

# Microelectronic Circuit Design

## Fifth Edition - Part II

### Solutions to Exercises

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## CHAPTER 6

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### Page 288

$$NM_L = 0.8V - 0.4V = 0.4 \text{ V} \quad | \quad NM_H = 3.6V - 2.0V = 1.6 \text{ V}$$

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### Page 290

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

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

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

$$\text{Checking: } V_{90\%} = V_L + 0.9 (\Delta V) = -2.6V + 0.9 [-0.6 - (-2.6)] = -0.8 \text{ V}$$

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

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### Page 291

$$\text{At } P = 1 \text{ mW: } PDP = 1 \text{ mW}(1 \text{ ns}) = 1 \text{ pJ}$$

$$\text{At } P = 3 \text{ mW: } PDP = 3 \text{ mW}(1 \text{ ns}) = 3 \text{ pJ}$$

$$\text{At } P = 20 \text{ mW: } PDP = 20 \text{ mW}(2 \text{ ns}) = 40 \text{ pJ}$$

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

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

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

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

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


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

$$31.4 \times 10^{-6} A = 6 \times 10^{-5} \frac{A}{V^2} \left( \frac{W}{L} \right)_S \left( 3.3 - 0.75 - \frac{0.1}{2} \right) 0.1 V^2 \rightarrow \left( \frac{W}{L} \right)_S = \frac{2.09}{1}$$


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

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

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$$R_{on} = \frac{1}{6 \times 10^{-5} \left( \frac{1.03}{1} \right) \left( 3.3 - 0.75 - \frac{0.2}{2} \right)} = 6.61 k\Omega \quad | \quad V_L = \frac{6.61k\Omega}{6.61k\Omega + 102k\Omega} 3.3V = 0.201 V$$

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


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$$K_n R = \left( 6 \times 10^{-5} \right) \left( \frac{1.03}{1} \right) \left( 1.02 \times 10^5 \right) = \frac{6.30}{V}$$

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


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### Page 305

Using MATLAB :

```
fzero(@(vh) ((vh - 1.9 - 0.5 * sqrt(0.6))^2 - 0.25(vh + 0.6)), 1) | ans = 1.5535
```

```
fzero(@(vh) ((vh - 1.9 - 0.5 * sqrt(0.6))^2 - 0.25(vh + 0.6)), 4) | ans = 3.2710
```

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$$V_H = 5 - \left[ 0.75 + 0.5 \left( \sqrt{V_H + 0.6} - \sqrt{0.6} \right) \right] \rightarrow V_H = 3.61 \text{ V}$$

```
fzero(@(vh) (5 - 0.75 - 0.5 * (sqrt(vh + 0.6) - sqrt(0.6)) - vh), 1) | ans = 3.6112
```

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

$$V_{TNL} = 0.6 + 0.5 \left( \sqrt{1.15 + 0.6} - \sqrt{0.6} \right) = 0.646 \text{ V}$$

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

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

$$V_{TNL} = 0.6 + 0.5 \left( \sqrt{1.1 + 0.6} - \sqrt{0.6} \right) = 0.631 \text{ V}$$

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

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

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

$$V_{TNL} = 0.75 + 0.5 \left( \sqrt{1.1 + 0.6} - \sqrt{0.6} \right) = 0.781 \text{ V}$$

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

**Page 310**

Using MATLAB :

```
fzero(@(vh) ((vh - 1.9 - 0.5 * sqrt(0.6))^2 - 0.25(vh + 0.6)), 1) | ans = 1.5535
```

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

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

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

$$\text{Checking: } I_{DD} = \frac{100 \times 10^{-6}}{2} \left( \frac{2}{1} \right) (2.5 - 0.235 - 0.6)^2 = 277 \mu A$$

