

Structural Design with Verilog

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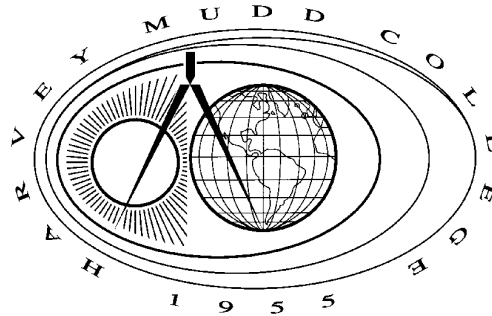


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1 Introduction

Entry of large digital designs at the schematic level is very time consuming and can be exceedingly tedious for circuits with wide datapaths that must be repeated for each bit of the data path. Hardware description languages (HDLs) provide a more compact textual description of a design. Verilog is a powerful language and offers several different levels of descriptions. The lowest level is the gate level, in which statements are used to define individual gates. In the structural level, more abstract `assign` statements and `always` blocks are used. These constructs are more powerful and can describe a design with fewer lines of code, but still provide a clearly defined relationship to actual hardware. The behavioral level of description is the most abstract, resembling C with function calls (called tasks), for and while loops, etc. Behavioral modeling describes what a design must do, but does not have an obvious mapping to hardware.

This Verilog documentation will focus on the structural level of description because it is efficient to code, yet offers a predictable mapping to hardware in the hands of a skilled user. A synthesis tool is used to translate the Verilog into actual hardware, such as logic gates on a custom Application Specific Integrated Circuit (ASIC) or configurable logic blocks (CLBs) on a Field Programmable Gate Array (FPGA). When you use Verilog to describe hardware that you will actually construct, it is extremely important to know what gates your code will describe. Otherwise, you are almost guaranteed to get something that you didn't want. Sometimes this means extra latches appearing in your circuit in places you didn't expect. Other times, it means that the circuit is much slower than required or takes far more gates than it would if more carefully described. Unfortunately, FPGA synthesis tools do not directly show you the gates synthesized from your code. Therefore, it is particularly easy to get into trouble and that much more important to understand what gates your code is implying.

There are two kinds of statements used to model logic. *Continuous assignment* statements always imply combinational logic. *Always* blocks can imply combinational logic or sequential logic, depending how they are used. It is critical to partition your design into combinational and sequential components and write Verilog in such a way that you get what you want. If you don't know whether a block of logic is combinational or sequential, you are very likely to get the wrong thing. A particularly common mistake is to use `always` blocks to model combinational logic, but to accidentally imply latches or flip-flops.

2 Modeling with Continuous Assignments

With schematics, a 32-bit adder is a complex design. It can be constructed from 32 full adder cells, each of which in turn requires about six 2-input gates. Verilog provides a much more compact description:

```
module adder(a, b, y);
    input    [31:0]  a, b;
    output   [31:0]  y;

    assign y = a + b;
endmodule
```

A Verilog module is like a "cell" or "macro" in schematics. It begins with a description of the inputs and outputs, which in this case are 32 bit busses. In the structural description style, the module may contain `assign` statements, `always` blocks, or calls to other modules.

During simulation, an `assign` statement causes the left hand side (`y`) to be updated any time the right side (`a/b`) changes. This necessarily implies combinational logic; the output on the left side is a function of the current inputs given on the right side. A 32-bit adder is a good example of combinational logic.

2.1 Bitwise Operators

Verilog has a number of *bitwise* operators that act on busses. For example, the following module describes four inverters.

```

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

    assign y = ~a;
endmodule

```

Similar bitwise operations are available for the other basic logic functions:

```

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

```

2.2 Comments & White Space

The previous examples showed two styles of comments, just like those used in C or Java. Comments beginning with `/*` continue, possibly across multiple lines, to the next `*/`. Comments beginning with `//` continue to the end of the line. It is important to properly comment complex logic so you can understand what you did six months from now or so that some poor slob assigned to fix your buggy code will be able to figure it out rather than calling you at 2 am with a question.

Verilog is not picky about the use of white space. Nevertheless, proper indenting and spacing is very helpful to make nontrivial designs readable. Verilog is case-sensitive. Be consistent in your use of capitalization and underscores in signal and module names.

2.3 Reduction Operators

Reduction operators imply a multiple-input gate acting on a single bus. For example, the following module describes an 8-input AND gate with inputs `A[0]`, `A[1]`, `A[2]`, ..., `A[7]`.

```

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

    assign y = &a;
endmodule

```

As one would expect, `|`, `^`, `~&`, and `~|` reduction operators are available for OR, XOR, NAND, and NOR as well. Recall that a multi-bit XOR performs parity, returning true if an odd number of inputs are true.

2.4 Other Operators

The conditional operator `?:` works like the same operator in C or Java and is very useful for describing multiplexers. It is called a ternary operator because it takes three inputs. If the first input is nonzero, the result is the expression in the second input. Otherwise, the result is the expression in the third input.

```

module mux2(d0, d1, s, y);
    input    [3:0] d0, d1;
    input    s;
    output   [3:0] y;

    assign y = s ? d1 : d0; // if s=1, y=d1, else y=d0
endmodule

```

A number of arithmetic functions are supported including +, -, *, <, >, <=, >=, ==, !=, <<, >>, / and %. Recall from other languages that % is the modulo operator: a%b equals the remainder of a when divided by b. These operations imply a vast amount of hardware. == and != (equality / inequality) on N-bit inputs require N 2-input XNORs to determine equality of each bit and an N-input AND or NAND to combine all the bits. Addition, subtraction, and comparison all require an adder, which is very expensive in hardware. Variable left and right shifts << and >> imply a barrel shifter. Multipliers are even more costly. Do not use these statements without contemplating the number of gates you are generating. Moreover, the implementations are not always particularly efficient for your problem. You'll probably be disappointed with the speed and gate count of a multiplier your synthesis tool produces from when it sees *. You'll be better off writing your own Booth-encoded multiplier if these constraints matter. Many synthesis tools choke on / and % because these are nontrivial functions to implement in combinational logic.

