

**LAB 3****Arithmetic Logic Unit****1. Purpose:**

In this lab students will design, simulate, build and test an Arithmetic Logic Unit (ALU), employing Quartus II as a development environment and the Altera DE2-115 board as experimental platform. ALU has to execute 16 different operations on two operands of 4 bits, and will provide a 4-bit result along with 4 status bits (Overflow, Sign, Zero, Carry). The input operands will be generated by slide switches, while the result and the status bits will be displayed on LEDs.

**2. Requirements of the Lab:**

The following will be submitted in your report.

- \* Functional and truth tables, equations and schematics of your design
- \* Log of what you did
- \* Screen shots of all schematics and waveform diagrams
- \* Compilation, simulation and downloading messages (if any)
- \* Test results

**3. Equipment and Supplies:**

- \* Quartus II (student edition or web edition)
- \* Altera DE2-115 board with
  - USB-Blaster cable - Power supply 12 VDC, 2A

**4. References:**

- 4.1. Chapter1 - 4 of the Text book: *Computer System Architecture*, Morris Mano, 3rd Ed.
- 4.2. Course notes *DE2-115 User Manual* posted in the *Documentation* section under the *Laboratories* tab of CEG2136 *Virtual Campus*.

**5. PreLab – Design of the ALU****5.1. ALU structure**

The Central Processing Unit (CPU) consists of a Control Unit (CU) and a Datapath (execution unit – EU) shown in the block diagram of Figure 1. The CPU's datapath contains registers to store data (A, B, C) and control (S) / status (V,Z,N,Cy) information, along an Arithmetic and Logic Unit (ALU). You have to design CPU's datapath that can perform arithmetic, shift and logic operations. Your datapath module will handle two types of signals:

- Data (inputs: A3-A0 and B3-B0, and outputs C3-C0) – marked in yellow
- Control/status: S3-S0/(V, Z, N, Cy) – marked in light blue in Fig. 1

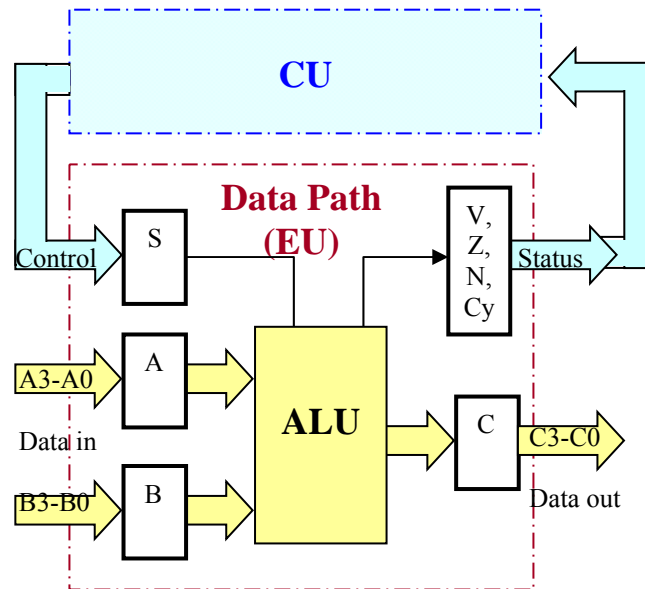


Figure 1: ALU block diagram

Figure 2 presents the ALU datapath. For testing purposes, since CU (the light-blue block in Figure 2) is not designed and built in this lab, CU is replaced and emulated by 4 DIP switches for generating the ALU control inputs (S3 - S0) and 4 LEDs to display the ALU's state indicators (V,Z,S,O). Operands A and B are generated manually by 8 DIP switches, while the result C is displayed by other 4 LEDs.

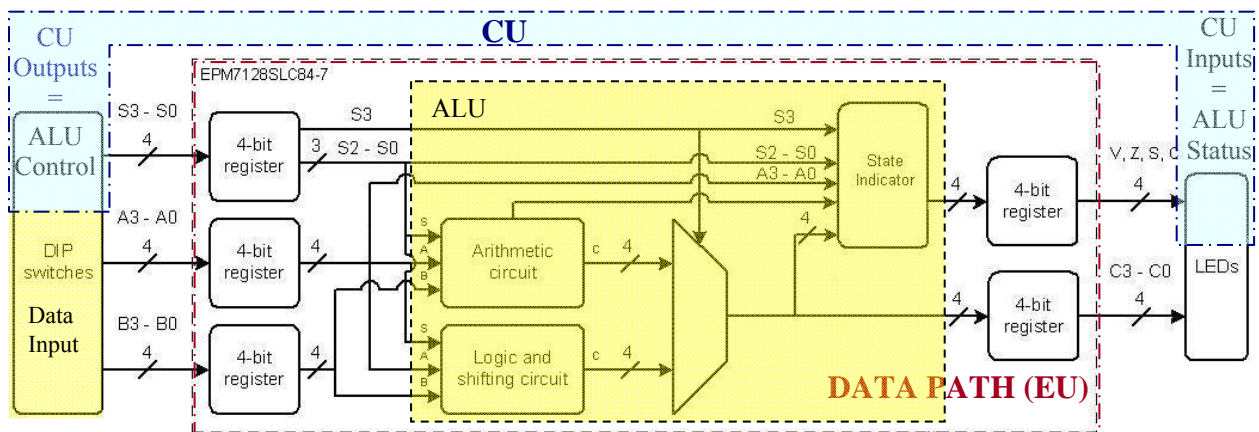


Figure 2: ALU datapath

ALU is a combinational circuit which can execute any of the 16 micro-operations of Table 1. The operation to be performed is set by the *control word* S3-S0 as follows:

- the control signal S3 selects either the Arithmetic Circuit (AC) or the Logic and Shifting Circuit (LSC) to perform the operation and send the result to the output C;
- the control signals S2, S1, and S0 define the operations to be performed by each circuit (AC or LSC).

