Laboratory Exercise 3

Latches, Flip-flops, and Registers

The purpose of this exercise is to investigate latches, flip-flops, and registers.

Part I

Altera FPGAs include flip-flops that are available for implementing a user's circuit. We will show how to make use of these flip-flops in Part IV of this exercise. But first we will show how storage elements can be created in an FPGA without using its dedicated flip-flops.

Figure 1 depicts a gated RS latch circuit. A style of VHDL code that uses logic expressions to describe this circuit is given in Figure 2. If this latch is implemented in an FPGA that has 4-input lookup tables (LUTs), then only one lookup table is needed, as shown in Figure 3a.

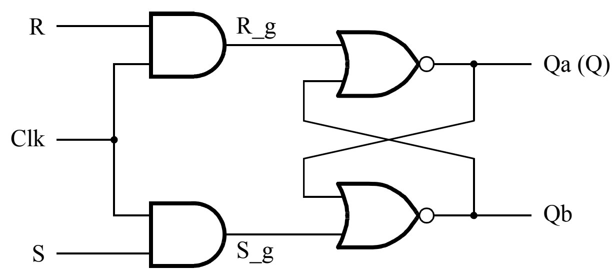
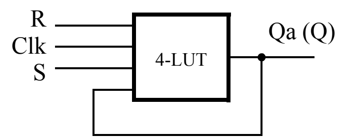


Figure 1: A gated RS latch circuit.

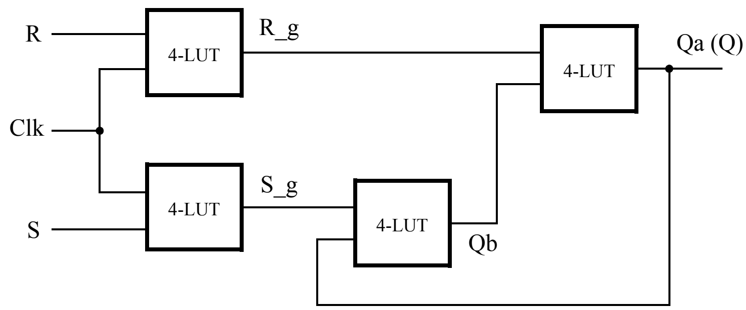
```
-- A gated RS latch desribed the hard way
LIBRARY ieee;
USE ieee.std_logic_1164.all;

ENTITY part1 IS
   PORT (  Clk, R, S : IN      STD_LOGIC;
           Q         : OUT     STD_LOGIC);
END part1;

ARCHITECTURE Structural OF part1 IS
   SIGNAL R_g, S_g, Qa, Qb : STD_LOGIC ;
   ATTRIBUTE keep : boolean;
   ATTRIBUTE keep of R_g, S_g, Qa, Qb : SIGNAL IS true;
BEGIN
   R_g <= R AND Clk;
   S_g <= S AND Clk;
   Qa <= NOT (R_g OR Qb);
   Qb <= NOT (S_g OR Qa);

   Q <= Qa;

END Structural;
```

Figure 2. Specifying the RS latch by using logic expressions.

Although the latch can be correctly realized in one 4-input LUT, this implementation does not allow its internal signals, such as R_g and S_g, to be observed, because they are not provided as outputs from the LUT. To preserve these internal signals in the implemented circuit, it is necessary to include a *compiler directive* in the code. In Figure 2 the directive *keep* is included by using a VHDL ATTRIBUTE statement; it instructs the Quartus II compiler to use separate logic elements for each of the signals R_g, S_g,Qa, and Qb. Compiling the code produces the circuit with four 4-LUTs depicted in Figure 3b.



(a) Using one 4-input lookup table for the RS latch.



(b) Using four 4-input lookup tables for the RS latch.

Figure 3. Implementation of the RS latch from Figure 1.

Create a Quartus II project for the RS latch circuit as follows:

1. Create a new project for the RS latch. Select as the target chip the Cyclone II EP2C20F484C7, which is the FPGA chip on the Altera DE1 board.
2. Generate a VHDL file with the code in Figure 2 and include it in the project.
3. Compile the code. Use the Quartus II RTL Viewer tool to examine the gate-level circuit produced from the code, and use the Technology Viewer tool to verify that the latch is implemented as shown in Figure 3b.
4. in QSim, create a Vector Waveform File (.vwf) which specifies the inputs and outputs of the circuit. Draw waveforms for the R and S inputs and use QSim to produce the corresponding waveforms for R_g, S_g, Qa, and Qb. Verify that the latch works as expected using both functional and timing simulation.

