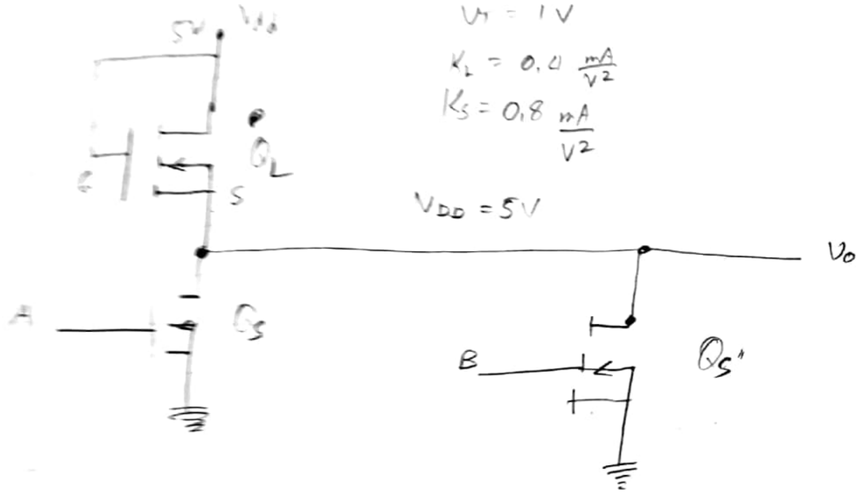
Digital Electronics NMOS



$V_T = 1V$

$K_L = 0.4 \frac{mA}{V^2}$

$K_S = 0.8 \frac{mA}{V^2}$

$V_{DD} = 5V$

a. NOR GATE

b. A = high, B is low $A = 3V$ $B = 0.5V$

Q_L saturated

$V_{GSS} = 3V$, trying to solve V_{DSS}

$V_{DSL} = 5V - V_{DSS} = 5V - V_0$

$I_{DSL} = I_{DSS}$

$\frac{K_L}{2}(V_{GSL} - V_T)^2 = K_S\left[(V_{GSS} - V_T)V_{DS} - \frac{V_{DS}^2}{2}\right]$

$\frac{0.2mA}{V^2}(4V - V_0)^2 = 0.8\frac{mA}{V^2}\left[(2V)V_0 - \frac{V_0^2}{2}\right]$

$(4V - V_0)(4V - V_0) = 4\left[2V_0 - \frac{V_0^2}{2}\right]$

$16 - 8V_0 + V_0^2 = 8V_0 - 2V_0^2$

$3V_0^2 - 16V_0 + 16 = 0$

$\boxed{V_0 = 1.33V}$

$\boxed{\text{PART D}}$

No, $V_0 < 1V = V_T$

c. Both Q_S are ON $V_{GSS'} = 3V$

$I_{DSL} = I_{DSS} \rightarrow 0.2\frac{mA}{V^2}(4V - V_0)^2 = \left(0.8\frac{mA}{V^2}\right)2\left[2V_0 - \frac{V_0^2}{2}\right]$

