

# Chapter 4

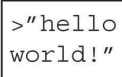


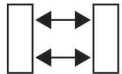
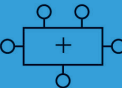

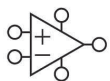


## ***Digital Design and Computer Architecture, 2<sup>nd</sup> Edition***

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David Money Harris and Sarah L. Harris

# Chapter 4 :: Topics

- Introduction
- Combinational Logic
- Structural Modeling
- Sequential Logic
- More Combinational Logic
- Finite State Machines
- Parameterized Modules
- Testbenches

Application Software	
Operating Systems	
Architecture	
Micro-architecture	
Logic	
Digital Circuits	
Analog Circuits	
Devices	
Physics	

# Introduction

- Hardware description language (HDL):
  - specifies logic function only
  - Computer-aided design (CAD) tool produces or *synthesizes* the optimized gates
- Most commercial designs built using HDLs
- Two leading HDLs:
  - **SystemVerilog**
    - developed in 1984 by Gateway Design Automation
    - IEEE standard (1364) in 1995
    - Extended in 2005 (IEEE STD 1800-2009)
  - **VHDL 2008**
    - Developed in 1981 by the Department of Defense
    - IEEE standard (1076) in 1987
    - Updated in 2008 (IEEE STD 1076-2008)



# HDL to Gates

- **Simulation**

- Inputs applied to circuit
- Outputs checked for correctness
- Millions of dollars saved by debugging in simulation instead of hardware

- **Synthesis**

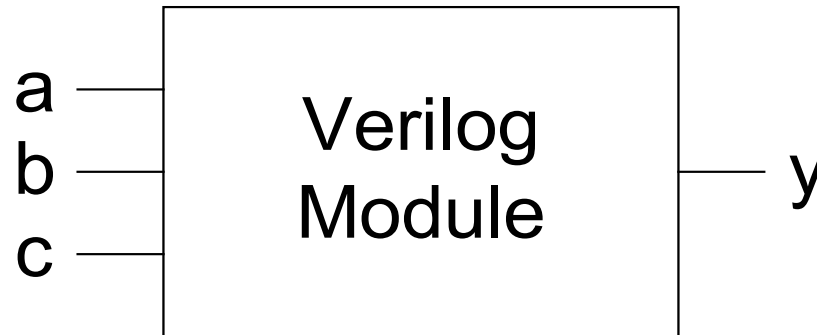
- Transforms HDL code into a *netlist* describing the hardware (i.e., a list of gates and the wires connecting them)

# HDL: **Hardware** Description Language

## **IMPORTANT:**

When using an HDL, think of the **hardware** the HDL should produce.

# SystemVerilog Modules



## Two types of Modules:

- **Behavioral:** describe what a module does
- **Structural:** describe how it is built from simpler modules

# Behavioral SystemVerilog

## SystemVerilog:

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

# Behavioral SystemVerilog

## SystemVerilog:

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

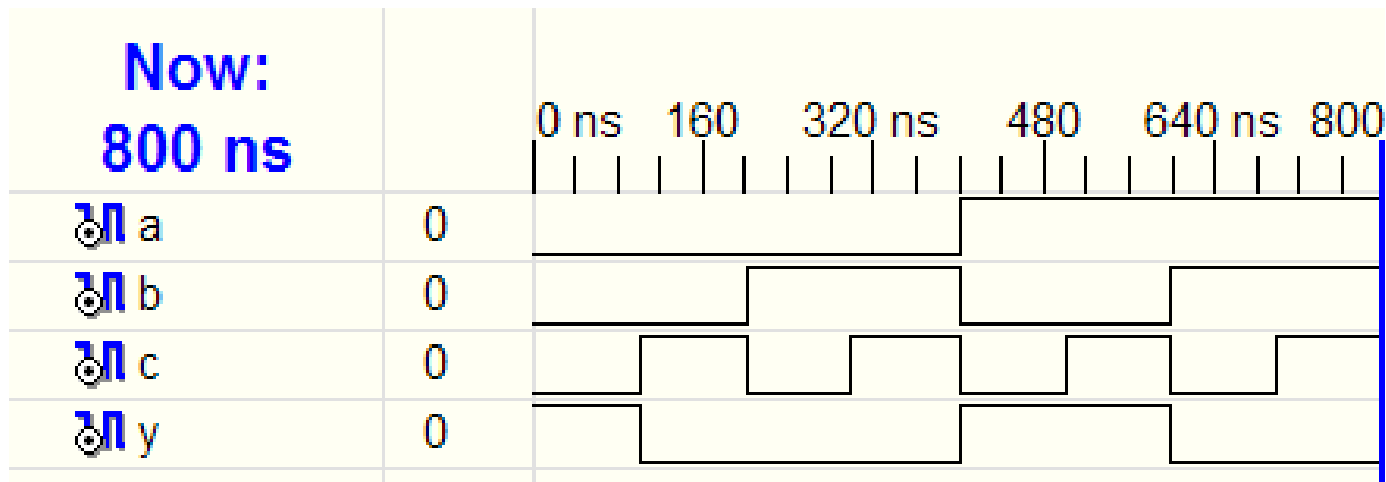
- module/endmodule: required to begin/end module
- example: name of the module
- Operators:
  - ~: NOT
  - &: AND
  - |: OR



# HDL Simulation

## SystemVerilog:

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

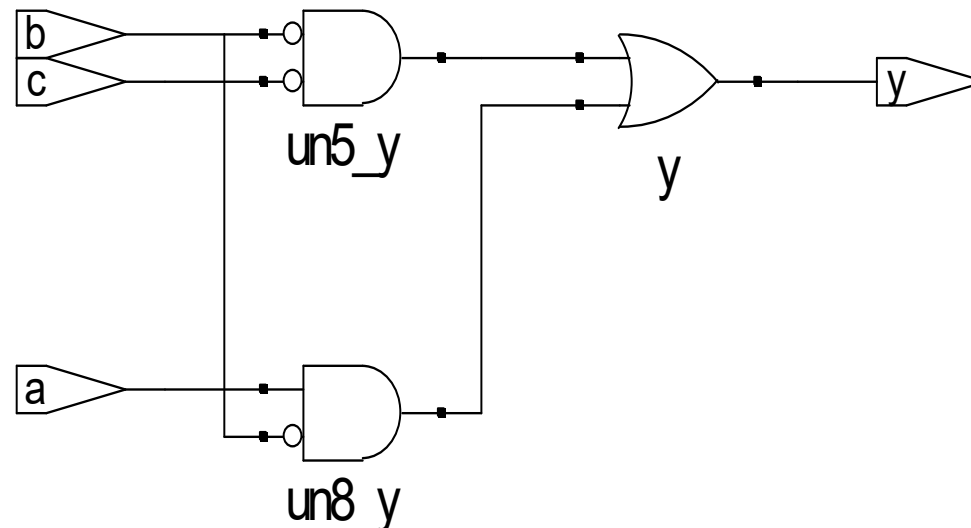


# HDL Synthesis

## SystemVerilog:

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

## Synthesis:



# SystemVerilog Syntax

- Case sensitive
  - **Example:** `reset` and `Reset` are not the same signal.
- No names that start with numbers
  - **Example:** `2mux` is an invalid name
- Whitespace ignored
- Comments:
  - `//` single line comment
  - `/*` multiline  
comment `*/`

