This figure belongs to Problem 14.15.

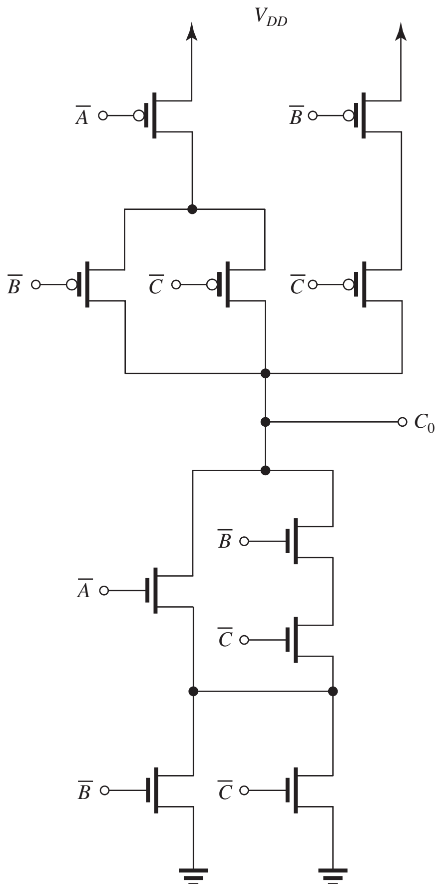


Figure 1

14.16 $NM_H = V_{OH} - V_{IH}$

$= 1.8 - 1.2 = 0.6$ V

$NM_L = V_{IL} - V_{OL}$

$= 0.9 - 0.2 = 0.7$ V

14.17 (a) $NM_H = V_{OH} - V_{IH}$

$= 1.8 - 1.3 = 0.5$ V

$NM_L = V_{IL} - V_{OL}$

$= 1.2 - 0.4 = 0.8$ V

(b)

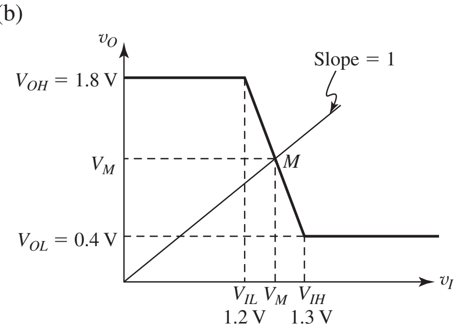


Figure 1

Refer to Fig. 1. Slope of the VTC in the transition region is:

$$\text{Slope} = \frac{V_{OH} - V_{OL}}{V_{IL} - V_{IH}}$$

$$= \frac{1.8 - 0.4}{1.2 - 1.3} = -14 \text{ V/V}$$

But the slope can also be expressed as

$$\text{Slope} = \frac{V_M - V_{OH}}{V_M - V_{IH}}$$

Thus,

$$\frac{V_M - 0.4}{V_M - 1.3} = -14$$

$\Rightarrow V_M = 1.24$ V

(c) The voltage gain in the transition region is equal to the slope found above, thus

Gain $= -14$ V/V

14.18 $NM_H = V_{OH} - V_{IH}$

$= 0.8V_{DD} - 0.6V_{DD} = 0.2V_{DD}$

$NM_L = V_{IL} - V_{OL}$

$= 0.4V_{DD} - 0.1V_{DD} = 0.3V_{DD}$

Width of transition region $= V_{IH} - V_{IL}$

$= 0.6V_{DD} - 0.4V_{DD} = 0.2V_{DD}$

For a minimum noise margin of 0.4 V, we have

$NM_H = 0.4$

$\Rightarrow 0.2V_{DD} = 0.4$

$\Rightarrow V_{DD} = 2$ V

14.19 $V_{IH} = 2$ V

$V_{IL} = 0.8$ V

$V_{OH\min} = 2.4$ V, $V_{OH\text{typ}} = 3.3$ V

$V_{OL\max} = 0.4$ V, $V_{OL\text{typ}} = 0.22$ V

(a) Worst-case $NM_H = V_{OH\min} - V_{IH}$

$= 2.4 - 2 = 0.4$ V

Worst-case $NM_L = V_{IL} - V_{OL\max}$

$= 0.8 - 0.4 = 0.4$ V

(b) Typical average power dissipation:

$$P_D = \frac{1}{2}(5 \times 3 + 5 \times 1)$$

$= 10$ mW

14.20 (a) Refer to Fig. 14.17.

