{k'_p \left(\frac{W}{L}\right)_p}}$$



$$R_n = \frac{1}{\beta_n (V_{DD} - V_{Tn})}$$

$$R_p = \frac{1}{\beta_n (V_{DD} - V_{Tn})}$$

fall time t_f $\quad \tau_n = R_n C_{out}$

rise time t_r $\quad \tau_p = R_p C_{out}$

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

MODEL

fall time	$t_f = 2.2\,\tau_n = \ln 9\ \tau_n$	$0.9\,V_{DD} \rightarrow 0.1\,V_{DD}$
rise time	$t_r = 2.2\,\tau_p = \ln 9\ \tau_p$	$0.1\,V_{DD} \rightarrow 0.9\,V_{DD}$
propagation delay time	$t_p = \frac{1}{2}(t_{pf} + t_{pr})$ $= 0.35(t_{pf} + t_{pr})$	$0.5\,V_{DD} \rightarrow 0.5\,V_{DD}$
propagation fall time propagation rise time	$t_{pf} = 0.7\,\tau_n = \ln 2\ \tau_n$ $t_{pr} = 0.7\,\tau_p = \ln 2\ \tau_p$	$V_{DD} \rightarrow 0.5\,V_{DD}$ $0 \rightarrow 0.5\,V_{DD}$

$$\tau_n = R_n(C_{para} + C_L)$$

$$\tau_p = R_p(C_{para} + C_L)$$

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

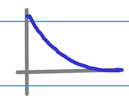
MODEL

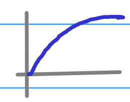
$$\left(\frac{W}{L}\right)_p = r\left(\frac{W}{L}\right)_n$$

$$r = \frac{\mu_n}{\mu_p} = \frac{k'_n}{k'_p} > 1$$

$$R_n = R_p = R = \frac{1}{\beta(V_{DD} - V_T)}$$

$$\begin{cases} V_{out}(t) = V_{DD}\left(1 - e^{-t/\tau}\right) \\ V_{out}(t) = V_{DD}\, e^{-t/\tau} \end{cases}$$





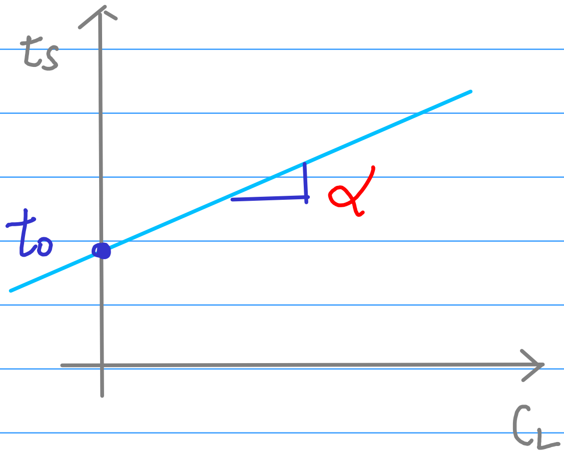
$$\tau = R C_{out} = R\left(C_{par} + C_L\right)$$

Generic Switching Delay

$$t_s = t_0 + \alpha C_L \quad \Rightarrow \quad t_s = t_r = t_f$$

Generic Switching Delay

$$t_s = t_0 + \alpha C_L$$



t_0 : zero delay

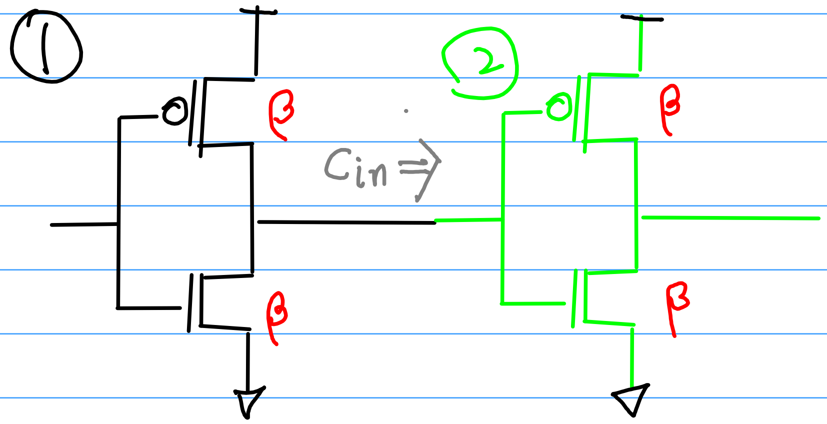
α : slope

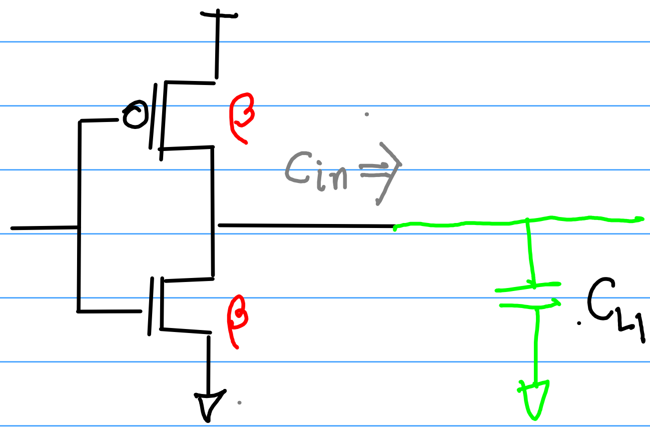
$$t \approx R\,C$$

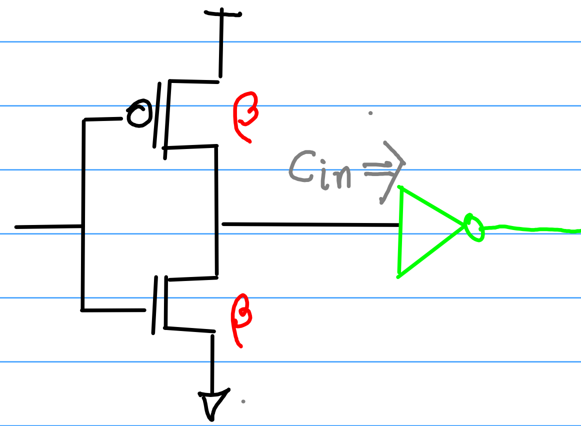
$$\alpha \propto \frac{1}{\beta(V_{DD} - V_T)}$$

