Example

For the BiCMOS gate shown in the following diagram,

use the average current method to estimate

1. the rise time \( t_r \),
2. the fall time \( t_f \), and
3. \( t_{PLH} \)

if \( C_L = 1pF \), \( \beta = 100 \), \( \mu_n C_{ox} = 4\mu_p C_{ox} = 0.3mA/V^2 \), \( V_{tn} = -V_{tp} = 0.5V\) and \( v_{BE} = 0.7V\)

for transistors that are ON. Neglect the body effect. Use \( V_{DD} = 3V \), \( W/L = 1\) for both FETs, and \( R_1 = R_2 = 20k\Omega\).

ANSWER:

1. To find \( t_r \), consider \( v_{IN} = 0V\), and the two conditions when \( v_{OUT} = 0.1 \times 3V = 0.3V\) and \( v_{OUT} = 0.9 \times 3V = 2.7V\).

On the first case there is enough voltage difference from the power supply to the output to provide \( Q_1 \) with a base-to-emitter voltage of 0.7V, and the transistor is ON.

\( t_r \) is the time it takes for \( v_{OUT} \) to go from 10\% to 90\% of \( V_{DD} \)

\( t_f \) is the time it takes for \( v_{OUT} \) to go from 90\% to 10\% of \( V_{DD} \)
Therefore the capacitor charging current is given by

\[ i_{\text{cap},1} = i_{c1} + i_{R1} = \beta i_{b1} + i_{R1} \]
\[ = \beta (i_{DP} - i_{R1}) + i_{R1} \]
\[ = \beta i_{DP} - (\beta - 1) \frac{0.7V}{R_1} \]

Since \( v_{SD,P} = 3V - 0.7V - 0.3V = 2.0V < v_{SG,P} + V_{ip} = 3V - 0V - 0.5V = 2.5V \), the pmosfet is operating in triode mode. Thus

\[ i_{D,P} = \frac{1}{2} \frac{0.3mA/V^2}{2} (2(2.5V)2V - (2V)^2) = 0.225mA \]

and

\[ i_{\text{cap},1} = 100(0.225mA) - (99) \frac{0.7V}{20k\Omega} = 22.5mA - 3.465mA = 19.035mA \]

For the second case the voltage difference between supply and output is only 0.3V and the transistor will be OFF. The capacitor current will be flowing through the \( Q_P \) and \( R_1 \). To find the current, consider the current equation

\[ i_{D,P} = \frac{1}{2} \frac{0.3mA/V^2}{2} (2(2.5V)v_{SD,P} - v_{SD,P}^2) = 37.5\mu A/V^2 (5v_{SD,P} - v_{SD,P}^2) \]

and

\[ V_{DD} - v_{OUT} = 0.3V = v_{SD,P} + 20k\Omega \times i_{D,P} \]

These equations will have to be satisfied simultaneously. Solving the second equation for \( i_{D,P} \), substituting into the first equation and rearranging, one obtains

\[ 0.3V - v_{SD,P} = 0.75V^{-1} ((5V)v_{SD,P} - v_{SD,P}^2) \]

which can be solved to get \( v_{DS,P} = 63.8mV \) and \( i_{D,P} = 11.81\mu A = i_{\text{cap},2} \). The small magnitude of this current indicates that once the transistor turns off, the capacitor charges at a considerably slower speed.

The average current is \( \frac{19.035mA + 0.01181mA}{2} = 9.52mA \) and

\[ t_r \approx 1pF \frac{2.7V - 0.3V}{9.52mA} = 252ps \]

2. To find \( t_f \), consider \( v_{IN} = 3V \), and the two conditions when \( v_{OUT} = 0.9 \times 3V = 2.7V \) and \( v_{OUT} = 0.1 \times 3V = 0.3V \).

When \( v_{OUT} = 2.7V \), \( Q_2 \) will be ON and \( v_{BE,2} = 0.7V \). Thus

\[ i_{\text{cap},3} = i_{c2} + i_{D,N} = \beta \left( i_{D,N} - \frac{0.7V}{20k\Omega} \right) + i_{D,N} = 101i_{D,N} - 3.5mA \]

For \( Q_N \), \( v_{DS,N} = 2.7V - 0.7V = 2V > v_{GS,N} - V_{in} = 3V - 0.7V - 0.5V = 1.8V \) so the NMOS is saturated and

\[ i_{D,N} = \frac{0.3mA/V^2}{2} (1.8V)^2 = 486\mu A \]
and
\[ i_{cap,3} = 101(0.486mA) - 3.5mA = 45.586mA \]

When \( v_{OUT} = 0.3V \), \( Q_2 \) will be OFF. The NMOS transistor will operate in triode mode with \( v_{GS,N} = 3V - 20k\Omega \times i_{D,N} \) and \( v_{DS,N} = 0.3V - 20k\Omega \times i_{D,N} \). The current equation is
\[
i_{cap,4} = i_{D,N} = \frac{0.3mA/V^2}{2} (2(3V - 20k\Omega \times i_{D,N} - 0.5V)(0.3V - 20k\Omega \times i_{D,N}) - (0.3V - 20k\Omega \times i_{D,N})^2)
\]

which after solving yields a current of only 0.24\( \mu \)A so it can be neglected.

The average current for discharging is thus about 22.8mA and
\[ t_f \simeq 1pF \frac{2.4V}{22.8mA} = 105ps \]

3. To estimate \( t_{PLH} \) we must consider \( v_{IN} = 0V \) and two values for the output: \( v_{OUT} = 0V \) and \( V_{OUT} = 1.5V \).

When \( v_{OUT} = 0V \), \( v_{SD,P} = 3V - 0.7V = 2.3V < v_{SG,P} + V_{tp} = 3V - 0.5V = 2.5V \), and \( Q_P \) operates in triode mode. Since there is enough voltage for \( Q_1 \) to be ON, the situation is similar to the one described for the above \( i_{cap,1} \), and charging current is
\[
i_{cap} = i_{e1} + i_{R1} = \beta i_{DP} - (\beta - 1) \frac{0.7V}{R_1}
\]
\[
i_{DP} = \frac{10.3mA/V^2}{2} (2(2.5V) 2.3V - (2.3V)^2) = 0.233mA
\]
\[
i_{cap} = 100 \times 0.233mA - 99 \times \frac{0.7V}{20k\Omega} = 19.8mA
\]

When \( v_{OUT} = 1.5V \), \( v_{SD,P} = 3V - 0.7V - 1.5V = 0.8V < v_{SG,P} + V_{tp} = 3V - 0.5V = 2.5V \), and \( Q_P \) operates in triode mode. Since there is enough voltage for \( Q_1 \) to be ON, the charging current is
\[
i_{cap} = 100i_{DP} - 99\frac{0.7V}{R_1}
\]
\[
i_{DP} = \frac{10.3mA/V^2}{2} (2(2.5V) 0.8V - (0.8V)^2) = 0.126mA
\]
\[
i_{cap} = 100 \times 0.126mA - 99 \times \frac{0.7V}{20k\Omega} = 9.135mA
\]

The average current is 14.5mA and
\[ t_{PLH} = 1pF \frac{1.5V}{14.5mA} = 104ps \]