3D RENDERING IN FPGA

CSEE 4840
Embedded System Design
Spring 2014

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Introduction

Our initial plan was to implement a Mario party game- The Ultimate Ball Balancer. The game involved the concept of a 3D plate on screen, with a ball on it. The user could use the controller to balance the ball on the plate. Through the course of the project, our focus shifted. We realized the difficulty of 3D Rendering, especially using Z-buffering and Rasterization mechanisms. We then decided to focus on this concept, and get it working.

The project aims to provide 3D Rendering of any object in the FPGA. Using the PS3 Controller, it is possible for the user to rotate the 3D object. For this, we have written a bunch of software and hardware modules. The project takes care of user inputs via a PS3 Controller. The final result seen by the user is the movement of a 3D plate based on the direction of the controller input. Given below, is the design flow for the 3D Rendering project.

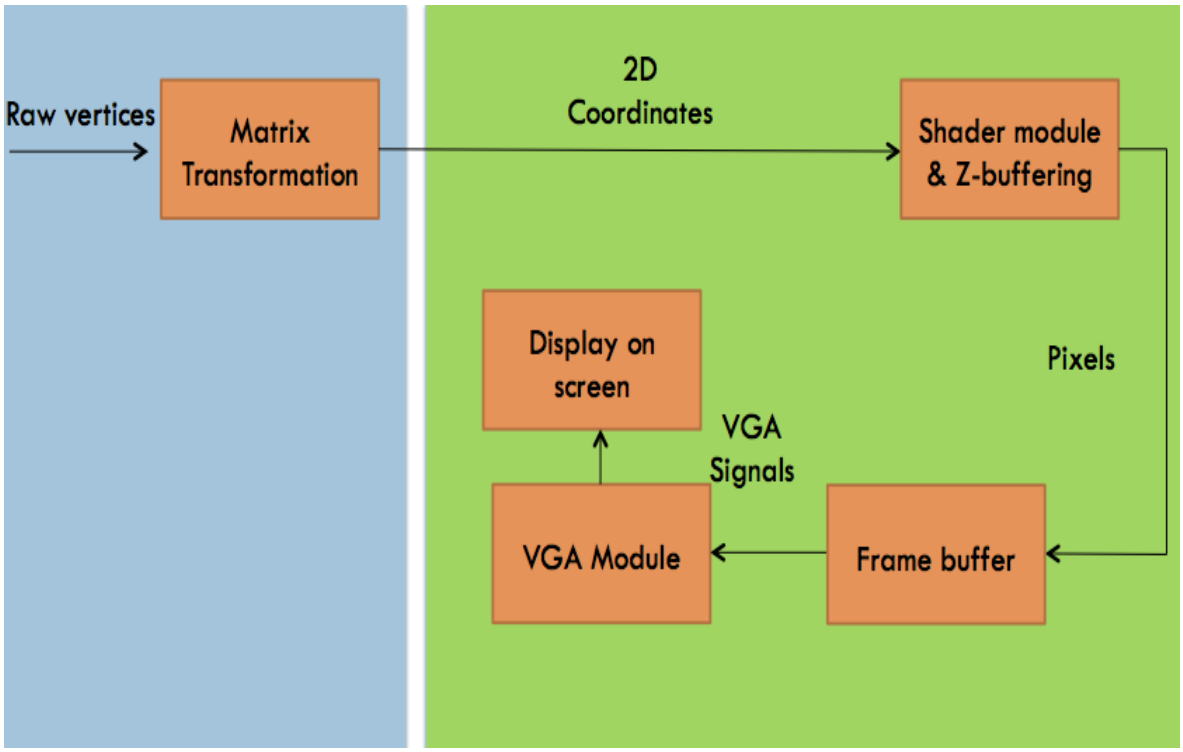


Figure 1: Design flow of 3D Rendering

System Overview

The high-level system overview is shown in Figure 2. The system takes input from the PS3 controller, and the output of the entire system, is the 3D object rotating on screen. The controller inputs are between 0 and 255. The display is implemented for a screen with pixel dimensions of 640x480. The hardware shader module involves a series of fixed-point arithmetic. We got a precision of 16 bits for the result at each step.

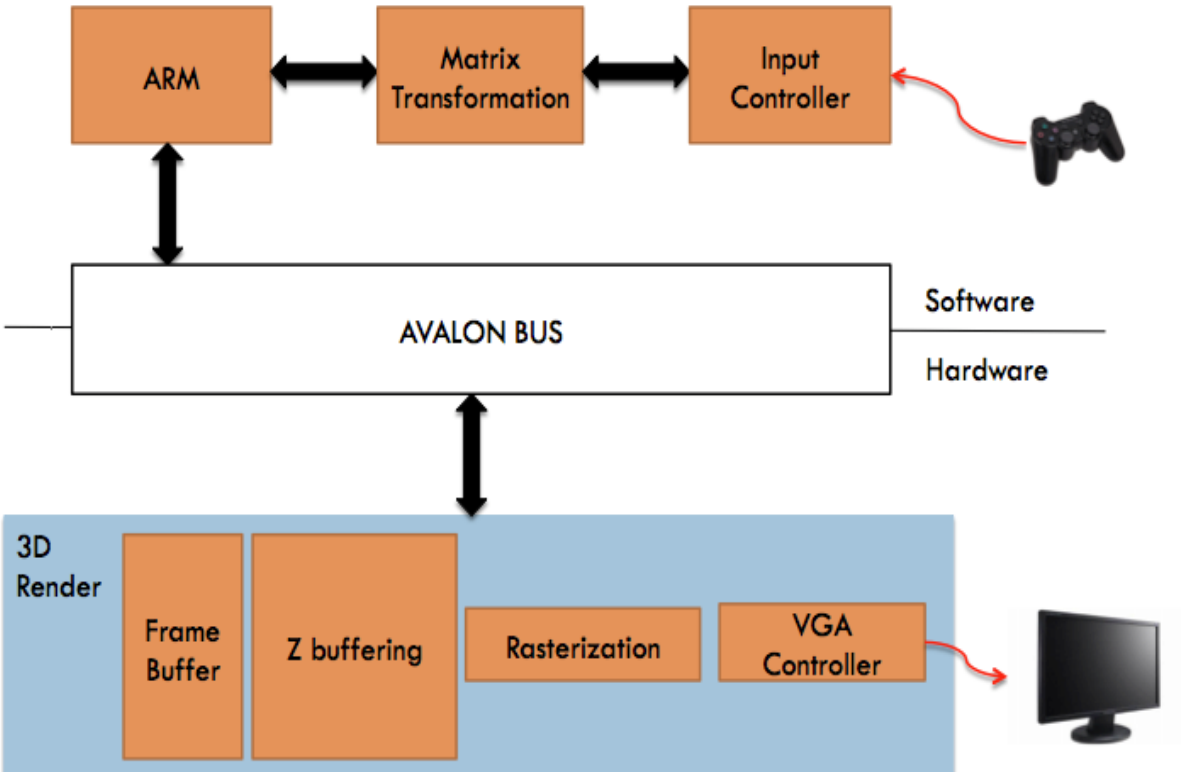


Figure 2: System Overview

Software Overview

The software components handle the controller input, its translation into the angle of rotation, which is fed as an input to the Matrix pipeline block. A device driver is written to carry out the software interfacing with hardware.

The software part typically consists of the following components:

- Software prototype
  - We completed the whole project on software before starting on Hardware. This was to ensure we got the mathematics of the transformations correct. Blender is used to draw the 3D model of our choice on software. It generates the vertices of all the triangles that make up the model
- PS3 Controller
  - Interface the controller, and mapping of the input from the controller to appropriate angle of rotation that is fed into the Matrix Transformation module
- Matrix Transformation/Pipeline
  - The mathematical calculation of the model that takes angles as inputs, and transforms them into 2D coordinates
- Software interfacing
  - Software driver to communicate with the hardware

Hardware Overview

The hardware component handles the crux of our project, which is the Shader and Rasterization module. To make the object seamless while rotating, Z-buffering was implemented. A frame buffer was used to store the 640x480 pixel values on screen, and interface with the VGA module.

- 3D Rendering of the model
  - Shader module - Takes the transformed 2D coordinates, and communicated with the VGA module to print the object on screen
  - Z-buffering - Fine tuning the object seen on screen, by considering the Z-axis, and how it affects an object when it rotates
- VGA Module – This block takes pixels as inputs. It performs Rasterization (not the conventional way; explained in detail in the 3D Render module) and displays the object on screen.

3D RENDER

Shader Module

Overview
The purpose of the shader module is to rasterize each triangle of the 3D object being rendered. The multiplication pipeline outputs three vertices representing the points of a triangle that have been projected onto a 2D screen. It determines which pixels reside within that triangle and calculates the depth of each pixel to compare against the depth of the old pixel at the same location. If the new pixel has less "depth" than the existing pixel it will be output to the screen. This preserves the "depth" effect of 3D objects when rendered onto a 2D screen. Multiple triangles are then output to display the object that is being modeled.

This section describes the algorithm used to implement the shader as well as the architecture of how it was implemented in the FPGA.

Algorithm

Overview
The algorithm we used was borrowed from the tutorial in reference [1] and uses a simple method of linear interpolation to rasterize a triangle. The basic idea is illustrated as follows.

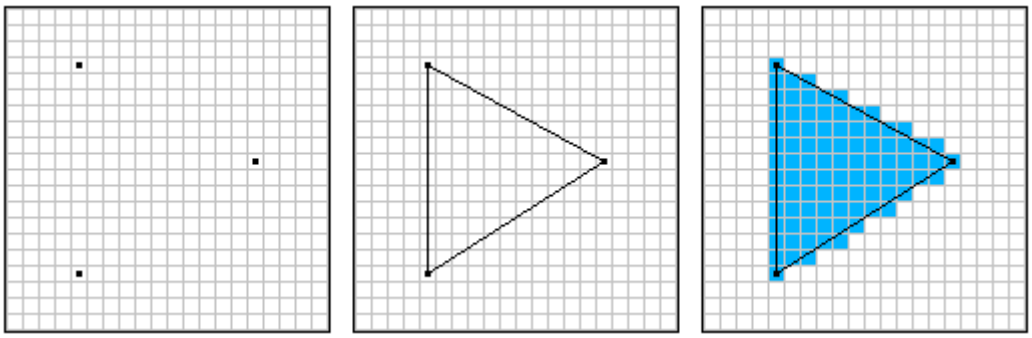


Figure 3: Image Ref: http://joshbeam.com/articles/triangle_rasterization/

Given three points of a triangle, the purpose of this algorithm is to determine the outline of the triangle as well as fill in the pixels horizontally from left-to-right until the entire triangle is shaded in. The depth of each pixel needs to be calculated and compared against an old pixel in that same location to determine whether the pixel needs to be drawn or not.

Sorting

The algorithm starts with 3 vertices P1, P2 and P3, each with (x, y, z) coordinates. The vertices need to be sorted with respect to their y coordinate so that you have either of the two triangle configurations shown below:

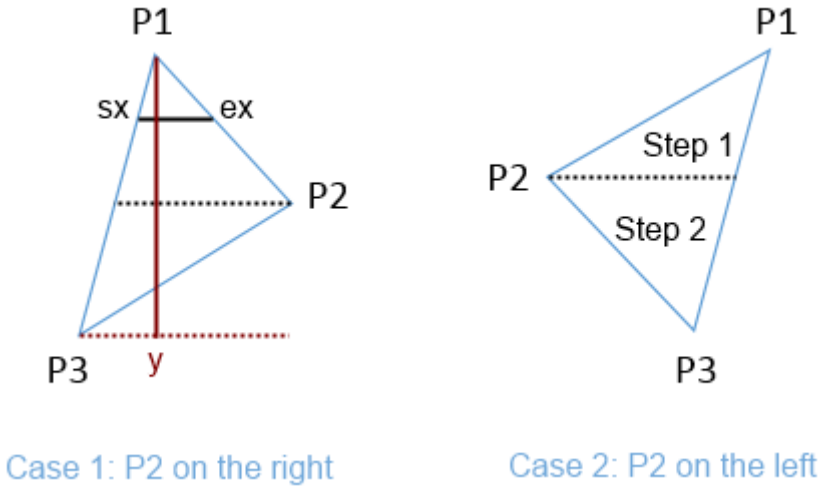


Figure 4: Triangles for rasterization, draw line

Note the difference in location in P2 between Case 1 and Case 2. The reason why this is important is because lines are drawn horizontally from left to right so it's important to know whether P2 resides to the left or right of the triangle.

To determine which case is being rasterized, the inverse slopes dP1P3 and dP1P2 are calculated and compared. If dP1P2 > dP1P3 then the triangle is in case 1 with P2 on the right. Alternatively, if dP1P2 < dP1P3, the triangle is in case 2 with P2 on the left.

Note that rasterizing the triangles is a two-step process where the triangle is divided into two as shown in case 2 above. Step1 in the figure is rasterized first followed by Step 2.

Gradients and Interpolation

Case 1, with P2 to the right of the triangle, will be used to illustrate the remaining aspects of the algorithm. The same process can easily be applied to case 2.

As mentioned, the triangle is filled horizontally from left-to-right and line-by-line in the positive y-direction until the triangle is filled. The endpoints of each line of the triangle are denoted by "sx" and "ex" in the figure above so we want to be able to determine "sx" and "ex" for each y-coordinate that spans the entire triangle. Furthermore, you can determine "sz" and "ez" which represent the z-value (depth) of the start and end points. Given P1, P2, P3 and location y that will span the entire height of the triangle, we can interpolate the coordinates (x, y and z) for every pixel that makes up the given triangle.

First we define the x, y and z coordinates of P1 P2 P3 as follows

P1 → p1x, p1y, p1z
P2 → p2x, p2y, p2z
P3 → p3x, p3y, p3z

Y → current height of the triangle

Note that Y = p1y when we first start and traverses the triangle until Y = p3y. Starting with Step 1 in case 1 above, the gradient with respect to the current Y value has to first be calculated. It is given as follows

$$gradient = \frac{Y - p1y}{p2y - p1y}$$

Given a value Y, you can determine how close you are to P2 from P1 in terms of a percentage. In other words, if you're at the starting point and Y = p1y, the "percentage of distance" you are at between P1 and P2 is 0. Likewise if Y = p2y, you're at the end of the triangle for Step 1 and the percentage of distance is 1 (i.e. 100%). As such, gradient will be a value between 0 and 1.

After calculating the gradient for a specific value Y, you can determine sx and ex as follows

sx = p1x + (p3x – p1x) * gradient
ex = p1x + (p2x – p1x) * gradient

Note that the z-values (depth) of the starting and ending pixels must be interpolated as well by applying the equation

zs = p1z + (p3z – p1z) * gradient
ze = p1z + (p2z – p1z) * gradient

Note that for stage 2 of the triangle, the equations change as follows

sx = p1x + (p3x – p1x) * gradient
ex = p2x + (p3x – p2x) * gradient
zs = p1z + (p3z – p1z) * gradient
ze = p2z + (p3z – p2z) * gradient

This process lets you calculate sx, ex, sz and ez to process and potentially draw every line in the triangle. This same process can be easily extended to Case 2 but must take into account the location of P2 (to the left of the object).

Scan Line

As described in the process above, you can determine sx, ex, sz and ez for every line (i.e. Y value) in your triangle. Without z-buffering, you can simply draw a line between sx and ez to fill in the entire triangle.