C_L

MODEL







reference case $\boxed{C_{in} = C_{L1}}$

Generic Switching Delay of 1

$$t_{s1} = t_0 + \alpha C_{L1}$$

$$= t_0 + \alpha C_{in}$$

$$C_{in} = C_{Gn} + C_{Gp}$$

$$= C_{ox}(A_{Gn} + A_{Gp}) \qquad A: \text{gate area}$$

the channel length L assumed

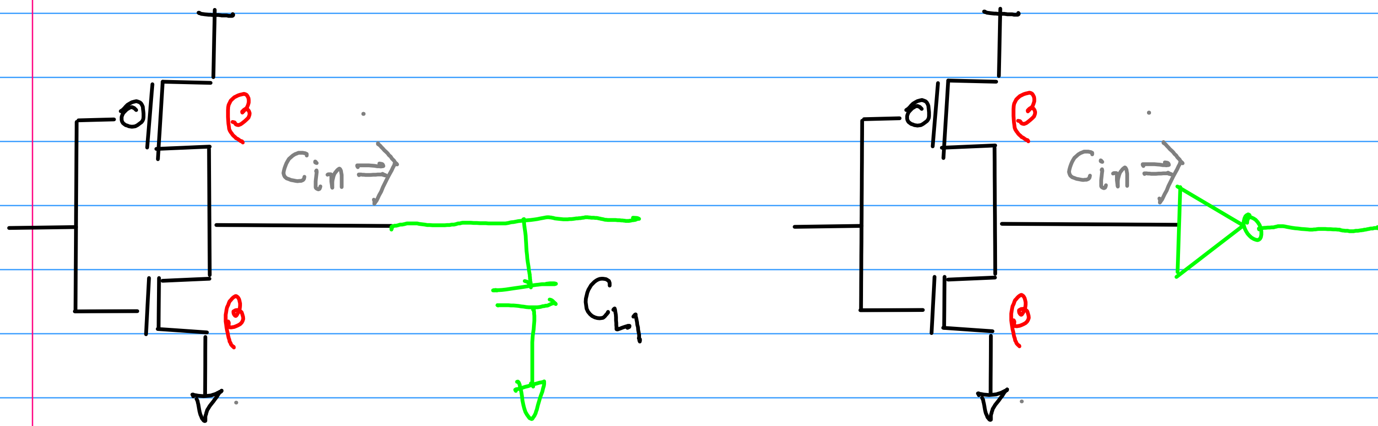
$$C_{in} = C_{ox} L (W_n + W_p)$$

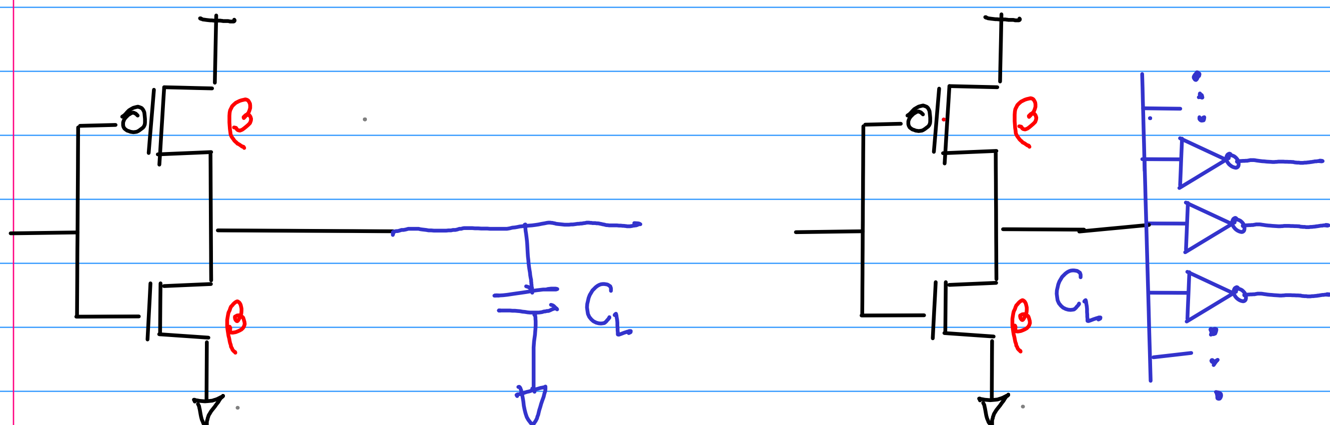
$$= C_{ox} L (W_n + r W_p)$$

$$= C_{ox} L W_n \cdot (1 + r)$$

$$= C_{Gn} (1 + r)$$

When $C_L \gg C_{in}$





to minimize t_s

$\alpha \downarrow \Rightarrow R \downarrow \Rightarrow \beta \uparrow \Rightarrow$ bigger size

speed v.s. area <u>tradeoff</u>

$$t_s = t_0 + \alpha C_L \qquad t \approx RC$$

$$\alpha \propto \frac{1}{\beta (V_{DD} - V_T)} \qquad C_L$$

to minimize t_s

$\alpha \downarrow \Rightarrow R \downarrow \Rightarrow \beta \uparrow \Rightarrow$ bigger size

speed v.s. area tradeoff

Scaling Factor S

$$\beta' = S\beta$$

$$R' = \frac{R}{S}$$

$$\alpha' = \frac{\alpha}{S}$$

$$t_s = t_0 + \underbrace{\frac{\alpha}{S}}_{R}\underbrace{C_L}_{C}$$

Compensation Factor $\frac{1}{S}$

enables a NOT gate drive larger values of C_L

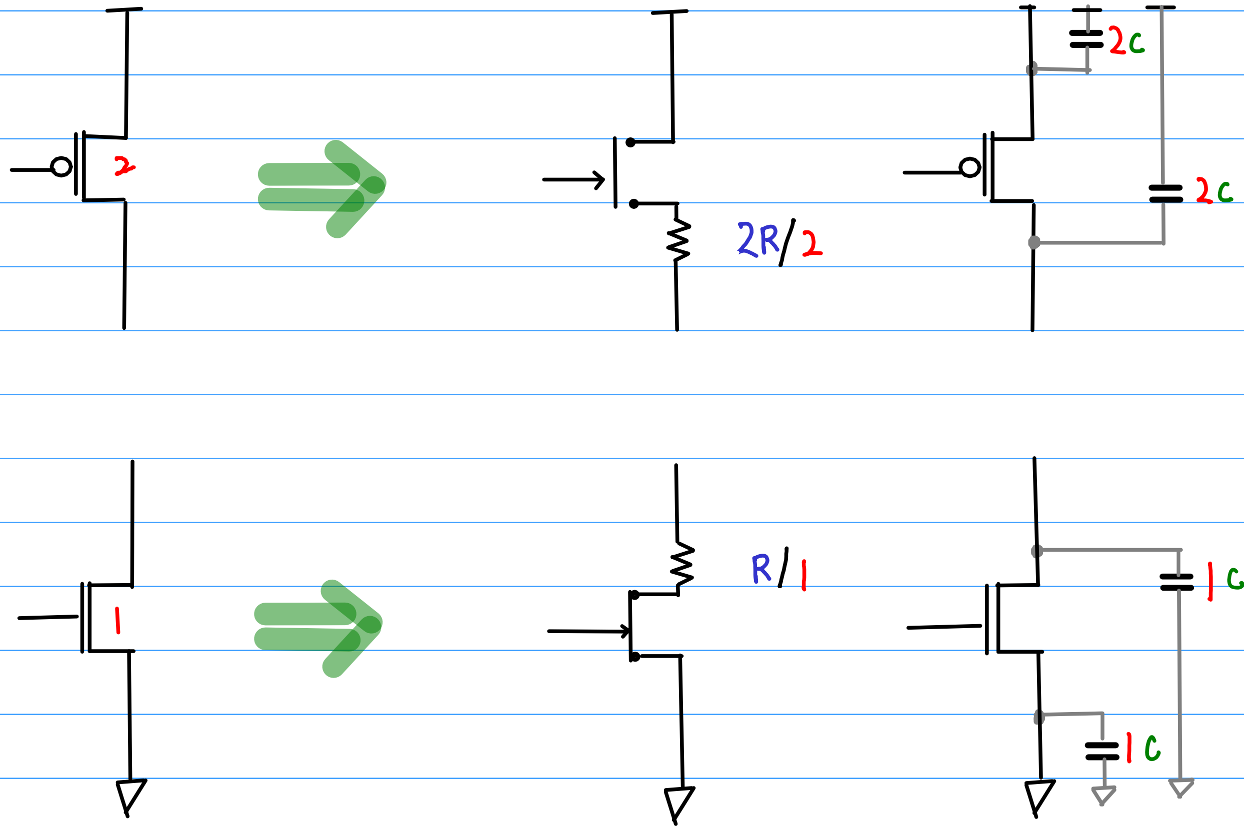
If $C_L = S\,C_{in}$ (increased by the scaling factor S)