$$V_{OL} = V_{DD}\,\frac{R_{\text{on}}}{R + R_{\text{on}}}$$

Similarly,

$$|\text{Slope}| = \frac{V_{OH}}{V_{IH} - V_{IL}}$$

$$50 = \frac{2}{0.816 - V_{IL}}$$

$\Rightarrow V_{IL} = 0.776$ V

$NM_H = V_{OH} - V_{IH}$

$= 2 - 0.816 = 1.184$ V

$NM_L = V_{IL} - V_{OL}$

$= 0.776 - 0 = 0.776$ V

Since we approximated the VTC in the transition region by a straight line, the large-signal voltage gain will be equal to the small-signal voltage gain,

$= -50$ V/V

14.23 Here, $V_{OH} = 1.2$ V, and $V_{OL} = 0.0$ V

Also, $V_{IH} - V_{IL} \leq 1.2/3 = 0.4$ V (1)

Now, the noise margins are "within 30% of one other." Thus, $NM_H = (1 + \pm 0.3)\, NM_L$ or $NM_L = (1 + \pm 0.3)\, NM_H$. Thus, they remain "within" either $NM_H = 1.3 NM_L$ or $NM_L = 1.3 NM_H$, in which case either $NM_L = 0.769 NM_H$ or $N_{MH} = 0.769 NM_L$

For the former case:

$0.769\,(V_{OH} - V_{IH}) = (V_{IL} - V_{OL})$ or

$0.769\,(1.2 - V_{IH}) = V_{IL} - 0$, whence

$V_{IL} = 0.923 - 0.769 V_{IH}$

Now, from (1), $V_{IH} = V_{IL} + 0.4$

Thus,

$V_{IL} = 0.923 - 0.769\,(V_{IL} + 0.4)$

$= 0.615 - 0.769 V_{IL}$

and $V_{IL} = 0.615/1.769 = 0.349$ V

whence $V_{IH} = 0.4 + 0.349 = 0.749$ V

Alternatively, $NM_H = 0.769 NM_L$ and

$(V_{OH} - V_{IH}) = 0.769\,(V_{IL} - V_{OL})$ or

$1.2 - V_{IH} = 0.769 V_{IL} - 0$ and

$V_{IH} = 1.2 - 0.769 V_{IL}$, with (1),

$V_{IL} + 0.4 = 1.2 - 0.769 V_{IL}$, and

$1.769 V_{IL} = 0.8$, whence $V_{IL} = 0.452$ V

and $V_{IH} = 0.4 + 0.452 = 0.852$

Thus, overall, $V_{OH} = 1.2$ V, $V_{OL} = 0.0$ V,

V_{IH} ranges from 0.749 V to 0.852 V, and

V_{IL} ranges from 0.349 V to 0.451 V, in

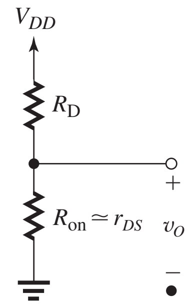
which case the margins can be as low as

$NM_L = V_{IL} - V_{OL} = 0.349$ V and

$NM_H = V_{OH} - V_{IH} = 1.2 - 0.852 = 0.348$ V

and as high as 0.451 V, and 0.451 V.

14.24



Equivalent circuit for output-low state

The output-high level for the simple inverter circuit shown in Fig. 14.12 of the text is

$V_{OH} = V_{DD} \Rightarrow V_{DD} = 1.2$ V.