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

$$60.6 \times 10^{-6} = 100 \times 10^{-6} \left( \frac{W}{L} \right)_S \left( 3.3 - 0.6 - \frac{0.2}{2} \right) 0.2 \rightarrow \left( \frac{W}{L} \right)_S = \frac{1.17}{1}$$

$$60.6 \times 10^{-6} = \frac{100 \times 10^{-6}}{2} \left( \frac{W}{L} \right)_L (0 - 1.44)^2 \rightarrow \left( \frac{W}{L} \right)_L = \frac{0.585}{1} = \frac{1}{1.71}$$

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

The W/L ratio of the load transistor remains unchanged:  $\left( \frac{W}{L} \right)_L = \frac{1.81}{1}$

**Page 320**

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

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

The W/L ratio of the load transistor remains unchanged:  $\left( \frac{W}{L} \right)_L = \frac{1.81}{1}$

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$M_{L1}$  is saturated for all three voltages.  $I_{DD} = \frac{40 \times 10^{-6}}{2} \left( \frac{1.11}{1} \right)_L \left[ -2.5 - (-0.6) \right]^2 = 80.1 \mu A$

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

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

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

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

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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$$P_{av} = \frac{2.5V(80\mu A)}{2} = 0.100 \text{ mW}$$


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**Page 328**

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

$$P_D = 10^{-12} F(2.5V)^2 (3.2 \times 10^9 \text{ Hz}) = 2 \times 10^{-4} W = 0.02 W \text{ or } 20 \text{ mW}$$


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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.

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

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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.

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

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

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


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$$t_r = 2.2RC = 2.2(28.8 \times 10^3 \Omega)(2 \times 10^{-13} F) = 12.7 \text{ ns}$$

$$\tau_{PLH} = 0.69RC = 0.69(28.8 \times 10^3 \Omega)(2 \times 10^{-13} F) = 3.97 \text{ ns}$$

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$$v_o(t) = V_F - (V_F - V_I) \exp\left(-\frac{t}{RC}\right) \quad | \quad v_o(\tau_{PHL}) = V_H - 0.5\left(\frac{V_H + V_L}{2}\right) = 2.5 - 1.15 = 1.35 \text{ V}$$

$$1.35 = 0.2 - (0.2 - 2.5) \exp\left(-\frac{\tau_{PHL}}{RC}\right) \rightarrow \tau_{PLH} = -RC \ln 0.5 = 0.69RC$$

$$v_o(t_1) = V_H - 0.1(V_H + V_L) = 2.5 + 0.23 = 2.27 \text{ V}$$

$$2.27 = 0.2 - (0.2 - 2.5) \exp\left(-\frac{t_1}{RC}\right) \rightarrow t_1 = -RC \ln 0.9$$

$$v_o(t_2) = V_L + 0.1(V_H + V_L) = 0.2 + 0.23 = 0.43 \text{ V}$$

$$0.43 = 0.2 - (0.2 - 2.5) \exp\left(-\frac{t_2}{RC}\right) \rightarrow t_2 = -RC \ln 0.1$$

$$t_f = t_2 - t_1 = -RC \ln 0.1 + RC \ln 0.9 = RC \ln 9 = 2.2RC$$

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$$t_f = 3.7(2.37 \times 10^3 \Omega)(2.5 \times 10^{-13} F) = 2.19 \text{ ns} \quad | \quad \tau_{PHL} = 1.2(2.37 \times 10^3 \Omega)(2.5 \times 10^{-13} F) = 0.711 \text{ ns}$$

$$t_r = 2.2(28.8 \times 10^3 \Omega)(2.5 \times 10^{-13} F) = 15.8 \text{ ns} \quad | \quad \tau_{PLH} = 0.69(28.8 \times 10^3 \Omega)(2.5 \times 10^{-13} F) = 4.97 \text{ ns}$$

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

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$$T = 2N\tau_{P0} = 2(401)(10^{-9} \text{ s}) = 802 \text{ ns} \quad | \quad f = \frac{1}{T} = \frac{1}{802 \text{ ns}} = 1.25 \text{ MHz}$$

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$$t_{P0} = \frac{L^2}{\mu_n(V_{DD} - V_{TN})} = \frac{(2.5 \times 10^{-5} \text{ cm})^2}{500 \frac{\text{cm}^2}{V - s} (0.75)(3.3V)} = 0.505 \text{ ps}$$

