Microelectronic Circuit Design Third Edition - Part II Solutions to Exercises

CHAPTER 6

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$NM_L = 0.8V - 0.4V = 0.4\ V \quad NM_H = 3.6V - 2.0V = 1.6\ V$

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$V_{10\%} = V_L + 0.1\left(\Delta V\right) = -2.6V + 0.1\left[-0.6 - \left(-2.6\right)\right] = -2.4\ V$ or

$V_{10\%} = V_H - 0.9\left(\Delta V\right) = -0.6V - 0.9\left[-0.6 - \left(-2.6\right)\right] = -2.4\ V$

$V_{90\%} = V_L + 0.9\left(\Delta V\right) = -2.6V + 0.9\left[-0.6 - \left(-2.6\right)\right] = -0.8\ V$ or

$V_{90\%} = V_H - 0.1\left(\Delta V\right) = -0.6V - 0.1\left[-0.6 - \left(-2.6\right)\right] = -0.8\ V$

$V_{50\%} = \dfrac{V_H + V_L}{2} = \dfrac{-0.6 - 2.6}{2} = -1.6\ V \quad t_r = t_4 - t_3 = 3\ ns \quad t_f = t_2 - t_1 = 5\ ns$

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At P = 1 mW : PDP $= 1mW\left(1ns\right) = 1\ pJ$

At P = 3 mW : PDP $= 3mW\left(1ns\right) = 3\ pJ$

At P = 20 mW : PDP $= 20mW\left(2ns\right) = 40\ pJ$

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$Z = \left(A + B\right)\left(B + C\right) = AB + AC + BB + BC = AB + BB + AC + BB + BC$

$Z = AB + B + AC + B + BC = B\left(A + 1\right) + AC + B\left(C + 1\right) = B + AC + B$

$Z = B + B + AC = B + AC$

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$$I_{DD} = \frac{P}{V_{DD}} = \frac{0.4mW}{2.5V} = 160\ \mu A \qquad R = \frac{V_{DD} - V_L}{I_{DD}} = \frac{2.5V - 0.2V}{160\mu A} = 14.4\ k\Omega$$

$$1.6x10^{-4}\,A = 10^{-4}\,\frac{A}{V^2}\left(\frac{W}{L}\right)_S\left(2.5 - 0.6 - \frac{0.2}{2}\right)0.2\ V^2 \rightarrow \left(\frac{W}{L}\right)_S = \frac{4.44}{1}$$

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$$I_{DD} = \frac{V_{DD} - V_L}{R} = \frac{3.3V - 0.1V}{102k\Omega} = 31.4\mu A$$

$$31.4x10^{-6}\,A = 6x10^{-5}\,\frac{A}{V^2}\left(\frac{W}{L}\right)_S\left(3.3 - 0.75 - \frac{0.1}{2}\right)0.1\ V^2 \rightarrow \left(\frac{W}{L}\right)_S = \frac{2.09}{1}$$

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$$0.15V = \frac{R_{on}}{R_{on} + 28.8k\Omega}2.5V \rightarrow R_{on} = 1.84\ k\Omega$$

$$\left(\frac{W}{L}\right)_S = \frac{1}{10^{-4}\left(2.5 - 0.60 - \frac{0.15}{2}\right)\left(1.84\text{k}\Omega\right)} \rightarrow \left(\frac{W}{L}\right)_S = \frac{2.98}{1}$$

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$$(i)\ R_{on} = \frac{1}{6x10^{-5}\left(\frac{1.03}{1}\right)\left(3.3 - 0.75 - \frac{0.2}{2}\right)} = 6.61\ k\Omega \quad V_L = \frac{6.61k\Omega}{6.61k\Omega + 102k\Omega}3.3V = 0.201\ V$$

$$(\text{ii})\ \left[\frac{1}{K_n R}\right] = \frac{V^2}{A}\frac{1}{\Omega} = V$$

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$$K_n R = \left(6x10^{-5}\right)\left(\frac{1.03}{1}\right)\left(1.02x10^5\right) = \frac{6.30}{V}$$

$$NM_H = 3.3 - 0.75 + \frac{1}{2(6.30)} - 1.63\sqrt{\frac{3.3}{6.30}} = 1.45\ V \qquad NM_L = 0.75 + \frac{1}{6.30} - \sqrt{\frac{2(3.3)}{3(6.30)}} = 0.318\ V$$

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$$(i)\ V_H = 2.5 - \left[0.6 + 0.75\left(\sqrt{V_H + 0.6} - \sqrt{0.6}\right)\right] \rightarrow V_H = 1.416\ V$$

$$(ii)\ 80x10^{-6} A = 100x10^{-6} \frac{A}{V^2}\left(\frac{W}{L}\right)_S\left(1.55 - 0.60 - \frac{0.15}{2}\right)0.15\ V^2 \rightarrow \left(\frac{W}{L}\right)_S = \frac{6.10}{1}$$

$$V_{TNL} = 0.6 + 0.5\left(\sqrt{.15 + 0.6} - \sqrt{0.6}\right) = 0.646\ V$$

$$80x10^{-6} A = \frac{100x10^{-6}}{2}\frac{A}{V^2}\left(\frac{W}{L}\right)_L\left(2.5 - 0.15 - 0.646\right)^2 V^2 \rightarrow \left(\frac{W}{L}\right)_L = \frac{0.551}{1} = \frac{1}{1.82}$$

$$(iii)\ 80x10^{-6} A = 100x10^{-6} \frac{A}{V^2}\left(\frac{W}{L}\right)_S\left(1.55 - 0.60 - \frac{0.1}{2}\right)0.1\ V^2 \rightarrow \left(\frac{W}{L}\right)_S = \frac{8.89}{1}$$

$$V_{TNL} = 0.6 + 0.5\left(\sqrt{.1 + 0.6} - \sqrt{0.6}\right) = 0.631\ V$$

$$80x10^{-6} A = \frac{100x10^{-6}}{2}\frac{A}{V^2}\left(\frac{W}{L}\right)_L\left(2.5 - 0.1 - 0.631\right)^2 V^2 \rightarrow \left(\frac{W}{L}\right)_L = \frac{0.511}{1} = \frac{1}{1.96}$$

