

RayCast Renderer Documentation

Contents

1	Overview	2
2	Core Classes and Concepts	2
2.1	Vec3 Class	2
2.2	Point Class	3
2.3	Color Class	4
2.4	Object Class	9
2.5	Ray Class	12
2.6	Ray Projection	15
2.7	Camera Class	16
2.8	Intersection Logic	20
2.9	Space Layout	24
3	Rendering Results and Examples	26
3.1	Simple Rendering	26
3.2	Complex Models	28
3.3	Rendering Errors and Fixes	31
3.4	Low Ray Density Impact	32
4	Supporting Visualizations and Code Representations	33
4.1	Image Class and Pixel Mapping	33
4.2	MeshReader and 3D File Format Handling	34

1 Overview

The RayCast Renderer is a project that implements a lightweight 3D rendering engine using ray tracing principles. This document explains the core components, functions, and test cases provided in the code, while incorporating all 43 provided images for illustrative purposes.

2 Core Classes and Concepts

2.1 Vec3 Class

The `Vec3` class represents 3D vectors, which are fundamental to defining directions, triangle vertices, and performing spatial operations such as normalization.

Features and Functionality:

- **Representation:** Each `Vec3` instance encapsulates three floating-point values (x, y, z).
- **Mathematical Operations:** Includes addition, subtraction, dot product, cross product, and normalization.
- **Normalization:** Ensures vectors have unit length for accurate calculations.

Example:

- A normalized vector is expressed as:

```
Direction = Vec3(x, y, z).normalize()
```

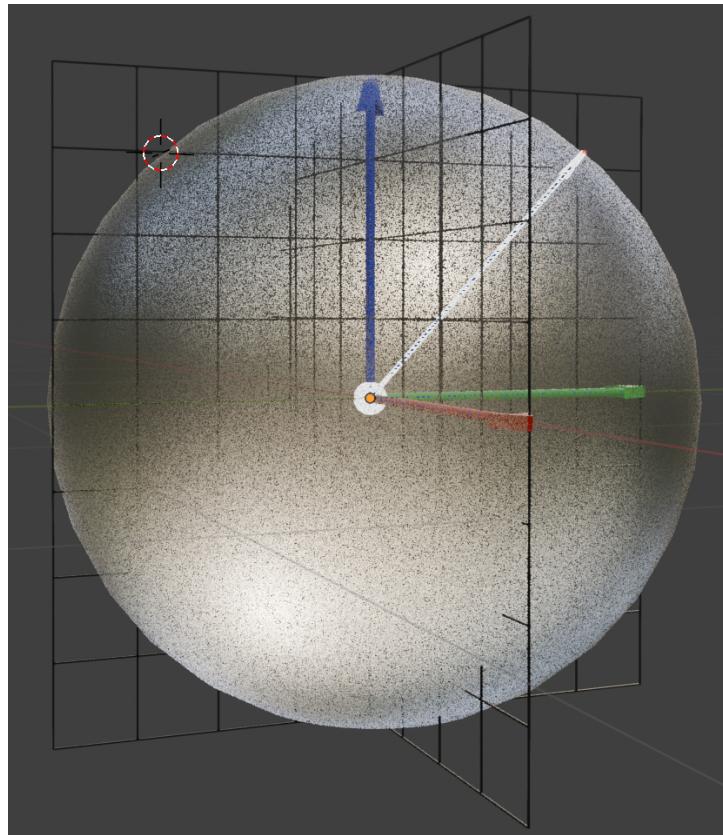


Figure 1: 3D Representation of the `Vec3` Class

Importance: The `Vec3` class underpins geometric and directional calculations.

2.2 Point Class

The Point class defines specific spatial locations in 3D space, forming the fundamental building blocks of the RayCast renderer. These points are used to define triangle vertices, ray origins, and other geometric constructs.

Features and Functionality:

- **Representation:** Each Point instance encapsulates three floating-point values (x, y, z), representing a fixed position in a 3D space.
- **Vertex Specification:** All geometric objects are represented as a collection of triangles. The vertices of each triangle are defined using the Point class.
- **Ray Origins:** Rays emitted from the camera originate at specific points in the 3D space.
- **Mathematical Operations:** Supports addition, subtraction, and interpolation for ray-triangle intersection tests and transformations.

Logic and Implementation:

- A triangle is represented by three points:

$$\text{Triangle} = \{\text{Point}(x_1, y_1, z_1), \text{Point}(x_2, y_2, z_2), \text{Point}(x_3, y_3, z_3)\}.$$

- A ray is expressed as:

$$\text{Ray}(t) = \text{Point}(x, y, z) + t \cdot \text{Vec3}(dx, dy, dz),$$

where t determines the position along the ray.

```

10
11  /**
12   * @class point
13   * @brief Represents a point in 3D space.
14   * The point class encapsulates a point defined by x, y, z coordinates.
15   * It provides methods to get and set these attributes, as well as to compute the distance
16   * to another point, translate the point by a vector, compute the midpoint between two points,
17   * and overload operators for addition, subtraction, and multiplication.
18   * Inherits from vec3 class.
19   */
20  class point : public vec3 {
21  public:
22      // Default constructor (origin point)
23      point() : vec3(0, 0, 0) {}
24

```

Figure 2: Point Class Code Representation

Visualization of Point Class Usage:

- **Point Definition:** Each vertex of a triangle is defined as a Point.

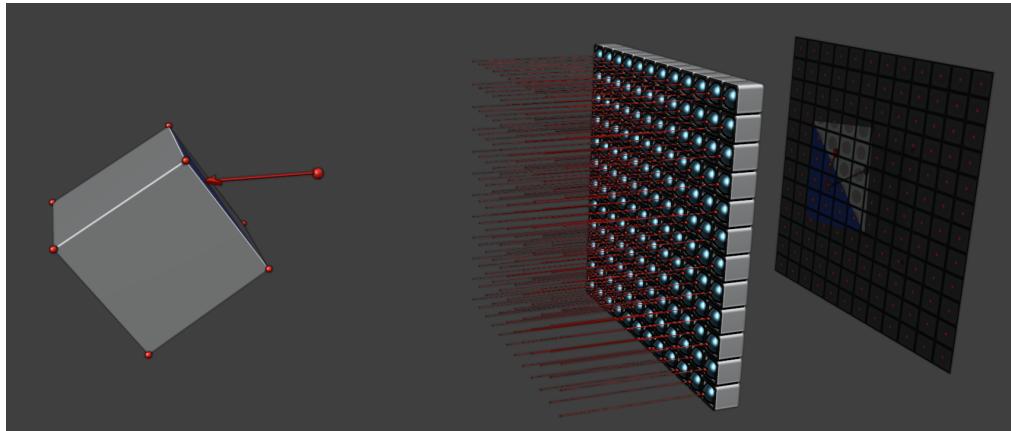


Figure 3: Spatial Layout of Points, Camera, and Objects

- **Ray Originating at a Point:** Points align ray origins with the camera's image plane.

```

14
15  /*
16   * @class camera
17   * @brief Represents a camera in 2D space.
18   * The camera class encapsulates a camera defined by a 2D array of gridRay.
19   * It provides methods to get and set these attributes, as well as to clear the camera.
20   * Inherits from color class.
21   *
22  */
23 v class camera {
24     private:
25         vector<vector<ray>> gridRay;
26         unsigned int width;
27         unsigned int height;
28         image img;

```

Figure 4: Camera Emitting Rays from Specific Points

- **Point Mapping in a Scene:** Demonstrates how Point instances define vertices.

```

void testSpaceCamera() {
    std::cout << "_____Space Test_____"

```

// Define the grid size
`unsigned int size = 100;`
`double step = 0.2;`

Figure 5: Low-Resolution Cube Render Highlighting Points as Vertices

Importance of the Point Class:

- Defines geometric objects, such as triangles.
- Ensures accurate spatial representation for ray casting.
- Supports intersection calculations for visibility and shading.

```

void testSpaceCamera() {
    std::cout << "_____Space Test_____"

```

// Define the grid size
`unsigned int size = 1000;`
`double step = 0.01;`

Figure 6: Higher-Resolution Cube Render Showing Enhanced Detail from Accurate Point Mapping

2.3 Color Class

The Color class is responsible for handling the RGB values used to define the surface colors of objects and the pixel colors in the rendered image. It plays a crucial role in producing visually accurate and appealing renders by enabling color assignment during ray-object intersections.

Features and Functionality:

- **RGB Representation:** Each Color instance stores three values (R, G, B) representing the red, green, and blue color intensities, typically ranging from 0 to 255.

- **Color Assignment:** During the rendering process, the `Color` class assigns specific colors to pixels based on the surfaces of intersected objects.
- **Blending and Interpolation:** Supports blending multiple colors to simulate effects such as shading or transitions between materials.

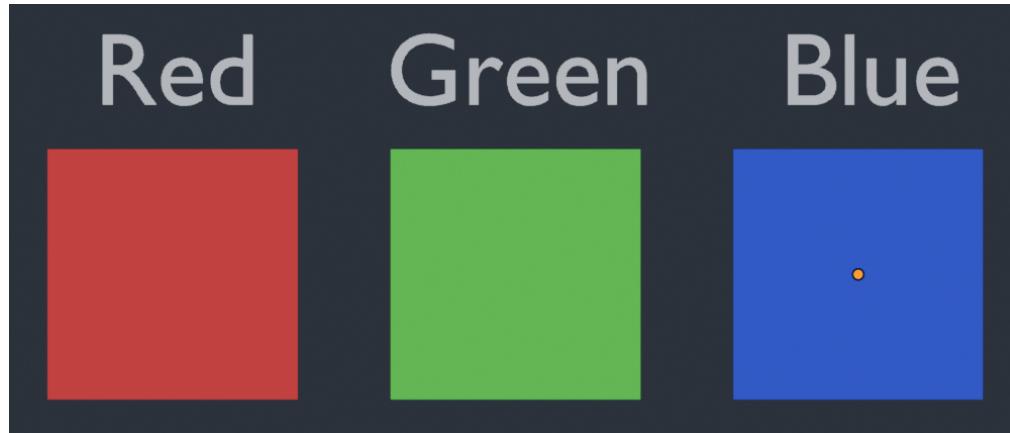


Figure 7: Representation of the Color Class Showing RGB Components

Logic and Implementation:

- Each triangle is assigned a specific `color`, determining its appearance in the final rendering.
- The renderer calculates the pixel color by associating the intersection of the ray object with the color of the corresponding triangle .
- For objects with gradients or dynamic shading, the `Color` class interpolates values to produce smooth transitions.

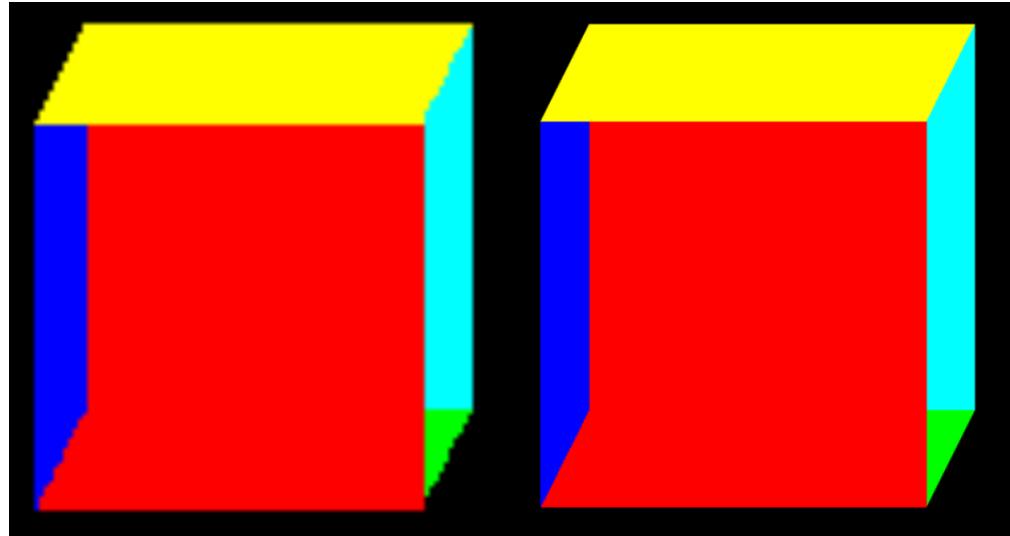


Figure 8: Example of a Rendering Error Where Incorrect Color Assignment Occurred

Visualization of Color Application:

- **Object Coloring:** Each triangle of an object is assigned a specific `Color`, creating a cohesive appearance when rendered.



Figure 9: Suzanne Model Rendered with a Uniform Blue Color



Figure 10: Suzanne Model Rendered with a Uniform Red Color

- **Multiple Color Assignments:** Objects can have varied colors for different triangles or regions.

```
void testSpaceCamera() {
    std::cout << "_____Space Test_____ " << std::endl;

    // Define the grid size
    unsigned int size = 100;
    double step = 0.2;
```

Figure 11: Cube Render Demonstrating Different Colors for Each Triangle

- **Corrected Render:** After fixing color assignment logic, objects are rendered with accurate colors.

