Exploration of New Approaches to Depth-Based Render Techniques Utilizing Pixel Synchronization

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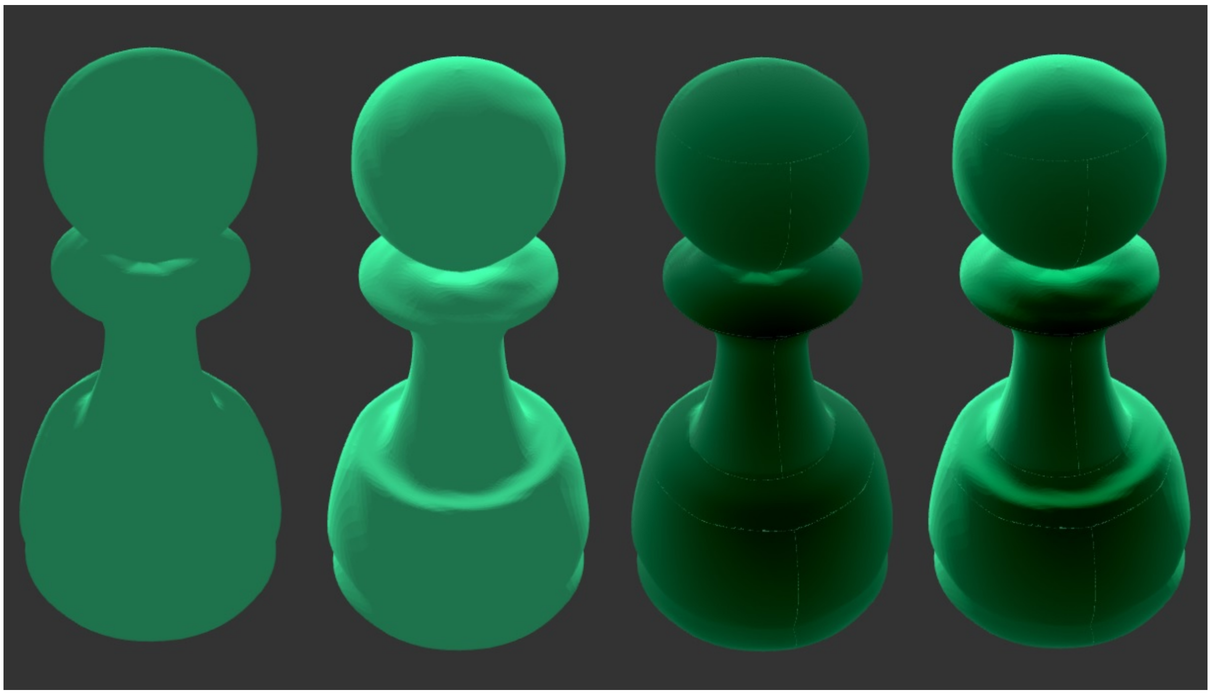

Contents

1 Introduction and Background

Since the advent of computer graphics, engineers have been trying to find new ways to create graphics hardware solutions intended to yield higher performance and image quality. However, image quality can mean many things to many people. Individuals may use grapchics hardware to create vibrant and abstract experiences, where others may create an experience where the images being created are as photorealistic as possible. The question that graphics hardware engineers must ask, is, "What can we make that will help developers create a higher quality experience?" For some GPU distributors, the solution comes with a concept called Pixel Synchronization.

Before we get into the gory details of what my project is all about, there are some key concepts that must be covered. This project utilized a lot of different concepts within Computer Science outside of the realm of graphics. We first need to cover what the hardware is and why it is different, then take a general look at the graphics pipeline, and finally discuss two key topics in parallel programming. My goal is to make sure my rationale for this project is completely clear.

1.1 Project Environment Details

At the beginning of this project, we did not have any choices, as far as what chip/chipset on which to run and test our code. The hardware we used has the Intel® Core i7, since this CPU/GPU includes the Iris™ Graphics Pro 5200. This project was developed as a desktop application on Windows 8.1, using the DirectX 11 SDK. Any and all references to Pixel Synchronization calls are done according to how they are implemented in the Intel DirectX extensions. Within the application, all HLSL code was compiled using the HLSL version 5.0, as any lower version does not support the extensions needed to access Pixel Synchronization.

1.2 The Graphics Pipeline

In modern computer graphics, we describe our objects mathematically as a group of vertices, then pass them to the graphics card where the vertices are connected and then drawn to the screen, given constraints we have originally passed. In the beginning, all we, as graphics programmers could do was tell the GPU to draw, but then our influence on the graphics was over. Later on, though, the ability to program stages of the pipeline became possible. With this programmability of the pipeline, graphics programmers now have the ability to create and define custom effects for the graphics card to carry out and process.

1.2.1 The Vertex Shader

The Vertex shader is the area of entry for every 3D point. Within the vertex shader, the GPU generally stores the key information and properties of each vertex, prior to passing it through to the later stages of the pipeline for these values to be interpolated. The purpose of this, is that it greatly reduces the amount of space needed to express the looks and properties of an object. If we can describe the key pieces of information at a few points on the object, the idea is that the GPU will be able to make informed assumptions about the other parts of the model where we have provided no information, thus filling in/connecting the dots.

1.2.2 The Pixel/Fragment Shader

Depending on Direct3D or OpenGL, this stage of the pipeline is either called the Pixel Shader or the Fragment Shader, respectively. Prior to the Pixel Shader stage, the 3D object has been transformed, and the object's properties have been interpolated across its entire surface. After this interpolation takes place, the GPU then decides where, in screen space, the object is, then runs the pixel shader to color those specific pixels. Most rendering techniques do most of their lighting effects and color computations at this stage of the pipeline to help create a smoother coloring of the model. In a traditional pipeline, the pixels are evluated in parallel, making rendering a potentially fast process. The tradeoff, however, is that with increased rendering speed comes a lack of knowledge of other parts of the object being evaluated. The more naive the pixel is about its neighbors or its surroundings, the quicker the computation will finish, and the final image displayed.

1.3 Parallel Programming

Pixel Synchronization and my implementation of these different render techniques borrow concepts from parallel computing. As vertices are passed through the pipeline and on to the pixel shader, these parts of the pipeline are actually happening in parallel for all of the different instances of vertices and pixels. The problem with doing anything depth-based in realtime graphics, is that each fragment or potential pixel doesn't really have any knowledge of any of the neighboring pixels, they do not execute in any specific order, either. In order to know if one potential pixel is deeper than another potential pixel, we need a predictable way of determining this. If we were to naively try to gather this information within the pixel shader, we would run in to a race condition. We also need a way to share this information across different instances of the pixel shader.

1.3.1 Shared Resources

To determine the depth of a certain spot of a 3D model within the pipeline, we need some sort of a way for the related potential pixels to communicate with each other. To do this, we use a feature of Direct3D 11 called Unordered Access Views. Unordered Access Views (UAVs) are basically a read/write texture that can only be accessed within the GPU, during the Pixel Shader stage. UAVs can be used in either a 1 or 2 dimensional array. The size of the UAV is specified to the graphics device before rendering begins. Within the shader, the programmer must take care to list the UAVs in the same order as they are initialized within the CPU side of the application. Once properly initialized, the UAVs are identified within the shader as RWTexture2D data structures.

1.3.2 Synchronization and Barriers

Oftentimes, in parallel programs, we must make sure our threads (or in the case of this project, pixels) are synchronized and executed in some sort of order. If we know that our programs are executed in some predictable order, it is easier for us to write more advanced algorithms or have guaranteed knowledge of what data lies at each checkpoint. If barriers did not exist, we come across **race conditions**. When an algorithm is written where race conditions exist, it is difficult, or impossible to predict the output of the algorithm, itself.

1.4 Pixel Synchronization

1.4.1 What is Pixel Synchronization?

With Pixel Synchronization, the pipeline is now capable of creating a barrier during the pixel shader stage per pixel, where multiple instances of the pixel being rendered will happen in-order, based on the primitive number. Parallel programming concepts such as barriers and synchronization have not before been possible within the real-time pipeline. To have this emerging hardware capability gives programmers the opportunity to approach existing render techniques from a new angle, potentially yielding higher performance and more spectacular images.

1.4.2 How Pixel Synchronization Works in Code

On the programmer side, there is not much coding overhead as far as initializing, then calling Pixel Synchronization. On the application side, the programmer must first check the hardware to make sure that the hardware is capable of Pixel Synchronization. This is the only thing to be done on the application side. Within the pixel shader, we have to first enable Pixel Synchronization with a call to **IntelExt_Init()**. Then, once we reach the part of our code that must be syncrhonized, we must call the pixel ordering function by calling **IntelExt_BeginPixelShaderOrdering()** (**NOTE:** These function calls are hardware specific. Please see section 1.1 on page 1 for details about the hardware used for this project). An important point to keep in mind is that this specific implementation of Pixel Synchronization lasts until the end of the Pixel Shader code. What this means, is that it is recommended that all code over which syncronization must occur should come as close to the end as possible. Listing 1.1 (below) shows how a bare bones Pixel Shader using Pixel Synchronization might look. For more information on how Pixel Synchronization works, please rever to section 6.3.

```
float4 PSExample(/*parameters...*/) : SV_TARGET
{

        //Variable Definitions

        IntelExt_Init();

        //all non synchronization-specific code;

        IntelExt_BeginPixelShaderOrdering();

        //all synchronization-specific code goes here
        //critical section must happen at the end.

        return finalColor;
}
```

Figure 1.1: How Pixel Synchronization Pixel Shader Code Might Look

2 Simple Subsurface Scattering

2.1 What is Subsurface Scattering?

Subsurface Scattering is a phenomenon which occurs when photons hit some sort of translucent material, such as skin, fat, milk, plant leaves, etc. The photons enter that material, scatter, then exit out of a different point. This phenomenon is constantly and naturally occuring in the real world, but it is a rather tough lighting effect or phenomenon to calculate in realtime graphics, since knowledge of the object, and sometimes its surrounding environment, is required to produce an image with accurate subsurface scattering effects. Even so, many approximate implementations have been developed to mimic this natural phenomenon as convincingly as possible, all while retaining performance/framerate.

All of the techniques out there attempt to find a fast way to build knowledge of the 3D object (what is its depth at a certain point, and where is it with respect to the light). The techniques that exist are either quite general, or are very complex, coding wise (further detail to come below). Pixel Synchronization offers a new approach to the subsurface scattering problem that is both straightforward and does not sacrifice performance.

2.2 Previous Implementations

As stated above, there exist approaches to approximating the subsurface scattering effect in realtime graphics. The two approaches detailed below have trade-offs, when it comes to generality or coding complexity. However, both methods are quite effective within the correct scope. With the Pixel Synchronization approach detailed in section 2.3 (pg.5), we hope to improve upon these two methods by creating a more detailed and accurate approach, while keeping the code intuitive.

2.2.1 Wrapping Approximation

This simple approach to a subsurface scattering approximation takes the calculation of the diffuse component of your standard Phong lighting equation, and basically "wraps" the diffuse around the object further than the standart diffuse calculation. For instance, is illustrated in the equation in Figure 2.1 (where L is the light vector and N is the normal vector).

$$diffuse = max(0, L \bullet N)$$

Figure 2.1: Standard diffuse calculation in smooth shading

However, when we apply the wrapping approximation, the equation for the diffuse component is slightly changed. In Figure 2.2, the programmer specifies a wrap value, or makes the value interactive to show the difference in realtime, then the value is applied to the existing equation as follows:

$$diffuse = max(0, ((L \bullet N) + wrap) \div (1 + wrap))$$

Figure 2.2: Diffuse Calculation in smooth shading with wrap value added

As can be seen by observing the above equations, the addition of the wrapping value in equation complicates it only slightly, but the effect of adding the is very apparent. The advantage to this approach is that it requires only a slight modification of Phong illumination. Within shader code, a graphics programmer could insert a hook in their shader code to show the difference between Phong Illumination with and without diffuse wrapping. For an idea on how this is implemented, refer to the code listing in figure 2.3.

```
1 float calc = dot(Normal, Light) + wrap) / 1 + wrap);
2 if(mode & DIFFUSE_WRAP) d = max(calc, 0);
3 else d = max(dot(Normal, Light), 0);
```

Figure 2.3: HLSL hook to determine whether or not to wrap the normal

In line 2, a bitwise 'and' operator is used to check if wrapping has been selected because all display mode settings are passed into the graphics program as a single unsigned integer (in OpenGL, this would be the same as passing in a single uniform variable to evaluate all user true-false settings. This saves time and space when passing these types of variables to the GPU). A more detailed discussion about this and why this approach for uniform variables is used can be found in section 6.6 on page 39, under the "Constant Buffers" item.

2.2.2 Depth Mapping

Given the nature of what Subsurface Scattering is, it is imperative to know the thickness of the object in question, such that the programmer can make a decision on how much light escapes the obejct at a different point. For this reason, a technique was developed called depth mapping. In the first pass, the scene is rendered from the light's position, toward the object, where we store the distance from the light to that location on the object. Another pass is made to measure where the ray has entered and exited, by mapping the depths to the object's texture space. Finally, in the render pass, we render the object from the camera's point of view, and for each point on the object being rendered, we find the point of entry and the point of exit for the specific ray pertaining to the current fragment of the object, then calculated the distance between the two. After this distance has been calculated, the new calculation of the diffuse light can be applied. For a visual representation of the render pass of the approach, see figure 2.5 on page 6.

The effect from this approach causes more of a subsurface scattering type of "lifelike glow" than the method detailed in Section 2.2.1. However, when this method is implemented, it requires three passes to render the image with correct depth information. Further, there is no intuitive way to project the the depth information with respect to the light to the object. To recap, here are the three render passes that take place.

2.3 Pixel Synchronization Accelerated Depth Mapping

The approach described in section 2.2.2 is the groundwork for the new Pixel Synchronization accelerated approach. The concept remains relatively the same, however, we are able to use a psuedo raytrace to guage the distance between two points in the same ray with increased ease. This more straighforward approach to depth mapping takes less time to code and yields no loss of performance.

First Pass
Render the object from the perspective of the light and record the distances from the light.

Second Pass
Calculate the distances between the entry and exit points of the light rays. These will be mapped, in texture space, to the object.

Third Pass
Use the depth calculations to scale the backfacing (with respect to the light) diffuse component of the object.

Figure 2.4: Description of the depth mapping approach to subsurface scattering

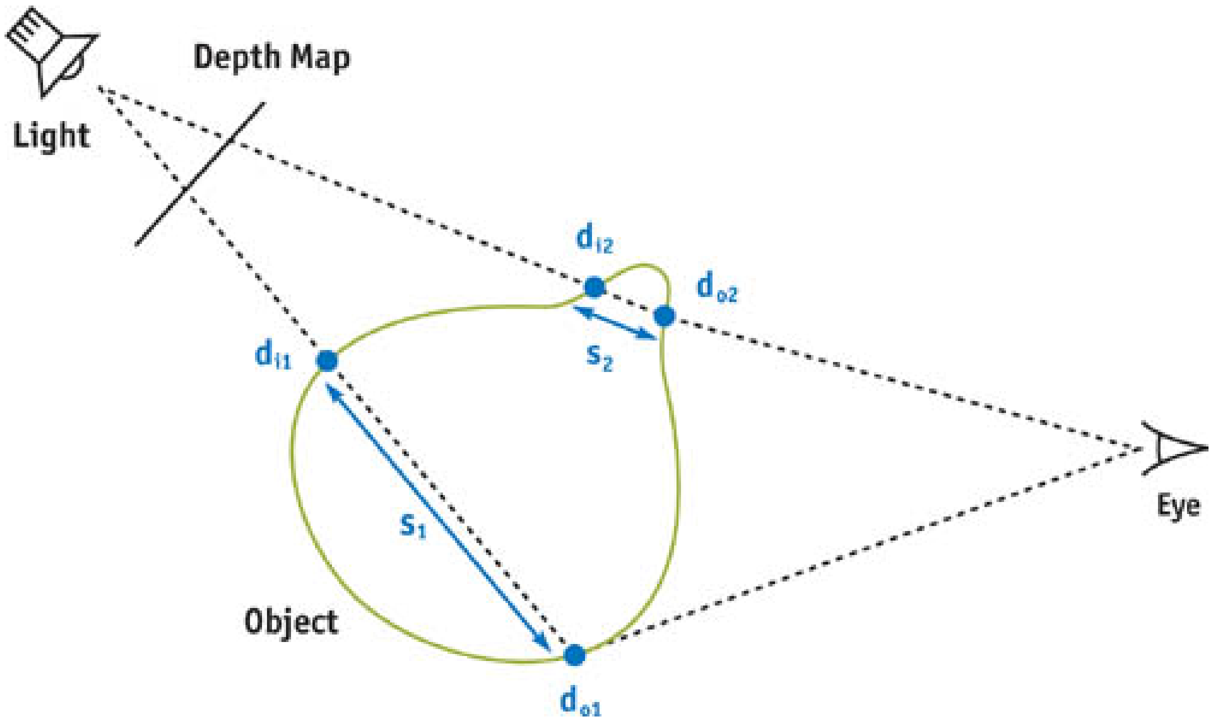

Figure 2.5: Diagram to visualize how the depth map is used to calculate the distance a light ray has traveled within a 3D object

2.3.1 In-Depth Description of Implementation

As stated above, the approach to this technique remains generally the same, but with a few differences. For clarity's sake, refer to the description in 2.4 as a reference to what the changes in the pixel shader based approach would be, in comparison to the description below.