When the output is low, the current drawn from the supply can be calculated as

$$I = \frac{V_{DD}}{R_D + R_{on}} = 30\ \mu\text{A}$$

Therefore: $R_D + r_{DS} = \dfrac{1.2}{30 \times 10^{-6}} = 40$ kΩ

Also:

$$V_{OL} = 0.05\ \text{V} = \frac{r_{DS}}{R_D + r_{DS}} \times V_{DD}$$

$$\Rightarrow r_{DS} = 40\ \text{k}\Omega \times \frac{0.05}{1.2} = 1.67\ \text{k}\Omega$$

Hence: $R_D = 40$ K $- 1.67$ K $= 38.3$ kΩ

$$r_{DS} = \frac{1}{\mu_n C_{ox} \dfrac{W}{L}(V_{GS} - V_t)}$$

$$= \frac{1}{500 \times 10^{-6} \times \dfrac{W}{L}(1.2 - 0.4)}$$

$= 1.67$ kΩ

$$\Rightarrow \frac{W}{L} = 1.5$$

When the output is low:

$P_D = V_{DD} I_{DD} = 1.2 \times 30\ \mu\text{A} = 36\ \mu\text{W}$

When the output is high, the transistor is off: $P_D = 0$ W

14.25 The output voltage swing $= R_{C1}I = 0.5$ V.

with $I_{EE} = 0.5$ mA, $R_{C1} = 1.0$ kΩ, similarly,

$R_{C2} = 1.0$ kΩ

$V_{OH} = V_{CC} = 2$ V

$V_{OL} = V_{CC} - R_{C1}I_{EE} = 1.5$ V

14.26 Refer to Example 14.2 on page 1107 of the text:

$V_{OH} = V_{DD} = 1.2$ V

The power drawn from the supply during the low-output state is

$P_{DD} = V_{DD}I_{DD} \Rightarrow 60\ \mu\text{W} = 1.2 \times I_{DD}$

$\Rightarrow I_{DD} = 50\ \mu$A

In this case:

$$I_{DD} = \frac{V_{DD} - V_{OL}}{R_D} \Rightarrow 50\ \mu\text{A} = \frac{1.2 - 0.05}{R_D}$$

$\Rightarrow R_D = 23$ kΩ

In order to determine $\frac{W}{L}$, we note that

$$k_nR_D = 1/V_X \text{ or } k'_n\frac{W}{L}R_D = \frac{1}{V_X}$$

Therefore, we need to first calculate V_X using Eq. (14.22) on page 1110 of the text.

$$V_{OL} = \frac{V_{DD}}{1 + \dfrac{V_{DD} - V_t}{V_X}} \text{ or equivalently}$$

$$0.05\text{ V} = \frac{1.2}{1 + \dfrac{1.2 - 0.4}{V_X}}$$

$$\Rightarrow V_X = \frac{0.8}{23} = 0.035\text{ V}$$

Hence, $k'_n\frac{W}{L}R_D = \frac{1}{V_x}$ gives

$$500 \times 10^{-6} \times \frac{W}{L} \times 23 \times 10^3 = \frac{1}{0.035} \Rightarrow \frac{W}{L} = 2.5$$

Using Eq. (14.12), we obtain

$V_{IL} = V_t + V_X = 0.4 + 0.035 = 0.435$ V

From Eq. (14.14) we obtain

$$V_M = V_t + \sqrt{2\,(V_{DD} - V_t)V_x + V^2{}_x} - V_x$$

$$= 0.4 + \sqrt{2\,(1.2 - 0.4)\,0.035 + 0.035^2} - 0.035$$

$V_M = 0.6$ V

From Eq. (14.20) we get

$$V_{IH} = V_t + 1.63\sqrt{V_{DD}V_x} - V_x$$

$$= 0.4 + 1.63\sqrt{1.2 \times 0.035} - 0.035 = 0.7\text{ V}$$

$NM_H = V_{OH} - V_{IH} = 1.2 - 0.7 = 0.5$ V

$NM_L = V_{IL} - V_{OL} = 0.435 - 0.05 = 0.385$ V

14.27 $V_t = 0.3V_{DD},\ V_M = V_{DD}/2$

From Eq. (14.13) on page 1108 of text, we obtain

$$V_x\Big|_{V_M = \frac{V_{DD}}{2}} = \frac{\left(\dfrac{V_{DD}}{2} - V_t\right)^2}{V_{DD}}$$