$16 - 8V_0 + V_0^2 = 16V_0 - 4V_0^2$

$5V_0^2 - 24V_0 + 16 = 0 \rightarrow \boxed{V_0 = 0.8V}$

RUID: 170002071

Atul Srivastava

Digital Electronics NMOS

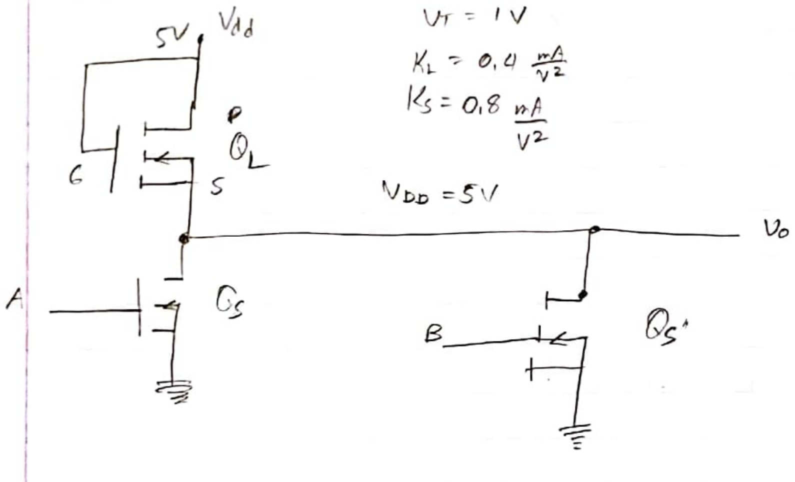
Problem 1

$V_T = 1V$

$K_L = 0.4 \frac{mA}{V^2}$

$K_S = 0.8 \frac{mA}{V^2}$

$V_{DD} = 5V$



a. NOR GATE

b. A is high, B is low $A = 3V$ $B = 0.5V$

Q_L saturated

$V_{gss} = 3V$, trying to solve V_{DSS}

$V_{gsL} = 5V - V_{DSS} = 5V - V_o$

$I_{DSL} = I_{DSS}$

$\frac{K_L}{2}(V_{gsL} - V_T)^2 = K_S[(V_{gss} - V_T)V_{DS} - \frac{V_{DS}^2}{2}]$

$0.2\frac{mA}{V^2}(4V - V_o)^2 = 0.8\frac{mA}{V^2}[(2V)V_o - \frac{V_o^2}{2}]$

$(4V - V_o)(4V - V_o) = 4[2V_o - \frac{V_o^2}{2}]$

$16 - 8V_o + V_o^2 = 8V_o - 2V_o^2$

$3V_o^2 - 16V_o + 16 = 0$

$\boxed{V_o = 1.33V}$

$\boxed{\text{PART D}}$

$\therefore$ No, $V_o < 1V = V_T$

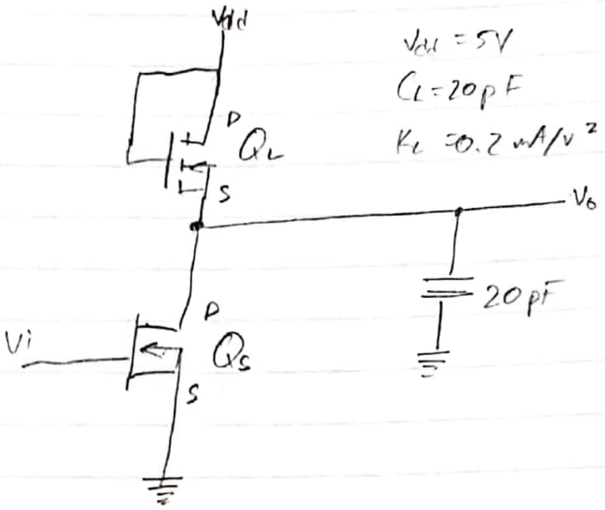
c. Both Q_s are ON $V_{gss}{}^2 = 3V$

$I_{DSL} = I_{DSS} \rightarrow 0.2\frac{mA}{V^2}(4V - V_o^2) = (0.8\frac{mA}{V^2})2[2V_o - \frac{V_o^2}{2}]$

$16 - 8V_o + V_o^2 = 16V_o - 4V_o^2$

$5V_o^2 - 24V_o + 16 = 0 \rightarrow \boxed{V_o = 0.8V}$

Problem 2



$V_{dd} = 5V$
$C_L = 20pF$
$K_L = 0.2\ mA/V^2$

$K_S = 1\ \frac{mA}{V^2}$
$V_T = 1\ V$

Q_S is ohmic $\longrightarrow$ $V_{DS} < V_{GS} - V_T$
$V_i = V_{gsS}$ $\qquad V_{iL} = V_T = 1V$
$V_0 = V_{DSS}$
$V_{iL} = V_i = 1V$

a. $V_{OH} = V_{DD} - V_T = 5V - 1V = 4V$ ← Highest possible value of V_0
b. V_{OL} @ $V_i = V_{OH} = 4V$
Q_S = Ohmic
Q_L = Saturated and ON, because $V_i = 4V$
$V_{GSS} = 4V$
$V_{GSL} = 5V - V_0$

ohmic saturated
$I_{DSS} = I_{DSL}$
$K_S\left[(V_{gsS} - V_T)V_{DS} - \frac{V_{DS}^2}{2}\right] = \frac{K_L}{2}(V_{gsL} - V_T)^2$
$1\times10^{-3}\frac{mA}{V^2}\left[(4V - 1V)V_0 - \frac{V_0^2}{2}\right] = \frac{0.2\times10^{-3}}{2}\frac{mA}{V^2}(4 - V_0)^2$
$0.1\times10^{-3}\frac{mA}{V^2}(4 - V_0)^2 = 1\times10^{-3}\frac{mA}{V^2}\left[3V_0 - \frac{V_0^2}{2}\right]$
$(4 - V_0)(4 - V_0) = 10\left(3V_0 - \frac{V_0^2}{2}\right)$
$16 - 8V_0 + V_0^2 = 30V_0 - 5V_0^2$
$6V_0^2 - 38V_0 + 16 = 0$
$2(3V_0^2 - 19V_0 + 8) = 0$
$\boxed{V_0 = 0.45\ V = V_{gss}}$

