
CMPE-630 Digital IC Design
Laboratory Exercise 7
Autolayout Design Techniques (HDL-Layout)

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Performed: 6 Nov 2019
Submitted: 13 Nov 2019

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By submitting this report, you attest that you neither have given nor have received any assistance (including writing, collecting data, plotting figures, tables or graphs, or using previous student reports as a reference), and you further acknowledge that giving or receiving such assistance will result in a failing grade for this course.

Your Signature: _____

1 Abstract

2 Design Methodology and Theory

The world of IC design is a very large and complex one. Engineering time is a critical factor when trying to create designs. An engineer tries to minimize power and cost, while maximizing performance. Modern ICs are very complex and manual engineer effort is not feasible. Fortunately, auto layout tools exist so that non-critical parts can be generated quickly. In this exercise, a single bit ALU and a 16-bit ALU were designed, automatically laid out and then power and timing results were extracted.

For all components designed in this exercise, VHDL was written to describe the functionality of the component. Leonardo Spectrum was used to turn the VHDL into synthesizable logic. The VHDL was then functionally tested with a test bench using Questa Sim. Next, a schematic for each ALU was generated with Pyxis.

2.1 Functional Simulation

The ALUs in this exercise had a simple 2 bit op-code which can be seen in Table 1.

Table 1: ALU Operations

OpCode	Operation	Operands
00	AND	A AND B
01	OR	A OR B
10	ADD	A + B
11	SUB	A - B

2.1.1 1 Bit ALU

The 1 Bit ALU designed in this exercise was created from behavioral VHDL (see Listing 10). A Questa Sim simulation was performed to test the functionality of the 1 bit ALU. The test bench can be seen in Listing 9. The test bench went through every op-code and every input. The resulting waveforms can be seen in Figure 1.

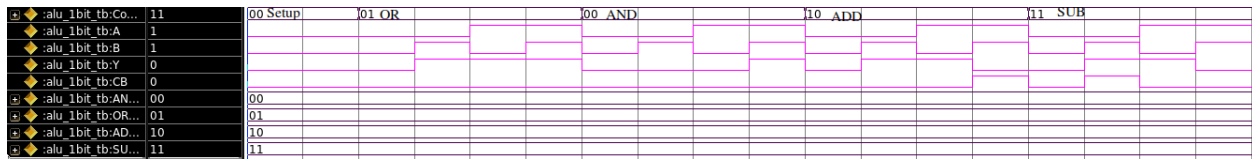


Figure 1: Functional Simulation of 1-bit ALU

The 1 Bit ALU functioned properly.

2.1.2 16 Bit ALU

The 16-bit ALU was created structurally with generically large structures. The VHDL that describes the ALU can be seen in Listing 12. While the 1-bit ALU could have a full test bench that tested every input, the 16-bit ALU was far too large to do the same. Instead, a few test cases were selected to test each function of the ALU. Each component in the ALU was previously tested, so

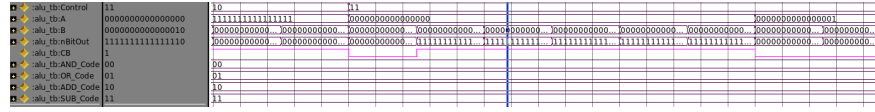


Figure 7: Functional Simulation of 16-bit ALU: Subtraction with negative result

Subtraction with the 16-bit ALU was correct, thus rounding out the functional testing of the design. Next, a schematic could be created.

2.2 Schematic

Schematics were generated by Pyxis Schematic Editor. The tool generated a nearly complete schematic(s), but the component layout needed adjustment as some inverters were overlapping.

2.2.1 1-Bit ALU

The 1-bit ALU schematic spanned one page and can be seen in Figure 8.

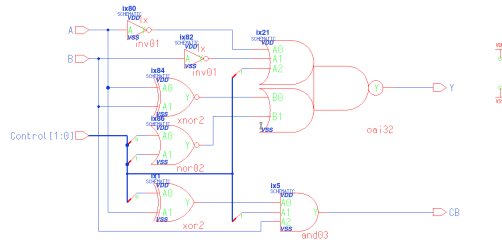


Figure 8: 1 Bit ALU Schematic

The 1-bit ALU is rather simple.

2.2.2 n-Bit ALU

Pyxis created 3 schematic sheets to satisfy the 16-bit ALU. This likely due to the structural nature of the ALU. The schematic can be seen in Figure 9 through Figure 11.

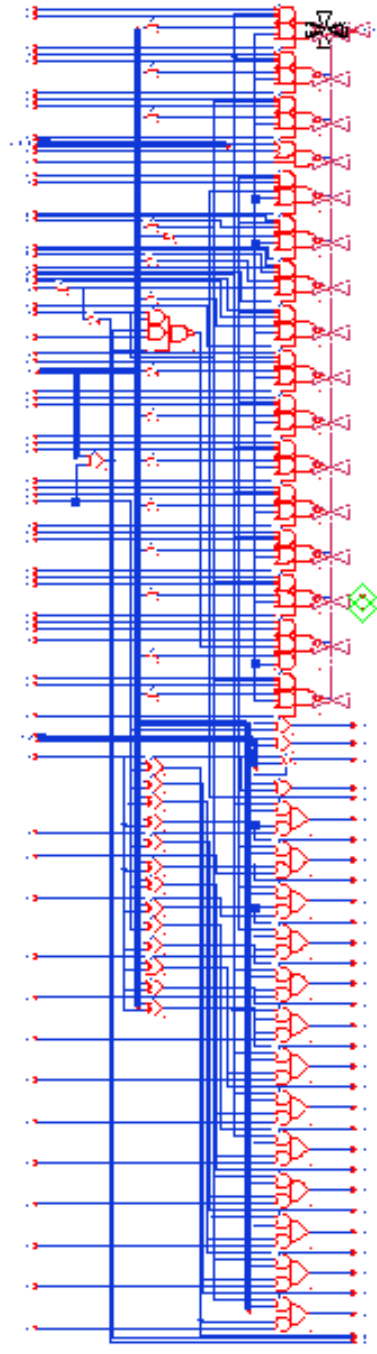


Figure 9: 16 Bit ALU Schematic Page 1

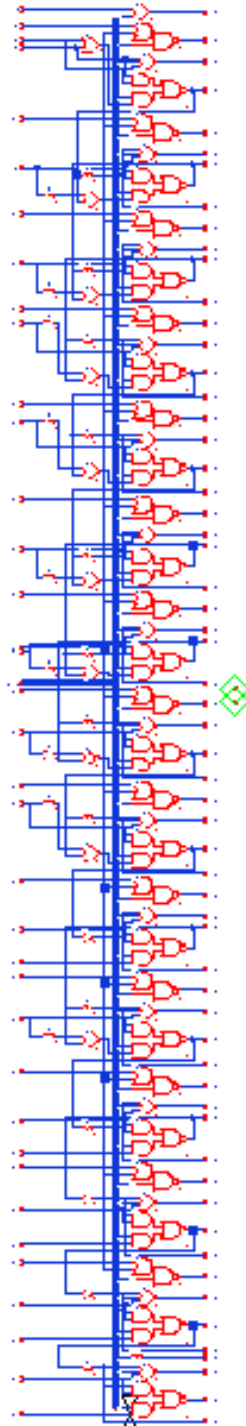


Figure 10: 16 Bit ALU Schematic Page 2

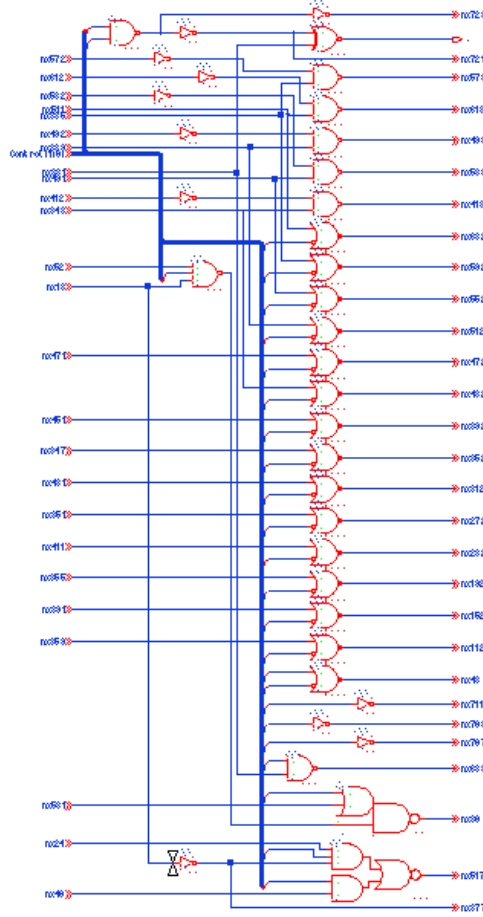


Figure 11: 16 Bit ALU Schematic Page 3

The 16-bit ALU is dramatically more complex than the single bit ALU.

3 Results and Analysis

The ALUs in this exercise had a layout created for them. Then the layout was compared to the schematic via a LVS check. Then timing data was extracted with a PEX extraction. A simulation was run off of the PEX results. Finally, static and dynamic power was measured from the circuit.

3.1 Layout

Pyxis was used to instantiate components from the schematic. Ports were added to the design before a floor plan was generated. To aid in the routing procedure, the area ratio was decreased from 1 to 0.7. Decreasing this area gives room between the cells to route wires. Standard cells were created with default settings. Power routing was run to ease the burden on auto routing and also to clean up the layout. Auto routing settings were adjusted to not route with poly silicon as this tends to cause stray gates. Additionally, the following settings were applied to aid in auto routing:

- Varying levels of routing completion time
- Slight preference for jogs over via to fill the area.

- Rip
- Under rip options:
 - Rips Most Aggressive
 - Automatic Rip Passes
 - Reroute
- Under Advanced:
 - Allow all directions for stubs
 - Via Options > Use via generator

3.1.1 1 Bit ALU

The one bit ALU can be seen in Figure 12.