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The NMOS switching transistor is in the linear region for  $v_o = V_L$ .

$$I_{DS} = 100 \times 10^{-6} \left( \frac{127}{1} \right)_L \left( 2.5 - 0.6 - \frac{0.2}{2} \right) [0.2] = 4.57 \text{ mA}$$

$$P_{av} = \frac{2.5V(4.57\text{mA})}{2} = 5.72 \text{ mW} \quad | \quad P_D = 10 \times 10^{-12} F (2.5V - 0.2V)^2 \left( \frac{1}{20 \times 10^{-9} s} \right) = 2.65 \text{ mW}$$

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We must increase the power by a factor of  $\left( \frac{20 \text{ pF}}{10 \text{ pF}} \right) \left( \frac{2 \text{ ns}}{1 \text{ ns}} \right) = 4$ ,

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

$$\left( \frac{W}{L} \right)_L = 4 \left( \frac{103}{1} \right) = \frac{412}{1} \quad | \quad \left( \frac{W}{L} \right)_S = 4 \left( \frac{127}{1} \right) = \frac{508}{1}$$

$$P_D = 20 \times 10^{-12} F (2.5V - 0.2V)^2 \left( \frac{1}{10^{-9} s} \right) = 106 \text{ mW}$$


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# CHAPTER 7

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## Page 362

$$(a) K_p = 40 \times 10^{-6} \left( \frac{20}{1} \right) = 800 \frac{\mu A}{V^2} \quad | \quad K_n = 100 \times 10^{-6} \left( \frac{20}{1} \right) = 2000 \frac{\mu A}{V^2} = 2.00 \frac{mA}{V^2}$$

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

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


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## Page 364

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

$M_N$  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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Both transistors are saturated since  $|V_{GS}| = |V_{DS}|$ .

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

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

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

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

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

$$v_I - 0.6 = \sqrt{10} (4 - v_I - 0.6) \rightarrow v_I = 2.727 V$$


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

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

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

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

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

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

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

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

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$$\text{Symmetrical Inverter: } \tau_P = 1.2R_{on}C = 1.2 \frac{10^{-12}F}{2(10^{-4})(2.5 - 0.6)} \Omega = 3.16 \text{ ns} \quad | \quad \tau_P = \frac{3.16ns}{5} = 0.63 \text{ ns}$$

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$$\text{Symmetrical Inverter: } R_{on} = \frac{\tau_P}{1.2C} = \frac{10^{-9}s}{1.2(5 \times 10^{-12}F)} = 167\Omega$$

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

### Page 371

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

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

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

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### Page 372

The current (i. e. the W/L ratios) needs to be scaled by the delay change.

To reduce the delay, we need to increase the current.

$$\left(\frac{W}{L}\right)_N = \frac{2}{1} \left(\frac{0.89}{0.71}\right) = \frac{2.51}{1} \quad | \quad \left(\frac{W}{L}\right)_P = \frac{5}{1} \left(\frac{0.89}{0.71}\right) = \frac{6.27}{1}$$

---

$$\left(\frac{W}{L}\right)_N = \frac{2}{1} \left(\frac{1.74}{1.58}\right) = \frac{2.20}{1} \quad | \quad \left(\frac{W}{L}\right)_P = \frac{5}{1} \left(\frac{1.74}{1.58}\right) = \frac{5.51}{1}$$

---

### Page 373

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

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

---

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

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

---

### Page 375

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 :  $i_{DP} = \frac{4 \times 10^{-5}}{2} \left(\frac{5}{1}\right) (1.25 - 0.6)^2 = 42.3 \mu A$

---

**Page 376**

$$(a) PDP \cong \frac{CV_{DD}^2}{5} = \frac{10^{-13} F (2.5V)^2}{5} = 0.13 pJ = 130 fJ$$

$$(b) PDP \cong \frac{CV_{DD}^2}{5} = \frac{10^{-13} F (3.3V)^2}{5} = 0.22 pJ = 220 fJ$$

$$(c) PDP \cong \frac{CV_{DD}^2}{5} = \frac{10^{-13} F (1.8V)^2}{5} = 0.065 pJ = 65 fJ$$

