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Real-Time Volumetric Lighting using SVOs

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Abstract

This thesis experiments with the data structure of a sparse voxel octree (SVO) to see if it may improve the performance of empty space ray marching in volumes. While ray marching is a somewhat new technique it is used more often in traversal of volumes. It can be used for realistic volumetric effects in computer games or it can be used in the medical field when examining and visualizing MRI scans. While it has many uses it is however very computationally heavy. The usage in real-time applications is therefore limited as the hardware must be able to maintain enough frames per second to satisfy the standard. Normally one would sample the volume with a fixed sample step in order to extract the information in the volume, even if there is just empty space. The idea of a sparse octree is that it allows the ray to take greater steps past this empty space and thus only sample the actual data. This thesis will explain how to implement and use an octree when rendering smoke in a volume, and showcasing the many challenges that comes with this. The result is compared with a three dimensional texture of the same smoke.

Keywords: Sparse voxel octree, ray marching, volume, real-time, 3D texture

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Contents

Chapter 1
Introduction

Many phenomena in the real world are hard to approximate and represent using geometric surfaces. This includes, but is not limited to, clouds, smoke, fire and explosions. The appearance of these effects is caused by the cumulative light emitted, scattered and absorbed by a huge number of particles. These effects are usually approximated today with particle systems, but as these are hard to get accurate effects of without using a lot of memory and computational power, they have their limits in real-time games. Another way of simulating this is the use of volumes.

Volume rendering is represented as a uniform three dimensional array of samples, which can be pre-computed or procedurally generated. The final image is created by sampling this volume by taking steps along the viewing rays and accumulating data throughout the volume. Often these volumes are represented with simple geometry such as a cube or a sphere, making it easy to check for enter and exit boundaries. However, using volume rendering is not cheap and is something that is hard to integrate with real-time standards. One issue is that if the volume contains a lot of empty spaces one would risk the computational power of sampling nothing, when it is the actual data one is interested in. To tackle this issue we introduce a sparse voxel octree as an alternative data representation of the volume, then traverse this octree in real-time on the GPU.

1.1 Background

1.1.1 OpenGL

OpenGL is an API for interacting with a graphics card. It provides a rendering pipeline that the graphics card can use to output images on the computer. The programming language GLSL is its high level shading language that enables programming of shaders in a C-style syntax. The main idea was to give programmers more direct control over the pipeline without having to use assembly language or hardware-specific languages.

The current version of GLSL is 4.5. With version 4.3 the Shader Storage Buffer Object (SSBO) was introduced [7], making it possible to allocate memory on the GPU and to dynamically read and write to this. Normal buffers like a Uniform Buffer Object has a size limit of at least 16KB. An SSBO has at least 16MB, but usually more depending on the available GPU memory at hand. This is important for this project as we need to send in large amounts of data for our tree.

1.1.2 Compute Shaders

In the regular OpenGL pipeline one works with triangles and pixels using the vertex shader and the fragment shader together with the rasterizer, see figure 1.1. These stages all have fixed input and output variables and are dependent on one another.

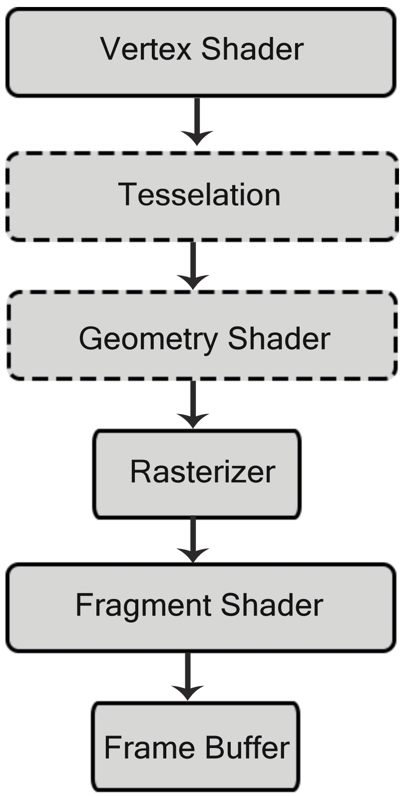


Figure 1.1: An example of the rendering pipeline. The dashed lines are optional stages.

A compute shader is a separate shader stage not used in the rendering pipeline. It is solely used for computing arbitrary information using the GPU's great parallelism. The compute shader does not have any defined input or output variables. It is up to the user to fetch and set these depending on the purpose of the shader. If a compute shader wants to take some value as input then it would have to fetch these as texture access, shader storage blocks, uniforms, images or other forms of interfaces. Likewise, to output something it must explicitly write to a shader storage block or an image.

How often a shader executes depends on what kind of shader it is. For example, vertex shaders execute once per input vertex and the fragment shaders execute on fragments generated by the rasterization stage. A compute shader does not have any pre-defined "space" it executes in, it is up to each shader to define. To define this we introduce the abstract concept of work groups.

A work group is the smallest amount of compute operations a user can execute. Any number of work groups may be executed and they are defined when invoking the compute operation, see figure 1.2. The space these groups work in is three dimensional, i.e. it has a number of X,Y and Z groups. Any of these may be set to 1, enabling a one, two or three dimensional compute depending on the application. However this merely determines how the coordinates are provided to the shader. In the end what counts is the number of invocations in the work group, that is the product of these three numbers.

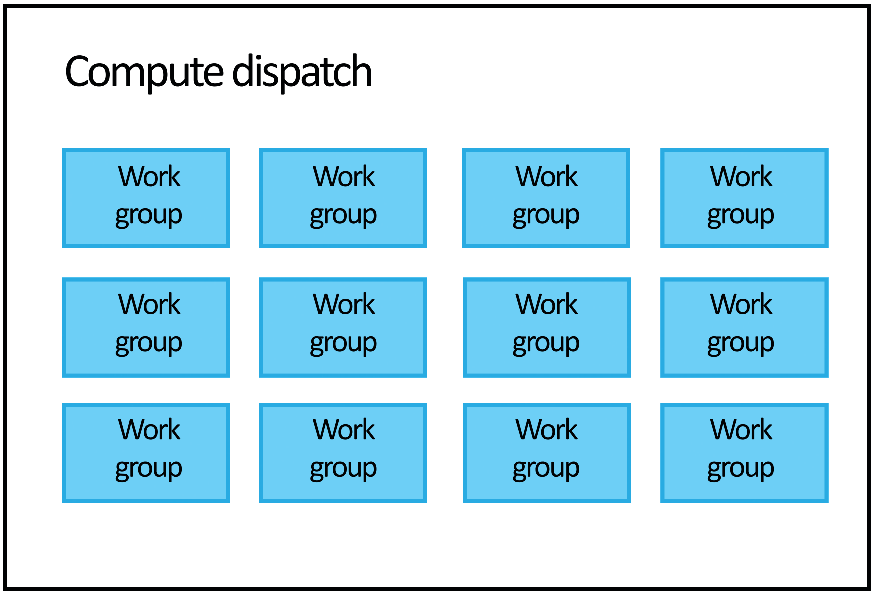


Figure 1.2: Illustration of work groups in a compute dispatch.

When computing these work groups the system can do so in any order. For example, for a given work group of (3,2,1) it could execute group (0,0,1) first, followed by (3,0,0), then jump to (2,1,2). This means that the compute shader should not rely on the order in which individual groups are processed. A single work group is not the same as a single compute shader invocation. Within a work group there may be many compute shader invocations. How many is defined by the compute shader itself and not by the call that executes it. This is the local size of the work group. If the local size is (128,1,1) and the group count is (16,8,64), this will give 1,048,576 separate shader invocations, each having a set of inputs that uniquely identifies that invocation.

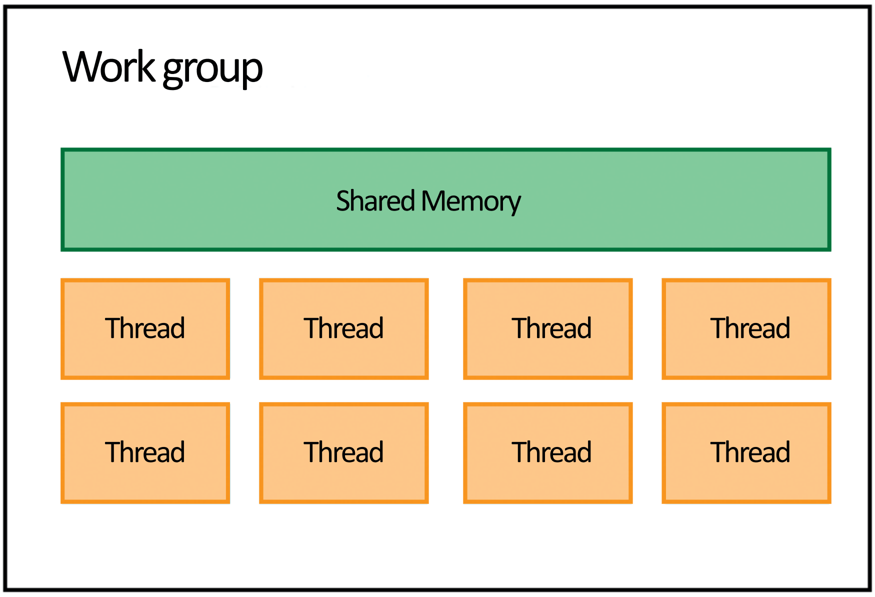


Figure 1.3: Illustration of the inside of a work group.

So within each work group we have a set of threads that run in parallel. We also have multiple work groups where each work group run independent of each other. Within each work group there is a shared memory available, see figure 1.3. Global variables in the compute shader may have the *shared* type assigned to them. This is unique for the compute shader and enables these variables to be written and read to by all the threads within the work group. However, everything in the compute shader is by default running asynchronously. There is no synchronization of the shared variables when writing and reading to and from these. It is up to the programmer to manually perform synchronization. To do this, we employ memory barriers.

By default the compute shader has access to the normal set of barriers available for shaders, such as the *memoryBarrierImage ()* or *memoryBarrierBuffer()* functions[6]. Two types of barriers are however more used within the compute shader. The *memoryBarrierShared()* command enables ordering of the shared variables. This barrier ensures that all memory transactions of shared variables between threads must be completed before proceeding beyond it. We say that all threads in a work group execute in parallel, but this does not mean that they all execute in lock-step. To ensure ordering we employ the *barrier()* function. This barrier is a bit different. As the previous barrier would synchronise the memory, it will not stop any thread from continuing executing. The *barrier()* function forces an explicit synchronization between all invocations within the work group. Execution within the work group will not continue past this barrier until all threads reach the barrier. Once past the barrier, all shared variables previously written to by the treads will be visible.

There are, however, limitations on how one can call the *barrier()* function. It is allowed to call the barrier from flow-control, but only if the flow-control is uniform. All expressions that lead to the *barrier()* must be dynamically uniform [5]. That is, if one executes the same compute shader, regardless of how different the data it fetches, every single execution must hit the exact same set of *barrier()* in the exact same order. If not, unpredicted synchronization errors may occur [4]. Consider the code snippet below. The *uniform* variable is a variable that is constant and can not change during execution.

```
if(uniform > 1.0){
    barrier();
}
```

This is ok since this condition can be evaluated at runtime, it will not change, and will pass or fail for every thread.

```
if(someVariable > 1.0){
    barrier();
}
```

May fail depending on whether *someVariable* changes during execution. It can not be guaranteed that each thread take this branch in the exact same way.

1.1.3 Ray marching

Ray marching is a three dimensional rendering technique that is often used with volumes and visualizing three dimensional data structures. Imagine an object in a space but you do not have any formula or triangles to describe it. The only thing you can find out is the distance to this object from any given point.

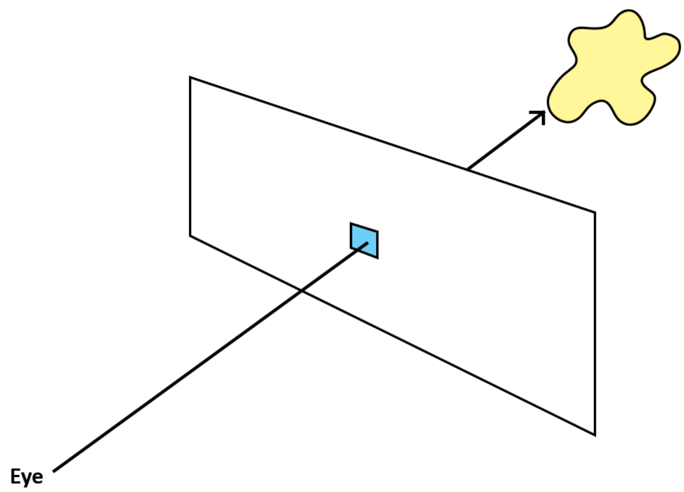


Figure 1.4: Illustration of the concept of ray casting. The blue square symbolizes a pixel on the plane. The yellow figure represents an object in our scene. For each pixel on the plane we shoot a ray and see what we hit.

