Cluster-Base Level of Detail Technique Analysis

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Abstract

This report presents the development of a real-time ClusterLOD Renderer designed for efficient rendering of large-scale scenes with complex geometry. The project addresses challenges in maintaining high visual fidelity, optimizing performance, and reducing memory usage, leveraging modern GPU techniques. Key methods include mesh partitioning, Quadric Error Metrics (QEM) simplification.

The motivation for this work stems from significant advancements in game engine technologies in recent years, particularly the introduction of Nanite and Lumen in Unreal Engine 5 in 2020. Nanite revolutionized mesh handling by enabling the efficient loading and use of massive geometry data in real-time scenes, while Lumen focused on indirect global illumination, delivering realistic lighting and reflections. While Lumen improves visual quality by simulating light transport, this project emphasizes addressing the challenges of rendering massive geometry datasets, akin to those targeted by Nanite.

This project primarily focuses on managing large-scale meshes by utilizing clustering techniques to achieve two core objectives: first, to parallelize and accelerate the QEM simplification algorithm, enabling efficient precomputation of mesh levels of detail; second, to allow piecewise Level of Detail (LOD) selection instead of traditional whole-mesh LOD selection. These innovations make it possible to dynamically adjust detail levels across different parts of a scene, optimizing both performance and memory usage in real-time applications.

By combining clustering, hierarchical data structures, and a GPU-driven pipeline, this work advances the state-of-the-art in real-time rendering, making it well-suited for applications requiring high-quality visuals and efficient resource utilization.

Contents

1 Introduction

1.1 Purpose

The motivation for this project originates from the impressive advancements showcased by Unreal Engine 5 (UE5) in 2020, particularly the Tomb Raider Cave demo. This demo demonstrated the capability to render billions of triangles in a single frame, all in real-time. Inspired by this, I aim to develop a similar system capable of rendering large-scale scenes in real-time, enabling the creation of more complex and immersive environments in games, ultimately enhancing realism.

While UE5's Lumen focuses on real-time global illumination by combining multiple global illumination algorithms, it works by accumulating radiance over time. It employs a 'render-SurfaceCache' to convert to and from VoxelSH spheres, achieving real-time results through temporal radiance accumulation. This allows Lumen to deliver highly realistic lighting in dynamic scenes.

Our project, however, focuses on Nanite, another groundbreaking technology introduced alongside Lumen. Nanite addresses the challenge of efficiently rendering vast numbers of triangles in large-scale scenes. Its core innovation lies in the ability to quickly select visible triangles and stream them into the GPU. This is essential for scenarios where scenes contain a high density of triangles but are viewed from a distance. In such cases, the resolution of the view often cannot match the scene's geometric detail, leading to significant overdraw, as multiple triangles may be rendered for a single pixel.

To solve this, an efficient Level of Detail (LOD) system is required. The LOD system dynamically adjusts the level of detail based on the viewpoint, reducing overdraw and improving rendering performance. This project aims to study and replicate these ideas, exploring how to implement a robust and efficient ClusterLOD rendering system.

1.2 Goal

The goal of this project is to develop a real-time ClusterLOD renderer for efficiently rendering large-scale scenes with complex geometries.

This problem can be divided into two main parts: precomputation and runtime pipeline.

In the **precomputation** stage, the tasks include:

1. **Mesh Partitioning:** Divide the mesh into multiple clusters, where each cluster represents a group of spatially adjacent triangles.
2. **QEM Simplification:** Simplify the clusters using the Quadric Error Metrics (QEM) algorithm, reducing the number of triangles while maintaining visual fidelity.
3. **LOD Hierarchy Construction:** Repeat the above process iteratively to generate a Level of Detail (LOD) hierarchy. Finally, build a Bounding Volume Hierarchy (BVH) to organize these LODs, enabling fast, compute-shader-based selection and streaming.