Both inputs and outputs are stored in buffer registers (D flip-flops synchronized with the same clock), A, B, and C, as shown in Figure 2. To operate at the highest speed, the ALU datapath should be provided with both operands (A and B) and control bits (S3-S0) at every consecutive clock. To insure a correct operation of the datapath, the total delay

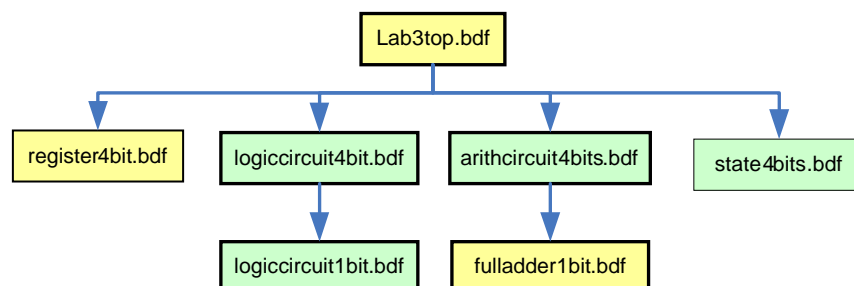
introduced by the ALU's circuits should be smaller than the clock's period and, as such, the datapath can execute a micro-operation at every clock. The results (C3-C0) and V, Z, S, Cy are provided on the next pulse following the change of A, B and S.

**Table 1: arithmetic and logic micro-operations**

Circuit	Control Word S3 S2 S1 S0	ALU Data Output	Micro-operation Description
Arithmetic circuit (AC)	0 0 0 0	$C \leftarrow A + B$	Addition
	0 0 0 1	$C \leftarrow A + B + 1$	Add with carry
	0 0 1 0	$C \leftarrow A$	Transfer A
	0 0 1 1	$C \leftarrow A + 1$	Increment A
	0 1 0 0	$C \leftarrow A + \bar{B}$	Subtraction A - B with borrow (using 1's complement of B gives a result lower by 1 than a conventional subtraction).
	0 1 0 1	$C \leftarrow A + \bar{B} + 1$	Subtraction A - B (use 2's complement of B)
	0 1 1 0	$C \leftarrow \bar{A}$	NOT A (complement A)
	0 1 1 1	$C \leftarrow \bar{A} + 1$	2's complement of A
Logic and shift circuit (LSC)	1 0 0 0	$C \leftarrow "0000"$	Reset C
	1 0 0 1	$C \leftarrow "1111"$	Set C
	1 0 1 0	$C \leftarrow A \wedge B$	A AND B
	1 0 1 1	$C \leftarrow A \vee B$	A OR B
	1 1 0 0	$C \leftarrow A \oplus B$	A EXCLUSIVE-OR B
	1 1 0 1	$C \leftarrow A \wedge \bar{B}$	Reset A bits selected by "mask" B
	1 1 1 0	$C \leftarrow ashl A$	Shift A left (signed multiplication by 2)
	1 1 1 1	$C \leftarrow ashr A$	Shift A right (signed division by 2)

## 5.2. Hierarchical design

Since both the input and the output signals of ALU have 4 bits, the most effective way to implement ALU is to devise it in a hierarchical manner. Files on the lowest level are 1-bit full adder and 1-bit logic and shift circuit (LSC). The intermediate files will consist of a 4-bit register, a 4-bit arithmetic circuit (AC), a 4-bit logic and shift circuit (LSC), and a state circuit. Finally, the file at the highest level will cover the complete circuit, loadable to the UP2 board. The relation between these files is shown in figure 3. The parts in yellow will be explained further in this document. For the preparation of this lab, you are required to design and test the circuits coloured in green, i.e., the 1-bit LSC, the 4-bit LSC, the 4-bit AC, and the state circuit.



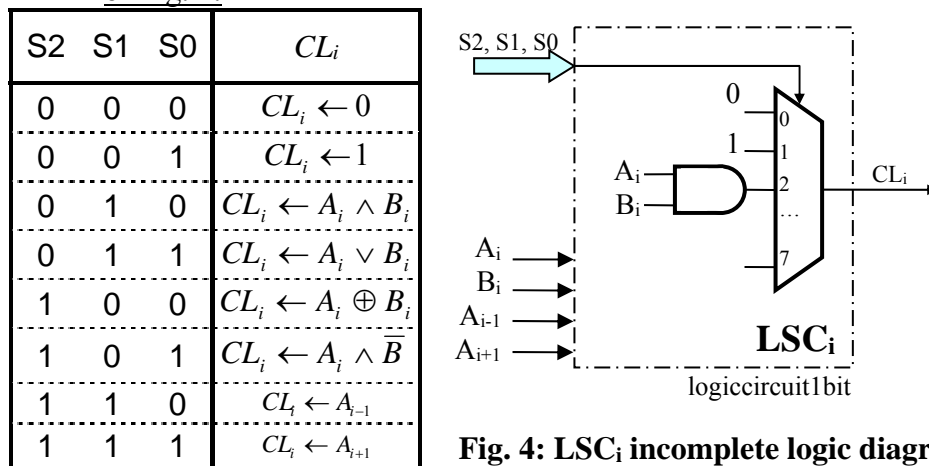
**Figure 3: Hierarchy of the files**

### 5.3. Design of Logic and Shift Circuit (LSC)

LSC operates at the bit level, which means that, e.g.  $C = A \text{ AND } B$  is interpreted as  $\{C_3, C_2, C_1, C_0\} = \{A_3 \text{ AND } B_3, A_2 \text{ AND } B_2, A_1 \text{ AND } B_1, A_0 \text{ AND } B_0\}$ .