The basic idea is simple. Imagine that your eye is the camera and the monitor you are looking at is the surface in some space, the image plane. For each pixel on this plane shoot a ray from you eye into the pixel and through. Find the closest object blocking the path of the ray and if it hits we can compute the color, shading or other attributes depending on the application. If it does not hit we may color it with some sky color or simply black. This is called ray casting, see figure 1.4.

There are different ways of calculating the intersection of an object. A ray tracer uses an analytical algorithm to solve for it. A ray marcher, however, uses a more approximate approach. By marching along the ray in steps, and for each step check how close we are to an object, we can create an approximate surface of this object and call it a hit. However, by taking too small steps the computation cost becomes too great and will effect the performance negatively. Likewise, taking too large steps will jeopardize the accuracy and may result in stepping over the object in question. To solve this we use distance fields.

Distance fields

Using distance fields we can enable a variable step size. By measuring the shortest distance to each object's surface in the scene for every step we take along the ray, we can make sure to only step forward that much without risking overshooting, see figure 1.5. To measure the distance to objects we use distance estimators.

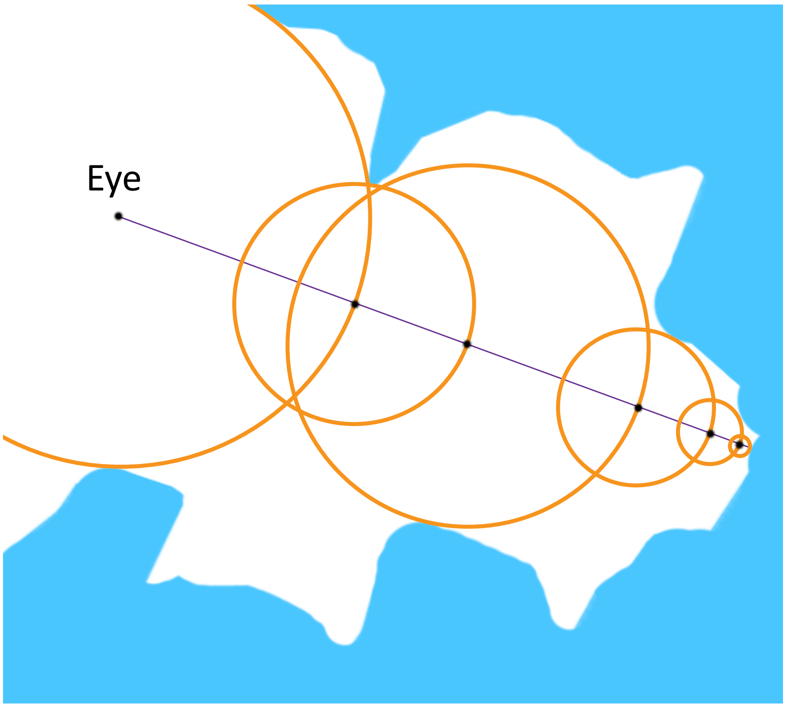


Figure 1.5: Illustration of variable step size using distance fields. The black dots represent the steps taken. The orange circles indicate the distance to the closest object, enabling a safe step length for that point. When we have reached a threshold of how close we should be, we say we hit the surface.

Distance estimators are compact functions that describe a geometric object in three dimensional space. The object could for example be a sphere, a box or a triangle. A function that gives a sphere with radius r at the origin in our scene would be:

```
float distSphere(vec3 p, float r) {
    return length(p) - r;
}
```

and a function for a box with position b is [13]:

```
float unsignedBox(vec3 p, vec3 b){
    return length(max(abs(p)-b,0.0));
}
```

These functions calculate the distance between a point p and itself. The functions can be signed or unsigned. A signed function returns the signed distance to this object. If we are inside the object we would get a negative distance. If we use an unsigned function of the same object we would still get a positive distance even if we are inside. The type of functions to use would matters when we calculate the surface normal of an object.

When the functions are used in combination of each another they are often called distance fields. Various operations can be done on these to create complex objects. For example, the union of two distance estimators is the minimum of these. The intersection is the maximum, and the complement gives the negated distance (needs to be signed). The distance estimators may be used with a repetition function, they can be rotated/translated and scaled. One can even deform functions by applying a displacement function to the original distance estimator function, creating complex figures. For example, one displacement function, where p is a point, could be:

$$sin(10 \cdot p.x) \cdot sin(20 \cdot p.y) \cdot sin(15 \cdot p.z) \tag{1.1}$$

To use it, we can apply:

```
float opDisplace( vec3 p ){
    float d1 = primitive(p);
    float d2 = displacement(p);
    return d1+d2;
}
```

where primitive is a distance estimator function.

1.1.4 Octree

Tree structures are often used to help sort and navigate through big volumes of data. They can be used to track generations of ancestors within a family or to group items with subcategories for easy overview of a company's warehouse volumes. A tree always starts with a root. This can be seen from any direction of the tree depending on the application, but usually the root node would be placed at the top of the tree. The root node has a number of children. The number is defined by the type of the tree. A binary tree would have two children per node and a quad tree would have four. These children are called siblings as they share the same parent. When a child gets children on its own, it naturally becomes parent to those children. Each node is located on a certain depth in the tree. The depth is the distance from the root to the node, the amount of steps. A node that has no children is called a leaf.

In the field of computer science the use of trees is very common. A tree can either be abstract or concrete. An abstract tree would be a tree that is not represented using any classes, often a big array ordered in a way that enables tree searches. A concrete tree would therefore be a tree that is represented with one or many classes for the nodes and structure of the tree. The tree used in this thesis is of the abstract type, but is built using a concrete class.

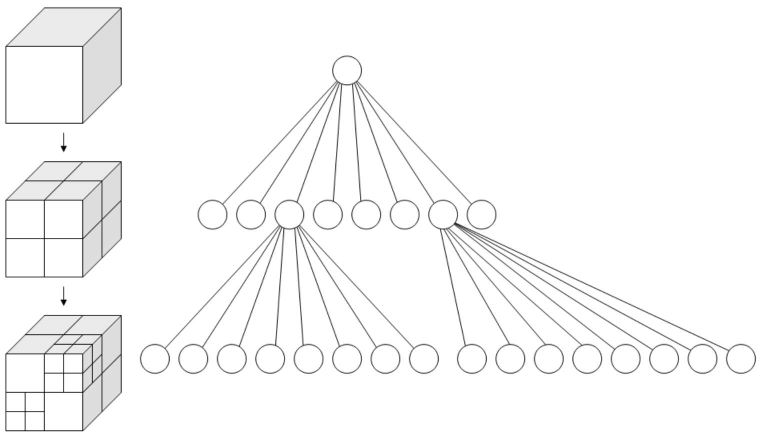


Figure 1.6: A visualization of a sparse octree where each child gets one eighth of the parent's size for each depth. Source: Wikipedia page for octree.

An octree is a tree structure where each parent invariably has eight children. The tree can be dense or sparse, see figure 1.6. If it is a dense tree then every parent at that specific depth will always have eight children, placing all the leaves at the greatest depth in the tree. This simplifies searches as we know that each depth has 8^{depth} nodes in it. The downside is that it takes up more storage space in the memory. A sparse tree is a tree where each node may not always have children. That is, a leaf may occur higher up in the tree as well at the bottom.

1.1.5 Voxels

Voxels are points of information in a regular grid in three dimensional space. They can contain whatever information that is relevant to the application, varying from, but not limited to, color, density or movement. As a pixel is a point on the screen, a voxel is a point in a volume. The size of the voxel depends on the holding cells size. In figure 1.6 each of the sub-cubes would be seen as a voxel. If the root would have no children then technically the whole root would be a voxel. Voxels typically do not hold their individual position alongside their data. Instead, their position is given by the relative position of other voxels, i.e. the position in the data structure that represents the three dimensional volume.

1.1.6 Noise

Perlin noise was developed by the American professor Ken Perlin in 1983 and it is commonly used today in the field if computer graphics when creating randomized behaviours or environments. The noise is a gradient type of noise which is most commonly implemented as a two, three or four dimensional function. Typically an implementation consists of three steps: the grid definition, computing the dot product between the distance-gradient vectors, and finally interpolation between these values.

In 2001 Ken Perlin updated his original perlin noise and came up with the algorithm for simplex noise. Simplex noise would tackle some limitations perlin noise has such as fewer directional artefacts, and in higher dimensions, computational cost. Some advantages simplex noise has over perlin noise:

- It is visually isotropic, it has no noticeable directional artefacts.
- Scales to higher dimensions (4D and 5D) with much less computational cost. The complexity is $O(n^2)$ with n dimensions compared to $O(2^n)$ for perlin.
- Overall lower computational cost as it has fewer multiplications.

In this thesis we use simplex noise to simulate smoke in our volume.

1.2 Related work

We use a sparse octree that builds on the work of Brandon Pelfrey [11] but general overview and information on how a sparse voxel octree functions and its details was found in the paper "Efficient Sparse Voxel Octrees" [10] by Samuli Laine and Tero Karras. Here they create a world which only consists of voxels and no geometry. They showcase how they order their octree structure in a minimalistic way and how they traverse this in real-time. Their aim is to store representations of large-scale scenes in the GPU memory and focuses on representing surfaces instead of volumes. To enhance the details of their images they add contour data to allow accurate surface placement within individual voxels.

In the paper "A Survey of Octree Volume Rendering Methods" [8] the author, Aaron Knoll, showcases different methods of volume rendering using octrees. He discusses the difference in direct and non-direct volume rendering. The non-direct method was used in the early days of volume rendering. Here they used the octree as a small memory footprint to extract a mesh pattern, triangles, from cells of volume. With this mesh they could render the volume as an isosurface. The direct method would be using the octree itself as the volume and integrate the rays intersection with this. While this is slow for a CPU it can be effective on a GPU by accumulating gradients across sequential cutting planes of the volume, stored as two dimensional textures. This no longer restricts the volume to be rendered as an isosurface. While it is faster on the GPU the bottleneck is the available memory on the GPU. To bypass this, he states it is necessary to store the volume outside of the GPU and page the data into the GPU's memory.

In this thesis we use the direct volume rendering method—there is no conversion of the octree data into another data type. The octree data is also constructed out-of-core, on the CPU, and is sent into GPU memory.

Amanatides and Woo [1] were the first to present the regular grid traversal algorithm, used in octree traversal, that is the basis of most derivative work, including the used Revelles algorithm. The idea is to compute the t values of the next subdivision planes along each axis and choose the smallest one in every iteration to determine what next node the ray pierces.

Knoll et al. [9] present an algorithm for ray tracing octrees containing volumetric data using different isosurface levels. It proceeds in a hierarchical fashion by first determining the order of the child nodes and then processing them recursively. This is not well suited for GPU implementation.

Crassin et al. [2] introduces a voxel rendering algorithm for the GPU that combines two traversal methods. The first stage casts rays at an octree using a kd-restart algorithm to avoid the need for a stack. The leaves of the octree are not normal leaves but instead bricks. The bricks are three dimensional grids that contain the voxel data. When a brick is reached the data is sampled. Bricks does not contain a single value but instead values of 16^3 or 32^3 voxels. This yields a lot of wasted memory if the data is not truly volumetric or fuzzy. However, three dimensional lookups supported by the hardware make the brick sampling efficient, with the bonus of the result being automatically anti-aliased. This algorithm also supports data managements between the CPU and GPU. While traversing the octree, the algorithm detects if there is data missing in the memory of the GPU. If so, the algorithm signals to the CPU that data is missing and the CPU then streams the missing data to the GPU. This feature enables that only a subset of data needs to reside in the GPU memory.

The traversal of our octree is mainly based on the paper by J. Revelles. et al. [14] with some modifications regarding the children indexes.

The noise creation is based on the works of Eliot Eshelman [3] where he describes a way of computing simplex noise in a simple fashion for both C++ and Python.

