University of Dublin,
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Computer Architecture I (CS2022)

Project 2 - Microcoded Instruction Set Processor

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Contents

1 VHDL Component Source Code

1.1 ALU Unit

```
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;

entity alu_unit is
   Port(
      a_in, b_in : in STD_LOGIC_VECTOR(15 downto 0);
      G_select : in STD_LOGIC_VECTOR(3 downto 0);
      V, C : out STD_LOGIC; -- flags
      G : out STD_LOGIC_VECTOR(15 downto 0)
   );

end alu_unit;

architecture Behavioral of alu_unit is

   --components in ALU
   --ripple adder
   Component RippleAdder
      Port(
         A, B : in STD_LOGIC_VECTOR(15 downto 0);
         Cin : in STD_LOGIC;
         Cout, V_out : out STD_LOGIC;
         G_out : out STD_LOGIC_VECTOR(15 downto 0)
      );
   End Component;
   --a b logic for and or xor not
   Component logic_circuit_a_b
      Port(
         a_logic_in, b_logic_in : in STD_LOGIC_VECTOR(15 downto 0);
         select_in : in STD_LOGIC_VECTOR(1 downto 0);
         logic_output_a_b : out STD_LOGIC_VECTOR(15 downto 0)
      );
   End Component;
   --b logic circuit
   Component logic_circuit_b
      Port(
         B : in STD_LOGIC_VECTOR(15 downto 0);
         S_in : in STD_LOGIC_VECTOR(1 downto 0);
         Y_out : out STD_LOGIC_VECTOR(15 downto 0)
      );
   End Component;
   --2-1 mux
   Component Mux2to16
      Port(
         In0, In1 : in STD_LOGIC_VECTOR(15 downto 0);
         s : in STD_LOGIC;
         Z : out STD_LOGIC_VECTOR(15 downto 0)
      );
   End Component;

   signal logic_out, logic_output_a_b, ripple_out : STD_LOGIC_VECTOR(15 downto 0);
```

```
begin
   --instantiation of components
   r_adder: RippleAdder PORT MAP(
         A => a_in,
         B => b_in,
         Cin => G_select(0),
         Cout => C,
         V_out => V,
         G_out => ripple_out
   );

   logic_circuit_a_b00: logic_circuit_a_b PORT MAP(
         a_logic_in => a_in,
         b_logic_in => b_in,
         select_in => G_select(2 downto 1),
         logic_output_a_b => logic_output_a_b
   );

   logic_circuit_b00 : logic_circuit_b PORT MAP(
         B => b_in,
         S_in => G_select(2 downto 1),
         Y_out => logic_out
   );

   mux_2_1600: Mux2to16 PORT MAP(
         In0 => ripple_out,
         In1 => logic_output_a_b,
         s => G_select(3),
         Z => G
   );

end Behavioral;
```

1.2 Control Address Register

```
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;
use IEEE.STD_LOGIC_ARITH.ALL;
use IEEE.STD_LOGIC_UNSIGNED.ALL;

entity ControlAddressRegister is
   Port( car_in : in STD_LOGIC_VECTOR(7 downto 0);
         s_car, reset : in STD_LOGIC;
         car_out : out STD_LOGIC_VECTOR(7 downto 0)
         );
end ControlAddressRegister;

architecture Behavioral of ControlAddressRegister is

begin
   process(reset, car_in)
   variable curr_car : STD_LOGIC_VECTOR(7 downto 0);
   variable temp_curr_car : integer;
   variable temp_inc_car : STD_LOGIC_VECTOR(7 downto 0);
```

```
   begin
      if(reset = '1') then curr_car := x"C0";
      elsif(s_car = '1') then curr_car := car_in;
      elsif(s_car = '0') then
         temp_curr_car := conv_integer(curr_car);
         temp_curr_car := temp_curr_car + conv_integer(1);
         temp_inc_car := conv_std_logic_vector(temp_curr_car, 8);
         curr_car := temp_inc_car;
      end if;
      car_out <= curr_car after 20ns;
   end process;
end Behavioral;
```

1.3 Control Memory

```
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;
use IEEE.STD_LOGIC_ARITH.ALL;
use IEEE.STD_LOGIC_UNSIGNED.ALL;

entity ControlMemory is
   Port( in_car : in STD_LOGIC_VECTOR(7 downto 0);
         MW, MM, RW, MD, MB, TB, TA, TD, PL, PI, IL, MC : out STD_LOGIC;
         FS_cm : out STD_LOGIC_VECTOR(4 downto 0);
         MS_cm : out STD_LOGIC_VECTOR(2 downto 0);
         NA : out STD_LOGIC_VECTOR(7 downto 0)
         );
end ControlMemory;

architecture Behavioral of ControlMemory is
   --instantiate an array for each given memory allocation
   type mem_array is array(0 to 255) of STD_LOGIC_VECTOR(27 downto 0);

begin
   memory_m : process(in_car)
   variable ControlMemory : mem_array := (
   --Module 0
   x"C020304", --0 start of intermediate value in register
   x"C020304", --1 immediate value in register
   x"C020304", --2 immediate value in register
   x"C020304", --3 immediate value in register
   x"C020304", --4 immediate value in register
   x"C020304", --5 immediate value in register
   x"C020304", --6 immediate value in register
   x"C020304", --7 end of immediate value in register
   x"C020224", --8 ADI -> add the immediate operand
   x"C02000C", --9 LDR -> load to register
   x"C020001", --A STR -> store in register
   x"C020014", --B INC -> increment the register's value by 1
   x"C0200E4", --C NOT -> compliment
   x"C020024", --D ADD -> add values from source and destination
   x"1228002", --E B -> branch unconditionally
   x"0000000", --F
```

```
--Module 1
x"0000000", --0
x"0000000", --1
x"C020000", --2
x"C020024", --3 ADD -> add values from source and destination
x"169A002", --4 BXX -> branch conditionally to area
x"C020024", --5 ADD -> add values from source and destination
x"C020024", --6 ADD -> add values from source and destination
x"C020024", --7
x"0000000", --8
x"0000000", --9
x"0000000", --A
x"0000000", --B
x"0000000", --C
x"0000000", --D
x"0000000", --E
x"0000000", --F

--Module 2
x"0000000", --0
x"0000000", --1
x"0000000", --2
x"0000000", --3
x"0000000", --4
x"0000000", --5
x"0000000", --6
x"0000000", --7
x"0000000", --8
x"0000000", --9
x"0000000", --A
x"0000000", --B
x"0000000", --C
x"0000000", --D
x"0000000", --E
x"0000000", --F

--Module 3
x"0000000", --0
x"0000000", --1
x"0000000", --2
x"0000000", --3
x"0000000", --4
x"0000000", --5
x"0000000", --6
x"0000000", --7
x"0000000", --8
x"0000000", --9
x"0000000", --A
x"0000000", --B
x"0000000", --C
x"0000000", --D
x"0000000", --E
x"0000000", --F

--Module 4
```

```
x"0000000", --0
x"0000000", --1
x"0000000", --2
x"0000000", --3
x"0000000", --4
x"0000000", --5
x"0000000", --6
x"0000000", --7
x"0000000", --8
x"0000000", --9
x"0000000", --A
x"0000000", --B
x"0000000", --C
x"0000000", --D
x"0000000", --E
x"0000000", --F

--Module 5
x"0000000", --0
x"0000000", --1
x"0000000", --2
x"0000000", --3
x"0000000", --4
x"0000000", --5
x"0000000", --6
x"0000000", --7
x"0000000", --8
x"0000000", --9
x"0000000", --A
x"0000000", --B
x"0000000", --C
x"0000000", --D
x"0000000", --E
x"0000000", --F

--Module 6
x"0000000", --0
x"0000000", --1
x"0000000", --2
x"0000000", --3
x"0000000", --4
x"0000000", --5
x"0000000", --6
x"0000000", --7
x"0000000", --8
x"0000000", --9
x"0000000", --A
x"0000000", --B
x"0000000", --C
x"0000000", --D
x"0000000", --E
x"0000000", --F

--Module 7
x"0000000", --0
```

```
x"0000000", --1
x"0000000", --2
x"0000000", --3
x"0000000", --4
x"0000000", --5
x"0000000", --6
x"0000000", --7
x"0000000", --8
x"0000000", --9
x"0000000", --A
x"0000000", --B
x"0000000", --C
x"0000000", --D
x"0000000", --E
x"0000000", --F

--Module 8
x"0000000", --0
x"0000000", --1
x"0000000", --2
x"0000000", --3
x"0000000", --4
x"0000000", --5
x"0000000", --6
x"0000000", --7
x"0000000", --8
x"0000000", --9
x"0000000", --A
x"0000000", --B
x"0000000", --C
x"0000000", --D
x"0000000", --E
x"0000000", --F

--Module 9
x"0000000", --0
x"0000000", --1
x"0000000", --2
x"0000000", --3
x"0000000", --4
x"0000000", --5
x"0000000", --6
x"0000000", --7
x"0000000", --8
x"0000000", --9
x"0000000", --A
x"0000000", --B
x"0000000", --C
x"0000000", --D
x"0000000", --E
x"0000000", --F

--Module A
x"0000000", --0
x"0000000", --1
```

```
x"0000000", --2
x"0000000", --3
x"0000000", --4
x"0000000", --5
x"0000000", --6
x"0000000", --7
x"0000000", --8
x"0000000", --9
x"0000000", --A
x"0000000", --B
x"0000000", --C
x"0000000", --D
x"0000000", --E
x"0000000", --F

--Module B
x"0000000", --0
x"0000000", --1
x"0000000", --2
x"0000000", --3
x"0000000", --4
x"0000000", --5
x"0000000", --6
x"0000000", --7
x"0000000", --8
x"0000000", --9
x"0000000", --A
x"0000000", --B
x"0000000", --C
x"0000000", --D
x"0000000", --E
x"0000000", --F

--Module C
x"C10C002", --0 IF fetching
x"0030000", --1 Exit signal
x"0000000", --2
x"0000000", --3
x"0000000", --4
x"0000000", --5
x"0000000", --6
x"0000000", --7
x"0000000", --8
x"0000000", --9
x"0000000", --A
x"0000000", --B
x"0000000", --C
x"0000000", --D
x"0000000", --E
x"0000000", --F

--Module D
x"0000000", --0
x"0000000", --1
x"0000000", --2
```

```
    x"0000000", --3
    x"0000000", --4
    x"0000000", --5
    x"0000000", --6
    x"0000000", --7
    x"0000000", --8
    x"0000000", --9
    x"0000000", --A
    x"0000000", --B
    x"0000000", --C
    x"0000000", --D
    x"0000000", --E
    x"0000000", --F

    --Module E
    x"0000000", --0
    x"0000000", --1
    x"0000000", --2
    x"0000000", --3
    x"0000000", --4
    x"0000000", --5
    x"0000000", --6
    x"0000000", --7
    x"0000000", --8
    x"0000000", --9
    x"0000000", --A
    x"0000000", --B
    x"0000000", --C
    x"0000000", --D
    x"0000000", --E
    x"0000000", --F

    --Module F
    x"0000000", --0
    x"0000000", --1
    x"0000000", --2
    x"0000000", --3
    x"0000000", --4
    x"0000000", --5
    x"0000000", --6
    x"0000000", --7
    x"0000000", --8
    x"0000000", --9
    x"0000000", --A
    x"0000000", --B
    x"0000000", --C
    x"0000000", --D
    x"0000000", --E
    x"0000000" --F
    );

variable addr : integer;
variable control_out : STD_LOGIC_VECTOR(27 downto 0);

begin
```

```
   addr := conv_integer(in_car);
   control_out := ControlMemory(addr);
   MW <= control_out(0);
   MM <= control_out(1);
   RW <= control_out(2);
   MD <= control_out(3);
   FS_cm <= control_out(8 downto 4);
   MB <= control_out(9);

   TB <= control_out(10);
   TA <= control_out(11);
   TD <= control_out(12);
   PL <= control_out(13);
   PI <= control_out(14);
   IL <= control_out(15);
   MC <= control_out(16);
   MS_cm <= control_out(19 downto 17);
   NA <= control_out(27 downto 20);
end process;

end Behavioral;
```

1.4 Datapath

```
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;

entity Datapath is
   Port( data_in, pc_in : in STD_LOGIC_VECTOR(15 downto 0);
         control_word : in STD_LOGIC_VECTOR(17 downto 0);
         clk_sig, TD, TA, TB : in STD_LOGIC;
         data_out, addr_out : out STD_LOGIC_VECTOR(15 downto 0);
         status_out : out STD_LOGIC_VECTOR(3 downto 0)
         );
end Datapath;

architecture Behavioral of Datapath is

   component RegFile
      Port( des_d, add_a, add_b : in STD_LOGIC_VECTOR(3 downto 0);
            Clk, load_in : in STD_LOGIC;
            data : in STD_LOGIC_VECTOR(15 downto 0);
            out_data_a, out_data_b : out STD_LOGIC_VECTOR(15 downto 0)
            );
   end component;

   component Mux2to16
      Port( In0, In1 : in STD_LOGIC_VECTOR(15 downto 0);
            s : in STD_LOGIC;
            Z : out STD_LOGIC_VECTOR(15 downto 0)
            );
   end component;

   component ZeroFill
      Port( SB_in : in STD_LOGIC_VECTOR(2 downto 0);
```

```
            zero_fill_out : out STD_LOGIC_VECTOR(15 downto 0)
            );
    end component;

    component FunctionUnit
        Port( FunctionSelect : in STD_LOGIC_VECTOR(4 downto 0);
              a_in, b_in : in STD_LOGIC_VECTOR(15 downto 0);
              N_fu, Z_fu, V_fu, C_fu : out STD_LOGIC;
              F : out STD_LOGIC_VECTOR(15 downto 0)
              );
    end component;

    signal mux_b_out, mux_d_out, mux_m_out, reg_file_out_a, reg_file_out_b, func_unit_out,
        zero_fill_out, pc_sig : STD_LOGIC_VECTOR(15 downto 0);
    signal dest_d, addr_a, addr_b, status_bits : STD_LOGIC_VECTOR(3 downto 0);

begin

    mux_b : Mux2to16 PORT MAP(
        In0 => reg_file_out_b,
        In1 => zero_fill_out,
        s => control_word(8),
        Z => mux_b_out
    );

    mux_d : Mux2to16 PORT MAP(
        In0 => func_unit_out,
        In1 => data_in,
        s => control_word(2),
        Z => mux_d_out
    );

    pc_sig <= pc_in;

    mux_m : Mux2to16 PORT MAP(
        In0 => reg_file_out_a,
        In1 => pc_sig,
        s => control_word(0),
        Z => mux_m_out
    );

    dest_d <= TD & control_word(17 downto 15);
    addr_a <= TA & control_word(14 downto 12);
    addr_b <= TB & control_word(11 downto 9);

    zero_fill : ZeroFill PORT MAP(
        SB_in => control_word(11 downto 9),
        zero_fill_out => zero_fill_out
    );

    reg_file : RegFile PORT MAP(
        des_d => dest_d,
        add_a => addr_a,
        add_b => addr_b,
        Clk => clk_sig,
```

```
      load_in => control_word(1),
      data => mux_d_out,
      out_data_a => reg_file_out_a,
      out_data_b => reg_file_out_b
   );

   data_out <= mux_b_out;
   addr_out <= mux_m_out;

   func_unit : FunctionUnit PORT MAP(
      FunctionSelect => control_word(7 downto 3),
      a_in => reg_file_out_a,
      b_in => mux_b_out,
      N_fu => status_bits(1),
      Z_fu => status_bits(0),
      V_fu => status_bits(3),
      C_fu => status_bits(2),
      F => func_unit_out
   );

   status_out <= status_bits;

end Behavioral;
```