# Structural Modeling - Hierarchy

```
module and3(input  logic a, b, c,  
            output logic y);  
    assign y = a & b & c;  
endmodule
```

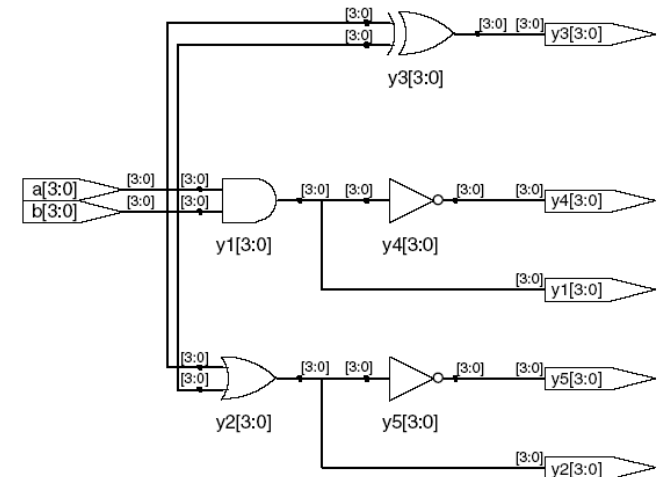
```
module inv(input  logic a,  
            output logic y);  
    assign y = ~a;  
endmodule
```

```
module nand3(input  logic a, b, c  
             output logic y);  
    logic n1;                                // internal signal  
  
    and3 andgate(a, b, c, n1);              // instance of and3  
    inv  inverter(n1, y);                   // instance of inv  
endmodule
```

# Bitwise Operators

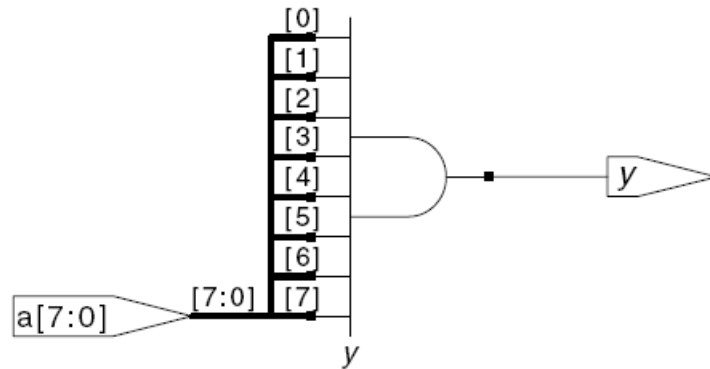
```
module gates(input  logic [3:0]  a, b,
             output logic [3:0] y1, y2, y3, y4, y5);
    /* Five different two-input logic
       gates acting on 4 bit busses */
    assign y1 = a & b;      // AND
    assign y2 = a | b;      // OR
    assign y3 = a ^ b;      // XOR
    assign y4 = ~(a & b);   // NAND
    assign y5 = ~(a | b);   // NOR
endmodule
```

// single line comment  
/\*...\*/ multiline comment



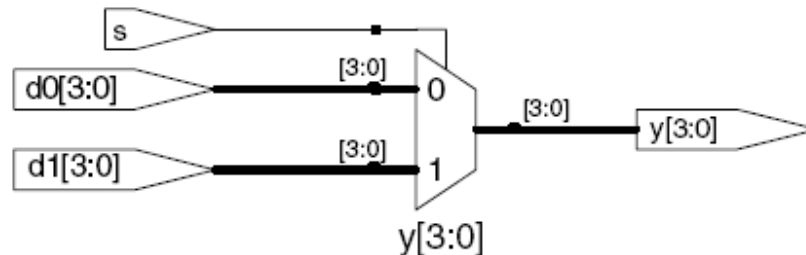
# Reduction Operators

```
module and8(input  logic [7:0] a,
            output logic      y);
    assign y = &a;
    // &a is much easier to write than
    // assign y = a[7] & a[6] & a[5] & a[4] &
    //           a[3] & a[2] & a[1] & a[0];
endmodule
```



# Conditional Assignment

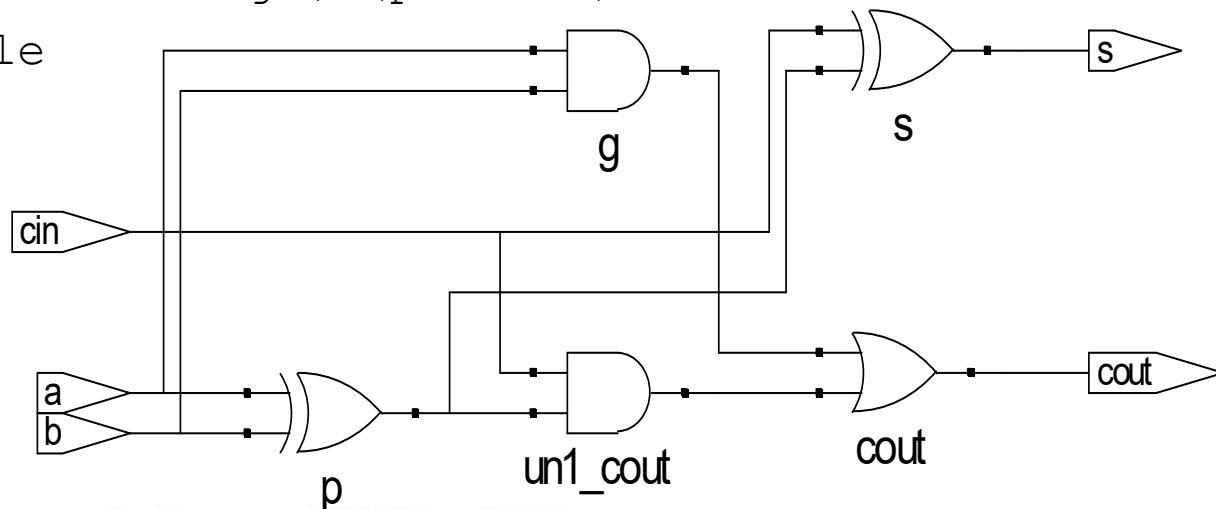
```
module mux2(input  logic [3:0] d0, d1,  
            input  logic      s,  
            output logic [3:0] y);  
    assign y = s ? d1 : d0;  
endmodule
```



? : is also called a *ternary operator* because it operates on 3 inputs: s, d1, and d0.

