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Advanced 3D Rendering : Adaptive Caustic Maps with GPGPU

Yong Piao
Worcester Polytechnic Institute

ADVANCED 3D RENDERING: ADAPTIVE CAUSTIC MAPS USING COMPUTE SHADER

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Yong Piao

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Professor Emmanuel Agu, Major Advisor

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Abstract

Graphics researchers have long studied real-time caustic rendering. The state-of-the-art technique Adaptive Caustic Maps provides a novel way to avoid densely sampling photons during a rasterization pass, and instead adaptively emits photons using a deferred shading pass. In this project, we present a variation of adaptive caustic maps for real-time rendering of caustics. Our algorithm is conceptually similar to Adaptive Caustic Maps but has a different implementation based on the general-purpose computing pipeline provided by OpenGL version 4.3. Our approach accelerates the photon splitting process using compute shaders and bypasses various other performance overheads, ultimately speeding up photon generation considerably.

Acknowledgements

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Introduction

Video games have become increasingly popular. “The industry is at around $22 billion for 2008 (conservative estimate) in the US[1] and $30 to $40 billion globally,” while “The movie industry is at $9.5 billion (US)[2] and $27 billion globally[3].” Due to the inter-disciplinary nature of video game development, video games have also brought benefits to the concept art, 3d modeling, and music industries.

Computer graphics plays a key role in the presentation of video games. It is the sole source of stimuli to the players’ visual perception. As a result, many game developers continuously seek to improve the visual realism in their games. Due to the interactive nature of video games, graphics must be presented at an interactive frame rate (25 FPS minimum). Therefore rendering speed is highly valued for any rendering technique in the field of real-time computer graphics.

Burdened with its firm requirement of high rendering speed and the limited processing speed of current rendering hardware, real-time rendering forces graphics researchers to seek rendering techniques that provide both high image quality and fast

[1] Frank Caron, June 18 2008. Ars Technica. http://arstechnica.com/news.ars/post/20080618-gaming-expected-to-be-a-68-billion-business-by-2012.html

[2] Thomas Mennecke, March 6, 2007. Slyck. http://www.slyck.com/story1436_MPAA_Reports_Record_Movie_Sales_in_2006

[3] Reuters, March 5 2008. ABC News. http://www.abc.net.au/news/stories/2008/03/06/2181568.htm

rendering speed. Nonetheless, real-time rendering is steadily heading towards photorealism with interactivity. For example, with Enlighten[4], a Global Illumination (GI) plug-in developed by Geomerics, it is now possible to simulate highly realistic first-bounce reflective light in real-time. Enlighten can make dynamic lights look highly realistic, however, as an example of commercial GI solution, Enlighten is limited to computing GI for diffuse transport[5]. The rendering of curved refractive, reflective surfaces with global illumination remains unsolved.

One key component of rendering curved refractive, reflective surfaces is caustics. In Optics, a caustic or caustic network is the envelope of light rays reflected or refracted by a curved surface or object[6]. *Figure. 1* shows 4 glass spheres rendered with various refraction indices. Clearly caustics contributes a lot to differentiating refractive and opaque objects, as well as improving the realism of the rendering.

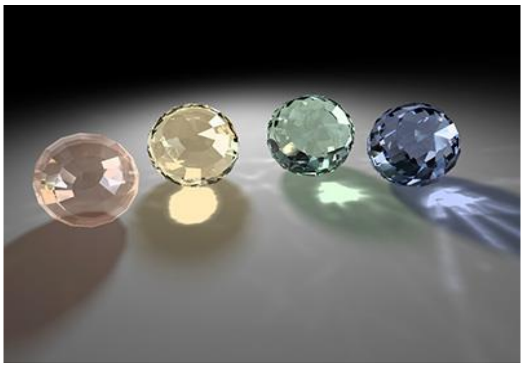


Figure 1: Example of caustics formed by refractive objects

[4] Geomeric, an ARM company, 2014. http://www.geomerics.com/enlighten/
[5] Jesper Mortensen. September 18, 2014. Technology in Unity 5, http://blogs.unity3d.com/2014/09/18/global-illumination-in-unity-5/
[6] Lynch DK and Livingston W, 2001. Color and Light in Nature. Cambridge University Press. ISBN 978-0-521-77504-5. Chapter 3.16 The caustic network, Google books preview

Figure. 2 is a photograph of an underwater scene; again clearly shows caustics is essential for the rendering of photorealistic computer images.

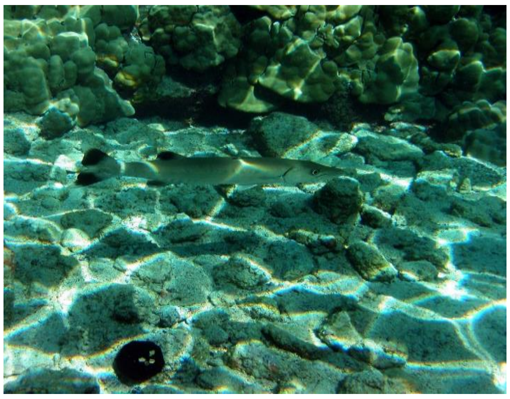


Figure 2: Photograph of an underwater scene

Many existing techniques provide rendering of caustics in real-time. There are techniques that use "image-space approximations [OB07, Wym05], object-space approximations [EMDT06, RH06], and ray-based [KBW06, SZS*08] approaches to allow applications to quickly simulate simple reflections and refractions, though fully accurate renderings generally remain too costly.”

Adaptive caustic maps [Wym09], provides a novel technique for adaptively sampling photons, allowing dynamic quality control for applications and at the same time improving rendering speed. It uses a hierarchical sampling method to avoid processing extraneous photons, thus greatly reduces the amount of unnecessary computation required when compared to basic caustic maps at the same image quality. Though much faster than before, adaptive caustic maps remains too costly for video games.

The Goal of this Major Qualifying Project (MQP) In this project, we present a variation of adaptive caustic maps for real-time rendering of caustics. Our algorithm is conceptually similar to adaptive caustic maps: traversing through a buffer of sample points, splitting them into more photons, and finally splatting photons onto a caustics texture. However, by using the general-purpose computing pipeline provided by OpenGL version 4.3, our approach uses compute shaders to perform the traversal process, and drawing indirectly using indirect command buffer to avoid CPU-side overheads.

The goal of this project is to use graphics hardware to solve the "poor parallelism during early traversal steps, and high memory consumption for photon storage" [Wym09] and to reduce the CPU-side overhead of Adaptive Caustic Maps. At the end our approach achieved great parallelism through compute shaders and removed CPU-side overhead completely.

Background

Graphics researchers have long studied Global Illumination algorithms. "The earliest path tracing techniques [Kaj86] demonstrated caustics from reflective and refractive objects." Unfortunately, computational costs prohibit real time use of path tracing for interactive media and games, and most fast global illumination algorithms restrict scenes to diffuse materials.

A number of researchers have already come up with advanced techniques to allow interactive rasterization of non-diffuse materials. For the purpose of this project, basic Caustic Mapping and Adaptive Caustic Maps will be illustrated to help provide a comparison to our project. For both techniques, when rendering caustics, scene geometry generally is separated into two categories, receiver geometry and refractor geometry. The receiver geometry receives the computed photon texture, e.g. floors, walls, and other background objects. The refractor geometry refract the photons that hit the geometry to create photon density map, e.g. glass spheres, metallic rings.

Basic Caustic Mapping

Below is the most basic, 3-step Caustic Mapping, taken from Caustics Mapping: An Image-Space Technique for Real-Time Caustics by Musawir *et al.* [Mus07]:

1. Obtain position texture of the receiver geometry from light's point of view.

2. Obtain position and front and back normal textures of the refractor geometry from light's point of view.
3. Construct caustic map texture based on the three textures obtained above.

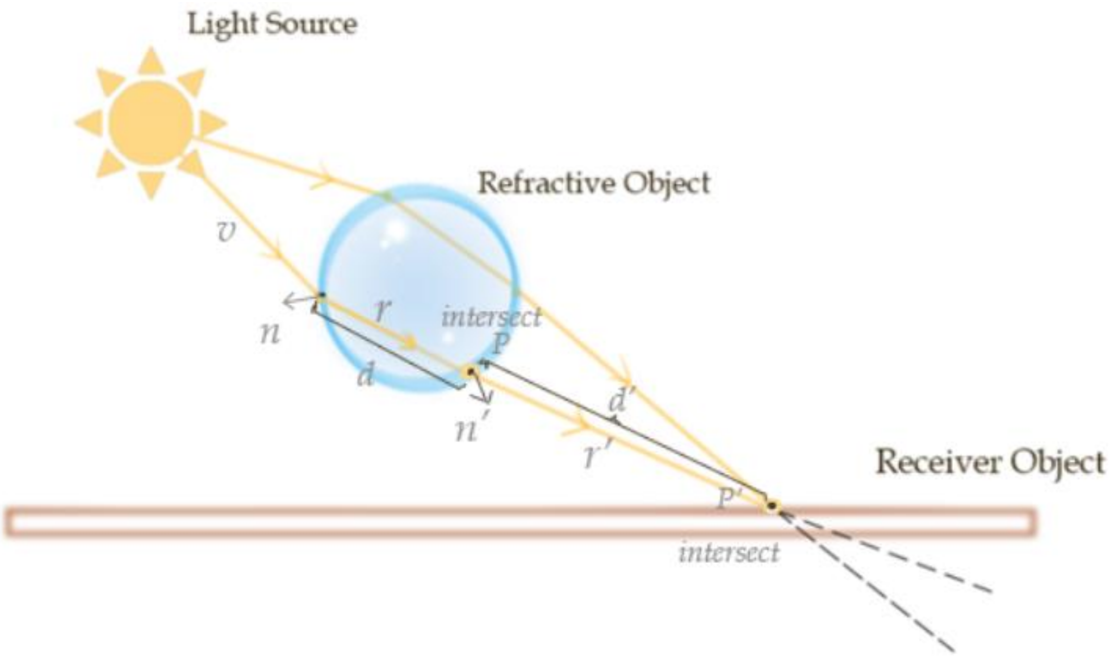


Figure 3: The caustic mapping process

Figure 3 illustrates the procedure of caustic mapping. There are always 2 refractions per light ray, because when light ray hits the refractive object, it is conceptually the same as entering the object. Every ray that enters a refractive object must also exit the refractive object to be captured by the receiver object. Therefore when rendering caustics with high fidelity, both front and back normal textures are needed for the correct calculation of refraction.

Musawir *et al.* also provide detailed explanation of the mathematics behind caustic mapping. Let *v* be the direction of the light ray, we can then access the light-view front normal texture to obtain the normal vector *n.* After refraction, the light ray *r* is produced. The direction of point *P* from the light is thus:

$$P = v + d * \overrightarrow{r},$$

Equation 1: Point of intersection of refracted ray [Mus07]

Although it is possible to render refractor position textures to find the root of the intersection, the depth values from normal textures can be utilized for obtaining a much finer result. This method is also inherently fast because depth textures can be added to the normal textures and handled by OpenGL:

$$Dist.x = (texture(RefractorDepth, vec3(vTCoord, 1)).z) * 2.0f - 1.0f$$
$$Dist.y = (texture(RefractorDepth, vec3(vTCoord, 0)).z) * 2.0f - 1.0f$$

$$Dist = NearFarInfo.x / (Dist * NearFarInfo.y - NearFarInfo.z)$$

$$d = Dist.y - Dist.x$$

Equation 2: Calculating front and back face intersection with depth values

In order to calculate the final exiting ray, one more refraction is needed. We repeat the process of calculating *P*, but instead use the new ray *r* as the incident ray direction and *n'* as the new normal vector to obtain *r'*. The back face refraction in the Caustic Mapping algorithm uses an iterative method derived from the Newton-Raphson algorithm for calculating the intersection with the receiver object, thus the distance *d'* can be derived as follows: [Mus07]

$$d_{k+1} = d_k - \frac{\hat{f}(d_k)}{\hat{f}'(d_k)}, \ where\ k = 0, 1, 2, 3, \ldots.$$

Equation 3: The Newton-Raphson algorithm [Mus07]

Equation 3 shows the Newton-Raphson algorithm for iteratively calculating the distance between two surfaces. We can thus obtain *P'* through plugging in *r'*, and *d'* to *Equation 1*.

Musawir *et al.* pointed out that "frustum limitation and aliasing" [Mus07] are the 2 main problems with this technique. Specifically the first issue pertaining to the algorithm is the view frustum limitation during rasterization of the caustic-map. Musawir *et al.* mentioned that this problem is "exactly like that of shadow mapping with point lights." [Mus07] If the caustics are formed outside the light's view frustum, they will not be captured on the caustic-map texture. Using an environment caustic map solves this problem at an overhead cost of rendering extra textures. However, Musawir *et al.* suggested that the dual paraboloid mapping technique proposed by Heidrich [Hei98], which has been applied to shadow mapping for omnidirectional light sources by Brabec *et al.* [Bra02], can also be utilized.

The second issue with Caustic Mapping is aliasing. Since "aliasing is inherent in all image-space algorithms," [Mus07], "the gaps between the point splats give a non-continuous appearance to the caustics." [Mus07] However, according to the author, "if there is a sufficient number of vertices in the refractive vertex grid, the gaps are significantly reduced." [Mus07]

Though unmentioned by Musawir *et al.*, we found Caustic Mapping inherently suffers from another problem. Since photons are first computed at some fixed sampling rate and either processed or discarded after determining photon irrelevancy, depending on the scene geometry, unused photons can waste a lot of memory. As illustrated by *Figure 4*, though the red photons are unused and will be discarded after creating the caustic map, the algorithm still have to first create a fixed-size photon buffer than contains lots of unused photons:

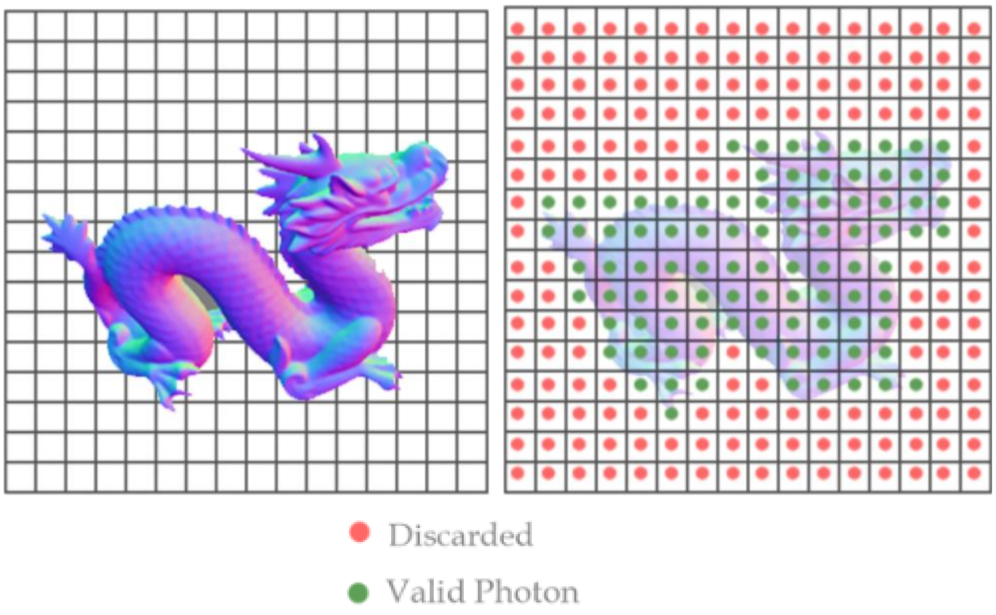


Figure 4: Photon buffer at resolution of 16^2 with many unused photons

Based on our estimation, if the light-view textures are rendered at 1024^2 resolution, considering the frustum limitation, rendering the dragon model from the view shown in Figure 4 will produce around 200,000 ~ 500,000 photons. Considering the image-space traversal of all texels in a 1024^2 resolution texture requires 1,048,576 iterations, about 50% ~ 80% of the samples will be discarded. As a result, more than half of the sampling time will be wasted and not reflected in the final image.