$$= \frac{(0.5V_{DD} - 0.3V_{DD})^2}{V_{DD}}$$

$\Rightarrow V_x = 0.04V_{DD}$

$V_{OH} = V_{DD}$

From Eq. (14.12), we get

$V_{IL} = V_t + V_x = 0.3V_{DD} + 0.04V_{DD}$

$= 0.34V_{DD}$

From Eq. (14.20), we obtain

$$V_{IH} = V_t + 1.63\sqrt{V_{DD}V_x} - V_x$$

$$= 0.3V_{DD} + 1.63\sqrt{V_{DD} \times 0.04V_{DD}} - 0.04V_{DD}$$

$= 0.586V_{DD}$

From Eq. (14.22), we get

$$V_{OL} = \frac{V_{DD}}{1 + [(V_{DD} - V_t)/V_x]}$$

$$= \frac{V_{DD}}{1 + \dfrac{V_{DD} - 0.3V_{DD}}{0.04V_{DD}}} = 0.054V_{DD}$$

$NM_H = V_{OH} - V_{IH}$

$= V_{DD} - 0.586V_{DD} = 0.414V_{DD}$

$NM_L = V_{IL} - V_{OL}$

$= 0.34V_{DD} - 0.054V_{DD} = 0.286V_{DD}$

For $V_{DD} = 1.2$ V:

$V_x = 0.048$ V, $V_{OH} = 1.2$ V, $V_{IL} = 0.408$ V,

$V_{IH} = 0.703$ V, $V_{OL} = 0.065$ V,

$NM_H = 0.50$ V, $NM_L = 0.34$ V

$P_D = V_{DD}I_D$

$$= V_{DD} \times \frac{V_{DD} - V_{OL}}{R_D}$$

Substituting for R_D from

$$R_D = \frac{1}{k_nV_x}$$

we obtain

$P_D = V_{DD}(V_{DD} - 0.054V_{DD}) \times k_n \times 0.04V_{DD}$

$$P_D = 0.038V_{DD}^3 \times k'_n\left(\frac{W}{L}\right)$$

$$= 0.038 \times 1.2^3 \times 0.5 \times 10^{-3}\left(\frac{W}{L}\right)$$

$$= 0.033\left(\frac{W}{L}\right),\ \text{mW}$$

For $V_M = \dfrac{V_{DD}}{2}$ we have

$$\frac{V_{DD}}{2} = V_t + \frac{V_{DD} - V_t}{\sqrt{r+1}}$$

$$\Rightarrow r = \left[\frac{V_{DD} - V_t}{(V_{DD}/2) - V_t}\right]^2 - 1$$

For $V_{DD} = 1.8$ V and $V_t = 0.4$ V (from Example 14.3) we obtain

$$r = \left(\frac{1.8 - 0.4}{0.9 - 0.4}\right)^2 - 1 = 6.84$$

14.30 Refer to Example 14.3 (page 1112 of text)

$$V_{OH} = V_{DD} = 1.2 \text{ V}$$

$$V_{OL} = (V_{DD} - V_t)\left[1 - \sqrt{1 - (k_p/k_n)}\right]$$

$$= (1.2 - 0.4)\left[1 - \sqrt{1 - \frac{1}{5}}\right]$$

$$= 0.084 \text{ V}$$

$$I_{DD} = \frac{1}{2}k_p(V_{DD} - V_t)^2$$

$$= \frac{1}{2} \times 0.1(1.2 - 0.4)^2$$

$$= 0.032 \text{ mA} = 32\ \mu\text{A}$$

$$P_{av} = \frac{1}{2}V_{DD}I_{DD} = \frac{1}{2} \times 1.2 \times 32 = 19.2\ \mu\text{W}$$