# Internal Variables

```
module fulladder(input  logic a, b, cin,  
                 output logic s, cout);  
    logic p, g;    // internal nodes  
  
    assign p = a ^ b;  
    assign g = a & b;  
  
    assign s = p ^ cin;  
    assign cout = g | (p & cin);  
endmodule
```





# Precedence

## Order of operations

Highest

~	NOT
*, /, %	mult, div, mod
+, -	add, sub
<<, >>	shift
<<<, >>>	arithmetic shift
<, <=, >, >=	comparison
==, !=	equal, not equal
&, ~&	AND, NAND
^, ~^	XOR, XNOR
, ~	OR, NOR
?:	ternary operator

Lowest

# Numbers

## Format: N'Bvalue

**N** = number of bits, **B** = base

**N'B** is optional but recommended (default is decimal)

Number	# Bits	Base	Decimal Equivalent	Stored
3'b101	3	binary	5	101
'b11	unsized	binary	3	00...0011
8'b11	8	binary	3	00000011
8'b1010_1011	8	binary	171	10101011
3'd6	3	decimal	6	110
6'o42	6	octal	34	100010
8'hAB	8	hexadecimal	171	10101011
42	Unsize	decimal	42	00...0101010



# Bit Manipulations: Example 1

```
assign y = {a[2:1], {3{b[0]}}}, a[0], 6'b100_010};
```

```
// if y is a 12-bit signal, the above statement produces:
```

```
y = a[2] a[1] b[0] b[0] b[0] a[0] 1 0 0 0 1 0
```

```
// underscores (_) are used for formatting only to make  
it easier to read. SystemVerilog ignores them.
```

# Bit Manipulations: Example 2

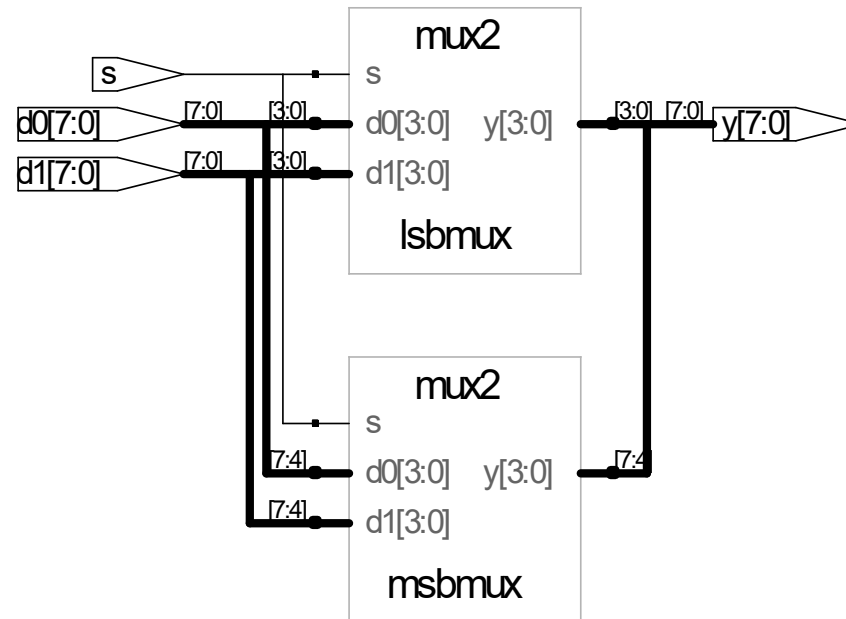
## SystemVerilog:

```

module mux2_8(input  logic [7:0] d0, d1,
              input  logic      s,
              output logic [7:0] y);

    mux2 lsbmux(d0[3:0], d1[3:0], s, y[3:0]);
    mux2 msbmux(d0[7:4], d1[7:4], s, y[7:4]);
endmodule

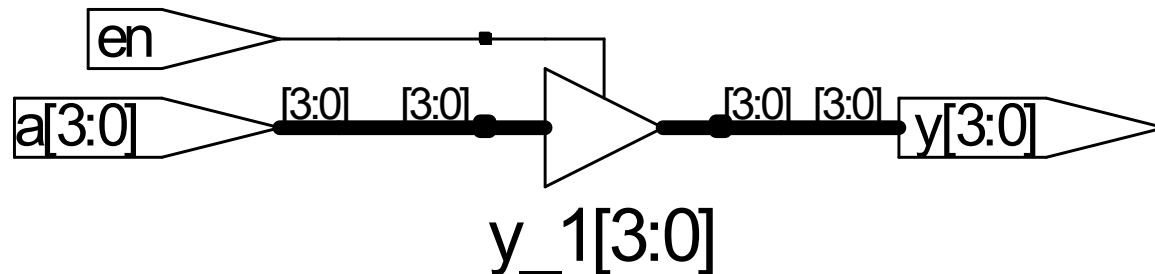
```



# Z: Floating Output

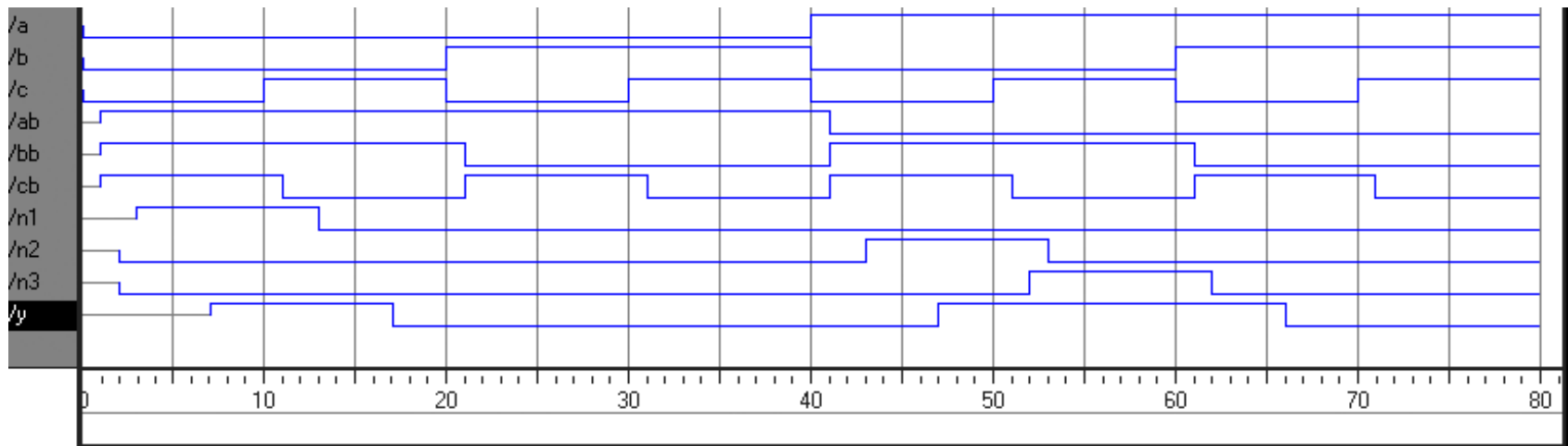
## SystemVerilog:

```
module tristate(input  logic [3:0] a,  
                input  logic      en,  
                output tri  [3:0] y);  
    assign y = en ? a : 4'bz;  
endmodule
```



