

Digital Design with SystemVerilog

CSEE W4840

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Synchronous Digital Design

Combinational Logic

Sequential Logic

Summary of Modeling Styles

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
```

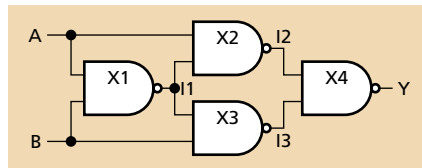
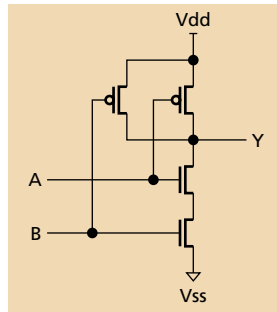
```
.ENDS
```

```
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
```



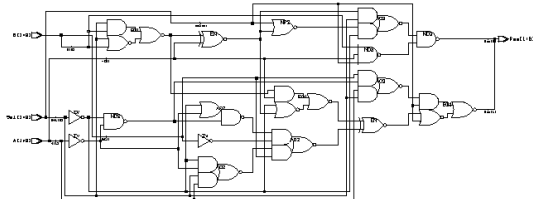
Why HDLs?

1990s: HDLs and Logic Synthesis

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

entity ALU is
port(A:   in unsigned(1 downto 0);
     B:   in unsigned(1 downto 0);
     Sel: in unsigned(1 downto 0);
     Res: out unsigned(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;
```



Separate but Equal: Verilog and VHDL



Verilog: More succinct, really messy

VHDL: Verbose, overly flexible, fairly messy

Part of languages people actually use identical

Every synthesis system supports both

SystemVerilog a newer version. Supports many more features.

Synchronous Digital Design

The Synchronous Digital Logic Paradigm

Gates and D flip-flops only

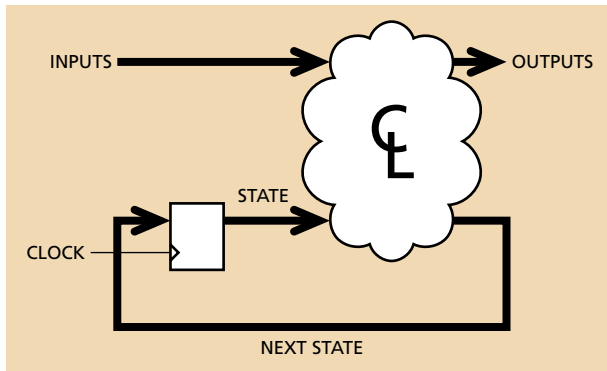
No level-sensitive latches

All flip-flops driven by the same clock

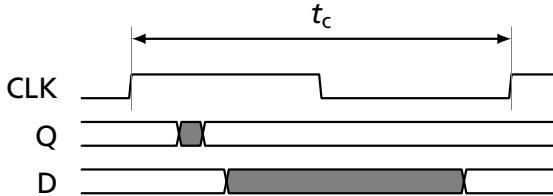
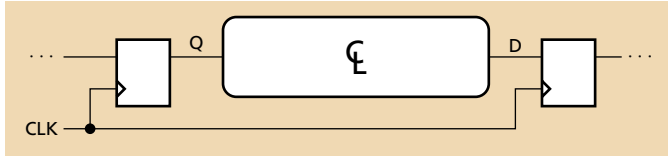
No other clock signals

