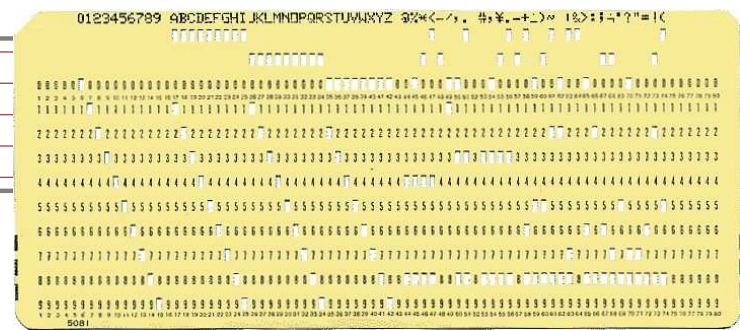


The VHDL Hardware Description Language

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NCTU, Summer 2005

Why HDLs?



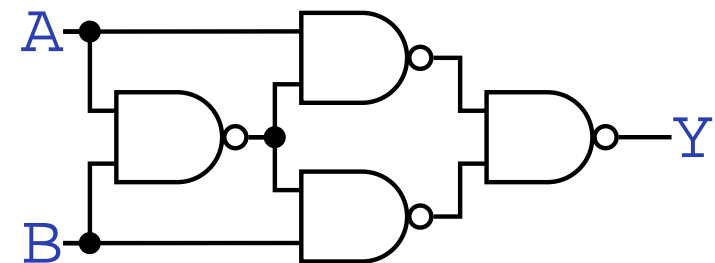
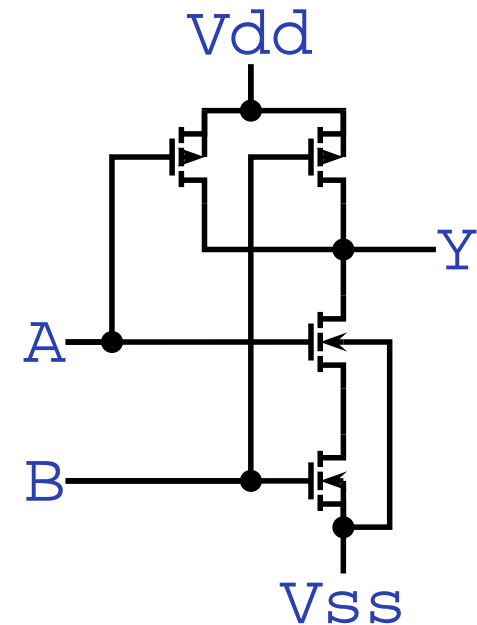
1970s: SPICE transistor-level netlists