3 Useful Constructs

3.1 Internal Signals

Often it is convenient to break a complex calculation into intermediate variables. For example, in a full adder, we sometimes define the propagate signal as the XOR of the two inputs A and B. The sum from the adder is the XOR of the propagate signal and the carry in. We can name the propagate signal using a wire statement, in much the same way we use local variables in a programming language.

```

module fulladder(a, b, cin, s, cout);
    input    a, b, cin;
    output   s, cout;

    wire    prop;

    assign prop = a ^ b;
    assign s = prop ^ cin;
    assign cout = (a & b) | (cin & (a | b));
endmodule

```

Technically, it is not necessary to declare single-bit wires. However, it is necessary to declare multi-bit busses. It is good practice to declare all signals. Some Verilog simulation and synthesis tools give errors that are difficult to decipher when a wire is not declared.

3.2 Precedence

Notice that we fully parenthesized the cout computation. We could take advantage of operator precedence to use fewer parentheses:

```

assign cout = a&b | cin&(a|b)

```

The operator precedence from highest to lowest is much as you would expect in other languages. AND has precedence over OR.

~	Highest
*, /, %	
+, -	
<<, >>	
<, <=, >, >=	
=, ==, !=	
&, ~&	
^, ~^	
, ~	
?:	Lowest

3.3 Constants

Constants may be specified in binary, octal, decimal, or hexadecimal. For example:

Number	# bits	Base	Decimal Equivalent	Stored
3'b101	3	Binary	5	101
'b11	unsized	Binary	3	000000..00011
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	unsized	Decimal	42	0000...00101010

It is good practice to specify the length of the number in bits, even though the second row shows that this is not strictly necessary. If you don't specify the length, one day you'll get bitten when Verilog assumes the constant has additional leading 0's that you didn't intend. Underscores in numbers are ignored and may be helpful in breaking long numbers into more readable chunks. If the base is omitted, the number is assumed to be decimal.

3.4 Hierarchy

Nontrivial designs are developed in a hierarchical form, in which complex modules are composed of submodules. For example, a 4-input MUX can be constructed from three 2-input multiplexers:

```

module mux4(d0, d1, d2, d3, s, y);
    input    [3:0] d0, d1, d2, d3;
    input    [1:0] s;
    output   [3:0] y;

    wire    [3:0] low, high;

    mux2 lowmux(d0, d1, s[0], low);
    mux2 highmux(d2, d3, s[0], high);
    mux2 finalmux(low, high, s[1], y);
endmodule

```

3.5 Tristates

It is possible to leave a bus floating rather than drive it to 0 or 1. This floating value is called 'z' in Verilog. For example, a tri-state buffer produces a floating output when the enable is false.

```

module tristate(a, en, y);
    input    [3:0] a;
    input    en;
    output   [3:0] y;

    assign y = en ? a : 4'bz;
endmodule

```

Floating inputs to gates cause undefined outputs, displayed as 'x' in Verilog. At startup, state nodes such as the internal node of flip-flops are also usually initialized to 'x', as we will see later.

We could define a multiplexer using two tristates so that the output is always driven by exactly one tristate. This guarantees there are no floating nodes.

```

module mux2(d0, d1, s, y);
    input    [3:0] d0, d1;
    input    s;
    output   [3:0] y;

    tristate t0(d0, ~s, y);
    tristate t1(d1, s, y);
endmodule

```

3.6 Bit Swizzling

Often it is necessary to work on parts of a bus or to concatenate (join together) signals to construct busses. The previous example showed using the least significant bit `s[0]` of a 2-bit select signal for some muxes and the most significant bit `s[1]` for the final mux. Use ranges to select subsets of a bus. For example, an 8-bit wide 2-input mux can be constructed from two 4-bit wide 2-input muxes:

```

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

```

The `{}` notation is used to concatenate busses. For example, the following 8x8 multiplier produces a 16-bit result, which is, placed on the upper and lower 8-bit result busses.

```

module mul(a, b, upper, lower);
    input    [7:0] a, b;
    output   [7:0] upper, lower;

    assign {upper, lower} = a*b;
endmodule

```

A 16-bit 2's complement number is sign-extended to 32-bits by copying the most significant bit to each of the upper 16 positions. The Verilog syntax concatenates 16 copies of `a[15]` to the 16-bit `a[15:0]` bus. You will get a warning from synthesis that `a` is a "feedthrough net." This means that the input "feeds through" to the output. `y[15:0]` should have the same value as `a[15:0]`, so this is what we intended. If you get a feedthrough net warning where you did not intend a feedthrough, check for a mistake in your Verilog.

```

module signextend(a, y);
    input    [15:0]  a;
    output   [31:0]  y;

    assign y = {16{a[15]}, a[15:0]};
endmodule

```

The next statement generates a bizarre combination of two busses. Don't confuse the 3-bit binary constant 3'b101 with bus b. Note that it was important to specify the length of 3 bits in the constant; otherwise many additional 0's might have appeared in the middle of y.

```
assign y = {a[2:1], 3{b[0]}, a[0], 3'b101, b[1:3]}
```

y =	a[2]	a[1]	b[0]	b[0]	b[0]	a[0]	1	0	1	b[1]	b[2]	b[3]
-----	------	------	------	------	------	------	---	---	---	------	------	------

4 Modeling with Always Blocks

Assign statements are reevaluated every time any term on the right hand side changes. Therefore, they must describe combinational logic. Always blocks are reevaluated only when signals in the header change. Depending on the form, always blocks may imply sequential or combinational circuits.

4.1 Flip-Flops

Flip-flops are described with an always @(posedge clk) statement:

```

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

    reg    [3:0] q;

    always @(posedge clk)
        q <= d;
endmodule

```

The body of the always statement is only evaluated on the rising (positive) edge of the clock. At this time, the output q is copied from the input d. The <= is called a nonblocking assignment. Think of it as a regular equals sign for now; we'll return to the subtle points later. Notice that it is used instead of assign inside the always block.

All the signals on the left hand side of assignments in always blocks must be declared as reg. This is a confusing point for new Verilog users. In this circuit, q is also the output. Declaring a signal as reg does not mean the signal is actually a register! All it means is it appears on the left side in an always block. We will see examples of combinational signals later that are declared reg but have no flip-flops.

