The VHDL Hardware Description Language

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1970s: SPICE transistor-level netlists

An XOR built from four NAND gates

```vhdl
.MODEL P PMOS
.MODEL N NMOS

.SUBCKT NAND A B Y Vdd Vss
M1 Y A Vdd Vdd P
M2 Y B Vdd Vdd P
M3 Y A X Vss N
M4 X B Vss Vss N
.ENDS

X1 A B I1 Vdd 0 NAND
X2 A I1 I2 Vdd 0 NAND
X3 B I1 I3 Vdd 0 NAND
X4 I2 I3 Y Vdd 0 NAND
```

Why HDLs?
Why HDLs?

1980s: Graphical schematic capture programs
1990s: HDLs and Logic Synthesis

library ieee;
use ieee.std_logic_1164.all;
use ieee.std_logic_unsigned.all;
use ieee.std_logic_arith.all;
entity ALU is
port( A: in std_logic_vector(1 downto 0);
    B: in std_logic_vector(1 downto 0);
    Sel: in std_logic_vector(1 downto 0);
    Res: out std_logic_vector(1 downto 0));
end ALU;
architecture behv of ALU is begin
process(A,B,Sel) begin
    case Sel is
    when "00" => Res <= A + B;
    when "01" => Res <= A + (not B) + 1;
    when "10" => Res <= A and B;
    when "11" => Res <= A or B;
    when others => Res <= "XX";
    end case;
end process;
end behv;
Two Separate but Equal Languages

Verilog and VHDL
Verilog: More succinct, less flexible, really messy
VHDL: Verbose, very (too?) flexible, fairly messy
Part of languages people actually use identical.
Every synthesis system supports both.
VHDL: Hierarchical Models

Process

process (Clk)
if clk'Event and
clk='1' then
Count <= Count + 1;
end if;
end process;

Signal

X <= (Y = '1') and (X = "110")

Dataflow Expression

Component

Component

Ports

in

in

out

out

inout
library ieee; -- part of IEEE library
use ieee.std_logic_1164.all; -- includes std_ulogic

entity full_adder is
  port(a, b, c : in std_ulogic;
       sum, carry : out std_ulogic);
end full_adder;

architecture imp of full_adder is
begin
  sum <= (a xor b) xor c; -- combinational logic
  carry <= (a and b) or (a and c) or (b and c);
end imp;
library ieee;
use ieee.std_logic_1164.all;

entity add2 is
  port (  
    A, B : in std_logic_vector(1 downto 0);
    C : out std_logic_vector(2 downto 0));
end add2;

architecture imp of add2 is
  component full_adder
    port (   
      a, b, c : in std_ulogic;
      sum, carry : out std_ulogic);
  end component;
  signal carry : std_ulogic;
  begin
    bit0 : full_adder port map (   
      a => A(0),
      b => B(0),
      c => '0',
      sum => C(0),
      carry => carry);
    bit1 : full_adder port map (   
      a => A(1),
      b => B(1),
      c => carry,
      sum => C(1),
      carry => C(2));
  end imp;
library ieee;
use ieee.std_logic_1164.all;

entity multiplexer_4_1 is
  port(in0, in1 : in std_ulogic_vector(15 downto 0);
       in2, in3 : in std_ulogic_vector(15 downto 0);
       s0, s1 : in std_ulogic;
       z : out std_ulogic_vector(15 downto 0));
end multiplexer_4_1;

architecture imp of multiplexer_4_1 is
begin
  z <= in0 when (s0 = '0' and s1 = '0') else in1 when (s0 = '1' and s1 = '0') else in2 when (s0 = '0' and s1 = '1') else in3 when (s0 = '1' and s1 = '1') else "XXXXXXXXXXXXXXXXXXXXX";
end imp;
library ieee;
use ieee.std_logic_1164.all;

entity multiplexer_4_1 is
  port(in0, in1 : in std_ulogic_vector(15 downto 0);
in2, in3 : in std_ulogic_vector(15 downto 0);
s0, s1 : in std_ulogic;
z : out std_ulogic_vector(15 downto 0));
end multiplexer_4_1;

