

EE 371 Lab 1
Introducing the Lab Environment
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Introduction:

In this first lab project, we have a number of things that we'd like to cover. The first is to introduce (or to refresh our knowledge about) the Altera DE1-SoC board and the Quartus II development environment and tools that we'll be using. The second is to refresh and to extend our working knowledge of the Verilog HDL and three of the four modeling levels supported by the language. The third is to learn and to work with an important and very useful tool, the logic analyzer that is included in the Quartus II IDE. The fourth is to take a preliminary look at failure modes analysis. Finally, for now, to begin learning a little about the C language. We will need C later in the quarter when we develop applications on an embedded NIOSII processor supported by the Altera environment.

As we do all of this, we will also begin learning a little about developing simple embedded systems and some of the things that we can do with them.

Prerequisites:

Familiarity with developing digital circuit models using the Verilog HDL, primitive logic devices such as gates, flip-flops, and latches, the logic design of combinational and sequential circuits at the device level, basic software data types and operations, as well as standard program design, development, and debugging techniques. A willingness to learn and to explore. No beer until the project is completed. I really mean it.

Cautions and Warnings:

Never try to run your circuit with the power turned off...unless you've perfected energy harvesting or have located a current bush in Sylvan Glen. Under such circumstances, the results are generally less than satisfying.

Since current is dq/dt , if you are running low on current, raise the DE1-SoC board to about the same level as the power supply and use short leads. This has the effect of reducing the dt in the denominator and giving you more current.

If your circuit is turning on too slowly, lower your breadboard so that it is substantially below the power supply. This enables the charge to get a running start before coming into your board. It will now turn on much faster.

Throwing your completed but malfunctioning implementation on the floor, stomping on it, and screaming 'work you stupid fool, work' is typically not the most effective debugging technique although it is perhaps one of the more satisfying.

When you are debugging you circuit, wiring it, taking it apart, and rewiring again several dozen times (or in the case of the FPGA, recompiling the code and reuploading it) does little to fix what may be a design error. Such an approach is not highly recommended, but, can keep you entertained for hours...particularly if you can convince your partner to do it.

Sometimes - but only in the most dire of situations - sacrificing small animals to the smoke demon living in your circuit does work. However, these are not included in your lab kit and

must be purchased separately from an outside vendor. Also, be aware that code gremlins are not affected by such sacrifices.

Alternately, blaming your lab partner(s) can work for a short time...until everyone finds out that you are really to blame.

Always keep only a single copy of your Verilog or C source code. This ensures that you will always have a maximum amount of disk space available for games, email, facebook, and some interesting pictures. If a code eating gremlin happens to destroy your only copy, not to worry, you can always retype and debug it again.

Debug Tips:

Adapted from Robin Panda.

One of the most important skills you will learn and practice in this class is how to debug your design. As mentioned above, completely disassembling and reassembling your circuit isn't helpful. It's entirely possible that you will repeat the same mistake that your design is incorrect, or your power supply is off, or you've misread a chip's part number and installed the wrong one. The ability to isolate your own problem will only pay off more later with more advanced designs when your instructors know nothing about the details of your design. The most useful question that you can ask yourself is, "**What *DOES* Work?**" You're already asking yourself, "What doesn't work?". If that question were easy to answer, you'd be done. This means a number of things....

Check the easiest things to check (and common mistakes) first. Do not assume things work unless you have at least some evidence so. Does the power supply actually put out the proper voltage (at your circuit)? Is the scope set to the right input, voltage, and mode? Did you get any warnings or errors when you compiled? Does your circuit always get really hot in the same place? Are there wires or semicolons laying about that shouldn't be? Is your circuit actually a burrito and not your circuit? (don't bring food in lab)

Ask yourself, When did it work last? If the answer is never and you just built a huge nest of wires with a book full of code and are expecting it to work correctly, you are risking pain and you'd better be lucky. Once you have this answer, you can temporarily assume that the old stuff that hasn't changed is still working and now you have a much smaller circuit (or piece of code) to debug.

What is the smallest suspect (chip, module, component, statement, etc) that is closest to the known good bits? Stick a probe (scope, print statement, dump) on the output of this and verify. If it looks what you expect, add it to your list of probably good components and repeat. ***This is a key point***...In order to see if what you see matches what you expect...you must know what you are expecting to see...sounds simple, but many people skip this part. If it doesn't, then maybe you've isolated the problem. Verify that the inputs to this piece are correct to be sure. If you can't verify the inputs, you chose the wrong component to test. Sometimes you need to make test code and/or test circuits to simplify the behavior to be able to verify. Always test closest to the inputs and known good bits. This means your Verilog needs to be correct before you worry about your circuit or claim your FPGA is broken.

Once you've got something, it doesn't mean that that component is broken. You also could be using it wrong, or chosen the wrong one. Make sure the component isn't it backwards. Make sure that you have connected power and ground. Understand the code your partner wrote. Double-check the datasheet to make sure it's specifications are what you expect. See

above on expecting things...Look for weaknesses: Is there a maximum output current that could explain why you're stuck at 0? Is some signal active-low?

