

# Laboratory Exercise 2

## Numbers and Displays

This is an exercise in designing combinational circuits that can perform binary-to-decimal number conversion and binary-coded-decimal (BCD) addition.

### Part I

We wish to display on the 7-segment displays *HEX3* to *HEX0* the values set by the switches  $SW_{15-0}$ . Let the values denoted by  $SW_{15-12}$ ,  $SW_{11-8}$ ,  $SW_{7-4}$  and  $SW_{3-0}$  be displayed on *HEX3*, *HEX2*, *HEX1* and *HEX0*, respectively. Your circuit should be able to display the digits from 0 to 9, and should treat the valuations 1010 to 1111 as don't-cares.

1. Create a new project which will be used to implement the desired circuit on the Altera DE2 board. The intent of this exercise is to manually derive the logic functions needed for the 7-segment displays. You should use only simple VHDL assignment statements in your code and specify each logic function as a Boolean expression.
2. Write a VHDL file that provides the necessary functionality. Include this file in your project and assign the pins on the FPGA to connect to the switches and 7-segment displays, as indicated in the User Manual for the DE2 board. The procedure for making pin assignments is described in the tutorial *Quartus II Introduction using VHDL Design*, which is available on the *DE2 System CD* and in the University Program section of Altera's web site.
3. Compile the project and download the compiled circuit into the FPGA chip.
4. Test the functionality of your design by toggling the switches and observing the displays.

### Part II

You are to design a circuit that converts a four-bit binary number  $V = v_3v_2v_1v_0$  into its two-digit decimal equivalent  $D = d_1d_0$ . Table 1 shows the required output values. A partial design of this circuit is given in Figure 1. It includes a comparator that checks when the value of  $V$  is greater than 9, and uses the output of this comparator in the control of the 7-segment displays. You are to complete the design of this circuit by creating a VHDL entity which includes the comparator, multiplexers, and circuit *A* (do not include circuit *B* or the 7-segment decoder at this point). Your VHDL entity should have the four-bit input  $V$ , the four-bit output  $M$  and the output  $z$ . The intent of this exercise is to use simple VHDL assignment statements to specify the required logic functions using Boolean expressions. Your VHDL code should not include any IF-ELSE, CASE, or similar statements.

Binary value	Decimal digits	
0000	0	0
0001	0	1
0010	0	2
...	...	...
1001	0	9
1010	1	0
1011	1	1
1100	1	2
1101	1	3
1110	1	4
1111	1	5

Table 1. Binary-to-decimal conversion values.

Perform the following steps:

1. Make a Quartus II project for your VHDL entity.
2. Compile the circuit and use functional simulation to verify the correct operation of your comparator, multiplexers, and circuit A.
3. Augment your VHDL code to include circuit B in Figure 1 as well as the 7-segment decoder. Change the inputs and outputs of your code to use switches  $SW_{3-0}$  on the DE2 board to represent the binary number  $V$ , and the displays  $HEX1$  and  $HEX0$  to show the values of decimal digits  $d_1$  and  $d_0$ . Make sure to include in your project the required pin assignments for the DE2 board.
4. Recompile the project, and then download the circuit into the FPGA chip.
5. Test your circuit by trying all possible values of  $V$  and observing the output displays.