In the **runtime pipeline**, the tasks include:

1. **LOD Selection and Streaming:** Select and stream visible clusters dynamically based on the view frustum and screen-space error metrics.
2. **Visibility Buffer Implementation:** Implement a visibility buffer to assist with cluster culling. Inspired by UE5, this involves using the visibility buffer from the previous frame to conservatively determine visible objects, followed by further culling calculations for remaining clusters.
3. **Deferred Shading Pipeline:** Integrate the visibility buffer into the deferred shading pipeline without disrupting its workflow.
4. **Real-time Effects:** Implement advanced real-time effects, including Screen Space Reflections (SSR), Screen Space Ambient Occlusion (SSAO), and Multi-Sample Anti-Aliasing (MSAA).
5. **Post-Processing Effects:** Apply effects such as bloom, tone mapping, and color grading to enhance the final rendered image.

By addressing both precomputation and runtime challenges, this project aims to create a high-performance ClusterLOD rendering system capable of handling the complexities of large-scale, detailed scenes in real-time.

2 Background and Related Work

2.1 Existing Techniques

Level of Detail (LOD) rendering is a critical technique for managing performance in real-time rendering. Various LOD methods have been developed to balance visual fidelity and computational cost. This section provides an overview of key LOD techniques:

1. **Discrete Level of Detail (DLOD):** Objects are preprocessed to generate multiple resolutions, such as high, medium, and low LODs. The appropriate LOD is selected at runtime based on the viewer's distance. While simple and efficient, this method may suffer from popping artifacts during transitions. This is generally generated by the artist and is not dynamic.

2. **Continuous Level of Detail (CLOD):** Instead of predefined levels, geometry is simplified dynamically in real-time, ensuring smooth transitions. This approach is commonly used in terrain rendering, such as the ROAM algorithm, but requires higher computational effort.

3. **Screen Space Error Metrics:** This method uses the projected size of objects on the screen to dynamically adjust LOD. By measuring pixel coverage, this technique ensures optimal resource allocation and minimizes overdraw.

4. **Cluster-Based LOD:** Introduced in Unreal Engine 5 as Nanite, this technique divides models into clusters and generates multi-level LODs. GPU-based parallel processing enables fast selection and streaming of visible clusters, making it suitable for large-scale, highly detailed scenes.

5. **Image-Based LOD (Billboarding):** Objects far from the camera are replaced with 2D textures mapped onto planes, significantly reducing geometry complexity. This technique is widely used for rendering vegetation and distant objects in large scenes.

6. **Geometry Shaders for LOD:** Geometry shaders dynamically adjust the level of detail during rendering. Although flexible, this approach may face performance bottlenecks for highly detailed models.

Each of these techniques offers unique advantages and trade-offs. In this project, we focus on Cluster-Based LOD to handle large-scale scenes with high geometric complexity, inspired by Nanite's efficient cluster-based streaming and selection pipeline.

2.2 Relevant Concepts

This section provides an overview of the key concepts used in this project: mesh partitioning, QEM simplification, and Bounding Volume Hierarchy (BVH).

2.2.1 Mesh Partitioning

Mesh partitioning is the process of dividing a mesh into smaller, spatially coherent clusters. This is essential for efficient processing and management of complex geometries in real-time rendering. One common approach is to use graph partitioning algorithms, such as those implemented in the METIS library. METIS works by representing the mesh as a graph, where vertices correspond to mesh elements (e.g., triangles) and edges represent adjacency relationships. By minimizing the edge cut between partitions, METIS ensures that clusters are spatially cohesive, which is critical for Level of Detail (LOD) systems and BVH construction.

2.2.2 QEM Simplification

Quadric Error Metrics (QEM) simplification is a widely-used algorithm for reducing the complexity of a mesh while preserving its visual fidelity. The core idea is to iteratively collapse edges by combining two vertices into one, minimizing the geometric error introduced by the operation. This section describes the steps of the QEM simplification algorithm and formulates the edge collapse operation mathematically.

Steps of QEM Simplification:

1. **Initialize Error Matrices:** For each vertex v_i in the mesh, calculate its associated quadric error matrix Q_i. This matrix is defined based on the sum of the squared distances to the planes of all triangles adjacent to v_i:

$$Q_i = \sum_{p \in \text{adjacent planes}} \mathbf{k}_p \mathbf{k}_p^T$$

   where $\mathbf{k}_p = [a, b, c, d]^T$ is the plane equation $ax + by + cz + d = 0$ normalized for each triangle plane adjacent to v_i. This 4 by 4 matrix can be used to calculate the distance from a point to a plane derived from [1].