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The high logic level is unchanged: $V_H = 2.11$

$$60x10^{-6}\,A = 50x10^{-6}\,\frac{A}{V^2}\left(\frac{W}{L}\right)_S\left(2.11-0.75-\frac{0.1}{2}\right)0.1\ V^2 \rightarrow \left(\frac{W}{L}\right)_S = \frac{9.16}{1}$$

$$V_{TNL} = 0.75+0.5\left(\sqrt{.1+0.6}-\sqrt{0.6}\right) = 0.781\ V$$

$$60x10^{-6}\,A = \frac{50x10^{-6}}{2}\frac{A}{V^2}\left(\frac{W}{L}\right)_L\left(3.3-0.1-0.781\right)^2 V^2 \rightarrow \left(\frac{W}{L}\right)_L = \frac{0.410}{1} = \frac{1}{2.44}$$

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$\gamma = 0 \rightarrow V_{TN} = 0.6V$ and $V_H = 2.5 - 0.6 = 1.9\ V \quad I_{DD} = 0$ for $v_O = V_H$

$$100x10^{-6}\left(\frac{10}{1}\right)\left(1.9-0.6-\frac{V_L}{2}\right)V_L = \frac{100x10^{-6}}{2}\left(\frac{2}{1}\right)\left(2.5-V_L-0.6\right)^2$$

$$6V_L^2-116.8V_L+3.61=0 \rightarrow V_L = 0.235V \quad I_{DD} = 100x10^{-6}\left(\frac{10}{1}\right)\left(1.9-0.6-\frac{0.235}{2}\right)0.235 = 278\ \mu A$$

$$\text{Checking: } I_{DD} = \frac{100x10^{-6}}{2}\left(\frac{2}{1}\right)\left(2.5-0.235-0.6\right)^2 = 277\ \mu A$$

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$$V_{TNL} = -1.5+0.5\left(\sqrt{0.2+0.6}-\sqrt{0.6}\right) = -1.44V$$

$$60.6x10^{-6} = \frac{100x10^{-6}}{2}\left(\frac{W}{L}\right)_L\left(0-1.44\right)^2 \rightarrow \left(\frac{W}{L}\right)_L = \frac{0.585}{1} = \frac{1}{1.71}$$

$$60.6x10^{-6} = 100x10^{-6}\left(\frac{W}{L}\right)_S\left(3.3-0.6-\frac{0.2}{2}\right)0.2 \rightarrow \left(\frac{W}{L}\right)_S = \frac{1.17}{1}$$

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$$I_{DS} = 100x10^{-6}\left(\frac{2.22}{1}\right)\left(2.5-0.6-\frac{0.2}{2}\right)0.2 = 79.9\ \mu A \text{ which checks.}$$

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The PMOS transistor is still saturated so $I_{DL} = 144\ \mu\text{A}$, and $V_H = 2.5\ V$.

$$144x10^{-6} = 100x10^{-6}\left(\frac{5}{1}\right)\left(2.5-0.6-\frac{V_L}{2}\right)V_L \rightarrow V_L = 0.158\ V$$

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Place a third transistor with $\frac{\text{W}}{\text{L}} = \frac{2.22}{1}$ in parallel with tansistors A and B.

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Place a third transistor in series with tansistors A and B.

The new W/L ratios of transistors A, B and C are $\frac{W}{L} = 3\frac{2.22}{1} = \frac{6.66}{1}$.

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M_{L1} is saturated for all three voltages. $I_{DD} = \frac{40x10^{-6}}{2}\left(\frac{1.11}{1}\right)_L \left[-2.5-\left(-0.6\right)\right]^2 = 80.1\ \mu A$

Note that the voltages in two rows are in error in the table.

11000 132 64.4 0 11111 64.6 31.9 31.9

The voltages can be estimated using the on - resistance method.

For the 11000 case, $R_{onA} = \frac{132mV - 64.4mV}{80.1\mu A} = 844\ \Omega$ $R_{onB} = \frac{64.4mV}{80.1\mu A} = 804\ \Omega$

For the 00101 case, $R_{onE} = \frac{64.4mV}{80.1\mu A} = 804\ \Omega$.

For the 01110 case, $R_{onC} = \frac{203mV - 132mV}{80.1\mu A} = 886\ \Omega$ $R_{onD} = \frac{132mV - 64.4mV}{80.1\mu A} = 844\ \Omega$

The voltage across a given conducting device is $I_D R_{on}$. Small variations in R_{on} are ignored.

ABCDE	Y (mV)	2 (mV)	3 (mV)	I_{DD} (uA)	ABCDE	Y (mV)	2 (mV)	3 (mV)	I_{DD} (uA)
00000	2.5 V	0	0	0	10000	2.5 V	2.5 V	0	0
00001	2.5 V	0	0	0	10001	2.5 V	2.5 V	0	0
00010	2.5 V	0	0	0	10010	2.5 V	2.5 V	2.5 V	0
00011	2.5 V	0	0	0	10011	200	130	64	80.1
00100	2.5 V	0	2.5 V	0	10100	2.5 V	2.5 V	2.5 V	0
00101	130	0	64	80.1	10101	130	130	64	80.1
00110	2.5 V	2.5 V	2.5 V	0	10110	2.5 V	2.5 V	2.5 V	0
00111	130	64	64	80.1	10111	100	83	64	80.1
01000	2.5 V	0	0	0	11000	130	64	0	80.1
01001	2.5 V	0	0	0	11001	130	64	0	80.1
01010	2.5 V	0	0	0	11010	130	64	64	80.1
01011	2.5 V	0	0	0	11011	110	43	22	80.1
01100	2.5 V	0	2.5 V	0	11100	130	64	64	80.1
01101	130	0	64	80.1	11101	66	32	32	80.1
01110	200	64	130	80.1	11110	110	64	87	80.1
01111	114	21	43	80.1	11111	65	32	32	80.1

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$$P_{av} = \frac{2.5V\left(80.1\ \mu A\right)}{2} = 0.100\ mW$$

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$$P_D = 10^{-12}F\left(2.5V\right)^2\left(32x10^6\,Hz\right) = 2x10^{-4}W = 200\ \mu W \quad \text{or} \quad 0.200\ mW$$

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(i) The inverter in Fig. 6.38(a) was designed for a power dissipation of 0.2 mW.

