

Verilog Tutorial - Edited for CS141

Lukasz Strozek

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Based on Weste and Harris and "Verilog According to Tom"

1 Introduction

Verilog is language commonly used in designing digital systems. It's a hardware description language, which means that it's substantially different from any other language you might have encountered so far. Even though it does have control flow statements and variables, it relies primarily on logic functions. Refer to any boolean logic reference for the necessary background information.

For an interested reader, Verilog, created in 1985, was initially only intended to be a simulation language (which means that you had to write your programs in Verilog to test them, and then rewrite them in a different language to actually implement your system. Imagine what a pain this would be!), but its market has grown substantially and right now it's the most widely used Hardware Description Language in the US.

2 Program Structure

Verilog programs are composed of a set of *modules*. Each module can be thought of as a function in C – it's a set of lower-level routines which can be reused in your main program. Thus, the Verilog programming model resembles one of an imperative programming language like C: the main program, composed of functions (each of which takes inputs as parameters and returns output values), itself takes inputs and returns outputs, mapped to some pins in your digital system. Below is an example of what a very simple Verilog program looks like

```
// A simple Verilog program that implements a not-too-complicated logic
// function of four variables: (A NAND B) NAND (C NAND D)
//
module mynand(in1, in2, out);
    input  in1, in2;
    output out;
```

```
        assign out = ~(in1 & in2);
endmodule

// This is the main program
//
module somefunction(p, q, p_b, q_b, o);
    input  p, q, p_b, q_b;
    output o;
    wire   w, w_b;

    mynand nand1(p, q, w);
    mynand nand2(p_b, q_b, w_b);
    mynand nand3(w, w_b, o);
endmodule
```

Let's analyze this program: first, it consists of a low-level module that implements a nand gate (called `mynand`) and the main program `somefunction` which uses three `mynand` modules. `mynand` takes three arguments: two of them are inputs and the third is the output, which is specified in the header of the module. The output wire is assigned a value – the logical NAND of `in1` and `in2`.

`somefunction` Takes four inputs and one output. It uses intermediate values `w` and `w_b` to wire up two NAND gates together with another NAND gate.

One important thing that you, a beginning Verilog user, need to consider is that module invocation and assignments are not imperative in nature. We are not really *assigning* anything to the variable called `out`. Similarly, `w` and `w_b` are not local variables. Instead, you should think of the statement `assign` as something that wires up the right-hand side with the left-hand side, and think of all inputs, outputs and intermediate values are physical wires. So all that `mynand` does is take `in1` and `in2` (whatever wires they may end up being), wire them up with an NAND and wire the output to `out`. So, calling `nand1(p, q, w)` simply wires up `p` and `q` in an NAND whose output becomes `w`. This visual representation (inputs and outputs as wires) will help you avoid many mistakes when coding your system in Verilog.

Sometimes (if you're using a foreign module for which you only have signal names) you may need to use the extended Verilog module calling syntax, which lets you rearrange the order of signals passed to the module. For example, you could replace `mynand nand1(p, q, w)` with the following:

```
mynand nand1(.out(w), .in1(p), .in2(q))
```

3 Syntax Basics

`assign` causes the left-hand side to be updated any time the right hand side changes. This is equivalent to saying that it wires up the left hand side with the right hand side. `assign` causes a permanent link between the two, in a sense that it makes no sense to reassign the same inputs and outputs.

`~ a` negates the input `a`. `a & b` ANDs the two inputs together, `a | b` ORs them together, while `^` performs a logical XOR on `a` and `b`. Hence,

`~(a | b)`

implements a NOR function.

Verilog uses C-style comments. `//` marks the beginning of a line of comments. Moreover, anything between `/*` and `*/` is also treated as a comment.

Verilog supports the C ternary operator, as in

```
assign y = s ? d1 : d0;
```

assigns `y` to `d1` if `s` is 1 and to `d0` otherwise. The ternary operator implements the simplest 2:1 multiplexer (you will learn about these later on in class).

Verilog also supports ordinary C operators like `+`, `-`, `*`, `<`, `>`, `<=`, `>=`, `==`, `!=`, `<<`, `>>`, `/` and `%`. A word of caution, though, is that some of these operators are really expensive in hardware. To implement a multiplier, a large number of gates need to be used, so when possible avoid using these. In particular, in class we will ask you to *never* use any of these operators unless *specifically* told to do so.

Operator precedence follows the rules present in the C syntax. The following table shows all the operators and their precedence, from highest to lowest:

```

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

```

Constants may be specified in many bases, though we will stick to binary and hexadecimal. To represent a number in binary, specify the length of the number in bits (though optional, this is highly recommended), followed by an apostrophe, followed by the sequence of zeroes and ones (leading zeroes may be omitted. For example, the number 5 can be specified as

```
8'b101
```

Hexadecimal numbers have an additional **h** after the apostrophe. A number 139 can be specified as

```
8'h8B
```

Omitted bases are treated as decimal numbers, but these will be stored with a number of leading zeroes, which leads to inefficient design. It is advantageous to use specified bases.

A special value, High-Z, can be used, and is denoted as a binary **z**, *e.g.*

```
4'bz
```

You will learn more about High-Z values later on in the course.

