

Digital Design with SystemVerilog

Prof. Stephen A. Edwards

Columbia University

Spring 2024

Synchronous Digital Design

Combinational Logic

Sequential Logic

Summary of Modeling Styles

Why HDLs?

1970s: SPICE transistor-level netlists

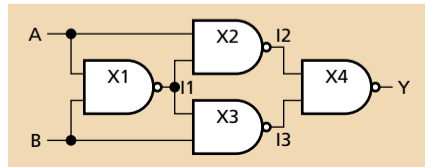
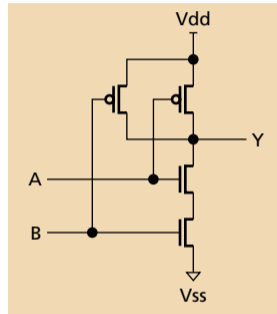


An XOR built from four NAND gates

```
.MODEL P PMOS
.MODEL N NMOS

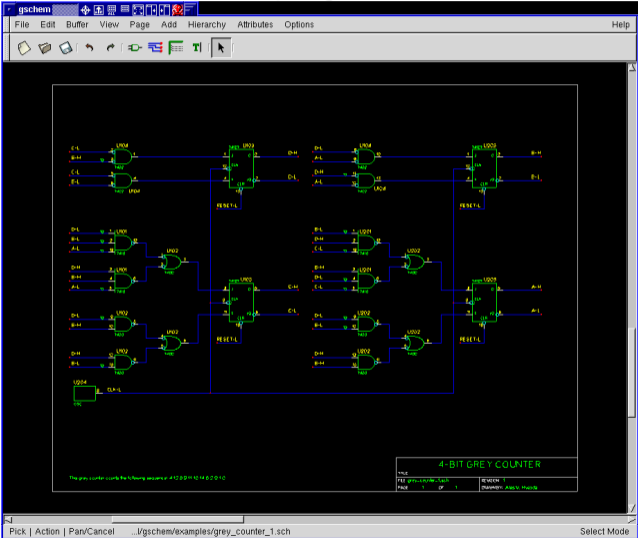
.SUBCKT NAND A B Y Vdd Vss
M1 Y A Vdd Vdd P
M2 Y B Vdd Vdd P
M3 Y A X Vss N
M4 X B Vss Vss N
.ENDS

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?

1980s: Graphical schematic capture programs

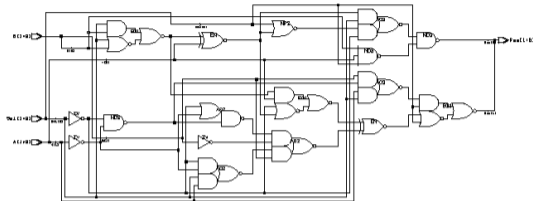


Why HDLs?

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

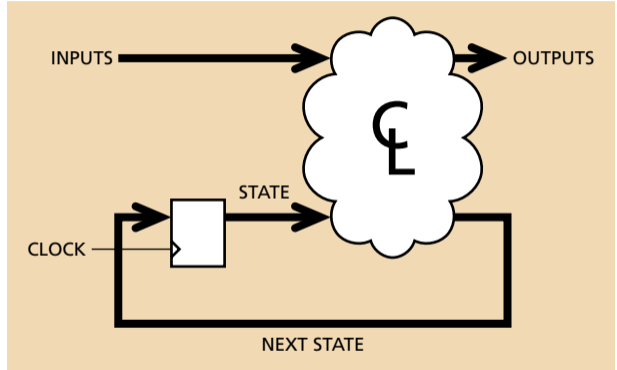
No level-sensitive latches

All flip-flops driven by the same clock

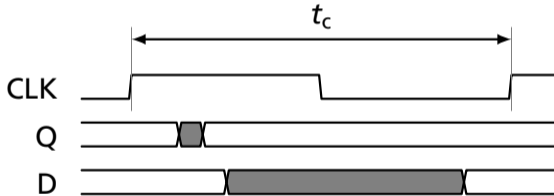
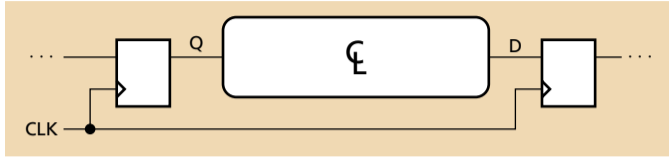
No other clock signals

Every cyclic path contains at least one flip-flop

No combinational loops



Timing in Synchronous Circuits

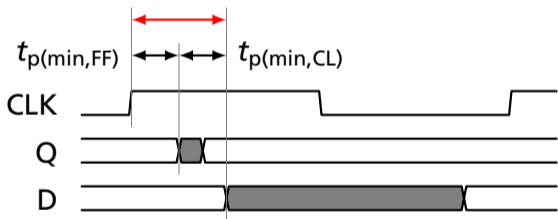


t_c : Clock period. E.g., 10 ns for a 100 MHz clock

Timing in Synchronous Circuits

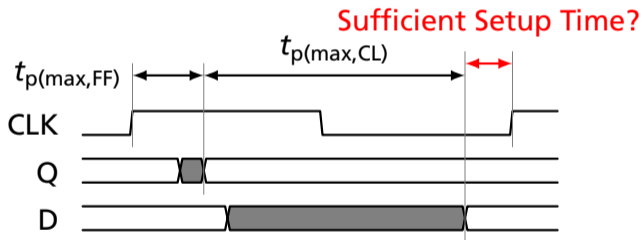
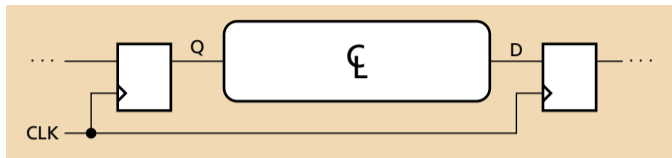


Sufficient Hold Time?



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