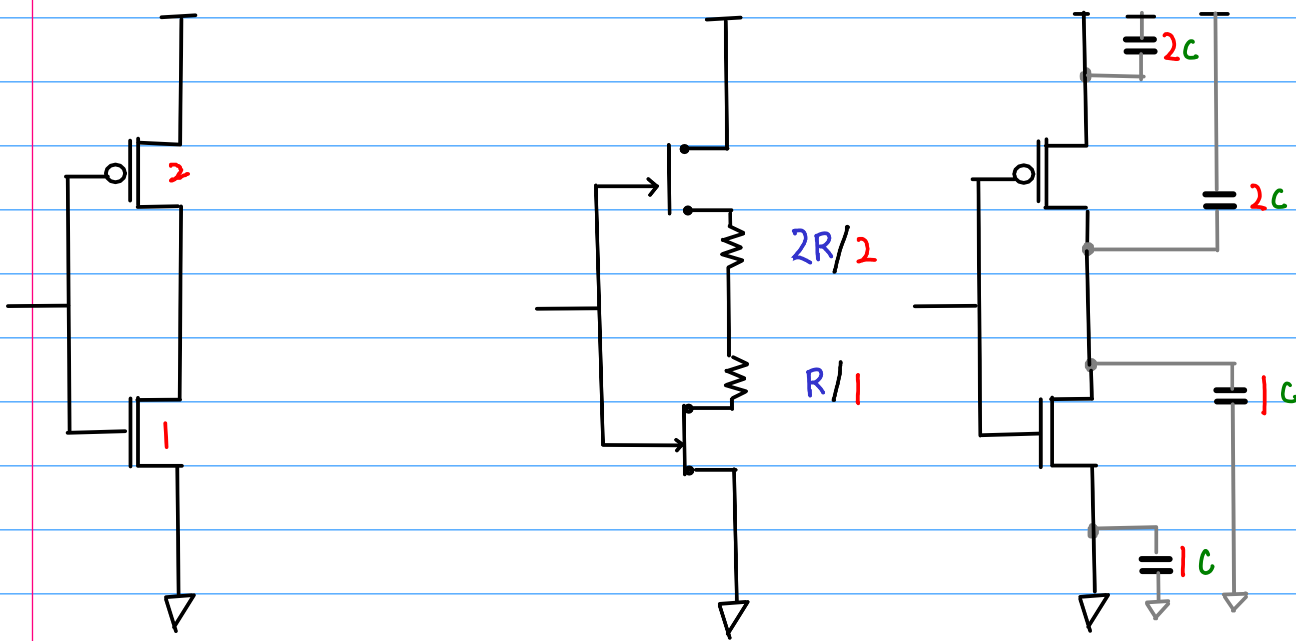
then the switching time is the same

RC Delay Model

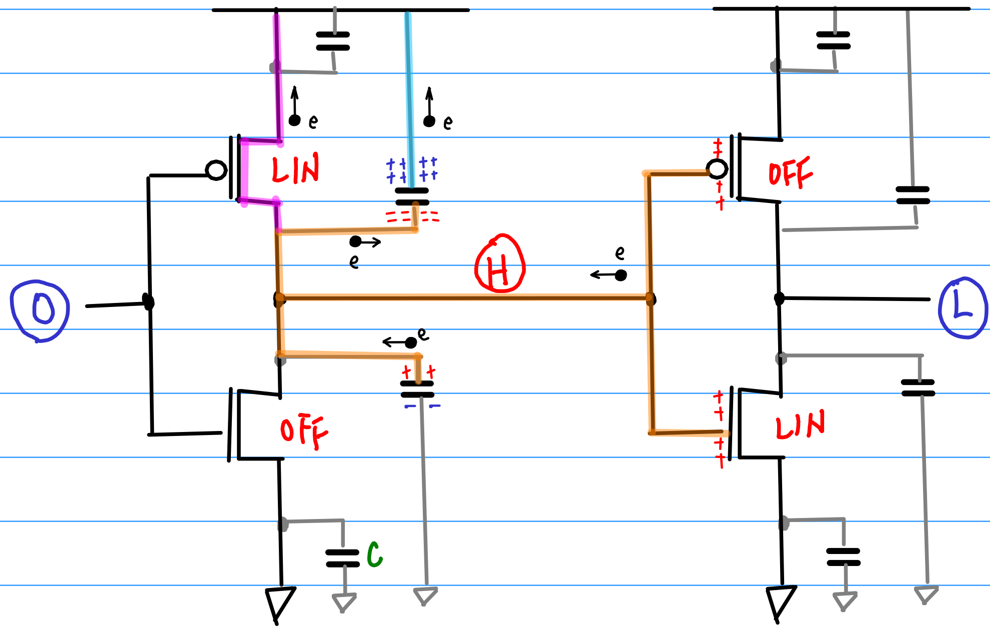
pMOS

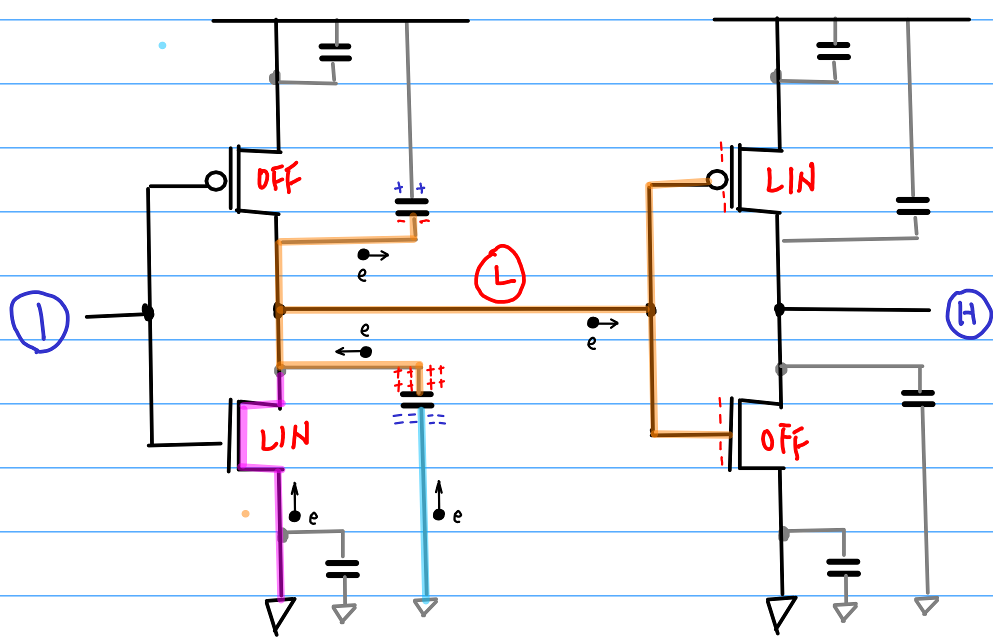
nMOS

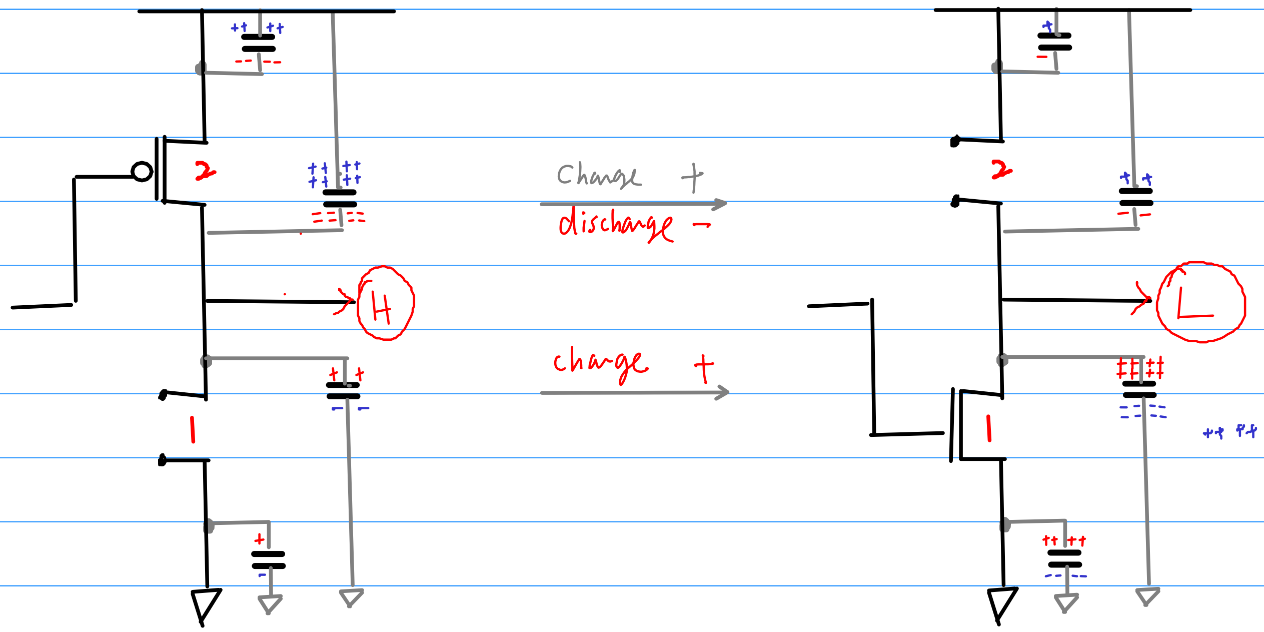




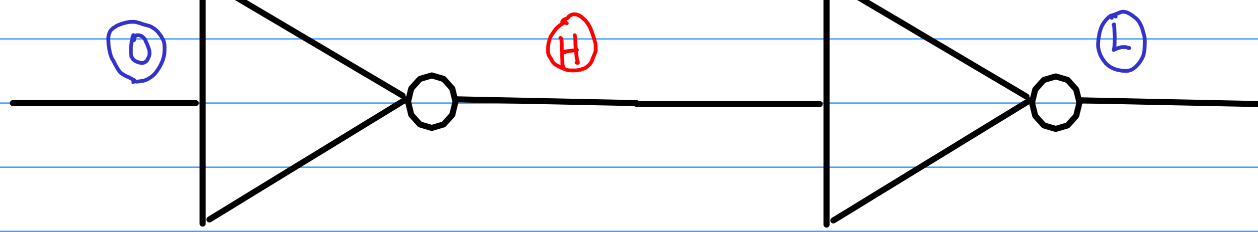
2
1
2R/2
R/1
2c
2c
1c
1c

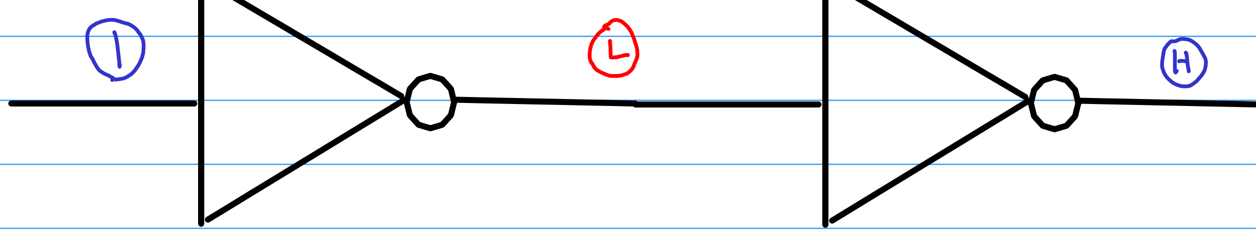

LIN
OFF
OFF
LIN
H
0
L
C
e