Temporal incoherency is another problem that we found with Caustic Mapping in interactive applications. The conclusion was that because Caustic Mapping only uses 2 layers of normal textures, the initial sample obtained from rendering the refractor geometry is crucial to the image quality. We noticed that fidelity of the image decreases if there are many overlapping faces. When the dragon model is rendered from its side, we can obtain normal textures similar to *Figure 5*:

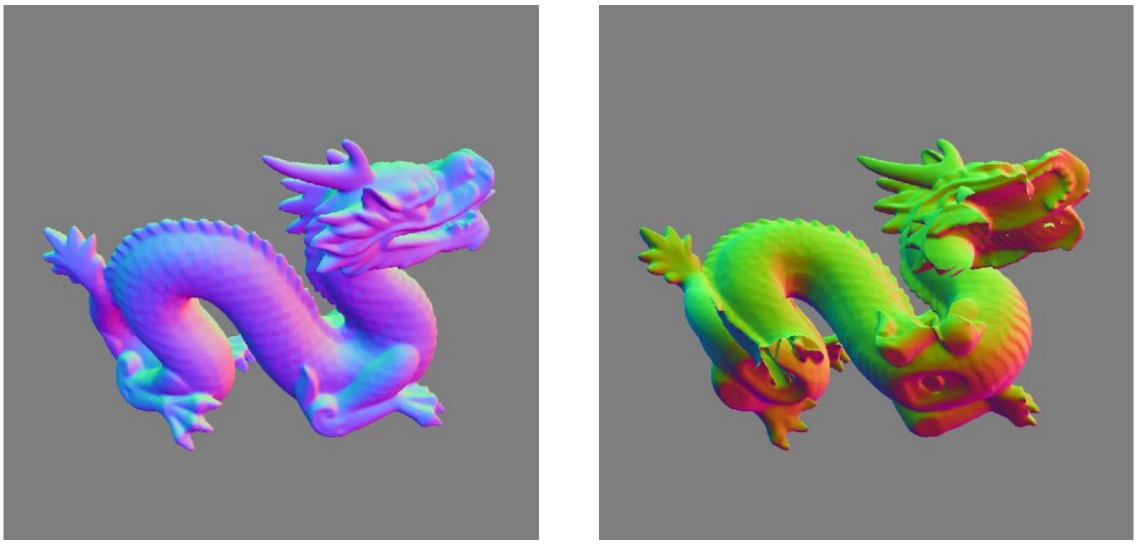


Figure 5: Normal textures of the dragon model rendered from the side

The side view camera helps minimizing the number of overlapping faces in the normal textures, therefore it helps converge the rendered result to ground truth. As shown in *Figure 5*, the result texture contains noticeable amount of caustics:

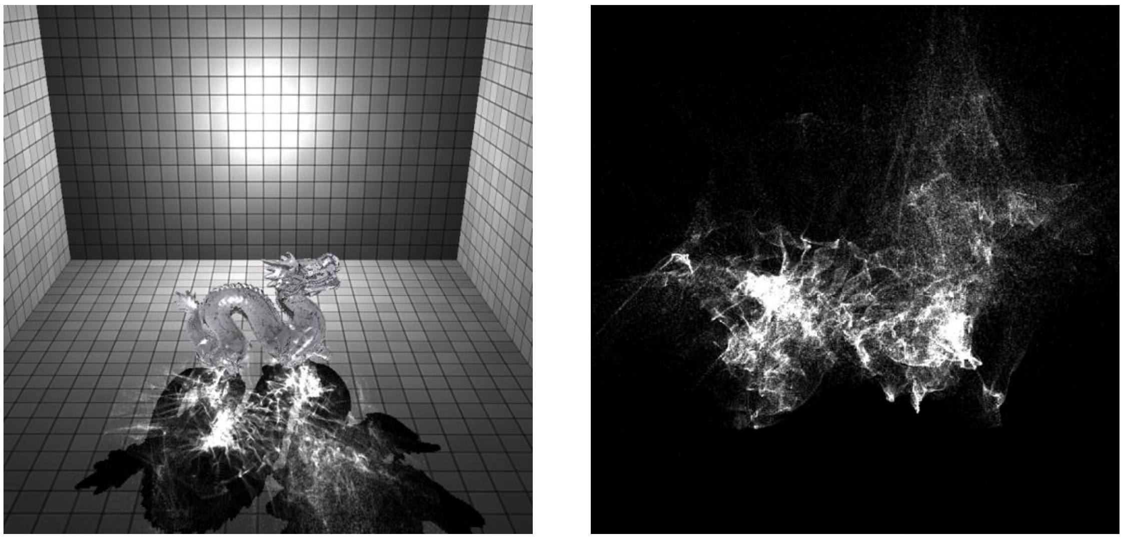


Figure 6: Result of rendering the dragon from the side

On the other hand, certain camera views can increase the number of overlapping faces, and reduce the surface area of valid normal texels. *Figure 7* shows the dragon rendered from the back. In this case, the normal textures contain many overlapping faces that cannot be accurately captured by 2 normal textures. This would not only impact the photon traversal process, but also reduce the number of samples to start with.

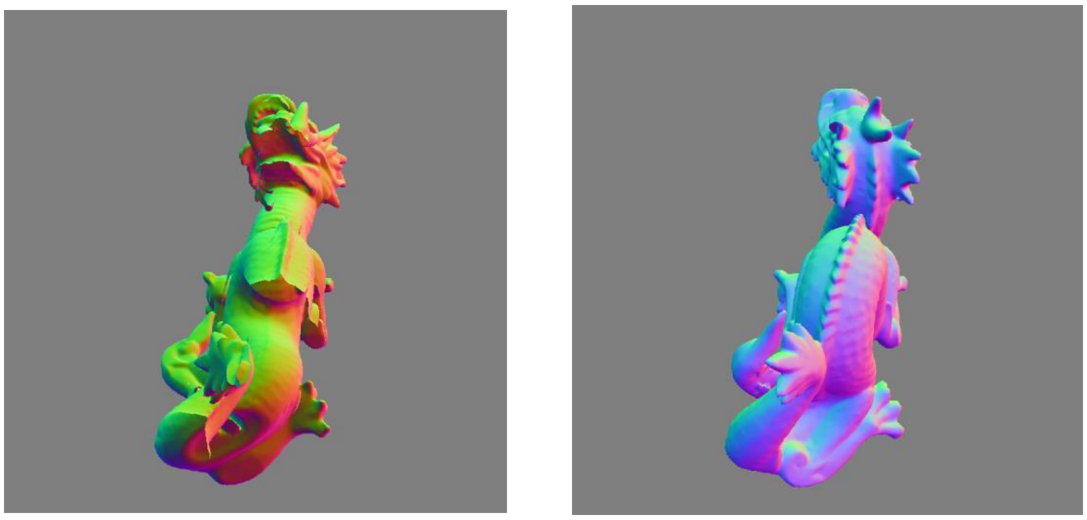


Figure 7: Normal textures of the dragon model rendered from the back

Figure 8 shows the result from using normal textures rendered from the back. Clearly the head and neck part of the normal textures cannot not provide the number of samples required to generate enough valid photons for a satisfying caustic texture.

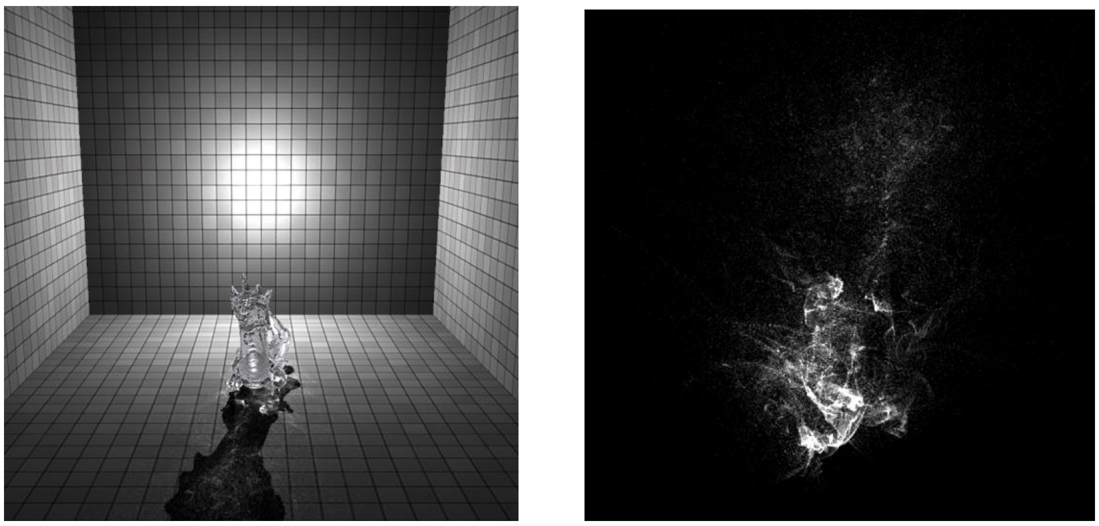


Figure 8: Result of rendering the dragon from the back

Adaptive Caustic Maps

The state-of-the-art Adaptive Caustic Maps [Wym09] overcomes the aliasing problem and the fix-sized photon buffer problem of Caustic Mapping through “emitting a few photons, and adaptively refining with additional photons until the desired quality is attained.” [Wym09] Algorithmically, since Wyman el al. propose to adaptively splitting photons, “instead of first creating a photon buffer and then processing it to generate a caustic map, these two steps become coupled.” [Wym09] Adaptive Caustic Maps “never creates an explicit photon buffer. Instead, an adaptive deferred shading pass that point-samples the geometry buffers allows us to emit photons adaptively.” [Wym09]

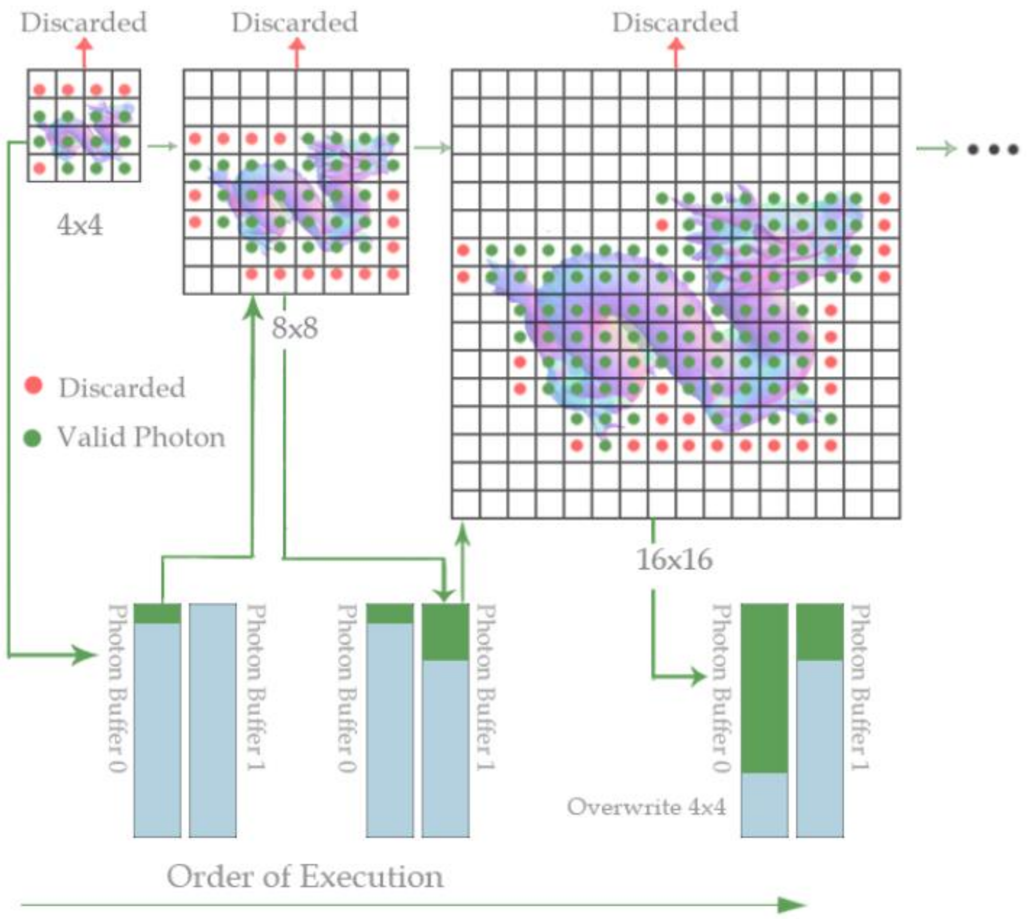


Figure 9: Workflow of Adaptive Caustic Maps

There is only one step in generating photons with Adaptive Caustic Maps. However it is up to the application how many times it would like to run the same step to increase the number of photons in the photon buffer. *Figure 9* illustrates the basic workflow of executing the photon splitting of Adaptive Caustic Maps three times with a 4^2 kernel to start with. Since only the valid photons from the previous pass will be used to split photons in a later iteration, the amount of unused photons generated is much less than basic Caustic Mapping. Also because Adaptive Caustic Maps does not process all normal texels in one shader pass, it requires the refractor normal textures to have hardware accelerated mip-maps enabled. The mip-map enabled refractor normal textures are used so the normal texels can be traversed as a quadtree, allowing the algorithm to greatly reduce extraneous photons.

As a result, Adaptive caustic maps reduces the overhead from processing extraneous photons and also allows applications to dynamically control of the level of detail for caustic map, ultimately making basic Caustic Mapping obsolete. While this technique made caustic mapping practical in real-time, it is still not fast enough for interactive media and games.

Problems with Adaptive Caustic Maps

There are three main points of concern with Adaptive Caustic Maps that this project addresses. Wyman *et al.* mentioned the first two in the paper: 1) "poor parallelism during early traversal steps, and 2) high memory consumption for photon storage provided challenges"[Wym09]. In addition, we also found an extant CPU-side overhead that was inevitable when Adaptive Caustic Maps was published.

Adaptive Caustic Maps makes heavy use of OpenGL "with the transform feedback and geometry shader extensions."[Wym09] Wyman *et al.* mentioned that "characteristics of the GPU stream processing model affected numerous design choices for Adaptive Caustic Maps as well as performance."[Wym09]. Clearly the GPU stream processing model with transform feedback suffers from poor parallelism and is imperfect for photon generation, which results in an impact on the performance of the algorithm.

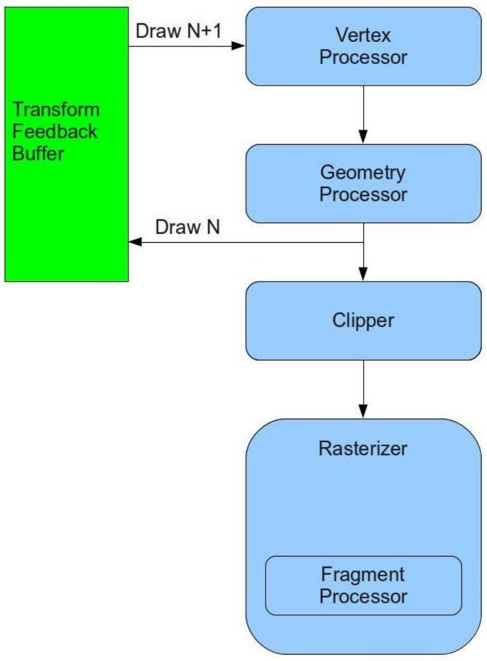


Figure 10: OpenGL rendering stages with transform feedback

Figure 10 illustrates the rendering stages of OpenGL with transform feedback enabled. Transform feedback is "the process of capturing Primitives generated by the Vertex Processing step(s), recording data from those primitives into Buffer Objects."[7] Transform feedback allows an application to "preserve the post-transform rendering state of an object and resubmit this data multiple times."[8] It made the use of vertex and geometry shader more flexible, allowing vertex and geometry shader to output data without a-priori knowledge of the output buffer size.

Since the number of output photons for Adaptive Caustic Maps is determined during

[7] The Khronos Group, 2010-2014. OpenGL Wiki. https://www.opengl.org/wiki/Transform_Feedback
[8] The Khronos Group, 2010-2014. OpenGL Wiki. https://www.opengl.org/wiki/Transform_Feedback

rendering, transform feedback comes in play where after executing the geometry shading stage, it gives the application a message containing the number of primitives generated during transform feedback. With this information, the application can perform a new photon traversal iteration with the output from the last iteration.