An XOR built from four NAND gates

```
.MODEL P PMOS
.MODEL N NMOS

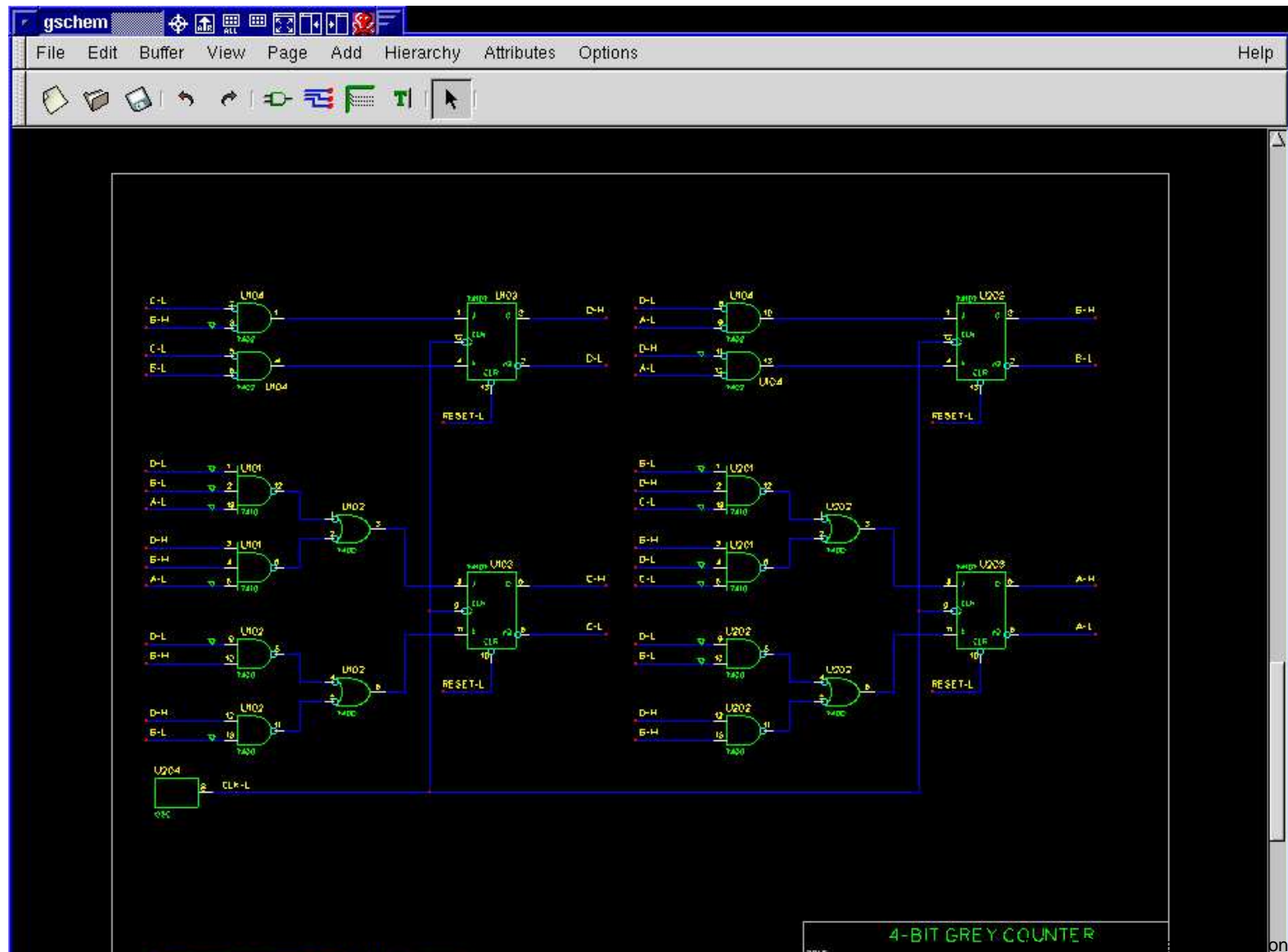
.SUBCKT NAND A B Y Vdd Vss
M1 Y A Vdd Vdd P
M2 Y B Vdd Vdd P
M3 Y A X Vss N
M4 X B Vss Vss N
.ENDS

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?

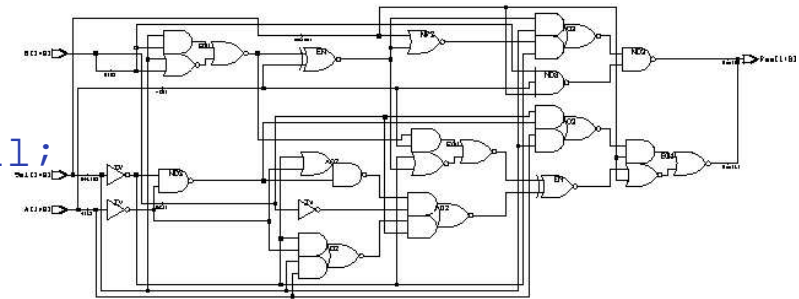
1980s: Graphical schematic capture programs



Why HDLs?

