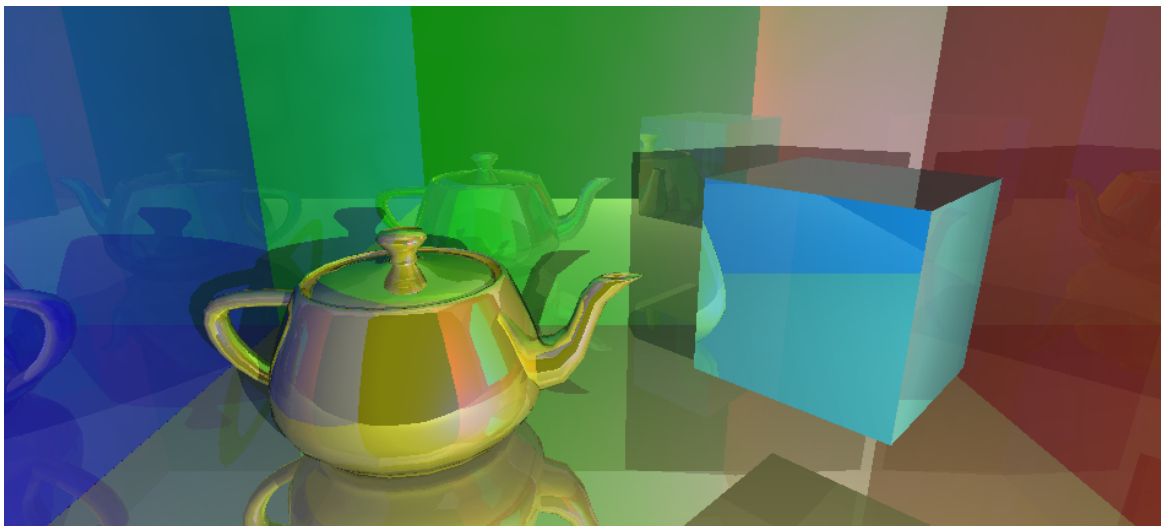University of Applied Sciences Basel (FHBB)
Diploma Thesis

DA07_0405_RayTracing on GPU

Ray Tracing on GPU

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Abstract

In this paper I present a way to implement Whitted style ("classic") recursive ray tracing on current generation consumer level GPUs using the OpenGL Shading Language (GLSL) and the Direct3D High Level Shading Language (HLSL). Ray tracing is implemented using a simplified, abstracted stream programming model for the GPU, written in C++.

A ray tracer on current graphics hardware reaches the speed of a good CPU implementation already. Combined with classic triangle based real time rendering, the GPU based ray tracing algorithm could already be used today for certain special effects in computer games.

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1. Introduction

Today, there are already computer games running in real time raytracing using clusters of PCs[14]. Now the questions is if future generations of GPUs (Graphics Processing Units) will make real time ray tracing possible on single CPU consumer computers.

Dual GPU solutions are entering the market, NVidia's SLI[1] and it seems Gigabyte will release a dual GPU one-board-solution with 2 GeForce 6600 GT[2]. There is a lot of promising development from GPU producers.

There have been several approaches to map ray tracing to GPUs. One is the approach described by Timothy J. Purcell[11], several of his ideas were used for this project.

The GPU Ray Tracer created for this paper – including the source code – is downloadable at the project site.[3] Be advised that the current version runs on NVidia GeForce 6 cards only.

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[1]http://www.nvidia.com

[2] http://www.tomshardware.com/hardnews/20041216_115811.html

[3]http://www.fhbb.ch/informatik/bvmm/

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2. Introduction to Ray Tracing

2.1. What is Ray Tracing ?

Ray tracing is a method of generating realistic images, in which the paths of individual rays of light are followed from the viewer to their points of origin.

The core concept of any kind of ray tracing algorithm is to efficiently find intersections of a ray with a scene consisting of a set of geometric primitives.

The scene to be rendered consists of a list of geometric primitives, which are usually simple geometric shapes such as as polygons, spheres, cones, etc. In fact, any kind of object can be used as a ray tracing primitive as long as it is possible to compute an intersection between a ray and the primitive.
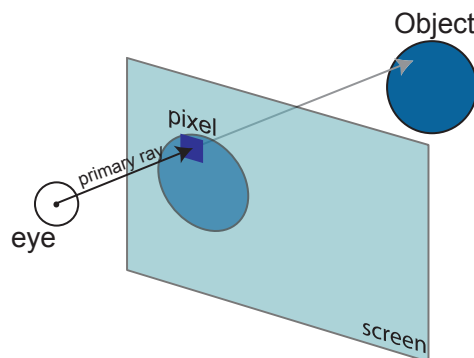
Figure 2.1.: Ray Tracing: Basic Concept

However, supporting triangles only[15] makes it easier to write, maintain, and optimize the ray tracer, and thus greatly simplifies both design and optimized implementation. Most scenes usually contain few "perfect spheres" or other high-level primitives. Furthermore most programs in the industry are exclusively based on triangular meshes.

Supporting triangles only does not really limit the kinds of scenes to be rendered, since all of these high-level primitives can usually be well approximated by triangles.

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2.2. Simple Ray Tracing Implementation

Turner Whitted[16] introduced a simple way to ray trace recursively.

```
RayRender
{
    for each pixel x,y
    {
        calculatePrimaryRay(x,y,ray);    // Ray originating from the
          camera/eye
        color = RayTrace(ray);           // Start Recursion for this
          pixel
        writePixel(x,y,color);           // write Pixel to Output Buffer
    }
}
```

```
Color RayTrace(Ray& ray)
{
  Color = BackgroundColor;
  RayIntersect(ray);
  if (ray.length < INFINITY)
  {
    color = RayShade(ray);
    if (ray.depth < maxDepth && contribution > minContrib)
    {
        if (ObjectIsReflective()) color += kr * RayTrace(reflected_ray);
        if (ObjectIsTransparent()) color += kt * RayTrace(transmitted_ray
          );
    }
  }
  return color;
}
```

```
Color RayShade(Ray &ray)
{
    for all light sources
    {
        shadowRay=GenerateShadowRay(ray, light[i]);
        if (shadowRay.length > light_distance) localColor +=
          CalcLocalColor();
    }
    return localColor;
}
```

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2.3. Accelerating Ray Tracing

Ray Tracing is time consuming because of the high number of intersection tests. Each ray has to be checked against all objects in a scene, so the primary approach to accelerate ray tracing is to reduce the total number of hit tests.

2.3.1. Using Spatial Data Structures

Finding the closest object hit by a ray requires the ray to be intersected with the primitives in the scene. A "brute force" approach of simply intersecting the ray with each geometric primitive is too expensive, therefore, accelerating this process usually involves traversing some form of an acceleration structure - in most cases a spatial data structure - is used to find objects nearby the ray. Spatial data structures are for example bounding volume hierarchies, BSP trees, kd trees, octrees, uniform grids, adaptive grids, hierarchical grids, etc.[2]

2.3.2. Eliminating Recursion

As shown in section 2.1, Ray tracing is usually used in a recursive manner. In order to compute the color of primary rays, recursive ray tracing algorithm casts additional, secondary rays creating indirect effects like shadows, reflection or refraction. It is possible to eliminate the need for recursion and to write the ray tracer in an iterative way which runs faster since we don't need function calls and the stack.

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3. GPU Programming

3.1. Programmable Graphics Hardware Pipeline

A pipeline is a sequence of steps operating in parallel and in a fixed order. Each stage receives its input from the prior stage and sends its output to the subsequent stage.
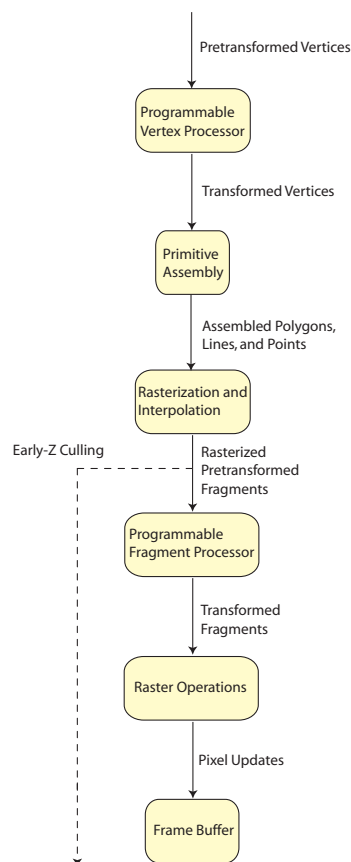

Figure 3.1.: Simplified Pipeline

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3.1.1. Programmable Vertex Processor

The vertex processor is a programmable unit that operates on incoming vertex attributes, such as position, color, texture coordinates, and so on. The vertex processor is intended to perform traditional graphics operations such as vertex transformation, normal transformation/normalization, texture coordinate generation, and texture coordinate transformation.

The vertex processor only has one vertex as input and only writes one vertex as output, therefore topological information of the vertices is not available to the vertex processor.