With experience, you will add more simple issues to the list of first checks and often find the problem before needing to be formal about your debugging. Eventually, your experience or intuition will fail you and you will need to check everything. I hope it's clear that the reason you're debugging is that one of your assumptions is wrong; you need to be a skeptic and think critically. Sometimes what was previously good got messed up and you need to revert to the old circuit/code to check. Sometimes you missed the part of the datasheet that says gravity pulls up. Sometimes that warning that you "always get" says something slightly different than you thought it did. Sometimes your TA or lab report gave you dodgy advice that makes no sense...

Background:

In this class, we will continue to work with the Altera tools and development environment on the DE1-SoC platform that you started to learn in EE 271. If you took EE 271 before we introduced the DE1-SoC board, not to worry, it's quite similar to the olde DE1. The platform is new and slightly different from what we've used previously. We've learned a lot, but there is still much more to know and we hope to take several steps in that direction this quarter. We also want to begin to learn the formal development process that we will be able to apply to our projects in the quarters ahead. Learning new components and tools is exciting and challenging. This is the fun part of engineering. Yes, and reading and understanding the documentation.

At the same time, sometimes it can be frustrating when the hardware or the software doesn't behave the way we want it to, or when, unfortunately, it behaves exactly the way that we have told it to, or when we can't immediately find the answer to our questions and problems. At this stage in learning engineering and about the engineering process, playing with the toys seems too often be the most exciting part...the documentation and so on, is seen as rather boring. In the real-world, though, the documentation is a critical part of all phases of the engineering development process – from initial design to final report. Doing it, doing it right, and doing it well can mean the difference between success or failure of a project, the malfunction of the system following delivery to the customer, or the possible loss of life while it is being used.

Sometimes your instructor or TA will have the answers to your questions and sometimes they won't. As we said in the opening, bear in mind that we're learning the environment and tools too – this platform and development environment are complex and are new to all of us. If we all work together to identify and solve problems as they occur, everyone benefits and we help to build for the next classes. The answers are there somewhere. Let's all work to find them.

Regardless of the specific platform/environment used, embedded systems development requires at least the following:

1. An environment in which to develop the application.
2. A target platform on which to execute the application.
3. A mechanism for programming or loading the application from the development environment onto the target platform.

Target platform is a term used loosely in industry to mean the actual piece of hardware that performs the computation and/or control – the place where our application will ultimately

run. Here, we will be utilizing pieces of hardware on a piece of hardware – a Cyclone V FPGA (Field Programmable Gate Array) and a collection of supporting peripheral devices. A target platform can be a simple a single chip (i.e. an Arduino or a PIC microprocessor), or as complicated as a feature-rich single board computer (build around a multicore high performance processor and possibly several programmable logic devices). Here, we'll work with one such programmable device. Building upon and extending what we learned in EE 271, we'll find that we can still do some really cool stuff with it. Just watch.

Despite the differences in physical characteristics, the target platform's purpose is the same: to run the application created by the developer. Here, and for the typical PLD (programmable logic device) based application, the hardware development/modeling language will be Verilog or VHDL, the application software will be written in the C language, and the target will be an FPGA.

In this context, we will use the Verilog HDL to *model* the hardware functionality of our system in the Quartus II environment. We will then *synthesize* the HDL model into the hardware pieces necessary to affect that functionality on the FPGA. *Modeling* and *synthesizing* are two different things; as we'll learn, they are looking at the design and the environment from two different perspectives. When we add a microprocessor to our designs, we will follow the same hardware development process, then, we will download a compiled C program to run on that processor which we put onto the FPGA.

A final piece of advice from John Fluke Sr. – founder of the Fluke Corporation to take with you. He built an international billion dollar corporation around these simple words.

Always give the customer a little more than they expected.

It's a good philosophy no matter what you are working on or where you are working.

Laboratory Environment:

Our laboratory environment comprises the DE1-SoC development board and the Quartus II IDE. The combination is a feature-rich set of tools that includes, on the hardware side:

- The Cyclone V FPGA,
- A static RAM (SRAM),
- A synchronous dynamic RAM (SDRAM),
- A Flash memory
- SD Card socket
- VGA support
- CODEC
- PS/2 mouse / keyboard I/O
- User I/O in the form of switches and LEDs
- A hard ARM processor and support for a soft NIOS II processor
- Three different oscillators for clock development

and, on the software side, a development environment that supports, among other things

- Graphical, HDL, or mixed design entry

- Simulation capability
- Synthesis of the HDL model for the target environment
- Multiple different views of the design
- Timing constraint analysis
- Logic analyzer capability
- A rich library of parts
- Support for user design components

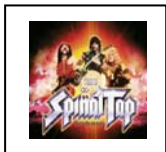
In this class, we will use many of these hardware and software features as we design and develop the various laboratory projects; the details regarding each of the components will be given as we need them.

Using the *Quartus II Development Environment*, Verilog models and C applications can be developed on a standard PC and then downloaded onto the target platform over a USB serial connection.

Objectives:

The major objectives of this project include:

- Introduce the laboratory environment: the development environment, the target platform, host PC, equipment, etc.
- Begin to work with the various Verilog modeling levels through the design, test, synthesis, download and execution of several different counter implementations.
- Learn the Verilog modeling tool *iVerilog*.
- Learn and use the Quartus II *Signal Tap* (it ain't *Spinal Tap*) logic analyzer to examine the output waveforms from the various counters.
- Learn a bit (more) about the Cyclone V FPGA.
- Begin to learn and work with a formal approach to design beginning with identifying the requirements and then formulating specifications and analyzing for possible failure modes.
- Begin to work with the C language, simple C programs, and the PC development environment.
- Learn to design, compile, and debug a C program on a host PC.