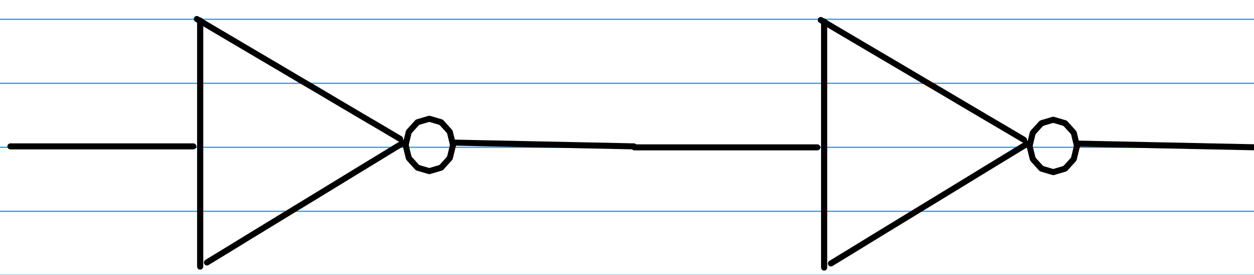

OFF
LIN
LIN
OFF
L
1
H
e

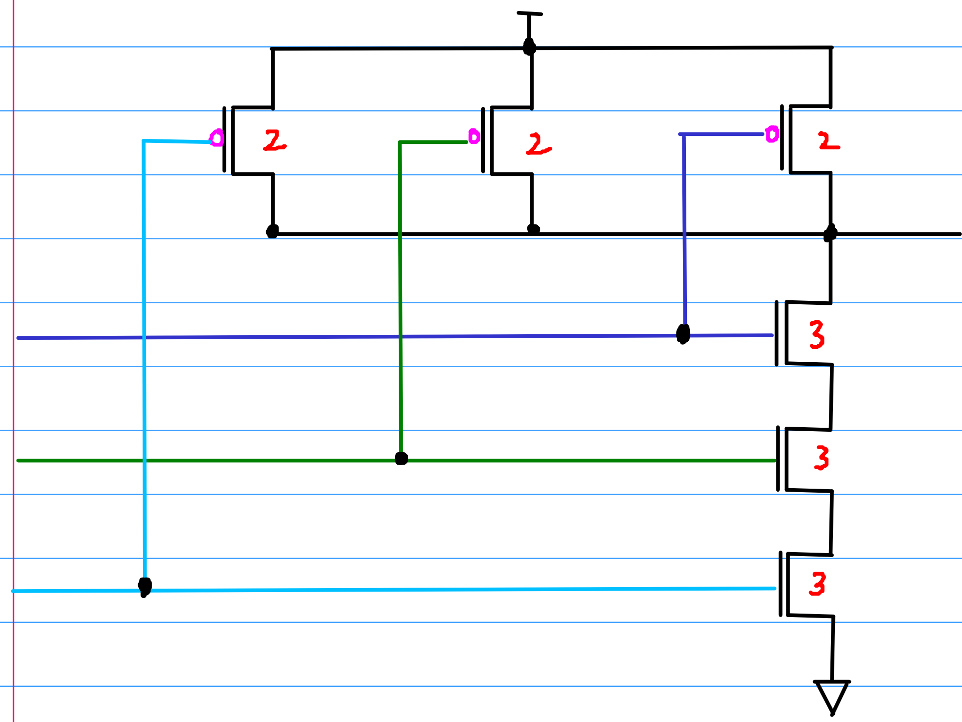


2
1
H
Charge +
discharge −
charge +
2
1
L

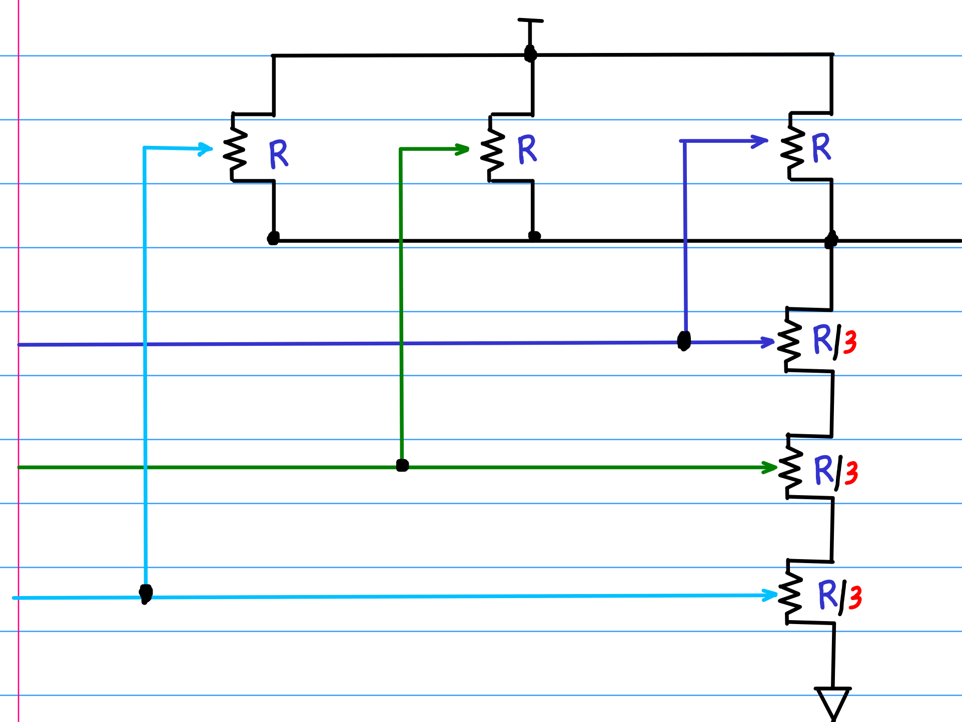

0
H
L


1
L
H

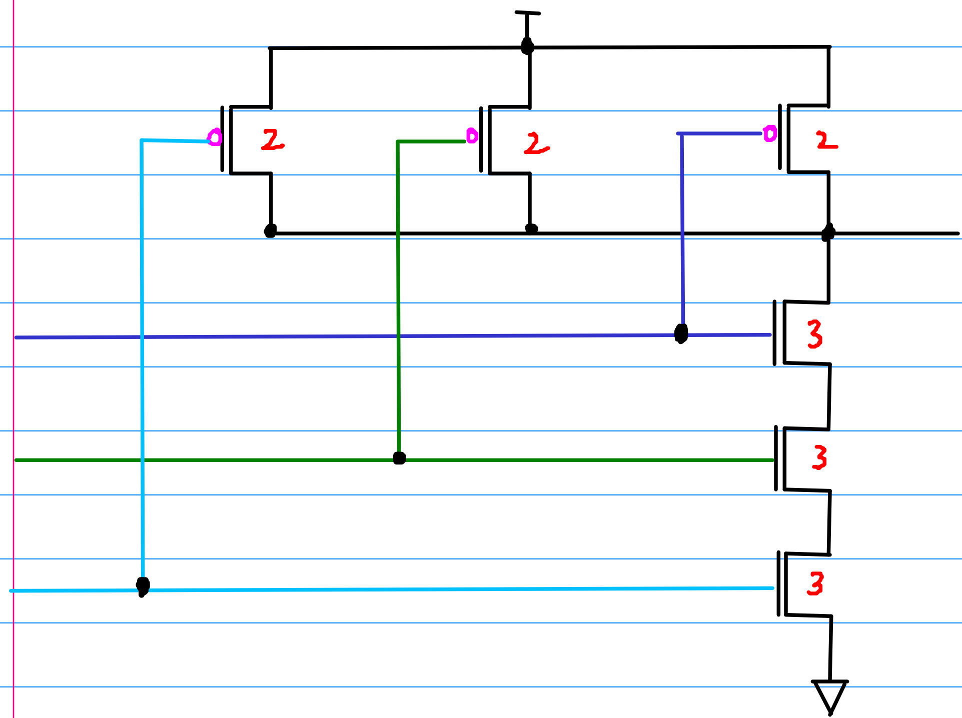




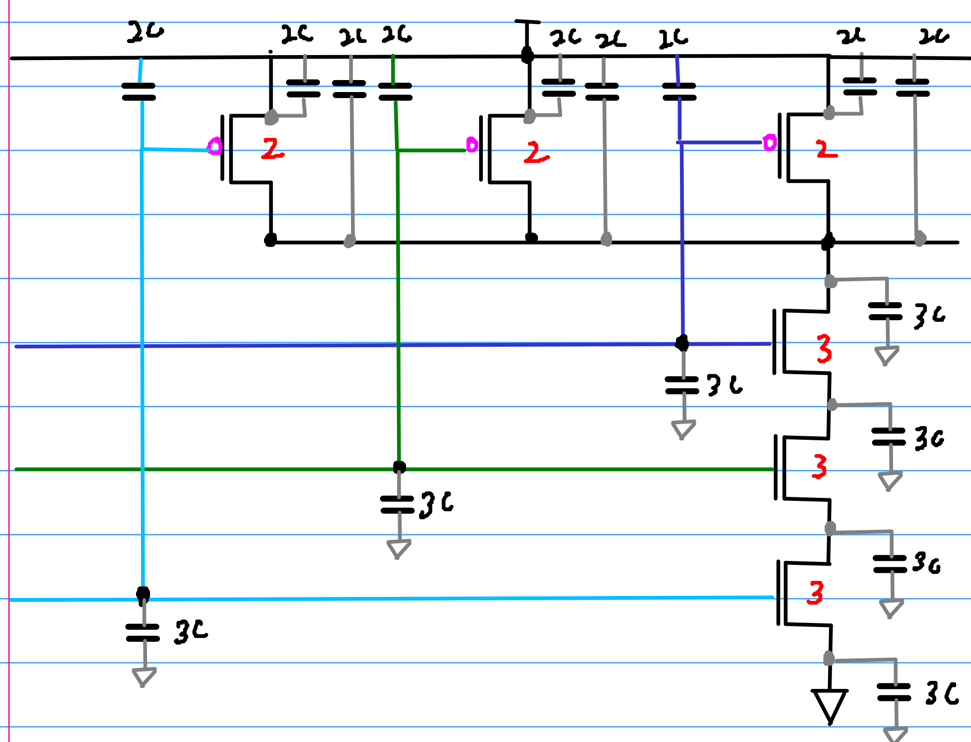
2
2
2
3
3
3



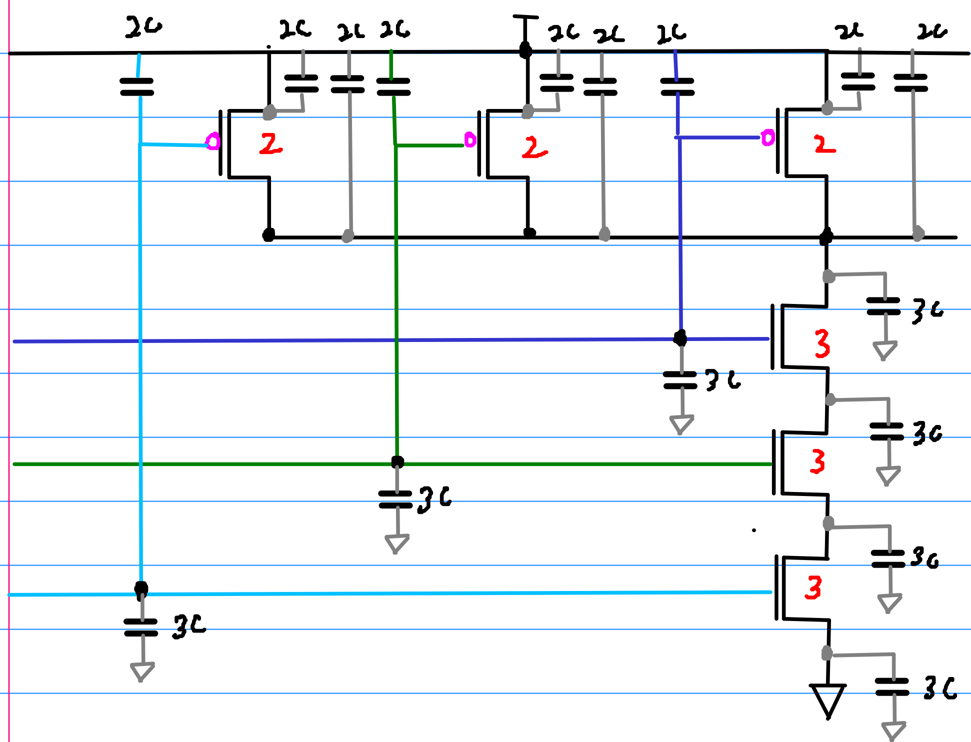
R
R
R
R/3
R/3