Every cyclic path contains at least one flip-flop

No combinational loops

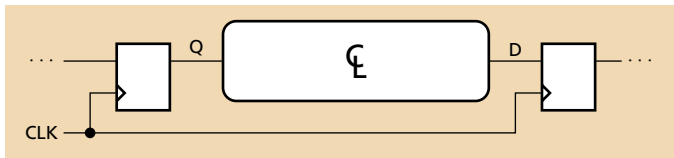


Timing in Synchronous Circuits

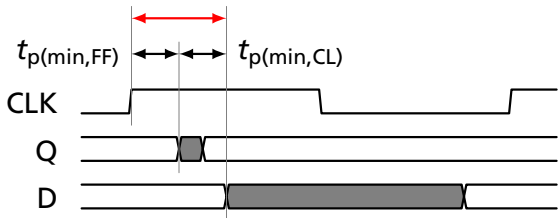


t_c : Clock period. E.g., 10 ns for a 100 MHz clock

Timing in Synchronous Circuits

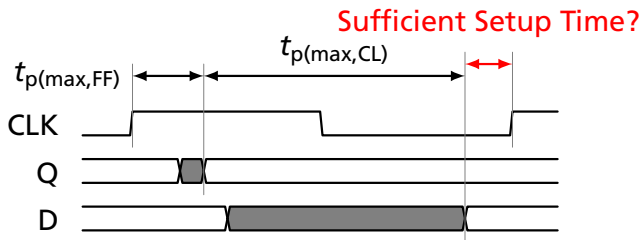
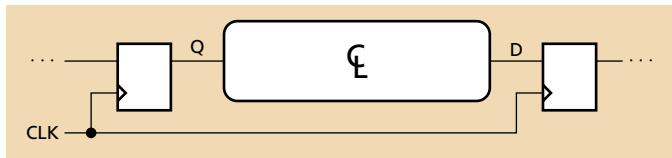


Sufficient Hold Time?



Hold time constraint: how soon after the clock edge can D start changing? Min. FF delay + min. logic delay

Timing in Synchronous Circuits



Setup time constraint: when before the clock edge is D guaranteed stable?
Max. FF delay + max. logic delay

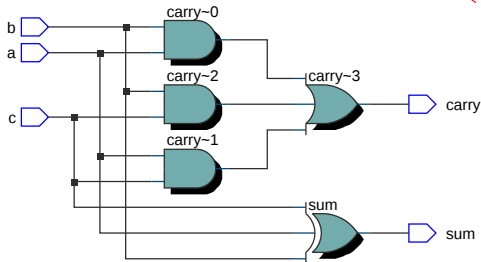
Combinational Logic

Full Adder

Single-line comment
Systems are built from modules

```
// Full adder  
module full_adder(input logic a, b, c,  
                  output logic sum, carry);  
  
    assign sum = a ^ b ^ c;  
    assign carry = a & b | a & c | b & c;  
  
endmodule
```

Module name
Input port
Data type: single bit
Port name
"Continuous assignment" expresses combinational logic
Expression



Operators and Vectors

Four-bit vector,
little-endian style

```
module gates(input  logic [3:0] a, b,  
             output logic [3:0] y1, y2, y3,  
             y4, y5);
```

```
/* Five groups of two-input logic gates  
   acting on 4-bit busses */
```

```
assign y1 = a & b;    // AND  
assign y2 = a | b;    // OR  
assign y3 = a ^ b;    // XOR  
assign y4 = ~(a & b); // NAND  
assign y5 = ~(a | b); // NOR
```

```
endmodule
```

Multi-line
comment

Reduction AND Operator

```
module and8(input  logic [7:0] a,
            output logic      y);

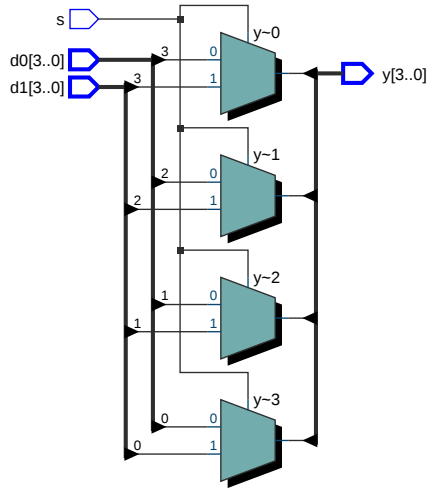
    assign y = &a;  // Reduction AND

    // Equivalent to
    // assign y = a[7] & a[6] & a[5] & a[4] &
    //           a[3] & a[2] & a[1] & a[0];

    // Also ~&a  NAND
    //         |a  OR
    //         ~|a NOR
    //         ^a  XOR
    //         ~^a XNOR
endmodule
```

