

# Laboratory Exercise 7

Memory and VGA Display  
November 4, 2019

## Learning Objectives

The purpose of this exercise is to learn how to create and use on-chip block random access memories (BRAMS) as well as use the video graphics adapter (VGA).

## Preparation Before the Lab

You are required to complete Parts I to III of the lab by writing and testing Verilog code and compiling it with Quartus. Show your schematic, Verilog, and simulations for Parts I to III and state diagrams for Parts II and III to the teaching assistants. You must simulate your circuit with ModelSim using reasonable test vectors you can justify.

## In-lab Work

You are required to implement and test all of Parts I to III of the lab. You need to demonstrate all parts to the teaching assistants.

## Part I

In addition to lookup tables (LUTs) and flip flops, the FPGA provides flexible embedded memory blocks that can be configured into various bit widths and depths along with many other parameters. To access these blocks you will use another feature of Quartus that can build modules of various functions. In this part of the lab exercise you will create a small RAM block and interact with it to understand how it works. Using the Quartus IP catalog you will first create a module for the desired memory and then test the memory module using the switches and HEX displays for inputs and outputs.

The memory module we would like to create is shown in Figure 1. It consists of a memory block, address register, data register and a control register. You can see that the address and input data are stored in a register as well as the Write Enable control signal. Using the registers means that the *DataOut* value will be stable for one clock cycle and allows the inputs to be changed after the rising clock edge in preparation for the next clock cycle. It is a small memory so that we can easily interact with it using the available switches and displays on the the DE1-SoC board.

A timing diagram showing reading of the memory is shown in Figure 2. Four locations at addresses *A0*, *A1*, *A2* and *A3* are accessed and the corresponding data *D0*, *D1*, *D2* and *D3* are read from those addresses, respectively. Figure 3 shows the timing for writing data to the memory. Observe that *WriteEn* is only high for addresses *A1* and *A2*. This means that only data words *D1* and *D2* are written, respectively.

Perform the following steps. Steps 1 through 13 are to be done for the prelab.

1. Open Quartus.
2. You will now create a memory module that you can include into your design. First, select Tools->IP Catalog
3. Open Installed IP->Library->Basic Functions->On Chip Memory->RAM:1-PORT

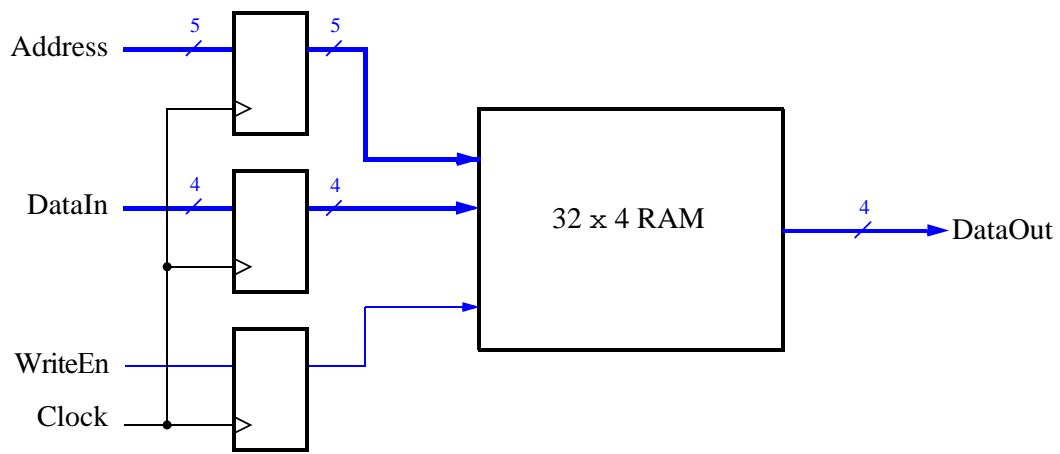


Figure 1: Schematic of the  $32 \times 4$  embedded memory module.