At startup, the q output is initialized to 'x. Generally, it is good practice to use flip-flops with reset inputs so that on power-up you can put your system in a known state. The reset may be either asynchronous or synchronous. Asynchronous resets occur immediately. Synchronous resets only change the output on the rising edge of the clock. Xilinx FPGAs have dedicated internal hardware to support initializing asynchronously resettable flip-flops on startup, so such flops are preferred.

```

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

    reg  [3:0] q;

    always @(posedge clk or posedge reset)
        if (reset) q <= 4'b0;
        else q <= d;
endmodule

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

    reg  [3:0] q;

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

```

Note that the asynchronously resettable flop evaluates the `always` block when either `clk` or `reset` rise so that it immediately responds to reset. The synchronously reset flop is not sensitized to reset in the `@` list, so it waits for the next clock edge before clearing the output.

One could also consider flip-flops with enables that only load the input when the enable is true. The following flip-flop retains its old value if both `reset` and `en` are false.

```

module flopenr(clk, reset, en, d, q); // asynchronous reset
    input      clk;
    input      reset;
    input      en;
    input  [3:0] d;
    output  [3:0] q;

    reg  [3:0] q;

    always @(posedge clk or posedge reset)
        if (reset) q <= 4'b0;
        else if (en) q <= d;
endmodule

```

4.2 Latches

`Always` blocks can also be used to model transparent latches, also known as D latches. When the clock is high, the latch is transparent and the data input flows to the output. When the clock is low, the latch goes opaque and the output remains constant.


```

module latch(clk, d, q);
    input      clk;
    input      [3:0] d;
    output     [3:0] q;

    reg        [3:0] q;

    always @(clk or d)
        if (clk) q <= d;
endmodule

```

The latch evaluates the `always` block any time either `clk` or `d` change. If the clock is high, the output gets the input. Notice that even though `q` is a latch node, not a register node, it is still declared as `reg` because it is on the left hand side of a `<=` in an `always` block.

Most Xilinx FPGAs do not support latches very well. If your code includes latches either intentionally or by accident, you will get a warning about “latch inferred in design” and should remove them.

4.3 Counters

Consider two ways of describing a four-bit counter with asynchronous reset. The first scheme implies a sequential circuit containing both the 4-bit flip-flop and an adder. The second scheme explicitly declares modules for the flip-flop and adder.

Either scheme is good for a simple circuit such as a counter. As you develop more complex finite state machines, it is a good idea to separate the next state logic from the flip-flops in your Verilog code. Verilog does not protect you from yourself here and there are many simple errors that lead to circuits very different than you intended.

```

module counter(clk, reset, q);
    input      clk;
    input      reset;
    output     [3:0] q;

    reg        [3:0] q;

    // counter using always block
    always @(posedge clk)
        if (reset) q <= 4'b0;
        else q <= q+1;
endmodule

module counter(clk, reset, q);
    input      clk;
    input      reset;
    output     [3:0] q;

    wire       [3:0] nextq;

    // counter using module calls
    flopr qflop(clk, reset, nextq, q);
    adder inc(q, 4'b0001, nextq); // assumes a 4-bit adder
endmodule

```

4.4 Combinational Logic

Always blocks imply sequential logic when some of the inputs do not appear in the @ stimulus list or might not cause the output to change. For example, in the flop module, d is not in the @ list, so the flop does not immediately respond to changes of d. In the latch, d is in the @ list, but changes in d are ignored unless clk is high. Always blocks can also be used to imply combinational logic if they are written in such a way that the output always is reevaluated given changes in any of the inputs.

The following code shows how to define a bank of inverters with an always block.

```
module inv(a, y);
    input    [3:0] a;
    output   [3:0] y;

    reg     [3:0] y;

    always @(a)
        y <= ~a;
endmodule
```

Similarly, the next example defines a 5 banks of different kinds of gates. Notice that the begin / end construct is necessary because multiple commands appear in the always block. This is analogous to { } block structure in C or Java. The begin / end was not needed in the flopr example because an if / else command counts as a single statement.

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

    reg     [3:0] y1, y2, y3, y4, y5;

    always @(a or b)
        begin
            y1 <= a & b; // AND
            y2 <= a | b; // OR
            y3 <= a ^ b; // XOR
            y4 <= ~(a & b); // NAND
            y5 <= ~(a | b); // NOR
        end
endmodule
```

These two examples are poor applications of always blocks for modeling combinational logic because they require more lines than the equivalent approach with assign statements as well as posing the risk of inadvertently implying sequential logic (see the bad circuit examples later). A better application of the always block is a decoder, which takes advantage of the case statement that may only appear inside an always block.

```

module decoder_always(a, y);
    input    [2:0] a;
    output   [7:0] y;

    reg      [7:0] y;

    // a 3:8 decoder
    always @(a)
        case (a)
            3'b000: y <= 8'b00000001;
            3'b001: y <= 8'b00000010;
            3'b010: y <= 8'b00000100;
            3'b011: y <= 8'b00001000;
            3'b100: y <= 8'b00010000;
            3'b101: y <= 8'b00100000;
            3'b110: y <= 8'b01000000;
            3'b111: y <= 8'b10000000;
        endcase
    endmodule

```

Using the case statement is probably clearer than a description of the same decoder using Boolean equations in an assign statement:

```

module decoder_assign(a, y);
    input  [2:0] a;
    output [7:0] y;

    assign y[0] = ~a[0] & ~a[1] & ~a[2];
    assign y[1] = a[0] & ~a[1] & ~a[2];
    assign y[2] = ~a[0] & a[1] & ~a[2];
    assign y[3] = a[0] & a[1] & ~a[2];
    assign y[4] = ~a[0] & ~a[1] & a[2];
    assign y[5] = a[0] & ~a[1] & a[2];
    assign y[6] = ~a[0] & a[1] & a[2];
    assign y[7] = a[0] & a[1] & a[2];
endmodule

```

Another even better example is the logic for a 7-segment display decoder, taken from Ciletti's Verilog book. The equivalent logic with assign statements describing the detailed logic for each bit would be very tedious. This more abstract approach is faster to write, clearer to read, and can be automatically synthesized down to an efficient logic implementation.

