

ELC 3338 Project Book

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Lab 1

Program Counter Register

During the course of this semester, we will build a 64-bit computer so that we can understand how it works. To do this, we will make a synthesizable machine in Verilog, a common hardware description language (HDL).

A computer runs a program by executing individual instructions in sequential order. The instructions are stored in memory and are accessed by their memory address. During each clock cycle, an instruction is fetched from memory and executed on the processor. The memory address of the next instruction to fetch is stored in a register called the Program Counter (PC). During Lab 1, we will build and test the Program Counter register. In Lab 2, we build an incrementer (to count to the next instruction) and a mux (to select between the incremented count or a new starting value).

1.1 Program Counter Register

In order to make the Program Counter, we are going to make a Verilog module that explains how to build a register (a D flip-flop). Let me unpack the previous sentence:

1. Verilog is a Hardware Description Language (HDL).
2. We write Verilog code to tell Vivado how we want our register module to behave.
3. Vivado reads our Verilog code and synthesizes a realizable digital hardware design that meets the behavior that we specified. Thank you Vivado!
4. Vivado also simulates the behavior of the hardware, allowing you to test your design without building/programming hardware.

Consider the Verilog 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 wire clk ,
    input wire reset ,
    input wire [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

```

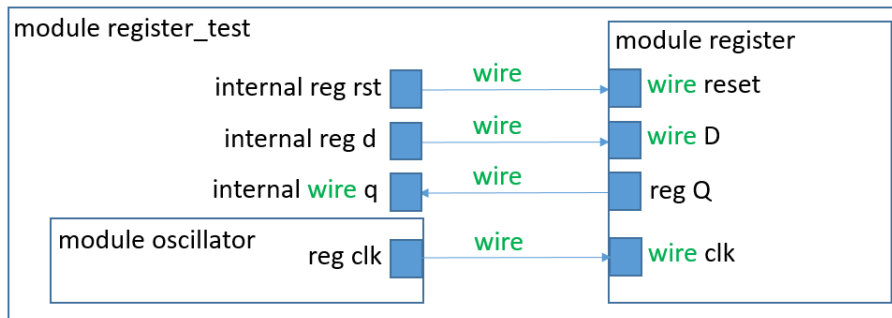
The first part is the header. We will use this same header each time. It tells the Verilog compiler to get all the data from a file called definitions.vh. The extension vh is a Verilog header. We use this to specify common pieces of data we will use across our design, so that all the components we build 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 (set to 64), which is the size of the memory addresses our computer will use (how many bits). Note that if we build things based around WORD, rather than the number 64, we can just change the value of WORD in the file and get a computer with a different size 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). Ports can be defined as either "wire" or "reg". This can be confusing to some students. Think of it this way:

1. Wire

- (a) A wire is just a conductor that connects one component or module to another.
- (b) The value on a wire can only be changed by using combinational logic.
- (c) It has no memory, meaning that the value on the wire is driven by the results of combinational logic at that particular moment.
- (d) Module inputs are always wires
- (e) Module outputs can be wires or regs.

Figure 1.1: Module Diagram.



- Internal regs are set in the 'initial' block or an 'always' block

2. Reg

- A reg more closely resembles a variable in software programming languages.
- A value of a reg can only be set by using sequential logic.
- A reg has memory, meaning that the value of the reg will remain the same until a sequential logic element updates it.
- You can directly set a reg to a value using a procedural assignment.
- Regs can be used internally in a module (neither input nor output), or they can be used as module outputs. They cannot be used as module inputs.

If you don't specify anything for the port type, 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-bit wires. One is the clock, which specifies the timing, and the other is reset, which clears the contents of the register (makes them 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 63 in this case, and the rightmost bit is 0¹. 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.

To help clarify this, please examine Figure 1.1, which shows the interconnection of the modules in this lab.

¹If 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.

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 is set to zero), otherwise the value of D is stored in Q. That is it. A nice, simple module. Please note that the provided register module is fully operational. You do not need to modify it.

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 to verify that the module works correctly. Consider the testbench in Listing 1.2.

Listing 1.2: Verilog code to test a register.