c. $V_{IL} = V_T = 1V$

d $V_O = 1V = V_{DSS}$

find V_{IH} for V_O V_{DD}

$V_{GSL} = 5V - 1V = 4V$

$I_{DSL} = I_{DSS}$

$\frac{K_L}{2}(V_{GSL} - V_T)^2 = K_S\left[(V_{GSS} - V_T)V_{DS} - \frac{V_{DS}^2}{2}\right]$

$0.1\frac{mA}{V^2}(4V - 1V)^2 = \frac{1mA}{V^2}\left[(V_{IH} - 1)1 - \frac{1}{2}\right]$

$0.9\frac{mA}{V^2} = \frac{1mA}{V^2}\left[V_{IH} - \frac{3}{2}\right]$

$0.9mA = 1mA\,V_{IH} - 1.5\frac{mA}{V^2}$

$\boxed{V_{IH} = 2.4V}$

e $I_{DS} = \frac{K_S}{2}[V_{GS} - V_T]^2 = 0.1\frac{mA}{V^2}[3-1]^2 = 0.4mA$

$V_{GSL}(av) = 5 - \frac{(0.9(4) + 0.1(4))}{2} = 3$

$I = Q = CV = \frac{C\Delta V}{\Delta T}$ $\quad$ $\Delta T = \frac{C\Delta V}{I}$

$I_O = I_{DSS} - I_{DSL}$

$I_{DSS} = \frac{K_S}{2}(V_{GSS} - V_T)^2 = \frac{1}{2}[4-1]^2 = 4.5mA$

$I_O = 4.5mA - 2mA = 2.5mA$

$\Delta T = \frac{20pF(3.2)}{2.5mA} = \boxed{15.6\,nS}$

f. Industry Standard Values of V_{IL}, V_{IH}, V_{OL}, V_{OH}

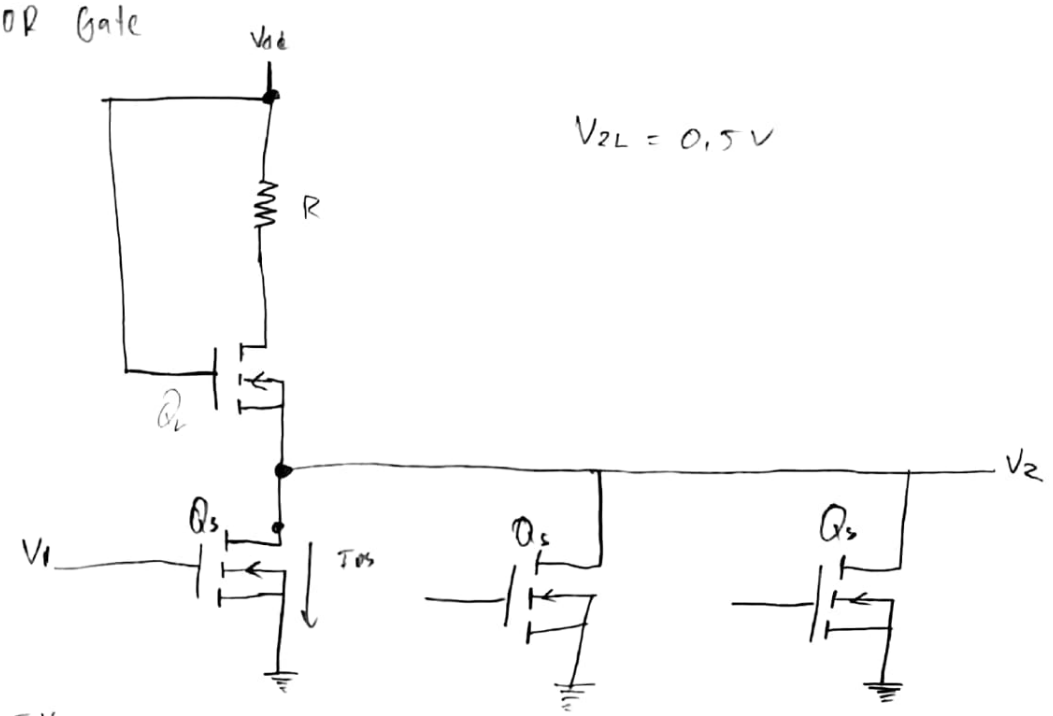
$V_{OL} = \frac{V_{DD} - V_T}{\sqrt{1+3K_R}} = \frac{5-1}{\sqrt{1+3(\frac{1}{0.2})}}$ $\quad$ $\boxed{V_{OL} = 1V}$