Designing and Building Verilog HDL Applications:

For those who are new to the DE1-SoC / Quartus II environment, Appendices B and C in the from the Brown and Vranesic 2nd edition text provide an excellent introduction to some of the material based upon the earlier DE1 system. These are posted on the class web page under documentation. There is also some very good introductory material from Altera on the class webpage under the documentation/DE1-SoC, Tutorials, and UserGuides subdirectory (Class Documentation hot button on the front of the class web page).

For the first part of the lab, we will design, build, test, and synthesize four different counting circuits that we will then program them onto and run on the Cyclone V FPGA. For each of the following designs, we will use Verilog as the top level. In a later part of this lab, these

will serve as our signal source as we begin to learn and to work the Quartus II, Signal Tap logic analyzer.

Each of the counters shall reset to an initial all 0's state. Following the first clock, each down counter shall move to the all 1's state and continue counting down from there.

The four counters are specified as follows:

1. A four stage (4 bit) ripple down counter, with active low reset.
 - a. Design the counter using a *gate or structural model*.
 - b. Use the D flip-flop model in the adjacent listing.
2. A four stage (4 bit) synchronous down counter, with active low reset.
 - a. Design the counter using a *dataflow model*.
 - b. Use the D flip-flop model in the adjacent listing.
3. A four stage (4 bit) synchronous Johnson down counter, with active low reset
 - a. Design the counter using a *behavioural model*.
4. A four stage (4 bit) synchronous down counter, with active low reset, using *schematic entry*.

```
module DFlipFlop(q, qBar, D, clk, rst);
    input D, clk, rst;
    output q, qBar;
    reg q;
    not n1 (qBar, q);
    always@ (negedge rst or posedge clk)
    begin
        if(!rst)
            q = 0;
        else
            q = D;
    end
endmodule
```

Working with iVerilog and gtkwave

As you move to industry as a co-op student or full time employee or to a graduate program, you will have the opportunity to work with tools that may be different from those you have learned earlier in your studies. Learning to work with different tools is an important skill to develop. Earlier in EE 271 you worked with *ModelSim*; in this project we are going to work with two different, but functionally equivalent tools called *iVerilog* and *gtkwave*. You can download and install Icarus Verilog on your personal machines or work with the programs on the lab machines or the remote desktop. If you install on your own machine, make certain that the path to the installation does not contain any spaces. The same is true for any file names.

Design and test each of the first three counters using *iVerilog*. Implement each design as two simple files, one containing only the counter module and a second, top-level file, containing the test bench and tester for that counter. You will have to include the logic to produce a clock for your counters in your test bench. Include the counter module into the top-level file using the directive

```
`include "fileName.v"
```

where *fileName.v* is your counter file and ` is the back tic, not the apostrophe '.

Verify the proper operation of each design using both the state and waveform (via *gtkwave*) outputs.

Working with *iVerilog* and *gtkwave* as design tools is rather straightforward. The following steps will get you up and running in short order.

Let's work with the simple system modeled by the multifile Verilog programs, *andorTop0.v* and *andOr0.v*, that follow.

```
// andorTop0.v

`include "andOr0.v"

module testBench;

    // connect the two modules
    wire [1:0]    X, Y;
    wire [1:0]    XandY, XorY;

    // declare an instance of the AND module
    AndOr  myAndOr (XandY[1:0], XorY[1:0], X[1:0], Y[1:0]);

    // declare an instance of the testIt module
    Tester  aTester (X[1:0], Y[1:0], XandY[1:0], XorY[1:0]);

    // file for gtkwave

    initial
    begin
        // these two files support gtkwave and are required
        $dumpfile("andor0.vcd");
        $dumpvars(1,myAndOr);
    end

endmodule
```

```
// andorTop0.v cont.

module Tester (xOut, yOut, XandYin, XorYin);

    input  [1:0]    XandYin, XorYin;
    output [1:0]    xOut, yOut;
    reg  [1:0]      xOut, yOut;

    parameter stimDelay = 20;

    initial // Response
    begin
        $display("\t\t xOut yOut \t XandYin XorYin \t Time ");
        $monitor("\t\t %b\t %b \t %b \t %b", xOut, yOut, XandYin,
                                                    XorYin, $time );
    end

    initial // Stimulus
    begin
        xOut = 'b00; yOut = 'b10;
        #stimDelay xOut = 'b10;
        #stimDelay yOut = 'b01;
        #stimDelay xOut = 'b11;

        #(2*stimDelay);           // needed to see END of simulation
        $finish;                  // finish simulation
    end

endmodule
```

```
// andOr0.v

// Compute the logical AND and OR of inputs A and B.
module AndOr(AandB, AorB, A, B);
    output [1:0]  AandB, AorB;
    input  [1:0]  A, B;

    and    myAnd [1:0] (AandB[1:0], A[1:0], B[1:0]);
    or     myOr  [1:0] (AorB[1:0], A[1:0], B[1:0]);
endmodule
```