The Conditional Operator: A Two-Input Mux

```
module mux2(input  logic [3:0] d0, d1,  
            input  logic      s,  
            output logic [3:0] y);  
  
    // Array of two-input muxes  
  
    assign y = s ? d1 : d0;  
endmodule
```



Operators in Precedence Order

!c -c &c ~&c

NOT, Negate, Reduction AND, NAND

|c ~|c ^c ~^c

OR, NOR, XOR, XNOR

a * b a / b a % b

Multiply, Divide, Modulus

a + b a - b

Add, Subtract

a << b a >> b

Logical Shift

a <<< b a >>> b

Arithmetic Shift

a < b a <= b a > b a >= b

Relational

a == b a != b

Equality

a & b a ^& b

AND

a ^ b a ~^ b

XOR, XNOR

a | b

OR

a ? b : c

Conditional

{a,b,c,d,r{e}})

Concatenation and Replication

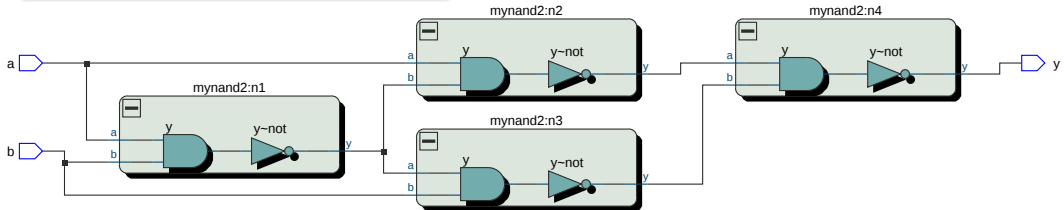
An XOR Built Hierarchically

```
module mynand2(input  logic a, b,  
               output logic y);  
    assign y = ~(a & b);  
endmodule
```

```
module myxor2(input  logic a, b,  
             output logic y);  
    logic abn, aa, bb;  
  
    mynand2 n1(a, b, abn),  
           n2(a, abn, aa),  
           n3(abn, b, bb),  
           n4(aa, bb, y);  
endmodule
```

Declare internal wires

n1: A mynand2
connected to a, b, and abn



Verilog Numbers

`16'h8_0F`

Number of Bits Value:
Base: b, o, d, or h _ are ignored
Zero-padded
Can include X and Z

`4'b1010 = 4'o12 = 4'd10 = 4'ha`
`16'h4840 = 16'b 100_1000_0100_0000`

A Decimal-to-Seven-Segment Decoder

always_comb:
combinational
logic in an
imperative style

Multiway
conditional

4'd5: decimal "5"
as a four-bit
binary number

Mandatory

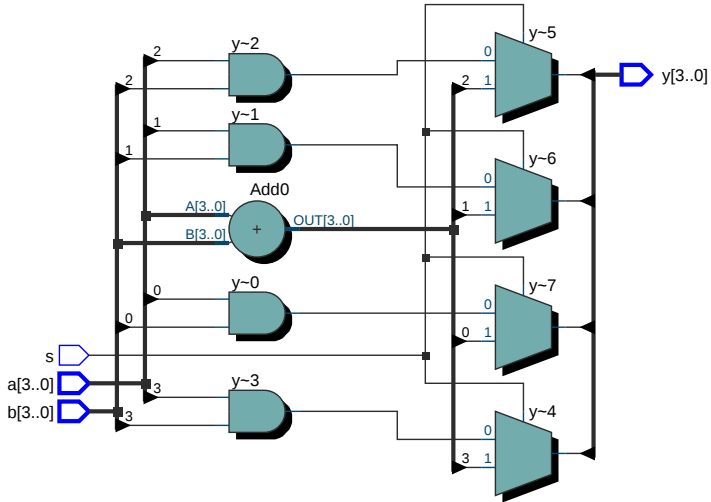
```
module dec7seg(input logic [3:0] a,  
               output logic [6:0] y);  
    always_comb  
        case (a)  
            4'd0:    y = 7'b111_1110;  
            4'd1:    y = 7'b011_0000;  
            4'd2:    y = 7'b110_1101;  
            4'd3:    y = 7'b111_1001;  
            4'd4:    y = 7'b011_0011;  
            4'd5:    y = 7'b101_1011;  
            4'd6:    y = 7'b101_1111;  
            4'd7:    y = 7'b111_0000;  
            4'd8:    y = 7'b111_1111;  
            4'd9:    y = 7'b111_0011;  
            default: y = 7'b000_0000;  
        endcase  
    endmodule
```

seven-bit
binary vector
(_ is ignored)