$V_{IH} = V_T + \frac{V_{OL}}{2} + \frac{(V_{DD} - V_{OL} - V_T)^2}{2K_R V_{OL}} = 1 + \frac{1}{2} + \frac{(5-1-1)^2}{2(\frac{1}{0.2})(1)} = 2.4$

$V_{IL} = V_T = \boxed{1V}$

$V_{OH} = V_{DD} - V_T = 5 - 1 = \boxed{4V = V_{OH}}$

Problem 3 NOR Gate



$V_{2L} = 0.5V$

a. $V_{DSS} = 0.5V$

$V_{GSL} = V_{GL} - V_{SL} = 5V - 0.5V = 4.5V$

$V_{DSL} = V_{GSL} - V_T = 4.5V - 1V = 3.5V$

$I_{DSL} = \frac{K_L}{2}(V_{gsL} - V_T)^2$

$I_{DSL} = \frac{0.25mA}{2V^2}(3.5V)^2 = \boxed{1.53\ mA}$

$R = \frac{5V - 3.5V - 0.5V}{1.53mA} = \boxed{654\ \Omega}$

b. $I_{DSS} = K_S\left[(V_{gss} - V_T)V_{DS} - \frac{V_{DS}^2}{2}\right]$

$1.53mA = K_S\left[(3V)\,0.5V - \frac{0.5^2}{2}\right]$

$\boxed{K_S = 1.11\ mA/V^2}$

c. All 3 Q_S ON, $K_S' = 3K_S$

$I_{DSS} = \left[K_S(V_{gss} - V_T)V_{DS} - \frac{V_{DS}^2}{2}\right]$

$I_{DSS} = V_{gss} - V_T - \left[(V_{gss} - V_T)^2 - 2\frac{I_{DSS}}{K_S}\right]^{1/2}$

$V_{DSS}' = 3V - \left[(3V)^2 - \left(\frac{2(1.53mA)}{3.33\frac{mA}{V^2}}\right)\right]^{1/2}$

$V_{DSS}' = 0.157$

$V_{DSL}' = 5V - 0.157V - (1.53mA)(654\Omega) = \boxed{3.842V}$

$V_{DSL}' = 5V - 1V - 0.157V = 3.843V$, which equals $V_{gsL} - V_T$, so Q_L is SAT

1.517

2.73 2.3575

2.3045

Problem 4 Referencing figure 6

$K_S = 4 \frac{mA}{V^2}$ $K_L = 2 \frac{mA}{V^2}$ $V_T = 1V$ (all) $V_{DD} = 5.0 V$

a. Find V_{OH} and V_{OL} for 1, 2, 3 inputs

$V_{OH} = V_{DD} - V_T = 5V - 1V = 4V$

$n I_{DSS} = I_{DSL}$

$n\left(K_S\left(V_{gsS} - V_T\right)V_{DS} - \frac{V_{DS}^2}{2}\right] = \frac{K_L}{2}\left(V_{gsL} - V_T\right)^2$

$n\left(4\frac{mA}{V^2}\right)(4V - 1V)V_0 - \frac{V_0^2}{2} = 1\frac{mA}{V^2}\left(5V - V_{DSS} - 1V\right)^2$

$4\frac{mA}{V^2}\left[3V_0 - \frac{V_0^2}{2}\right] = (4 - V_0)(4 - V_0)$

$n(12V_0 - 2V_0^2) = 16 - 8V_0 + V_0^2$

n=1 $3V_0^2 - 20V_0 + 16 = 0$ $\boxed{V_0 = 0.93V}$

n=2 $24V_0 - 4V_0^2 = 16 - 8V_0 + V_0^2$

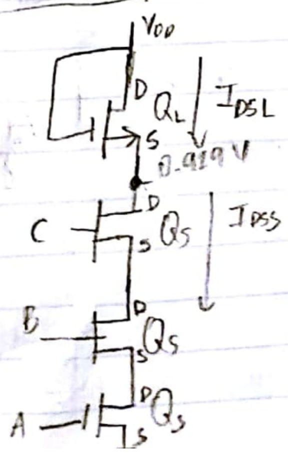
$5V_0^2 - 32V_0 + 16 = 0$ $\boxed{V_0 = 0.547V}$