architecture usewith of multiplexer_4_1 is
  signal sels : std_ulogic_vector(1 downto 0);
begin
  sels <= s1 & s0; -- Vector concatenation

  with sels select
  begin
    z <=
    in0 when "00",
in1 when "01",
in2 when "10",
in3 when "11",
"XXXXXXXXXXXXXXXXX" when others;
  end with;
end usewith;
library ieee;
use ieee.std_logic_1164.all;

entity dec1_8 is
port (sel : in std_logic_vector(2 downto 0); res : out std_logic_vector(7 downto 0));
end dec1_8;

architecture imp of dec1_8 is
begin
res <= "00000001" when sel = "000" else
  "00000010" when sel = "001" else
  "00000100" when sel = "010" else
  "00001000" when sel = "011" else
  "00010000" when sel = "100" else
  "00100000" when sel = "101" else
  "01000000" when sel = "110" else
  "10000000";
end imp;
library ieee;
use ieee.std_logic_1164.all;

entity priority is
  port ( 
    sel : in std_logic_vector(7 downto 0); 
    code : out std_logic_vector(2 downto 0)); 
end priority;

architecture imp of priority is
begin
  code <= "000" when sel(0) = '1' else 
          "001" when sel(1) = '1' else 
          "010" when sel(2) = '1' else 
          "011" when sel(3) = '1' else 
          "100" when sel(4) = '1' else 
          "101" when sel(5) = '1' else 
          "110" when sel(6) = '1' else 
          "111" when sel(7) = '1' else 
          "---"; -- "---" is "don't care"
end imp;
library ieee;
use ieee.std_logic_1164.all;
use ieee.std_logic_arith.all;
use ieee.std_logic_unsigned.all;

entity adder is
  port (  
    A, B : in  std_logic_vector(7 downto 0);
    CI  : in  std_logic;
    SUM : out std_logic_vector(7 downto 0);
    CO  : out std_logic);
end adder;

architecture imp of adder is
  signal tmp : std_logic_vector(8 downto 0);
  begin
    tmp <= conv_std_logic_vector((conv_integer(A) +  
                                conv_integer(B) +  
                                conv_integer(CI)), 9);

    SUM <= tmp(7 downto 0);
    CO  <= tmp(8);
  end imp;
library ieee;
use ieee.std_logic_1164.all;
use ieee.std_logic_unsigned.all;

entity alu is
  port (  
    A, B : in  std_logic_vector(7 downto 0);
    ADD  : in  std_logic;
    RES  : out std_logic_vector(7 downto 0));
end alu;

architecture imp of alu is
begin
  RES <= A + B when ADD = '1' else  
      A - B;
end imp;
library ieee;
use ieee.std_logic_1164.all;
use ieee.std_logic_unsigned.all;

entity comparator is
    port ( 
        A, B : in std_logic_vector(7 downto 0);
        GE   : out std_logic);
end comparator;

architecture imp of comparator is
begin
    GE <= '1' when A >= B else '0';
end imp;
library ieee;
use ieee.std_logic_1164.all;

data: std_logic is
entity rippleadder is
    port (a, b : in std_logic_vector(3 downto 0);
        cin : in std_logic;
        sum : out std_logic_vector(3 downto 0);
        cout : out std_logic);
end rippleadder;

architecture imp of rippleadder is
    signal c : std_logic_vector(4 downto 0);
begin
    c(0) <= cin;
    G1: for m in 0 to 3 generate -- at compile time
        sum(m) <= a(m) xor b(m) xor c(m);
        c(m+1) <= (a(m) and b(m)) or (b(m) and c(m)) or
                 (a(m) and c(m));
    end generate G1;
    cout <= c(4);
end imp;
library ieee;
use ieee.std_logic_1164.all;

entity flipflop is
  port (Clk, D : in std_logic;
        Q : out std_logic);
end flipflop;

architecture imp of flipflop is
begin
  process (Clk) -- Process sensitive to Clk
  begin
    if (Clk'event and Clk = '1') then -- Rising edge
      Q <= D;
    end if;
  end process P1;
end imp;
library ieee;
use ieee.std_logic_1164.all;