```

module seven_seg_display_decoder(data, segments);
    input    [3:0] data;
    output   [6:0] segments;

    reg      [6:0] segments;

    // Segment #      abc_defg      hex equivalent
    parameter BLANK = 7'b111_1111; // h7F
    parameter ZERO  = 7'b000_0001; // h01
    parameter ONE   = 7'b100_1111; // h4F
    parameter TWO   = 7'b001_0010; // h12
    parameter THREE = 7'b000_0110; // h06
    parameter FOUR  = 7'b100_1100; // h4C
    parameter FIVE  = 7'b010_0100; // h24
    parameter SIX   = 7'b010_0000; // h20
    parameter SEVEN = 7'b000_1111; // h0F
    parameter EIGHT = 7'b000_0000; // h00
    parameter NINE  = 7'b000_0100; // h04

    always @(data)
        case (data)
            0: segments <= ZERO;
            1: segments <= ONE;
            2: segments <= TWO;
            3: segments <= THREE;
            4: segments <= FOUR;
            5: segments <= FIVE;
            6: segments <= SIX;
            7: segments <= SEVEN;
            8: segments <= EIGHT;
            9: segments <= NINE;
            default: segments <= BLANK;
        endcase
endmodule

```

This example shows the use of parameters to define constants to make the code more readable. The case statement has a default to display a blank output when the input is outside the range of decimal digits.

Finally, compare two descriptions of a priority encoder that sets one output true corresponding to the most significant input that is true. The `if` statement can appear in `always` blocks and makes the logic very natural. The `assign` statements synthesize to the same results, but are less clear to read. Note that `a[3]` is another example of a feedthrough net because `y[3] = a[3]`.

```

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

    reg      [3:0] y;

    always @(a)
        if      (a[3]) y <= 4'b1000;
        else if (a[2]) y <= 4'b0100;
        else if (a[1]) y <= 4'b0010;
        else if (a[0]) y <= 4'b0001;
        else      y <= 4'b0000;
endmodule

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

    assign y[3] = a[3];
    assign y[2] = a[2] & ~a[3];
    assign y[1] = a[1] & ~|a[3:2];
    assign y[0] = a[0] & ~|a[3:1];
endmodule

```

It is very easy to accidentally imply sequential logic with `always` blocks when combinational logic is intended. The resulting bugs can be difficult to track down. Therefore, it is safer to use `assign` statements than `always` blocks to imply combinational logic. Nevertheless, the convenience of constructs such as `if` or `case` that must appear in `always` blocks justifies the modeling style as long as you thoroughly understand what you are doing.

4.5 Memories

Verilog has an array construct used to describe memories. The following module describes a 64 word x 16 bit RAM that is written when `wrb` is low and otherwise read.

```

module ram(addr, wrb, din, dout);
    input    [5:0]  addr;
    input                    wrb;
    input    [15:0] din;
    output   [15:0] dout;

    reg      [15:0] mem[63:0]; // the memory
    reg      [15:0] dout;

    always @(addr or wrb or din)
        if (~wrb) mem[addr] <= din;
        else dout <= mem[addr];

endmodule

```

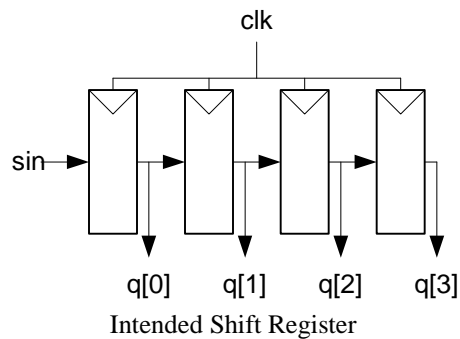
FPGAs have a limited number of bits of RAM on board. Large memories are extremely expensive. In the Xilinx Foundation tools, it is more efficient to specify a RAM or ROM using the LogiBLOX tool.

4.6 Blocking and Nonblocking Assignment

Verilog supports two types of assignments inside an `always` block. *Blocking assignments* use the `=` statement. *Nonblocking assignments* use the `<=` statement. Do not confuse either type with the `assign` statement, which cannot appear inside `always` blocks at all.

A group of blocking assignments inside a `begin/end` block are evaluated sequentially, just as one would expect in a standard programming language. A group of nonblocking assignments are evaluated in parallel; all of the statements are evaluated before any of the left hand sides are updated. This is what one would expect in hardware because real logic gates all operate independently rather than waiting for the completion of other gates.

For example, consider two attempts to describe a shift register. On each clock edge, the data at `sin` should be shifted into the first flop. The first flop shifts to the second flop. The data in the second flop shifts to the third flop, and so on until the last element drops off the end.



```
module shiftreg(clk, sin, q);
    input      clk;
    input      sin;
    output [3:0] q;

    // This is a correct implementation using nonblocking assignment

    reg [3:0] q;

    always @(posedge clk)
        begin
            q[0] <= sin; // <= indicates nonblocking assignment
            q[1] <= q[0];
            q[2] <= q[1];
            q[3] <= q[2];
            // it would be even more better to write q <= {q[2:0], sin};
        end
endmodule
```

The nonblocking assignments mean that all of the values on the right hand sides are assigned simultaneously. Therefore, `q[1]` will get the original value of `q[0]`, not the value of `sin` that gets loaded into `q[0]`. This is what we would expect from real hardware. Of course all of this could be written on one line for brevity.

Blocking assignments are more familiar from traditional programming languages, but inaccurately model hardware. Consider the same module using blocking assignments. When `clk` rises, the Verilog says that `q[0]` should be copied from `sin`. Then `q[1]` should be copied from the new value of `q[0]` and so forth. All four registers immediately get the `sin` value.