Design a circuit which implements all logic and shift functions as shown in the bottom half of Table 1 (with  $S_3=1$ ). LSC is built from four **1-bit Logic and Shift Circuit (LSC)**. Such a 1-bit module has 3 control inputs ( $S_2, S_1$ , and  $S_0$ ), two logic inputs ( $A_i$  and  $B_i$ ), two additional inputs for left and right shifts ( $A_{i-1}$  and  $A_{i+1}$ ), and an output ( $CL_i$ ) whose truth table is detailed below. A starting point for the logic diagram of **1-bit LSC** is suggested below;

5.3.1. Add all the logic gates that are required to complete the  $LSC_i$  logic diagram of Fig. 4.



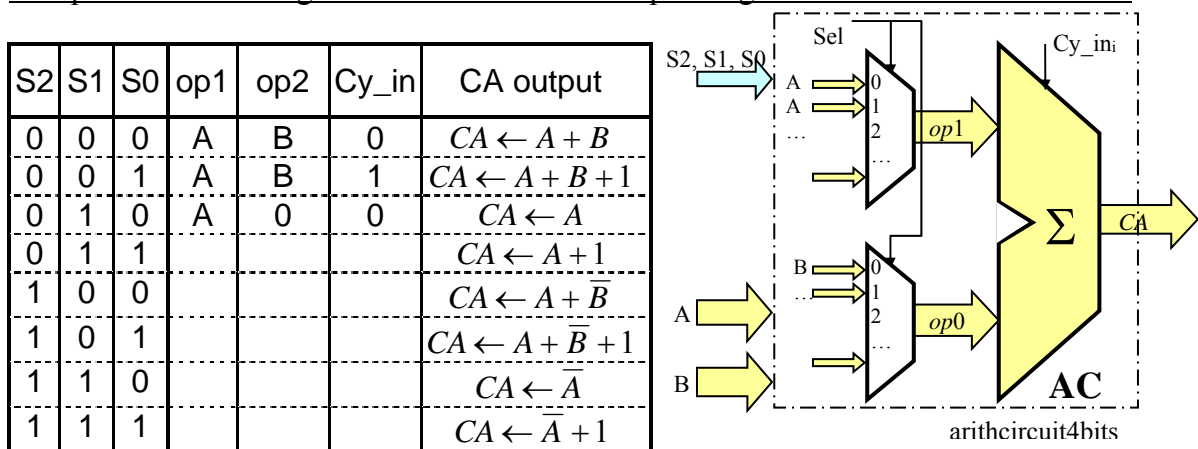
**Fig. 4:  $LSC_i$  incomplete logic diagram**

5.3.2. Use the 1-bit LSC module that you designed above to build a 4-bit logic and shift circuit LSC. Your final design should have 3 control inputs ( $S_2 - S_0$ ), 8 data inputs ( $A_3 - A_0$  and  $B_3 - B_0$ ), and 4 data outputs ( $CL_3 - CL_0$ ). Your design will be captured in the *logiccircuit4bit* file.

### 5.4. Design of Arithmetic Circuit (AC)

5.4.1. The block diagram of the Arithmetic Circuit (AC) is shown in Fig. 5. AC consists of a **4-bit full adder ( $\Sigma$ )** which calculates the output CA as a function of operands  $op1$  and  $op0$ , and of the micro-operation select bits  $S_2, S_1$  and  $S_0$ , as described in Table 1.

Complete the following truth table with the corresponding values derived from Table 1.



**Fig. 5: AC block diagram**

5.4.2. Note that the data inputs A3 - A0 and B3 - B0 should not be connected directly to the inputs of multiplexers for op1 and op2, since you might need some minimal logic to insure full compliance with the truth table. A trivial solution is to implement op1 and op0 with 8-to-1 multiplexers. Start your design by analyzing what inputs are to be brought to op1 and op0 for each combination of S2 and S1, only.

Derive a cost effective solution from this analysis using a 4-to-1 multiplexer.

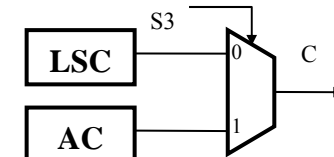
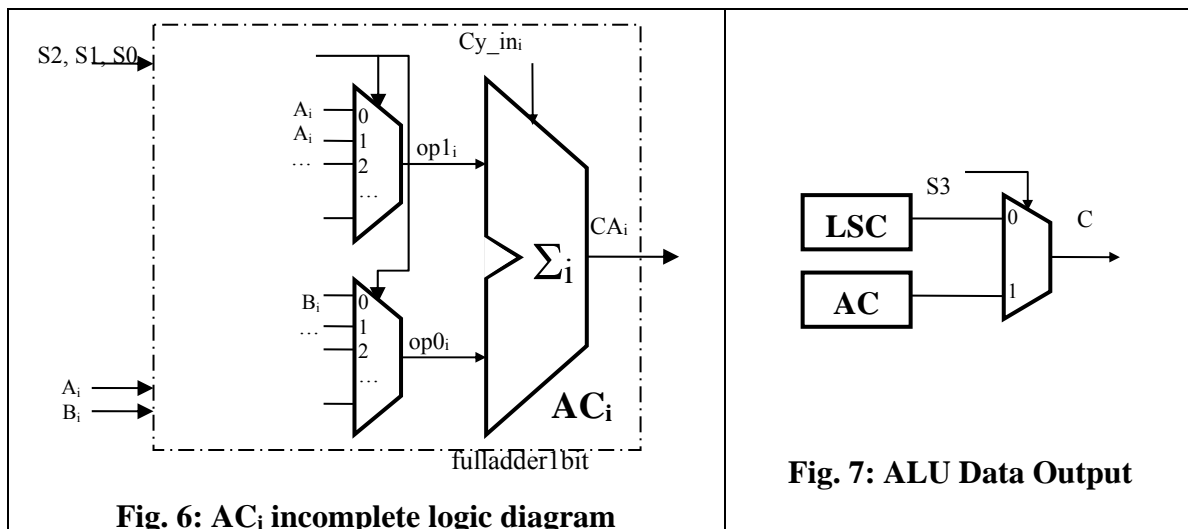
5.4.3. Derive the equation of  $Cy_i$  in terms of the select bits S2, S1 and S0.

5.4.4. Complete the block diagram of  $AC_i$  of Fig. 6 with logic components that implement the conclusions you drew above (5.4.1 - 5.4.2):

- replace the multiplexor symbols with the ones resulted at 5.4.2;
- add more wires and other logic components between module's inputs ( $A_i$ ,  $B_i$ , S2, S1 and S0) and multiplexers' inputs to implement the AC table;
- implement  $Cy$  equation.

This  $AC_i$  schematic will be later captured in the *fulladder1bit.bdf* file in Quartus II.

Note:  $\Sigma_i$  is based on the *full adder* shown in Figure 7.