Due to the implementation of the GPU stream processing model of OpenGL, transform feedback requires that the application always binds input and output buffers to different buffer targets. As shown in *Figure 9*, Adaptive Caustic Maps must flip-flop between 2 buffers during photon splitting. This not only introduces increasingly heavy CPU-side overheads, but also requires two large buffers that are big enough to contain all information generated from the last iteration. Before each new iteration, the application must bind input and output buffers to new buffer targets, therefore the more iterations of traversal the application decides to perform, the heavier the CPU-side overhead becomes.

Poor parallelism also occurs because when sampling a photon, Adaptive Caustic Maps must use the vertex shader to pass a point primitive to the geometry shader. OpenGL strictly requires that a vertex shader can only process one vertex at a time, making loop unroll impossible to perform.

In addition, Adaptive Caustic Maps requires the application to pass in new drawing arguments and setting appropriate uniforms for sampling, which also becomes an increasingly expensive CPU-side overhead as the number of iteration increases.

Our approach is conceptually similar to Adaptive Caustic Maps; in fact the math involved is nearly identical. We also use hardware accelerated mip-maps on normal textures and perform quad-tree traversal to reduce extraneous photons as Adaptive Caustic Maps. However, instead of using the geometry shader and transform feedback, we use the new general-purpose processing pipeline of OpenGL to perform the most expensive photon traversal process instead of using geometry shader with transform feedback. Our approach solves two main problems of Adaptive Caustic Maps with great parallelism and zero CPU-side overhead.

Compute Shader

In order to understand the new traversal process, it is crucial to have a basic understanding of the compute shader. In 2012, OpenGL 4.3 introduced arbitrary compute shaders. It is revolutionary to performing general-purpose computation on the GPU, allowing highly optimized, parallel tasking for caustic photon traversal. It allows applications to smoothly pass the data from general-purpose computing pipeline to the drawing pipeline, ultimately benefiting any real-time rendering algorithm that can make use of general-purpose computation. In the case of caustic mapping, photon splitting is a perfect example of a general-purpose computation task that can become highly parallel through the use of compute shader.

Compute shaders operate differently from other shader stages and is completely separate from the drawing pipeline. While all of the other shaders have a well-defined set of input and output values, though some build-in and some user-defined, compute shader does not. When an application executes a compute shader, it provides the compute shader with a set of parameters specifying the number of invocations to execute the program.

In its most basic form, if a very simple compute shader, such as one that increments a variable atomically by 1, is asked by the application to execute with 240 invocations, the variable will be incremented by 240. However a real compute shader is slightly different. A real compute shader has the concept of a work group (a grouping of GPU threads); and an application can specify the number of work groups to execute.

While the number of work groups that a compute shader is executed is defined by the application, the work groups are actually organized in three dimensional space. Therefore the application must provide the X, Y, and Z values specifying the "compute space" for the compute shader. An example would be splitting 240 into X=24, Y=10, and Z = 1. As a result, an application can specify the number work groups of a compute space, a compute shader can define the number of "workers" in a work group. In addition, every compute shader has a three-dimensional local size, again customizable via X, Y, and Z values, specifying the number of invocations triggered by a work group. As a result, the total invocation count must take into account the number of work groups and the size of work groups.

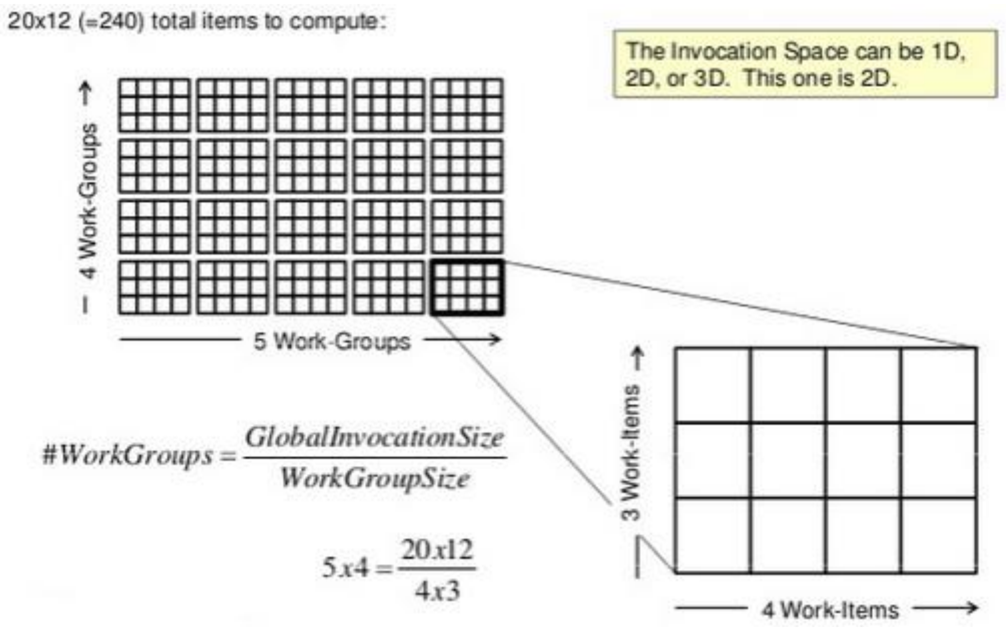

20x12 (=240) total items to compute:
The Invocation Space can be 1D, 2D, or 3D. This one is 2D.
4 Work-Groups
5 Work-Groups
3 Work-Items
4 Work-Items
$\#WorkGroups = \frac{GlobalInvocationSize}{WorkGroupSize}$
$5x4 = \frac{20x12}{4x3}$

Figure 11: Compute shader work groups[9]

Figure. 11 illustrates an example of a compute space specification. There are 4 by 5, a total of 20 work groups. In addition, the compute shader defines that each work group has a size of 4 by 3 by 1, a total of 12 invocations. Therefore each time this compute task is dispatched, the program will be run a total of 240 times.

Since the application can freely control how many times a compute shader is executed, it should be simple to imagine how to traverse through a 64^2 sampling kernel. One may choose to distribute the 64^2 sampling invocations by any appropriate work

[9]The Khronos Group, 2010-2014. http://www.slideshare.net/Khronos_Group/how-to-use-and-teach-opengl-compute-shaders

group specification, for the purpose of this project, we chose to keep the Z size at 1 for ease of visualization.

One potential problem with working with compute shaders is the compute space might end up dispatching more invocations than needed. If the application needs to iterate through a total of 17 elements in a buffer, there is no value of integer X such that $X^2 = 17$, because 17 is a prime number. The least possible resolution for a texture that contains more than 17 pixels is $5^2 = 25$. Since the application only requires 17 computations, the extra 8 invocations must return immediately and not change any data. One way to accomplish this is to use the OpenGL compute shader built-in inputs to calculate the global invocation ID prior to performing a task, thereby giving the 25 invocations IDs from 0 to 24 respectively. With a globally unique ID for each invocation, to achieve a total of 17 invocations, the compute shader can set any invocation with an ID equal to or higher than 17 to immediately return.

Indirect Dispatch

Before stepping into the implementation, it is also crucial to know about the indirect compute dispatch feature. As described above, the application can specify the size of the compute workspace, which means the CPU must calculate the number of work groups needed and send this data to the GPU. However during its calculation and data transfer, the GPU stands completely idle, as a result making this time period a CPU-side overhead.

To combat this issue, OpenGL provides a feature to let the GPU autonomously dispatch a compute task, in which case the application need not to specify the number of work groups to execute. To use this feature, the application must bind a buffer containing 3 unsigned integers to the indirect command buffer target. Once the buffer is created, it is up to the shaders to decide how to change the data in the buffer, therefore making it possible to autonomously use the GPU to determine the workspace size for a compute shader.

Indirect Draw

Similar to indirect dispatch, the indirect draw feature allows the GPU to autonomously draw without passing arguments from the CPU. Our approach uses indirect draw to further reduce the CPU-size overhead. To use this feature, the application must bind a buffer containing 4 unsigned integers to the indirect command buffer target. Once the buffer is created, the GPU can dynamically change the vertex count to correspond to the current drawing settings.

Methodology

In summary, our approach uses compute shaders and indirect draw to replace geometry shader and transform feedback used by Adaptive Caustic Maps. We reckon that the repetitive task of computing millions of photons through Adaptive Caustic Maps renders the OpenGL drawing pipeline unfit. The iterative photon splitting of the original Adaptive Caustic Maps, on the other hand, is a perfect example of a general-purpose computation task that can be accelerated with compute shaders. In addition, with compute shaders, it is possible to read and write from the same buffer using atomic operations, avoiding flip-flopping between buffers. In the end, our approach solves two main problems of Adaptive Caustic Maps with great parallelism and zero CPU-side overhead.

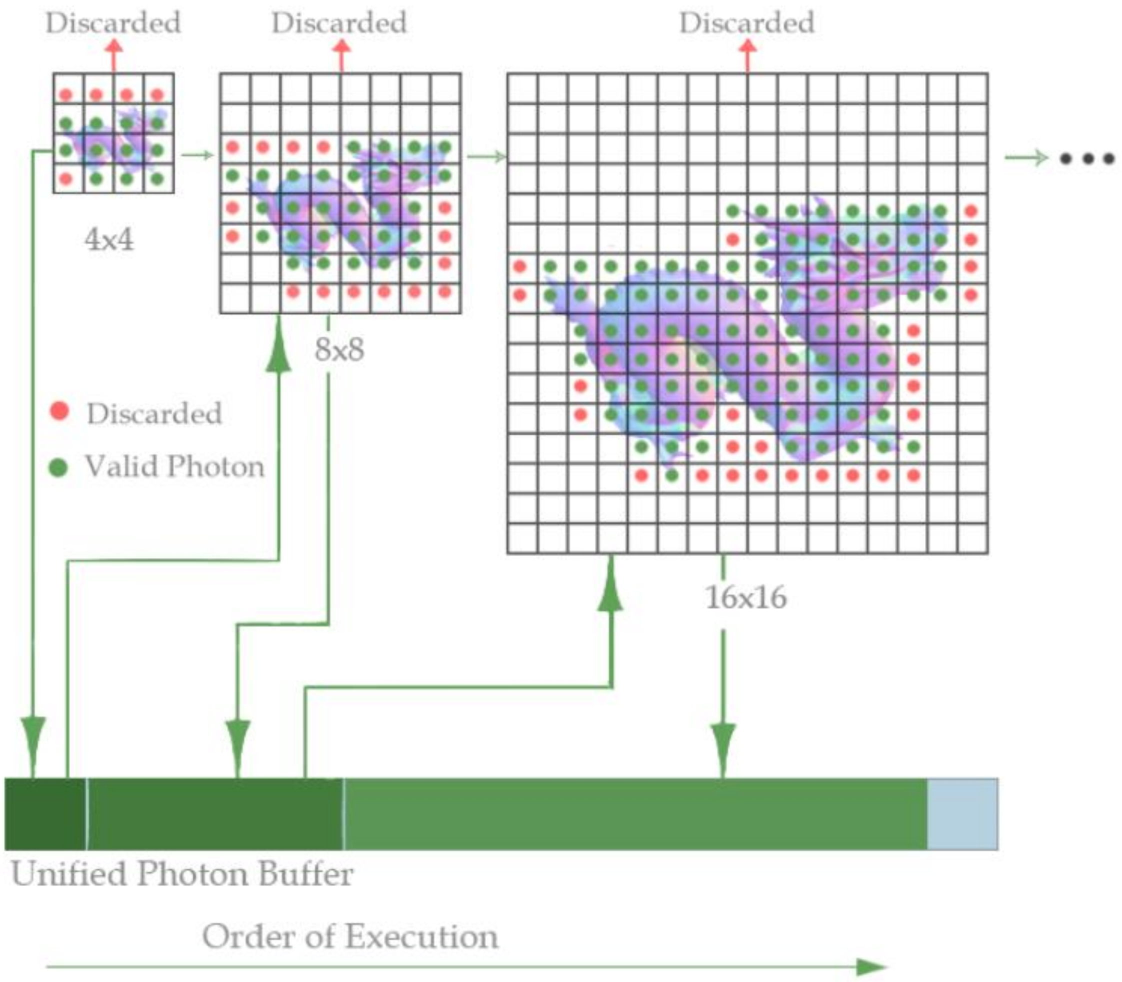


Figure 12: Workflow of our approach with compute shaders

Figure 12 illustrates the workflow of our approach. As opposed to the original Adaptive Caustic Maps, our approach uses only one photon buffer. It is made possible because with proper synchronization, compute shaders can read and write to the same buffer. As a result, our approach does not have flip-flopping between input and output buffers like the original implementation, thus removes the CPU-side overhead from re-binding buffers completely.

We also use the compute shader work groups to achieve parallelism during photon traversal. Since a compute shader dispatch can specify the number of work groups and the size of a work group, it inherently allows the shader to perform loop unroll on the repetitive sampling operation.

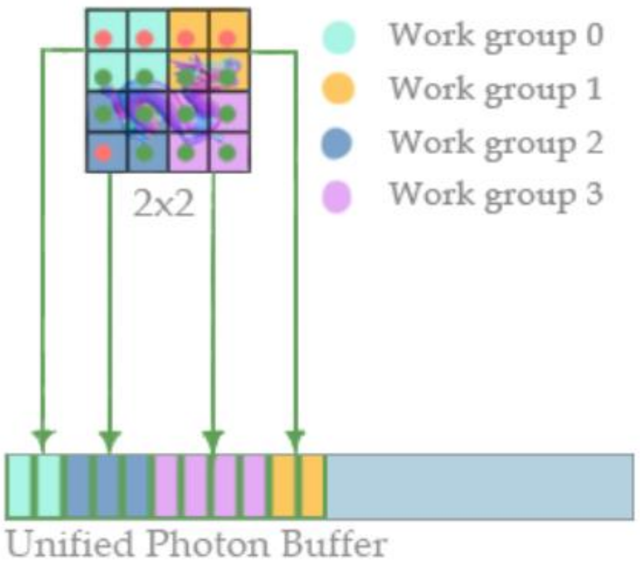


Figure 13: Traversing a 4^2 kernel with 4 work groups

Figure 13 illustrates traversing a 4^2 photon buffer with 4 work groups. Instead of dispatching 16 work groups, we can choose to increase the size of the work group to obtain high parallelism. It is important to notices that with the work group size being 2x2x1, the number of work groups to dispatch is 2x2 instead of 4x4. In the end, we found parallelism through compute shader work groups provides a major performance increase. We also provide performance analysis on different work group sizes in the results section.

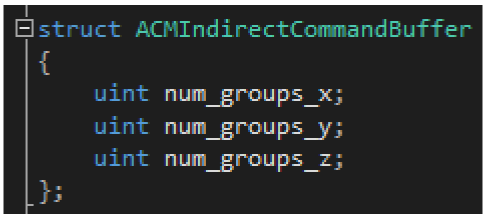
Synchronization of invocations in the compute shader is conceptually similar to multi-threaded programming. OpenGL provides an atomic counter feature that can be used to coordinate between different invocations. Upon validation of a photon, the invocation handling that photon will increment the atomic counter, so that no other invocation will use the old atomic counter value for calculating the write index.

Implementation

With a basic understanding of the compute shader and indirect dispatch, it is possible to go through the caustic map generation process.