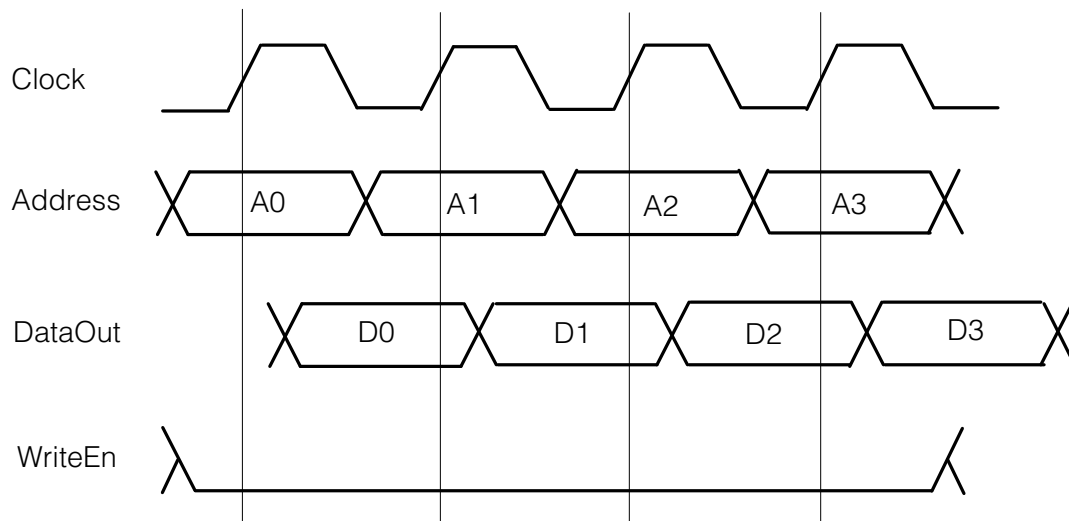


Figure 2: Timing diagram for read operations.

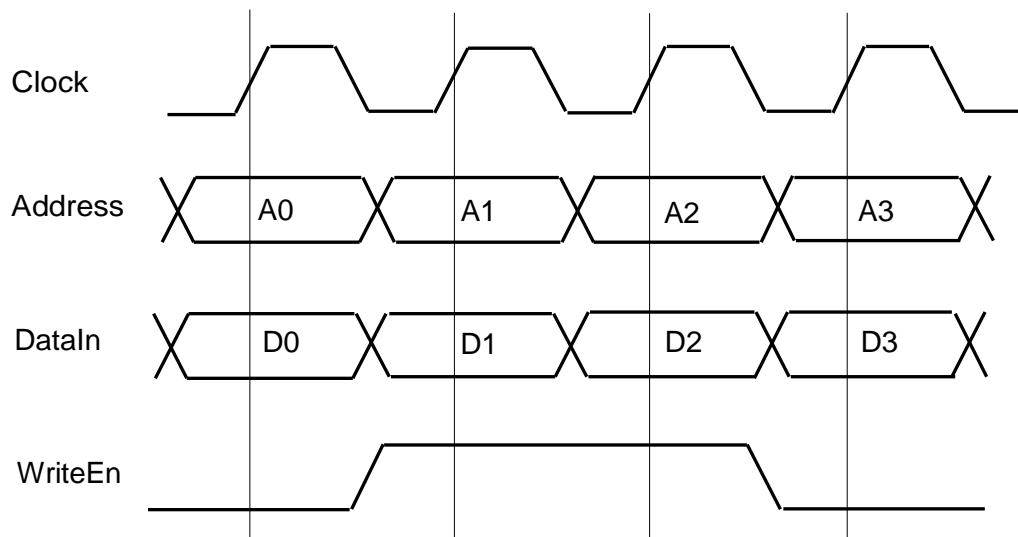


Figure 3: Timing diagram for write operations. Note that only addresses A1 and A2 are written.

4. Browse to the folder or directory where you want to build your project. This is where the file for the memory module will be created. Call the file *ram32x4.v*. Choose the IP variation to be Verilog and click OK.
5. Select a 4-bit wide (width of 'q' output bus) memory with 32 words. Leave the memory block type as *Auto* and use a *Single Clock*. Click Next.
6. **Unselect q as a registered port.**
7. Click Finish and Finish again to generate the new Verilog file, *ram32x4.v*.
8. Examine the newly created Verilog file. Observe that it declares a module with the required ports as shown in Figure 1. You can now instantiate the module into any design.
9. Instantiate the *ram32x4* module into a top-level Verilog module that connects to the inputs and outputs in the following way: Connect **SW[3:0]** to the data inputs, **SW[8:4]** to the address inputs, **SW[9]** to the Write Enable input and use **KEY[0]** as the clock input. Show the address on HEX5 and HEX4, the input data on HEX2 and the data output of the memory on HEX0.
10. Create a new Quartus project and add your top-level module file and *ram32x4.v*.
11. Draw a schematic describing the circuit and explain it to the TA as part of your preparation.
12. Simulate your circuit with ModelSim for a variety of input settings, ensuring the output waveforms are correct. Show that you can read and write to the memory at several locations. You must show this to the TA as part of your preparation.
13. Compile the project.
14. Download the compiled circuit into the FPGA chip. Test the functionality of the circuit.