Vertex processing on GPU uses a limited number of mathemathical operations on floating-point vectors (two, three or four components). Operations include add, multiply, multiply-add, dot product, minumum, and maximum. Hardware support for vector negation and component-wise swizzling [1] is used to provide negation, subtraction, and cross products. The hardware also adds support for many utility functions like approximations of exponential, logarithmic, and trigonometric functions.

3.1.2. Primitive Assembly and rasterization

After vertex processing all vertex attributes are completely determined. The vertex data is then sent to the stage called Primitive Assembly. At this point vertex data is assembled into complete primitives. Points, lines, triangles, quads etc. may require clipping to the view frustum or application specified clip planes. The rasterizer may also discard polygons that are front or backfacing (culling).

3.1.3. Programmable Fragment Processor

The programmable fragment processor has most of the operations as the programmable vertex processor provides. In addition the fragment processor requires texture operations to access texture images. On current generation GPUs, floating-point values are supported.

The fragment processor is intended to perform traditional graphics operations such as operations on interpolated values, texture access, texture application, fog, and color sum.

To support parallelism at the fragment processing level, fragment programs only write one pixel. Newer GPUs provide multiple rendering target support which allows to write up to 4 fragments to 4 different render targets in one fragment program.

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[1]Swizzling is the ability to reorder vector components arbitrarily.

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3.1.4. Raster Operations

Each fragment is checked based on a number of tests, including scissor, alpha, stencil, and depth tests. After those tests a blending operation combines the final color with the correpsonding pixel's color value. On newer graphics cards depth testing can actually be done before calling the fragment processor ("Early-Z Culling"), and would not execute the fragment program if it is rejected[9]. This is useful for very long fragment programs.

3.2. Examples of Common Shader Applications

Shader Programs are usually very small programs, mainly used in computer games for special effects. There are many possible applications and only a few are presented here, without going into detail.
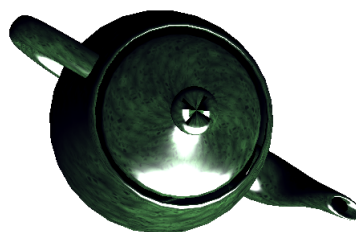
3.2.1. Advanced Lighting Model

Figure 3.2.: Cook-Torrance Lighting Model

The processing of every fragment (fragment shader) makes it possible to implement (advanced) lighting models – like the Cook-Torrance lighting model[5] – using a per fragment calculation.

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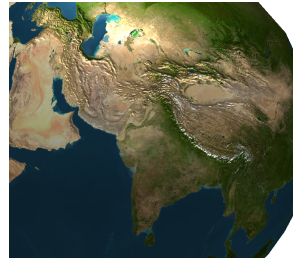
3.2.2. Bump Mapping

Figure 3.3.: Bump Mapping

Lighting calculations can be done in a different coordinate system like a TBN (tangent-binormal-normal) orthonormal base ("Texture Space"). This allows to easily implement bump mapping[3] in real time rendering applications.

3.2.3. Non Photorealistic Rendering

Figure 3.4.: Non Photorealisic Rendering - Cartoon Effects

Using tricks, it is possible to add special effects like cartoon-like[6] rendering. Such rendering is specially used in computer games.

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4. Stream Programming on GPU

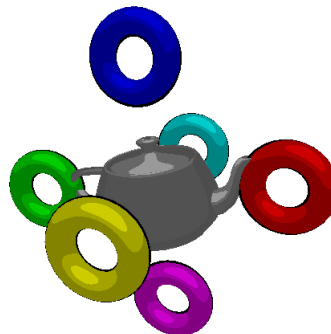There are several approaches to abstract the GPU to a streaming graphics processor. One such implementation is Brook for GPUs, a compiler and runtime implementation of the brook stream program language[4] for GPUs. Another approach is Sh[8], a metaprogramming language for GPUs, which also has a stream abstraction.

However, the approach used here is to hand-code a general purpose GPU program in GLSL and HLSL with a simple abstracted streaming model controlled in C++.

4.1. Streaming Model for GPUs

Shading languages are different from conventional programming languages. A GPU is not a serial processor, GPUs are based on a dataflow computational model - a streaming model. Computation occurs in response to data that flows through a sequence of processing steps. A function is executed on a set of input records (fragments) and outputs a set of output records (pixels). Stream processors typically refer to this function as "Kernel" and to the set of data as a "stream".

For the ray tracer and for other general purpose programs on GPU, it makes sense to abstract words like "fragment" or "pixel" to a higher level name, and to create a model to simplify the design of such programs.

4.1.1. Definitions

Stream A stream is a set of data. All data is of the same type. Stream elements can only be accessed read-only or write-only.

Data Array A data array is a set of data of the same type. Data arrays provide random access ("Gather").

Kernel Kernels are small programs operating on streams. Kernels take a stream as input and produce a stream as ouput. Kernels may also access several static data arrays. A kernel is allowed to reject input data and write no output.

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4.1.2. Implementing the Model on GPU

Stream Streams are floating point textures with render target support.

Data Array data arrays are floating point textures.

Kernel Kernels are fragment shader programs.

A GPU fragment program can read from any location from textures ("gather"), but cannot write to arbitrary global memory ("scatter"). The output of the fragment program is an image in global memory, with each fragment computation corresponding to a separate pixel in that image. So we have an "input stream" and an "output stream" to consider. The "output stream" may become an input of another kernel - or for loops an input of the same kernel.

Stream Generator
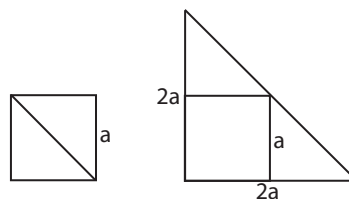
Figure 4.1.: Stream Generator

A view port sized quad is a stream generator. To execute the fragment shader, pixels have to be generated: A view port sized quad must be used so that one fragment per pixel is generated. In OpenGL this can be achieved with the following code snippets:

Listing 4.1: initializing

```
glViewport(0, 0, w, h);
glMatrixMode(GL_PROJECTION);
glLoadIdentity();
gluOrtho2D(-1, 1, -1, 1);
glMatrixMode(GL_MODELVIEW);
glLoadIdentity();
```

Listing 4.2: Drawing the quad

```
glBegin(GL_QUADS);
glTexCoord2f(0,0); glVertex3f(-1,-1,-0.5f);
```

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```
glTexCoord2f(1,0); glVertex3f( 1,-1,-0.5f);
glTexCoord2f(1,1); glVertex3f( 1, 1,-0.5f);
glTexCoord2f(0,1); glVertex3f(-1, 1,-0.5f);
glEnd();
```

The quad could also be generated using one triangle only, and adjust the viewport so that only a quad is drawn.

Process Flow of a General purpose GPU program

The usual process flow of a general purpose GPU program is:

1. Draw a quad, texels are mapped to pixels 1:1

2. Run a SIMD program (shader program, kernel) over each fragment

3. Resulting Texture-Buffer (output stream) can be treated as input texture (input stream) on the next pass.

4.2. C++ Implementation

4.2.1. Kernel and Array Definition

The C++ implementation uses 3 classes:

GPUStreamGenerator to generate a data stream (i.e. draw a quad).

GPUFloatArray to use as an input- or output-array.

GPUKernel to specifiy a GPU program and add input- and output arrays to it.

Listing 4.3: Example: Kernel and Array Definition

```
GPUKernel* K = new GPUKernel(shaderFX, "ProgramName");
GPUFloatArray D* = new GPUFloatArray(width,height,4);


K->addInput(D, "VariableName");
K->addOutput(D);


K->execute(); // Start Kernel.
```

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This example creates one array which will be used as input and output for the kernel. This information has to be set one time and then it is possible to start the kernel with "execute". Using an **Occlusion Query**[1], the function "execute" returns the actual number of values (pixels) written to the output array.

Figure 4.2.: Visualisation of a kernel that is called one time

4.2.2. Loops and Termination Conditions

As we saw in last section, it is possible to retrieve the number of values that were actually written to the output array. This leads to another function, "loop". If `K->loop()` is called, the kernel is executed until no values are written. This is dangerous, because it could lead to an infinte loop, so the kernel requires some sort of termination condition. It is in the response of the kernel programmer to take care of that. `n = K->loop()` returns the total number of performed kernel calls.

Listing 4.4: HLSL Example: Termination Condition

```
struct pixel
{
    float4 color : COLOR;
};

pixel demo(varying_data IN)
{
    pixel OUT;
    OUT.color = tex2D(tex0,IN.texCoord);
    OUT.color.r += 0.01;
    if (OUT.color.r >= 1.0) discard;
    return OUT;
}
```

In this HLSL example the value of the first component (pixel red component) is increased by 0.01. If the value reaches 1.0, the fragment is rejected and nothing will be drawn. Imagine an array full of random values in the range $[0, 1]$. When you loop

---

[1]Occlusion Queries are generally used to enable Occlusion Culling - a technique to accellerate rendering by not rendering hidden objects. In general purpose GPU programming this technique is used to count values.

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this kernel it will run until all values are 1.0, but there is no way to tell in advance how many kernel calls are necessary to reach this state.

Figure 4.3.: Visualisation of a (terminating) kernel which can be used for loops

4.3. Kernel Chains

Kernels can be chained together (sequence) or same Kernels can be called several times, using repetition or loops as shown in 4.2.2.

4.3.1. Sequence

A sequence is simply a chain of (usually) different kernels, each is called atleast 1 time. The result of a previous kernel may be used as input for subseqent kernel.
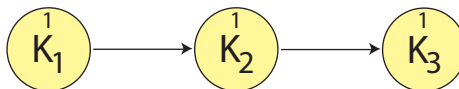

Figure 4.4.: Sequence

Listing 4.5: C++ Program to Implement a Sequence

