ECE 207 – FIRST ORDER RC CIRCUITS – INVESTIGATION 13
SWITCHING SPEEDS OF CMOS GATES

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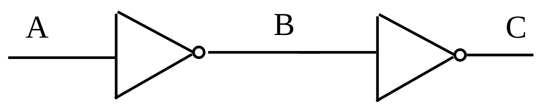
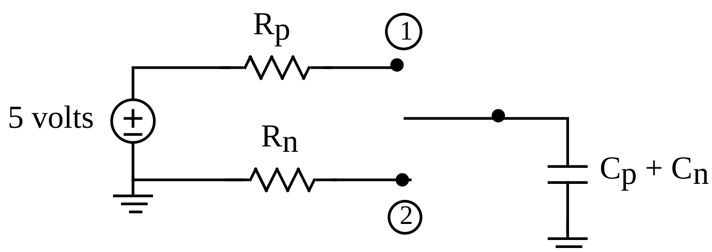
To do "well" on this investigation you must not only get the right answers but must also do neat, complete and concise writeups that make obvious what each problem is, how you're solving the problem and what your answer is. You also need to include drawings of all circuits as well as appropriate graphs and tables.

We know from the last investigation that if two CMOS gates are connected as follows



then we can model the interface between them by the following circuit

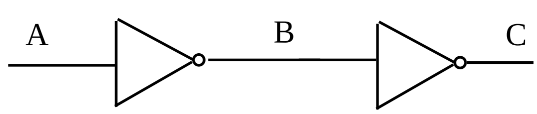


where R_p, R_n, C_p and C_n are the equivalent resistances and capacitances of the PMOS and NMOS transistors. Note that

a. When the switch is connect to node 1 then first inverter is in the **pull-up** phase with $V_A \leq V_{tl}$ and V_B increasing to 5 volts as the capacitors charge up.
b. When the switch is connect to node 2 then first inverter is in the **pull-down** phase with $V_A \geq V_{th}$ and V_B decreasing to 0 volts as the capacitors discharge.

The objective of this investigation is to calculate the pull-up and pull-down times for our CMOS inverters and in the process identify some basic properties of RC circuits with constant inputs and switches.

1. Given two CMOS inverters connected as follows

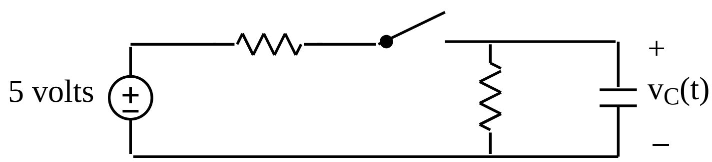


with R_n = 1K, C_n = 5 fF, R_p = 1.5K and C_p = 10 fF

a. Draw the equivalent circuit during pull-up
b. Find and sketch V_B during pull-up. What is τ_{pu}
c. How long does it take V_B to increase from 0 volts to V_{th} = 4 volts
d. Draw the equivalent circuit during pull-down
e. Find and sketch V_B during pull-down. What is τ_{pd}
f. How long does it take V_B to decrease from 5 volts to V_{tl} = 1 volts
g. Which takes longer: pull-up or pull-down

2. Which inverters have the faster pull-up and pull-down times: CMOS inverters with R_{n1} = 1K, C_{n1} = 5 fF, R_{p1} = 1.5K and C_{p1} = 10 fF or CMOS inverters with with R_{n2} = 2K, C_{n2} = 10 fF, R_{p2} = 1.5K and C_{p2} = 10 fF.

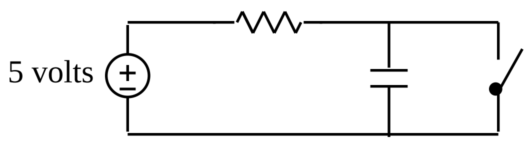
3. The objective of this and the next several problems is to develop two basic properties of capacitors circuits with switches and **constant inputs** like those in Problem (1). The first observation is that if a switch opens or closes at time t = 0 in a circuit like the following



then the voltage across the capacitor will not change instantaneously. In particular