The ALU Data Output is provided by AC or LSC as dictated by the control signal S3. The block diagram of Fig. 7 employs 2-to-1 multiplexers to select AC or LSC to be loaded into register C.

Your final circuit of the ALU data flow should have 3 control inputs (S2 - S0), 8 data inputs (A3 - A0 and B3 - B0), 4 data outputs (C3 - C0) and the most significant carry bits, which will be used for the status circuit.

### 5.5. ALU status register

The ALU results are characterized by four status bits (C, S, Z, and V), which are defined as follows:

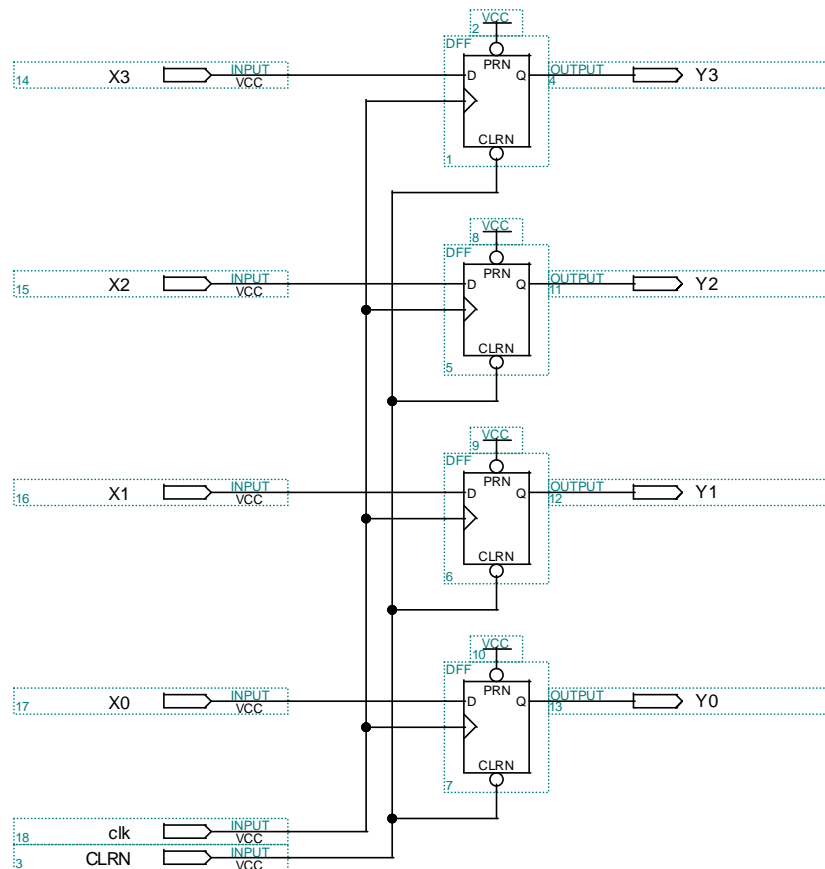
- Bit Cy (carry) is set to 1 only when the operation is an arithmetic operation and its carry output is 1. It is cleared to 0 if the carry is 0.
- Bit S (sign) is set to 1 if the most significant bit of the result C3 is one..
- Bit Z (zero) is set to 1 only if the output of the ALU contains all 0's. It is set to 0 otherwise.
- Bit V (overflow) is set to 1 only when an overflow occurs when performing operations on signed numbers in 2's complement representation (exclusive-OR of the 2 most significant carries).

Derive the logic equations of the status bits and implement them with conventional gates.

## 6. Procedure

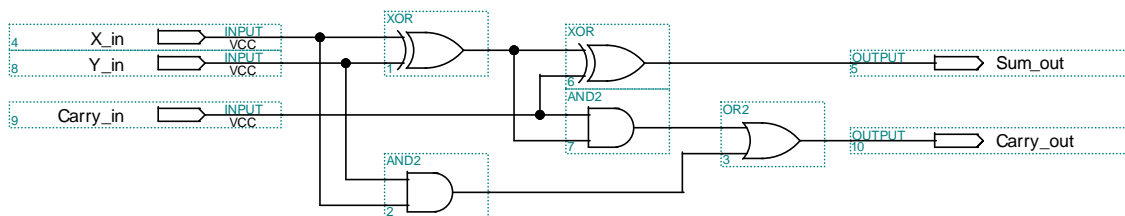
### PART I – Design

- 6.1.** Use Quartus II to capture the following graphic file, which implements a 4-bit register. Use D-type flip-flops (symbol “dff”). Save your file under the name “register4bits.bdf” (using standard names will help your TAs to check your circuit if needed).



**Figure 8: Diagram of a 4-bit register**

- 6.2. Choose **Set as Top Level Entity** (assign the open file to the project), select **EP4CE115F29C7** and make sure you compile your file without errors (you do not need to assign pines at this stage).  
Go to the section **Fitter Summary** to check the percentage of the resources of the chip that are used by the file “*register4bits.fit.rpt*”. Create a symbol for the register which could be used later on.
- 6.3. Use the graphic editor of Quartus to draw the circuit diagram of your 1-bit *Logic and Shift Circuit (LSC)* into a schematic file and save it as “*logiccircuit1bit.bdf*”.  
To enter the symbol of multiplexer 74151 make a right-click, select **Insert >> Symbol**, and type “74151” in the dialogue window **Name**. **If you have decided to use the multiplexer lpm\_mux (to obtain bonus points), the block symbol can be created by launching the MegaWizard Plug-In Manager under the Symbol window. Select “Create a new custom megafunction variation”, specify the output files name and proceed to the on-screen instructions.** If the multiplexer does not appear in the form that you prefer, you can make a right click, and you can reverse it horizontally or vertically. Assign the file open to the project, compile the file, and create a symbol.
- 6.4. Capture your 4-bit logic and shift circuit LSC to a file which you will call “*logiccircuit4bits.bdf*”. Assign the open file to the project, compile it, and create a symbol. Which percentage of the resources of the chip do you use for this file?
- 6.5. Capture the full adder of Figure 9 in a file called “*fulladder1bit.bdf*.” Add the other logic components that are needed to implement the logic circuit ACi that you developed from Fig. 6. Repeat the necessary steps to create the corresponding symbol.