Part II

Figure 4 shows the circuit for a gated D latch.

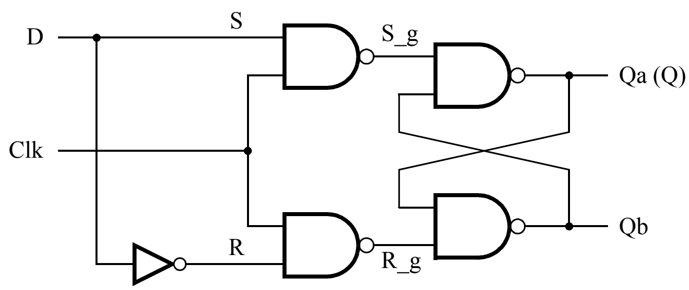


Figure 4. Circuit for a gated D latch.

Perform the following steps:

1. Create a new Quartus II project. Generate a VHDL file using the style of code in Figure 2 for the gated D latch. Use the *keep* directive to ensure that separate logic elements are used to implement the signals R, S_g, R_g,Qa, and Qb.
2. Select as the target chip the Cyclone II EP2C20F484C7 and compile the code. Use the Technology Viewer tool to examine the implemented circuit.
3. Verify that the latch works properly for all input conditions by using functional simulation. Examine the timing characteristics of the circuit by using timing simulation.
4. Create a new Quartus II project which will be used for implementation of the gated D latch on the DE1 board. This project should consist of a top-level entity that contains the appropriate input and output ports (pins) for the DE1 board. Instantiate your latch in this top-level entity. Use switch SW_0 to drive the *D* input of the latch, and use SW_1 as the *Clk* input. Connect the Q output to $LEDR_0$.
5. Recompile your project and download the compiled circuit onto the DE1 board.
6. Test the functionality of your circuit by toggling the D and *Clk* switches and observing the Q output.

Part III

Figure 5 shows the circuit for a master-slave D flip-flop.

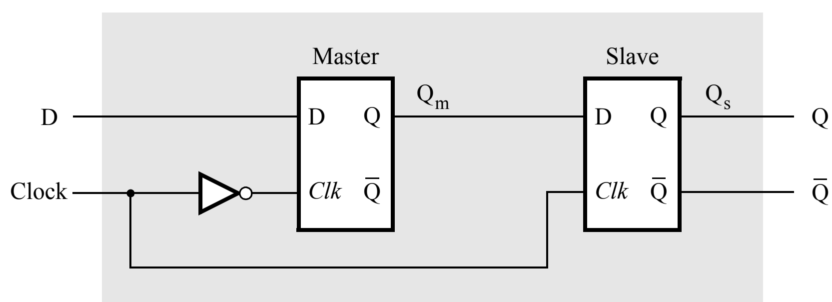


Figure 5. Circuit for a master-slave D flip-flop.

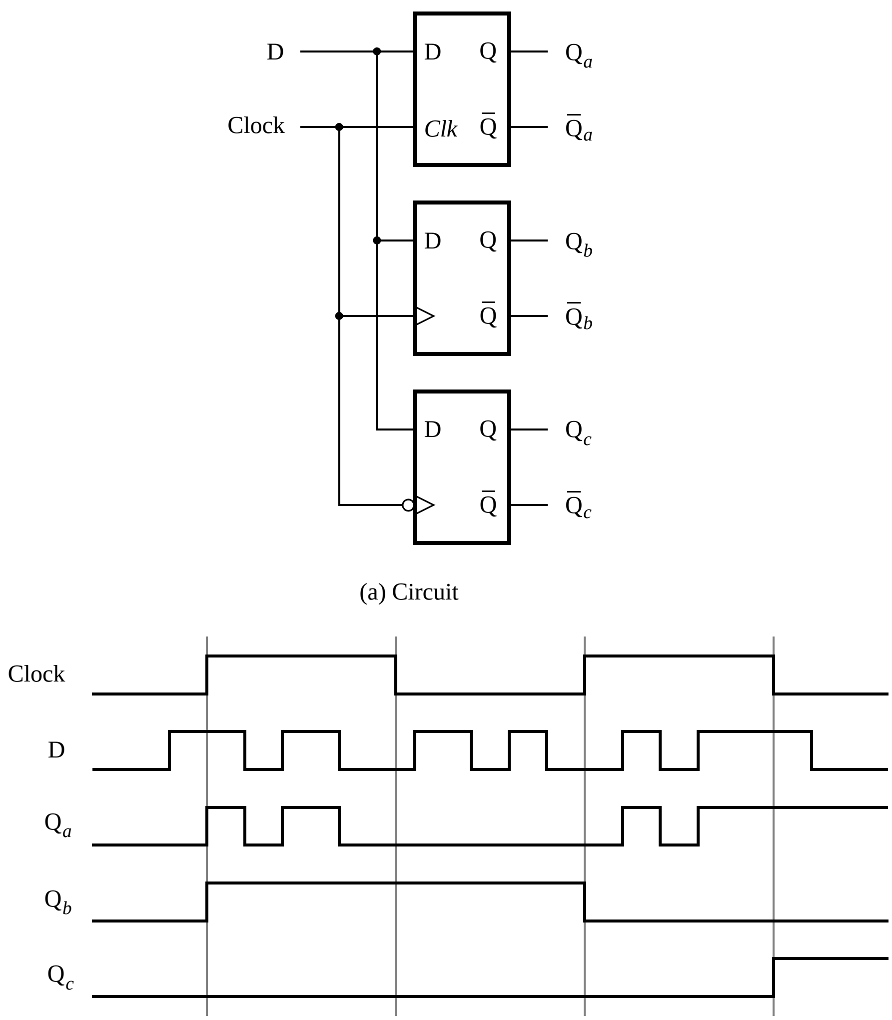
Perform the following:

1. Create a new Quartus II project. Generate a VHDL file that instantiates two copies of your gated D latch entity from Part II to implement the master-slave flip-flop.

2. Include in your project the appropriate input and output ports for the Altera DE1 board. Use switch SW_0 to drive the D input of the flip-flop, and use SW_1 as the *Clock* input. Connect the Q output to $LEDR_0$.
3. Compile your project.
4. Use the Technology Viewer to examine the D flip-flop circuit, and use simulation to verify its correct operation.
5. Download the circuit onto the DE1 board and test its functionality by toggling the D and *Clock* switches and observing the Q output.

Part IV

Figure 6 shows a circuit with three different storage elements: a gated D latch, a positive-edge triggered D flip-flop, and a negative-edge triggered D flip-flop.



(a) Circuit

(b) Timing diagram

Figure 6. Circuit and waveforms for Part IV.

Implement and simulate this circuit using Quartus II software as follows:

1. Create a new project.
2. Write a VHDL file that instantiates the three storage elements. For this part you should no longer use the *keep* directive (that is, the VHDL ATTRIBUTE statement) from Parts I to III. Figure 7 gives a behavioral style of VHDL code that specifies the gated D latch in Figure 4. This latch can be implemented in one 4-input lookup table. Use a similar style of code to specify the flip-flops in Figure 6.
3. Compile your code and use the Technology Viewer to examine the implemented circuit. Verify that the latch uses one lookup table and that the flip-flops are implemented using the flip-flops provided in the target FPGA.
4. In QSim, create a Vector Waveform File (.vwf) which specifies the inputs and outputs of the circuit. Draw the inputs D and *Clock* as indicated in Figure 6. Use functional simulation to obtain the three output signals. Observe the different behavior of the three storage elements.

```
LIBRARY ieee ;
USE ieee.std_logic_1164.all ;

ENTITY latch IS
   PORT ( D, Clk    : IN     STD_LOGIC ;
          Q         : OUT    STD_LOGIC) ;
END latch ;

ARCHITECTURE Behavior OF latch IS
BEGIN
   PROCESS ( D, Clk )
   BEGIN
      IF Clk = '1' THEN
         Q <= D ;
      END IF ;
   END PROCESS ;
END Behavior ;
```

Figure 7. A behavioral style of VHDL code that specifies a gated D latch.

Part V

We wish to display the hexadecimal value of a 8-bit number A on the two 7-segment displays, $HEX3-2$. We also wish to display the hex value of a 8-bit number B on the two 7-segment displays, $HEX1-0$. The values of A and B are inputs to the circuit which are provided by means of switches SW_{7-0}. This is to be done by first setting the switches to the value of A and then setting the switches to the value of B; therefore, the value of A must be stored in the circuit.

1. Create a new Quartus II project which will be used to implement the desired circuit on the Altera DE1 board.
2. Write a VHDL file that provides the necessary functionality. Use KEY_0 as an active-low asynchronous reset, and use KEY_1 as a clock input. Include the VHDL file in your project and compile the circuit.
3. Assign the pins on the FPGA to connect to the switches and 7-segment displays, as indicated in the User Manual for the DE1 board.
4. Recompile the circuit and download it into the FPGA chip.
5. Test the functionality of your design by toggling the switches and observing the output displays.