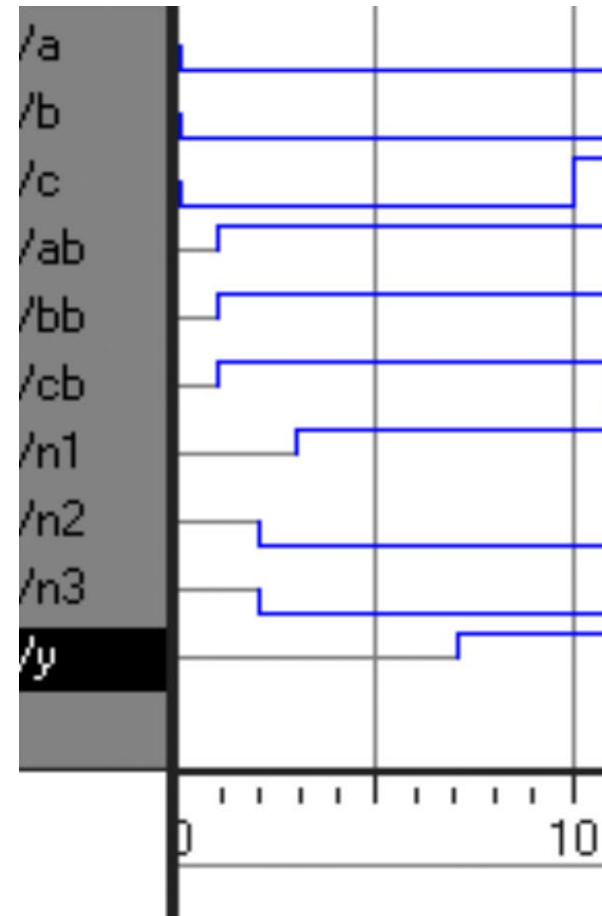
# Delays

```
module example(input  logic a, b, c,  
               output logic y);  
    logic ab, bb, cb, n1, n2, n3;  
    assign #1 {ab, bb, cb} = ~{a, b, c};  
    assign #2 n1 = ab & bb & cb;  
    assign #2 n2 = a & bb & cb;  
    assign #2 n3 = a & bb & c;  
    assign #4 y = n1 | n2 | n3;  
endmodule
```



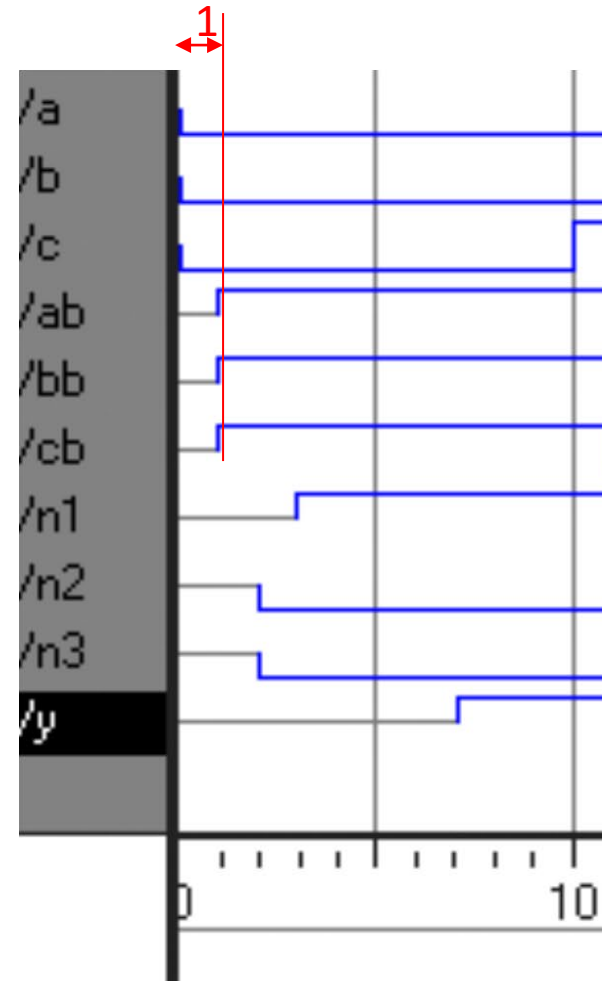
# Delays

```
module example(input  logic a, b, c,  
               output logic y);  
    logic ab, bb, cb, n1, n2, n3;  
    assign #1 {ab, bb, cb} =  
            ~{a, b, c};  
    assign #2 n1 = ab & bb & cb;  
    assign #2 n2 = a & bb & cb;  
    assign #2 n3 = a & bb & c;  
    assign #4 y = n1 | n2 | n3;  
endmodule
```



# Delays

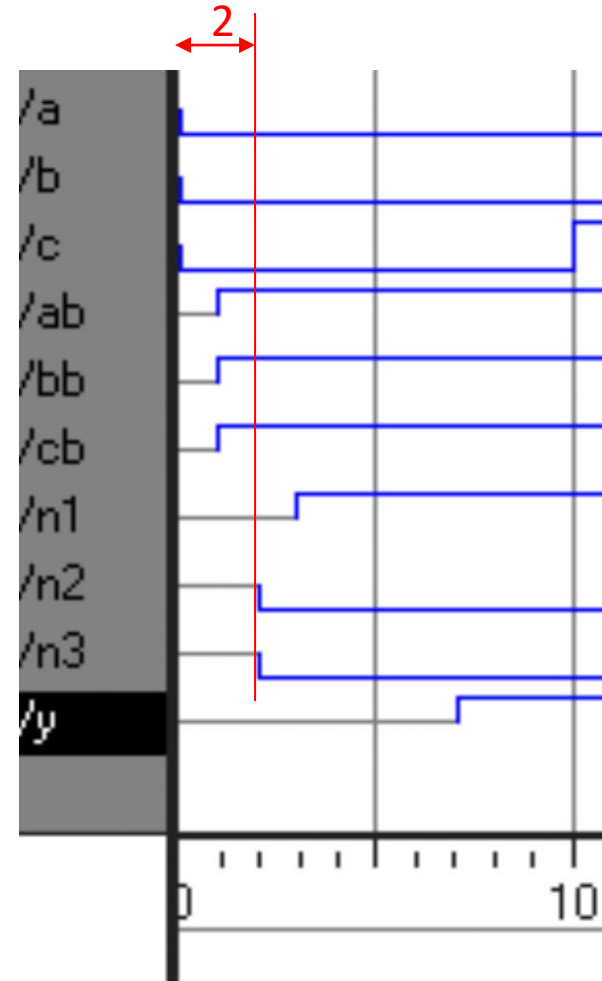
```
module example(input logic a, b, c,  
               output logic y);  
  logic ab, bb, cb, n1, n2, n3;  
  assign #1 {ab, bb, cb} =  
           ~{a, b, c};  
  assign #2 n1 = ab & bb & cb;  
  assign #2 n2 = a & bb & cb;  
  assign #2 n3 = a & bb & c;  
  assign #4 y = n1 | n2 | n3;  
endmodule
```