1. Create a Verilog source file for the circuit or system that you are modeling using Notepad++ or your favorite editor. In Notepad++, from the menu bar, select *Language* then *V* then *Verilog*. The tool will now properly format your code for the Verilog language. Above we have the files *andorTop0.v* and *andOr0.v*.
As above, to provide the data for the *gtkwave* tool, you must structure your test bench as...

```

module testBench;

    // connect the two modules
    wire inputs;
    wire outputs;

    // declare an instance of the MyDesign module
    MyDesign    myDesign(outputs, inputs);

    // declare an instance of the Tester module
    Tester      myTester (outputs, inputs);

    // file specifications for gtkwave
    initial
    begin
        // dump file is for dumping all the variables in a simulation
        $dumpfile("gfxFile.vcd");

        // dumps all the variables in module myDesign and below
        // but not modules instantiated in myDesign into the dump
        // file.
        $dumpvars(1,myDesign);
    end

endmodule

```

1. On your PC, go to the *Start* button and select *run*. Enter *cmd* and navigate to where your source file is.

2. Create an executable by typing
 iverilog andorTop0.v
 which produces a file named *a.out*

or specify the name of the output file by typing
 iverilog -o andorTop0 andorTop0.v
 which produces a file named *andorTop0*

3. Run the executable by typing either
 vvp a.out

or

vvp andorTop0

as appropriate.

In addition to executing your program and producing a state output, the vvp tool will also produce a file with a .vcd extension that we use as the input to gtkwave. If we named the dumpfile above *andor0.vcd*, this is the file that the vvp tool will produce.

4. To run the *gtkwave* tool to get the timing diagram, type
 gtkwave andor0.vcd

to create the initial display window,

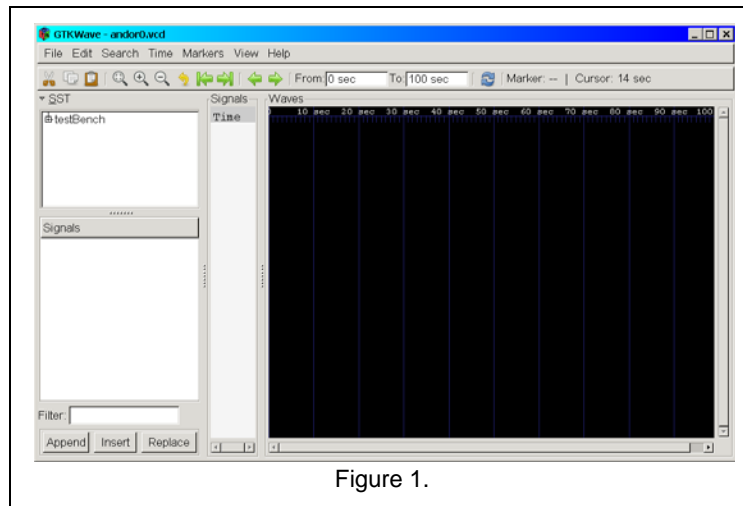


Figure 1.

Select and expand *testBench* then *myAndOr* to provide a list of signals that can be displayed. Choose then click on a displayed signal then select *Insert* to add that signal waveform to the timing diagram.

The following diagram displays all of the top-level signals for the module instance *myAndOr*.

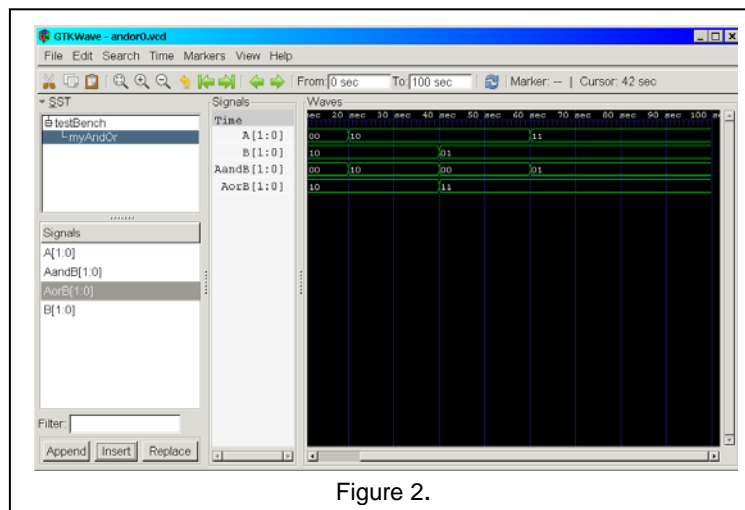


Figure 2.

Working with Quartus II and the DE1-SoC Board

We will now move to the DE1-SoC board and work with the Quartus II environment. As noted earlier, for those who are new to the DE1-SoC / Quartus II environment, Appendices B and C from the Brown and Vranesic 2nd edition text provide an excellent introduction to some of the material based upon the earlier DE1 system. These are posted on the class web page under documentation. There is also some very good introductory material from Altera on the class webpage under the documentation/DE1-SoC, Tutorials, and UserGuides subdirectory (Class Documentation hot button on the front of the class web page).

Looking at the Details

For this phase of the project, use the LEDs on the DE1-SoC board to display and verify the counter outputs and one of the switches to generate the reset input.