"blocking
assignment":
use in always_comb

Imperative Combinational Logic

```
module comb1(  
  input logic [3:0] a, b,  
  input logic s,  
  output logic [3:0] y);  
  
  always_comb  
    if (s)  
      y = a + b;  
    else  
      y = a & b;  
  
endmodule
```

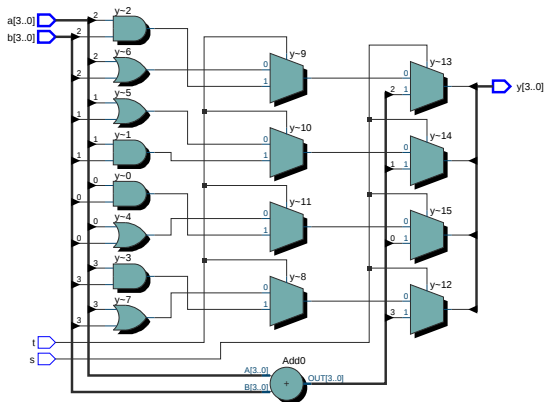


Both `a + b` and `a & b` computed, mux selects the result.

Imperative Combinational Logic

```
module comb2(  
  input logic [3:0] a, b,  
  input logic s, t,  
  output logic [3:0] y);  
  
  always_comb  
    if (s)  
      y = a + b;  
    else if (t)  
      y = a & b;  
    else  
      y = a | b;  
  
endmodule
```

All three expressions computed
in parallel. Cascaded muxes
implement priority
(s over t).

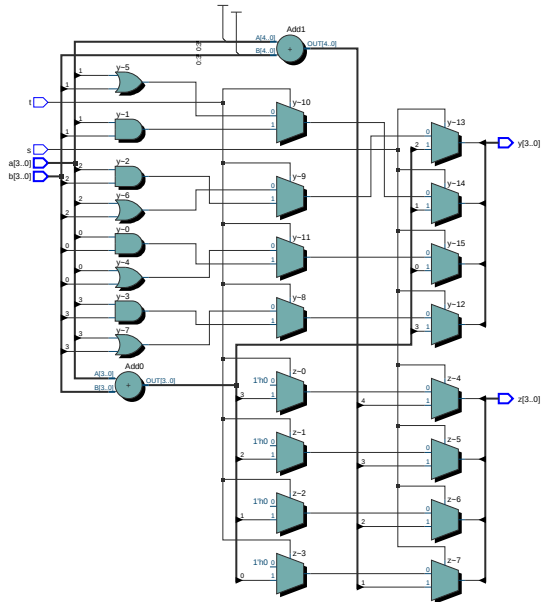


s	t	y
1	—	a + b
0	1	a & b
0	0	a b

Imperative Combinational Logic

```
module comb3(  
    input logic [3:0] a, b,  
    input logic s, t,  
    output logic [3:0] y, z);  
  
    always_comb begin  
        z = 4'b0;  
        if (s) begin  
            y = a + b;  
            z = a - b;  
        end else if (t) begin  
            y = a & b;  
            z = a + b;  
        end else  
            y = a | b;  
        end  
    end  
endmodule
```

Separate mux cascades for y and z.
One copy of $a + b$.



An Address Decoder

```
module adecode(input logic [15:0] address,
               output logic RAM, ROM,
               output logic VIDEO, IO);

always_comb begin
    {RAM, ROM, VIDEO, IO} = 4'b 0;
    if (address[15])
        RAM = 1;
    else if (address[14:13] == 2'b 00 )
        VIDEO = 1;
    else if (address[14:12] == 3'b 101)
        IO = 1;
    else if (address[14:13] == 2'b 11 )
        ROM = 1;
end
endmodule
```

Vector concatenation

Default:
all zeros

Select bit 15

Select bits 14, 13, & 12

Omitting defaults for *RAM*, etc. will give “construct does not infer purely combinational logic.”