Z-buffering however requires that you do further interpolations to determine the z-values of each pixel in the line being processed. This is done similarly to before where for each x value, a gradient is calculated, followed by a linear interpolation using the zs and ze values calculated for the current line

gradient = (x – sx) / (ex – sx)

z = zs + (ze – zs) * gradient

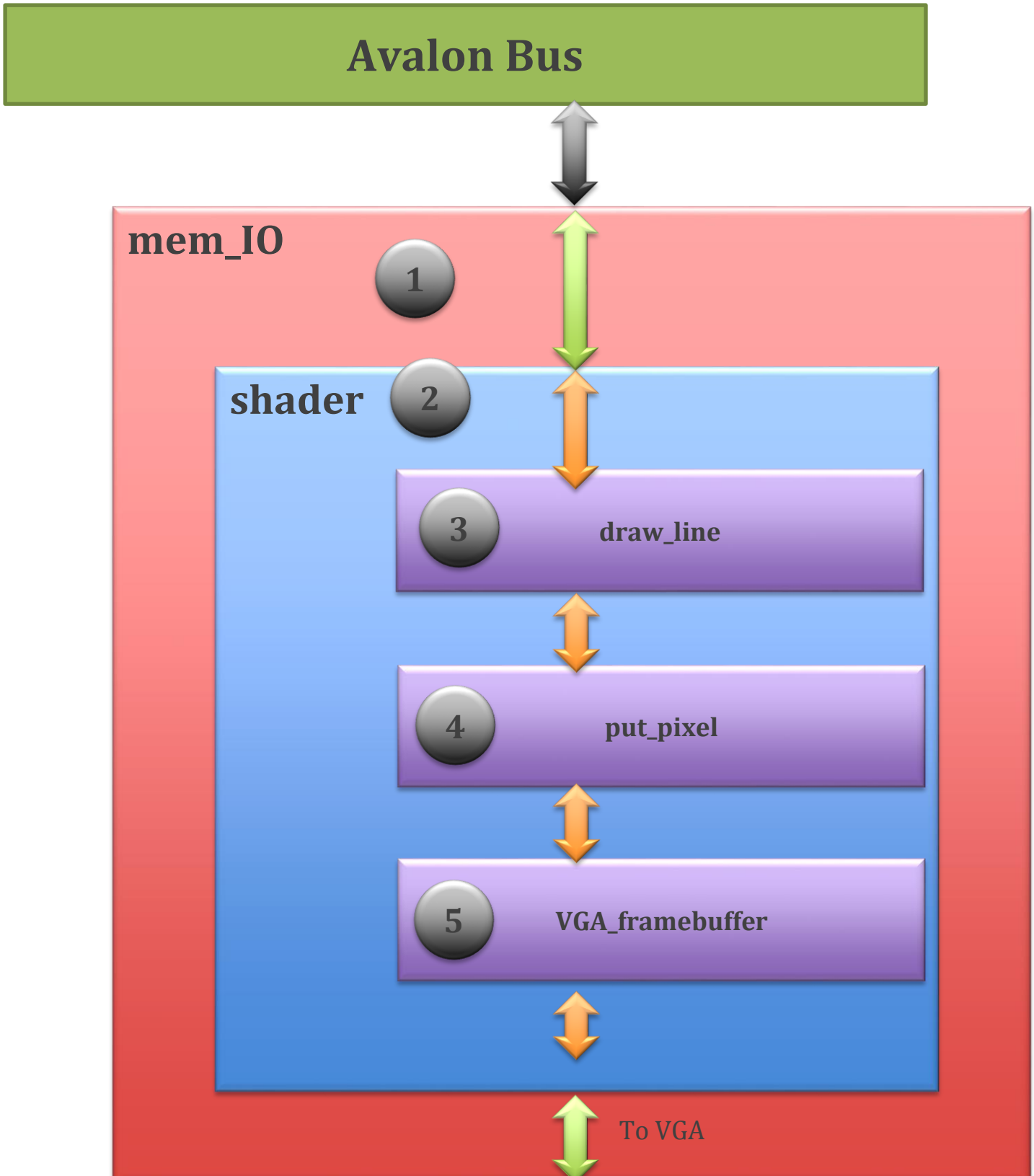
Conclusion

This rasterizing algorithm allows you to identify the location of the pixels within a triangle defined by 3 vertices. It also allows you to determine the z-value of each pixel in the triangle to implement z-buffering.

Hardware Implementation

Overview

The block diagram for the shader module is shown below. Each block 1-5 is described briefly and the code is commented for further detail.



An overview of the hardware is as follows:

1. mem_IO – This is a simple memory mapped I/O interface that is connected to the Avalon bus. This is the main HW/SW interface. It is used to pass vertices from the software multiplier pipeline to the shader module. It also passes color as well as control signals for hiding the screen during frame updates and clearing the screen which includes clearing the frame buffer.
2. shader – This is the main shader module. It accepts vertices from the memory mapped I/O interface. It sorts the vertices and calculates dP1P2 and dP1P3 as described in the algorithm to determine which triangle configuration we have (i.e. Case 1 with P2 on the right or Case 2 with P2 on the left). Once determined, for each Y coordinate of the triangle from top-to-bottom, the shader passes the sorted pixels to the draw_line module which contains the logic to draw the line on the screen with the help of the put_pixel and VGA_framebuffer blocks.
3. draw_line – This module takes sorted pixel values and a specific Y coordinate and outputs sx, ex and zs, ze as described in the algorithm above. Once calculated, it sends these values to put_pixel and signals put_pixel for the next stage in the pipeline.
4. put_pixel – This module accepts the sx, ex, zs and ze coordinates as well as the current Y coordinate and does the interpolation to calculate the z-values for each pixel. Each pixel along with its z value is sent to the VGA_framebuffer module to be printed to the screen.
5. The VGA_framebuffer module contains the frame buffer and z-buffer memories. It takes pixel coordinates, x, y and z, along with a pixel color and start signal to determine if a pixel should be written to the frame buffer and therefore output to the screen. Before writing a pixel to the frame buffer, it checks the z-buffer to see if the current pixel being written should overwrite the existing pixel at the same location. The VGA_framebuffer module also contains logic to handle two signals called hide_screen and clear_screen that are passed in from software from the Avalon bus.

Hardware Designs

Number Representation

We used our software prototype to confirm the types and resolution of the numbers in our application. This tables lists the fixed-point representation of the data we used throughput the hardware.

Value	Signed/Unsigned	Range	Total Bits	Integer Bits	Fractional Bits
Pixel/Vertex/Coordinate	Signed	[480, 640]	16	10	5
Gradient	Signed	[-1, 1]	16	1	14
z-value	Unsigned	[11,12]	11	4	7
Pixel color	Unsigned	[0, 3]	2	2	0

Memory Budget

Module	Bytes
Framebuffer	65536
z-buffer	360448

The following peripheral blocks were also created to support the pipeline operations:

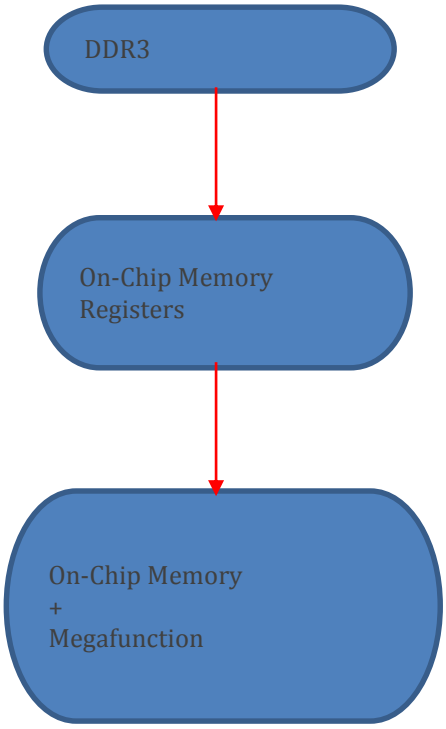
- divider – Divider that does fixed point signed division
- divider14 – Higher resolution divider that does fixed point signed division with 14-bits used for calculating gradients
- interpolate – does interpolation functionality as described in the algorithm section
- Interpolate7 – higher resolution interpolate function used for the interpolated z-buffer values. The result is a fixed point number with 7 bits used for the fractional part

MEMORY TESTING AND OPTIMIZATION

We started with DDR3 for our memory module, as our initial calculation for rendering the 3D graphics needed a lot of memory.

62 vertices → 48 bits per vertex = 720 bytes
120 faces → (3*6) bits each face = 120*18 = 270 bytes { 6 bits for using the vertex index, as to which vertices form the faces }
640*480 Framebuffer and 16bits to for pixel color(use R & G)→ 640*480*16 = 616KB
Z buffer 11bit for each pixel → 11*640*480 = 423KB

After this mad calculation we realized we had to use DDR3.
Below is how we progressed through the testing and implementation stages.



We spent lot of time figuring about the DDR3 specification. The module below shows the structural coding that we came up with after implementing the DDR3 design in QSYS.

```
//=======================================================
//  Structural coding
//=======================================================


   DDR3_Qsys u0 (
      .clk_clk                       (OSC_50_B3B), //                 clk.clk
      .reset_reset_n                 (RESET_n), //               reset.reset_n
      .memory_mem_a                  (DDR3_A), //              memory.mem_a
      .memory_mem_ba                 (DDR3_BA), //                    .mem_ba
      .memory_mem_ck                 (DDR3_CK_p), //                  .mem_ck
      .memory_mem_ck_n               (DDR3_CK_n), //                  .mem_ck_n
      .memory_mem_cke                (DDR3_CKE), //                   .mem_cke
      .memory_mem_cs_n               (DDR3_CS_n), //                  .mem_cs_n
      .memory_mem_dm                 (DDR3_DM), //                    .mem_dm
      .memory_mem_ras_n              (DDR3_RAS_n), //                 .mem_ras_n
      .memory_mem_cas_n              (DDR3_CAS_n), //                 .mem_cas_n
      .memory_mem_we_n               (DDR3_WE_n), //                  .mem_we_n
      .memory_mem_reset_n            (DDR3_RESET_n), //            .mem_reset_n
      .memory_mem_dq                 (DDR3_DQ),            //              .mem_dq
      .memory_mem_dqs                (DDR3_DQS_p),         //          .mem_dqs
      .memory_mem_dqs_n              (DDR3_DQS_n),           //          .mem_dqs_n
      .memory_mem_odt                (DDR3_ODT),             //          .mem_odt
      .oct_rzqin                     (DDR3_RZQ),           //         oct.rzqin
      );
```

Problems we ran into while working with DDR3

We started with DDR3 but we soon realized that it was tricky to get it working. We might have used two masters, one on the HPS and the other on the FPGS side to get it working. We also tried to generate the controller module for the DDR3 controller using megafunction wizard, but even after 8-9 hours the wizard was not able to produce the controller module.

We also felt that the timing synchronization would have been tricky with the DDR3 controller. We were looking into fast slave but we haven't used fast slave in the course so far and getting it to work with all the specifications would have been cumbersome.

Implementing using on-chip registers+megafucntion

So we switched to on-chip memory registers. We cut down the details of the design to save on the memory. We removed the number of vertices, faces that we had in our 3D model to save on the memory. We ran it in the software prototype(blender) with the reduced details and the figure was smooth enough, so we decided to go ahead with it.

We tested if throwing in values on the on-chip memory registers could work for our design and we concluded we could go with it. We tested if we were able to address the memory registers this way and read and write those registers, also we took help from professor's slides where he implements framebuffer in similar fashion.

Initially the modules that we implemented showed high memory utilization of about 80-85%. We even ran into memory shortage while compiling the modules few times. We figured out megafunction optimizes the memory utilization by somehow using memory registers in a better manner. So we then implemented our modules including the Z buffer using megafunction. Modules that we compiled with this design in Quartus had comparatively low memory utilization (60%).

SOFTWARE MODULES

Software Prototype

Our initial proof of concept for the project was verified on Software. We used Python to write, verify the entire shader module. The basis for the hardware was this software prototype, and replicated the shader module on hardware, and compared it with software. We cannot reiterate enough how important Software prototyping and ModelSim (to test hardware design) have been to our project.

The software prototype was used with the help of this Tutorial. The tutorial was in C/Java. We implemented it on Python.

Controller Specification

Game controller

The original ball balance game by Nintendo used the accelerometer on its devices to control gameplay. It is the most intuitive way to play the game, compared to using thumb sticks or D-pads, as it helps perfectly map the plate being displayed onscreen with the device the player is holding.

We set out to find a controller that met the following requirements for use as an input device:

- Built in accelerometer
- Connects via USB
- Has a reasonable amount of documentation online

The Wii remote was not ideal even though it had tons of documentation online, as it used Bluetooth to communicate. We figured that writing Bluetooth drivers from scratch would be quite tedious and take too much time away from the core part of the project. At the same time we didn't want to completely rely on packages provided online, as we didn't have a full understanding on how they worked.

So we settled for…

Sony DualShock 3™

This controller seemed to have met all our requirements. However, we later realized that the documentation for the controller was actually quite poor for our case. While we wanted to write a driver from scratch, most of the documentation online for Linux involved using complex joystick packages.
Considering that we wished we had better documentation ourselves, we hope that this section will help any future hackers implement a simple software package that can read from the Sony DualShock 3.

Quirks

The controller will not automatically report any events (such as button presses) upon being plugged in, while sniffing the USB packets. The controller needs to be changed to an "operational" mode using a HID_REQ_GET_REPORT command.

Windows, Mac OS X and Linux with kernels >= 2.6.21 have the necessary drivers to talk to set it to "operational" mode and talk to it. However, the Linaro distribution does not have the necessary module to do this (even though it has a kernel >= 2.6.21).

We found out that our version of the Kernel was compiled without many of the useful HID modules. The specific module that is required is 'hid-sony.c'. Upon getting more documentation from Professor Edwards on how to compile our own Kernels, we went through 'menuconfig' and selected the module under 'Device Drives → HID → Additional Drivers'.

Now, we can start reading from the controller.

Reverse Engineering

Now, we needed to know what data the controller was sending to us. We need to do two things to accomplish this:

1. We need to know what the Device ID was
2. How to sniff the packets coming out from it

1) We installed a very useful utility called 'lsusb' on our distribution and used it to determine the controller's Device ID.

2) We used a program called 'USBTrace' on Windows to determine what the 'SetupPacket' was to start receiving data from the controller by connecting it up to the software.

We then utilized a Python library called PyUSB to allow us to talk to the controller through the USB protocol without too many lines of code. All we needed to do was send the 'SetupPacket' to the controller and let the controller inundate us with status data.

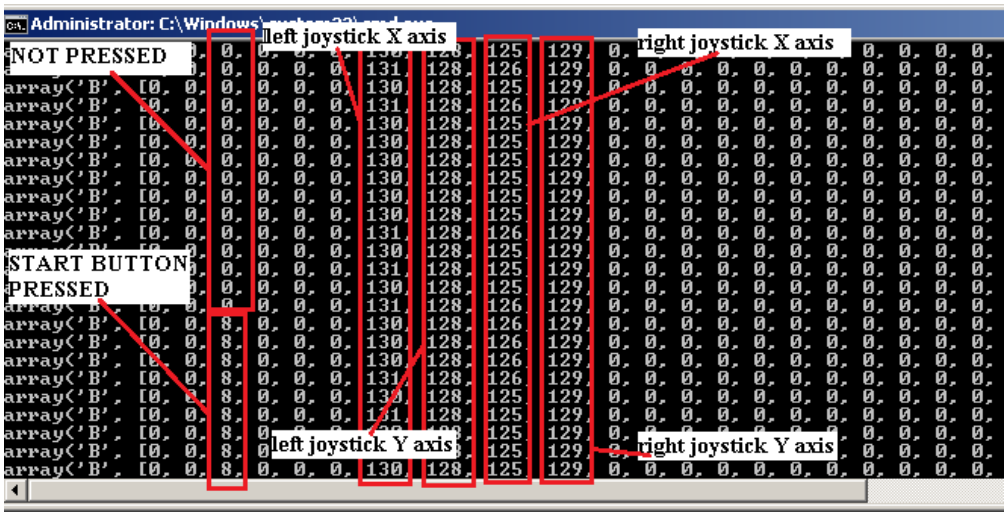
The packets contain a wealth of information, from accelerometers to pressure sensitivity of every button press.

Snippet of the Python Code

```
import usb.core
import usb.util
import sys

# Scanning the tree for our DualShock 3 controller
controller = usb.core.find(idVendor=0x054c, idProduct=0x0268)

reattach = False
if controller.is_kernel_driver_active(0):
    reattach = True
    controller.detach_kernel_driver(0)

# Error message for device if not found
if controller is None:
    raise ValueError('Device not found')

# Set the active configuration. With no arguments, the first configuration will be the active one
controller.set_configuration()

while True:

        # Our "SetupPacket"
```

```
ret = controller.ctrl_transfer(0xa1, 0x1, 0x0101, 0x0, 0x31)

        # Prints out all the packets coming out from the controller
print ret
```

Output



Mapping

Once we could see the statuses generated by the controller, we identified values in array 41, 42, 43 and 44 of 'ret' as being the relevant data for X and Y axis tilt. The values went from 0 – 110 for a 90-degree tilt on the X-axis in the anticlockwise direction, and from 255 – 142 for a 90-degree tilt in the opposite direction.

These values are in array indices 42 and 44. Array indices 41 and 43 indicate the quadrant in which the rotation is taking place for either axis, and can be either '1' (clockwise) or '2' (anti-clockwise).

Snippet of Python code to convert readings to degrees

```
# Check for anti-clockwise rotation on the x-axis
   if ret[41] == 2:
     if ret[42] <= 110 and ret[42] >= 0:
       xaxis = ret[42]*90/110

            # Limit maximum to 90 degrees
       if xaxis > 90:
         xaxis = 90

# Check for clockwise rotation on the x-axis
 if ret[41] == 1:
     if ret[42] <= 255 and ret[42] >= 142:
```

```
        xaxis = (ret[42] - 255)*90/113

            # Limit maximum to 90 degrees
        if xaxis < -90:
          xaxis = -90

# Check for anti-clockwise rotation on the y-axis
 if ret[43] == 2:
     if ret[44] <= 110 and ret[44] >= 0:
        yaxis = ret[44]*90/110

            # Limit maximum to 90 degrees
        if yaxis > 90:
          yaxis = 90

# Check for clockwise rotation on the y-axis
 if ret[43] == 1:
     if ret[42] <= 255 and ret[42] >= 142:
        yaxis = (ret[44] - 255)*90/115

            # Limit maximum to 90 degrees
        if yaxis < -90:
          yaxis = -90
```

Interface to Matrix Multipliers

The tilt data in degrees is then fed to C code to use for matrix multiplications on the plate's vertices. This is very easy to do using Python's OS module. In this instance, the Python script acts as a wrapper to bridge the controller output to the FPGA through device drivers.