To develop a clock for each counter, start with the 50 MHz oscillator - ***Do not use one of the switches on the DE1-SoC board as the clock to your counters*** - and divide the signal down sufficiently that you will be able to see the counter outputs change.

The following Verilog code fragment illustrates one way to do this.

```
module MyModule(....., iClk, .....);
    input iClk;                                // connect to system 50 MHz clock
    reg [21:0] tBase;                          // system time base
    always@(posedge iClk) tBase <= tBase + 1'b1;
    .....
    always@ (posedge tBase[20])                // select a frequency
    .....
endmodule
```

Create a separate project using the Quartus II IDE for each of the first three counters you designed earlier. Add the counter module Verilog file to the respective projects, synthesize, then download each onto the DE1-SoC board. Verify the proper operation of each using the LEDs on the DE1-SoC board.

Create the fourth counter using a schematic entry project using the Quartus II IDE. Review the Appendices B and C from the Brown and Vranesic 2nd edition text on the class web page. Make the top-level module a Verilog module. Verify the proper operation of the design using the LEDs on the DE1-SoC board.

Next, design and verify a gate level model for each of the first three counters. These must be your original designs. You can use the D flip-flop model given earlier.

Finally, using the *RTL viewer* under the *Netlist Viewer* tool in Quartus, examine the physical implementation that a tool such as Quartus creates from a Verilog source file as part of the synthesis process and compare that with one produced by hand.

Compare and contrast the *structural*, *dataflow*, and *behavioural* level Quartus synthesized *gate level* implementations of the three counters with their *gate level* equivalents that you designed. Are there differences and if so, what are they and are they important? Why or why not?

Learning the Tools – The Signal Tap II Logic Analyzer:

In this portion of the lab we will work with a very handy tool for testing, debugging, and troubleshooting complex digital circuits and systems. This tool is called a *logic analyzer*. It gives us the ability to simultaneously examine the extended temporal behavior of a large number of signals. Such a task would be impossible using traditional tools such as an oscilloscope or voltmeter or would require some very fancy probe work.

In the Quartus II environment, the logic analyzer is available as a software tool that is included in the file downloaded onto the FPGA where it is connected directly to the circuit being tested. Typically, however, the device appears alongside our other stimulus and

measurement tools as a piece of hardware. None-the-less, we will still be able to control and make many of the same measurements that we would using the hardware instrument.

There is a very good introductory tutorial from Altera on the Signal Tap II on the class webpage under the *documentation/Tutorials* subdirectory (Class Documentation hot button on the front of the class web page).

1. In the Quartus II IDE, setup and configure the Signal Tap II logic analyzer to display the inputs and outputs of each of the four counters you designed in part 1 as they are running on the DE1-SoC board. Configure the Signal Tap II to trigger on the trailing (rising) edge of the input reset signal.
2. Configure the Signal Tap II to trigger on and capture and display data following the third state in each of your counters.
3. How do the displayed signal outputs compare with the ideal signals?

Failure Modes Analysis – What Could Possibly Go Wrong?

As an engineer, designing something, building it, and getting it to work properly and reliably is an exciting part of the job. Getting that first LED to turn on is often a major milestone and accomplishment in the process and almost worth getting a beer to celebrate. However, getting the design to work is not the end of the job.

Examining our design and asking how, where, and when it might fail is equally, if not more, important. In this part of the project, we want to take a first look at potential failure modes and failure analysis. Such a practice, known as Failure Modes and Effects Analysis (FMEA) is commonly used in many industries where product safety and reliability are critical.

As our first step, we will take a very high-level view. For this initial step, we will limit our investigation to the various signals in our system and to three kinds of failure modes: *SA0*, *SA1*, and *Bridge*. These are a signal *Stuck At 0* or *Stuck At 1* or two signals incorrectly/unintentionally connected together called a *bridge*.

We look at each input, output, and internal signal in the system and ask: What are the effects if any of the three failure modes occurs on or to that signal and what are the consequences and severity of such a failure on the operation of the system? In a more complete analysis, we determine the probability of each fault occurring as we assess the risk if such a fault should occur.

A typical set of ground rules for conducting such an analysis are:

1. Only one failure mode exists at a time.
2. All inputs (including software commands) to the system or subsystem being analyzed are present and at nominal values.
3. Sufficient power is available to the system.

As our first exercise in conducting such an analysis,

1. Each team member must select and analyze one of the gate level implementations of the first three counters subject to the stated ground rules. Each person must select a different counter.
2. For the selected counter, examine each input, output, and internal signal and analyze the effects on the counter of a SA0 or SA1 fault on that signal and on the operation of that counter. We will defer bridge faults until later.
3. Include your analysis in your final report.

Learning the C Language – The First Steps:

We will conclude this project by beginning to learn the first steps of the formal engineering design process and about working with the C language and the CodeBlocks development environment on a PC. This is an open source too and can be downloaded and installed on your own PC.

<http://www.codeblocks.org/>

We will first work with the development environment. To do so, we will start with a known good C program. Then, we will work through the first steps of the development cycle with a program that we write.

Working with C in the PC Environment

Building a Program

1. Using CodeBlocks on your PC, create a project then add the C file project0.c. You can find project0.c in the Lab1 folder on the class web page.