Sequential Logic

A D-Flip-Flop

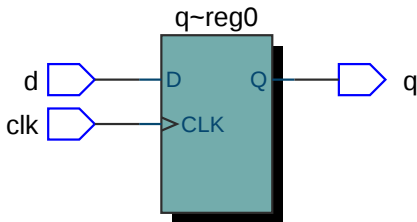
always_ff introduces
sequential logic

```
module mydff(input  logic clk,  
             input  logic d,  
             output logic q);  
  
    always_ff @(posedge clk)  
        q <= d;  
  
endmodule
```

Triggered by the
rising edge of clk

Copy d to q

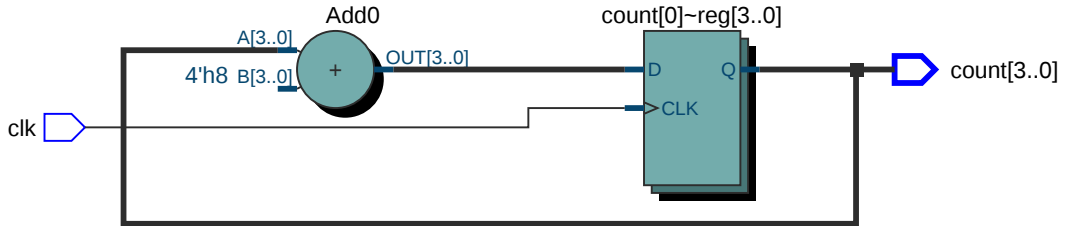
Non-blocking assignment:
happens "just after" the rising edge



A Four-Bit Binary Counter

```
module count4(input logic clk,  
              output logic [3:0] count);  
  
  always_ff @(posedge clk)  
    count <= count + 4'd 1;  
  
endmodule
```

Width optional
but good style



A Decimal Counter with Reset, Hold, and Load

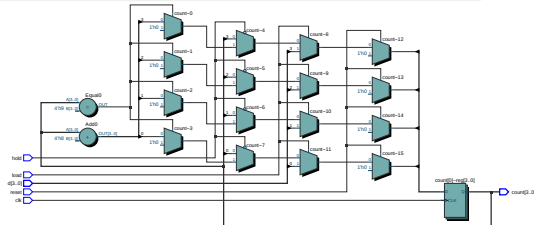
```

module dec_counter(input logic      clk,
                  input logic      reset, hold, load,
                  input logic [3:0] d,
                  output logic [3:0] count);

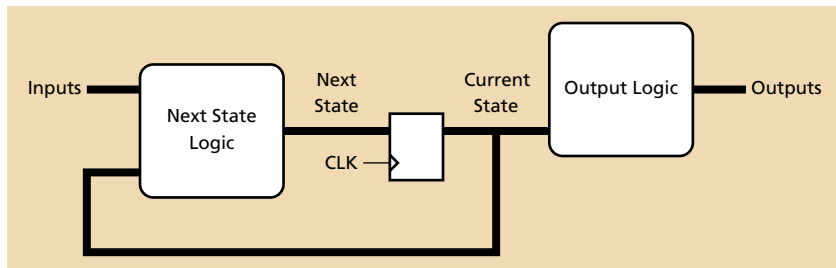
always_ff @(posedge clk)
    if (reset)          count <= 4'd 0;
    else if (load)      count <= d;
    else if (~hold)
        if (count == 4'd 9) count <= 4'd 0;
        else            count <= count + 4'd 1;

endmodule

```



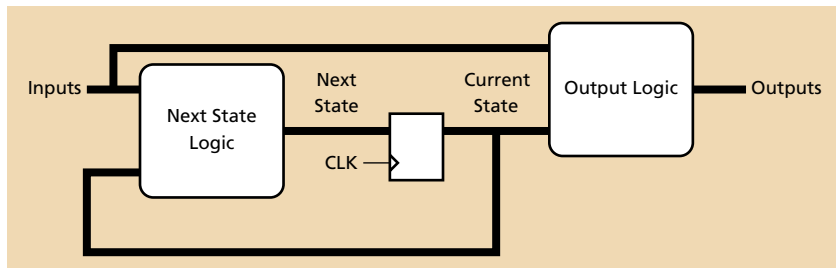
Moore and Mealy Finite-State Machines



The Moore Form:

Outputs are a function of *only* the current state.

