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Procedural Terrain and Volumetric Cloud Generation for Interactive Gameplay

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Chapter 1

Introduction

This thesis explores the implementation of real-time procedural terrain generation and volumetric cloud rendering using C++ and OpenGL. The goal is to create a fully explorable 3D environment in which the user can pilot an aircraft through dynamically generated landscapes and clouds, all while maintaining high rendering performance.

Procedural content generation enables infinite, non-repeating environments without the need for handcrafted assets. Volumetric clouds further enhance immersion by simulating complex atmospheric phenomena. Together, these systems form the foundation of a lightweight, yet visually rich virtual world.

The main inspirations for this work come from Sebastian Lague’s development series [1] and community shaders such as those found on Shadertoy [2]. However, unlike these examples — which either depend on high-level engines or focus on isolated effects — this project aims to build everything from scratch, including the rendering pipeline, asset management, and interaction systems.

Following conventions are used throughout the document:

- **Vector:** \vec{x}
- **Unit Vector:** \hat{x}
- **Length of a vector:** $\|\vec{x}\|$
- **A point:** \mathbf{x}
- **Matrix:** A
- **Dot product of two vectors:** $\vec{a} \cdot \vec{b}$ or $\langle \vec{a}, \vec{b} \rangle$

Chapter 2

User documentation

To ensure that the program runs as smoothly as I have tested on my machine the recommended hardware is at least a 3050TI Nvidia Graphics card (with min 4GB ram), and at least 8GB of RAM. The game is shipped as a zip file exclusively for windows so all the required files are inside of it and can be played just by running the executable. For other OS, it must be built using the source files.

2.1 The goal of the game

This project serves mainly as a demonstration of the implementation so no complicated features are implemented. However, to make the game playable the user is assigned with a single task. The goal of the game is drop packages at some predefined coordinates which are randomly selected as soon as the package is dropped. The package can be dropped in some predefined circle of radius around the target coordinates. So the steps can be summarized as:

- Fly around and explore the world.
- Fly to the target coordinates.
- When you see a sign on the screen, drop the package. And go to the next coordinates.
- Settings can be manually configured as desired, which change the shape and scale of the clouds.
- The airplane's properties can also be configured using the menu.

A navigation bar is also added at the bottom of the screen which is just a projection of the players coordinates on the x - z plane, this bar can be used for reaching the target coordinates as will be momentarily described.

2.2 Playing the game



Figure 2.1: First look

The image above provides a first look at the game, the config menu can be hidden using either the cross button or by pressing the key **F1**. Currently there is no way to change the airplane model from inside the game, the only way to do that is to change the source files.

2.2.1 The controls

Following keys can be used to control the aircraft:

W: Go forward (apply thrust)

D or **→**: Tilt the plane towards right.

A or **←**: Tilt the plane towards left.

↑: Tilt the plane downwards.

↓: Tilt the plane upwards.

space-bar: Drop the package

Q: Rotate the aircraft around the UP axis to the left.

E: Rotate the aircraft around the UP axis to the right.

2.2.2 Understanding the navigation bar

The navigation bar can be understood by looking at the picture below

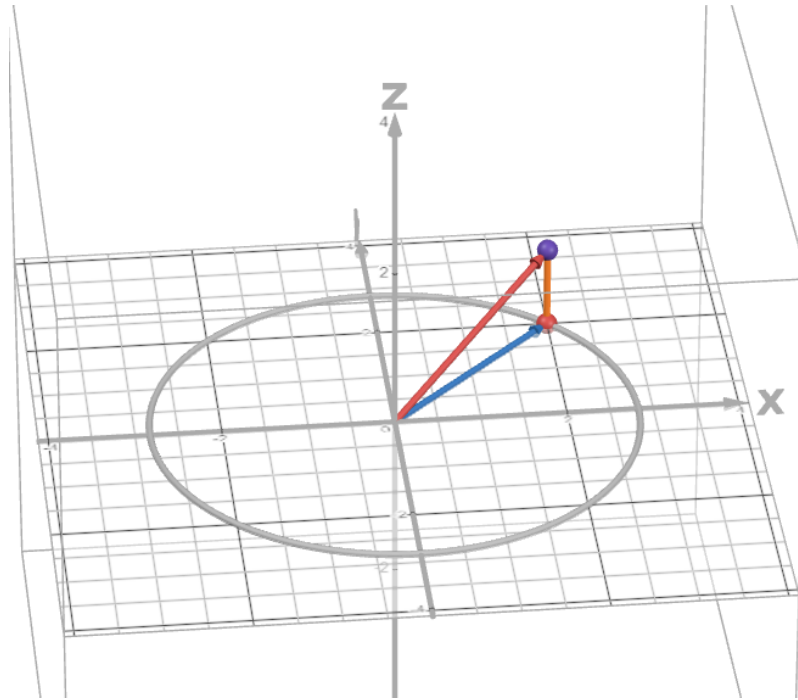


Figure 2.2: Projection of a point in 3d onto the plane

If the vector in red is current velocity vector of the airplane and the blue vector is its projection onto the horizontal plane then this vector is exactly where the black arrow points in the navigation bar.

The blue blinking dot is where the current target position is, it is relative meaning that the distance is scaled and capped so it remains within the navigation bar but if you're closer to the target then the blue point moves inside the circle indicating that you're near the target.

2.2.3 Dropping the package

When you are within the pre-specified acceptable radius of the target a text as show in Figure 2.3 appears on the screen.

At which point you can press **space-bar** to drop the package and move to the next assigned point in the navigation bar.



Figure 2.3: Text indicating the drop point

2.3 Understanding the config menu

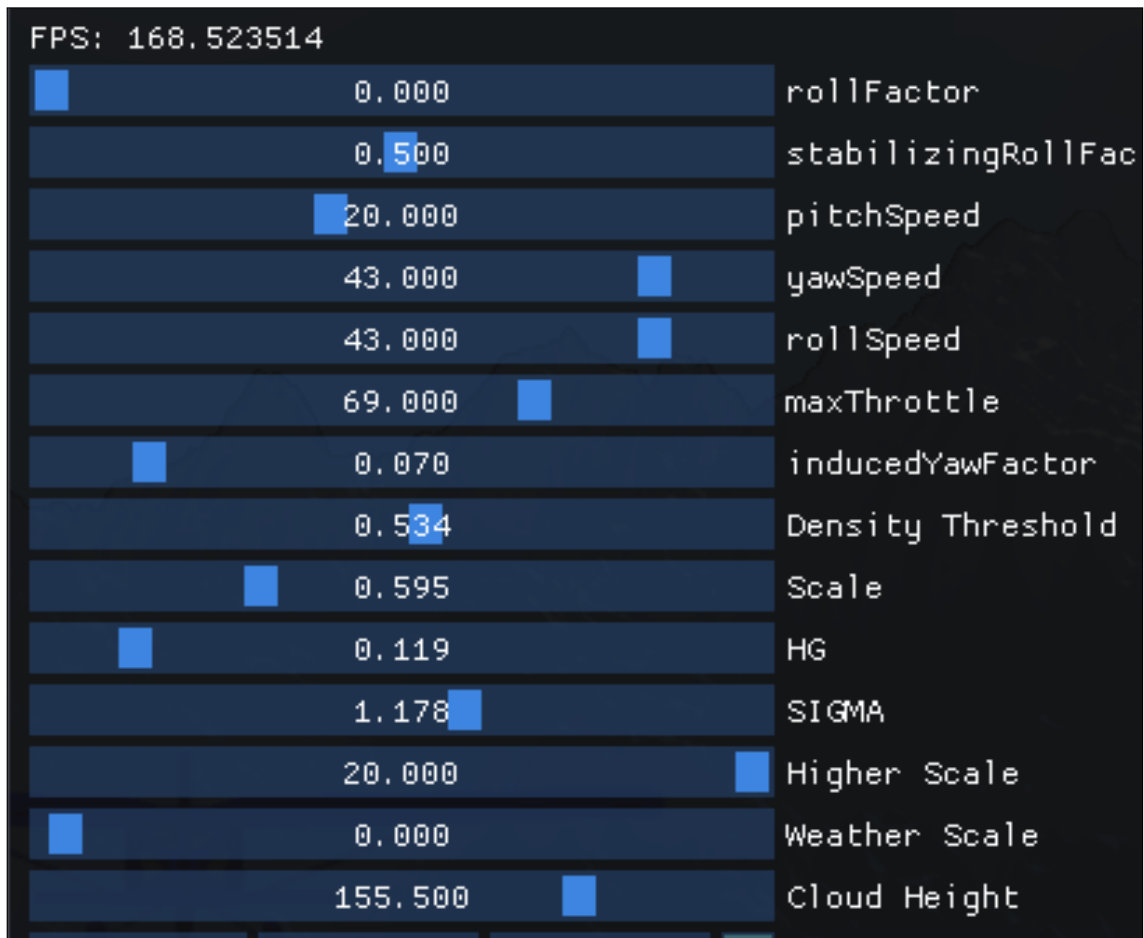


Figure 2.4: The configuration menu

The first 7 configuration parameters (until **inducedYawFactor**) are for the aircraft. And they control/define the following things:

Aircraft parameters	
<i>Parameter</i>	<i>Description</i>
<i>rollFactor</i>	How much emphasis should be put on the roll control given by the user, the total roll torque is a weighted sum of user's roll and the stabilizing roll.
<i>stabilizingRoll</i>	How much emphasis should be put on the stabilizing the aircraft, for example, if the aircraft is traveling fast it has a tendency to align itself towards the center, this parameter controls how strongly that should happen.
<i>pitchSpeed</i>	Factor by which changes to the current pitch should be applied.
<i>yawSpeed</i>	Factor by which changes to the current yaw should be applied.
<i>rollSpeed</i>	Factor by which changes to the current roll should be applied.
<i>maxThrottle</i>	Factor by which the force in the forward direction should be applied when the user presses W
<i>inducedYawFactor</i>	When the airplane tilts around the z axis, i.e it rolls there is also an induced yaw on it, this parameter determines how strong that induced yaw should be.