To reduce the power by a factor of two, we must reduce the W/L ratios by a factor of 2.

$$\left(\frac{W}{L}\right)_L = \frac{1}{2}\left(\frac{1}{1.68}\right) = \frac{1}{3.36} \qquad \left(\frac{W}{L}\right)_S = \frac{1}{2}\left(\frac{4.71}{1}\right) = \frac{2.36}{1}$$

(ii) To increase the power by a factor of $\frac{4\text{mW}}{0.2\text{mW}}$, we must increase the W/L ratios by a factor of 20.

$$\left(\frac{W}{L}\right)_L = 20\left(\frac{1.81}{1}\right) = \frac{36.2}{1} \qquad \left(\frac{W}{L}\right)_S = 2\left(\frac{2.22}{1}\right) = \frac{44.4}{1}$$

(iii) To reduce the power by a factor of three, we must reduce the W/L ratios by a factor of 3.

$$\left(\frac{W}{L}\right)_L = \frac{1}{3}\left(\frac{1.81}{1}\right) = \frac{0.603}{1} = \frac{1}{1.66} \qquad \left(\frac{W}{L}\right)_A = \frac{1}{3}\left(\frac{3.33}{1}\right) = \frac{1.11}{1} \qquad \left(\frac{W}{L}\right)_{BCD} = \frac{1}{3}\left(\frac{6.66}{1}\right) = \frac{2.22}{1}$$

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$$t_r = 2.2\left(28.8x10^3\Omega\right)\left(2x10^{-13}F\right) = 12.7\ ns \qquad \tau_{PLH} = 0.69\left(28.8x10^3\Omega\right)\left(2x10^{-13}F\right) = 3.97\ ns$$

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$$t_f = 3.7\left(2.37x10^3\Omega\right)\left(2.5x10^{-13}F\right) = 2.19\ ns \qquad \tau_{PHL} = 1.2\left(2.37x10^3\Omega\right)\left(2.5x10^{-13}F\right) = 0.711\ ns$$

$$t_r = 2.2\left(28.8x10^3\Omega\right)\left(2.5x10^{-13}F\right) = 15.8\ ns \qquad \tau_{PLH} = 0.69\left(28.8x10^3\Omega\right)\left(2.5x10^{-13}F\right) = 4.97\ ns$$

$$\tau_P = \frac{0.711\ ns + 4.97\ ns}{2} = 2.84\ ns$$

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(i) The PMOS transistor is saturated for $v_O = V_L$. $\quad I_{DD} = \frac{40x10^{-6}}{2}\left(\frac{23.7}{1}\right)_L\left[-2.5-\left(-0.6\right)\right]^2 = 1.71\ mA$

$$P_{av} = \frac{2.5V\left(1.71mA\right)}{2} = 2.14\ mW \quad P_D = 5x10^{-12}F\left(2.5V-0.2V\right)^2\left(\frac{1}{2x10^{-9}s}\right) = 13.2\ mW$$

(ii) We must increase the power by a factor of $\frac{20\text{pF}}{5\text{pF}}\left(\frac{2\text{ns}}{1\text{ns}}\right) = 8$,

so the W/L ratios must also be increased by a factor of 8.

$$\left(\frac{W}{L}\right)_L = 8\left(\frac{23.7}{1}\right) = \frac{190}{1} \qquad \left(\frac{W}{L}\right)_S = 8\left(\frac{47.4}{1}\right) = \frac{379}{1} \qquad P_D = 20x10^{-12}F\left(2.5V-0.2V\right)^2\left(\frac{1}{10^{-9}s}\right) = 106\ mW$$

CHAPTER 7

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$(a)\ K_p = 40x10^{-6}\left(\frac{20}{1}\right) = 800\ \frac{\mu A}{V^2} \qquad K_n = 100x10^{-6}\left(\frac{20}{1}\right) = 2000\ \frac{\mu A}{V^2} = 2.00\ \frac{mA}{V^2}$

$(b)\ V_{TN} = 0.6 + 0.5\left(\sqrt{2.5+0.6} - \sqrt{0.6}\right) = 1.09\ V$

$(c)\ V_{TP} = -0.6 - 0.75\left(\sqrt{2.5+0.7} - \sqrt{0.7}\right) = -1.31\ V$

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(a) For $v_I = 1V,\ V_{GSN} - V_{TN} = 1 - 0.6 = 0.4V$ and $V_{GSP} - V_{TP} = -1.5 + 0.6 = -0.9V$

M_N is saturated for $v_O \geq 0.4\ V$. M_P is in the triode region for $v_O \geq 1.6\ V$. $\therefore\ 1.6\ V \leq v_O \leq 2.5\ V$

(b) M_P is saturated for $v_O \leq 1.6\ V$. $\therefore\ 0.4\ V \leq v_O \leq 1.6\ V$

(c) M_N is in the triode region for $v_O \leq 0.4\ V$. M_P is saturated for $v_O \leq 1.6\ V$. $\therefore\ 0 \leq v_O \leq 0.4\ V$

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$$\left(\frac{W}{L}\right)_P = \frac{K_n}{K_p}\left(\frac{W}{L}\right)_N = 2.5\left(\frac{10}{1}\right) = \frac{25}{1}$$

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(i) Both transistors are saturated since $|V_{GS}| = |V_{DS}|$.