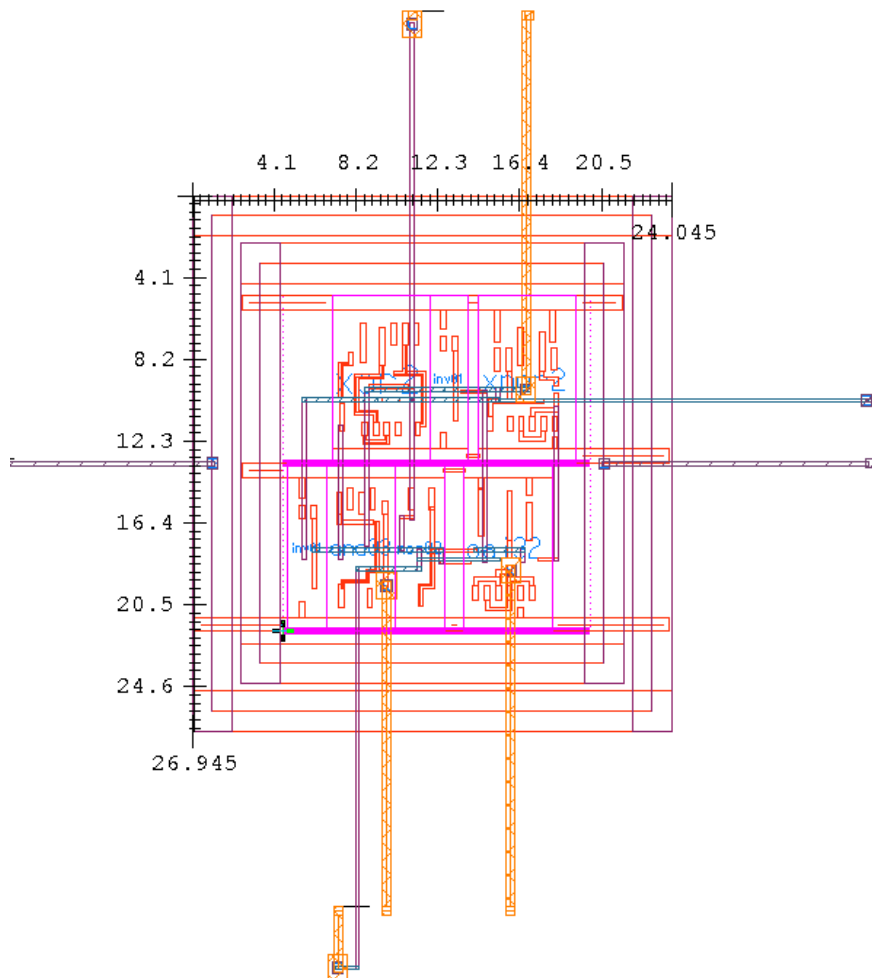


Figure 12: 1 Bit ALU Layout

The 1-bit ALU was $24.045\mu\text{m}$ wide and $26.945\mu\text{m}$ tall, for a total area of $647.893\mu\text{m}^2$.

3.1.2 16 Bit ALU

The one bit ALU can be seen in Figure 13.

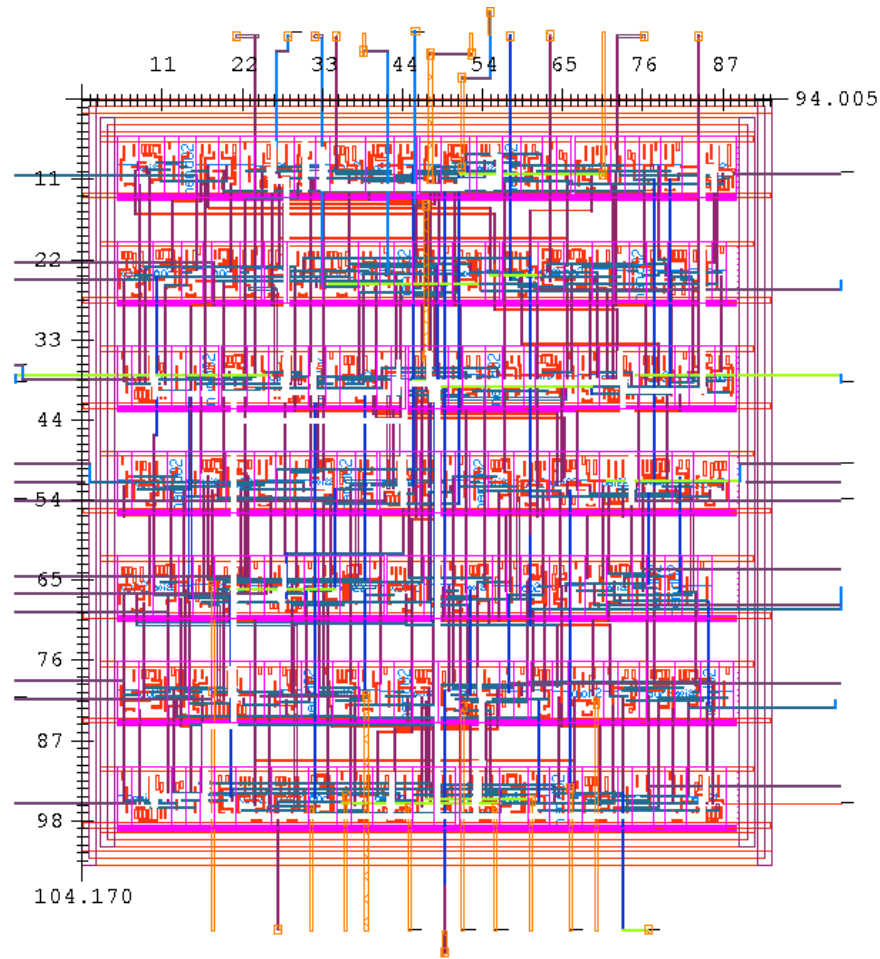


Figure 13: 16 Bit ALU Layout

The 1-bit ALU was $94.005\mu\text{m}$ wide and $104.170\mu\text{m}$ tall, for a total area of $9792.5\mu\text{m}^2$.

3.2 Timing

A SPICE file was written for each ALU, which was based off of the PEX extraction netlist. Eldo was used to run the simulation and ezwave was used to view the waveform and measure rise time, fall time, and propagation delay.

The simulation was run for worst case conditions which are laid out in Figure 14.

Simulation Parameters	
Vdd (V)	1.08
Temp (°C)	125
Load (fF)	120

Figure 14: Simulation Parameters

The maximum input and throughput frequencies were calculated from the measured timing values according to Equation 1 and Equation 2 respectively.

$$F_{input,max} = \frac{1}{t_{rise} + t_{fall}} \quad (1)$$

Equation 1: Max Input Frequency

$$F_{throughput,max} = \frac{1}{T_{P,HL} + T_{P,LH}} \quad (2)$$

Equation 2: Max Throughput Frequency

3.2.1 1 Bit ALU

It was found that subtraction was by far the slowest operation, with the timing difference visible in the waveforms. The SPICE file used to extract timing can be found in Listing 16. The waveform and measurements can be seen in Figure 15.

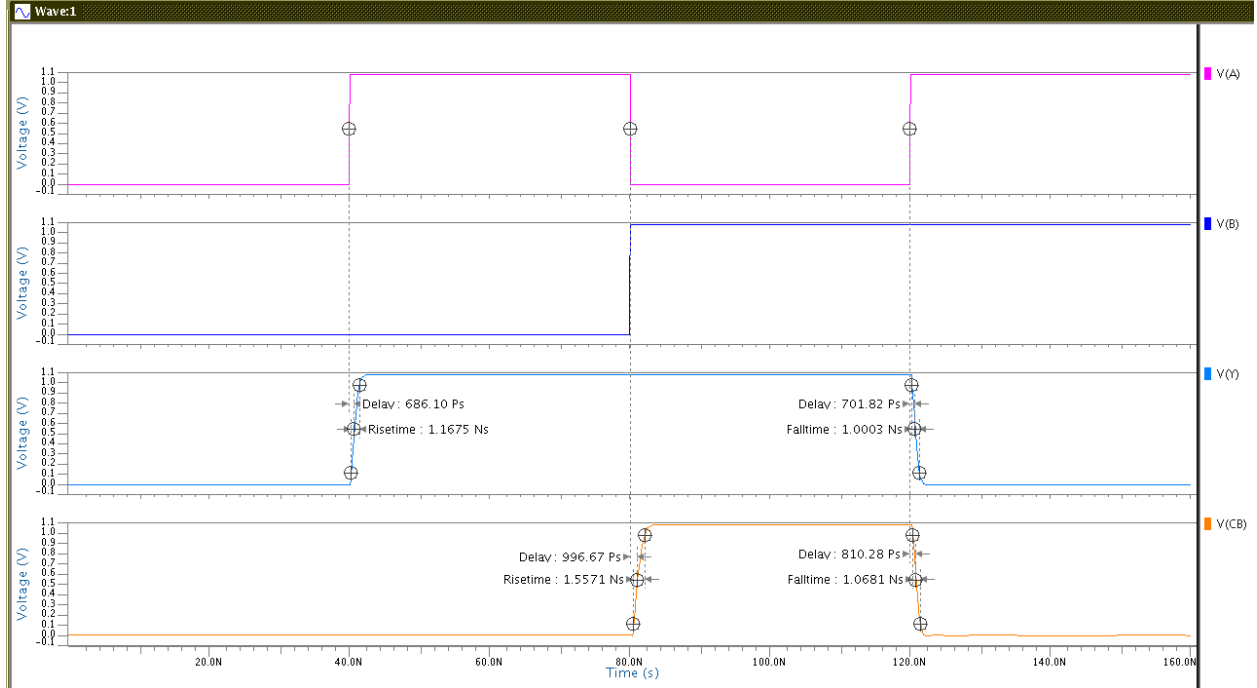


Figure 15: 1 Bit ALU Worst Case Timing Simulation

The rise time was recorded in Table 2.

Table 2: 1-Bit ALU Worst Case Rise Time

Output	Rise Time (ps)	A	B	Operation
Y	1167.5	1	0	SUB
Carry	1557.1	0	1	SUB

The fall time was recorded in Table 3.

Table 3: 1-Bit ALU Worst Case Fall Time

Output	Fall Time (ps)	A	B	Operation
Y	1001.3	1	1	SUB
Carry	1068.1	1	1	SUB

The propagation delay from high output to low output was recorded in Table 4.

Table 4: 1-Bit ALU Worst Case Propagation Time High to Low

Output	Tp,HL (ps)	A	B	Operation
Y	701.8	1	1	SUB
Carry	810.3	1	1	SUB

The propagation delay from low output to high output was recorded in Table 5.

Table 5: 1-Bit ALU Worst Case Propagation Time Low to High

Output	Tp,LH (ps)	A	B	Operation
Y	686.1	1	0	SUB
Carry	996.7	0	1	SUB

The frequency response was calculated and recorded in Table 6.

Table 6: 1-Bit ALU Calculated Max Frequency

Output	Finput,max (MHz)	Fthroughput,max (MHz)
Y	461.08	720.51
Carry	380.92	553.40

3.2.2 16 Bit ALU

The first SPICE file for the 16-bit ALU did not properly force the inputs, resulting in the waveform shown in Figure 16.