entity flipflop_reset is
    port (Clk, Reset, D : in std_ulogic;
          Q       : out std_ulogic);
end flipflop_reset;

architecture imp of flipflop_reset is
begin
    P1: process (Clk)
    begin
        if (Clk'event and Clk = '1') then
            if (Reset = '1') then Q <= '0';
            else Q <= D;
            end if;
        end if;
    end process P1;
end imp;
library ieee;
use ieee.std_logic_1164.all;
use ieee.std_logic_unsigned.all;

data type: A;

entity counter is
  port(
    Clk, Reset : in std_logic;
    Q : out std_logic_vector(3 downto 0));
end counter;

architecture imp of counter is
  signal count : std_logic_vector(3 downto 0);
  begin
    process (Clk)
    begin
      if (Clk'event and Clk = '1') then
        if (Reset = '1') then
          count <= "0000";
        else
          count <= count + 1;
        end if;
      end if;
    end process;

    Q <= count; -- copy count to output
  end imp;

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library ieee;
use ieee.std_logic_1164.all;

entity shifter is
port ( 
    Clk : in std_logic;
    SI : in std_logic;
    SO : out std_logic);
end shifter;

architecture impl of shifter is
    signal tmp : std_logic_vector(7 downto 0);
begin
    process (Clk)
    begin
        if (Clk'event and Clk = '1') then
            for i in 0 to 6 loop -- unrolled at compile time
                tmp(i+1) <= tmp(i);
            end loop;
            tmp(0) <= SI;
        end if;
    end process;

    SO <= tmp(7); -- Copy to output
end impl;
A small RAM

```vhdl
library ieee;
use ieee.std_logic_1164.all;
use ieee.std_logic_unsigned.all;

entity ram_32_4 is
    port (
        Clk : in std_logic;
        WE : in std_logic; -- Write enable
        EN : in std_logic; -- Read enable
        addr : in std_logic_vector(4 downto 0);
        di : in std_logic_vector(3 downto 0); -- Data in
        do : out std_logic_vector(3 downto 0)); -- Data out
end ram_32_4;

architecture imp of ram_32_4 is
    type ram_type is array(31 downto 0) of
        std_logic_vector(3 downto 0);
    signal RAM : ram_type;
    begin
        process (Clk)
        begin
            if (Clk'event and Clk = '1') then
                if (en = '1') then
                    if (we = '1') then
                        RAM(conv_integer(addr)) <= di;
                        do <= di;
                    else
                        do <= RAM(conv_integer(addr));
                        end if;
                    end if;
                end if;
            end process;
        end imp;
```
A small ROM

library ieee;
use ieee.std_logic_1164.all;
use ieee.std_logic_unsigned.all;

entity rom_32_4 is
  port(
    Clk : in std_logic;
    en : in std_logic; -- Read enable
    addr : in std_logic_vector(4 downto 0);
    data : out std_logic_vector(3 downto 0));
end rom_32_4;

architecture imp of rom_32_4 is
  type rom_type is array (31 downto 0) of std_logic_vector(3 downto 0);
  constant ROM : rom_type :=
    ('0001', '0010', '0011', '0100', '0101', '0110', '0111', '1000',
     '1001', '1010', '1100', '1101', '1110', '1111', '0000', '0100',
     '0101', '0110', '0111', '1000', '1001', '1010', '1011', '1100',
     '1101', '1110', '1111', '0000', '0010');
begin
  process (Clk)
  begin
    if (Clk'event and Clk = '1') then
      if (en = '1') then
        data <= ROM(conv_integer(addr));
      end if;
    end if;
  end process;
end imp;
Rocket Science: FSMs

- Present State
- Next State
- Clock
- Inputs
- Outputs
- Combinational Logic

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Structure of FSMs in VHDL

entity myFSM is
  port( ... );
end myFSM;

architecture imp of myFSM is
  constant STATE1 := "...";
  constant STATE2 := "...";
  signal current_state, next_state : ...