Pre-Traversal Initialization

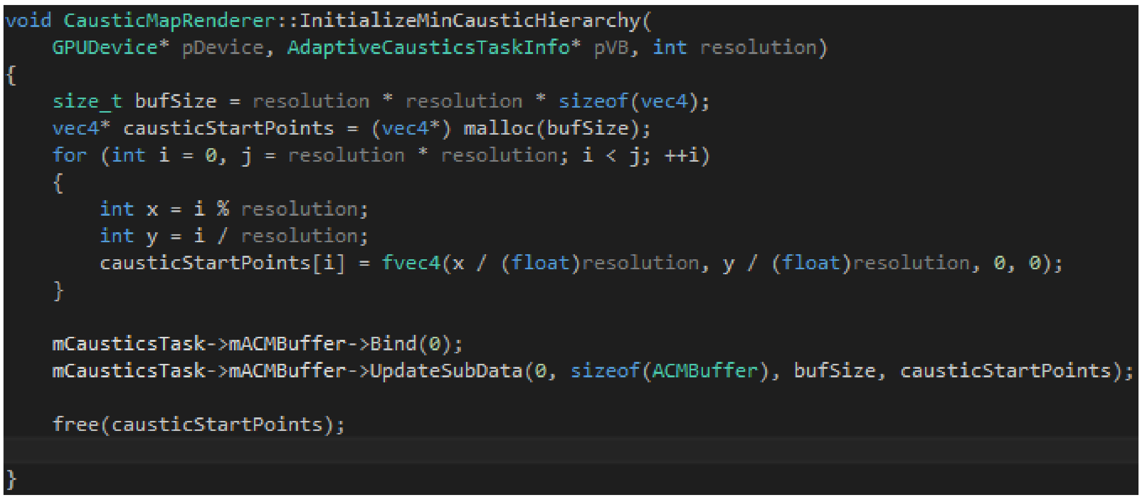
First, the application must create a structure containing 3 unsigned integers that can be used as an indirect command buffer, as shown in *Figure 14*:



```
struct ACMIndirectCommandBuffer
{
    uint num_groups_x;
    uint num_groups_y;
    uint num_groups_z;
};
```

Figure 14: Structure of the indirect command buffer

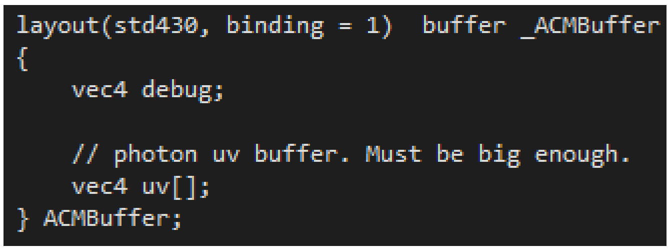
Then, the application must create a sampling kernel on initialization. *Figure 15* shows an example of creating a two-dimensional sampling kernel with the x and y values representing the u and v coordinates for texture sampling:



```
void CausticMapRenderer::InitializeMinCausticHierarchy(
    GPUDevice* pDevice, AdaptiveCausticsTaskInfo* pVB, int resolution)
{
    size_t bufSize = resolution * resolution * sizeof(vec4);
    vec4* causticStartPoints = (vec4*) malloc(bufSize);
    for (int i = 0, j = resolution * resolution; i < j; ++i)
    {
        int x = i % resolution;
        int y = i / resolution;
        causticStartPoints[i] = fvec4(x / (float)resolution, y / (float)resolution, 0, 0);
    }

    mCausticsTask->mACMBuffer->Bind(0);
    mCausticsTask->mACMBuffer->UpdateSubData(0, sizeof(ACMBuffer), bufSize, causticStartPoints);

    free(causticStartPoints);

}
```

Figure 15: Sampling kernel initialization

After generating the sampling kernel, we immediately copy the data to a photon buffer as if these sampling points are actual photons. The photon buffer is a 1-demensional array used to store sampling points that will be used in the splatting process, as shown in *Figure 16*:



```
layout(std430, binding = 1)  buffer _ACMBuffer
{
    vec4 debug;

    // photon uv buffer. Must be big enough.
    vec4 uv[];
} ACMBuffer;
```

Figure 16: Photon buffer layout

The actual photon traversal process is broken up into 3 stages, each representing a complete compute shader program: initialization, traversal, and post-traversal statistics.

The initialization shader is run once per frame; its sole purpose is to initialize data buffers such as the indirect command buffer and various other parameters required for photon traversal completely on the GPU to minimize CPU-size overhead. For example, if the application decides to deploy a 64^2 sampling kernel, the initialization shader can set the primitive count to 4096, and use this number to set the values in the indirect command buffer to X=64, Y=64, Z=1, so that the traversal shader can be dispatched, again without sending any uniform data from the CPU to the GPU. *Figure. 17* shows a code snippet of the initialization shader used in the demo program:

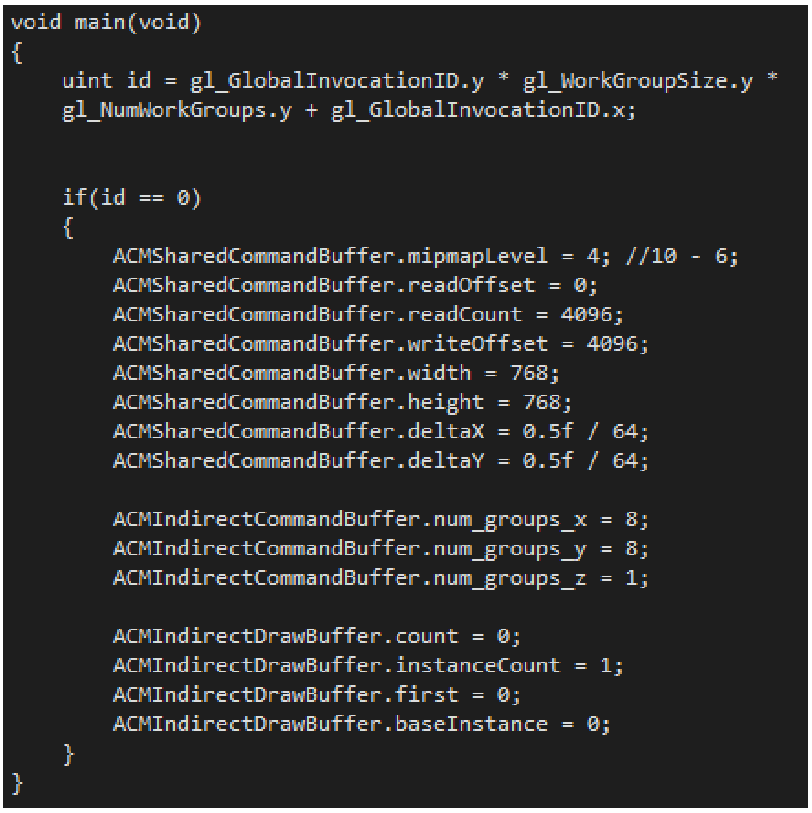

```
void main(void)
{
    uint id = gl_GlobalInvocationID.y * gl_WorkGroupSize.y *
    gl_NumWorkGroups.y + gl_GlobalInvocationID.x;


    if(id == 0)
    {
        ACMSharedCommandBuffer.mipmapLevel = 4; //10 - 6;
        ACMSharedCommandBuffer.readOffset = 0;
        ACMSharedCommandBuffer.readCount = 4096;
        ACMSharedCommandBuffer.writeOffset = 4096;
        ACMSharedCommandBuffer.width = 768;
        ACMSharedCommandBuffer.height = 768;
        ACMSharedCommandBuffer.deltaX = 0.5f / 64;
        ACMSharedCommandBuffer.deltaY = 0.5f / 64;

        ACMIndirectCommandBuffer.num_groups_x = 8;
        ACMIndirectCommandBuffer.num_groups_y = 8;
        ACMIndirectCommandBuffer.num_groups_z = 1;

        ACMIndirectDrawBuffer.count = 0;
        ACMIndirectDrawBuffer.instanceCount = 1;
        ACMIndirectDrawBuffer.first = 0;
        ACMIndirectDrawBuffer.baseInstance = 0;
    }
}
```

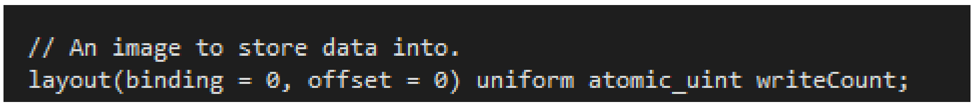
Figure 17: The initialization shader

Notice the num_groups_x and num_groups_y in the ACMIndirectCommandBuffer are set to 8 and 8, which seems to not produce the right amount of photons. It is because the traversal shader uses a work group of size 8 by 8 by 1, therefore ultimately the number of invocations is 8^4=4096.

Since our approach uses one photon buffer for all iterations, read and write offsets are required to into the 1-dimensional photon buffer correctly. In the first traversal, the read offset is 0 because the traversal shader should read the sampling points defined by the kernel generated during application initialization. The write offset is 4096 because the application stores the 64^2 sampling point grid into a 1-dimensional array, and in order to utilize all sampling points in the kernel, none should ever be over-written. To achieve so we append new data to the end of the buffer instead of overwriting previous data. Effectively, a read offset of 0 and read count of 4096 provides traversal shader the input indices, and a write offset of 4096 tells the shader where to append the new photons. Without going into much detail, the post-traversal statistics shader is used to update these parameters to prepare for the next traversal.

Traversal

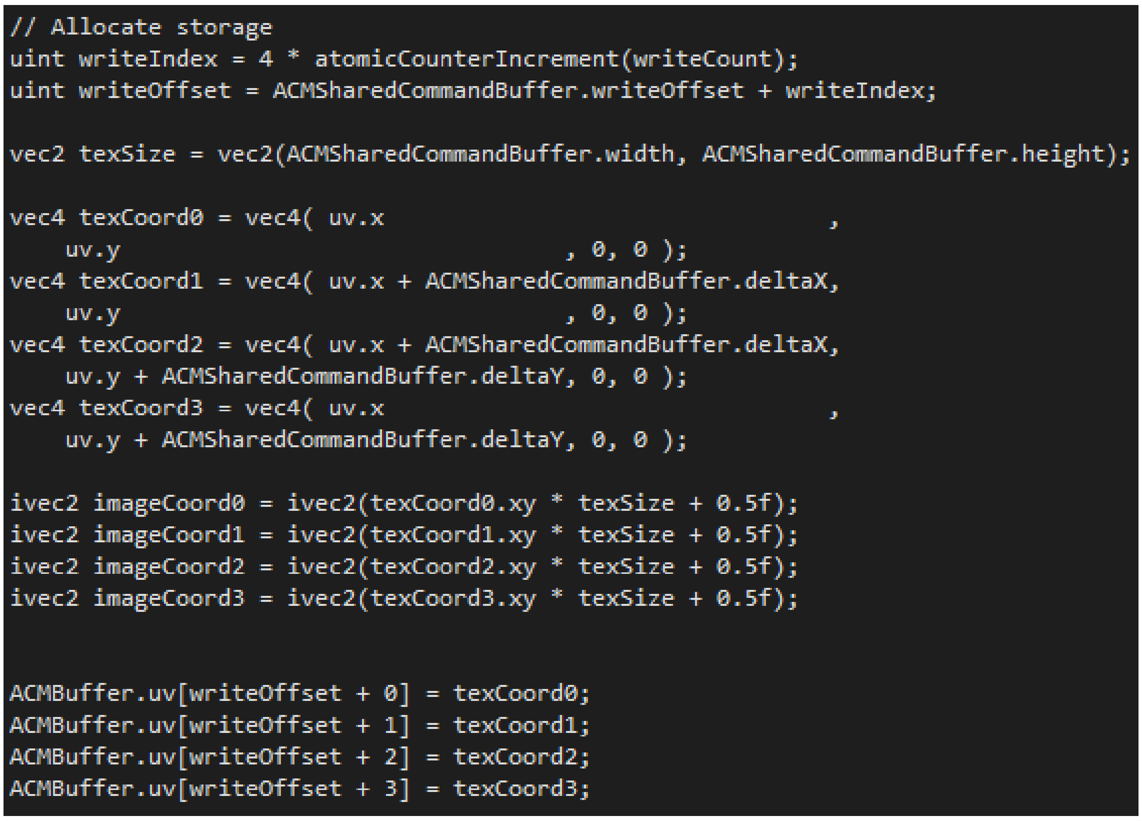
After initialization, it is now possible to run the traversal shader. Writing the data to the photon buffer is tricky, because the compute shader is highly parallel, buffer access must be manually synchronized with the atomic counter. An atomic counter can be declared in a compute shader, as shown in *Figure 18*:



```
// An image to store data into.
layout(binding = 0, offset = 0) uniform atomic_uint writeCount;
```

Figure 18: Declaring an atomic counter in GLSL

Each time a valid photon is read, the traversal shader increments the write count counter by 1. Combined with the write offset, the shader can obtain the next available buffer index for writing photon data. *Figure 19* illustrates the process of incrementing the atomic counter, calculating the new write index, calculating the new sample points and finally writing the data to the buffer:

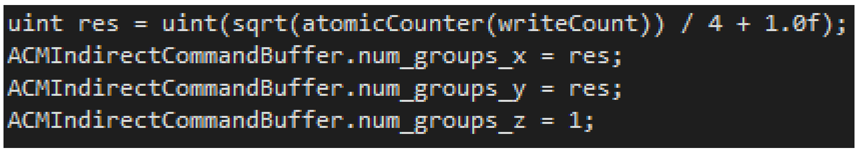


```
// Allocate storage
uint writeIndex = 4 * atomicCounterIncrement(writeCount);
uint writeOffset = ACMSharedCommandBuffer.writeOffset + writeIndex;

vec2 texSize = vec2(ACMSharedCommandBuffer.width, ACMSharedCommandBuffer.height);

vec4 texCoord0 = vec4( uv.x                                ,
    uv.y                                , 0, 0 );
vec4 texCoord1 = vec4( uv.x + ACMSharedCommandBuffer.deltaX,
    uv.y                                , 0, 0 );
vec4 texCoord2 = vec4( uv.x + ACMSharedCommandBuffer.deltaX,
    uv.y + ACMSharedCommandBuffer.deltaY, 0, 0 );
vec4 texCoord3 = vec4( uv.x                                ,
    uv.y + ACMSharedCommandBuffer.deltaY, 0, 0 );

ivec2 imageCoord0 = ivec2(texCoord0.xy * texSize + 0.5f);
ivec2 imageCoord1 = ivec2(texCoord1.xy * texSize + 0.5f);
ivec2 imageCoord2 = ivec2(texCoord2.xy * texSize + 0.5f);
ivec2 imageCoord3 = ivec2(texCoord3.xy * texSize + 0.5f);


ACMBuffer.uv[writeOffset + 0] = texCoord0;
ACMBuffer.uv[writeOffset + 1] = texCoord1;
ACMBuffer.uv[writeOffset + 2] = texCoord2;
ACMBuffer.uv[writeOffset + 3] = texCoord3;
```

Figure 19: Writing new photons to the photon buffer

Post-Traversal Statistics

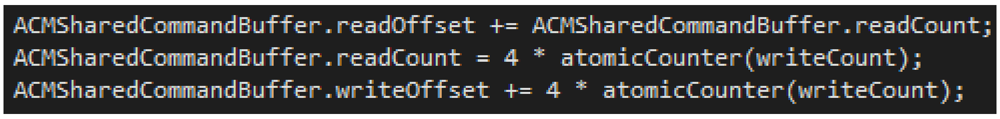
After each traversal, post-traversal statistics shader will update the parameters to the appropriate values for another traversal. It uses the write count counter from the traversal shader to update the number of work groups for the indirect command buffer, as shown in *Figure. 20*:



```
uint res = uint(sqrt(atomicCounter(writeCount)) / 4 + 1.0f);
ACMIndirectCommandBuffer.num_groups_x = res;
ACMIndirectCommandBuffer.num_groups_y = res;
ACMIndirectCommandBuffer.num_groups_z = 1;
```

Figure 20: Code snippet of post-traversal statistics shader

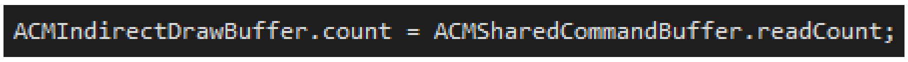
The statistics shader also needs to update the read and write offset and the read count, as shown in *Figure 21*:



```
ACMSharedCommandBuffer.readOffset += ACMSharedCommandBuffer.readCount;
ACMSharedCommandBuffer.readCount = 4 * atomicCounter(writeCount);
ACMSharedCommandBuffer.writeOffset += 4 * atomicCounter(writeCount);
```

Figure 21: Update read and write parameters in the statistics shader

Because the statistics shader does not know whether or not the application would like to perform another iteration of photon traversal, it must also update the indirect command buffer for splatting the photons, as shown in *Figure 22*:

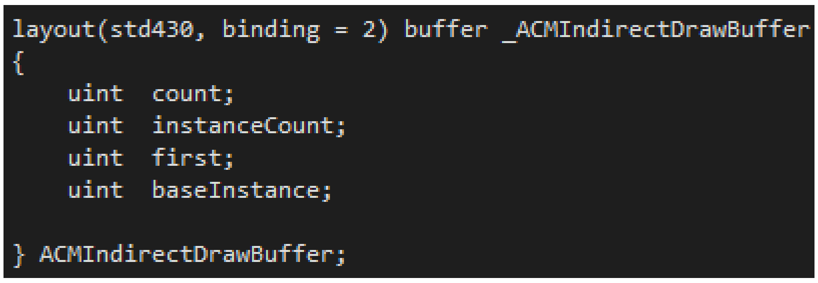


```
ACMIndirectDrawBuffer.count = ACMSharedCommandBuffer.readCount;
```

Figure 22: Update draw count in the statistics shader

Splatting with Indirect Draw

The application can decide how many iterations of traversal it would like to perform easily because nearly all data used for photon traversal is self-contained on the GPU. After a satisfying number of traversals, the application can use the indirect draw command buffer to splat the photons onto a texture. *Figure. 23* illustrates the structure of indirect draw command buffer used by OpenGL:



```
layout(std430, binding = 2) buffer _ACMIndirectDrawBuffer
{
    uint  count;
    uint  instanceCount;
    uint  first;
    uint  baseInstance;

} ACMIndirectDrawBuffer;
```

Figure 23: Structure of indirect draw command buffer

We can visualize the photons as a point cloud with lots of vertices, so the instance count is always set to 1. First and base instance are set to 0; they are offset variables unneeded for the purpose of this project.