**Figure 9: Logic diagram of a full adder** (marked  $\Sigma$  in Fig. 6)

- 6.6. Use the graphic editor of Quartus to draw the circuit diagram of your **4-bit full adder (AC)** into a schematic file and save it as “*arithcircuit4bits.bdf*”. Repeat the necessary steps to create the corresponding symbol. What percentage of the resources of the chip you use for this file? Is the *arithmetic circuit* more complex than the logic and shift circuit?
- 6.7. Enter the ALU status circuit (called “State Indicator” in the diagram of Fig. 2) in a graphic file named “*state4bits.bdf*”. Repeat the necessary steps to create its symbol.
- 6.8. Combine your registers (A, B, C), arithmetic circuit (AC), logic and shift circuit (LSC) and the status indicator in a top-level graphic file (named *Lab3top.bdf* in Fig. 3.) to synthesize the ALU datapath as presented in Fig.2. (The top level diagram of a different ALU is presented as an example in Figure 10 - annexed at the end of this document).
- 6.9. Assign the current file to the project. Assign pine 83 to the clock, and pine 1 to

CLRN, but leave all the other signals without assignments. Compile the file: the engine of routing and placement will assign all the other pins for you.

### PART II - Simulation


6.10. Create a file of test vectors (.vwf) to verify your ALU datapath as follows:

- Choose **Edit >> Grid Size...** and enter 50ns. Note that your circuit should function in a satisfactory way with a size of grid of 20ns and a period of clock of 40ns, provided that you devised it correctly; even the most ineffective circuits should have enough time between each clock pulse!
- Choose **Edit >> End Time...** and enter 2.0us.
- Choose **Edit >> Insert Node or Bus ...** in order to import all the inputs and all the outputs in .vwf.
- Set up the clock signals and CLRN; note that CLRN (reset signal for the D flip flops of the 4-bit register) is active low, such that the registers are asynchronously forced to 0 until CLRN is deactivated by bringing it to high).
- The sequence of micro-operations that you have to use in order to test the correctness of your circuit is given in Table 5. Fill in the empty columns of the Table 5 with the appropriate values of the control signals (S3, S2, S1, S0) and the 2 operands (A and B) that are needed to perform the corresponding RTL micro-operations. Evaluate the result (C) and the ALU state indicators (V,Z,N,Cy) the execution of each micro-operation, and fill out corresponding cells accordingly. Convert these values to hexadecimal (S<sub>16</sub>, A<sub>16</sub>, B<sub>16</sub>, C<sub>16</sub>, St<sub>16</sub>) to simplify comparing with the simulations' results.

**Table 5: Sequence of micro-operations to simulate**

Clock Cycle	RTL Micro-operations	S3	S2	S1	S0	A←op1	B←op2	C	V,Z,N,Cy	S <sub>16</sub>	A <sub>16</sub>	B <sub>16</sub>	C <sub>16</sub>	St <sub>16</sub>
1	$A \leftarrow "1010", B \leftarrow "0011", C \leftarrow A \wedge \bar{B}$													
2	$A \leftarrow "0110", C \leftarrow \text{ashl } A$													
3	$A \leftarrow "0011", B \leftarrow "0101", C \leftarrow A + B$													
4	$A \leftarrow "1100", C \leftarrow A + 1$													
5	$A \leftarrow "0011", B \leftarrow "0101", C \leftarrow A \oplus B$													
6	$A \leftarrow "1010", C \leftarrow \bar{A}$													
7	$C \leftarrow "0000"$													
8	$A \leftarrow "0101", B \leftarrow "0011", C \leftarrow A + \bar{B} + 1$													
9	$A \leftarrow "1110", C \leftarrow A$													
10	$A \leftarrow "0110", C \leftarrow \bar{A} + 1$													
11	$A \leftarrow "0101", B \leftarrow "0011", C \leftarrow A \wedge B$													
12	$A \leftarrow "0001", B \leftarrow "0010", C \leftarrow A + B + 1$													
13	$A \leftarrow "1101", C \leftarrow \text{ashr } A$													
14	$A \leftarrow "0110", B \leftarrow "0101", C \leftarrow A + \bar{B}$													
15	$C \leftarrow "1111"$													
16	$A \leftarrow "1100", B \leftarrow "1010", C \leftarrow A \vee B$													



Set up the ALU control (S) and data (A and B) input signals of the .vwf file in accord with the values you just put in Table 5. It is strongly recommended to group your signals to simplify the data entry and reading. To group A3 - A0, assuming that A3 is the MSB and A0 is the LSB, please make sure that A3 is on the upper part of your time diagrams while A2, A1 and A0 should follow below it. To group A3-A0, first select A3, then press on the shift key and click on A0. Then, made a right click and choose **Group...**, give a name to this group, choose the format of posting into binary, and select **OK**. To enter a value for the group, use the mouse to select a signal on the beach of time wanted, and then click on the icon  on the right of the screen. A window will open and ask for a new value.

6.11. Start simulation, and compare the outputs of your simulated ALU with the calculated values of C and St in your Table 5. **Note that there is a time delay at the ALU output which is caused by the input/output registers!** If some elements of your circuit do not function correctly, it is imperative to correct them at this stage. Finally make a capture of the simulation screen for your lab report.

6.12. Use **Assignments >> Pins...** to assign the rest of the pins as indicated in Table 6.

**Table 6: Pin Assignments for the final circuit**

Signal	Pin Location	Component
S3	PIN_Y23	SW17
S2	PIN_Y24	SW16
S1	PIN_AA22	SW15
S0	PIN_AA23	SW14
A3	PIN_AD27	SW3
A2	PIN_AC27	SW2
A1	PIN_AC28	SW1
A0	PIN_AB28	SW0
B3	PIN_AB26	SW7
B2	PIN_AD26	SW6
B1	PIN_AC26	SW5
B0	PIN_AB27	SW4
C3	PIN_F21	LEDR3
C2	PIN_E19	LEDR2

C1	PIN_F19	LEDR1
C0	PIN_G19	LEDR0
V	PIN_E24	LEDG3
Z	PIN_E25	LEDG2
S	PIN_E22	LEDG1
Cy	PIN_E21	LEDG0
CLK	PIN_Y2	50 MHz oscillator
CLRN	PIN_AA24	SW13

### **PART III - Testing Experiment**

6.13. Connect the ALU input pins (S, A, B) to slide switches, and its output pins (C, St) to LEDs. Program EP4CE115F29C7 and verify that your ALU functions correctly for each row of Table 5. Use your simulation and the calculated values of C and St to check the outputs displayed on LEDs.