From the statement of Exercise 14.5, we have

$$V_M = V_t + \frac{V_{DD} - V_t}{\sqrt{r+1}}$$

where $r = k_n/k_p = 5$, thus

$$V_M = 0.4 + \frac{1.2 - 0.4}{\sqrt{5+1}}$$

$$= 0.73 \text{ V}$$

14.31 (a) To obtain $V_M = V_{DD}/2$, the inverter must be matched, thus

$$\frac{W_p}{W_n} = \frac{\mu_n}{\mu_p} = 2.5$$

$$\Rightarrow W_p = 2.5W_n = 2.5 \times 1.5 \times 65 = 244 \text{ nm}$$

Silicon area $= W_nL_n + W_pL_p$

$$= 1.5 \times 65 \times 65 + 2.5 \times 1.5 \times 65 \times 65$$

$$= 1.5 \times 65 \times 65(1 + 2.5)$$

$$= 22{,}181 \text{ nm}^2$$

(b) $V_{OH} = V_{DD} = 1$ V

$$V_{OL} = 0 \text{ V}$$

To obtain V_{IH}, we use Eq. (14.35):

$$V_{IH} = \frac{1}{8}(5V_{DD} - 2V_t)$$

$$= \frac{1}{8}(5 \times 1 - 2 \times 0.35)$$

$$= 0.5375 \text{ V}$$

To obtain V_{IL}, we use Eq. (14.36):

$$V_{IL} = \frac{1}{8}(3V_{DD} + 2V_t)$$

$$= \frac{1}{8}(3 \times 1 + 2 \times 0.35)$$

$$= 0.4625 \text{ V}$$

The noise margins can now be found as

$$NMH = V_{OH} - V_{IH}$$

$$= 1 - 0.5375 = 0.4625 \text{ V}$$

$$NM_L = V_{IL} - V_{OL}$$

$$= 0.4625 - 0 = 0.4625 \text{ V}$$

The noise margins are equal at approximately 0.46 V; a result of the matched design of the inverter.

(c) Since the inverter is matched, the output resistances in the two states will be equal. Thus,

$$r_{DSP} = r_{DSN} = 1\Big/\left[(\mu_n C_{ox})\left(\frac{W}{L}\right)_n (V_{DD} - V_t)\right]$$

$$= \frac{1}{0.47 \times 1.5(1 - 0.35)} = 2.18 \text{ k}\Omega$$

14.32 $V_{OH} = 2.5$ V

$$V_{OL} = 0 \text{ V}$$

(a) For the matched case we have

$$W_p = 3.5W_n$$

$$V_M = \frac{1}{2}V_{DD} = 1.25 \text{ V}$$

Eq. (14.35): $V_{IH} = \dfrac{1}{8}(5\ V_{DD} - 2\ V_t)$

$$= \frac{1}{8}(5 \times 2.5 - 2 \times 0.5)$$

$$= 1.4375 \text{ V}$$

Eq. (14.36): $V_{IL} = \dfrac{1}{8}(3\ V_{DD} + 2\ V_t)$

$$= \frac{1}{8}(3 \times 2.5 + 2 \times 0.5)$$

$$= 1.0625 \text{ V}$$

$$NM_H = NM_L = 1.0625 \text{ V}$$

Silicon area $= W_nL_n + W_pL_p$

$$= 1.5 \times 0.25 \times 0.25 + 3.5 \times 1.5 \times 0.25 \times 0.25$$

$$= 4.5 \times 1.5 \times 0.25^2 = 0.42\ \mu\text{m}^2$$

(b) $W_p = W_n$ (minimum-size design):

Eq. (14.40): $r = \sqrt{\frac{\mu_p}{\mu_n}\frac{W_p}{W_n}} = \sqrt{\frac{1}{3.5} \times 1} = 0.53$

Eq. (14.39): $V_M = \frac{r(V_{DD} - |V_{tp}|) + V_{tn}}{r+1}$

$= \frac{0.53(2.5 - 0.5) + 0.5}{0.53 + 1}$

$= 1.02$ V

Thus, V_M shifts to the left by 0.23 V. Assuming V_{IL} shifts by approximately the same amount, then

$V_{IL} \simeq 1.0625 - 0.23 \simeq 0.83$ V

Since $NM_L = V_{IL}$, NM_L will be reduced by approximately 22% (relative to the matched case).

Silicon area $= W_nL_n + W_pL_p$

$= 1.5 \times 0.25 \times 0.25 + 1.5 \times 0.25 \times 0.25$

$= 3 \times 0.25^2 = 0.19\ \mu\text{m}^2$

which is a reduction of 55% relative to the matched case.