**Page 381**

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

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

**Page 386**

There are two NMOS transistors in series in the BC and BD NMOS paths and three PMOS transistors in the ADC PMOS path. Therefore:

$$\left(\frac{W}{L}\right)_{N-A} = \frac{2}{1} \quad | \quad \left(\frac{W}{L}\right)_{N-BCD} = 2\left(\frac{2}{1}\right) = \frac{4}{1} \quad | \quad \left(\frac{W}{L}\right)_{P-ADC} = 3\left(\frac{5}{1}\right) = \frac{15}{1} \quad | \quad \left(\frac{W}{L}\right)_{P-B} = \frac{1}{\frac{1}{5} - \frac{1}{15}} = \frac{7.5}{1}$$

**Page 392**

$$\beta = \left( \frac{50 pF}{50 fF} \right)^{\frac{1}{2}} = 31.6 \quad \tau_p = 31.6 \tau_o + 31.6 \tau_o = 63.2 \tau_o$$

---

$$z = e^{\ln z} \quad | \quad z^{\frac{1}{\ln z}} = \left( e^{\ln z} \right)^{\frac{1}{\ln z}} = e$$

---

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

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

$$A_6 = (1 + 3.16 + 10 + 31.6 + 100 + 316) A_o = 462 A_o$$

$$A_7 = (1 + 2.68 + 7.20 + 19.3 + 51.8 + 139 + 373) A_o = 594 A_o$$

## Page 393

From the figure, 10/1 devices give a maximum  $R_{on}$  of  $4 \text{ k}\Omega$ . The W/L ratios must be 4 times larger in order to reduce the maximum  $R_{on}$  to  $1 \text{ k}\Omega$ .  $\therefore \left(\frac{W}{L}\right) = 4\left(\frac{10}{1}\right) = \frac{40}{1}$

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# CHAPTER 8

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**Page 417**

$$(a) \ NS = \frac{2^8 \cdot 2^{20}}{2^7 \cdot 2^{10}} = 2^{11} = 2048 \text{ segments} \quad | \quad (b) \ NS = \frac{2^{30}}{2^9 \cdot 2^{10}} = 2^{11} = 2048 \text{ segments}$$

---

**Page 418**

$$(a) \ N = 2^8 \cdot 2^{20} = 2^{28} = 268,435,456$$

$$(b) \ I_{DD} = \frac{0.05W}{3.3V} = 15.2 \text{ mA} \quad | \quad \text{Current/cell} = \frac{15.2\text{mA}}{2^{28}\text{cells}} = 56.4 \text{ pA}$$

---

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

---

**Page 421**

$$\text{For } M_{A1}, \ V_{MIN} = 1 \text{ V: } i_1 = 60 \times 10^{-6} \left( \frac{1}{1} \right) \left( 3 - 0.7 - \frac{1}{2} \right) (1) = 108 \text{ } \mu A$$

$$\text{For } M_{A2}, \ V_{MIN} = 0.46 \text{ V: } i_1 = 60 \times 10^{-6} \left( \frac{1}{1} \right) \left( 1.5 - 1.04 - \frac{0.46}{2} \right) 0.46 = 6.35 \text{ } \mu A$$

---

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

$$i_1 = 60 \times 10^{-6} \left( \frac{1}{1} \right) \left( 5 - 1 - \frac{2.5}{2} \right) 2.5 = 413 \text{ } \mu A$$

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

$$V_{TN2} = 1 + 0.6 \left( \sqrt{2.5 + 0.6} - \sqrt{0.6} \right) = 1.592V \quad i_2 = \frac{60 \times 10^{-6}}{2} \left( \frac{1}{1} \right) \left( 5 - 2.5 - 1.592 \right)^2 = 24.8 \text{ } \mu A$$