```
'include "definitions.vh"

module register_test;

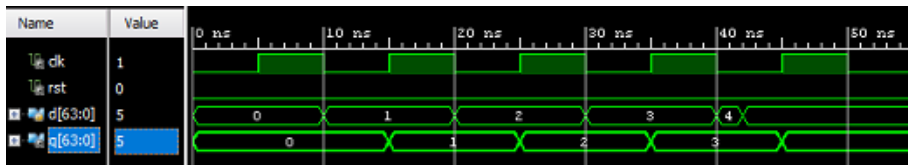
wire clk;
reg rst;
reg['WORD - 1:0] d;
wire['WORD - 1:0] q;

oscillator clk_gen(clk);

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

initial
begin
    rst = 0;
    d<='WORD'd0; #CYCLE;
    d<='WORD'd1; #CYCLE;
    d<='WORD'd2; #CYCLE;
    rst = 1;
    d<='WORD'd3; #CYCLE;
    d<='WORD'd4; #('CYCLE/5);
    rst = 0;
```

Figure 1.2: Timing diagram.



```

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. The clock signal will be driven by a module named 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' section (it runs once at the start then never again). The initial section sets the value of the inputs then waits a CYCLE. The last couple of 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 L^AT_EX for Your Write-up

This section was originally written by Dr. Schubert, so any first person references are from Dr. Schubert.

All that is left is to write it up. I am going to have you use L^AT_EX to do your lab reports. Note how I include files, programs, and images. It is worth noting that L^AT_EX will automatically make the table of contents and bibliography for you also.

Why use L^AT_EX ? There are lots of reasons, 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.
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, \TeX is 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 is². 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. 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 we could describe in this brief intro, including commands to let you define new commands and environments. We will

²For 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.

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.

1.3.2 Compile Process

One thing that will help you a lot in working with L^AT_EX is how the compile process works. T_EX 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. T_EX 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 T_EX (we didn't even have L^AT_EX 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 T_EX compiles I had to do could take 10 minutes even in the 1990's). Bibliographies are handled by an external program called BibT_EX, which reads the .aux file to find the references (thus you need to run L^AT_EX 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. L^AT_EX 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 L^AT_EX reads all this in and places both the bibliography and the cross references. This means that to get a bibliography in you must run L^AT_EX BibT_EX, L^AT_EX then L^AT_EX 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.

1.3.3 Getting Started with LaTeX

Now that you have some background knowledge, we need to learn how to build a document on your computer. There are many ways to do this, including text editors and command line tools. I prefer using a more user-friendly editing and building environment. While there are numerous options available, I choose to use `TeXStudio`. It is installed on all ECS computers, and it is available for free download at home. For each lab, you will want to make a copy of `LabN.tex` and name it `Lab1.tex`, `Lab2.tex`, etc. After creating `Lab1.tex`, I would recommend opening `Lab1.tex` and building it before making any changes. Then make some changes, rebuild, and view those changes in the PDF that is generated. Steps to build a document in `TeXStudio` are:

1. Open `TeXStudio` on your lab computer
2. Use the menus open `Lab1.tex`
3. Click on the double green arrow icon near the top. If you hover over it, it says "Build & View".
4. This should produce a PDF document on the right side of the `TeXStudio` window

This document should build properly as long as you don't modify it. Once you start editing, it is possible that you will get compile errors. These errors are listed in the bottom pane of `TeXStudio`. Like many compilers, they are sometimes cryptic and don't lead you directly to the problem. The most common problem (by far) is using an underscore with using the escape character (backslash) first. For example, look at the `fetch1.tex` file to see how I made this `example_of_how_to_use_underscores`.

Note that all code and image references are relative to where the `.tex` document is located in the file system. It is important that you maintain the same file structure that I gave you so that these references are simple and consistent.

