ELC 3338 Project Book

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Lab 1

Introduction

In the Labs for this course we will be building a 32-bit computer, so we can understand how it works and how we can make a synthesizable machine in a hardware description language (HDL) like Verilog. In this lab we will be building the counter that sequences all our computer's instructions.

A computer has to execute one instruction after another. We will be building a system to count sequentially from some starting number. Since this counter will be used to keep our program running in order, it is called the program counter. Our system needs to hold its value, count, and be able to change the starting value. We will break this into three components: a register (to hold the data), an incrementer (to count), and a mux (to select the count or a new starting value). For today we will just build the register, simulate it, and show how to write up the lab.

1.1 Program Counter

The register is called the program counter, since it holds the actual count. It is the heart of our system so it is where we will start. We are going to make a module that explains how to build a register in Verilog. Consider the code in Listing 1.1. It is made up of three sections: a header (which has the include command), a port list or interface (which specifies the signals coming in or going out of our module), and a body or implementation (which describes how to build it).

Listing 1.1: Verilog code to make a register.

```
`include "definitions.vh"

module register(
    input clk,
    input reset,
    input  [`WORD-1:0] D,
```

```
    output reg [`WORD-1:0] Q=`WORD'b0
    );

    always @(posedge(clk),posedge(reset)) begin
        if (reset==1'b1)
            Q<=`WORD'b0;
        else
            Q <= D;
    end
endmodule
```

The first part is the header. We will use this same header each time. It tells the Verilog compiler to get all the data from a file called definitions.vh. The extension vh is a Verilog header. We use this to specify common pieces of data we will use across our design, so that all the components we build will be consistent. By putting them in one file, we make it easier to maintain, and prevent mistakes that can happen easily by having multiple copies of these basic pieces of data. For our first component the piece of data we will be using is WORD, which is the size of data our computer will use (how many bits). We will be using 32-bits, but note that if we build things based around WORD, rather than the number 32, we can just change the value of WORD in the file and get a computer with a different size (say 64) with a couple key strokes.

The second part is the port list or interface. In this area we specify what signals are coming in (input), going out (output), or could go either direction (inout). For outputs only, we could also have the output driven by a register (reg) or not (wire). The other two types (input and inout) are only wires. If you don't specify anything for any of the port types, you will get a wire - it is the default. In our case we have four signals: three inputs, and one output that is a register. The first two inputs are single wires. One is the clock, which specifies the timing, and the other is reset, which clears the contents (makes the zero). The final input is the value we want to store in memory, and I have called it D, following the convention of digital logic. D has multiple bits that are numbered from WORD-1 down to 0. Thus the leftmost bit is 31 in this case, and the rightmost bit is 0[1]. If you changed WORD to be 64, this would automatically become 63 down to 0, which would resize the input. Pretty cool[2]! The output Q (also the digital logic conventional name) is a register (it will hold its value) and should also be of size WORD and follow the same order as the input D.

The final section is the body or implementation. It is composed of a single thread of code, that will keep running (hence always). It will run one time every time there is a positive edge (0 to 1 transition) for either the clock or reset. Reset has higher priority, so if reset is asserted the register is cleared (Q

[1] If you want to be technical this is called little endian, since the little end (the least significant or unit bit) is going into the first memory location (bit 0). If you reversed the order by putting the 0 first and the WORD-1 last it would be big endian, since the big end (most significant bit) would go in the lowest addressed bit.

[2] I grew up in the 80's so I reserve the right to say cool, rad, tubular, or any other 80's-ism. :)

is set to zero), otherwise the value of D is stored it Q. That is it. A nice, simple module.

1.2 Testbench

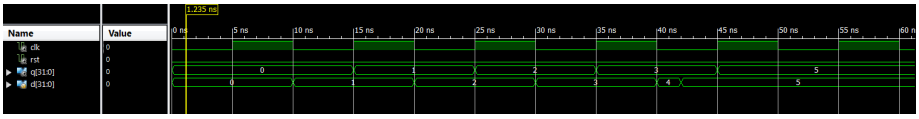
We now want to test this. To test it, we need to tell the simulator to build a copy (instantiate) the module, and then we will need to supply the inputs and look at the outputs. Consider the testbench in Listing 1.2.