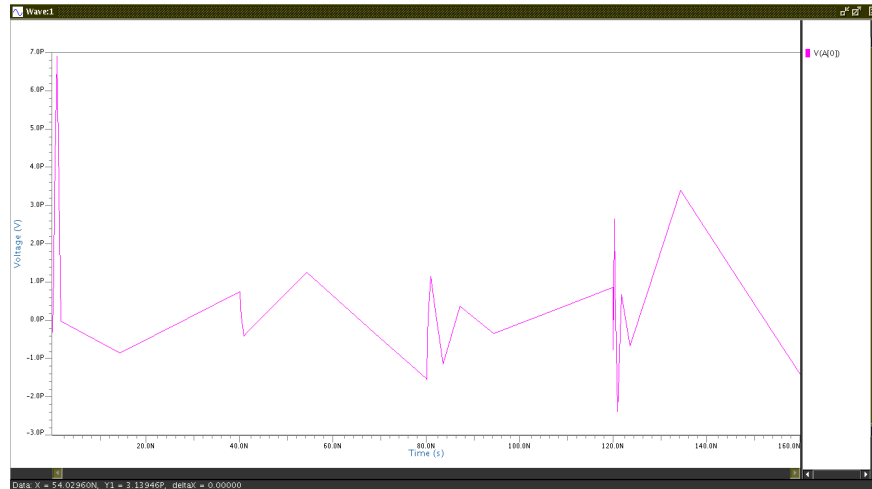


Figure 16: Simulation with Incorrect Forces

Listing 17 shows final the SPICE file used to simulate the 16-Bit ALU. The waveform with timing measurement can be seen in Figure 17.

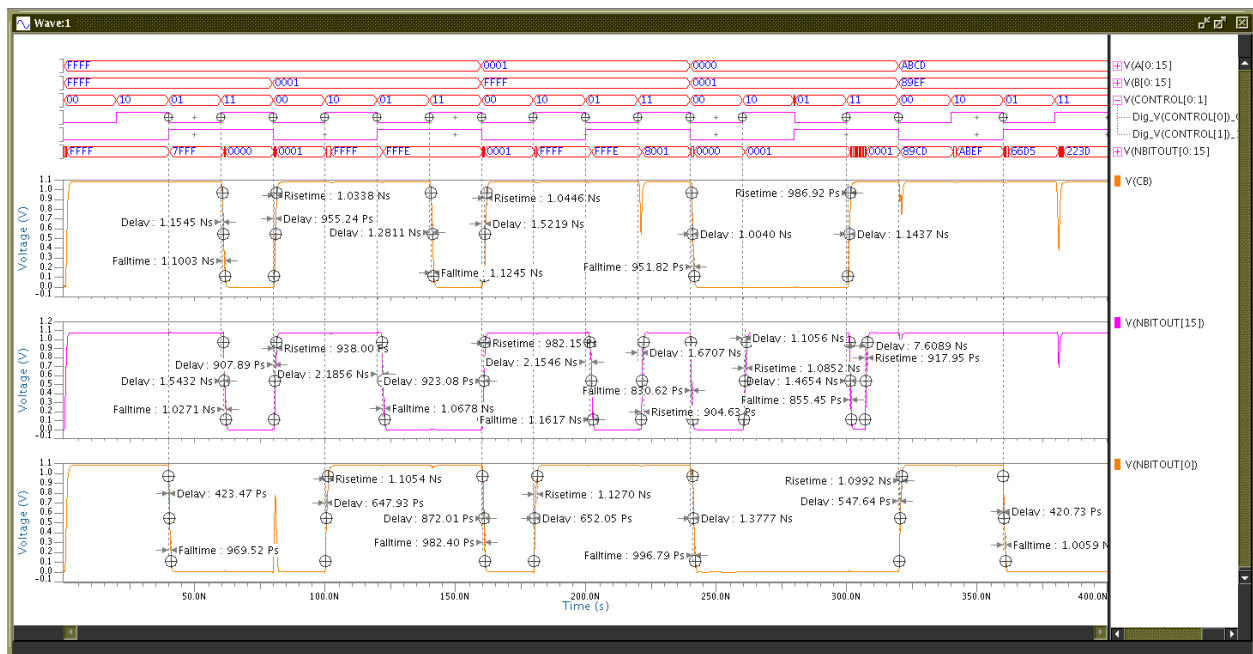


Figure 17: 16-Bit ALU Timing Waveforms

The timing measurements were recorded in Table 7 through Table 10.

Table 7: 16-Bit ALU Worst Case Rise Time

Input		Output	Rise Time (ps)			
A	B	Y	Op	Y	Op	CB
0x0000	0x0000	Y[15]	11	938.0	11	1033.8
0xFFFF	0xFFFF	Y[15]	11	938.0	01	1124.5
0xFFFF	0x0001	Y[15]	11	982.2	11	1044.6
0x0001	0xFFFF	Y[15]	01	904.63	00	1044.6
0x0000	0x0001	Y[0]	00	1085.2	01	986.9
0xABCD	0x89EF	Y[15]	01	917.9	11	951.8

Table 8: 16-Bit ALU Worst Case Fall Time

Input		Output	Fall Time (ps)			
A	B	Y	Op	Y	Op	CB
0x0000	0x0000	Y[15]	01	1100.3	01	1027.1
0xFFFF	0xFFFF	Y[15]	10	1067.0	10	1033.8
0xFFFF	0x0001	Y[15]	11	830.6	01	1124.5
0x0001	0xFFFF	Y[15]	10	1161.7	11	951.8
0x0000	0x0001	Y[0]	00	996.8	10	1005.9
0xABCD	0x89EF	Y[15]	01	855.5	01	969.5

Table 9: 16-Bit ALU Worst Case Propagation Time High to Low

Input		Output	Tp,HL (ps)			
A	B	Y	Op	Y	Op	CB
0x0000	0x0000	Y[15]	01	907.9	01	1154.5
0xFFFF	0xFFFF	Y[15]	10	2185.6	10	1281.1
0xFFFF	0x0001	Y[15]	11	2154.6	01	1004.0
0x0001	0xFFFF	Y[15]	10	1670.7	11	1143.7
0x0000	0x0001	Y[0]	00	1377.7	10	920.7
0xABCD	0x89EF	Y[15]	01	1465.4	01	872.0

Table 10: 16-Bit ALU Worst Case Propagation Time Low to High

Input		Output	Tp,LH (ps)			
A	B	Y	Op	Y	Op	CB
0x0000	0x0000	Y[15]	11	2185.6	11	955.2
0xFFFF	0xFFFF	Y[15]	11	2154.6	01	1521.9
0xFFFF	0x0001	Y[15]	11	1670.7	11	1143.7
0x0001	0xFFFF	Y[15]	01	1085.2	00	947.6
0x0000	0x0001	Y[0]	00	1099.2	01	1047.9
0xABCD	0x89EF	Y[15]	01	7608.9	11	1127.0

The frequency response for the 16-bit ALU was recorded in Table 11.

Table 11: 16-Bit ALU Calculated Max Frequency

A	B	Finput,max (MHz)		Fthroughput,max (MHz)	
		Y	CB	Y	CB
0x0000	0x0000	490.60	485.22	323.26	474.00
0xFFFF	0xFFFF	498.75	463.33	230.40	356.76
0xFFFF	0x0001	551.63	461.02	261.42	465.61
0x0001	0xFFFF	483.95	500.90	362.86	478.17
0x0000	0x0001	480.31	501.81	403.73	507.98
0xABCD	0x89EF	563.89	520.48	110.20	500.25

Considering the increase in complexity between the 1-bit and 16-bit ALU, the performance difference is rather small. The slowest frequency for the 1-bit ALU was 381MHz while the slowest frequency for the 16-bit ALU was 110MHz.

3.3 Power

The power drawn by each ALU was measured using Eldo. This was done by modifying the timing SPICE file to include static and dynamic power usage. The maximum power is drawn when the most amount of transistors are turned on. To capture this, power was measured when all output bits were high. For the 1-Bit ALU this occurred from 70ns to 130ns, for the 16-Bit ALU this occurred from 90ns to 150ns. The power draw was recorded in Table 12.

Table 12: ALU Power Draw

ALU	Static Power (nW)	Dynamic Power (uW)
1-Bit	6303.8	317.8
16-Bit	90463	2922.6

The 16-bit ALU consumed about 10 times the power as single bit ALU. This shows how more computation power drastically increases power draw.

4 Conclusion

While this exercise was successful, Overall, this exercise was successful.

5 Question

The 16-Bit ALU was created with generic VHDL, so creating a 4-bit ALU was simple. The routing actually proved more challenging than the 16-bit ALU. The 4-bit ALU's performance slotted in between the 1 and 16-bit ALU. The timing was recorded in Table 13.

Table 13: Frequency Response of Manual Layout 4-Bit Ripple Adder and Auto Layout 4-Bit ALU

4-Bit Ripple Adder		4-Bit ALU		Difference	
Finput(Hz)	Ftput(Hz)	Finput(Hz)	Ftput(Hz)	Finput	Ftput
302.92	232.32	424.48	531.51	40.13%	128.78%
290.69	244.16	360.85	523.40	24.14%	114.37%

It would be expected that the ALU would be slower than just the adder, however this was not the case. This is likely because the automatic tools were more competent than inexperienced manual layout.

6 Appendix

6.1 VHDL

Listing 1: Controller-16Bit VHDL

```

0  ---Company      : RIT
   ---Author       : Brandon Key
   ---Created      : 02/18/2018
   ---
5  ---Project Name : Lab 3
   ---File        : Controller_16Bit.vhd
   ---
   ---Entity       : Controller_16Bit
   ---Architecture : behav
10  ---
   ---Tool Version : VHDL '93
   ---Description  : *SPECIAL controller, DO NOT USE OUTSIDE THIS PROJECT*
   ---              : Takes 4 bit control signal bit
   ---              : Figures out the proper output
15  ---

library IEEE;
use IEEE.STD_LOGIC_1164.ALL;
use IEEE.numeric_std.all;
20  ---use work.controlcodes.all;

entity Controller_16Bit is
    generic (n : integer := 16);
    port(
25      Control : in std_logic_vector(1 downto 0);

      ADD_SUB_In : in std_logic_vector(N-1 downto 0);
      OR_In      : in std_logic_vector(N-1 downto 0);
      AND_In     : in std_logic_vector(N-1 downto 0);
30      ADD_SUB_SEL : out std_logic;

      nBitOut : out std_logic_vector(N-1 downto 0)
    );
35 end Controller_16Bit;

architecture behav of Controller_16Bit is

    constant AND_Code : std_logic_vector(1 downto 0) := "00";
    constant OR_Code  : std_logic_vector(1 downto 0) := "01";
    constant ADD_Code : std_logic_vector(1 downto 0) := "10";
    constant SUB_Code : std_logic_vector(1 downto 0) := "11";
40

begin
45  ---Proces to set the select signal when subtraction should occur

```

```

ADD_SUB_SEL_proc: with Control select
    ADD_SUB_SEL <= '1' when SUB_Code,
                  '0' when others;

nBitOut_proc: with Control select
    nBitOut <= ADD_SUB_In when ADD_Code,
              ADD_SUB_In when SUB_Code,
              OR_In when OR_Code,
              AND_In when AND_Code,
              (others => '0') when others;

end  behav;