$\frac{K_n}{2}\left(V_{GSN} - V_{TN}\right)^2 = \frac{K_p}{2}\left(V_{GSP} - V_{TP}\right)^2 \qquad K_n = K_p \qquad |V_{TN}| = |V_{TP}|$

$V_{GSN} = -V_{GSP} \rightarrow v_I = V_{DD} - v_I \rightarrow v_I = \frac{V_{DD}}{2}$

(ii) $\frac{10K_p}{2}\left(V_{GSN} - V_{TN}\right)^2 = \frac{K_p}{2}\left(V_{GSP} - V_{TP}\right)^2 \rightarrow \sqrt{10}\left(V_{GSN} - V_{TN}\right) = -V_{GSP} + V_{TP}$

$\sqrt{10}\left(v_I - 0.6\right) = 4 - v_I - 0.6 \rightarrow v_I = 1.273\ V$

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$$K_R = \frac{K_n\left(\frac{W}{L}\right)_N}{K_p\left(\frac{W}{L}\right)_P} = \frac{K_n}{K_p} = 2.5$$

$$V_{IH} = \frac{2K_R\left(V_{DD} - V_{TN} + V_{TP}\right)}{\left(K_R - 1\right)\sqrt{1 + 3K_R}} - \frac{\left(V_{DD} - K_R V_{TN} + V_{TP}\right)}{K_R - 1}$$

$$V_{IH} = \frac{2(2.5)(2.5 - 0.6 - 0.6)}{(2.5 - 1)\sqrt{1 + 3(2.5)}} - \frac{(2.5 - 2.5(0.6) - 0.6)}{2.5 - 1} = 1.22V$$

$$V_{OL} = \frac{\left(K_R + 1\right)V_{IH} - V_{DD} - K_R V_{TN} - V_{TP}}{2K_R} = \frac{(2.5 + 1)1.22 - 2.5 - 2.5(0.6) + 0.6}{2(2.5)} = 0.174V$$

$$V_{IL} = \frac{2\sqrt{K_R}\left(V_{DD} - V_{TN} + V_{TP}\right)}{\left(K_R - 1\right)\sqrt{K_R + 3}} - \frac{\left(V_{DD} - K_R V_{TN} + V_{TP}\right)}{K_R - 1}$$

$$V_{IL} = \frac{2\sqrt{2.5}(2.5 - 0.6 - 0.6)}{(2.5 - 1)\sqrt{2.5 + 3}} - \frac{(2.5 - 2.5(0.6) - 0.6)}{2.5 - 1} = 0.902V$$

$$V_{OH} = \frac{\left(K_R + 1\right)V_{IL} + V_{DD} - K_R V_{TN} - V_{TP}}{2} = \frac{(2.5 + 1)0.902 + 2.5 - 2.5(0.6) + 0.6}{2} = 2.38V$$

$$NM_H = V_{OH} - V_{IH} = 2.38 - 1.22 = 1.16\ V \qquad NM_L = V_{IL} - V_{OL} = 0.902 - 0.174 = 0.728\ V$$

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C should be 0.75 pF, and the delay in the inverter in Fig. 7.13(b) should be 1.6 ns.

$$(\text{i})\ \text{Symmetrical Inverter: } \tau_P = 1.2R_{onn}C = 1.2\frac{0.75x10^{-12}F}{2\left(10^{-4}\right)(2.5 - 0.6)}\Omega = 2.4\ ns$$

$$(\text{ii})\ \text{Symmetrical Inverter: } R_{onn} = \frac{\tau_P}{1.2C} = \frac{10^{-9}s}{1.2\left(5x10^{-12}F\right)} = 167\Omega$$

$$\left(\frac{W}{L}\right)_N = \frac{1}{R_{onn}K_n^{'}\left(V_{GS} - V_{TN}\right)} = \frac{1}{167\left(10^{-4}\right)(2.5 - 0.6)} = \frac{31.5}{1} \qquad \left(\frac{W}{L}\right)_P = 2.5\left(\frac{W}{L}\right)_N = 78.8$$

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The inverters need to be increased in size by a factor of $\frac{280\text{ps}}{250\text{ps}} = 1.12.$

$$\left(\frac{W}{L}\right)_N = 1.12\left(\frac{3.77}{1}\right) = \frac{4.22}{1} \qquad \left(\frac{W}{L}\right)_P = 1.12\left(\frac{9.43}{1}\right) = \frac{10.6}{1}$$

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$$\left(\frac{W}{L}\right)_N = \left(\frac{3.77}{1}\right)\left(\frac{3.3-0.75}{3.3-0.5}\right) = \frac{3.43}{1} \qquad \left(\frac{W}{L}\right)_P = \left(\frac{9.43}{1}\right)\left(\frac{3.3-0.75}{3.3-0.5}\right) = \frac{8.59}{1}$$

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$$\tau_{PHL} = 2.4R_{onn}C = \frac{2.4C}{K_n(V_{GS}-V_{TN})} = \frac{2.4C}{K_n(2.5-0.6)} = 1.26\frac{C}{K_n}$$

$$\tau_{PLH} = 2.4R_{onp}C = \frac{2.4C}{K_p(V_{GS}-V_{TN})} = \frac{2.4C}{K_p(2.5-0.6)} = 1.26\frac{C}{K_p}$$

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$$\tau_{PHL} = 2.4R_{onn}C = \frac{2.4C}{K_n(V_{GS}-V_{TN})} = \frac{2.4C}{K_n(3.3-0.75)} = 0.94\frac{C}{K_n}$$

$$\tau_{PLH} = 2.4R_{onp}C = \frac{2.4C}{K_p(V_{GS}-V_{TN})} = \frac{2.4C}{K_p(3.3-0.75)} = 0.94\frac{C}{K_p}$$

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The inverter in Fig. 7.12 is a symmetrical design, so the maximum current occurs for $v_O = v_I = \frac{V_{DD}}{2}$.