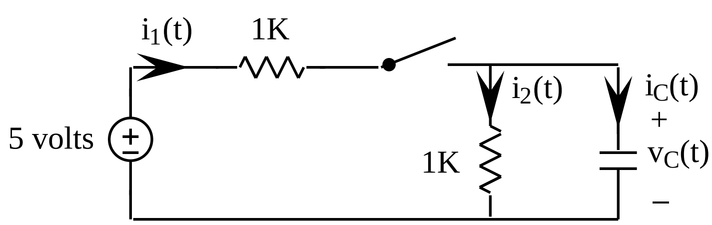
$$v_C(0-) = v_C(0+)$$

where $v_C(0-)$ is the voltage across the capacitor just before the switch opens or closes and $v_C(0+)$ is the voltages just after the switch opens or closes. The reason is that it takes time for the charges to move on and off the capacitor plates - as we've seen in our calculations. The only "exception" is, of course, in circuits like



which will generate sparks if you short circuit the capacitor.

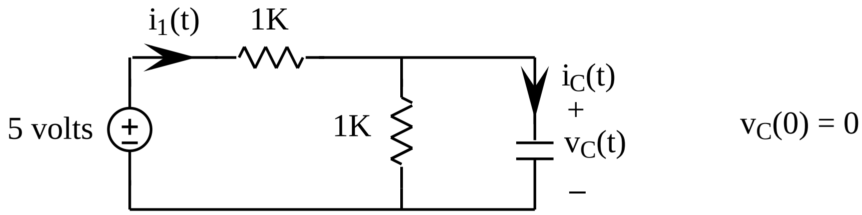
Given the following circuit



with switch opening at time t = 0 and $v_C(0-)$ = 2 volts

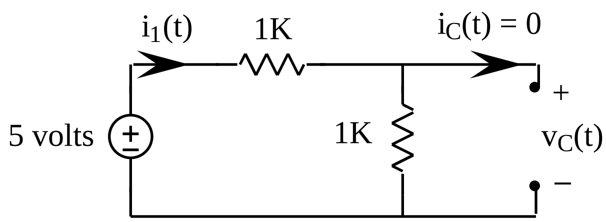
a. Find $i_1(0-)$, $i_2(0-)$ and $i_C(0-)$
b. Find $v_C(0+)$, $i_1(0+)$, $i_2(0+)$ and $i_C(0+)$

4. The objective of this problem is to see what's going in RC circuits with **constant inputs** like the following



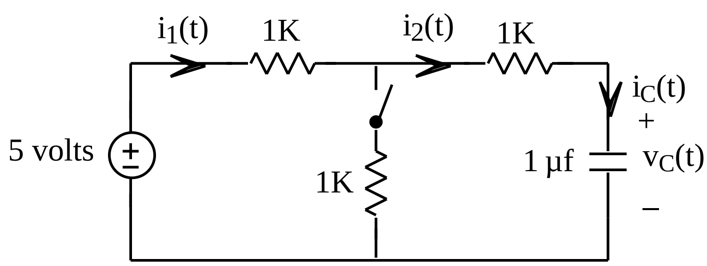
after the capacitor is charged up - when the circuit is in its **steady state**

a. Find and sketch $v_C(t)$ and $i_C(t)$ as the capacitor charges up
b. What are $v_C(t)$, $i_C(t)$ and $i_1(t)$ after the capacitor has charged up
c. From parts (a) and (b) we see that once the capacitor charges up $i_C(t) = 0$. What this means is that once an RC circuit with a **constant input** is in the steady state - once the capacitor has charged up - then we can replace it with an open circuit as follows



Memorize this result. Then make use of it to calculate the steady state values of $i_1(t)$ and $v_C(t)$. Make sure you get the same results as you got in part (b).

5. Given that the following circuit is in the steady state just before the switch opens at $t = 0$



a. First draw the equivalent circuit for when $t < 0$ and find $i_1(0–)$, $i_2(0–)$, $i_C(0–)$ and $v_C(0–)$
b. Now draw what the circuit looks like at time $t = 0+$ and find $i_1(0+)$, $i_2(0+)$, $i_C(0+)$ and $v_C(0+)$
c. What was the time constant τ when the switch was closed.
d. What's the time constant τ after the switch opens