Table 2.1: Aircraft parameters

Weather parameters	
<i>Parameter</i>	<i>Description</i>
<i>Density Threshold</i>	The clouds have density between 0 and 1 at points in space, this determines the minimum density the point must to have to be rendered.
<i>Scale</i>	The scale at which the clouds should be sampled from the noise textures, lower values result in bigger fluffier clouds, higher values make them smaller and closer.

<i>Parameter</i>	<i>Description</i>
<i>HG</i>	The Henyey-Greenstein constant (further described in developer documentation).
<i>SIGMA</i>	The transmittance factor of the clouds.
<i>Higher Scale</i>	The scale at which noise from high frequency noise textures should be sampled from. Empirically, this was found to give good results between 15 and 20.
<i>Weather Scale</i>	The scale at which the parameters for the weather (i.e where clouds can be) should be sampled from the weather texture (due to the noise textures I have, this value should be extremely small).
<i>Cloud Height</i>	Height at which the clouds should be.

Table 2.2: Weather parameters

Chapter 3

Developer documentation

3.1 Building the code

There are currently two ways of building the code on Windows OS either with Visual Studio and using **vcpkg** as the package manager or with **MinGW** and manually building the packages (which I have deprecated but it's possible and I have put it in a separate branch).

First the following steps must be fulfilled to start developing (on windows):

- Install **vcpkg** and add it to your path.
- Run the `integrate install` command so Visual Studio can detect it.
- Install CMake.

3.1.1 Building with CMake

To make it easier to download the required packages, a powershell script `install_dependencies.ps1` is provided with the code which installs all the required dependencies.

Then the project can be built with CMake either by running `build_for_vs.ps1` script or by doing the following in the shell:

```
1 mkdir build
2 cd build
3 cmake .. -G "Visual Studio 17 2022" -A x64 -DCMAKE_TOOLCHAIN_FILE=%
  PATH_TO_VCPKG%/scripts/buildsystems/vcpkg.cmake
```

Code 3.1: Building with CMake

You can replace generator with your compiler of liking, MinGW, for instance (if you have the packages installed). Replace the tool chain file path to your vcpkg path.

CMake was chosen because of its cross-platform support. If, for instance, you want to build on linux and have the required packages then you can build using the same CMake file, in which case it will generate a Makefile instead of the VS solution.

3.2 Design and the rendering pipeline

This sections describes how the components fit together and in what order the things are rendered before proceeding to explain all steps in detail.

3.2.1 The OpenGL Rendering Pipeline

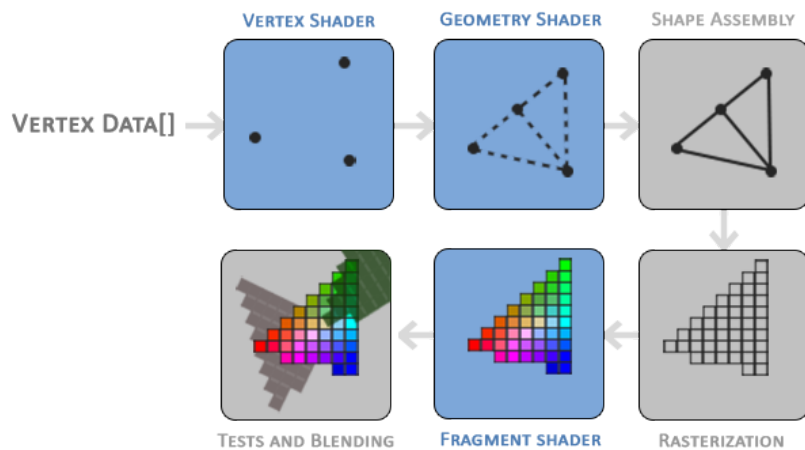


Figure 3.1: The OpenGL Pipeline
[3]

First let's look at the OpenGL rendering pipeline in Figure 3.1. The only procedures that we are concerned with at the moment are Vertex and Fragment shaders. Geometry shaders will be described at a later stage when they are needed.

Definition 1. Shaders Shaders are programs that run on the GPU, there are various ways to send data to shaders. In the code, I mainly send data through vertex buffers or through uniforms.

Without going into too much depth, vertex shaders transform vertices from local space to normalized device coordinates and fragment shaders are used for choosing the colors (as depicted in the picture above).

3.2.2 Vertex Shader Convention

The code snippet below describes how a typical vertex shader looks like in the code:

```
1 layout (location = 0) in vec3 aPos;
2
3 uniform mat4 proj;
4 uniform mat4 view;
5 uniform mat4 model;
6
7 void main() {
8     gl_Position = proj * view * model * vec4(aPos, 1.0);
9 }
```

Code 3.2: Vertex shader convention

In this document, I will be representing the projection matrix as **P**, view as **V**, and model as **M**. In some vertex shaders there is also a local transformation matrix because I sometimes like to dissect the model matrix into two matrices the model and the local matrix, the former puts the object into the world space and the local transformation is responsible for any rotation or scaling.

3.2.3 Shader loader

To make it easier to load, compile and use shaders the engine comes with a Shader loading class. The design of the shader loader/manager is inspired by the one on LearnOpenGL [3]. This class is responsible for allocating and destructing the shaders. A different class is also defined specifically for loading Compute shaders which will be described later. However, the interface for using and setting the uniform variables is identical for both classes.

Uniform variables can easily be set using this shader class, as illustrated in the code snippet below (all such functions can be found in the header file):

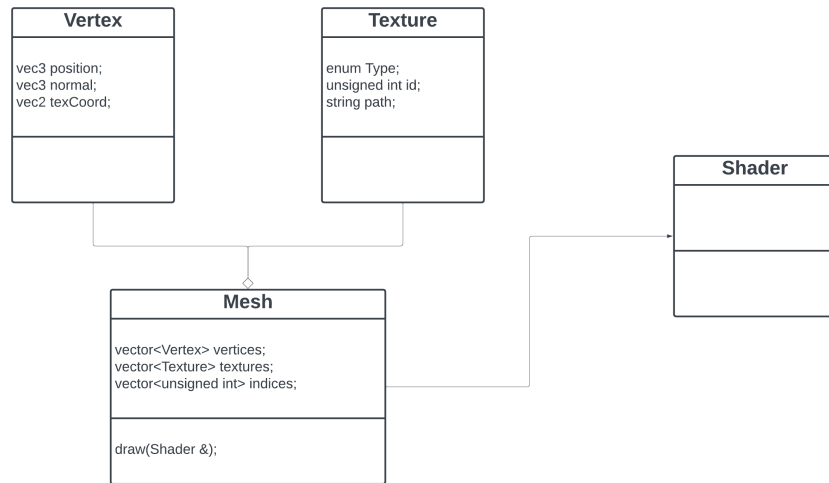
```
1 Shader myShader {"vertexSource.glsl", "fragmentSource.glsl"};
2 myShader.use();
```

```
3 myShader.setVec3("cameraPos", glm::vec3(0.0f));
```

Code 3.3: Shader class usage example

3.2.4 Mesh handling

In OpenGL the mesh data must be transferred to a **VBO (Vertex Buffer Object)** first and then the **VBO** must be bound to a **VAO (Vertex Array Object)**, instructions for how to parse the data in **VBO** must also be explicitly defined and optionally a drawing order of vertices can also be defined in a **EBO (Element Buffer Object)**. To make this simpler a **Mesh** class comes with the engine. This is also inspired by an implementation on LearnOpenGL [3]. The figure below gives a rough UML of how the mesh class is structured.


Figure 3.2: Mesh Class
[3]

Meshes for 3d can be generated easily using a mapping $f(u, v) \rightarrow \langle x, y, z \rangle$. Some simple examples are given in `funcs.h` and `funcs.cpp`. For instance, a sphere can be generated using the function: $f(\theta, \phi) \rightarrow \langle \cos \theta \cos \phi, \sin \phi, \sin \theta \cos \phi \rangle$, where $\theta \in [0, 2\pi]$, $\phi \in [-\frac{\pi}{2}, \frac{\pi}{2}]$. The normal vector for a sphere \hat{n} is, of course, the same as $f(\theta, \phi)$. An implementation for generating the mesh of a torus is also given; a simple version of which can be derived by taking the parametric equation of a circle and translating it along, say, the x axis by rt : $C(\theta) = \langle r \cos \theta + rt, r \sin \theta, 0 \rangle$. If $\mathbf{R}_y(\phi)$ is the rotation around y axis then the torus is $f(\theta, \phi) = \mathbf{R}_y(\phi)C(\theta)$ where $\theta, \phi \in [0, 2\pi]$.