1.3 Problem and contribution

The issue we are trying to address in this thesis is an issue of optimization. When sampling volumetric data in a volume using a standard medium as the container, e.g. a three dimensional texture, one may sample huge volumes of empty space. This empty space contains no real informations describing the actual volume we want to render, therefore a waste in computational power.

To tackle this we introduce an alternative medium to hold the volumetric data—an octree. This will enable us to mark out the empty space in the volume and skip past all this when sampling. That is, we do not sample empty space, only values that represent the real volume.

1.4 Report structure

In the beginning of chapter 2 we first describe the overall layout of the implementation. We then go more into details of each key stage of the implementation. In chapter 3 we show the result of our implementation, both in numbers and visually. This is followed up by a discussion in chapter 4 and finally a conclusion is given in chapter 5.

Chapter 2
Implementation

On the GPU we implement a ray marcher engine with support for distance fields, phong shading (basic light calculations that gives highlights on objects), the octree traversal algorithm and support for using three dimensional textures. This was done with a compute shader using GLSL version 4.5.

Outside of the shader, on the CPU using C++, we first calculate the noise that is used to fill our three dimensional texture and octree. Then we go through the octree to retrieve the octree array. This array is used by the traversal algorithm, inside the compute shader, when traversing the octree in real time. The array represents a linear one dimension data structure of the three dimensional octree. This enables us to to make fast indexing when traversing. The three dimensional texture along with the array is sent to the shader and is later used when sampling the volume.

In the shader we ray march each pixel. Depending on what we hit we calculate the color for this pixel. When the color is determined we write the color to an empty texture that is bound to the shader. This texture is then sent through the regular graphics pipeline to be displayed on our screen.

The octree and the three dimensional texture are comparable as they both represent the same volume. In the case of the texture, it only holds points in a non-ordered structure, apart from the order we enter our noise. It also does not distinguish empty space from non-empty. The octree orders the smoke in a more hierarchical way utilizing the nodes position, (x, y, z), in regards to each other and will not include empty space more than saying there is nothing here.

2.1 Full screen quad

To get an image from our compute shader we have to bind our texture that comes from the shader to a buffer—a container to store the texture in memory. This buffer is called the full screen quad and can be seen as the quad where we will paint our image on. The quad is constructed using a float array containing the four corner coordinates of the screen. These coordinates are then used to create two triangles that will be used when drawing the final image, see figure 2.1.

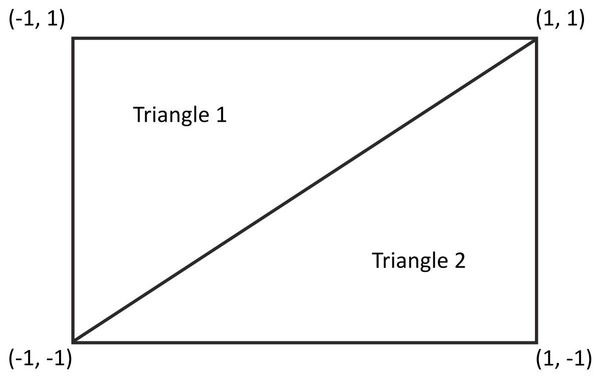


Figure 2.1: A full screen quad. The coordinates represent the OpenGL window coordinates.

For each cycle we will call the *renderScene()* function and run a compute dispatch on our compute shader. We bind an empty texture to it that is the size of our window, in this case 1024 x 768. The compute shader will ray march each pixel in the window and write the resulting color to the appropriate place in the texture. When the texture is filled we bind this to our screen buffer and proceed with showing it as a normal texture in the fragment shader using the float array as texture coordinates.

2.2 Noise

To construct our noise we loop over each dimension, x, y and z, where $x, y, x \in (0, res)$, res being the resolution of the noise. For each combination of coordinates we call the noise function:

```
float noise = scaled_octave_noise_3d(octaves,
                                     persistence,
                                     scale,
                                     lowBound,
                                     highBound,
                                     x, y, z);
```

This function takes a number of parameters and scales the final noise value from $[-1, 1]$ to $[lowBound, highBound]$. For each iteration in the noise function a higher frequency and lower amplitude function will be added to the original base function. The persistence, $[0, 1]$, sets how much of the last octave will be added. A higher persistence will include more from each octave. Scale sets the frequency of the noise.

In this thesis we use the parameters *scaled_octave_noise_3d(8, 1, 0.0015, -70, 400, x, y, z)* . The reason why we scale it past the max value of 255 and below 0 for colors is simply to spread out the noise, making more empty space in our smoke. In addition, we do not include noise values below 255 either. This is because we want even more space, but also because higher resolutions of noise would reach the max amount of memory the application could use when creating the octree. The project was conducted using Visual Studio Ultimate 2013 and by default every project was set to run in 32-bit mode. Enabling long addresses in the application will however increase the available memory to about 4GB. If the project would have been built in a 64-bit environment the memory issue would not be as much of a limit.

2.3 Constructing the octree

The octree is implemented with help of two classes. The *octree* class is the main class containing tree operations such as inserting and initialisation of the tree. The other class is the *octreePoint* class which is a simple class that represents a point in the tree. This class has attributes for holding the noise value and its own position and also retrieving this position. The *octree* class holds information about its center, its half dimension, children and an octree point. The half dimension parameter is the distance from the origin and outwards of the current node. For example, setting the root's origin to 0 and its half dimension to (2, 2, 2) would yield a root node spanning from (-2, -2, -2) to (2, 2, 2) with a size of 4^3.

To create a tree we first invoke the tree class' constructor, setting the origin of the tree, its half dimension and setting all the children and its octree point equal to null. The children follow a simple pattern in which the nodes are placed. Plus means that the position in that dimension is greater than the origin of this node, minus indicates less than. A visual representation can be seen in figure 2.2. For each noise value we generate we insert it into our tree as a node.

```
Child:  0 1 2 3 4 5 6 7
x:      - - - - + + + +
y:      - - + + - - + +
z:      - + - + - + - +
```

When inserting a new node in the tree we must first consider three cases:

1. The node is an interior node, it has eight children.
As parents never store data themselves we find out where in its eight children this new node would be positioned and make a recursive call to insert into that child's position.

2. The node is a leaf, it has no children and its data is equal to null.
We are in a region where there is no data, store the noise data here.

3. The node is a leaf but its data is not null.
Save the current node temporarily, split the current node into eight children and insert the temporary and the new node into the new children. This may happen several times if the points tend to lay close to each other.

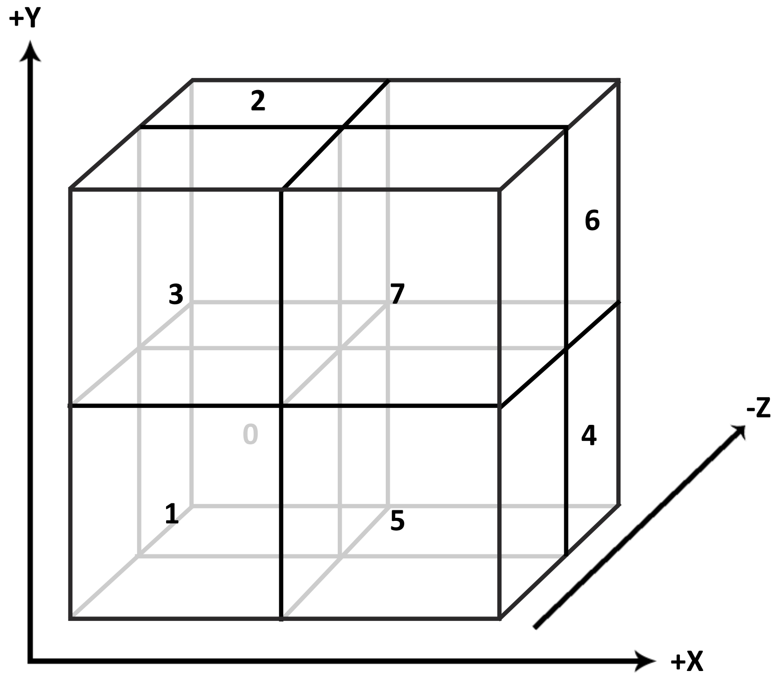


Figure 2.2: Child order in the octree.

To calculate at what index position in the children the new node would go, we use a bitwise OR operation. Given the new node's coordinates we check each dimension against the origin of the current node in regards to the layout pattern given above:

```
int oct = 0;
if (point.x >= origin.x) oct |= 4;
if (point.y >= origin.y) oct |= 2;
if (point.z >= origin.z) oct |= 1;
return oct;
```

A pseudo code of the octree creation algorithm can be seen in algorithm 1.

```
Initialize tree;
input : An octree point
while has input do
    if isLeafeNode then
        if data == NULL then
            data ← point;
        else
            /* We are at a leaf but there is already data
               here, split the node and insert recursively.
               */
            oldPoint ← data;
            data ← NULL;
            for i ← 0 to 8 do
                newOrigin ← origin;
                newOrigin.xyz ← calculate new dimensions;
                children[i] ← new octree(newOrigin, halfDimension · 0.5f);
            end
            /* Re-insert old and new point.                    */
            children[getOctantContainingPoint(oldPoint)] → insert(oldPoint);
            children[getOctantContainingPoint(point)] → insert(point);
        end
    else
        children[getOctantContainingPoint(point)] → insert(point);
    end
end
```

Algorithm 1: Octree creation.

2.3.1 The octree array

When the tree is built we need to construct our array so we can send this to our compute shader. To do this, we traverse our tree, starting at the node in a depth-first fashion. The array will not include the root, the first level of the volume, as this is redundant. Each parent will have eight slots in the array. A parent whose any of its children have data in them, either as a leaf or another parent, is given a positive number that is the index in the array where the start of its eight children is. Leafs have negative numbers and empty space is represented as a zero. An array constructed with a low resolution noise can be seen in figure 2.3.

When invoking the function we suffice it with an empty array of the type *vector*, that will become the octree's array. We start at the root, first checking so that its child at index zero is not NULL. If so, we push the root value and return the list. If not, we begin our decent. First we count this node's active children, which can be either leaves or other parents, and keep track of what index they have. As a vector array does not have a variable size it is necessary to change its size as the number of values grows. We resize our vector by plus eight and iterates over the active children. If this child is a leaf, we extract its noise value and insert it in the array at the right index. If not, we set this index in the array to point eight steps ahead and recursively go through this parent's children by calling the same function. A pseudo-code of the algorithm can be seen in algorithm 2.

```
----------
index 16 value 24
index 17 value 88
index 18 value 128
index 19 value 200
index 20 value 248
index 21 value 312
index 22 value 376
index 23 value 440
----------
index 24 value 32
index 25 value -225
index 26 value 40
index 27 value 48
index 28 value 56
index 29 value 64
index 30 value 72
index 31 value 80
----------
index 32 value 0
index 33 value 0
index 34 value 0
index 35 value 0
index 36 value 0
index 37 value 0
index 38 value -236
index 39 value -233
----------
```

Figure 2.3: Showcasing a portion of the array when a noise resolution of 32 is used. Between two lines lies the eight children to the parent who is pointing to the start of this set. Negative values represent a leaf, positive values are pointers from the parent to its first child. A value of zero indicates empty space.

```
input  : int localIndex, int& treeIndex, vector<int>& treeResults
output: A filled treeResults array
Initialize: localIndex ← 0, treeIndex ← 0;

localIndex ← treeIndex;
if children[0] == NULL then
    push-back value and return;
end
create activeChildren array;
for k ← 0 to 8 do
    if children[k] is active then
        activeChildren ← k;
    end
end
resize treeResult by 8;
for i ← 0 to activeChildren.size() do
    childIndex ← activeChildren[i];
    if children[childIndex] is a leaf then
        treeResult[localIndex + childIndex] ← value of leaf;
    else
        treeIndex ← treeIndex +8;
        treeResults[localIndex + childIndex] ← treeIndex;
        children[childIndex] → getArray(localIndex, treeIndex, treeResults);
    end
end
```

Algorithm 2: Array retrieval algorithm.