---

**Page 423**

$$\text{For } M_{A1} \text{ and } M_{A2}, \ V_{MIN} = 1 \text{ V: } i = 60 \times 10^{-6} \left( \frac{1}{1} \right) \left( 3 - 0.7 - \frac{1}{2} \right) (1) = 108 \text{ } \mu A$$

---

### Page 424

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

$$i_1 = \frac{60 \times 10^{-6}}{2} \left( \frac{1}{1} \right) \left( 5 - 1 \right)^2 = 480 \mu A$$

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

$$i_1 = \frac{60 \times 10^{-6}}{2} \left( \frac{1}{1} \right) \left( 5 - 1 \right)^2 = 480 \mu A$$

---

### Page 426

(a) 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.  $i_1 = 60 \times 10^{-6} \left( \frac{1}{1} \right) \left( 3 - 0 - 0.7 - \frac{1.9}{2} \right) 1.9 = 154 \mu A$

(b) From Table 6.10:  $t_f = 3.7 R_{on} C = 3.7 \frac{50 \times 10^{-15} F}{60 \times 10^{-6} (3 - 0.7)} = 1.34$  ns

(c)  $V_{MIN} = 1$  V |  $i_1 = 60 \times 10^{-6} \left( \frac{1}{1} \right) \left( 3 - 0 - 0.7 - \frac{1}{2} \right) 1 = 108 \mu A$

---

### Page 427

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

---

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

---

### Page 428

$$(a) \Delta V = \frac{V_C - V_{BL}}{\frac{C_{BL}}{C_C} + 1} = \frac{1.9 - 0.95}{\frac{49C_C}{C_C} + 1} V = 19.0 \text{ mV} \quad | \quad \Delta V = \frac{V_C - V_{BL}}{\frac{C_{BL}}{C_C} + 1} = \frac{0 - 0.95}{\frac{49C_C}{C_C} + 1} V = -19.0 \text{ mV}$$

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

---

### Page 429

(a) 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.  $i_D = 60 \times 10^{-6} \left( \frac{2}{1} \right) \left( 3 - 0.7 - \frac{1.5}{2} \right) 1.5 = 279 \mu A$

(b)  $V_{MIN} = 1$  V |  $i_D = 60 \times 10^{-6} \left( \frac{2}{1} \right) \left( 3 - 0.7 - \frac{1}{2} \right) 1 = 216 \mu A$

**Page 432**

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

$$\therefore i_D = \frac{1}{2} (60 \times 10^{-6}) \left( \frac{5}{1} \right) (1.33 - 0.7)^2 = 59.5 \mu A \quad | \quad P_D = 2(59.5 \mu A)(3V) = 0.357 mW$$

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

$$(b) V_{DS} = 1.33 V, V_{GS} - V_{TN} = 1.33 - 0.7 = 0.63 V, V_{SAT} = 1 V \rightarrow V_{MIN} = 0.67 V$$

$$i_D = (60 \times 10^{-6}) \left( \frac{5}{1} \right) \left( 0.63 - \frac{0.63}{2} \right) (0.63) = 59.5 \mu A \quad | \quad P_D = 2(59.5 \mu A)(3V) = 0.357 mW$$


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$$\text{Equating drain currents: } \frac{1}{2} (25 \times 10^{-6}) \left( \frac{2}{1} \right) (2.5 - V_o - 0.6)^2 = \frac{1}{2} (60 \times 10^{-6}) \left( \frac{2}{1} \right) (V_o - 0.6)^2$$

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

$$i_D = \frac{1}{2} (25 \times 10^{-6}) \left( \frac{2}{1} \right) (2.5 - 1.11 - 0.6)^2 = 15.6 \mu A \quad | \quad P_D = 2(15.6 \mu A)(2.5V) = 78.0 \mu W$$

$$\text{Checking: } \frac{1}{2} (60 \times 10^{-6}) \left( \frac{2}{1} \right) (1.11 - 0.6)^2 = 15.6 \mu A$$

---

**Page 433**

$$R_{on} = \frac{1}{60 \times 10^{-6} (3 - 1.3 - 1)} = 23.8 k\Omega \quad | \quad \tau = 23.8 k\Omega (25 fF) = 0.595 ns$$


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**Page 436**

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

$$P_D = 5(0.2 mW) = 1.0 mW$$


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**Page 437**

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


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**Page 439**

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  $V_{TN} \leq 2$  V.