First Pass

This pass remains relatively the same. We take this pass to map which pixel from the perspective of the light. However, we map the object to the screen with respect to its texture coordinates. This way, we guarantee that all of the object is being seen and processed by the GPU. For a better idea of what this means, see the listing 4.6 on page 17. More specifically, see lines 6 through 8. Here, we take the text coordinates, then convert them into a space spanning from -1 to 1 in the x and y axes. Then, when these positions are passed from the vertex to the pixel shader, they are converted to screen space.

After this screen space conversion, we calculate and store the distance of each part of the model from the light source. Following this, we then map which rays intersect which parts of the model in 3D space. This is why we also store and keep track of the 3D position of the model, as seen on line 11 in listing 4.6. We map these ray values (which coincide with the pixels) to another texture, which we will use in the next pass as a "mask." For an idea of these mappings, refer to 4.7 on page 18. We use Unordered Access Views to accomplish these mappings (6.1, page 32).

Second Pass

This pass is from the perspective of the light, but this time, we project the correct object into space, rather than its texture coordinates. The only difference here, is that $output.svposition$ gets $mul(final, position)$ rather than the calculated screen space coordinates as it does in line 9 of figure 4.6. However, within the Pixel Shader this time, we create our shallow mask. This is basically a UAV-created depth buffer to keep the shallowest positions with respect to the light. To see how this is implemented within the shader, please see listing 4.8 on page 18. With the aid of Pixel Synchronization, we can determine which parts of the object are closest to (facing) the light.

Third Pass

The final render pass remains the same as what we had in the approach on page 5. We take the current depth, with respect to the light, then compare it to the corresponding member of the shallow mask. For a coding example, turn to page 8 and see figure 2.6. The code block from lines 6 to 25 show how to both get the ray and the current light-based depth of the object, compare them, and then re evaluate the diffuse component, originally calculated above this section Other parts of the shader were edited out for the sake of readability and clarity. There will be a complete discussion on the code within $PSHader2()$ later on in this paper. We can get away with using array notation, since UAVs support access via array notation, and not with a call to $sample()$.

```
float4 PShader2(...)
{

        /*...*/

        if (!(mode & PHONG_RENDER))
        {
          uint2 lightCoords;

          lightCoords.x = fromLightX[uv];
          lightCoords.y = fromLightY[uv];

          float mdepth = uvDepth[uv];

          float shallow = Shallow[lightCoords];
          if ((mode & PIXSYNC_OFF) &&
              (uvDepth[uv] > Shallow[lightCoords])){

                  float4 lColor = lightcol;
                  lColor -=
                    (uvDepth[uv] - Shallow[lightCoords]) * 3;

                  diffuse += lColor;
          }
        }

        /*...*/
}
```

Figure 2.6: Render Pass from perspective of camera

3 Refraction

Refraction is a visual phenomenon that occurs when a translucent object, such as a glass figurine, bends light in such a way that it distorts the image beyond it. This is how real-life lenses accomplish vision correction, or the image of an object gets distorted when it is submerged in water. As humans, we rely on refraction a great deal, so we are very, very used to seeing this effect on a day-to-day basis. There are many ways to accomplish the approximate effect of refraction on the GPU. The first approach, detailed in section 3.1, is a simple refraction algorithm, that takes into account only the front face of the object to compute the color of the object at that point.

3.1 "Fake" Convex Object Refraction

The most used approach to refraction is to just bounce the viewing "ray" once on the front surface of the object, then samples the cubemap to return a color. In code, this effect requires just a Vertex and Pixel Shader.

3.1.1 Vertex Shader

All of the heavy-lifting for refraction is done within the Vertex Shader (3.1). Given the proper transform and rotation matrices, the refract vector is computed within the Vertex shader. Essentially, the distance between

3.2 Better Convex Refraction With Pixel Synchronization

The idea behind this approach is to create a volumetric representation of the scene which stores the object's surface normals, with respect to the eye. For the render step, we could step through this voxelization at the entrypoint, then trace the first refracted ray to the exit point, refract again, then return this double-refracted color to give a more accurate coloring of the pixel.

3.2.1 Shader-Based Description of Implementation

To get our volumetric representation, I attempted (see section **??** for more details) to utilize the shader to take care of that for me. Using Pixel Ordering, I tried to create a voxel- based representation of the entire scene. I tried to use two 3D textures to accomplish this. One 3D texture would have $unsignedint$ representations of every voxel element saying whether it was inside, outside, or on the face of the object within the scene:

0: outside of the object

1: on the object's face

2: inside of the object

The suface normals are stored in another 3-D texture. We would first mark all of the spaces according to the above description. The surface normal texture is populated at the beginning of populating this unsigned integer texture. How this texture is populated can be better described by the code within figure 3.3. On line 8, we begin our loop to populate the 3D texture. As can be seen, pixel ordering has been invoked within this shader. So, what we

```
VOUT VShader(...)
{

        VOUT output;

        output.svPos = mul(WVP, pos);
        output.Pos = mul(WVP, pos);
        float4 norm = mul(Rotation, normal);


        float diffusebrightness =
                        saturate(dot(norm, LightVector));

        float3 ECPosition = mul(World, pos).xyz;
        float3 eyeDir = float3(0.0f, 0.0f, 0.0f) - ECPosition;

        output.Color = AmbientColor;

        output.Color += LightColor * diffusebrightness;
        output.Normal = norm;
        output.texCoord = texCoord;

        float3 reflectVector = refract(norm, eyeDir, -.90);

                output.vRef = reflectVector;


        return output;
}
```

Figure 3.1: Vertex shader for simple refraction

do is step through our $unsignedint$ Texture3D at every pixel address, in order. this way, we are able to indicate which parts of the scene are inside or outside of the model. We keep another 3D texture to keep track of the surface normals. The idea behind this, was once we hit an index in the $unsignedint$ Texture3D of value 1, we could then use that index where the 1 value is to refract the ray further, since that is where the surface normal at that point is stored in the other Texture3D. Using these textures in tandem serves as a good way to trace through a solid object to find the accurate refraction. However, I didn't get as far as a tracing stage to my algorithm, as there are fundamental aspects of this algorithm that GPU compilers do not allow to happen, due to memory access restrictions. This will be covered in more detail in section **??**, where the implementations will be discussed. However, the source code for this attempted demo will still be included in my final source code.

```
float4 PShader( VOUT input ) : SV_TARGET
{
        float3 bounceVec = input.vRef.xyz;

        float4 newColor =
         SkyMap.Sample(ObjSamplerState, normalize(bounceVec));

        return newColor;
}
```

Figure 3.2: Pixel shader for simple refraction

```
float4 PShader(...)
{

        IntelExt_Init();
        IntelExt_BeginPixelShaderOrdering();

        /*...*/

        uint3 tempi = voxPos;

        [loop]
        for (i = voxPos.z + 1; i < 512; i++)
        {
                tempi.z = i;
                unsigned int cond = VoxMask[tempi];
                if (cond == 0)
                {
                        VoxMask[tempi] = 2;
                        continue;
                }
                else if(cond == 2)
                {
                        VoxMask[tempi] = 0;
                        continute;
                }
                break;
        }
        /*...*/
}
```

Figure 3.3: Populating the *unsigned int* 3D texture.

4 Implementation Discussion

This section will detail important parts of code in-depth such that a majority of questions may be answered. The idea is that another student may be able to pick up the code I have implemented and quickly understand what decisions were made and why, which pieces of code depend on others, and so on. This way, changes can be made in an effective, informed manner, rather than with a trial-and-error approach, which can prove to be far less efficient.

4.1 Boilerplate Code

A majority of the Boilerplate functionality stays consistend between the two code bodies. As this is the case, the explanation of code setup, initialization and variable meanings will take place here. However, this section must not be considered to be a comprehensive tutorial on DirectX, but help explain some of its differences to OpenGL, as the latter is used in this University's Curriculum.

4.1.1 Defining our Window

This code is straightforward, but could seem a bit foreign to a programmer who has not programmed in windows before. Right at the beginning of the program, two things must happen. Firstly, a window class must be defined and then registered with the operating system as seen in figure 4.1. Within this code snippet, the important lines are 6, 7, and 12.

Line 6: Here, the programmer is stating that this window will be redrawn.

Line 7: This is a pointer to a separate function called WindowProc. WindowProc is where all of the messages and interactions with that window will be coded. In other words, WindowProc will execute every time there is a message to the window.

Line 12: This is where the program attempts to register the window class with the operating system. In otherwords, this determines whether the program has permission to create windows of this type of class.

If successfull with this portion, the program may now attempt to create a window instance, as seen in the code snippet in figure 4.2. After the variable, $hWnd$, has been populated, it will be used later to link a D3D device. Another point worth noting is that the window size used was 1920x1080, as part of this project was to ensure that this effect could be used on a window size that is commonly used within industry for video games and scientific visualizations.

4.1.2 Direct3D Setup

When the program is ready to initialize direct3D, all it needs is for the calling process to pass the pointer to the window instance to which the Direct3D device will be tied. As there is a very excellent tutorial website(listed below), There will not be any code included within this portion.

The most important difference between Direct3D and OpenGL is the use of COM Objects. COM (Component Object Model) Objects are Microsoft's way of making interprocess communication, or even IO with peripherals easier. In this case, Direct3D devices are represented with COM objects. As this is the case, there are slightly different ways to interact with the GPU when using Direct3D. For more information, please refer to http://www.directxtutorial.com, or microsoft's own documentation online.

```
WNDCLASSEX wc;

ZeroMemory(&wc, sizeof(WNDCLASSEX));

wc.cbSize = sizeof(WNDCLASSEX);
wc.style = CS_HREDRAW | CS_VREDRAW;
wc.lpfnWndProc = WindowProc;
wc.hInstance = hInstance;
wc.hCursor = LoadCursor(NULL, IDC_ARROW);
wc.lpszClassName = L"WindowClass";

if (!RegisterClassEx(&wc))
{
        int nResult = GetLastError();
        MessageBox(NULL,
                L"DirectX window class creation failed\r\n",
                L"Window Class Failed",
                MB_ICONERROR);
        exit(EXIT_FAILURE);
}
```

Figure 4.1: Creating and registering a Window Class

```
RECT wr = { 0, 0, SCREEN_WIDTH, SCREEN_HEIGHT };
AdjustWindowRect(&wr, WS_OVERLAPPEDWINDOW, FALSE);

hWnd = CreateWindowEx(NULL,
        L"WindowClass",
        L"Pawlowski Pixel Ordering Research",
        WS_OVERLAPPEDWINDOW,
        300,
        300,
        wr.right - wr.left,
        wr.bottom - wr.top,
        NULL,
        NULL,
        hInstance,
        NULL);

ShowWindow(hWnd, nCmdShow);
```

Figure 4.2: Create and Show the Window

4.1.3 Constant Buffer Values Explained

For this code base, the same Constant buffer was used for each of the demonstrations bundled within the SSS visual studio project. This decision was made because a good number of the values within the constant buffer were re- used in the other demonstrations. That said, there are many values within this constant buffer. The constant buffer is defined in both the application and the shader as follows:

```
__declspec(align(16))
struct CBUFFER
{
        D3DXMATRIX Final;
        D3DXMATRIX Rotation;
        D3DXMATRIX modelView;
        D3DXVECTOR4 LightVector;
        D3DXCOLOR LightColor;
        D3DXCOLOR AmbientColor;
        D3DXVECTOR4 LightPos;
        unsigned int mode;
};
```

The first line, **__declspc(align(16))**, is included to demonstrate yet another way to avoid the Constant Buffer creation error, where a struct is not of a size that is divisible by 16, as detailed in the "Constant Buffers" item in section 6.5. A majority of these member values are easy to understand their use; however, there is one value, **mode**, whose utility is not as readily apparent.

Since there are conditions as far as what technique to use, or what to render, this could be a rather space-consuming constant buffer, if each condition were to be stored inside of its own variable. However, with bitmasking and bitwise arithmetic, all of these boolean values can be stored in a single integer. For more information on how the bitmasked values are set up, refer to the DXApp.cpp file included in the SSS directory of the project. All values are set to a certain bit, which means that they are all contiguous powers of two. This approach for storing booleans is a benefit in that it is not time or space intensive for the Application to send these boolean values to the GPU.

4.2 SubSurface Scattering Shader Walkthrough

4.2.1 Pass 1

For the first render pass, texture-based knowledge of the model must be stored. As will be detailed in section 4.3, this pass was added to ensure all texture space is covered when passing the model through the pipeline. Within this pass, the scene is projected from the perspective of the light, toward the object. After the model has been transformed, the texture coordinates of each vertex is passed throught he pipeline as the X and Y of the SV_POSITION HLSL semantic. This maps the entire surface of the model to the viewport. If this pass were to be rendered to the screen, it would look like figure 4.3. As can be seen, the different portions of the pawn model are easily discernable. However, other objects take the entire screen space, as seen in figure 5.10.
Mapping the model's surface to the screen through texture space is a necessary step, as it guarantees that all of the model is rendered, thus information is stored at all possible locations in the model's texture space. The results of the implementation in section 4.3 will illustrate why this pass is necessary.