Both transistors are saturated. $i_{DN} = \frac{10^{-4}}{2}\left(\frac{2}{1}\right)(1.25-0.6)^2 = 42.3\ \mu A$

Checking: $i_{DP} = \frac{4x10^{-5}}{2}\left(\frac{5}{1}\right)(1.25-0.6)^2 = 42.3\ \mu A$

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$$PDP \cong \frac{CV_{DD}^2}{5} = \frac{10^{-13}F(2.5V)^2}{5} = 0.13\ pJ \qquad PDP \cong \frac{CV_{DD}^2}{5} = \frac{10^{-13}F(3.3V)^2}{5} = 0.22\ pJ$$

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Remove the NMOS and PMOS transistors connected to input E, and ground the source of the NMOS transistor connected to input D. The are now 4 NMOS transistors in series, and

$$\left(\frac{\mathrm{W}}{\mathrm{L}}\right)_N = 4\left(\frac{2}{1}\right) = \frac{8}{1} \qquad \left(\frac{\mathrm{W}}{\mathrm{L}}\right)_P = \frac{5}{1}$$

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There are two NMOS transistors in series in the AB and CD NMOS paths, and three PMOS transistors in the ACE and BDE PMOS paths. Therefore:

$$\left(\frac{W}{L}\right)_{N-ABCD} = 2\left(\frac{2}{1}\right) = \frac{4}{1} \qquad \left(\frac{W}{L}\right)_{N-E} = \frac{2}{1} \qquad \left(\frac{W}{L}\right)_{P} = 3\left(\frac{5}{1}\right) = \frac{15}{1}$$

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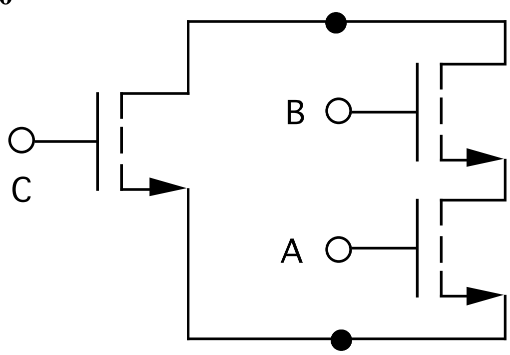

AB+C

$$P = CV_{DD}^2 f = \left(50x10^{-12}F\right)\left(5V\right)^2\left(10^7\,Hz\right) = 12.5\ mW$$

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$$\beta = \left(\frac{50\,pF}{50\,fF}\right)^{\frac{1}{2}} = 31.6 \qquad \tau_P = 31.6\tau_o + 31.6\tau_o = 63.2\tau_o \qquad | \qquad z = e^{\ln z} \quad | \quad z^{\frac{1}{\ln z}} = \left(e^{\ln z}\right)^{\frac{1}{\ln z}} = e$$

$$\beta = \left(\frac{50\,pF}{50\,fF}\right)^{\frac{1}{7}} = 2.683$$

$$1,\ 2.68\ ,\ 2.683^2 = 7.20,\ 2.683^3 = 19.3,\ 2.683^4 = 51.8,\ 2.683^5 = 139,\ 2.683^6 = 373$$

$$A_6 = \left(1 + 3.16 + 10 + 31.6 + 100 + 316\right)A_o = 462\,A_o$$

$$A_7 = \left(1 + 2.68 + 7.20 + 19.3 + 51.8 + 139 + 373\right)A_o = 594\,A_o$$

CHAPTER 8

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$$NS = \frac{2^8 \bullet 2^{20}}{2^7 \bullet 2^{10}} = 2^{11} = 2048 \text{ segments} \qquad NS = \frac{2^{30}}{2^9 \bullet 2^{10}} = 2^{11} = 2048 \text{ segments}$$

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$$(i)\ N = 2^8 \bullet 2^{20} = 2^{28} = 268{,}435{,}456 \quad I_{DD} = \frac{0.05W}{3.3V} = 15.2\ mA \quad \text{Current/cell} = \frac{15.2\text{mA}}{2^{28}\,cells} = 56.4\ pA$$

(ii) Reverse the direction of the substrate arrows, and connect the substrates of the PMOS transistors to V_{DD}.

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M_{A1} : At t = 0^+, $V_{GS} - V_{TN} = 4V$ and $V_{DS} = 2.5V$, so transistor M_{A1} is operating in the triode region.

$$i_1 = 60x10^{-6}\left(\frac{1}{1}\right)\left(5 - 1 - \frac{2.5}{2}\right)2.5 = 413\ \mu A$$

M_{A2} : At t = 0^+, $V_{GS} = V_{DS}$, so transistor M_{A2} is operating in the saturation region.

$$V_{TN2} = 1 + 0.6\left(\sqrt{2.5 + 0.6} - \sqrt{0.6}\right) = 1.592V \qquad i_2 = \frac{60x10^{-6}}{2}\left(\frac{1}{1}\right)\left(5 - 2.5 - 1.592\right)^2 = 24.8\ \mu A$$

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M_{A1} : At t = 0^+, $V_{GS} = V_{DS}$, so transistor M_{A1} is operating in the saturation region.

$$i_1 = \frac{60x10^{-6}}{2}\left(\frac{1}{1}\right)\left(5 - 1\right)^2 = 480\ \mu A$$

M_{A2} : At t = 0^+, $V_{GS} = V_{DS}$, so transistor M_{A2} is operating in the saturation region.

$$i_1 = \frac{60x10^{-6}}{2}\left(\frac{1}{1}\right)\left(5 - 1\right)^2 = 480\ \mu A$$