2.4 Ray marching

To be able to ray march we first need to define our ray:

$$r(t) = (x_o, y_o, z_o) + (x_d, y_d, z_d) \cdot t \tag{2.1}$$

or in short:

$$r(t) = o + d \cdot t \tag{2.2}$$

where o is the origin of the ray, our camera, and d is the direction of the ray. t is a scalar used to step along the ray. A positive t moves us towards the scene while a negative would move us behind the camera. For ray marching one often sets a constant maximum amount of steps to take before considering this ray to not have hit anything. If the maximum number of steps are too low it might result in artefacts between objects. If it is too high the computational cost would be too great, risking losing frames per second. In this thesis we define a variable called *MAXSTEPS* that tells us how many steps are allowed to be taken on the ray. This variable is calculated from the volume's size and the length of the steps we take in the volume. The code below shows the calculations made to compute the *MAXSTEPS* variable. *volumeStepSize* is the step length we take in the volume when sampling. *h1* is the hypotenuse of the bottom plane in the volume. *maxSteps* is the diagonal in the volume. The multiplication of 3.2 is just to increase the amount of steps a bit further to eliminate artefacts.

```
const float volumeStepSize = 0.1;
float volumeScale = VOLUMESIZE / volumeStepSize;
float h1 = sqrt(volumeScale * volumeScale + volumeScale * volumeScale);
int maxSteps = int(sqrt(h1*h1 + volumeScale * volumeScale)*3.2);
#define MAXSTEPS maxSteps
```

As we fire our ray from our camera through our imaginary plane and into the scene, for each point we measure the distance between two objects. The first object is the volume, represented as a cube. The second is the platform beneath the cube, represented as a flattened cube. The shortest of these distances is denoted $dist$. To check if we hit an object we check $dist$ against a threshold called *EPSILON*. This threshold has the value of 0.0005 and indicated that we have to march along the ray until be are below this to ensure a hit. As we are running a variable step size we multiply this *EPSILON* by the scalar t. If we are not within the threshold we increase t by $dist$. If we hit the platform beneath we apply a simple phong shader to it that interacts with our movable light source in the scene.

If we are running the three dimensional texture and we hit the volume we stop using a variable step size and instead sample at a constant step size of 0.1. If this value is too great we might risk oversampling the texture which from some angles will give visual artefacts. If the value is too low we might risk sampling the same thing multiple times, with an increase in computational power. If we are running the octree we instead invoke the traversal algorithm. This enables us to skip the empty space and only sample the actual data, see figure 2.4 for the difference in the two data types.

2.4.1 Traversing the octree

The octree is traversed using a loop and a stack. On the stack we save, for each node we enter, parameters for entry and exit points in all dimensions, the current node we are standing in varying from 0 to 7, the node index we are standing in in the tree array and the length dimensions. The stack is ordered as an array where each of the named variables are grouped as a struct. The struct is accessed with a stack pointer, telling us where in the array we are. In the loop we check which child index we are piercing and enters that node's sub-tree. When so the stack pointer increases by 1. If we hit or exit a node the stack pointer gets subtracted by 1. The loop is continued as long as we are not leaving the stack, checking if the stack pointer is < 0.

When hitting the volume with the octree enabled we first initiate the entry and exit variables used by the algorithm. These are based on the origin and direction of the ray. The algorithm only works for positive ray direction. If we encounter a negative ray in any dimension we invert its direction and position in that dimension. We also set one of three variables a, $a2$ or $a4$ to either 1, 2 or 4 depending on if it was the z, y or x direction that was inverted. These will be used to modify the child index to enter as the algorithm assumes a child order in the tree that is mirrored in the z-axis in regard to the order of the built tree. If a ray direction is equal to 0 we substitute this by 0.00001 to eliminate division by zero.

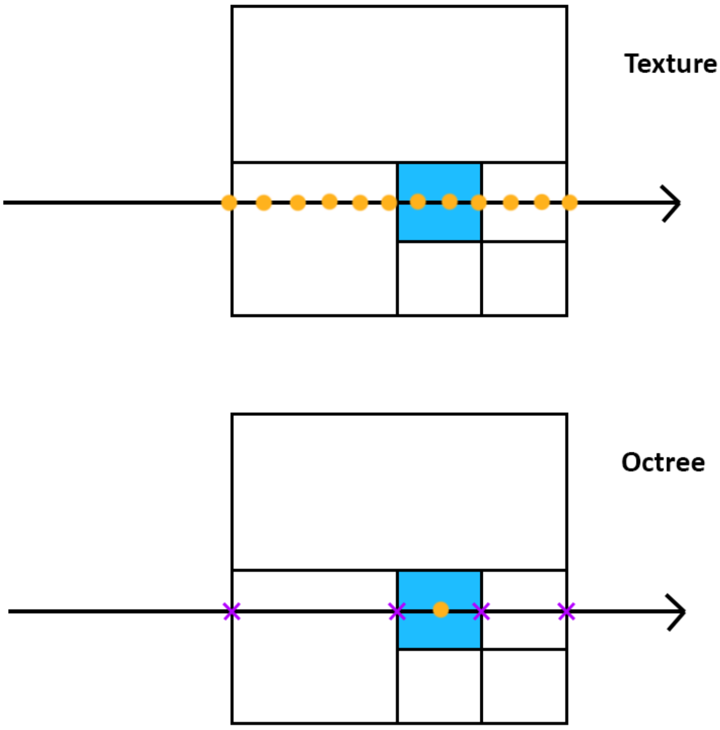


Figure 2.4: Difference of how the two data structures are sampled. The orange dots are the sampling points, the purple crosses are operations in the octree. In the texture we take small steps throughout the volume, even if we hit empty space—the white areas. In the octree we instead see that this area is empty and thus skip this region and only sample the valid data, the noise—the blue region.

To initiate the values of the root node we calculate the entry and exit point for the node in each dimension using slabs. These points will be used throughout the algorithm to decide which node we would hit next as we pierce the volume. A slab can be seen as a plane either spanning the XY, XZ or the YZ plane. To get the entry and exit point we check the intersection of two slabs in each dimension, think of it as two planes on each side of a cube. A two dimensional example in the x dimension is given in figure 2.5. The principal for three dimensions is the same.

To calculate the entry point, t_{xmin}, we use:

$$t_{xmin} = (x_{min} - o_x)/d_x \tag{2.3}$$

and the exit point, t_{xmax}, is similarly given by:

$$t_{xmax} = (x_{max} - o_x)/d_x \tag{2.4}$$

The calculations of the six intersection points will be passed down the algorithm as we descend the structure and enter smaller and smaller cubes. But before we do that we

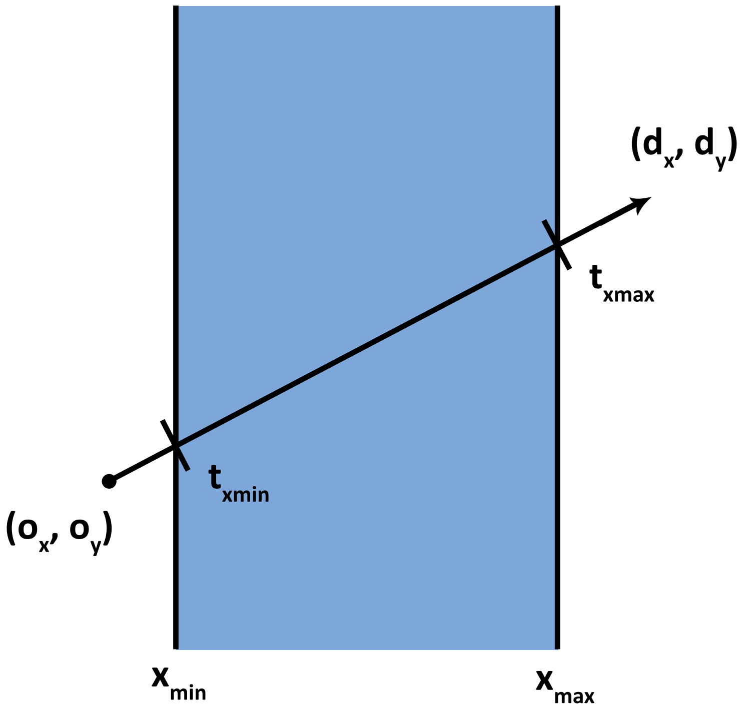


Figure 2.5: A two dimensional slab intersection. o is the origin of the ray and d its direction. x_{min} and x_{max} are the cube's min and max value of x. t_{xmin} and t_{xmax} are the intersection points of the two slabs.

calculate the distance this ray is travelling in the volume, the root, by taking the distance between the exit and entry point. $tx1$ would translate into t_{xmax} and so forth.

```
float r = min(min(tx1, ty1), tz1) + 1;
float e = max(max(tx0, ty0), tz0) - 1;

float res = r - e;
return res;
```

The ± 1 is there to give some margin against errors, otherwise we risk artefacts in the volume.

After all the variables have been initiated we begin our descent. We check which index of the root's children we first pierce with our ray and enters it. When we reach a node in the tree we check for four different cases:

1. Are we leaving the current node?
We do this by evaluating if any of the most positive slab exits are less than zero, i.e. if $tx1$, $ty1$ or $tz1$ is negative. If so, we go up one step in the algorithm and proceed to process the next node in line.

2. Hit empty space?
If this node's value is zero then it represent empty space. If so, go back one step and process the next node in line.

3. Is it a leaf?
If the value of the current node is negative this indicates that we have hit a leaf. If so, we use the same method as described above to get the distance this ray is travelling in the node. This is weighted with the nodes' noise value. Thereafter we go up one step and continue our traversal by processing the next node in line.

4. We hit a parent.
When so, we calculate the point that lies between max and min of each dimension by multiplying their sum by 0.5 and call these tim where $i \in (x, y, z)$ We save these plus the node and the exit and entry points to the stack and call a function to see what plane of the new node we would hit with our current exit and entry point. This is done by comparing tim with the entry points. For example, if we enter the XY plane we know that the ray would either enter node number four, two or six. When knowing what index we first enter we go down this sub-tree and continue our traversal.

By doing this we check each node that is intersected by our ray in the octree. When all the nodes that are intersected have been evaluated we have accumulated a noise value that we integrate with the scene behind the volume. If the value reaches over 1 in any state of the traversal we exit and call this a saturated smoke value that is to be coloured in the smoke's color with no transparency. After the traversal we instantly step past our volume and proceed to march as normal.

Chapter 3
Results

3.1 Measurements

To test the implementations we measure the frames per second (FPS) of our application in various camera positions. We compare the traversal of the octree with the sampling from the three dimensional texture. The resolution of the smoke varies from 32 units up to 512 units and for each resolution we measure octree build time and array build time in seconds. We also measure the size of the array and the number of elements we skip due to too low noise value. The resolution of our windows is 1024 x 768. The tests were conducted on a computer with an Intel Xeon E5-1620 3.50GHz CPU, 64GB of memory and a Radeon HD 7970 with 4GB of video memory by AMD. The time was measured using the function *glutGet(GLUT_ELAPSED_TIME)* before and after the code snippet measured. The difference of these two values is taken and divided by 1000. The FPS was measured in a similar fashion with addition of a frame counter that we increase each time the *renderScene()* function ended.

In table 3.1 we can see the construction time of the octree and the array, the size of this array—how many elements it contains, and the number of skipped noise values due to the value of the noise being too low.

Resolution	32	64	128	256	512
Octree(s)	0.126	0.947	6.802	48.855	334.720
Array (s)	0.145	3.736	9.832	39.020	853.710
Array (size)	27 352	189 312	1 125 912	5 031 160	18 436 176
Elements skipped	14 649	140 958	1 426 183	14 068 363	125 195 663

Table 3.1: Build time in seconds, size of the array and number of skipped elements in different resolutions.

Table 3.2 shows the average FPS in the various resolutions. We also compare FPS in the resolution 128 when we change the size of the volume. That is, we increase the x, y and z dimensions of our cube that holds our volume, making it physically bigger, see figure 3.6, 3.7 and 3.8. The standard size of the volume is 8.