Snippet of Python Code

```
# Passing arguments to the C executable using the command line interface
os.system("./main " + str(yaxis) + " " + str(xaxis) + " " + str(stop) + " " + str(prev_stop))
```

Additional Features

Due to the nature of our VGA framebuffer design, the plate wasn't being displayed perfectly due to glitches in timing. In order to showcase our implementation of Z-Buffering in hardware, we used the 'X' button on the controller to freeze a particular render on the screen to be admired.

To do this, we just checked for value '64' on the 3rd array index of 'ret'. It is '0' when not pressed and '64' when pressed.

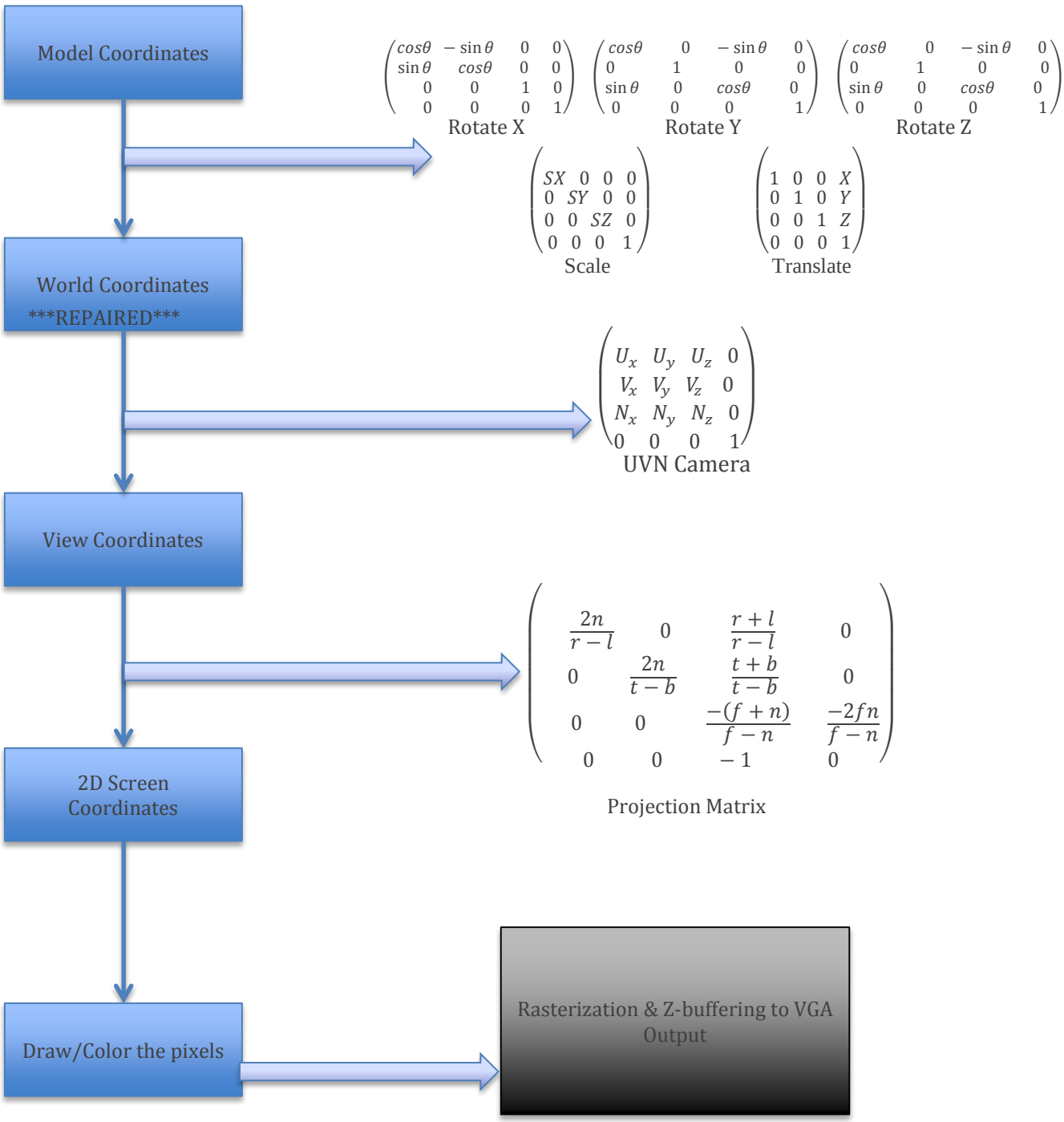
Suggested Improvements

If we had a little more time in our hands, we would have loved to take full advantage of the Bluetooth functionality on the DualShock 3. There are currently many software packages that enable pairing using Bluetooth on Linux, such as QTSixA and Sixad.

In general, initial pairing can be done over a USB cable. After the connection is established, one can read data from a Bluetooth USB dongle using a HCI module in the Kernel.

Matrix Transformation Pipeline

A 3D object is modeled using a collection of vertices in 3D space (x,y,z). The vertices can be connected to form the surfaces of the 3d object. The surfaces can be filled in using any number of methods according to the model. To project a 3D object onto a 2D screen, the models vertices undergo a series of matrix multiplications to transform the 3D vertices into 2D coordinates that can then be displayed on the screen. The rendering pipeline we will use for our project is shown in Figure 3



In our model, the vertices are represented using four coordinates (x, y, z, w). The addition of the ‘w’ coordinate makes these Homogeneous coordinates, which are used to simplify the operations, involved for 3D rendering. The ‘w’ can be used for other rendering purposes such as shadows, which will be out of the scope of this project. Here we describe each of the coordinate blocks in the pipeline and the matrix operations that transform the vertices from one domain to another.

i. The Model Coordinates

Each surface in the 3D model to be displayed is considered to be a collection of triangles. The triangles are defined by a set of vertices. To start with, the x,y,z coordinates are defined relative to the center of the object which is a vertex at (0,0,0). We want to be able to rotate, translate and scale our model. Each of the above transformations requires a matrix to be multiplied with the vertices. The model matrix is a product of the following matrices; the 3 rotation matrices (for x, y and z axes) scale and translate matrices.

ii. The World Coordinates

After model matrices are applied to the vertices, the model went from being in Model Space (all vertices defined relative to the center of the model) to World Space (all vertices defined relative to the center of the world).

To understand the view matrix, consider a camera moving around your world space. If the camera looking at the entire world rotates 3 units to the right, it is equivalent to your world space rotating 3 units to the left. The view matrix defines which point in world space is being viewed. In other words, it describes the direction the camera is pointed in. In our project, we plan on keeping the camera/view fixed while moving the object/world.

The method we will use to generate the view matrix is the “UVN Camera”. The details of this method can be found in [1] and [2].

The U, V and N vectors that make up the view matrix are described.

> N - The vector from the camera to its target. Also known as the 'look at' vector in some 3D literature. This vector corresponds to the Z-axis.
>
> V - When standing upright this is the vector from your head to the sky. If you are writing a flight simulator and the plane is reversed that vector may very well point to the ground. This vector corresponds to the Y-axis.
>
> U - This vector points from the camera to its "right" side". It corresponds to the X-axis.

For our project, we plan to place the plate object along the z-axis so that the movement of the camera will be minimal. The world coordinates are transformed into the view coordinates (all vertices defined relative to the camera) after multiplying the vertices by the view matrix.

iii. The View Coordinates

Once we have the view coordinates, we need to convert the 3D Coordinates into 2D Coordinates that represent the 3D object being projected onto a 2D screen. This requires another matrix transformation. The matrix generated at this step is called the Projection matrix. It defines the window that the 3D coordinates will be projected onto. There are 6 main parameters: near, far, left, right, top and bottom. Near and far are used to specify the camera's field of view, that is, how near and far the camera is able to see. Left, right, top and bottom represent the boundaries of the display in their respective directions. Note that the left and right boundaries are dependent on the angle of view of the camera, which can be specified in the software. The top and bottom boundaries are dependent on the aspect ratio of the display. These parameters are listed in the equations below and the dependencies are reflected in these equations.

n = near
size=near*tan (angle_of_view/2.0)
left= -size = *l*
right= size = r
bottom= -size/aspect_ratio = b
top = size / aspect_ratio = t

See references [3] and [4] for details on how the projection matrix is derived.

iv. The 2D Coordinates:

After the projection transformation, we have the 2D space vertices, which can be used for displaying the model on screen. To fill in the model's surfaces, we use a basic rasterization algorithm that includes z - buffering. A set of three vertices represents a triangle, which is the primitive shape that makes up the surface of an object. Figure 4 shows a sample triangle defined by vertices P1, P2 and P3.

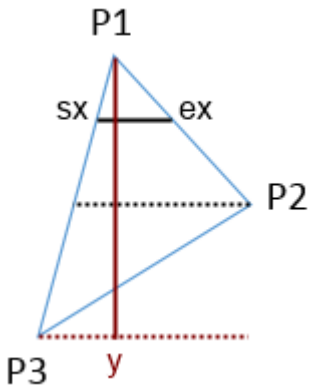


Figure Triangle defined by 3 vertices

The three vertices allow us to calculate the gradient of lines P1-P2 and P1-P3. Using these gradients, we can determine sx and ex, which represent the start location and end location of the triangle, for each value y. Similarly, we can calculate a sz and ez which represents the start and end z-coordinates that correspond to the sx and ex values. Given these values, we can determine the boundaries of the triangle that needs to be rasterized.

The addition of the z coordinate can tell us if particular pixels should reside in front of other pixels, which maintain the 3D look of the object when projected on the screen.

Driver for interfacing with Hardware

For every clock cycle, we are writing a set of x, y and z coordinate values to the ioctl. Our driver is written as an FSM that is using states to trigger what has to be done when. The refresh rate of the clock for the pixels is 50 MHz

We tested the software-hardware interfacing by performing the following steps, considering a simple cube as our object to be rendered:

- We hard coded one set of vertices (obtained from the Python prototype). When this was passed to the hardware, a single triangle was displayed on screen.
- When we tried two triangles, there was no issue either.
- The interesting thing was, when we tried displaying three or more triangles, only the first and last triangles were displayed.
- We had to add a sleep cycle of 500ms, as you will see in our program, to let all the triangles be displayed on screen.

Once a cube was rendered correctly, we tried our luck with the plate, and it worked! We had a plate on screen. But there were a few color issues of the triangles. This is when we decided to implement Z-buffering on hardware, and make the plate look clean and smooth.

Next, when we tried including the controller into this picture, we were facing another problem with respective to synchronization. The pixels were being transferred faster than the time taken for the VGA block to read it. To solve this issue, we had to add additional sleep cycles on software.

Pixel Values

After the rotation values are provided by the Python wrapper and consumed by the matrix pipeline, transformation matrices are generated and are applied to every vertex as listed in vga_led.h.

Each face points to three vertices, and each vertex now has three pixel values after transformation. Thus we create a single dimensional array (‘pixellist’) of size (NUM_OF_FACES)*9 and store every pixel value, so that it becomes easier to access and send down to the hardware.

Since the hardware uses fixed-point arithmetic, we scale each pixel by 32, so that a good amount of precision is preserved as an integer value and then will be shifted appropriately.

Control Logic

For each face to be printed on the screen, we dump 9 indices from ‘pixellist’. These 9 indices correspond to 3 vertices as described about. However, we added 3 additional control signals, taking the total number of values sent to the Avalon Bus to 12. The three control signal are the following:

1. Colour: We need to print a different colour for each face so that we get a perception of depth, which is important for a 3D representation of an object. 2 bits represent this signal, to represent 4 different colours. We have 3 different shades of blue, from light to dark and black, to clear screen.
2. Show/Hide Screen: We want to wait till all the polygons have been printed to the framebuffer before displaying it. This is largely for aesthetic reasons, as watching a render face by face can be jarring. A single bit represents this signal.
3. Clear frame: Since we have implemented only one framebuffer, we need to clear it before we can write a new face. So we essentially resend the same render but paint everything black, so that it gives the same effect as a cleared screen. Unfortunately, this causes our renders to flicker. A single bit represents this signal.

CONCLUSION AND RESULTS

Challenges Faced

- Screen refresh
- Fixed-point, signed arithmetic in FPGA
- Z-buffer implementation due to resolution
- Limited memory resources, difficult to get DDR3 working
- Coloring of the triangle in the 3D model
- A race against the clock

Lessons Learnt

- Plan well in advance
- We ran into quite a few issues with the external memory. On-chip registers are much easier to implement, but difficult to optimize. Thank god for MegaFunction
- Compiling on FPGA is time consuming. We've never appreciated ModelSim more for making our lives so much easier
- Software prototyping was invaluable
- Priorities change as project progresses
- Get help from other groups! We tried doing everything on our own, but could have benefited from others' work
- Strategize properly; make the wise choice when you have options! We underestimated a lot of our choices, for example with memory, using rasterization Vs. ray casting
- We stopped work on a lot of modules, as and when we realized they were infeasible

Role of each individual

- Earvin Caceres – Software prototype of the whole project in Python, 3D Rendering on Hardware (Shader module, VGA Module, Rasterization and Z-buffering)
- Gautham Vunnam – Kernel modification, Controller interfacing, Software translation, Matrix Transformation Pipeline
- Garvit Singh – Memory configuration, testing, and optimization
- Annjana Ramesh – Software interfacing and testing of the hardware module

REFERENCES

[1] http://ogldev.atspace.co.uk/www/tutorial13/tutorial13.html
[2] http://blog.db-in.com/cameras-on-opengl-es-2-x/
[3] http://www.songho.ca/opengl/gl_projectionmatrix.html
[4] http://blog.db-in.com/cameras-on-opengl-es-2-x/
[5] http://blogs.msdn.com/b/davrous/archive/2013/06/21/tutorial-part-4-learning-how-to-write-a-3d-software-engine-in-c-ts-or-js-rasterization-amp-z-buffering.aspx