```
// 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
```

Single-line comment

Systems are built from modules

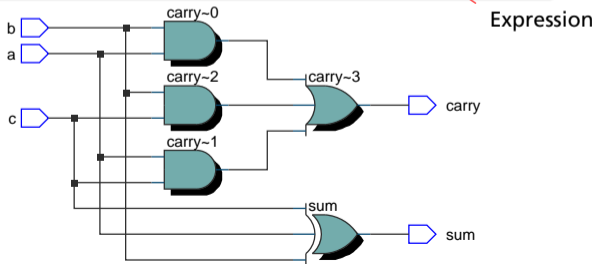
Module name

Input port

Data type: single bit

Port name

"Continuous assignment" expresses combinational logic



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
```

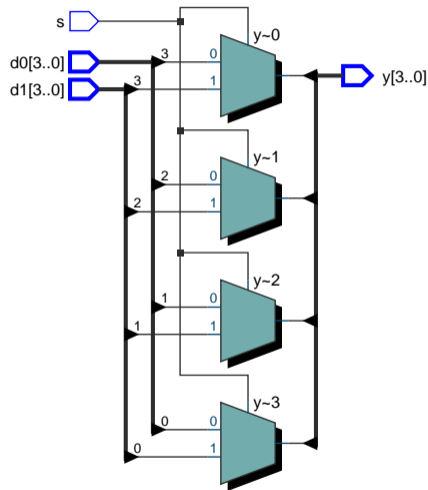
Multi-line
comment

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

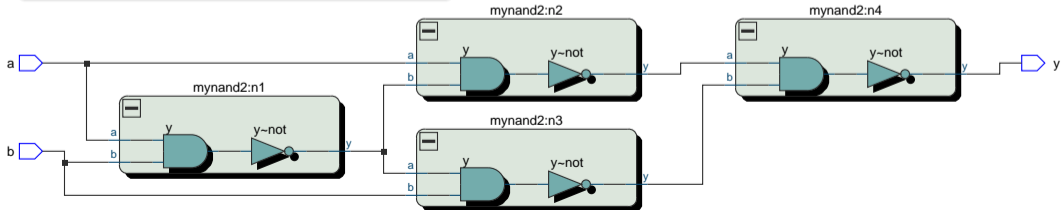
!c -c &c ~&c	NOT, Negate, Reduction AND, NAND
c ~ c ^c ~^c	OR, NOR, XOR, XNOR
a * b a / b a % b	Multiply, Divide, Modulus
a + b a - b	Add, Subtract
a << b a >> b	Logical Shift
a <<< b a >>> b	Arithmetic Shift
a < b a <= b a > b a >= b	Relational
a == b a != b	Equality
a & b a ^& b	AND
a ^ b a ~^ b	XOR, XNOR
a b	OR
a ? b : c	Conditional
{a,b,c,d,r{e}}}	Concatenation and Replication