(c) $W_p = 2W_n$ (a compromise design):

Eq. (14.40): $r = \sqrt{\frac{\mu_p}{\mu_n}\frac{W_p}{W_n}} = \sqrt{\frac{1}{3.5} \times \frac{2}{1}}$

$= 0.756$

Eq. (14.39): $V_M = \frac{r(V_{DD} - |V_{tp}|) + V_{tn}}{r+1}$

$= \frac{0.756(2.5 - 0.5) + 0.5}{0.756 + 1}$

$= 1.15$ V

Thus, relative to the matched case the switching point (V_M) is shifted left by $(1.25 - 1.15) = 0.1$ V. Assuming that V_{IL} is reduced by approximately the same amount, then

$V_{IL} = 1.0625 - 0.1 = 0.9625$ V

Thus, NM_L which equals V_{IL} is reduced by about 9% (relative to the matched case).

Silicon area $= W_nL_n + W_pL_p$

$= 1.5 \times 0.25 \times 0.25 + 2 \times 1.5 \times 0.25 \times 0.25$

$= 3 \times 1.5 \times 0.25^2$

$= 0.28\ \mu\text{m}^2$

Compared to the matched case, the silicon area is reduced by 33%.

14.33 Q_N will be operating in the triode region, thus

$$I_{Dn} = k_n'\left(\frac{W}{L}\right)_n\left[(V_{DD} - V_{tn})V_O - \frac{1}{2}V_O^2\right]$$

For $V_{tn} = 0.3V_{DD}$ and $V_O = 0.1V_{DD}$, we have

$$I_{Dn} = k_n'\left(\frac{W}{L}\right)_n \left[(V_{DD} - 0.3V_{DD}) \times 0.1V_{DD} - \frac{1}{2} \times 0.1^2 V_{DD}^2\right]$$

$= k_n'(W/L)_n(0.07V_{DD}^2 - 0.005V_{DD}^2)$

$= 0.065k_n'(W/L)_nV_{DD}^2$ Q.E.D.

For $V_{DD} = 1.3$ V, $k_n' = 0.5$ mA/V^2 and $I_{Dn} = 0.1$ mA, we have

$0.1 = 0.065 \times 0.5(W/L)_n \times 1.3^2$

$\Rightarrow \left(\frac{W}{L}\right)_n = 1.82$

14.34 For $v_I = +1.5$ V, Q_N will be conducting and operating in the triode region while Q_P will be off. Thus, the incremental resistance to the left of node A will be r_{DSN},

$r_{DSN} = \frac{1}{k_n(V_I - V_{tn})}$

$= \frac{1}{0.2(1.5 - 0.5)} = 5\ \text{k}\Omega$

Thus,

$v_a = 100\left(\frac{5}{5 + 100}\right)$

$= 4.8$ mV

For $v_I = -1.5$ V, Q_N will be off but Q_P will be operating in the triode region with a resistance r_{DSP},

$r_{DSP} = \frac{1}{k_p(V_{SGP} - |V_{tp}|)}$

$= \frac{1}{0.04(1.5 - 0.5)} = 25\ \text{k}\Omega$

Thus,

$v_a = 100\left(\frac{25}{25 + 100}\right) = 20$ mV

14.35 From Eq. (14.39) we have

$V_M = \frac{r(V_{DD} - |V_{tp}|) + V_{tn}}{r+1}$

$rV_M + V_M = r(V_{DD} - |V_{tp}|) + V_{tn}$

$r(V_{DD} - |V_{tp}| - V_M) = V_M - V_{tn}$

$\Rightarrow r = \frac{V_M - V_{tn}}{V_{DD} - |V_{tp}| - V_M}$ Q.E.D.