```

Listing 2: nBitAdderSubtractor-4Bit VHDL

```

0  -----
--Company      : RIT
--Author       : Brandon Key
--Created      : 02/18/2018
--
5  --Project Name : Lab 3
--File         : nBitAdderSubtractor_4Bit.vhd
--
--Entity       : nBitAdderSubtractor_4Bit
--Architecture : struct
10 --
--Tool Version : VHDL '93
--Description  : Entity and structural description of an adder subtractor
--              : SEL = 0 : A+B = Y
--              : SEL = 1 : A-B = Y
15 -----

library IEEE;
use IEEE.STD_LOGIC_1164.ALL;
use IEEE.numeric_std.all;

20 entity nBitAdderSubtractor_4Bit is
    generic (n : integer := 16);
    port(
25     A,B : in  std_logic_vector(n-1 downto 0);
        SEL : in  std_logic;
        Y  : out std_logic_vector(n-1 downto 0);
        CB : out std_logic
    );
end  nBitAdderSubtractor_4Bit;

30 architecture struct of nBitAdderSubtractor_4Bit is

    component full_adder is
        port(A,B,Cin : in  std_logic;
35         Sum,Cout : out std_logic
        );
    end component full_adder;

    --Create an array to hold all of the carries
    type carry_array is array (n-1 downto 0) of std_logic;
    signal c_array : carry_array;

    signal BXOR_SEL : std_logic_vector( (n-1) downto 0);

```



```

45 begin
    --Generate the xor statements to be mapped to the full adders
    XORator : for i in 0 to n-1 generate
        B_XOR_SEL(i) <= B(i) xor SEL;
50 end generate XORator;

    generate_adders : for i in 0 to n-1 generate
        i_first: if i = 0 generate
            --The first adder gets SEL as the Cin
55         adder : full_adder port map(
                A => A(i),
                B => B_XOR_SEL(i),
                Cin => SEL,
                Sum => Y(i),
60                Cout => c_array(i)
            );
        end generate i_first;

        i_last : if i = (n-1) generate
65         --The last adder doesn't have a carry out
        adder : full_adder port map(
                A => A(i),
                B => B_XOR_SEL(i),
                Cin => c_array(i-1),
70                Sum => Y(i),
                Cout => c_array(i)
            );
        end generate i_last;

75         --Middle adders
        i_mid : if (i /= 0) and (i /= (n-1)) generate
            adder : full_adder port map(
                A => A(i),
                B => B_XOR_SEL(i),
80                Cin => c_array(i-1),
                Sum => Y(i),
                Cout => c_array(i)
            );
        end generate i_mid;

85     end generate generate_adders;

    CB <= c_array(n-1) xor SEL;

90 end struct;

```

Listing 3: FullAdder VHDL

```

0  --Company      : RIT
   --Author       : Brandon Key
   --Created      : 02/18/2018
   --
5  --Project Name : Lab 3
   --File        : Full_Adder.vhd
   --
   --Entity       : Full_Adder

```

```

--Architecture : behav
--
10 --Tool Version : VHDL '93
--Description : Entity and behavioral description of a full adder

--
15
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;

entity Full_Adder is
20     port (A,B,Cin : in std_logic;
           Sum,Cout : out std_logic
           );
end Full_Adder;

25 architecture behav of Full_Adder is
begin
    --uses select assignment to implement the truth table of a full adder

30     sum_proc: with std_logic_vector'(Cin&A&B) select
        Sum <= '0' when "000",
                '1' when "001",
                '1' when "010",
                '0' when "011",
35                '1' when "100",
                '0' when "101",
                '0' when "110",
                '1' when "111",
                '0' when others;

40     Cout_proc: with std_logic_vector'(Cin&A&B) select
        Cout <= '0' when "000",
                '0' when "001",
                '0' when "010",
                '1' when "011",
45                '0' when "100",
                '1' when "101",
                '1' when "110",
                '1' when "111",
                '0' when others;

50
end behav;

```

Listing 4: ALU-16Bit-tb VHDL

```

0 --
-- Company: RIT
-- Engineer: Brandon Key
--
-- Create Date: 17:51:58 02/28/2018
5 -- Design Name:
-- Module Name: /home/ise/DSDII/Lab/Lab3/SourceCode/ALU_16Bit_tb.vhd
-- Project Name: Lab3
-- Target Device:
-- Tool versions:
10 -- Description:
--

```

```

-- VHDL Test Bench Created by ISE for module: ALU_16Bit
--
-- Dependencies:
15 --
-- Revision:
-- Revision 0.01 - File Created
-- Additional Comments:
--
20 -- Notes:
-- This testbench has been automatically generated using types std_logic and
-- std_logic_vector for the ports of the unit under test.  Xilinx recommends
-- that these types always be used for the top-level I/O of a design in order
-- to guarantee that the testbench will bind correctly to the post-implementation
25 -- simulation model.

```

```

LIBRARY ieee;
USE ieee.std_logic_1164.ALL;
USE ieee.numeric_std.ALL;
30 --use work.globals.all;
--use work.controlcodes.all;

ENTITY ALU_16Bit_tb IS
END ALU_16Bit_tb;
35

ARCHITECTURE behavior OF ALU_16Bit_tb IS

    constant AND_Code : std_logic_vector(1 downto 0) := "00";
    constant OR_Code  : std_logic_vector(1 downto 0) := "01";
40    constant ADD_Code : std_logic_vector(1 downto 0) := "10";
    constant SUB_Code : std_logic_vector(1 downto 0) := "11";

    type testRecordArray is array (natural range <>) of std_logic_vector(2 downto 0)
    ;

45    constant n:integer := 16;
    -- "Time" that will elapse between test vectors we submit to the component.
    constant TIME_DELTA : time := 50 ns;

50    -- Component Declaration for the Unit Under Test (UUT)
    COMPONENT ALU_16Bit
    PORT(
        Control : IN  std_logic_vector(1 downto 0);
        A : IN  std_logic_vector(N-1 downto 0);
55        B : IN  std_logic_vector(N-1 downto 0);
        nBitOut : OUT std_logic_vector(N-1 downto 0);
        CB : OUT std_logic
    );
    END COMPONENT;
60

    --Inputs
    signal Control : std_logic_vector(1 downto 0) := (others => '0');
    signal A : std_logic_vector(N-1 downto 0) := (others => '0');
65    signal B : std_logic_vector(N-1 downto 0) := (others => '0');

    --Outputs
    signal nBitOut : std_logic_vector(N-1 downto 0);
    signal CB : std_logic;

```

```

70  -- No clocks detected in port list. Replace <clock> below with
    -- appropriate port name

BEGIN

75  -- Instantiate the Unit Under Test (UUT)
    uut: ALU_16Bit
    PORT MAP (
80      Control => Control,
        A => A,
        B => B,
        nBitOut => nBitOut,
        CB => CB
    );

85

    -- Stimulus process
    stim_proc: process
        --create a function to make a vector a string
90        function vec2str(vec : std_logic_vector) return string is
            variable stmp:string(vec'left+1 downto 1);
        begin
            for i in vec'reverse_range loop
                if vec(i) = '1' then
95                    stmp(i+1) := '1';
                elsif vec(i) = 'U' then
                    stmp(i+1) := 'U';
                else
                    stmp(i+1) := '0';
100                end if;
            end loop;
            return stmp;
        end vec2str;

105        procedure check_add(
            constant in1 : in natural;
            constant in2 : in natural;
            constant res_expected : in natural;
            constant CB_expected : in std_logic) is
110            variable res : natural;
        begin
            -- Assign values to circuit inputs.
            A <= std_logic_vector(to_unsigned(in1, A'length));
            B <= std_logic_vector(to_unsigned(in2, B'length));
115            Control <= ADD_Code;

            wait for TIME_DELTA;
            -- Check output against expected result.
120            res := to_integer(unsigned(nBitOut));
            assert ((res = res_expected) and (CB = CB_expected))
            report "" & integer'image(in1) & "+" &
                integer'image(in2) & "=" &
                integer'image(res_expected) & "!=" &
                integer'image(res) &
125                "" &
                "CB exp: " & std_logic'image(CB_expected) &
                "Got: " & std_logic'image(CB)

```

```

130     severity error;
end procedure check_add;

135 procedure check_sub(
    constant in1 : in natural;
    constant in2 : in natural;
135     constant res_expected : in natural;
    constant CB_expected : in std_logic) is
    variable res : natural;
    begin
        -- Assign values to circuit inputs.
140     A <= std_logic_vector(to_unsigned(in1, A'length));
        B <= std_logic_vector(to_unsigned(in2, B'length));
        Control <= SUB_Code;

145     wait for TIME_DELTA;
        -- Check output against expected result.
        res := to_integer(unsigned(nBitOut));
        assert ((res = res_expected) and (CB = CB_expected))
150     report "" & integer'image(in1) & "-" &
        integer'image(in2) & "=" &
        integer'image(res_expected) & "!=" &
        integer'image(res) &
        " " &
        "CB exp: " & std_logic'image(CB_expected) &
155     "Got: " & std_logic'image(CB)
        severity error;
end procedure check_sub;

160 procedure check_or(
    constant in1 : in natural;
    constant in2 : in natural;
    constant res_expected : in natural) is
    variable res : natural;
165     begin
        -- Assign values to circuit inputs.
        A <= std_logic_vector(to_unsigned(in1, A'length));
        B <= std_logic_vector(to_unsigned(in2, B'length));
        Control <= OR_Code;

170     wait for TIME_DELTA;
        -- Check output against expected result.
        res := to_integer(unsigned(nBitOut));
        assert ((res = res_expected) and (CB = '0'))
175     report "" & integer'image(in1) & "+" &
        integer'image(in2) & "=" &
        integer'image(res_expected) & "!=" &
        integer'image(res) &
        " " &
        "CB: " & std_logic'image(CB)
180     severity error;
end procedure check_or;

185 procedure check_and(
    constant in1 : in natural;