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

$$2 \geq 0.7 + \gamma(\sqrt{3+0.6} - \sqrt{0.6}) \rightarrow \gamma \leq 1.158 \text{ V}^{0.5}$$

---

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

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

Assume linear region operation.

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

$$V_o^2 - 2.4V_o + 0.16 = 0 \rightarrow V_o = 68.6 \text{ mV}$$

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# CHAPTER 9

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**Page 458**

$$\frac{i_{C2}}{i_{C1}} = \exp\left(\frac{0.2V}{0.025V}\right) = 2.98 \times 10^3 \quad | \quad \frac{i_{C2}}{i_{C1}} = \exp\left(\frac{0.3V}{0.025V}\right) = 1.63 \times 10^5 \quad | \quad \frac{i_{C2}}{i_{C1}} = \exp\left(\frac{0.4V}{0.025V}\right) = 8.89 \times 10^6$$

---

**Page 459**

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

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

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**Page 460**

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

$$I_{B3}R_C = 4.42\mu A(2k\Omega) = 8.84 mV \ll 0.7 V \quad | \quad I_{B4}R_C = 5.10\mu A(2k\Omega) = 10.2 mV \ll 0.7 V$$

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**Page 462**

$$V_H = 0 - 0.7 = -0.7 V \quad | \quad V_L = 0 - 0.2mA(2k\Omega) - 0.7V = -1.1 V$$

$$V_{REF} = \frac{-0.7V + (-1.10V)}{2} = -0.9 V \quad | \quad \Delta V = -0.7V - (1.1V) = -0.4 V$$

---

**Page 469**

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

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**Page 466**

$$P = 3.3V(0.3mA + 0.2mA) = 1.65 \text{ mW} \quad | \quad P = 3.3V(0.357mA + 0.2mA) = 1.84 \text{ mW}$$

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

---

From the graph, the VTC slope is -1 for  $V_{IL} = -1.08 \text{ V}$ ,  $V_{OH} = -0.71 \text{ V}$  and

$$V_{IH} = -0.91 \text{ V}, V_{OL} = -1.28 \text{ V}. \quad NM_H = -0.71 - (-0.91) = 0.20 \text{ V}. \quad NM_L = -1.08 - (-1.28) = 0.20 \text{ V}$$

---

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

---

$$R_{EE} = \frac{-1.7V - (-5.2V)}{0.20mA} = 17.5 \text{ k}\Omega \quad | \quad I_E = \frac{-1.4V - (-5.2V)}{18 \text{ k}\Omega} = 0.211 \text{ mA} \quad | \quad R_{C1} = \frac{0.4V}{0.211mA} = 1.90 \text{ k}\Omega$$


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**Page 467**

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

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

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

$$\text{Based upon analysis above, } R_C = \frac{0.6V}{325\mu A} = 1.85 \text{ k}\Omega$$

---

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

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


---

**Page 469**

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


---

**Page 470**

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


---

**Page 471**

The transistor's power dissipation is

$$P = V_{CB}I_C + V_{BE}I_E = 5V \left( 2.55mA \frac{50}{51} \right) + 0.7V(2.55mA) = 14.3 \text{ mW}$$

The total power dissipation in the circuit is

$$P = V_{CC}I_C + V_{EE}I_E = 5V \left( 2.55mA \frac{50}{51} \right) + 5V(2.55mA) = 25.3 \text{ mW}$$

$$\text{For } v_O = -3.7V, I_E = \frac{-3.7 - (-5)}{1300} - \frac{3.7}{5000} = 260 \mu A.$$

$$\text{At the Q-point, } I_E = \frac{-0.7 - (-5)}{1300} - \frac{0.7}{5000} = 3.17 \text{ mA}$$