1.5 Decoder 4-9 Bit

```
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;

entity Decoder4to9 is
   Port( A0, A1, A2, A3 : in STD_LOGIC;
         Q0, Q1, Q2, Q3, Q4, Q5, Q6, Q7, Q8 : out STD_LOGIC
         );
end Decoder4to9;

architecture Behavioral of Decoder4to9 is

begin
   Q0 <= ((not A0) and (not A1) and (not A2) and (not A3)) after 1ns; --0000
   Q1 <= ((A0) and (not A1) and (not A2) and (not A3)) after 1ns; --1000
   Q2 <= ((not A0) and (A1) and (not A2) and (not A3)) after 1ns; --0100
   Q3 <= ((A0) and (A1) and (not A2) and (not A3)) after 1ns; --1100
   Q4 <= ((not A0) and (not A1) and (A2) and (not A3)) after 1ns; --0010
   Q5 <= ((A0) and (not A1) and (A2) and (not A3)) after 1ns; --1010
   Q6 <= ((not A0) and (A1) and (A2) and (not A3)) after 1ns; --0110
   Q7 <= ((A0) and (A1) and (A2) and (not A3)) after 1ns; --1110
   Q8 <= ((not A0) and (not A1) and (not A2) and (A3)) after 1ns; --0001

end Behavioral;
```

1.6 Extended Programme Counter

```
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;

entity ExtendedProgrammeCounter is
   Port( SR_SB : in STD_LOGIC_VECTOR(5 downto 0);
         ExtendedProgrammeCounter : out STD_LOGIC_VECTOR(15 downto 0)
         );
end ExtendedProgrammeCounter;

architecture Behavioral of ExtendedProgrammeCounter is
   signal extended_signal : STD_LOGIC_VECTOR(15 downto 0);
begin
   extended_signal(5 downto 0) <= SR_SB;
   extended_signal(15 downto 6) <= "0000000000" when SR_SB(5) = '0' else "1111111111";
   ExtendedProgrammeCounter <= extended_signal;

end Behavioral;
```

1.7 Full Adder

```
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;

entity FullAdder is
   Port(
         X, Y, Cin : in STD_LOGIC;
         Cout, S : out STD_LOGIC
      );
end FullAdder;

architecture Behavioral of FullAdder is
   signal S0, S1, S2 : STD_LOGIC;
begin
   S0 <= (X xor Y) after 1ns;
   S1 <= (Cin and S0) after 1ns;
   S2 <= (X and Y) after 1ns;
   S <= (S0 xor Cin) after 1ns;
   Cout <= (S1 or S2) after 1ns;

end Behavioral;
```

1.8 Function Unit

```
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;

entity FunctionUnit is
   Port(
      FunctionSelect : in STD_LOGIC_VECTOR(4 downto 0); -- 5 input
      a_in, b_in : in STD_LOGIC_VECTOR(15 downto 0);
      N_fu, Z_fu, V_fu, C_fu : out STD_LOGIC;
      F : out STD_LOGIC_VECTOR(15 downto 0)
   );
```

```
end FunctionUnit;

architecture Behavioral of FunctionUnit is

   --2 to 1 mux
   Component Mux2to16
      Port(
         In0, In1 : in STD_LOGIC_VECTOR(15 downto 0);
         s : in STD_LOGIC;
         Z : out STD_LOGIC_VECTOR(15 downto 0)
      );
   End Component;
   --shifter
   Component shifter
      Port(
         B : in STD_LOGIC_VECTOR(15 downto 0);
         S : in STD_LOGIC_VECTOR(1 downto 0);
         IL, IR : in STD_LOGIC;
         H : out STD_LOGIC_VECTOR(15 downto 0)
      );
   End Component;
   --alu
   Component alu_unit
      Port(
         a_in, b_in : in STD_LOGIC_VECTOR(15 downto 0);
         G_select : in STD_LOGIC_VECTOR(3 downto 0);
         V, C : out STD_LOGIC; -- flags
         G : out STD_LOGIC_VECTOR(15 downto 0)
      );
   End Component;

   signal H_out, ALU_out, mux_out : STD_LOGIC_VECTOR(15 downto 0);

begin
   shifter00: shifter PORT MAP(
      B => b_in,
      S => FunctionSelect(3 downto 2),
      IL => '0',
      IR => '0',
      H => H_out
   );

   mux_2_1600: Mux2to16 PORT MAP(
      In0 => ALU_out,
      In1 => H_out,
      s => FunctionSelect(4),
      z => mux_out
   );

   alu: alu_unit PORT MAP(
      a_in => a_in,
      b_in => b_in,
      G_select => FunctionSelect(3 downto 0),
      V => V_fu,
      C => C_fu,
```

```
      G => ALU_out
   );

   F <= mux_out;
   N_fu <= mux_out(15);
   Z_fu <= (mux_out(15) or mux_out(14) or mux_out(13) or mux_out(12) or mux_out(11)
           or mux_out(10) or mux_out(9) or mux_out(8) or mux_out(7) or mux_out(6)
           or mux_out(5) or mux_out(4) or mux_out(3) or mux_out(2) or mux_out(1) or
               mux_out(0));

end Behavioral;
```

1.9 Instruction Register

```
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;

entity Instructions is
   Port( IR_in : in STD_LOGIC_VECTOR(15 downto 0);
         IL_in : in STD_LOGIC;
         Opcode : out STD_LOGIC_VECTOR(6 downto 0);
         DR_out, SA_out, SB_out : out STD_LOGIC_VECTOR(2 downto 0)
         );
end Instructions;

architecture Behavioral of Instructions is

begin
   Opcode <= IR_in(15 downto 9) after 1ns when IL_in = '1';
   DR_out <= IR_in(8 downto 6) after 1ns when IL_in = '1';
   SA_out <= IR_in(5 downto 3) after 1ns when IL_in = '1';
   SB_out <= IR_in(2 downto 0) after 1ns when IL_in = '1';

end Behavioral;
```

1.10 Logic Circuit A-B

```
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;

entity logic_circuit_a_b is
   Port(
      a_logic_in, b_logic_in : in STD_LOGIC_VECTOR(15 downto 0);
      select_in : in STD_LOGIC_VECTOR(1 downto 0);
      logic_output_a_b : out STD_LOGIC_VECTOR(15 downto 0)
   );
end logic_circuit_a_b;

architecture Behavioral of logic_circuit_a_b is

begin
   logic_output_a_b <=  (a_logic_in and b_logic_in) after 1ns when select_in = "00" else
                        (a_logic_in or b_logic_in) after 1ns when select_in = "01" else
                        (a_logic_in xor b_logic_in) after 1ns when select_in = "10" else
                        (not (a_logic_in)) after 1ns;
```

```
end Behavioral;
```

1.11 Logic Circuit B

```
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;

entity logic_circuit_b is
   Port(
      B : in STD_LOGIC_VECTOR(15 downto 0);
      S_in : in STD_LOGIC_VECTOR(1 downto 0);
      Y_out : out STD_LOGIC_VECTOR(15 downto 0)
   );
end logic_circuit_b;

architecture Behavioral of logic_circuit_b is

   --mux 2-1 component
   Component Mux2to1
   Port(
      B_i, S0, S1 : in STD_LOGIC;
      Y_i : out STD_LOGIC
   );
   End Component;

begin
   mux00: Mux2to1 PORT MAP(
      B_i => B(0),
      S0 => S_in(0),
      S1 => S_in(1),
      Y_i => Y_out(0)
   );

   mux01: Mux2to1 PORT MAP(
      B_i => B(1),
      S0 => S_in(0),
      S1 => S_in(1),
      Y_i => Y_out(1)
   );

   mux02: Mux2to1 PORT MAP(
      B_i => B(2),
      S0 => S_in(0),
      S1 => S_in(1),
      Y_i => Y_out(2)
   );

   mux03: Mux2to1 PORT MAP(
      B_i => B(3),
      S0 => S_in(0),
      S1 => S_in(1),
      Y_i => Y_out(3)
   );
```

```
    mux04: Mux2to1 PORT MAP(
        B_i => B(4),
        S0 => S_in(0),
        S1 => S_in(1),
        Y_i => Y_out(4)
    );

    mux05: Mux2to1 PORT MAP(
        B_i => B(5),
        S0 => S_in(0),
        S1 => S_in(1),
        Y_i => Y_out(5)
    );

    mux06: Mux2to1 PORT MAP(
        B_i => B(6),
        S0 => S_in(0),
        S1 => S_in(1),
        Y_i => Y_out(6)
    );

    mux07: Mux2to1 PORT MAP(
        B_i => B(7),
        S0 => S_in(0),
        S1 => S_in(1),
        Y_i => Y_out(7)
    );

    mux08: Mux2to1 PORT MAP(
        B_i => B(8),
        S0 => S_in(0),
        S1 => S_in(1),
        Y_i => Y_out(8)
    );

    mux09: Mux2to1 PORT MAP(
        B_i => B(9),
        S0 => S_in(0),
        S1 => S_in(1),
        Y_i => Y_out(9)
    );

    mux10: Mux2to1 PORT MAP(
        B_i => B(10),
        S0 => S_in(0),
        S1 => S_in(1),
        Y_i => Y_out(10)
    );

end Behavioral;
```

1.12 Memory Module

```
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;
use IEEE.STD_LOGIC_ARITH.ALL;
use IEEE.STD_LOGIC_UNSIGNED.ALL;

entity Memory is
   Port( address_mem : in STD_LOGIC_VECTOR(15 downto 0);
         write_data : in STD_LOGIC_VECTOR(15 downto 0);
         mem_write : in STD_LOGIC;
         read_data : out STD_LOGIC_VECTOR(15 downto 0)
         );
end Memory;

architecture Behavioral of Memory is
   --512 bit memory array
   type mem_array is array(0 to 511) of STD_LOGIC_VECTOR(15 downto 0);
begin
   mem_process : process(address_mem, write_data, mem_write)
   variable data_mem : mem_array := (
      --module 00
      x"0000", --0
      x"0000", --1 store in reg 0
      x"0241", --2 store in reg 1
      x"0482", --3 store in reg 2
      x"06C3", --4 store in reg 3
      x"0904", --5 store in reg 4
      x"0B45", --6 store in reg 5
      x"0D86", --7 store in reg 6
      x"0FC7", --8 store in reg 7
      x"11BE", --9 ADD -> add operands
      x"1230", --A LDR -> load to r0 from memory
      x"1401", --B STR -> store from r1 into memory address
      x"1650", --C INC -> increment value in r2 by 1 and store in r1
      x"1928", --D CMP -> compliment value in r5 and store in r4
      x"1A9B", --E ADD -> adds values and stores into r2 via r3
      x"1C52", --F BCH -> branch unconditionally

      --module 01
      x"2652", --0 ADD STR r1 -> add and store into r1
      x"2802", --1 BCZ -> branch conditionally if z is set, skipping the next add instruction
      x"2A5B", --2 ADD STR r1 -> add and stores into r1
      x"2D9B", --3 ADD STR r6 -> add and stores into r6
      x"2F9B", --4 ADD STR r6 -> add and stores into r6
      x"0000",
      x"0000",
      x"0000",
      x"0000",
      x"0000",
      x"0000",
      x"0000",
      x"0000",
      x"0000",
      x"0000",
```

```
x"0000",

--module 02
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",

--module 03
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",

--module 04
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",

--module 05
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",

--module 06
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",

--module 07
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",

--module 08
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",

--module 09
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",

--module 0A
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
```

```
--module 0B
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",

--module 0C
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",

--module 0D
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",

--module 0E
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",

--module 0F
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",

--module 10
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",

--module 11
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",

--module 12
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",

--module 13
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
```

```
--module 14
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",

--module 15
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",

--module 16
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",

--module 17
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",

--module 18
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",

--module 19
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",

--module 1A
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",

--module 1B
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",

--module 1C
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",
x"0000", x"0000", x"0000", x"0000",

--module 1D
```

```
      x"0000", x"0000", x"0000", x"0000",
      x"0000", x"0000", x"0000", x"0000",
      x"0000", x"0000", x"0000", x"0000",
      x"0000", x"0000", x"0000", x"0000",

      --module 1E
      x"0000", x"0000", x"0000", x"0000",
      x"0000", x"0000", x"0000", x"0000",
      x"0000", x"0000", x"0000", x"0000",
      x"0000", x"0000", x"0000", x"0000",

      --module 1F
      x"0000", x"0000", x"0000", x"0000",
      x"0000", x"0000", x"0000", x"0000",
      x"0000", x"0000", x"0000", x"0000",
      x"0000", x"0000", x"0000", x"0000"
   );

   variable addr : integer range 0 to 511;
   variable addr_out : STD_LOGIC_VECTOR(15 downto 0);

   begin
      addr := conv_integer(address_mem(8 downto 0));
      addr_out := data_mem(addr);
      if mem_write = '1' then
         data_mem(addr) := write_data;
      else read_data <= addr_out;
      end if;
   end process;

end Behavioral;
```