NOTE: Make sure the RUN/PROG switch (SW19; leftmost toggle switch) is set to RUN.

### **Submission of the report**

The following parts must be included in your report:

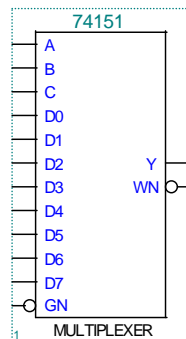
1. Diagrams of your circuits along with the truth tables and the equations that you derived;
2. A short discussion on how you designed your circuit; and
3. An image of your file of simulation (.vwf). You can break it in several images if it is necessary.

The TA must check that your circuit functions both in simulation **AND** on the DE2-115 board **before** you leave the laboratory.

## APPENDICES

In the following are given the functional descriptions of some of the multiplexers you may want to use to implement your ALU circuit.

The symbol and truth table of an **8-to-1 multiplexer (74151)** are given below. Note how in the table, A, B, and C are the lines of selection of the multiplexer, and thus do not correspond to A, B, and C of our ALU!

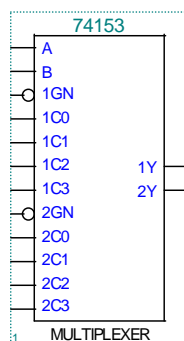


**Figure 3: Symbol of multiplexer 74151**

Inputs				Output
Selection			Enable	
C	B	A	GN	Y
X	X	X	1	0
0	0	0	0	D0
0	0	1	0	D1
0	1	0	0	D2
0	1	1	0	D3
1	0	0	0	D4
1	0	1	0	D5
1	1	0	0	D6
1	1	1	0	D7

**Table 2: Truth table of multiplexer 74151**

The symbol and the truth table of **dual multiplexer 4-to-1 74153** are shown below. Note that the two multiplexers share the same lines of selection A and B (it is an unfortunate coincidence, as these A and B do not have any relationship with the ALU inputs which carry the same name!)

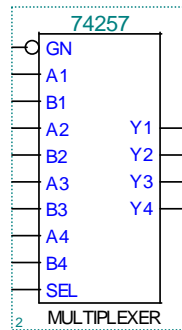


**Figure 4: Symbol of the dual multiplexer 74153**

Inputs			Output
Selection		Enable	
B	A	GN	Y
X	X	1	0
0	0	0	C0
0	1	0	C1
1	0	0	C2
1	1	0	C3

**Table 3: Truth table of the dual multiplexer 74153**

The truth table and the symbol of the **quadruple multiplexer 2-to-1 74257** are given below:



Inputs		Output
Selectio n	Enabl e	
A	GN	Y
X	1	Z (high impedance)
0	0	A
1	0	B

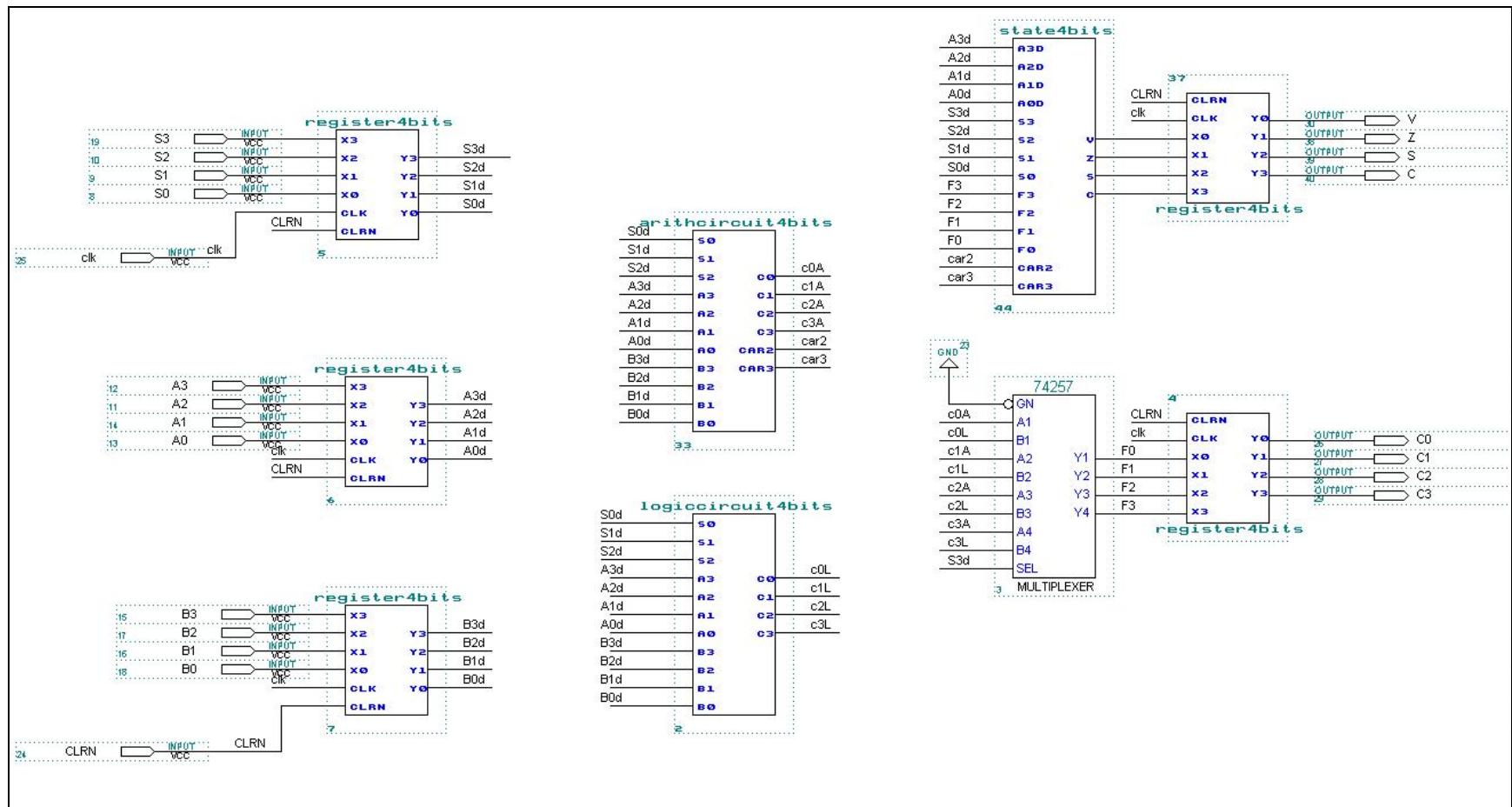
**Figure 5: Symbol of the quadruple multiplexer 74257**