In figure 4.6, the key code lines are lines 5 through 9. Here, the program is converting

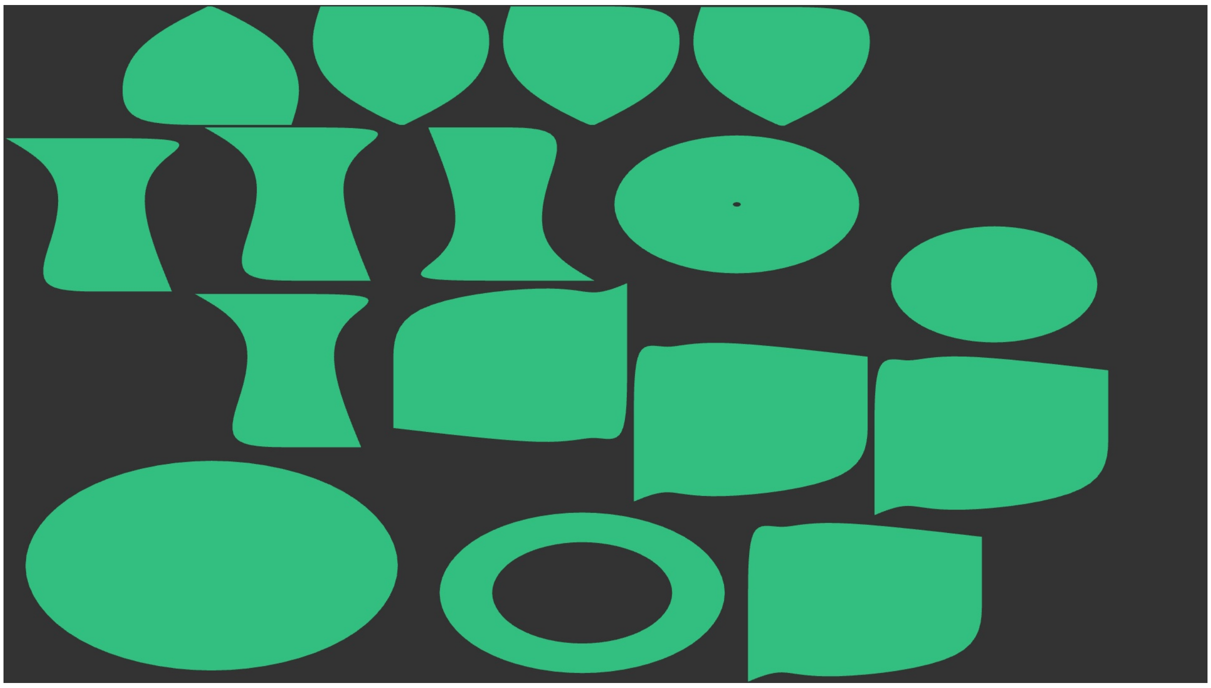
Figure 4.3: Pawn Model's Surface Unwrapped With Respect to Texture Space

Figure 4.4: Cube Model's Surface Unwrapped With Repsect to Texture Space, Shown to Illustrate a Model Whose Surface Spans the entire texture coordinate range

the texture coordinates to a value ranging from -1 to 1, which forces the texture coordinates to be interpolated and displayed on the screen. On line 10, the program is ensureng that the 3D coordinates are still being passed through. These coordinates are given an orthogonal projection. This is key for storing which portions of the model are on which pixel position if the model were to be projected correctly into screen space through the pipeline. In other words, the program is keeping track of the model's 3D position, such that it can be used to store information within the pixel shader.

The Pixel Shader for this pass, figure 4.7, the program finds what the screen-space position should have been for the correctly projected 3D model (lines 3, 7 through 9, 13 and 14) and stores them into UAV textures representing the X and Y coordinates of the model's screen position from the perspective of the light (lines 16 and 17). These values are stored as individuals, as tuples have a difficult time being used in a UAV when using Pixel Synchronization. These are stored at the texture coordinates, as texture coordinates stay at the same location of the model's surface, regardless of the model's orientation in space. Lastly, the depth with respect to the light's position is stored in a depth UAV. Writing this pass to the screen yields a result that can look somewhat like an abstract painting, such as figure 4.5.

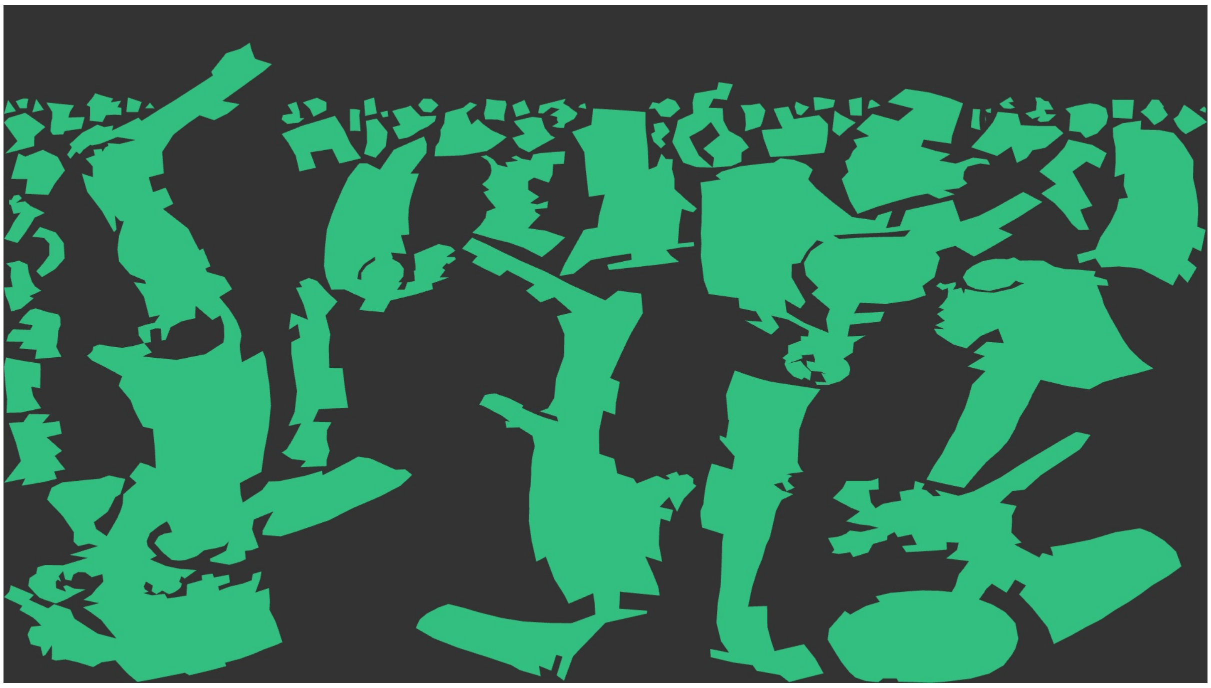

Figure 4.5: Log Model's Surface Unwrapped With Repsect to Texture Space

4.2.2 Pass 2

Now that depth information regarding the model has been gathered, the second pass is where the pixel synchronization happens. The vertex shader in this pass stays relatively the same as the previous pass; however, the projected model coordinates are passed to the SV_POSITION semantic, rather than the converted texture coordinates, as in the previous pass. To see how the shallow buffer is created, refer to figure 4.8. Within this pixel shader, the depth with respect to the light is recorded for every pixel/ fragment. Then, the pixels are ordered, and then shallowest depth at that pixel location is recorded.
The main purpose of this pass is to map which part of the model is shallowest to the light at a certain pixel position. With the utilization of pixel synchronization, this is a very straightforward process, with a guarantee against race conditions. With the help of the information gathered from the previous pass, the indexing and access of this information is straightforward. The image that would be output to the screen is far less interesting than the texture-space rendering, as it is an orthogonal view of the object from the perspective of the

```
VOut VShader(...)
{
        VOut output;

        float2 movedCoords = texCoord * 2;
                movedCoords.x -= 1;
                movedCoords.y -= 1;
        float4 svPos = float4(movedCoords, 0.0, 1.0);
        output.svposition = svPos;
        output.position = mul(final, position);

        // set the ambient light
        output.color = ambientcol;


        float4 norm1 = normalize(mul(rotation, normal));
        float diffusebrightness = saturate(dot(norm1,lightvec));
        float4 norm = normalize(mul(final, normal));

        //output.color += lightcol * diffusebrightness;

        output.UVs.x = texCoord.x * SCREEN_WIDTH;
        output.UVs.y = texCoord.y * SCREEN_HEIGHT;

        output.normal = norm;

        output.camera = mul(final, lightPos);

        output.mode = mode;


        return output;
}
```

Figure 4.6: Vertex Shader for first Pass of Depth Map accelerated by Pixel Synchronization

light, as seen in figure 4.9. The purpose of the orthogonal projection is such that we get a true trajectory of the light through the model, and not a trajectory that follows perspective foreshortening. It is important to note that, within this pass, the object must be contained within the boundaries of the view volume, otherwise key texture-based information will be missed for large portions of the model. However, it is important to maximize the amount of screen space filled by the model for this path, to give as detailed depth information as possible.

4.2.3 Pass 3

For the final pass, the graphics program applies phong illumination from the perspective of the eye position with a perspective foreshortening projection. In addition to phong illumination,

```
float4 PShader(...) : SV_TARGET
{
        float2 svPos = position.xy;
        float mdepth = distance(position, camera);
        uint2 uv = UVs;

        svPos.y = 0 - svPos.y;
        svPos += 1;
        svPos = svPos / 2;

        float2 newPos;

        newPos.x = svPos.x * SCREEN_WIDTH;
        newPos.y = svPos.y * SCREEN_HEIGHT;

        fromLightX[uv] = newPos.x;
        fromLightY[uv] = newPos.y;
        uvDepth[uv] = mdepth;

        return color;
}
```

Figure 4.7: Pixel Shader from first pass of Pixel Synchronization-Accelerated depth mapping.

```
float4 POShader(...) : SV_TARGET
{
        uint2 pixelAddr = svposition.xy;

        float pos = distance(position, camera);

        IntelExt_Init();
        IntelExt_BeginPixelShaderOrdering();

        if (pos < Shallow[pixelAddr])
        {
                Shallow[pixelAddr] = pos;
        }

        return color;

}
```

Figure 4.8: Pixel Ordering step of the alternate approach to depth mapping

the depth-based calculations are applied to the final colors of the image, as well. To keep things simple, the color's diffuse brightness is scaled based upon its orientation to the light, and its model-specific depth, based upon that orientation. As this is a modified Phong Illumination

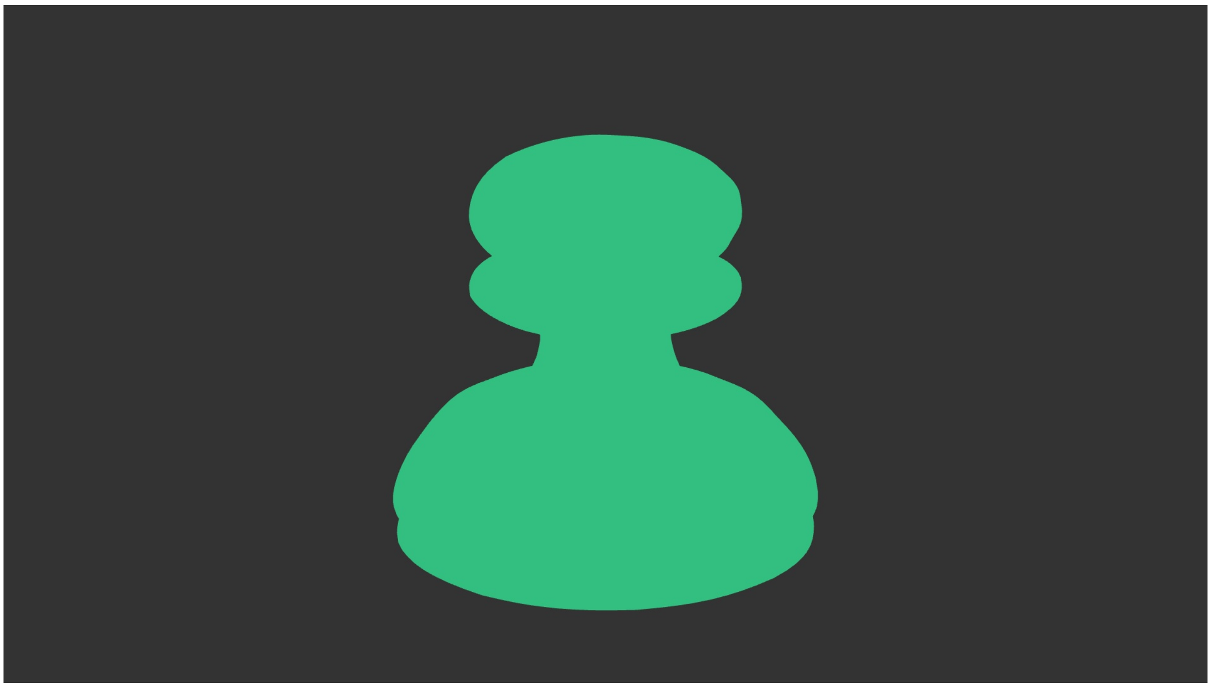

Figure 4.9: Orthogonal Projection of Pawn Model with repsect to the light.

technique with added depth information, the Vertex Shader is nothing different from what has already been seen. The same Pixel Shader, PShader2(), is used for three different render modes. Figure 4.10 details the portion of the shader that adds the depth information to the coloring of the image. As such, each section will discuss a different piece of the greater pixel shader function.

In this portion of the pixel shader, the program is checking to see if the SubSurface Scattering effect is activated. If so, the XY coordinates for the part of the model that is being processed (with respect to the light's view), the depth, and the shallow buffer are all referenced. The depth difference is then calculated and exaggerated by a factor of 3. The constant 3 was chosen in this case, as this best illustrated the effect without making it too exaggerated or underexaggerated. The variable, $lColor$, then subtracts this value from all of its components, then this color is added to the diffuse component of the pixel's final coloring. This is because when the subsurface scattering phenomenon takes place, the 'glow' of the object does take influence from the color of the light, as well as the object's diffuse color.

4.3 Bad Render Function and Shader Walkthrough

This first attempt at utilizing pixel shaders was retained within the project to prove why the initial information gathering pass is so necessary. For the sake of speed, it seems as though the graphics pipeline, on the hardware on which this project was run, makes choices to round some values. As this is the case, there are coordinate values that do not get properly interpolated across the pipeline. This results in texture holes, as members of the UAV do not end up being populated. For an idea of what this would look like, refer to figure 4.11.
The hypothesis that the pipeline was causing texture holes was corroborated when the unwrapping of the model's surface with respect to texture space was completed. As soon as the model was first unwrapped, then pixel synchronization based upon depth was taken into account,

```

                                /* ... */

if (!(mode & PHONG_RENDER))
{
        uint2 lightCoords;

        lightCoords.x = fromLightX[uv];
        lightCoords.y = fromLightY[uv];

        float mdepth = uvDepth[uv];

        float shallow = Shallow[lightCoords];

        if ((mode & PIXSYNC_OFF) &&
                (uvDepth[uv] > Shallow[lightCoords])){

                float4 lColor = lightcol;
                lColor -= (uvDepth[uv] -
                        Shallow[lightCoords]) * 3;

                diffuse += lColor;
        }
}

                                /* ... */
```

Figure 4.10: Chunk of Pixel Shader for final pass of the the Pixel Ordering-powered Subsurface Scattering technique

all texture holes disappeared, giving a consistent, cohesive shadow/glow effect from the subsurface scatter approximation. Further attempts were made to make this implementation work, such as forcing the pipeline optimizations to be turned off, but not attempts yielded any different results in the image. For a larger version of figure 4.11, refer to page 49.

4.4 Culling Demo Render Function and Shader Walkthrough

This demo was implemented to test to raw effect of pixel synchronization on the performance of the graphics pipeline. The performance results can be seen above. This demo had three different modes. One was a "No Cull" mode, which is self-explanatory. This mode was included in the demo, such that a measurement of performance could be taken when all of the model is rendered. There is a "Hardware Cull" mode, where measurements are taken for performance as well. All performance measurements are taken to compare against the "Software Cull" mode. The Software Cull mode is where culling within the shader takes place, witht he help of Pixel Synchronization. The purpose of culling within the shader was to give a visual result between the "No Cull" and the "Software Cull" modes.