```

module shiftreg(clk, sin, q[3:0]);
    input      clk;
    input      sin;
    output     [3:0] q;

    // This is a bad implementation using blocking assignment

    reg       [3:0] q;

    always @(posedge clk)
    begin
        q[0] = sin; // = indicates blocking assignment
        q[1] = q[0];
        q[2] = q[1];
        q[3] = q[2];
    end
endmodule

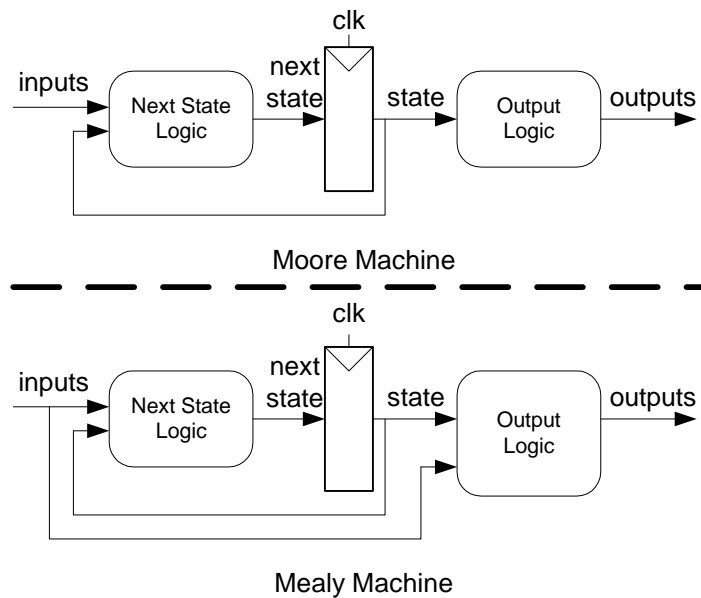
```

The moral of this illustration is to always use nonblocking assignment in `always` blocks when writing structural Verilog. With sufficient cleverness, such as reversing the orders of the four commands, one might make blocking assignments work correctly, but they offer no advantages and great risks.

Finally, note that each `always` block implies a separate block of logic. Therefore, a given `reg` may be assigned in only one `always` block. Otherwise, two pieces of hardware with shorted outputs would be implied.

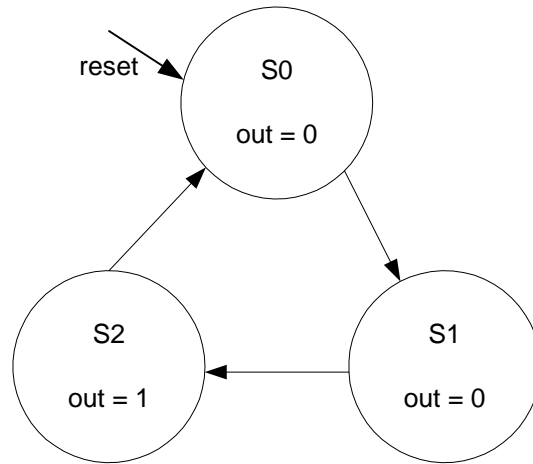
5 Finite State Machines

There are two styles of designing finite state machines. In Mealy machines, the output is a function of the current state and inputs. In Moore machines, the output is a function of only the current state. The styles are illustrated below.



FSMs are modeled in Verilog with an `always` block defining the state registers and combinational logic defining the next state and output logic.

Let us first consider a very simple finite state machine with one output and no inputs, a divide by 3 counter. The output should be asserted every three clock cycles. A state transition diagram for a Moore state machine is given below. The output value is labeled in each state because the output is only a function of the state.



Divide-by-3 Counter State Transition Diagram


```

module divideby3FSM(clk, reset, out);
    input        clk;
    input        reset;
    output       out;

    reg          [1:0] state;

    reg          [1:0] nextstate;

    parameter    S0 = 2'b00;
    parameter    S1 = 2'b01;
    parameter    S2 = 2'b10;

    // State Register

    always @(posedge clk or posedge reset)
        if (reset) state <= S0;
        else       state <= nextstate;

    // Next State Logic

    always @(state)
        case (state)
            S0: nextstate <= S1;
            S1: nextstate <= S2;
            S2: nextstate <= S0;
            default: nextstate <= S0;
        endcase

    // Output Logic

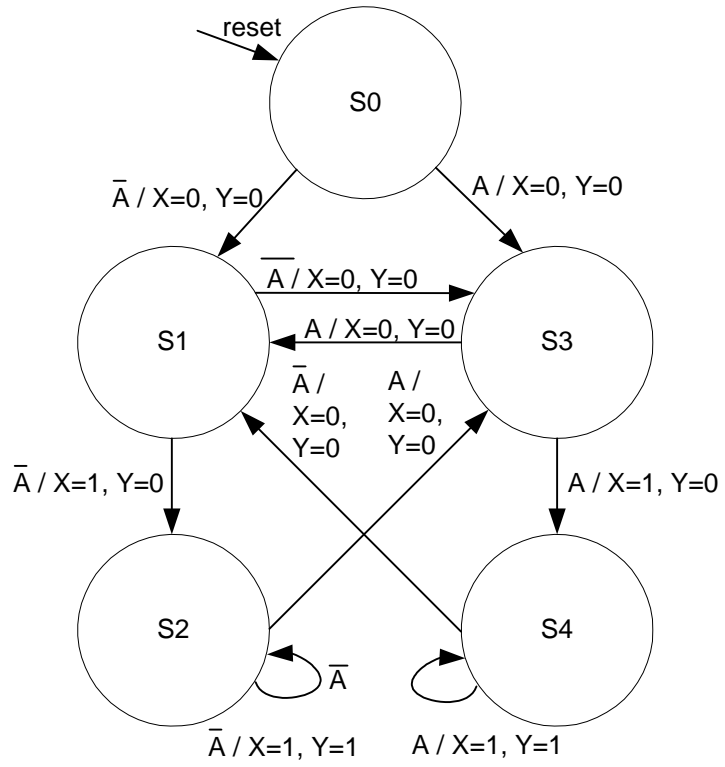
    assign out = (state == S2);

endmodule

```

The FSM model is divided into three portions: the state register, next state logic, and output logic. The state logic describes an asynchronously resettable flip-flop that resets to an initial state and otherwise advances to the computed next state. Defining states with parameters allows the easy modification of state encodings and makes the code easier to read. The next state logic computes the next state as a function of the current state and inputs; in this example there are no inputs. A `case` statement in an `always @(state or inputs)` block is a convenient way to define the next state. It is important to have a default if not all cases are enumerated; otherwise the `nextstate` would not be assigned in the undefined cases. This implies that `nextstate` should keep its old value, which would require the existence of latches. Finally, the output logic may be a function of the current state alone in a Moore machine or of the current state and inputs in a Mealy machine. Depending on the complexity of the design, `assign` statements, `if` statements, or `case` statements may be most readable and efficient.

The next example shows a finite state machine with an input `A` and two outputs. Output `X` is true when the input is the same now as it was last cycle. Output `Y` is true when the input is the same now as it was for the past two cycles. This is a Mealy machine because the output depends on the current inputs as well as the state. The outputs are labeled on each transition after the input. The state transition diagram is shown below:



History Finite State Machine