```

```

constant in2 : in natural;
constant res_expected : in natural) is
190 variable res : natural;
begin
    -- Assign values to circuit inputs.
    A <= std_logic_vector(to_unsigned(in1, A'length));
    B <= std_logic_vector(to_unsigned(in2, B'length));
195 Control <= AND_Code;

    wait for TIME_DELTA;
    -- Check output against expected result.
200 res := to_integer(unsigned(nBitOut));
    report "" & integer'image(in1) & "+" &
           integer'image(in2) & "=" &
           integer'image(res_expected);

205 assert ((res = res_expected) and ( CB = '0' ))
    report "!=" &
           integer'image(res) &
           " " &
           "CB: " & std_logic'image(CB)
210 severity error;
end procedure check_and;

begin
215

    --wait for the outputs to stabilize
    wait for 100 ns;

    --check_add(4,5,9,0);
    --check_add(65535, 2, 1, 1);
220 --check_sub(1234, 234, 1000, 0);
    --check_sub(1, 2, 1, 1);

    control <= OR_Code;
    A <= "0111010101110101";
    B <= "1001110100101101";
225 wait for 50 ns;

    control <= AND_Code;
    wait for 50 ns;
230

    -- Test adder
    for x in (0) to (5) loop
235         for y in 5432 to 5438 loop
            control <= ADD_Code;
            A <= std_logic_vector(to_unsigned(x, A'length));
            B <= std_logic_vector(to_unsigned(y, B'length));
            wait for 50 ns;

240             assert(nBitOut = std_logic_vector(to_unsigned(x+y, A'length) ) )
            report("Bad Add = " & vec2str(nBitOut)
                   & " expected = " & vec2str( std_logic_vector(to_unsigned(x+y, A'
length)) ) )
245             & " A = " & vec2str(A)
            & " B = " & vec2str(B)

```

```

    );
    end loop;
end loop;

250 for x in ((2**N)-3) to ((2**N)-1) loop
    for y in 0 to 3 loop
        control <= ADD.Code;
        A <= std_logic_vector(to_unsigned(x, A'length));
        B <= std_logic_vector(to_unsigned(y, B'length));
255        wait for 50 ns;

        assert(nBitOut = std_logic_vector(to_unsigned(x+y, A'length)) )
        report("Bad Add = " & vec2str(nBitOut)
            & " expected = " & vec2str( std_logic_vector(to_unsigned(x+y, A'
length)) )
260            & " A = " & vec2str(A)
            & " B = " & vec2str(B)
        );
    end loop;
end loop;

265 -- Test suber
for x in 0 to 5 loop
    for y in 0 to 5 loop
        control <= SUB.Code;
270        A <= std_logic_vector(to_unsigned(x, A'length));
        B <= std_logic_vector(to_unsigned(y, B'length));
        wait for 50 ns;

        assert(nBitOut = std_logic_vector(to_signed(x-y, A'length)) )
275        report("Bad Sub = " & vec2str(nBitOut)
            & " expected = " & vec2str( std_logic_vector(to_signed(x-y, A'length)) )
            & " A = " & vec2str(A)
            & " B = " & vec2str(B)
        );
280    end loop;
end loop;

for x in 12345 to 12350 loop
285    for y in 5 to 7 loop
        control <= SUB.Code;
        A <= std_logic_vector(to_unsigned(x, A'length));
        B <= std_logic_vector(to_unsigned(y, B'length));
        wait for 50 ns;

290        assert(nBitOut = std_logic_vector(to_signed(x-y, A'length)) )
        report("Bad Sub = " & vec2str(nBitOut)
            & " expected = " & vec2str( std_logic_vector(to_signed(x-y, A'length)) )
            & " A = " & vec2str(A)
295            & " B = " & vec2str(B)
        );
    end loop;
end loop;

300

```

```

        wait;
    end process;

END;
```

Listing 5: Controller-4Bit VHDL

```

0  -----
   --Company      : RIT
   --Author       : Brandon Key
   --Created      : 02/18/2018
   --
5  --Project Name : Lab 3
   --File        : Controller_4Bit.vhd
   --
   --Entity       : Controller_4Bit
   --Architecture : behav
10 --
   --Tool Version : VHDL '93
   --Description  : *SPECIAL controller , DO NOT USE OUTSIDE THIS PROJECT*
   --              : Takes 4 bit control signal bit
   --              : Figures out the proper output
15 -----

library IEEE;
use IEEE.STD_LOGIC_1164.ALL;
use IEEE.numeric_std.all;
20 --use work.controlcodes.all;

entity Controller_4Bit is
    generic (n : integer := 16);
    port(
25         Control : in  std_logic_vector(1 downto 0);

         ADD_SUB_In : in std_logic_vector(N-1 downto 0);
         OR_In      : in std_logic_vector(N-1 downto 0);
         AND_In     : in std_logic_vector(N-1 downto 0);
30
         ADD_SUB_SEL : out std_logic;

         nBitOut : out std_logic_vector(N-1 downto 0)
        );
35 end Controller_4Bit;

architecture behav of Controller_4Bit is

    constant AND_Code : std_logic_vector(1 downto 0) := "00";
    constant OR_Code  : std_logic_vector(1 downto 0) := "01";
    constant ADD_Code : std_logic_vector(1 downto 0) := "10";
    constant SUB_Code : std_logic_vector(1 downto 0) := "11";
40

begin
45
    --Proces to set the select signal when subtraction should occur
    ADD_SUB_SEL_proc: with Control select
        ADD_SUB_SEL <= '1' when SUB_Code,
                       '0' when others;
50

    nBitOut_proc: with Control select
```



```

nBitOut <= ADD_SUB.In when ADD.Code,
            ADD_SUB.In when SUB.Code,
            OR.In when OR.Code,
55      AND.In when AND.Code,
            (others => '0') when others;

end  behav;

```

Listing 6: nBitOR-4Bit VHDL

```

0  ---Company      : RIT
   ---Author      : Brandon Key
   ---Created     : 1/22/2018
   ---
5  ---Project Name : Lab 1
   ---File        : nBitOR_4Bit.vhd
   ---
   ---Entity      : nBitOR_4Bit
   ---Architecture : Dataflow
10  ---
   ---Tool Version : VHDL '93
   ---Description  : Entity and structural description of an OR gate
   ---
15 library IEEE;
   use IEEE.STD_LOGIC_1164.ALL;

   entity nBitOR_4Bit is
       generic (n : integer := 16);
20   port (A,B : in  std_logic_vector(n-1 downto 0);
          Y : out std_logic_vector(n-1 downto 0)
        );
   end nBitOR_4Bit;

25 architecture Dataflow of nBitOR_4Bit is
   begin
       Y <= A or B;--- bitwise or
   end Dataflow;

```

Listing 7: ALU-4Bit VHDL

```

0  ---Company      : RIT
   ---Author      : Brandon Key
   ---Created     : 02/18/2018
   ---
5  ---Project Name : Lab 3
   ---File        : ALU_4Bit.vhd
   ---
   ---Entity      : ALU_4Bit
   ---Architecture : struct
10  ---
   ---Tool Version : VHDL '93
   ---Description  : ALU_4Bit
   ---
15 library IEEE;
   use IEEE.STD_LOGIC_1164.ALL;

```

```

package globals is
    constant N : integer := 16;
20 end globals;

library IEEE;
use IEEE.STD_LOGIC_1164.ALL;

25 package controlcodes is
    constant AND_Code : std_logic_vector(1 downto 0) := "00";
    constant OR_Code  : std_logic_vector(1 downto 0) := "01";
    constant ADD_Code : std_logic_vector(1 downto 0) := "10";
30    constant SUB_Code : std_logic_vector(1 downto 0) := "11";
end controlcodes;

library IEEE;
35 use IEEE.STD_LOGIC_1164.ALL;
use IEEE.numeric_std.all;
use work.controlcodes.all;
use work.globals.all;

40 entity ALU_4Bit is
    port(
        Control : in std_logic_vector(1 downto 0);
        A,B      : in std_logic_vector(N-1 downto 0);
        nBitOut  : out std_logic_vector(N-1 downto 0);
45        CB      : out std_logic
    );
end ALU_4Bit;

architecture struct of ALU_4Bit is
50
    --constant N : integer := 4;

    signal ADD_SUB_Out : std_logic_vector(N-1 downto 0);
    signal OR_Out      : std_logic_vector(N-1 downto 0);
55    signal AND_Out    : std_logic_vector(N-1 downto 0);

    signal ADD_SUB_SEL : std_logic;

60 begin

    nBitAdderSubtractor_4Bit : entity work.nBitAdderSubtractor_4Bit
        generic map (N => N)
        port map ( A => A, B => B, SEL => ADD_SUB_SEL, Y => ADD_SUB_Out, CB => CB);

65

    nBitOR_4Bit : entity work.nBitOR_4Bit
        generic map (N => N)
        port map ( A => A, B => B, Y => OR_Out);

70

    nBitAND_4Bit : entity work.nBitAND_4Bit
        generic map (N => N)
        port map ( A => A, B => B, Y => AND_Out);

75

```

```

Controller_4Bit : entity work.Controller_4Bit
    generic map (N => N)
    port map(
80      Control      => Control ,
      ADD.SUB_In   => ADD.SUB_Out,
      OR_In        => OR_Out ,
      AND_In       => AND_Out ,
      ADD.SUB_SEL  => ADD.SUB_SEL,
85      nBitOut     => nBitOut
    );

end struct;

```

Listing 8: nBitAND-4Bit VHDL

```

0  ---
---Company      : RIT
---Author       : Brandon Key
---Created      : 1/22/2018
---
5  ---Project Name : Lab 1
---File         : nBitAND_4Bit.vhd
---
---Entity       : nBitAND_4Bit
---Architecture : Dataflow
10 ---
---Tool Version : VHDL '93
---Description  : Entity and structural description of an AND gate
---
15 library IEEE;
use IEEE.STD_LOGIC_1164.ALL;

entity nBitAND_4Bit is
    generic (n : integer := 16);
20    port(A,B : in  std_logic_vector(n-1 downto 0);
        Y : out std_logic_vector(n-1 downto 0)
        );
end nBitAND_4Bit;

25 architecture Dataflow of nBitAND_4Bit is
    begin
        Y <= A AND B;--- bitwise or
end Dataflow;

```

Listing 9: ALU-1Bit-tb VHDL

```

0  ---
--- Company: RIT
--- Engineer: Brandon Key
---
--- Create Date: 17:51:58 02/28/2018
5  --- Design Name:
--- Module Name: /home/ise/DSDII/Lab/Lab3/SourceCode/ALU_1Bit_tb.vhd
--- Project Name: Lab3
--- Target Device:
--- Tool versions:
10 --- Description:
---

```

```

-- VHDL Test Bench Created by ISE for module: ALU_1Bit
--
-- Dependencies:
15 --
-- Revision:
-- Revision 0.01 - File Created
-- Additional Comments:
--
20 -- Notes:
-- This testbench has been automatically generated using types std_logic and
-- std_logic_vector for the ports of the unit under test. Xilinx recommends
-- that these types always be used for the top-level I/O of a design in order
-- to guarantee that the testbench will bind correctly to the post-implementation
25 -- simulation model.