1.13 Microprogramme Controller

```
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;

entity MicroprogrammeController is
   Port( IR : in STD_LOGIC_VECTOR(15 downto 0);
         status_bits : in STD_LOGIC_VECTOR(3 downto 0);
         reset_mpc : in STD_LOGIC;
         control_word_mpc : out STD_LOGIC_VECTOR(17 downto 0);
         PC_out : out STD_LOGIC_VECTOR(15 downto 0);
         TD_mpc, TA_mpc, TB_mpc, MW_mpc : out STD_LOGIC
         );
end MicroprogrammeController;

architecture Behavioral of MicroprogrammeController is
   component ControlMemory
      Port( in_car : in STD_LOGIC_VECTOR(7 downto 0);
            MW, MM, RW, MD, MB, TB, TA, TD, PL, PI, IL, MC : out STD_LOGIC;
            FS_cm : out STD_LOGIC_VECTOR(4 downto 0);
            MS_cm : out STD_LOGIC_VECTOR(2 downto 0);
            NA : out STD_LOGIC_VECTOR(7 downto 0)
            );
```

```
    end component;

    component Mux2to8
        Port( In0_NA, In1_opcode : in STD_LOGIC_VECTOR(7 downto 0);
              S_mc : in STD_LOGIC;
              out_car : out STD_LOGIC_VECTOR(7 downto 0)
              );
    end component;

    component Mux8to1
        Port( In_zero, In_one, In_n, In_z, In_c, In_v, In_not_c, In_not_z : in STD_LOGIC;
              S_ms : in STD_LOGIC_VECTOR(2 downto 0);
              out_s_car : out STD_LOGIC
              );
    end component;

    component ControlAddressRegister
        Port( car_in : in STD_LOGIC_VECTOR(7 downto 0);
              s_car, reset : in STD_LOGIC;
              car_out : out STD_LOGIC_VECTOR(7 downto 0)
              );
    end component;

    component Instructions
        Port( IR_in : in STD_LOGIC_VECTOR(15 downto 0);
              IL_in : in STD_LOGIC;
              Opcode : out STD_LOGIC_VECTOR(6 downto 0);
              DR_out, SA_out, SB_out : out STD_LOGIC_VECTOR(2 downto 0)
              );
    end component;

    component ProgrammeCounter
        Port( PC_module_in : in STD_LOGIC_VECTOR(15 downto 0);
              PL_module_in, PI_module_in, reset : in STD_LOGIC;
              PC_module_out : out STD_LOGIC_VECTOR(15 downto 0)
              );
    end component;

    component ExtendedProgrammeCounter
        Port( SR_SB : in STD_LOGIC_VECTOR(5 downto 0);
              ExtendedProgrammeCounter : out STD_LOGIC_VECTOR(15 downto 0)
              );
    end component;

    --signalling
    signal control_word_sig : STD_LOGIC_VECTOR(17 downto 0);
    signal opcode_sig, car_out_sig, out_car_sig, na_sig : STD_LOGIC_VECTOR(7 downto 0);
    signal out_s_car_sig, mc_sig, il_sig, pl_sig, pi_sig : STD_LOGIC;
    signal ms_cm_sig, sa_sig, sb_sig, dr_sig : STD_LOGIC_VECTOR(2 downto 0);
    signal extend_in : STD_LOGIC_VECTOR(5 downto 0);
    signal extend_out : STD_LOGIC_VECTOR(15 downto 0);

begin
    control_mem_mpc : ControlMemory PORT MAP(
        in_car => car_out_sig,
```

```
   MW => mw_mpc,
   MM => control_word_sig(0),
   RW => control_word_sig(1),
   MD => control_word_sig(2),
   MB => control_word_sig(8),
   TB => tb_mpc,
   TA => ta_mpc,
   TD => td_mpc,
   PL => pl_sig,
   PI => pi_sig,
   IL => il_sig,
   MC => mc_sig,
   FS_cm => control_word_sig(7 downto 3),
   MS_cm => ms_cm_sig,
   NA => na_sig
);

mux2to8_mpc : mux2to8 PORT MAP(
   In0_NA => na_sig,
   In1_opcode => opcode_sig,
   S_mc => mc_sig,
   out_car => out_car_sig
);

mux8to1_mpc : Mux8to1 PORT MAP(
   In_zero => '0',
   In_one => '1',
   In_z => status_bits(0),
   In_n => status_bits(1),
   In_c => status_bits(2),
   In_v => status_bits(3),
   In_not_z => not status_bits(0),
   In_not_c => not status_bits(2),
   S_ms => ms_cm_sig,
   out_s_car => out_s_car_sig
);

car_mpc : ControlAddressRegister PORT MAP(
   car_in => out_car_sig,
   s_car => out_s_car_sig,
   reset => reset_mpc,
   car_out => car_out_sig
);

instructions_mpc : Instructions PORT MAP(
   IR_in => IR,
   IL_in => il_sig,
   Opcode => opcode_sig(6 downto 0),
   DR_out => dr_sig,
   SA_out => sa_sig,
   SB_out => sb_sig
);

extended_mpc : ExtendedProgrammeCounter PORT MAP(
   SR_SB => extend_in,
```

```
      ExtendedProgrammeCounter => extend_out
   );

   pc_mpc : ProgrammeCounter PORT MAP(
      PC_module_in => extend_out,
      PL_module_in => pl_sig,
      PI_module_in => pi_sig,
      reset => reset_mpc,
      PC_module_out => pc_out
   );

   extend_in(5 downto 3) <= dr_sig;
   extend_in(2 downto 0) <= sb_sig;
   opcode_sig(7) <= '0';

   control_word_sig(17 downto 15) <= dr_sig;
   control_word_sig(14 downto 12) <= sa_sig;
   control_word_sig(11 downto 9) <= sb_sig;
   control_word_mpc <= control_word_sig;

end Behavioral;
```

1.14 Mux 2-1 Bit

```
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;

entity Mux2to1 is
   Port(
        B_i, S0, S1 : in STD_LOGIC;
        Y_i : out STD_LOGIC
      );
end Mux2to1;

architecture Behavioral of Mux2to1 is

begin
   Y_i <=  S0 after 1ns when B_i = '1' else
           S1 after 1ns when B_i = '0' else
           '0' after 1ns;

end Behavioral;
```

1.15 Mux 2-8 Bit

```
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;

entity Mux2to8 is
   Port( In0_NA, In1_opcode : in STD_LOGIC_VECTOR(7 downto 0);
        S_mc : in STD_LOGIC;
        out_car : out STD_LOGIC_VECTOR(7 downto 0)
        );
end Mux2to8;
```

```
architecture Behavioral of Mux2to8 is

begin
   out_car <=  In0_NA after 1ns when S_mc='0' else
               In1_opcode after 1ns when S_mc='1' else
               x"00" after 20ns;

end Behavioral;
```

1.16 Mux 2-16 Bit

```
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;

entity Mux2to16 is
   Port( In0, In1 : in STD_LOGIC_VECTOR(15 downto 0);
         s : in STD_LOGIC;
         Z : out STD_LOGIC_VECTOR(15 downto 0)
      );
end Mux2to16;

architecture Behavioral of Mux2to16 is

begin
   Z <=  In0 after 1ns when s='0' else
         In1 after 1ns when s='1' else
         x"0000" after 1ns;

end Behavioral;
```

1.17 Mux 3-1 Bit

```
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;

entity mux_3_1 is
   Port(
      In0, In1, In2 : in STD_LOGIC;
      S0, S1 : in STD_LOGIC;
      Z : out STD_LOGIC
      );
end mux_3_1;

architecture Behavioral of mux_3_1 is

begin
   Z <=  In0 after 1ns when S0 = '0' and S1 = '0' else
         In1 after 1ns when S0 = '0' and S1 = '1' else
         In2 after 1ns when S0 = '1' and S1 = '0' else
         '0' after 1ns;

end Behavioral;
```

1.18 Mux 8-1 Bit

```
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;

entity Mux8to1 is
   Port( In_zero, In_one, In_n, In_z, In_c, In_v, In_not_c, In_not_z : in STD_LOGIC;
         S_ms : in STD_LOGIC_VECTOR(2 downto 0);
         out_s_car : out STD_LOGIC
         );
end Mux8to1;

architecture Behavioral of Mux8to1 is

begin
   out_s_car <=  In_zero after 1ns when S_ms = "000" else
                 In_one after 1ns when S_ms = "001" else
                 In_c after 1ns when S_ms = "010" else
                 In_v after 1ns when S_ms = "011" else
                 In_z after 1ns when S_ms = "100" else
                 In_n after 1ns when S_ms = "101" else
                 In_not_c after 1ns when S_ms = "110" else
                 In_not_z after 1ns when S_ms = "111";

end Behavioral;
```

1.19 Mux 9-16 Bit

```
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;

entity Mux9to16 is
   Port( In0, In1, In2, In3, In4, In5, In6, In7, In8 : in STD_LOGIC_VECTOR(15 downto 0);
         S0, S1, S2, S3 : in STD_LOGIC;
         Z : out STD_LOGIC_VECTOR(15 downto 0)
         );
end Mux9to16;

architecture Behavioral of Mux9to16 is

begin
   Z <=  In0 after 5ns when S0='0' and S1='0' and S2='0' and S3='0' else
         In1 after 5ns when S0='1' and S1='0' and S2='0' and S3='0' else
         In2 after 5ns when S0='0' and S1='1' and S2='0' and S3='0' else
         In3 after 5ns when S0='1' and S1='1' and S2='0' and S3='0' else
         In4 after 5ns when S0='0' and S1='0' and S2='1' and S3='0' else
         In5 after 5ns when S0='1' and S1='0' and S2='1' and S3='0' else
         In6 after 5ns when S0='0' and S1='1' and S2='1' and S3='0' else
         In7 after 5ns when S0='1' and S1='1' and S2='1' and S3='0' else
         In8 after 5ns when S0='0' and S1='0' and S2='0' and S3='1' else
         x"0000" after 5ns;
end Behavioral;
```

1.20 Programme Counter

```
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;
use IEEE.STD_LOGIC_ARITH.ALL;
use IEEE.STD_LOGIC_UNSIGNED.ALL;

entity ProgrammeCounter is
   Port( PC_module_in : in STD_LOGIC_VECTOR(15 downto 0);
         PL_module_in, PI_module_in, reset : in STD_LOGIC;
         PC_module_out : out STD_LOGIC_VECTOR(15 downto 0)
         );
end ProgrammeCounter;

architecture Behavioral of ProgrammeCounter is
begin
   process(reset, PL_module_in, PI_module_in)
   variable current_PC : STD_LOGIC_VECTOR(15 downto 0);
   variable temp_curr_PC : integer;
   variable temp_inc_PC : STD_LOGIC_VECTOR(15 downto 0);

   begin
      if(reset = '1') then current_PC := x"0000";
      elsif(PL_module_in = '1') then
         current_PC := current_PC + PC_module_in;
      elsif(PI_module_in = '1') then
         temp_curr_PC := conv_integer(current_PC); -- get current allocation
         temp_curr_PC := temp_curr_PC + conv_integer(1); -- increment
         temp_inc_PC := conv_std_logic_vector(temp_curr_PC, 16); -- cast from int to vector
         current_PC := temp_inc_PC; -- store as current PC
      end if;
      PC_module_out <= current_PC after 2ns;
   end process;

end Behavioral;
```

1.21 Project 2 Top Level

```
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;

entity Proj2 is
   Port( Clk, reset : in STD_LOGIC
         );
end Proj2;

architecture Behavioral of Proj2 is

   component Datapath
      Port( data_in, pc_in : in STD_LOGIC_VECTOR(15 downto 0);
            control_word : in STD_LOGIC_VECTOR(17 downto 0);
            clk_sig, TD, TA, TB : in STD_LOGIC;
            data_out, addr_out : out STD_LOGIC_VECTOR(15 downto 0);
            status_out : out STD_LOGIC_VECTOR(3 downto 0)
            );
```

```
    end component;

    component MicroprogrammeController
        Port( IR : in STD_LOGIC_VECTOR(15 downto 0);
              status_bits : in STD_LOGIC_VECTOR(3 downto 0);
              reset_mpc : in STD_LOGIC;
              control_word_mpc : out STD_LOGIC_VECTOR(17 downto 0);
              PC_out : out STD_LOGIC_VECTOR(15 downto 0);
              TD_mpc, TA_mpc, TB_mpc, MW_mpc : out STD_LOGIC
              );
    end component;

    component Memory
        Port( address_mem : in STD_LOGIC_VECTOR(15 downto 0);
              write_data : in STD_LOGIC_VECTOR(15 downto 0);
              mem_write : in STD_LOGIC;
              read_data : out STD_LOGIC_VECTOR(15 downto 0)
              );
    end component;

    signal mm_read_data, mpc_pc_out, dp_data_out, dp_address_out : STD_LOGIC_VECTOR(15 downto
        0);
    signal mpc_control_word : STD_LOGIC_VECTOR(17 downto 0);
    signal dp_status_out : STD_LOGIC_VECTOR(3 downto 0);
    signal mpc_TD, mpc_TA, mpc_TB, mpc_MW : STD_LOGIC;

begin
    data_path : Datapath PORT MAP(
        data_in => mm_read_data,
        pc_in => mpc_pc_out,
        control_word => mpc_control_word,
        clk_sig => Clk,
        TD => mpc_TD,
        TA => mpc_TA,
        TB => mpc_TB,
        data_out => dp_data_out,
        addr_out => dp_address_out,
        status_out => dp_status_out
    );

    micro_pc : MicroprogrammeController PORT MAP(
        IR => mm_read_data,
        status_bits => dp_status_out,
        reset_mpc => reset,
        control_word_mpc => mpc_control_word,
        PC_out => mpc_pc_out,
        TD_mpc => mpc_TD,
        TA_mpc => mpc_TA,
        TB_mpc => mpc_TB,
        MW_mpc => mpc_MW
    );

    memory_module : Memory PORT MAP(
        address_mem => dp_address_out,
        write_data => dp_data_out,
```

```
      mem_write => mpc_MW,
      read_data => mm_read_data
   );

end Behavioral;
```

1.22 Register

```
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;

entity Reg16 is
   Port( D : in STD_LOGIC_VECTOR(15 downto 0);
         load0, load1, Clk : in STD_LOGIC;
         Q : out STD_LOGIC_VECTOR(15 downto 0)
      );
end Reg16;

architecture Behavioral of Reg16 is

begin
   process (Clk)
      begin
         if(rising_edge(Clk)) then
            if((load0 = '1') and (load1 = '1')) then
               Q <= D after 5ns;
            end if;
         end if;
   end process;

end Behavioral;
```