Rendering Output with Corrected Logic:

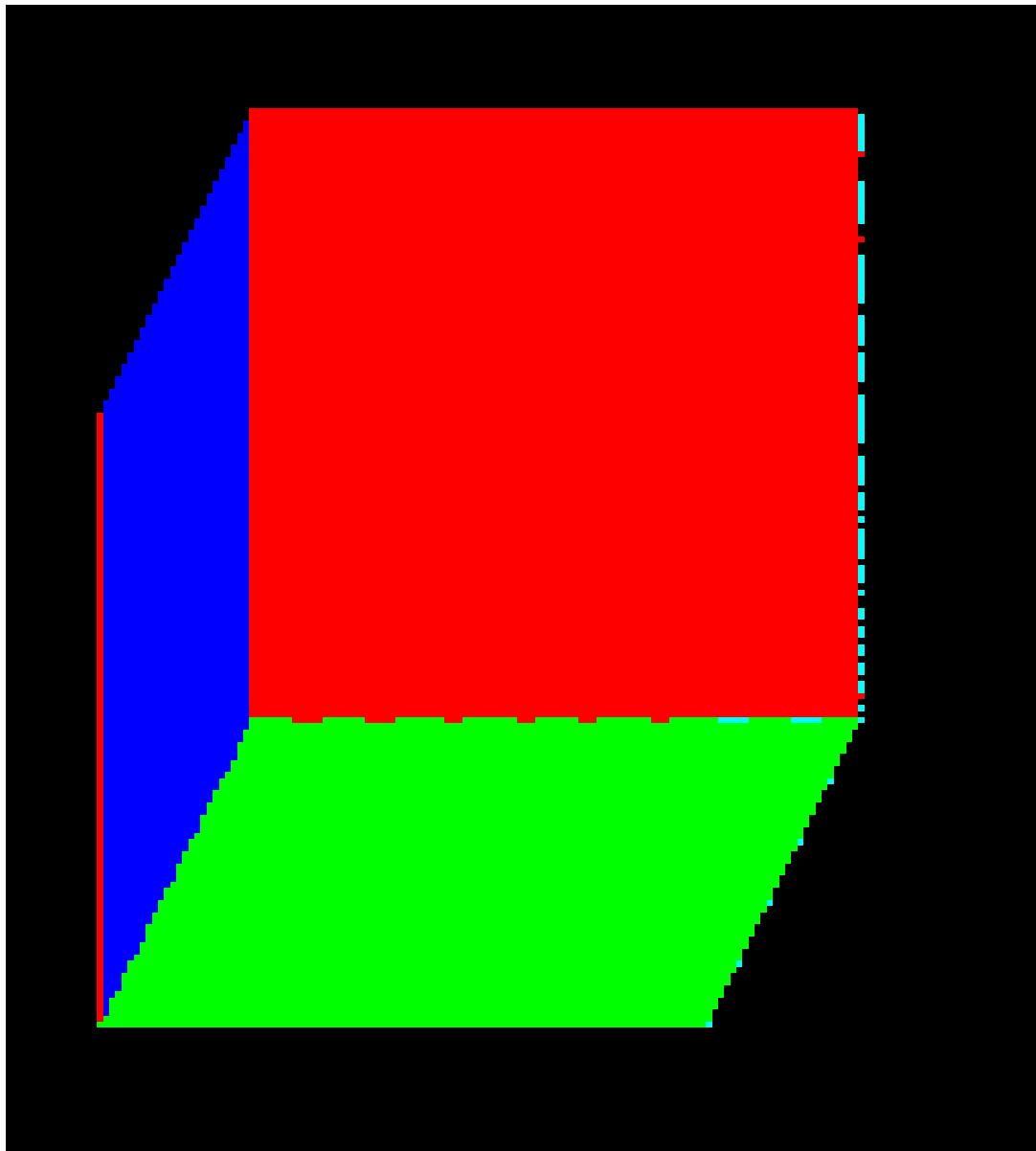


Figure 12: Final Render of Cube with Correct Color Assignments

Initial Rendering Error and Fix:

```

void getPixel(unsigned int i, unsigned int j, object obj, ray r1) {
    // Iterate through the color map vertices
    for (auto const& x : obj.colorMap) {
        // Get the vertices as an array
        array<point, 3> arr = {x.first[0], x.first[1], x.first[2]};

        // Check if the ray intersects with the current triangle
        point* val = gmath::intersect3d1(r1, arr.data());

        if (val != nullptr) {
            // Set the pixel in the image
            double leng = gmath::distance(r1.getOrigine(),*(val));
            cout << "Length: " << leng << endl;

            img.set(i, j, x.second);
            distance[i][j] = leng;
            // Debugging: Output the intersection and color
            //cout << "Intersection at Pixel (" << i << ", " << j << "): " << *val << endl;
            //cout << "Color: " << x.second << endl;

            // Clean up memory and exit the loop (first valid intersection found)
            delete val;
            return;
        }
    }
}

```

Figure 13: Original Rendering Output Highlighting Color Assignment Errors

Code Fix for Correct Color Assignments:

```

void getPixel(unsigned int i, unsigned int j, object obj, ray r1) {
    double distance=9999999999999999;
    // Iterate through the color map vertices
    for (auto const& x : obj.colorMap) [
        // Get the vertices as an array
        array<point, 3> arr = {x.first[0], x.first[1], x.first[2]};

        // Check if the ray intersects with the current triangle
        point* val = gmath::intersect3d1(r1, arr.data());

        if (val != nullptr) {
            // Set the pixel in the image
            double leng = gmath::distance(r1.getOrigine(),*(val));
            delete val;
            //cout << "Length: " << leng << endl;
            //cout << "Distance: " << distance[i][j] << endl;

            if(distance >= leng)
            {
                distance = leng;
                img.set(i, j, x.second);
                // Debugging: Output the intersection and color
                //cout << "Intersection at Pixel (" << i << ", " << j << "): " << *val << endl;
                //cout << "Color: " << x.second << endl;
            }

            //cout << "distance: " << distance[i][j] << endl;
            // Clean up memory and exit the loop (first valid intersection found)
        }
    ]

    // If no intersection is found, set a default color (e.g., black)
    img.set(j, i, blackColor); // Default: Black
    // cout << "No intersection at Pixel (" << i << ", " << j << ")" << endl;
}

```

Figure 14: Code Implementation for Fixing Color Assignment Errors

Significance of the Fix:

- Accurate color assignments for each triangle in the scene.
- Improved visual fidelity and realism in the rendered image.
- A reliable framework for rendering more complex scenes without similar errors.

Importance of the Color Class:

- Enables realistic visualization of objects by assigning colors to surfaces.
 - Supports dynamic effects like gradients or shadows through interpolation.
 - Ensures that rendering results are visually coherent and meet aesthetic goals.
-

2.4 Object Class

The `Object` class represents 3D models within the RayCast Renderer. It defines the geometry, color mapping, and properties of objects in the scene. Objects are composed of multiple triangles, which are the fundamental building blocks for 3D models.

Features and Functionality:

- **Triangle Representation:** Each `Object` is modeled as a collection of triangles, with each triangle defined by three vertices (`Point` instances).
- **Color Mapping:** The `Object` class associates each triangle with a specific color (`Color` instance), allowing precise control over the visual appearance of the object.
- **Intersection Testing:** The `Object` class supports efficient ray-triangle intersection testing, enabling the renderer to identify which parts of the object are visible in the scene.



Figure 15: Representation of the Object Class Code and Its Components

Logic and Implementation:

- Each object consists of a list of triangles, where each triangle stores:
 - Its three vertices (instances of the `Point` class).
 - Its associated color (instance of the `Color` class).
- During rendering, the ray-object intersection logic evaluates each triangle for potential intersections with the ray.

```

17
18  /**
19   * @class object
20   * @brief Represent an abstract entity that holds the graphical data of an object.
21   * The object class holds a 2D vector of pixels representing the object's graphical data.
22   * and maps an array of 3 elements to a color. aka vertex color map.
23   */
24  class object {
25  public:
26    point globalPosition;
27    vec3 globalRotation;
28    point globalRotation;
29    vec3 localRotation;
30    object* parent;
31
32    // 2D vector of pixels representing the object's graphical data.
33    vector<vector<point>> vertices;
34    // Dictionary to link an array of 3 elements to a color.
35    map<array<point, 3>, color> colorMap;
36

```

Figure 16: Detailed Code Representation of the Object Class

Visualization of Object Class Usage:

- **Simple Geometry:**

Objects such as cubes or planes are created using a small number of triangles. For example:

```

void testSpaceCamera() {
    std::cout << "_____Space Test_____" << std::endl;

    // Define the grid size
    unsigned int size = 100;
    double step = 0.2;

```

Figure 17: Low-Resolution Cube Render Composed of Several Triangles

- **Complex Geometry:**

More detailed models, such as the Suzanne model, are created using a large number of smaller triangles.

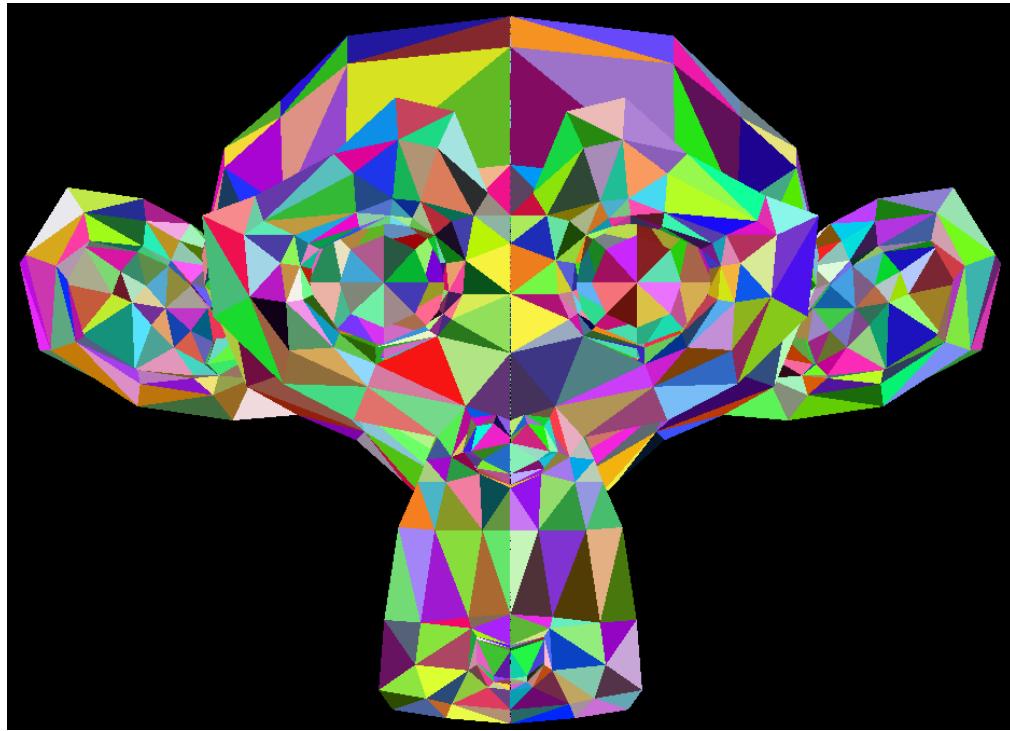


Figure 18: Suzanne Model Rendered with Triangular Mesh Representation

- **Wire frame Representation:**

The `Object` class supports visualization of the object's wire frame, showing how triangles form the overall structure.

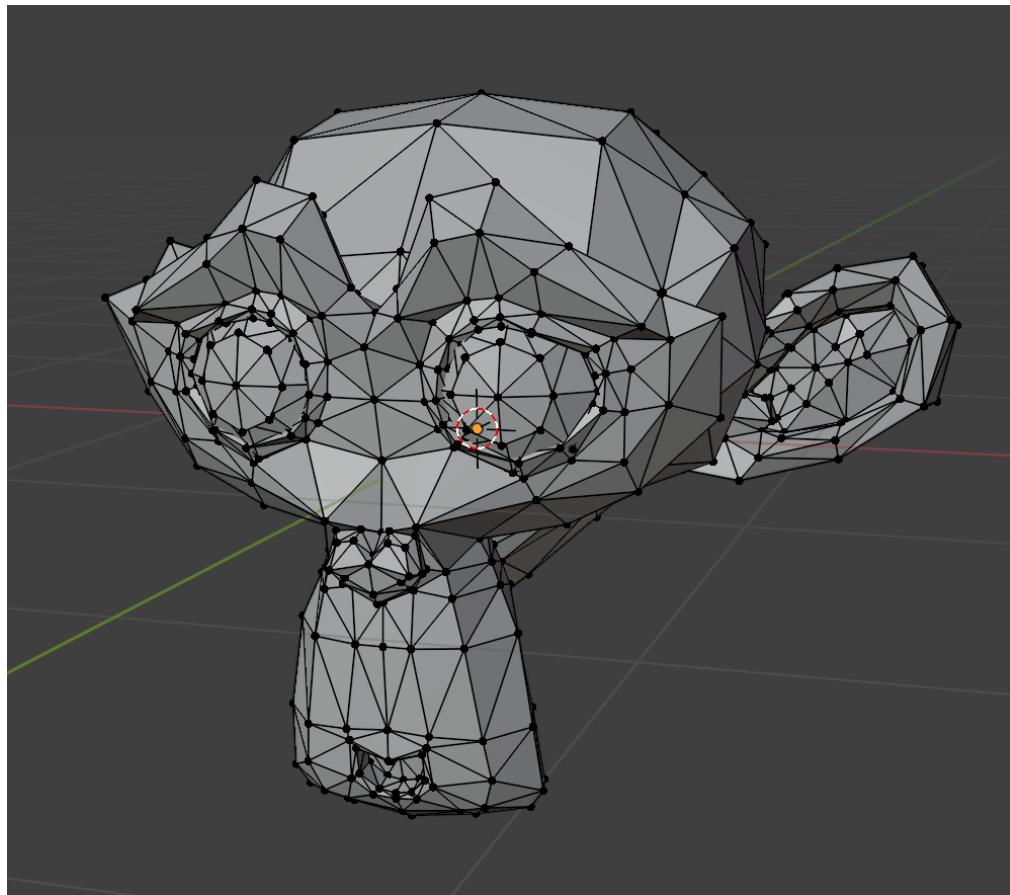


Figure 19: Wireframe View of the Suzanne Model

- **Multiple Objects:**

The RayCast Renderer supports scenes with multiple objects, each defined as an instance of the `Object` class.

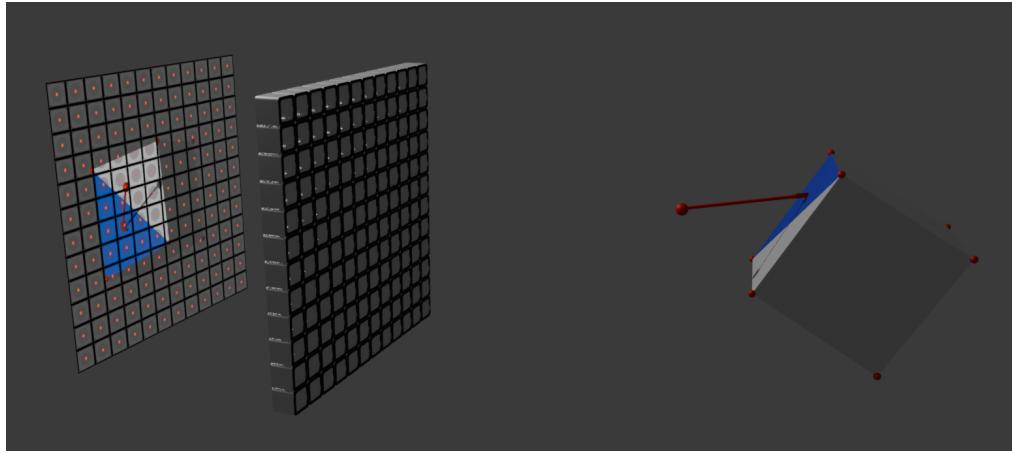


Figure 20: Scene with Multiple Objects Defined Using the Object Class

Importance of the Object Class:

- Provides the foundation for creating 3D geometry in the scene.
 - Supports efficient ray-triangle intersection testing for accurate rendering.
 - Enables detailed color mapping, wireframe visualization, and rendering of complex shapes.
-

2.5 Ray Class

The `Ray` class is the core medium for transmitting information from the camera to the scene in the RayCast Renderer. It defines a ray as an origin point and a direction vector. Each ray corresponds to a single pixel in the final image and determines visibility, color, and shading by interacting with objects in the 3D space.