The "Software Cull" mode utilizes 2 UAV textures. One is a clear mask, and the other

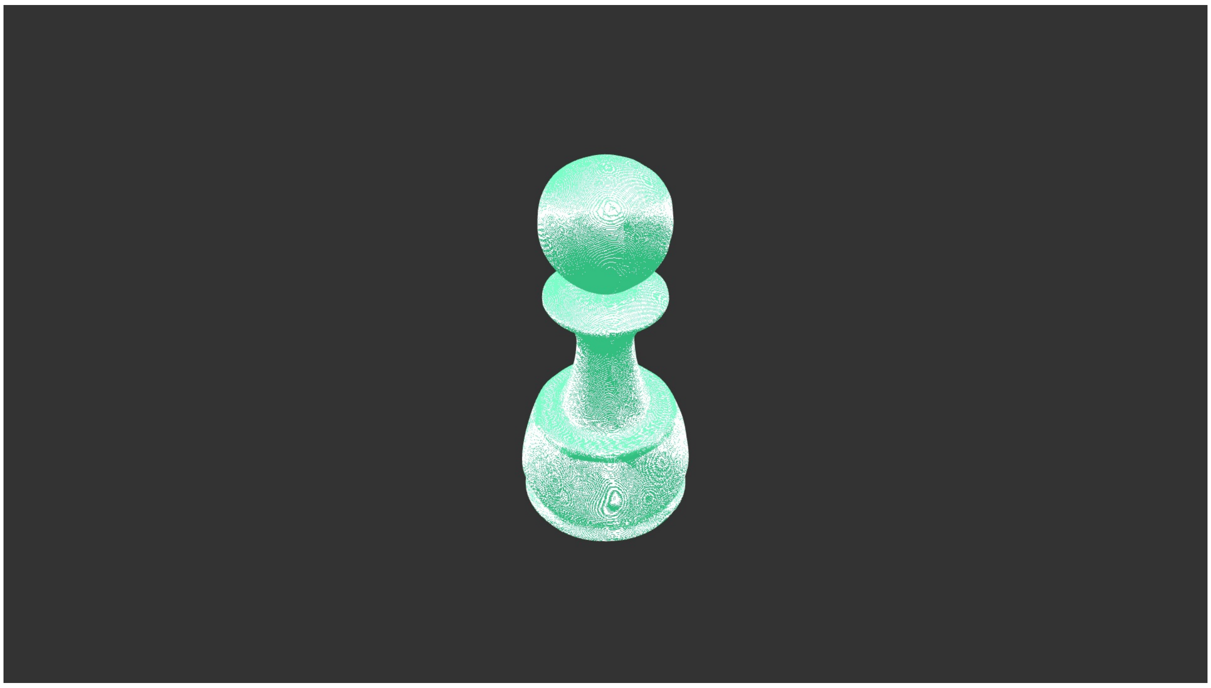
Figure 4.11: Pawn Rendered with the Attempted 2-Pass technique, colors exaggerated to better show the negative effect of this attempt.

keeps track of the shallowest depth. The code in figure 4.12 demonstrates how this works. In short, if the software cull flag is set, the shader program accesses the ClearMask UAV to see if another pixel at that location had been previously processed. If the pixel has not been processed previously, update the clear mask, and set the depth of the current pixel in flight in the cDepth UAV. If a pixel at that location has already been processed, check if the current pixel in flight is more shallow than the previous pixel. If so, overwrite this pixel location. If not, discard the current pixel in flight.

4.5 Refraction Attempt

This implementation was attempted, but not successful, as there was a limitation within the compiler that does not allow looping within the shader that depends on values within or related to the UAV. As this was the case, the attempted implementation is still a part of this project, though the shader compiler throws an error and terminates execution. This portion of the project also revealed the performance hit that is taken when the application side clears a UAV. This implementation would have executed in two passes.

4.5.1 Application-Side Overview

The biggest point to note is about a UAV in the format of a 3D texture, or 2D Texture Array.

4.5.2 Shader Overview

First Pass

For the first pass, the idea was to step through the entire view volume as a single chunk of voxels. The clear mask is a 3D texture, and is populated with volume-based

```
                              /* ... */

if ((mode & CULL_RENDER_MODE) && (mode & CULL_RENDER_SHADER))
{
        IntelExt_Init();
        IntelExt_BeginPixelShaderOrdering();

                uint2 pixAddr = svposition.xy;

        switch (clearMask[pixAddr]){
        case 0:
                cDepth[pixAddr] = svposition.z;
                clearMask[pixAddr]++;
                break;
        default:
                if (cDepth[pixAddr] < svposition.z) discard;
                break;
        }

}

                              /* ... */
```

Figure 4.12: Software Culling Code Block Within PShader2

information of the scene (is this element inside, outside, or the surface of the model?). The error in the shader occurred within this pass. The implementation of this shader checked a conditional to see which values to set in the voxel mask. The values and what they indicated were as follows:

0: Voxel is outside of the model

1: Voxel is on the surface of the model

2: Voxel is inside of the model

Three values were used, such that if the render pass were to traverse the voxel mask and go from a value of 2 to a value of zero in the unit direction of the refracted ray, it would be known that the surface had been overshot. In the case of an overshot, there would be a backtrack process. However, the implementation never reached that case, as an informed decision was made regarding the feasibility of this demo. Despite this, a workaround was found for this first pass such that the error stopped being thrown. The solution was to set $VoxMask[CurrentPosition]$ to $(VoxMask[CurrentPosition]+1)\%3$. Figure 4.13 shows how this would look in code.

Second Pass

The second pass would have back culling active, and each pixel would trace through the model's voxelized representation in the unit direction of the refraction. After a surface

```
[loop]
for (i = voxPos.z + 1; i < VoxMask.GetZDimension(); i++)
{
        tempi.z = i;
        VoxMask[tempi] = (VoxMask[tempi] + 1) % 3;

}
```

Figure 4.13: New loop logic for the population of the voxel mask

was found, indicated by the voxelized clear mask, a second refract would take place based upon the stored normal vector at that location. After that refract took place, the cube/sphere mapped texture would be sampled to return the color at that pixel. The second pass was never implemented, as the first pass never successfully completed the testing phase, until after the decision to cease development of this demo. Regardless of the workaround found in the First Pass, there is no real way to work around having to check values inside of the Voxel Mask inside of the UAV, as checking conditions is key to traversal.

5 Findings

There are a lot of quirks and behaviors that have been logged throughout the entirety of this project. Firstly, I'd like to touch on the performance metrics of my project, and compare how it stacks up with existing algorithms, performance-wise, and also give a side-by-side comparison of the output images to show whether or not utilizing pixel synchronization to simulate a depth- based technique, such as a Subsurface Scattering approximation is worth it.

Following performance metrics, I will write about my observations of how the hardware, itself works, UAVs, and how they work, and then small coding oddities I found along my way toward my finishing my project. Included will be photos demonstrating behavior, along with explanations and recommendations on how to deal with these issues. The following sections are key to knowing how this hardware works, to extend to projects that use explore this same type of hardware (nVidia's Pixel Interlock technology, for example). Reading through this section should save time on the setup and boilerplate side of things.

5.1 Performance Metrics

5.1.1 Raw Performance Check of Pixel Synchronization

With the data provided by figure 5.1, the two results behaved in a generally predictable manner, with Hardware Culling being the fastest of the three options, with no culling coming in second, and shader-side, or software culling, coming in last. The trend for all three modes of the demo are to drop noticeably when the polygon count increases. However, there is a noticeable dip between the first three models. The low-resolution pawn actually has consistently poorer performance when rendered than the cube, which is to be expected, but the GPU performs worse when rendering the Sphere model, than it does with the Simple Pawn Model. The best and most logical explanation would be that the lower resolution pawn model is defined within its '.obj' file in such a way that causes the GPU to do more work, where the Sphere Model, on the other hand, is defined such that the GPU can more easily render it.

There was an interesting trend between the No-Cull mode and the Software Cull mode, as well. The comparison between these two modes is key, as the Hardware culling mode does not pass all polygons and potential pixels through to the pixel shader stage, and these other two modes do. To get an idea of the raw toll of which pixel Synchronization takes, the results of these two modes were compared. In figure 5.3, the raw difference in framerate is shown, not a percentage. As can be seen, the actual numbered difference in frames varies only slightly, until a model much larger than the others is used. Then, the difference drops significantly. When compared with the Framerate output values given in figure 5.1, it can be concluded that Pixel Synchronization hinders performance with decreasing significance as the primitive assembly stage becomes more of the bottleneck. In other words, the more vertices the GPU has to process, the smaller the performance hit incurred by Pixel Synchronization. This conclusion can be further corroborated by examining 5.4. At first glance, this plot follows the same pattern as figure 5.3. However, this shows that the percentage of performance hit that is incurred decreases with model size. It is up to the programmer to make informed decisions about the size of models on which to run pixel synchronization. However, for culling, it is recommended that hardware culling be used wherever possible, unless the goal is to use pixel synchronization on a single-pass.

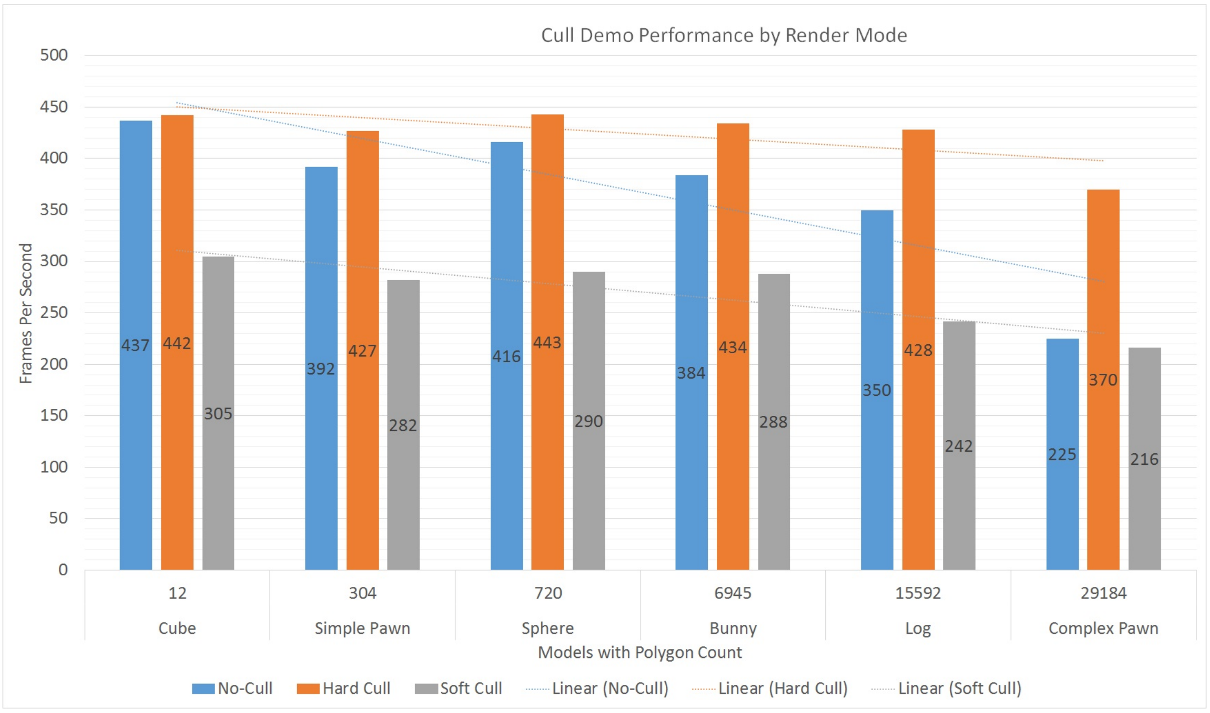

Figure 5.1: Cluster Bar Visualization of Framerates, Sorted by Polygon Size of various models.

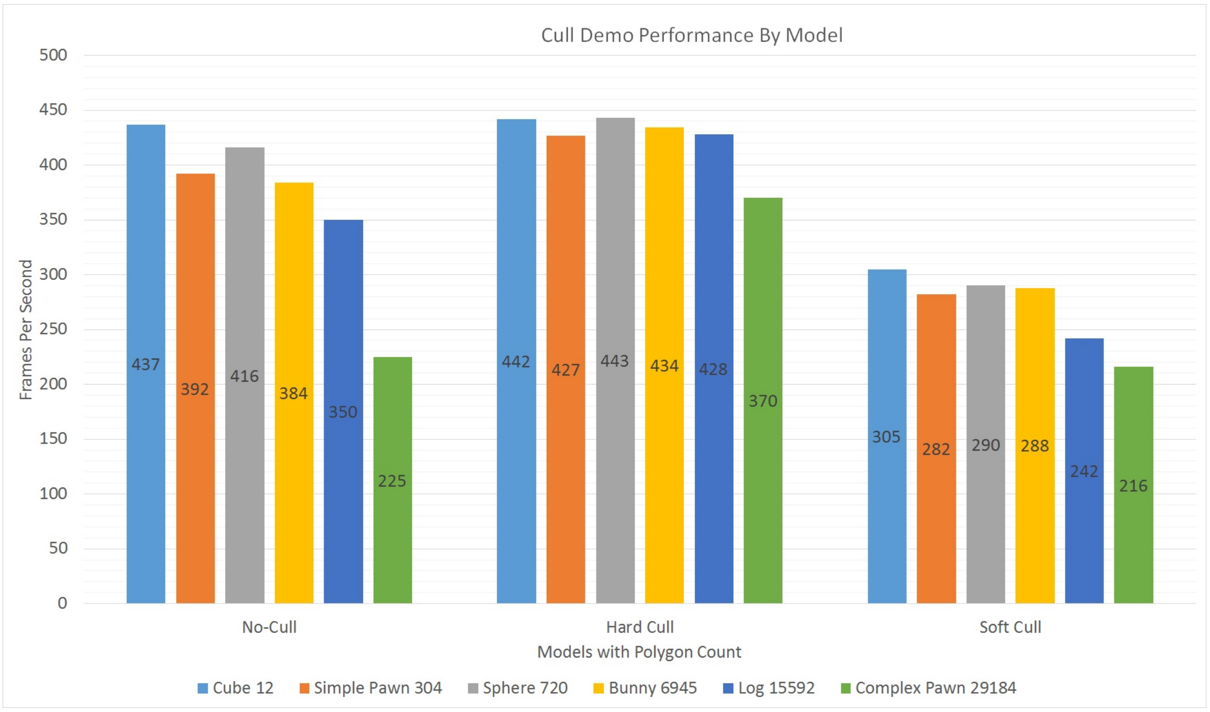

Figure 5.2: Cluster Bar Visualization of Framerates, Sorted by Model

5.1.2 Subsurface Scattering

The results from figure 5.5 are just as expected, with Phong illumination winning out, performance wise. However, the performance of the Subsurface Scattering technique is high enough that it would be a viable technique for use, as it does not tax the GPU so much as to drop the performance to a less-than desirable frame rate. For increased image quality, it