1.4 Your Assignment

You are to:

1. Finish the testbench in Listing 1.2 by testing several additional cases. For instance, what happens when `D` is set at different points during the clock cycle, or if `D` is set for longer than a single clock cycle. Also, reset is not currently being tested. Does reset work properly? Does the register work properly after reset has been cleared?
2. Create an Expected Results Table for your testbench. An example Expected Results Table is at `ARM-Lab/testfiles/Lab1_Register_ExpectedResultsTable.xlsx`. The idea behind the Expected Results Table is that you identify how you think the system should operate. If you don't know how it should work, you will not know whether your simulation results are correct.

3. Run a simulation and generate a timing diagram.
4. Write up a lab report in \LaTeX following the lab format in `LabN.tex` and generate `Lab1.pdf`.
5. Upload `Lab1.pdf` file to Canvas.

Lab 2

Program Counter Incrementer and Mux

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. There are several ways that the program counter is updated:

1. If the program does not branch (via an if statement, while loop, etc), then the program counter should advance to the next address (add 4 bytes) each clock cycle.
2. If the conditions of a conditional branch are met, then the program counter should be updated with the branch destination address.
3. If an unconditional branch or jump occurs, then the program counter should be updated with the branch destination address.
4. If an interrupt or error occurs, then the program counter should be updated with the interrupt or error handler address.

The instructions will be fetched in sequential order the majority of the time.

2.1 Incrementer

We will build a program counter incrementer by making a simple adder. Later in our computer we will need another adder, so we will re-use this code. When used as the program counter, we will pass it a 4 because each instruction is 32-bits long (even though it is a 64-bit computer) and we want to increment to the next instruction in memory. Most machines are byte addressable, because one ASCII character (a char in c/c++) is a byte. For a machine with 32-bit instructions like we are using, that would mean that each instruction would be 4 bytes later in memory ($32/8 = 4$ bytes). Therefore, we will be adding 4 to the program counter each time we want to increment the program counter.

An adder is very simple in Verilog. 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.

In this lab you will make your own adder and a testbench for the adder. Your adder module should be called 'adder' and should have inputs of **a_in** and **b_in**. The output should be **add_out**. HINT: this should be very easy. Verilog is a Hardware Description Language, so use Verilog to describe what you want to do. Don't make it complicated. The adder code should be stored in ARM-Lab/code/0_common/adder.v. You will need to create this file.

2.2 Input Selection via Mux

We will also 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 bit 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 are constants and cannot be changed later in the module. 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 (64 bits), but later we will also need to switch register addresses (5 bits). Rather than write two muxes, we will make one and then use the parameter to change the size when they are declared. The mux starter code is located in ARM-Lab/code/0_common/mux.v.

Listing 2.1: Verilog code to make a mux.

```
'include "definitions.vh"

module mux#(
    parameter SIZE=8)(
        input  [SIZE-1:0] a_in ,
        input  [SIZE-1:0] b_in ,
        input  control ,
        output [SIZE-1:0] mux_out
    );

    // add mux code here

endmodule
```

Create a testbench for the mux. Note that if the parameter is not set by the testbench, the mux module will set the inputs and outputs to be the default of

Figure 2.1: Expected Results Table

	0-10	10-20	20-30	30-35	35-55	55-65
a	0	55	55	1	1	1
b	5	5	59000	59000	24	8
add_out	5	60	59055	59001	25	9

8. We are going to change this to test it as a 64 bit mux. In your testbench, instead of creating your mux module using `mux UUT(...`, define the parameter as 64 by changing it to be `mux#(64) UUT(...`. You can also do the dot notation as was done for the ports, but there are usually so few parameters you don't need to. Now come up with good values to test your mux so you are confident it works.

2.3 Expected Results Table

In order to verify that our modules work properly, we will create an Expected Results Table and compare our expected results with our simulation results. The Expected Results Table is not only critical for your own verification of your module, but it is also something that I will use heavily in grading the lab reports. In your lab reports, I need to be able to easily compare your expected results with your actual results. Of course, I will examine your test bench code as well so that I can check that your expected results are correct as well. The Expected Results Table should be done in Excel. It should have simulation time values across the top and signal names along the left-hand side. The order of the signal names in your table must match the order of the signal names in your simulation results. Then you should fill in each block of the table with the expected value for that particular signal at that particular time. Please use decimal numbers for all values in the expected results and the simulation results. See Figure 2.1 for an example Expected Results Table.