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(i) At t = 0^+, $V_{GS} - V_{TN} = 3 - 0.7 = 2.3$ V and $V_{DS} = 1.9$ V, so transistor M_A is operating in the triode region.

$$i_1 = 60x10^{-6}\left(\frac{1}{1}\right)\left(3 - 0.7 - \frac{1.9}{2}\right)1.9 = 154\ \mu A \qquad t_f = 3.6R_{on}C = 3.6\frac{50x10^{-15}F}{60x10^{-6}\left(3 - 0.7\right)} = 1.30\ ns$$

$$(ii)\ V_C = V_{BL} - V_{TN} \quad V_C = 3 - \left[0.7 + 0.5\left(\sqrt{V_C + 0.6} - \sqrt{0.6}\right)\right] \rightarrow V_C = 1.89\ V \quad | \quad V_C = 3 - 0.7 = 2.3V$$

$$(iii)\ n = \frac{CV}{q} = \frac{25x10^{-15}F\left(1.89V\right)}{1.60x10^{-19}C} = 2.95 \text{ x } 10^5 \text{electrons}$$

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$$\Delta V = \frac{V_C - V_{BL}}{\frac{C_{BL}}{C_C}+1} = \frac{1.9-0.95}{\frac{49C_C}{C_C}+1}V = 0.019\ V \qquad \Delta V = \frac{V_C - V_{BL}}{\frac{C_{BL}}{C_C}+1} = \frac{0-0.95}{\frac{49C_C}{C_C}+1}V = -0.019\ V$$

$$\tau = R_{on}\frac{C_C}{\frac{C_C}{C_{BL}}+1} = 5k\Omega\frac{25fF}{\frac{1}{49}+1} = 0.123\ ns \quad \text{or} \quad \tau \cong R_{on}C_C = 5k\Omega\left(25fF\right) = 0.125\ ns$$

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At t = 0^+, $V_{GS} - V_{TN} = (3-0) - 0.7 = 2.3\ V$ and $V_{DS} = 1.5\ V$, so transistor M_{A2} is operating in the triode region. $i_D = 60x10^{-6}\left(\frac{2}{1}\right)\left(3-0.7-\frac{1.5}{2}\right)1.5 = 279\ \mu A$

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(i) In setting the drain currents equal, we see that the change in W/L cancels out, and the voltages remain the same.

$$\therefore i_D = \frac{1}{2}\left(60x10^{-6}\right)\left(\frac{5}{1}\right)\left(1.33-0.7\right)^2 = 59.5\ \mu A \quad P_D = 2\left(59.5\mu A\right)\left(3V\right) = 0.357\ mW$$

As a check, the current should scale with W/L: $i_D = \frac{5}{2}\left(23.5\mu A\right) = 58.8\ \mu A$

$$(ii)\ \frac{1}{2}\left(25x10^{-6}\right)\left(\frac{2}{1}\right)\left(2.5 - V_O - 0.6\right)^2 = \frac{1}{2}\left(60x10^{-6}\right)\left(\frac{2}{1}\right)\left(V_O - 0.6\right)^2$$

$$1.4V_O^2 + 0.92V_O - 2.746 = 0 \rightarrow V_O = 1.11V$$

$$i_D = \frac{1}{2}\left(25x10^{-6}\right)\left(\frac{2}{1}\right)\left(2.5-1.11-0.6\right)^2 = 15.6\ \mu A \quad P_D = 2\left(15.6\mu A\right)\left(2.5V\right) = 78.0\ \mu W$$

Checking: $\frac{1}{2}\left(60x10^{-6}\right)\left(\frac{2}{1}\right)\left(1.11-0.6\right)^2 = 15.6\ \mu A$

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$$R_{on} = \frac{1}{60x10^{-6}\left(3-1.3-1\right)} = 23.8\ k\Omega \qquad \tau = 23.8k\Omega\left(25fF\right) = 0.595\ ns$$

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For all possible input combinations there will be two inverters and 3 output lines in the low state.

$$P_D = 5\left(0.2mW\right) = 1.0\ mW$$

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$$\left(\frac{W}{L}\right)_L = \frac{2}{2.22}\left(\frac{1.81}{1}\right) = \frac{1.63}{1}$$

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(i) For a 0 - V input, all transistors will be on and the input nodes will all discharge to 0 V.

For the 3 - V input, the nodes will all charge to 3 V as long as $V_{TN} \le 2V$.

$V_{TN} = 0.7 + 0.5\left(\sqrt{3+0.6} - \sqrt{0.6}\right) = 1.26\ V$. Thus the nodes will all be a 3 V.

$2 \ge 0.7 + \gamma\left(\sqrt{3+0.6} - \sqrt{0.6}\right) \rightarrow \gamma \le 1.158$

(ii) The output will drop below $V_{DD}/2$. For the PMOS device, $\left|V_{GS} - V_{TP}\right| = 3 - 1.9 - 0.7 = 0.4V$.

The PMOS transistor will be saturated. For the NMOS device, $\left|V_{GS} - V_{TP}\right| = 1.9 - 0.7 = 1.2V$.