This concludes the caustics traversal and splat process with compute shader. We found out that cache optimizations within compute work groups impacts the sampling speed, and different work group sizes can impact performance significantly, so we tested various work group sizes and found a work group size of 8 by 8 by 1 to be the most optimal in our situation. One may find it different depending on her hardware and shader implementation.

Results and Discussions

Results presented below were benchmarked on an 8-core Intel Xeon processor at 3.0GHz with a GeForce GTX 980. Adaptive Caustic Maps using transform feedback:

98,000 photons/ms (4096^2, 3,300,000 photons / 35FPS)

Our implementation using compute shaders:

410,000 photons/ms (8192^2, 19,000,000 photons / 25FPS)

Best cases						
	FPS/Workgroup Size					
Iterations	resolution	1 x 1	2 x 2	4 x 4	8 x 8	16 x 16
6	64	122	117	123	123	120
7	128	118	113	118	119	118
8	256	113	110	115	116	115
9	512	106	107	112	111	110
10	1024	85	97	102	101	99
11	2048	50	65	72	73	72
12	4096	20	33	36	37	37

Table 1: Best case scenario framerate with different workgroup sizes

Worst cases						
	FPS/Workgroup Size					
Iterations	resolution	1 x 1	2 x 2	4 x 4	8 x 8	16 x 16
6	64	113	108	114	113	112
7	128	109	105	110	111	109
8	256	104	102	108	108	107
9	512	96	98	104	102	103
10	1024	73	85	90	88	87
11	2048	35	49	54	54	54
12	4096	11	18	21	22	21

Table 2: Worst case scenario framerate with different workgroup sizes

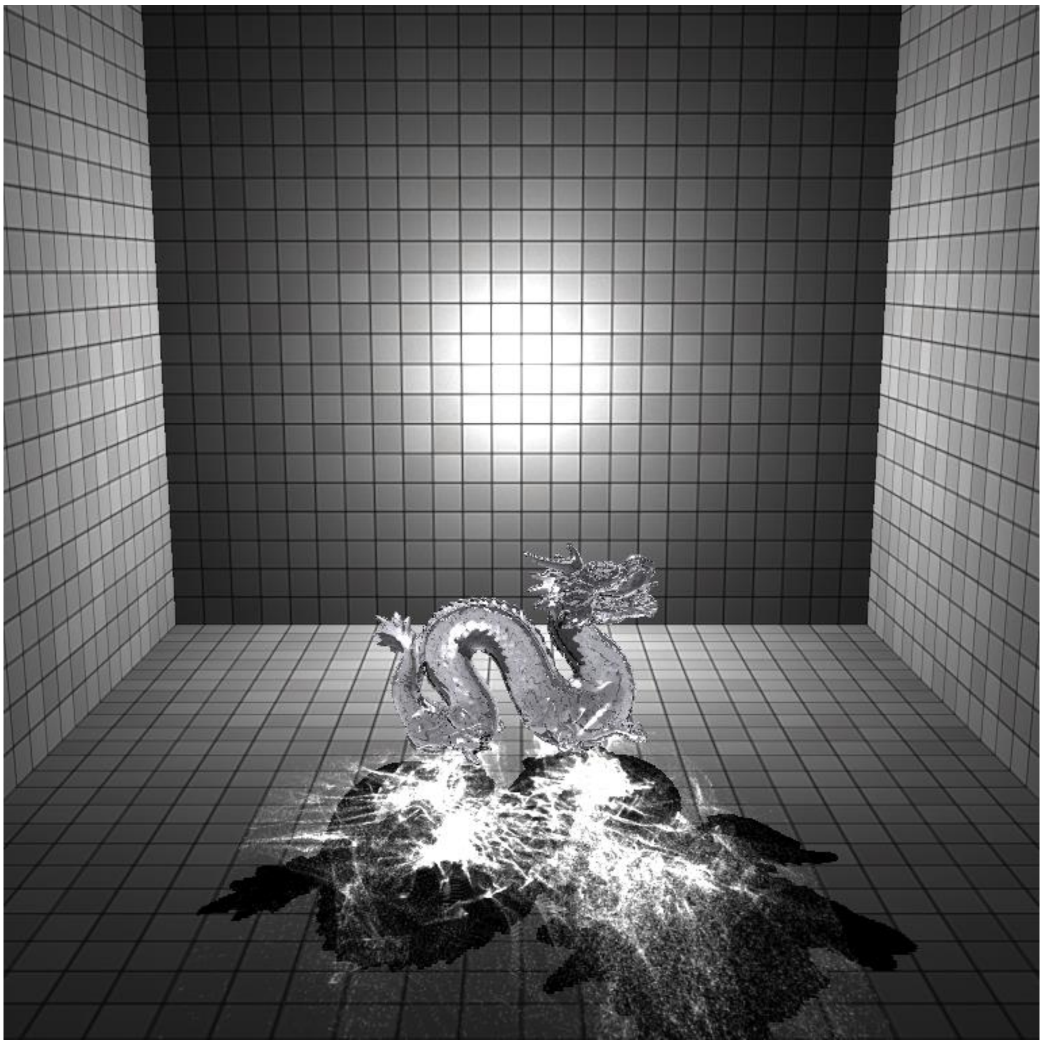


Figure 24: Render result with a 4096^2 photon buffer.

As shown in *Figure 24*, our result contains more noise than the original implementation. It is due to the texture sampling operation on mip-map enabled textures unable to perform linear interpolation correctly. It is perhaps due to a bug with the graphics driver of our development hardware. We are still investigating this issue during the writing of this paper.

Figure 25 – Figure 31 presented below illustrate an example of 7 levels of caustic detail that may be adopted by interactive media and games:

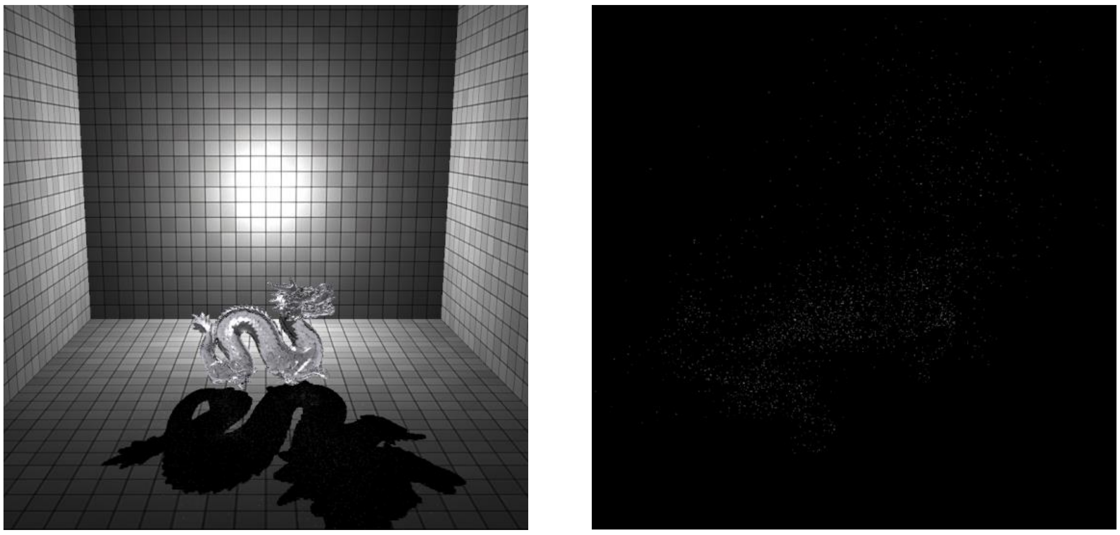


Figure 25: Caustic map rendered at 64^2

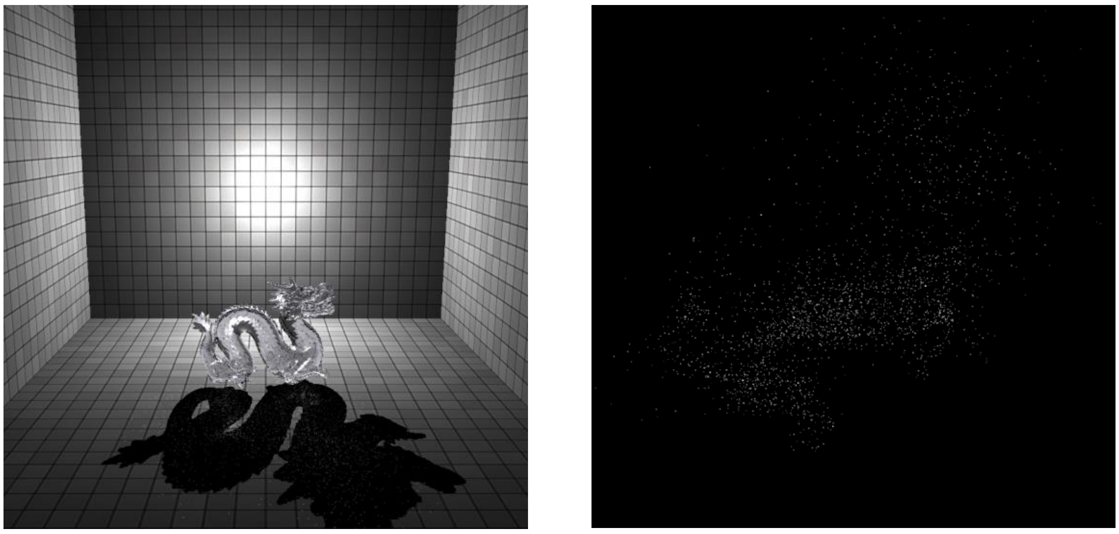


Figure 26: Caustic map rendered at 128^2

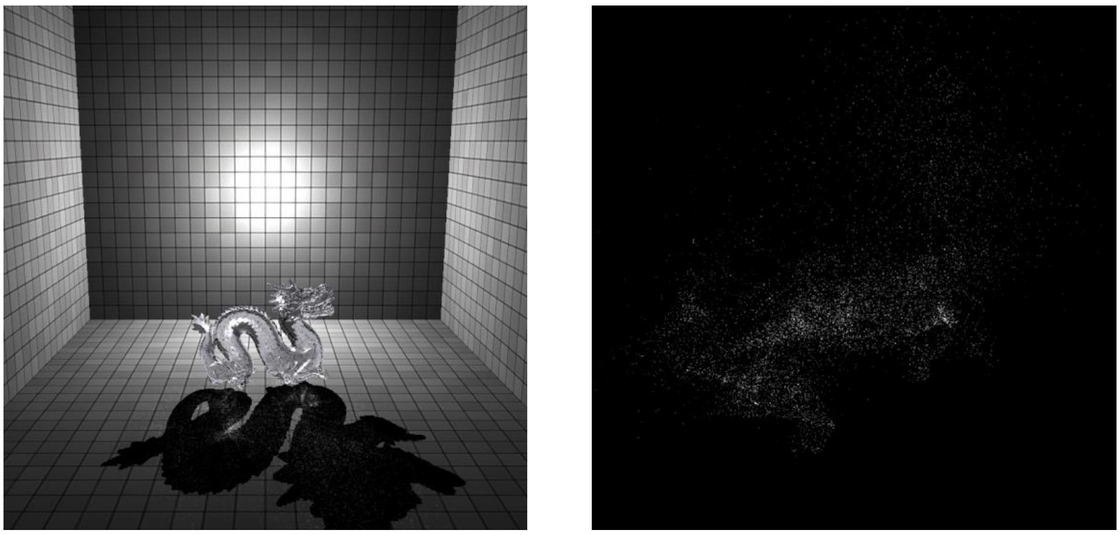


Figure 27: Caustic map rendered at 256^2

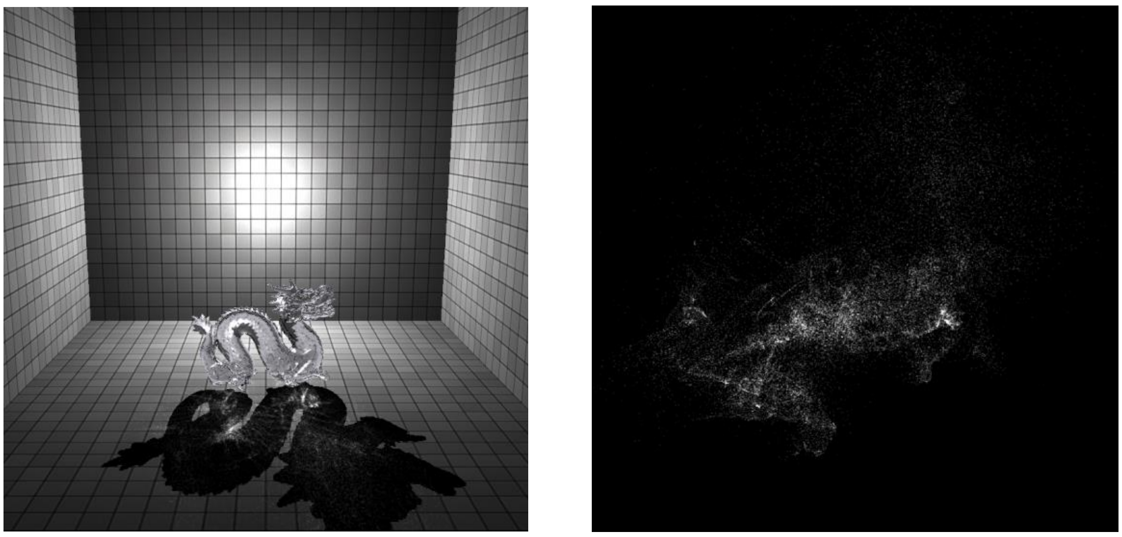


Figure 28: Caustic map rendered at 512^2

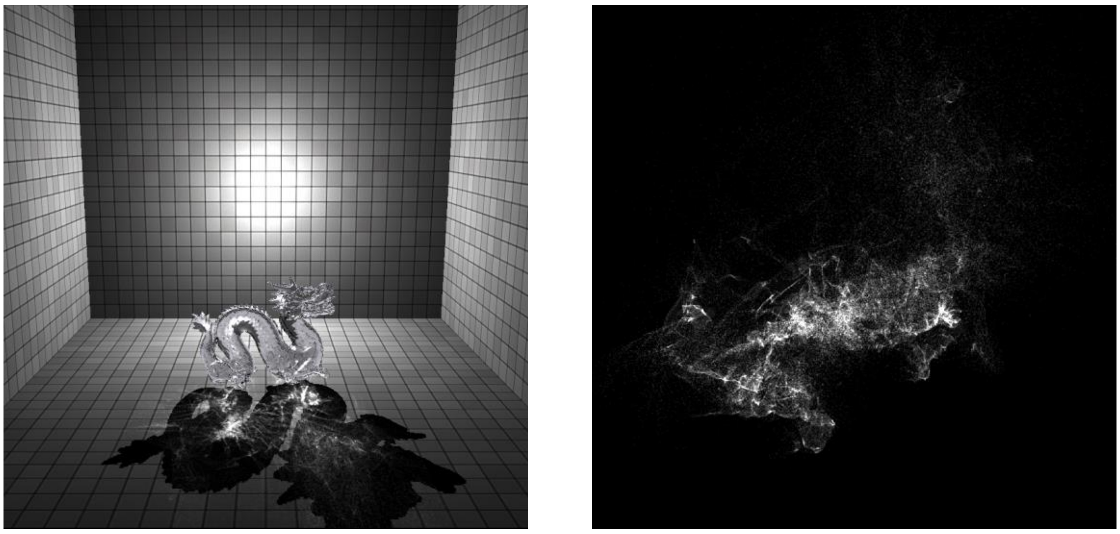


Figure 29: Caustic map rendered at 1024^2

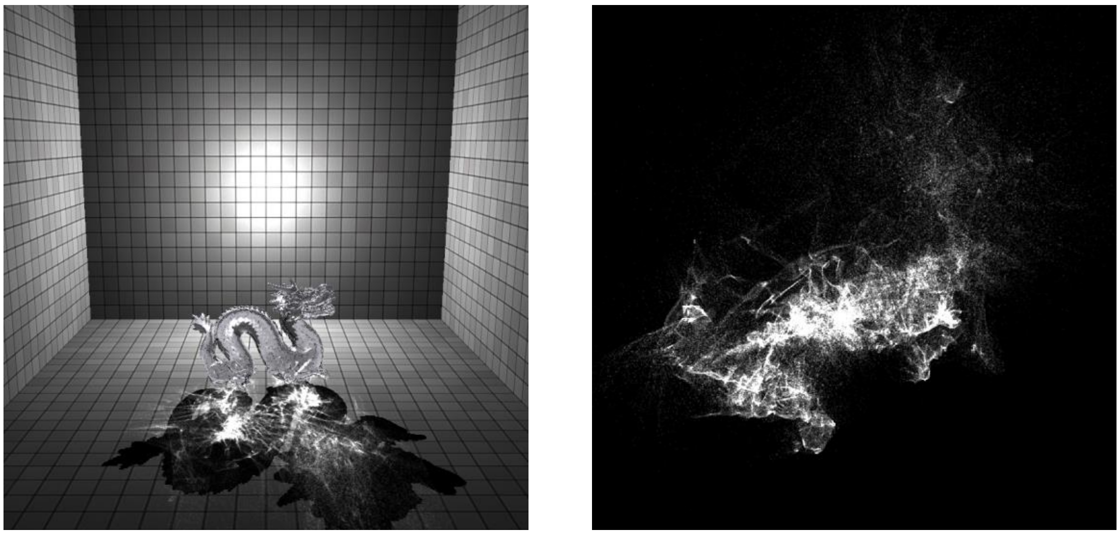


Figure 30: Caustic map rendered at 2048^2

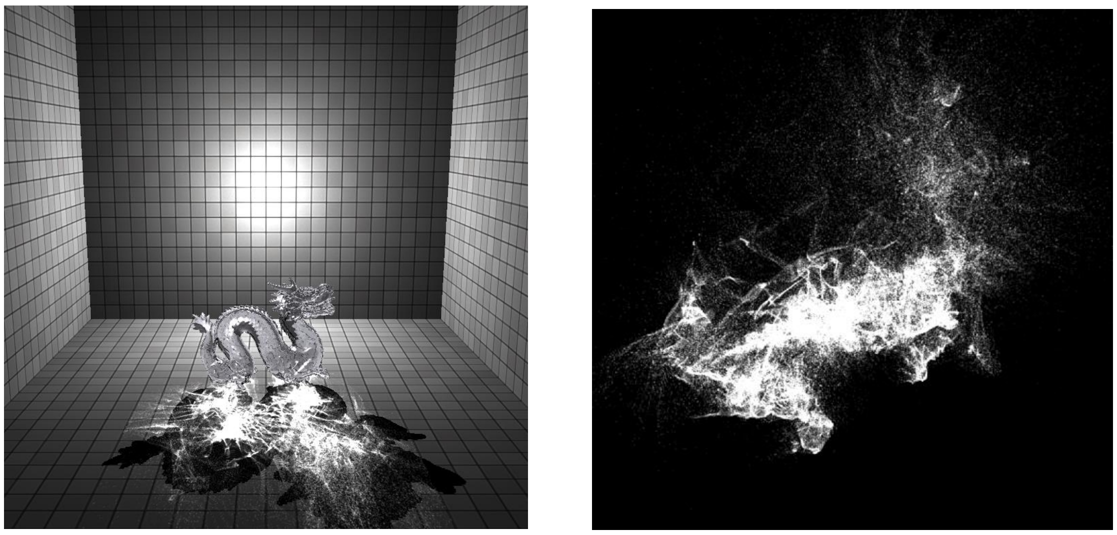


Figure 31: Caustic Map rendered at 4096^2

Figure 32 shows the best case scenarios of rendering caustics at different caustic map resolutions. Best case scenarios are when objects are rendered at such an angle so that it happens to generate the least amount of valid pixels in the normal textures.

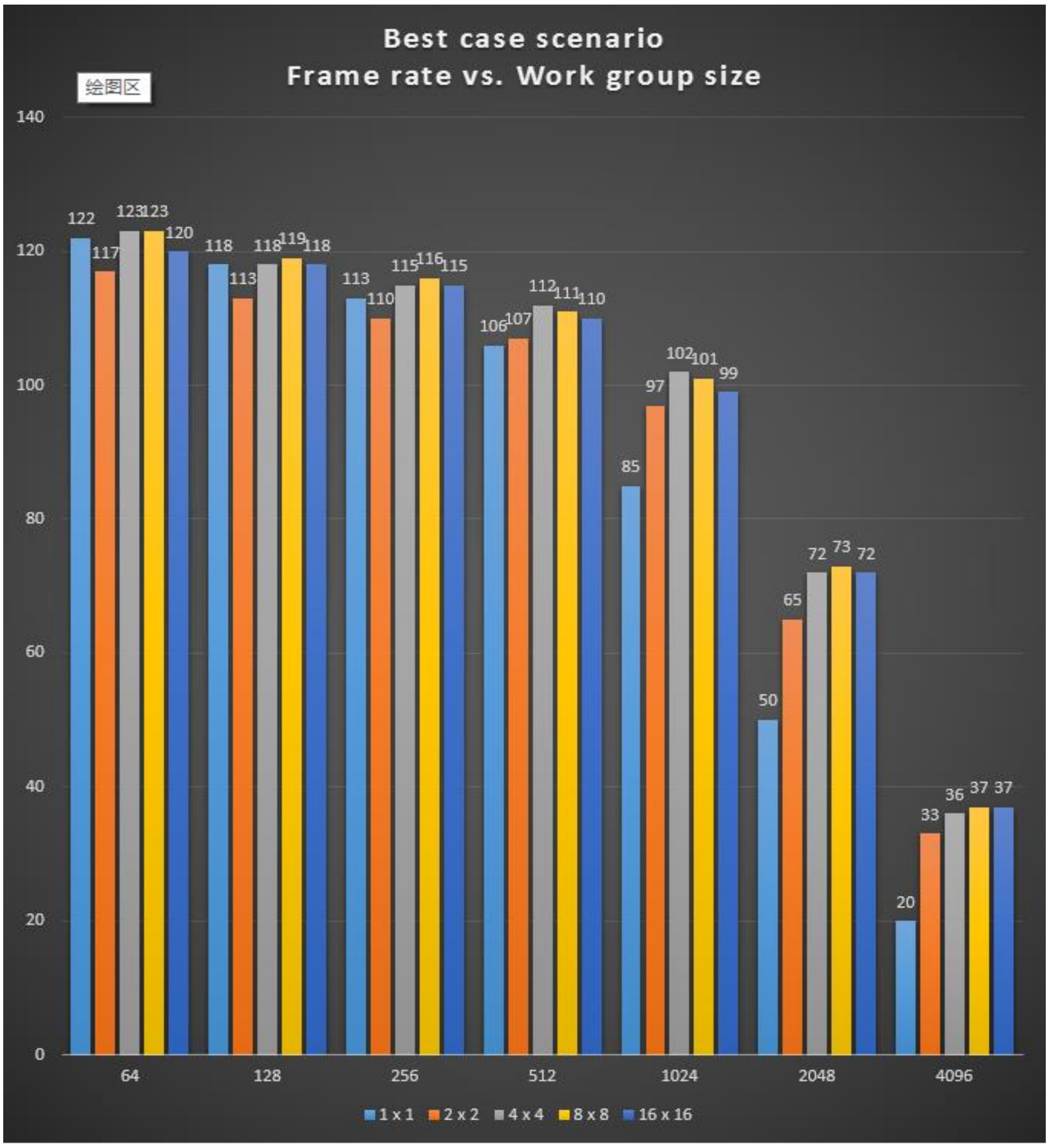


Figure 32: Chart of best case scenario frame rate vs. work group size

Worst case scenarios are when objects are rendered at such an angle so that it happens to generate the most amount of valid pixels in the normal textures.

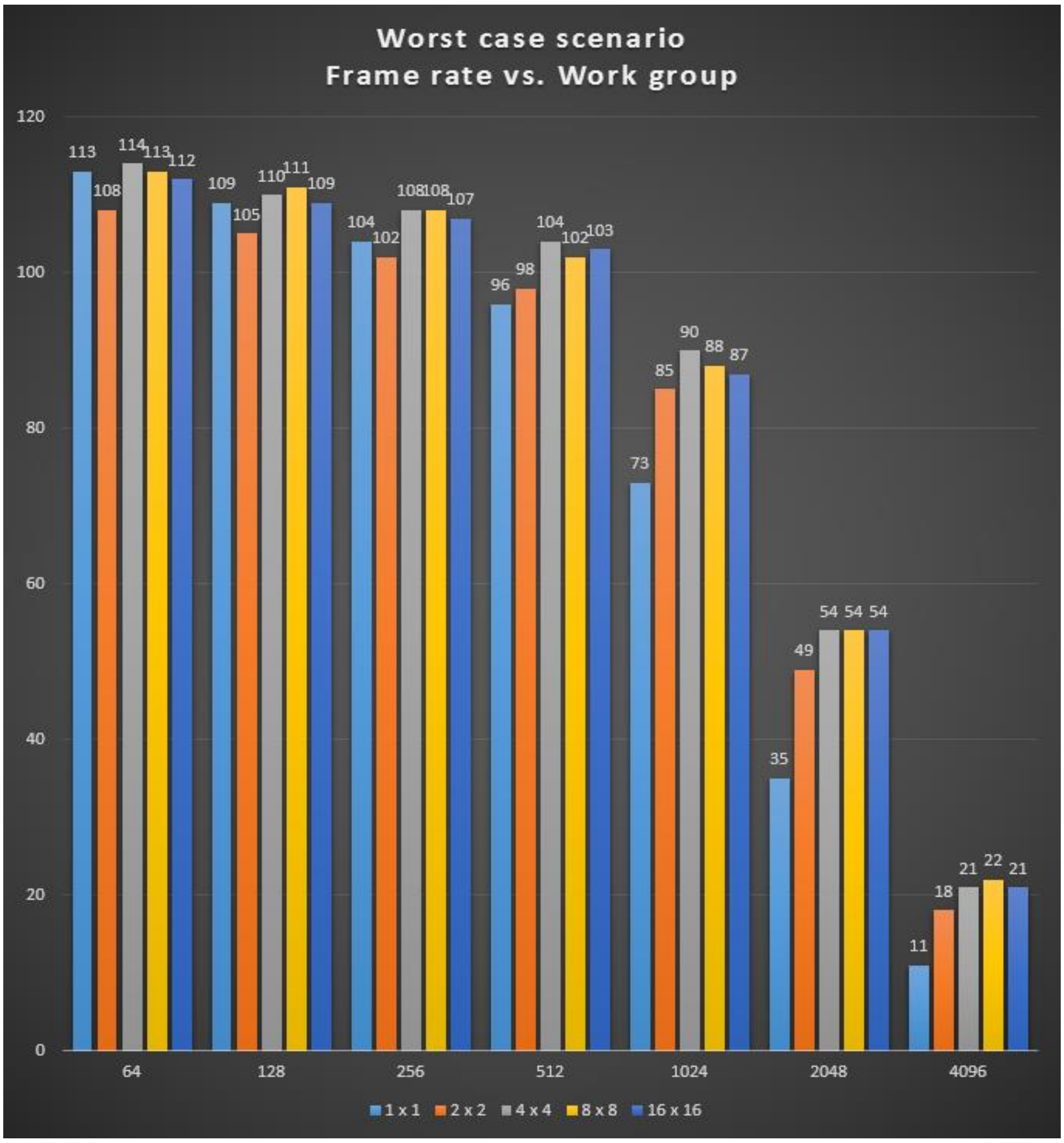


Figure 33: Chart of worst case scenario framerate vs. work group size

Both *Figure 32* and *Figure 33* demonstrate great performance increase with parallelism through compute shaders. We find 8x8x1 to be the most optimal work group size for caustic maps with 2048^2 or higher resolutions.

Without loss of generality, we think any previously expensive real-time rendering algorithm that requires massive general-purpose computation can greatly benefit from using the compute shader. The compute pipeline is highly optimized for parallel computations and is very flexible because there are no input or output constraints like the traditional drawing pipeline. No doubt there are still many optimizations that can be done to push this boundary even further.

Conclusions and Recommendations

In this project, we have presented an implementation of the Adaptive Caustics Maps algorithm that uses compute shaders and indirect draw to eliminate previously occurring bottlenecks. Though the performance increase turned out to be higher than expected, we think there is still room for improvement. Perhaps there will be a major performance increase by optimizing the compute shader instructions and also performing loop unroll within the compute shader in addition to our utilization of work group based parallelism.

We also think reusing part of the photon buffer that will not be used anymore is a possible direction for reducing memory consumption for high quality caustic maps. For example, after 3 photon traversal iterations, photons from the first and second iterations have expired and can perhaps be managed for reuse. Perhaps one can implement the compute shader to not only append to the end of the buffer, but also write to expired areas.

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Images:

http://image.slidesharecdn.com/refraccin-de-la-luz-1202762581536876-3/95/refraccin-de-la-luz-11-728.jpg?cb=1202755382. Accessed on May 3, 2015.

http://upload.wikimedia.org/wikipedia/commons/thumb/e/ea/Great_Barracuda,_corals,_sea_urchin_and_Caustic_(optics)_in_Kona,_Hawaii_2009.jpg/1059px-Great_Barracuda,_corals,_sea_urchin_and_Caustic_(optics)_in_Kona,_Hawaii_2009.jpg. Accessed on May 3, 2015.

http://ogldev.atspace.co.uk/www/tutorial28/pipeline.jpg. Accessed on May 3, 2015.