**Table 4: Truth table of the quadruple multiplexer 74257**

**Note** that the use of multiplexers 74151, 74153 and 74257 is not compulsory. In fact, you can get **5% bonus** if you use the component *lpm-mux* instead of these multiplexers. Figure 12 gives an example of this multiplexer.

## EXAMPLES

The following appendices present samples from related previous designs of other ALU's.



Annexed Figure 10: Diagram of complete ALU

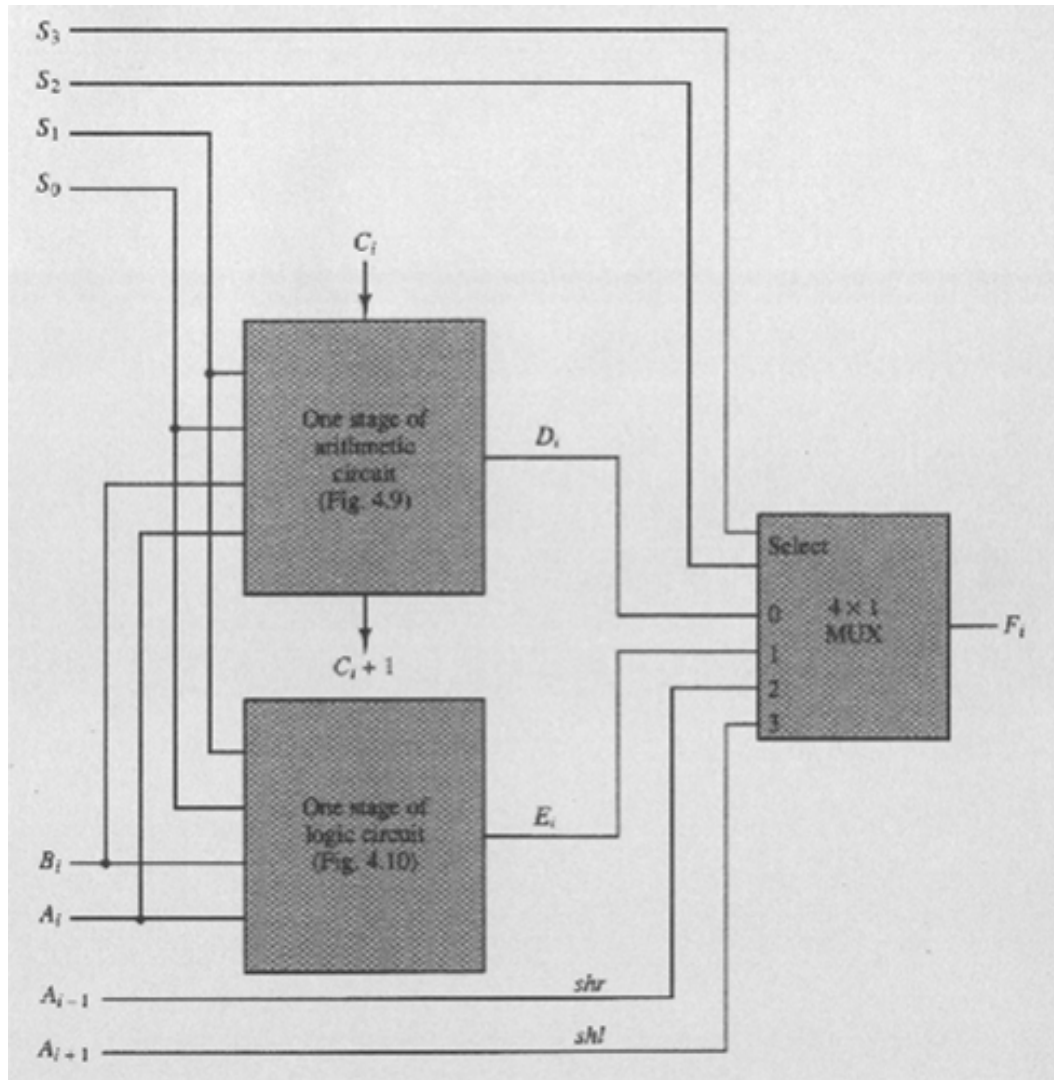


Figure 11: Arithmetic logic unit

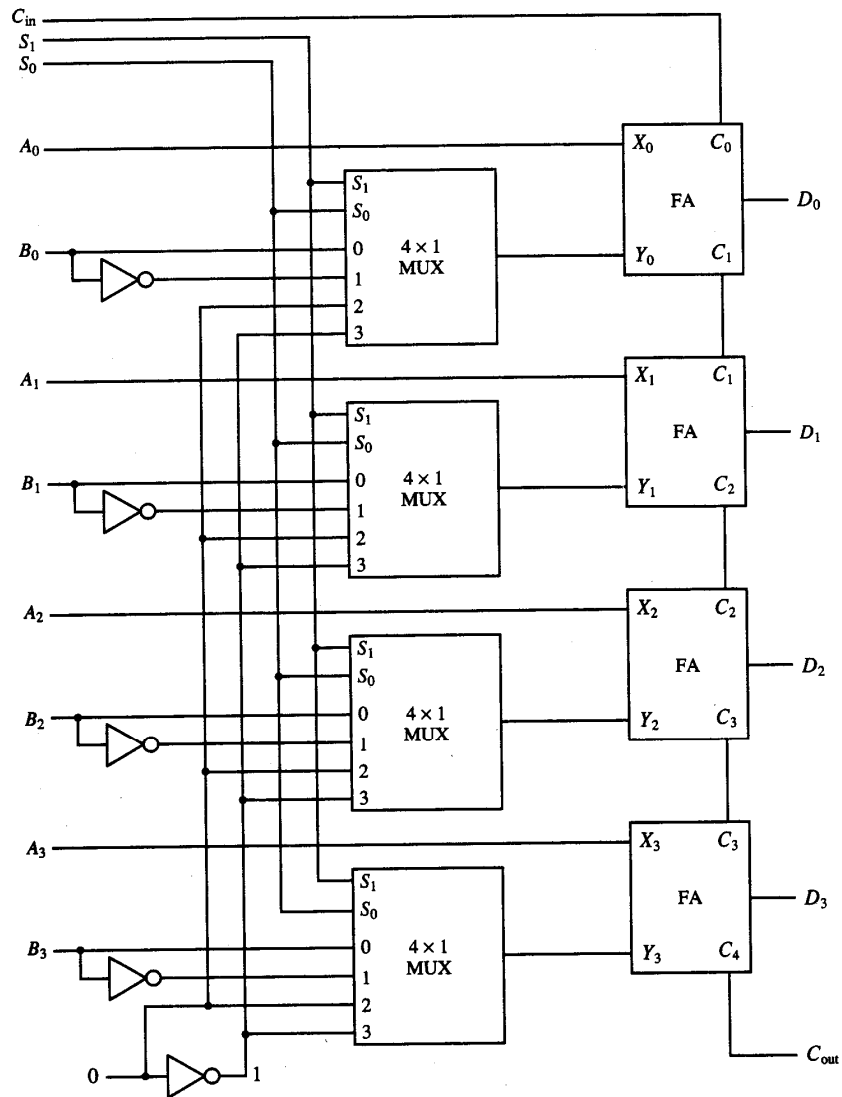


Figure 12: Arithmetic circuit of 4-bit

Table 7: Shift and function table of an arithmetic logic unit

Operation select					Operation	Function
$S_3$	$S_2$	$S_1$	$S_0$	$C_{in}$		
0	0	0	0	0	$F = A$	Transfer $A$