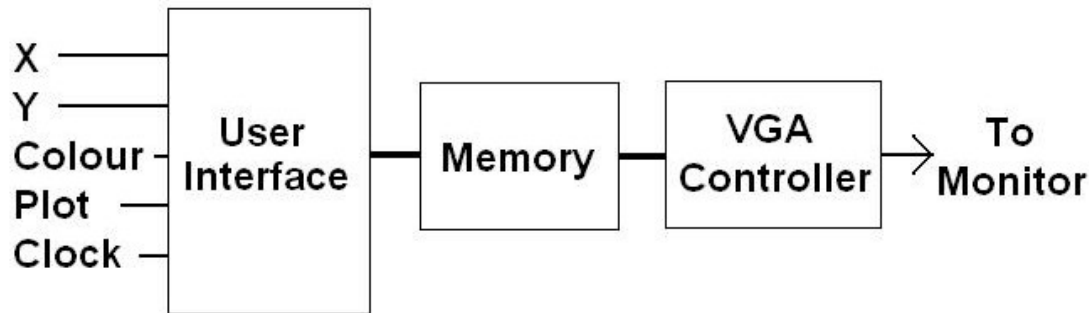


Figure 4: VGA adapter module schematic. Resetn is not shown.

## Part II

For this part you will learn how to display simple images on the VGA display. Your task is to design a circuit to draw a *filled* square on the screen at any location in any colour. You are provided with a VGA adapter module that provides the functionality of accepting a coordinate, known as a pixel, on the screen and a colour to draw at that pixel. The VGA adapter that you will use is shown in Figure 4. The inputs to the adapter module are similar to the memory interface in Part I. The (X,Y) inputs specify a pixel location on the screen while *Colour* specifies the pixel colour. Note that (X,Y) = (0,0) is the top left corner of the screen. The *Plot* input is a write enable signal that tells the controller to update the pixel specified by (X,Y) with the value *Colour* at the next clock edge. The outputs of the adapter drive the off-chip video digital-to-analogue converters (DACs) that subsequently drive the monitor.

### If you want to learn more about VGA and the VGA adapter

You are given enough information in this lab sheet to use the VGA adapter module, but if you are curious to learn more about the details you can get more information at [http://www.eecg.toronto.edu/~jayar/ece241\\_08F/vga/](http://www.eecg.toronto.edu/~jayar/ece241_08F/vga/). For example, in your projects, you may want to change the resolution and colour quality, in which case you should look at “Changing Adapter Parameters”. If you stick to using the names of the ports used at that site, you will get the correct pin mapping through the `DE1_SoC.qsf` file that you have been provided, except for two port names that changed as described in the next paragraph.

A word of caution if you want to try the example code at that web site. You will see mention of the DE1 and DE2 boards. You are using the DE1-SoC, so the examples may not work directly. In particular, watch for the names of two signals in the old examples. The signals were changed from `VGA_BLANK` and `VGA_SYNC` to `VGA_BLANK_N` and `VGA_SYNC_N`, respectively, for the DE1-SoC so you will have to change any of the example code accordingly. The files you are provided for this lab are for the DE1-SoC and will not need the above modification.

### Constraints and Colour Coding

To make things a bit easier, you will work with a screen that is 160 pixels wide by 120 pixels high. Compare this with standard VGA, which is  $640 \times 480$  pixels and your HD TV at  $1920 \times 1080$  pixels. We are also using only three bits for the colour of a pixel. The three bits correspond to red, green, and blue, which is called an *RGB* colour coding. There is one bit for each colour so if you want to draw red, then input (1,0,0) as the colour bits. You can combine colours as well, such as (0,1,1). A very fancy display may have 24 bits per colour. An important consideration is the amount of memory required to store the pixels. The reason why we are using a very small screen with only three bits per pixel is so that we only need a small memory. In Figure 4 you will see the memory block, which is called the *frame buffer*. Through the user interface, a user can update the contents of the frame buffer. The *VGA Controller* in Figure 4 continuously reads the frame buffer and displays the image in the frame

buffer by driving the signals that are sent to the monitor.