```

```

LIBRARY ieee;
USE ieee.std_logic_1164.ALL;
USE ieee.numeric_std.ALL;
30 --use work.globals.all;
--use work.controlcodes.all;

ENTITY ALU_1Bit_tb IS
END ALU_1Bit_tb;
35

ARCHITECTURE behavior OF ALU_1Bit_tb IS

    CONSTANT AND_Code : std_logic_vector(1 DOWNTO 0) := "00";
    CONSTANT OR_Code  : std_logic_vector(1 DOWNTO 0) := "01";
40    CONSTANT ADD_Code : std_logic_vector(1 DOWNTO 0) := "10";
    CONSTANT SUB_Code  : std_logic_vector(1 DOWNTO 0) := "11";

    TYPE testRecordArray IS ARRAY (NATURAL RANGE <>) OF std_logic_vector(2 DOWNTO 0)
    ;
    CONSTANT TIME_DELTA : TIME := 50 ns;
45    -- Component Declaration for the Unit Under Test (UUT)
    COMPONENT ALU_1Bit
        PORT (
            Control : IN std_logic_vector(1 DOWNTO 0);
            A : IN std_logic;
50            B : IN std_logic;
            Y : OUT std_logic;
            CB : OUT std_logic
        );
    END COMPONENT;
55    --Inputs
    SIGNAL Control : std_logic_vector(1 DOWNTO 0) := (OTHERS => '0');
    SIGNAL A : std_logic := '0';
    SIGNAL B : std_logic := '0';

    --Outputs
60    SIGNAL Y : std_logic;
    SIGNAL CB : std_logic;
BEGIN

    -- Instantiate the Unit Under Test (UUT)
65    uut : ALU_1Bit
    PORT MAP(
        Control => Control,
        A => A,
        B => B,

```

```

70      Y => Y,
      CB => CB
    );
    -- Stimulus process
    stim_proc : PROCESS
75      --create a function to make a vector a string
      FUNCTION vec2str(vec : std_logic_vector) RETURN STRING IS
        VARIABLE stmp : STRING(vec'LEFT + 1 DOWNT0 1);
      BEGIN
        FOR i IN vec'reverse_range LOOP
80          IF vec(i) = '1' THEN
            stmp(i + 1) := '1';
          ELSIF vec(i) = 'U' THEN
            stmp(i + 1) := 'U';
          ELSE
85            stmp(i + 1) := '0';
          END IF;
        END LOOP; RETURN stmp;
      END vec2str;

90    BEGIN
      --wait for the outputs to stabilize
      WAIT FOR 100 ns;

      control <= OR_Code;
95      A <= '0';
      B <= '0';
      WAIT FOR 50 ns;
      A <= '0';
      B <= '1';
100     WAIT FOR 50 ns;
      A <= '1';
      B <= '0';
      WAIT FOR 50 ns;
      A <= '1';
      B <= '1';
105     WAIT FOR 50 ns;

      control <= AND_Code;
110     A <= '0';
      B <= '0';
      WAIT FOR 50 ns;
      A <= '0';
      B <= '1';
      WAIT FOR 50 ns;
115     A <= '1';
      B <= '0';
      WAIT FOR 50 ns;
      A <= '1';
      B <= '1';
120     WAIT FOR 50 ns;

      control <= ADD_Code;
      A <= '0';
      B <= '0';
125     WAIT FOR 50 ns;
      A <= '0';
      B <= '1';
      WAIT FOR 50 ns;

```

```

130     A <= '1';
        B <= '0';
        WAIT FOR 50 ns;
        A <= '1';
        B <= '1';
        WAIT FOR 50 ns;
135
        control <= SUB_Code;
        A <= '0';
        B <= '0';
        WAIT FOR 50 ns;
140     A <= '0';
        B <= '1';
        WAIT FOR 50 ns;
        A <= '1';
        B <= '0';
145     WAIT FOR 50 ns;
        A <= '1';
        B <= '1';
        WAIT FOR 50 ns;
150
        WAIT;
    END PROCESS;

END;

```

Listing 10: ALU-1Bit VHDL

```

0  ---Company      : RIT
   ---Author       : Brandon Key
   ---Created      : 02/18/2018
   ---
5  ---Project Name : Lab 3
   ---File         : ALU.vhd
   ---
   ---Entity       : ALU
   ---Architecture : struct
10 ---
   ---Tool Version : VHDL '93
   ---Description  : ALU
   ---
15 library IEEE;
   use IEEE.STD_LOGIC_1164.ALL;

   package controlcodes is
       constant AND_Code : std_logic_vector(1 downto 0) := "00";
       constant OR_Code  : std_logic_vector(1 downto 0) := "01";
20      constant ADD_Code : std_logic_vector(1 downto 0) := "10";
       constant SUB_Code : std_logic_vector(1 downto 0) := "11";
   end controlcodes;

25 library IEEE;
   use IEEE.STD_LOGIC_1164.ALL;
   use IEEE.numeric_std.all;
   use work.controlcodes.all;

30 entity ALU_1Bit is

```

```

    port(
        Control : in std_logic_vector(1 downto 0);
        A,B      : in std_logic;
        Y        : out std_logic;
35      CB      : out std_logic
    );
end ALU_1Bit;

architecture behav of ALU_1Bit is
40
begin

    Y_proc: with Control select
        Y <= A xor B when ADD_Code,
45      A xor B when SUB_Code,
        A or B when OR_Code,
        A and B when AND_Code,
        '0' when others;

    CB_proc: with Control select
50      CB <= A and B when ADD_Code,
        (not A) and B when SUB_Code,
        '0' when OR_Code,
        '0' when AND_Code,
55      '0' when others;

end behav;

```

Listing 11: ALU-4Bit-tb VHDL

```

0  ---
--- Company: RIT
--- Engineer: Brandon Key
---
--- Create Date: 17:51:58 02/28/2018
5 --- Design Name:
--- Module Name: /home/ise/DSDII/Lab/Lab3/SourceCode/ALU_4Bit_tb.vhd
--- Project Name: Lab3
--- Target Device:
--- Tool versions:
10 --- Description:
---
--- VHDL Test Bench Created by ISE for module: ALU_4Bit
---
--- Dependencies:
15 ---
--- Revision:
--- Revision 0.01 - File Created
--- Additional Comments:
---
20 --- Notes:
--- This testbench has been automatically generated using types std_logic and
--- std_logic_vector for the ports of the unit under test. Xilinx recommends
--- that these types always be used for the top-level I/O of a design in order
--- to guarantee that the testbench will bind correctly to the post-implementation
25 --- simulation model.

LIBRARY ieee;
USE ieee.std_logic_1164.ALL;

```

```

USE ieee.numeric_std.ALL;
30 --use work.globals.all;
--use work.controlcodes.all;

ENTITY ALU_4Bit_tb IS
END ALU_4Bit_tb;
35

ARCHITECTURE behavior OF ALU_4Bit_tb IS

    constant AND_Code : std_logic_vector(1 downto 0) := "00";
    constant OR_Code  : std_logic_vector(1 downto 0) := "01";
40    constant ADD_Code : std_logic_vector(1 downto 0) := "10";
    constant SUB_Code : std_logic_vector(1 downto 0) := "11";

    type testRecordArray is array (natural range <>) of std_logic_vector(2 downto 0)
    ;

45    constant n:integer := 16;
    -- "Time" that will elapse between test vectors we submit to the component.
    constant TIME_DELTA : time := 50 ns;

50    -- Component Declaration for the Unit Under Test (UUT)
    COMPONENT ALU_4Bit
    PORT(
        Control : IN  std_logic_vector(1 downto 0);
        A : IN  std_logic_vector(N-1 downto 0);
55        B : IN  std_logic_vector(N-1 downto 0);
        nBitOut : OUT std_logic_vector(N-1 downto 0);
        CB : OUT std_logic
    );
    END COMPONENT;
60

    --Inputs
    signal Control : std_logic_vector(1 downto 0) := (others => '0');
    signal A : std_logic_vector(N-1 downto 0) := (others => '0');
65    signal B : std_logic_vector(N-1 downto 0) := (others => '0');

    --Outputs
    signal nBitOut : std_logic_vector(N-1 downto 0);
    signal CB : std_logic;
70    -- No clocks detected in port list. Replace <clock> below with
    -- appropriate port name

BEGIN

75    -- Instantiate the Unit Under Test (UUT)
    uut: ALU_4Bit
    PORT MAP (
        Control => Control,
80        A => A,
        B => B,
        nBitOut => nBitOut,
        CB => CB
    );
85

```

```

-- Stimulus process
stim_proc: process
--create a function to make a vector a string
90  function vec2str(vec : std_logic_vector) return string is
    variable stmp:string(vec'left+1 downto 1);
    begin
        for i in vec'reverse_range loop
            if vec(i) = '1' then
95              stmp(i+1) := '1';
            elsif vec(i) = 'U' then
                stmp(i+1) := 'U';
            else
                stmp(i+1) := '0';
100            end if;
        end loop;
        return stmp;
    end vec2str;

105  procedure check_add(
    constant in1 : in natural;
    constant in2 : in natural;
    constant res_expected : in natural;
    constant CB_expected : in std_logic) is
110  variable res : natural;
    begin
        -- Assign values to circuit inputs.
        A <= std_logic_vector(to_unsigned(in1, A'length));
        B <= std_logic_vector(to_unsigned(in2, B'length));
115  Control <= ADD_Code;

        wait for TIME_DELTA;
        -- Check output against expected result.
120  res := to_integer(unsigned(nBitOut));
        assert ((res = res_expected) and (CB = CB_expected))
        report "" & integer'image(in1) & "+" &
            integer'image(in2) & "=" &
            integer'image(res_expected) & "!=" &
125  integer'image(res) &
            " " &
            "CB exp: " & std_logic'image(CB_expected) &
            "Got: " & std_logic'image(CB)
            severity error;
130  end procedure check_add;

    procedure check_sub(
    constant in1 : in natural;
    constant in2 : in natural;
135  constant res_expected : in natural;
    constant CB_expected : in std_logic) is
    variable res : natural;
    begin
        -- Assign values to circuit inputs.
140  A <= std_logic_vector(to_unsigned(in1, A'length));
        B <= std_logic_vector(to_unsigned(in2, B'length));
        Control <= SUB_Code;

        wait for TIME_DELTA;
145