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

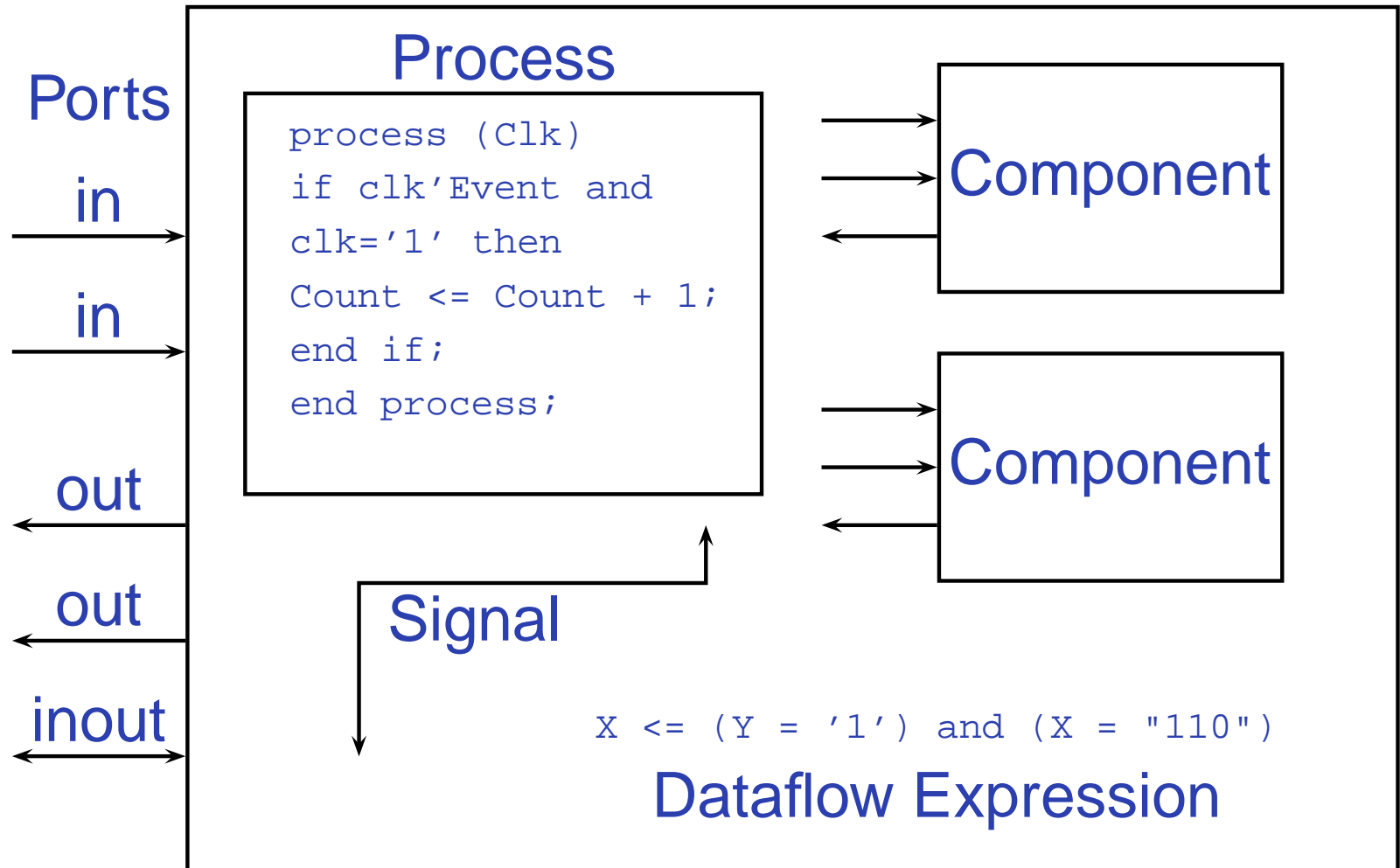
Verilog: More succinct, less flexible, really messy

VHDL: Verbose, very (too?) flexible, fairly messy

Part of languages people actually use identical.

Every synthesis system supports both.

VHDL: Hierarchical Models

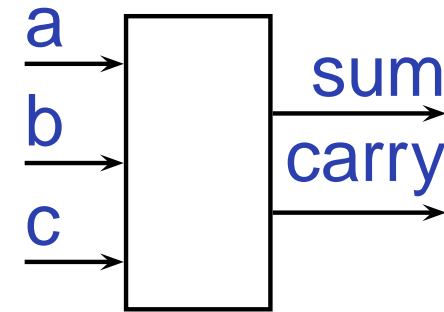


Basic VHDL: Full Adder