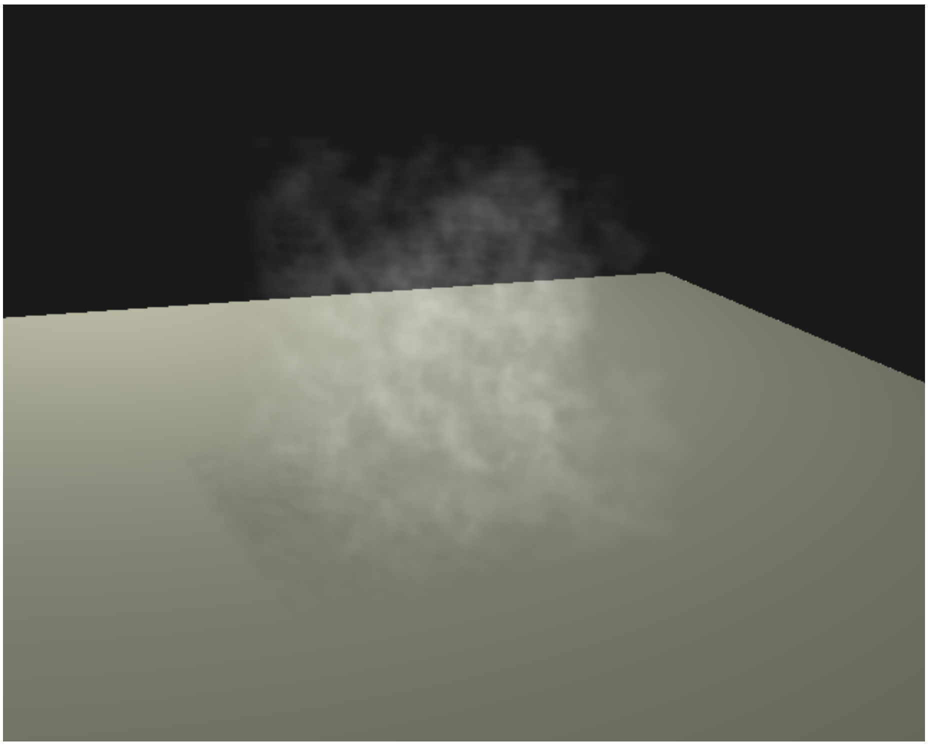
Resolution	32	64	128	128 VS 16	128 VS 32	128 VS 64	256	512
3D texture	111	111	111	59	27	13	111	111
Octree	30	14	9	6	4	3	4	2

Table 3.2: Average FPS in different resolutions. VS stands for volume size. The standard volume size used is 8.

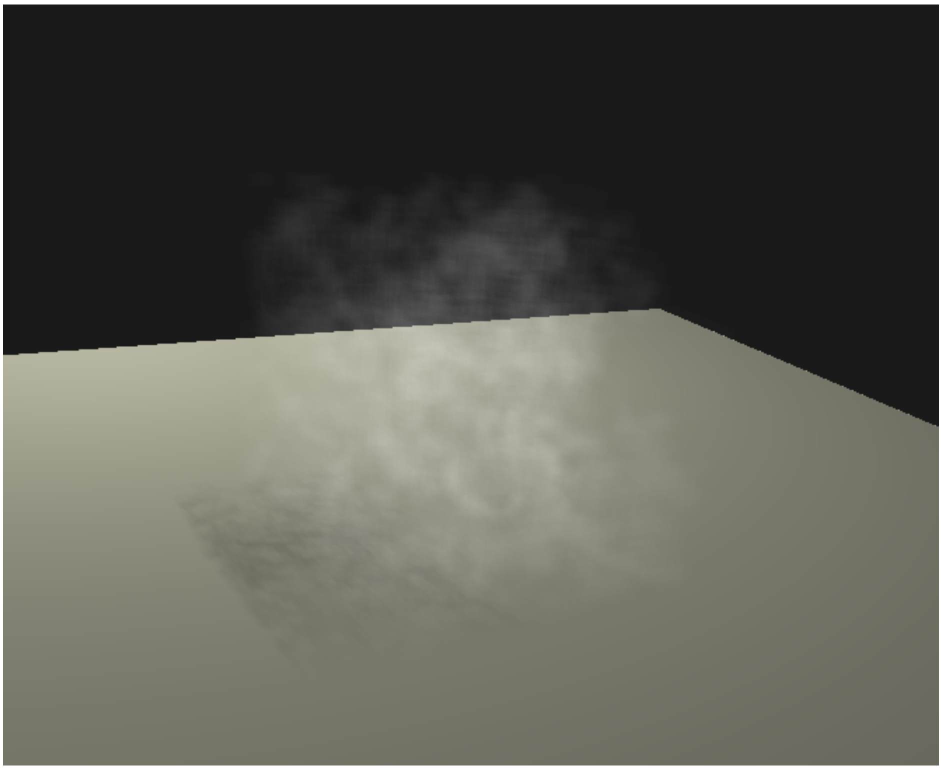
3.2 Visual comparison

We see some tiny differences between the two versions. The most noticeable difference is the saturation of the two versions—the difference in thickness of the smoke. At the lower resolutions, see figure 3.1 and 3.2, there is almost no difference i saturation. When we increase the resolution to 128 and above, see figures 3.3, 3.4 and 3.5, we see that the two version start to sample differently. In this case we are undersampling the texture. Figure 3.6, 3.7 and 3.8 showcases the difference when the size of the volume increases. Here we can see that the texture is oversampled compared to the octree.

The shadow below the noise is only sampled from the three dimensional texture, even if the octree version is running. The shadow can be controlled in real-time by moving the light source—also changing the appearance of the platform which is rendered using a phong shader.

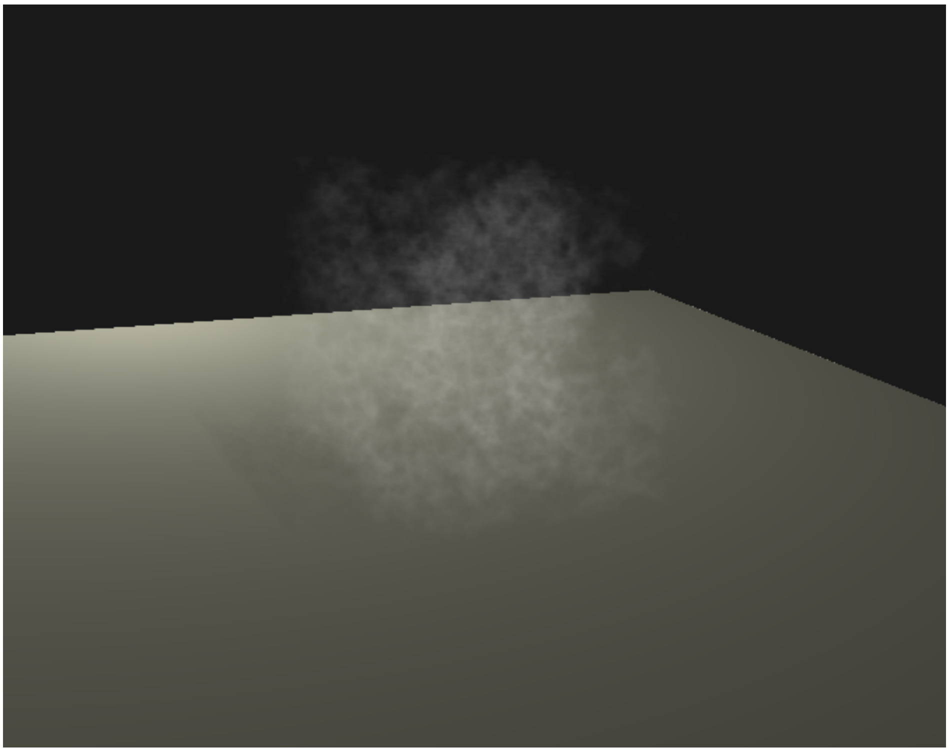


(a) Texture

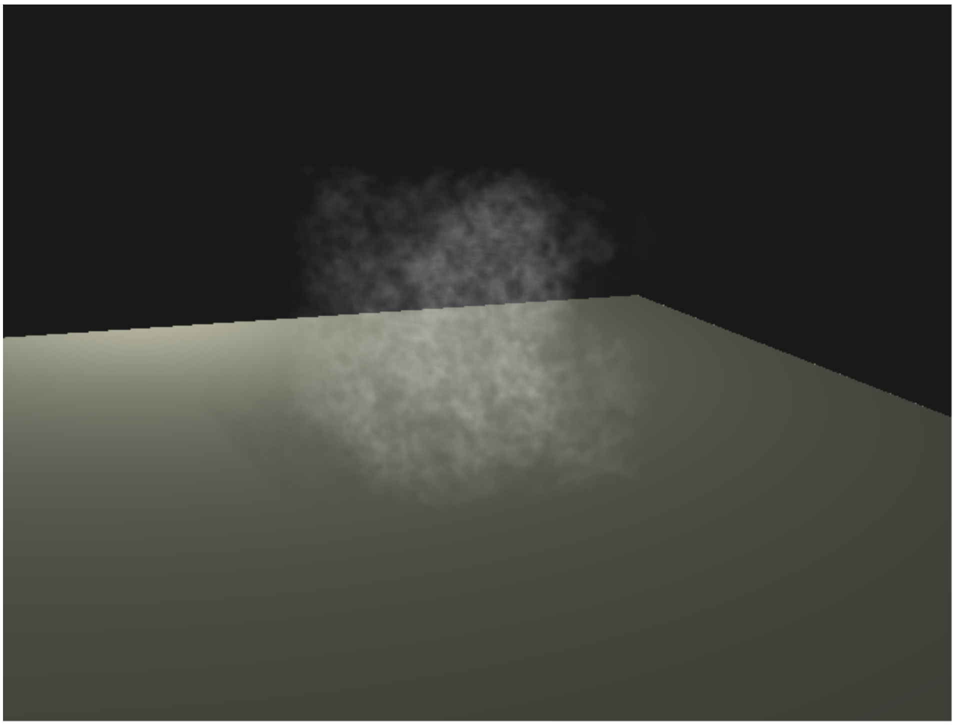


(b) Octree

Figure 3.1: Comparison of texture and octree with a resolution of 32.