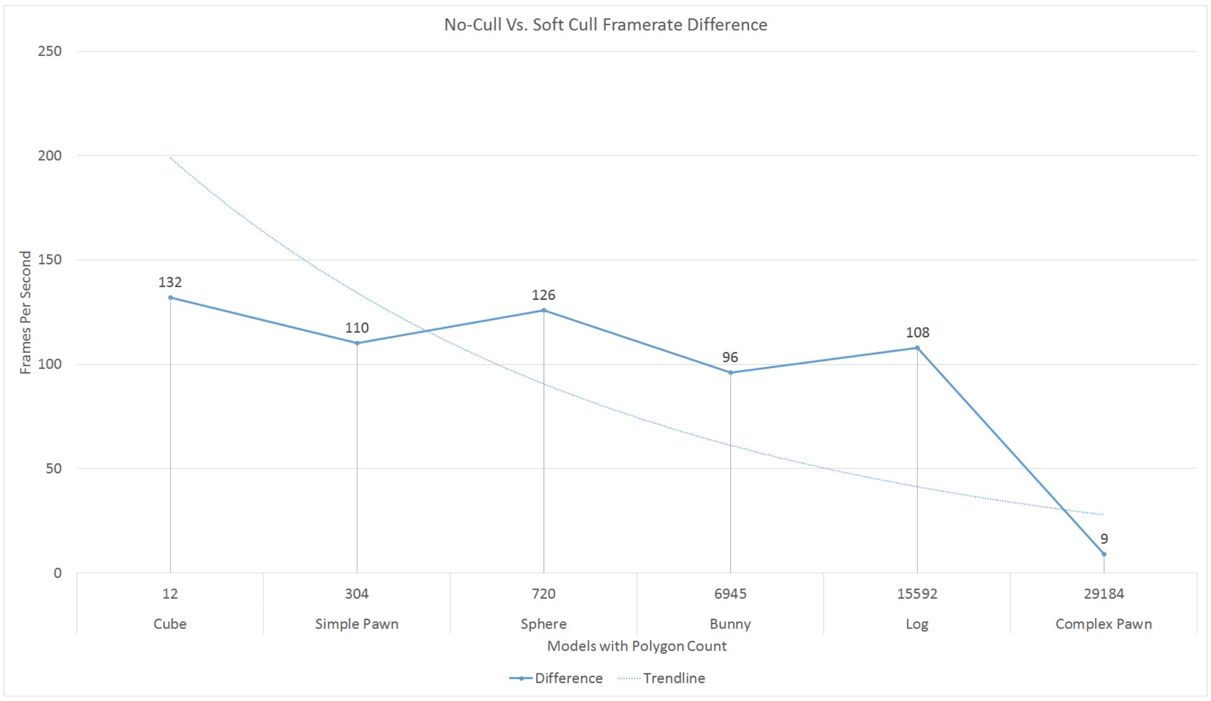

Figure 5.3: Plot of Differences of No-Cull Vs. Soft Cull Framerates

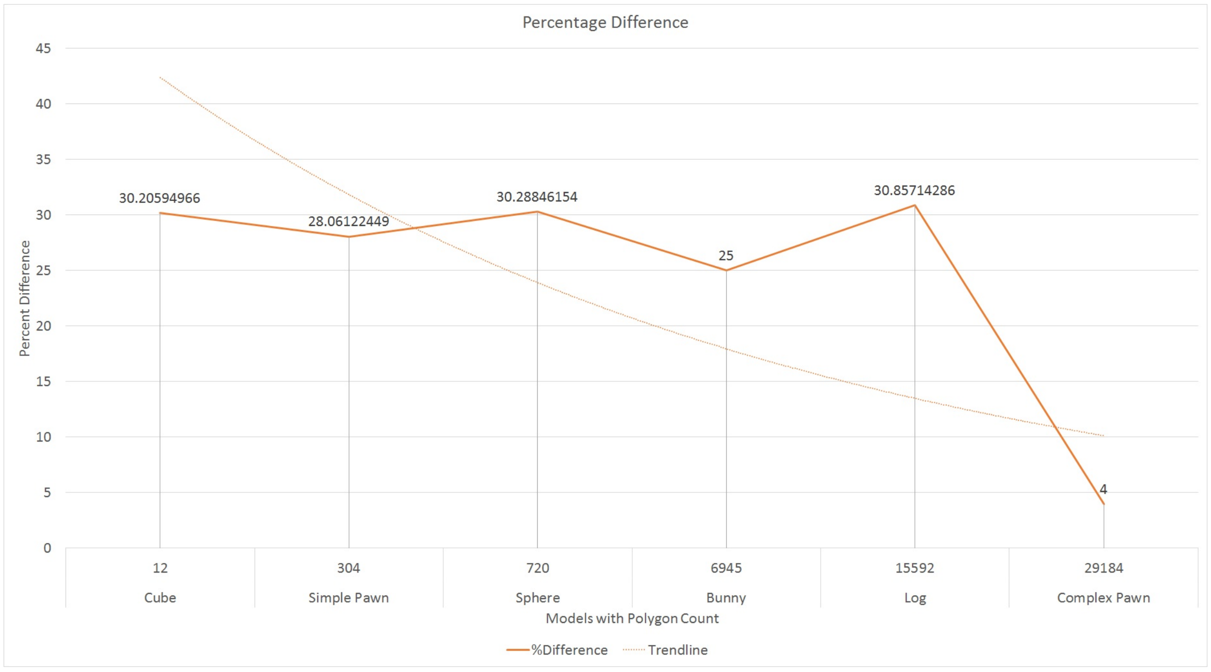

Figure 5.4: Plot of Differences of No-Cull Vs. Soft Cull Framerates

can be safely concluded that pixel synchronization can help in accomplishing straightforward solutions to depth-based rendering techniques.
Figure refpic:SSSPerTechnique shows an interesting phenomenon. Consider the left group of the bar graph. The pattern of the leftmost three members is the same as it has been throughout the other parts of the demo. However, on the right grouping, the pattern is flipped. One hypothesis that was devised and tested (results in figure 5.7) was that it was the size of the screen space that was taken up by the orthogonal pixel synchronization step

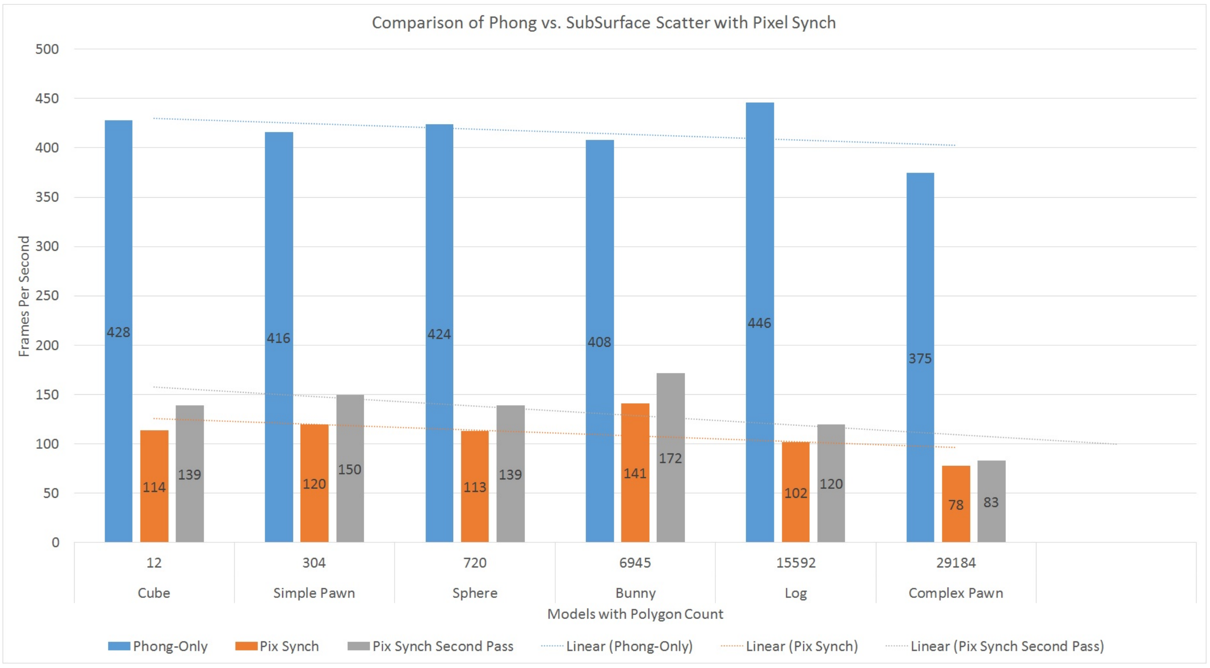

Figure 5.5: difference between the regular 1-pass phong illumination, timing of 2nd and 3rd passes of pixel synch SSS technique

was where the pawn model gained a performance advantage over the other two models in question. However, as can be seen within figure 5.7, this does not end up being the case. This suggested that the bottleneck could be happening during the first pass, where the models are unwrapped with respect to texture space, which led to a new hypothesis that the more texture coordinates that were covered by the model, higher the performance hit, as the information gathering and storing process takes longer, as more indices of the texture space are being accessed.

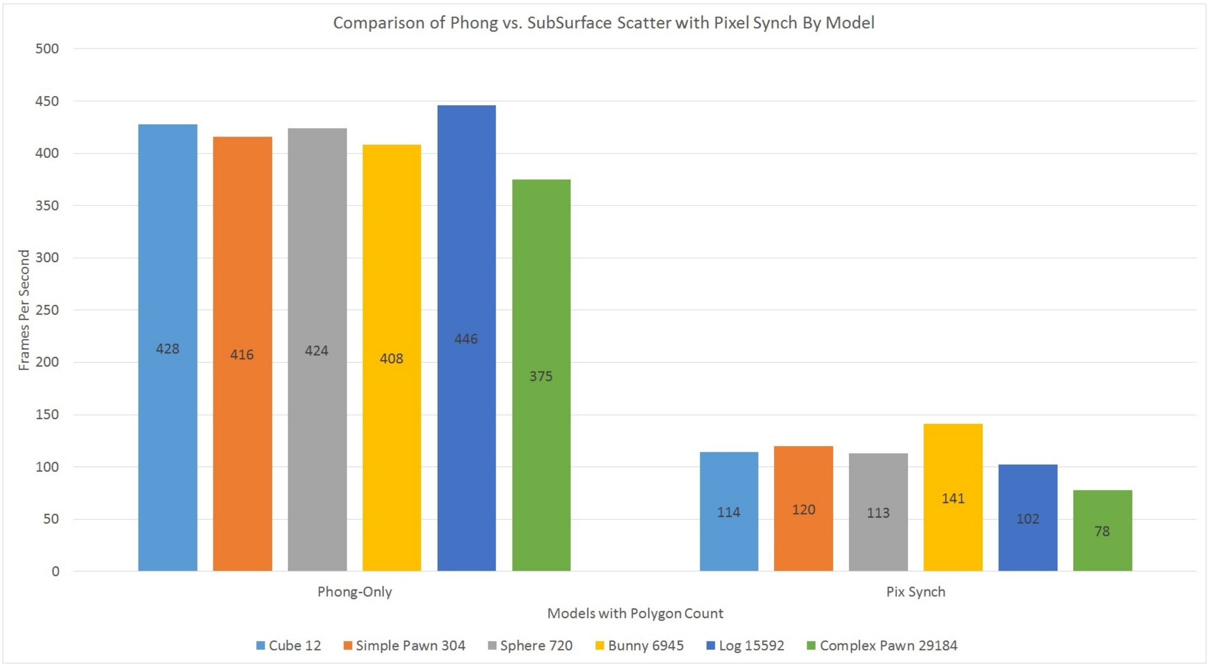

Figure 5.6: each model's performance, grouped by technique

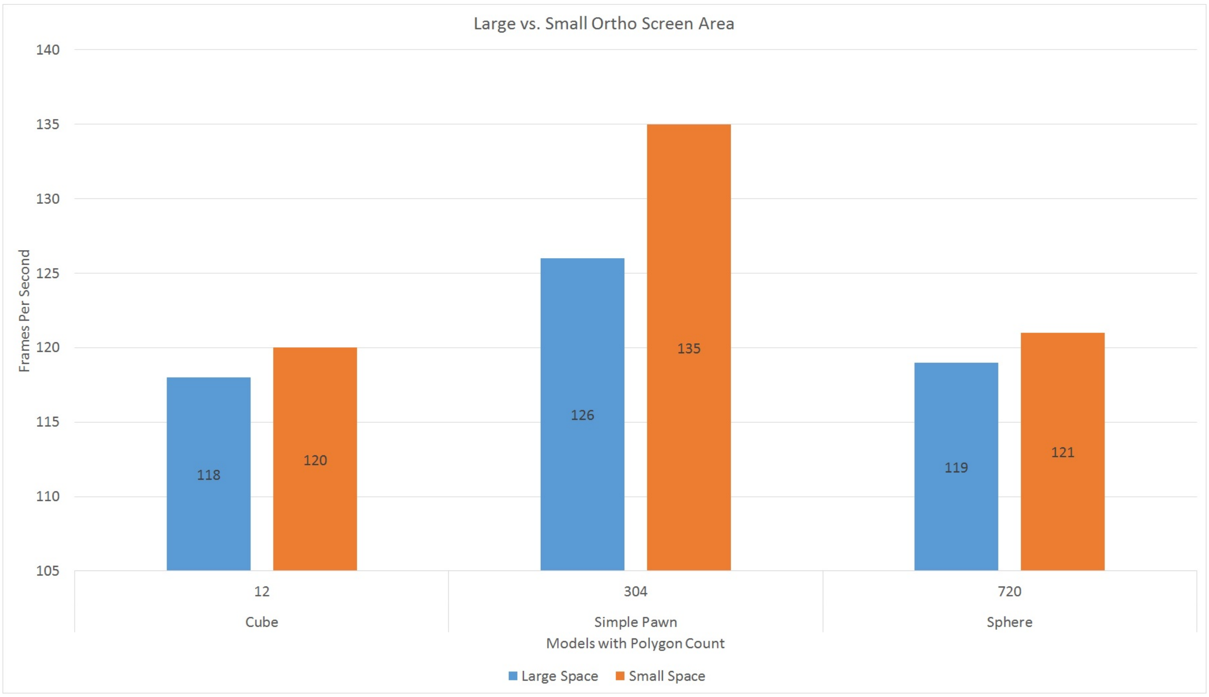

Figure 5.7: Comparison of screen space taken up by model in pixel synchronization step

Consider figures 5.8, 5.9 and 5.10. As can be seen, the pawn's texture space takes up the least screen space in the first pass. Further, regardless of the number of vertices within the model, the more pixels that are in flight, the longer a render pass will take to complete. This conclusion can be corroborated with the graph in figure 5.11. The amount of gray space (pixels never dispatched) seems to correlate with the performance results. As such, it is safe to conclude that the bottleneck for models with sufficiently low vertex counts seems to be the first pass for gathering depth and screen space knowledge, from the perspective of the light source.

5.1.3 Refraction

The attempt at utilizing pixel synchronization to accomplish refraction was not successful. This being the case, there are no graphs or comparisons of performance for this portion. However, a formal definition of the algorithm will be provided, such as to give a hypothetical evaluation on performance costs with comparison to the simple solution to refraction.

From a high-level perspective, the simple refraction algorithm can be defined in two steps. These steps assume that the skybox, or cube map, has already been processed and rendered, and the steps below take place for each pixel.

Step 1: calculate the bounce of the eye's ray against the surface normal.

Step 2: map the direction of this bounce to a location of the environment texture.

With such a simple set of steps, it can be said that for each pixel, this algorithm runs in constant time, O(1), as it has no other dependencies upon other pixels, or tracing over another data structure. With this simple implementation in mind, consider the following steps for the more accurate refraction approximation. There are two render passes within this method:

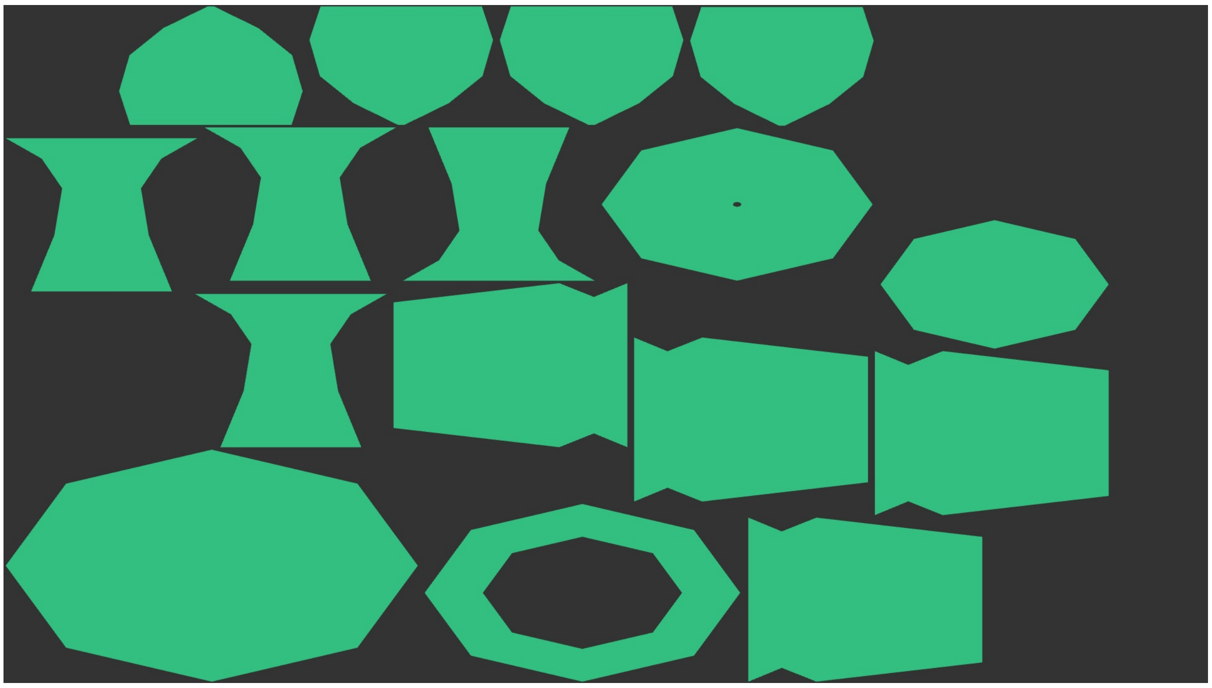
Figure 5.8: Texture space rendering of low-res pawn model