2.4 Your Assignment

You are to:

1. Write an adder.
2. Write a testbench for the adder.
3. Create an Expected Results Table for the adder.
4. Update the mux starter code to operate as a mux.
5. Write a testbench for the mux.
6. Create an Expected Results Table for the mux.

7. Run a simulation and generate a timing diagram for each testbench.
8. Compare your Simulation Results with your Expected Results Table and resolve discrepancies.
9. Write up a lab report in \LaTeX following the lab format in `LabN.tex` and generate a pdf file.
10. Upload the pdf to Canvas.

Lab 3

Fetch Stage

We are ready to build our fetch unit. To do this, we will make one more module, our instruction memory. Then we will make a module to assemble all of our units together.

3.1 Instruction Memory Module

The instructions are stored in memory, and are accessed by using the address where they are stored. You can think of memory like a giant hotel for our data. Each piece of data is stored in a room (memory location), which we can find by its room number (memory address). To get a piece of data stored in memory (like an instruction) we need to take its address, go to that location, and grab the data. In Verilog, a bunch of memory locations that are accessed by an address is called an array. Arrays in Verilog are declared like they are in C; the data type is specified, then the name, then the array size. To store the instructions, we will need an array of 32-bit numbers (definitions.vh defines `INSTR_LEN` as 32), which means the data type must be `reg['INSTR_LEN-1:0]`. After the name is specified (imem in this case), we are going to use a parameter called `SIZE` to specify how many elements the array has: `[SIZE-1:0]`.

The other interesting thing about this code is how to initialize the memory. The default size of the memory is 1024 elements, so we do not want to initialize this memory element by element in the code. Fortunately Verilog gives you two functions to do this automatically: `$readmemb` and `$readmemh`. The last letter specifies the base (binary or hexadecimal) of the data in the file. White space separates fields, but the underscore character is ignored and thus can be used to make the values in a number more readable. The `readmemb` function will be used to read the file `'IMEMFILE` and store the bits in the imem array. This is done one time on initialization. Then, you can access that data in imem at any time after that.

`'IMEMFILE` is defined in definitions.vh, and I provide this file, which contains instructions. However, you will need to update definitions.vh to point to

your testfiles section rather than mine, or else it will look for mine and not find the file.

Listing 3.1: Instruction Memory

```
'include "definitions.vh"

module instr_mem#(
    parameter SIZE=1024)(
    // Add ports here
    );

    // imem is the instruction memory itself
    // imem is initially populated by reading
    // a file one time in the initial section
    reg['INSTR.LEN - 1:0] imem [SIZE-1:0];

    // Add code here to output the correct instruction

    // initialize instruction memory from a file
    initial
        $readmemb('IMEMFILE, imem);

endmodule
```

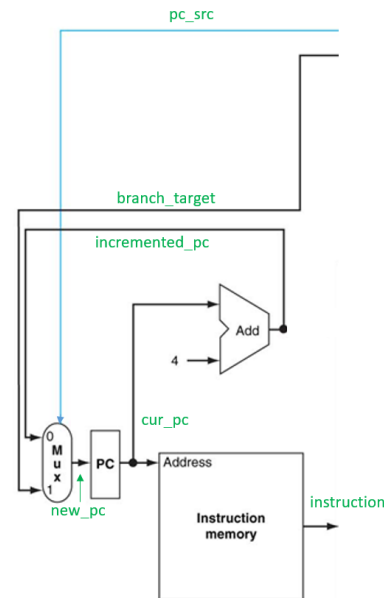
Starter code for the instruction memory module is given in Listing 3.1. The starter code provides the instruction memory array (imem) and it provides code that populates the imem array with values from a file during initialization. You need to add the ports to the module and add code to find the correct instruction and output it. You only want to update the instruction on the positive edge of the clock. To find the correct instruction, an address (program counter value) must be passed into the module.