1.23 Register File

```
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;

entity RegFile is
   Port( des_d, add_a, add_b : in STD_LOGIC_VECTOR(3 downto 0);
         Clk, load_in : in STD_LOGIC;
         data : in STD_LOGIC_VECTOR(15 downto 0);
         out_data_a, out_data_b : out STD_LOGIC_VECTOR(15 downto 0)
         );
end RegFile;

architecture Behavioral of RegFile is
   component Reg16
      Port( D : in STD_LOGIC_VECTOR(15 downto 0);
            load0, load1, Clk : in STD_LOGIC;
            Q : out STD_LOGIC_VECTOR(15 downto 0)
            );
   end component;

   component Decoder4to9
      Port( A0, A1, A2, A3 : in STD_LOGIC;
```

```
            Q0, Q1, Q2, Q3, Q4, Q5, Q6, Q7, Q8 : out STD_LOGIC
            );
    end component;

    component Mux2to16
        Port( In0, In1 : in STD_LOGIC_VECTOR(15 downto 0);
              s : in STD_LOGIC;
              Z : out STD_LOGIC_VECTOR(15 downto 0)
              );
    end component;

    component Mux9to16
        Port( In0, In1, In2, In3, In4, In5, In6, In7, In8 : in STD_LOGIC_VECTOR(15 downto 0);
              S0, S1, S2 : in STD_LOGIC;
              Z : out STD_LOGIC_VECTOR(15 downto 0)
              );
    end component;

    signal load_reg0, load_reg1, load_reg2, load_reg3, load_reg4, load_reg5, load_reg6,
        load_reg7, load_reg8 : STD_LOGIC;
    signal reg0_q, reg1_q, reg2_q, reg3_q, reg4_q, reg5_q, reg6_q, reg7_q, reg8_q, out_sig_a,
        out_sig_b : STD_LOGIC_VECTOR(15 downto 0);

begin
    --reg0
    reg0: Reg16 PORT MAP(
        D => data,
        load0 => load_reg0,
        load1 => load_in,
        Clk => Clk,
        Q => reg0_q
    );

    --reg1
    reg1: Reg16 PORT MAP(
        D => data,
        load0 => load_reg1,
        load1 => load_in,
        Clk => Clk,
        Q => reg1_q
    );

    --reg2
    reg2: Reg16 PORT MAP(
        D => data,
        load0 => load_reg2,
        load1 => load_in,
        Clk => Clk,
        Q => reg2_q
    );

    --reg3
    reg3: Reg16 PORT MAP(
        D => data,
        load0 => load_reg3,
```

```
   load1 => load_in,
   Clk => Clk,
   Q => reg3_q
);

--reg4
reg4: Reg16 PORT MAP(
   D => data,
   load0 => load_reg4,
   load1 => load_in,
   Clk => Clk,
   Q => reg4_q
);

--reg5
reg5: Reg16 PORT MAP(
   D => data,
   load0 => load_reg5,
   load1 => load_in,
   Clk => Clk,
   Q => reg5_q
);

--reg6
reg6: Reg16 PORT MAP(
   D => data,
   load0 => load_reg6,
   load1 => load_in,
   Clk => Clk,
   Q => reg6_q
);

--reg7
reg7: Reg16 PORT MAP(
   D => data,
   load0 => load_reg7,
   load1 => load_in,
   Clk => Clk,
   Q => reg7_q
);

--reg8
reg8: Reg16 PORT MAP(
   D => data,
   load0 => load_reg8,
   load1 => load_in,
   Clk => Clk,
   Q => reg8_q
);

DesDecoder4to9 : Decoder4to9 PORT MAP(
   A0 => des_d(0),
   A1 => des_d(1),
   A2 => des_d(2),
   A3 => des_d(3),
```

```
      Q0 => load_reg0,
      Q1 => load_reg1,
      Q2 => load_reg2,
      Q3 => load_reg3,
      Q4 => load_reg4,
      Q5 => load_reg5,
      Q6 => load_reg6,
      Q7 => load_reg7,
      Q8 => load_reg8
   );

   Mux9to16A : Mux9to16 PORT MAP(
      In0 => reg0_q,
      In1 => reg1_q,
      In2 => reg2_q,
      In3 => reg3_q,
      In4 => reg4_q,
      In5 => reg5_q,
      In6 => reg6_q,
      In7 => reg7_q,
      In8 => reg8_q,
      S0 => add_b(0),
      S1 => add_b(1),
      S2 => add_b(2),
      Z => out_sig_a
   );

   Mux9to16B : Mux9to16 PORT MAP(
      In0 => reg0_q,
      In1 => reg1_q,
      In2 => reg2_q,
      In3 => reg3_q,
      In4 => reg4_q,
      In5 => reg5_q,
      In6 => reg6_q,
      In7 => reg7_q,
      In8 => reg8_q,
      S0 => add_b(0),
      S1 => add_b(1),
      S2 => add_b(2),
      Z => out_sig_b
   );

   out_data_a <= out_sig_a;
   out_data_b <= out_sig_b;

end Behavioral;
```

1.24 Ripple Adder

```
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;

entity RippleAdder is
   Port(
        A, B : in STD_LOGIC_VECTOR(15 downto 0);
        Cin : STD_LOGIC;
        Cout, V_out : out STD_LOGIC;
        G_out : out STD_LOGIC_VECTOR(15 downto 0)
      );

end RippleAdder;

architecture Behavioral of RippleAdder is

   Component FullAdder
      Port(
         X, Y, Cin : in STD_LOGIC;
         Cout, S : out STD_LOGIC
         );
   End Component;

   --signals - 16 carry bits and 1 output
   signal C0, C1, C2, C3, C4, C5, C6, C7, C8, C9, C10, C11, C12, C13, C14, C15, C_out :
       STD_LOGIC;

begin
   full_adder_00: FullAdder PORT MAP(
      X => A(0),
      Y => B(0),
      Cin => Cin,
      Cout => C0,
      S => G_out(0)
   );

   full_adder_01: FullAdder PORT MAP(
      X => A(1),
      Y => B(1),
      Cin => C0,
      Cout => C1,
      S => G_out(1)
   );

   full_adder_02: FullAdder PORT MAP(
      X => A(2),
      Y => B(2),
      Cin => C1,
      Cout => C2,
      S => G_out(2)
   );

   full_adder_03: FullAdder PORT MAP(
      X => A(3),
```

```
   Y => B(3),
   Cin => C2,
   Cout => C3,
   S => G_out(3)
);

full_adder_04: FullAdder PORT MAP(
   X => A(4),
   Y => B(4),
   Cin => C3,
   Cout => C4,
   S => G_out(4)
);

full_adder_05: FullAdder PORT MAP(
   X => A(5),
   Y => B(5),
   Cin => C4,
   Cout => C5,
   S => G_out(5)
);

full_adder_06: FullAdder PORT MAP(
   X => A(6),
   Y => B(6),
   Cin => C5,
   Cout => C6,
   S => G_out(6)
);

full_adder_07: FullAdder PORT MAP(
   X => A(7),
   Y => B(7),
   Cin => C6,
   Cout => C7,
   S => G_out(7)
);

full_adder_08: FullAdder PORT MAP(
   X => A(8),
   Y => B(8),
   Cin => C7,
   Cout => C8,
   S => G_out(8)
);

full_adder_09: FullAdder PORT MAP(
   X => A(9),
   Y => B(9),
   Cin => C8,
   Cout => C9,
   S => G_out(9)
);

full_adder_10: FullAdder PORT MAP(
```

```
      X => A(10),
      Y => B(10),
      Cin => C9,
      Cout => C10,
      S => G_out(10)
   );

   full_adder_11: FullAdder PORT MAP(
      X => A(11),
      Y => B(11),
      Cin => C10,
      Cout => C11,
      S => G_out(11)
   );

   full_adder_12: FullAdder PORT MAP(
      X => A(12),
      Y => B(12),
      Cin => C11,
      Cout => C12,
      S => G_out(12)
   );

   full_adder_13: FullAdder PORT MAP(
      X => A(13),
      Y => B(13),
      Cin => C12,
      Cout => C13,
      S => G_out(13)
   );

   full_adder_14: FullAdder PORT MAP(
      X => A(14),
      Y => B(14),
      Cin => C13,
      Cout => C14,
      S => G_out(14)
   );

   full_adder_15: FullAdder PORT MAP(
      X => A(15),
      Y => B(15),
      Cin => C14,
      Cout => C15,
      S => G_out(15)
   );

   --carry
   Cout <= C_out;
   --overflow
   V_out <= (C_out xor C15);

end Behavioral;
```

1.25 Shifter

```
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;

entity shifter is
   Port(
      B : in STD_LOGIC_VECTOR(15 downto 0);
      S : in STD_LOGIC_VECTOR(1 downto 0);
      IL, IR : in STD_LOGIC;
      H : out STD_LOGIC_VECTOR(15 downto 0)
   );
end shifter;

architecture Behavioral of shifter is

   --2 to 1 mux
   Component mux_3_1
      Port(
         In0, In1, In2, S0, S1 : in STD_LOGIC;
         Z : out STD_LOGIC
      );
   End Component;

begin
   mux00: mux_3_1 PORT MAP(
      In0 => B(0),
      In1 => B(1),
      In2 => IL,
      S0 => S(0),
      S1 => S(1),
      Z => H(0)
   );

   mux01: mux_3_1 PORT MAP(
      In0 => B(1),
      In1 => B(2),
      In2 => B(0),
      S0 => S(0),
      S1 => S(1),
      Z => H(1)
   );

   mux02: mux_3_1 PORT MAP(
      In0 => B(2),
      In1 => B(3),
      In2 => B(1),
      S0 => S(0),
      S1 => S(1),
      Z => H(2)
   );

   mux03: mux_3_1 PORT MAP(
      In0 => B(3),
      In1 => B(4),
```

```
   In2 => B(2),
   S0 => S(0),
   S1 => S(1),
   Z => H(3)
);

mux04: mux_3_1 PORT MAP(
   In0 => B(4),
   In1 => B(5),
   In2 => B(3),
   S0 => S(0),
   S1 => S(1),
   Z => H(4)
);

mux05: mux_3_1 PORT MAP(
   In0 => B(5),
   In1 => B(6),
   In2 => B(4),
   S0 => S(0),
   S1 => S(1),
   Z => H(5)
);

mux06: mux_3_1 PORT MAP(
   In0 => B(6),
   In1 => B(7),
   In2 => B(5),
   S0 => S(0),
   S1 => S(1),
   Z => H(6)
);

mux07: mux_3_1 PORT MAP(
   In0 => B(7),
   In1 => B(8),
   In2 => B(6),
   S0 => S(0),
   S1 => S(1),
   Z => H(7)
);

mux08: mux_3_1 PORT MAP(
   In0 => B(8),
   In1 => B(9),
   In2 => B(7),
   S0 => S(0),
   S1 => S(1),
   Z => H(8)
);

mux09: mux_3_1 PORT MAP(
   In0 => B(9),
   In1 => B(10),
   In2 => B(8),
```

```
   S0 => S(0),
   S1 => S(1),
   Z => H(9)
);

mux10: mux_3_1 PORT MAP(
   In0 => B(10),
   In1 => B(11),
   In2 => B(9),
   S0 => S(0),
   S1 => S(1),
   Z => H(10)
);

mux11: mux_3_1 PORT MAP(
   In0 => B(11),
   In1 => B(12),
   In2 => B(10),
   S0 => S(0),
   S1 => S(1),
   Z => H(11)
);

mux12: mux_3_1 PORT MAP(
   In0 => B(12),
   In1 => B(13),
   In2 => B(11),
   S0 => S(0),
   S1 => S(1),
   Z => H(12)
);

mux13: mux_3_1 PORT MAP(
   In0 => B(13),
   In1 => B(14),
   In2 => B(12),
   S0 => S(0),
   S1 => S(1),
   Z => H(13)
);

mux14: mux_3_1 PORT MAP(
   In0 => B(14),
   In1 => B(15),
   In2 => B(13),
   S0 => S(0),
   S1 => S(1),
   Z => H(14)
);

mux15: mux_3_1 PORT MAP(
   In0 => B(15),
   In1 => IR,
   In2 => B(14),
   S0 => S(0),
```

```
      S1 => S(1),
      Z => H(15)
   );


end Behavioral;
```

1.26 Zero Fill

```
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;

entity ZeroFill is
   Port( SB_in : in STD_LOGIC_VECTOR(2 downto 0);
         zero_fill_out : out STD_LOGIC_VECTOR(15 downto 0)
         );
end ZeroFill;

architecture Behavioral of ZeroFill is
   signal ZeroFill : STD_LOGIC_VECTOR(15 downto 0);
begin
   ZeroFill(2 downto 0) <= SB_in;
   ZeroFill(15 downto 3) <= "0000000000000";
end Behavioral;
```

2 Component Test Benches

2.1 Control Address Register

```
LIBRARY ieee;
USE ieee.std_logic_1164.ALL;

ENTITY ControlAddressRegister_TB IS
END ControlAddressRegister_TB;

ARCHITECTURE behavior OF ControlAddressRegister_TB IS

    -- Component Declaration for the Unit Under Test (UUT)

    COMPONENT ControlAddressRegister
    PORT(
         car_in : IN std_logic_vector(7 downto 0);
         s_car : IN std_logic;
         reset : IN std_logic;
         car_out : OUT std_logic_vector(7 downto 0)
        );
    END COMPONENT;


   --Inputs
   signal car_in : std_logic_vector(7 downto 0) := (others => '0');
   signal s_car : std_logic := '0';
   signal reset : std_logic := '0';

   --Outputs
   signal car_out : std_logic_vector(7 downto 0);

BEGIN

   -- Instantiate the Unit Under Test (UUT)
   uut: ControlAddressRegister PORT MAP (
          car_in => car_in,
          s_car => s_car,
          reset => reset,
          car_out => car_out
        );

   -- Stimulus process
   stim_proc: process
   begin
      wait for 5ns;
      reset <= '1';

      wait for 30ns;
      reset <= '0';

      wait for 30ns;
      car_in <= x"01";

      wait for 30ns;
```

```
      car_in <= x"A1";
      s_car <= '1';

      wait;
   end process;

END;
```