3.2.5 Model loading

The first implementation was done with a custom object file loader, however, it is infeasible to write a complete model loader that triangulates the vertices, supports multiple formats, and parses the texture files accurately. So, the decision to use **assimp** was made. The **Model** class is basically a wrapper around **assimp** functionality. This implementation was also motivated by the one provided on LearnOpenGL [3], however, contrary to that implementation this one is more optimized and handles the loading of materials more accurately.

The figure below can be used as a reference for understanding the code in the **Model** class.

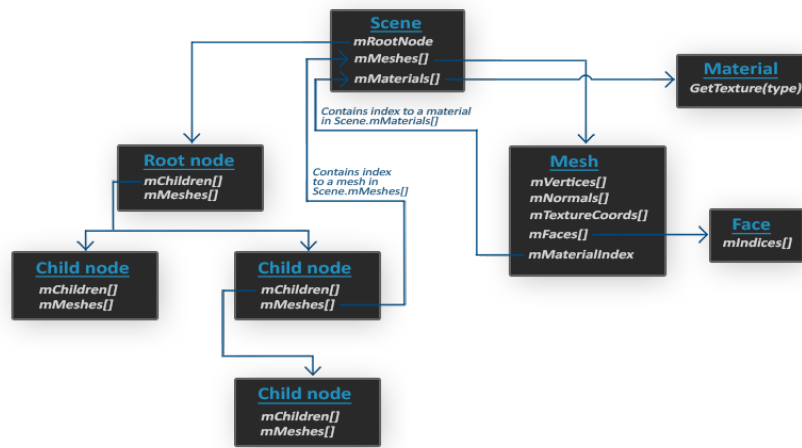


Figure 3.3: Assimp Structure
[3]

A model can be thought of as a collection of meshes, so the rough UML diagram of the class below should make sense:

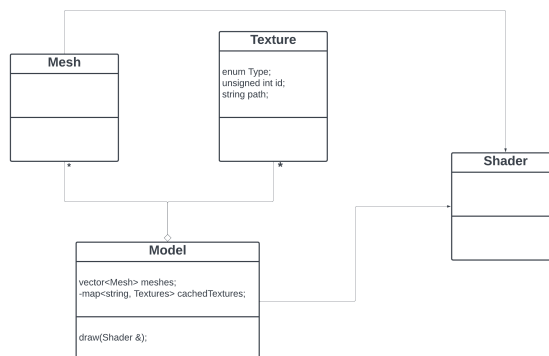


Figure 3.4: Model class UML

Since models can have multiple diffuse and specular textures, they must be defined in the shaders in following convention. Diffuse textures must follow the following naming `texture_diffuse[1..]`, specular textures must be named as `texture_specular[1..]`.

3.2.6 Camera class and the camera transform

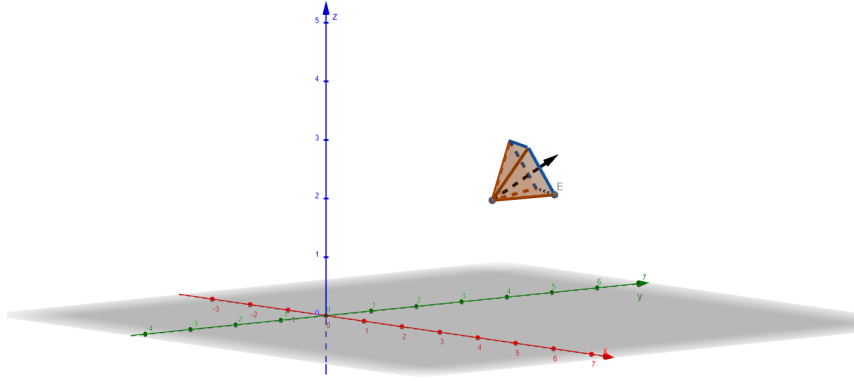


Figure 3.5: Simple Camera example

The camera can be imagined as a vector in the figure above. It sits at a point \mathbf{p} looking in direction $\hat{\mathbf{d}}$. Contrary to some common implementations, which store a `lookAt` variable to store what point the camera is looking at, I only store the direction which can be dissected into two components: pitch (rotation around the x – axis), represented as ϕ , and yaw (rotation around the y – axis) which is represented as θ . Similar to what was done in the meshes section 3.2.4, it can be observed that these define a spherical coordinate system and we can get $\hat{\mathbf{d}}$ as follows:

$$\hat{\mathbf{d}} = \langle \cos \theta \cos \phi, \sin \phi, \sin \theta \cos \phi \rangle \quad (3.1)$$

However, the pitch is constrained to avoid distortions so, $\phi \in [-\frac{\pi}{4}, \frac{\pi}{4}]$. An absolute up direction vector is also defined for the camera which I will denote as $\hat{\mathbf{u}}$ and $\hat{\mathbf{u}} = \langle 0, 1, 0 \rangle$. The projection matrix works by assuming that the camera is looking in the negative z – axis and is sitting at the origin. So \mathbf{V} must be the matrix that puts the camera in this position. \mathbf{V} must first translate the camera to the origin and then apply the inverse rotation of the current camera rotation.

If \vec{p} is the position vector of the camera, then let $\mathbf{T}_{-\vec{p}}$ represent the translation matrix that translates by $-\vec{p}$.

The current rotation matrix of the camera can be obtained by getting the front (but flipped because the camera starts by looking in the negative z -axis), right, and up vectors of the camera:

$$\begin{aligned}\hat{f} &= \text{front} = -\hat{d} \\ \hat{r} &= \text{right} = \hat{d} \times \hat{u} \\ \hat{a} &= \text{up} = \hat{r} \times \hat{d}\end{aligned}$$

The rotation matrix is then:

$$\mathbf{R} = [\hat{r} \quad \hat{a} \quad \hat{f}]$$

This can be imagined as where the $\hat{i}, \hat{j}, \hat{k}$ vectors land after the transformation.

We want the inverse of this matrix. Since this is an orthonormal matrix, the inverse is the transpose of the matrix:

$$\mathbf{R}^{-1} = \mathbf{R}^T$$

Thus, the final view matrix is:

$$\mathbf{V} = \mathbf{R}^T \mathbf{T}_{-\vec{p}}$$

The `Camera` class in the code provides the above functionalities, and the view matrix can be easily obtained by calling the `camera.getView()` method.

3.2.7 Audio Manager

The engine includes an audio manager capable of playing 2D sounds. Currently, there is no implementation available for 3D audio playback. This component serves as a wrapper around the functionality provided by **OpenAL**. Audio files are loaded using **libsndfile**, and the engine currently supports only the **WAV** format.

The following code snippet demonstrates a basic usage example:

```
1 #include <audio_manager.h>
2 #include <iostream>
3
4 int main()
5 {
6     AudioManager audioMgr;
```

```
7   audioMgr.play2d("soundfile.wav", /*loop*/ false);
8   std::cin.get(); // prevent exiting
9 }
```

Code 3.4: Audio Manager example

3.2.8 OpenGL Frame Buffer Objects and the FrameBuffer Class

OpenGL provides Frame Buffer Objects (FBOs), which can be thought of as off-screen rendering targets—similar to virtual canvases or pseudo-windows that you can draw on. Instead of rendering directly to the screen, FBOs allow rendering to a texture or render buffer. This is particularly useful for post-processing effects, shadow mapping, and deferred rendering techniques.

The `FrameBuffer` class in the engine serves as a wrapper around OpenGL’s FBO functionality, simplifying the creation, configuration, usage, and memory management of frame buffer objects. It provides functionality to bind the FBO, with the option to clear it upon binding.

For simplicity, this implementation constructs the FBO using textures (rather than **Renderbuffer Objects**), as most parts of the engine require the ability to read from the framebuffer. A depth buffer is also included. These design choices can be modified in the future to support more flexible configurations.

A simple example is provided below:

```
1 #include <framebuffer.h>
2 #include <iostream>
3
4 int main()
5 {
6     // Ensure OpenGL context is active before using the FrameBuffer
7     FrameBuffer framebuffer;
8     framebuffer.bind();
9
10    // All OpenGL draw calls will now render to the frame buffer
11    // ...
12
13    framebuffer.unbind();
14 }
```

```

15 // Access the color and depth texture IDs if needed
16 GLuint colorTex = framebuffer.textureId;
17 GLuint depthTex = framebuffer.depthTextureId;
18
19 // Or, draw the FBO's content directly to the screen
20 framebuffer.draw();
21 }

```

Code 3.5: Frame Buffer example

3.2.9 Architecture

The UML diagram below represents a simplified architecture of the whole game and shows how the components connect to each other.