```

module historyFSM(clk, reset, a, x, y);
    input        clk;
    input        reset;
    input        a;
    output       x, y;

    reg          [2:0] state;

    reg          [2:0] nextstate;

    parameter    S0 = 3'b000;
    parameter    S1 = 3'b010;
    parameter    S2 = 3'b011;
    parameter    S3 = 3'b100;
    parameter    S4 = 3'b101;

    // State Register

    always @(posedge clk or posedge reset)
        if (reset) state <= S0;
        else       state <= nextstate;

    // Next State Logic

    always @(state or a)
        case (state)
            S0:  if (a) nextstate <= S3;
                  else nextstate <= S1;
            S1:  if (a) nextstate <= S3;
                  else nextstate <= S2;
            S2:  if (a) nextstate <= S3;
                  else nextstate <= S2;
            S3:  if (a) nextstate <= S4;
                  else nextstate <= S1;
            S4:  if (a) nextstate <= S4;
                  else nextstate <= S1;
            default: nextstate <= S0;
        endcase

    // Output Logic

    assign x = (state[1] & ~a) | (state[2] & a);
    assign y = (state[1] & state[0] & ~a) | (state[2] & state[0] & a);

endmodule

```

The output logic equations depend on the specific state encoding and were worked out by hand. A more general approach is independent of the encodings and requires less thinking, but might require more gates and code:

```

// Output Logic

always @(state or a)
  case (state)
    S0:  begin
          x <= 0; y <= 0;
        end
    S1:  if (A) begin
          x <= 0; y <= 0;
        end else begin
          x <= 1; y <= 0;
        end
    S2:  if (A) begin
          x <= 0; y <= 0;
        end else begin
          x <= 1; y <= 1;
        end
    S3:  if (A) begin
          x <= 1; y <= 0;
        end else begin
          x <= 0; y <= 0;
        end
    S4:  if (A) begin
          x <= 1; y <= 1;
        end else begin
          x <= 0; y <= 0;
        end
  endcase

```

One might be tempted to simplify the case statement. For example, case S4 might be reduced to:

```

// bad simplification of S4
S4:  if (A) begin
      y <= 1;
    end else begin
      x <= 0; y <= 0;
    end

```

The designer reasons that to get to state S4, we must have passed through state S3 with A high, setting x high. Therefore, the assignment of x is optimized out of S4 when A is high. This is incorrect reasoning. The modified approach implies sequential logic. Specifically, a latch is implied that holds the old value of x when x is not assigned. The latch holds its output under a very peculiar set of circumstances; A and the state must be used to compute the latch clock signal. This is undoubtedly not what you want, but was very easy to imply. The moral of this example is that if any signal gets assigned in any branch of an if or case statement, it must be assigned in all branches lest a latch be implied.

6 Verilog Style Guidelines

If you follow these style guidelines, you will avoid many of the common Verilog pitfalls and will produce code that is easier for you or others to modify in the future.

6.1 General Guidelines

1. Use only nonblocking assignments inside always blocks.

2. Define your combinational logic using `assign` statements when practical. Only use `always` blocks to define combinational logic if constructs like `if` or `case` make your logic much clearer or more compact.
3. When modeling combinational logic with an `always` block, if a signal is assigned in any branch of an `if` or `case` statement, it must be assigned in all branches.
4. Partition your design into leaf cells and non-leaf cells. Leaf cells contain `assign` statements or `always` blocks but do not instantiate other cells. Non-leaf cells instantiate other cells but contain no logic. Minor exceptions to this guideline may be made to keep the code readable.
5. Use a design style with positive edge-triggered flip-flops as your only sequential elements. Avoid SR latches, negative edge-triggered flops, and transparent latches.
6. Use parameters to define state names and constants.
7. Properly indent your code, as shown in the examples in this guide.
8. Use comments liberally.
9. Use meaningful signal names. Use `a`, `b`, `c`, ... for generic logic gate inputs. Use `x`, `y`, `z` for generic combinational outputs and `q` for a generic state element output. Use descriptive names for nongeneric cells. Do not use `foo`, `bar`, or `baz`!
10. Be consistent in your use of capitalization and underscores.

6.2 Xilinx Hints

1. Use only positive edge-triggered flip-flops. Avoid `@(negedge clk)` and latches.
2. Be certain not to inadvertently imply latches. If you do and are targeting the Spartan family of FPGAs, which do not have built-in latches, you will get the following warning, which you should fix. The warning will not appear when targeting the 4000XL or SpartanXL families that have latches, but you should still be careful not to inadvertently create logic that implies latches.

Warning: Latch inferred in design '...' read with 'hdlin_check_no_latch'. (HDL-307)

3. Provide an asynchronous reset to all of your flip-flops with a common signal name. If you do, Xilinx will automatically tie this reset to the chip's global reset and reset your flip-flops on power-up. If not, Xilinx will give you the following warnings. Fix the warning by providing a proper reset to all elements.

Warning: No net is connected to the set/reset pin of Cell '/' q_reg<0>' /Q_reg'. (FPGA-GSRMAP-16)
Warning: No global set/reset (GSR) net could be used in the design because there is not a unique net that sets or resets all the sequential cells. (FPGA-GSRMAP-5)

4. Provide a common clock to all of your flip-flops whenever possible.
5. If you get any "Bus Conflict" messages or X's in your simulation, be sure to find their cause and fix the problem.

7 Bad Circuit Examples

This section includes examples of a number of bad circuits produced by common Verilog coding errors. Some examples include the results of synthesis using Synopsys' Design Analyzer and/or the Xilinx Foundation tools.

7.1 Incorrect stimulus list

The following circuit was intended to be a transparent latch, but the `d` input was omitted from the stimulus list. When synthesized with Synopsys or Xilinx, it still produces a transparent latch, but with the warning:

*Warning: Variable 'd' is being read
 in routine notquitealatch line 8 in file 'J:/Classes/E155/Fall2000/synopsys/notquitealatch.v',
 but does not occur in the timing control of the block which begins*

there. (HDL-180)

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

    reg       [3:0] q;

    always @(clk) // left out 'or d'
        if (clk) q <= d;
endmodule
```