```
K1.execute();
K2.execute();
K3.execute();
```

4.3.2. For-loop

If same kernel has to be called a known number times, this can be abbreviated with a simple for. The generated output data has to be used as input data or it makes no sense to use a loop.
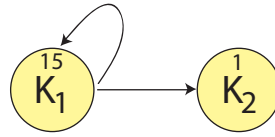
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Figure 4.5.: for

Listing 4.6: C++ Program to Implement a For-Loop

```
for (int i=0;i<15;i++) K1.execute();
K2.execute();
```

4.3.3. While Loop over one kernel

If a kernel has to be looped until its internal termination condition is reached (as shown in 4.2.2) then it can be done using `K->loop()`.

Figure 4.6.: While-Loop over one kernel
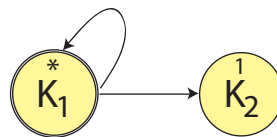
Listing 4.7: C++ Program to Implement a While-Loop

```
K1.loop();
K2.execute();
```

4.3.4. While-Loop over several kernels

It is not possible to use `loop()` if you want to loop over several kernels. Usually the 2nd kernel contains the termination condition in this case. This scenario cannot be reduced to one kernel in general.
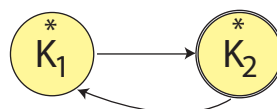

Figure 4.7.: While-Loop over several kernels

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Listing 4.8: C++ Program to Implement a While-Loop over several kernels

```cpp
int n=0;
while(n!=1)
{
    n=0;
    K1.execute();
    if (K2.execute()==0) n++;
}
```

4.3.5. Nested-While-Loop

Sometimes loops may be nested, this situation is also easy to implement.

Listing 4.9: C++ Program to Implement a Nested-While-Loop

```cpp
int n=0;
while(n!=2)
{
    n=0;
    if (K1.loop()==1) n++;
    if (K2.loop()==1) n++;
}
```

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5. Ray Tracing on GPU

5.1. Choosing the Acceleration Structure

The uniform grid is the easiest spatial data structure to implement on current generation GPUs, because there is minimal data access when traversing it and traversal is linear. In a uniform grid the scene is uniformly divided into voxels and those voxels containing triangles or part of a triangle obtain a reference to this triangle.
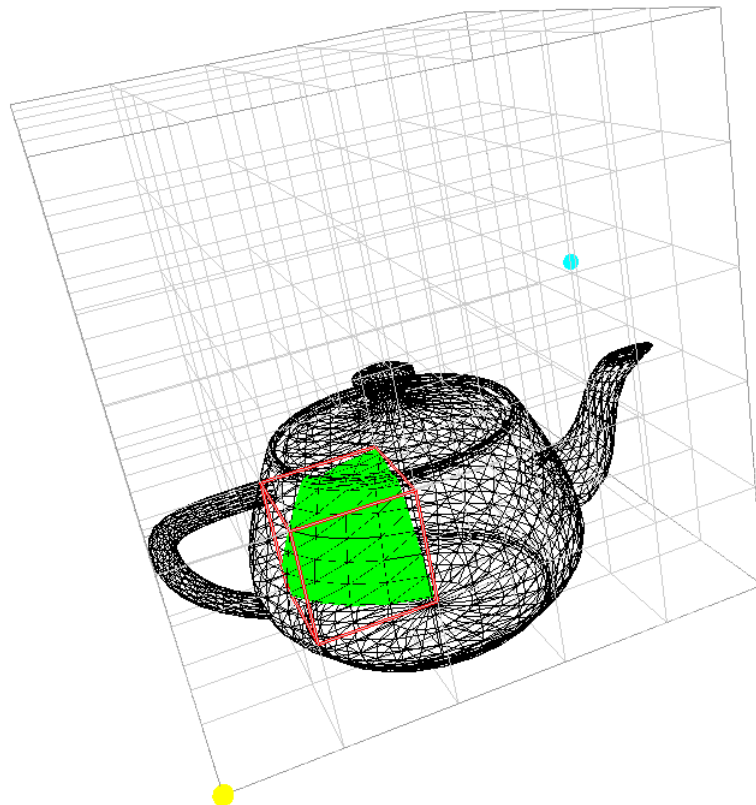

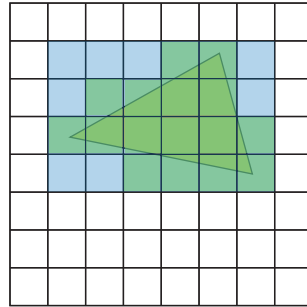Figure 5.1.: Spatial Data Structure: Uniform Grid

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Figure 5.2.: In the uniform grid, the triangle is referenced in every cell containing a part of the triangle

5.1.1. Creating the Uniform Grid

A simple approach can be used to create the uniform grid.
For all triangles T_i in the scene:

1. Calculate the bounding cells (b_1, b_2) of Triangle T_i

2. Test triangle-box intersection: T_i with every cell $C_j \in (b_1, b_2)$

3. If triangle-box intersection returned true, add a reference of T_i to C_j.
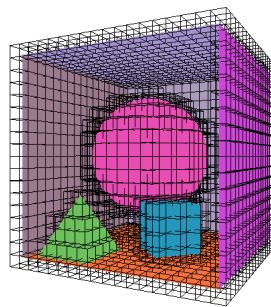
Figure 5.3.: Scene Converted to Uniform Grid

The uniform grid is generated on CPU and stored in textures. This restricts the current implementation rendering static scenes only. We will learn more about storing data in textures in section 5.3.

5.1.2. Traversing the Uniform Grid

John Amanatides and Andrew Woo[1] presented a way to traverse the grid fast using a 3D-DDA (digital differential) algorithm. With slight modifications, this algorithm can be mapped to the GPU.

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Figure 5.4.: Traversing Uniform Grid using a 3D-DDA Algorithm

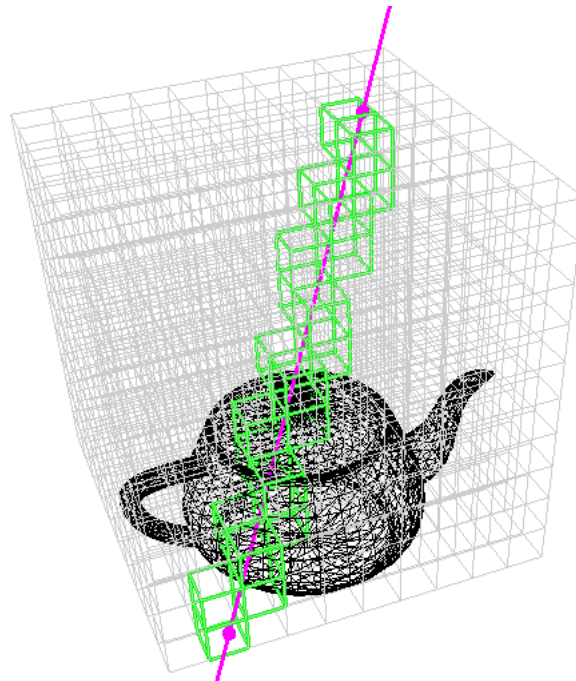Because it is a very important algorithm for this approach of the ray tracer, it is explained in detail, including full source code (which is missing in the original paper of Amanatides/Woo).

The algorithm consists of two steps: initialization and incremental traversal.

Initialization

During the initialization the voxel-position of the origin of the ray is calculated. This can be done with the function "world2voxel" which transforms world coordinates (x, y, z) to voxel coordinates (i, j, k).

```
vec3 world2voxel(vec3 world)
{
    vec3 ijk = (world − g1) / _len; // component−wise division
    ijk = INTEGER(ijk);
    return ijk;
}
```

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$g1$	Start point (in world coordinates) of the grid.
$\_len$	Vector containing voxel size in x,y, and z direction.
$curpos$	Current position on ray (world coordinates).
$\_r$	Size of grid (r, r, r).
$raydir$	Direction of the ray.
$voxel$	Current voxel position.

Next step is to calculate the positions at which the ray crosses the voxel boundaries in x-, y-, and z-direction. The positions are stored in variables $tMaxX$, $tMaxY$, and $tMaxZ$.