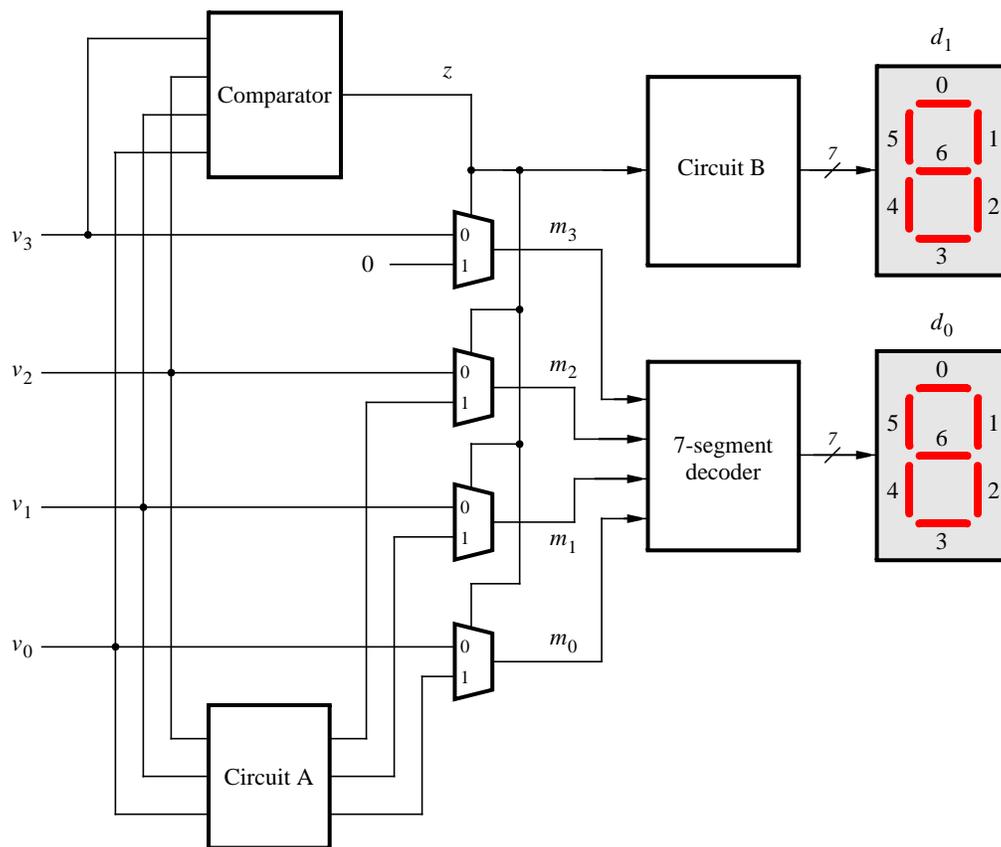


Figure 1. Partial design of the binary-to-decimal conversion circuit.

### Part III

Figure 2a shows a circuit for a *full adder*, which has the inputs  $a$ ,  $b$ , and  $c_i$ , and produces the outputs  $s$  and  $c_o$ . Parts b and c of the figure show a circuit symbol and truth table for the full adder, which produces the two-bit binary sum  $c_o s = a + b + c_i$ . Figure 2d shows how four instances of this full adder entity can be used to design a circuit that adds two four-bit numbers. This type of circuit is usually called a *ripple-carry* adder, because of the way that the carry signals are passed from one full adder to the next. Write VHDL code that implements this circuit, as described below.

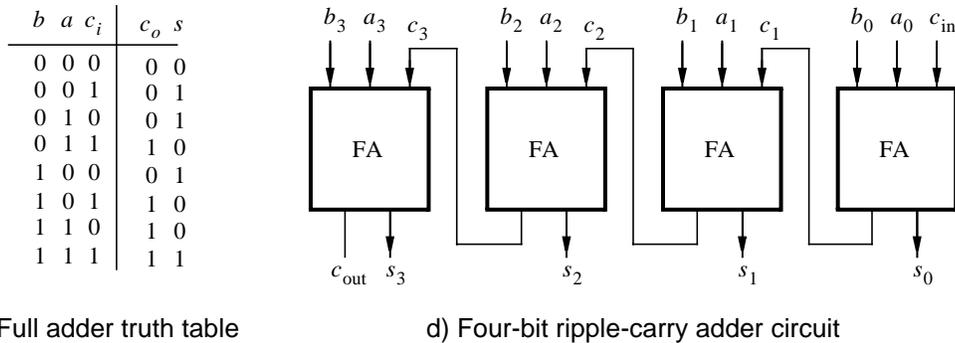
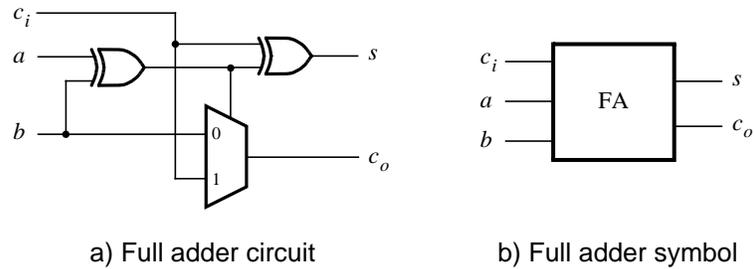


Figure 2. A ripple-carry adder circuit.

1. Create a new Quartus II project for the adder circuit. Write a VHDL entity for the full adder subcircuit and write a top-level VHDL entity that instantiates four instances of this full adder.
2. Use switches  $SW_{7-4}$  and  $SW_{3-0}$  to represent the inputs  $A$  and  $B$ , respectively. Use  $SW_8$  for the carry-in  $c_{in}$  of the adder. Connect the  $SW$  switches to their corresponding red lights LEDR, and connect the outputs of the adder,  $c_{out}$  and  $S$ , to the green lights LEDG.
3. Include the necessary pin assignments for the DE2 board, compile the circuit, and download it into the FPGA chip.
4. Test your circuit by trying different values for numbers  $A$ ,  $B$ , and  $c_{in}$ .

#### Part IV

In part II we discussed the conversion of binary numbers into decimal digits. It is sometimes useful to build circuits that use this method of representing decimal numbers, in which each decimal digit is represented using four bits. This scheme is known as the *binary coded decimal* (BCD) representation. As an example, the decimal value 59 is encoded in BCD form as 0101 1001.