Similarly, the b input in the following combinational logic was omitted from the stimulus list of the always block. Synopsis successfully created the intended logic, but gave the warning:

*Warning: Variable 'b' is being read
in routine gates line 7 in file 'J:/Classes/E155/Fall2000/synopsys/gates.v',
but does not occur in the timing control of the block which begins
there. (HDL-180)*

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

    reg     [3:0] y1, y2, y3, y4, y5;

    always @(a) // missing 'or b'
    begin
        y1 <= a & b; // AND
        y2 <= a | b; // OR
        y3 <= a ^ b; // XOR
        y4 <= ~(a & b); // NAND
        y5 <= ~(a | b); // NOR
    end
endmodule
```

Don't depend on your synthesizer doing the right thing when an input is omitted. If you see such a warning, correct your code.

The next example is supposed to model a multiplexer, but the author incorrectly wrote @(posedge s) rather than @(s). This would result in meaningless logic because s must be high immediately after the positive edge of s. The Xilinx tools give the following error message:

Error: clock variable s is being used as data. (HDL-175)

```

module badmux(d0, d1, s, y);
    input    [3:0] d0, d1;
    input    s;
    output   [3:0] y;

    reg     [3:0] y;

    always @(posedge s)
        if (s) y <= d1;
        else y <= d0;

endmodule

```

7.2 Missing begin/end block

In the following example, two variables are supposed to be assigned in the always block. The begin/end block is missing.

Synopsys gives the following error trying to read the design. Xilinx gives the same error.

Error: syntax error at or near token '[' (File: J:/Classes/E155/Fall2000/synopsys/flop2.v Line: 10) (VE-0)
Error: Can't read 'verilog' file 'J:/Classes/E155/Fall2000/synopsys/flop2.v'. (UID-59)

```

module notquiteatwobitflop(clk, d, q);
    input    clk;
    input    [1:0] d;
    output   [1:0] q;

    reg     [1:0] q;

    always @(posedge clk)
        q[1] = d[1];
        q[0] = d[0];
endmodule

```

7.3 Undefined Outputs

In the next example of a finite state machine, the user intended out1 to be high when the state is 0 and out2 to be high when the state is 1. However, the code neglects to ever set the outputs low.

```

module FSMbad(clk, a, out1, out2);
  input      clk;
  input      a;
  output     out1, out2;

  reg        state;
  reg        out1, out2;

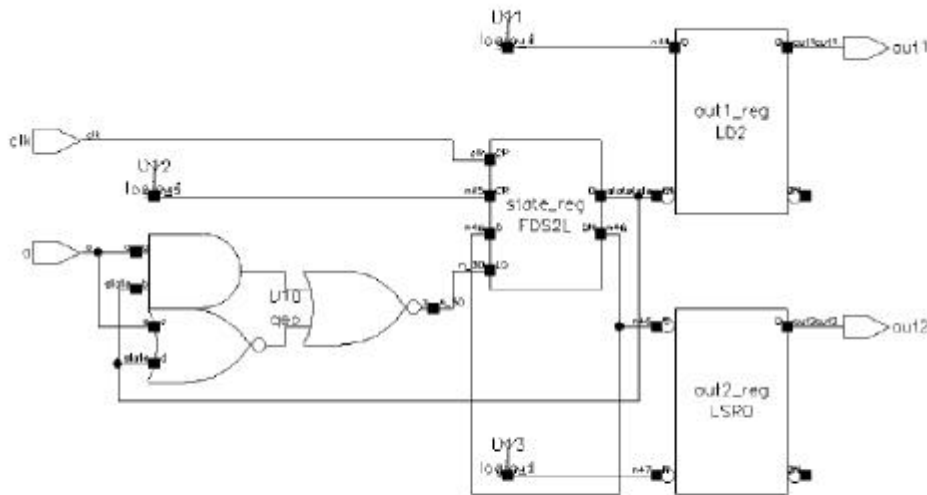
  always @(posedge clk)
    if (state == 0) begin
      if (a) state <= 1;
    end else begin
      if (~a) state <= 0;
    end

  always @(state) // neglect to set out1/out2 to 0
    if (state == 0) out1 <= 1;
    else             out2 <= 1;

endmodule

```

The FSM synthesizes into a circuit with an SR latch and a transparent latch that can set the output high but never reset the output low, as shown below:



design : FSM	designer : David Harris	date : 8/10/100
technology : ls1_10k	company : Harvey Mudd College	sheet : 1 of 1

A fixed version of the code eliminates the latches from the synthesized result.


```

module FSMgood(clk, a, out1, out2);
    input        clk;
    input        a;
    output       out1, out2;

    reg          state;
    reg          out1, out2;

    always @(posedge clk)
        if (state == 0) begin
            if (a) state <= 1;
        end else begin
            if (~a) state <= 0;
        end

    always @(state)
        if (state == 0) begin
            out1 <= 1;
            out2 <= 0;
        end else begin
            out2 <= 1;
            out1 <= 0;
        end