R/3

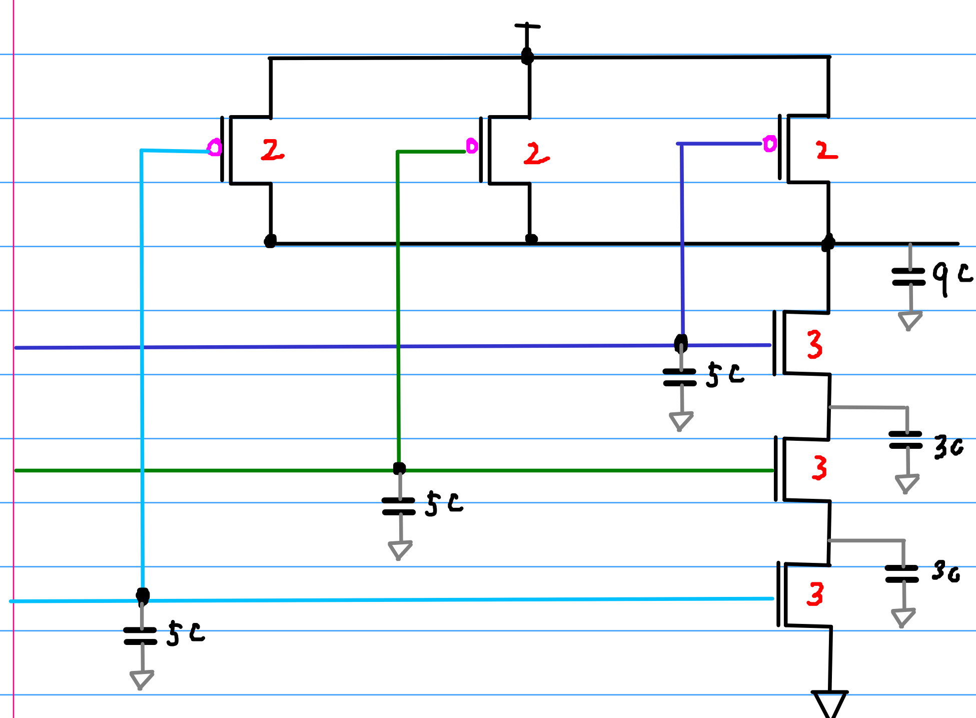


2
2
2
3
3
3

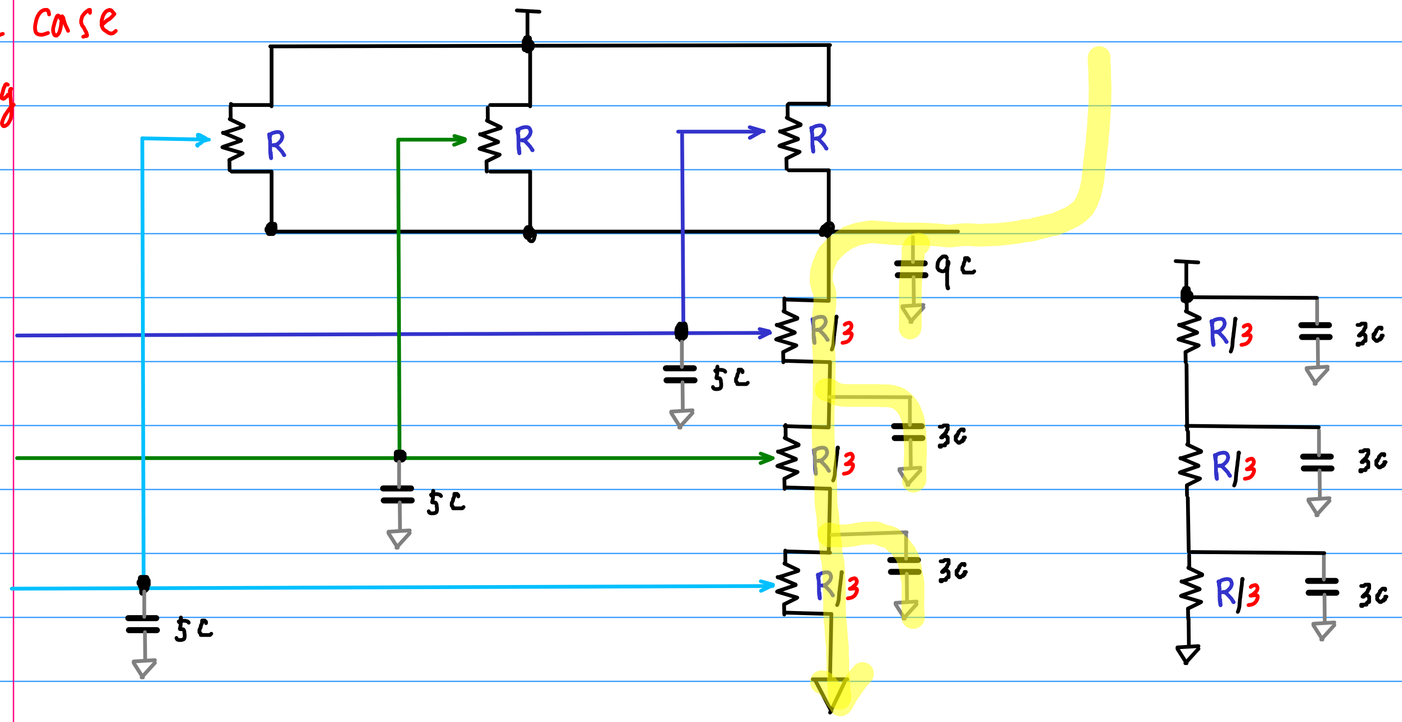


2C
2C
2C
2C
2C
2C
2C
2C
2C
2
2
2
3C
3
3C
3C
3
3C
3C
3
3C
3C

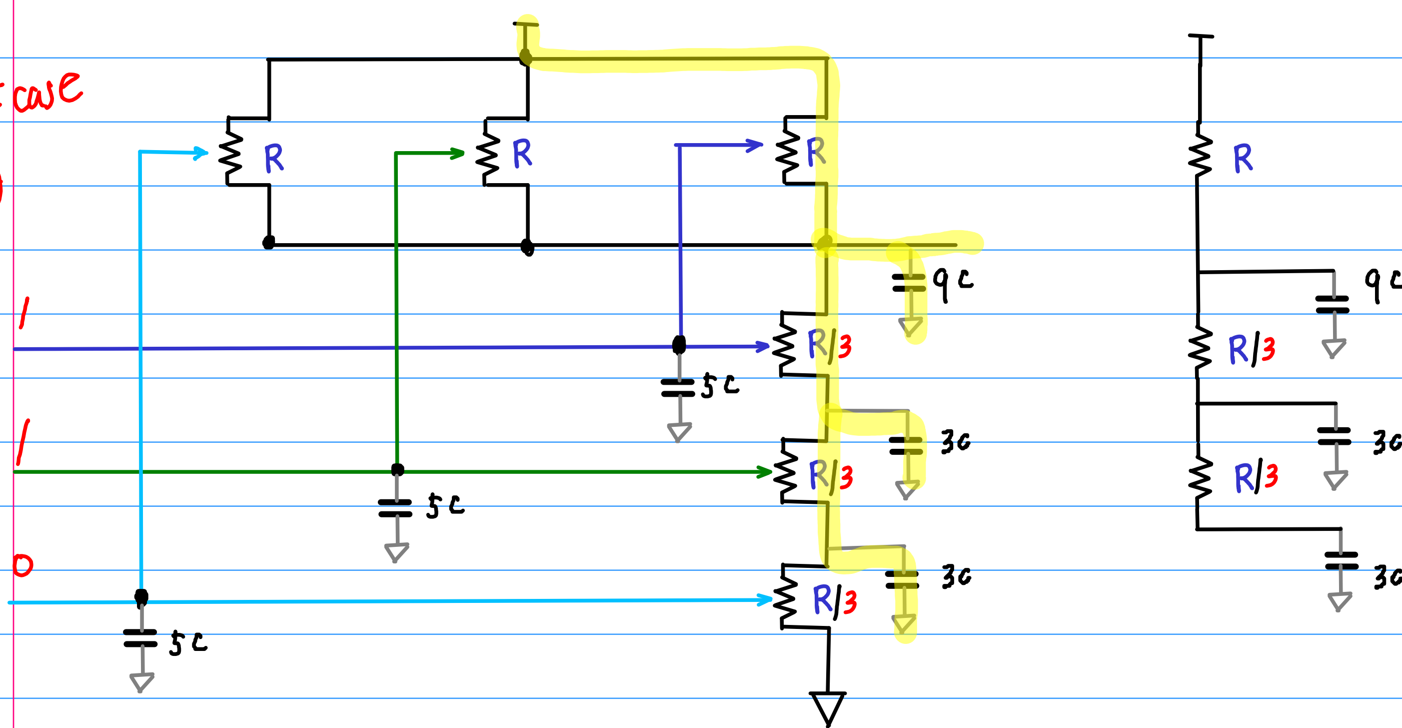

2c
2c
2c
2c
2c
2c
2c
2c
2c
2
2
2
3c
3
3c
3
3c
3
3c
3c
3c
3c


2
2
2
9c
3
5c
3
3c
5c
3
3c
5c

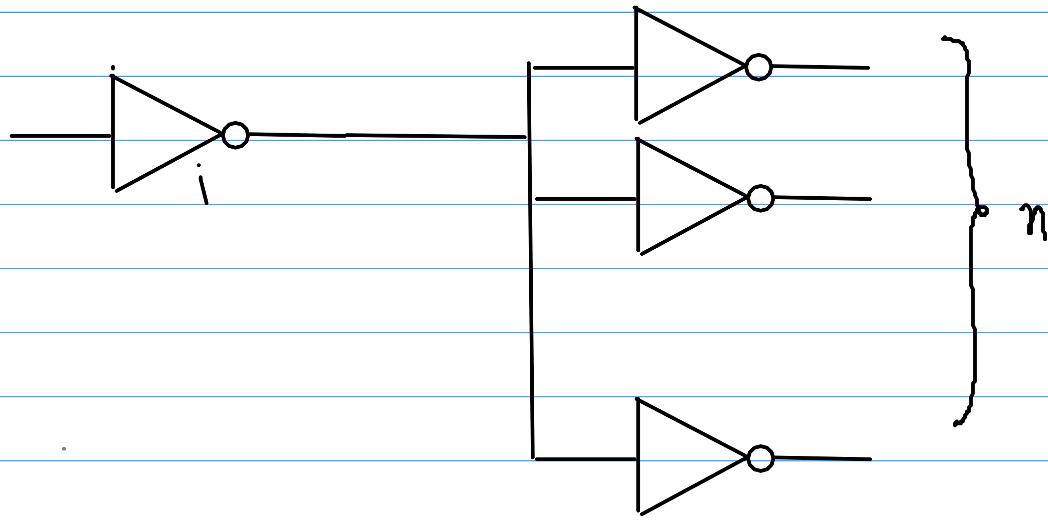
Worst case falling



