1 Boolean Logic

In digital electronics, it is often important to get certain outputs based on your inputs, as laid out by a truth table. Truth tables map directly to Boolean expressions, and Boolean expressions map directly to logic gates. However, in order to minimize the number of logic gates needed to implement a circuit, it is often useful to simplify long Boolean expressions.

We can simplify expressions using the nine key laws of Boolean algebra:

Name	AND Form	OR form
Commutative	$AB = BA$	$A + B = B + A$
Associative	$AB(C) = A(BC)$	$A + (B + C) = (A + B) + C$
Identity	$1A = A$	$0 + A = A$
Null	$0A = 0$	$1 + A = 1$
Absorption	$A(A + B) = A$	$A + AB = A$
Distributive	$(A + B)(A + C) = A + BC$	$A(B + C) = AB + AC$
Idempotent	$A(A) = A$	$A + A = A$
Inverse	$A(\overline{A}) = 0$	$A + \overline{A} = 1$
De Morgan's	$\overline{AB} = \overline{A} + \overline{B}$	$\overline{A + B} = \overline{A}(\overline{B})$

Simplify the following Boolean expressions:

1.1 (a) $(A + B)(A + \overline{B})C$

(b) $\overline{A}\,\overline{B}\,\overline{C} + \overline{A}B\overline{C} + AB\overline{C} + A\overline{B}\,\overline{C} + ABC + A\overline{B}C$

(c) $\overline{A(\overline{B}\,\overline{C} + BC)}$

2   Combinational Logic Design

Logic gates can be connected together to create a variety of useful functions. In this question, we will implement a simplified version of the memory write mask for the RISC-V CPU. The memory write mask looks at the store instruction given and decides which of the four bytes (in one word of memory) to write to. It is four bits long - each bit is one if we should write to the corresponding byte, but zero if we shouldn't. For simplicity, assume that all memory addresses used in store instruction are word-aligned. Here's a truth table for the simpified memory mask:

| Instruction	funct3	Out
sb	000	0001
sh	001	0011
sw	010	1111
(undefined)	011-111	xxxx

The x's for the final entry of the table indicates that any output is fine in that case.

2.1 Write out and simplify boolean expressions for each of the output bits in terms of the funct3 (input) bits f_2, f_1, f_0.

2.2 Draw out the boolean circuit for this memory write mask based on your simplified expressions above. You may use constants 0 and 1, and the logic gates AND, OR, NOT.
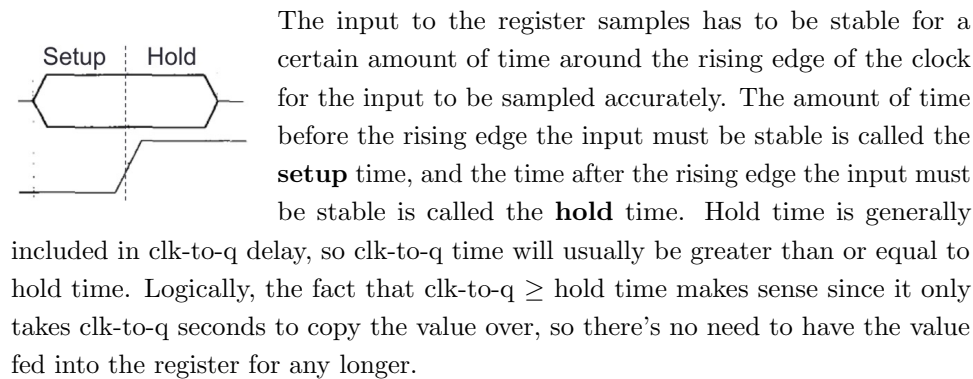
3   State Intro