Once the module is complete, write a testbench for the instr_mem module (instr_mem_test). Verify that the instr_mem module operates correctly by using 5 different program counter values. Program counter values should be a multiple of 4 since instructions are 4 bytes long and should not be higher than 52 because there are a limited number of instructions in the data file. Set the program counter values at different times within the clock cycle to ensure that the instruction is updating on the positive edge of the clock. In order to confidently verify operation, you are required to create an Expected Results Table for your testbench and compare your Simulation Results with it. Please show all values in decimal in the Expected Results Table and the Simulation Results.

3.2 Fetch Stage

Now we need to connect it together. The components of our instruction fetch (sometimes called ifetch or just fetch) stage are shown in Figure 3.1.

Figure 3.1: Instruction Fetch Stage.



Any wire (or reg) that comes into or goes out of the figure are input or output ports of the iFetch module. In Figure 3.1, the blue wire is a control signal and comes ultimately from the control unit, which you will build in the decode stage. Wires (or regs) that are completely contained in the figure are local to the iFetch module and are thus defined internally in the module. The one exception to this is the current program counter (`cur_pc`). While there is no reason (at this point) that it must be output from the iFetch module, you must still make it an output so that it shows up on your simulation results, helping you to keep track of the program counter for the instruction that is currently executing. Also, it will be required when we start pipelining our datapath in Lab 12.

While the input and output signals are easily identified by the diagram, you must also determine the size of each signal and whether it is a wire or reg. When you look at the figure I cut from a figure in the book, note that I labeled every wire on the diagram in green. For the sake of consistency and debugging, it is required that you use these names.

IMPORTANT NOTE: Throughout your entire project, your signal names should follow the convention of the Freescale Semiconductor Verilog guide, which states that signal names should be all lower case, with words separated by an underscore.

Once you have figured out all your connecting signals (wires and regs), you should identify the components you are going to use. We have already created the modules, so now we just need to tell Verilog to instantiate them in the iFetch module and connect them together. Create the iFetch module in a new file called `iFetch.v` in the `code/1_fetch` directory.

3.3 Fetch Testbench

Once you have made your connections, you should test the operation of the iFetch module by creating `iFetch_test.v`. You know you checked your individual modules, but there could be errors, or unexpected behavior when you put them together. Sometimes weird timings between modules causes signals to be missed and such.

Your testbench should create an instance of the iFetch module, set the inputs

into the iFetch module, and verify that the correct outputs are produced. You should test both sequential operation (PC incrementing by 4) and branching. When you test branching, keep in mind that my provided instruction file (instrData.data) only contains 14 instructions, so don't branch beyond the end of the file. Make sure to verify that, after branching, the system continues sequentially from that branch address. I recommend a test like:

1. Start off by allowing 5 instructions to execute sequentially.
2. Then branch forward to instruction by setting pc_src to 1 and setting the branch target to 36.
3. Then set pc_src back to 0 and allow instructions 11-13 to execute.
4. Then branch back to instruction 6 and allow the program run to completion.

As we progress through this lab, you will learn how critical timing is. Please look at the cur_pc value and the instruction value and verify that the instruction that was fetched is the correct instruction, according to instrData.data and the current program counter. Note that no instruction should be fetched in the first 5ns, as this is a half clock cycle and does not have a rising edge.

I have included a file called delay.v in code/0_common. It includes a module that inputs a clock signal and outputs a clock signal that is delay by some number of ns. This will be useful when resolving timing issues.

In order to confidently verify correct operation, you are required to create an Expected Results Table for your testbench and compare your simulation results with it.

3.4 Your Assignment

You are to:

1. Finish the instruction memory module.
2. Write a testbench for the instruction memory module.
3. Create an Expected Results Table for this testbench.
4. Verify the results of this testbench by comparing the Expected Results Table with the Simulation Results.
5. Finish the fetch stage.
6. Write a testbench for the fetch stage.
7. Create an Expected Results Table for this testbench.
8. Verify the results of this testbench by comparing the Expected Results Table with the Simulation Results.

9. Write up a lab report in \LaTeX following the lab format in `LabN.tex` and generate a pdf file.
10. Upload the pdf to Canvas.