n=3 $36V_0 - 6V_0^2 = 16 - 8V_0 + V_0^2$

$7V_0^2 - 44V_0 + 16 = 0$ $\boxed{V_0 = 0.388\ V}$

Problem 5 $K_S = 12\frac{mA}{V^2}$ $K_L = 2\frac{mA}{V^2}$ $V_T = 1V$ $V_{DD} = 5V$

a. NMOS 3-input NAND



$K_S' = K_S/3$

$I_{DSS} = I_{DSL}$

$\frac{K_S}{3}\left[\left(V_{gsS} - V_T\right)V_{DS} - \frac{V_{DS}^2}{2}\right] = \frac{K_L}{2}\left(V_{gsL} - V_T\right)^2$

$V_{gsL} = V_{DD} - V_{DSS}$

$V_{OH} = 5V - 1V = 4V$

$V_{gsS} = 4V$

$\frac{4mA}{V^2}\left[(3V)V_0 - \frac{V_0^2}{2}\right] = \frac{1mA}{V^2}\left(4 - V_0\right)^2$

$12V_0 - 2V_0^2 = 16 - 8V_0 + V_0^2$

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2.494

$3V_o^2 - 20V_o + 16 = 0$

$\boxed{V_o = 0.93\ V = V_{OL}}$

b. $I_{DS} = \frac{K_s}{3}\left[(V_{gss} - V_T)V_{DSS} - \frac{1}{2}V_{DSS}^2\right]$

$I_{DSS} = 4\,mA\left[(4 - 1)0.929 - \frac{1}{2}0.929^2\right)$

$I_{DSS} = 9.43\ mA$

$I_{DSL} = 1\ \frac{mA}{V^2}\left[(3.07)^2\right] = 9.43\ mA$

For Q_1 $\left(\frac{K_s}{2}\right)V_{DSS}^2 - K_s(V_{GSS} - V_T)V_{DSS} + I_{DS} = 0$

$\left(\frac{12\,mA/V^2}{2}\right)V_{DSS}^2 - 12(V_{gss} - V_T)V_{DSS} + I_{DS} = 0$

$6V_{DSS}^2 - 12(4 - V_T)V_{DSS} + 9.43 = 0$

For Q_1 $6V_{DSS}^2 - 12(4-1)V_{DSS} + 9.43 = 0$

$\boxed{V_{DSS} = 0.275\ V}$

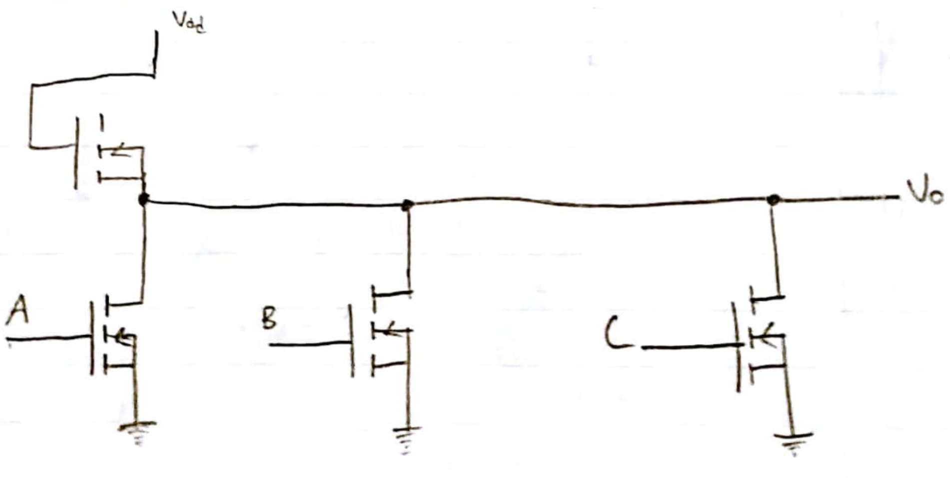
For Q_2 $6V_{DSS}^2 - 12(4 - 1 - 0.275)V_{DSS} + 9.43 = 0$