### Your Circuit

Your circuit will accept an X and Y location as input, as well as a colour. The circuit should then draw a  $4 \times 4$  pixel square whose *upper-left* corner is at the (X,Y) location specified by the input. The square should be filled with the colour specified by the switches. The filled square should be drawn when KEY[1] (*Plot*) is pressed. KEY[2] should cause the entire screen to be cleared to black (*Black*). Note that black corresponds to (0,0,0). KEY[0] should be the system active low *Reset*. It is used to reset the FSM and registers (it does not clear the screen). SW[9:7] should be used for the colour. SW[6:0] should be used to input (X,Y). Notice that although the VGA adapter has  $160 \times 120$  pixels, we don't have enough switches to be able to specify the coordinates separately and to the full range of X. For X we need eight bits and for Y we need seven bits. We are short one switch for eight bits, so we will just use seven switches and only be able to access the first 128 columns of the display. To set a value for X, first set SW[6:0] and press KEY[3] to load a register with the X value. This load should also set the most significant bit of X to 0, i.e., the eighth bit. Then set the Y value on SW[6:0] before pressing KEY[1] to draw the square.

After a square has been drawn, your circuit should allow additional squares to continue to be drawn (say, at different locations in possibly different colours). The high-level design of the circuit for the system is given in Figure 5. It contains three major blocks:

- (a) The VGA adapter responsible for the drawing of pixels on the screen.
- (b) The datapath that contains arithmetic circuitry and registers, controlled by the FSM, that compute the (X,Y) values that are fed into the VGA Adapter to draw the  $4 \times 4$  filled square.
- (c) A finite state machine that serves as a controller for the datapath. Some output control lines are shown in Figure 5 as examples. You may put in whatever you require.

### How to think about this design

An important part of doing design is to first think through the steps you can take to get to the final design. As you start to deal with greater and greater complexity, you must realize that you cannot build everything at once and then hope that it will all work the first time you try to test it. You should take incremental steps, but first read through the next section, "The Required Steps" to see what you are being asked to deliver as the final product and for some pointers to some important information.

To make the design of this Part II more incremental, what can you start with that demonstrates some basic functionality and helps you understand how the VGA adapter works? The ultimate goal is to draw a  $4 \times 4$  filled square. How do you do that? You have to draw one pixel, move to the next pixel, draw it, etc. Your FSM will need to be changing the pixel address to reach the appropriate pixels and writing the colour value at each pixel. However, what can you do first that is simpler, but achieves important functionality?

1. Try just drawing one pixel on the screen. This will use a much simpler FSM, so it will be easier to get working. Note that one pixel will be quite small, so you may need to look very carefully to find it if you are testing on the board. In simulation, you just want to see that the correct inputs make it to the VGA adapter. Make the first pixel red. This requires you to load the X register, set Y, and the colour on the switches. Then hit KEY[1] to plot the pixel. Change the colour to green, hit KEY[1], then blue, hit KEY[1] and see if the pixel colour changes accordingly. This will test that you can input X and Y correctly and input the correct colour. If you can do this, then you know that you are reading the switches and using the VGA adapter correctly.