Listing 1.2: Verilog code to test a register.

```
`include "definitions.vh"


module test_regs;

wire clk;
wire rst=0;
reg[`WORD-1:0] d;
wire[`WORD-1:0] q;

oscillator clk_gen(clk);

register UUT(
    .clk(clk),
    .reset(rst),
    .D(d),
    .Q(q)
    );

initial
begin
    d<='WORD'd0; #`CYCLE;
    d<='WORD'd1; #`CYCLE;
    d<='WORD'd2; #`CYCLE;
    d<='WORD'd3; #`CYCLE;
    d<='WORD'd4; #(`CYCLE/5);
    d<='WORD'd5; #(`CYCLE*4/5);
end
endmodule
```

Like our register it starts with our standard header, but this time there are no ports! A testbench is providing all the signals to simulate the inputs to the unit under test (UUT) and thus does not need them. This is how Verilog finds a top level simulation module - there are no ports. In the body (implementation) we have a bunch of things. First all the signals to our UUT must be declared.

Figure 1.1: Timing diagram.



Outputs always must go to wires (the outputs are driving them, and only wires can be driven). Often inputs become registers since you will want to specify a value and have it continue till you give it a new value, though some can be wires if you had another unit that was supplying the values from its outputs. In our case, the clock signal will be driven by a module names oscillator, which will give us a nice square wave with period CYCLE, which is another constant defined in our definitions.vh file. The code thus makes an oscillator and a register, then runs the initial thread (it runs once at the start then never again) The initial thread sets the value of the input then waits a CYCLE. The last couple delays are not full cycles. I did this for two reasons:

1. To show you how to make Verilog do calculations for you.

2. To remind you that the input won't necessarily be nice and perfectly timed to your register. Unsynchronized signals happen, and is a frequent cause of problems, hence the need to test.

This is by no means an exhaustive testbench, but run it and look at the output. Does it do what you expect? What else might you want to test? Add this to your testbench and run it again to see if the register works.

1.3 Using LaTeX for Your Write-up

Alls that is left is to write it up. I am going to have you use LaTeX to do your labs. Note how I include files, programs, and images. It is worth noting that LaTeX will automatically make the table of contents and bibliography for you also. To top it off you only need a text editor as the files are just ASCII files. To generate the document you run the command pdflatex and pass it the main file, and it will generate a pdf.

Why use LaTeX ? There are lots, but here are a few that matter in this course

1. It typesets programs from the actual source, no need to copy the program and have spell checkers and grammar editors mess things up.

2. It quickly and correctly handles equations (important given our math use).

3. It automatically handles table of contents and bibliographies.

4. It is free, and generates high quality documents (book quality) - it is open source since before open source.

5. It is used in publication of research documents.

6. It is the only large program believed to be error free in its source code, and have no missing features (development is complete!)

1.3.1 Background

TeX refers to both a language for typesetting and the program (compiler actually) that does the typesetting. LaTeX is a macro package which sits on top of TeX and provides additional functionality, and has become synonymous with the language variant (dialect) of TeX which it created. Since LaTeX is hugely popular and really useful, TeX and LaTeX have become synonymous to most people, and I will treat it so from now on. A note on pronunciation: TeX is in Greek letters - tau epsilon chi and hence is pronounced 'tek' not tex (similar for LaTeX which is pronounced 'lay-tek' not latex).