2.2 Control Memory

```
LIBRARY ieee;
USE ieee.std_logic_1164.ALL;

ENTITY ControlMemory_TB IS
END ControlMemory_TB;

ARCHITECTURE behavior OF ControlMemory_TB IS

    -- Component Declaration for the Unit Under Test (UUT)

    COMPONENT ControlMemory
    PORT(
         in_car : IN std_logic_vector(7 downto 0);
         MW : OUT std_logic;
         MM : OUT std_logic;
         RW : OUT std_logic;
         MD : OUT std_logic;
         MB : OUT std_logic;
         TB : OUT std_logic;
         TA : OUT std_logic;
         TD : OUT std_logic;
         PL : OUT std_logic;
         PI : OUT std_logic;
         IL : OUT std_logic;
         MC : OUT std_logic;
         FS_cm : OUT std_logic_vector(4 downto 0);
         MS_cm : OUT std_logic_vector(2 downto 0);
         NA : OUT std_logic_vector(7 downto 0)
        );
    END COMPONENT;


   --Inputs
   signal in_car : std_logic_vector(7 downto 0) := (others => '0');

   --Outputs
   signal MW : std_logic;
   signal MM : std_logic;
   signal RW : std_logic;
   signal MD : std_logic;
   signal MB : std_logic;
   signal TB : std_logic;
   signal TA : std_logic;
   signal TD : std_logic;
   signal PL : std_logic;
```

```
   signal PI : std_logic;
   signal IL : std_logic;
   signal MC : std_logic;
   signal FS_cm : std_logic_vector(4 downto 0);
   signal MS_cm : std_logic_vector(2 downto 0);
   signal NA : std_logic_vector(7 downto 0);

BEGIN

   -- Instantiate the Unit Under Test (UUT)
   uut: ControlMemory PORT MAP (
          in_car => in_car,
          MW => MW,
          MM => MM,
          RW => RW,
          MD => MD,
          MB => MB,
          TB => TB,
          TA => TA,
          TD => TD,
          PL => PL,
          PI => PI,
          IL => IL,
          MC => MC,
          FS_cm => FS_cm,
          MS_cm => MS_cm,
          NA => NA
        );

   -- Stimulus process
   stim_proc: process
   begin
      wait for 10ns;
      in_car <= x"00";

      wait for 10ns;
      in_car <= x"08";

      wait for 10ns;
      in_car <= x"0D";

      wait;
   end process;

END;
```

2.3 Decoder 4-9 bit

```
LIBRARY ieee;
USE ieee.std_logic_1164.ALL;

ENTITY Decoder4to9_TB IS
END Decoder4to9_TB;

ARCHITECTURE behavior OF Decoder4to9_TB IS
```

```
    -- Component Declaration for the Unit Under Test (UUT)

    COMPONENT Decoder4to9
    PORT(
         A0 : IN std_logic;
         A1 : IN std_logic;
         A2 : IN std_logic;
         A3 : IN std_logic;
         Q0 : OUT std_logic;
         Q1 : OUT std_logic;
         Q2 : OUT std_logic;
         Q3 : OUT std_logic;
         Q4 : OUT std_logic;
         Q5 : OUT std_logic;
         Q6 : OUT std_logic;
         Q7 : OUT std_logic;
         Q8 : OUT std_logic
        );
    END COMPONENT;


   --Inputs
   signal A0 : std_logic := '0';
   signal A1 : std_logic := '0';
   signal A2 : std_logic := '0';
   signal A3 : std_logic := '0';

   --Outputs
   signal Q0 : std_logic;
   signal Q1 : std_logic;
   signal Q2 : std_logic;
   signal Q3 : std_logic;
   signal Q4 : std_logic;
   signal Q5 : std_logic;
   signal Q6 : std_logic;
   signal Q7 : std_logic;
   signal Q8 : std_logic;

BEGIN

   -- Instantiate the Unit Under Test (UUT)
   uut: Decoder4to9 PORT MAP (
          A0 => A0,
          A1 => A1,
          A2 => A2,
          A3 => A3,
          Q0 => Q0,
          Q1 => Q1,
          Q2 => Q2,
          Q3 => Q3,
          Q4 => Q4,
          Q5 => Q5,
          Q6 => Q6,
          Q7 => Q7,
```

```
      Q8 => Q8
    );

-- Stimulus process
stim_proc: process
begin
   wait for 5ns;
   A0 <= '0';
   A1 <= '0';
   A2 <= '0';
   A3 <= '0';

   wait for 5ns;
   A0 <= '1';
   A1 <= '0';
   A2 <= '0';
   A3 <= '0';

   wait for 5ns;
   A0 <= '0';
   A1 <= '1';
   A2 <= '0';
   A3 <= '0';

   wait for 5ns;
   A0 <= '1';
   A1 <= '1';
   A2 <= '0';
   A3 <= '0';

   wait for 5ns;
   A0 <= '0';
   A1 <= '0';
   A2 <= '1';
   A3 <= '0';

   wait for 5ns;
   A0 <= '1';
   A1 <= '0';
   A2 <= '1';
   A3 <= '0';

   wait for 5ns;
   A0 <= '0';
   A1 <= '1';
   A2 <= '1';
   A3 <= '0';

   wait for 5ns;
   A0 <= '1';
   A1 <= '1';
   A2 <= '1';
   A3 <= '0';

   wait for 5ns;
```

```
      A3 <= '1';

      wait for 5ns;
      A0 <= '0';
      A1 <= '0';
      A2 <= '0';

      wait for 5ns;
      A0 <= '1';
      A1 <= '0';
      A2 <= '0';

      wait for 5ns;
      A0 <= '0';
      A1 <= '1';
      A2 <= '0';
   end process;

END;
```

2.4 Extended Programme Counter

```
LIBRARY ieee;
USE ieee.std_logic_1164.ALL;

ENTITY ExtendedProgrammeCounter_TB IS
END ExtendedProgrammeCounter_TB;

ARCHITECTURE behavior OF ExtendedProgrammeCounter_TB IS

    -- Component Declaration for the Unit Under Test (UUT)

    COMPONENT ExtendedProgrammeCounter
    PORT(
         SR_SB : IN std_logic_vector(5 downto 0);
         ExtendedProgrammeCounter : OUT std_logic_vector(15 downto 0)
        );
    END COMPONENT;


   --Inputs
   signal SR_SB : std_logic_vector(5 downto 0) := (others => '0');

   --Outputs
   signal ExtendedProgrammeCounter : std_logic_vector(15 downto 0);

BEGIN

   -- Instantiate the Unit Under Test (UUT)
   uut: ExtendedProgrammeCounter PORT MAP (
          SR_SB => SR_SB,
          ExtendedProgrammeCounter => ExtendedProgrammeCounter
        );

   -- Stimulus process
```

```
   stim_proc: process
   begin
      wait for 10ns;
      SR_SB <= "010110";

      wait for 10ns;
      SR_SB <= "110110";

      wait;
   end process;

END;
```

2.5 Instruction Register

```
LIBRARY ieee;
USE ieee.std_logic_1164.ALL;

ENTITY Instructions_TB IS
END Instructions_TB;

ARCHITECTURE behavior OF Instructions_TB IS

    -- Component Declaration for the Unit Under Test (UUT)

    COMPONENT Instructions
    PORT(
         IR_in : IN std_logic_vector(15 downto 0);
         IL_in : IN std_logic;
         Opcode : OUT std_logic_vector(6 downto 0);
         DR_out : OUT std_logic_vector(2 downto 0);
         SA_out : OUT std_logic_vector(2 downto 0);
         SB_out : OUT std_logic_vector(2 downto 0)
        );
    END COMPONENT;


   --Inputs
   signal IR_in : std_logic_vector(15 downto 0) := (others => '0');
   signal IL_in : std_logic := '0';

   --Outputs
   signal Opcode : std_logic_vector(6 downto 0);
   signal DR_out : std_logic_vector(2 downto 0);
   signal SA_out : std_logic_vector(2 downto 0);
   signal SB_out : std_logic_vector(2 downto 0);

BEGIN

   -- Instantiate the Unit Under Test (UUT)
   uut: Instructions PORT MAP (
          IR_in => IR_in,
          IL_in => IL_in,
          Opcode => Opcode,
          DR_out => DR_out,
```

```
        SA_out => SA_out,
        SB_out => SB_out
      );

   -- Stimulus process
   stim_proc: process
   begin
      wait for 10ns;
      IR_in <= "1111111000001010";

      wait for 5ns;
      IL_in <= '1';

      wait for 10ns;
      IR_in <= "0000000110110000";
      IL_in <= '0';

      wait for 5ns;
      IL_in <= '1';

      wait;
   end process;

END;
```

2.6 Memory Module

```
LIBRARY ieee;
USE ieee.std_logic_1164.ALL;

ENTITY Memory_TB IS
END Memory_TB;

ARCHITECTURE behavior OF Memory_TB IS

    -- Component Declaration for the Unit Under Test (UUT)

    COMPONENT Memory
    PORT(
         address_mem : IN std_logic_vector(15 downto 0);
         write_data : IN std_logic_vector(15 downto 0);
         mem_write : IN std_logic;
         read_data : OUT std_logic_vector(15 downto 0)
        );
    END COMPONENT;


   --Inputs
   signal address_mem : std_logic_vector(15 downto 0) := (others => '0');
   signal write_data : std_logic_vector(15 downto 0) := (others => '0');
   signal mem_write : std_logic := '0';

   --Outputs
   signal read_data : std_logic_vector(15 downto 0);
```

```
BEGIN

   -- Instantiate the Unit Under Test (UUT)
   uut: Memory PORT MAP (
          address_mem => address_mem,
          write_data => write_data,
          mem_write => mem_write,
          read_data => read_data
        );

   -- Stimulus process
   stim_proc: process
   begin
      wait for 10ns;
      address_mem <= x"0000";

      wait for 10ns;
      address_mem <= x"0001";

      wait for 10ns;
      address_mem <= x"0006";

      wait for 10ns;
      address_mem <= x"0007";

      wait;
   end process;

END;
```

2.7 Mux 2-8 Bit

```
LIBRARY ieee;
USE ieee.std_logic_1164.ALL;

ENTITY Mux2to8_TB IS
END Mux2to8_TB;

ARCHITECTURE behavior OF Mux2to8_TB IS

    -- Component Declaration for the Unit Under Test (UUT)

    COMPONENT Mux2to8
    PORT(
         In0_NA : IN std_logic_vector(7 downto 0);
         In1_opcode : IN std_logic_vector(7 downto 0);
         S_mc : IN std_logic;
         out_car : OUT std_logic_vector(7 downto 0)
        );
    END COMPONENT;


   --Inputs
   signal In0_NA : std_logic_vector(7 downto 0) := (others => '0');
   signal In1_opcode : std_logic_vector(7 downto 0) := (others => '0');
```

```
   signal S_mc : std_logic := '0';

   --Outputs
   signal out_car : std_logic_vector(7 downto 0);

BEGIN

   -- Instantiate the Unit Under Test (UUT)
   uut: Mux2to8 PORT MAP (
         In0_NA => In0_NA,
         In1_opcode => In1_opcode,
         S_mc => S_mc,
         out_car => out_car
       );

   -- Stimulus process
   stim_proc: process
   begin
      In0_NA <= x"FF";
      In1_opcode <= x"AA";

      wait for 20ns;
      S_mc <= '1';

      wait;
   end process;

END;
```

2.8 Mux 8-1 Bit

```
LIBRARY ieee;
USE ieee.std_logic_1164.ALL;

ENTITY Mux8to1_TB IS
END Mux8to1_TB;

ARCHITECTURE behavior OF Mux8to1_TB IS

    -- Component Declaration for the Unit Under Test (UUT)

    COMPONENT Mux8to1
    PORT(
         In_zero : IN std_logic;
         In_one : IN std_logic;
         In_n : IN std_logic;
         In_z : IN std_logic;
         In_c : IN std_logic;
         In_v : IN std_logic;
         In_not_c : IN std_logic;
         In_not_z : IN std_logic;
         S_ms : IN std_logic_vector(2 downto 0);
         out_s_car : OUT std_logic
       );
    END COMPONENT;
```

```
   --Inputs
   signal In_zero : std_logic := '0';
   signal In_one : std_logic := '0';
   signal In_n : std_logic := '0';
   signal In_z : std_logic := '0';
   signal In_c : std_logic := '0';
   signal In_v : std_logic := '0';
   signal In_not_c : std_logic := '0';
   signal In_not_z : std_logic := '0';
   signal S_ms : std_logic_vector(2 downto 0) := (others => '0');

   --Outputs
   signal out_s_car : std_logic;

BEGIN

   -- Instantiate the Unit Under Test (UUT)
   uut: Mux8to1 PORT MAP (
          In_zero => In_zero,
          In_one => In_one,
          In_n => In_n,
          In_z => In_z,
          In_c => In_c,
          In_v => In_v,
          In_not_c => In_not_c,
          In_not_z => In_not_z,
          S_ms => S_ms,
          out_s_car => out_s_car
        );

   -- Stimulus process
   stim_proc: process
   begin
      wait for 5ns;
      In_one <= '1';
      In_c <= '1';
      In_v <= '1';
      In_not_z <= '1';

      wait for 5ns;
      S_ms <= "001";

      wait for 5ns;
      S_ms <= "010";

      wait for 5ns;
      S_ms <= "011";

      wait for 5ns;
      S_ms <= "100";

      wait for 5ns;
      S_ms <= "101";
```

```
      wait for 5ns;
      S_ms <= "110";

      wait for 5ns;
      S_ms <= "111";

      wait for 5ns;

      wait;
   end process;

END;
```