APPENDIX

SOFTWARE FILES

```
*********************************************************************************
/*
 * main.c
 * Userspace program that communicates with the vga device driver
 * primarily through ioctls
 *
 * Source Code:
 *
 * Stephen A. Edwards
 * Columbia University
 *
 * Modified by:
 *
 * Gautham Vunnam
 * Columbia University
 */

#include <stdio.h>
#include <unistd.h>
#include "vga_led.h"
#include <sys/ioctl.h>
#include <sys/types.h>
#include <sys/stat.h>
#include <fcntl.h>
#include <string.h>
#include <unistd.h>
#include <math.h>
#include "mat_operations.h"
#include "data.h"

int vga_led_fd;  // vga_led file descriptor

int main(int argc, char *argv[]) {


  vga_led_arg_t vla;
  int i, j=0, facenumber = 0,k;
     char color = 1;
  static const char filename[] = "/dev/vga_led";
  unsigned int coords[12];
  unsigned int z;

     // matrix objects

     float xw, yw, zw;

     float adjusted_vertices[62][4];
     float adjusted_vertex[4][1];
     float vertex[4][1];
     float rotation[4][4];
     float transform[4][4];
     float temp[4][4];
     float world[4][4];
```

```
    float temp41[4][1];

    float pixels[62][3];
    int pixellist[1080];

    getRotationMatrix(-atoi(argv[1]), -atoi(argv[2]), 180, rotation);

    dotProduct44(TRANSLATE, rotation, temp);
    dotProduct44(temp, SCALE, world);
    dotProduct44(PROJECTION, VIEW, temp);
    dotProduct44(temp, world, transform);


    for(i = 0; i < 62; i++)
    {
      for(j = 0; j < 4; j++)
      {
            vertex[j][0] = vertices[i][j];
      }

      dotProduct41(transform, vertex, adjusted_vertex);

      scaleMat41(adjusted_vertex, 1/adjusted_vertex[3][0], temp41);

      xw = ((640 / 2.0) * temp41[0][0]) + (0 + (640 / 2.0));
      yw = ((480 / 2.0) * temp41[1][0]) + (0 + (480 / 2.0));
      zw = ((9) / 2.0) * temp41[2][0] + ((11) / 2.0);

      pixels[i][0] = xw;
      pixels[i][1] = yw;
      pixels[i][2] = zw;

    }

    for(i = 0; i < 120; i++)
    {
      pixellist[i*9] = (int) pixels[faces[i][0]][0]*32;
      pixellist[i*9 + 1] = (int) pixels[faces[i][0]][1]*32;
      pixellist[i*9 + 2] = (int) pixels[faces[i][0]][2]*32;
      pixellist[i*9 + 3] = (int) pixels[faces[i][1]][0]*32;
      pixellist[i*9 + 4] = (int) pixels[faces[i][1]][1]*32;
      pixellist[i*9 + 5] = (int) pixels[faces[i][1]][2]*32;
      pixellist[i*9 + 6] = (int) pixels[faces[i][2]][0]*32;
      pixellist[i*9 + 7] = (int) pixels[faces[i][2]][1]*32;
      pixellist[i*9 + 8] = (int) pixels[faces[i][2]][2]*32;
    }


/* just open vga driver like it's a file
   using the file descriptor specified earlier */
if ( (vga_led_fd = open(filename, O_RDWR)) == -1) {
  fprintf(stderr, "could not open %s\n", filename);
  return -1;
}

      if((atoi(argv[3]) != 1) && (atoi(argv[4]) == 1))
      {
      for (i = 0; i<1080; i += 9) {

            coords[0] = pixellist[i];
            coords[1] = pixellist[i+1];
```

```
                coords[2] = pixellist[i+2];
                coords[3] = pixellist[i+3];
                coords[4] = pixellist[i+4];
                coords[5] = pixellist[i+5];
                coords[6] = pixellist[i+6];
                coords[7] = pixellist[i+7];
                coords[8] = pixellist[i+8];

                if (facenumber < 40) {
                        color = 3;
                }

                else if (facenumber >= 40 && facenumber < 79) {
                        color = 2;
                }

                else {
                        color = 1;
                }

                coords[10] = 0;

                // first time around send a color and write screen
                coords[9] = 0;  // send plate color
                coords[11] = 1;  // clear the screen

                if (facenumber == 119) {
                        coords[10] = 0; // show screen
                }
                else {
                        coords[10] = 1; // hide screen
                }

                write_coordinates(coords);

                facenumber++;
                usleep(1000);
        }

        }
          if(atoi(argv[4]) != 1)
{
           for (i = 0; i<1080; i += 9) {

                coords[0] = pixellist[i];
                coords[1] = pixellist[i+1];
                coords[2] = pixellist[i+2];
                coords[3] = pixellist[i+3];
                coords[4] = pixellist[i+4];
                coords[5] = pixellist[i+5];
                coords[6] = pixellist[i+6];
                coords[7] = pixellist[i+7];
                coords[8] = pixellist[i+8];

                if (facenumber < 40) {
                        color = 3;
                }

                else if (facenumber >= 40 && facenumber < 79) {
                        color = 2;
                }
```

```
        else {
                color = 1;
        }

        coords[10] = 0;

        if (facenumber == 119) {
                coords[10] = 0; // show screen
        }
        else {
                coords[10] = 1; // hide screen
        }


        // first time around send a color and write screen
        coords[9] = color;  // send plate color
        coords[11] = 0;  // don't clear the screen

        write_coordinates(coords);

        facenumber++;
        usleep(1000);
}
}
   usleep(2000);  // wait 10 sec for the screen to clear

   if(atoi(argv[3]) != 1)
   {
   for (i = 0; i<1080; i += 9) {

        coords[0] = pixellist[i];
        coords[1] = pixellist[i+1];
        coords[2] = pixellist[i+2];
        coords[3] = pixellist[i+3];
        coords[4] = pixellist[i+4];
        coords[5] = pixellist[i+5];
        coords[6] = pixellist[i+6];
        coords[7] = pixellist[i+7];
        coords[8] = pixellist[i+8];

        if (facenumber < 40) {
                color = 3;
        }

        else if (facenumber >= 40 && facenumber < 79) {
                color = 2;
        }

        else {
                color = 1;
        }

        coords[10] = 0;

        // first time around send a color and write screen
        coords[9] = 0;  // send plate color
        coords[11] = 1;  // don't clear the screen

        if (facenumber == 119) {
                coords[10] = 0; // show screen
```

```
                }
                else {
                        coords[10] = 1; // hide screen
                }

                write_coordinates(coords);

                facenumber++;
                usleep(1000);
        }

        }

  return 0;

}
```

```
 /* mat_operations.c
 * Matrix transformation pipeline
 *
 */
#include <math.h>
#include "mat_operations.h"


void dotProduct44(float a[4][4], float b[4][4], float c[4][4]) {

     int i, j, k;
     float sum = 0;

     for (i = 0; i < 4; i++) {
       for (j = 0; j < 4; j++) {
              sum = 0;
              for (k = 0; k < 4; k++) {
                     sum = sum + a[i][k] * b[k][j];
              }
              c[i][j] = sum;
       }
     }
}

void scaleMat41(float a[4][1], float scale, float b[4][1]) {

     int i, j, k;
     float sum = 0;

     for (i = 0; i < 4; i++) {


              b[i][0] = a[i][0]*scale;
     }
}

void dotProduct41(float a[4][4], float b[4][1], float c[4][1]) {

     int i, j, k;
     float sum = 0;

     for (i = 0; i < 4; i++) {
```

```
      for (j = 0; j < 1; j++) {
            sum = 0;
            for (k = 0; k < 4; k++) {
                  sum = sum + a[i][k] * b[k][j];
            }
            c[i][j] = sum;
      }
    }
}

void printMatrix(int row, int col, float m[row][col]) {
    int i, j;

    printf ("------------------------\n");

    for (i = 0; i < row; i++) {
      for (j = 0; j < col; j++) {
            printf(" %f ", m[i][j]);
      }
      printf("\n");
    }

    printf ("------------------------\n");
}

void getRotationMatrix(int angle_x, int angle_y, int angle_z, float m[4][4]) {

    float rad_x = angle_x * .01743;
    float rad_y = angle_y * .01743;
    float rad_z = angle_z * .01743;

    float temp[4][4];

    float rotate_x[4][4] = {{1, 0, 0, 0}, {0, 1, 0, 0}, {0, 0, 1, 0}, {0, 0,
0, 1}};
    float rotate_y[4][4] = {{1, 0, 0, 0}, {0, 1, 0, 0}, {0, 0, 1, 0}, {0, 0,
0, 1}};
    float rotate_z[4][4] = {{1, 0, 0, 0}, {0, 1, 0, 0}, {0, 0, 1, 0}, {0, 0,
0, 1}};

    rotate_x[1][1] = cos(rad_x);
    rotate_x[1][2] = sin(rad_x);
    rotate_x[2][1] = -sin(rad_x);
    rotate_x[2][2] = cos(rad_x);

    rotate_y[0][0] = cos(rad_y);
    rotate_y[0][2] = -sin(rad_y);
    rotate_y[2][0] = sin(rad_y);
    rotate_y[2][2] = cos(rad_y);

    rotate_z[0][0] = cos(rad_z);
    rotate_z[0][1] = -sin(rad_z);
    rotate_z[1][0] = sin(rad_z);
    rotate_z[1][1] = cos(rad_z);

    dotProduct44(rotate_y, rotate_x, temp);
    dotProduct44(rotate_z, temp, m);
}
```

```
/*vga_led.c
 * Device driver for the VGA LED Emulator
 *
 * A Platform device implemented using the misc subsystem
 *
 * Stephen A. Edwards
 * Columbia University
 *
 * References:
 * Linux source: Documentation/driver-model/platform.txt
 *               drivers/misc/arm-charlcd.c
 * http://www.linuxforu.com/tag/linux-device-drivers/
 * http://free-electrons.com/docs/
 *
 * "make" to build
 * insmod vga_led.ko
 *
 * Check code style with
 * checkpatch.pl --file --no-tree vga_led.c
 */


/* header files used only those from kernel sources */
/* typically need these headers for a device driver */
#include <linux/module.h> // define module_init() and module_exit() functions
#include <linux/init.h>
#include <linux/errno.h>
#include <linux/version.h>
#include <linux/kernel.h>
#include <linux/platform_device.h>
#include <linux/miscdevice.h>
#include <linux/slab.h>
#include <linux/io.h>
#include <linux/of.h>
#include <linux/of_address.h>
#include <linux/fs.h>
#include <linux/uaccess.h>
#include "vga_led.h"

#define DRIVER_NAME "vga_led"

/*
 * Information about our device
 */
struct vga_led_dev {
     resource_size_t start; /* Address of start of registers */
     resource_size_t size;
     void __iomem *virtbase; /* Where registers can be accessed in memory */
} dev;


static void write_coor(int coor, unsigned int val)
{
     iowrite16(val, dev.virtbase + coor*2); // mult by 2 since we write 16-bits
(2bytes) at a time
}

/*
 * Handle ioctl() calls from userspace:
 * Read or write the segments on single digits.
 * Note extensive error checking of arguments
```

```
 */
static long vga_led_ioctl(struct file *f, unsigned int cmd, unsigned long arg)
{
     vga_led_arg_t vla;
     switch (cmd) {
     case VGA_LED_WRITE_DIGIT:
       if (copy_from_user(&vla, (vga_led_arg_t *) arg,
                          sizeof(vga_led_arg_t)))
             return -EACCES;
       if (vla.coor > 12)
             return -EINVAL;
       write_coor(vla.coor, vla.val);
       break;

     default:
       return -EINVAL;
     }

     pr_info("in the ioctl function");

     return 0;
}

/* The operations our device knows how to do */
static const struct file_operations vga_led_fops = {
     .owner          = THIS_MODULE,
     .unlocked_ioctl = vga_led_ioctl,
};

/* Information about our device for the "misc" framework -- like a char dev */
static struct miscdevice vga_led_misc_device = {
     .minor          = MISC_DYNAMIC_MINOR,
     .name           = DRIVER_NAME,
     .fops           = &vga_led_fops,
};

/*
 * Initialization code: get resources (registers) and display
 * a welcome message
 */
static int __init vga_led_probe(struct platform_device *pdev)
{
     int ret;
     struct resource res;

     /* Register ourselves as a misc device: creates /dev/vga_led */
     ret = misc_register(&vga_led_misc_device);

     /* Get the address of our registers from the device tree */
     ret = of_address_to_resource(pdev->dev.of_node, 0, &res);
     if (ret) {
       ret = -ENOENT;
       goto out_deregister;
     }

     /* Make sure we can use these registers */
     if (request_mem_region(res.start, resource_size(&res),
                            DRIVER_NAME) == NULL) {
       ret = -EBUSY;
       goto out_deregister;
     }
```

```
      dev.start = res.start;
      dev.size = resource_size(&res);

      /* Arrange access to these registers */
      dev.virtbase = of_iomap(pdev->dev.of_node, 0);
      if (dev.virtbase == NULL) {
        ret = -ENOMEM;
        goto out_release_mem_region;
      }

      return 0;

out_release_mem_region:
      release_mem_region(res.start, resource_size(&res));
out_deregister:
      misc_deregister(&vga_led_misc_device);
      return ret;
}

/* Clean-up code: release resources */
static int vga_led_remove(struct platform_device *pdev)
{
      iounmap(dev.virtbase);
      release_mem_region(dev.start, dev.size);
      misc_deregister(&vga_led_misc_device);
      return 0;
}

/* Which "compatible" string(s) to search for in the Device Tree */
#ifdef CONFIG_OF
static const struct of_device_id vga_led_of_match[] = {
      { .compatible = "altr,vga_led" },
      {},
};
MODULE_DEVICE_TABLE(of, vga_led_of_match);
#endif

/* Information for registering ourselves as a "platform" driver */
static struct platform_driver vga_led_driver = {
      .driver  = {
        .name  = DRIVER_NAME,
        .owner = THIS_MODULE,
        .of_match_table = of_match_ptr(vga_led_of_match),
      },
      .remove  = __exit_p(vga_led_remove),
};

/* Called when the module is loaded: set things up */
static int __init vga_led_init(void)
{
      pr_info(DRIVER_NAME ": init\n");
      return platform_driver_probe(&vga_led_driver, vga_led_probe);
}

/* Called when the module is unloaded: release resources */
static void __exit vga_led_exit(void)
{
      platform_driver_unregister(&vga_led_driver);
      pr_info(DRIVER_NAME ": exit\n");
}
```

```
module_init(vga_led_init); // correspond to user space command insmod
module_exit(vga_led_exit); // correspond to user space command rmmod

MODULE_LICENSE("GPL");
MODULE_AUTHOR("Stephen A. Edwards, Columbia University");
MODULE_DESCRIPTION("VGA 7-segment LED Emulator");
```

```
// mat_operations.h

#ifndef MAT_OPERATIONS_H
#define MAT_OPERATIONS_H

#include <stdlib.h>
#include <stdio.h>
#include <math.h>

// matrix dot products
void dotProduct44(float a[4][4], float b[4][4], float c[4][4]);
void dotProduct41(float a[4][4], float b[4][1], float c[4][1]);
void getRotationMatrix(int angle_x, int angle_y, int angle_z, float m[4][4]);
void printMatrix(int row, int col, float m[row][col]);
void scaleMat41(float a[4][1], float scale, float b[4][1]) ;


#endif
```

```
//vga_led.h

#ifndef _VGA_LED_H
#define _VGA_LED_H

#include <linux/ioctl.h>

#define NUM_COORDS 12
#define NUM_PIXELS 108

/* used to specify the location of the center of the ball */
typedef struct {
     int coor; // specifies x(0) or y(1)
     unsigned int  val;  // coordinate of ball center
} vga_led_arg_t;

// 120 faces with corresponding vertice indexes
int faces[120][3] = {
     {0, 1, 2},
     {0, 3, 1},
     {0, 4, 3},
     {0, 5, 4},
     {0, 6, 5},
     {0, 7, 6},
     {0, 8, 7},
     {0, 9, 8},
     {0, 10, 9},
     {0, 11, 10},
     {0, 12, 11},
     {0, 13, 12},
     {0, 14, 13},
```

```
{0, 15, 14},
{0, 16, 15},
{0, 17, 16},
{0, 18, 17},
{0, 19, 18},
{0, 20, 19},
{0, 2, 20},
{21, 22, 23},
{21, 23, 24},
{21, 24, 25},
{21, 25, 26},
{21, 26, 27},
{21, 27, 28},
{21, 28, 29},
{21, 29, 30},
{21, 30, 31},
{21, 31, 32},
{21, 32, 33},
{21, 33, 34},
{21, 34, 35},
{21, 35, 36},
{21, 36, 37},
{21, 37, 38},
{21, 38, 39},
{21, 39, 40},
{21, 40, 41},
{21, 41, 22},
{18, 19, 42},
{8, 43, 44},
{17, 18, 45},
{1, 46, 47},
{7, 44, 48},
{6, 48, 49},
{17, 50, 51},
{5, 49, 52},
{15, 16, 51},
{4, 52, 53},
{14, 15, 54},
{3, 53, 46},
{14, 55, 56},
{13, 56, 57},
{12, 57, 58},
{11, 58, 59},
{2, 47, 60},
{10, 59, 61},
{20, 60, 42},
{8, 9, 61},
{22, 47, 46},
{24, 23, 46},
{24, 53, 52},
{25, 52, 49},
{27, 26, 49},
{28, 27, 48},
{28, 44, 43},
{29, 43, 61},
{30, 61, 59},
{31, 59, 58},
{32, 58, 57},
{33, 57, 56},
{34, 56, 55},
{35, 55, 54},
```

```
        {37, 36, 54},
        {37, 51, 50},
        {39, 38, 50},
        {40, 39, 45},
        {40, 42, 60},
        {41, 60, 47},
        {45, 18, 42},
        {7, 8, 44},
        {50, 17, 45},
        {2, 1, 47},
        {6, 7, 48},
        {5, 6, 49},
        {16, 17, 51},
        {4, 5, 52},
        {54, 15, 51},
        {3, 4, 53},
        {55, 14, 54},
        {1, 3, 46},
        {13, 14, 56},
        {12, 13, 57},
        {11, 12, 58},
        {10, 11, 59},
        {20, 2, 60},
        {9, 10, 61},
        {19, 20, 42},
        {43, 8, 61},
        {23, 22, 46},
        {53, 24, 46},
        {25, 24, 52},
        {26, 25, 49},
        {48, 27, 49},
        {44, 28, 48},
        {29, 28, 43},
        {30, 29, 61},
        {31, 30, 59},
        {32, 31, 58},
        {33, 32, 57},
        {34, 33, 56},
        {35, 34, 55},
        {36, 35, 54},
        {51, 37, 54},
        {38, 37, 50},
        {45, 39, 50},
        {42, 40, 45},
        {41, 40, 60},
        {22, 41, 47}
};

// Vertices for all 120 faces of the plate
float vertices[62][4] = {
        {0., 0., 0., 1.},
        {-0.309, 0., 0.9511, 1.},
        {0., 0., 1., 1.},
        {-0.5878, 0., 0.809, 1.},
        {-0.809, 0., 0.5878, 1.},
        {-0.9511, 0., 0.309, 1.},
        {-1., 0., -0., 1.},
        {-0.9511, 0., -0.309, 1.},
        {-0.809, 0., -0.5878, 1.},
        {-0.5878, 0., -0.809, 1.},
        {-0.309, 0., -0.9511, 1.},
```

```
        {0., 0., -1., 1.},
        {0.309, 0., -0.9511, 1.},
        {0.5878, 0., -0.809, 1.},
        {0.809, 0., -0.5878, 1.},
        {0.9511, 0., -0.309, 1.},
        {1., 0., 0., 1.},
        {0.9511, 0., 0.309, 1.},
        {0.809, 0., 0.5878, 1.},
        {0.5878, 0., 0.809, 1.},
        {0.309, 0., 0.9511, 1.},
        {-0., 0.1903, 0., 1.},
        {-0., 0.1903, 0.4789, 1.},
        {-0.148, 0.1903, 0.4554, 1.},
        {-0.2815, 0.1903, 0.3874, 1.},
        {-0.3874, 0.1903, 0.2815, 1.},
        {-0.4554, 0.1903, 0.148, 1.},
        {-0.4789, 0.1903, 0., 1.},
        {-0.4554, 0.1903, -0.148, 1.},
        {-0.3874, 0.1903, -0.2815, 1.},
        {-0.2815, 0.1903, -0.3874, 1.},
        {-0.148, 0.1903, -0.4554, 1.},
        {0., 0.1903, -0.4789, 1.},
        {0.148, 0.1903, -0.4554, 1.},
        {0.2815, 0.1903, -0.3874, 1.},
        {0.3874, 0.1903, -0.2815, 1.},
        {0.4554, 0.1903, -0.148, 1.},
        {0.4789, 0.1903, 0., 1.},
        {0.4554, 0.1903, 0.148, 1.},
        {0.3874, 0.1903, 0.2815, 1.},
        {0.2815, 0.1903, 0.3874, 1.},
        {0.148, 0.1903, 0.4554, 1.},
        {0.4743, 0.1903, 0.6528, 1.},
        {-0.6528, 0.1903, -0.4743, 1.},
        {-0.7674, 0.1903, -0.2493, 1.},
        {0.6528, 0.1903, 0.4743, 1.},
        {-0.2493, 0.1903, 0.7674, 1.},
        {-0., 0.1903, 0.8068, 1.},
        {-0.8068, 0.1903, 0., 1.},
        {-0.7674, 0.1903, 0.2493, 1.},
        {0.7674, 0.1903, 0.2493, 1.},
        {0.8068, 0.1903, 0., 1.},
        {-0.6528, 0.1903, 0.4743, 1.},
        {-0.4743, 0.1903, 0.6528, 1.},
        {0.7674, 0.1903, -0.2493, 1.},
        {0.6528, 0.1903, -0.4743, 1.},
        {0.4743, 0.1903, -0.6528, 1.},
        {0.2493, 0.1903, -0.7674, 1.},
        {0., 0.1903, -0.8068, 1.},
        {-0.2493, 0.1903, -0.7674, 1.},
        {0.2493, 0.1903, 0.7674, 1.},
        {-0.4743, 0.1903, -0.6528, 1.}
};

// Default world view matrix
float VIEW[4][4] = {
        {1, 0, 0, 0},
        {0, 1, 0, 0},
        {0, 0, 1, -5},
        {0, 0, 0, 1}
};
```

```
// Default world projection matrix
float PROJECTION[4][4] = {
     {2.4178, 0,      0, 0},
     {0,      2.4178, 0, 0},
     {0,      0,     -2, -3},
     {0,      0,     -1, 0}
};

float TRANSLATE[4][4] = {
     {1, 0, 0, 0},
     {0, 1, 0, 0},
     {0, 0, 1, 0},
     {0, 0, 0, 1}
};

float SCALE[4][4] = {
     {1, 0, 0, 0},
     {0, 1, 0, 0},
     {0, 0, 1, 0},
     {0, 0, 0, 1}
};


/* ioctls and their arguments */
#define VGA_LED_WRITE_DIGIT _IOW('q', 1, vga_led_arg_t *)
#define VGA_LED_READ_DIGIT  _IOR('q', 2, vga_led_arg_t *)

#endif
```

```
#ps3.py
#controller parse
import usb.core
import usb.util
import sys
import os

# Scanning the tree for our DualShock 3 controller
controller = usb.core.find(idVendor=0x054c, idProduct=0x0268)

# In case the resource is busy
reattach = False
if controller.is_kernel_driver_active(0):
    reattach = True
    controller.detach_kernel_driver(0)

# Error message for device if not found
if cotroller is None:
    raise ValueError('Device not found')

# Set the active configuration. With no arguments, the first configuration will
be the active one
controller.set_configuration()

# Initialising values
xaxis = 0
yaxis = 0
temp_xaxis = 0
temp_yaxis = 0
prev_stop = 0
```

```
lock = 0
stop = 0

while True:

  # Our “SetupPacket”
  ret = dev.ctrl_transfer(0xa1, 0x1, 0x0101, 0x0, 0x31)

  # Check for anti-clockwise rotation on the x-axis
  if ret[41] == 2:
    if ret[42] <= 110 and ret[42] >= 0:
      xaxis = ret[42]*90/110

      # Limit maximum to 90 degrees
      if xaxis > 90:
      xaxis = 90

  # Check for clockwise rotation on the x-axis
  if ret[41] == 1:
    if ret[42] <= 255 and ret[42] >= 142:
      xaxis = (ret[42] - 255)*90/113

      # Limit maximum to 90 degrees
      if xaxis < -90:
        xaxis = -90

  # Check for anti-clockwise rotation on the y-axis
  if ret[43] == 2:
    if ret[44] <= 110 and ret[44] >= 0:
      yaxis = ret[44]*90/110

      # Limit maximum to 90 degrees
      if yaxis > 90:
        yaxis = 90

  # Check for clockwise rotation on the y-axis
  if ret[43] == 1:
    if ret[42] <= 255 and ret[42] >= 142:
      yaxis = (ret[44] - 255)*90/115

      # Limit maximum to 90 degrees
      if yaxis < -90:
        yaxis = -90

  # Check if 'X' has been pressed, set the stop flag if so
  if ret[3] == 64:
    stop = 1

  # Clear the stop flag if 'X' has been released
  if ret[3] == 0:
    stop = 0

  # This logic sends the pervious rotation values again, so that the
framebuffer can clear the previous render before
  # printing the new one
  if stop == 0:
    lock = 0
    if prev_stop == 1:
      os.system("./hello " + str(temp_yaxis) + " " + str(temp_xaxis) + " " +
str(stop) + " " + str(prev_stop))
      else:
```

```
        os.system("./hello " + str(yaxis) + " " + str(xaxis) + " " + str(stop)
+ " " + str(prev_stop))

      # Storing the previous rotation values
      temp_yaxis = yaxis
      temp_xaxis = xaxis
      prev_stop = 0

    # If the 'X' button has been pressed, send the previous rotation values and
stop sending any new values to prevent
    # the current from being overwritten in the framebuffer
    if stop == 1:
      if lock == 0:
        os.system("./hello " + str(temp_yaxis) + " " + str(temp_xaxis) + " " +
str(stop) + " " + str(prev_stop))
        lock = 1
        prev_stop = 1
```

```
//Makefile
ifneq (${KERNELRELEASE},)

# KERNELRELEASE defined: we are being compiled as part of the Kernel
        obj-m := vga_led.o

else

# We are being compiled as a module: use the Kernel build system

     KERNEL_SOURCE := /usr/src/linux # specify where kernel src is
        PWD := $(shell pwd)

default: module main

main:
     gcc -o main main.c mat_operations.c -lm

module:
     ${MAKE} -C ${KERNEL_SOURCE} SUBDIRS=${PWD} modules

clean:
     ${MAKE} -C ${KERNEL_SOURCE} SUBDIRS=${PWD} clean
     ${RM} hello

socfpga.dtb : socfpga.dtb
     dtc -O dtb -o socfpga.dtb socfpga.dts

endif
```