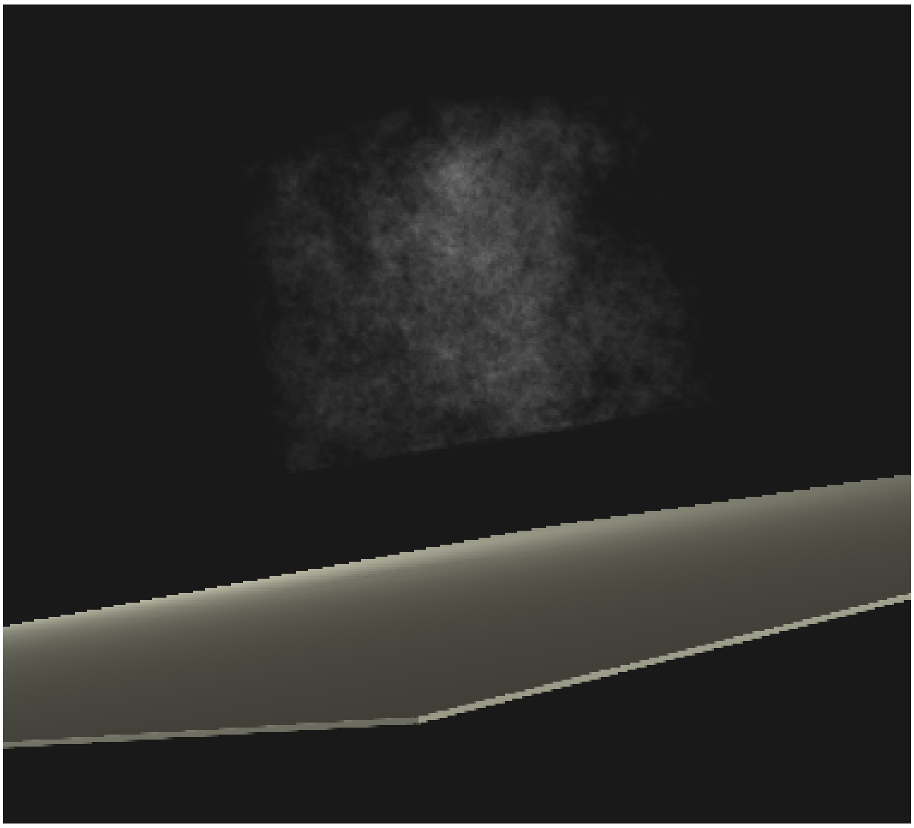


(a) Texture

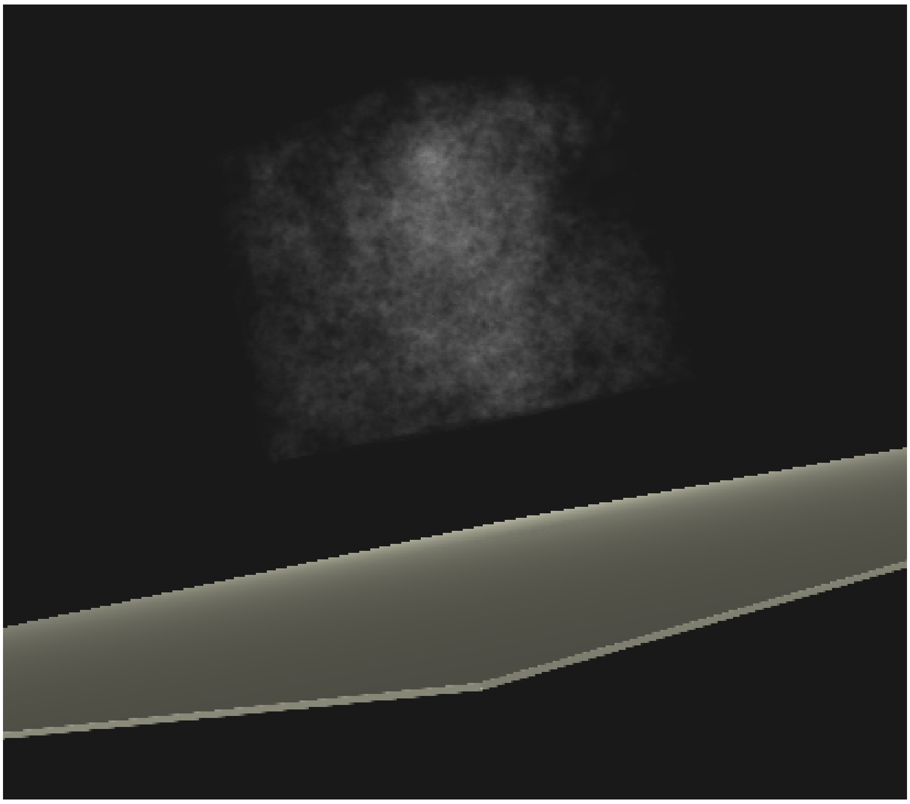


(b) Octree

Figure 3.2: Comparison of texture and octree with a resolution of 64.

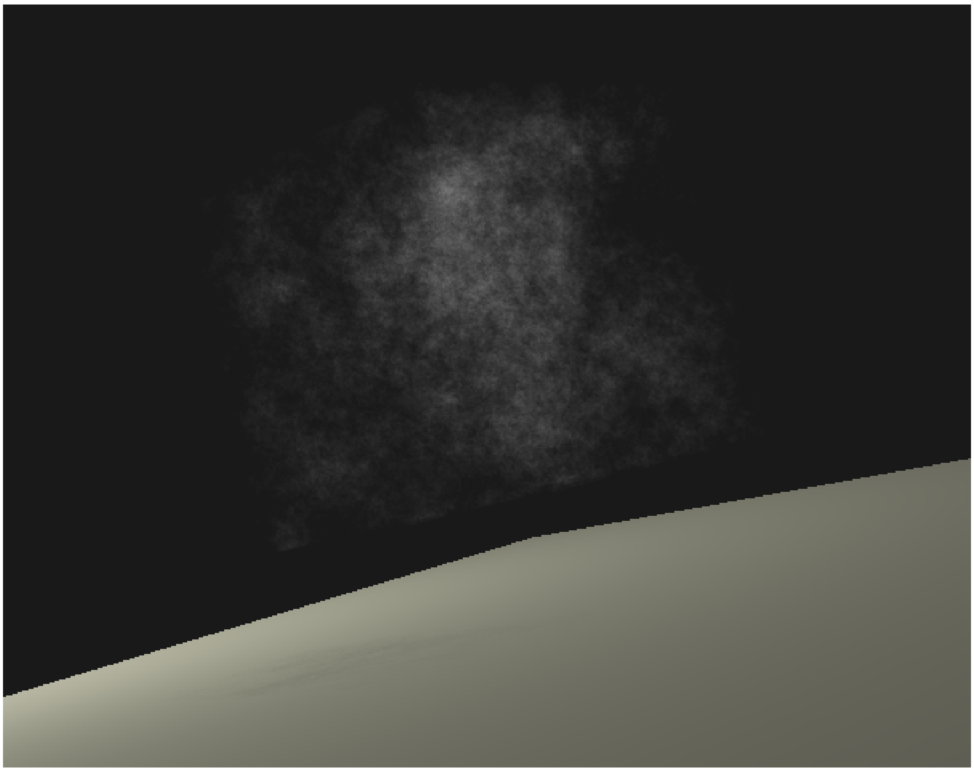


(a) Texture

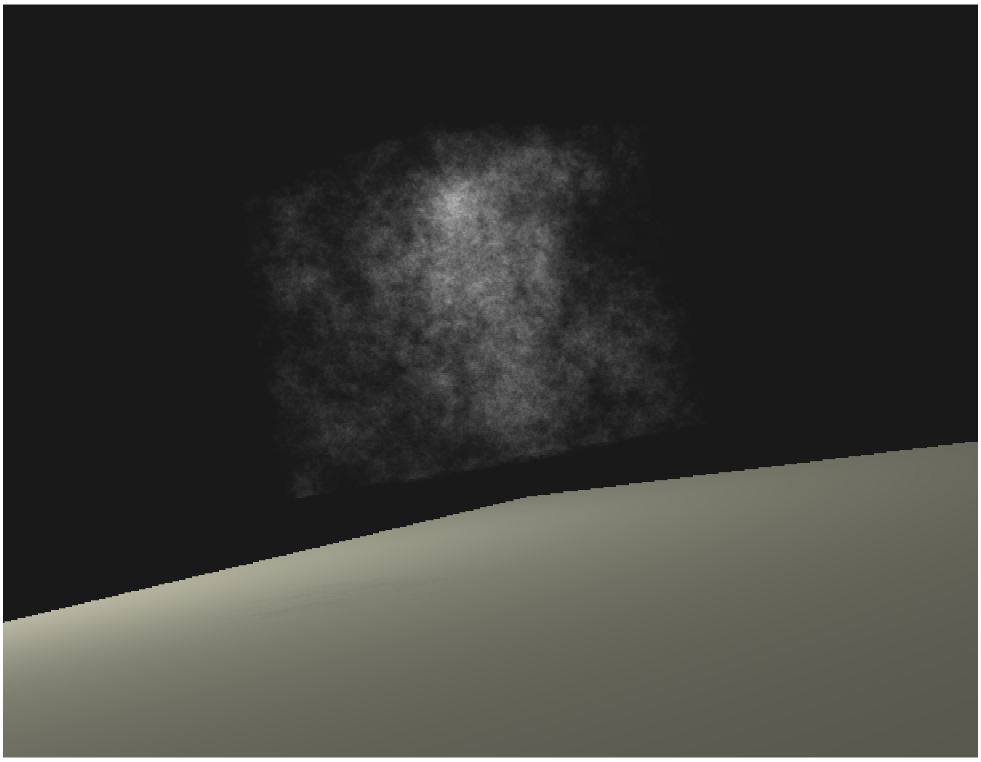


(b) Octree

Figure 3.3: Comparison of texture and octree with a resolution of 128.

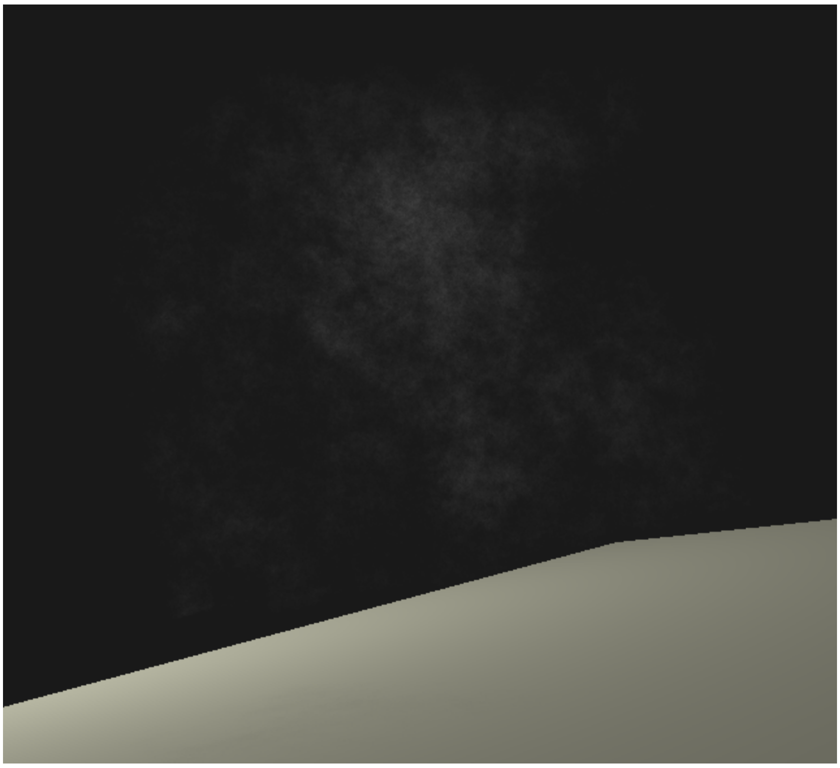


(a) Texture

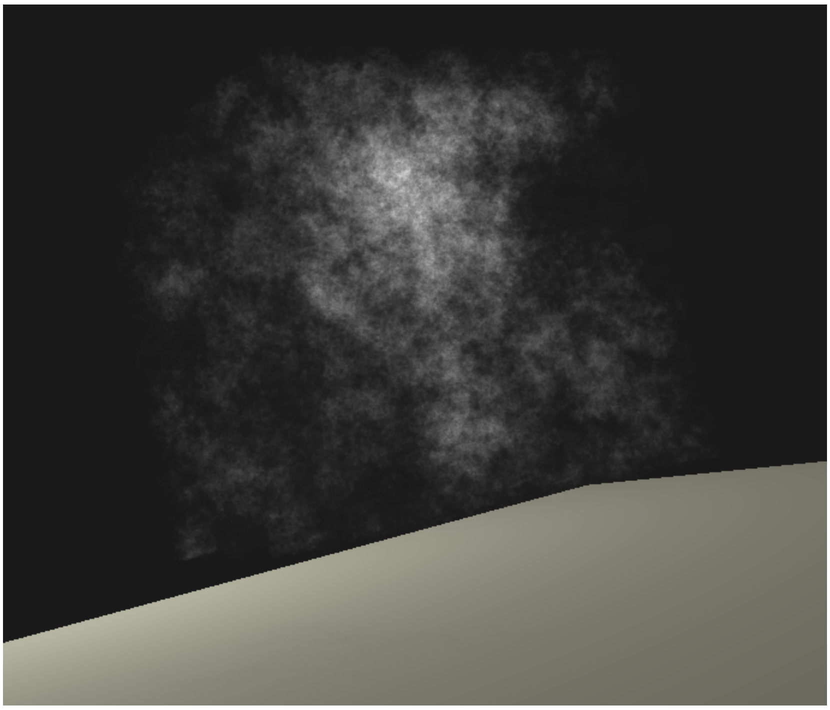


(b) Octree

Figure 3.4: Comparison of texture and octree with a resolution of 256.