Features and Functionality:

- **Definition:** A `Ray` is defined by:
 - `Point`: The origin of the ray, typically corresponding to the camera's position or the image plane.
 - `Vec3`: The direction of the ray, indicating its trajectory in the 3D space.
- **Mathematical Representation:** A ray is mathematically expressed as:

$$\text{Ray}(t) = \text{Origin} + t \cdot \text{Direction},$$

where t is a scalar that determines the position along the ray.

- **Ray Casting:** Rays are cast from the camera through the image plane into the 3D scene to determine intersections with objects.

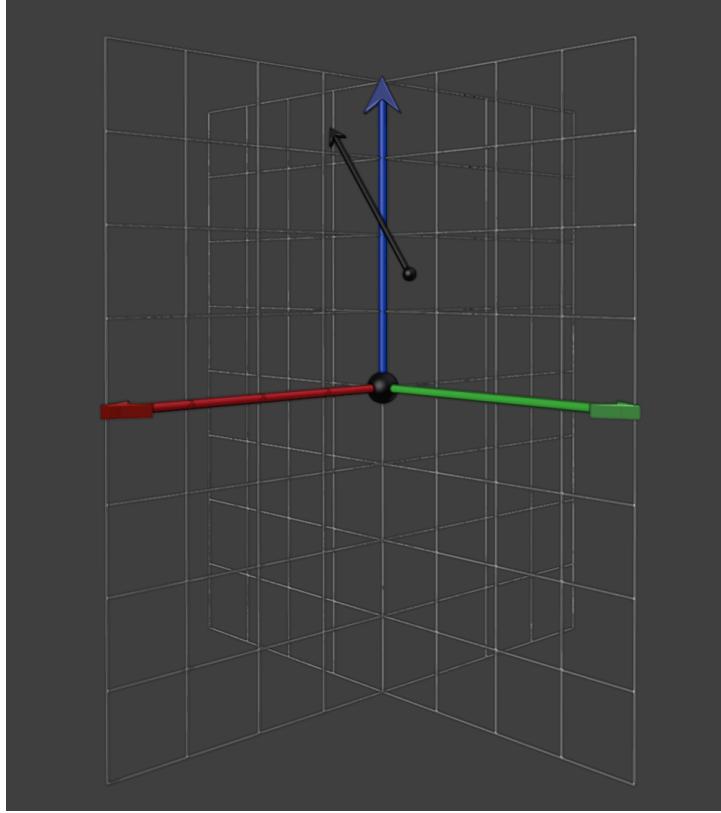


Figure 21: Representation of the Ray Class Showing Its Components

Logic and Implementation:

- **Ray Generation:** The camera generates a grid of rays, with each ray corresponding to a pixel in the image. These rays are then tested against the scene to determine which objects are visible.
- **Ray-Object Interactions:** Each ray is checked for intersections with objects in the scene. The intersection logic determines:
 - Which object the ray hits first.
 - The exact point of intersection.
 - The color or shading of the intersected object at the intersection point.

```

13
14 /*
15  * @class ray
16  * @brief Represents a ray in 3D space.
17  * The ray class encapsulates a ray defined by an origin point and a direction vector.
18  * It provides methods to get and set these attributes, as well as to compute a point at a distance t along the ray.
19  */
20 class ray {
21 private:
22     point origin;
23     vec3 direction;
24 public:

```

Figure 22: Detailed Code Implementation of the Ray Class

Visualization of Ray Class Usage:

- **Ray Projection:** Rays are projected from the camera into the 3D scene, aligned with the image plane's pixel grid.

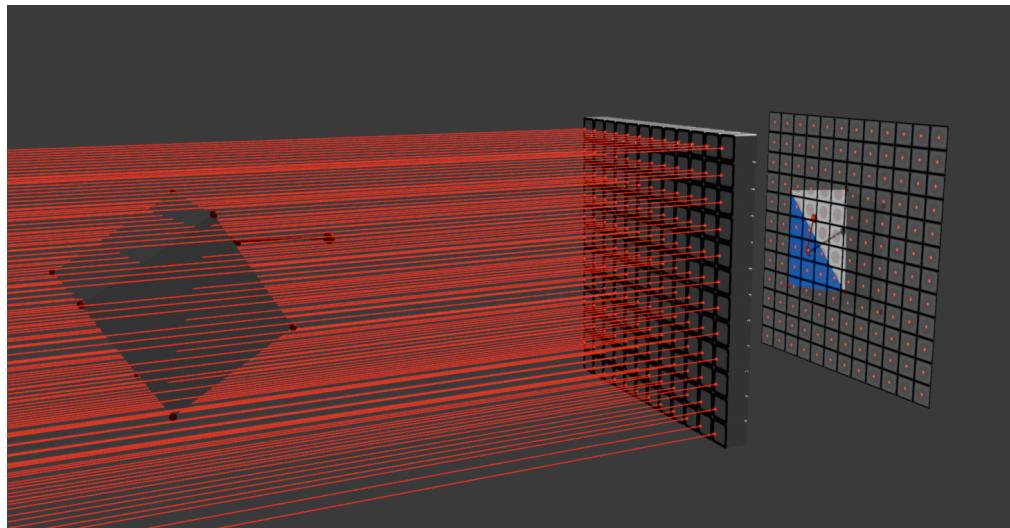


Figure 23: Camera Projecting Rays Corresponding to a 12x12 Pixel Grid

- **Ray Projection:** Rays are projected from the camera into the 3D scene, aligned with the image plane's pixel grid with realistic projection.

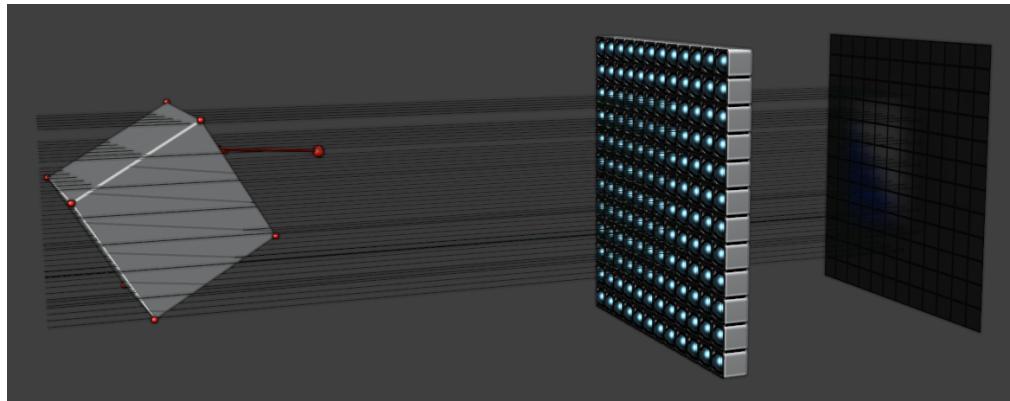


Figure 24: Camera Projecting Rays Corresponding to a 12x12 Pixel Grid realistic resoltuion.

- **Realistic Projection:** Demonstrates how rays interact with objects in the scene to produce accurate render results.

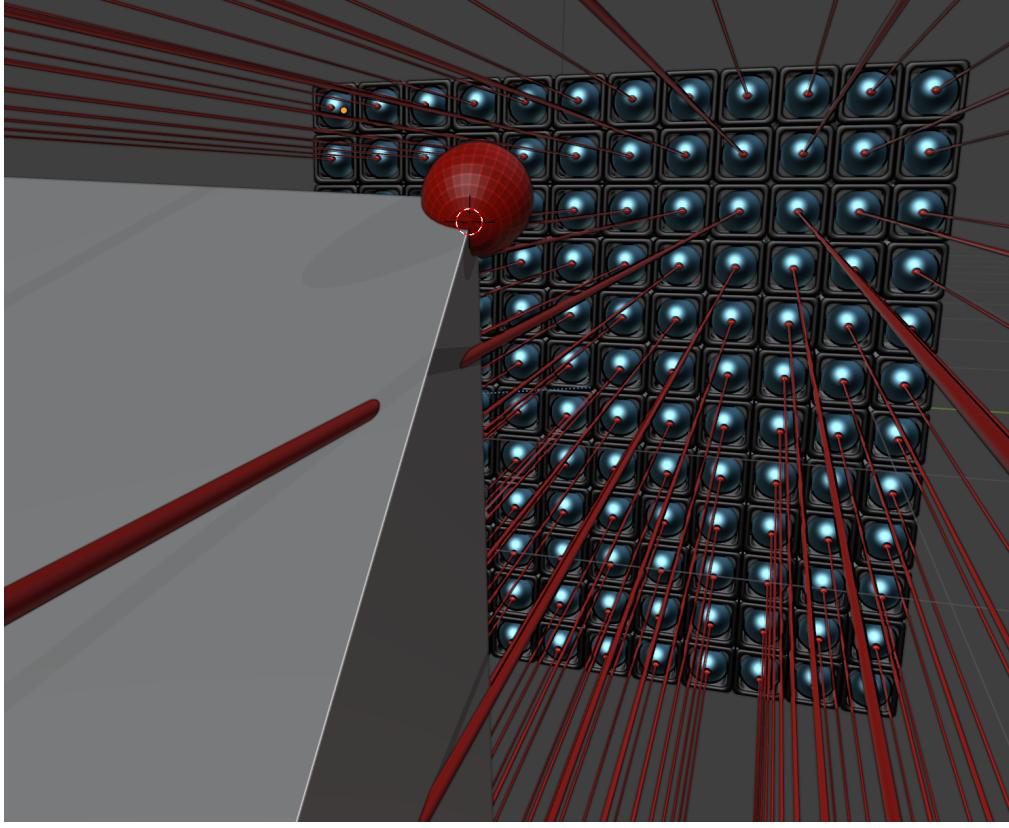


Figure 25: Realistic Ray Projection Respecting the 12x12 Resolution

Importance of the Ray Class:

- Forms the backbone of the rendering process by transmitting visual information from the camera to the scene.
 - Enables accurate visibility and shading calculations through ray-object intersections.
 - Serves as a foundational element for more advanced rendering techniques, such as reflection and refraction.
-

2.6 Ray Projection

Ray projection is the process by which the camera generates a grid of rays corresponding to pixels on the image plane. These rays traverse the 3D scene, determining which objects are visible and their corresponding pixel colors.

Features and Functionality:

- **Ray Generation:** The camera creates rays for each pixel in the image. The direction of each ray is calculated based on the camera's orientation and field of view.
- **Pixel Mapping:** Each ray corresponds to a specific pixel in the final image, ensuring accurate rendering.
- **Depth Perspective:** Ray projection incorporates perspective distortion, making closer objects appear larger in the rendered image.

Logic and Implementation:

- **Grid-Based Projection:** Rays are cast through a grid representing the image plane. Each grid cell corresponds to one pixel.
- **Direction Calculation:** The direction of each ray is determined by mapping pixel coordinates to 3D space using the camera's position, orientation, and field of view.
- **Pixel-Color Mapping:** The color of each pixel is updated based on the intersection of its corresponding ray with objects in the scene.

Visualization of Ray Projection:

- **Grid Layout:** The camera casts rays through a structured grid, ensuring alignment with the image plane.

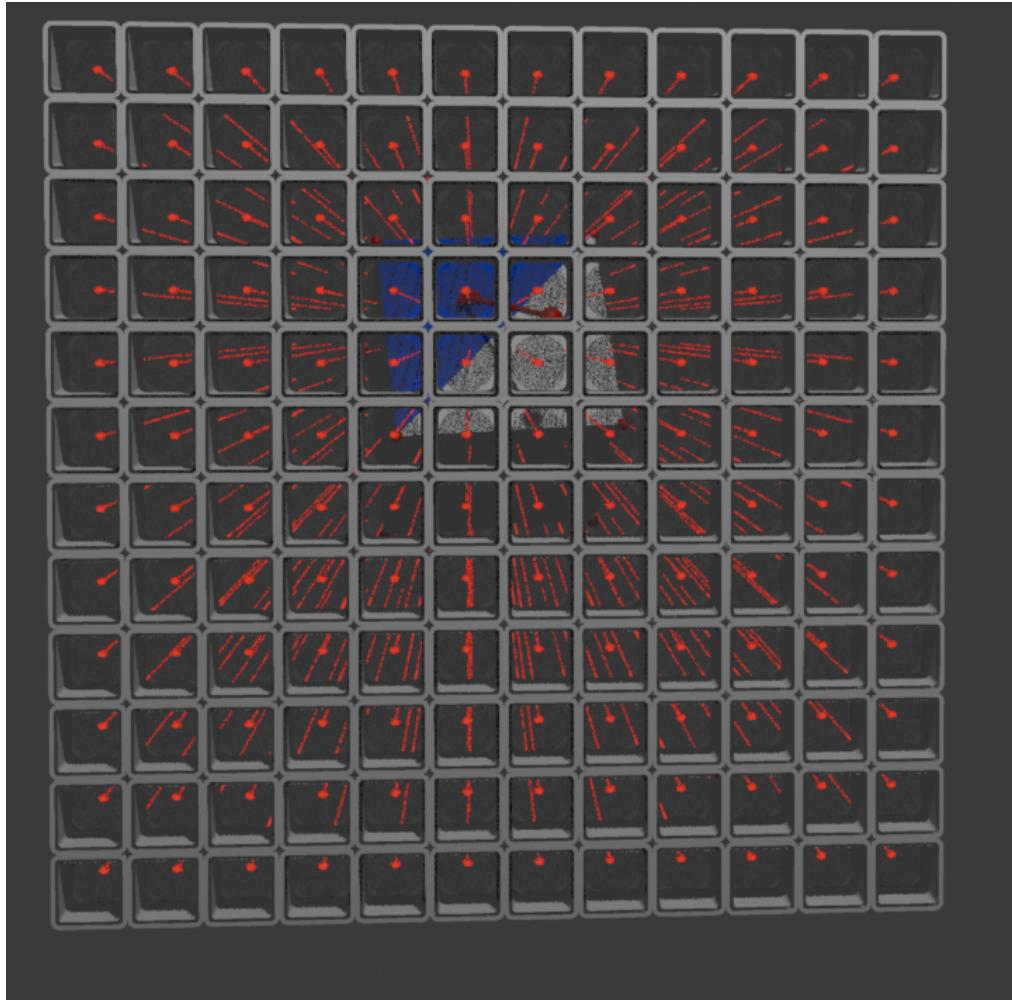


Figure 26: Front View of Rays Projecting Through the Image Plane

Importance of Ray Projection:

- Maps the 2D image plane to the 3D scene, enabling accurate pixel rendering.
 - Captures depth and perspective, essential for lifelike rendering.
 - Forms the basis for advanced effects like reflections and refractions by extending the ray projection logic.
-

2.7 Camera Class

The `Camera` class represents the virtual viewpoint in the 3D space. It serves as the origin for all rays, projecting them into the scene to determine visibility, shading, and pixel colors. The camera's position, orientation, and field of view control how the scene is captured and rendered.