HARDWARE FILES

```
/*mem_IO.sv
*
 * Avalon memory-mapped peripheral
 */

module mem_IO(input logic      clk,
              input logic                reset,
              input logic [15:0]    writedata,
              input logic                write,
              input logic             chipselect,
              input logic [7:0]      address,  // two bits needed for x,y
coordinates

              output logic [7:0] VGA_R, VGA_G, VGA_B,
              output logic     VGA_CLK, VGA_HS, VGA_VS, VGA_BLANK_n,
              output logic     VGA_SYNC_n);


 typedef enum logic [11:0] {S0, S1} state_t;
 state_t state;

logic                      start, done;
logic [15:0]   v1x, v1y, v1z;
logic [15:0]   v2x, v2y, v2z;
logic [15:0]   v3x, v3y, v3z;
logic [15:0]   pixel_color;
logic               clear_screen;
logic               hide_screen;

shader shader_inst(.*);

   always_ff @(posedge clk)
       if (reset) begin
              state <= S0;
              start <= 1;
       end
     else if (chipselect && write) begin
       case (address)

              /**** Total of 12  addresses to write to
                 0-8: vertices of face to draw
                     9  : 2-bits representing 3 colors to draw. 0 represents
black
                 10 : hide screen signal to hide the display
                     11 : clear screen signal to clear the screen  *****/

              // vertices
              8'd0 : v1x <= writedata;
              8'd1 : v1y <= writedata;
              8'd2 : v1z <= writedata;
              8'd3 : v2x <= writedata;
              8'd4 : v2y <= writedata;
              8'd5 : v2z <= writedata;
              8'd6 : v3x <= writedata;
              8'd7 : v3y <= writedata;
              8'd8 : v3z <= writedata;
```

```
		// color
		8'd9 : pixel_color <= writedata;

		// hide and clear screen signals
		8'd10: begin

			if (writedata == 1) begin
				hide_screen <= 1;
			end
			else begin
				hide_screen <= 0;
			end
		end

		8'd11: begin

			if (writedata == 1) begin
				clear_screen <= 1;
			end

			else begin
				clear_screen <=0;
			end

			// after the last data item is sent start the shader
operation
			state <= S0;
			start <= 1;

		end

	 endcase
	end

	 else begin
		 case (state)
			S0: begin
				if (start) begin
					if (done) begin
						state <= S1;
					end
				end
			end

			S1: begin
				start <= 0;
				state <= S0;
			end
		endcase
	 end
endmodule
```

```
///Shader module


module shader  (
                                input logic                     clk,
                                input logic             reset,
```

```
                                input logic                     start,

                                input logic [15:0]   v1x, v1y, v1z,
                                input logic [15:0]   v2x, v2y, v2z,
                                input logic [15:0]   v3x, v3y, v3z,

                                input logic  [15:0] pixel_color,
                                input logic               clear_screen,
                                input logic                     hide_screen,

                                output logic [7:0] VGA_R, VGA_G, VGA_B,
                                output logic     VGA_CLK, VGA_HS, VGA_VS,
VGA_BLANK_n, VGA_SYNC_n,
                                output logic         done

                                );

    ////////////////////////////////
    //
    //  for sorting input vertices
    //
    ////////////////////////////////


    logic [15:0]   p1x, p1y, p1z;
    logic [15:0]   p2x, p2y, p2z;
    logic [15:0]   p3x, p3y, p3z;

    ////////////////////////////////
    //
    //  divider signals and modules
    //
    ////////////////////////////////


    logic [15:0] dp1p2, dp1p2num, dp1p2den;
    logic [15:0] dp1p3, dp1p3num, dp1p3den;

    // divider signals
    logic start_div;  // start divides
    logic done_div1;  // done dividing
    logic done_div2;

    // divider modules i need for this section
    divider inv_slope1 (clk, reset, start_div, dp1p2num, dp1p2den, dp1p2,
done_div1);
    divider inv_slope2 (clk, reset, start_div, dp1p3num, dp1p3den, dp1p3,
done_div2);


    ////////////////////////////////
    //
    //  draw signals and modules
    //
    ////////////////////////////////


    // draw line signals
    logic rst_draw, start_draw, done_draw;
    logic [15:0] sx1, ex1;
    logic [15:0] pax, pay, paz;
```

```
    logic [15:0] pbx, pby, pbz;
    logic [15:0] pcx, pcy, pcz;
    logic [15:0] pdx, pdy, pdz;
    logic [15:0] y_coord;
    logic [15:0] start_y, end_y;
    logic [15:0] sx, ex;
    logic draw_line_done;


    // wires
    logic line_done;
    logic bresenham_start;
    logic bresenham_done;
    logic pixel_write;
    logic [10:0] pixel_x, pixel_y;
    logic [15:0] z_wire1, z_wire2;
    logic [10:0]  z_buff_wire;



      draw_line draw(
                                                .clk(clk), .reset(reset),
.start(start_draw),
                                                .bresenham_done(bresenham_done),
.y_coord(y_coord),
                                                .pax(pax), .pay(pay), .paz(paz),
.pbx(pbx), .pby(pby), .pbz(pbz),
                                                .pcx(pcx), .pcy(pcy), .pcz(pcz),
.pdx(pdx), .pdy(pdy), .pdz(pdz),
                                                .done(draw_line_done),
.draw(bresenham_start), .start_x(sx), .end_x(ex),
                                                .zout1(z_wire1), .zout2(z_wire2)
                                            );

      put_pixel put_pixel_inst(
                                                  .clk(clk),
.reset(reset), .start(bresenham_start),
                                                  .x0(sx),
.y0(y_coord), .x1(ex), .y1(y_coord),

.plot(pixel_write), .x(pixel_x), .y(pixel_y), .done(bresenham_done),
                                                  .z1(z_wire1),
.z2(z_wire2), .z_out(z_buff_wire)
                                                );

      VGA_framebuffer screen(
                                                .clk50(clk),
.reset(reset), .x(pixel_x), .y(pixel_y), .z(z_buff_wire),

    .pixel_color(pixel_color), .pixel_write(pixel_write),
.clear_screen(clear_screen),
                                                .VGA_R(VGA_R),
.VGA_G(VGA_G), .VGA_B(VGA_B), .hide_screen(hide_screen),
                                                .VGA_CLK(VGA_CLK),
.VGA_HS(VGA_HS), .VGA_VS(VGA_VS), .VGA_BLANK_n(VGA_BLANK_n),
.VGA_SYNC_n(VGA_SYNC_n)

                                               );


    ////////////////////////////////
```

```
	//
	//  state defs
	//
	////////////////////////////////

	typedef enum logic [6:0] {S0, S1, S2, S3, S4, S5, S6} state_t;
	state_t state;



	////////////////////////////////////////////////////////
	//
	// Start Shader FSM
	//
	////////////////////////////////////////////////////////


	always_ff @(posedge clk) begin
	  if (reset) begin
		state <= S0;
		done <= 0;
	  end

	  else begin
		case (state)

			S0: begin  // sorting state
				done <= 0;
				if (start) begin

					// sort incoming vertices
					if ((v1y < v2y) & (v1y < v3y)) begin  // if V1
is the smallest vertex
						p1x = v1x;  // first vertex is V1
						p1y = v1y;
						p1z = v1z;

						if (v2y > v3y) begin  // if V2 is
bigger than V3,
							p2x = v3x;  // second vertex is
V3
							p2y = v3y;
							p2z = v3z;

							p3x = v2x;  // third vertex is V2
							p3y = v2y;
							p3z = v2z;
						end

						else begin  // if V3 is bigger than V2,
							p2x = v2x;  // second vertex is
V2
							p2y = v2y;
							p2z = v2z;

							p3x = v3x;  // third vertex is V3
							p3y = v3y;
							p3z = v3z;
						end
```

```
                                end

                                else if ((v2y < v1y) & (v2y < v3y)) begin  //
if V2 is the largest vertex
                                       p1x = v2x;  // first vertex is V2
                                       p1y = v2y;
                                       p1z = v2z;

                                       if (v1y > v3y) begin  // if V1 is
bigger than V3,
                                              p2x = v3x;  // second vertex is
V1
                                              p2y = v3y;
                                              p2z = v3z;

                                              p3x = v1x;  // third vertex is V3
                                              p3y = v1y;
                                              p3z = v1z;
                                       end

                                       else begin  // if V2 is bigger than V1,
                                              p2x = v1x;  // second vertex is
V3
                                              p2y = v1y;
                                              p2z = v1z;

                                              p3x = v3x;  // third vertex is V2
                                              p3y = v3y;
                                              p3z = v3z;
                                       end
                                end

                                else begin
                                       p1x = v3x;  // first vertex is V2
                                       p1y = v3y;
                                       p1z = v3z;

                                       if (v1y > v2y) begin  // if V1 is
bigger than V3,
                                              p2x = v2x;  // second vertex is
V1
                                              p2y = v2y;
                                              p2z = v2z;

                                              p3x = v1x;  // third vertex is V3
                                              p3y = v1y;
                                              p3z = v1z;
                                       end

                                       else begin  // if V2 is bigger than V1,
                                              p2x = v1x;  // second vertex is
V3
                                              p2y = v1y;
                                              p2z = v1z;

                                              p3x = v2x;  // third vertex is V2
                                              p3y = v2y;
                                              p3z = v2z;
                                       end
                                end
                                state <= S1;
```

```
                        end
                    end

                    S1: begin  // calculate numerators and denominators for
inverse slopes
                        if (p2y > p1y) begin
                            dp1p2num = p2x - p1x;
                            dp1p2den = p2y - p1y;
                        end
                        else begin    // forces dp1p2 to 0 if slope is
negative
                            dp1p2num = 0;
                            dp1p2den = 1;
                        end

                        if (p3y > p1y) begin
                            dp1p3num = p3x - p1x;
                            dp1p3den = p3y - p1y;
                        end
                        else begin  // forces dp1p3 to 0 if slope is negative
                            dp1p3num = 0;
                            dp1p3den = 1;
                        end

                        state <= S2;
                    end


                    S2: begin
                        start_div <= 1; // divide the inverse slopes

                        if (done_div1 & done_div2) begin  // wait until the
divides are done
                            state <= S3;
                            start_div <= 0;
                        end
                    end


                    S3: begin  // at this point inverse slopes dp1p2 and dp1p3
are ready

                        //
                        start_y = p1y >> 5;
                        end_y = (p3y >> 5) + 1;
                        y_coord = start_y;

                        state <= S4;
                    end


                    S4: begin  // sort vertices to be drawn for given y_coord.
this determines if we're in Step1 or Step2 of the triangle
                        if (dp1p2num * dp1p3den > dp1p3num * dp1p2den) begin
                            if ( (y_coord << 5) < p2y) begin
                                pax = p1x;
                                pay = p1y;
                                paz = p1z;

                                pbx = p3x;
                                pby = p3y;
```

```
                pbz = p3z;

                pcx = p1x;
                pcy = p1y;
                pcz = p1z;

                pdx = p2x;
                pdy = p2y;
                pdz = p2z;
        end

        else begin
                pax = p1x;
                pay = p1y;
                paz = p1z;

                pbx = p3x;
                pby = p3y;
                pbz = p3z;

                pcx = p2x;
                pcy = p2y;
                pcz = p2z;

                pdx = p3x;
                pdy = p3y;
                pdz = p3z;
        end
end

else begin
        if ( (y_coord << 5) < p2y) begin
                pax = p1x;
                pay = p1y;
                paz = p1z;

                pbx = p2x;
                pby = p2y;
                pbz = p2z;

                pcx = p1x;
                pcy = p1y;
                pcz = p1z;

                pdx = p3x;
                pdy = p3y;
                pdz = p3z;
        end

        else begin
                pax = p2x;
                pay = p2y;
                paz = p2z;

                pbx = p3x;
                pby = p3y;
                pbz = p3z;

                pcx = p1x;
                pcy = p1y;
                pcz = p1z;
```

```
                                        pdx = p3x;
                                        pdy = p3y;
                                        pdz = p3z;
                                end
                        end
                        state <= S5;
                end



                S5: begin
                        start_draw <= 1; // draw current line

                        if (draw_line_done) begin               // wait until
the draw is done before we change states
                                y_coord = y_coord + 1;          // increment
the y coordinate for next line to draw
                                start_draw <= 0;                        //
make sure to set start_draw back to 0 when we're done
                                state <= S6;
                        end
                end


                S6: begin

                        if (y_coord < end_y) begin
                                state <= S4;                    // jump back
to S3 to draw the next line for new y_coord
                        end

                        else begin  // here we've finished shading the
current triangle
                                done <= 1;
                                state <= S0;                // go back to
reset state
                        end
                end  // end state S5

            endcase
       end
     end
endmodule
```

```
//DETERMINES START X AND END X, FOR EVERY LINE IN TRIANGLE
module draw_line(input logic clk,
                          input logic reset,
                          input logic start,
                          input logic bresenham_done,
                          input logic [15:0] y_coord,
                          input logic [15:0] pax, pay, paz,
                          input logic [15:0] pbx, pby, pbz,
                          input logic [15:0] pcx, pcy, pcz,
                          input logic [15:0] pdx, pdy, pdz,

                          output logic done,
                          output logic draw,
                          output logic [15:0] zout1, zout2,
                          output logic [15:0] start_x, end_x
                          );
```

```
    typedef enum logic [8:0] {S0, S1, S2, S3, S4, S5, S6, S7, S8} state_t;
    state_t state;


    // internal signals
    logic [15:0] gradient1num, gradient1den;
    logic [15:0] gradient2num, gradient2den;
    logic [15:0] gradientznum, gradientzden;
    logic [15:0] gradient1;
    logic [15:0] gradient2;
    logic [15:0] gradientz;
    logic [15:0] temp_y;

    logic [15:0] sx, ex, z1, z2, z;
    logic [15:0] temp_x;

    // signals requred for the dividers
    logic rst_div;        // reset signal for divider
    logic start_div;  // start divides
    logic done_div1;  // done dividing
    logic done_div2;
    logic done_div3;

    // dividers required
    divider14 div1(clk, reset, start_div, gradient1num, gradient1den,
gradient1, done_div1);
    divider14 div2(clk, reset, start_div, gradient2num, gradient2den,
gradient2, done_div2);
    divider14 div3(clk, reset, start_div, gradientznum, gradientzden,
gradientz, done_div3);

    // signals for interpolation modules
    logic start_int;
    logic done_int_sx;
    logic done_int_ex;
    logic done_int_z1;
    logic done_int_z2;
    logic done_int_z;


    // interpolation module initialization
    interpolate interpolate_sx( .clk(clk), .start(start_int), .reset(reset),
                                                        .min_val(pax),
.max_val(pbx), .gradient(gradient1),