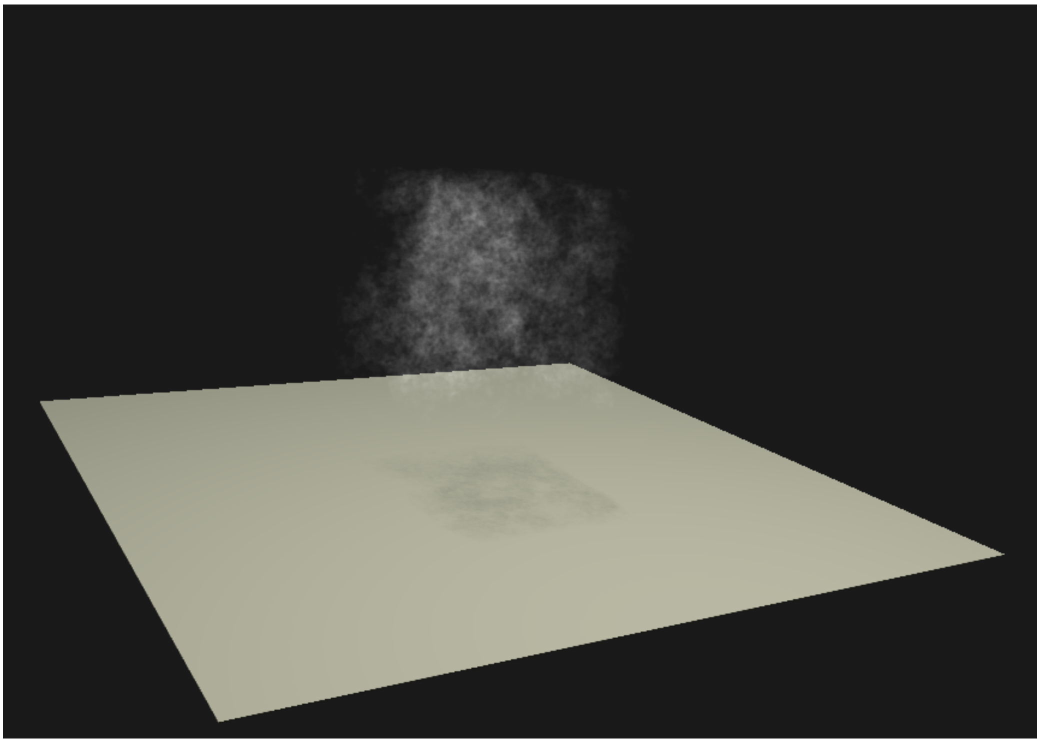


(a) Texture

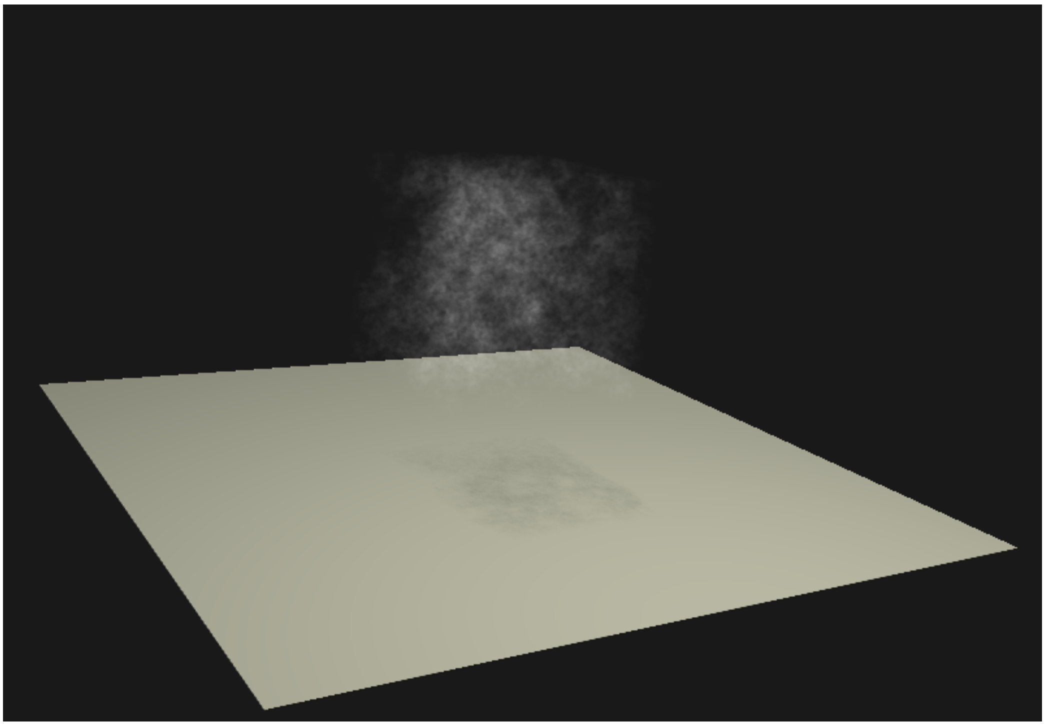


(b) Octree

Figure 3.5: Comparison of texture and octree with a resolution of 512.

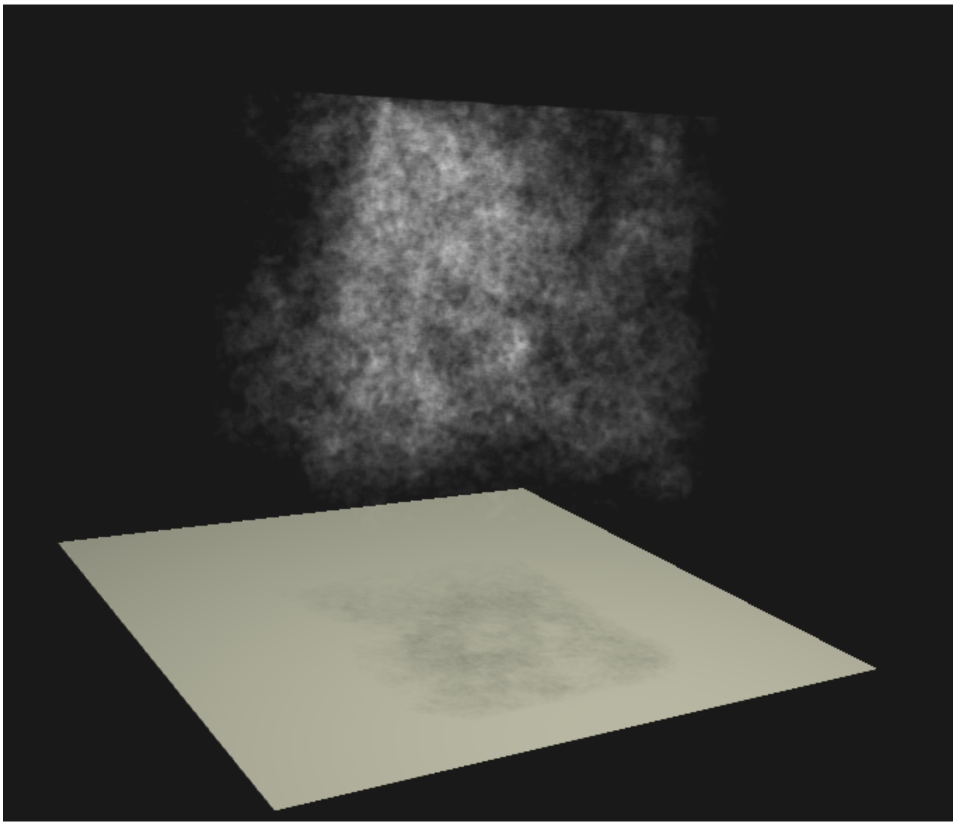


(a) Texture

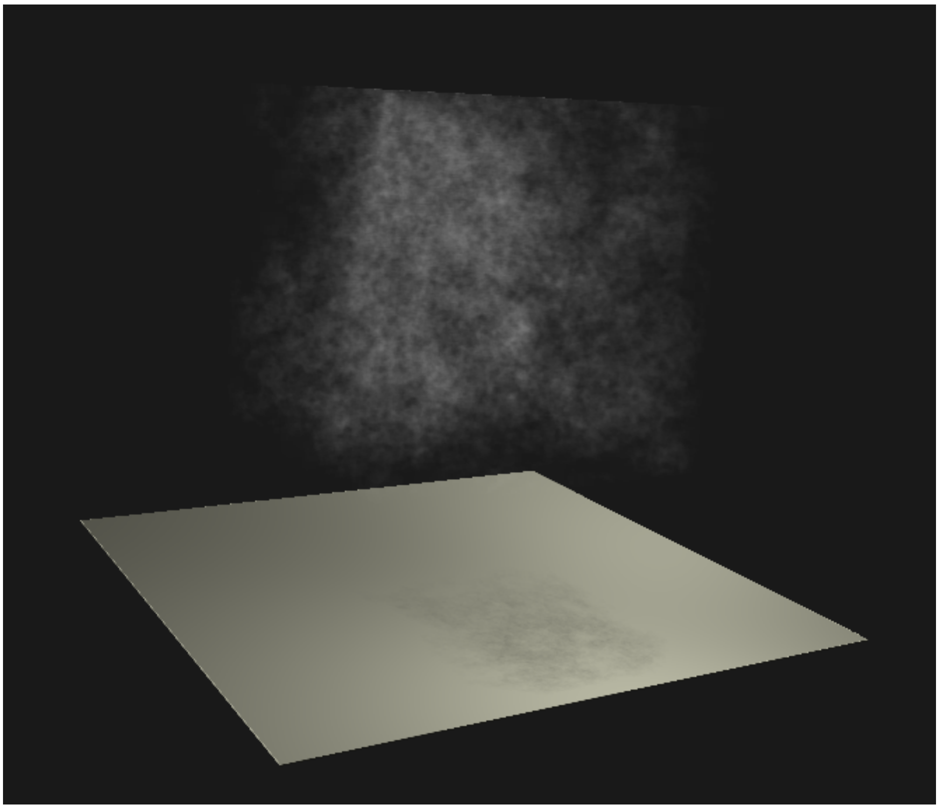


(b) Octree

Figure 3.6: Comparison with a resolution of 128 and a volume size of 16.

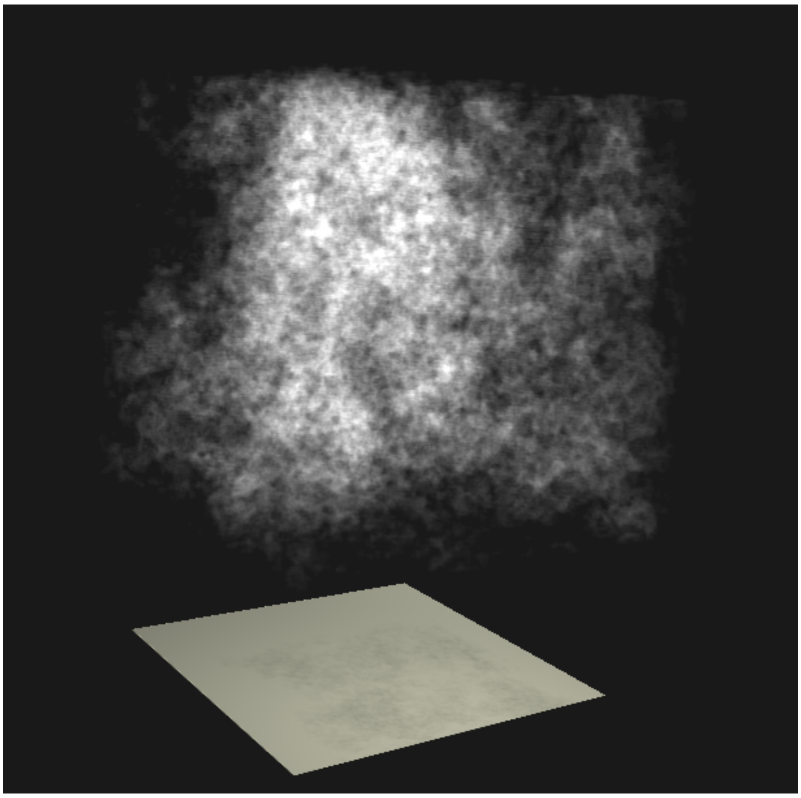


(a) Texture

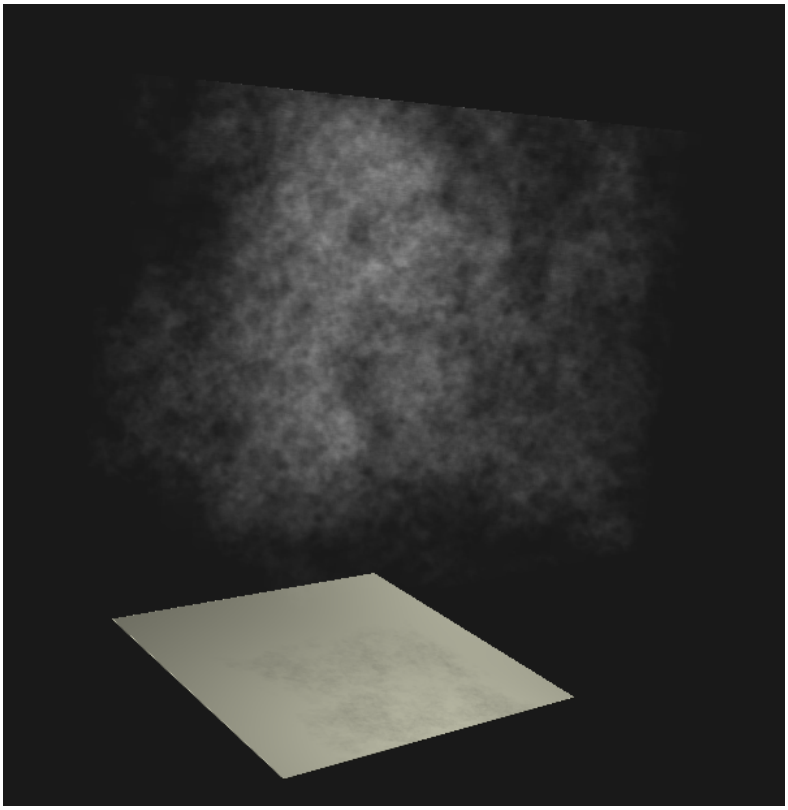


(b) Octree

Figure 3.7: Comparison with a resolution of 128 and a volume size of 32.