TeX is not a WYSIWYG (what you see is what you get) typesetting program like many editors you are familiar with, as it was designed to be a tagged language like the more recent html (yes, TeXis older). The idea is not to spend time thinking about how it should look, but rather to classify what it is and let the automated standards set the text by what the text is[3]. To provide flexibility and extension (and it was designed by one of the greatest computer scientists, Donald Knuth) it was set up as a programming language with a compiler. You will thus interact with several different programs, an ASCII text editor (to write the files), a TeX application to compile them, a pdf or dvi viewer to look at the output, and potential helper apps like dvi2ps, dvi2pdf, and their viewers. Since LaTeX is a programming language, we have a comment character % that I had to escape by putting a \before it to make it print. Whitespace past the first space (word separation) is ignored, except for a blank line, which means start a new paragraph. More than one blank line is ignored. To get more space, you issue a command, such as `\vspace{.25in}`, which puts a quarter inch of vertical space. LaTeX also knows pt (points), px (pixels), pc (pica), mm (millimeters), cm (centimeters), em (width of an 'm'), and many more. By default the space is not placed if it does not separate some object (i.e. at the top of a page), but you can force it by using `\vspace*{.25in}`. Starred commands are just versions of the main command.

There are many more commands than I can describe in this brief intro, including commands to let you define new commands and environments. We will not need too many fancy commands, we only need to describe the commands to include figures, code, and equations. If you want to learn more, then I have links to free manuals online at r2labs.org.

[3]For instance, note the chapter, section, and subsection commands in the tex files. LaTeX assigns a number, records it, the title, and page so it can automatically put it in the table of contents for you.

1.3.2 Compile Process

One thing that will help you a lot in working with LaTeX is how the compile process works. TeX is a two pass compiler, but it does only one pass each time it runs. Allow me a brief introduction to compilers, which is a great course if you can take it.

When you are compiling a file you have control statements (branches, loops, conditional execution statements like if or switch/case) that require you to know how many program lines ahead or behind something is in the assembled code, which you will not know at the start. While you are often just putting in a flag or label to be handled by the assembler later, you in truth don't even know if they actually put the destination of the transfer of control, and thus have an error. One easy way of handling this is to run through the process twice, collecting labels and such the first time and then doing the compile the second time through, which is what a two pass compiler does. TeX collects all the labels, notes all the chapter, section, and other structures, identifies all the bibliography references, and so on and puts them in a special auxiliary file for the next pass. It will also create a DVI file, which has most things right, but will lack table of contents, references, bibliography, and such. The second time through it already has the information before the file runs so it reads that first and uses it to create a fully correct output.

A logical question at this point is why not just have it run twice on its own? Well, in the 1980's computers were small and slow, so each run of TeX(we didn't even have LaTeX at first) took an appreciable amount of time. If you know the compile process, there are times you only have to run things once, like small spelling changes not in a title, chapter, etc. Allowing people to do only one pass at a time was a big advantage (some TeX compiles I had to do could take 10 minutes even in the 1990's). Bibliographies are handled by an external program called BibTeX, which reads the .aux file to find the references (thus you need to run LaTeX first), then pulls the data from the .bib files you specify in the calling command in your .tex file and creates a .bbl file. The .bbl file contains all the info formatted how the bibliography should look. LaTeX reads this in the first pass and copies it over to the .aux file and resolves the links to the text references. The next run of LaTeXreads all this in and places both the bibliography and the cross references. This means that to get a bibliography in you must run LaTeX BibTeX, LaTeX then LaTeX once more. You only need to do this if you add new reference, which in the labs will be once, provided you don't delete those intermediary files.

1.4 Your Assignment

You are to:

1. Finish the testbench in Listing 1.2.

2. Run a simulation and generate a timing diagram like I did.

3. Write up a lab report in LaTeX following the lab format in `LabN.tex` and generate a pdf file.

4. Upload the pdf and all the Verilog files to the course LMS.

Lab 2

Program Counter

As mentioned in the last lab, the program counter is a register that is one word in length. It holds the address in memory of the next instruction to be fetched and executed. A typical program counter has to deal with a variety of situations that could change the program counter.

1. The program counter should advance to the next address (add one word offset) each cycle.
2. If the conditions of a conditional branch are met, the destination of the branch is the next instruction.
3. If an uncondtitional branch or jump occurs, the destination is the branch's destination.
4. If an interrupt or error occurs, then the next value of the program counter should be the appropriate handler.

The most typical is the computer must fetch instructions in sequential order.