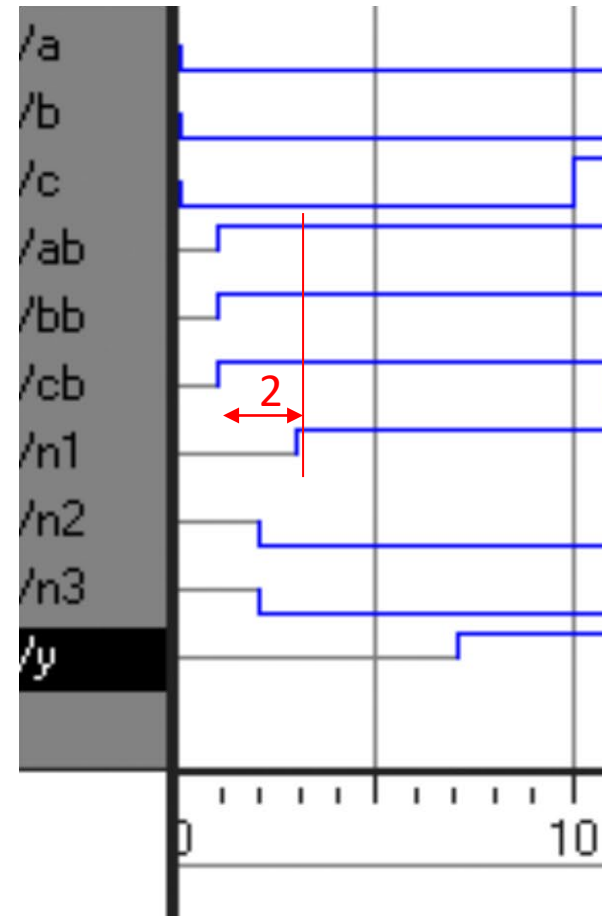
# Delays

```
module example(input logic a, b, c,  
               output logic y);  
    logic ab, bb, cb, n1, n2, n3;  
    assign #1 {ab, bb, cb} =  
            ~{a, b, c};  
    assign #2 n1 = ab & bb & cb;  
    assign #2 n2 = a & bb & cb;  
    assign #2 n3 = a & bb & c;  
    assign #4 y = n1 | n2 | n3;  
endmodule
```



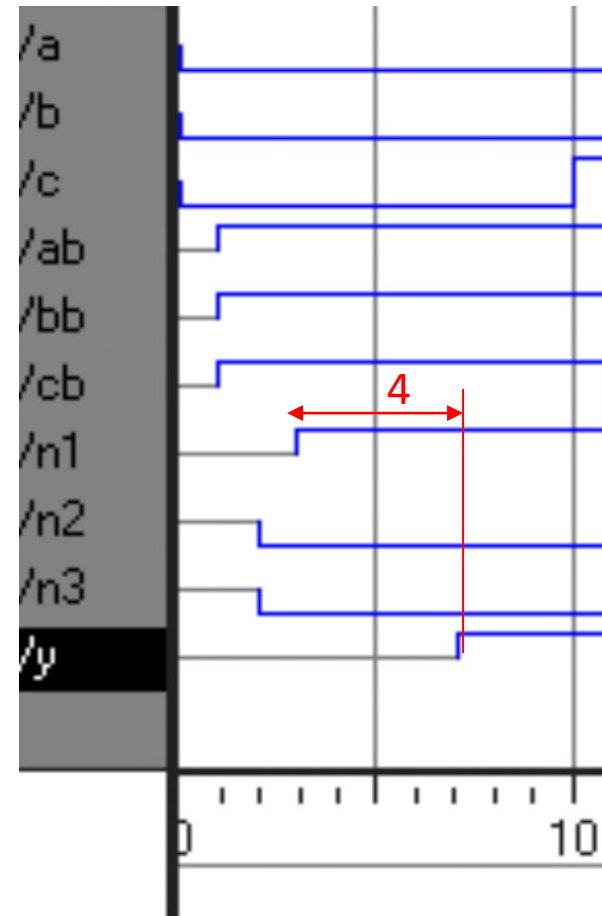
# Delays

```
module example(input logic a, b, c,  
               output logic y);  
    logic ab, bb, cb, n1, n2, n3;  
    assign #1 {ab, bb, cb} =  
            ~{a, b, c};  
    assign #2 n1 = ab & bb & cb;  
    assign #2 n2 = a & bb & cb;  
    assign #2 n3 = a & bb & c;  
    assign #4 y = n1 | n2 | n3;  
endmodule
```



# Delays

```
module example(input logic a, b, c,  
               output logic y);  
    logic ab, bb, cb, n1, n2, n3;  
    assign #1 {ab, bb, cb} =  
            ~{a, b, c};  
    assign #2 n1 = ab & bb & cb;  
    assign #2 n2 = a & bb & cb;  
    assign #2 n3 = a & bb & c;  
    assign #4 y = n1 | n2 | n3;  
endmodule
```



# Sequential Logic

- SystemVerilog uses **idioms** to describe latches, flip-flops and FSMs
- Other coding styles may simulate correctly but produce incorrect hardware

# Always Statement

## General Structure:

```
always @(sensitivity list)
    statement;
```

Whenever the event in sensitivity list occurs,  
statement is executed

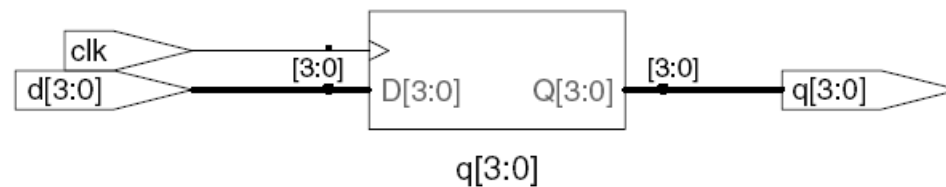


# D Flip-Flop

```
module flop(input logic      clk,
            input logic [3:0] d,
            output logic [3:0] q);

    always_ff @(posedge clk)
        q <= d;                // pronounced "q gets d"

endmodule
```



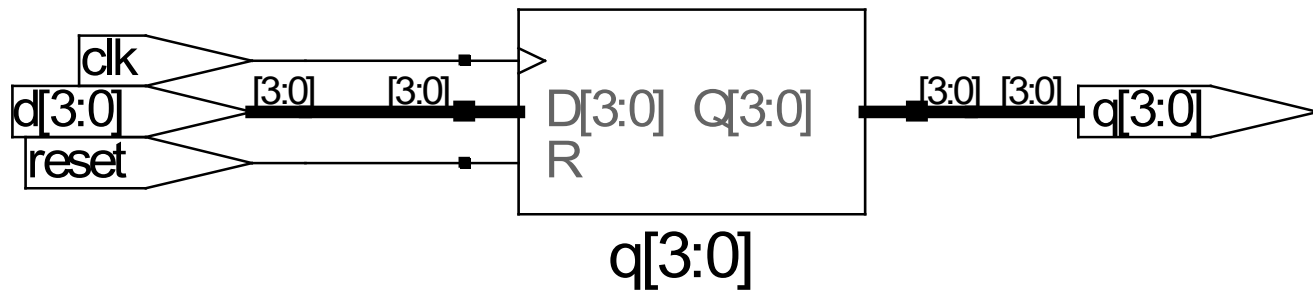
# Resettable D Flip-Flop

```
module flopr(input  logic      clk,  
             input  logic      reset,  
             input  logic [3:0] d,  
             output logic [3:0] q);
```

```
    // synchronous reset
```

```
    always_ff @(posedge clk)  
        if (reset) q <= 4'b0;  
        else      q <= d;
```

```
endmodule
```