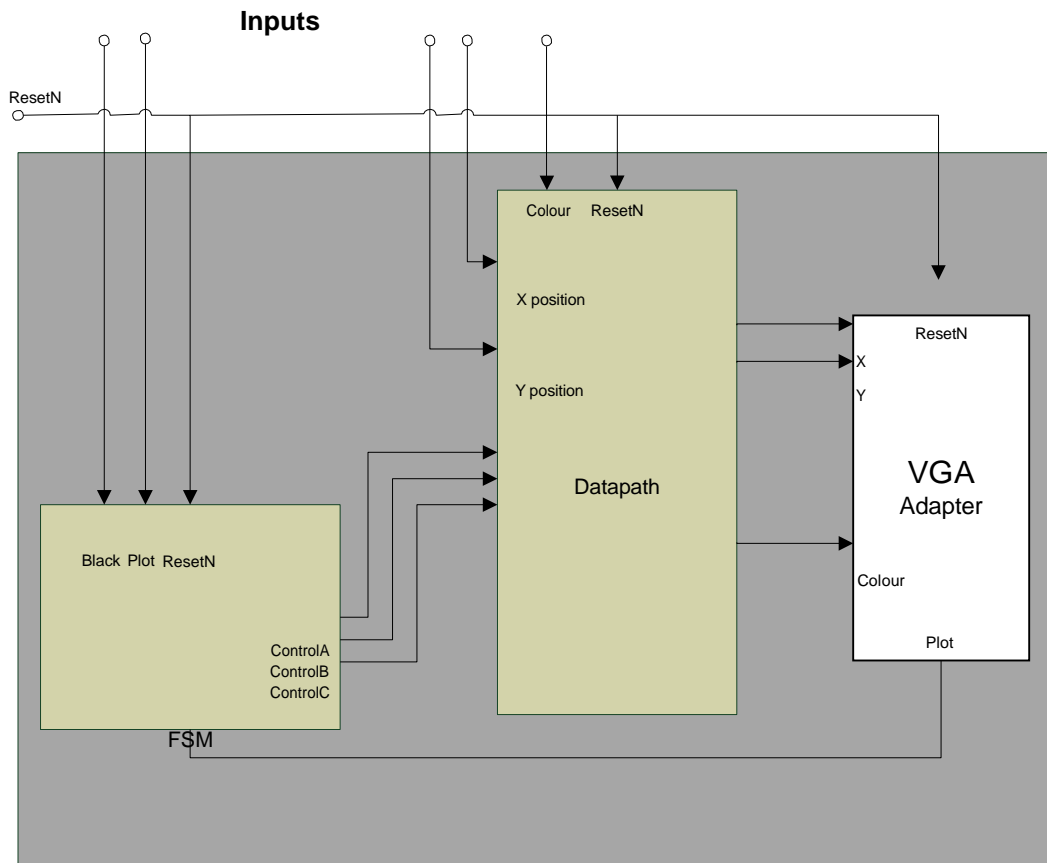


Figure 5: Design Overview - State Machine, Datapath and VGA Adapter. Although not shown, the ResetN signal should be connected to all the registers in the circuit (including the FSM state registers).

2. Now, you can try plotting the  $4 \times 4$  square knowing that you already have the ability to draw one pixel. If you have problems with this step, then the problem is most likely in the new code that you have added, so you can focus your debugging on that code.
3. You also need to clear the screen, i.e., make the screen all black. Do this next. It will require a slightly different function that writes (0,0,0) into all pixels.
4. At this point, you will have achieved all the functionality required for this part.

### The Required Steps

Perform the following steps. Steps 1 through 4 are to be done for the prelab. It is strongly recommended that you go through the incremental steps outlined in the previous section to arrive at the final design that you will present as your prelab work here.

1. Design (draw the schematic and write verilog) and simulate a datapath that implements the required functionality.
2. Design (draw a state diagram and write verilog) and simulate an FSM that controls the implemented datapath.
3. Since the VGA adapter connects to an external circuit, it is not so easy to simulate your entire top-level design. We will try and skip the step of combining the controller and datapath for simulation, which you really should do and you may still need to do this if things do not work. You should at least verify the outputs from the datapath (inputs to the VGA adapter) are correct.
4. Build your top-level design. You will find some skeleton code that incorporates the VGA adapter in the file `lab7-part2.zip`. If you examine the code carefully, you will note that it refers to a file called `black.mif`. This initializes the frame buffer when the FPGA is first configured. In this case, it creates an all-black image. The BMP2MIF handout in Resources will explain how to use this file for arbitrary images.
5. Compile and implement the design on the FPGA using Quartus.

## Part III

In this next part we will create a simple animation of the box from Part II by having it bounce around the screen. The colour of the box ( $4 \times 4$  pixels) will be selected by the switches but now the (X,Y) location of the box will be controlled by your circuit and will change over time. Since your circuit is providing the X value, you now can also generate all 8 bits so that you can access the full screen in this part. To accomplish the animation, your circuit will have to make it seem as though the box is seamlessly moving around the screen. It will do this by erasing and redrawing the box each time it is to be moved. We would like the box to always move in a diagonal fashion at five pixels per second. The VGA adapter updates the monitor at 60Hz or 60 frames-per-second, meaning that the entire contents of the frame buffer are output to the monitor every 1/60th of a second. Your circuit should only erase and redraw the box no faster than this rate.

You should use a counter to track how much time has passed. The counter should count for 1/60th of a second. You should also use a second counter to track how many frames have elapsed. If we want the box to move at five pixels per second, the box should only move one pixel every 12 frames.