You can define constants with `parameter`, for example:

```
parameter SEVEN = 4'b0111;
```

Finally, if you want to explicitly specify a delay of a statements, you can do it by following the keyword with a pound-number, as in the following example:

```
assign #42 y = ~a
```

4 Buses

You will notice soon that one-bit signals are simply not enough. Instead of tediously defining hundreds of input and output wires and wiring them separately, Verilog supports buses, *i.e.* collections of wires on which similar functions are performed. To define a bus, specify the highest and the lowest bit of a bus in square brackets next to the signal's name. For example,

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

    assign y = ~a;
endmodule
```

defines two four-wire buses (remember that we count from zero!) and assigns `y` to be a NOT of `a`, *i.e.* each wire in `y` is hooked up to a corresponding wire in `a` by a NOT gate. Note that all bitwise operations (described in the previous section) work on buses, too.

Sometimes a need may emerge to collapse, or *reduce* a bus to a single wire with some function. Reduction operators let you take all wires of a bus, connect them to a single multi-input function, and assign the output to a single wire. These operators are `&`, `|`, `^`, `~&` and `~|`, placed *in front* of the bus, for AND, OR, XOR, NAND and NOR respectively. For example,

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

    assign y = &a;
endmodule;
```

implements an 8-input, 1-output AND gate. Note that a multi-input XOR is a parity function, returning 1 if an odd number of inputs are 1.

It is also possible to take subsets of wires from buses. This is achieved by specifying the high and the low wire used in square brackets. For example, if `a` and `b` are 8-bit buses, the following is used to AND the high four bits of `a` and the low four bits of `b`:

```
and4(a[7:4], b[3:0])
```

Moreover, it is possible to combine buses. This is achieved by grouping buses (or subsets of buses) in curly braces, prefixing repeated components with a number. Grouped buses may appear on the left-hand side, as well as the right-hand side of an expression. For example, to create a 16-bit bus composed of three copies of a 4-bit bus, two upper bits of another 4-bit bus, and two zeroes as the least significant bits, we would write

```
input  [3:0]  a, b;
output [15:0] y;

assign y = {3{a[3:0]}, b[3:2], 2'b00}
```

Do you see why specifying lengths of binary constants is a good idea?

5 Combining Values

All Verilog signals have one of four values at a time. These values are:

- 0 – Low (false)
- 1 – High (true)
- X – Undefined
- Z – High-Z (floating, high impedance)

You will learn about a High-Z value later on in the course. For now it should suffice to say that a High-Z is something like an “unimportant” value, so if two wires are combined, High-Z always gives way to the other value. The table below explains what happens if you combine values:

	0	1	X	Z
0	0	X	X	0
1	X	1	X	1
X	X	X	X	X
Z	0	1	X	Z

So combining a 0 and a High-Z, for instance, results in a 0. Let’s show an example of tristate (0, 1, and High-Z) logic:

```
module tristate(a, en, y);
```

```
    input  [3:0] a;
    input          en;
    output [3:0] y;

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

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
```

Let's see what exactly is going on here. First a `tristate` buffer module is defined. This buffer will simply carry its input over if enable `en` is 1, or output High-Z otherwise. Then, a `mux2` module wires up two such buffer in a way that exactly one is High-Z and the other one is either 0 or 1. Notice that both tristate buffers have been wired to the same output – `y`. This is allowed since High-Z is combined with a 0 or a 1 here.

6 More Complex Language Constructs

`always` is a statement that lets you define blocks of code, in which assignments will only happen as selected signals (specified in the header of the statement) change. For example,

```
input  a, d
reg    out

always @(a or d)
    out = d
```

sets `out` to `d` only if the value of `a` or the value of `d` changes. Notice a slightly different syntax (we're using the word `or` as opposed to the symbol `|`, and `=` instead of `assign`). Another possibility is to specify that an assignment happens on the rising (or falling) clock edge. If `clk` is the clock input,

```
always @(posedge clk)
```

achieves this task. Notice that all signals on the left-hand side of the = sign inside **always** blocks must be declared as **reg**, not **wire**. All such signals will be initialized to X (see section on four values in Verilog).

If you need to perform more than one operation under the **always** block, you need to enclose the operations with **begin** and **end**.

always is most often combined with **if** (and possibly **else if** and **else**) to create powerful sequential logic systems. Study the following example:

```
always begin
    if (a==2'b01) b = 2'b01;
    else if (a>2'b01) begin
        b = a;
        c = 1;
    end
end
```

Two possible assignment syntaxes are $a = b$ and $a \leq b$. The difference lies in concurrency – all expressions of the former type are evaluated sequentially while all expressions of the latter type are evaluated in parallel. For example,

```
a <= b
b <= a
```

swaps the values of **a** and **b** while

```
a = b
b = a
```

simply sets both **a** and **b** to the previous value of **b** (the second assignment is using the value of **a** from the first assignment). Concurrent assignment can get really confusing and so it is recommended that you use the sequential =.

One very useful construct, which only works in the **always** block, is **case**. The following example shows how to construct a decoder (a logic device which takes a k -wire wide bus which carries a binary number l ($0 \leq l \leq 2^k - 1$), and outputs a 2^k -wire wide bus such that the only wire that's set to 1 is wire l):

```
module my_decoder(a, y);
  input  [2:0] a;
  output [7:0] y;
  reg    [7:0] y;

  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
```

The expression inside of `case` may also be a concatenated bus, for example

```
case ({a, b})
```

will help you draw out a truth table for a two-input logic.

`casez` is a variation of `case` which allows the use of Don't-cares in the constants being evaluated. For instance, the following is acceptable:

```
casez (a)
  3'b0???: y = 1'b0;
  3'b101:  y = 1'b0;
  3'b100:  y = 1'b1;
  3'b11?:  y = 1'b1;
endcase
```

7 Common errors

Below is a brief list of common errors that you may commit writing modules in Verilog:

- You are using sequential logic outside of the `always` block, or unnecessarily using combinational logic in the `always` block (unless `case` is necessary)
- You are getting Verilog's `X` values. Make sure all outputs are defined, you don't short-circuit outputs (wire outputs to more than one module without a High-Z) and that your `if-else` logic works correctly (you're not skipping any cases)
- You are missing `begin-end` block in your `always` statement