Select

- File →New Project

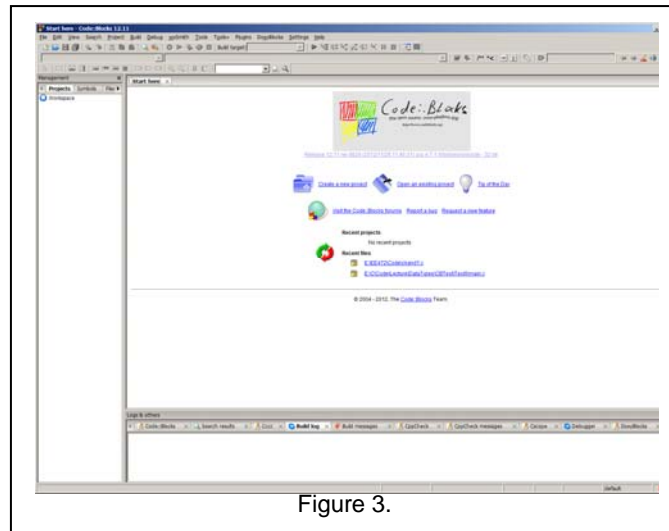


Figure 3.

2. In the pop-up window select:

- Next

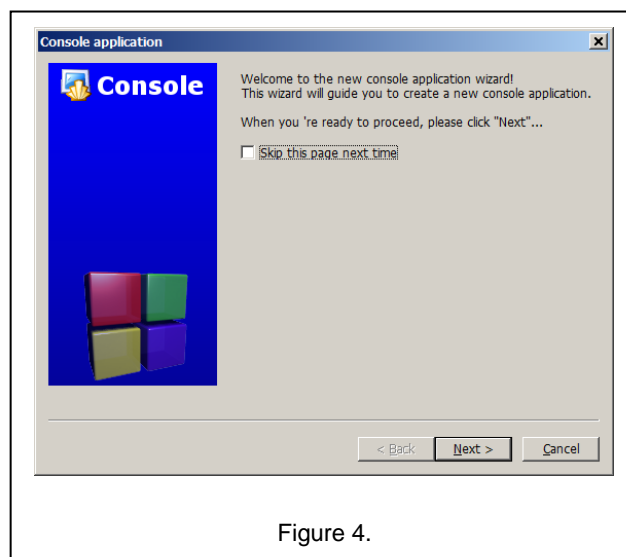
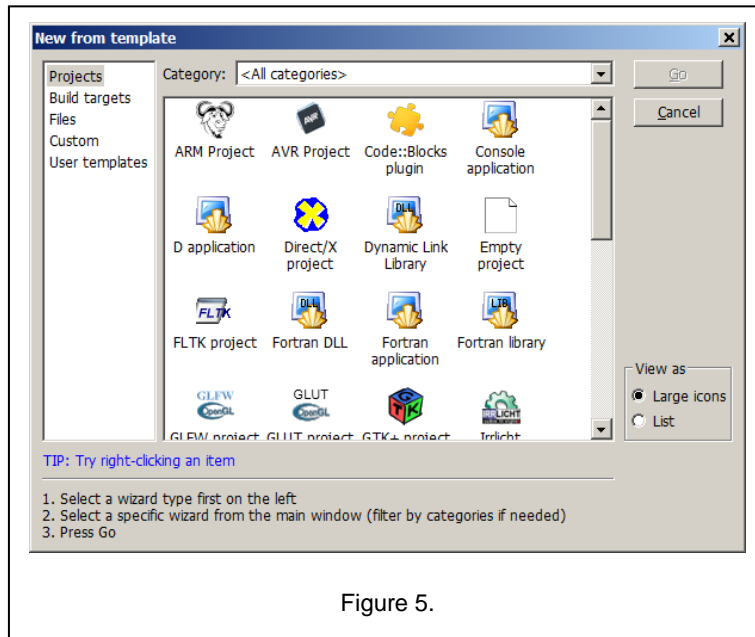
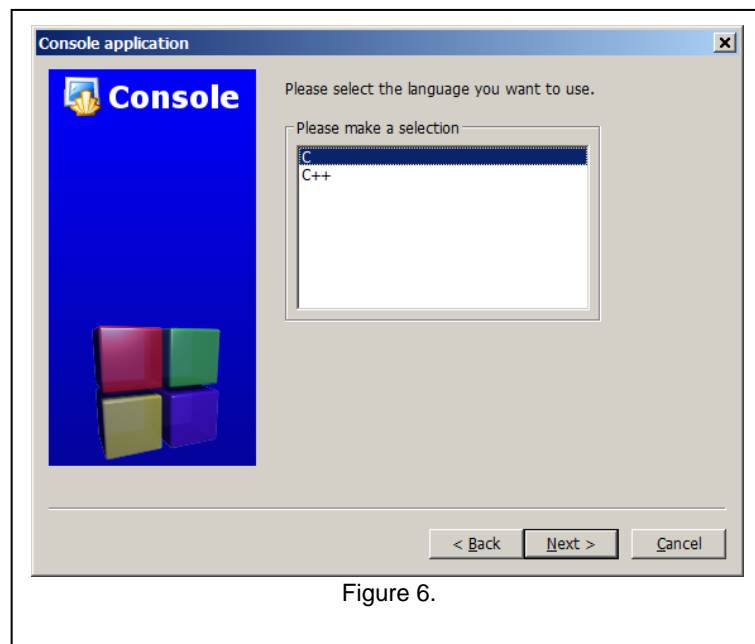


Figure 4.