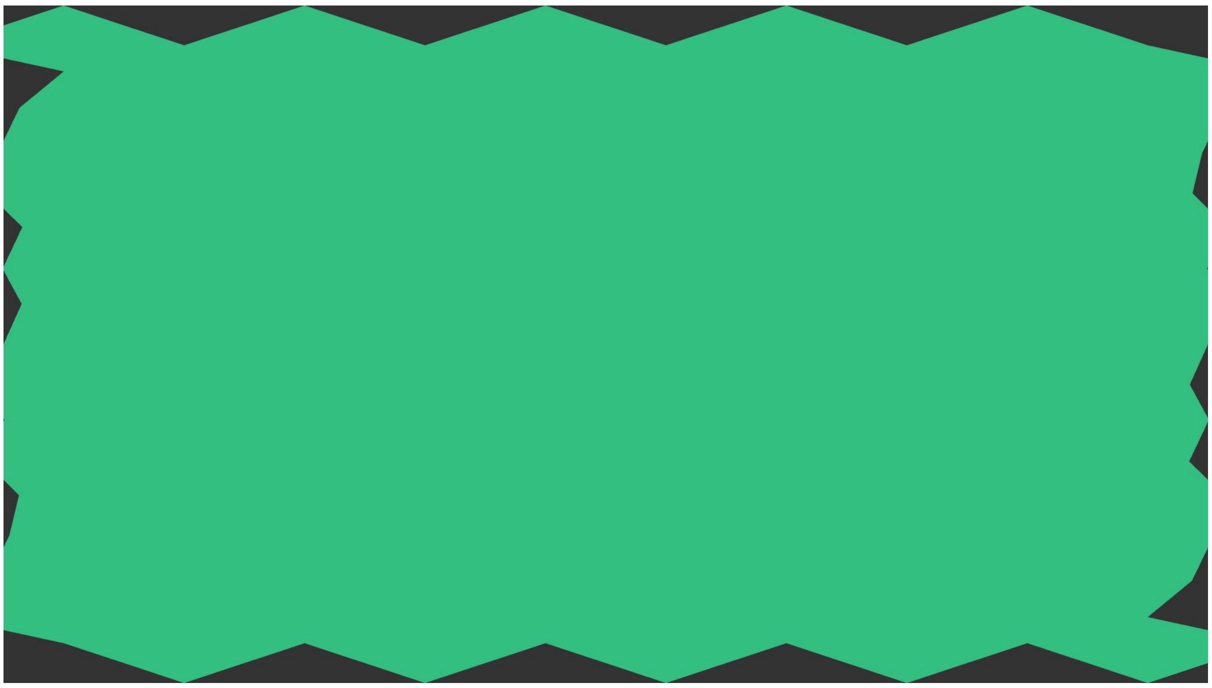
Figure 5.9: Texture space rendering of sphere

Render Pass 1:

Step 1: Store surface normal at the object's location within a 3D texture that encases the entire view volume.

Step 2: Mark current location to indicate it is at the surface of the model. Mark all subsequent locations in the Z direction to indicate that they are either inside of outside of the model (explained in figure 4.13).

Figure 5.10: Texture space rendering of cube

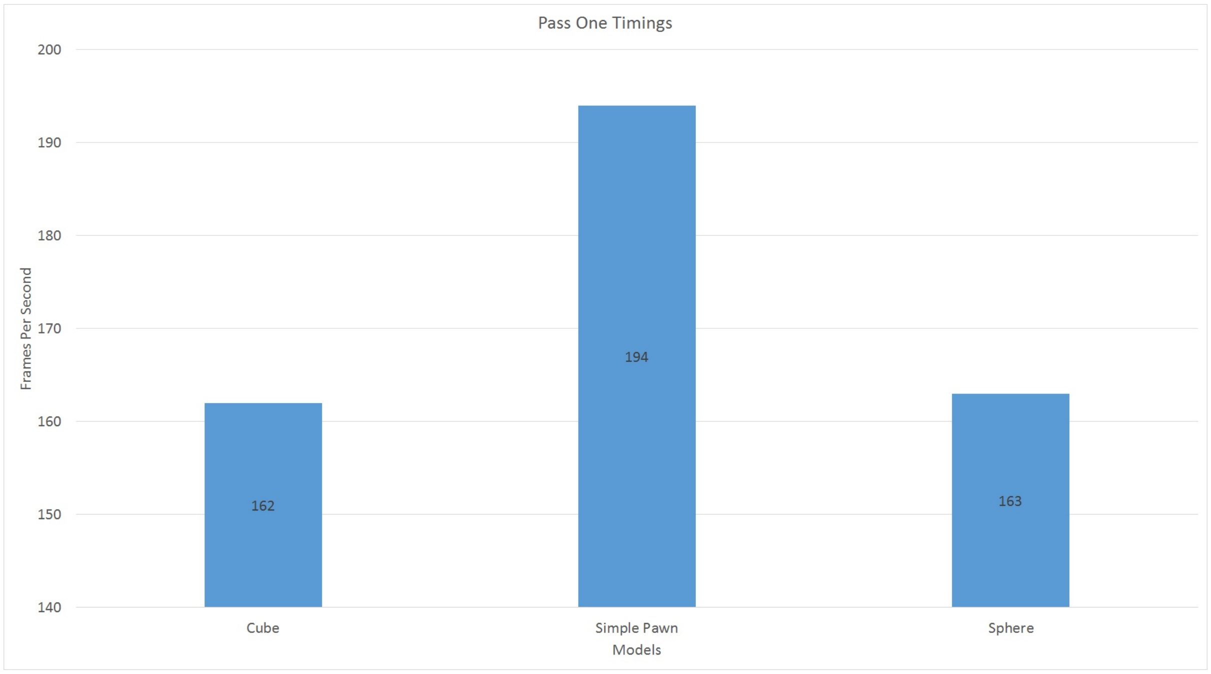

Figure 5.11: Texture space render performance

Render Pass 2:

Step 1: Calculate ray bounce relative to pixel's surface normal.

Step 2: Trace through the scene while within the object in the unit direction of the ray bounce, until the surface is found again.

Step 3: Calculate additional ray bounce.

Step 4: Sample environment texture from resulting bounce.

Considering the first pass only, Step 2 requires that each pixel step through a texture. In this case, it is assumed that the texture is N^3 in size. This means that in the worst case, each pixel would take linear, O(N), time to complete its execution. Render Pass 2 is more complex than the first, as there is more than just data gathering happening at this point in the algorithm. In Step 2, the gathered data is traversed in the unit direction of the ray bounce. this being the case, the ray now moves in the x, y an z directions. However, even though this could be 3N time, it is simplified to general linear, O(N), time. Overall, the total runtime can be expressed as follows:

$$TotalRenderTime = RenderCall + O(N) + RenderCall + O(N) \tag{1}$$

Within grahpics, even linear time algorithms can be quite costly to performance, as this linear run time applies to every pixel within the pipeline. What this equation translates to, basically, is that were this algorithm were to be implemented, the designer of the implementation must make a careful hardware-specific decision about how large the texture should be to acheive an optimum balance between performance and image quality.

6 Observations

6.1 Creating and Using Unordered Access Views

When using pixel synchronization, Unordered Access Views (UAVs) are key to allowing a programmer to get all he or she can out of the pixel synch capability. UAVs are set up to use on the application side, and can be used on the GPU side after certain specifications are made. Firstly, we must create and define the UAV on the application side of our program.

We first create a texture for our UAV on the application side. To create our texture, we have to create a description to send to the system, then create a texture by that description (fig. 6.1). Notice in the code on line 10, we populate a member of **texDesc** called **BindFlags**, and specify that this texture will be used for unordered access. The population of this flag does not mean the UAV will be set up and ready for use.

We must map a UAV instance to that texture (fig. 6.2). We must first describe the instance of the UAV to the program. We do this in a very similar way to how we described our texture. However the description structure is now of type **D3D11_UNORDERED_ACCESS_VIEW_DESC** instead of **D3D11_TEXTURE2D_DESC**. As a quick note, the texture description can be interchangeable among **D3D11_TEXTURE1D_DESC**, **D3D11_TEXTURE2D_DESC** or **D3D11_TEXTURE3D_DESC** you must make sure that the dimension of the UAV description matches what you have described and created for your texture. If no error occurs after executing the code in figure 6.2, then we are only a couple of small, yet key, steps to utilizing UAVs within our code.

Now that we have a texture created, and a UAV instance bound to that texture, we must now tell the GPU when we want to utilize the UAV and where exactly we want that UAV to be mapped, register wise, on the GPU side. We do this by making a call to the GPU to not only set the render target, but also the UAVs tied to this render pass. So, we change the set render target call, as shown in figure 6.3.

After we change this call, we know exactly in which registers our UAVs will live. So, following that, we make sure to specify where these UAVs live on the shader side as a global variable, as shown in figure 6.4. A few things to note: In the code, The token "DataType" should be replaced with whatever datatype was specified (**unsigned int**, **float***). Something to consider, though, is that each element within a UAV texture is limited to 32 bits. I recommend **float3** only be used in very specific cases, where precision is not paramount, as you are only able to specify a format of DXGI_FORMAT_R11G11B10_FLOAT, which means that a programmer is only given 11 bits for the first and second channels, and 10 bits for the third channel. There are special registers in HLSL shaders in which we must utilize for the use of UAVs. There are 8 of these registers, and they are preceded with a 'u'. By specifying our register, we know exactly what the datatype and makeup of that UAV is, by what we have defined on the application side.

To reiterate, a UAV is a texture that has been mapped to a read/write register on the GPU. Since it is a texture, we can also sample from it. This behavior exists for the following reason: say we populate this UAV texture in one shader pass, then want to read from it within a different one. This can be accomplished in two ways, but some programmers prefer

```
D3D11_TEXTURE2D_DESC texDesc;
ZeroMemory(&texDesc, sizeof(texDesc));
texDesc.Width = SCREEN_WIDTH;
texDesc.Height = SCREEN_HEIGHT;
texDesc.MipLevels = 1;
texDesc.ArraySize = 1;
texDesc.SampleDesc.Count = 1;
texDesc.SampleDesc.Quality = 0;
texDesc.Usage = D3D11_USAGE_DEFAULT;
texDesc.BindFlags = D3D11_BIND_UNORDERED_ACCESS;
texDesc.Format = DXGI_FORMAT_R32_FLOAT;

//We then use our description to create our texture.

HRESULT texRes = dev->CreateTexture2D(&texDesc, NULL, &pUAVTex);

//We always have a hook to check if our
//device-side calls were successful.
if (texRes != S_OK)
{
        MessageBox(HWND_DESKTOP,
                L"Texture Creation Unsuccessful!",
                L"Texture Error!", MB_OK);
        exit(EXIT_FAILURE);
}
```

Figure 6.1: Describing and creating the 2D texture that we will use for our UAV.

to sample from the texture using the sample intrinsic, rather than indexing it like a UAV. To do so, we would have to specify that we want our texture to be used as both a UAV and a read-in texture, by changing the bind flags from **D3D11_BIND_UNORDERED_ACCESS** to **D3D11_BIND_UNORDERED_ACCESS** | **D3D11_BIND_SHADER_RESOURCE**. This allows us to also tie a texture sampler to the same texture that a UAV is bound to. However, to smaple from the texture, we must firt unplug it from the program as a UAV and plug it back in as a sampled texture. This means that writing to a texture, then sampling from it in the same pass would not be allowed (nor would it be very practical). A good use for setting a texture as both a UAV and a Sampled Texture would be in a case such as the Subsurface Scattering demo, where we store the depth of each fragment, with respect to the light in one pass, as well as which ray passes through that fragment.

6.2 Unordered Access View Limitations and Recommendations

UAVs are quite useful in the grand scheme of things, but how useful they can be, really depends on the amount of memory the GPU has at its disposal, and whether or not the data the programmer would like to store must be iterated over. The memory bandwidth issue is not necessarily a pressing one for the demo presented within this paper, but it could present itself as an issue for larger projects, if not monitered.

```
D3D11_UNORDERED_ACCESS_VIEW_DESC UAVdesc;
ZeroMemory(&UAVdesc, sizeof(UAVdesc));

UAVdesc.Format = DXGI_FORMAT_R32_FLOAT;
UAVdesc.ViewDimension = D3D11_UAV_DIMENSION_TEXTURE2D;
UAVdesc.Texture2D.MipSlice = 0;

HRESULT UAVRes =
        dev->CreateUnorderedAccessView(pUAVTex,
                &UAVdesc, &pUAV[1]);

if (UAVRes != S_OK){
        MessageBox(HWND_DESKTOP,
                L"Our UAV view was not successful...",
                L"UAV Error!", MB_OK);
        exit(EXIT_FAILURE);
}
```

Figure 6.2: Mapping our UAV to the texture we created in figure 6.1

UAVs cannot be looped over within a shader. What this means, is that if a programmer would like to search for a value within a UAV, this is not possible and the HLSL compiler will not even compile the programmer's shader. This means that any sort of iteration over dynamic data within a pixel shader is not possible at this time. I speculate that this is done as a precaution to keep programmers from shooting themselves in the foot, or creating an infinite loop within the GPU, which could cause trouble in the form of Denial of Service. However, if the programmer sets up their UAV diligently within the shader, this should never be the case.

Another issue is that application side UAVs and their Shader-side counterparts are seemingly very disparate entities within code. A programmer must be very diligent in keeping track which UAVs are tied to which textures, what datatype is associated with said UAV, whether or not the UAV is bound, and if bound, to which register. However, following all of the bookkeeping steps, UAVs make shaders more powerful.

As mentioned above, there are 8 UAV registers available on the hardware on which I ran my code. However, we may only bind 7 UAVs at a time, since one of these UAV registers is actually reserved for the render target (if we are utilizing UAVs within a pass that renders to screen). When designing a graphics program, remember to keep track of how many Read/Write datastructures needed within the GPU, and which can be sampled as textures at any point. It is also recommended that a programmer become very familiar with data packing algorithms, such that the 32 bits per each UAV element is used to as much of its capacity as possible. Packing data efficiently will lead to a far more efficient HLSL program, as long as the pack/unpack functions are quick.

There remain other issues while using UAVs, including the following:

Clearing UAVs

```
//we change from this call...
devcon->OMSetRenderTargets(
                    numTargets,
                    &RenderTargetViews,
                    DepthBuffer);

//...to this call...
devcon->OMSetRenderTargetsAndUnorderedAccessViews(
                    numTargets,
                    &RenderTargetViews,
                    DepthBuffer,
                    UAVStartSlot,
                    NumUAVS,
                    &UAVs,
                    UAVInitialCounts);
```

Figure 6.3: Comparison of the two OMSetRenderTargets*() calls.

```
RWTextureXD<[DataType]> UAVName : register(uY);
```

Figure 6.4: General layout of UAV declaration on the shader side Where **X** is a dimension from 1 to 3, and **Y** is a register number from 0 to 7.

Clearing a UAV on the application side can be quite expensive, and seems to scale quite a bit with the size of the UAV. For instance, within my refract code, I have a UAV that points to a Texture3D that greatly slows down the performance of the application. Please see figure (make figure) for a visual explanation. It is up to the programmer's discression to discern a 'sweet spot' size for their UAVs to get equal parts quality and performance. As can be seen in the graph, having a large UAV can really slow down a render pass.

Uninitialized UAVs

Within HLSL code, the compiler allows the programmer to define a RWTextureXD, as demonstrated in figure 6.4, at any time. There is no check from the compiler to see if there is a UAV register that has been initialized to a texture. The reason why is because shader programs are compiled and linked prior to setting any UAVs. In other words, the HLSL compiler allows this because it is trusting the programmer to populate that register with a texture when it comes time to run the shader program. However, if a UAV is never initialized or populated, the programmer may still reference that RWTexture, but any writes to or reads from will not work. In most cases, any read or write will cause the program to crash. Any methods specific to RWTexture can still be executed, such as RWTexture2D.GetDimensions(). However, the X and Y dimensions returned will just be zero. This is an easily avoidable pitfall, so long as the programmer keeps track of his or her UAVs accordingly.