0	0	0	0	1	$F = A + 1$	Increment $A$
0	0	0	1	0	$F = A + B$	Addition
0	0	0	1	1	$F = A + \overline{B} + 1$	Add with carry
0	0	1	0	0	$F = A + \overline{B}$	Subtract with borrow
0	0	1	0	1	$F = A + \overline{B} + 1$	Subtraction
0	0	1	1	0	$F = A - 1$	Decrement $A$
0	0	1	1	1	$F = A$	Transfer $A$
0	1	0	0	$\times$	$F = A \wedge B$	AND
0	1	0	1	$\times$	$F = A \vee B$	OR
0	1	1	0	$\times$	$F = A \oplus B$	XOR
0	1	1	1	$\times$	$F = \overline{A}$	Complement $A$
1	0	$\times$	$\times$	$\times$	$F = \text{shr } A$	Shift right $A$ into $F$
1	1	$\times$	$\times$	$\times$	$F = \text{shl } A$	Shift left $A$ into $F$

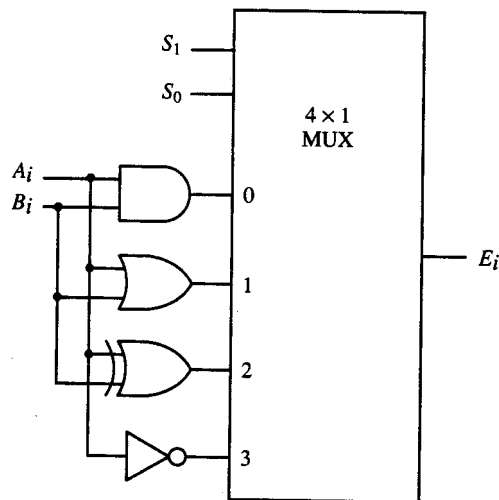


Figure 13: Logic unit



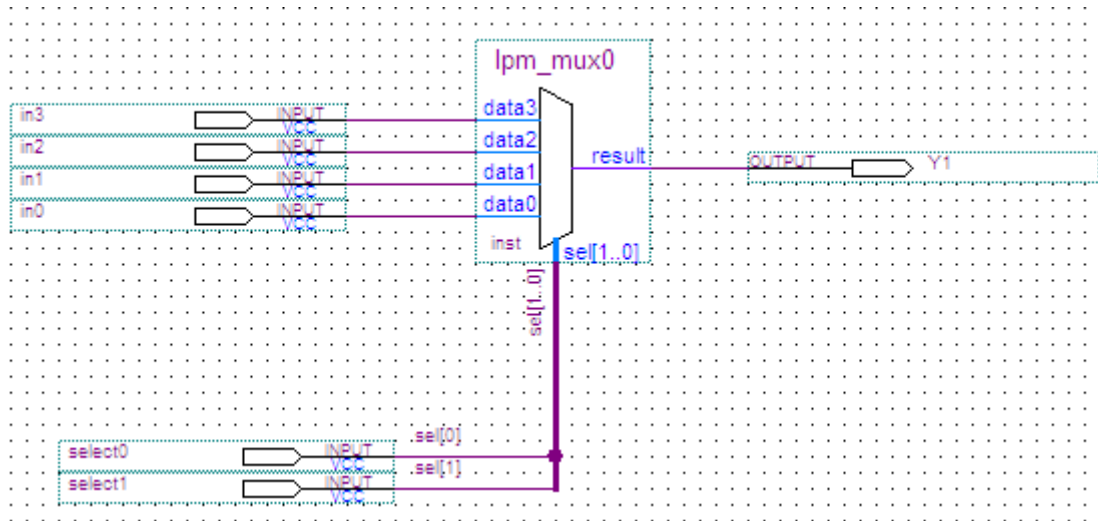


Figure 14: Example of a multiplexer lpm-mux