An XOR Built Hierarchically

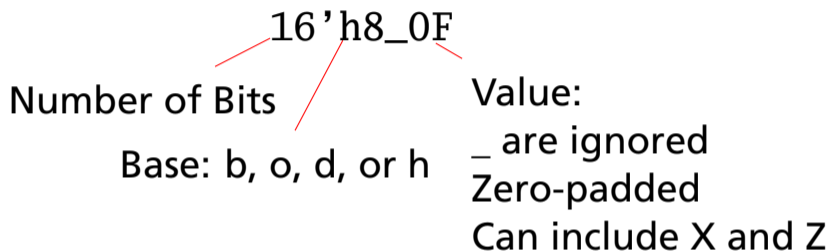
```
module mynand2(input logic a, b,  
              output logic y);  
    assign y = ~(a & b);  
endmodule  
  
module myxor2(input logic a, b,  
            output logic y);  
    logic abn, aa, bb;  
  
    mynand2 n1(a, b, abn),  
          n2(a, abn, aa),  
          n3(abn, b, bb),  
        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

Declare internal wires

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



Verilog Numbers



`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

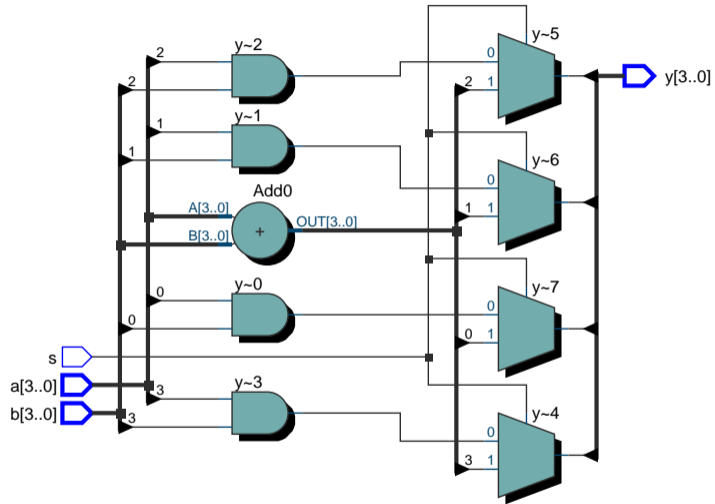
```
module dec7seg(input logic [3:0] a,  
               output logic [6:0] y);  
    always_comb  
        case (a)  
            4'd0:    y = 7'b111_1110;  
            4'd1:    y = 7'b011_0000;  
            4'd2:    y = 7'b110_1101;  
            4'd3:    y = 7'b111_1001;  
            4'd4:    y = 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

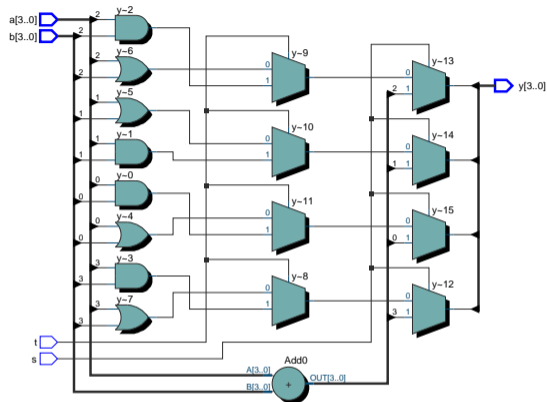
```
module comb1(  
  input logic [3:0] a, b,  
  input logic s,  
  output logic [3:0] y);  
  
  always_comb  
    if (s)  
      y = a + b;  
    else  
      y = a & b;  
  
endmodule
```



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
```



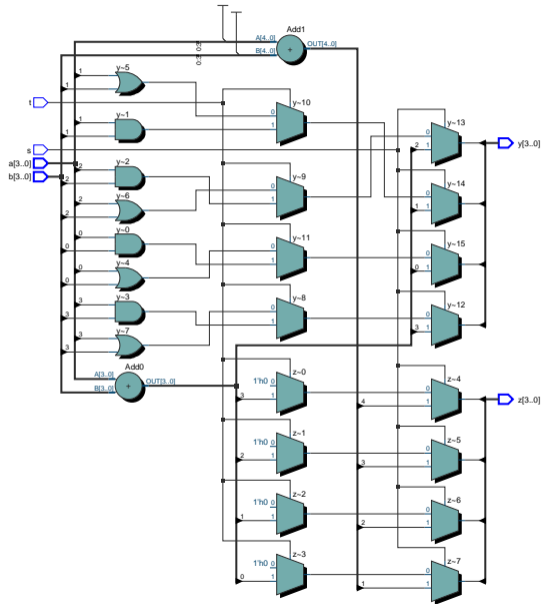
All three expressions computed in parallel. Cascaded muxes implement priority (s over t).

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  
  
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

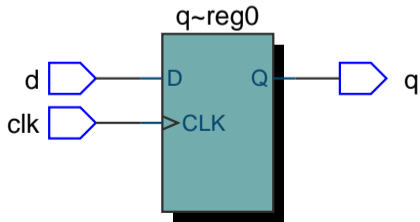
always_ff introduces sequential logic