$\boxed{V_{DSS} = 0.3055\ V}$

For Q_3 $6V_{DSS}^2 - 12(4 - 1 - 0.275 - 0.3055)V_{DSS} + 9.43 = 0$

$\boxed{V_{DSS} = 0.350\ V}$

Problem 6 NMOS NOR GATE



Question #6 NMOS continued

a. $V_{OH} = V_{DD} - V_T = 5V - 1V = \boxed{4V}$

b. $K_S^* = 3 K_S = \frac{3mA}{V^2}$

$I_{DSS} = I_{DSL}$

$K_S\left[(V_{gsS} - V_T)V_{DS} - \frac{V_{DS}^2}{2}\right] = \frac{K_L}{2}(V_{gsL} - V_T)^2$

$\frac{3mA}{V^2}\left[(3V - 1V)V_{DS} - \frac{V_{DS}^2}{2}\right] = 0.1\frac{mA}{V^2}(4 - V_0)^2$

$30\frac{mA}{V^2}\left[2V_{DS} - \frac{V_{DS}^2}{2}\right] = (4 - V_0)(4 - V_0)$

$60V_0 - 15V_0^2 = 16 - 8V_0 + V_0^2$

$16V_0^2 + 68V_0 + 16$

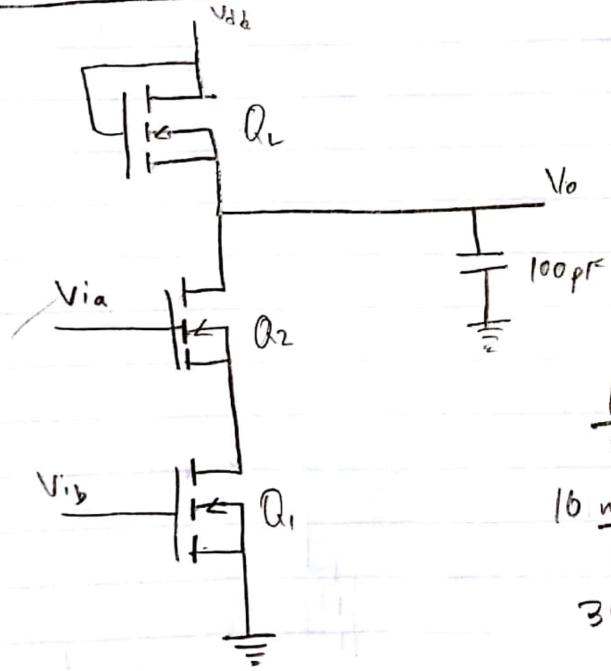
$V_0 = V_{DSS} = \boxed{0.25V}$

c. $I_{DSL} = I_{DSS} = 3\left[(V_{gss} - V_T)V_{DS} - \frac{V_{DS}^2}{2}\right]$

$= 3\left[(3-1).25 - \frac{.25^2}{2}\right]$

$\boxed{I_{DSS} = 1.41mA}$

Question #7: NMOS Gate



a. $I_{DSS} = \frac{K_S}{2}\left[(V_{gss} - V_T)V_{DSS} - \frac{V_{DSS}^2}{2}\right]$

$I_{DSS} = \frac{1mA}{V^2}\left[(4-1)0.454 - \frac{0.454^2}{2}\right]$

$\boxed{I_{DS} = 1.26 mA}$

b. $V_{OH} = V_{DD} - V_T = 5V - 1V = \boxed{4V}$

c. V_{OL}

$I_{DSS} = I_{DSL}$

$\frac{K_S}{2}\left[(V_{gsS} - V_T)V_{DSS} - \frac{V_{DSS}^2}{2}\right] = \frac{K_L}{2}\left[V_{gsL} - V_T\right]^2$

$16\frac{mA}{V^2}\left[(4-1)V_{OL} - \frac{V_{OL}^2}{2}\right] = (4 - V_0)^2$

$30V_{OL} - 5V_{OL}^2 = 16 - 8V_0 + V_0^2$

$6V_{OL}^2 + 38V_{OL} + 16$

$\boxed{V_{OL} = 0.454V}$

use in Part A

Question #7 NMOS gate continued

e. t_f of output voltage (80% to 20% of V_{OH})

$I_{DSL} = \frac{K_L}{2}[V_{gs} - V_t]^2 = \frac{0.1mA}{2V^2}[4-1]^2 = 0.4mA$

$V_{gsL}(\text{average}) = 5 - \frac{(0.8(4) + 0.2(4))}{2} = 3V$

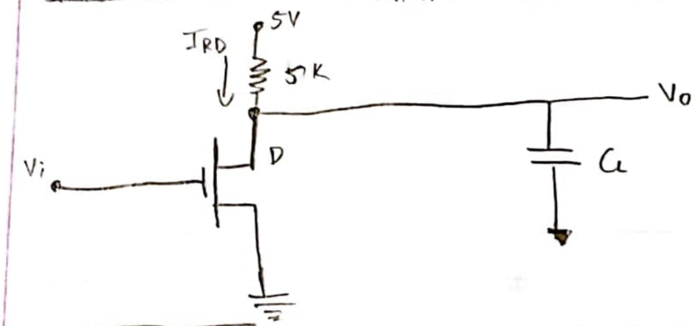
$I = Q = CV = \frac{C\Delta V}{\Delta T} \qquad \Delta T = \frac{C\Delta V}{I}$