Features and Functionality:

- **Positioning:** The camera is defined by its position in the 3D space, represented as a `Point`.
- **Orientation:** The camera's orientation is controlled by a directional vector (`Vec3`), which determines where the camera is looking.
- **Field of View (FOV):** Defines the angular extent of the scene captured by the camera. A wider FOV results in more of the scene being visible but may introduce distortion.
- **Ray Generation:** The camera generates rays corresponding to each pixel in the virtual image plane, which are cast into the 3D scene.

```

14
15 /*
16     * @class camera
17     * @brief Represents an camera in 2D space.
18     * The camera class encapsulates an camera defined by a 2D array of gridRay.
19     * It provides methods to get and set these attributes, as well as to clear the camera.
20     * Inherits from color class.
21     *
22 */
23 class camera {
24     private:
25         vector<vector<ray>> gridRay;
26         unsigned int width;
27         unsigned int height;
28         image img;

```

Figure 27: Representation of the Camera Class

Logic and Implementation:

- **Ray Casting:** The camera projects rays through a grid corresponding to the image resolution. Each ray is defined by:
$$\text{Ray}(t) = \text{Origin} + t \cdot \text{Direction}.$$
- **Pixel Mapping:** Each ray corresponds to a specific pixel on the virtual image plane. The color of the pixel is determined based on the intersection of the ray with objects in the scene.
- **Projection:** The camera's FOV, combined with its resolution, determines the spacing and direction of the rays, ensuring accurate perspective projection.

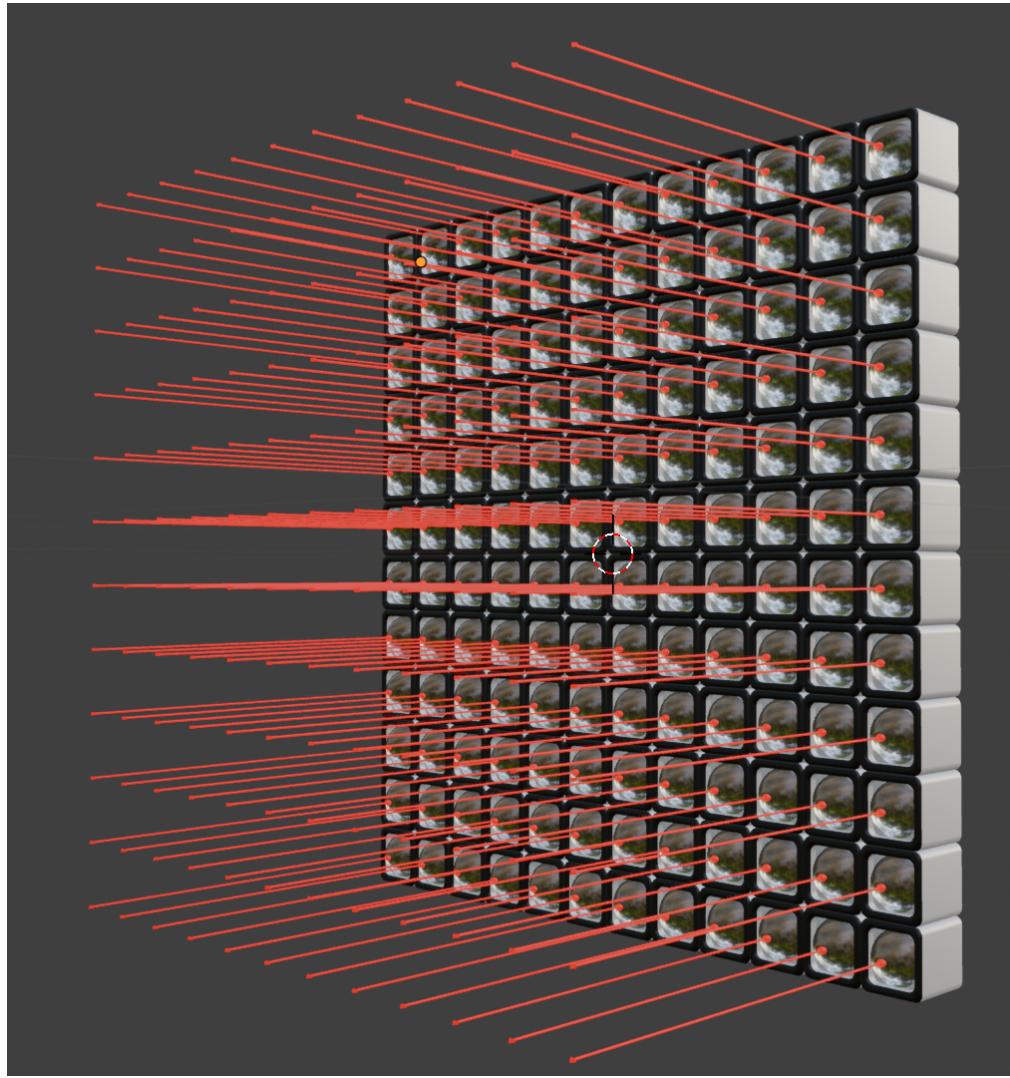


Figure 28: Illustration of Camera Functionality and Ray Generation

Visualization of Camera Class Usage:

- **Ray Projection:** The camera casts rays through an image plane grid into the 3D space. Each ray corresponds to a specific pixel in the rendered image.

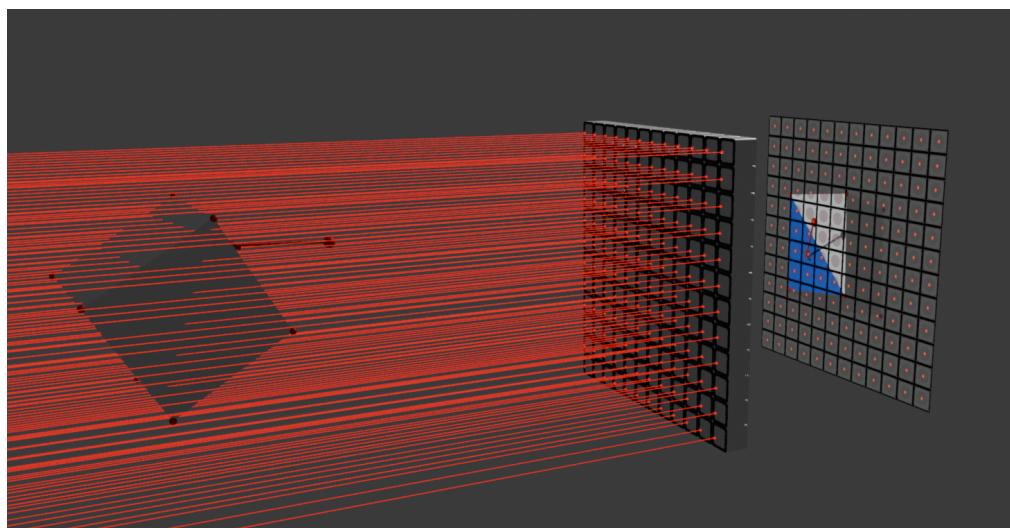


Figure 29: Camera Projecting Rays Corresponding to a 12x12 Pixel Grid

- **Front View of Ray Casting:** A front view of the camera showing rays originating from its position and projecting into 3D space.

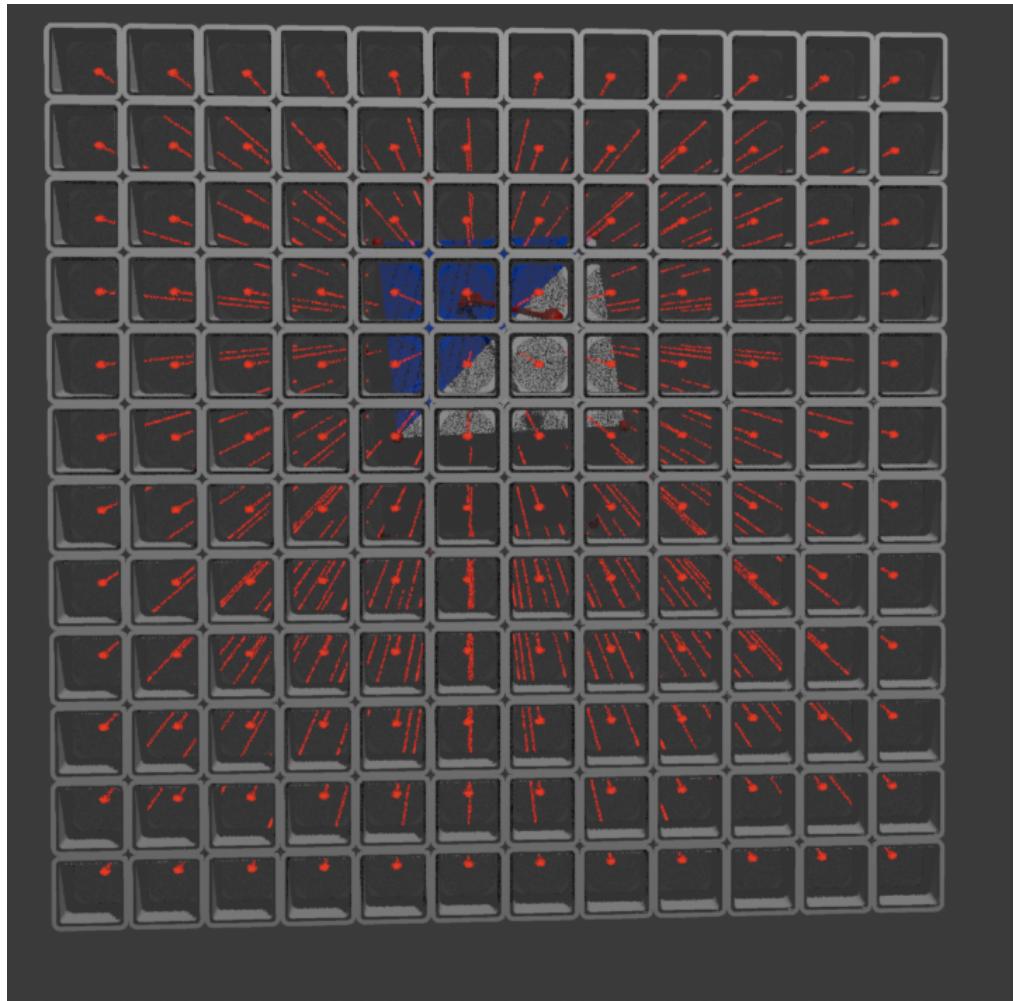


Figure 30: Front View of Camera Projecting Rays into the Scene

- **Realistic Projection:** Demonstrates how the camera captures depth and perspective using ray projections.

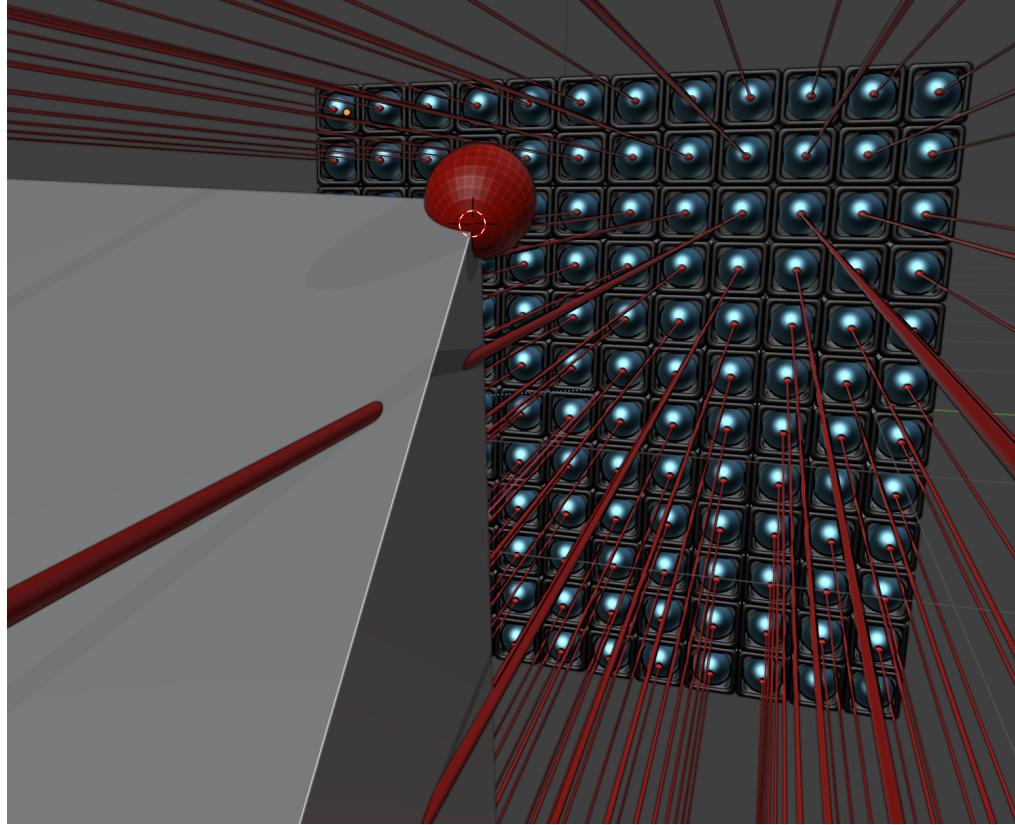


Figure 31: Realistic Projection of Rays Respecting the Scene Setup

- **Side View of Ray Paths:** Shows how rays pass through the image plane and intersect with objects in the 3D scene.

