Closed book and notes except for one 8.5 in × 11 in sheet of paper. Show reasoning for full credit. There are 4 problems and 100 points. Note: complex quantities are shown in **boldface** type. All transistors and diodes (if any) are silicon at room temperature unless otherwise noted. The table of Laplace transforms is included at the end.

\[ V_{out} - V_+ = \frac{V_+ - 3V}{5k\Omega} \]
\[ V_{out} - V_+ = 2V_+ - 6V \]
\[ V_+ = \frac{(V_{out} + 6V)}{3} = \frac{12V}{3} = 4V \]
\[ \text{If } V_{out} = 0, V_+ = 6V/3 = 2V \]

1. **(≈ 40 points)** For the op-amp in the circuit above, \( A_o = 200000 \). Assume \( V_{out} = 6V \) if \( V_+ > V_- \), \( V_{out} = 0 \) if \( V_+ < V_- \) and the currents into the + and - inputs are negligible.

   (a) When \( V_{in} = 0 \), \( V_{out} = 6V \). Find \( V_+ \).

   (b) Find the values of \( V_{in} \) for which the output high-to-low (\( V_d \)) and low-to-high (\( V_u \)) transitions occur. \( V_d = 4V \) when \( V_{in} = V_+ (6V/V_{out} = 6V) \).

   (c) Make a graph of \( V_{out} \) vs. \( V_{in} \) for \( 0 \leq V_{in} \leq 6V \) indicating the transition voltages \( V_d \) and \( V_u \). How would you classify this circuit (i.e., does it have a name)? **Schmitt Trigger**.

   (d) In the circuit below, a resistor to 6V, a capacitor to ground and a grounding switch have been added at the input. The switch is closed, grounding \( V_{in} \). The switch is then opened at \( t = 0 \). Capacitor charges through \( R \) toward 6V. Output changes state when \( V_{in} = V_d = 6V \).

   i. Find an expression for \( V_{in}(t) \) for \( t > 0 \).

   ii. Make a sketch of \( V_{out}(t) \) for \( t > 0 \). For what value of \( t \) does \( V_{out} \) change state? Evaluate your answer. \( V_d = 6V(1 - e^{-t/RC}) \).

   iii. Explain how to make this circuit into a relaxation oscillator by changing one connection. **For relaxation oscillator counter top load of \( R \) to \( V_{out} \).**

\[ C = 0.001uF \]
\[ R = 10k\Omega \]
\[ R = 10k\Omega \]
\[ V = 6V \]
\[ V_{in} = 3V \]
\[ V_+ = 4V \]
\[ V_{out} = 6V \]
\[ t = 10^{-4} \times 10^{-8} = 0.11 \text{ ms} \]
2. (≈ 10 points)

(a) Use the theorems of Boolean algebra to write the following function in lowest order "sum-of-products" form (i.e., minterms):

\[ F_2 = (A \bar{B})(A \bar{B}) = (A + B)(\bar{A} + \bar{B}) = \bar{A}B + A\bar{B} \]

(b) What common function is this?

\[ \equiv A \oplus B \quad (\text{exclusive or}) \]

3. (≈ 34 points)

(a) Use the Karnaugh maps below to express the corresponding functions in simplified form. Assign each "don't care" cell (if any) to be 0 or 1 as needed to allow simplifying the function as much as possible.

\[ F_3 = \bar{B}C + A\bar{B} + \bar{A}BC \]

(b) Implement function \( F_4 \) in "two-stage" logic using only multiple input NAND gates \{\} and inverters. (Remember that De Morgan says that a NAND is equivalent to an OR with inverted inputs.)

(c) Implement function \( F_3(A, B, C) \) using the 4-input multiplexer shown below. The variables \( A \) and \( B \) are connected to the selection lines. You also have available \( C, \bar{C}, +5 \text{ V} \) and ground. Show the logic connections required for each multiplexer input to implement the function. Hint: Each column in the Karnaugh map for \( F_3 \) corresponds to one \( \text{mux} \) input:

\[ \begin{align*}
A, B = 0, 0 & \leftrightarrow I_0 = C \\
A, B = 0, 1 & \leftrightarrow I_1 = \bar{C} \\
A, B = 1, 1 & \leftrightarrow I_2 = \bar{C} (\text{ground}) \\
A, B = 1, 0 & \leftrightarrow I_3 = 1 (+5 \text{ V})
\end{align*} \]
4. (≈ 16 points)

(a) In the circuit above, the p-channel enhancement mode MOSFETs have $V_t = -1.5 \text{ V}$ and the n-channel enhancement mode MOSFETs have $V_t = 1.5 \text{ V}$.

Consider the case with both $A$ and $B$ low (0 V). State which MOSFETs are “on,” which are “off” and estimate the output voltage. (see diagram)

(b) Another logic circuit is given below.

   i. Are the diodes in the circuit p-n silicon junction diodes? If not, what kind of diodes are they? They are not p-n junctions. They are metal-semiconductor diodes - Schottky diodes.

   ii. What do they do to improve the performance of the circuit?

   They have a forward voltage drop of 0.5 V

   so the BJT base-collector diodes are kept below their cut-in voltage for forward bias

   and the BJT remains in the active region, does not reach saturation.

   This reduces charge storage and speeds up the turn-off time of the BJT.