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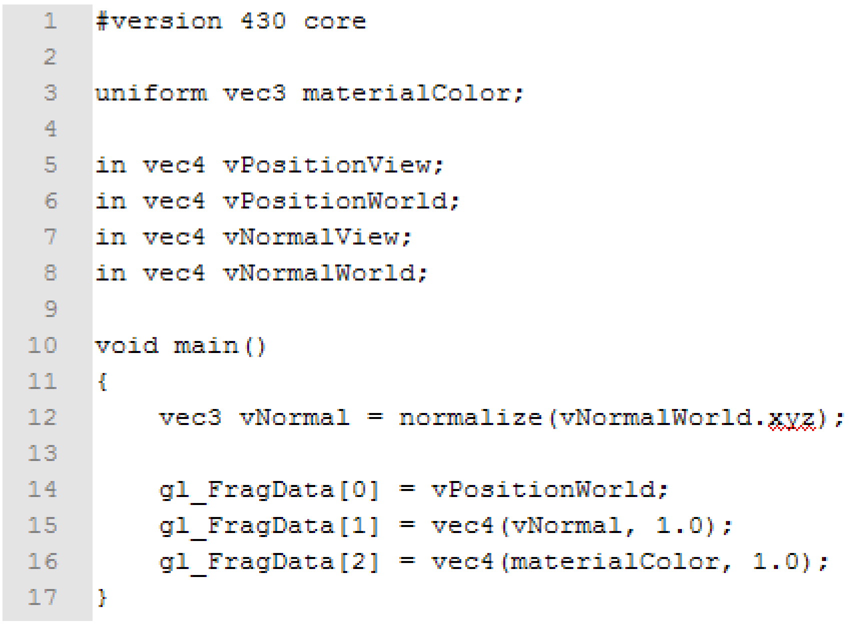
Appendix

Complete shader code:

RenderEyeSpacePosition.vert

```
#version 430 core

attribute vec4 vPosition;
attribute vec3 vNormal;

uniform mat4 World;
uniform mat4 View;
uniform mat4 Proj;

out vec4 vPositionView;
out vec4 vPositionWorld;
out vec4 vNormalView;
out vec4 vNormalWorld;



void main()
{
    vNormalView = View * World * vec4(vNormal, 0.0);
    vNormalWorld = World * vec4(vNormal, 0.0);
    vPositionView = View * World * vPosition;
    vPositionWorld = World * vPosition;
    gl_Position =  Proj * vPositionView;
}
```

RenderEyeSpacePosition.frag



```
#version 430 core

uniform vec3 materialColor;

in vec4 vPositionView;
in vec4 vPositionWorld;
in vec4 vNormalView;
in vec4 vNormalWorld;

void main()
{
    vec3 vNormal = normalize(vNormalWorld.xyz);

    gl_FragData[0] = vPositionWorld;
    gl_FragData[1] = vec4(vNormal, 1.0);
    gl_FragData[2] = vec4(materialColor, 1.0);
}
```

RenderFrontAndBackNormals.vert

```
#version 430

//  We're going to output the object's surface normal
//     in the fragment shader, so make sure to pass down
//     the eye-space surface normal to the fragment level.
//
//  However, since we're going to output BOTH front and back
//     facing surfaces in the same pass, we need to determine
//     if this certex is front-facing or back-facing
//     (the dot produt)

in vec4 vPosition;
in vec3 vNormal;

out vec4 vPositionWorld;
out vec4 vPositionView;
out vec4 vPositionProj;

out vec4 vNormalWorld;
out vec4 vNormalView;

out float distanceView;

uniform mat4 World;
uniform mat4 View;
uniform mat4 Proj;

void main()
{
    vNormalView = transpose(inverse(View * World)) * vec4(vNormal, 0.0);
    vNormalWorld = World * vec4(vNormal, 0.0);
    vPositionWorld = World * vPosition;
    vPositionView = View * vPositionWorld;
    vPositionProj = Proj * vPositionView;

    vNormalView.w = dot( normalize(vNormalView.xyz), -normalize(vPositionView.xyz) );
    distanceView = length( vPositionView.xyz );

    gl_Position = vPositionProj;
}
```

RenderFrontAndBackNormals.geom

```
#version 430 core

layout(triangles) in;
layout(triangle_strip, max_vertices = 3) out;



in vec4 vPositionWorld[];
in vec4 vPositionView[];
in vec4 vPositionProj[];

in vec4 vNormalWorld[];
in vec4 vNormalView[];

in float distanceView[];

out vec4 gNormalView;

// Output the surface normal to one of two different
//     rendering layers, based upon if it is front or back geometry.
//     Also, pass down the surface normal to the frag shader and
//     store the eye-space distance to the fragment in the
//     alpha channel of this texture (we'll negate this distance
//     if we're back facing, as a flag).

void main( void )
{
    gl_Layer        = vNormalView[0].w < 0.0 ? 1 : 0;
    float back      = 1;//vNormalView[0].w < 0.0 ? -1 : 1;

    //causticsDebugBuffer.second = vNormalView[1].w;
    //causticsDebugBuffer.third = vNormalView[2].w;

    gl_Position     = vPositionProj[0];
    // View space normal
    gNormalView.xyz = vNormalView[0].xyz;
    // Facing direction flag
    gNormalView.w = back * distanceView[0].x;
    EmitVertex();

    gl_Position     = vPositionProj[1];
    // View space normal
    gNormalView.xyz = vNormalView[1].xyz;
    // Facing direction flag
    gNormalView.w = back * distanceView[1].x;
    EmitVertex();

    gl_Position     = vPositionProj[2];
    // View space normal
    gNormalView.xyz = vNormalView[2].xyz;
    // Facing direction flag
    gNormalView.w = back * distanceView[2].x;
    EmitVertex();

    EndPrimitive();
}
```

RenderFrontAndBackNormals.frag

```
#version 430 core

in vec4 gNormalView;

layout(std430, binding = 0)  buffer _causticsDebugBuffer
{
    // Debug.
    float first;
    float second;
    float third;
    float fourth;

} causticsDebugBuffer;

// Output the surface normal to texture
out vec4 Output;

void main( void )
{
    causticsDebugBuffer.first = 10.0f;

    // Eye space normal
    Output.rgb = normalize(gNormalView.xyz);
    // Facing direction flag
    Output.a = max( gNormalView.w, 0.0 );
}
```

AdaptiveCausticsPreTraversalProcess.comp

```
#version 430 core

// An image to store data into.
layout(binding = 0, offset = 0) uniform atomic_uint writeCount;

layout (binding = 1) uniform sampler2DArray refractorNormal;

layout(std430, binding = 0) buffer _ACMSharedCommandBuffer
{
    uint mipmapLevel; // 3
    uint readOffset; // 0
    uint readCount; // 64 * 64 = 4096
    uint writeOffset; // 4096
    uint width;
    uint height;
    float deltaX;
    float deltaY;

} ACMSharedCommandBuffer;

layout(std430, binding = 1) buffer _ACMIndirectCommandBuffer
{
    uint num_groups_x;
    uint num_groups_y;
    uint num_groups_z;

} ACMIndirectCommandBuffer;

layout(std430, binding = 2) buffer _ACMIndirectDrawBuffer
{
    uint  count;
    uint  instanceCount;
    uint  first;
    uint  baseInstance;

} ACMIndirectDrawBuffer;

layout (local_size_x = 1, local_size_y = 1) in;

void main(void)
{
    uint id = gl_GlobalInvocationID.y * gl_WorkGroupSize.y *
    gl_NumWorkGroups.y + gl_GlobalInvocationID.x;

    if(id == 0)
    {
        ACMSharedCommandBuffer.mipmapLevel = 4; //10 - 6;
        ACMSharedCommandBuffer.readOffset = 0;
        ACMSharedCommandBuffer.readCount = 4096;
        ACMSharedCommandBuffer.writeOffset = 4096;
        ACMSharedCommandBuffer.width = 768;
        ACMSharedCommandBuffer.height = 768;
        ACMSharedCommandBuffer.deltaX = 0.5f / 64;
        ACMSharedCommandBuffer.deltaY = 0.5f / 64;

        ACMIndirectCommandBuffer.num_groups_x = 8;
        ACMIndirectCommandBuffer.num_groups_y = 8;
        ACMIndirectCommandBuffer.num_groups_z = 1;

        ACMIndirectDrawBuffer.count = 0;
        ACMIndirectDrawBuffer.instanceCount = 1;
        ACMIndirectDrawBuffer.first = 0;
        ACMIndirectDrawBuffer.baseInstance = 0;
    }
}
```

AdaptiveCausticsTraversal.comp

Part 1:

```glsl
#version 430 core

// An image to store data into.
layout(binding = 0, offset = 0) uniform atomic_uint writeCount;
layout(binding = 0, offset = 4) uniform atomic_uint storageCounter2;

layout (rgba32f, binding = 0) uniform image2D data;
layout (binding = 1) uniform sampler2DArray refractorNormal;

layout(std430, binding = 0) buffer _ACMSharedCommandBuffer
{
    uint mipmapLevel; // 3
    uint readOffset; // 0
    uint readCount; // 64 * 64 = 4096
    uint writeOffset; // 4096
    uint width;
    uint height;
    float deltaX;
    float deltaY;

} ACMSharedCommandBuffer;

layout(std430, binding = 1)  buffer _ACMBuffer
{
    vec4 debug;

    // photon uv buffer. Must be big enough.
    vec4 uv[];
} ACMBuffer;



layout (local_size_x = 8, local_size_y = 8, local_size_z = 1) in;


```

AdaptiveCausticsTraversal.comp

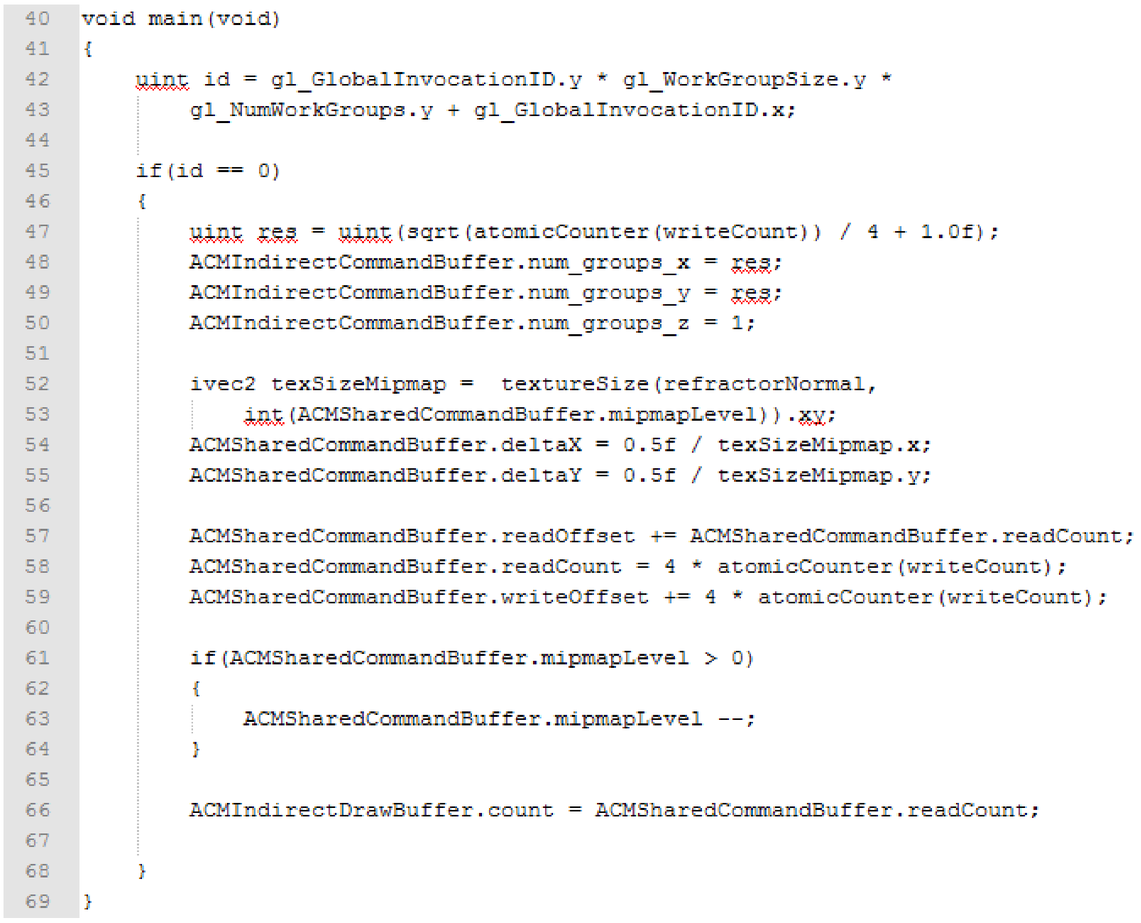
Part 2:

```
void main(void)
{
    // local constants
    uint readIndex =
    gl_GlobalInvocationID.y * gl_WorkGroupSize.y * gl_NumWorkGroups.y +
    gl_GlobalInvocationID.x;

    if(readIndex >= ACMSharedCommandBuffer.readCount)
    {
        // unneeded computation
        return;
    }

    vec4 uv = ACMBuffer.uv[ACMSharedCommandBuffer.readOffset + readIndex];

    ivec2 mipmapTexSize =  textureSize(refractorNormal,
        int(ACMSharedCommandBuffer.mipmapLevel)).xy;
    ivec2 iTCoordMipmap = ivec2(uv.xy * mipmapTexSize);
    vec4 color = texelFetch(refractorNormal, ivec3(iTCoordMipmap, 1),
        int(ACMSharedCommandBuffer.mipmapLevel));

    if(color.a == 0)
    {
        //uint unusedCount = atomicCounterIncrement(storageCounter2);
        vec2 texSize = vec2(ACMSharedCommandBuffer.width, ACMSharedCommandBuffer.height);
        imageStore(data, ivec2(uv.xy * texSize), vec4(0.3, 0.3, 0.3, 1));
    }
    else
    {
        // Allocate storage
        uint writeIndex = 4 * atomicCounterIncrement(writeCount);
        uint writeOffset = ACMSharedCommandBuffer.writeOffset + writeIndex;

        vec2 texSize = vec2(ACMSharedCommandBuffer.width, ACMSharedCommandBuffer.height);

        vec4 texCoord0 = vec4( uv.x                                ,
            uv.y                                , 0, 0 );
        vec4 texCoord1 = vec4( uv.x + ACMSharedCommandBuffer.deltaX,
            uv.y                                , 0, 0 );
        vec4 texCoord2 = vec4( uv.x + ACMSharedCommandBuffer.deltaX,
            uv.y + ACMSharedCommandBuffer.deltaY, 0, 0 );
        vec4 texCoord3 = vec4( uv.x                                ,
            uv.y + ACMSharedCommandBuffer.deltaY, 0, 0 );

        ivec2 imageCoord0 = ivec2(texCoord0.xy * texSize + 0.5f);
        ivec2 imageCoord1 = ivec2(texCoord1.xy * texSize + 0.5f);
        ivec2 imageCoord2 = ivec2(texCoord2.xy * texSize + 0.5f);
        ivec2 imageCoord3 = ivec2(texCoord3.xy * texSize + 0.5f);


        ACMBuffer.uv[writeOffset + 0] = texCoord0;
        ACMBuffer.uv[writeOffset + 1] = texCoord1;
        ACMBuffer.uv[writeOffset + 2] = texCoord2;
        ACMBuffer.uv[writeOffset + 3] = texCoord3;

    }
}
```

AdaptiveCausticsPostTraversalProcess.comp
Part 1:

```
#version 430 core

// An image to store data into.
layout(binding = 0, offset = 0) uniform atomic_uint writeCount;

layout (binding = 1) uniform sampler2DArray refractorNormal;

layout(std430, binding = 0) buffer _ACMSharedCommandBuffer
{
    uint mipmapLevel; // 3
    uint readOffset; // 0
    uint readCount; // 64 * 64 = 4096
    uint writeOffset; // 4096
    uint width;
    uint height;
    float deltaX;
    float deltaY;

} ACMSharedCommandBuffer;

layout(std430, binding = 1) buffer _ACMIndirectCommandBuffer
{
    uint num_groups_x;
    uint num_groups_y;
    uint num_groups_z;

} ACMIndirectCommandBuffer;

layout(std430, binding = 2) buffer _ACMIndirectDrawBuffer
{
    uint  count;
    uint  instanceCount;
    uint  first;
    uint  baseInstance;

} ACMIndirectDrawBuffer;

layout (local_size_x = 1, local_size_y = 1) in;
```

AdaptiveCausticsPostTraversalProcess.comp
Part 2:



```
void main(void)
{
    uint id = gl_GlobalInvocationID.y * gl_WorkGroupSize.y *
        gl_NumWorkGroups.y + gl_GlobalInvocationID.x;

    if(id == 0)
    {
        uint res = uint(sqrt(atomicCounter(writeCount)) / 4 + 1.0f);
        ACMIndirectCommandBuffer.num_groups_x = res;
        ACMIndirectCommandBuffer.num_groups_y = res;
        ACMIndirectCommandBuffer.num_groups_z = 1;

        ivec2 texSizeMipmap =  textureSize(refractorNormal,
            int(ACMSharedCommandBuffer.mipmapLevel)).xy;
        ACMSharedCommandBuffer.deltaX = 0.5f / texSizeMipmap.x;
        ACMSharedCommandBuffer.deltaY = 0.5f / texSizeMipmap.y;

        ACMSharedCommandBuffer.readOffset += ACMSharedCommandBuffer.readCount;
        ACMSharedCommandBuffer.readCount = 4 * atomicCounter(writeCount);
        ACMSharedCommandBuffer.writeOffset += 4 * atomicCounter(writeCount);

        if(ACMSharedCommandBuffer.mipmapLevel > 0)
        {
            ACMSharedCommandBuffer.mipmapLevel --;
        }

        ACMIndirectDrawBuffer.count = ACMSharedCommandBuffer.readCount;

    }
}
```