You will implement the circuit in two steps. First, you will design the datapath for a module that is able to draw (or erase) the image at a given location. The datapath of this circuit will basically be the circuit used for Part II. In addition, you will need two counters that will contain the current (X,Y) location of the box as well as two single-bit direction registers (horizontal and vertical) that will track the direction the box is moving. The (X,Y) counters will be able to count up or count down since the box can be moving in any direction on the screen. The two single-bit

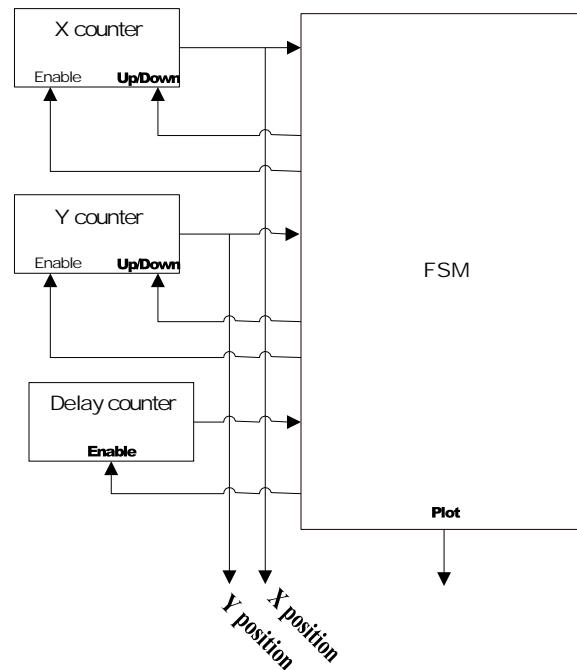


Figure 6: Rough schematic for your animated image circuit. There may be signals and pieces missing.

direction registers will track the current diagonal direction of the box (up-left, up-right, down-left, down-right). To implement the *bounce* off the edges of the screen, the current location of the box and direction of travel should be used to update the direction registers. For example, if the box is moving in the down-right direction and the next position of the box would move it off the bottom of the screen, the vertical direction bit would be flipped indicating the box should start moving in an up-right direction. Likewise, if the box was moving in the down-right direction and the next position of the box was further than the right edge of the screen, the horizontal direction bit would be flipped indicating the box should start moving in a down-left direction.

A rough schematic of your circuit is shown in Figure 6. It is not complete and most likely lacks some pieces and some signals. Consider it only as a starting point.

Use the same switches as you used in Part II, as needed. Remember that X and Y are no longer input from the switches.

A rough outline of the algorithm is as follows:

1. Reset the 1/60th second Delay Counter and the Frame Counter. Reset Counter *X* and Counter *Y* to correspond to the *upper-left* corner of the screen. Reset the direction registers to indicate down-right. By doing this, the box always starts moving from the upper-left corner of the screen and moves in a down-right direction. You can choose how you encode the directions in terms of what a 1 means in the direction register.
2. Use the Part II datapath to draw the box in the current location.
3. Reset the 1/60th second Delay Counter and the Frame Counter. Then count 12 frames.
4. Use your Part II datapath to erase the current box.
5. Update Counter *X*, Counter *Y* based on the direction registers. Update the direction registers themselves (if necessary).
6. Go to Step 2.

Implement the circuit by completing the following steps. Steps 1 through 4 are to be done for the prelab.



1. Design (draw the schematic and write verilog) and simulate a datapath that implements the required functionality.
2. Design (draw state diagram and write verilog) and simulate an FSM that controls the implemented datapath.
3. Again, since the VGA adapter connects to an external circuit, it is not so easy to simulate your entire top-level design. We will try and skip the step of combining the controller and datapath for simulation, which you really should do and you may still need to do this if things do not work. You should at least verify the outputs from the datapath (inputs to the VGA adapter) are correct.
4. Build your top-level design.
5. Compile and implement the design on the FPGA using Quartus.

## A Note About Simulating with the VGA Adapter

If you include the VGA adapter, and later some of the other IP blocks (functional blocks of Verilog) you may use in your projects, such as the keyboard controller, you will need to include some Altera simulation libraries (ex., `lpm_ver`, `altera_mf_ver`).

The following shows how to add a library in your Modelsim scripts:

```
vsim -L altera_mf_ver <module-name>
```

If you need to add several libraries, then you will need additional `-L library name` flags.