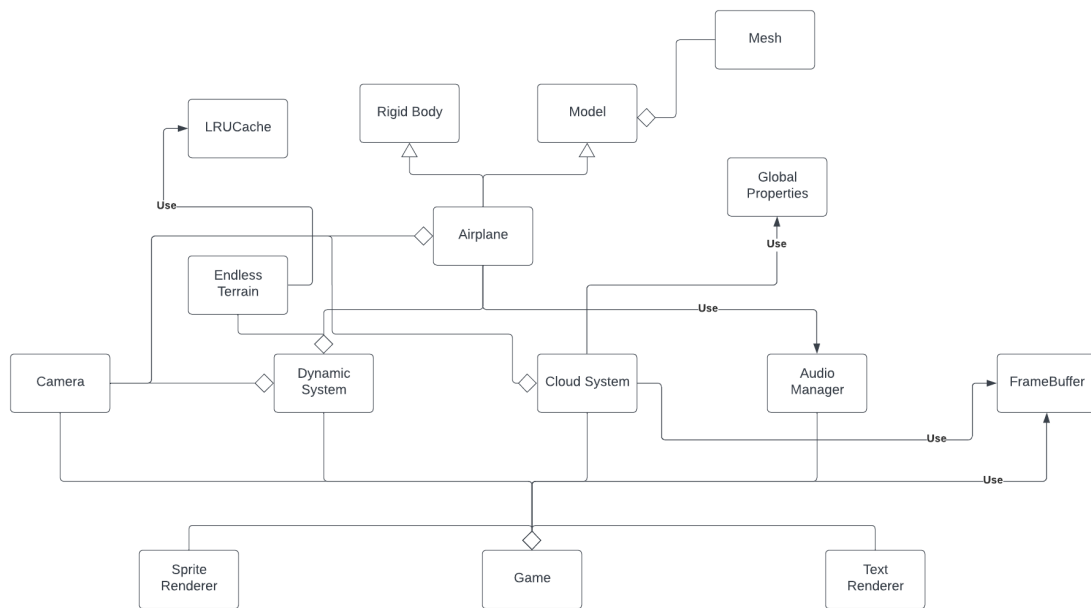


Figure 3.6: Architecture

The main components i.e endless terrain, cloud system, rigid body, and airplane are explained the following sections.

3.3 Procedural Terrain

3.3.1 Generating a chunk

Definition 2 (Chunk). A *chunk* refers to a rectangular mesh of predefined size, where each vertex contains height and normal vector information. Chunks serve as the basic building blocks for terrain generation and rendering.

In most implementations where non-repetitive chunks are required, noise algorithms are commonly used. The algorithm I have chosen is **Perlin Noise** [4], which is implemented in `perlin.cpp`. Assuming, for now that we have some sort of a Perlin noise implementation available, a chunk that only has height data may be generated as simply as the following pseudo code shows:

```
1 def generateChunkData(size, scale):
2     chunkData = ChunkData(size, size)
3     for i in range(size):
4         for j in range(size):
5             x = j * scale
6             y = i * scale
7             chunkData.height[i, j] = perlin(x, y)
8     return chunkData
```

Code 3.6: Chunk generation

Next, we will explore how to extend this basic chunk with additional data such as normals and how to tile these chunks together for a continuous terrain. We will also dive into techniques such as Level of Detail (LOD) and early culling, which help improve performance and rendering efficiency in large terrains. First, let's simplify Perlin Noise and look at how to calculate normals for our chunk data.

3.3.2 Perlin Noise

This section does not aim to provide a detailed theoretical explanation of the Perlin Noise algorithm. For a formal treatment, the reader is encouraged to refer to the original paper by Ken Perlin [4]. For a more intuitive and visual explanation, see the video referenced in [5].

Perlin Noise is a type of gradient noise that aims at generating smooth noise. If we, for instance, take a look at white noise where each pixel can be thought of as

having a uniform probability of having a value between 0 and 1. The generated map as illustrated in Figure 3.7 looks completely random and this would never work as a height map as the height of a terrain is continuous.

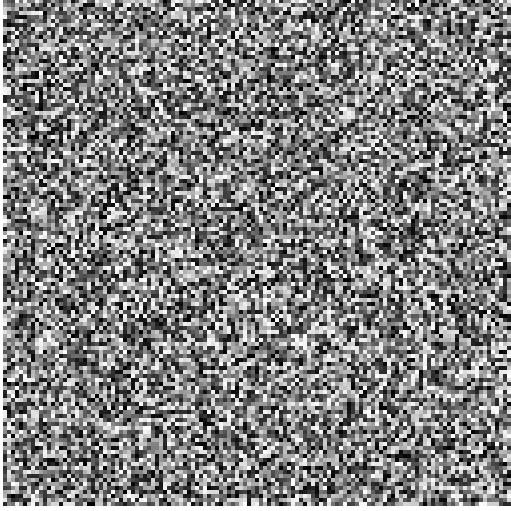


Figure 3.7: White Noise

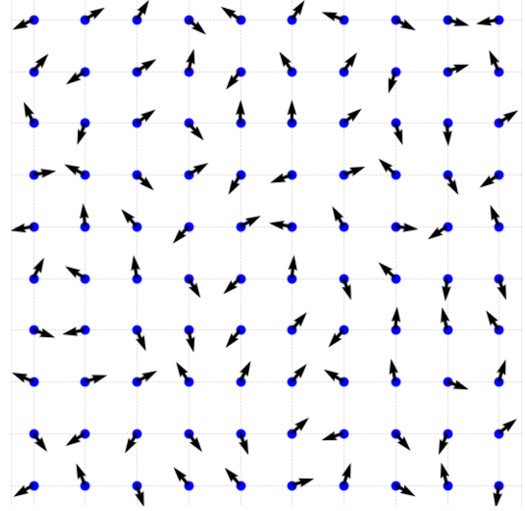


Figure 3.8: Perlin Grid

Before looking into how Perlin noise works, let's define the `lerp` function.

Definition 3 (`lerp`). Lerp is defined as :

$$\text{lerp}(a, b, p) = a + p(b - a)$$

Perlin noise works by dividing the plane into a grid, assigning a random gradient vector at each vertex, as shown in Figure 3.8. Consider a single grid cell, and label the corners as follows:

- Top-left: P_{tl} with gradient \vec{v}_{tl}
- Top-right: P_{tr} with gradient \vec{v}_{tr}
- Bottom-left: P_{bl} with gradient \vec{v}_{bl}
- Bottom-right: P_{br} with gradient \vec{v}_{br}

Let $U = (U_x, U_y)$ be a point inside the cell, and let (u, v) be the fractional parts of (U_x, U_y) relative to the cell.

Define direction vectors from each corner to U :

$$\vec{d}_{tl} = U - P_{tl}, \quad \vec{d}_{tr} = U - P_{tr}, \quad \vec{d}_{bl} = U - P_{bl}, \quad \vec{d}_{br} = U - P_{br}$$

Next, compute the dot products:

$$G_{tl} = \langle \vec{v}_{tl}, \vec{d}_{tl} \rangle, \quad G_{tr} = \langle \vec{v}_{tr}, \vec{d}_{tr} \rangle, \quad G_{bl} = \langle \vec{v}_{bl}, \vec{d}_{bl} \rangle, \quad G_{br} = \langle \vec{v}_{br}, \vec{d}_{br} \rangle$$

A smoothing function is used to interpolate values:

$$g(t) = 6t^5 - 15t^4 + 10t^3$$

Finally, the noise value at point U is computed using bilinear interpolation:

$$\text{noise}(U_x, U_y) = \text{lerp}(\text{lerp}(G_{tl}, G_{tr}, g(u)), \text{lerp}(G_{bl}, G_{br}, g(u)), g(v))$$

3.3.3 Calculating normals

In general, given a parametric surface $f(u, v)$ it is possible to obtain surface normal at specific points by the following formula:

$$\hat{n} = \frac{\frac{\partial f}{\partial u} \times \frac{\partial f}{\partial v}}{\left\| \frac{\partial f}{\partial u} \times \frac{\partial f}{\partial v} \right\|}$$

One way to imagine this is to see that $\frac{\partial f}{\partial u}$ and $\frac{\partial f}{\partial v}$ span the plane that is tangent to the surface, so their cross product gives the normal vector. For a more mathematically sound argument, you can refer to Paul's Online Notes [6]. In our case the mesh is made up of triangles as seen in Figure 3.9 but we can still calculate surface normals using cross products.

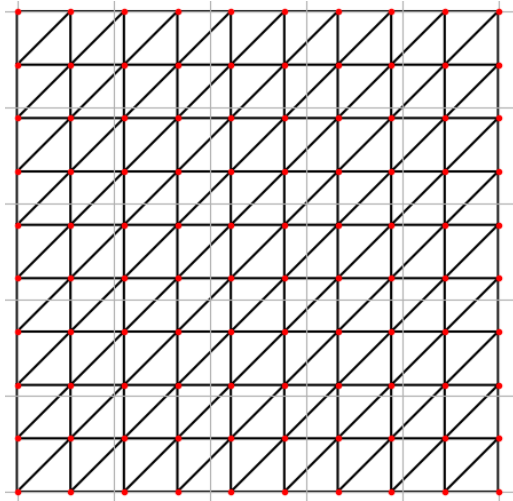


Figure 3.9: Mesh

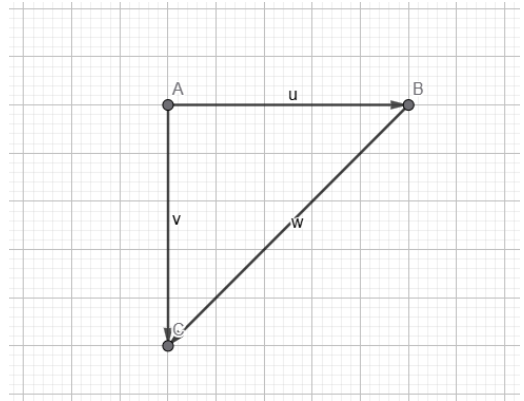


Figure 3.10: Calculating normal of a triangle

As Figure 3.10 shows we can calculate the normal at vertex **A** by calculating $u \times v$ (or $v \times u$ this direction is usually checked empirically) where u and v are the vectors of the triangle. This figure is 2d but it can be imagined the all 3 points **A**, **B**, and **C** are at different heights but the math works the same.