2. **Select Candidate Edges:** Identify all edges in the mesh that are candidates for collapsing. An edge is defined by two vertices v_i and v_j.

3. **Compute Collapse Cost:** For each edge (v_i, v_j), calculate the combined quadric error matrix:

$$Q_{ij} = Q_i + Q_j$$

The optimal new position v' is computed by minimizing the quadric error:

$$\text{Error}(v') = v'^T Q_{ij} v'$$

where $v' = [x, y, z, 1]^T$. To find the position v' that minimizes this error, the following steps are taken:

(a) Represent Q_{ij} as:

$$Q_{ij} = \begin{bmatrix} A & b \\ b^T & c \end{bmatrix}$$

where A is a 3×3 matrix, b is a 3×1 vector, and c is a scalar.

(b) Solve for v' if A is invertible:

$$v' = -A^{-1} b$$

(c) If A is singular (not invertible), choose v' as one of the following:

- Vertex v_i,
- Vertex v_j,
- The midpoint of (v_i, v_j): $\frac{v_i + v_j}{2}$.

Compare the quadric error values at these candidate positions and select the one with the smallest error.

4. **Edge Collapse Error:** The quadric error associated with collapsing an edge (v_i, v_j) is defined as:

$$\text{Error}(v') = v'^T Q_{ij} v'$$

where Q_{ij} is the combined quadric matrix of v_i and v_j. This error represents the deviation of the simplified surface from the original.

5. **Collapse Edge:** Collapse the edge (v_i, v_j) into the new vertex v'. Update the mesh connectivity and recompute affected triangles to reflect the collapse.

6. **Repeat Until Target Simplification:** Continue collapsing edges with the lowest cost until the target number of triangles or the desired error threshold is reached.

By iteratively applying the steps described above, QEM simplifies the mesh while maintaining its essential geometric features, making it an ideal choice for real-time LOD rendering.

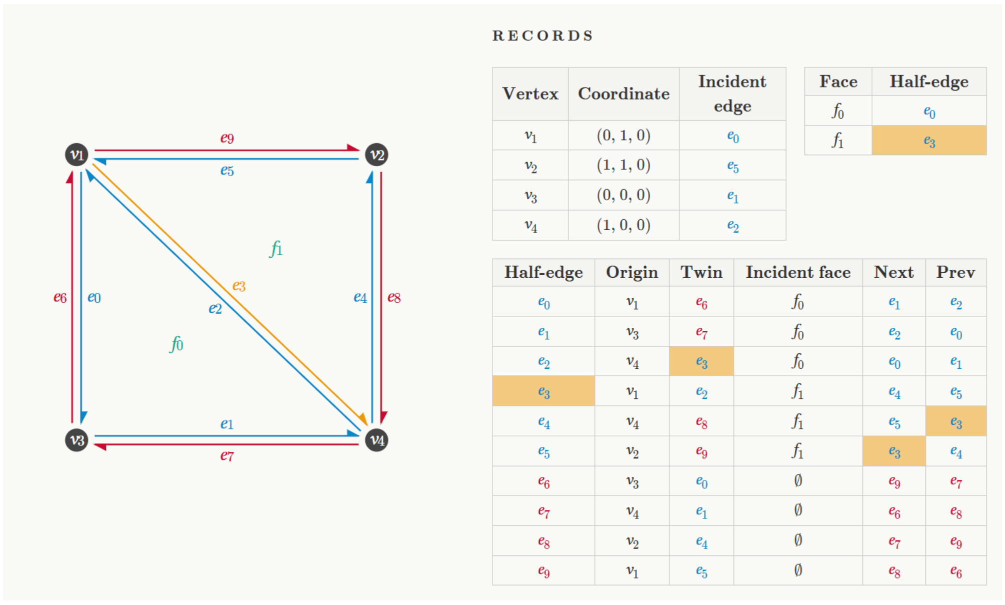
2.2.3 Bounding Volume Hierarchy (BVH)