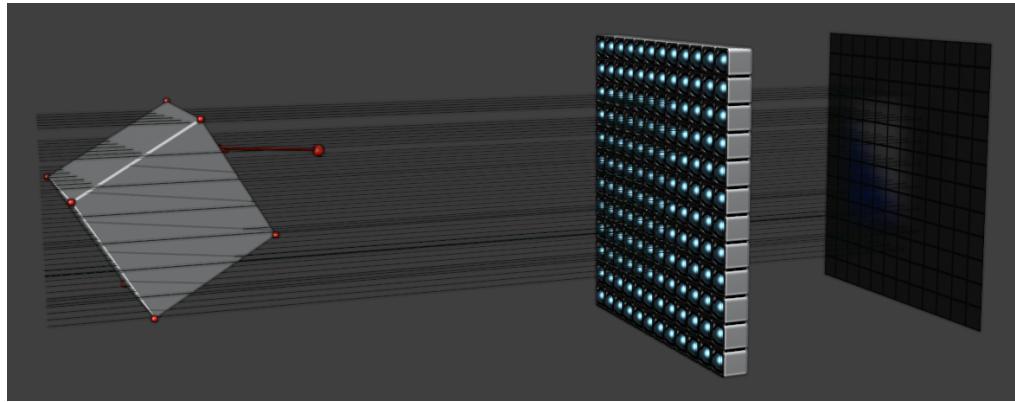


Figure 32: Side View of Ray Paths Projecting Pixel Colors

Importance of the Camera Class:

- Defines the viewpoint and perspective for the rendered scene.
 - Controls how rays are cast into the 3D space, determining pixel visibility and shading.
 - Serves as the foundation for advanced techniques such as depth of field and camera motion effects.
-

2.8 Intersection Logic

The intersection logic is the core computational process that determines whether a ray intersects an object (triangle) in the 3D scene. This logic is essential for identifying visible objects, calculating shading, and generating the final image.

Features and Functionality:

- **Intersection Tests:** The renderer calculates whether and where a ray intersects each triangle in the scene using geometric algorithms.
- **Closest Intersection:** For each ray, only the closest intersection (if any) is recorded to ensure correct visibility.
- **Ray-Triangle Algorithm:** The intersection logic implements a mathematical algorithm to determine if a ray intersects a triangle. This includes:
 - Solving for t in the ray equation:

$$\text{Ray}(t) = \text{Origin} + t \cdot \text{Direction.}$$
 - Ensuring t is positive (the intersection is in front of the ray origin).
 - Checking if the intersection point lies within the bounds of the triangle using barycentric coordinates.

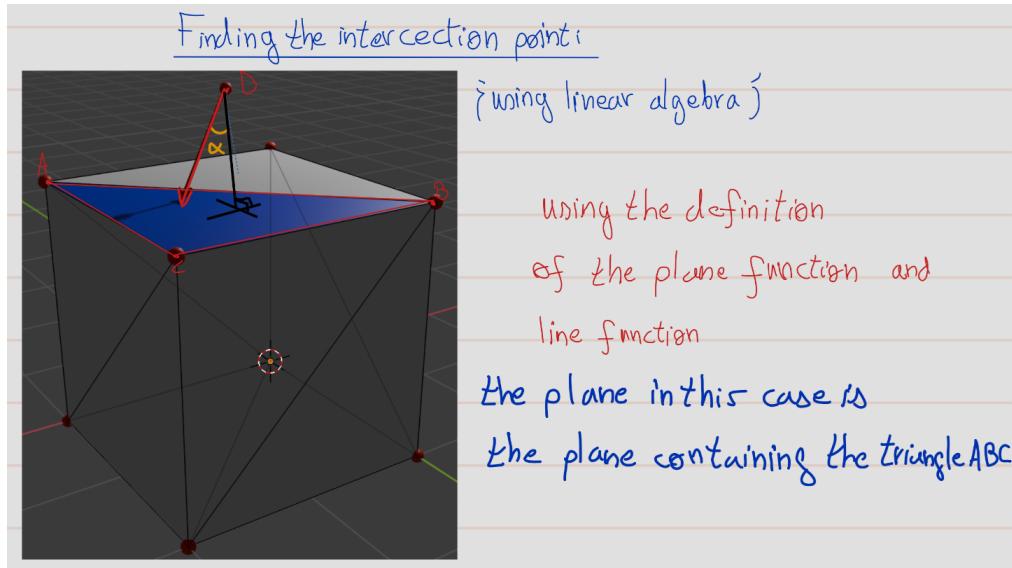


Figure 33: Step 1: Ray-Triangle Intersection Logic Overview

Logic and Implementation:

- The renderer iterates through all triangles in the scene for each ray.
- For each triangle:
 - Calculate the intersection point using the ray-triangle algorithm.
 - Verify that the intersection lies inside the triangle.
 - Compare the t value of the intersection with previously recorded intersections to find the closest point.
- If an intersection is found, the pixel color is updated with the triangle's color.

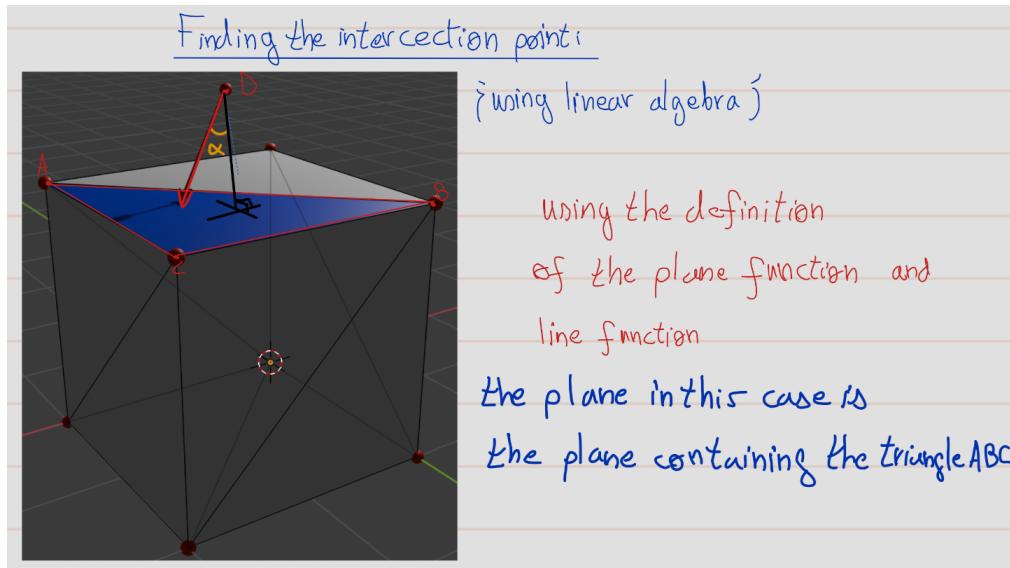


Figure 34: Step 1: Detailed Logic for Verifying Triangle Boundaries

$$t = \frac{n_1 \cdot p_1 - n_1 \cdot a_1 + n_2 \cdot p_2 - n_2 \cdot a_2 + n_3 \cdot p_3 - n_3 \cdot a_3}{-(n_1 b_1 + n_2 b_2 + n_3 b_3)}$$

$$L(t) \begin{cases} a_1 + b_1 t = x \\ a_2 + b_2 t = y \\ a_3 + b_3 t = z \end{cases}$$

$$t = \frac{n \cdot (A - O)}{n \cdot d}$$

n : normal plane
 A : vertex of the triangle
 O : ray origin
 d : ray direction

Figure 35: Step 2: Detailed Logic for Verifying Triangle Boundaries

Visualization of Intersection Logic in Action:

- Error Due to Incorrect Logic:** Mistakes in intersection calculations can result in rendering errors. Below is an example of such an error.

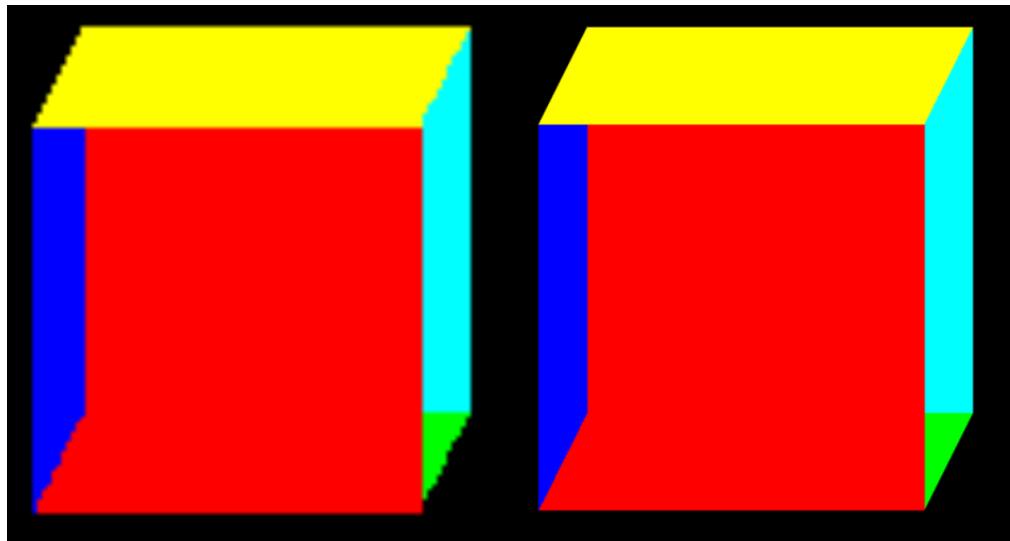


Figure 36: Rendering Error Caused by Incorrect Intersection Logic

- **Fixed Intersection Logic:** After correcting the intersection logic, the rendered result accurately displays the object's geometry.

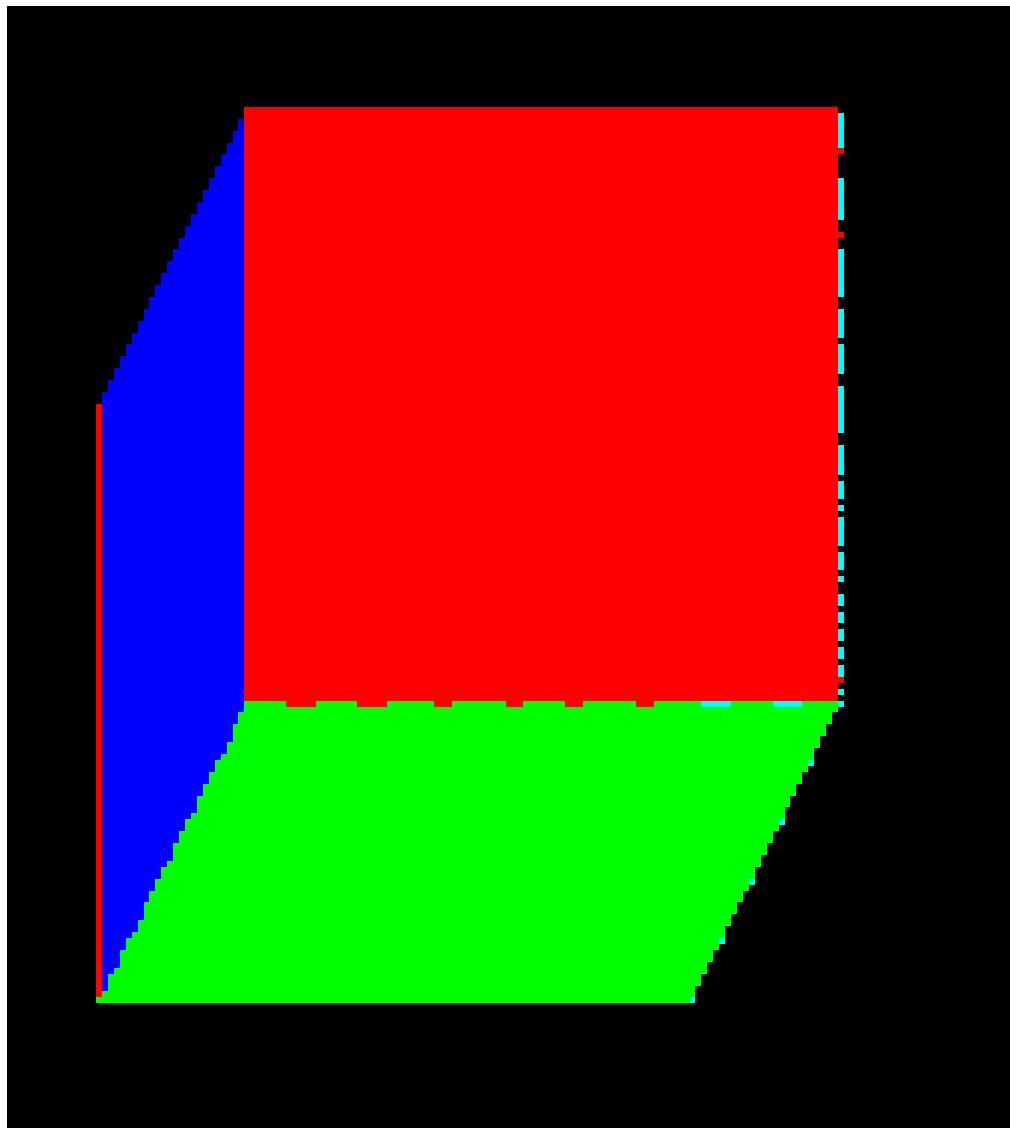


Figure 37: Corrected Rendering Result After Fixing Intersection Logic

Importance of Intersection Logic:

- Identifies which objects and surfaces are visible to the camera.
 - Ensures correct layering and depth in the rendered image by selecting the closest intersection.
 - Forms the foundation for more advanced rendering techniques, such as reflections and shadows.
-

2.9 Space Layout

The 3D space layout defines the spatial organization of objects, the camera, and their relationships. It ensures that rays are cast in the correct direction relative to the scene, enabling accurate rendering.

Features and Functionality:

- **Object Placement:** Objects are positioned within a coordinate system that represents the 3D space.
- **Camera Positioning:** The camera is placed in the 3D space, with its orientation and field of view determining the direction of rays.
- **Coordinate System:** The space layout uses a Cartesian coordinate system (x, y, z) to define object positions, camera orientation, and ray directions.
- **Scene Composition:** The space layout facilitates the composition of scenes with multiple objects, ensuring that relationships like depth and perspective are accurately represented.