```

```

-- Check output against expected result.
res := to_integer(unsigned(nBitOut));
assert ((res = res_expected) and ( CB = CB_expected ))
report "" & integer'image(in1) & "-" &
150 integer'image(in2) & "=" &
integer'image(res_expected) & "!=" &
integer'image(res) &
" " &
"CB exp: " & std_logic'image(CB_expected) &
155 "Got: " & std_logic'image(CB)
severity error;
end procedure check_sub;

160 procedure check_or(
constant in1 : in natural;
constant in2 : in natural;
constant res_expected : in natural) is
variable res : natural;
165 begin
-- Assign values to circuit inputs.
A <= std_logic_vector(to_unsigned(in1, A'length));
B <= std_logic_vector(to_unsigned(in2, B'length));
Control <= OR_Code;

170

wait for TIME_DELTA;
-- Check output against expected result.
res := to_integer(unsigned(nBitOut));
175 assert ((res = res_expected) and ( CB = '0' ))
report "" & integer'image(in1) & "+" &
integer'image(in2) & "=" &
integer'image(res_expected) & "!=" &
integer'image(res) &
180 " " &
"CB: " & std_logic'image(CB)
severity error;
end procedure check_or;

185

190 procedure check_and(
constant in1 : in natural;
constant in2 : in natural;
constant res_expected : in natural) is
variable res : natural;
195 begin
-- Assign values to circuit inputs.
A <= std_logic_vector(to_unsigned(in1, A'length));
B <= std_logic_vector(to_unsigned(in2, B'length));
Control <= AND_Code;

200

wait for TIME_DELTA;
-- Check output against expected result.
res := to_integer(unsigned(nBitOut));
report "" & integer'image(in1) & "+" &
integer'image(in2) & "=" &
integer'image(res_expected);

```

```

205     assert ((res = res_expected) and ( CB = '0' ))
        report "!=" &
            integer'image(res) &
                " " &
                "CB: " & std_logic'image(CB)
210     severity error;
end procedure check_and;

begin

215     --wait for the outputs to stabilize
    wait for 100 ns;

    --check_add(4,5,9,0);
    --check_add(65535, 2, 1, 1);
220     --check_sub(1234, 234, 1000, 0);
    --check_sub(1, 2, 1, 1);

    control <= OR_Code;
225     A <= "0111010101110101";
    B <= "1001110100101101";
    wait for 50 ns;

    control <= AND_Code;
230     wait for 50 ns;

    -- Test adder
    for x in (0) to (5) loop
235         for y in 5432 to 5438 loop
            control <= ADD_Code;
            A <= std_logic_vector(to_unsigned(x, A'length));
            B <= std_logic_vector(to_unsigned(y, B'length));
            wait for 50 ns;

240             assert(nBitOut = std_logic_vector(to_unsigned(x+y, A'length) ) )
                report("Bad Add = " & vec2str(nBitOut)
                    & " expected = " & vec2str( std_logic_vector(to_unsigned(x+y, A'
length)) ) )
                    & " A = " & vec2str(A)
                    & " B = " & vec2str(B)
245             );
        end loop;
    end loop;

250     for x in ((2**N)-3) to ((2**N)-1) loop
        for y in 0 to 3 loop
            control <= ADD_Code;
            A <= std_logic_vector(to_unsigned(x, A'length));
            B <= std_logic_vector(to_unsigned(y, B'length));
255             wait for 50 ns;

            assert(nBitOut = std_logic_vector(to_unsigned(x+y, A'length) ) )
                report("Bad Add = " & vec2str(nBitOut)
                    & " expected = " & vec2str( std_logic_vector(to_unsigned(x+y, A'
length)) ) )
                    & " A = " & vec2str(A)
                    & " B = " & vec2str(B)
260             );
        end loop;
    end loop;
end;

```

```

        );
        end loop;
    end loop;
265
-- Test suber
    for x in 0 to 5 loop
        for y in 0 to 5 loop
            control <= SUB.Code;
270
            A <= std_logic_vector(to_unsigned(x, A'length));
            B <= std_logic_vector(to_unsigned(y, B'length));
            wait for 50 ns;

            assert(nBitOut = std_logic_vector(to_signed(x-y, A'length)) )
275
            report("Bad Sub = " & vec2str(nBitOut)
                & " expected = " & vec2str( std_logic_vector(to_signed(x-y, A'length)) )
                & " A = " & vec2str(A)
                & " B = " & vec2str(B)
            );
280
        end loop;
    end loop;

    for x in 12345 to 12350 loop
285
        for y in 5 to 7 loop
            control <= SUB.Code;
            A <= std_logic_vector(to_unsigned(x, A'length));
            B <= std_logic_vector(to_unsigned(y, B'length));
            wait for 50 ns;
290

            assert(nBitOut = std_logic_vector(to_signed(x-y, A'length)) )
            report("Bad Sub = " & vec2str(nBitOut)
                & " expected = " & vec2str( std_logic_vector(to_signed(x-y, A'length)) )
                & " A = " & vec2str(A)
                & " B = " & vec2str(B)
295
            );
        end loop;
    end loop;
300

    wait;
    end process;
305
END;

```

Listing 12: ALU-16Bit VHDL

```

0
--Company      : RIT
--Author       : Brandon Key
--Created      : 02/18/2018
--
5
--Project Name : Lab 3
--File         : ALU_16Bit.vhd
--
--Entity       : ALU_16Bit
--Architecture : struct

```

```

10  --
    --Tool Version : VHDL '93
    --Description  : ALU_16Bit
    -----

15  library IEEE;
    use IEEE.STD_LOGIC_1164.ALL;

    package globals is
        constant N : integer := 16;
20  end globals;

    library IEEE;
    use IEEE.STD_LOGIC_1164.ALL;

25  package controlcodes is
        constant AND_Code : std_logic_vector(1 downto 0) := "00";
        constant OR_Code  : std_logic_vector(1 downto 0) := "01";
        constant ADD_Code : std_logic_vector(1 downto 0) := "10";
30  constant SUB_Code : std_logic_vector(1 downto 0) := "11";
    end controlcodes;

    library IEEE;
35  use IEEE.STD_LOGIC_1164.ALL;
    use IEEE.numeric_std.all;
    use work.controlcodes.all;
    use work.globals.all;

40  entity ALU_16Bit is
        port(
            Control : in std_logic_vector(1 downto 0);
            A,B      : in std_logic_vector(N-1 downto 0);
            nBitOut  : out std_logic_vector(N-1 downto 0);
45  CB           : out std_logic
        );
    end ALU_16Bit;

    architecture struct of ALU_16Bit is
50
        --constant N : integer := 4;

        signal ADD_SUB_Out : std_logic_vector(N-1 downto 0);
        signal OR_Out      : std_logic_vector(N-1 downto 0);
55  signal AND_Out        : std_logic_vector(N-1 downto 0);

        signal ADD_SUB_SEL : std_logic;

60  begin

        nBitAdderSubtractor_16Bit : entity work.nBitAdderSubtractor_16Bit
            generic map (N => N)
            port map ( A => A, B => B, SEL => ADD_SUB_SEL, Y => ADD_SUB_Out, CB => CB);

65  nBitOR_16Bit : entity work.nBitOR_16Bit
            generic map (N => N)

```

```

70     port map ( A => A, B => B, Y => OR_Out);

nBitAND_16Bit : entity work.nBitAND_16Bit
    generic map (N => N)
    port map ( A => A, B => B, Y => AND_Out);
75

Controller_16Bit : entity work.Controller_16Bit
    generic map (N => N)
    port map(
80         Control      => Control,
        ADD_SUB_In    => ADD_SUB_Out,
        OR_In         => OR_Out,
        AND_In        => AND_Out,
        ADD_SUB_SEL    => ADD_SUB_SEL,
        nBitOut       => nBitOut
85     );

end struct;

```

Listing 13: nBitOR-16Bit VHDL

```

0  -----
--Company      : RIT
--Author       : Brandon Key
--Created      : 1/22/2018
--
5  --Project Name : Lab 1
--File         : nBitOR_16Bit.vhd
--
--Entity       : nBitOR_16Bit
--Architecture : Dataflow
10 --
--Tool Version : VHDL '93
--Description  : Entity and structural description of an OR gate
-----

15 library IEEE;
use IEEE.STD_LOGIC_1164.ALL;

entity nBitOR_16Bit is
    generic (n : integer := 16);
20     port(A,B : in std_logic_vector(n-1 downto 0);
        Y : out std_logic_vector(n-1 downto 0)
        );
end nBitOR_16Bit;

25 architecture Dataflow of nBitOR_16Bit is
    begin
        Y <= A or B;-- bitwise or
    end Dataflow;

```

Listing 14: nBitAdderSubtractor-16Bit VHDL

```

0  -----
--Company      : RIT
--Author       : Brandon Key
--Created      : 02/18/2018
--

```

```

5  --Project Name : Lab 3
   --File       : nBitAdderSubtractor_16Bit.vhd
   --
   --Entity      : nBitAdderSubtractor_16Bit
   --Architecture : struct
10  --
   --Tool Version : VHDL '93
   --Description  : Entity and structural description of an adder subtractor
   --              : SEL = 0 : A+B = Y
   --              : SEL = 1 : A-B = Y
15  -----

library IEEE;
use IEEE.STD_LOGIC_1164.ALL;
use IEEE.numeric_std.all;
20
entity nBitAdderSubtractor_16Bit is
    generic (n : integer := 16);
    port(
25        A,B : in  std_logic_vector(n-1 downto 0);
        SEL : in  std_logic;
        Y   : out std_logic_vector(n-1 downto 0);
        CB  : out std_logic
    );
end nBitAdderSubtractor_16Bit;
30
architecture struct of nBitAdderSubtractor_16Bit is

    component full_adder is
        port(A,B,Cin : in  std_logic;
35            Sum,Cout : out std_logic
        );
    end component full_adder;

    --Create an array to hold all of the carries
40    type carry_array is array (n-1 downto 0) of std_logic;
    signal c_array : carry_array;

    signal B_XOR_SEL : std_logic_vector( (n-1) downto 0);

45 begin

    --Generate the xor statements to be mapped to the full adders
    XORator : for i in 0 to n-1 generate
        B_XOR_SEL(i) <= B(i) xor SEL;
50    end generate XORator;

    generate_adders : for i in 0 to n-1 generate
        i_first : if i = 0 generate
            --The first adder gets SEL as the Cin
55            adder : full_adder port map(
                A => A(i),
                B => B_XOR_SEL(i),
                Cin => SEL,
                Sum => Y(i),
                Cout => c_array(i)
60            );
        end generate i_first;

```

```

65     i_last : if i = (n-1) generate
        --The last adder doesn't have a carry out
        adder : full_adder port map(
            A => A(i),
            B => B_XOR_SEL(i),
            Cin => c_array(i-1),
70            Sum => Y(i),
            Cout => c_array(i)
        );
        end generate i_last;

75     --Middle adders
    i_mid : if (i /= 0) and (i /= (n-1)) generate
        adder : full_adder port map(
            A => A(i),
            B => B_XOR_SEL(i),
80            Cin => c_array(i-1),
            Sum => Y(i),
            Cout => c_array(i)
        );
        end generate i_mid;

85     end generate generate_adders;

    CB <= c_array(n-1) xor SEL;

90 end struct;