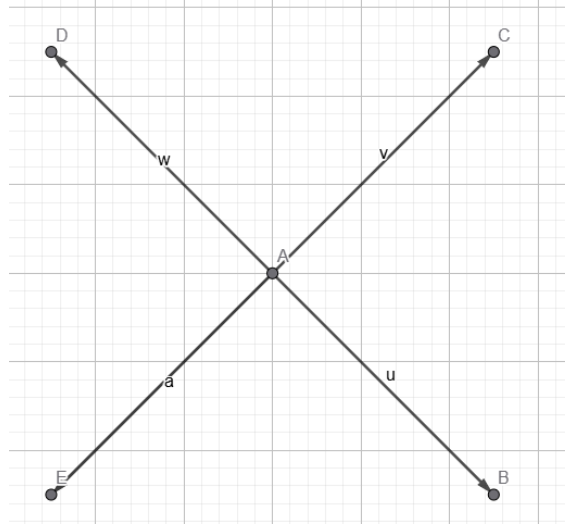


Figure 3.11: Normal Calculation

However, vertex **A** is in multiple triangles. Figure 3.11 shows my approach for calculating the normals. I take the 4 vertices around **A** let's call them $\mathbf{a}_0 \dots \mathbf{a}_3$ in either counterclockwise or clockwise ordering (depending on which way defines the vectors in the up direction). Then the normal vector can be calculated as follows:

$$\vec{n} = \frac{1}{4} \sum_{i=0}^{i=3} (\mathbf{a}_i - \mathbf{A}) \times (\mathbf{a}_{(i+1) \bmod 4} - \mathbf{A})$$

Which is the average of the the normal vectors for each of the 4 triangles. For this to work correctly, you must ensure the vertices are in the correct ordering.

As the picture above suggests, this breaks down at the edges of the mesh. To circumvent this issue, I pad the mesh with extra set of vertices that is used just for the calculation of normals.

So, the pseudocode with normals looks something like this:

```

1 def generateChunkData(size, scale):
2     heightData = Matrix(size + 2, size + 2) // matrix with num rows,
        cols = size + 2
3     for i in range(size + 2):
4         for j in range(size + 2):
5             x = j * scale

```

```
6     y = i * scale
7     heightData[i, j] = noise(x, y)
8
9     chunkData = ChunkData(size, size)
10    for i in range(1, size):
11        for j in range(1, size):
12            vs = getNeighbors(i, j) //should return list of 4 neighbors
13                                     in the correct order
14            vertex = Vector(i, heightData[i, j] ,j)
15            normal = Vector(0, 0, 0)
16            for k in range(4):
17                a = vs[k]
18                b = vs[(k + 1) % 4]
19                normal += cross(a-vertex, b-vertex)
20            mag = normal.magnitude()
21            if mag != 0:
22                normal /= mag
23            chunkData[i-1, j-1].height = heightData[i, j]
24            chunkData[i-1, j-1].normal = normal
25    return chunkData
```

Code 3.7: Chunk generation Part 2

3.3.4 Geometry Shaders and verifying the correctness of the normals

It still needs to be checked if the normals calculated are actually correct and one way of doing that is to visualize them using geometry shaders. A tutorial for which can be found on LearnOpenGL [3]. The **Shader** class provided with the engine takes an optional third argument -the geometry shader source file- so, integrating it into the existing system is easy.

A geometry shader can take primitives as input (a triangle in our case) and can output primitives. For each vertex of the triangle we can emit a line with two vertices one at the original vertex, the other one in the direction of the normal but scaled by some constant α .

The scene must be rendered twice once with the normal shader and again with the geometry shader. Figure 3.12 was obtained using this pipeline:

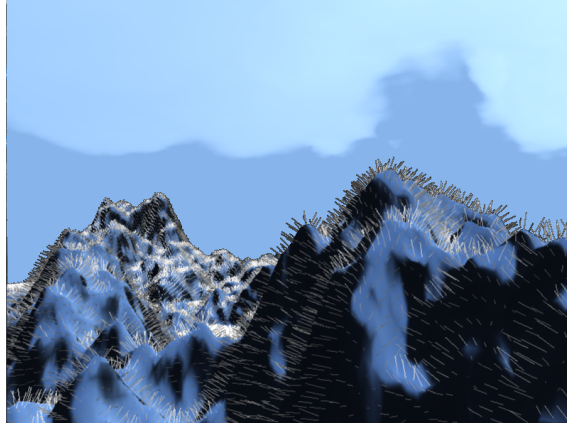


Figure 3.12: Visualizing Terrain Normals

3.3.5 Tiling the chunks

Once we have the chunk generation function above it's not too hard to tile them. Since Perlin Noise accepts (x, y) as the arguments we just need to make sure when going from one chunk to the next we give the correct coordinates to Perlin Noise. To do this, I extended the chunk generation function to accept one more argument: its `center`, using this it calculates the noise as it previously did from its top left corner but this time shifted by the `center` coordinates.

The following pseudocode explains how it is done:

```
1 def generateChunkData(size, center, scale):
2     heightData = Matrix(size + 2, size + 2) // matrix with num rows,
        cols = size + 2
3     tlX = (size - 1) / -2.0 // top left x
4     tlY = (size - 1) / 2.0 // top left y
5     for i in range(-1, size + 1):
6         for j in range(-1, size + 1):
7             x = (center.x + tlX + j) * scale
8             y = (center.y + tlY - i) * scale
9             heightData[i, j] = noise(x, y)
10
11 //rest remains same
```

Code 3.8: Chunk generation Part 3

If the loop started from 0, then `center.x + tlX` would give the x-coordinate of the current chunk. However, at index (0,0), we actually want to sample from the previous chunk's coordinate space due to the padding added for normal calculation.

Therefore, the loop must begin at -1 to correctly align the noise sampling with the padded grid.

3.3.6 Level Of Detail (LOD)

It's important for a better FPS to render the chunks near the player at a higher level of detail than those that are further away. LOD can be thought of in this case as the number of vertices in a given area or volume.

To do this I first create a mesh and then further lower resolution meshes are created by skipping some vertices in the original mesh such that the first and the last vertices are not skipped because the mesh must extend from and to the same points. This begs the question then what should be the size of the original mesh? Consider a 1d mesh of size 10 as the picture below 3.13 illustrates. We cannot skip every 2nd vertex because then we will have $\langle 0, 2, 4, 6, 8 \rangle$ and the last 9th vertex would be skipped.



Figure 3.13: 1D mesh

So, if k is the skip factor and s is the size of the mesh, then for us to be able to create a mesh, k must divide $s - 1$. We need to find s such that $s - 1$ has a lot of divisors, and a commonly chosen number is 241 since every number from 1 to 6 divides 240 so we can create a mesh that has $\frac{1}{6}$ of the vertices in the original mesh.

A common approach for this is to generate these meshes on the fly as a function of the distance from the player's coordinates. However, I found this method to not match my FPS goals. So, what I do instead is create the 6 LOD meshes beforehand and give the corresponding mesh its height and normal data through a texture. Height and normal data are stored in a texture, where both of them are packed into a `vec4` using the red, green, blue, and alpha channels. Each mesh then simply samples from this texture to obtain terrain shape and lighting information.

Unlike traditional LOD systems that generate meshes at runtime based on camera distance, this approach precomputes multiple LOD meshes and uses texture data

to drive the final geometry. This reduces runtime computation and improves FPS stability at the cost of some memory overhead.

The image 3.14 below illustrates how **LOD** meshes look like in practice.

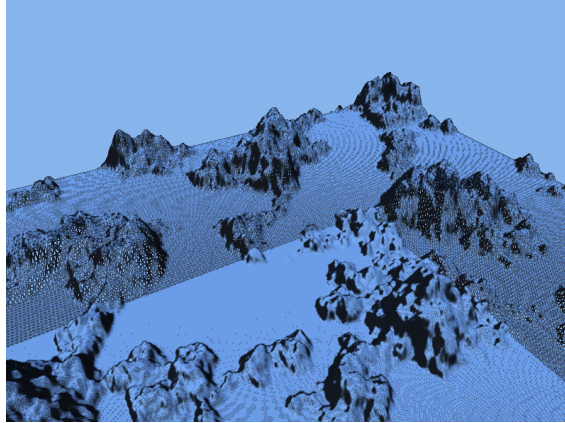


Figure 3.14: Visualizing LOD Terrain

3.3.7 Multithreading

It is not feasible to draw and generate new chunks on the same thread; for instance, we may need to generate 9 chunks at once, which would block the main render loop and drop the frame rate. To avoid this, a new thread is dispatched for generating data for each chunk. Since the meshes are already pre-generated (as discussed in the LOD section), the data needed is just height and normals. Figure 3.15 illustrates this pipeline.