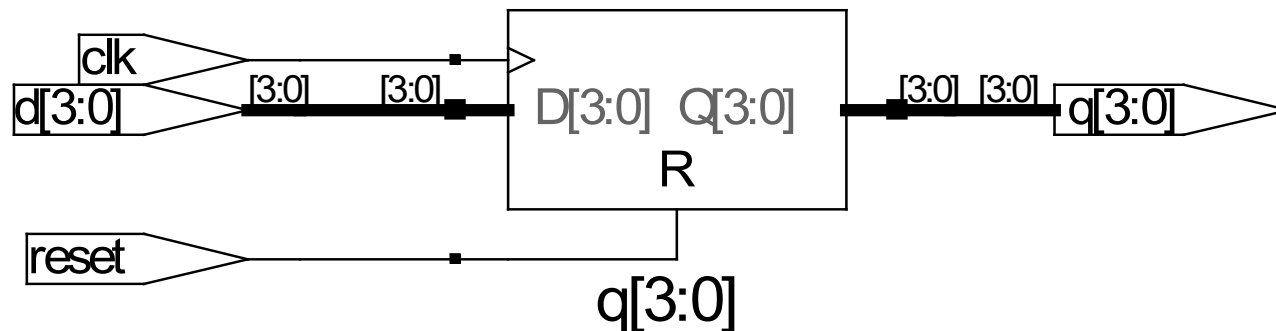
# Resettable D Flip-Flop

```
module flopr(input logic clk,  
            input logic reset,  
            input logic [3:0] d,  
            output logic [3:0] q);
```

```
    // asynchronous reset
```

```
    always_ff @(posedge clk, posedge reset)  
        if (reset) q <= 4'b0;  
        else      q <= d;
```

```
endmodule
```





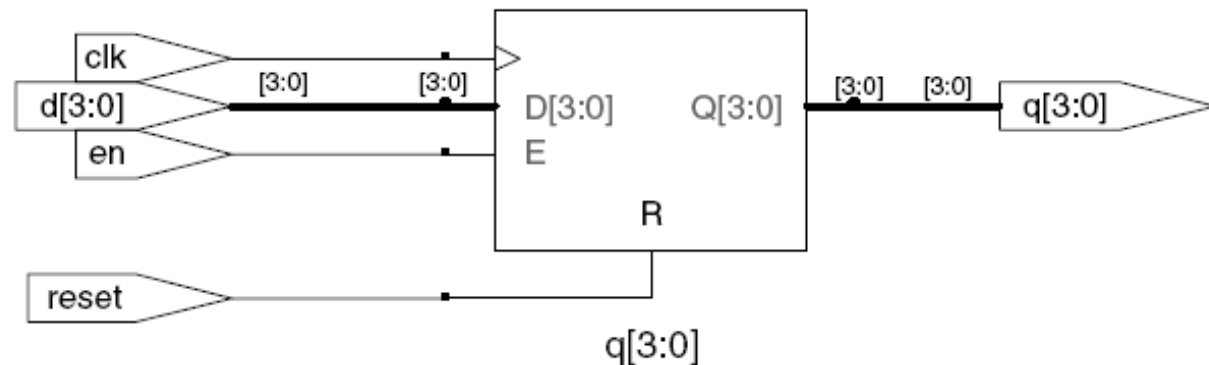
# D Flip-Flop with Enable

```
module flopren(input  logic      clk,
               input  logic      reset,
               input  logic      en,
               input  logic [3:0] d,
               output logic [3:0] q);
```

```
    // asynchronous reset and enable
```

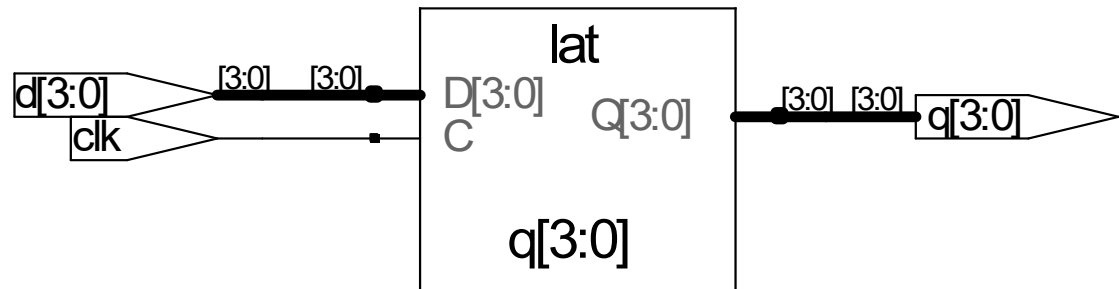
```
    always_ff @(posedge clk, posedge reset)
        if      (reset) q <= 4'b0;
        else if (en)    q <= d;
```

```
endmodule
```



# Latch

```
module latch(input logic clk,  
             input logic [3:0] d,  
             output logic [3:0] q);  
  
    always_latch  
        if (clk) q <= d;  
  
endmodule
```



**Warning:** We don't use latches in this text. But you might write code that inadvertently implies a latch. Check synthesized hardware – if it has latches in it, there's an error.



# Other Behavioral Statements

- Statements that must be inside `always` statements:
  - `if / else`
  - `case, casez`

# Combinational Logic using always

```
// combinational logic using an always statement
module gates(input  logic [3:0] a, b,
              output logic [3:0] y1, y2, y3, y4, y5);
    always_comb          // need begin/end because there is
    begin                // more than one statement in always
        y1 = a & b;      // AND
        y2 = a | b;      // OR
        y3 = a ^ b;      // XOR
        y4 = ~(a & b);   // NAND
        y5 = ~(a | b);   // NOR
    end
endmodule
```

**This hardware could be described with assign statements using fewer lines of code, so it's better to use assign statements in this case.**

# Combinational Logic using case

```
module sevenseg(input  logic [3:0] data,
                 output logic [6:0] segments);

    always_comb
        case (data)
            //                                abc_defg
            0: segments =                    7'b111_1110;
            1: segments =                    7'b011_0000;
            2: segments =                    7'b110_1101;
            3: segments =                    7'b111_1001;
            4: segments =                    7'b011_0011;
            5: segments =                    7'b101_1011;
            6: segments =                    7'b101_1111;
            7: segments =                    7'b111_0000;
            8: segments =                    7'b111_1111;
            9: segments =                    7'b111_0011;
            default: segments = 7'b000_0000; // required
        endcase
    endmodule
```