Assume linear region operation.

$$\frac{40\text{x}10^{-6}}{2}\left(\frac{5}{1}\right)\left(-1.1+0.7\right)^2 = 100\text{x}10^{-6}\left(\frac{2}{1}\right)\left(1.9-0.7-\frac{V_O}{2}\right)V_O$$

$V_O^2 - 2.4V_O + 0.16 = 0 \rightarrow V_O = 68.6\ mV$

CHAPTER 9

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$$\frac{i_{C2}}{i_{C1}} = \exp\left(\frac{0.2V}{0.025V}\right) = 2.98\ x\ 10^3 \qquad \frac{i_{C2}}{i_{C1}} = \exp\left(\frac{0.4V}{0.025V}\right) = 8.89\ x\ 10^6 \qquad \left(2.98x10^3\right)^2 = 8.88\ x\ 10^6$$

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The current must be reduced by 5 while the voltages remain the same.

$$I_{EE} = \frac{300\mu A}{5} = 60\ \mu A \qquad R_C = 5\left(2k\Omega\right) = 10\ k\Omega$$

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$$I_B = \frac{I_E}{\beta_F + 1} \qquad I_{B3} = \frac{92.9\mu A}{21} = 4.42\ \mu A \qquad I_{B4} = \frac{107\mu A}{21} = 5.10\ \mu A$$

$$I_{B3}R_C = 4.42\mu A\left(2k\Omega\right) = 8.84\ mV << 0.7\ V \qquad I_{B4}R_C = 5.10\mu A\left(2k\Omega\right) = 10.2\ mV << 0.7\ V$$

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$$V_H = 0 - 0.7 = -0.7\ V \ \mid\ V_L = 0 - 0.2mA\left(2k\Omega\right) - 0.7V = -1.1\ V$$

$$\Delta V = \text{-}0.7V\ \text{-}\left(1.1V\right) - 0.4\ V \ \mid\ V_{REF} = \frac{-0.7V + \left(-1.10V\right)}{2} = -0.9\ V$$

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$$NM_H = NM_L = \frac{0.4V}{2} - 0.025V\left[1 + \ln\left(\frac{0.4}{0.025} - 1\right)\right] = 0.107\ V$$

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(i) $P = 3.3V\left(0.3mA + 0.2mA\right) = 1.65mW \qquad P = 3.3V\left(0.357mA + 0.2mA\right) = 1.84mW$

$$NM_H = NM_L = \frac{0.6V}{2} - 0.025V\left[1 + \ln\left(\frac{0.6}{0.025} - 1\right)\right] = 0.20\ V$$

(ii) From the graph, the VTC slope is -1 for $V_{IL} = -1.08\ V$, $V_{OH} = -0.71\ V$ and $V_{IH} = -0.91\ V$, $V_{OL} = -1.28\ V$. $NM_H = -0.71 - \left(-0.91\right) = 0.20\ V$. $NM_L = -1.08 - \left(-1.28\right) = 0.20\ V$

(iii) The voltages remain the same. Thus the currents must be reduced by a factor of 3, and the resistor values must be increase by a factor of 3.

(v) $R_{EE} = \dfrac{-1.7V - \left(-5.2V\right)}{0.20mA} = 17.5\ k\Omega \quad I_E = \dfrac{-1.4V - \left(-5.2V\right)}{18\ k\Omega} = 0.211\ mA \quad R_{C1} = \dfrac{0.4V}{0.211mA} = 1.90\ k\Omega$

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(a) For all inputs low: $I_{EE} = \dfrac{-1-0.7-(-5.2)}{11.7}\dfrac{V}{k\Omega} = 299\mu A$

$\dfrac{\Delta V}{2} = V_H - V_{REF} = -0.7-(-1) = 0.3\ V \quad \Delta V = 0.6\ V \quad R_{C2} = \dfrac{0.6V}{299\mu A} = 2.00\ k\Omega$

For an inputs high: $I_{EE} = \dfrac{-0.7-0.7-(-5.2)}{11.7}\dfrac{V}{k\Omega} = 325\mu A \quad R_{C1} = \dfrac{0.6V}{325\mu A} = 1.85\ k\Omega$

(b) Based upon analysis above, $R_C = \dfrac{0.6V}{325\mu A} = 1.85\ k\Omega$

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For all inputs low: $I_{EE} = \dfrac{-1-0.7-(-5.2)}{11.7}\dfrac{V}{k\Omega} = 299\mu A$

$\dfrac{\Delta V}{2} = V_H - V_{REF} = -0.7-(-1) = 0.3\ V \quad \Delta V = 0.6\ V \quad R_C = \dfrac{0.6V}{299\mu A} = 2.00\ k\Omega$

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$R_E = \dfrac{V_E-(-V_{EE})}{0.3mA} = \dfrac{0-0.7-(-5.2V)}{0.3}\dfrac{V}{mA} = 15.0\ k\Omega$

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(a) For $I_E = 0$, $v_O = -5.2$ V. (b) For $I_E = 0$, $v_O = -5.2\text{V}\dfrac{10\text{k}\Omega}{10\text{k}\Omega+15\text{k}\Omega} = -2.08\ V$

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(i) The transistor's power dissipation is $P = V_{CB}I_C + V_{BE}I_E = 5V\left(2.55mA\dfrac{50}{51}\right) + 0.7V(2.55mA) = 14.3\ mW$

The total power dissipation in the circuit is $P = V_{CC}I_C + V_{EE}I_E = 5V\left(2.55mA\dfrac{50}{51}\right) + 5V(2.55mA) = 25.3\ mW$

For $v_O = -3.7V$, $I_E = \dfrac{-3.7-(-5)}{1300} - \dfrac{3.7}{5000} = 260\ \mu A.$ At the Q-point, $I_E = \dfrac{-0.7-(-5)}{1300} - \dfrac{0.7}{5000} = 3.17\ mA$

The transistor's power dissipation is $P = V_{CB}I_C + V_{BE}I_E = 5V\left(3.17mA\dfrac{50}{51}\right) + 0.7V(3.17mA) = 17.8\ mW$

(*ii*) $-4\text{V} = -5.2\text{V}\dfrac{10\text{k}\Omega}{10\text{k}\Omega + R_E} \rightarrow R_E = 3.00\ k\Omega$

$I_E = \dfrac{5.2V}{3k\Omega} = 1.73\ mA \quad I_E = \dfrac{-4-(-5.2)}{3000} - \dfrac{4}{10000} = 0 \quad I_E = \dfrac{4-(-5.2)}{3000} + \dfrac{4}{10000} = 3.47\ mA$

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Increase the value of each resistor by a factor of 10.