You are to design a circuit that adds two BCD digits. The inputs to the circuit are BCD numbers  $A$  and  $B$ , plus a carry-in,  $c_{in}$ . The output should be a two-digit BCD sum  $S_1S_0$ . Note that the largest sum that needs to be handled by this circuit is  $S_1S_0 = 9 + 9 + 1 = 19$ . Perform the steps given below.

1. Create a new Quartus II project for your BCD adder. You should use the four-bit adder circuit from part III to produce a four-bit sum and carry-out for the operation  $A + B$ . A circuit that converts this five-bit result, which has the maximum value 19, into two BCD digits  $S_1S_0$  can be designed in a very similar way as the binary-to-decimal converter from part II. Write your VHDL code using simple assignment statements to specify the required logic functions—do not use other types of VHDL statements such as IF-ELSE or CASE statements for this part of the exercise.

- Use switches  $SW_{7-4}$  and  $SW_{3-0}$  for the inputs  $A$  and  $B$ , respectively, and use  $SW_8$  for the carry-in. Connect the  $SW$  switches to their corresponding red lights LEDR, and connect the four-bit sum and carry-out produced by the operation  $A + B$  to the green lights LEDG. Display the BCD values of  $A$  and  $B$  on the 7-segment displays  $HEX6$  and  $HEX4$ , and display the result  $S_1S_0$  on  $HEX1$  and  $HEX0$ .
- Since your circuit handles only BCD digits, check for the cases when the input  $A$  or  $B$  is greater than nine. If this occurs, indicate an error by turning on the green light  $LEDG_8$ .
- Include the necessary pin assignments for the DE2 board, compile the circuit, and download it into the FPGA chip.
- Test your circuit by trying different values for numbers  $A$ ,  $B$ , and  $c_{in}$ .

## Part V

Design a circuit that can add two 2-digit BCD numbers,  $A_1A_0$  and  $B_1B_0$  to produce the three-digit BCD sum  $S_2S_1S_0$ . Use two instances of your circuit from part IV to build this two-digit BCD adder. Perform the steps below:

- Use switches  $SW_{15-8}$  and  $SW_{7-0}$  to represent 2-digit BCD numbers  $A_1A_0$  and  $B_1B_0$ , respectively. The value of  $A_1A_0$  should be displayed on the 7-segment displays  $HEX7$  and  $HEX6$ , while  $B_1B_0$  should be on  $HEX5$  and  $HEX4$ . Display the BCD sum,  $S_2S_1S_0$ , on the 7-segment displays  $HEX2$ ,  $HEX1$  and  $HEX0$ .
- Make the necessary pin assignments and compile the circuit.
- Download the circuit into the FPGA chip, and test its operation.

## Part VI

In part V you created VHDL code for a two-digit BCD adder by using two instances of the VHDL code for a one-digit BCD adder from part IV. A different approach for describing the two-digit BCD adder in VHDL code is to specify an algorithm like the one represented by the following pseudo-code:

```

1   $T_0 = A_0 + B_0$ 
2  if ( $T_0 > 9$ ) then
3     $Z_0 = 10$ ;
4     $c_1 = 1$ ;
5  else
6     $Z_0 = 0$ ;
7     $c_1 = 0$ ;
8  end if
9   $S_0 = T_0 - Z_0$ 

10  $T_1 = A_1 + B_1 + c_1$ 
11 if ( $T_1 > 9$ ) then
12    $Z_1 = 10$ ;
13    $c_2 = 1$ ;
14 else
15    $Z_1 = 0$ ;
16    $c_2 = 0$ ;
17 end if
18  $S_1 = T_1 - Z_1$ 
19  $S_2 = c_2$ 

```

It is reasonably straightforward to see what circuit could be used to implement this pseudo-code. Lines 1, 9, 10, and 18 represent adders, lines 2-8 and 11-17 correspond to multiplexers, and testing for the conditions  $T_0 > 9$  and  $T_1 > 9$  requires comparators. You are to write VHDL code that corresponds to this pseudo-code. Note that you can perform addition operations in your VHDL code instead of the subtractions shown in lines 9 and 18. The intent of this part of the exercise is to examine the effects of relying more on the VHDL compiler to design the circuit by using IF-ELSE statements along with the VHDL  $>$  and  $+$  operators. Perform the following steps:

1. Create a new Quartus II project for your VHDL code. Use the same switches, lights, and displays as in part V. Compile your circuit.
2. Use the Quartus II RTL Viewer tool to examine the circuit produced by compiling your VHDL code. Compare the circuit to the one you designed in Part V.
3. Download your circuit onto the DE2 board and test it by trying different values for numbers  $A_1A_0$  and  $B_1B_0$ .

## **Part VII**

Design a combinational circuit that converts a 6-bit binary number into a 2-digit decimal number represented in the BCD form. Use switches  $SW_{5-0}$  to input the binary number and 7-segment displays *HEX1* and *HEX0* to display the decimal number. Implement your circuit on the DE2 board and demonstrate its functionality.

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