$I_o = I_{DS} - I_{DSL}$ (now SAT)

$I_{DSS} = \frac{K_S}{2}(V_{GSS} - V_t)^2 = \frac{1}{2}(3)^2 = 4.5mA \rightarrow I_o = 4.5mA - 0.4mA = 4.1mA$

$\Delta T = \frac{C\Delta V}{I} = \frac{100pF\ (2.4V)}{4.1mA} = \boxed{58.5nS}$

Question #8 NMOS Inverter with Resistor Load



A. $\boxed{V_{OH} = 5V}$, no current through resistor

B. $\frac{V_{DD} - V_{DS}}{R_D} = I_{DS} = K_S\left[(V_{gs} - V_T)V_{DS} - \frac{V_{DS}^2}{2}\right]$

$\frac{5 - V_{DS}}{5K} = 1 \times 10^{-3}\left[(4)V_{DS} - \frac{V_{DS}^2}{2}\right]$

$5 - V_{DS} = 20V_{DS} - 2.5V_{DS}^2$

$2.5V_{DS}^2 - 21V_{DS} + 5 = 0$

$\boxed{V_{OL} = 0.245V}$

C. $V_{IL} = V_T = \boxed{1V}$

d. V_{IH} for $V_o = V_{IL}$ $V_o = 1V$

$\frac{5 - 1}{5K} = I_{DS} = K_S\left[(V_{gs} - 1)1 - \frac{1}{2}\right)$

$4 = 5[V_{gs} - 1.5] \qquad V_{DS} < V_{gs} - V_t$ ✓

$\boxed{V_{gs} = 2.3V = V_{IH}}$

e. $I_{DSL} = I_{DSS}$ (through resistor) $= 0.5\ mA = \frac{2.5V}{5k}$

$I_{DSS}(av) = K_S\left[(V_{GSS} - V_T)V_{DSS} - \frac{V_{DSS}^2}{2}\right]$

$I_{DSS}(av) = \left[(5 - 1)2.5 - \frac{2.5^2}{2}\right] = 6.875\ mA$

$I_D(av) = 6.875\ mA - 0.5\ mA$

$T = \frac{4(20pF)}{6.375} = \boxed{12.55\ ns}$

f. Industry Standard Value of V_{IL}, V_{IH}, V_{OL}, V_{OH}

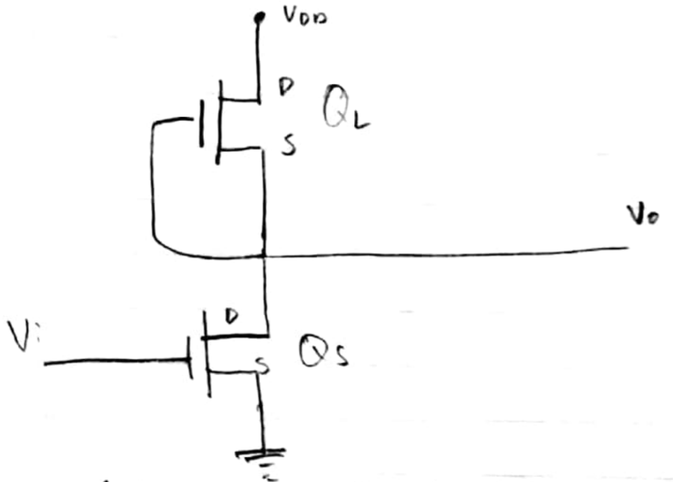
$V_{OL} = \frac{V_{DD} - V_T}{\sqrt{1 + 3k_R}} = \frac{5 - 1}{\sqrt{1 + 3(\frac{1}{0.2})}} = \boxed{1V}$

$V_{IH} = V_T + \frac{V_{OL}}{2} + \frac{(V_{DD} - V_{OL} - V_T)^2}{2k_R + V_{OL}} \Rightarrow 1 + \frac{1}{2} + \frac{(5 - 1 - 1)^2}{2(\frac{1}{0.2})(1)}$ $\boxed{V_{IH} = 2.4V}$