(a) Texture



(b) Octree

Figure 3.8: Comparison with a resolution of 128 and a volume size of 64.

Chapter 4
Discussion

The construction time of the octree and its array is hardly noticeable in the lower resolutions, 32 and 64, with a total time varying from 0.271 to 4.683 seconds. As soon as the long addresses is utilized, we increase the resolution, the time increases drastically by about a factor of eight for each increase. The time it takes to construct the array is almost in every case slower than construction the tree itself. This is because the tree construction algorithm never restarts at the root node for each insert. The array construction uses a depth first approach and therefore is forced to go through every node in the tree, plus some internal list iterations. With the chosen algorithm for building the tree it is not more beneficial to try and construct the array at the same time as the tree is constructed. This is because we split nodes during construction and re-insert the old together with the new one, reordering the tree multiple times during building. We also notice that the size of the array plus the number of elements skipped is greater than the resolution cubed. This is because we include zeroes in the array size, representing the empty space in that region of the tree. As the resolution gets higher the majority of the points get removed due to too low noise level. This is intended as we want more empty space to showcase possible speed benefits. But as we can see, the frames per second when using the octree is nowhere near the values when using the three dimensional texture. This is because the traversal algorithm used contains a non dynamically uniform flow-control sequence. To explain this we have to mention the difference in branching between CPUs and GPUs as the paper of Revelles algorithm, the algorithm used for traversing the octree, was only evaluated on the CPU.

To obtain high performance on modern CPUs they are all pipelined. This means that they consist of smaller parts that may partly process an instruction and send the result to the next stage in the pipeline. After they sent their result they immediately start on the next instruction. Obviously, this requires the knowledge of what instruction to process next. If we have a purely linear program this is not hard to predict, just take the next line of code. But by having a branch that is based upon a condition, that in some cases might be variable (non uniform), makes it impossible to know which instruction to process next. To fix this we either program in a branch-less manner or we rely on the CPUs ability to apply branch predictions. A branch prediction is simply a guess based on the condition to either go down path a or path b. As a CPU generally has deep pipelines, it is imperative to be able to accurately predict whether a branch might be taken or not. If its prediction is successful the penalty for branching is often just minor. If it fails, the CPU stalls some clock cycles, flushes the pipeline and refills with the correct address. Depending on the size and complexity of the different branches, the overall cost for this is not that grave.

The GPU handles this differently. As we recall, compute shaders invoke several parallel threads to run their code. This is favourable as a GPU is made for massive parallel executions. There are many shader cores running asynchronously and each core can run multiple threads. This all functions well as long as we are executing the same code at the same time within a core. When we do the opposite, creating a conditional branch, the GPU has to decide what to do. We have created a situation where threads within a core, depending on the condition, execute different instructions and may therefore have diverged from the rest of the core's threads. A GPU does *not* have branch predictions. Instead, when this happens the GPU utilizes the single instruction multiple data (SIMD) control mechanism. What this means is that when multiple threads diverge within a core the GPU halts every thread that is not taking this branch. After the threads that took the branch have finished, the GPU in series run the remaining threads that did not take the branch. This means that in worst case the GPU runs all the branches in series after one another, taking as long time as all the branches combined. The SIMD works well when we have fewer coherent branches, but for many incoherent branches the result can be expensive. This is a general approach and its effectiveness is highly dependent on the type of graphics card used and implementations of such control mechanisms. [12]

Unfortunately the traversal algorithm chosen appears to be very divergent. As soon as the loop for the traversal became non dynamically uniform we instantaneous lost about 40 FPS. This was noticed during testing when we first observed the drop in FPS. We tried to only fill half of the volume with smoke to see if it made any difference. There was no difference in the FPS. Even with a complete empty volume the drop in FPS was there. When limiting the amount of times the loop could run we noticed that it usually runs between 100 and 250 times, depending on the resolution. This seemed ok but even if the limit was set to 1 the drop in FPS was there. We might have gained a few FPS by limiting the loop to 1 but not near the lost 40. So our conclusion were that the low FPS were not connected to the amount of times the loop was running, instead that the loop became non dynamically uniform. We tried to change the algorithm and rework its flow in many ways. By setting the used stack as shared would give us back almost all the FPS, but another problem arose. The smoke would appear pixelated and flicker a lot. This is because the threads were not synchronizing the use of the stack. But a second problem occurred.

As we explained in the compute shader section, 1.1.2, to be able to synchronize the use of a the shared stack we have to have a dynamically uniform flow-control. As the algorithm itself is relying on going down different sub-children, depending on what child index one stands in right now, and changing this index in the sub-routines, the nature of this algorithm's flow-control is non uniform. If we had a dynamically uniform algorithm, not only could we gain back the lost 40 FPS, but we could also set the stack to shared, gaining additional FPS. We believe using a different traversal algorithm, either a stack-less one or an algorithm with much less branching, would heavily benefit the speed at which we can render a frame.

Visually the two types look almost the same shape-wise. There are some differences in the lower resolutions that is worth noting. When we have a single point in the volume with nothing around it the texture would display this as a tiny area of smoke, but in the octree this would show as a large cube. This is because there is no other data around this single point, or too few, pushing this node further down the tree. This difference gets less noticeable when increasing the resolution.

Even though we scale the amount of noise we pick up in regards to the volume size it is hard to get these two version alike. Overall we think that the octree represents the more accurate noise value picked up. This scaling can be observed by comparing the resolution of 128 and 256, seen in figure 3.3 and 3.4. As we pack more data into the volume, while maintaining its size, the traversal of the octree will always pick up every single node that the ray crosses and their respective noise value. For the three dimensional texture it could happen that the data points get so packed that we unintentionally skip some values, undersampling.

When changing the size of the actual volume we observe that the saturation of the noise is affected in the texture, see figures 3.6, 3.7 and 3.8. Here we see a case of oversampling in the texture. This effect gets more and more pronoun as the volume grows. Meanwhile, we can observe a constant saturation in the octree, regardless of the size of the volume. We could have tried to implement a variable step size for the texture depending on the size of the volume. But the main problem still remains, it is very hard to know if we are over- or undersampling. Besides the ocular measurements one could try to measure the difference using a picture comparison program. This will then calculate how much the two pictures actually differ per pixel by comparing its color. However, this might not yield useful numbers. For this to work we have to make sure that the texture samples each value only once—neither under- nor oversampling. This is extremely hard to check as we have no boundaries in the texture itself. Even if the two pictures look exactly alike, there might still be difference in the actual noise value for each pixel. This will give a false reading as soon as the values only differ by one or more units.

The FPS with the texture stays the same independent of the resolution. This is logical as we still take the same amount of steps in the volume. For the octree, with higher resolutions comes longer traversals, thereby change in FPS. By doubling the volume we loose about 50% of our FPS in the texture and about 30% with the octree. By increasing the size even further we still halve our FPS for each step, although the octree is affected less by the size difference. The small difference in FPS for the octree could be the small difference in camera positions. If we would have exactly the same amount of pixels of smoke for both the texture and the octree, regardless of the size, the octree would not loose any FPS as the resolution is the same. The number of steps in the texture would however increase.

Chapter 5
Conclusion

The goal of this thesis was to see if traversing an octree in real-time with a lot of empty space would be faster than sampling a three dimensional texture. The results show that with the chosen traversal algorithm it is not, independent of the amount of empty space in the volume. This is because the algorithm is non dynamically uniform. The octree does however scale better in speed when the resolution of the noise stays the same but the volume size increases. It also has more accurate noise saturation than the texture. Therefore the visuals look better with the octree, with some differences on lower resolutions. The build time and memory consumption when building the octree and its array is reasonable for lower and medium resolutions. The project might benefit to have been build in a 64-bit version, eliminating the memory limit. Furthermore, if we would have used a traversal algorithm that is dynamically uniform the speed of the octree would most likely surpass the speed of the texture. Enabling the stack to be shared would probably yield even greater speed gains. With these improvements we are sure this approach of rendering volumes will be viable in real-time applications.

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INSTITUTIONEN FÖR DATAVETENSKAP | LUNDS TEKNISKA HÖGSKOLA | PRESENTATIONSDAG 2015-08-28

EXAMENSARBETE Real-Time Volumetric Lighting Using SVOs
STUDENT Victor Strömberg
HANDLEDARE Michael Doggett (LTH)
EXAMINATOR Flavius Gruian

Att rita rök snabbare på en dator

POPULÄRVETENSKAPLIG SAMMANFATTNING **Victor Strömberg**

Dagens datorgrafik strävar ständigt efter att skapa mer verklighetstrogna bilder. För att kunna lägga in fler detaljer i bilden måste vi förbättra det sätt vi gör det på. Således testar vi ett alternativt sätt att rita upp rök i en dator snabbare.

Inledning

För att på ett snabbare sätt kunna rita verklighetstrogna bilder med grafikkortet i en dator så är det viktigt att förbättra, optimera, denna process. Man vill med andra ord förkorta den tid det tar att rita en bild. Desto mer man kan rita upp på kort tid, desto detaljrikare kan bilderna bli. Utan optimering så kan bildsekvenserna upplevas som sega och de tenderar att släpa efter.

Vid simulering av rök eller då man exempelvis skall visualisera bilder från en magnetröntgen använder man sig av volymer när man ritar bilderna i datorn. En volym kan anta olika former av tredimensionella kroppar. En enkel och vanlig form är en kub. I kuben finns data som representerar den volym man vill rita. Det är väldigt krävande att låta datorn rita volymer och därför är optimering av sådana processer av stort intresse.

Ray marching

När man ritar volymer så använder man sig av en teknik som heter *ray marching*. Tänk dig att du tar en bild med en vanlig kamera och från ditt öga så skjuter du ut strålar. Varje stråle träffar och går igenom en punkt på fotot du tänker ta. Strålen fortsätter genom fotot och ut i verkligheten och träffar det du vill fotografera. Beroende på vad strålen träffar så blir denna punkt som strålen gått igenom färgad olika. Tänk dig nu att när vi skjuter en stråle så hoppar vi också fram på denna med små steg. För varje steg vi flyttar oss framåt på strålen så kollar vi om vi har träffat nått. Detta är konceptet för ray marching.

Problem

När vi träffar vår volym så börjar vi ta ännu mindre steg genom hela volymen. För varje litet steg vi tar så hämtar vi information från volymen om hur röken ser ut just här för denna stråle. Finns det ingen information att hämta här, volymen är tom, så försöker vi ändå hämta den. Detta är slöseri med beräkningskraft och vi vill i stället försöka optimera detta så att vi inte behöver hämta information som ändå inte ger oss någonting.

Lösning

För att möjliggöra en optimering byggs en trädstruktur, ett så kallat *octree*, upp av röken. Med hjälp av denna struktur kan vi dela in volymen i bitar. Dessa bitar kan då säga oss om det finns information här som vi kan använda. Är det tomt, så talar vårt octree om det för oss och hoppar då förbi allt detta tomrum direkt. Därmed kan vi spara beräkningskraft.

Resultat

Resultaten visar att metoden har potential, men det sätt vi frågar vårt octree på omöjliggör en optimering. Detta beror på hårdvarubegränsningar i dagens grafikkort som grundar sig i dess oförmåga att förutspå och hantera komplexa förgreningar av kod. Octree:t ger dock ett mer noggrant värde av röken då vi varken hämtar för mycket eller för lite information om den i volymen. Detta resulterar i en mer visuellt korrekt återgiven rök.