For $V_{DD} = 1.3$ V, $V_{tn} = |V_{tp}| = 0.4$ V, to obtain $V_M = 0.6V_{DD}$, we need

$$r = \frac{0.6 \times 1.3 - 0.4}{1.3 - 0.4 - 0.6 \times 1.3}$$

$$= 3.167$$

But,

$$r = \sqrt{\frac{\mu_p}{\mu_n}\frac{W_p}{W_n}}$$

$$3.167 = \sqrt{\frac{1}{4} \times \frac{W_p}{W_n}}$$

$$\frac{W_p}{W_n} = 3.167^2 \times 4 = 40.1$$

14.36 The current reaches its peak at $v_I = V_M = \dfrac{V_{DD}}{2}$. At this point, both Q_N and Q_P are operating in the saturation region and conducting a current

$$I_{DP} = I_{DN} = \frac{1}{2}k_n'\left(\frac{W}{L}\right)_n\left(\frac{V_{DD}}{2} - V_t\right)^2$$

$$= \frac{1}{2} \times 500 \times 1.5\left(\frac{1.3}{2} - 0.4\right)^2$$

$$= 23.4\ \mu\text{A}$$

14.37 Refer to Example 14.4 (page 1121 of text) except here:

$V_{DD} = 1.3$ V, $V_{tn} = |V_{tp}| = 0.4$ V, $\mu_n = 4\ \mu_p$, and $\mu_n C_{ox} = 0.5$ mA/V^2. Also, Q_N and Q_P have $L = 0.13\ \mu$m and $(W/L)_n = 1.5$.

(a) For $V_M = V_{DD}/2 = 0.65$ V, the inverter must be matched, thus

$$\frac{W_p}{W_n} = \frac{\mu_n}{\mu_p} = 4$$

Since $W_n/L = 1.5$, $W_n = 1.5 \times 0.13 = 0.195\ \mu$m. Thus,

$$W_p = 4 \times 0.195 = 0.78\ \mu\text{m}$$

For this design, the silicon area is

$$A = W_n L + W_p L = L(W_n + W_p)$$

$$= 0.13(0.195 + 0.78) = 0.127\ \mu\text{m}^2$$

(b) $V_{OH} = V_{DD} = 1.3$ V

$V_{OL} = 0$ V

To obtain V_{IH}, we use Eq. (14.35):

$$V_{IH} = \frac{1}{8}(5V_{DD} - 2V_t)$$

$$= \frac{1}{8}(5 \times 1.3 - 2 \times 0.4)$$

$$= 0.7125\ \text{V}$$

To obtain V_{IL}, we use Eq. (14.36):

$$V_{IL} = \frac{1}{8}(3V_{DD} + 2V_t)$$

$$= \frac{1}{8}(3 \times 1.3 + 2 \times 0.4)$$

$$= 0.5875\ \text{V}$$

We can now compute the noise margins as

$$N_{MH} = V_{OH} - V_{IH} = 1.3 - 0.7125$$

$$= 0.5875\ \text{V} \simeq 0.59\ \text{V}$$

$$NM_L = V_{IL} - V_{OL} = 0.5875 - 0$$

$$= 0.5875\ \text{V} \simeq 0.59\ \text{V}$$

For $v_I = V_{IH} = 0.7125$ V, we can obtain the corresponding value of v_O by substituting in Eq. (14.34):

$$v_O = V_{IH} - \frac{V_{DD}}{2} = 0.7125 - 0.65 = 0.0625\ \text{V}$$

Thus, the worst-case value of V_{OL} is $V_{O\max} = 0.0625 \simeq 0.06$ V, and the noise margin NM_L reduces to

$$NM_L = 0.5875 - 0.0625 = 0.5250\ \text{V}$$

or approximately 0.53 V.

From symmetry, we can obtain the value of v_O corresponding to $v_I = V_{IL}$ as

$$v_O = V_{DD} - 0.0625$$

$$= 1.3 - 0.0625 = 1.2375\ \text{V} \simeq 1.24\ \text{V}$$

Thus, the worst-case value of V_{OH} is $V_{OH\min} \simeq 1.24$ V, and the noise margin NM_H is reduced to

$$NM_H = V_{OH\min} - V_{IH}$$

$$= 1.2375 - 0.7125 = 0.5250\ \text{V}$$

or approximately 0.53 V.

Note that the reduction in the noise margin (about 0.06 V) is slight.

(c) The output resistance of the inverter in the low-output state is

$$r_{DSN} = \frac{1}{\mu_n C_{ox}(W/L)_n(V_{DD} - V_{tn})}$$

$$= \frac{1}{0.5 \times 1.5(1.3 - 0.4)} = 1.48\ \text{k}\Omega$$