There are two basic types of circuits: combinational logic circuits and state elements. **Combinational logic** circuits simply change based on their inputs after whatever propagation delay is associated with them. For example, if an AND gate (pictured below) has an associated propagation delay of 2ps, its output will change based on its input as follows:
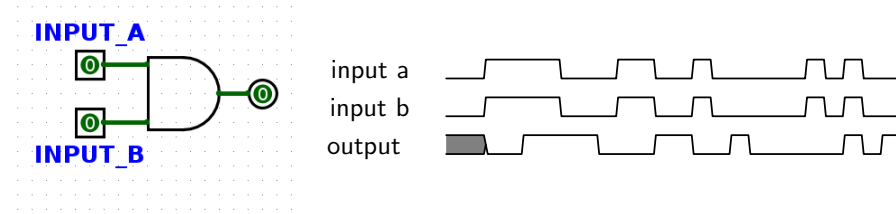

You should notice that the output of this AND gate *always* changes 2ps after its inputs change.

State elements, on the other hand, can *remember* their inputs even after the inputs change. State elements change value based on a clock signal. A rising edge-triggered register, for example, samples its input at the rising edge of the clock (when the clock signal goes from 0 to 1).

Like logic gates, registers also have a delay associated with them before their output will reflect the input that was sampled. This is called the **clk-to-q** delay. ("Q" often indicates output). This is the time between the rising edge of the clock signal and the time the register's output reflects the input change.

The input to the register samples has to be stable for a certain amount of time around the rising edge of the clock for the input to be sampled accurately. The amount of time before the rising edge the input must be stable is called the **setup** time, and the time after the rising edge the input must be stable is called the **hold** time. Hold time is generally included in clk-to-q delay, so clk-to-q time will usually be greater than or equal to hold time. Logically, the fact that clk-to-q $\geq$ hold time makes sense since it only takes clk-to-q seconds to copy the value over, so there's no need to have the value fed into the register for any longer.

For the following register circuit, assume **setup** of 2.5ps, **hold** time of 1.5ps, and a **clk-to-q** time of 1.5ps. The clock signal has a period of 13ps.
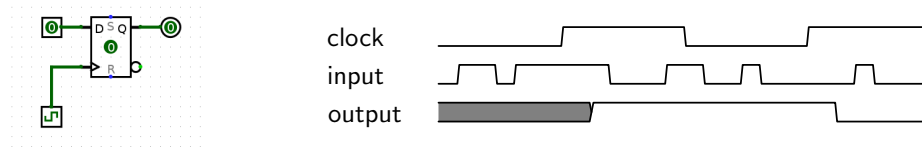

You'll notice that the value of the output in the diagram above doesn't change immediately after the rising edge of the clock. Until enough time has passed for the output to reflect the input, the value held by the output is garbage; this is represented by the shaded gray part of the output graph. Clock cycle time must be small enough that inputs to registers don't change within the hold time and large enough to account for clk-to-q times, setup times, and combinational logic delays.

3.1   For the following circuit, fill out the timing diagram. The clock period (rising edge to rising edge) is 8ps. For every register, clk-to-q delay is 2ps, setup time is 4ps, and hold time is 2ps.