UAV Order is important

Programmers using UAVs in their shader code must keep track of the order in which their they are given to the GPU when Binding their UAVs and Render Target(s). Seeing as this is only possible if the UAVs are kept in an array, it is good to keep a note of which UAVs are meant for certain purposes. If multiple sets of UAVs are needed, it is recommended these UAV sets are named accordingly. While rendering, shader code is allowed to access UAVs as a datatype that conflicts with what a programmer might have defined at that UAV slot, because every element in a UAV texture is 32 bits. This makes it quite difficult to catch potential errors, unless diligent precautionary measures are taken.

6.3 Pixel Synchronization Behavior

The Behavior of Pixel Synchronization can be confusing, unless if we take time to understand what it actually does. However, let us first take the time to figure out how prepare it for use on the application side. In order to see if the Iris extensions are available, the programmer must include the following files into his or her C++ code: *ID3D10Extensions.h*, *IGFXExtensionsHelper.h* and *IGFXExtensionHelper.cpp*. These three files can be found within the github repository in the IGFXExtensions folder. After including these files in your C++ application, the programmer may now use the IGFX namespace. To initialize these extensions, simply execute the following commands during the DirectX setup function (in this project, this part of code is called **InitD3D()**). As is shown in figure 6.5, to initialize Iris Extensions on the application is quite simple. This is because Iris Extensions are meant to happen without having to be too visible to the DirectX side of code. After we initialize our graphics extensions, we can see which extensions we have available to us, if any. Now that we have this information, our program can make informed decisions on what kind of hardware it has at its disposal to accomplish render techniques. As this demo is meant only for Iris extensions, a decision was made to not utilize this available extension check to enhance robustness of the program.

```
//global variable...
IGFX::Extensions myExtensions;

//Within setup code...
HRESULT res = IGFX::Init(dev);
if(res == S_OK) myExtensions =
        IGFX::getAvailableExtensions(dev);
```

Figure 6.5: Intel Iris extension setup on the application side.

After we ensure our program/Direct3D device can use Pixel Synchronization, there isn't anything more that the GPU device requires from the application, itself. Now, all we must do is specify when, inside of our pixel shader, we want to synchronize our pixels, and that's it! For an actual shader code snippet of this, please refer to the snippet in section 1.4.2, figure 1.1. Recall that the Pixel Shader must include *IntelExtensions.hlsl*.

So at this point, we should be able to initialize Iris Extensions and invoke Pixel Synchronization. However, as programmers, we can't very well utilize Pixel Synchronization without first knowing how it behaves.

When invoked, it is known that Pixel Synchronization first creates a barrier for all shaders in flight at the same pixel position. Following this barrier, we know that all shaders that hit this barrier are ordered by Primitive ID. The question is, "How does this ordering occur?" The answer is actually quite straightforward. They appear to be ordered by primitive number because they are ordered by order of submission from the vertex stage. Knowing that this happens, whether the pixels actually accomplish a front-back or back-front sorting depends on how the model was defined within its object file.

Knowing that the ordering takes place as such, it is not safe to assume that the ordering will take place the way the programmer wants to. As a result, this begs the question: What is the benefit of Pixel Synchronization, exactly? The benefit of this extension comes from the fact that we can guarantee a portion of memory will be read/written without data races. This allows for programmers to accomplish much more within the pixel shader than has been done before. To be able to accomplish sorting based upon depth within the shader is a remarkable thing. However, there are some workarounds that must take place. As it was mentioned in section 6.2, we cannot loop over our UAVs, but one thing we are able to do is make create a 'mask' that keeps track of what depth of a Texture3D or Texture2D array has not been written to, then write to that. After this step, we can sort through the UAV as a sampled texture in a later pass, such that we can do something meaningful with the information.

6.4 Coding and Behavior Quirks

As this project deals with raw DirectX, there are a lot of places in code which could serve as confusing pitfalls. These pieces of code range from application or CPU-side issues, or even within the pipeline itself. This section is meant to detail some of those more common pitfalls and also point out some behavior inherent to the pipeline or hardware that are not the programmer's fault.

6.4.1 Working With the GPU Device on the Application Side

Just the same as in OpenGL applications, DirectX applications allow the program to continue even if there is an error or failure within the graphics device. For this reason, self-error checking is a very important practice when building a graphics program from scratch. Within a DirectX application, this can be easily done, as the appropriate device and device context related functions return a datatype called HRESULT. By checking this HRESULT, a programmer can get a good idea of what type of error is happening within his or her code. However, this doesn't encompass all errors. There are some instances in which a call to the GPU can cause an internal error, and force the device to unplug itself from the program. The instance in which this "Device Removed Error" occurred most commonly for this project was when attempting to create a UAV texture that was too large for the program. If the program is allowed to let itself run without having this error caught, other errors will occur down the line, and in the best case, the program will yield a viewport full of garbage.

6.4.2 Pipeline Behavior

The most fascinating behavior of the pipeline during this project was finding that the pipeline may make rounding errors during the interpolation phase of the pipeline. These rounding errors were made apparent when attempting to work with a UAV that was a larger resolution than 512x512 pixels in the Subsurface Scattering Demo. If the texture was too high of a resolution, the resulting depth-based shadow would cause an immense amount of artifacts. This was mitigated when using a lower resolution texture. The only conclusion I could draw from this was that there were rounding errors taking place within the interpolation stage, forcing certain indices of the texture to be missed. Screenshots and a graph demonstrating this behavior can be found on page(put pictures into this document now, ok thanks).

6.4.3 Placement of Pixel Synchronization call

As state previously, making a call to pixel synchronization creates a critical section within a pixel shader. The catch to this, however, is that, beginning with the pixel synchronization call, the rest of the pixel shader is a critical section until the end of the shader. Since this is the case, it is highly recommended that all operations that are not dependant upon synchronization happen prior to the barrier to mitigate the number of operations that must be ordered. However, if the pixel shader does not have many operations taking place, it may not be a noticeable difference to have the non-dependant code within the critical section. Code with pixel syncronization saw a 10% drop in frames per second, compared to the same code with the barrier removed.

6.4.4 Vertices are Still the Bottleneck

As the vertices have been processed and all values have been interpolated across the pipeline at the point of the Pixel Shader, a bigger influence on runtime will still be the number of vertices used to define the 3D object. For instance, this project contains two pawn models. One is very low resolution with a smal number of faces, and the other has been smoothed and vertices have been added. The runtime still scales with the number of vertices, regardless of any influence of pixel synchronization.

6.5 Suggestions and Advice When Using Pixel Synchronization

Pixel Synchronization melds the world of graphics and parallelism even further, by adding the capabilites of barriers to the end of the graphics pipeline. However, to take advantage of this capability to the fullest, some practices in parallel programming must be taken up within graphics programming.

Design the Critical Section

Since our critical section will be ordered and will execute one-at-a-time, the programmer must do what he or she can to keep that section of code lean. To make sure our critical section is as lean as possible, it is recommended that the programmer evaluate and design the pixel shader to make smart, informed decisions on what operations can happen outside or inside of the ordered section of code. One very simple rule is that any write to or read from shared memory must take place within a critical section. As a translation, any access to memory that would require a mutex in a parallel program should be accessed inside of the Pixel Sync critical section.

Know the Necessary Relationships

Having multiple render passes per object in a scene is quite costly. However, a good way to mitigate erroneous passes is to think about the relationship between the object and, in the case of Subsurface Scattering, the light source. In the case of Subsurface scattering, we know that the depth information stored at that object does not change until either the object or the light changes their orientation within the scene. A flag can be inserted into the program such that if either of the two involved entities change their orientation or position, the Pixel Ordering passes are activated to gather the new depth information. Executing Pixel Ordering passes based upon a condition has the potential to vastly speed up the runtime of a graphics progrom that uses this functionality to implement effects such as subsurface scattering, and help to make a case for its viability in practical use.

Keep the UAVs a reasonable size

One of the biggest hits to performance was using a UAV texture that was quite large. UAVs that were large ended up incurring a rather larger performance hit. To mitigate this, it is recommended to find a "sweet spot" between quality and performance. Along with the performance of the shaders with the UAV, it takes quite a bit of time to clear these UAVs with each rendering of the scene. This was made very apparent when creating a Texture3D UAV of size 800^3.

Take Advantage of Having a Texture Be Both a UAV and a Sampled Texture

Sampling a texture takes less time than indexing a UAV. As this is the case, it is recommended that the programmer access the texture with a Sampler if the shader is only reading from the texture, and not Read/Writing. This will help ensure that the final render pass is as fast as possible.

6.6 General Suggestions and Advice

When writing raw DirectX, there are some pitfalls and coding tricks that are necessary to point out. However, paying attention to these pitfalls and tricks won't necessarily make a programmer's DirectX application bug-free, but knowledge and consideration of these suggestions and advice could save debugging and head-scratching time.

Constant Buffers

Constant Buffers are how DirectX approaches application-specific variables within the GPU. For instance, if the programmer would like to include an interactive coefficient for brightness of a light source, he or she would do so by creating a constant buffer that held that coeffiecient, then updating it on the application side prior to rendering. OpenGL approaches this by using Uniform Variables, all of which have their own ID number on the GPU and are updated one-by-one.

If a programmer has multiple values to pass into his or her DirectX program, it can be done by adding multiple members to the constant buffer data structure. This reduces the communication to/from the GPU to just one instance, while updating the entire buffer. However, it is important that the definition of the struct on the GPU side mirrors the application side's definition. Further, take note that the Constant Buffer's size must be a multiple of 16. This is so the call to copy the information from the application to GPU will always be a predicatable size for the GPU. To mitigate problems, the creation of the constant buffer in the Subsurface Scattering Demo added the size of the constant buffer, mod 16. For a better idea, please consider the code snippet below. On line 5 in the below code snippet, the multiple of 16 size constraint is accounted for by adding the size of the buffer, mod 16. This means that the constant buffer could have anywhere from 0 to 15 bytes of extra space. Another way to account for the multiple of 16 size constraint is to add pad variables to the constant buffer, itself. Some programmers prefer this method, as it gives the padding a representation in the form of a defined datatype.

```
 1  D3D11_BUFFER_DESC bd;
 2  ZeroMemory(&bd, sizeof(bd));
 3
 4  bd.Usage = D3D11_USAGE_DEFAULT;
 5  bd.ByteWidth = sizeof(CBUFFER) + (sizeof(CBUFFER) % 16);
 6  bd.BindFlags = D3D11_BIND_CONSTANT_BUFFER;
 7
 8  HRESULT bres = dev->CreateBuffer(&bd, NULL, &pCBuffer);
 9
10  if (bres != S_OK)
11  {
12          MessageBox(HWND_DESKTOP,
13                  L"FAILED␣CONSTANT␣BUFFER␣CREATION",
14                  L"CBUFFER␣ERROR", MB_OK);
15          exit(EXIT_FAILURE);
16  }
17  devcon->VSSetConstantBuffers(0, 1, &pCBuffer);
```

Learn the HLSL Semantics

In HLSL a Semantic is an optional string that identifies the intended usage of return data. These semantics are quite useful in telling the GPU how to interpolate values across the pipeline. For instance, consider the following Data Structure defined in HLSL:

```
struct VOut
{
        float4 svposition : SV_POSITION;
        float4 color : COLOR;
        float4 position : POSITION;
        float2 UVs : TEXCOORD;
        float4 normal : NORMAL;
        float4 camera : CAMERA;
        float3 lightVec : NORMAL1;
        float4 lightCol : COLOR1;
        uint mode : MODE;
        float4 rotNorm : NORMAL2;
        float3 eyeVec : NORMAL3;
};
```

This is a data structure defined within the shader file, such that the vertex shader can pass many values to the pipeline. Some sematics are built in, but some others are programmer-defined. In this case, the only programmer-defined semantic would be MODE. The use for mode will be covered in the implementation discussion. Notice the differences between the SV_POSITION and POSITION semantics. These two Semantics tell the pipeline how to interpolate these values. As can be seen in the listed Shaders, both the SV_POSITON and POSITION members get the same value in the vertex shader. However, SV_POSITION gets interpolated into X/Y screen positons, and POSITION gets interpolated in the same -1 to 1 space for the X/Y/Z position given to it. Once a fragment or pixel shader has completed its running, the computed color is assigned to the pixel at the X/Y SV_POSITION. These semantics are a great way to keep track of values passed across the pipeline, and helps shed a little bit more light on what they are, and what they are used for.

Invest Time into Learning a Good Menuing Library

Creating a menu window for this project could have been made a lot simpler with a proper menuing library, instead of building it from scratch. The advantage of using a premade menuing library is that many of the functionalities of buttons can be linked in a simple call, rather than using the vanilla window class. For instance, within the Subsurface Scattering code, the menu was built entirely from scratch, and had to have its own window process, where it must check the state of global variables with which the buttons on the menu are tied to, and checked/unchecked, or presed without a convenient construct for relationship. The problem with this approach is that the relationship between the menu's buttons and what they are supposed to indicate, where they are located on the menu window, and which checkboxes are related to each other all must be managed explicitly by the programmer. In short, to save time, it is highly recommended that a menuing library be used, so as to avoid any extra debugging that does not have anything directly to do with the project.

Further, using the raw windows framework to create a menu doesn't abstract away anything for the programmer; every bit of the subclasses that the menu window holds are at the most raw level. For a better idea, please see the code below:

```
hGBButton = CreateWindowEx(
        NULL,
        L"BUTTON" ,
        L"GOOD/BAD" ,
        WS_TABSTOP | WS_VISIBLE | WS_CHILD | BS_AUTOCHECKBOX,
        50,
        20,
        100,
        24,
        hWnd,
        (HMENU)GOODBAD_BUTTON,
        GetModuleHandle(NULL) ,
        NULL);
```

```
SendMessage(hGBButton,
         WM_SETFONT,
         (WPARAM)hfDefault,
         MAKELPARAM(FALSE, 0));

Button_SetCheck(hGBButton, true);
```

To make a button without any menuing library, we must define a new window instance which lives inside of the current window, $hWnd$, define its size and position within the window, whether it is a checkbox button, and pass messages to and from the button, itself. The last line of the listing is meant to show that the programmer must set whether the checkbox is checked or unchecked, which implies that the programmer must track the value associated with that button and change that value accordingly. In short, without a proper Menuing library, building a menu can become quite convoluted and confusing.

Use Separate Render Functions

To demonstrate different effects, there could be potentially many differences in setup and dispatching of the GPU. For instance, the difference between the regular Phong Illumination technique and the Subsurface Scattering algorithm utilizing pixel synchronization are quite different, as far as how many UAVs must be set and bound to the render target and the number of passes. To keep the code readable and to mitigate too many conditionals within the render function, it is recommended that each render technique get its own render function.

If render techniques are not separated into different render functions, there could be mistakes made that could skew timing measurements. For instance, within the Subsurface Scattering Project, the Phong Illumination technique had been measured to perform at about the same framerate as the Pixel Synch Subsurface Scatter. As it turns out, what was happening was that the two setup render passes were still being executed, then the information was basically just being ignored. However, problems such as this are specific to the programmer, and not necesarily a general problem. For readability and clearcut management of code, splitting render techniques into their own separate functions is recommended.

7 Conclusion and Recommended Future Work

Coming to conclusions and figuring a roadmap for any potential future work for a project is almost as important as the project, itself. The following sections will detail what conclusions this project has presented, as far as the usefulness and viability of Pixel Synchronization, then potential avenues for further exploration will be detailed in the latter section. Those ideas are just to jumpstart the thinking of any student who wishes to undertake a project using pixel synchronization, and are not the only ideas worth persuing.