A Bounding Volume Hierarchy (BVH) is a tree-like data structure used to organize objects in a 3D space. Each node in the BVH contains a bounding volume (e.g., an axis-aligned bounding box) that encapsulates a subset of the scene's geometry. BVHs are widely used in real-time rendering for tasks like frustum culling, ray tracing, and LOD selection. By hierarchically grouping objects, BVHs enable efficient spatial queries and reduce the computational cost of rendering. In the context of ClusterLOD, BVHs are constructed to organize LOD levels, allowing for fast selection and streaming of visible clusters based on the view frustum and screen-space error metrics.

These concepts—mesh partitioning, QEM simplification, and BVH—form the foundation of the ClusterLOD system implemented in this project, enabling efficient processing and rendering of large-scale scenes.

2.2.4 Half Edge Data Structures

The Half-Edge Data Structure is a widely used representation for polygonal meshes in computer graphics, particularly for applications requiring efficient traversal and modification of mesh connectivity. It provides a flexible and efficient way to store and access vertices, edges, and faces in a mesh.



RECORDS

Vertex	Coordinate	Incident edge
v_1	(0, 1, 0)	e_0
v_2	(1, 1, 0)	e_5
v_3	(0, 0, 0)	e_1
v_4	(1, 0, 0)	e_2

Face	Half-edge
f_0	e_0
f_1	e_3

Half-edge	Origin	Twin	Incident face	Next	Prev
e_0	v_1	e_6	f_0	e_1	e_2
e_1	v_3	e_7	f_0	e_2	e_0
e_2	v_4	e_3	f_0	e_0	e_1
e_3	v_1	e_2	f_1	e_4	e_5
e_4	v_4	e_8	f_1	e_5	e_3
e_5	v_2	e_9	f_1	e_3	e_4
e_6	v_3	e_0	$\emptyset$	e_9	e_7
e_7	v_4	e_1	$\emptyset$	e_6	e_8
e_8	v_2	e_4	$\emptyset$	e_7	e_9
e_9	v_1	e_5	$\emptyset$	e_8	e_6

Figure 1: Illustration of the Half-Edge Data Structure. Each edge is represented as two half-edges, with references to vertices, faces, and other half-edges.[2]

Basic Structure The Half-Edge Data Structure represents a mesh using three core components: This structure allows efficient traversal of the mesh and adjacency queries, such as

Component	**Description**
HalfEdge	Each edge in mesh split into two directed half-edges. Each half-edge stores: • *origin* which is the start vertex. • *next half-edge* in the current face (forming a circular linkedlist). • *twin half-edge* (the opposite direction of the same edge). • *face* it belongs to.
Vertex	Each vertex stores: • *position* in 3D space (e.g., (x, y, z)). • *outgoing half-edge* originate from this vertex. (can be random)
Face	Each face stores: • *bounding half-edges.* (can be random)

Table 1: Core components of the Half-Edge Data Structure.

finding all vertices adjacent to a given vertex or all edges adjacent to a face.

Traversal Algorithms Below are example pseudocode implementations for common traversal tasks using the Half-Edge Data Structure.

Traversing a Face To traverse all the half-edges forming a face:

```
function traverse_face(start_half_edge):
    current_half_edge = start_half_edge
    do:
        print(current_half_edge.start_vertex)
        current_half_edge = current_half_edge.next
    while current_half_edge != start_half_edge
```

Listing 1: Pseudocode for traversing a face.

Finding All Adjacent Vertices To find all vertices adjacent to a given vertex:

```
function find_adjacent_vertices(start_vertex):
    current_half_edge = start_vertex.outgoing_half_edge
    do:
        adjacent_vertex = current_half_edge.twin.start_vertex
        print(adjacent_vertex)
        current_half_edge = current_half_edge.twin.next
    while current_half_edge != start_vertex.outgoing_half_edge
```

Listing 2: Pseudocode for finding adjacent vertices.