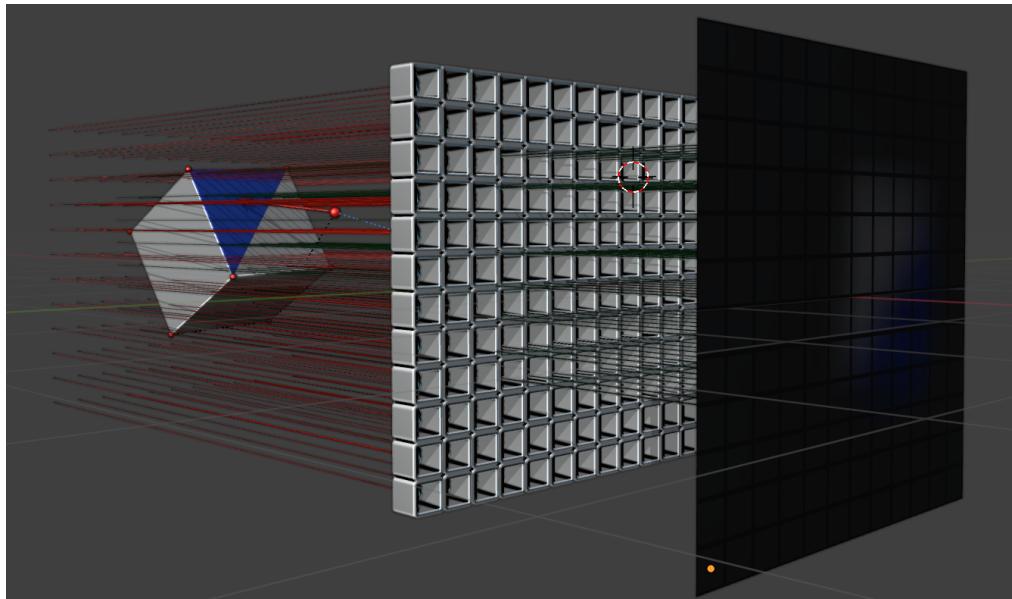


Figure 38: Logical Layout of Camera, Objects, and Rays in 3D Space

Logic and Implementation:

- **Object Placement:** Objects are placed using their position vectors (`Point` instances), which define their location in the 3D space.
- **Camera Orientation:** The camera's position and orientation are defined using a position vector and direction vector (`Vec3`), ensuring that rays are cast toward the intended objects.
- **Ray Casting:** Rays are generated from the camera's position and projected into the scene based on the image plane grid. These rays traverse the 3D space and test for intersections with objects.

```

14
15 /*
16     * @class camera
17     * @brief Represents an camera in 2D space.
18     * The camera class encapsulates an camera defined by a 2D array of gridRay.
19     * It provides methods to get and set these attributes, as well as to clear the camera.
20     * Inherits from color class.
21     *
22 */
23 class camera {
24     private:
25         vector<vector<ray>> gridRay;
26         unsigned int width;
27         unsigned int height;
28         image img;

```

Figure 39: Camera Positioned in Space, Emitting Rays Toward Objects

Visualization of Space Layout:

- **Scene Composition:** The layout organizes multiple objects within the same 3D space, ensuring proper alignment and depth perception.

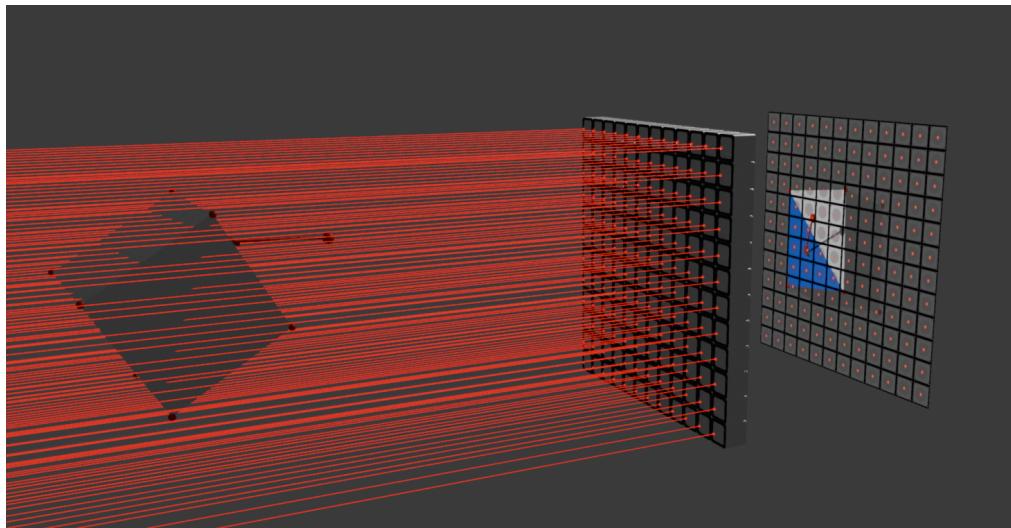


Figure 40: Camera Casting Rays into a Scene with Multiple Objects

- **Ray Interaction with Objects:** Demonstrates how rays traverse the 3D space and intersect with objects to determine visibility and shading.
- **Perspective View:** The layout ensures that perspective and depth are accurately captured, as shown in a rendered scene.

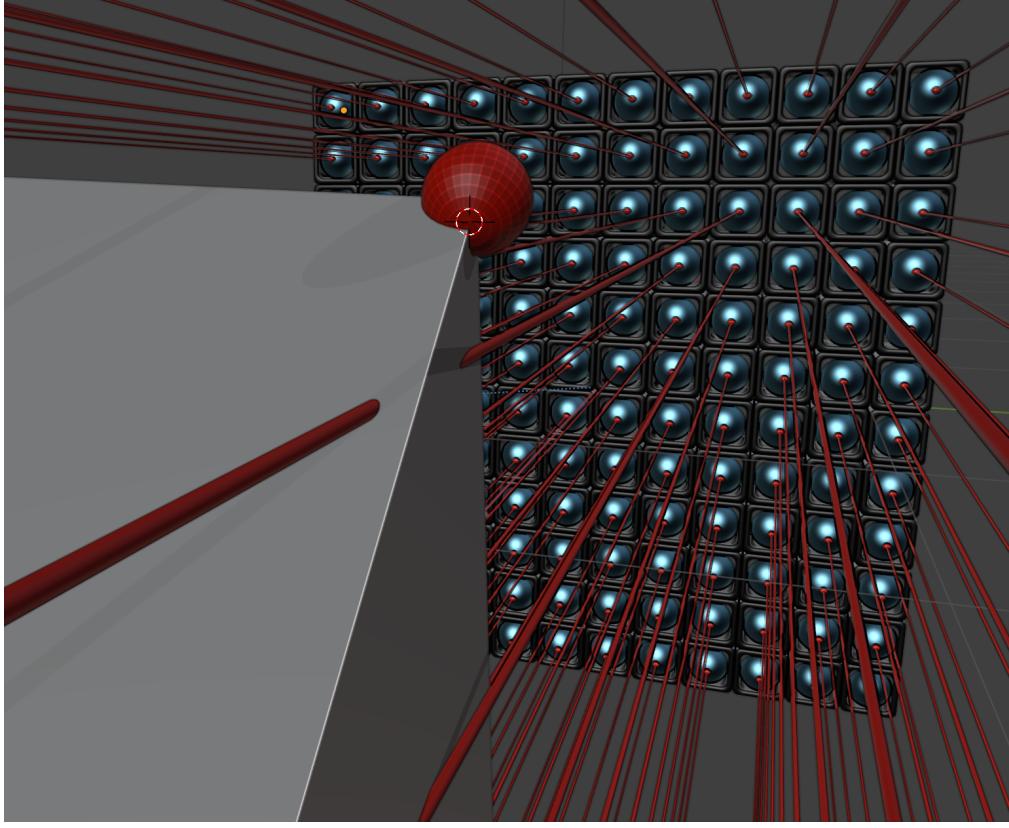


Figure 41: Realistic Projection Capturing Depth and Perspective in the Scene

Importance of Space Layout:

- Ensures that objects, camera, and rays are correctly aligned for accurate rendering.
 - Facilitates realistic depth and perspective, enabling lifelike scene composition.
 - Provides a logical framework for organizing complex scenes with multiple objects.
-

3 Rendering Results and Examples

The rendering results showcase the effectiveness of the RayCast Renderer in capturing object geometry, perspective, and shading. By demonstrating renders of simple and complex models, this section highlights the renderer's capabilities and the impact of parameters such as resolution and ray density.

3.1 Simple Rendering

Simple rendering involves basic geometric objects, such as cubes, rendered at varying resolutions. These examples illustrate how the renderer translates 3D geometry into 2D pixels with increasing levels of detail.

Examples:

- **Low Resolution:** Demonstrates the basic structure of a cube with minimal detail.

```

void testSpaceCamera() {
    std::cout << "____Space Test_____" << std::endl;

    // Define the grid size
    unsigned int size = 100;
    double step = 0.2;

```

Figure 42: Cube Rendered at Low Resolution

- **Medium Resolution:** Shows improved edge clarity and surface detail.

```

void testSpaceCamera() {
    std::cout << "____Space Test_____" << std::endl;

    // Define the grid size
    unsigned int size = 1000;
    double step = 0.01;

```

Figure 43: Cube Rendered at Medium Resolution

- **Detail Comparison:** Highlights the differences in quality between low, medium, and high-resolution renders.

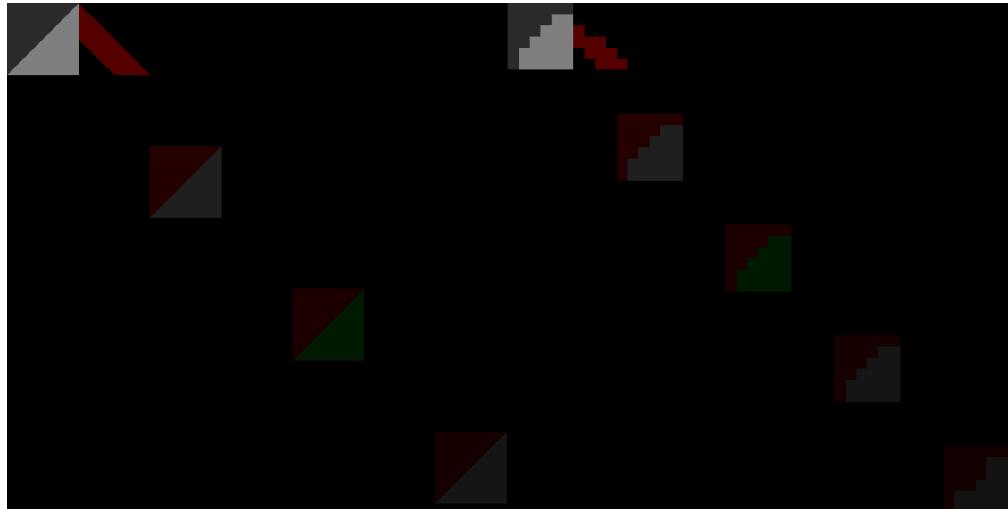


Figure 44: Comparison of Cube Renders at Different Resolutions

- **High Resolution:** Captures detailed edges and smooth surfaces, showcasing the renderer's precision. Increasing the resolution size and decreasing the step intervals produces higher detail and denser pixel projections.

```

void testSpaceCamera() {
    std::cout << "____Space Test_____" << std::endl;

    // Define the grid size
    unsigned int size = 100;
    double step = 0.2;

```

Figure 45: Low-resolution cube render highlighting basic structure.

```

void testSpaceCamera() {
    std::cout << "_____Space Test_____"
        << std::endl;

    // Define the grid size
    unsigned int size = 1000;
    double step = 0.01;

```

Figure 46: Medium-resolution cube render showing improved detail.

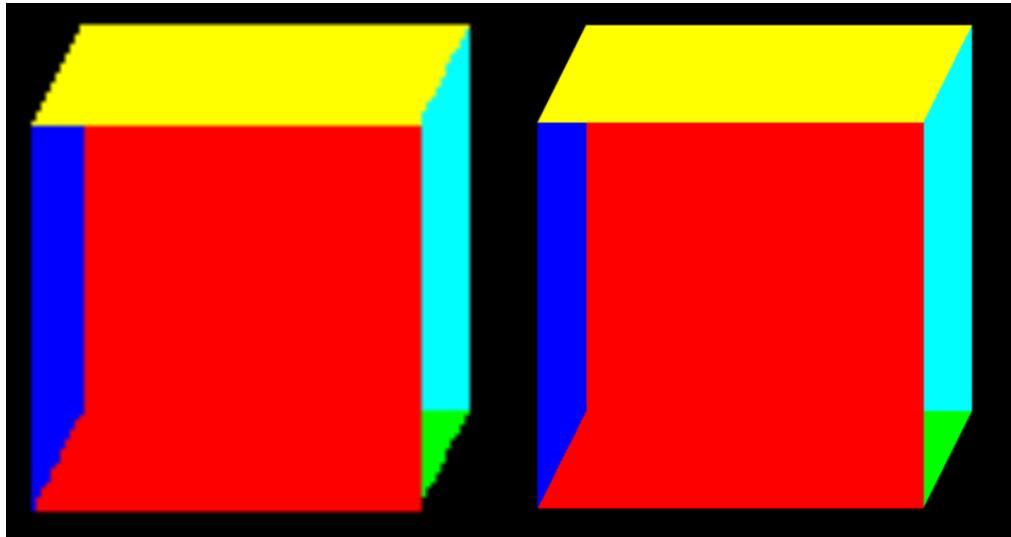


Figure 47: High-resolution cube render with enhanced detail and smooth surfaces.

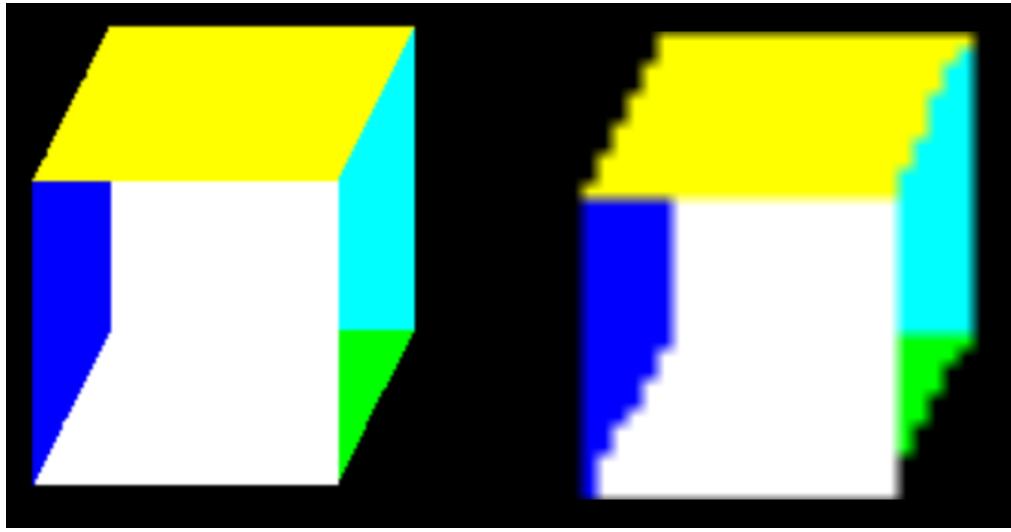


Figure 48: Comparison of renders showcasing detail improvements across resolutions.