```
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;
```

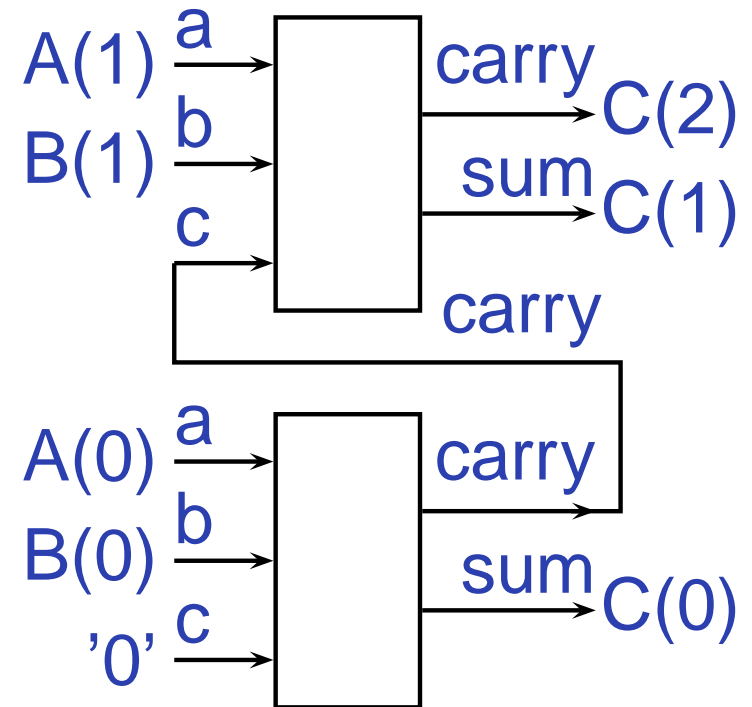
VHDL: Two-bit Counter