3 Objective List

3.1 Precomputation Steps

DONE	Mesh Partitioning with METIS.
DONE	Quadric Error Metrics (QEM) Simplification.
INPROGRESS	Construction of the LOD Hierarchy.
NOT STARTED	BVH Construction for LOD levels.
DONE	Index Buffer Generation.

3.2 Runtime Pipeline

NOT STARTED	LOD Selection and Streaming.
NOT STARTED	Visibility Buffer Implementation.
DONE	Deferred Shading Pipeline.
SOMEWHAT DONE	Screen Space Reflections.
SOMEWHAT DONE	Post Processing Effects.

4 Implementation

As you can see from both the code and the report, this project is barely finished. In this section, I will elaborate on the reasons behind this and the challenges encountered during the implementation. The project required multiple redesigns and rewrites of critical components, including the mesh structure and associated algorithms.

The entire Mesh structure was redesigned three times, and the Mesh Partitioning algorithm was rewritten three times. Additionally, the Quadric Error Metrics (QEM) algorithm was rewritten twice, the Mesh Consolidator was reimplemented, and the ‘objDecoder‘ was rewritten once before reverting to the original version.

The first implementation did not involve any additional Mesh structure. All edge and face information was generated on the fly, and the METISPartitionKWay method was used for partitioning. However, this approach was prohibitively slow and unsuitable for practical use. Moreover, since QEM required edge information, it became clear that an upgrade to the mesh structure was necessary.

The redesign adopted a recursive strategy using METISPartitionRecursive. This approach recursively bisected the mesh, allowing each subdivision to spawn a new thread for parallel execution. This improved the partitioning performance significantly.

At this point, I discovered the Half-Edge Data Structure, which seemed promising due to its efficient querying capabilities. However, implementing and maintaining a robust Half-Edge structure proved to be extremely challenging. Constructing the data structure itself consumed a significant amount of time as every pointer had to correctly reference the appropriate edge. Despite the difficulties, I managed to construct a functioning Half-Edge structure.

When combining the Half-Edge structure with QEM edge collapse, the complexity increased exponentially. Maintaining a robust Half-Edge data structure while reducing edges became nearly impossible. This involved:

- Removing the inner edges of the face to be collapsed.
- Merging adjacent edges’ twins.
- Reassigning all edges connected to a vertex to another edge.

These steps frequently broke the previous and next pointers in the Half-Edge structure, resulting in infinite loops in face traversal algorithms. Additionally, numerous corner cases such as boundary edges, back-to-back faces, and back-to-back edges caused further complications. After three days and 36 hours of debugging without success, I abandoned using the Half-Edge structure for QEM.

I then moved to a simpler structure called EdgeMesh, which uses an unordered map to map vertex pairs to edges without directionality. This structure made implementing the METISPartitionRecursive and QEM algorithms much easier. Despite spending additional time debugging, I successfully implemented QEM using this structure. However, a new problem arose: optimizing even a moderately complex model, such as the Stanford Bunny (140,000 faces), took 38 minutes.

Parallelizing the QEM algorithm for clusters introduced global memory race conditions that I was unable to resolve. Consequently, I abandoned both of my QEM implementations.

Out of options, I turned to a third-party library called FastQEM. After downloading and building the binary, I tested it on the Stanford Bunny, which completed in just 0.5 seconds. This drastic improvement suggested that the library employed optimizations I was unaware of, and it became apparent that my QEM implementation had issues. Currently, my workflow involves:

- Performing an initial METIS partition on the mesh.
- Exporting the partitioned mesh as an '.obj' file.
- Running the FastQEM binary on the exported mesh.
- Loading the optimized mesh back into my project.

The latest progress involves attempting to integrate this workflow into a streamlined loop. However, the project is far from completion, and it is clear that it cannot be finished on time.

5 Bibliography

References

[1] Michael Garland and Paul S. Heckbert. *Surface Simplification Using Quadric Error Metrics*. `https://www.cs.cmu.edu/~./garland/Papers/quadrics.pdf`. Accessed: 2024-11-19. 1997.

[2] Jerry Yin. *Half-Edge Data Structure*. `https://jerryyin.info/geometry-processing-algorithms/half-edge/`. Accessed: 2024-11-05. 2019.