2.9 Mux 9-16 Bit

```
LIBRARY ieee;
USE ieee.std_logic_1164.ALL;

ENTITY Mux9to16_TB IS
END Mux9to16_TB;

ARCHITECTURE behavior OF Mux9to16_TB IS

    -- Component Declaration for the Unit Under Test (UUT)

    COMPONENT Mux9to16
    PORT(
         In0 : IN std_logic_vector(15 downto 0);
         In1 : IN std_logic_vector(15 downto 0);
         In2 : IN std_logic_vector(15 downto 0);
         In3 : IN std_logic_vector(15 downto 0);
         In4 : IN std_logic_vector(15 downto 0);
         In5 : IN std_logic_vector(15 downto 0);
         In6 : IN std_logic_vector(15 downto 0);
         In7 : IN std_logic_vector(15 downto 0);
         In8 : IN std_logic_vector(15 downto 0);
         S0 : IN std_logic;
         S1 : IN std_logic;
         S2 : IN std_logic;
         S3 : IN std_logic;
         Z : OUT std_logic_vector(15 downto 0)
        );
    END COMPONENT;


   --Inputs
   signal In0 : std_logic_vector(15 downto 0) := (others => '0');
   signal In1 : std_logic_vector(15 downto 0) := (others => '0');
   signal In2 : std_logic_vector(15 downto 0) := (others => '0');
   signal In3 : std_logic_vector(15 downto 0) := (others => '0');
   signal In4 : std_logic_vector(15 downto 0) := (others => '0');
   signal In5 : std_logic_vector(15 downto 0) := (others => '0');
   signal In6 : std_logic_vector(15 downto 0) := (others => '0');
   signal In7 : std_logic_vector(15 downto 0) := (others => '0');
```

```
   signal In8 : std_logic_vector(15 downto 0) := (others => '0');
   signal S0 : std_logic := '0';
   signal S1 : std_logic := '0';
   signal S2 : std_logic := '0';
   signal S3 : std_logic := '0';

   --Outputs
   signal Z : std_logic_vector(15 downto 0);

BEGIN

   -- Instantiate the Unit Under Test (UUT)
   uut: Mux9to16 PORT MAP (
         In0 => In0,
         In1 => In1,
         In2 => In2,
         In3 => In3,
         In4 => In4,
         In5 => In5,
         In6 => In6,
         In7 => In7,
         In8 => In8,
         S0 => S0,
         S1 => S1,
         S2 => S2,
         S3 => S3,
         Z => Z
       );

   -- Stimulus process
   stim_proc: process
   begin
      In0 <= x"FFFF";
      In1 <= x"EEEE";
      In2 <= x"DDDD";
      In3 <= x"CCCC";
      In4 <= x"BBBB";
      In5 <= x"AAAA";
      In6 <= x"9999";
      In7 <= x"8888";
      In8 <= x"7777";

      wait for 10ns;
      S0 <= '1';
      S1 <= '0';
      S2 <= '0';

      wait for 10ns;
      S0 <= '0';
      S1 <= '1';
      S2 <= '0';

      wait for 10ns;
      S0 <= '1';
      S1 <= '1';
```

```
      S2 <= '0';

      wait for 10ns;
      S0 <= '0';
      S1 <= '0';
      S2 <= '1';

      wait for 10ns;
      S0 <= '1';
      S1 <= '0';
      S2 <= '1';

      wait for 10ns;
      S0 <= '0';
      S1 <= '1';
      S2 <= '1';

      wait for 10ns;
      S0 <= '1';
      S1 <= '1';
      S2 <= '1';

      wait for 10ns;
      S3 <= '1';

      wait for 10ns;
      S0 <= '1';
      S1 <= '0';
      S2 <= '0';

      wait for 10ns;
      S0 <= '0';
      S1 <= '1';
      S2 <= '0';

      wait for 10ns;
      S0 <= '1';
      S1 <= '1';
      S2 <= '0';

   end process;

END;
```

2.10 Programme Counter

```
LIBRARY ieee;
USE ieee.std_logic_1164.ALL;

ENTITY ProgrammeCounter_TB IS
END ProgrammeCounter_TB;

ARCHITECTURE behavior OF ProgrammeCounter_TB IS

    -- Component Declaration for the Unit Under Test (UUT)
```

```
    COMPONENT ProgrammeCounter
    PORT(
         PC_module_in : IN std_logic_vector(15 downto 0);
         PL_module_in : IN std_logic;
         PI_module_in : IN std_logic;
         reset : IN std_logic;
         PC_module_out : OUT std_logic_vector(15 downto 0)
        );
    END COMPONENT;


   --Inputs
   signal PC_module_in : std_logic_vector(15 downto 0) := (others => '0');
   signal PL_module_in : std_logic := '0';
   signal PI_module_in : std_logic := '0';
   signal reset : std_logic := '0';

   --Outputs
   signal PC_module_out : std_logic_vector(15 downto 0);

BEGIN

   -- Instantiate the Unit Under Test (UUT)
   uut: ProgrammeCounter PORT MAP (
          PC_module_in => PC_module_in,
          PL_module_in => PL_module_in,
          PI_module_in => PI_module_in,
          reset => reset,
          PC_module_out => PC_module_out
        );

   -- Stimulus process
   stim_proc: process
   begin
      wait for 5ns;
      reset <= '1';
      PC_module_in <= x"0000";

      wait for 5ns;
      reset <= '0';

      wait for 5ns;
      PI_module_in <= '1';
      PC_module_in <= x"0002";

      wait for 20ns;
      PI_module_in <= '0';
      PL_module_in <= '1';
      PC_module_in <= x"000F";

      wait;
   end process;

END;
```

2.11 Project 2 Top Level

```
LIBRARY ieee;
USE ieee.std_logic_1164.ALL;

ENTITY Proj2_TB IS
END Proj2_TB;

ARCHITECTURE behavior OF Proj2_TB IS

    -- Component Declaration for the Unit Under Test (UUT)

    COMPONENT Proj2
    PORT(
         Clk : IN std_logic;
         reset : IN std_logic
        );
    END COMPONENT;


   --Inputs
   signal Clk : std_logic := '0';
   signal reset : std_logic := '0';

   -- Clock period definitions
   constant Clk_period : time := 10 ns;

BEGIN

   -- Instantiate the Unit Under Test (UUT)
   uut: Proj2 PORT MAP (
          Clk => Clk,
          reset => reset
        );

   -- Clock process definitions
   Clk_process :process
   begin
      Clk <= '0';
      wait for Clk_period/2;
      Clk <= '1';
      wait for Clk_period/2;
   end process;


   -- Stimulus process
   stim_proc: process
   begin
      reset <= '1';
      wait for 40ns;

      reset <= '0';
      wait;
   end process;
END;
```

2.12 Register File

```
LIBRARY ieee;
USE ieee.std_logic_1164.ALL;

ENTITY RegFile_TB IS
END RegFile_TB;

ARCHITECTURE behavior OF RegFile_TB IS

    -- Component Declaration for the Unit Under Test (UUT)

    COMPONENT RegFile
    PORT(
         des_d : IN std_logic_vector(3 downto 0);
         add_a : IN std_logic_vector(3 downto 0);
         add_b : IN std_logic_vector(3 downto 0);
         Clk : IN std_logic;
         load_in : IN std_logic;
         data : IN std_logic_vector(15 downto 0);
         out_data_a : OUT std_logic_vector(15 downto 0);
         out_data_b : OUT std_logic_vector(15 downto 0)
        );
    END COMPONENT;


   --Inputs
   signal des_d : std_logic_vector(3 downto 0) := (others => '0');
   signal add_a : std_logic_vector(3 downto 0) := (others => '0');
   signal add_b : std_logic_vector(3 downto 0) := (others => '0');
   signal Clk : std_logic := '0';
   signal load_in : std_logic := '0';
   signal data : std_logic_vector(15 downto 0) := (others => '0');

   --Outputs
   signal out_data_a : std_logic_vector(15 downto 0);
   signal out_data_b : std_logic_vector(15 downto 0);

   -- Clock period definitions
   constant Clk_period : time := 10 ns;

BEGIN

   -- Instantiate the Unit Under Test (UUT)
   uut: RegFile PORT MAP (
          des_d => des_d,
          add_a => add_a,
          add_b => add_b,
          Clk => Clk,
          load_in => load_in,
          data => data,
          out_data_a => out_data_a,
          out_data_b => out_data_b
        );
```

```
-- Clock process definitions
Clk_process :process
begin
   Clk <= '0';
   wait for Clk_period/2;
   Clk <= '1';
   wait for Clk_period/2;
end process;

-- Stimulus process
stim_proc: process
begin
   load_in <= '1'
   des_d <= "0000";
   data <= x"FFFF";
   wait for 10ns;

   des_d <= "0001";
   data <= x"EEEE";
   wait for 10ns;

   des_d <= "0010";
   data <= x"DDDD";
   wait for 10ns;

   des_d <= "0011";
   data <= x"CCCC";
   wait for 10ns;

   des_d <= "0100";
   data <= x"BBBB";
   wait for 10ns;

   des_d <= "0101";
   data <= x"AAAA";
   wait for 10ns;

   des_d <= "0110";
   data <= x"9999";
   wait for 10ns;

   des_d <= "0111";
   data <= x"8888";
   wait for 10ns;

   des_d <= "1000";
   data <= x"7777";
   wait for 10ns;

   load_in <= '0';
   add_a <= "0000";
   add_b <= "0111";
   wait for 5ns;

   add_a <= "0001";
```

```
      add_b <= "0110";
      wait for 5ns;

      add_a <= "0010";
      add_b <= "0101";
      wait for 5ns;

      add_a <= "0011";
      add_b <= "0100";
      wait for 5ns;

      add_a <= "1000";
      add_b <= "1111";
      wait for 5ns;

      wait;
   end process;
END;
```

2.13 Zero Fill

```
LIBRARY ieee;
USE ieee.std_logic_1164.ALL;

ENTITY ZeroFill_TB IS
END ZeroFill_TB;

ARCHITECTURE behavior OF ZeroFill_TB IS

    -- Component Declaration for the Unit Under Test (UUT)

    COMPONENT ZeroFill
    PORT(
         SB_in : IN std_logic_vector(2 downto 0);
         zero_fill_out : OUT std_logic_vector(15 downto 0)
        );
    END COMPONENT;


   --Inputs
   signal SB_in : std_logic_vector(2 downto 0) := (others => '0');

   --Outputs
   signal zero_fill_out : std_logic_vector(15 downto 0);

BEGIN

   -- Instantiate the Unit Under Test (UUT)
   uut: ZeroFill PORT MAP (
          SB_in => SB_in,
          zero_fill_out => zero_fill_out
        );

   -- Stimulus process
   stim_proc: process
```

```
   begin
      wait for 10ns;
      SB_in <= "110";
      wait;
   end process;

END;
```

3 Results of Test Benches

The testbenches show the results of the operands performed by each component within the arithmetic state machine, where the top-level test bench clearly shows the contents and the resulting changes in the registers over time.

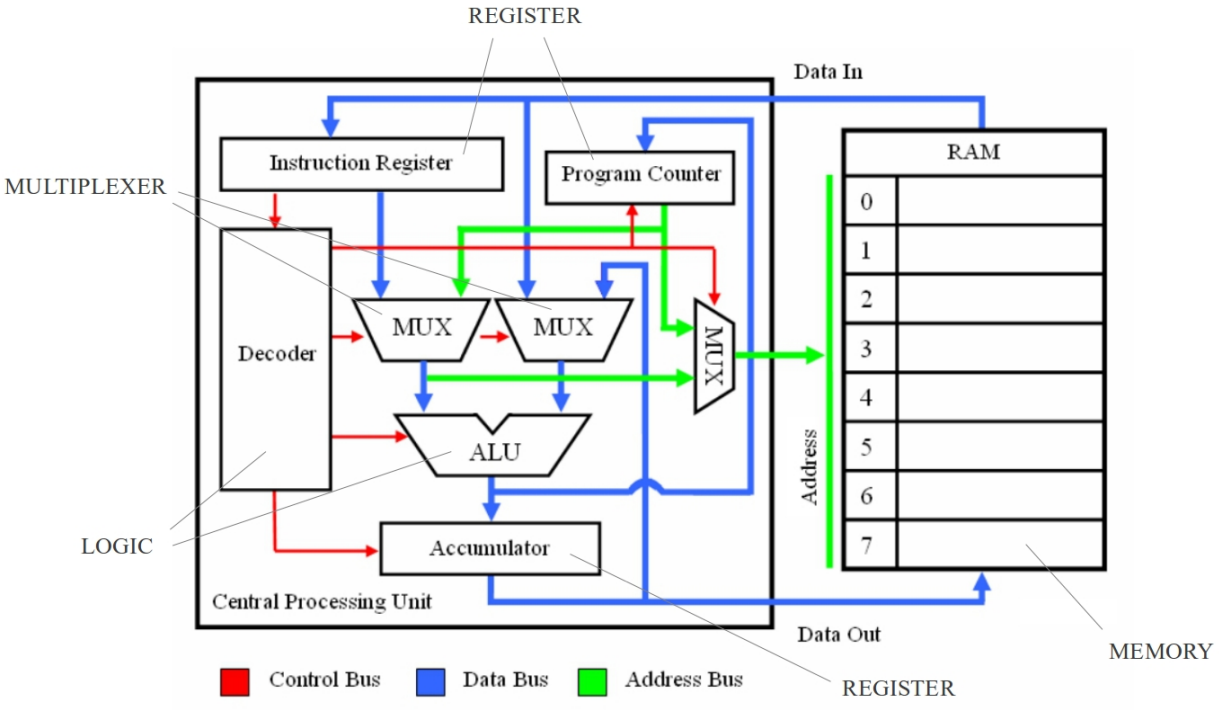
Please note that to prevent this report being excessively long and hard to staple together, the test benches and results for projects 1a and 1b have been omitted, but the source code has been included. Only items modified or added for project 2 have been included. Each module functions as intended, and test benches for the overall CPU datapaths, logic, and memory seem to pertain to what results should be for operands fetched, decoded, executed and stored.