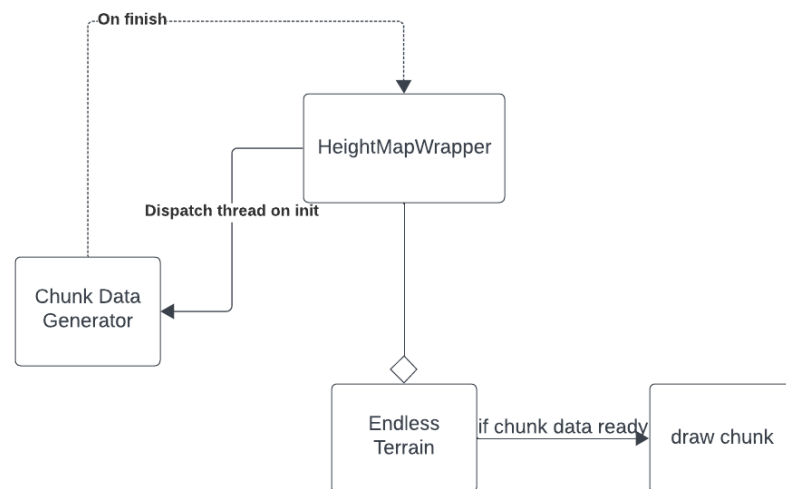


Figure 3.15: Chunk Drawing Pipeline

The `EndlessTerrain` class only draws a chunk once its data is ready. When a chunk is needed, it initializes a `HeightMapWrapper` instance, passing in the chunk center. This wrapper then launches a new thread to request height and normal data from the `ChunkDataGenerator` (which is just a simple function in the code). Once the data is computed, it is returned via a callback function, completing the pipeline.

IMPORTANT:

It is crucial to note that OpenGL operates strictly on a single thread—all OpenGL commands must be issued from the same thread that initialized the OpenGL context. Because of this, the `HeightMapWrapper` class handles all computation on the CPU first. Once the data is available (from the background thread), it schedules OpenGL commands to upload the data to the GPU as a texture, all on the main thread.

3.3.8 Caching and the `LRUCache` class

Imagine we generate 9 chunks around the player for a single frame, to avoid re-generating them in the next one we must cache them. A straightforward solution would be to use a hashmap where the key is the center of the chunk and the value is the corresponding height map. However, this approach leads to an unbounded cache, which can eventually exhaust system memory.

To solve this, I used the `LRUCache` class that comes with the engine—a bounded version of the classic hashmap. If the maximum cache size is n and a new key is inserted when the cache is full, the least recently used (LRU) key is evicted to make space.

Since `LRUCache` is a well-known data structure, its full implementation details are omitted. However, figure 3.16 illustrates its core design using a doubly linked list, which should provide enough insight into how the code operates.

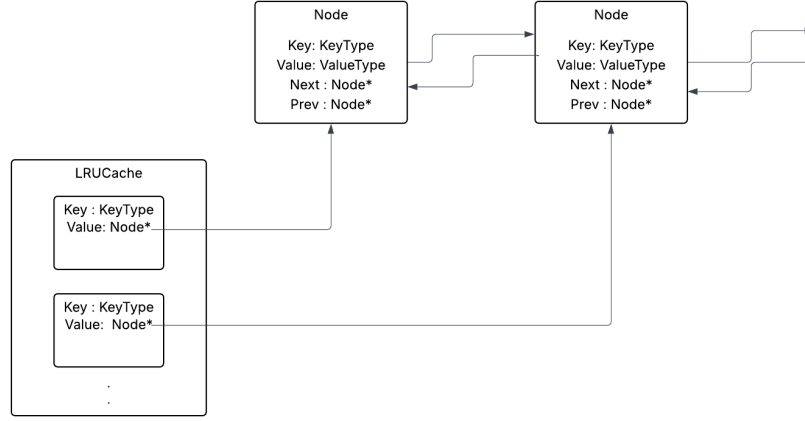


Figure 3.16: LRU Cache design

3.3.9 Early Culling

Notice that the methods above issue generate and draw commands for chunks that are not in the view frustum of the player. This introduces an overhead that can be easily avoided. For instance, the chunks that are behind the player can be omitted. To address this, I use a simple directional culling approach: Say, \vec{d} is the direction of the camera and \mathbf{P} is its position, when we are generating the i_{th} chunk with center \mathbf{C}_i around the player, let $\vec{v} = \mathbf{P} - \mathbf{C}_i$ be the direction of the chunk. We only generate data for the chunk if $\langle \vec{d}, \vec{v} \rangle > 0$ that is, both of those vectors point in the same direction. Note that if \vec{v} is 2 dimensional that \vec{d} must be projected on to the plane. In the code provided, \mathbf{P} is projected onto the $x - z$ plane and so is \vec{d} .

Result: This optimization led to a significant performance gain—FPS improved, and memory usage dropped from around 500 MB to around 100MB.

3.4 Volumetric Clouds

This section explains my implementation of volumetric clouds. Before delving into the details, I would like to acknowledge the resources that were instrumental in my work and would like to thank the online community: [1] [2] [7] [8] [9] [10] [11] [12] [13].

3.4.1 Ray Marching

Before rendering clouds, it's essential to understand the basics of ray marching. Ray marching is a technique where we trace rays for each pixel on the screen. Unlike ray tracing, which requires information about polygonal geometry, ray marching only requires access to a signed distance function (sdf).

A signed distance function for an object O and a point P returns the distance from P to the nearest point on O 's surface. It is:

- positive if P is outside the object
- negative if P is inside
- and zero if P lies on the surface

For example, the signed distance function for a sphere is:

$$\text{sdf}(p) = \|p - c\| - r$$

where c is the center and r is the radius of the sphere.

A ray is defined by its origin P and direction \vec{d} . We represent it as a function of time:

$$R(t) = P + \vec{d}t$$

If there are multiple objects in the scene, the scene's overall signed distance function is defined as:

$$\text{sdf}_{\text{world}}(P) = \min_{\text{objects}} \text{sdf}_{\text{object}}(P)$$

Ray marching works by advancing the ray by the distance given by the sdf at each step, as illustrated in the following code snippet:

```
1 int MAX_STEPS = 1000;
2 float MIN_DIST = 1e-4;
3 float MAX_DIST_TRAVEL = 1e3;
4
5 vec3 trace(Ray r) // returns light info
6 {
7     vec3 currentPos = r.pos;
8     float totalDistTraveled = 0.0;
9
10    for (int i = 0; i < MAX_STEPS; ++i)
11    {
```

```

12     currentPos = r.pos + r.direction * totalDistTraveled;
13     float dist = sdf_world(currentPos);
14
15     if (dist < 0) break;
16
17     else if (dist < MIN_DIST) {
18         // do light calculation
19         return /* light info */;
20     }
21
22     if (totalDistTraveled > MAX_DIST_TRAVEL) break;
23
24     totalDistTraveled += dist;
25 }
26 return vec3(0.0);
27 }

```

Code 3.9: Basic Ray Marching

The illustration in Figure 3.17 shows this process in 2D, which can be interpreted as a top-down view of a 3D scene.

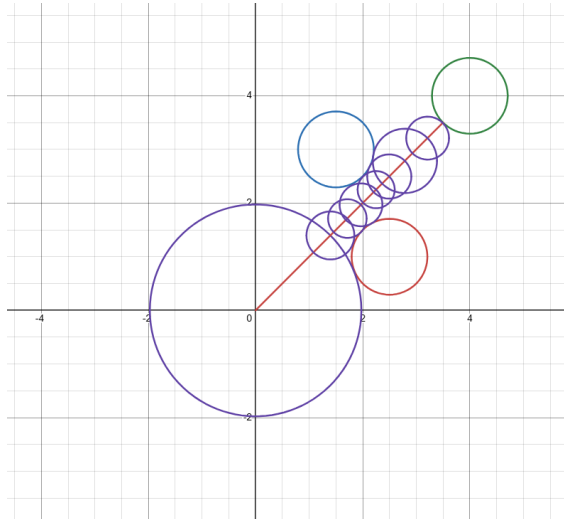


Figure 3.17: Ray marching example

When $\text{sdf}(p) = 0$, the surface near point p can be locally approximated by the equation $\text{sdf}(p) = 0$. For an implicit surface $f(x, y, z) = c$ (which can be thought of as a equipotential surface in 3D or level curve in 2D), the surface normal is given by the gradient:

$$\nabla f = \left\langle \frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z} \right\rangle$$

Using a symmetric finite difference approximation:

$$\frac{df}{dx} \approx \frac{f(x+h) - f(x-h)}{2h}$$

we can approximate the normal at point p from the signed distance function as:

$$\vec{n} = \left\langle \text{sdf}(p + h\hat{i}) - \text{sdf}(p - h\hat{i}), \text{sdf}(p + h\hat{j}) - \text{sdf}(p - h\hat{j}), \text{sdf}(p + h\hat{k}) - \text{sdf}(p - h\hat{k}) \right\rangle$$