```

Listing 15: nBitAND-16Bit VHDL

```

0  --Company      : RIT
   --Author       : Brandon Key
   --Created      : 1/22/2018
   --
5  --Project Name : Lab 1
   --File         : nBitAND_16Bit.vhd
   --
   --Entity       : nBitAND_16Bit
   --Architecture : Dataflow
10  --
   --Tool Version : VHDL '93
   --Description  : Entity and structural description of an AND gate
   --
15 library IEEE;
   use IEEE.STD_LOGIC_1164.ALL;

   entity nBitAND_16Bit is
       generic (n : integer := 16);
20       port(A,B : in std_logic_vector(n-1 downto 0);
            Y : out std_logic_vector(n-1 downto 0)
            );
       end nBitAND_16Bit;

25 architecture Dataflow of nBitAND_16Bit is
   begin
       Y <= A AND B; -- bitwise or
   end Dataflow;

```


6.2 SPICE

Listing 16: 1Bit ALU SPICE

```
0 * Example circuit file for simulating PEX

.OPTION DOTNODE
.HIER /

5 .INCLUDE "/home/bxk5113/Pyxis_SPT_HEP/ic_projects/Pyxis_SPT/digicdesign/ALU_1Bit/
  ALU_1Bit.cal/ALU_1Bit.pex.netlist"

.LIB /home/bxk5113/Pyxis_SPT_HEP/ic_reflibs/tech_libs/generic13/models/lib.eldo TT

* - Instantiate your parasitic netlist and add the load capacitor
10 ** FORMAT :
* XLAYOUT [all inputs as listed by the ".subckt" line in the included netlist, in
  the order that they appear there] [name of the subcircuit as listed in the
  included netlist]
XLAYOUT CB Y A B CONTROL[1] CONTROL[0] ALU_1Bit
C1 Y 0 120f
C2 CB 0 120f

15

* - Analysis Setup - DC sweep
* FORMAT : .DC [name] [low] [high] [step]
*.DC VFORCE_A 0 1.2 0.01

20

* - Analysis Setup - Trans
* FORMAT : .TRAN [start time] [end time] [time step]
.TRAN 0 160n 0.001n

25

* --- Forces
* FORMAT --- PULSE : [name] [port] [reference (0 means ground)] PULSE [low] [high] [
  delay] [fall time] [rise time] [pulse width] [period]
*
* FORMAT --- DC : [name] [port] [reference (0 means ground)] DC [voltage]
*

30
VFORCE_A A 0 PULSE (0 1.08 40n 0.1n 0.1n 40n 80n)
VFORCE_B B 0 PULSE (0 1.08 80n 0.1n 0.1n 80n 160n)
VFORCE_C1 CONTROL[1] 0 DC 1.08
VFORCE_C0 CONTROL[0] 0 DC 1.08

35
VFORCE_VDD VDD 0 DC 1.08
VFORCE_VSS VSS 0 DC 0

* --- Waveform Outputs
40 .PLOT TRAN V(A)
.PLOT TRAN V(B)
.PLOT TRAN V(CONTROL[1])
.PLOT TRAN V(CONTROL[0])
.PLOT TRAN V(Y)
45 .PLOT TRAN V(CB)

* --- Params
```

```

.TEMP 125

* — Power Measurement
.measure tran static_pwr AVG power from=90ns to=150ns
.measure tran inst_pwr MAX power from=90ns to=150ns

```

Listing 17: 6Bit ALU SPICE

```

0 * Example circuit file for simulating PEX

.OPTION DOTNODE
.HIER /

5 .INCLUDE "/home/bxk5113/Pyxis_SPT_HEP/ic_projects/Pyxis_SPT/digicdesign/ALU_16Bit/
  ALU_16Bit.cal/ALU_16Bit.pex.netlist"

.LIB /home/bxk5113/Pyxis_SPT_HEP/ic_reflibs/tech_libs/generic13/models/lib.eldo TT

* - Instantiate your parasitic netlist and add the load capacitor
10 ** FORMAT :
* XLAYOUT [all inputs as listed by the ".subckt" line in the included netlist, in
  the order that they appear there] [name of the subcircuit as listed in the
  included netlist]
XLAYOUT CB NBITOUT[15] NBITOUT[14] NBITOUT[13] NBITOUT[12] NBITOUT[11] NBITOUT[10]
  NBITOUT[9] NBITOUT[8] NBITOUT[7] NBITOUT[6] NBITOUT[5] NBITOUT[4] NBITOUT[3]
  NBITOUT[2] NBITOUT[1] NBITOUT[0] A[15] A[14] A[13] A[12] A[11] A[10] A[9] A[8] A
  [7] A[6] A[5] A[4] A[3] A[2] A[1] A[0] B[15] B[14] B[13] B[12] B[11] B[10] B[9] B
  [8] B[7] B[6] B[5] B[4] B[3] B[2] B[1] B[0] CONTROL[1] CONTROL[0] ALU_16Bit

* Output Capacitance
15 C_CB CB 0 120f
C_NBITOUT[15] NBITOUT[15] 0 120f
C_NBITOUT[14] NBITOUT[14] 0 120f
C_NBITOUT[13] NBITOUT[13] 0 120f
C_NBITOUT[12] NBITOUT[12] 0 120f
20 C_NBITOUT[11] NBITOUT[11] 0 120f
C_NBITOUT[10] NBITOUT[10] 0 120f
C_NBITOUT[9] NBITOUT[9] 0 120f
C_NBITOUT[8] NBITOUT[8] 0 120f
C_NBITOUT[7] NBITOUT[7] 0 120f
25 C_NBITOUT[6] NBITOUT[6] 0 120f
C_NBITOUT[5] NBITOUT[5] 0 120f
C_NBITOUT[4] NBITOUT[4] 0 120f
C_NBITOUT[3] NBITOUT[3] 0 120f
C_NBITOUT[2] NBITOUT[2] 0 120f
30 C_NBITOUT[1] NBITOUT[1] 0 120f
C_NBITOUT[0] NBITOUT[0] 0 120f

* - Analysis Setup - DC sweep
35 * FORMAT : .DC [name] [low] [high] [step]
*.DC VFORCE_A 0 1.2 0.01

* - Analysis Setup - Trans
* FORMAT : .TRAN [start time] [end time] [time step]
40 .TRAN 0 400n 0.001n

* — Forces
* FORMAT — PULSE : [name] [port] [reference (0 means ground)] PULSE [low] [high] [

```

```

    delay] [fall time] [rise time] [pulse width] [period]
*
45 * FORMAT — DC      : [name] [port] [reference (0 means ground)] DC [voltage]
*

VFORCE_C1 CONTROL[1] 0 PULSE (0 1.08 40n 0.1n 0.1n 40n 80n)
VFORCE_C0 CONTROL[0] 0 PULSE (0 1.08 20n 0.1n 0.1n 20n 40n)

50 VFORCE_VDD VDD 0 DC 1.08
VFORCE_VSS VSS 0 DC 0

VFORCE_A[0] A[0] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 011001 R
55 VFORCE_A[1] A[1] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 011000 R
VFORCE_A[2] A[2] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 011001 R
VFORCE_A[3] A[3] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 011000 R
VFORCE_A[4] A[4] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 011001 R
VFORCE_A[5] A[5] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 011000 R
60 VFORCE_A[6] A[6] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 011001 R
VFORCE_A[7] A[7] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 011001 R
VFORCE_A[8] A[8] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 011001 R
VFORCE_A[9] A[9] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 011001 R
VFORCE_A[10] A[10] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 011000 R
65 VFORCE_A[11] A[11] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 011000 R
VFORCE_A[12] A[12] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 011001 R
VFORCE_A[13] A[13] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 011001 R
VFORCE_A[14] A[14] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 011000 R
VFORCE_A[15] A[15] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 011101 R
70 VFORCE_B[0] B[0] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 010101 R
VFORCE_B[1] B[1] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 010100 R
VFORCE_B[2] B[2] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 010100 R
VFORCE_B[3] B[3] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 010100 R
VFORCE_B[4] B[4] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 010101 R
75 VFORCE_B[5] B[5] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 010100 R
VFORCE_B[6] B[6] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 010100 R
VFORCE_B[7] B[7] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 010101 R
VFORCE_B[8] B[8] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 010101 R
VFORCE_B[9] B[9] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 010101 R
80 VFORCE_B[10] B[10] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 010101 R
VFORCE_B[11] B[11] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 010100 R
VFORCE_B[12] B[12] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 010101 R
VFORCE_B[13] B[13] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 010101 R
VFORCE_B[14] B[14] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 010101 R
85 VFORCE_B[15] B[15] 0 PBIT 0 1.08 0 0 0.01n 0 0.01n 80n 011111 R

90
* — Waveform Outputs
.PLOT TRAN V(CB)
.PLOT TRAN V(NBITOUT[15])
.PLOT TRAN V(NBITOUT[14])
95 .PLOT TRAN V(NBITOUT[13])
.PLOT TRAN V(NBITOUT[12])
.PLOT TRAN V(NBITOUT[11])
.PLOT TRAN V(NBITOUT[10])
.PLOT TRAN V(NBITOUT[9])
100 .PLOT TRAN V(NBITOUT[8])
.PLOT TRAN V(NBITOUT[7])

```

```

105 .PLOT TRAN V(NBITOUT[6])
.PLOT TRAN V(NBITOUT[5])
.PLOT TRAN V(NBITOUT[4])
.PLOT TRAN V(NBITOUT[3])
.PLOT TRAN V(NBITOUT[2])
.PLOT TRAN V(NBITOUT[1])
.PLOT TRAN V(NBITOUT[0])
.PLOT TRAN V(A[15])
110 .PLOT TRAN V(A[14])
.PLOT TRAN V(A[13])
.PLOT TRAN V(A[12])
.PLOT TRAN V(A[11])
.PLOT TRAN V(A[10])
115 .PLOT TRAN V(A[9])
.PLOT TRAN V(A[8])
.PLOT TRAN V(A[7])
.PLOT TRAN V(A[6])
.PLOT TRAN V(A[5])
120 .PLOT TRAN V(A[4])
.PLOT TRAN V(A[3])
.PLOT TRAN V(A[2])
.PLOT TRAN V(A[1])
.PLOT TRAN V(A[0])
125 .PLOT TRAN V(B[15])
.PLOT TRAN V(B[14])
.PLOT TRAN V(B[13])
.PLOT TRAN V(B[12])
.PLOT TRAN V(B[11])
130 .PLOT TRAN V(B[10])
.PLOT TRAN V(B[9])
.PLOT TRAN V(B[8])
.PLOT TRAN V(B[7])
.PLOT TRAN V(B[6])
135 .PLOT TRAN V(B[5])
.PLOT TRAN V(B[4])
.PLOT TRAN V(B[3])
.PLOT TRAN V(B[2])
.PLOT TRAN V(B[1])
140 .PLOT TRAN V(B[0])
.PLOT TRAN V(CONTROL[1])
.PLOT TRAN V(CONTROL[0])

145 * — Params
.TEMP 125

* — Power Measurement
.measure tran static_pwr AVG power from=90ns to=150ns
150 .measure tran inst_pwr MAX power from=90ns to=150ns

```