endmodule

```

7.4 Incomplete Specification of Cases

The next examples show an incomplete specification of input possibilities. The priority encoder fails to check for the possibility of no true inputs. It therefore incorrectly implies latches to hold the previous output when all four inputs are false! The four-input OR gate controls the latch. There is a race condition between the latch control and the latch data that might lead to incorrect results even if this were the intended operation.

Synopsys gives the following message during synthesis. The astute designer will detect the problem by knowing that a priority encoder should be a combinational circuit and therefore have no memory devices.

*Inferred memory devices in process in routine priority_always line 7 in file
'J:/Classes/E155/Fall2000/synopsys/priority.v'.*

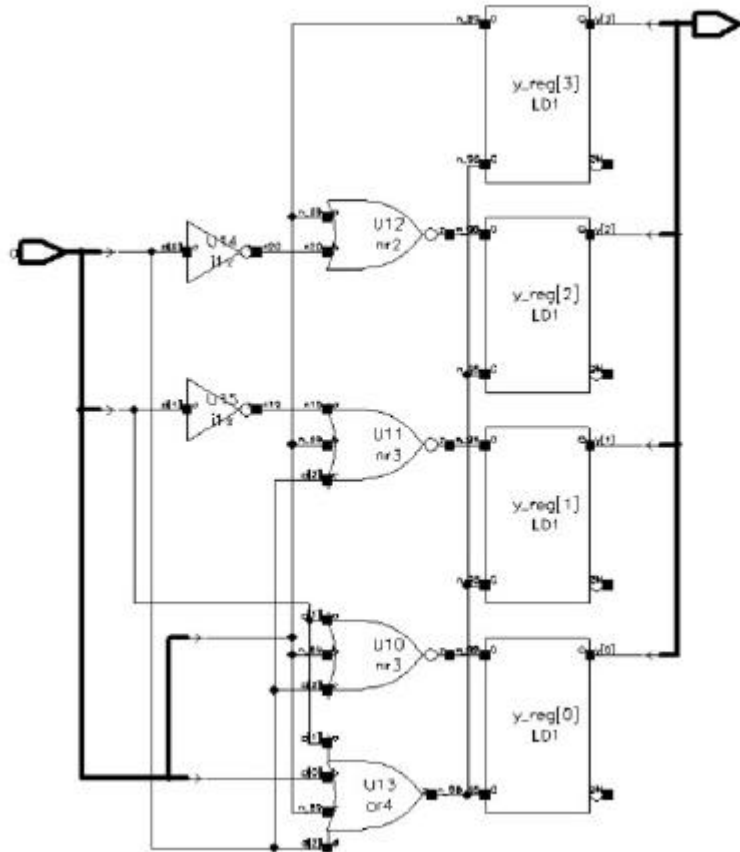
```

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

  reg    [3:0] y;

  always @(a)
    if    (a[3]) y <= 4'b1000;
    else if (a[2]) y <= 4'b0100;
    else if (a[1]) y <= 4'b0010;
    else if (a[0]) y <= 4'b0001;
    // else      y <= 4'b0000;
endmodule

```



Priority encoder with implied latches because of missing else

The next example of a seven-segment display decoder shows the same type of problem in a case statement.

```

module seven_seg_display_decoder(data, segments);
    input    [3:0] data;
    output   [6:0] segments;

    reg      [6:0] segments;

    // Segment #          abc_defg      hex equivalent
    parameter BLANK = 7'b111_1111; // h7F
    parameter ZERO  = 7'b000_0001; // h01
    parameter ONE   = 7'b100_1111; // h4F
    parameter TWO   = 7'b001_0010; // h12
    parameter THREE = 7'b000_0110; // h06
    parameter FOUR  = 7'b100_1100; // h4C
    parameter FIVE  = 7'b010_0100; // h24
    parameter SIX   = 7'b010_0000; // h20
    parameter SEVEN = 7'b000_1111; // h0F
    parameter EIGHT = 7'b000_0000; // h00
    parameter NINE  = 7'b000_0100; // h04

    always @(data)
        case (data)
            0: segments <= ZERO;
            1: segments <= ONE;
            2: segments <= TWO;
            3: segments <= THREE;
            4: segments <= FOUR;
            5: segments <= FIVE;
            6: segments <= SIX;
            7: segments <= SEVEN;
            8: segments <= EIGHT;
            9: segments <= NINE;
            // default: segments <= BLANK;
        endcase
endmodule

```

Similarly, it is a common mistake to forget the default in next-state or output logic in a FSM.

```

module divideby3FSM(clk, reset, out);
    input        clk;
    input        reset;
    output       out;

    reg          [1:0] state;

    wire         [1:0] nextstate;

    parameter    S0 = 2'b00;
    parameter    S1 = 2'b01;
    parameter    S2 = 2'b10;

    // State Register

    always @(posedge clk or posedge reset)
        if (reset) state <= S0;
        else       state <= nextstate;

    // Next State Logic

    always @(state)
        case (state)
            S0: nextstate <= S1;
            S1: nextstate <= S2;
            S2: nextstate <= S0;
            //default: nextstate <= S0;
        endcase

    // Output Logic

    assign out = (state == S2);

endmodule

```

7.5 Shorted Outputs

Bad code may sometimes lead to shorted outputs of gates. For example, the tristate drivers in the following multiplexer should have mutually exclusive enable signals, but instead are both active simultaneously and produce a conflict when `d0` and `d1` are not equal.

Synthesis may not report any errors. However, during simulation, you will observe X's rather than 0's or 1's when the bus is simultaneously being driven high and low. You may also get a "Bus Conflict" warning message.

```

module mux2(d0, d1, s, y);
    input    [3:0] d0, d1;
    input    s;
    output   [3:0] y;

    tristate t0(d0, s, y); // should have been ~s
    tristate t1(d1, s, y);
endmodule

```

Another cause of shorted outputs is when a `reg` is assigned in two different `always` blocks. For example, the following code tries to model a flip-flop with asynchronous reset and asynchronous set. The first

always block models the reset and ordinary operation. The second always block attempts to incorporate the asynchronous set. Synthesis infers a separate piece of hardware for each always block, with a shorted output. Xilinx reports the following error:

Error: the net '/ver1/q' has more than one driver (FPGA-CHECK-5)

The module also produces a warning because the second always block implies a latch.

```
module floprs(clk, reset, set, d, q);
    input        clk;
    input        reset;
    input        set; // force q true
    input        d;
    output       q;

    reg          q;

    always @(posedge clk or posedge reset)
        if (reset) q <= 0;
        else q <= d;

    always @(set)
        if (set) q <= 1;
endmodule
```

8 Advanced Techniques

It would be nice to add advanced techniques here including:

- ?? Test fixture design
 - ?? memreadh
 - ?? ==, !=
 - ?? Accessing internal state nodes
 - ?? Assertions and \$display
 - ?? initial statements
 - ?? forever loops and clock generation
 - ?? delays
- ?? Xilinx techniques: interfacing with LogiBLOX cells and schematics
- ?? flush out commands:
 - ?? casex, casez
 - ?? transistor modeling
 - ?? UDPs
- ?? Gate-level Modeling