# Combinational Logic using case

- case statement implies combinational logic **only if** all possible input combinations described
- Remember to use `default` statement



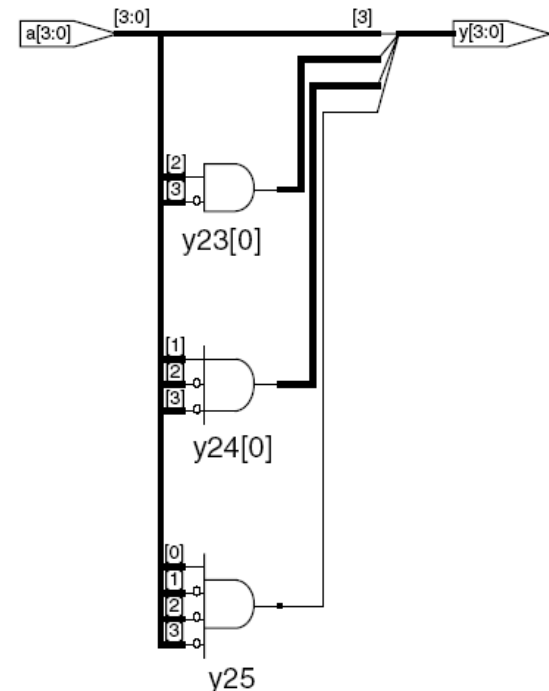
# Combinational Logic using casez

```

module priority_casez(input  logic [3:0] a,
                      output logic [3:0] y);

  always_comb
    casez (a)
      4'b1???: y = 4'b1000; // ? = don't care
      4'b01??: y = 4'b0100;
      4'b001?: y = 4'b0010;
      4'b0001: y = 4'b0001;
      default: y = 4'b0000;
    endcase
endmodule

```

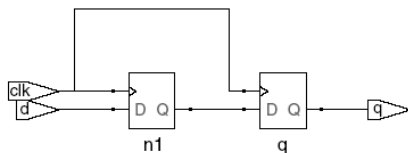


# Blocking vs. Nonblocking Assignment

- `<=` is **nonblocking** assignment
  - Occurs simultaneously with others
- `=` is **blocking** assignment
  - Occurs in order it appears in file

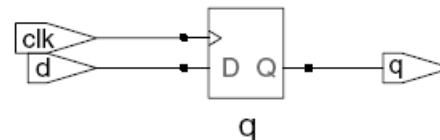
```
// Good synchronizer using
// nonblocking assignments
module syncgood(input logic clk,
                input logic d,
                output logic q);

  logic n1;
  always_ff @(posedge clk)
  begin
    n1 <= d; // nonblocking
    q  <= n1; // nonblocking
  end
endmodule
```



```
// Bad synchronizer using
// blocking assignments
module syncbad(input logic clk,
               input logic d,
               output logic q);

  logic n1;
  always_ff @(posedge clk)
  begin
    n1 = d; // blocking
    q  = n1; // blocking
  end
endmodule
```





# Rules for Signal Assignment

- **Synchronous sequential logic:** use `always_ff` @ (`posedge clk`) and nonblocking assignments (`<=`)

```
always_ff @ (posedge clk)
    q <= d; // nonblocking
```

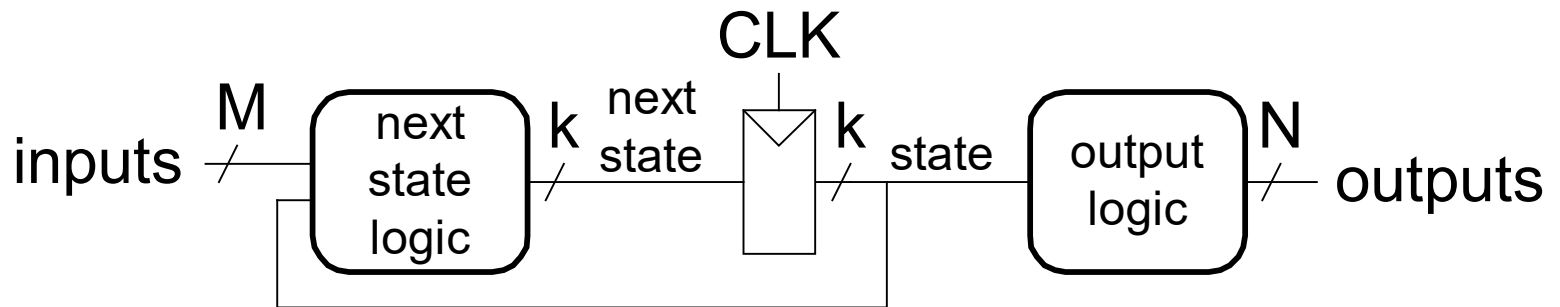
- **Simple combinational logic:** use continuous assignments (`assign...`)

```
assign y = a & b;
```

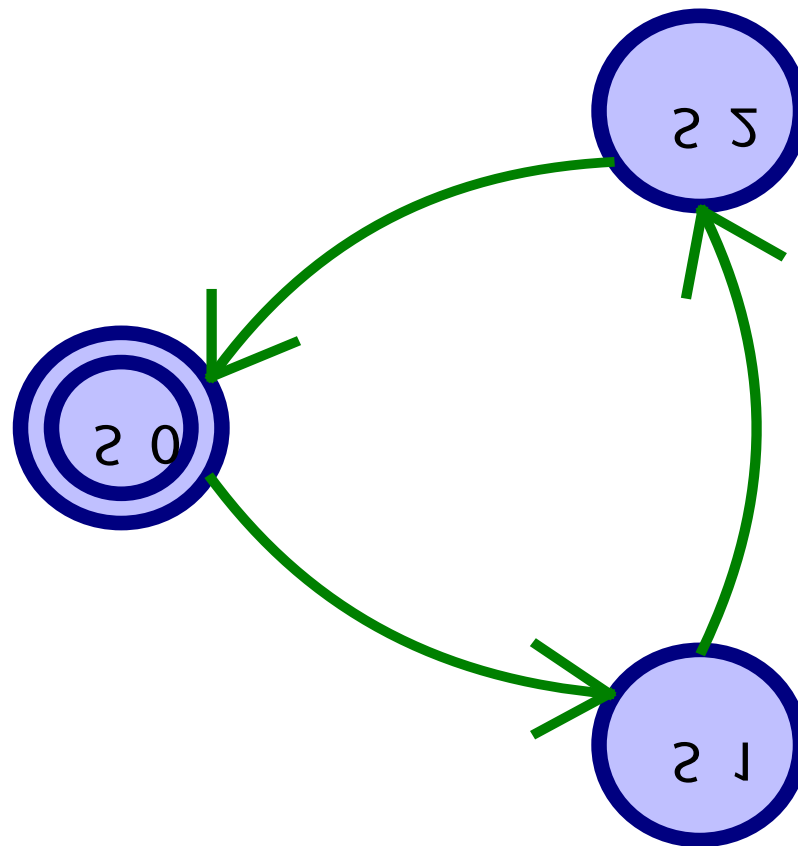
- **More complicated combinational logic:** use `always_comb` and blocking assignments (`=`)
- Assign a signal in **only one** `always` statement or continuous assignment statement.