```
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_u logic;
      sum, carry   : out std_u logic);
  end component;
  signal carry : std_u logic;
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;
```



Four-to-one multiplexer: when...else

```
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
         "XXXXXXXXXXXXXXXXXX";
end imp;
```

Four-to-one mux: with...select

```
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
        z <=
            in0          when "00",
            in1          when "01",
            in2          when "10",
            in3          when "11",
            "XXXXXXXXXXXX" when others;
end usewith;
```

Three-to-eight Decoder

```
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;
```

Priority Encoder



```
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;
```

Integer Arithmetic



```
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;
```

A Very Simple ALU

```
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;
```

Arithmetic Comparison

```
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;
```

Generate: Ripple-carry adder

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

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

architecture imp of rippleadder is
    signal c : std_ulogic_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;
```


Basic Flip-Flop



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

entity flipflop is
  port (Clk, D : in  std_ulogic;
        Q      : out std_ulogic);
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;
```

Flip-Flop with Synchronous Reset

```
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;
```

Four-bit binary counter



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

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;
```

Eight-bit serial in/out shift register

```
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



```
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

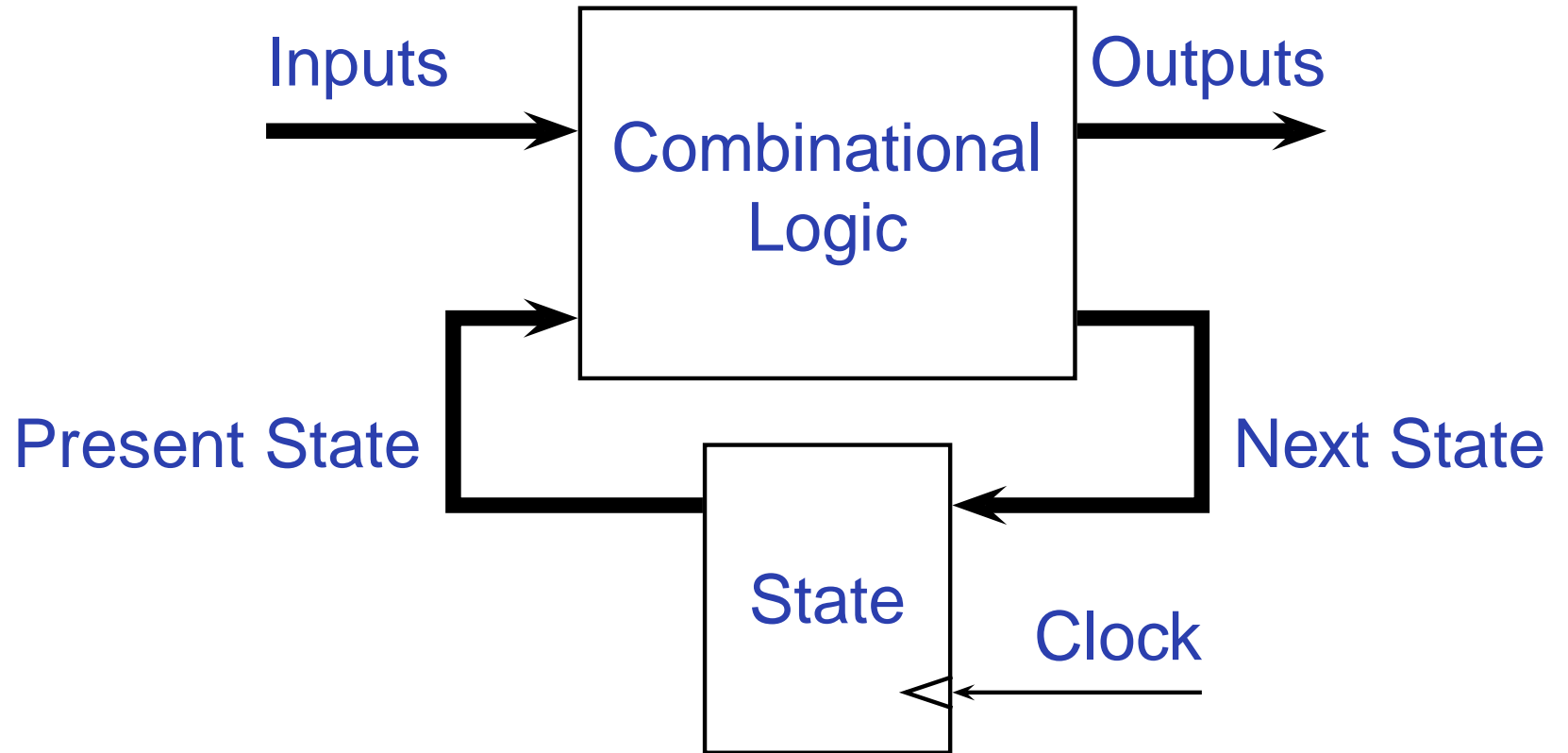
```
library ieee;
use ieee.std_logic_1164.all;
use ieee.std_logic_unsigned.all;

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", "1011", "1100", "1101", "1110", "1111", "0001",
     "0010", "0011", "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



Structure of FSMs in VHDL

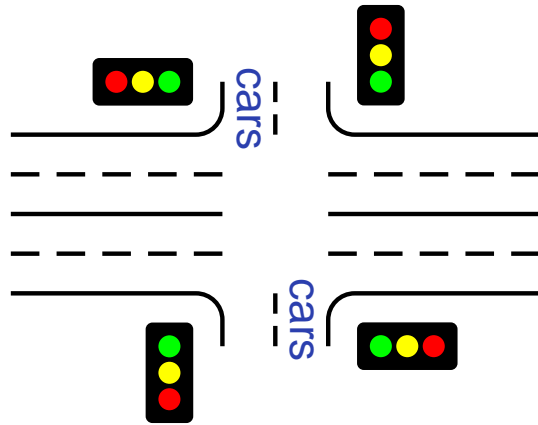
```
entity myFSM is
  port( ... );
end myFSM;