2.1 Incrementer

We will build an incrementer, by making a simple adder, then we just have to pass it a 1. Later in our computer we will need another adder, so this will let us re-use the code. We pass it a 1 because our memory will be word addressable. Word addressable means the smallest unit of memory that has its own address is a word. Most machines are byte addressable, because one ASCII character (a char in c/c++) is a byte. For a 32 bit word like we are using, that would mean $32/8 = 4$ bytes to a word or each instruction would be 4 addresses later. The book follows this convention so it will have +4 when it increments its program counter.

An adder is very simple in Verilog, see listing 2.1. We start by pulling in our definitions so we have our word size. We then declare our ports, which in this

case I made all wires as I want to show you another way to define a unit, beside an always thread. There are two inputs (the two numbers to be added) and one output (the result). All the ports are size word because they hold integers. The actual definition is then one line. Assign means to take a command and make it permanently define the value of a wire. It can only be to a wire (not a reg) as it must continuously assign a value, and regs cannot be continuously driven. We then just give the simple code that the output is the sum of the two inputs, just like in C or an always thread. That is it.

Listing 2.1: Verilog code to make an adder.

```
`include "definitions.vh"

module adder(
    input [`WORD-1:0] Ain,
    input [`WORD-1:0] Bin,
    output [`WORD-1:0] add_out
    );
    assign add_out = Ain+Bin;
endmodule
```

In this lab you will make your own testbench. The easiest way to do this is to use ISE's built in testbench generator.

1. Add a new source. There are several ways to do this. You can right click on the FPGA in the source window (upper left window) and select add a new source, or go to the project menu and select add a new source.

2. When the dialog comes up, select Verilog testbench, give it a name and verify the path is where you want it.

3. In the next dialog window it will ask you which module to test, and select adder (assuming you have already included the adder, if not do so and repeat).

4. Finish.

It will make a test bench for you, create reg's for the inputs to the UUT and wires for the outputs. It also instantiates the module as UUT, and creates an initial thread to do the stimulus. You can now add whatever you feel is a good test for the adder. Do some easy to verify checks then some that will test carry and rolling over. What else do you think you should you check?

2.2 Input Selection via Mux

We will need to be able to choose between normal advancing (sequential stepping) and branching (loops, if statements, etc.). We will use a multiplexor (mux) to do this. A mux is a simple device that connects one of the inputs to

the outputs based on how the selector is set. If the selector is 0 then input 0 is connected to the output, and if the selector is 1 then input 1 is connected to the output. One interesting addition in this block of code is the addition of a size parameter. Parameters are passed before the normal ports and are used to configure the code to meet a requirement at the time of construction. Note parameters cannot change later. The = 8 defines the default value if nothing is specified. In this case we are using parameters to set the number of wires that compose the inputs and output. In our problem we will need some muxes to switch entire words (32 bits), but later we will also need to switch register addresses (5 bits). Rather than write two registers, we will make one and then use the parameter to change the size when they are declared.

Listing 2.2: Verilog code to make a mux.

```
`include "definitions.vh"

module mux#(
    parameter SIZE=8)(
    input [SIZE-1:0] Ain,
    input [SIZE-1:0] Bin,
    input control,
    output [SIZE-1:0] mux_out
    );
    assign mux_out = control?Bin:Ain;
endmodule
```

Create a testbench for the mux like you did for the adder. Note the parameter is not used, and it set the inputs and outputs to be the default of 8. We are going to change this to test it as a 5 bit mux. Find the line that starts `mux UUT(...` and change it to be `mux#(5) UUT(...` You can also do the dot notation as was done for the ports, but there are usually so few paramters you don't need to. Make sure you change the size of the regs and the wire that are sent to the UUT from 7:0 to 4:0. Now come up with good values to test your mux so you are confident it works. Ask yourself, what could go wrong, and how can I test it?

2.3 Your Assignment

You are to:

1. Write a testbench for the adder in Listing 2.1.
2. Write a testbench for the mux in Listing 2.2.
3. Run a simulation and generate a timing diagram for each.
4. Write up a lab report in LaTeX following the lab format in `LabN.tex` and generate a pdf file.

5. Upload the pdf and all the Verilog files to the course LMS.