.done(done_int_sx), .val(sx) );

    interpolate interpolate_ex( .clk(clk), .start(start_int), .reset(reset),
                                                        .min_val(pcx),
.max_val(pdx), .gradient(gradient2),

.done(done_int_ex), .val(ex) );

    interpolate interpolate_z1( .clk(clk), .start(start_int), .reset(reset),
                                                        .min_val(paz),
.max_val(pbz), .gradient(gradient1),

.done(done_int_z1), .val(z1) );

    interpolate interpolate_z2( .clk(clk), .start(start_int), .reset(reset),
```

```
                                                        .min_val(pcz),
.max_val(pdz), .gradient(gradient2),

.done(done_int_z2), .val(z2) );



     always_ff @(posedge clk) begin
       temp_y = y_coord << 5;
       if (reset) begin
              state <= S0;
       end

       else begin
              case (state)

                     S0: begin

                            ////////////////////////////////////
                            //
                            //  Calculate num and den
                            //  of the gradients
                            //
                            ////////////////////////////////////

                            if (start) begin

                                   if (pay != pby) begin
                                          gradient1num = temp_y - pay;
                                          gradient1den = pby - pay;
                                   end
                                   else begin
                                          gradient1num = 1;
                                          gradient1den = 1;
                                   end

                                   if (pcy != pdy) begin
                                          gradient2num = (temp_y - pcy);
                                          gradient2den = (pdy - pcy);
                                   end
                                   else begin
                                          gradient2num = 1;
                                          gradient2den = 1;
                                   end

                                   rst_div <= 1; // reset the dividers to get
them ready
                                   state <= S1;
                            end

                     end


                     S1: begin

                            ////////////////////////////////////////////////
                            //
                            //  Since we have num and den for each gradient,
                            //  we can now divide these values to get the
                            //  actual gradients.
                            //
```

```
                        ////////////////////////////////////////////////

                        rst_div <= 0;       // bring reset back to 0
                        start_div <= 1;   // start the dividers

                        if (done_div1 & done_div2) begin
                                start_div <= 0;
                                state <= S2;
                        end
                end


                S2: begin

                        start_int <= 1; // start all interpolations

                        if (done_int_z1 & done_int_z2 & done_int_ex &
done_int_sx ) begin  // wait until the interpolations are done

                                start_int <= 0; // deassert the interpolations

                                // output z1 and z2 for z-buffer calculations
                                zout1 = z1;
                                zout2 = z2;

                                if (sx > ex) begin
                                        temp_x = sx;
                                        start_x = ex >> 5;
                                        end_x = temp_x >> 5;
                                end

                                else begin
                                        start_x = sx >> 5;
                                        end_x = ex >> 5;
                                end

                                draw <= 1;
                                state <= S3;
                        end
                end


                S3: begin  // figure out temp_product for gradient1

                        // at this point we have sx, ex, z1 and z2. need to
calculate gradients for z
                        draw <= 0;

                        if (bresenham_done) begin  // when bresenham is done
                                done <= 1;
                        end

                        if (~start) begin  // wait until start is deasserted
                                done <= 0;
                                state <= S0;
                        end;
                end

        endcase
      end
    end
```

```
endmodule
```

```
//CALCULATES Z VALUES, AND SENDS TO FRAME BUFFER
module put_pixel(input logic clk, reset,
                            input logic start,
                            input logic [15:0] x0, y0, x1, y1,
                            input logic [15:0] z1, z2,

                            output logic plot,
                            output logic [10:0] x, y,
                            output logic [10:0] z_out,
                            output logic done);

     typedef enum logic [9:0] {S0, S1, S2, S3, S4, S5, S6, S7, S8} state_t;
     state_t state;

     logic [15:0] x_coord;
     logic [15:0] y_coord;
     logic [15:0] z_coord;


     // divider stuff
     logic [15:0] gradientnum, gradientden, gradient;
     logic start_div;  // start divides
     logic done_div;

     // dividers required
     divider14 div1(clk, reset, start_div, gradientnum, gradientden, gradient,
done_div);

     // signals for interpolation modules
     logic start_int;
     logic done_int;

     // higher resolution interpolate block
     interpolate7 interpolate_inst( .clk(clk), .start(start_int),
.reset(reset),
                                                          .min_val(z1 << 2),
.max_val(z2 << 2), .gradient(gradient), // z1 and z2 need to be promoted to Q7
for a higher resolution interpolation
                                                              .done(done_int),
.val(z_coord) );


     always_ff @(posedge clk) begin
       if (reset) begin
              done <= 0;
              state <= S0;
       end

       else begin
              case (state)

                     S0: begin  // get initial signals to start with
                            if (start) begin
                                   x_coord = x0;
                                   y_coord = y0;
                                   x = x_coord;
                                   y = y0;
                                   state <= S1;
```

```
                        end
                end

                S1: begin
                        if (x1 == x0) begin // if start x and end x are the
same -> force gradient to 0
                                gradientnum = 0;
                                gradientden = 1;
                        end

                        else begin
                                gradientnum = (x_coord << 5) - (x0 << 5);
                                gradientden = (x1 << 5) - (x0 << 5);
                        end

                        start_div = 1;

                        if(done_div) begin
                                start_div <= 0;
                                start_int <= 1; // since gradients are
available, start interpolation for z-value
                                state <= S2;
                        end
                end

                S2: begin
                        if(done_int) begin  // when interpolation for z is
done
                                z_out <= (z_coord);
                                start_int <= 0;
                                plot <= 1;
                                state <= S3;
                        end
                end


                S3: begin
                        plot = 0;  // de-assert plot signal
                        x_coord = x_coord + 1;  // increment x_coord to place
next pixxel in the line
                        state <= S4;
                end


                S4: begin
                        if (x_coord > x1) begin  // check if we've exceeded
ex. If so, we're done with the line and we can finish
                                done <= 1;
                                state <= S5;
                        end
                        else begin  // otherwise keep going to the next x-
value
                                x = x_coord;
                                state <= S6;
                        end
                end

                S5: begin  // clean up the signals
                        done <= 0;
                        state <= S0;
                end
```

```
                    S6: begin
                          state <= S1;
                    end
                endcase
        end
      end
endmodule
```

```
///VGA FRAME BUFFER

module VGA_framebuffer(
 input logic     clk50, reset,
 input logic [10:0]  x,  // pixel x_coordinate
 input logic [10:0]  y,  // pixel y_coordinate
 input logic [10:0]  z,  // pixel z_coordinate
 input logic [15:0]              pixel_color,
 input logic                           pixel_write,
 input logic                           clear_screen,
 input logic                           hide_screen,

 output logic [7:0] VGA_R, VGA_G, VGA_B,
 output logic           VGA_CLK, VGA_HS, VGA_VS, VGA_BLANK_n, VGA_SYNC_n);

/*
 * 640 X 480 VGA timing for a 50 MHz clock: one pixel every other cycle
 *
 *HCOUNT 1599 0             1279       1599 0
 *                _________________             ________
 * ___________|    Video      |_____________|  Video
 *
 *
 * |SYNC| BP |<-- HACTIVE -->|FP|SYNC| BP |<-- HACTIVE
 *       _____________________      _____________
 * |____|       VGA_HS          |____|
 */

   parameter HACTIVE      = 11'd 1280,
             HFRONT_PORCH = 11'd 32,
             HSYNC        = 11'd 192,
             HBACK_PORCH  = 11'd 96,
             HTOTAL       = HACTIVE + HFRONT_PORCH + HSYNC + HBACK_PORCH;
//1600

   parameter VACTIVE      = 10'd 480,
             VFRONT_PORCH = 10'd 10,
             VSYNC        = 10'd 2,
             VBACK_PORCH  = 10'd 33,
             VTOTAL       = VACTIVE + VFRONT_PORCH + VSYNC + VBACK_PORCH; //525


     // Horizontal counter
   logic [10:0]             hcount;
   logic                       endOfLine;

   always_ff @(posedge clk50 or posedge reset)
     if (reset)          hcount <= 0;
     else if (endOfLine) hcount <= 0;
     else             hcount <= hcount + 11'd 1;
```

```
assign endOfLine = hcount == HTOTAL - 1;

// Vertical counter
logic [9:0]                       vcount;
logic                        endOfField;

always_ff @(posedge clk50 or posedge reset)
  if (reset) vcount <= 0;
  else if (endOfLine)
    if (endOfField)   vcount <= 0;
    else              vcount <= vcount + 10'd 1;

assign endOfField = vcount == VTOTAL - 1;

// Horizontal sync: from 0x520 to 0x57F
// 101 0010 0000 to 101 0111 1111
assign VGA_HS = !( (hcount[10:7] == 4'b1010) & (hcount[6] | hcount[5]));
assign VGA_VS = !( vcount[9:1] == (VACTIVE + VFRONT_PORCH) / 2);

assign VGA_SYNC_n = 1; // For adding sync to video signals; not used for VGA


  logic                       blank;
// Horizontal active: 0 to 1279     Vertical active: 0 to 479
// 101 0000 0000  1280         01 1110 0000  480
// 110 0011 1111  1599         10 0000 1100  524
assign blank = ( hcount[10] & (hcount[9] | hcount[8]) ) |
                              ( vcount[9] | (vcount[8:5] == 4'b1111) );


  logic    [1:0]         framebuffer [262143:0];  // 640 x 480
  logic    [18:0]        read_address, write_address;

  assign write_address = x + (y << 9) + (y << 7);
  assign read_address = (hcount >> 1) + (vcount << 9) + (vcount << 7);


  /*************************************************************
  *
  *
  *        Pixel write code using z-buffering
  *
  *
  *************************************************************/

  logic zbuffer_clear, zbuffer_write;
  logic  [10:0] zbuffer_rdata;
  logic  [10:0] zbuffer_wdata;
  logic  [18:0] temp_addr;
  logic write_fb;

  // initialize zbuffer RAM block
  zbuffer zbuffer_shader (
  .aclr(zbuffer_clear),
  .address(write_address[17:0]),
  .clock(clk50),
  .data(zbuffer_wdata),
  .wren(zbuffer_write),
  .q(zbuffer_rdata));

  typedef enum logic [2:0] {S0, S1, S2} state_t;
```

```
	state_t state;

	always_ff @ (posedge clk50) begin
	  if (reset) begin
		write_fb <= 0;
		zbuffer_clear <= 0;
		zbuffer_write <= 0;
		state <= S0;
	  end

	  else begin
		case (state)
			S0: begin
				if (pixel_write) begin

					if (clear_screen) begin
						zbuffer_wdata <= 11'b0000000000;
					end

					else begin
						zbuffer_wdata <= z;
					end
					state <= S1;
				end

			end

			S1: begin

				if (clear_screen) begin
					write_fb <= 1;
					zbuffer_write <= 1;
				end

				else if (zbuffer_rdata == 0) begin  // first time
around will be 0
					write_fb <= 1;  // so just draw the pixels
					zbuffer_write <= 1;
				end

				else if (zbuffer_rdata >= z) begin  // otherwise
check the z buffer with the new incoming z
					write_fb <= 1;
					zbuffer_write <= 1;
				end

				state <= S2;
			end

			S2: begin
				// cleanup signals
				write_fb <= 0;
				zbuffer_write <= 0;
				zbuffer_clear <= 0;
				state <= S0;  // go to S0 and wait for next pixel
write
			end

		endcase
	  end
	end
```

```
    logic [1:0]                         pixel_read;

    always_ff @(posedge clk50) begin
      if (write_fb) framebuffer[write_address] <= pixel_color[1:0];

      if (hcount[0]) begin
            pixel_read <= framebuffer[read_address];
            VGA_BLANK_n <= ~blank;  // sync blank with read pixel data
      end
    end

    assign VGA_CLK = hcount[0];  // 25MHz clock

    always_ff @(posedge clk50) begin

      if (hide_screen) begin

            {VGA_R, VGA_G, VGA_B} = 24'h0;  // hide the screen from any
updates

      end
      else if (pixel_read == 2'b01) begin
            {VGA_R, VGA_G, VGA_B} = {8'hca, 8'he1, 8'hff};  // light blue
      end
      else if (pixel_read == 2'b10) begin
            {VGA_R, VGA_G, VGA_B} = {8'h48, 8'h76, 8'hff};  // medium blue
      end
      else if (pixel_read == 2'b11) begin
            {VGA_R, VGA_G, VGA_B} = {8'h27, 8'h40, 8'hab};  // dark blue
      end
      else begin
            {VGA_R, VGA_G, VGA_B} = 24'h0;
      end
    end

endmodule
```

```
/////// MEGAFUNCTION GENERATED  FILE FOR MEMORY RAM BLOCK USED FOR Z BUFFERING
// megafunction wizard: %RAM: 1-PORT%
// GENERATION: STANDARD
// VERSION: WM1.0
// MODULE: altsyncram

// ============================================================
// File Name: zbuffer.v
// Megafunction Name(s):
//            altsyncram
//
// Simulation Library Files(s):
//            altera_mf
// ============================================================
// ************************************************************
// THIS IS A WIZARD-GENERATED FILE. DO NOT EDIT THIS FILE!
//
// 13.1.1 Build 166 11/26/2013 SJ Full Version
// ************************************************************


//Copyright (C) 1991-2013 Altera Corporation
```

```
//Your use of Altera Corporation's design tools, logic functions
//and other software and tools, and its AMPP partner logic
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//(including device programming or simulation files), and any
//associated documentation or information are expressly subject
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//Agreement, or other applicable license agreement, including,
//without limitation, that your use is for the sole purpose of
//programming logic devices manufactured by Altera and sold by
//Altera or its authorized distributors.  Please refer to the
//applicable agreement for further details.


// synopsys translate_off
`timescale 1 ps / 1 ps
// synopsys translate_on
module zbuffer (
     aclr,
     address,
     clock,
     data,
     wren,
     q);

     input     aclr;
     input   [17:0]  address;
     input     clock;
     input   [10:0]  data;
     input     wren;
     output  [10:0]  q;
`ifndef ALTERA_RESERVED_QIS
// synopsys translate_off
`endif
     tri0      aclr;
     tri1      clock;
`ifndef ALTERA_RESERVED_QIS
// synopsys translate_on
`endif

     wire [10:0] sub_wire0;
     wire [10:0] q = sub_wire0[10:0];

     altsyncram     altsyncram_component (
                    .aclr0 (aclr),
                    .address_a (address),
                    .clock0 (clock),
                    .data_a (data),
                    .wren_a (wren),
                    .q_a (sub_wire0),
                    .aclr1 (1'b0),
                    .address_b (1'b1),
                    .addressstall_a (1'b0),
                    .addressstall_b (1'b0),
                    .byteena_a (1'b1),
                    .byteena_b (1'b1),
                    .clock1 (1'b1),
                    .clocken0 (1'b1),
                    .clocken1 (1'b1),
                    .clocken2 (1'b1),
                    .clocken3 (1'b1),
```

```
                    .data_b (1'b1),
                    .eccstatus (),
                    .q_b (),