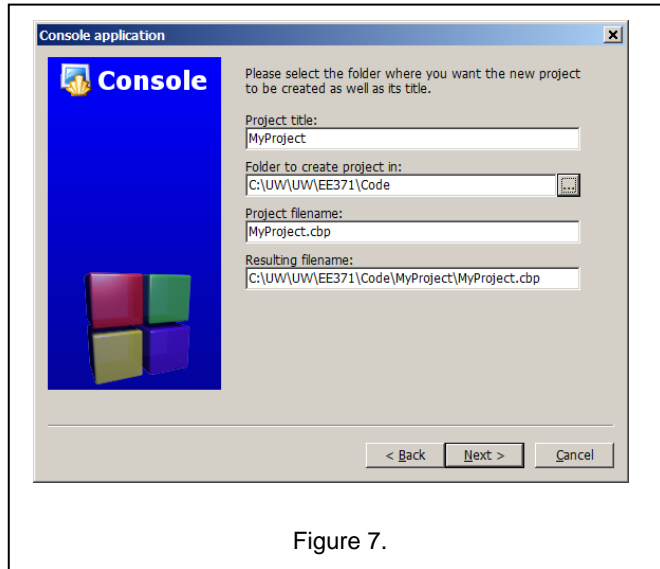
3. In the pop-up window select:
- Console Application



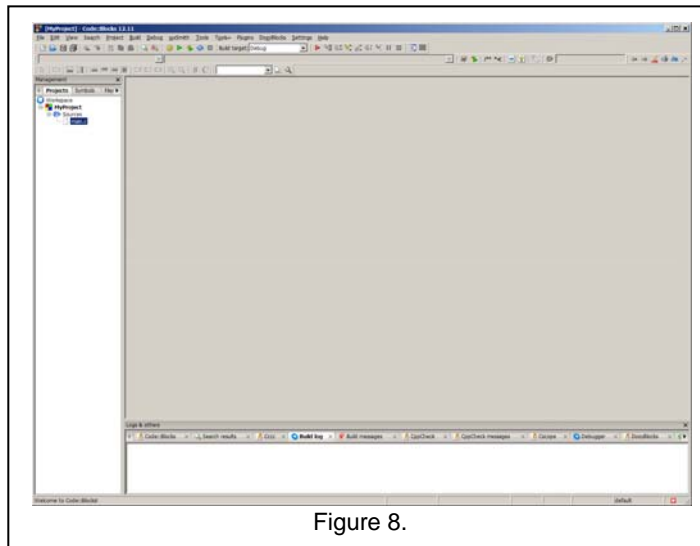
4. In the pop-up window select:
- C then Next



5. In the pop-up window
 - Give the project a Title, Location, and Name
 - Select Next then Finish



6. In the in the left hand pane of the workspace window that pops up
 - Select main.cUsing the right mouse button, select
 - Remove this file from project



7. Using the right mouse button, select MyProject
 - Select Add Files

8. In the window that pops up, browse to where you have saved project0.c.
 - Select the file and select Open to add it to the project.
9. In the window that pops up,
 - Select OK

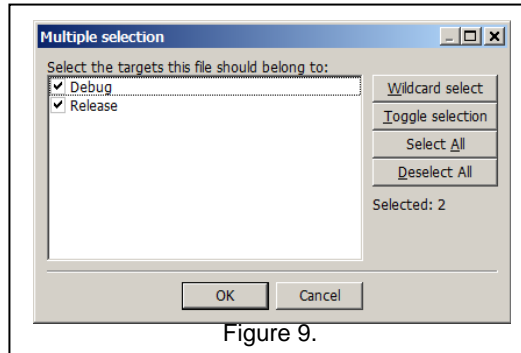


Figure 9.