3.2 Complex Models

The renderer's ability to handle intricate geometry is demonstrated through renders of complex models, such as a Dahlia flower and the Suzanne model.

- **Dahlia Flower:** The render captures the delicate geometry of the Dahlia flower, highlighting the renderer's ability to process fine details.

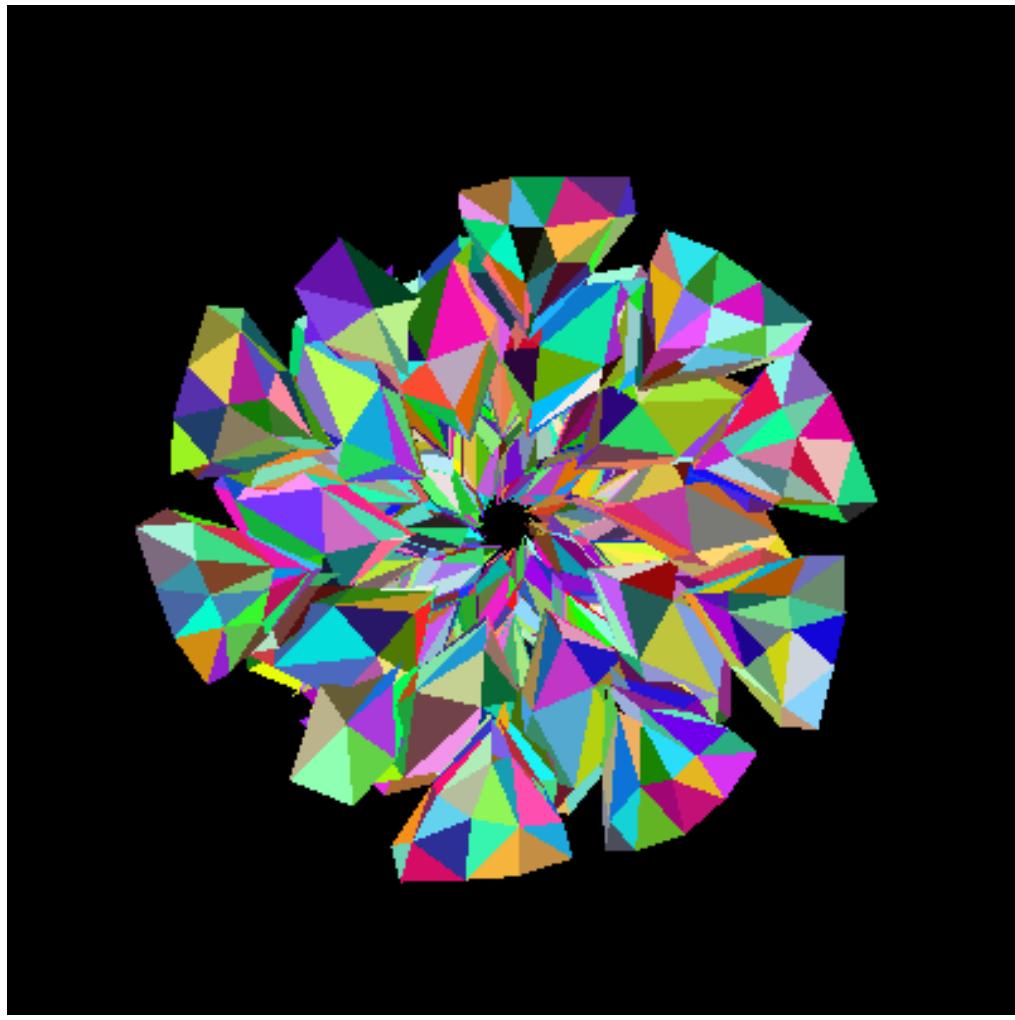


Figure 49: Rendered Dahlia Flower with Fine Detail

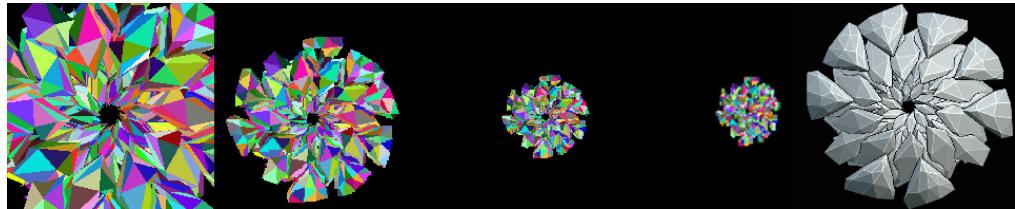


Figure 50: Rendered Dahlia Flower with Fine Detail full step

- **Suzanne Model:** Suzanne, a standard rendering benchmark, showcases the renderer's capability to handle complex shapes and shading.

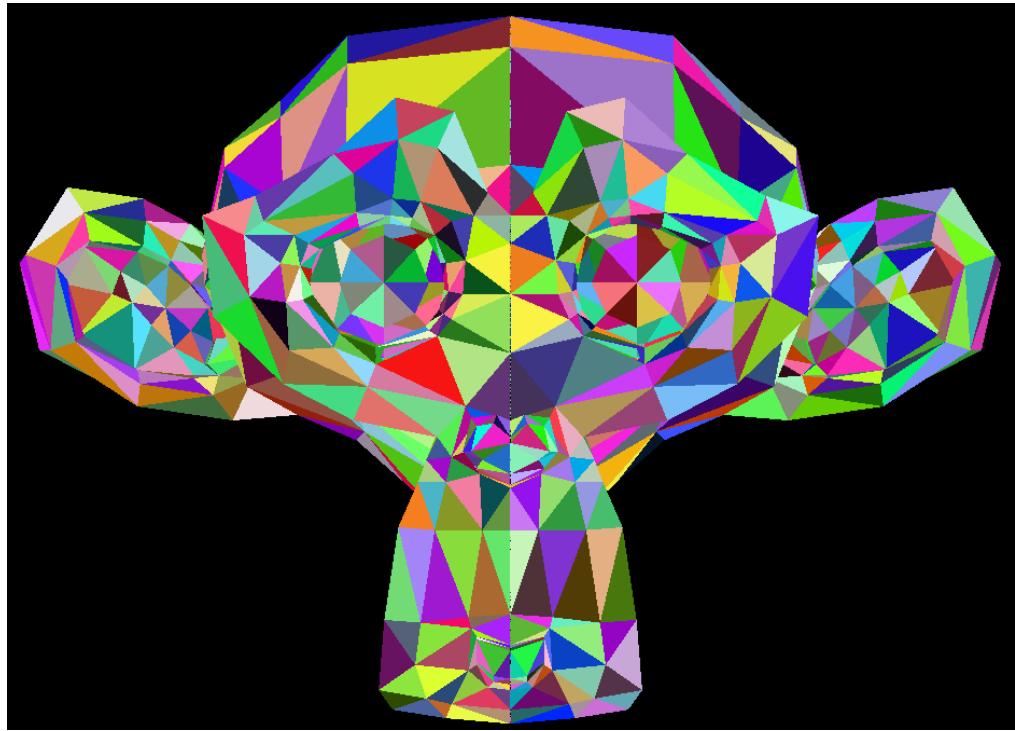


Figure 51: Rendered Suzanne Model with Complex Geometry

- **Wireframe Visualization:** A wireframe render of the Suzanne model shows how triangles form the underlying structure.

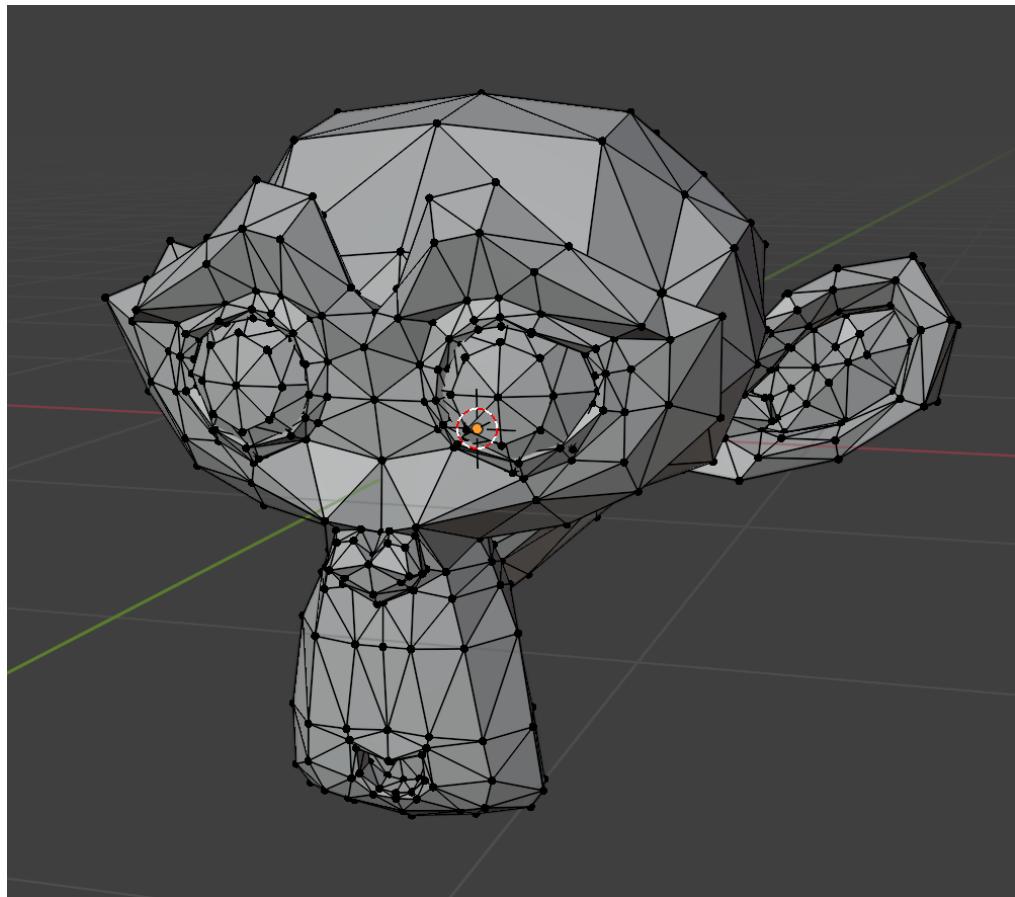


Figure 52: Wireframe View of Suzanne Model Showing Triangular Structure

3.3 Rendering Errors and Fixes

This section highlights common rendering issues, such as incorrect order or logic errors, and their resolution.

- **Rendering Error:** An example of a rendering error caused by incorrect logic, resulting in misplaced geometry or colors.

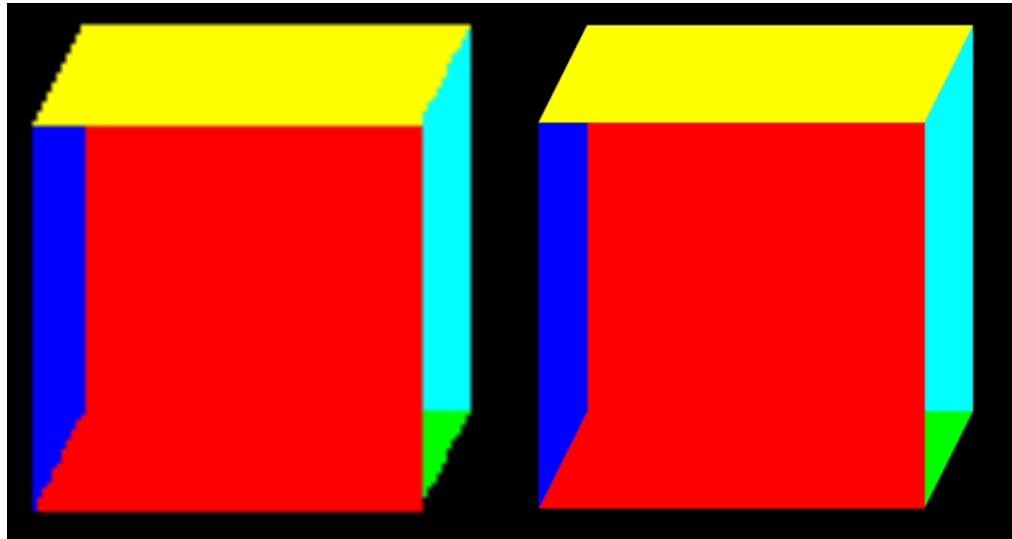


Figure 53: Rendering Error Due to Incorrect Logic

- **Fixed Rendering:** After resolving the error, the renderer produces accurate and visually correct results.