AdaptiveCausitcsDrawDebug.comp

```
#version 430 core

// An image to store data into.
layout(binding = 0, offset = 0) uniform atomic_uint writeCount;
layout(binding = 1, offset = 4) uniform atomic_uint storageCounter2;

layout (rgba32f, binding = 0) uniform image2D data;
layout (binding = 1) uniform sampler2DArray refractorNormal;

layout(std430, binding = 0) buffer _ACMSharedCommandBuffer
{
    uint mipmapLevel; // 3
    uint readOffset; // 0
    uint readCount; // 64 * 64 = 4096
    uint writeOffset; // 4096
    uint width;
    uint height;
    float deltaX;
    float deltaY;

} ACMSharedCommandBuffer;

layout(std430, binding = 1)  buffer _ACMBuffer
{
    vec4 debug;

    // photon uv buffer. Must be big enough.
    vec4 uv[];
} ACMBuffer;



layout (local_size_x = 1, local_size_y = 1) in;


void main(void)
{
    // local constants
    vec2 texRes = vec2(ACMSharedCommandBuffer.width, ACMSharedCommandBuffer.height);

    vec2 TCoord = vec2(gl_GlobalInvocationID.xy) / texRes;
    ivec2 mipmap =  textureSize(refractorNormal, int(ACMSharedCommandBuffer.mipmapLevel)).xy;
    ivec2 iTCoord = ivec2(TCoord * mipmap);
    vec4 debugColor = texelFetch(refractorNormal, ivec3(iTCoord, 1),
        int(ACMSharedCommandBuffer.mipmapLevel));
    imageStore(data, ivec2(gl_GlobalInvocationID.xy), debugColor);

}
```

CausticsSplat.vert

Part 1:

```
#version 430 core

in vec4 vPosition;
in vec2 vTCoord;

out vec4 Temp[6];

uniform float TanLightFovy2;
uniform vec4 NearFarInfo;
uniform vec4 RefractionIndexInfo;
uniform mat4 LightProj;

uniform sampler2DArray RefractorNorm;
uniform sampler2DArray RefractorDepth;
uniform sampler2D ReceiverDepth;

// An image to store data into.
//layout(binding = 0, offset = 0) uniform atomic_uint writeCount;
//layout(binding = 1, offset = 4) uniform atomic_uint storageCounter2;

//layout (rgba32f, binding = 0) uniform image2D data;
//layout (binding = 1) uniform sampler2DArray refractorNormal;

layout(std430, binding = 0) buffer _ACMSharedCommandBuffer
{
    uint mipmapLevel; // 3
    uint readOffset; // 0
    uint readCount; // 64 * 64 = 4096
    uint writeOffset; // 4096
    uint width;
    uint height;
    float deltaX;
    float deltaY;
} ACMSharedCommandBuffer;

layout(std430, binding = 1)  buffer _ACMBuffer
{
    vec4 debug;

    // photon uv buffer. Must be big enough.
    vec4 uv[];
} ACMBuffer;
```

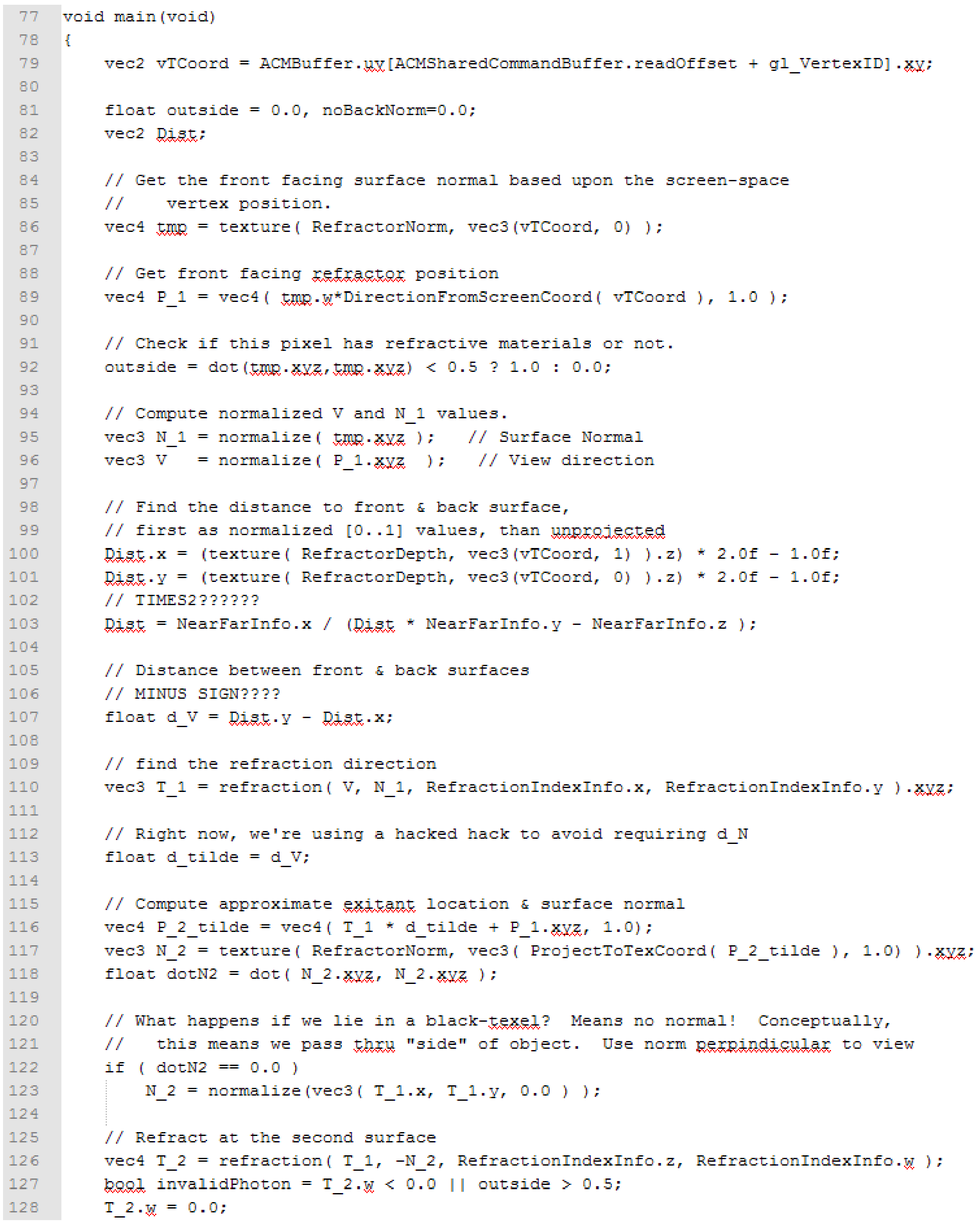
CausticsSplat.vert

Part 2:

```
// This takes an eye-space (actually light-space since
//    our "eye" is at the light here) position and converts
//    it into a image-space (u,v) position.  This simply
//    applies the GL projection matrix and homogeneous
//    divide.
vec2 ProjectToTexCoord( vec4 eyeSpacePos )
{
    vec4 projLoc = LightProj * eyeSpacePos;
    return ( 0.5*(projLoc.xy / projLoc.w) + 0.5 );
}

// A simple refraction function (similar to the GLSL refraction, except
//    is is correct, not some pseudo refraction!)
vec4 refraction( vec3 incident, vec3 normal, float ni_nt, float ni_nt_sqr )
{
    vec4 returnVal;
    float tmp = 1.0;
    float IdotN = dot( -incident, normal );
    float cosSqr = 1.0 - ni_nt_sqr*(1.0 - IdotN*IdotN);
    return ( cosSqr <= 0.0 ?
             vec4( normalize(reflect( incident, normal )), -1.0 ) :
             vec4( normalize( ni_nt * incident +
                (ni_nt* IdotN - sqrt( cosSqr )) * normal ), 1.0 ) );
}

// Takes a screen coordinate and turns it into a 3D vector pointing
//   in the correct direction (in eye-space)
vec3 DirectionFromScreenCoord( vec2 texPos )
{
    vec3 dir = vec3(TanLightFovy2 * 2.0 * texPos - TanLightFovy2, -1.0 );
    return normalize( dir );
}
```

CausticsSplat.vert

Part 3:



```
void main(void)
{
    vec2 vTCoord = ACMBuffer.uv[ACMSharedCommandBuffer.readOffset + gl_VertexID].xy;

    float outside = 0.0, noBackNorm=0.0;
    vec2 Dist;

    // Get the front facing surface normal based upon the screen-space
    //    vertex position.
    vec4 tmp = texture( RefractorNorm, vec3(vTCoord, 0) );

    // Get front facing refractor position
    vec4 P_1 = vec4( tmp.w*DirectionFromScreenCoord( vTCoord ), 1.0 );

    // Check if this pixel has refractive materials or not.
    outside = dot(tmp.xyz,tmp.xyz) < 0.5 ? 1.0 : 0.0;

    // Compute normalized V and N_1 values.
    vec3 N_1 = normalize( tmp.xyz );   // Surface Normal
    vec3 V   = normalize( P_1.xyz  );   // View direction

    // Find the distance to front & back surface,
    // first as normalized [0..1] values, than unprojected
    Dist.x = (texture( RefractorDepth, vec3(vTCoord, 1) ).z) * 2.0f - 1.0f;
    Dist.y = (texture( RefractorDepth, vec3(vTCoord, 0) ).z) * 2.0f - 1.0f;
    // TIMES2??????
    Dist = NearFarInfo.x / (Dist * NearFarInfo.y - NearFarInfo.z );

    // Distance between front & back surfaces
    // MINUS SIGN????
    float d_V = Dist.y - Dist.x;

    // find the refraction direction
    vec3 T_1 = refraction( V, N_1, RefractionIndexInfo.x, RefractionIndexInfo.y ).xyz;

    // Right now, we're using a hacked hack to avoid requiring d_N
    float d_tilde = d_V;

    // Compute approximate exitant location & surface normal
    vec4 P_2_tilde = vec4( T_1 * d_tilde + P_1.xyz, 1.0);
    vec3 N_2 = texture( RefractorNorm, vec3( ProjectToTexCoord( P_2_tilde ), 1.0) ).xyz;
    float dotN2 = dot( N_2.xyz, N_2.xyz );

    // What happens if we lie in a black-texel?  Means no normal!  Conceptually,
    //   this means we pass thru "side" of object.  Use norm perpindicular to view
    if ( dotN2 == 0.0 )
        N_2 = normalize(vec3( T_1.x, T_1.y, 0.0 ) );

    // Refract at the second surface
    vec4 T_2 = refraction( T_1, -N_2, RefractionIndexInfo.z, RefractionIndexInfo.w );
    bool invalidPhoton = T_2.w < 0.0 || outside > 0.5;
    T_2.w = 0.0;
```

CausticsSplat.vert

Part 4:

```
    // Scale the vector so that it's got a unit-length z-component
    vec4 tmpT2 = T_2 / -T_2.z;

    // Compute the texture locations of ctrPlusT2 and refractToNear.
    float index, minDist = 1000.0, deltaDist = 1000.0;
    for (index = 0.0; index < 2.0; index += 1.0)
    {
        float texel = texture( ReceiverDepth,
            ProjectToTexCoord( P_2_tilde + tmpT2 * index ) ).x;
        float distA = -(NearFarInfo.x / (texel * NearFarInfo.y - NearFarInfo.w)) +
            P_2_tilde.z;
        if ( abs(distA-index) < deltaDist )
        {
            deltaDist = abs(distA-index);
            minDist = index;
        }
    }

    // Do our final iteration to home in on the final photon position.
    //   10 iterations is usually enough.
    for (float index = 0.0; index < 10.0; index += 1.0)
    {
        float texel1 = texture( ReceiverDepth,
            ProjectToTexCoord( P_2_tilde + minDist * tmpT2 ) ).x;
        minDist = -(NearFarInfo.x / (texel1 * NearFarInfo.y - NearFarInfo.w)) +
            P_2_tilde.z;
    }

    // OK, find the projected photon position in the caustic map.
    vec4 photonPosition   = P_2_tilde + minDist * tmpT2;
    vec4 projectedPhoton = LightProj * vec4( photonPosition.xyz, 1.0 );
    projectedPhoton /= projectedPhoton.w;

    // Pass down this data (either to the splatting code or to the
    //     code that checks adjacent photons for convergence)
    gl_Position = projectedPhoton;
    Temp[1] = photonPosition;
    Temp[0] = invalidPhoton ? vec4(1.0) : vec4(0.0);
    Temp[2] = projectedPhoton;
    Temp[3] = vec4(1.0, 1.0, 1.0, 1.0);//texture( spotLight, gl_Position.xy );
    Temp[3].w = floor(512.0*gl_Position.y)+gl_Position.x;

    gl_PointSize = invalidPhoton ? 0.0 : 3.0;
    Temp[4].z = 3.0;
    Temp[4].xy = projectedPhoton.xy * 0.5 + 0.5;
    Temp[4].w = 4.0;
    Temp[5] = vec4(0.0);
}
```

CausticsSplat.frag

Part 1:

```
#version 430 core

in vec4 Temp[6];
out vec4 Output;

// splatResolutionModifier is an intensity modifier that results
//   from changing various resolution parameters using the user
//   interface, scene file, or simply traversal through the hierarchy.
//   In order to keep the correct splat intensity, we need to know
//   what level of subdivision has been applied to this photon.
uniform float splatResolutionModifier;

// Since our gl_FragCoord is in image space, we need to know how
//   big this image is if we plan to use the gl_FragCoord to do
//   useful things independent of resolution.
uniform float renderBufRes;

layout(std430, binding = 0) buffer _ACMSharedCommandBuffer
{
    uint mipmapLevel; // 3
    uint readOffset; // 0
    uint readCount; // 64 * 64 = 4096
    uint writeOffset; // 4096
    uint width;
    uint height;
    float deltaX;
    float deltaY;
} ACMSharedCommandBuffer;

layout(std430, binding = 1)  buffer _ACMBuffer
{
    vec4 debug;

    // photon uv buffer. Must be big enough.
    vec4 uv[];
} ACMBuffer;
```

CausticsSplat.frag

Part 2:

```
void main(void)
{
    // We'll fix our Gaussian splat size at just under 3 pixels.  Set
    //    Gaussian distribution parameters.
    float splatSize = 2.5;
    float sizeSqr = splatSize*splatSize;
    float isInsideGaussian = 0.0;

    // We need to compute how far this fragment is from the center of the splat.
    //    We could do this using point sprites, but our experience is the final
    //    framerate is significantly faster this way.  You may find differently.
    vec2 fragLocation = gl_FragCoord.xy;
    vec2 pointLocation = (Temp[2].xy * 0.5 + 0.5) * renderBufRes;

    // Gaussian from Graphics Gems I,
    // "Convenient anti-aliasing filters that minimize bumpy sampling"
    float alpha = 0.918;
    float beta_x2 = 3.906;     // == beta*2 == 1.953 * 2;
    float denom = 0.858152111; // == 1 - exp(-beta);
    float distSqrToSplatCtr = dot(fragLocation - pointLocation, fragLocation - pointLocation);
    float expResults = exp( -beta_x2*distSqrToSplatCtr/sizeSqr );

    //  Are we even inside the Gaussian?
    isInsideGaussian = ( distSqrToSplatCtr/sizeSqr < 0.25 ? 1.0 : 0.0 ) ;

    // Make sure the Gaussian intensity is properly normalized.
    float normalizeFactor = 10.5 * sizeSqr / 25.0;

    // Compute the Gaussian intensity
    expResults = alpha + alpha*((expResults-1.0)/denom);

    vec4 a = Temp[3];
    // Now compute the fragment color.  Note:Temp[3] is the spotlight color.
    //    Combine the intensity modifier, the check if we're inside the gaussian,
    //    and the normalized splat intensity.
    Output = Temp[3] * vec4( splatResolutionModifier *
        isInsideGaussian * expResults / normalizeFactor );

}
```