```
// transform voxel coordinates to world coordinates
float voxel2worldX(float x) { return x * _len.x + g1.x; }
float voxel2worldY(float y) { return y * _len.y + g1.y; }
float voxel2worldZ(float z) { return z * _len.z + g1.z; }

if (raydir.x < 0.0) tMax.x=(voxel2worldX(voxel.x) - curpos.x) / raydir.x;
if (raydir.x > 0.0) tMax.x=(voxel2worldX((voxel.x+1.0)) - curpos.x) / raydir.x;
if (raydir.y < 0.0) tMax.y=(voxel2worldY(voxel.y) - curpos.y) / raydir.y;
if (raydir.y > 0.0) tMax.y=(voxel2worldY((voxel.y+1.0)) - curpos.y) / raydir.y;
if (raydir.z < 0.0) tMax.z=(voxel2worldZ(voxel.z) - curpos.z) / raydir.z;
if (raydir.z > 0.0) tMax.z=(voxel2worldZ((voxel.z+1.0)) - curpos.z) / raydir.z;
```

Incremental Traversal

$tDeltaX$, $tDeltaY$, $tDeltaZ$ indicate how far along the ray must move to equal the corresponding length (in x,y,z direction) of the voxel (length stored in $\_len$).

Another set of variables to calculate are $stepX$, $stepY$, $stepZ$ which are either -1 or 1 depending whether the voxel in direction of the ray is incremented or decremented. To reduce the number of instructions, it is possible to define variables $outX$, $outY$, $outZ$ that specifiy the first value that is outside the grid, if negative -1 or if positive $\_r$.[1]

```
stepX = 1.0; stepY = 1.0; stepZ = 1.0;
outX = _r; outY = _r; outZ = _r;
if (raydir.x <  0.0) {stepX = -1.0; outX = -1.0;}
if (raydir.y <  0.0) {stepY = -1.0; outY = -1.0;}
if (raydir.z <  0.0) {stepZ = -1.0; outZ = -1.0;}
```

Now the actual traversal can start. It is looped until a voxel with non-empty "Voxel Index" is found or if traversal falls out of the grid.

```
bool c1 = bool(tMax.x < tMax.y);
```

---

[1]The original proposal of the voxel traversal algorithm calculates these values during initialization. Becacause of the limited storage capacity of the GPU version, it is calculated during traversal.

```
bool c2 = bool(tMax.x < tMax.z);
bool c3 = bool(tMax.y < tMax.z);

if (c1 && c2)
{
  voxel.x += stepX;
  if (voxel.x==outX) voxel.w=-30.0; // out of voxel space
  tMax.x += tDelta.x;
}
else if (((c1 && !c2) || (!c1 && !c3 )))
{
  voxel.z += stepZ;
  if (voxel.z==outZ) voxel.w=-30.0; // out of voxel space
  tMax.z += tDelta.z;
}
else if (!c1 && c3)
{
  voxel.y += stepY;
  if (voxel.y==outY) voxel.w=-30.0; // out of voxel space
  tMax.y += tDelta.y;
}