10. If you double click the file project0.c, you should now have something like...

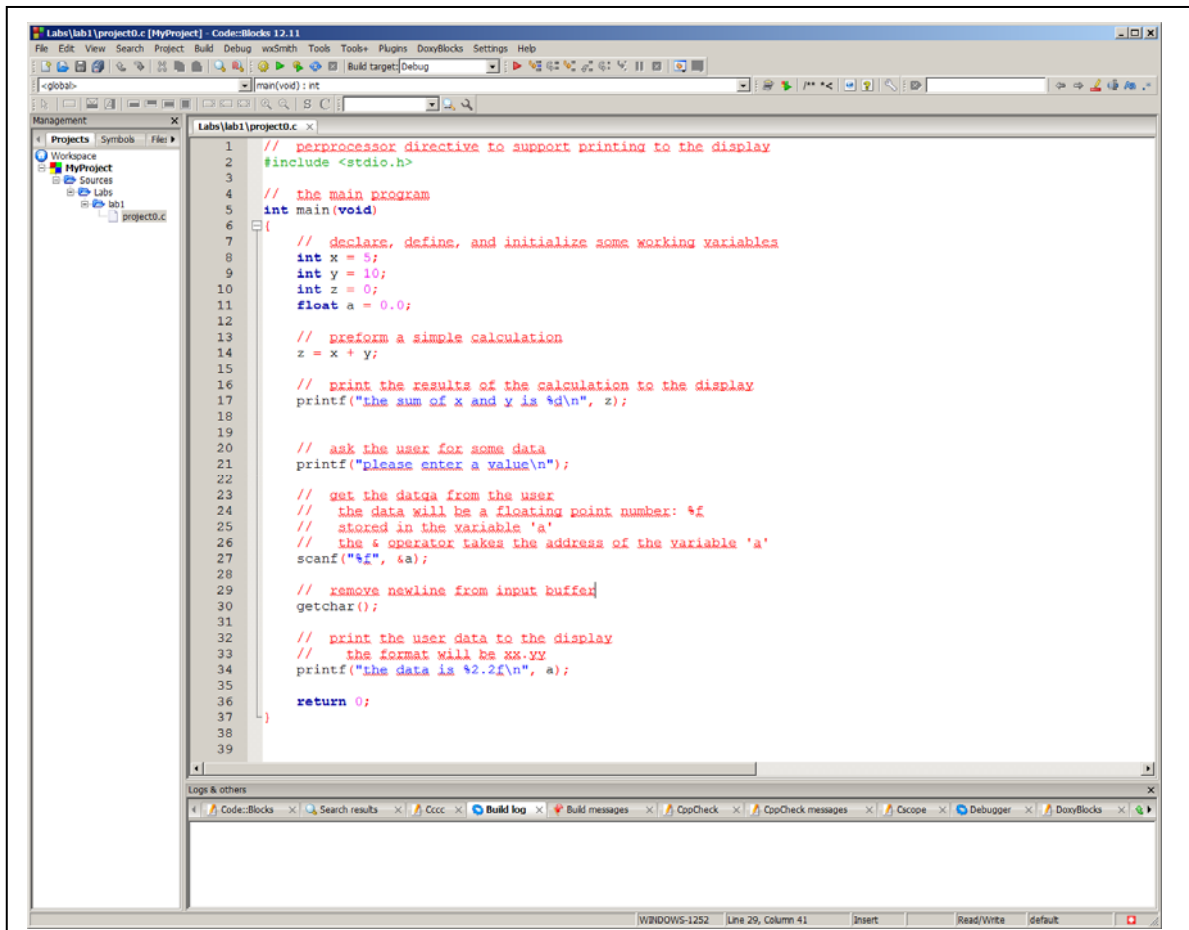


Figure 9.

11. Now compile and execute the program.

- Select Build → Build or press Ctrl-F9

There should be no errors – if there are, then bad copying.

To run the program, press Ctrl F10

The program should print the first two lines and halt waiting for input from the user.
The results printed for the value of z may be different for you project.

Here the number 23.4 is entered and the remaining lines are then printed.

```
the sum of x and y is 15
please enter a value
23.4
the data is 23.40
Press any key to continue
```

Creating Your Own Design

Today we have an increasingly global economy coupled with lower airfares (a bit hard to tell, though today). To aid in supporting that economy and overcome the mess we've created, we need to travel and buy cool stuff.

As our first C program, we will design a simple currency calculator so that we can buy stuff faster.

Some of the things that we'd like to be able to do with our calculator include: specifying the exchange rate, converting an amount in dollars into the foreign currency, and converting an amount of the foreign currency into dollars. Being able to buy a beer in the local currency is always important.

As we go through the development cycle, we produce the following

1. A short requirements document for the calculator. The document should have the following sections:
 - ✓ Abstract
 - ✓ Introduction
 - ✓ Inputs to the calculator
 - ✓ Outputs from the calculator
 - ✓ Major Functions

The each input and output should have a brief textual description of what it is and its purpose.

Each major function should have a brief textual description of what it is and its behavior.

2. A design specification for the calculator. The document should have the following sections:
 - ✓ Abstract
 - ✓ Introduction

- ✓ Inputs to the calculator
- ✓ Outputs from the calculator
- ✓ Major Functions

Each input and output should now also include as part of its description the range of legal values and a brief textual description of what possible errors might occur and their consequences.

3. A C program that implements all of the features and capabilities specified in your design specification for your currency calculator.

Deliverables:

A lab demo showing...

1. The four working counters each of which meets the specified requirements.
2. Signal Tap II waveforms of the outputs of each of your four counters, triggered as specified.
3. A working C calculator program that meets the specified requirements.

A lab report that complies with the *Lab Format* specification given on the *Workload and Grading* page of the class web page. Ensure that your report contains:

1. The annotated Verilog and C source code for all applications both on the DE1-SoC board and on the PC.
2. Representative screen shots showing the results of testing the various counter designs.
3. Representative screen shots showing the logic analyzer outputs for the various counter designs.
4. Your three failure modes analyses.
5. Your requirements document and design specification for your currency calculator.
6. Representative screen shots showing the results of testing your calculator.
7. Answers to any questions above.
8. Other things that you deem to be important.
9. Anything that we haven't thought of.
10. Signature page, signed and stating that the report and its contents are solely your team's work and cites outside references for work that is not your own.