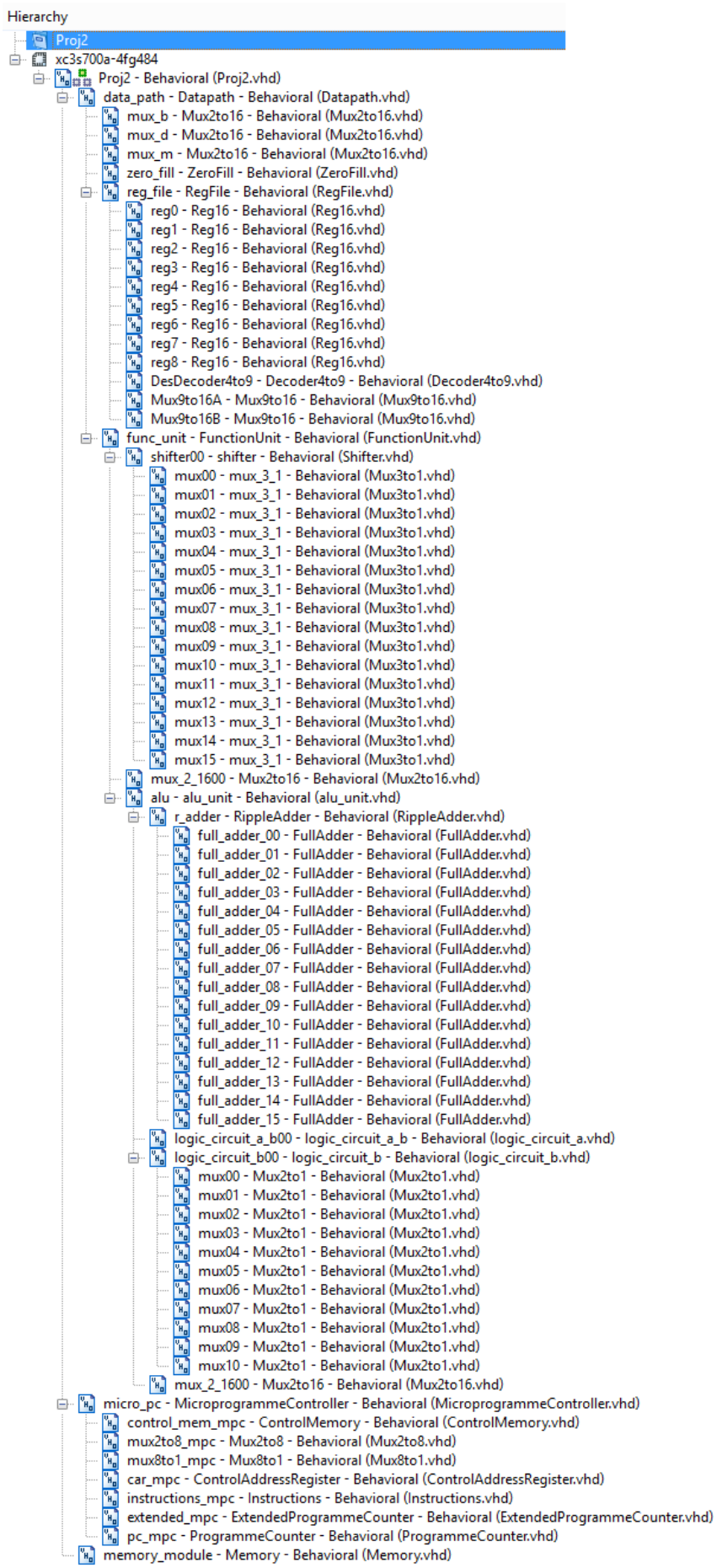
The register count has increased to 9, with an additional bit being provided for register selection, as well as for the decoder from 3-bit to 4-bit. All components within the datapath and logic units are also 16-bit operation width.

Memory and control memory have been added with sized 512x16 and 256x28, each with 16-bit width buses that utilise 9 least significant bits of the adddresses provided in order to index to the 512 bit memory size.

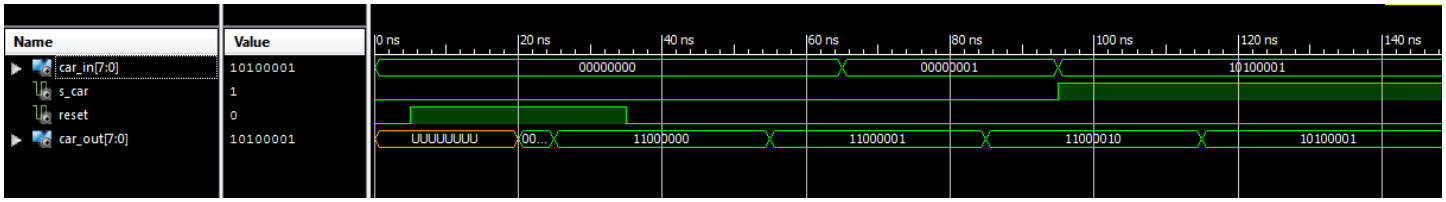
Microprogramme operations have been implemented for control memory. Each change and resulting operation in time via the register testbench is reflected by loading, add immediate operand (ADI), load to register (LDR), store to register (STR), increment (INC), inverse (NOT), add (ADD), unconditional branch (BCH), and conditional branch (BXX). These instructions pertain to modifying the contents of the registers in memory at given time intervals, and are more easily seen in the control memory and memory module components through micro-operations performed.

Within memory, machine code has also been written that demonstrates the use of the given operations above as micro-operations injectively corresponding to the machine code.

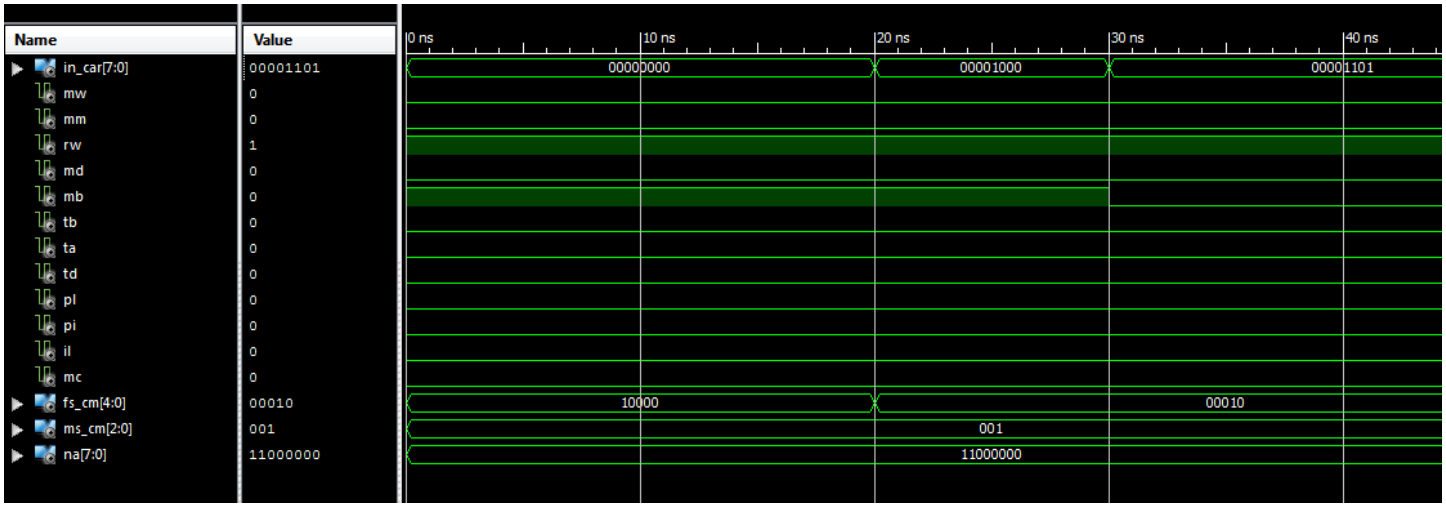



Hierarchy
Proj2
xc3s700a-4fg484
Proj2 - Behavioral (Proj2.vhd)
data_path - Datapath - Behavioral (Datapath.vhd)
mux_b - Mux2to16 - Behavioral (Mux2to16.vhd)
mux_d - Mux2to16 - Behavioral (Mux2to16.vhd)
mux_m - Mux2to16 - Behavioral (Mux2to16.vhd)
zero_fill - ZeroFill - Behavioral (ZeroFill.vhd)
reg_file - RegFile - Behavioral (RegFile.vhd)
reg0 - Reg16 - Behavioral (Reg16.vhd)
reg1 - Reg16 - Behavioral (Reg16.vhd)
reg2 - Reg16 - Behavioral (Reg16.vhd)
reg3 - Reg16 - Behavioral (Reg16.vhd)
reg4 - Reg16 - Behavioral (Reg16.vhd)
reg5 - Reg16 - Behavioral (Reg16.vhd)
reg6 - Reg16 - Behavioral (Reg16.vhd)
reg7 - Reg16 - Behavioral (Reg16.vhd)
reg8 - Reg16 - Behavioral (Reg16.vhd)
DesDecoder4to9 - Decoder4to9 - Behavioral (Decoder4to9.vhd)
Mux9to16A - Mux9to16 - Behavioral (Mux9to16.vhd)
Mux9to16B - Mux9to16 - Behavioral (Mux9to16.vhd)
func_unit - FunctionUnit - Behavioral (FunctionUnit.vhd)
shifter00 - shifter - Behavioral (Shifter.vhd)
mux00 - mux_3_1 - Behavioral (Mux3to1.vhd)
mux01 - mux_3_1 - Behavioral (Mux3to1.vhd)
mux02 - mux_3_1 - Behavioral (Mux3to1.vhd)
mux03 - mux_3_1 - Behavioral (Mux3to1.vhd)
mux04 - mux_3_1 - Behavioral (Mux3to1.vhd)
mux05 - mux_3_1 - Behavioral (Mux3to1.vhd)
mux06 - mux_3_1 - Behavioral (Mux3to1.vhd)
mux07 - mux_3_1 - Behavioral (Mux3to1.vhd)
mux08 - mux_3_1 - Behavioral (Mux3to1.vhd)
mux09 - mux_3_1 - Behavioral (Mux3to1.vhd)
mux10 - mux_3_1 - Behavioral (Mux3to1.vhd)
mux11 - mux_3_1 - Behavioral (Mux3to1.vhd)
mux12 - mux_3_1 - Behavioral (Mux3to1.vhd)
mux13 - mux_3_1 - Behavioral (Mux3to1.vhd)
mux14 - mux_3_1 - Behavioral (Mux3to1.vhd)
mux15 - mux_3_1 - Behavioral (Mux3to1.vhd)
mux_2_1600 - Mux2to16 - Behavioral (Mux2to16.vhd)
alu - alu_unit - Behavioral (alu_unit.vhd)
r_adder - RippleAdder - Behavioral (RippleAdder.vhd)
full_adder_00 - FullAdder - Behavioral (FullAdder.vhd)
full_adder_01 - FullAdder - Behavioral (FullAdder.vhd)
full_adder_02 - FullAdder - Behavioral (FullAdder.vhd)
full_adder_03 - FullAdder - Behavioral (FullAdder.vhd)
full_adder_04 - FullAdder - Behavioral (FullAdder.vhd)
full_adder_05 - FullAdder - Behavioral (FullAdder.vhd)
full_adder_06 - FullAdder - Behavioral (FullAdder.vhd)
full_adder_07 - FullAdder - Behavioral (FullAdder.vhd)
full_adder_08 - FullAdder - Behavioral (FullAdder.vhd)
full_adder_09 - FullAdder - Behavioral (FullAdder.vhd)
full_adder_10 - FullAdder - Behavioral (FullAdder.vhd)
full_adder_11 - FullAdder - Behavioral (FullAdder.vhd)
full_adder_12 - FullAdder - Behavioral (FullAdder.vhd)
full_adder_13 - FullAdder - Behavioral (FullAdder.vhd)
full_adder_14 - FullAdder - Behavioral (FullAdder.vhd)
full_adder_15 - FullAdder - Behavioral (FullAdder.vhd)
logic_circuit_a_b00 - logic_circuit_a_b - Behavioral (logic_circuit_a.vhd)
logic_circuit_b00 - logic_circuit_b - Behavioral (logic_circuit_b.vhd)
mux00 - Mux2to1 - Behavioral (Mux2to1.vhd)
mux01 - Mux2to1 - Behavioral (Mux2to1.vhd)
mux02 - Mux2to1 - Behavioral (Mux2to1.vhd)
mux03 - Mux2to1 - Behavioral (Mux2to1.vhd)
mux04 - Mux2to1 - Behavioral (Mux2to1.vhd)
mux05 - Mux2to1 - Behavioral (Mux2to1.vhd)
mux06 - Mux2to1 - Behavioral (Mux2to1.vhd)
mux07 - Mux2to1 - Behavioral (Mux2to1.vhd)
mux08 - Mux2to1 - Behavioral (Mux2to1.vhd)
mux09 - Mux2to1 - Behavioral (Mux2to1.vhd)
mux10 - Mux2to1 - Behavioral (Mux2to1.vhd)
mux_2_1600 - Mux2to16 - Behavioral (Mux2to16.vhd)
micro_pc - MicroprogrammeController - Behavioral (MicroprogrammeController.vhd)
control_mem_mpc - ControlMemory - Behavioral (ControlMemory.vhd)
mux2to8_mpc - Mux2to8 - Behavioral (Mux2to8.vhd)
mux8to1_mpc - Mux8to1 - Behavioral (Mux8to1.vhd)
car_mpc - ControlAddressRegister - Behavioral (ControlAddressRegister.vhd)
instructions_mpc - Instructions - Behavioral (Instructions.vhd)
extended_mpc - ExtendedProgrammeCounter - Behavioral (ExtendedProgrammeCounter.vhd)
pc_mpc - ProgrammeCounter - Behavioral (ProgrammeCounter.vhd)
memory_module - Memory - Behavioral (Memory.vhd)