//check if (voxel.x, voxel.y, voxel.z) contains data
test(voxel);
```

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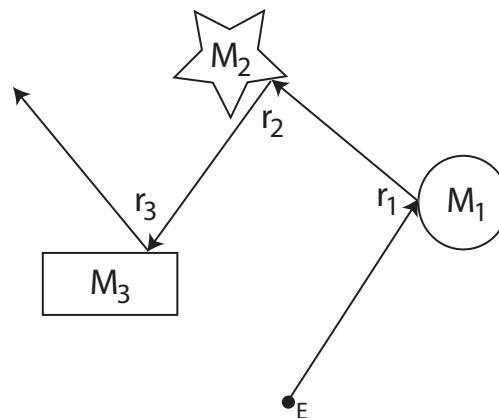## 5.2. Removing Recursion

5.2.1. Reflection

Figure 5.5.: Ray Path

The equation to calculate the color at iteration i can be obtained by simply removing the recursion: calculate the color for 1 ray, then for 2 rays, then for 3 rays and so on, and then prove the result with complete induction. The result for n iterations is:

$$c(n) = \sum_{j=1}^{n} M_j (\prod_{i=1}^{j-1} r_i)(1 - r_j) \tag{5.1}$$

r_i	Reflection coefficient of material i
M_i	Color of material i
n	Maximal number of iterations

Table 5.1.: Variables

Equation 5.1 is very easy to implement, fast to calculate, and not very memory intense.

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$R = 1,\ color = (0,0,0)$		$color = color + R \cdot M_1$	Iteration 1
	$R = R \cdot r_1$	$color = color - R \cdot M_1$	
		$color = color + R \cdot M_2$	Iteration 2
	$R = R \cdot r_2$	$color = color - R \cdot M_2$	
	...	...	
		$color = color + R \cdot M_n$	Iteration n
	$R = R \cdot r_n$	$color = color - R \cdot M_n$	

"Iteration buffer R" can be stored as a float and the color as a 3-component-float vector. Memory requirement is invariant over the total number of iterations: if floats are stored as 32 bit, only 128 bit memory is required (per pixel) to store the total result of all iterations.

5.2.2. Refraction

It would be possible to add support to transmissive rays in a similar way like reflection. The problem is for every transmissive ray, there could also be a reflective ray. One simple approach would be to add a new ray-texture for every transmissive object in the scene: Every ray would follow a different path which means to add a new texture per object. But this would be very memory intensive and would require too many additional passes. To keep the GPU based Ray Tracer simple, transmissive rays are not used.

Adding refraction on the CPU would be an easy task since we can add new rays anytime and are not limited to predefined memory.

5.3. Storing the 3D Scene

The whole scene, stored in a uniform grid structure, has to be mapped to texture memory. The layout is similar to that of Purcell et al. [12]. Each cell in the Voxel Index structure contains a pointer to an element list. The element list points to the actual element data, the triangles. As stated in 2.1, for optimal performance the ray tracer should only use triangles as element data, but it would be possible to support other shapes like perfect spheres here, for example a real time ray tracing game using a lot of spheres, but for now, only triangles are used.

The approch presented here uses 2D textures to store the scene. Voxel Index and Grid Element are 32 bit floating point textures with 1 color component, Element Data is a 32 bit floating point texture with 4 components. Element data has to be aligned, so access in a 2D texture is optimal, one triangle must always be on the same "line" in the 2D texture.

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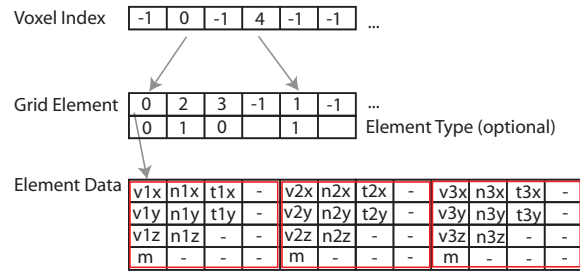
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Figure 5.6.: Storing the uniform grid structure in textures

For bigger scenes, it would be possible to split the scene uniformly and store it in different textures. NVidia based GPUs support a 32 bit (s23e8), single precision floating point format that is very close to the IEEE 754[2] standard. Theoretically it would be possible to address 2^{24}, over 16 million triangles, in a scene, but current generation consumer graphics hardware has limited memory of 256 MB[3], so the maximum number of triangles would be around 1 million triangles.