$V_{IL} = V_T = 1V$

$V_{OH} = V_{DD} - V_T = 5 - 1 = \boxed{4V}$

Question #9 $V_T = -3V$



a. Q_L SAT $\quad Q_S$ OHMIC TRIODE

K_S $\boxed{V_{OH} = V_{DD} = 5V}$

b. $I_{DSL} = I_{DSS}$

$\frac{K_L}{2}(V_{GSL} - V_T)^2 = \frac{K_S}{1}\left[(V_{GSS} - V_T)V_{DSS} - \frac{V_{DSS}^2}{2}\right]$

$\frac{K_L}{2}(0 - V_T)^2 = \frac{K_S}{1}\left[(V_{GSS} - V_T)V_{OL} - \frac{V_{OL}^2}{2}\right]$

$9 = 10\left[V_{OL} - \frac{V_{OL}^2}{2}\right]$

$5V_{OL}^2 - 40V_{OL} + 9 = 0$

$\boxed{V_{OL} = 0.232\ V}$

c. V_{IL}

Q_S = OFF, then $V_{IL} = V_T = 1V \rightarrow V_{IL} = 1V$

d. $\frac{V_{DD} - V_0}{R_D} = K_S\left[(V_{GSS} - V_T)V_{DSS} - \frac{V_{DSS}^2}{2}\right]$

$\frac{5 - 0.232}{5k} = 1\left[(V_{IH} - 1)1 - \frac{1^2}{2}\right] \rightarrow \boxed{V_{IH} = 2.4V}$

e. $V_{RD}(av) = \frac{5(90\%) + 5(10\%)}{2} = 2.5V$ $\quad \Delta V_C \quad 4.5 - 0.5V = 4V$

$I_{RD}(av) = \frac{V_{RD}(av)}{R_D} = \frac{2.5}{5k} = 0.5$

$I_{DSL}(av) = \frac{K_L}{2}(V_{GSL} - V_T)^2 = \frac{K_L}{2}(0 - V_{TL})^2 = \frac{0.2}{2}(-V_{TL})^2 \rightarrow \frac{0.2}{2}(0-1)^2 = 0.1$

$\rightarrow 1 - 0.1 = \boxed{0.9mA}$

$I_D(av) = 6.875 - 0.9 = 5.975mA$; $T_F = \frac{4 \times 20pF}{5.975} \rightarrow \boxed{13.39nS}$

Question #10 $\quad \phi = 0.3 \quad \gamma = 0.5$

i) $V_{OL} = \frac{V_{DD} - V_{T2}}{\sqrt{1 + 3K_R}} = \frac{5 - 1.25}{\sqrt{1 + 3(\frac{0.2}{1})}} \Rightarrow \boxed{V_{OL} = 0.93V}$

$V_{TL} = V_T + \gamma\left[(V_{SB} + 2\phi_F\right]^{1/2} - (2\phi_F)^{1/2}$

$= 1 + 0.5\left[(5 + 2(0.3))^{1/2} - (2(0.3))^{1/2}\right.$

$\boxed{V_{TL} = 1.25}$

$V_{IH} = V_T + \frac{V_{OL}}{2} + \frac{(V_{DD} - V_{OL} - V_{TL})^2}{2(K_R)V_{OL}} \Rightarrow 1 + \frac{0.93}{2} + \frac{(5 - 0.93 - 1.25)^2}{2(\frac{0.2}{1})0.93}$

$\boxed{V_{IH} = 2.31V}$

$V_{IL} = V_T = 1V = \boxed{1V}$

$V_{IL} = V_T = 1V \quad \boxed{V_{IL} = 1V}$

$V_{OH} = V_{DD} - V_{TL} \rightarrow 5 - 0.5\left[\sqrt{V_{OH} + 0.6} - 0.77\right]$

$\boxed{V_{OH} = 3.39V}$

9c.

$$V_{IL} = \frac{V_{TS} - V_{TL}}{(k_R^2 + k_R)^{1/2}} = 1.55\,V$$

$$V_{OH} = V_{DD} + V_{TL}\left[1 - \left[\frac{k_R}{k_R^2+1}\right]^{1/2}\right] \rightarrow 3.32\,V$$

$$V_{IH} = \frac{V_{TS} - 2V_{TL}}{(3k_R)^{1/2}} \Rightarrow 2.55\,V$$

$$V_{OL} = \frac{-V_{TL}}{(3k_R)^{1/2}} \rightarrow 0.775\,V$$