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$$R_C = \frac{\Delta V}{I_{EE}} = \frac{0.6V}{0.5mA} = 1.2k\Omega \qquad \tau_P = 0.69(1.2k\Omega)(2\,pF) = 1.66\ ns$$

$$P = 5.2V(0.5+0.1+0.1)mA = 3.64mW \qquad PDP = 6.0\ pJ$$

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For $v_O = V_H$, $I_C = 0$, and $P = 0$. $P = V_{DD}I_{DD} = 5V(2.43mA) = 12.1\ mA$

Increase R by a factor of 10: $R = 10(2k\Omega) = 20k\Omega.$

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$$(i)\ \ \Gamma = \exp\left(\frac{0.1}{0.0258}\right) = 48.2 \qquad I_B \geq \frac{10A}{20}\left[\frac{1+\dfrac{20}{0.1(48.2)}}{1-\dfrac{11}{48.2}}\right] = 3.34\ A \qquad \beta_{FOR} = \frac{10A}{3.34A} = 3.00$$

$$(ii)\ \ \alpha_R = \frac{0.2}{0.2+1} = \frac{1}{6} \qquad I_B \geq \frac{10A}{20}\left[\frac{1+\dfrac{20}{0.2(54.6)}}{1-\dfrac{6}{54.6}}\right] = 1.59\ A$$

$$(iii)\ \ \Gamma = \exp\left(\frac{0.15}{0.025}\right) = 403 \qquad I_B \geq \frac{10A}{20}\left[\frac{1+\dfrac{20}{0.1(403)}}{1-\dfrac{11}{403}}\right] = 0.769\ A$$

$$(iv)\ \ V_T = \frac{1.38x10^{-23}(273+150)}{1.60x10^{-19}} = 36.5\ mV \qquad V_{CEMIN} = 36.5mV\ \ln\left(\frac{0.05+1}{0.05}\right) = 111\ mV$$

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$$\Gamma = 54.6 \quad \alpha_R = \frac{0.25}{1+0.25} = \frac{1}{5} \quad I_B \geq \frac{10mA}{40}\left[\frac{1+\dfrac{40}{0.25(54.6)}}{1-\dfrac{5}{54.6}}\right] = 1.08\ mA \quad \beta_{FOR} = \frac{10mA}{1.08mA} = 9.24$$

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$$(i)\ \ 1ns = 6.4ns\ln\left(\frac{1mA - I_{BR}}{\dfrac{2.5mA}{40.7} - I_{BR}}\right) \qquad 1.169 = \frac{1mA - I_{BR}}{0.0614mA - I_{BR}} \rightarrow I_{BR} = -5.49\ mA$$

$$(ii)\ \ i_{CMAX} = \frac{V_{CC} - V_{CE}}{\beta_F} \cong \frac{5-0}{2500} = 2.5mA \qquad Q_{XS} = 6.4ns\left(1mA - \frac{2.5mA}{40.7}\right) = 6.01\ pC$$

$$Q_F = i_F\tau_F = 2.5mA(0.25ns) = 0.625\ pC \qquad Q_{XS} >> Q_F$$

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$$(i)\ \ v_I = V_L = 0.15\ V \qquad I_{IL} = -\frac{5-0.95}{4000} = -1.01\ mA \qquad V_{BE2} = V_L + V_{CESAT1}$$

Using the value of V_{CESAT} in Fig.9.32, $V_{BE2} = 0.15 + 0.04 = 0.19\ V$

A better estimate is $V_{CESAT1} = 25mV\ \ln\left(\frac{2+1}{2}\right) = 10.1\ mV$

$$V_{BE2} = 0.15 + 0.010 = 0.16\ V$$

$$(ii)\ \ v_I = V_H = 5\ V \qquad I_{IH} = 2\frac{5-1.5}{4000} = 1.75\ mA \qquad V_{BE2} = 0.8\ V$$

Using Eq. (5.29), $V_{BESAT} = 0.025V\ln\dfrac{0.875mA + \left(1-\frac{2}{3}\right)(2.4mA)}{10^{-15}A\left[\frac{1}{40} + \left(1-\frac{2}{3}\right)\right]} = 0.729\ V$

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$$(i)\ \ 5V - N(2k\Omega)\beta_R I_B \geq 1.5V \quad I_B = \frac{5-1.5}{4000} = 0.875mA$$

$$\beta_R \leq \frac{3.5V}{5(2k\Omega)(0.875mA)} = 0.4 \qquad \beta_R \leq \frac{3.5V}{10(2k\Omega)(0.875mA)} = 0.2$$

$$(ii)\ \ I_{B2} = (2+1)\frac{5-1.5}{4000} = 2.63\ mA \qquad 2.43mA + N(1.01mA) \leq 28.3(2.63mA) \rightarrow N \leq 71$$

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$v_I = V_L$ and $v_O = 0$: $I_{B4} = \dfrac{5 - V_{B4}}{1600} = \dfrac{5 - (0 + 0.7 + 0.7)}{1600} = 2.25mA \quad I_L = 41 I_{B4} = 92.3\ mA$

$5 - 1600\dfrac{I_L}{41} - 0.7 - 0.7 \geq 3 \qquad \dfrac{5 - (3 + 0.7 + 0.7)}{1600} = 0.375mA \qquad I_L = 41 I_{B4} = 15.4\ mA$

$V_{CE} = 5 - 130\Omega I_C - V_O = 5V - 130\Omega(15.4mA) - 3.7 = -0.702V$

Oops! - the transistor is not forward active. Assume saturation with $V_{CESAT} = 0.15V$.

$I_L = I_B + I_C = \dfrac{5 - (0.8 + 0.7 + 3.0)}{1600} + \dfrac{5 - (0.15 + 0.7 + 3)}{130} = 9.16\ mA$