This normal vector is then used in lighting calculations.¹

3.4.2 Ray Marching for rendering volumes

For rendering volumetric surfaces like clouds instead of using *sdf* functions a fixed step size δ is chosen and the ray is moved forward by this step size at each step. At each point P in space density is sampled and the rendering is done based on how much density was observed, how much light passed through and so on. More details are in the following section but first for clouds my implementation makes a rectangular area in the sky where the clouds can be, this is a axis aligned bounding box (AABB). First, a check is done to see if the ray intersects this box; if yes, only then is the ray marched through the box. Next, we derive the intersection of a ray with AABB. Remember that a ray is given as $R(T) = P + \vec{d}t$. An axis aligned box can be defined by its top left coordinates and bottom right coordinates denoted as b_{min}, b_{max} .

$$\begin{aligned} b_{min} &\leq P + \vec{d}t \leq b_{max} \\ b_{min} - P &\leq \vec{d}t \leq b_{max} - P \end{aligned}$$

which gives 3 inequalities:

$$\begin{aligned} \frac{(b_{min,x} - P_x)}{\vec{d}_x} &\leq t \leq \frac{(b_{max,x} - P_x)}{\vec{d}_x} \\ \frac{(b_{min,y} - P_y)}{\vec{d}_y} &\leq t \leq \frac{(b_{max,y} - P_y)}{\vec{d}_y} \\ \frac{(b_{min,z} - P_z)}{\vec{d}_z} &\leq t \leq \frac{(b_{max,z} - P_z)}{\vec{d}_z} \end{aligned}$$

¹This reasoning was derived independently (so it's more intuitive than rigorous) but is consistent with standard SDF-based normal estimation techniques used in ray marching.

if $[t_{min}, t_{max}]$ is the intersection of those intervals, then the ray intersects the box if $t_{max} \geq t_{min}$ with t_{min} being the nearest point of intersection and t_{max} being the furthest. If the point is inside the box then clearly, $t_{min} < 0$ in this case we return t_{max} as the intersection t . if $t_{max} < 0$, the box must be behind the ray, so there is no intersection.

3.4.3 Worley Noise

Worley noise is a type of cellular noise that we are going to use for generating density textures for clouds. Typically, Worley noise works by choosing n random feature points, in my code I have taken the liberty to call them anchor points. Then for a pixel at location p we calculate its value:

$$v_p = \min_{anchors} \|p - a_i\|$$

v_p for all pixels should be normalized such that $0 \leq v_p \leq 1$. Figure 3.18 visualizes how this looks like.

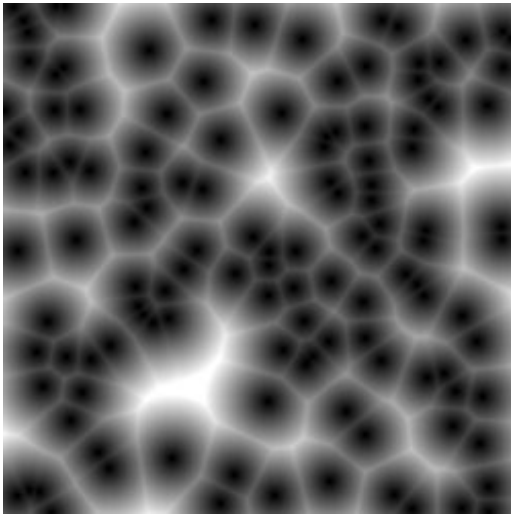


Figure 3.18: Worley Noise [14]

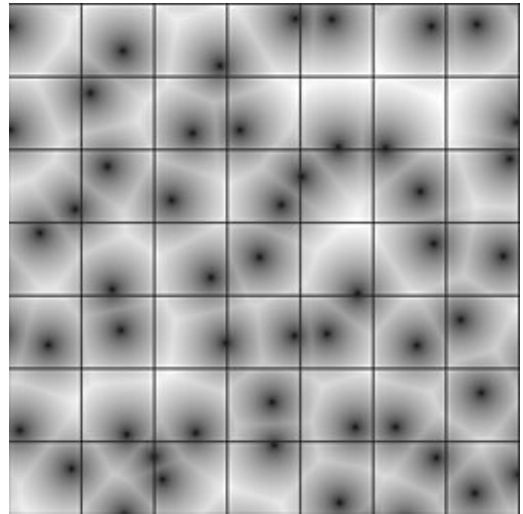


Figure 3.19: Grid Based Worley Noise [14]

However, the naïve approach is computationally expensive, since it requires computing distances from each pixel to all anchor points—scaling poorly as the number of anchors increases. To make it efficient, a grid-based approach is used: the space is divided into regular grid cells, and one anchor point is placed in each cell.

Now, the nearest anchor point for any given pixel can only lie within its own grid cell or one of the adjacent cells. This reduces the number of distance checks significantly.

Normalization becomes straightforward as well: in 2D, the maximum possible distance to a corner in a unit grid cell is $\sqrt{2}$ (assuming the grid cells are of unit area), so the normalized score s_p is:

$$s_p = \frac{v_p}{\sqrt{2}}$$

Similarly, in 3D, the normalization factor becomes $\sqrt{3}$:

$$s_p = \frac{v_p}{\sqrt{3}}$$

A more useful version in our case is **Inverted Worley Noise** which is calculated as $1 - s_p$. This gives the bubbly shapes that clouds have as the figure 3.20 below illustrates:

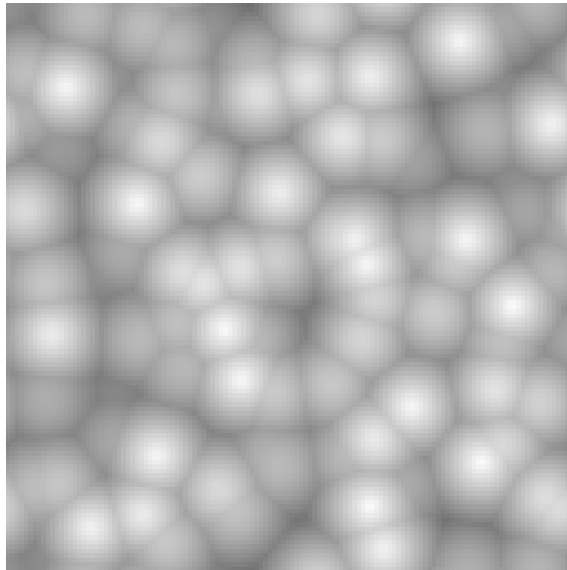


Figure 3.20: Inverted Worley Noise

In the following sections when I say Worley noise, I mean Inverted Worley Noise unless otherwise stated.

3.4.4 Making Tileable Worley Noise

As we will see in the following sections, Inverted Worley noise is used for generating 3D density textures which must be tileable. This means for a pixel on the edge

we must take into consideration the cell that is on the other edge (imagine wrapping the grid around like a torus) and the anchor point it contains. My approach for this was to use what I called a deterministic random function which always produces the same value for the same input. The code snippet below shows how it works:

```
1 //returns anchor points for grid cell at position pos
2 def det_random(pos : tuple):
3     random.seed(hash(pos))
4     return [random.random() for i in range(len(pos))]
```

Code 3.10: Deterministic Random Function

Given some grid coordinates this function generates the anchor point for that cell, even though the anchor point itself is random, it will always give the same anchor point for a given grid cell (in that sense it is deterministic). This way we don't have to store these anchor points. Then we can get the score (or the color) for a pixel as follows:

```
1 //returns anchor points for grid cell at position pos
2 NUM_TILES = #number of tiles (boxes)
3 BOX_WIDTH = WIDTH / NUM_TILES
4 BOX_HEIGHT = HEIGHT / NUM_TILES
5 MAX_DIST = sqrt(BOX_WIDTH * BOX_WIDTH + BOX_HEIGHT * BOX_HEIGHT)
6 def get_color(x, y):
7     color = 0.0
8     min_d = float('inf')
9
10    #get tile coordinates
11    tileX = x // BOX_WIDTH
12    tileY = y // BOX_HEIGHT
13
14    #iterate over neighbor tiles
15    for i in range(-1, 2):
16        for j in range(-1, 2):
17            neighbor_y = (tileY + i) % NUM_TILES
18            neighbor_x = (tileX + j) % NUM_TILES
19            anchor_offsetX, anchor_offsetY = det_random((neighbor_x,
20                                                         neighbor_y))
21
22    #rescale to actual coordinates, note these are not wrapped
23    anchor_x = (tileX + j + anchor_offsetX) * BOX_WIDTH
24    anchor_y = (tileY + i + anchor_offsetY) * BOX_HEIGHT
```

```
24
25     min_d = min(min_d, dist((x, y), (anchor_x, anchor_y)))
26 color = min_d/MAX_DIST
27 #inverted Worley
28 return (1 - color)
```

Code 3.11: Tileable Worley Noise

All textures used in the game were pre generated using Python and the corresponding code can be found in the `noise_scripts` subdirectory.