Moore and Mealy Finite-State Machines



The Mealy Form:

Outputs may be a function of *both* the current state and the inputs.

A mnemonic: *Moore* machines often need *more* states.

Moore-style: Sequential Next-State Logic

```
module moore_tlc(input logic  clk, reset,
                 input logic  advance,
                 output logic  red, yellow, green);

enum logic [2:0] {R, Y, G} state; // Symbolic state names

always_ff @(posedge clk) // Moore-style next-state logic
    if (reset)          state <= R;
    else case (state)
        R: if (advance) state <= G;
        G: if (advance) state <= Y;
        Y: if (advance) state <= R;
        default:        state <= R;
    endcase

assign red    = state == R; // Combinational output logic
assign yellow = state == Y; // separated from next-state logic
assign green  = state == G;

endmodule
```

Mealy-style: Combinational output/next state logic

```
module mealy_tlc(input logic  clk, reset,
                 input logic  advance,
                 output logic  red, yellow, green);

typedef enum logic [2:0] {R, Y, G} state_t;
state_t state, next_state;

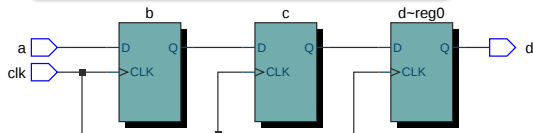
always_ff @(posedge clk)
    state <= next_state;

always_comb begin // Mealy-style next state and output logic
    {red, yellow, green} = 3'b0; // Default: all off and
    next_state = state;          // hold state
    if (reset)                   next_state = R;
    else case (state)
        R: begin red = 1;    if (advance) next_state = G; end
        G: begin green = 1;  if (advance) next_state = Y; end
        Y: begin yellow = 1; if (advance) next_state = R; end
        default:            next_state = R;
    endcase
end

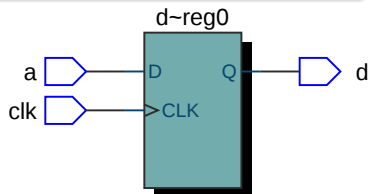
endmodule
```

Blocking vs. Nonblocking assignment

```
module nonblock(input    clk,  
               input logic a,  
               output logic d);  
  
logic b, c;  
  
always_ff @(posedge clk)  
begin  
    b <= a;      Nonblocking  
    c <= b;      assignment:  
    d <= c;      All run on the  
end              clock edge  
  
endmodule
```



```
module blocking(input    clk,  
               input logic a,  
               output logic d);  
  
logic b, c;  
  
always_ff @(posedge clk)  
begin  
    b = a;      Blocking  
    c = b;      assignment:  
    d = c;      Effect felt by  
end              next statement  
  
endmodule
```



Summary of Modeling Styles

```

module styles_tlc(input logic  clk, reset,
                  input logic  advance,
                  output logic red, yellow, green);
enum logic [2:0] {R, Y, G} state;

always_ff @(posedge clk)           // Imperative sequential
    if (reset) state <= R;         // Non-blocking assignment
    else case (state)              // Case
        R: if (advance) state <= G; // If-else
        G: if (advance) state <= Y;
        Y: if (advance) state <= R;
        default: state <= R;
    endcase

always_comb begin                  // Imperative combinational
    {red, yellow} = 2'b 0;        // Blocking assignment
    if (state == R) red = 1;      // If-else
    case (state)                  // Case
        Y: yellow = 1;
        default: ;
    endcase;
end

assign green = state == G;        // Cont. assign. (comb)
endmodule

```