process (clk) -- State holding element process
begin
  if (clk'event and clk = '1') then
    current_state <= next_state;
  end if
end process;

process (inputs...) -- Outputs and next state function
begin
  if (reset = '1') then
    next_state <= STATE1;
  else
    case current_state is
      when STATE1 =>
        output1 <= '1';
        next_state <= STATE2;
      when STATE2 =>
        ...
        next_state <= STATE3;
      end case;
  end if;
end process;
end imp;
The Traffic Light Controller

This controls a traffic light at the intersection of a busy highway and a farm road. Normally, the highway light is green but if a sensor detects a car on the farm road, the highway light turns yellow then red. The farm road light then turns green until there are no cars or after a long timeout. Then, the farm road light turns yellow then red, and the highway light returns to green. The inputs to the machine are the car sensor, a short timeout signal, and a long timeout signal. The outputs are a timer start signal and the colors of the highway and farm road lights.

FSM for the Traffic Light Controller

- C: Car sensor
- S: Short timeout
- L: Long timeout
- T: Start timer

Diagram:

- HG: \( \bar{C} + \bar{L} \)
- HY: \( \bar{S} \)
- FY: S/T
- FG: CL/T

Transition:
- HG \( \rightarrow \) HY: CL/T
- HY \( \rightarrow \) FG: S/T
- FG \( \rightarrow \) FY: \( \bar{C} + L/T \)
- FY \( \rightarrow \) HG: S/T

Farmland:

- St: Hwy Farm
- HG: G R
- HY: Y R
- FG: R G
- FY: R Y

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library ieee;
use ieee.std_logic_1164.all;

entity tlc is
  port ( 
    clk : in std_ulogic;
    reset : in std_ulogic;
    cars : in std_ulogic;
    short : in std_ulogic;
    long : in std_ulogic;
    highway_yellow : out std_ulogic;
    highway_red : out std_ulogic;
    farm_yellow : out std_ulogic;
    farm_red : out std_ulogic;
    start_timer : out std_ulogic);
end tlc;
Traffic Light Controller in VHDL (2)

architecture imp of tlc is
signal current_state, next_state : std_ulogic_vector;
constant HG : std_ulogic_vector := "00";
constant HY : std_ulogic_vector := "01";
constant FY : std_ulogic_vector := "10";
constant FG : std_ulogic_vector := "11";
begin

P1: process (clk) -- Sequential process
begin
  if (clk’event and clk = ’1’) then
    current_state <= next_state;
  end if;
end process P1;
-- Combinational process
-- Sensitive to input changes, not clock

P2: process (current_state, reset, cars, short, long)
begin
    if (reset = '1') then
        next_state <= HG;
        start_timer <= '1';
    else
        case current_state is
            when HG =>
                highway_yellow <= '0';
                highway_red <= '0';
                farm_yellow <= '0';
                farm_red <= '1';
                if (cars = '1' and long = '1') then
                    next_state <= HY;
                    start_timer <= '1';
                else
                    next_state <= HG;
                    start_timer <= '0';
                end if;
        end case;
    end if;
end process;
when HY =>
    highway_yellow <= '1';
    highway_red <= '0';
    farm_yellow <= '0';
    farm_red <= '1';
    if (short = '1') then
        next_state <= FG;
        start_timer <= '1';
    else
        next_state <= HY;
        start_timer <= '0';
    end if;

when FG =>
    highway_yellow <= '0';
    highway_red <= '1';
    farm_yellow <= '0';
    farm_red <= '0';
    if (cars = '0' or long = '1') then
        next_state <= FY;
        start_timer <= '1';
    else
        next_state <= FG;
        start_timer <= '0';
    end if;
when FY =>
    highway_yellow <= '0';
    highway_red   <= '1';
    farm_yellow   <= '1';
    farm_red      <= '0';
    if (short = '1') then
        next_state  <= HG;
        start_timer <= '1';
    else
        next_state  <= FY;
        start_timer <= '0';
    end if;

when others =>
    next_state <= "XX";
    start_timer <= 'X';
    highway_yellow <= 'X';
    highway_red   <= 'X';
    farm_yellow   <= 'X';
    farm_red      <= 'X';
end case;
end if;
end process P2;

end imp;