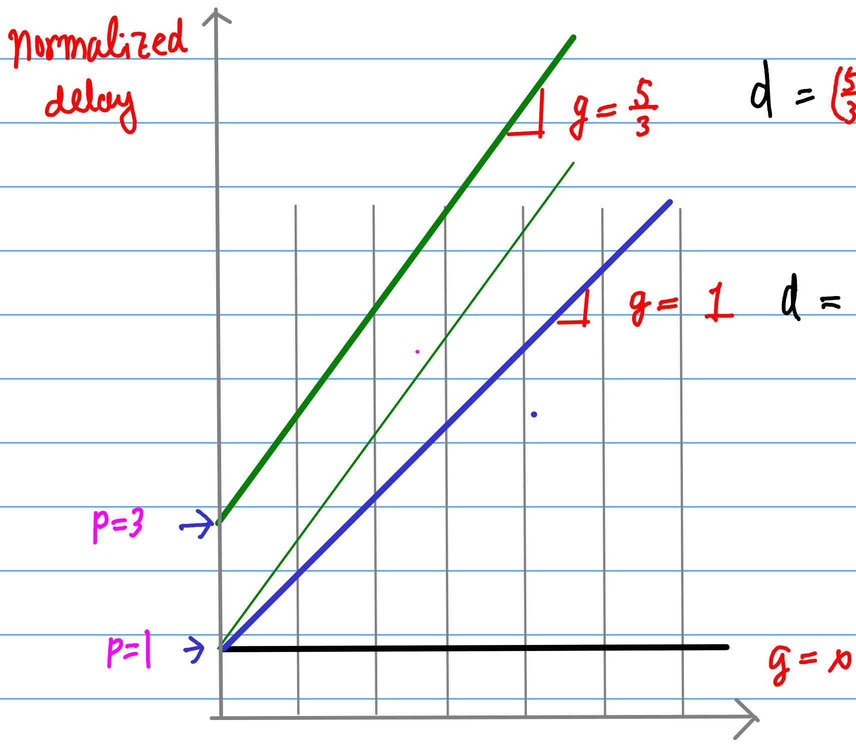
worst case rising



0



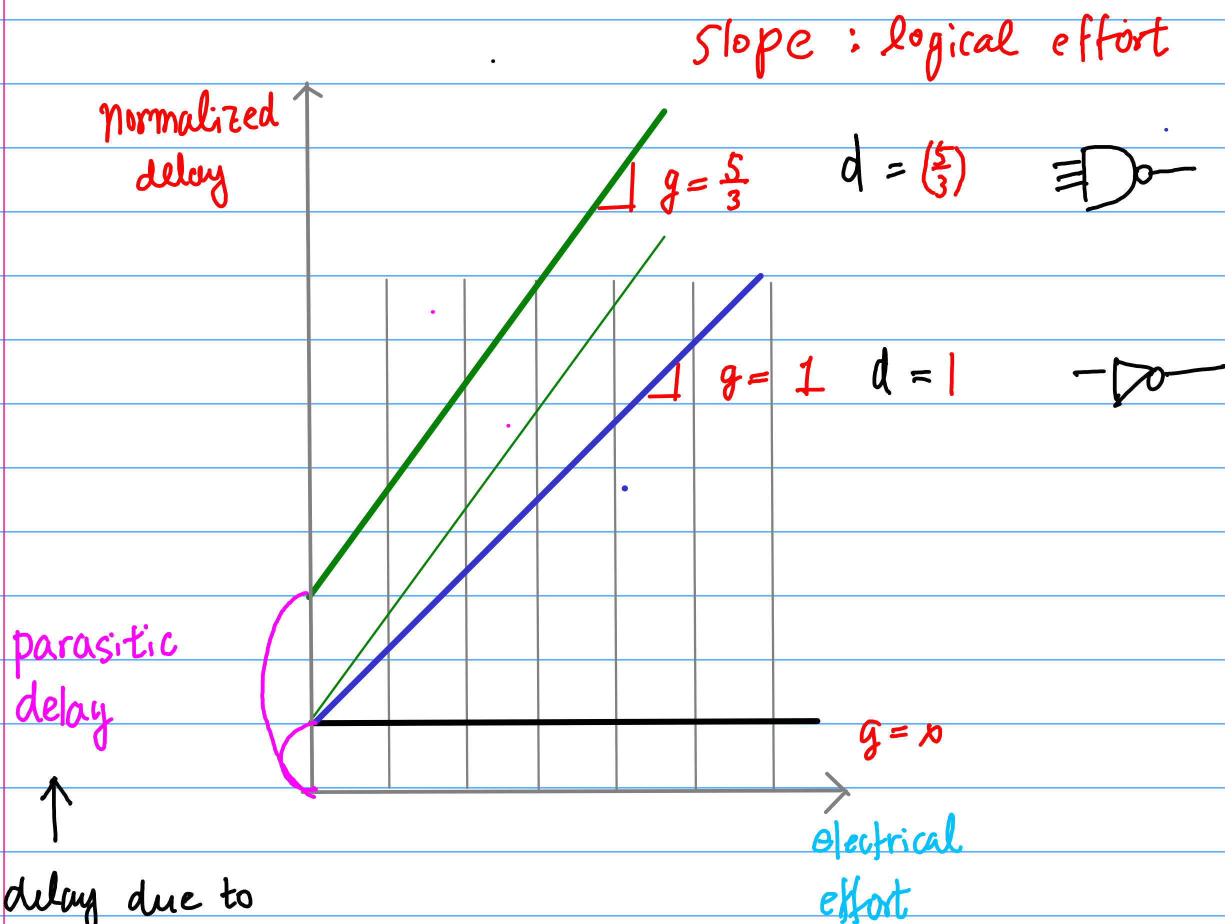
Linear Delay Model



$d = \left(\frac{5}{3}\right) h + 3$

$d = 1 \cdot h + 1$

$h = \frac{C_{out}}{C_{in}}$



delay due to
only internal cap
without external load cap

$$\boxed{d = g \cdot h + p}$$

k c c

Fall Time Calculation

$$i = -C_{out}\frac{dV_{out}}{dt} = \frac{V_{out}}{R_n}$$