7.1 Conclusions About the Utility of Pixel Synchronization

7.1.1 Key Observations

Before going into what conclusions were drawn, it is worth detailing the key observations that took place, as these shaped the conclusions. The following are a list of observations, and some may be repeats from previous sections of this paper.

UAVs limit potential

The UAV limitation described above in section 6.2. The restriction of iterating over a UAV is, while understandable, diminishes the number of algorithms that can potentially be run on a synchronized pixel shader. As discussed above, this restriction is in place such that the programmer does not, by either accident or design, put a program onto the GPU hardware that creates a Denial of Service. Despite this limitation, there are workarounds, however, such workarounds would add an extra pass to a programmer's algorithm. For instance, one workaround could be to iterate over a Sampled texture, then using it as a UAV in the next pass. However, at this point, the idea of being able to use a UAV is shadowed by the fact that the programmer would be better off just keeping the texture bound to a sampler and doing a traditional render to texture and read from texture.

Performance Hit of Pixel Sync Scaled With the Size of the Model.

As demonstrated in this project, the performance hit scaled as it should have with the size of the model. This piece of hardware is as unobtrusive to the original pipeline as it possibly can be, and the size of the model doesn't affect performance any differently than it used to. Even though the performance hit scales as it should, that is not to say that it is not recommended that the programmer choose the critical section wisely. The smaller the critical section, the fewer the operations that must happen in- order. If at all possible, the best critical section would be one where only writes to the UAV take place. However, since most algorithms rely on reads and writes, this is a very tough case to acheive.

Pixel Synchronization Orders Pixels Based Upon When They Were Submitted

Seeing as the pixels are ordered based upon submission, and not depth, means that the programmer must still keep track of which pixels are deeper than others, when doing any sort of depth-based calculation. However, so long as the programmer designs the algorithm such that there is a quick check, depth- based decisions can be made in the same pass rather easily. Such an example of this is with the software culling example included in the Sub-Surface Scattering demo.

Pixel Synchronization is a Per-Pixel Mutex

As stated before, Pixel Synchronization's main purpose is to eliminate race conditions within Pixel Shaders. As such, Pixel Synchronization is a fantastic tool for naive calculations such as blending or transparency, since a pixel need only read/write a single value. Any algorithm that requires a naive addition or subtraction is already very well set up for the use of Pixel Synchronization. However, since this inherent mutex is in place, there are still many interesting solutions to be found within its use.

With Pixel Synchronization, a programmer would be able to write a shadow mapping shader program with fewer render passes. All that must happen for the depth-based part of the shadow map is for the pass with respect to the light to mark which surfaces it can hit. Following that calculation, the render pass shader could make an informed decision on which parts of objects to illuminate, and which parts of objects not to illuminate.

7.2 What the Findings Mean

Given the findings, there are a number of conclusions we can draw from this project. We can safely say that Pixel Synch is a great tool for a set of problems, careful design decisions will help make Pixel Synch algorithms relatively unobtrusive to runtime, all hardware could benefit from such a capability, and increased UAV functionality within the shader could unlock more potential.

For Certain problems, Pixel Synch is a Great Tool

Of course, Pixel Synchronization is not the be-all, end-all solution to increasing a graphics program's efficiency or quality. There are many key factors that attribute to the amount of utility that Pixel Synchronization will provide. If a graphics programmer were to be implementing a data-parallel rendering algorithm, this feature is quite useful. Any sort of depth-based problem would benefit very much from the use of Pixel Synchronization. In some cases, it can aid in performance, and in others, it can simply aid in simplifying the algorithm for readability, or reduce the amount of information the algorithm needs to run. As for the case of Subsurface Scattering, Pixel Synchronization was used to increase the quality of the image, and nothing more. After a small tweak to the Subsurface Scattering algorithm, the program was able to run at a performance similar to Phong Illumination in some cases.

When designing a Pixel Synch Algorithm, Do So Carefully

When finding a method of utilizing pixel synchronization for a rendering algorithm, there are important aspects to keep track of; for example:

- How much memory does the GPU have?
- What size of texture would work for this algorithm?

- How much of the Pixel Shader must happen after Pixel Synchronization?

There are other factors among the above three questions, but those seem to be the most fundamental and most considered when designing algorithms using Pixel Synchronization. Throughout the project, the GPU memory size, texture size and size of the critical section were the main factors within the design. After finding a "sweet-spot" answer to these questions, the Pixel Synchronization stage was able to be fit into the rendering algorithm in a way that was relatively unobtrusive to runtime.

Pixel Synchronization Would Be a Welcome Addition on All Graphics Hardware

Seeing as Pixel Synchronization has had such an impressive effect on a CPU/GPU, It seems as though this capability would have great potential on larger discrete graphics hardware. Since the beginning of this project, this has become the case for nVidia hardware, with the introduction of nVidia's "Pixel Interlock" technology. Seeing this concept make the jump to discrete graphics hardware indicates a promising future for Pixel Synchronization. However, there must be more exploration and experimentation as far as what ideas this could lend itself well to.

Trusting the Programmer to Loop Over UAV Textures Will Be Beneficial

As previously stated, the HLSL shader compiler does not allow for a loop to have a condition that depends upon a read from a UAV. This could be a restriction based upon the fact that Pixel Synchronization is not a widely used extension and the compiler simply assumes that there will not be ordered access to the UAV elements. If the compiler were to allow conditionals within loop constructs which depended on information within the UAV, the potential of Pixel Synchronization would grow immensely. At the very least, it would be good for the programmer to be able to set a flag for the HLSL compiler that says, "trust me, I'm using pixel synchronization." Had this been the case for this project, a completed refraction demo would be a part of the final product.

If the programmers are ever allowed to loop over UAVs, there would be potential to create well-informed, voxelized representations of a scene, to aid in simple refraction, ray-tracing or a more precise SubSurface Scattering algorithm. However, in order for ordered traversal through a UAV to be viable, more execution units would be beneficial, otherwise resolution would have to take a hit to keep performance at a respectable level. With time, however, the hardware industry would sort this limitation out.

7.3 Where to Go From Here

This project answered the questions it set out to answer. However, that does not neccessarily mean that the exploration should be complete. Since we know what exactly the capabilities are of Pixel Synchronization, understand the concepts, how to set it up for use, there are a number of directions this project could continue. Should one so choose, there are a number of options chose to delve deeper into the algorithm implemented for this project, or breadth-wise, by exploring Pixel Synchronization on discrete graphics hardware.

7.3.1 Finding a Viable Workaround for Looping Over UAVs

In an effort to give a complete working version of the refract demo utilizing UAVs and Pixel Ordering, a small workaround was attempted and ended up not solving the problem. To prevent time wasting, that method will be described here. As can be seen in the code snippet in figure 7.1.

```
IntelExt_Init();
IntelExt_BeginPixelShaderOrdering();

//set clearMask, if it hasn't been, already.

//we will loop through the voxel mask
//to determine where the inside of the model is.
/*      /--number meanings--/
        0: Outside of Model
        1: Model Edge
        2: Inside Model
*/

VoxMap[voxPos] = normal; //store this into the vox map.

uint i;
uint3 tempi = voxPos;
uint tempArr[512];
VoxMask[voxPos] = 1;//we are at the edge of the model

[loop]
for (i = voxPos.z; i < 512; i++){
        tempi.z = i;
        uint temp = VoxMask[tempi];
        tempArr[i] = temp;
}
```

Figure 7.1: Initialization of Temporary Array

The code within figure 7.1 is attempting to copy members of the voxel mask, which will be described more in-depth within section 4.5. The idea behind this was, once these values were copied over to the temporary array, they could be looped upon with conditions, then updated. Following the update of the temporary array, the shader would finally update the UAV in the z direction at the pixel's x/y position. However, the roadblock, here, is that the HLSL compiler optimizes the code such that the actual evaluation loop doesn't reference the temporary array, but still references the address within the UAV. This means that the compiler actually sets the address of the array elements to the address of the UAV values, instead of copying the value to a fresh piece of memory.

This phenomenon took place in a portion of code in the Subsurface Scattering, where a different workaround was implemented. However, that same workaround does not translate itself in a logical or functional way to this specific problem. When this phenomenon was occurring within the SSS implementation, what was happening was that a variable was being assigned to a value that lived within the UAV address space, and whenever that variable was manipulated, so, too, was the value within the UAV. If there were some sort of programming construct within HLSL that forced an explicit copy, this problem could be easily mitigated. However, with a substantial amount of searching, it was concluded that this type of explicitly forced copy of information to a new address did not exist.

If a future graduate student could find or develop a way to mitigate this probelm, it would be a very worthwhile direction in which to take this project, especially with one or two practical uses of this workaround, such as finishing the Refraction implementation. However, recall that the purpose of this refraction implementation was to find a to accurately refract through assymmetrical objects, such as the cow, teapot, etc., as symmetrical obects can be defined mathematically, thus the use of Pixel Ordering to gain knowledge of the object would not be necessary. For instance, it is quite easy to gain knowledge of an entire cube within a shader, if the parameters of the cube are known and passed to the pipeline. Thus, an accurately refracting a cube, sphere or prism would be quite straightforward.

7.3.2 Pixel Synch Used With Geometry Shaders

Geometry Shaders may be written such that multiple instances of the same model can be rendered or processed within the same pass, thus moving the rendering bottleneck for something like a particle system (where particles have a non- trivial geometry) from the render call to the Geometry shader. As a technique this saves the application side of the program, thus the program as a whole, a lot of time, since a position uniform does not have to be updated between renders of each particle instance.

To elaborate, consider a simulation of a herd of Zebra. Since all zebra could share the same geometry, it would make sense if the GPU were able to process the vertices for the model once, then duplicate the model as many times as needed within the Geometry Shader portion of the pipeline. With this being the case, if the programmer would like to implement any sort of depth-based effect, Pixel Synchronization would lend itself quite well to this problem.

Using Pixel Synchronization, information for shadow mapping could be found in a straightforward manner, and shadows would be cast on the appropriate members of the herd, and also the plane on which they are standing. Pixel Synchronization could also be utilized in this instance to pair both the shadow mapping and the subsurface scattering technique such that a scene with a set of semi-opaque pawns may more realistically interact with light.

For a final idea, consider a floating set of transparent objects such as vases or cows. Pixel Synchronization could be used to voxelize the scene of floating transparent objects, such that the objects could refract through one-another. This approach is very similar to a ray-trace. The advantage of tracing within the pixel shader is that the first collision has already taken place, as the Pixel or Fragment shader does not process portions of the scene with no geometry. Such an approach would be highly expensive, but highly impressive.

Remember that all of these techniques, utilizing a geometry shader would be restricted to multiple objects with the same geometry, as we may only duplicate a model within the Geometry shader and not create new models within this shader. Even so, it would be a worthwhile experiment to conduct, as a geometry shader plus pixel synchronization could lend itself well to certain practical effects, such as stained glass windows or cups on a table.

7.3.3 Hack the Pipeline and Use Pixel Synchronization for Parallel Algorithms

This would be purely for the fun of doing so. A student could find a set of different parallel problems, such as the N-Body problem, and implement the compute step within a pixel shader and then compare this with compute shader and compute language implementations. My initial hypothesis is that the Pixel Synchronization version will take more time, since there has to be a dummy vertex process stage and then a pass through the pipeline before the computations within the pixel shader could take place, but it would be an interesting experiment to see how a programmer can get a pixel shader to interact with data that lives strictly within the GPU between passes, and keep the data coherent. Prior to pixel synchronization, such an experiment would never have been able to take place, since there existed no real way to implement any meaningful parallel algorithm in the graphics pipeline.

7.3.4 Benchmarking the Efficiency of Pixel Ordering/Interlock on Discrete Hardware, Compared to an Integrated Grahpics Architecture

Even taking the provided implementation of Subsurface Scattering and porting it to an nVidia-supported piece of code would suffice. Key pieces of information to look for would be the proportion of the performance hit, as it is obvious without experiment that the efficiency of a modern discrete graphics hardware solution will always be greater than that of its integrated counterparts. This information would be important for graphics programmers to know, such that a programmer can confidently say whether or not a certain pixel-ordering technique developed on one piece of hardware will scale well to a different distributor's hardware, and if not, what types of optimizations must be made, or should the Pixel Synch Technique on a certain piece of hardware be abandoned altogether.

8 Images of Results

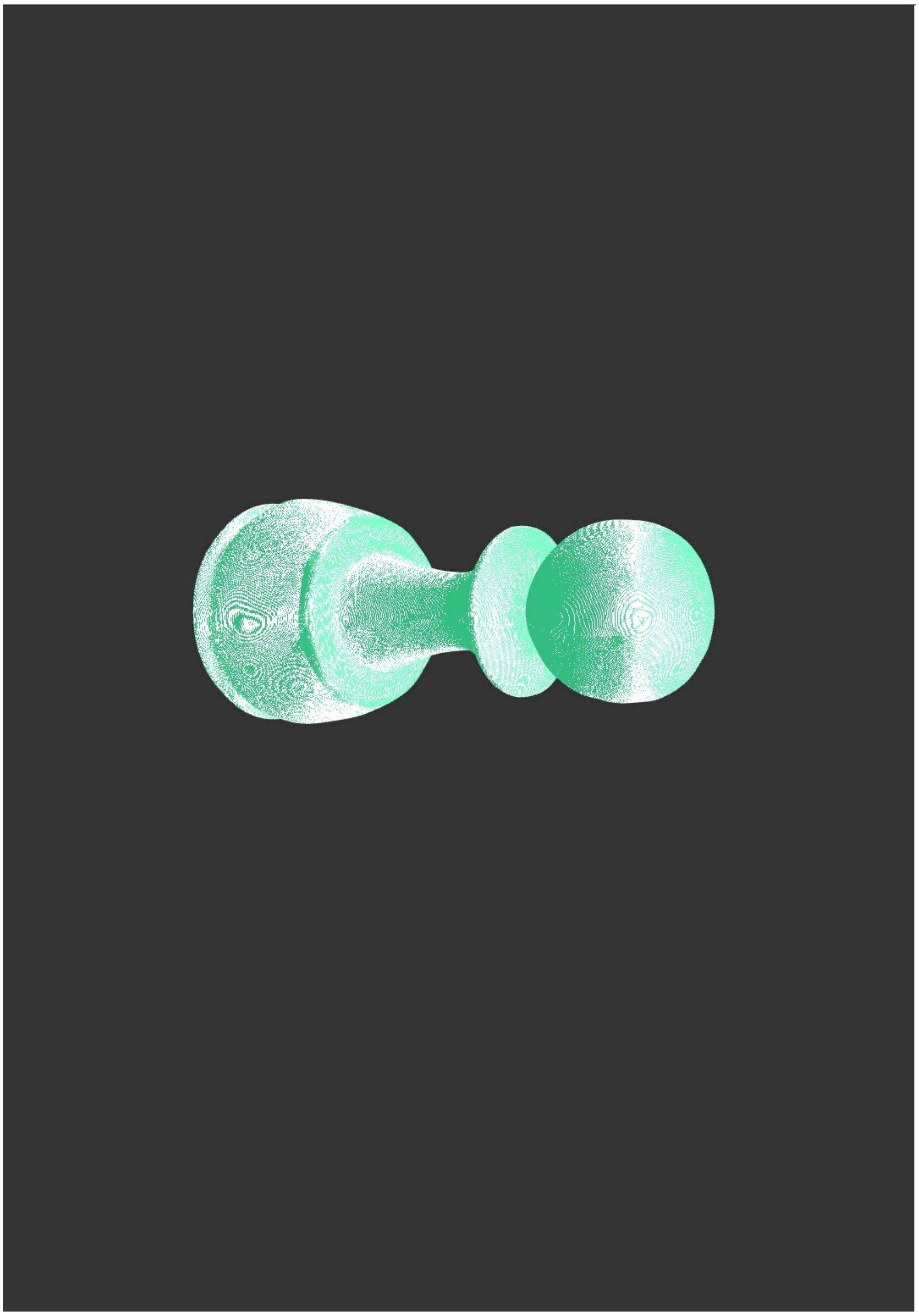

Figure 8.1: High Resolution image of first attempt at pixel synchronization subsurface scattering approximation.