                    .rden_a (1'b1),
                    .rden_b (1'b1),
                    .wren_b (1'b0));
    defparam
      altsyncram_component.clock_enable_input_a = "BYPASS",
      altsyncram_component.clock_enable_output_a = "BYPASS",
      altsyncram_component.intended_device_family = "Cyclone V",
      altsyncram_component.lpm_hint = "ENABLE_RUNTIME_MOD=NO",
      altsyncram_component.lpm_type = "altsyncram",
      altsyncram_component.numwords_a = 262144,
      altsyncram_component.operation_mode = "SINGLE_PORT",
      altsyncram_component.outdata_aclr_a = "CLEAR0",
      altsyncram_component.outdata_reg_a = "CLOCK0",
      altsyncram_component.power_up_uninitialized = "FALSE",
      altsyncram_component.read_during_write_mode_port_a =
"NEW_DATA_NO_NBE_READ",
      altsyncram_component.widthad_a = 18,
      altsyncram_component.width_a = 11,
      altsyncram_component.width_byteena_a = 1;


endmodule

// ============================================================
// CNX file retrieval info
// ============================================================
// Retrieval info: PRIVATE: ADDRESSSTALL_A NUMERIC "0"
// Retrieval info: PRIVATE: AclrAddr NUMERIC "0"
// Retrieval info: PRIVATE: AclrByte NUMERIC "0"
// Retrieval info: PRIVATE: AclrData NUMERIC "0"
// Retrieval info: PRIVATE: AclrOutput NUMERIC "1"
// Retrieval info: PRIVATE: BYTE_ENABLE NUMERIC "0"
// Retrieval info: PRIVATE: BYTE_SIZE NUMERIC "8"
// Retrieval info: PRIVATE: BlankMemory NUMERIC "1"
// Retrieval info: PRIVATE: CLOCK_ENABLE_INPUT_A NUMERIC "0"
// Retrieval info: PRIVATE: CLOCK_ENABLE_OUTPUT_A NUMERIC "0"
// Retrieval info: PRIVATE: Clken NUMERIC "0"
// Retrieval info: PRIVATE: DataBusSeparated NUMERIC "1"
// Retrieval info: PRIVATE: IMPLEMENT_IN_LES NUMERIC "0"
// Retrieval info: PRIVATE: INIT_FILE_LAYOUT STRING "PORT_A"
// Retrieval info: PRIVATE: INIT_TO_SIM_X NUMERIC "0"
// Retrieval info: PRIVATE: INTENDED_DEVICE_FAMILY STRING "Cyclone V"
// Retrieval info: PRIVATE: JTAG_ENABLED NUMERIC "0"
// Retrieval info: PRIVATE: JTAG_ID STRING "NONE"
// Retrieval info: PRIVATE: MAXIMUM_DEPTH NUMERIC "0"
// Retrieval info: PRIVATE: MIFfilename STRING ""
// Retrieval info: PRIVATE: NUMWORDS_A NUMERIC "262144"
// Retrieval info: PRIVATE: RAM_BLOCK_TYPE NUMERIC "0"
// Retrieval info: PRIVATE: READ_DURING_WRITE_MODE_PORT_A NUMERIC "3"
// Retrieval info: PRIVATE: RegAddr NUMERIC "1"
// Retrieval info: PRIVATE: RegData NUMERIC "1"
// Retrieval info: PRIVATE: RegOutput NUMERIC "1"
// Retrieval info: PRIVATE: SYNTH_WRAPPER_GEN_POSTFIX STRING "0"
// Retrieval info: PRIVATE: SingleClock NUMERIC "1"
// Retrieval info: PRIVATE: UseDQRAM NUMERIC "1"
// Retrieval info: PRIVATE: WRCONTROL_ACLR_A NUMERIC "0"
// Retrieval info: PRIVATE: WidthAddr NUMERIC "18"
// Retrieval info: PRIVATE: WidthData NUMERIC "11"
```

```
// Retrieval info: PRIVATE: rden NUMERIC "0"
// Retrieval info: LIBRARY: altera_mf altera_mf.altera_mf_components.all
// Retrieval info: CONSTANT: CLOCK_ENABLE_INPUT_A STRING "BYPASS"
// Retrieval info: CONSTANT: CLOCK_ENABLE_OUTPUT_A STRING "BYPASS"
// Retrieval info: CONSTANT: INTENDED_DEVICE_FAMILY STRING "Cyclone V"
// Retrieval info: CONSTANT: LPM_HINT STRING "ENABLE_RUNTIME_MOD=NO"
// Retrieval info: CONSTANT: LPM_TYPE STRING "altsyncram"
// Retrieval info: CONSTANT: NUMWORDS_A NUMERIC "262144"
// Retrieval info: CONSTANT: OPERATION_MODE STRING "SINGLE_PORT"
// Retrieval info: CONSTANT: OUTDATA_ACLR_A STRING "CLEAR0"
// Retrieval info: CONSTANT: OUTDATA_REG_A STRING "CLOCK0"
// Retrieval info: CONSTANT: POWER_UP_UNINITIALIZED STRING "FALSE"
// Retrieval info: CONSTANT: READ_DURING_WRITE_MODE_PORT_A STRING
"NEW_DATA_NO_NBE_READ"
// Retrieval info: CONSTANT: WIDTHAD_A NUMERIC "18"
// Retrieval info: CONSTANT: WIDTH_A NUMERIC "11"
// Retrieval info: CONSTANT: WIDTH_BYTEENA_A NUMERIC "1"
// Retrieval info: USED_PORT: aclr 0 0 0 0 INPUT GND "aclr"
// Retrieval info: USED_PORT: address 0 0 18 0 INPUT NODEFVAL "address[17..0]"
// Retrieval info: USED_PORT: clock 0 0 0 0 INPUT VCC "clock"
// Retrieval info: USED_PORT: data 0 0 11 0 INPUT NODEFVAL "data[10..0]"
// Retrieval info: USED_PORT: q 0 0 11 0 OUTPUT NODEFVAL "q[10..0]"
// Retrieval info: USED_PORT: wren 0 0 0 0 INPUT NODEFVAL "wren"
// Retrieval info: CONNECT: @aclr0 0 0 0 0 aclr 0 0 0 0
// Retrieval info: CONNECT: @address_a 0 0 18 0 address 0 0 18 0
// Retrieval info: CONNECT: @clock0 0 0 0 0 clock 0 0 0 0
// Retrieval info: CONNECT: @data_a 0 0 11 0 data 0 0 11 0
// Retrieval info: CONNECT: @wren_a 0 0 0 0 wren 0 0 0 0
// Retrieval info: CONNECT: q 0 0 11 0 @q_a 0 0 11 0
// Retrieval info: GEN_FILE: TYPE_NORMAL zbuffer.v TRUE
// Retrieval info: GEN_FILE: TYPE_NORMAL zbuffer.inc FALSE
// Retrieval info: GEN_FILE: TYPE_NORMAL zbuffer.cmp FALSE
// Retrieval info: GEN_FILE: TYPE_NORMAL zbuffer.bsf FALSE
// Retrieval info: GEN_FILE: TYPE_NORMAL zbuffer_inst.v FALSE
// Retrieval info: GEN_FILE: TYPE_NORMAL zbuffer_bb.v TRUE
// Retrieval info: LIB_FILE: altera_mf
```

```
/** INTERPOLATE MODULE */
module interpolate ( input logic clk,
                                        input logic start,
                                        input logic reset,
                                        input logic [15:0] min_val,
                                        input logic [15:0] max_val,
                                        input logic [15:0] gradient,

                                        output logic done,
                                        output logic [15:0] val );

    ////////////////////////
    //
    //  internal signals
    //
    ////////////////////////

    logic [31:0] temp_product;  // Q.19 format
    logic [31:0] product;  // Q.19 format

    typedef enum logic [8:0] {S0, S1, S2, S3, S4, S5, S6, S7, S8} state_t;
    state_t state;
```

```
      always_ff @(posedge clk) begin
        if (reset) begin
               done <= 0;
               state <= S0;
        end
        else begin
               case (state)


                      S0: begin  // calculate the product term
                             done <= 0;
                             if (start) begin
                                    temp_product = (max_val - min_val) * gradient;
                                    state <= S1;
                             end
                      end



                      S1: begin  // get magnitude of product term
                             if (temp_product[31]) begin
                                    product = ~(temp_product - 1);
                             end
                             else begin
                                    product = temp_product;
                             end
                             state <= S2;
                      end



                      S2: begin  // shift to get Q.5
                             if (temp_product[31]) begin
                                    product = ~(product >> 14) + 1;
                             end
                             else begin
                                    product = product >> 14;
                             end
                             state <= S3;
                      end



                      S3: begin

                             if (gradient[15]) begin  // gradient < 0
                                    val = min_val;  // gradient = 0;
                             end

                             else if ( (gradient >> 14) >= 1) begin
                                    val = min_val + (max_val - min_val); //
gradient = 1;
                             end

                             else begin
                                    val = min_val + product;
                             end

                             done <= 1;  // we're done!

                             if (~start) begin
```

```
                                state <= S0;
                        end
                end


        endcase
    end
  end

endmodule
```

```
/** HIGH RESOLUTION INTERPOLATE - USED FOR Z BUFFERING- 7 BITS FRACTIONAL, 3
BITS INTEGER UNSIGNED**/
module interpolate7 ( input logic clk,
                                        input logic start,
                                        input logic reset,
                                        input logic [15:0] min_val, // Q.7
format
                                        input logic [15:0] max_val, // Q.7
format
                                        input logic [15:0] gradient,// Q.14
format

                                        output logic done,
                                        output logic [15:0] val );

  //////////////////////////
  //
  //  internal signals
  //
  //////////////////////////

  logic [31:0] temp_product;  // Q.21 format
  logic [31:0] product;  // Q.21 format

  typedef enum logic [8:0] {S0, S1, S2, S3, S4, S5, S6, S7, S8} state_t;
  state_t state;

  always_ff @(posedge clk) begin
    if (reset) begin
          done <= 0;
          state <= S0;
    end
    else begin
          case (state)


                S0: begin  // calculate the product term
                      done <= 0;
                      if (start) begin
                            temp_product = (max_val - min_val) * gradient;
                            state <= S1;
                      end
                end



                S1: begin  // get magnitude of product term
                      if (temp_product[31]) begin
                            product = ~(temp_product - 1);
                      end
```

```
                        else begin
                                product = temp_product;
                        end
                        state <= S2;
                end



                S2: begin  // shift to get Q.11
                        if (temp_product[31]) begin
                                product = ~(product >> 14) + 1;
                        end
                        else begin
                                product = product >> 14;
                        end
                        state <= S3;
                end



                S3: begin

                        // clamps gradient between 0 and 1

                        if (gradient[15]) begin  // gradient < 0
                                val = (min_val);
                        end

                        else if ( (gradient >> 14) >= 1) begin
                                val = (min_val + (max_val - min_val)); //
gradient = 1;
                        end

                        else begin
                                val = (min_val + product);
                        end

                        done <= 1;  // we're done!

                        if (~start) begin
                                state <= S0;
                        end
                end


            endcase
      end
    end

endmodule
```

```
/* SIGNED FIXED POINT DIVIDER */
module divider(input clk,
                        input reset,
                        input start,
                        input logic [15:0] num,
                    input logic [15:0] den,

                        output logic [15:0] result,
                        output logic done);
```

```
    typedef enum logic [3:0] {S0, S1, S2, S3} state_t;
    state_t state;

    logic [15:0] temp_num;
    logic [15:0] temp_den;
    logic [15:0] temp_result;

    always_ff @(posedge clk) begin
      done <= 0;
      if (reset) begin
             state <= S0;
      end

      else begin
             case (state)
                    S0: begin
                           if (start) begin
                                  if (num[15] & den[15]) begin  // if both the
num and den are negative
                                         // divide only the magnitudes
                                         temp_num = ~(num - 1);
                                         temp_den = ~(den - 1);
                                         state <= S1;
                                  end

                                  // following two conditions make sure the
result is negative

                                  else if (num[15] & ~den[15]) begin  // if only
num is negative
                                         temp_num = ~(num - 1);  // get
magnitude of the numerator
                                         temp_den = den;
                                         state <= S2;
                                  end

                                  else if (~num[15] & den[15]) begin // if only
den is negative
                                         temp_num = num;
                                         temp_den = ~(den - 1);
                                         state <= S2;
                                  end

                                  else begin  // both numbers are positive
                                         temp_num = num;
                                         temp_den = den;
                                         state <= S1;
                                  end
                           end
                    end

                    S1: begin  // result is positive
                           result = (temp_num << 10) / (temp_den << 5);
                           done <= 1;

                           if (~start) begin
                           done <= 0;
                                  state <= S0;
                           end
                    end
```

```
                    S2: begin  // result is negative
                           temp_result = (temp_num << 10) / (temp_den << 5);
                           result = ~(temp_result) + 1; // maintains Qx.5 format
                           done <= 1;

                           if (~start) begin
                                  done <= 0;
                                  state <= S0;
                           end
                    end

             endcase
       end

     end

endmodule
```

```
/* HIGH RESOLUTION DIVIDER WITH 14 BITS FOR THE FRACTION NUMBER, 1 BIT FOR
INTEGER AND SIGNED BIT*/
module divider14(input clk,
                           input reset,
                           input start,
                           input logic [15:0] num,
                        input logic [15:0] den,

                           output logic [15:0] result,
                           output logic done);

     typedef enum logic [3:0] {S0, S1, S2, S3} state_t;
     state_t state;

     logic [15:0] temp_num;
     logic [15:0] temp_den;
     logic [31:0] temp_result;

     always_ff @(posedge clk) begin
       done <= 0;
       if (reset) begin
              state <= S0;
       end

       else begin
              case (state)
                    S0: begin
                           if (start) begin
                                  if (num[15] & den[15]) begin  // if both the
num and den are negative
                                         // divide only the magnitudes
                                         temp_num = ~(num - 1);
                                         temp_den = ~(den - 1);
                                         state <= S1;
                                  end

                                  // following two conditions make sure the
result is negative

                                  else if (num[15] & ~den[15]) begin  // if only
```

```
num is negative
                                        temp_num = ~(num - 1);  // get
magnitude of the numerator
                                        temp_den = den;
                                        state <= S2;
                                    end

                                    else if (~num[15] & den[15]) begin // if only
den is negative
                                        temp_num = num;
                                        temp_den = ~(den - 1);
                                        state <= S2;
                                    end

                                    else begin  // both numbers are positive
                                        temp_num = num;
                                        temp_den = den;
                                        state <= S1;
                                    end
                                end
                            end

                            S1: begin  // result is positive
                                temp_result = (temp_num << 16) / (temp_den << 2);
                                result = temp_result[15:0];
                                done <= 1;

                                if (~start) begin
                                done <= 0;
                                    state <= S0;
                                end
                            end


                            S2: begin  // result is negative
                                temp_result = (temp_num << 16) / (temp_den << 2);
                                result = ~(temp_result[15:0]) + 1; // maintains Qx.14
format
                                done <= 1;

                                if (~start) begin
                                    done <= 0;
                                    state <= S0;
                                end
                            end

                    endcase
                end

            end

endmodule
```