$$V_{out}(t) = V_{DD}\, e^{-t/\tau_n}$$

$$\tau_n = R_n C_{out}$$

$$t = \tau_n \ln\left(\frac{V_{DD}}{V_{out}}\right)$$

$$t_f = t_y - t_x = \tau_n \ln\left(\frac{V_{DD}}{0.1\,V_{DD}}\right) - \tau_n \ln\left(\frac{V_{DD}}{0.9\,V_{DD}}\right)$$
$$= \tau_n \ln(9)$$

$$t_{HL} = t_f \cong 2.2\,\tau_n$$

Rise Time Calculation

$$i = -C_{out}\frac{dV_{out}}{dt} = \frac{V_{DD} - V_{out}}{R_p}$$

$$V_{out}(t) = V_{DD}\left[1 - e^{-t/\tau_p}\right]$$

$$\tau_p = R_p C_{out}$$

$$t = \tau_p \ln\left(\frac{V_{DD}}{V_{out}}\right)$$

$$t_f = t_v - t_u = \tau_p \ln\left(\frac{V_{DD}}{0.1\,V_{DD}}\right) - \tau_n \ln\left(\frac{V_{DD}}{0.9\,V_{DD}}\right)$$

$$= \tau_p \ln(9)$$

$$t_{LH} = t_r \cong 2.2\,\tau_p$$