# Finite State Machines (FSMs)

- **Three blocks:**
  - next state logic
  - state register
  - output logic



# FSM Example: Divide by 3



The **double circle** indicates the reset state

# FSM in SystemVerilog

```
module divideby3FSM (input  logic clk,
                    input  logic reset,
                    output logic q);

    typedef enum logic [1:0] {S0, S1, S2} statetype;
    statetype state, nextstate;

    // state register
    always_ff @ (posedge clk, posedge reset)
        if (reset) state <= S0;
        else       state <= nextstate;

    // next state logic
    always_comb
        case (state)
            S0:     nextstate = S1;
            S1:     nextstate = S2;
            S2:     nextstate = S0;
            default: nextstate = S0;
        endcase

    // output logic
    assign q = (state == S0);
endmodule
```



# Parameterized Modules

## 2:1 mux:

```
module mux2
    #(parameter width = 8)    // name and default value
    (input  logic [width-1:0] d0, d1,
     input  logic              s,
     output logic [width-1:0] y);
    assign y = s ? d1 : d0;
endmodule
```

## Instance with 8-bit bus width (uses default):

```
mux2 myMux(d0, d1, s, out);
```

## Instance with 12-bit bus width:

```
mux2 #(12) lowmux(d0, d1, s, out);
```



# Testbenches

- HDL that tests another module: *device under test* (dut)
- Not synthesizable
- Types:
  - Simple
  - Self-checking
  - Self-checking with testvectors

# Testbench Example

- Write SystemVerilog code to implement the following function in hardware:

$$y = \overline{b}\overline{c} + a\overline{b}$$

- Name the module `sillyfunction`

# Testbench Example

- Write SystemVerilog code to implement the following function in hardware:

$$y = \overline{b}\overline{c} + a\overline{b}$$

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



# Simple Testbench

```
module testbench1();  
    logic a, b, c;  
    logic y;  
    // instantiate device under test (dut)  
    sillyfunction dut(a, b, c, y);  
    // apply inputs one at a time  
    initial begin  
        a = 0; b = 0; c = 0; #10;  
        c = 1; #10;  
        b = 1; c = 0; #10;  
        c = 1; #10;  
        a = 1; b = 0; c = 0; #10;  
        c = 1; #10;  
        b = 1; c = 0; #10;  
        c = 1; #10;  
    end  
endmodule
```



# Self-checking Testbench

```
module testbench2();  
    logic a, b, c;  
    logic y;  
    sillyfunction dut(a, b, c, y); // instantiate dut  
    initial begin // apply inputs, check results one at a time  
        a = 0; b = 0; c = 0; #10;  
        if (y !== 1) $display("000 failed.");  
        c = 1; #10;  
        if (y !== 0) $display("001 failed.");  
        b = 1; c = 0; #10;  
        if (y !== 0) $display("010 failed.");  
        c = 1; #10;  
        if (y !== 0) $display("011 failed.");  
        a = 1; b = 0; c = 0; #10;  
        if (y !== 1) $display("100 failed.");  
        c = 1; #10;  
        if (y !== 1) $display("101 failed.");  
        b = 1; c = 0; #10;  
        if (y !== 0) $display("110 failed.");  
        c = 1; #10;  
        if (y !== 0) $display("111 failed.");  
    end  
endmodule
```

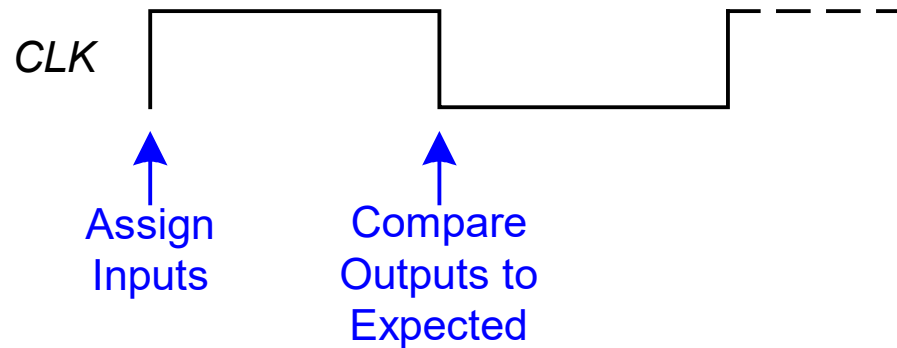


# Testbench with Testvectors

- Testvector file: inputs and expected outputs
- Testbench:
  1. Generate clock for assigning inputs, reading outputs
  2. Read testvectors file into array
  3. Assign inputs, expected outputs
  4. Compare outputs with expected outputs and report errors

# Testbench with Testvectors

- Testbench clock:
  - assign inputs (on rising edge)
  - compare outputs with expected outputs (on falling edge).



- Testbench clock also used as clock for synchronous sequential circuits

# Testvectors File

- File: `example.tv`
- contains vectors of `abc_yexpected`

000\_1

001\_0

010\_0

011\_0

100\_1

101\_1

110\_0

111\_0



# 1. Generate Clock

```
module testbench3();  
    logic          clk, reset;  
    logic          a, b, c, yexpected;  
    logic          y;  
    logic [31:0] vectornum, errors;    // bookkeeping variables  
    logic [3:0] testvectors[10000:0]; // array of testvectors  
  
    // instantiate device under test  
    sillyfunction dut(a, b, c, y);  
  
    // generate clock  
    always          // no sensitivity list, so it always executes  
    begin  
        clk = 1; #5; clk = 0; #5;  
    end
```

## 2. Read Testvectors into Array

```
// at start of test, load vectors and pulse reset
```

```
initial
begin
    $readmemb("example.tv", testvectors);
    vectornum = 0; errors = 0;
    reset = 1; #27; reset = 0;
end
```

```
// Note: $readmemb reads testvector files written in
// hexadecimal
```

### 3. Assign Inputs & Expected Outputs

```
// apply test vectors on rising edge of clk
always @(posedge clk)
    begin
        #1; {a, b, c, yexpected} = testvectors[vectornum];
    end
```



## 4. Compare with Expected Outputs

```
// check results on falling edge of clk
always @(negedge clk)
    if (~reset) begin // skip during reset
        if (y !== yexpected) begin
            $display("Error: inputs = %b", {a, b, c});
            $display("  outputs = %b (%b expected)", y, yexpected);
            errors = errors + 1;
        end
    end

// Note: to print in hexadecimal, use %h. For example,
//          $display("Error: inputs = %h", {a, b, c});
```

## 4. Compare with Expected Outputs

```
// increment array index and read next testvector
    vectornum = vectornum + 1;
    if (testvectors[vectornum] === 4'bx) begin
        $display("%d tests completed with %d errors",
            vectornum, errors);
        $finish;
    end
end
endmodule
```

// **===** and **!==** can compare values that are 1, 0, x, or z.