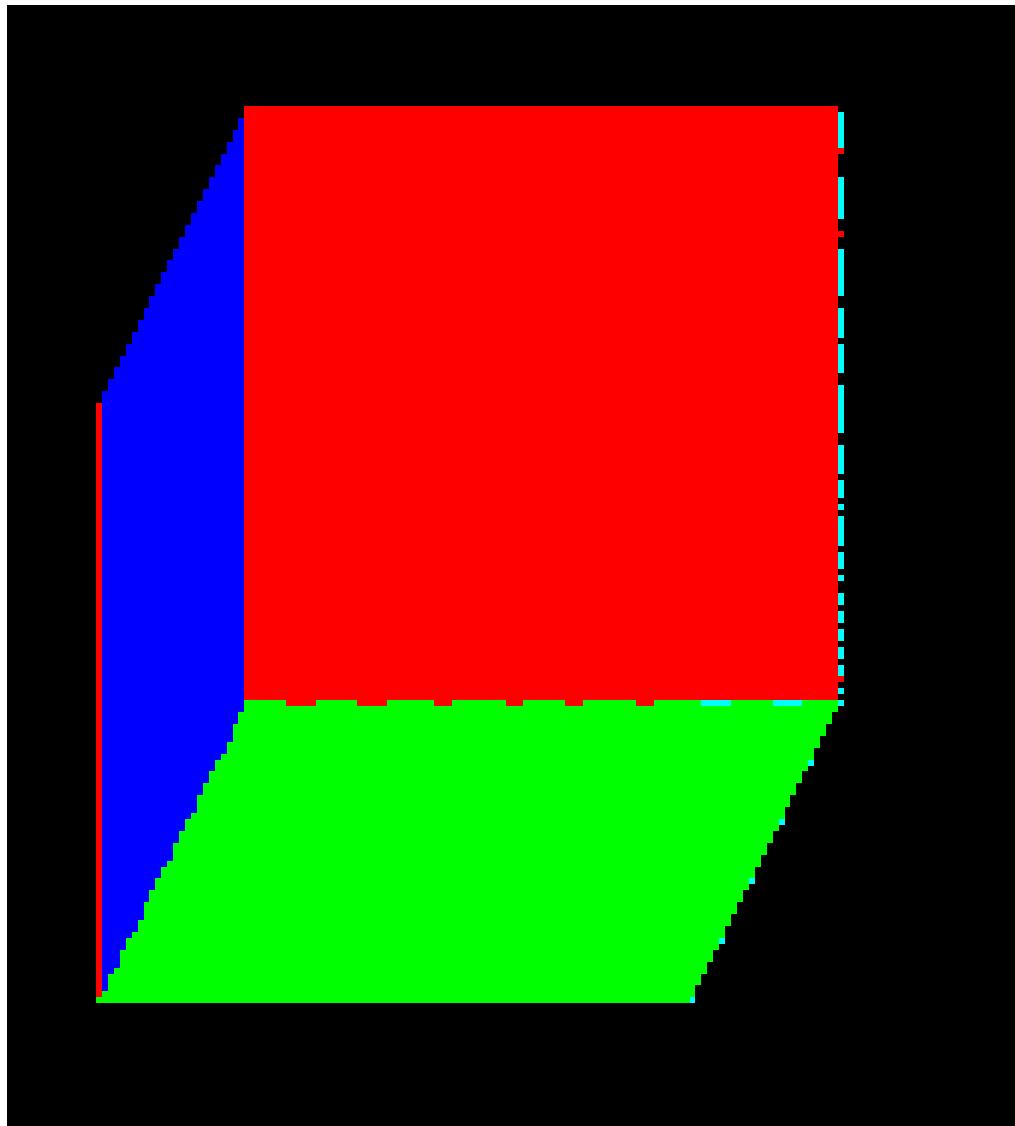


Figure 54: Corrected Rendering After Fixing Logic Errors

3.4 Low Ray Density Impact

The density of rays affects the detail and accuracy of the rendered image. Low ray density can result in missing or distorted details, as shown below.

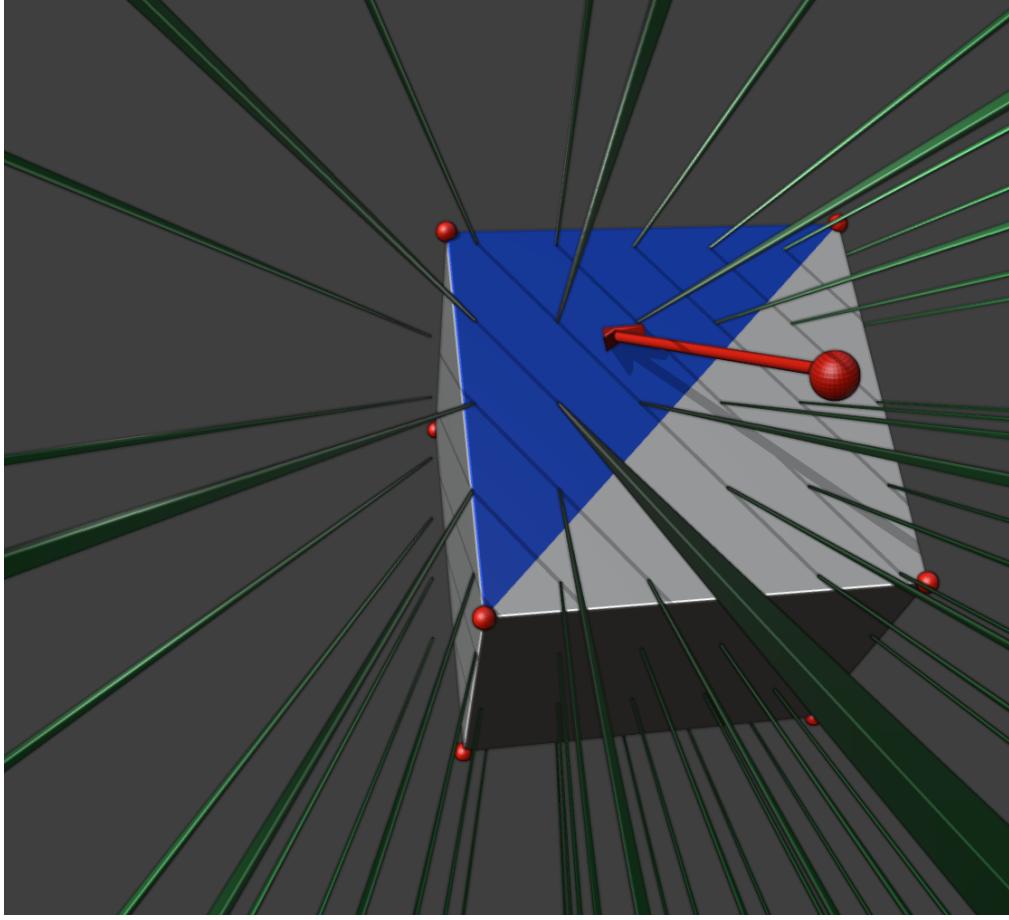


Figure 55: Effect of Low Ray Density on Detail Accuracy

Importance of Ray Density:

- Ensures accurate representation of fine details.
 - Reduces artifacts caused by insufficient sampling.
 - Improves overall rendering quality and realism.
-

4 Supporting Visualizations and Code Representations

4.1 Image Class and Pixel Mapping

The `Image` class is responsible for managing the pixel-by-pixel mapping of ray intersection results to the output image. It acts as the container for pixel data, storing color information for each ray intersection and rendering the final image.

Features:

1. **Pixel Storage:** Each pixel corresponds to a specific ray's intersection result, containing color and intensity data.
2. **Pixel Mapping:** The `Image` class ensures accurate mapping of computed ray data to its corresponding pixel on the output grid.

```

13
14 ~ /**
15  * @class image
16  * @brief Represents an image in 2D space.
17  * The image class encapsulates an image defined by a 2D array of pixels.
18  * It provides methods to get and set these attributes, as well as to clear the image.
19  * Inherits from color class.
20  *
21 */
22 ~ class image []
23 private:
24     vector<vector<color>> pixels;
25     unsigned int width;
26     unsigned int height;

```

Figure 56: Image Class Code Representation

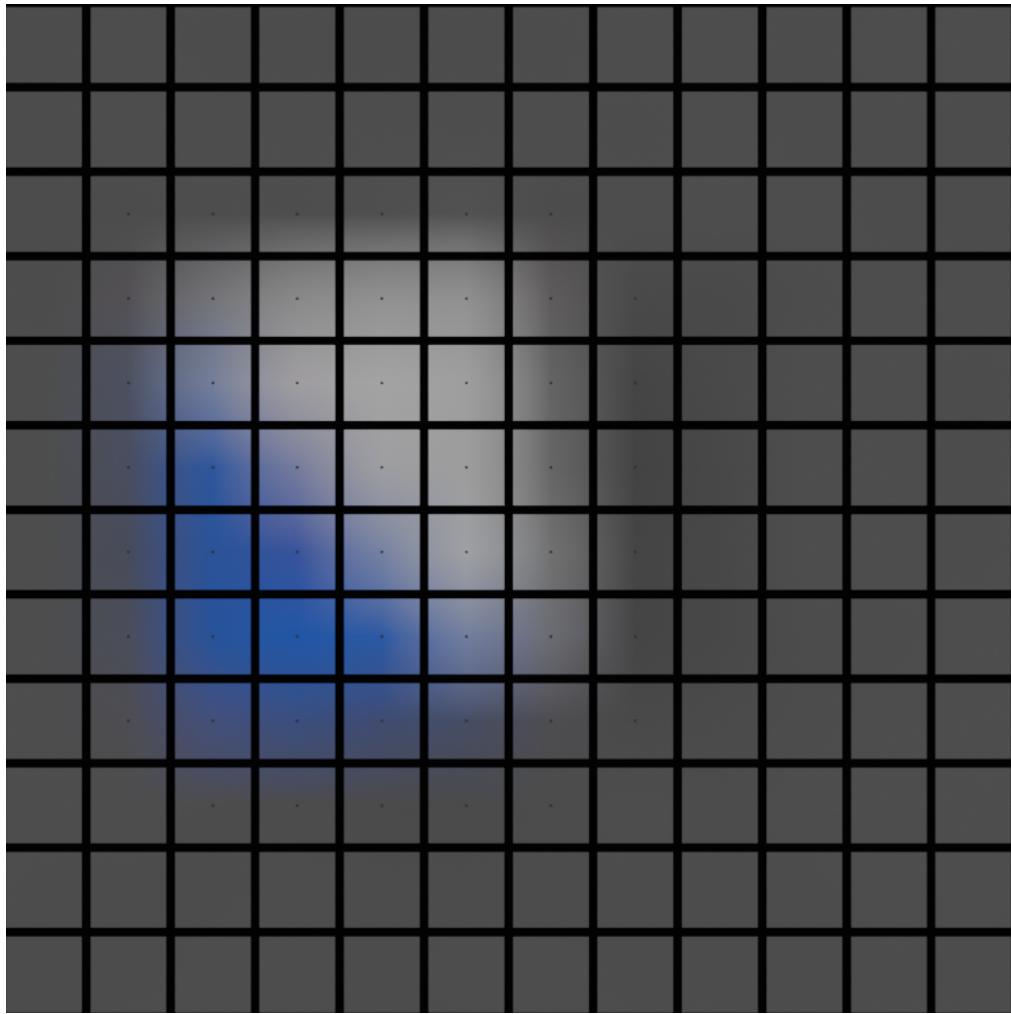


Figure 57: Detailed Code Representation of Image Class

The above figures illustrate the structure and logic behind the `Image` class, showcasing how it facilitates the storage and rendering of pixel data.

4.2 MeshReader and 3D File Format Handling

The `MeshReader` class is designed to load and parse external 3D model files. It converts the vertices, faces, and other geometric information into a format that the renderer can use for ray intersection tests.

Features:

1. **File Parsing:** Supports common 3D file formats, extracting vertex and face data for use in the rendering process.

2. **Data Conversion:** Converts 3D model data into internal data structures like triangles and points, which the RayCast Renderer can process.

```
≡ face_coordinates.txt
1  (0.468750,-0.757812,0.242188);(0.500000,-0.687500,0.093750);(0.562500,-0.671875,0.242188)
2  (-0.500000,-0.687500,0.093750);(-0.468750,-0.757812,0.242188);(-0.562500,-0.671875,0.242188)
3  (0.562500,-0.671875,0.242188);(0.546875,-0.578125,0.054688);(0.625000,-0.562500,0.242188)
4  (-0.546875,-0.578125,0.054688);(-0.562500,-0.671875,0.242188);(-0.625000,-0.562500,0.242188)
5  (0.500000,-0.687500,0.093750);(0.351562,-0.617188,-0.023438);(0.546875,-0.578125,0.054688)
6  (-0.351562,-0.617188,-0.023438);(-0.500000,-0.687500,0.093750);(-0.546875,-0.578125,0.054688)
7  (0.437500,-0.765625,0.164062);(0.351562,-0.718750,0.031250);(0.500000,-0.687500,0.093750)
8  (-0.351562,-0.718750,0.031250);(-0.437500,-0.765625,0.164062);(-0.500000,-0.687500,0.093750)
9  (0.351562,-0.781250,0.132812);(0.203125,-0.742188,0.093750);(0.351562,-0.718750,0.031250)
10 (-0.203125,-0.742188,0.093750);(-0.351562,-0.781250,0.132812);(-0.351562,-0.718750,0.031250)
11 (0.351562,-0.718750,0.031250);(0.156250,-0.648438,0.054688);(0.351562,-0.617188,-0.023438)
12 (-0.156250,-0.648438,0.054688);(-0.351562,-0.718750,0.031250);(-0.351562,-0.617188,-0.023438)
13 (0.140625,-0.742188,0.242188);(0.156250,-0.648438,0.054688);(0.203125,-0.742188,0.093750)
14 (-0.140625,-0.742188,0.242188);(-0.156250,-0.648438,0.054688);(-0.078125,-0.656250,0.242188)
15 (0.273438,-0.796875,0.164062);(0.140625,-0.742188,0.242188);(0.203125,-0.742188,0.093750)
16 (-0.140625,-0.742188,0.242188);(-0.273438,-0.796875,0.164062);(-0.203125,-0.742188,0.093750)
17 (0.242188,-0.796875,0.242188);(0.203125,-0.742188,0.390625);(0.140625,-0.742188,0.242188)
18 (-0.203125,-0.742188,0.390625);(-0.242188,-0.796875,0.242188);(-0.140625,-0.742188,0.242188)
19 (0.203125,-0.742188,0.390625);(0.078125,-0.656250,0.242188);(0.140625,-0.742188,0.242188)
20 (-0.203125,-0.742188,0.390625);(-0.078125,-0.656250,0.242188);(-0.156250,-0.648438,0.437500)
21 (0.351562,-0.718750,0.453125);(0.156250,-0.648438,0.437500);(0.203125,-0.742188,0.390625)
22 (-0.351562,-0.718750,0.453125);(-0.156250,-0.648438,0.437500);(-0.351562,-0.617188,0.515625)
```

Figure 58: Example of a Supported 3D File Format

```
1 ∵ /**
2  * @file MeshReader.h
3  * @brief Defines the MeshReader class for reading text files to extract mesh data.
4  */
5
6 ∵ #ifndef MESH_READER_H
7 #define MESH_READER_H
8
9 ∵ #include <string>
10 #include <vector>
11 #include <fstream>
12
13 #include "point.h"
14
15 using namespace std;
16 ∵ /**
17 * @class MeshReader
18 * @brief Represents a mesh reader for reading text files to extract mesh data.
19 * The MeshReader reads a text file that has lines each line contains a set of vertices that
20 * represent a face each vector position is seperated by a semicolon and each coordinate is seperated by a comma.
21 */
22 ∵ class MeshReader {
23 public:
24     vector<vector<string>> verticesString;
25     MeshReader(string filename)
```

Figure 59: MeshReader Class Representation

These visualizations highlight how the `MeshReader` class facilitates the integration of complex 3D models into the rendering pipeline, enabling accurate and efficient handling of external assets.