clk
in
s0
s1
out
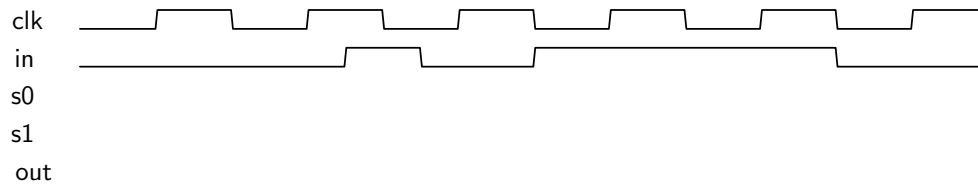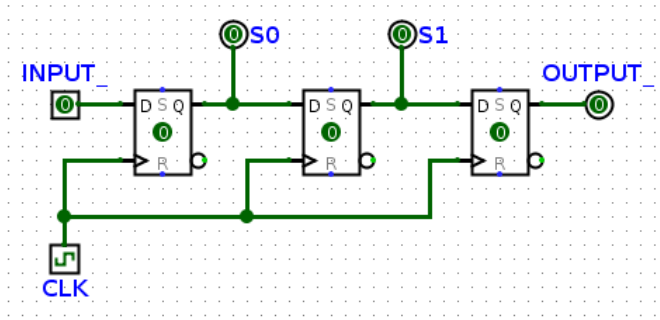
3.2   In the circuit below, RegA and RegB have setup, hold, and clk-to-q times of 4ns, all logic gates have a delay of 5ns, and RegC has a setup time of 6ns. What is the maximum allowable hold time for RegC? What is the minimum acceptable clock cycle time for this circuit, and clock frequency does it correspond to?
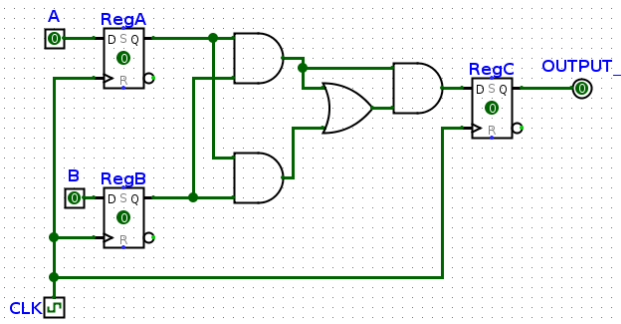

Conceptual questions:

3.3   Simplifying boolean logic expressions will not affect the performance of the hardware implementation.

3.4   The fewer logic gates, the faster the circuit (assuming each gate has the same propagation delays).

4   Finite State Machines

Automatons are machines that receive input and use various states to produce output. A finite state machine is a type of simple automaton where the next state

and output depend only on the current state and input. Each state is represented by a circle, and every proper finite state machine has a starting state, signified either with the label "Start" or a single arrow leading into it. Each transition between states is labeled [input]/[output].

4.1 What pattern in a bitstring does the FSM below detect? What would it output for the input bitstring "011001001110"?
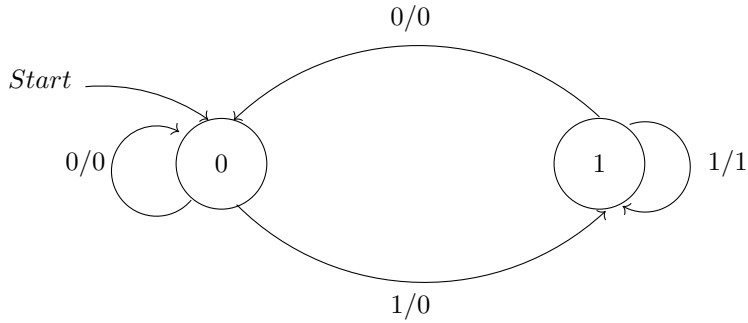
4.2 Fill in the following FSM for outputting a 1 whenever we have two repeating bits as the most recent bits, and a 0 otherwise. You may not need all states.
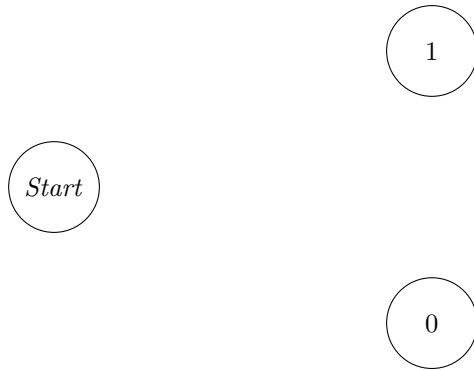
4.3 Draw an FSM that will output a 1 if it recognizes the regex pattern {10+1}. (That is, if the input forms a pattern of a 1, followed by one or more 0s, followed by a 1.)