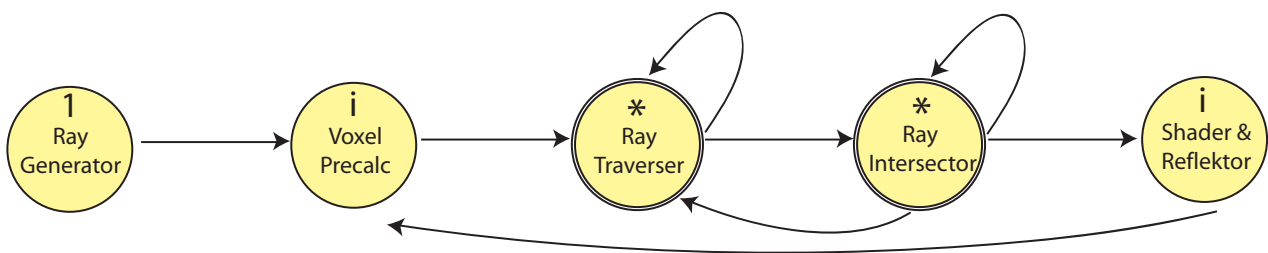
5.4. Kernels for Ray Tracing

Figure 5.7.: Kernel Sequence Diagram of the Simple Ray Tracer

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[2]http://grouper.ieee.org/groups/754/
[3]Some models already have 512 MB graphics memory, but are still a rarity.

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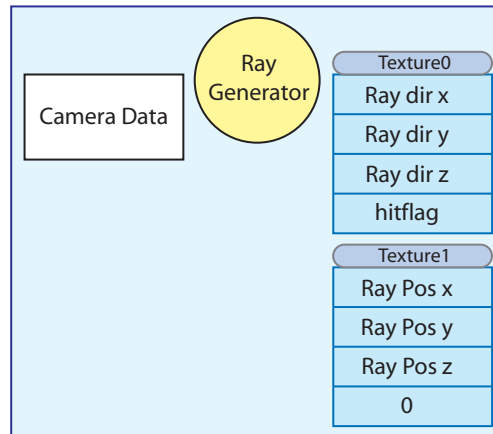Abteilung

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5.4.1. Primary Ray Generator

Figure 5.8.: Primary Ray Generator

The primary ray generator receives camera data and generates rays for each pixel. Rays are tested for intersection and if the bounding box of the grid is not hit, the rays are rejected. If the bounding box is hit, the start point of the ray is set to the hit point.
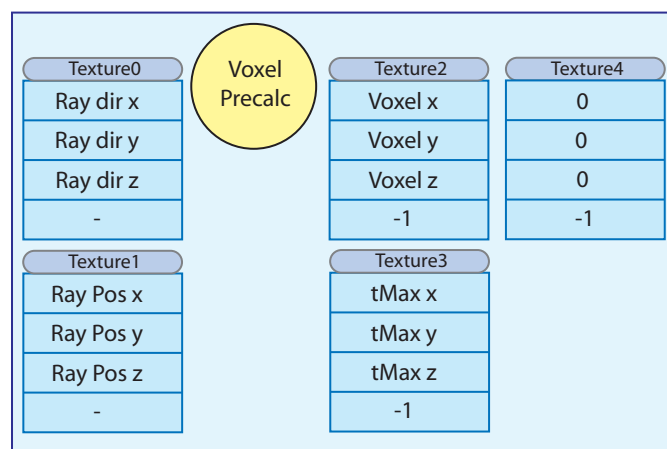
5.4.2. Voxel Precalculation

Figure 5.9.: Voxel Precalculation

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The voxel precalculation kernel takes a ray as input and calculates the starting voxel (in voxel coordinates) and $tMax$, which was described in 5.1.2.
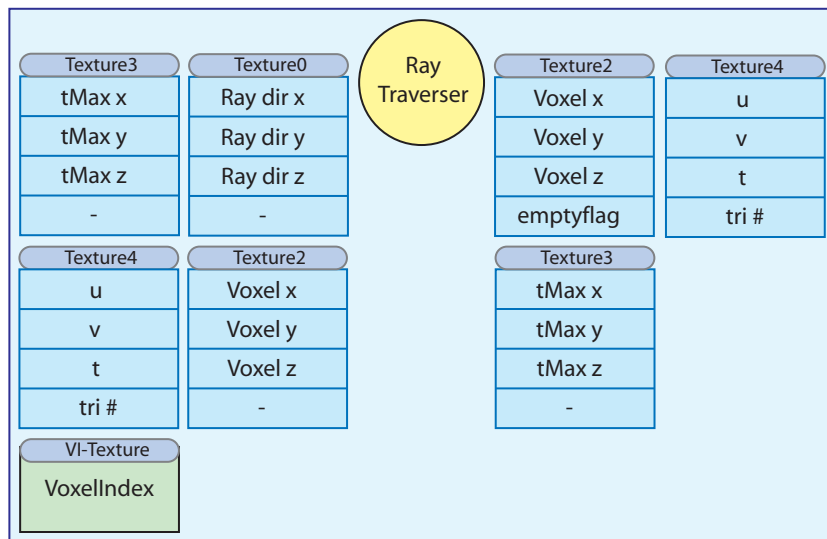
5.4.3. Ray Traverser

Figure 5.10.: Ray Traverser

The traverser checks if the current voxel contains elements (triangles). If triangles are found, the ray is set to a "wait-state", those triangles are ready to be checked for intersection, but during ray traversal there is nothing more to do, they are rejected for further traversal operations. If current voxel is empty, next voxel will be calculated using a GPU port of the voxel traversal algorithm presented by John Amanatides and Andrew Woo[1]. The information if triangles are in voxels, is stored in the "Voxel Index" texture. A value of -1 means there are no triangles to check, otherwise it contains a value pointing to a "Grid Element" Texture, containing the list of triangles for that voxel. If the end of the grid is reached, the ray is set to a "overflow-state" and is not processed anymore.

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active	traverse Grid
wait	ready to check intersections
dead	ray doesn't hit grid (was already rejected in voxel precalculation)
inactive	a valid hit point was found
overflow	traversal left voxel space (no valid hits)

Table 5.2.: ray traversing state

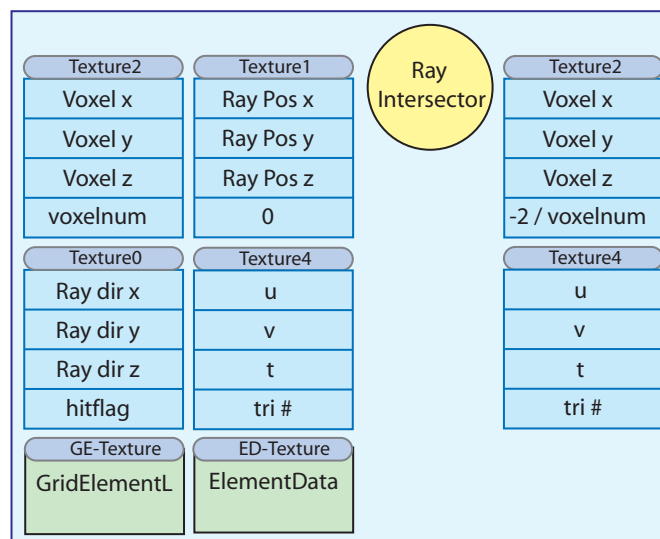### 5.4.4. Ray Intersector

Figure 5.11.: Ray Intersector

The ray intersector receives those rays previously set to "wait-state" and a current triangle number to intersect. If last triangle was processed without a hit, it sets this ray back to "active-state". If a valid hit was found the ray is set to "inactive-state".

5.5. Early-Z Culling

As mentioned in 3.1.4, current graphics cards support Early-Z optimization. The "Ray Intersector" only processes those rays that are in "wait-state". With Early-Z

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culling rays that are in different states can be masked out by adding an additional pass which sets the depth-values of those rays that don't need processing to 1.0. Same can be done for traversal: only rays that are in "active-state" require updates.

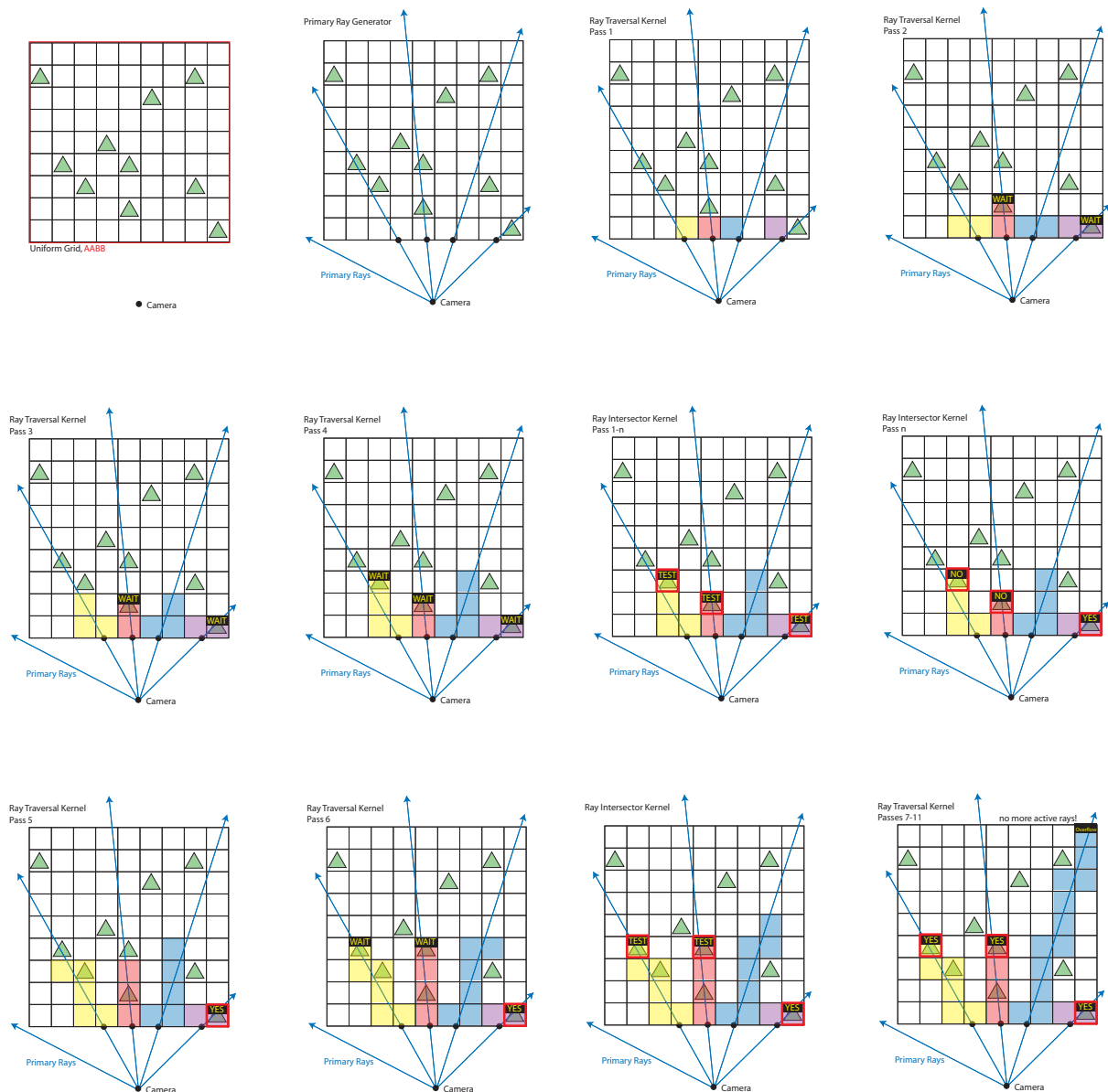## 5.6. Load Balancing Traversing and Intersection Loop

Figure 5.12.: Example Traverse/Intersection Loop