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
```

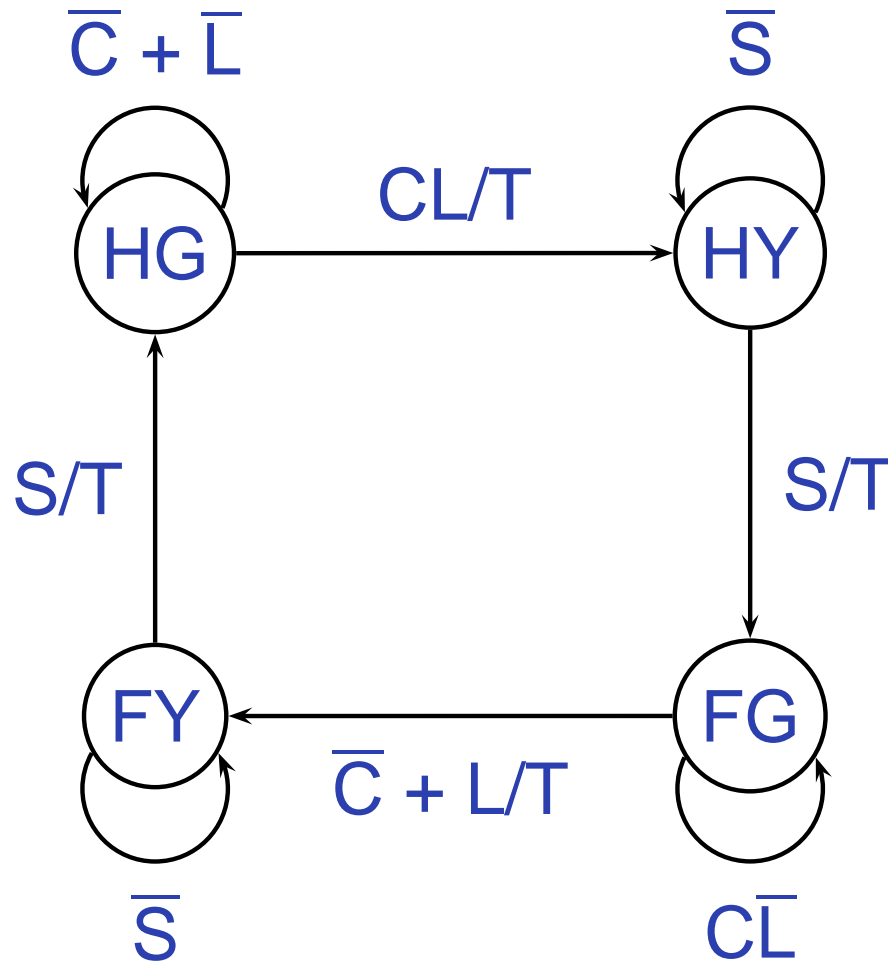

The Traffic Light Controller



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.

Source: Mead and Conway, *Introduction to VLSI Systems*, 1980, p. 85.

FSM for the Traffic Light Controller



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

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

Traffic Light Controller in VHDL (1)

```
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;
```

Traffic Light Controller in VHDL (3)

```
-- 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;
```

Traffic Light Controller in VHDL (4)

```
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;
```

Traffic Light Controller in VHDL (5)

```
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;
```