The transistor's power dissipation is

$$P = V_{CB}I_C + V_{BE}I_E = 5V \left( 3.17mA \frac{50}{51} \right) + 0.7V(3.17mA) = 17.8 \text{ mW}$$

---

$$(a) -4V = -5.2V \frac{10k\Omega}{10k\Omega + R_E} \rightarrow R_E = 3.00 k\Omega$$

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


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**Page 473**

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

**Page 476**

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

$$P = 5.2V(0.5 + 0.1 + 0.1)mA = 3.64 \text{ mW} \quad | \quad PDP = 6.0 \text{ pJ}$$


---

**Page 479**

$$R_{C2} = R_{C1} = \frac{0 - V_L}{I_{EE}} = \frac{0.4V}{0.5mA} = 800 \Omega \quad | \quad P = I_{EE}V_{EE} = 0.5mA(2.8V) = 1.40 mW$$

$$PDP = 1.4mW(50ps) = 70 fJ$$

---

$$I_{EF} = \frac{I_{EE}}{2} = 250 \mu A \quad | \quad P = I_{EE}V_{EE} = 0.25mA(2.8V) = 0.70 mW$$

---

$$V_H = 0 \quad | \quad V_L = -0.2 V \quad | \quad V_{Bias} = -0.1 V \quad | \quad V_{BH} = -0.7 \quad | \quad V_{BL} = -0.9 V \quad | \quad V_{BiasB} = -0.8 V$$

$$V_{AH} = -1.4 \quad | \quad V_{AL} = -1.6 V \quad | \quad V_{BiasA} = -1.5 V$$

$$-V_{EE} = V_{AH} - 0.7V - 0.7V = -1.4 - 0.7 - 0.7 = -2.8 V \quad | \quad -V_{EE} = -2.8 V$$

---

$$V_H = 0 V, \quad V_L = -0.4 V, \quad : \quad \text{The C-level bias is } V_{BiasC} = \frac{V_H + V_L}{2} = -0.2 V$$

Using the level shifter in Fig. 9.27,

$$V_{BH} = -0.7 \quad | \quad V_{BL} = -1.1 V \quad | \quad V_{BiasB} = -0.9 V$$

$$V_{AH} = -1.4 \quad | \quad V_{AL} = -1.8 V \quad | \quad V_{BiasA} = -1.6 V$$

$$-V_{EE} = V_{emitterA} - 0.7V = -0.7 = -2.8 V \quad | \quad -V_{EE} = -2.8 V$$

**Page 484**

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

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

**Page 486**

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


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


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


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$$V_T = \frac{1.38 \times 10^{-23} (273 + 150)}{1.60 \times 10^{-19}} = 36.5 \text{ mV} \quad | \quad V_{CEMIN} = 36.5 \text{ mV} \ln\left(\frac{0.05+1}{0.05}\right) = 111 \text{ mV}$$


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**Page 487**

$$\Gamma = \exp\left(\frac{0.1}{0.025}\right) = 54.6 \quad | \quad \alpha_R = \frac{0.25}{1+0.25} = \frac{1}{5}$$

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


---

**Page 489**

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


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

$$Q_F = i_F \tau_F = 2.5mA(0.25ns) = 0.625 \text{ pC} \quad | \quad Q_{XS} \gg Q_F$$


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

$$5 - 1600 \frac{I_L}{41} - 0.7 - 0.7 \geq 3 \rightarrow I_L \leq 15.4 \text{ mA}$$

$$I_{B4} = \frac{5 - (3 + 0.7 + 0.7)}{1600} = 0.375 \text{ mA} \quad | \quad I_L = 41I_{B4} = 15.4 \text{ mA}$$

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

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

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

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BiCMOS NAND gate: Replace the CMOS NOR-gate with a two-input CMOS NAND-gate, and connect its output to the bases of  $Q_3$  and  $Q_4$ .

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