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One major problem is that both the intersector and the traverser kernel require loops and both depend from eachother. The easiest way would be to loop the traverser until no rays are in "active" state, then loop the intersector kernel until no rays are in "wait" state. This is very inefficient, because the number of kernel calls has to be minimal to prevent z-culling operations to dominate the calculations. The ray intersector should only be called if enough rays are in "wait" state and ready for intersection. And the ray traverser should only be called if enough rays are ready for traversal. Experiments show that performing intersections once 20% of the rays require intersection produce the minimal number of kernel calls[12].

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6. Results

6.1. Implementation

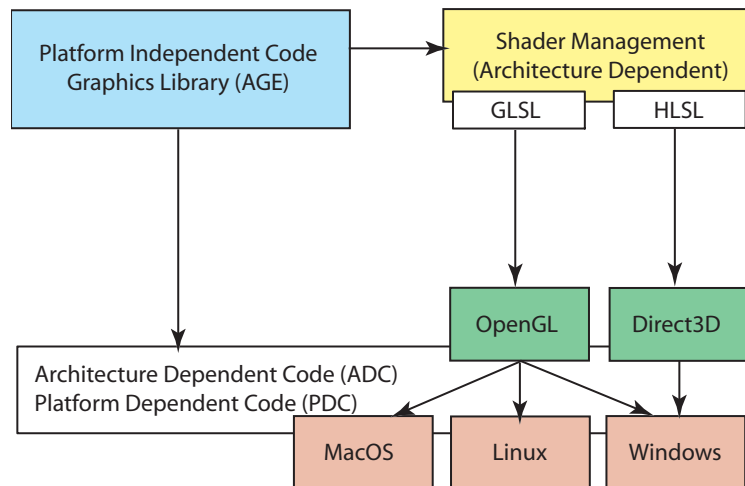The raytracer was implemented in both Direct3D (HLSL) and in OpenGL (GLSL).

Figure 6.1.: Application Model

Unfortunately, at the time of writing this, no current GLSL driver runs the ray tracer on GPUs without problems[1]. NVidia provides a tool NVemulate which allows to run GLSL programs using software emulation. The GLSL ray tracer worked fine using software emulation, so it seems to be an issue with current driver. Future driver versions will most likely fix this problem. Using NVidia Cg for the OpenGL port may have worked, but it wasn't an option since GLSL is standard of the upcoming OpenGL 2.0 release.

The HLSL version works fine on NVidia GeForce 6 based graphics cards.

It would probably be easy to port the ray tracer to ATI graphics cards, but right now – due to lack of such a card for testing and developing – the demo application only runs on NVidia GeForce 6 cards. Implementing early Z-culling is very fragile and needs a separate implementation for every graphics card.

---

[1]Tested with NVidia drivers: 66.93, 67.02, 71.24

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There are only little optimizations in the current HLSL/GLSL code, there is room for much improvement. For this first implementation, clarity was the most important factor.
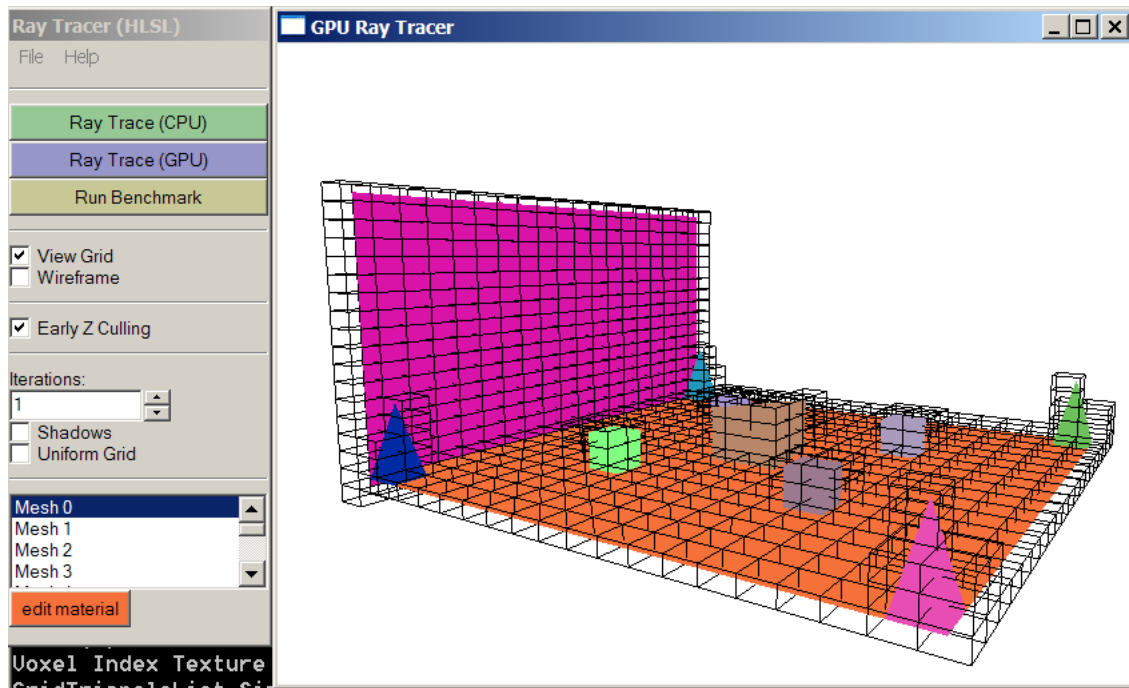

Figure 6.2.: Screenshot of the Demo Application

6.2. Benchmark

Rendering a scene can be done on both CPU and GPU. Both implementations use the same approach (uniform grid, non recursive ray tracing), which allows benchmarking, however both versions have potential for optimizations.

6.2.1. Demo Scenes

There are 3 scenes. Scene A only has a few polygons, B has low polygon objects distributed in the scene and C has high and low polygon objects distributed in the scene.

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Scene	Description	Triangles
A	3 Boxes	36
B	Cubes distributed in room	2064
C	High and low polygon objects	61562

Table 6.1.: Demo Scenes A,B, and C
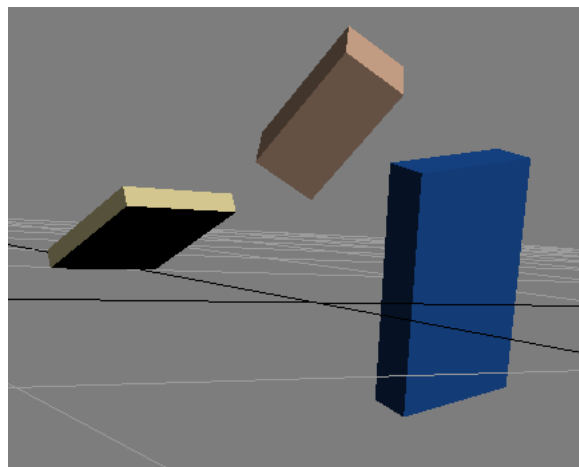
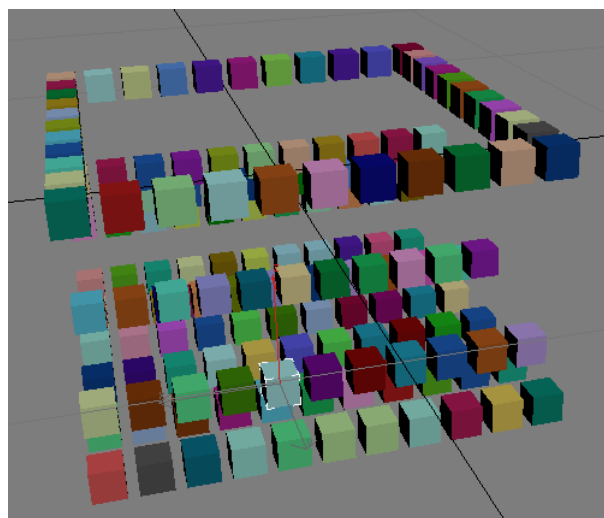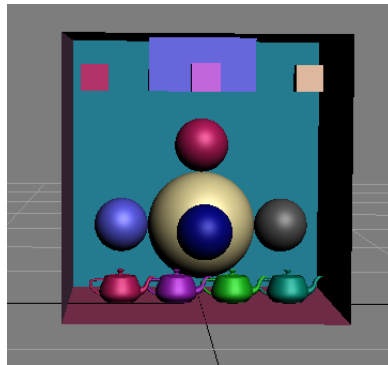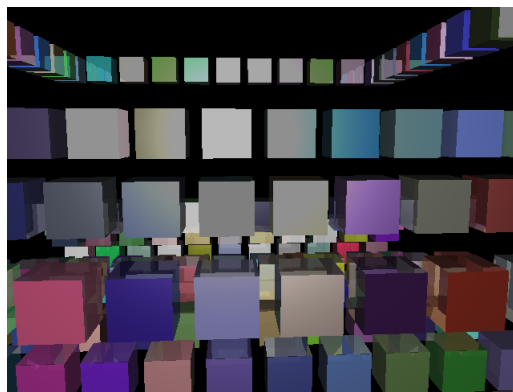Figure 6.3.: Scene A

Figure 6.4.: Scene B

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Figure 6.5.: Scene C

Figure 6.6.: Scene B - Ray Traced
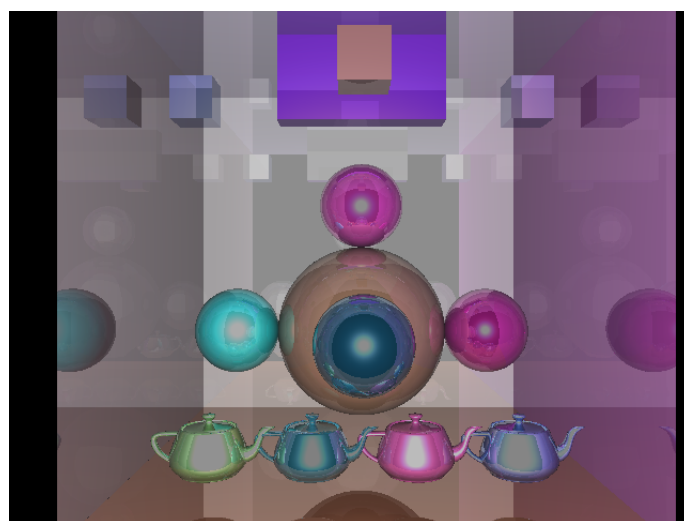
Figure 6.7.: Scene C - Ray Traced

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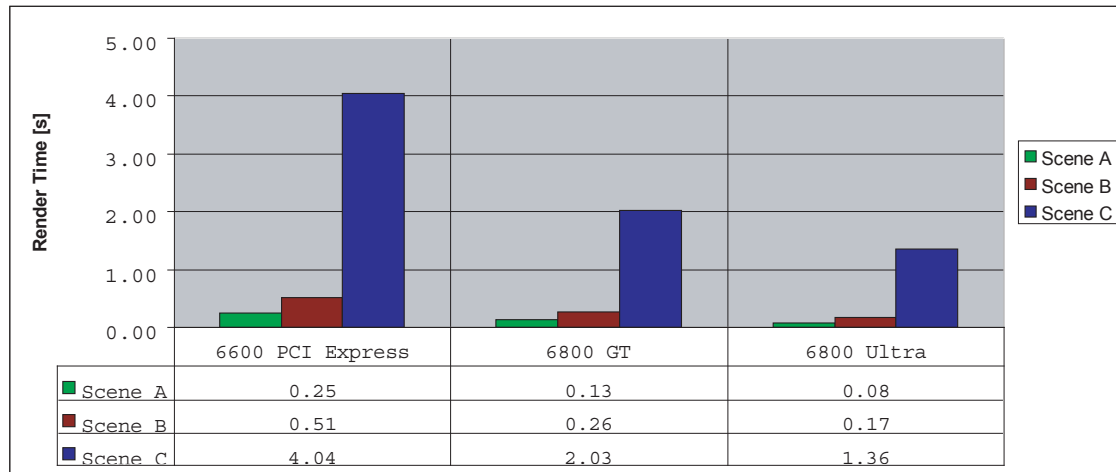
6.2.2. Result: GPU

Figure 6.8.: Render Time for Different GPUs, Grid Size: 20x20x20

	6600 PCI Express	6800 GT	6800 Ultra