3.4.5 Fractional Brownian Motion

Nearly all noise functions used in procedural generation benefit from a technique called **Fractional Brownian Motion** (fBM). It enhances basic noise by layering multiple octaves—copies of the noise function with increasing frequency and decreasing amplitude—to produce a more complex, self-similar structure reminiscent of fractals. This gives a more natural, detailed appearance when zoomed in.

The following code shows a typical fBM implementation:

```
1 FREQ_MULT = 2.0
2 AMPL_MULT = 0.5
3
4 def fbm(x, y, octaves):
5     ampl = 1 #amplitude
6     freq = 1 #frequency
7     value = 0.0
8     max_val = 0.0
9
10    for i in range(octaves):
11        value += ampl * noise(x, y)
12        max_val += ampl
13        ampl *= AMPL_MULT
14        x *= FREQ_MULT
15        y *= FREQ_MULT
16
17    return value/MAX_NOISE_VAL # normalized
```

Code 3.12: Fractional Brownian Motion

Imagine a plot of a signal, the code above adds higher and higher frequency values of the signal with lower amplitudes to itself to make it appear self-similar.

3.4.6 Perlin Worley Noise

The inverted Worley noise is combined with Perlin noise to add detail to the low-density regions of Perlin noise, creating textures that result in puffier-looking clouds—a technique originating from Guerrilla Games [7]. Before presenting the formula used to combine the two types of noise, we first define the remap function.

Definition 4 (Remap function).

$$\text{Remap}(a, \text{old_min}, \text{old_max}, \text{new_min}, \text{new_max}) = \\ \text{new_min} + (\text{new_max} - \text{new_min}) \frac{a - \text{old_min}}{\text{old_max} - \text{old_min}}$$

Let p represent Perlin noise and w the inverted Worley noise. The Perlin-Worley noise is computed as:

Definition 5 (Perlin Worley Noise).

$$\text{PerlinWorley}(p, w) = \text{remap}(p, 0.0, 1.0, w, 1.0)$$

The figures below shows how FBM worley noise combined with Perlin noise looks like.

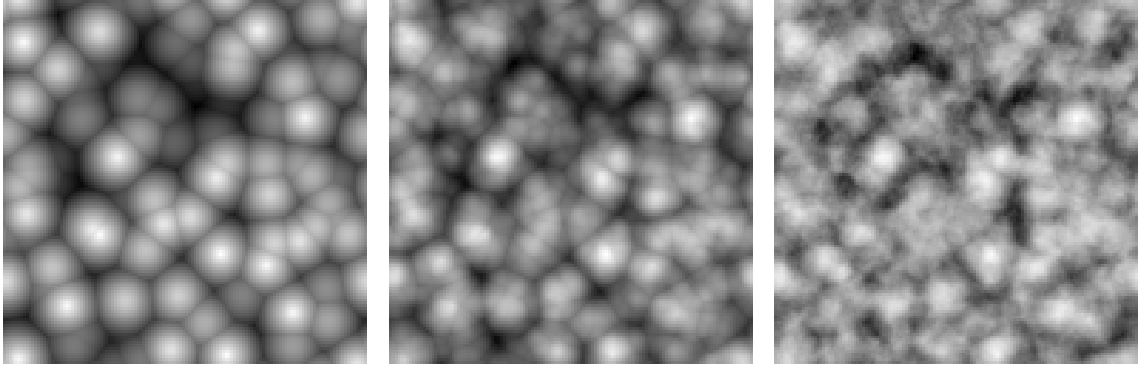


Figure 3.21: Worley Noise

Figure 3.22: FBM Worley Noise

Figure 3.23: Perlin Worley Noise

3.4.7 Textures And Sampling Density For Clouds

One of the 3D textures for clouds contains Perlin-Worley noise in the red channel, and Worley noise of increasing Frequencies in the green, blue, and alpha channels, this is referred to as the low frequency noise texture and its size is $128 \times 128 \times 128$. The base cloud is obtained as follows [13]:

```
1 float getCloudDensity(vec3 p)
2 {
3     /*
4     normalize p before hand
5     to be able to sample nicely from the texture,
6     in the code, this is usually done by multiply
7     p with a uniform scale variable.
8     */
9     vec4 low_freq = texture(cloudTexture, p);
10    float wfbm = 0.625 * low_freq.g + 0.25 * low_freq.b + 0.125 *
        low_freq.a;
11    float baseCloud = Remap(low_frequency_noises.r, wfbm-1.0, 1.0,
        0.0, 1.0);
12
13    return baseCloud;
14
15 }
```

Code 3.13: Base Cloud

Another 3D texture referred to as high frequency noise texture contains Worley noise of increasing Frequencies, its size is $32 \times 32 \times 32$, and this is used for adding details on the edges of the clouds – this step can be optimized, as we only need to add details to those clouds that are near a certain threshold to the camera.

The last texture that I use is called a weather texture that contains following values [13]:

- Cloud Coverage: The percentage of cloud coverage in the sky
- Precipitation: The chance that clouds will rain (This is not used in my code)
- Cloud Type: A value of 0.0 indicates stratus, 0.5 indicates stratocumulus, and 1.0 indicates cumulus clouds.

I found the following code snippet on [10] for getting the density of of a cloud based on its type which is given by the weather map:

```
1
2 #define STRATUS_GRADIENT vec4(0.0, 0.1, 0.2, 0.3)
3 #define STRATOCUMULUS_GRADIENT vec4(0.02, 0.2, 0.48, 0.625)
4 #define CUMULUS_GRADIENT vec4(0.00, 0.1625, 0.88, 0.98)
```

```
5
6 float getDensityForCloudOfType(float heightFraction, float
   cloudType){
7     float stratusFactor = 1.0 - clamp(cloudType * 2.0, 0.0, 1.0);
8     float stratoCumulusFactor = 1.0 - abs(cloudType - 0.5) * 2.0;
9     float cumulusFactor = clamp(cloudType - 0.5, 0.0, 1.0) * 2.0;
10
11     vec4 baseGradient = stratusFactor * STRATUS_GRADIENT +
        stratoCumulusFactor * STRATOCUMULUS_GRADIENT + cumulusFactor
        * CUMULUS_GRADIENT;
12
13     float result = remap(heightFraction, baseGradient.x,
        baseGradient.y, 0.0, 1.0) * remap(heightFraction,
        baseGradient.z, baseGradient.w, 1.0, 0.0);
14     return result;
15 }
```

Code 3.14: Calculating Specific Cloud Density

To understand what this function is doing, we imagine that the `cloudType` is 0, in which case the `baseGradient` will just be `STRATUS_GRADIENT` which defines how the density for the stratus cloud should be. Since stratus clouds are at lower height, the first remap in line 13 is saying: the density should increase from 0.1 to 0.2 height, the second remap is saying: the density should decrease from height 0.2 to 0.3, their multiplication gives a gradient (a quadratic function) that is plotted in the image 3.24 below:

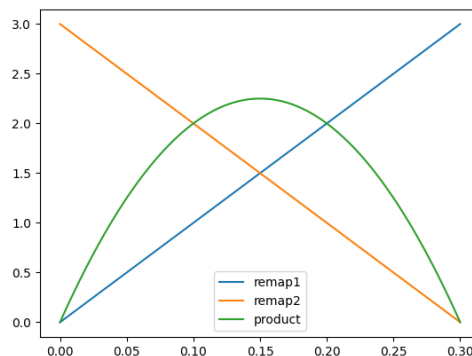


Figure 3.24: Height Gradient of Stratus Cloud

The base cloud above is then enhanced the following way [13] [10]:

```
1 float getCloudDensity(vec3 p)
2 {
3     /*baseCloud same as above
4     boundsMin, boundsMax are the min, max coords of the bounding
5     rectangle (AABB)
6     */
7     /*this line is not needed if your coverage texture is good
8     enough.*/
9     baseCloud = max(baseCloud-densityThreshold, 0.0)
10
11     heightFraction = (p.y - boundsMin.y)/(boundsMax.y-boundsMin.y)
12     weatherData = getWeatherTexture(p); //get data from weather
13     texture
14
15     float heightGradient = getDensityForCloudOfType(weatherData.r);
16     baseCloud *= heightGradient;
17
18     float coverage = clamp(weatherData.g, 0., 1.) *
19     coverageMultiplier;
20     float coverageCloud = remap(baseCloud, coverage, 1., 0., 1.);
21     coverageCloud *= coverage;
22     float finalCloud = coverageCloud;
23
24     if (finalCloud > 0)
25     {
26         /*make sure to scale p here too*/
27         high_freq = texture(cloudHighTexture, p);
28         float highFBM = high_freq.r * .625 + high_freq.g * .25 +
29             high_freq.b * .125;
30         /*introduce some height based turbulence*/
31         float highModifier = mix(highFBM, 1.0-highFBM, saturate(
32             heightFraction * 10.0));
33         /*add details to edges of the cloud (where density is lower
34         )*/
35         finalCloud = remap(finalCloud, highModifier*0.2, 1.0, 0.0,
36             1.0);
37     }
38     return finalCloud;
39 }
```

Code 3.15: Density For Cloud

Chapter 4

Conclusion

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In case your thesis received financial support from a project or the university, it is usually required to indicate the proper attribution in the thesis itself. Special thanks can also be expressed towards teachers, fellow students and colleagues who helped you in the process of creating your thesis.

Appendix A

Simulation results

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