```
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

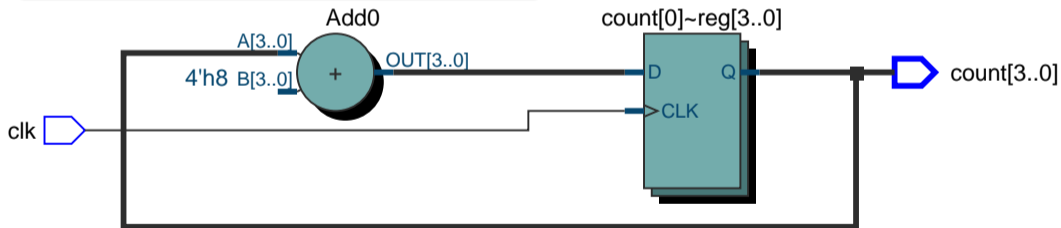
Non-blocking assignment:
happens "just after" the rising edge



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

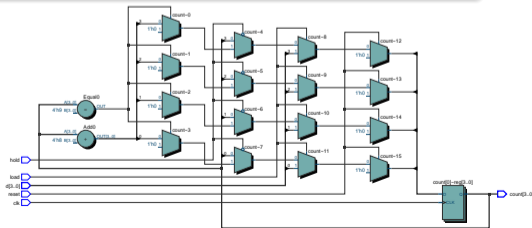


A Decimal Counter with Reset, Hold, and Load

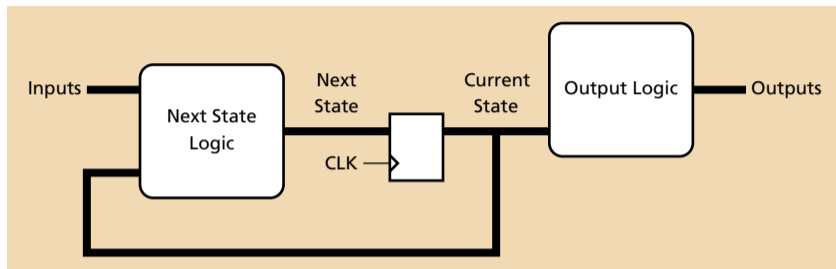
```
module dec_counter(input logic      clk,
                  input logic      reset, hold, load,
                  input logic [3:0] d,
                  output logic [3:0] count);

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
```



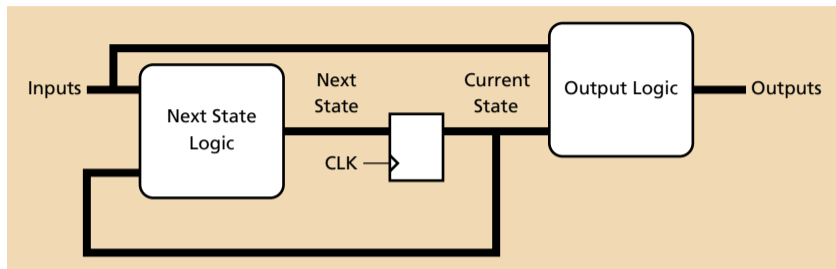
Moore and Mealy Finite-State Machines



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
```

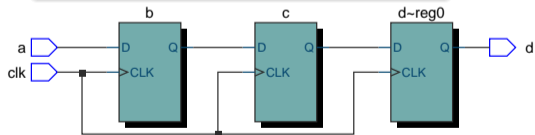

Blocking vs. Nonblocking assignment

```
module nonblock(input clk,
               input logic a,
               output logic d);

logic b, c;

always_ff @(posedge clk)
begin
    b <= a;           Nonblocking
                     assignment:
    c <= b;           All run on the
                     clock edge
    d <= c;
end

endmodule
```

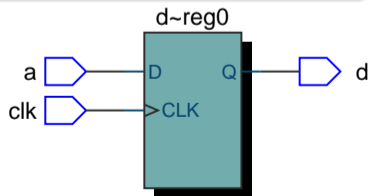


```
module blocking(input clk,
               input logic a,
               output logic d);

logic b, c;

always_ff @(posedge clk)
begin
    b = a;           Blocking
                    assignment:
    c = b;           Effect felt by
                    next statement
    d = c;
end

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

```