Scene A	0.25	0.13	0.08
Scene B	0.51	0.26	0.17
Scene C	4.04	2.03	1.36

	2x2x2	10x10x10	20x20x20	30x30x30
Scene A	0.06	0.05	0.08	0.11

	2x2x2	10x10x10	20x20x20	30x30x30
Scene B	1.32	0.22	0.17	0.32

	2x2x2	10x10x10	20x20x20	30x30x30
Scene C	36.2	4.03	1.36	1.32

Figure 6.9.: Render Time: Different Grid Size, GeForce 6800 Ultra

All images were rendered into a 256x256 image/texture.

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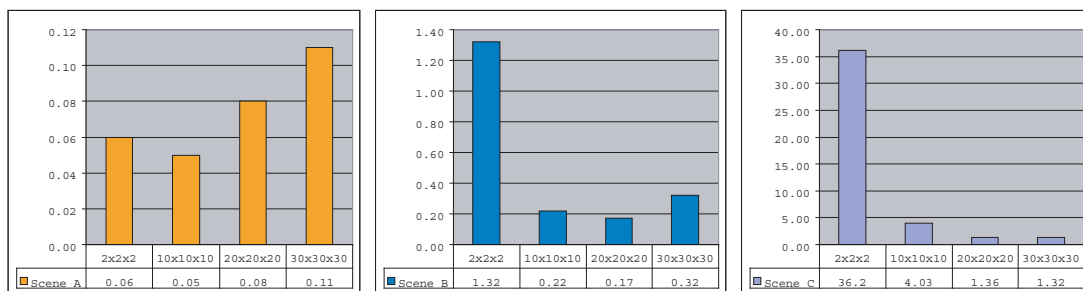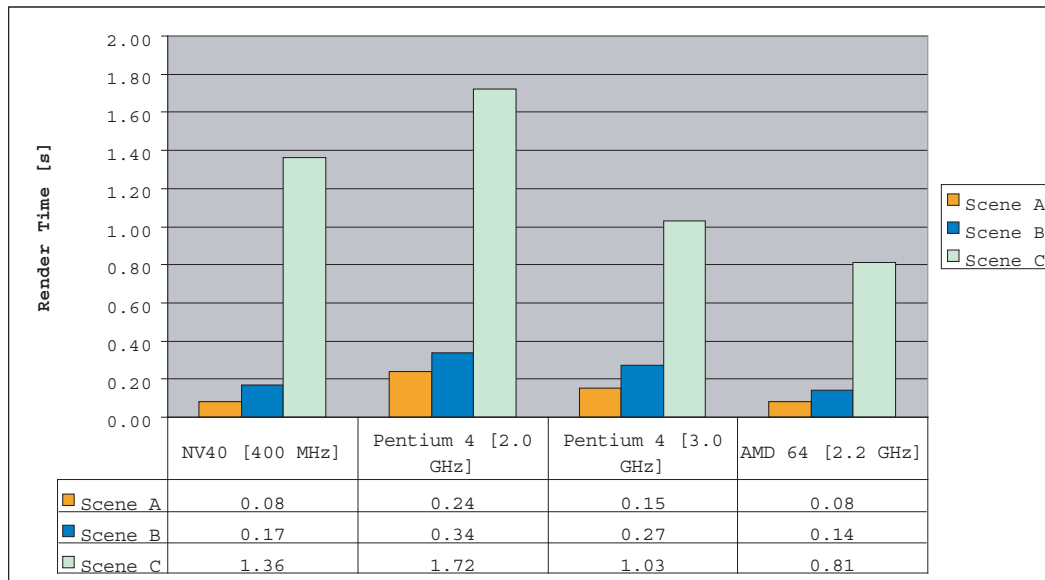Nordwestschweiz

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6.2.3. Result: GPU vs. CPU

	NV40 [400 MHz]	Pentium 4 [2.0 GHz]	Pentium 4 [3.0 GHz]	AMD 64 [2.2 GHz]
Scene A	0.08	0.24	0.15	0.08
Scene B	0.17	0.34	0.27	0.14
Scene C	1.36	1.72	1.03	0.81

Figure 6.10.: GPU vs. CPU: 1 Iteration

	Scene A: CPU	Scene A: GPU	Scene B: CPU	Scene B: GPU	Scene C: CPU	Scene C: GPU
2 Iterations	0.32	0.15	0.56	0.34	3.24	2.79
3 Iterations	0.4	0.24	0.68	0.51	4.58	4.24
5 Iterations	0.57	0.42	0.88	0.85	6.93	7.14
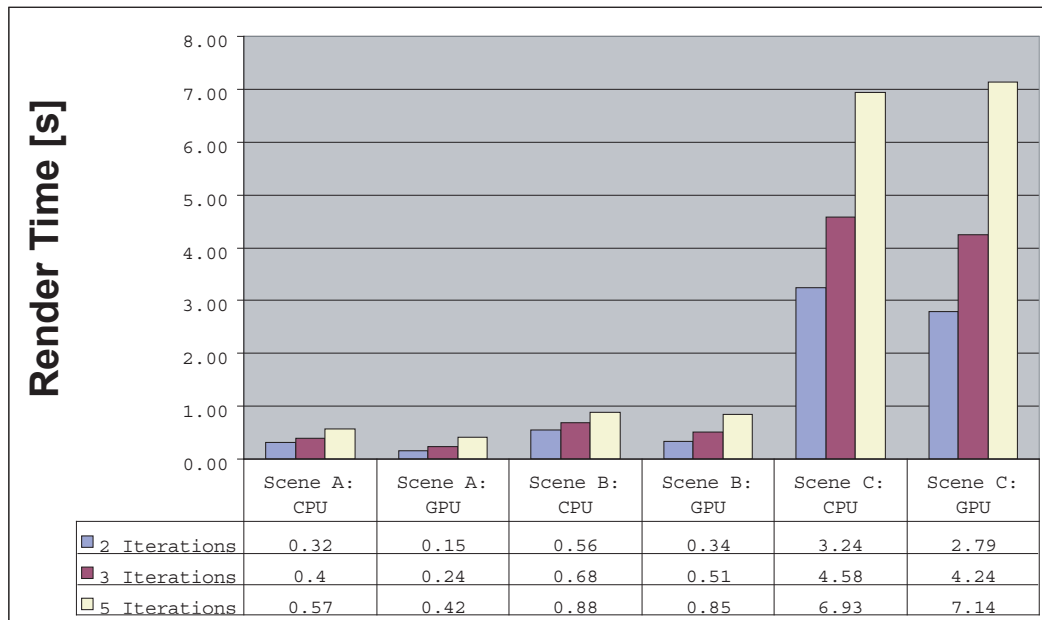
Figure 6.11.: CPU vs. GPU: Different Iterations: Pentium 4 [2.0 GHz] vs. NVidia
GeForce 6800 Ultra

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All images were rendered into a 256x256 image/texture.

6.3. Observations

A higher number iterations usually lead to a high amount of additional early-z culling passes and usually at a iteration depth of 4+ only few rays are still active. Using a high number of z-culling passes for only a few rays is very inefficent.

6.4. Possible Future Improvements

- Support for Textures, both procedural and bitmap based.

- Add transparent materials and use refraction.

- Implement GPU based Path Tracing.

- The application could be extended to support ray traced shadows in real time rendering[2].

- Animated objects - with limited polygons - could be added to the static scene using a bounding box hierarchy.

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[2]Regular triangle based real time rendering which is currenty used in computer games is meant here.

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7. Conclusion

Experiments with a lot of different scenes showed that ray tracing on GPU is feasible.

Although there is enough computing power in a GPU, Ray Tracing is not yet much faster than an equal CPU implementation. There is also a possible instability with certain hardware configurations. On Pentium based machines there are no errors when ray tracing with GPU, while on a AMD64 system there were artifacts when rendering bigger scenes.

If GPU hardware would allow multipassing as presented in 4.1 directly on hardware - without the need of a CPU / occlusion query based control - a major gain in performance would be possible.

GPUs don't have much RAM and there are hardware specific limitations when rendering high resolution meshes with a lot of textured objects.

However, if the current trend of enhancing graphics cards continues the same way like past years, future generations of GPUs will make real time ray tracing in computer games possible, provided that stability of graphics card drivers will be better.
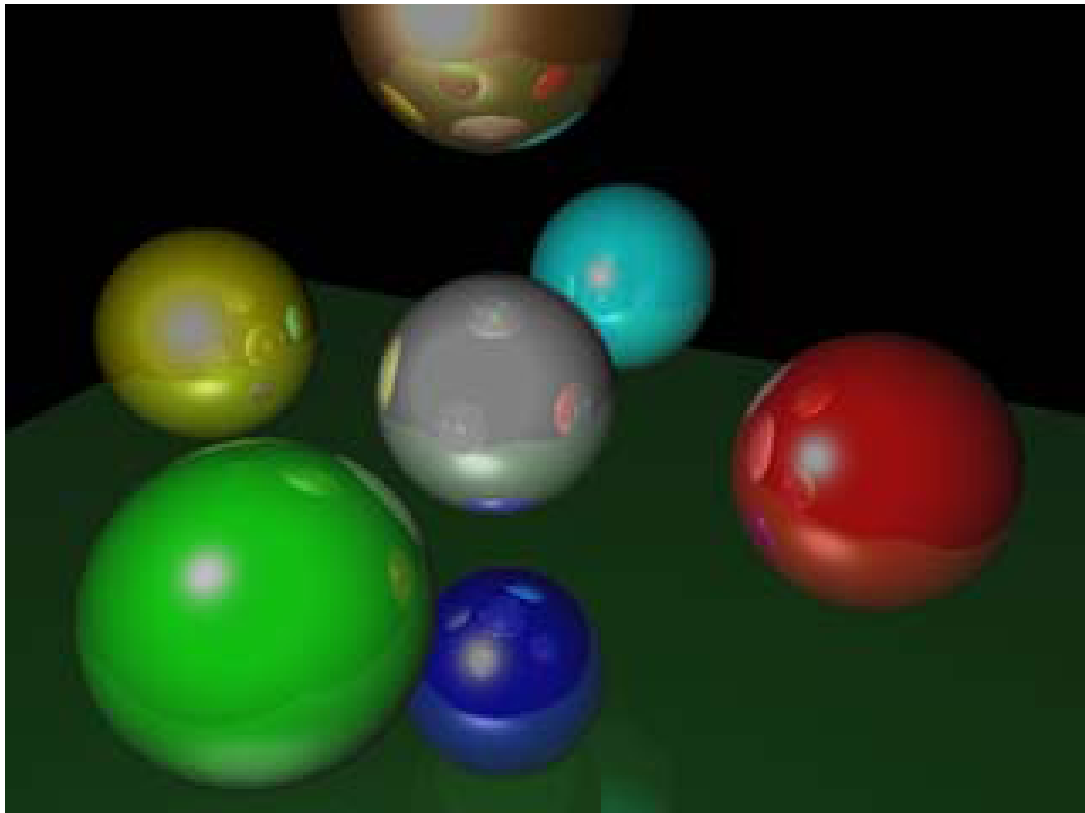
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A. Screenshots

Figure A.1.: Mesh based Spheres

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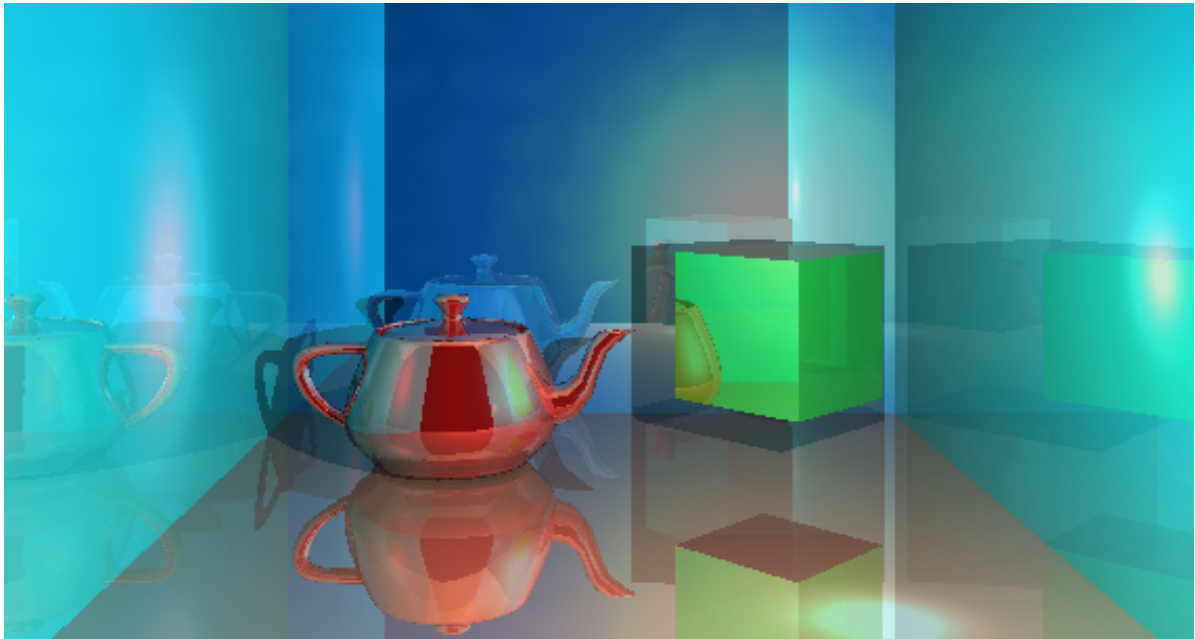
Figure A.2.: Reflect Box

Figure A.3.: Teapot (60k Triangles)

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