SOFTWARE PROTOTYPE FILES IN PYTHON

```
######pygpu - RENDER MODULE in python
import numpy as np
import pygame
from math import *
from constants import *

# Class to describe a Camera object
class Camera(object):

     def __init__(self, position, target):
       self.position = position  # camera position in the 3d world
       self.target = target         # where the camera is looking (location)


# Class to describe a Mesh object
class Mesh(object):

     def __init__(self, vertices, faces, name, position, rotation):
       self.name = name             # mesh name
       self.vertices = vertices  # collection of (x,y,z) vertices to define mesh
       self.faces = faces        # collections of faces to define the mesh
       self.position = position  # its position in the 3d world
       self.rotation = rotation  # rotation state of the mesh


# Class to define the face of a mesh
# Face objects simply index the vertices index to get the
# three vertices of a face
class Face(object):
     def __init__(self, a, b, c):
       self.a = a  # faces are triangles so have a set of 3 indexes
       self.b = b
       self.c = c


# Class to define the rendering device
class Device(object):

     # constructor initializes frame buffer
     def __init__(self, pixel_width, pixel_height):
       self.pixel_width = pixel_width
       self.pixel_height = pixel_height

       pygame.init()  # init pygame
       self.main_clock = pygame.time.Clock()
       self.display = pygame.display.set_mode((self.pixel_width,
self.pixel_height), 0, 32)  # create display

       self.depth_buffer = np.full( (self.pixel_width, self.pixel_height),
MAX_VAL)

     # clear screen to one solid color
     def clear(self, color):
       self.display.fill(color)
       self.depth_buffer[:] = MAX_VAL  # clear depth buffer

     # set pixel
```

```
    def put_pixel(self, x, y, z, color):
      #print "z buffer shows: " + str(self.depth_buffer[x][y])
      #print "current z is: " + str(z)

      if self.depth_buffer[x][y] < z:
            #print "not drawing this"
            return  # ignore put pixel if depth buffer is less than z

      self.depth_buffer[x][y] = z
      self.display.set_at((x,y), color)


    # update output
    def update_display(self):
      pygame.display.update()


    # transform 3d coords to window coords using the transformaton matrix
    def project_to_window(self, vertex, transform_matrix):
      # get clipped coordinates (to window)
      clip_coords = np.dot(transform_matrix, vertex)

      # get normalized device coordinates
      n_coords = clip_coords / float(clip_coords[3])

      # now translate into window coordinates
      viewport_x = 0  # specify x coordinate of bottom left-most point
      viewport_y = 0 # specify y coordinate of bottom left-most point
      viewport_w = self.pixel_width
      viewport_h = self.pixel_height

      xw = ((viewport_w / 2.0) * n_coords[0]) + (viewport_x + (viewport_w /
2.0))
      yw = ((viewport_h / 2.0) * n_coords[1]) + (viewport_y + (viewport_h /
2.0))
      zw = ((FAR - NEAR) / 2.0) * n_coords[2] + ((FAR + NEAR) / 2.0)

      return (xw, yw, zw)


    # does clipping to make sure only pixels on screen will be drawn
    def draw_point(self, point, color):
      x = point[X]
      y = point[Y]
      z = point[Z]

      self.put_pixel(int(x), int(y), z, color)


    # draw line b/t two points using Bresenham's algorithm
    def draw_line(self, point0, point1):
      x0 = int(point0[0])
      y0 = int(point0[1])
      x1 = int(point1[0])
      y1 = int(point1[1])

      dx = abs(x1 - x0)
      dy = abs(y1 - y0)

      if x0 < x1:
            sx = 1
```

```
        else:
                sx = -1

        if y0 < y1:
                sy = 1
        else:
                sy = -1

        err = dx - dy

        while True:
                point_to_draw = (x0, y0)
                self.draw_point(point_to_draw)

                # check if we're done
                if ((x0 == x1) and (y0 == y1)):
                        break

                # otherwise update our point
                e2 = 2 * err

                if e2 > -dy:
                        err -= dy
                        x0 += sx

                if e2 < dx:
                        err += dx
                        y0 += sy

        # clamp value between 0 and 1
      def clamp(self, value, min_val = 0, max_val = 1):
        return max( float(min_val), min(float(value), float(max_val)) )


      # interpolate the value between 2 vertices
      # min is the starting point, max is the ending
      def interpolate(self, min_val, max_val, gradient):
        val = float(min_val) + ( float(max_val) - float(min_val) ) *
self.clamp(float(gradient))
        return val

      # draw line between two points left to right
      # papb -> pcpd
      def process_scan_line(self, y, pa, pb, pc, pd, color):
        # gradient between vertex a and vertex b
        if pa[Y] != pb[Y]:
                gradient1 = (y - pa[Y]) / (pb[Y] - pa[Y])
        else:
                gradient1 = 1

        # gradient between  vertex c and vertex d
        if pc[Y] != pd[Y]:
                gradient2 = (y - pc[Y]) / (pd[Y] - pc[Y])
        else:
                gradient2 = 1


        # compute sx and ex
        sx = int(self.interpolate(pa[X], pb[X], gradient1))
        ex = int(self.interpolate(pc[X], pd[X], gradient2))
```

```
        # starting z and ending z
        z1 = self.interpolate(pa[Z], pb[Z], gradient1)
        z2 = self.interpolate(pc[Z], pd[Z], gradient2)

        for x in range(sx, ex):  # draw a point from startx to finish x
                gradient = (float(x) - float(sx)) / (float(ex) - float(sx))

                z = self.interpolate(z1, z2, gradient)

                self.draw_point((x, y, z), color)

    # function to draw the triangle given 2 points and the color
    def draw_triangle(self, p1, p2, p3, color):
        # first sort p1, p2 and p3 so that p1 is at the top
        # followed by p2 and then p3

        if p1[Y] > p2[Y]:
                temp = p2
                p2 = p1
                p1 = temp

        if p2[Y] > p3[Y]:
                temp = p2
                p2 = p3
                p3 = temp

        if p1[Y] > p2[Y]:
                temp = p2
                p2 = p1
                p1 = temp

        # now calculate inverse slopes
        if p2[Y] - p1[Y] > 0:
                dp1p2 = ( float(p2[X]) - float(p1[X]) ) / ( float(p2[Y]) -
float(p1[Y]) )
        else:
                dp1p2 = 0.0

        if p3[Y] - p1[Y] > 0:
                dp1p3 = ( float(p3[X]) - float(p1[X]) ) / ( float(p3[Y]) -
float(p1[Y]) )
        else:
                dp1p3 = 0.0


        # now draw scan line for the triangles
        start_y = int(p1[Y])
        end_y = int(p3[Y]) + 1

        if dp1p2 > dp1p3:
                for y in range(start_y, end_y):
                        if y < p2[Y]:
                                self.process_scan_line(y, p1, p3, p1, p2, color)
                        else:
                                self.process_scan_line(y, p1, p3, p2, p3, color)
        else:
                for y in range(start_y, end_y):
                        if y < p2[Y]:
                                self.process_scan_line(y, p1, p2, p1, p3, color)
                        else:
                                self.process_scan_line(y, p2, p3, p1, p3, color)
```

```
    # main rendor function that re-computes each vertex projection each frame
    def render(self, camera, meshes):
      view = view_matrix(camera, UP_VECTOR)

      # generate projection matrix
      aspect_ratio = float(self.pixel_height) / float(self.pixel_width)
      projection = perspective_projection(NEAR, FAR, ANGLE_OF_VIEW,
aspect_ratio)

      for mesh in meshes:
            # generate world matrix for the mesh
            rotation_angles = (mesh.rotation[0], mesh.rotation[1],
mesh.rotation[2])
            translations = (mesh.position[0], mesh.position[1],
mesh.position[2])
            world = world_matrix(SCALING, rotation_angles, translations)

            # generate final transform matrix
            transform_matrix = np.dot(view, world)
            transform_matrix = np.dot(projection, transform_matrix)

            faceindex = 0
            for face in mesh.faces:  # now render each face on the screen
                  # first define the three vertices of the face to be drawn
                  vertex_a = mesh.vertices[face.a]
                  vertex_b = mesh.vertices[face.b]
                  vertex_c = mesh.vertices[face.c]


                  # convert teh 3-d vertices to 2-d pixels that can be drawn
on the screen
                  pixel_a = self.project_to_window(vertex_a,
transform_matrix)
                  pixel_b = self.project_to_window(vertex_b,
transform_matrix)
                  pixel_c = self.project_to_window(vertex_c,
transform_matrix)

                  # color triangles
                  color = 2 + (faceindex % len(mesh.faces)) * 100 /
len(mesh.faces)
                  #if faceindex == 0 or faceindex ==1:
                  #      color_vec = (255, 255, 0, 255)
                  #else:
                  color_vec = (color, color, color, 255)
                  self.draw_triangle(pixel_a, pixel_b, pixel_c, color_vec)
                  faceindex += 1

                  # draw a line between each pixel
                  #self.draw_line(pixel_a, pixel_b)
                  #self.draw_line(pixel_b, pixel_c)
                  #self.draw_line(pixel_c, pixel_a)


##################################
#
#   Matrix transform functions
#
##################################
```

```
# create scale matrix
def scale_matrix(cx, cy, cz):
     scale = np.identity(4)  # start with 4x4 identity matrix
     scale[0, 0] = cx
     scale[1, 1] = cy
     scale[2, 2] = cz

     return scale

def translate_matrix(dx, dy, dz):
     trans = np.identity(4)
     trans[0, 3] = dx
     trans[1, 3] = dy
     trans[2, 3] = dz

     return trans

def rotate_matrix_x(angle):
     rad = angle * 0.01743  # pi/180 = 0.01743

     rotate = np.identity(4)
     rotate[1, 1] = cos(rad)
     rotate[1, 2] = sin(rad)
     rotate[2, 1] = -sin(rad)
     rotate[2, 2] = cos(rad)

     return rotate

def rotate_matrix_y(angle):
     rad = angle * 0.01743  # pi/180 = 0.01743

     rotate = np.identity(4)
     rotate[0, 0] = cos(rad)
     rotate[0, 2] = -sin(rad)
     rotate[2, 0] = sin(rad)
     rotate[2, 2] = cos(rad)

     return rotate

def rotate_matrix_z(angle):
     rad = angle * 0.01743  # pi/180 = 0.01743

     rotate = np.identity(4)
     rotate[0, 0] = cos(rad)
     rotate[0, 1] = -sin(rad)
     rotate[1, 0] = sin(rad)
     rotate[1, 1] = cos(rad)

     return rotate

def orthographic_projection(near, far, left, right, bottom, top):
     ortho = np.zeros((4, 4))

     # first column changes
     ortho[0, 0] = 2.0 / (right - left)

     # second column changes
     ortho[1, 1] = 2.0 / (top - bottom)
```

```
        # third column changes
        ortho[2, 2] = -2.0 / (far - near)

        # fourth column changes
        ortho[0, 3] = -(right + left) / (right - left)
        ortho[1, 3] = -(top + bottom) / (top - bottom)
        ortho[2, 3] = -(far + near) / (far - near)
        ortho[3, 3] = 1

        return ortho

def perspective_projection(near, far, angle_of_view, aspect_ratio):
        # start with some maths needed to get the matrix
        rad_view = angle_of_view * 0.01743  # change angle of view to rads
        size = near * tan(rad_view / 2.0)
        left = -size
        right = size
        bottom = -size / aspect_ratio
        top = size / aspect_ratio

        persp = np.zeros((4, 4))
        # first column changes
        persp[0, 0] = 2.0 * near / (right - left)

        # second column changes
        persp[1, 1] = 2 * near / (top - bottom)

        # third column changes
        persp[0, 2] = (right + left) / (right - left)
        persp[1, 2] = (top + bottom) / (top - bottom)
        persp[2, 2] = -(far + near) / (far - near)
        persp[3, 2] = -1.0

        # fourth column changes
        persp[2, 3] = -(2 * far * near) / (far - near)
        return persp



# create the vew matrix where you pass the camera object
def view_matrix(camera, up):
        # first specify the translation matrix based on camera position
        translate = translate_matrix(camera.position[0], camera.position[1],
camera.position[2])
        translate = np.linalg.inv(translate)  # invert translate matrix

        # create target and up vectors
        target_vector = np.array([camera.target[0], camera.target[1],
camera.target[2]])
        up_vector = np.array([up[0], up[1], up[2]])

        # now get camera rotation matrix based on tutorial
http://ogldev.atspace.co.uk/www/tutorial13/tutorial13.html
        N = target_vector
        N = N / np.linalg.norm(N)  #  need to normalize N array

        U = up_vector
        U = U / np.linalg.norm(U)  # need to normalize U array
        U = np.cross(U, target_vector)

        V = np.cross(N, U)
```

```
    # generate matrix based on U,V,N vectors
    rotate = np.identity(4)  # start with identity matrix
    rotate[0, 0] = U[0]
    rotate[0, 1] = U[1]
    rotate[0, 2] = U[2]

    rotate[1, 0] = V[0]
    rotate[1, 1] = V[1]
    rotate[1, 2] = V[2]

    rotate[2, 0] = N[0]
    rotate[2, 1] = N[1]
    rotate[2, 2] = N[2]

    view = np.dot(rotate, translate)

    return view


def world_matrix(scale_factors, rotation_angles, translations):
    # scale the object
    scale = scale_matrix(scale_factors[0], scale_factors[1], scale_factors[2])
    # rotate the object
    rotate_x = rotate_matrix_x(rotation_angles[0])
    rotate_y = rotate_matrix_y(rotation_angles[1])
    rotate_z = rotate_matrix_z(rotation_angles[2])

    # translate the object
    translate = translate_matrix(translations[0], translations[1],
translations[2])

    world = np.dot(rotate_x, scale)
    world = np.dot(rotate_y, world)
    world = np.dot(rotate_z, world)
    world = np.dot(translate, world)
    return world
```

```
#### app.y
#### application that uses the above pygpu render module

from pygpu import *
import numpy as np
import pygame
import json

def load_mesh_from_json(filename):
    meshes = []  # list of meshes we will return

    json_data = open(filename)  # open json file to read
    data = json.load(json_data) # load the data for parsing

    num_meshes = len(data["meshes"])  # holds number of meshes in model

    for mesh_index in range(num_meshes):

      # first get vertices and indices array
      vertices_array = data["meshes"][mesh_index]["vertices"]
      indices_array = data["meshes"][mesh_index]["indices"]
```

```
        # get uvCount (i have no idea what this is???)
        uv_count = int(data["meshes"][mesh_index]["uvCount"])
        vertices_step = 1

        # determines how many of the vertices we
        # want to use from the json file. we don't
        # need all of them
        if uv_count == 0:
                vertices_step = 6
        elif uv_count == 1:
                vertices_step = 8
        elif uv_count == 2:
                vertices_step = 10

        # get number of vertices we care about
        vertices_count = len(vertices_array) / vertices_step

        # get number of faces we care about which is size of arr / 3 (a,b,c)
        faces_count = len(indices_array) / 3

        # get the vertices array
        vertices = []  # init empty vertices list
        for index in range(vertices_count):
                x = float(vertices_array[index * vertices_step])
                y = float(vertices_array[index * vertices_step + 1])
                z = float(vertices_array[index * vertices_step + 2])
                w = 1

                vertices.append(np.matrix([[x], [y], [z], [w]]))


        # get the faces array
        faces = []  # init empty faces list
        for index in range(faces_count):
                a = int(indices_array[index * 3])
                b = int(indices_array[index * 3 + 1])
                c = int(indices_array[index * 3 + 2])

                faces.append(Face(a, b, c))


        # get the position specified in blender
        px = float(data["meshes"][mesh_index]["position"][0])
        py = float(data["meshes"][mesh_index]["position"][1])
        pz = float(data["meshes"][mesh_index]["position"][2])

        position = (px, py, pz)

        # get mesh name
        name = data["meshes"][mesh_index]["name"]

        # set default rotation values
        rotation = (0, 0, 180)

        # now we have all of the mesh data so we can create he mesh object
        new_mesh = Mesh(vertices, faces, name, position, rotation)

        meshes.append(new_mesh)  # add new mesh to our meshes array

    return meshes
```

```
##########################################
#                                                    #
#                   main program                   #
#                                                  #
##########################################


####### code to create a new rendering device #######
my_device = Device(500, 500)  # screen 100 x 100


####### code to create a new camera ######
camera_position = (0, 0, 5)  # move 5 units along the z axis
camera_target = (0.0, 0.0, 1.0)  # pointed straight at z axis
my_camera = Camera(camera_position, camera_target)


####### code to load in mesh from json file #######
meshes = load_mesh_from_json("monkey.babylon")


done = False

while not done:

     for event in pygame.event.get():
       if event.type == pygame.QUIT:  # wait for user to close window
              done = True
              break

     if done:
       break

     my_device.clear((0, 0, 0, 255))  # clear screen
     # rotate cube slightly during each frame rendered
     for mesh in meshes:
       mesh.rotation = (mesh.rotation[0] , mesh.rotation[1] + 40,
mesh.rotation[2]) # move mesh position slightly
       my_device.render(my_camera, meshes)  # render meshes
       my_device.update_display()  # update display
```

```
##CONSTANTS.PY-HOLDS the constants of the programs-easy to modify

# important constants
NEAR = 1  # how close to you you can see
FAR = 10  # how far out you can see
ANGLE_OF_VIEW = 45.0  # angle of view in front of you
UP_VECTOR = (0, 1, 0)  # direction of camera UP. leave at (0, 1, 0) for now
SCALING = (1.0, 1.0, 1.0)  # object scaling
MAX_VAL = 9999


# indicies
X = 0
Y = 1
Z = 2
W = 4
```