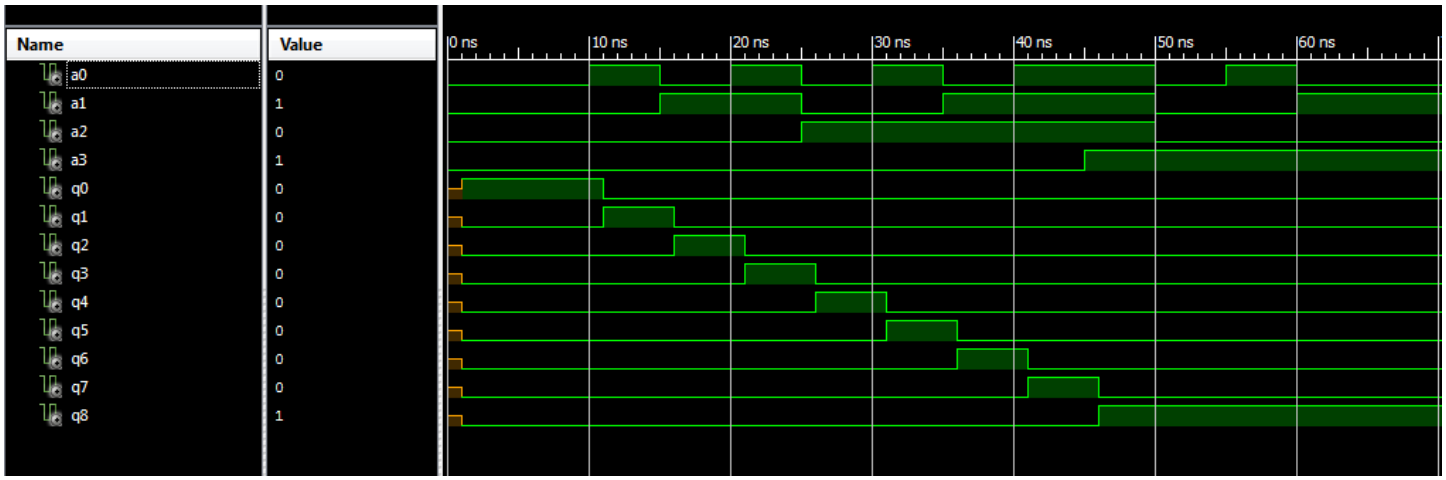
3.1 Control Address Register



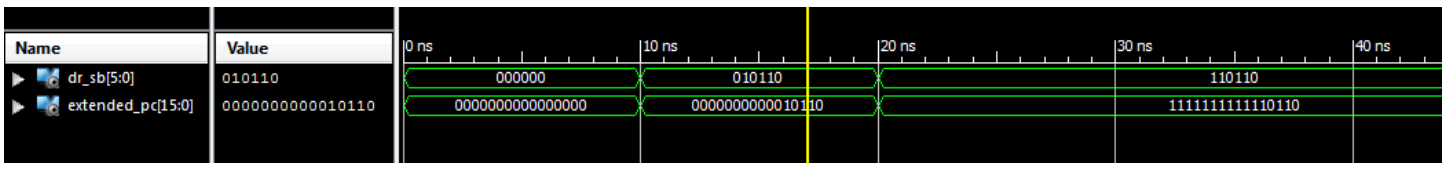
3.2 Control Memory



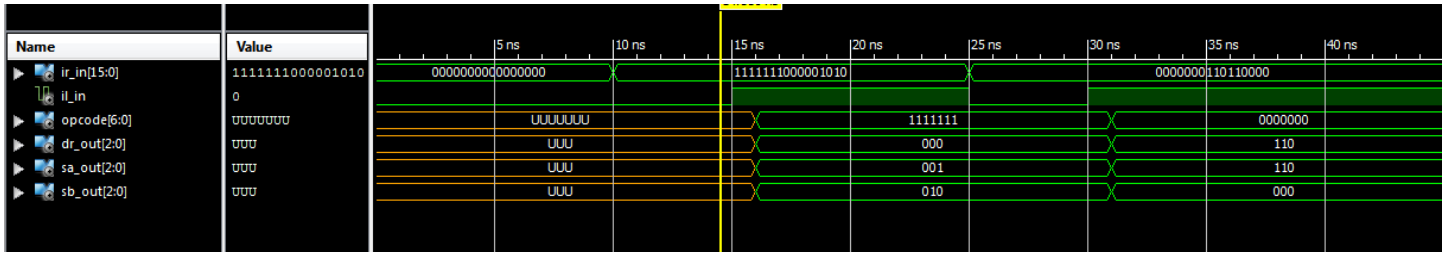
3.3 Decoder 4-9 bit



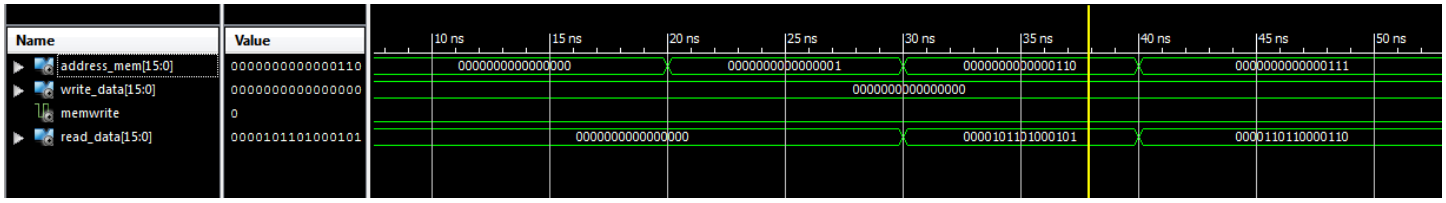
3.4 Extended Programme Counter



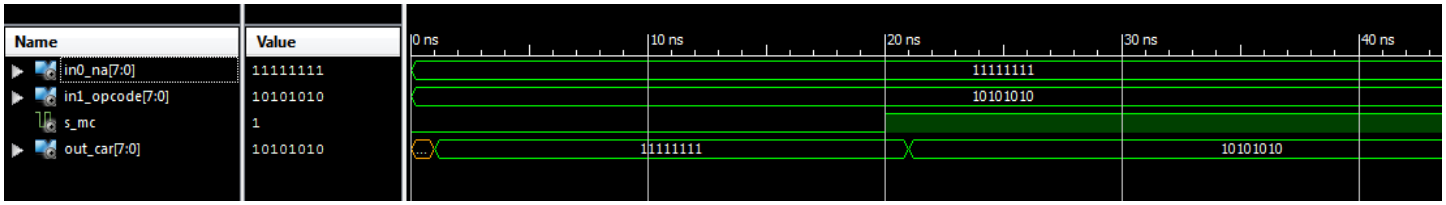
3.5 Instruction Register



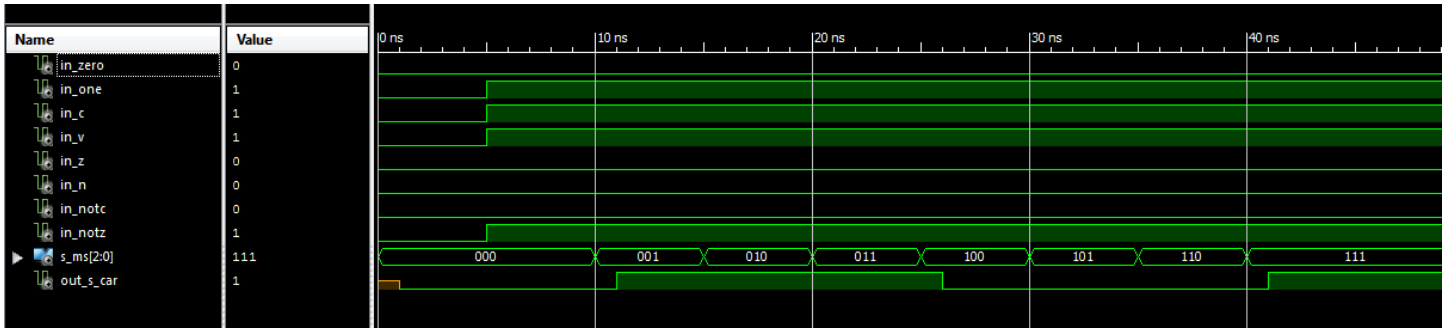
3.6 Memory Module



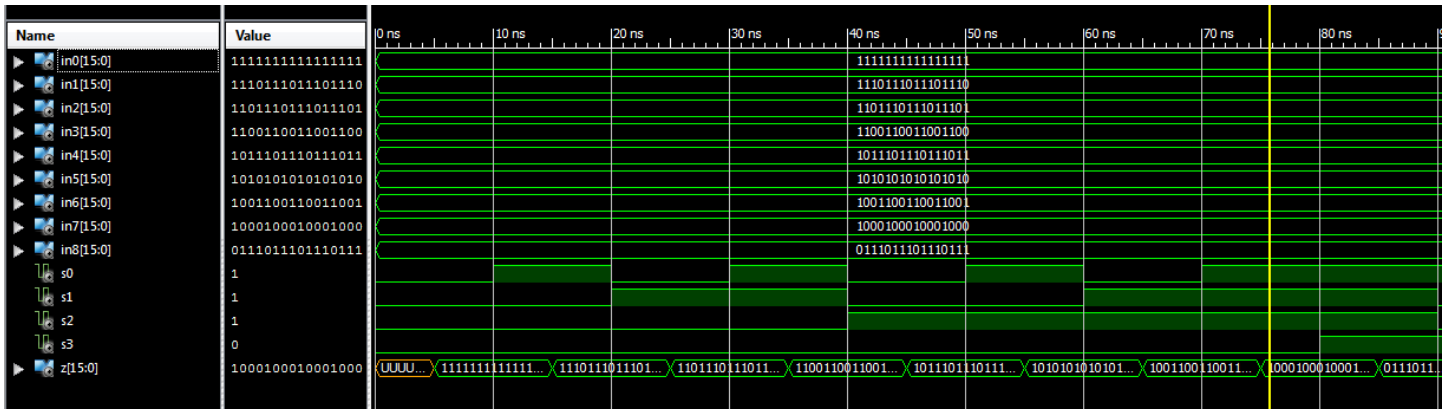
3.7 Mux 2-1 Bit



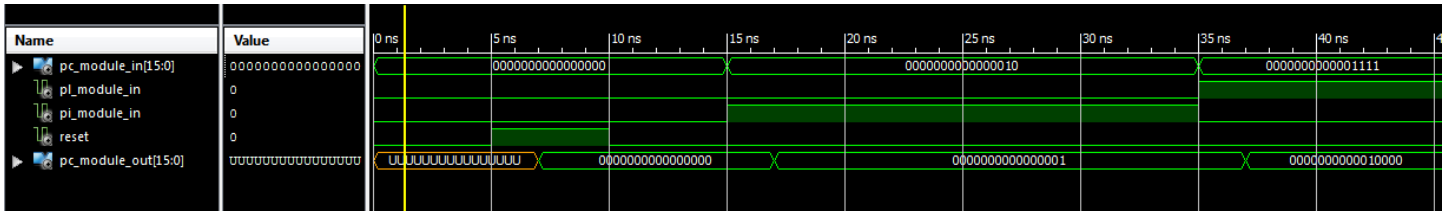
3.8 Mux 8-1 Bit



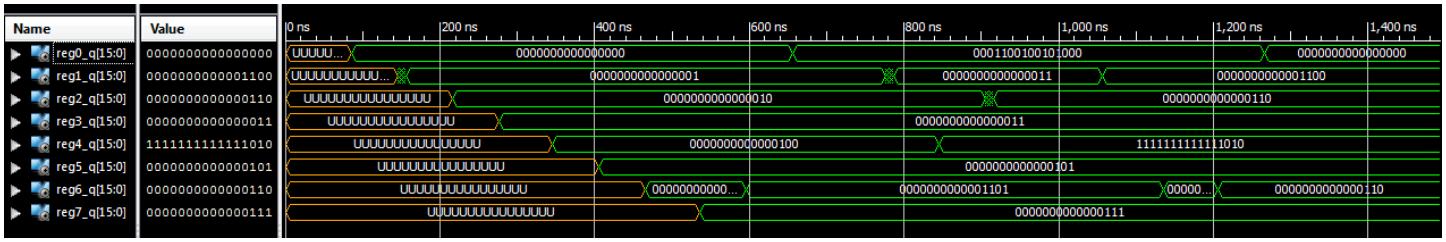
3.9 Mux 9-16 Bit



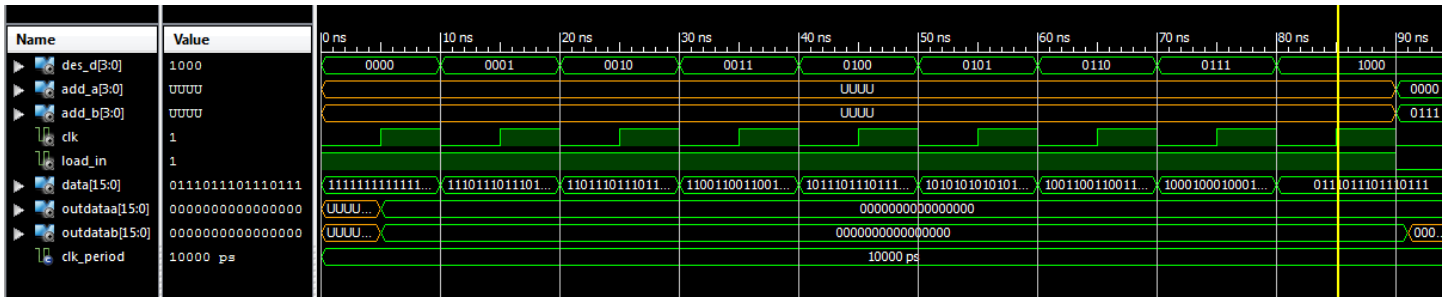
3.10 Programme Counter

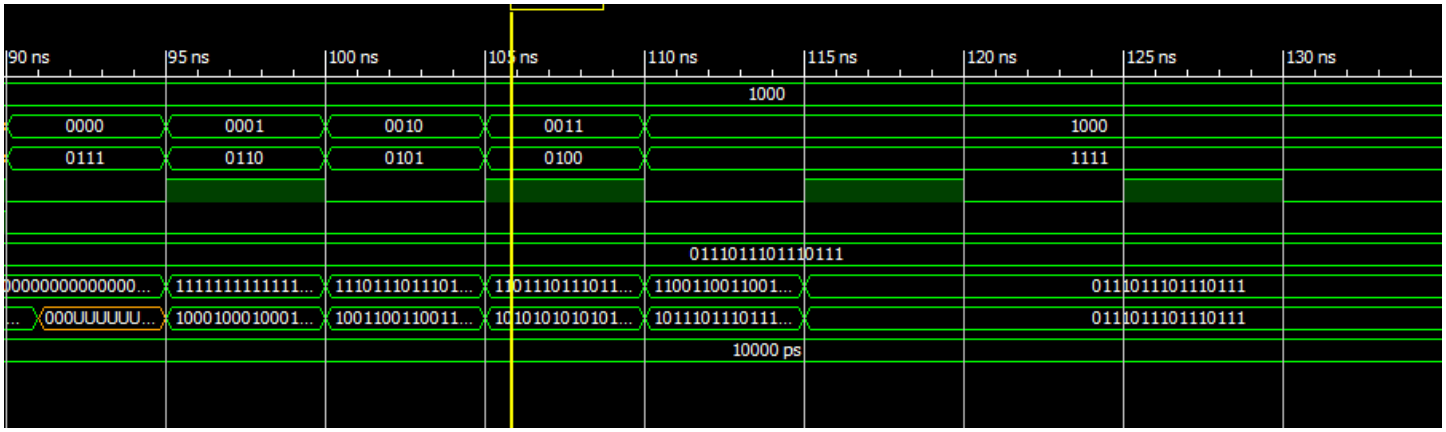


3.11 Project 2 Top Level



3.12 Register File





3.13 Zero Fill