Geometry Processing

Extra Session

The Nanite System in Unreal Engine 5

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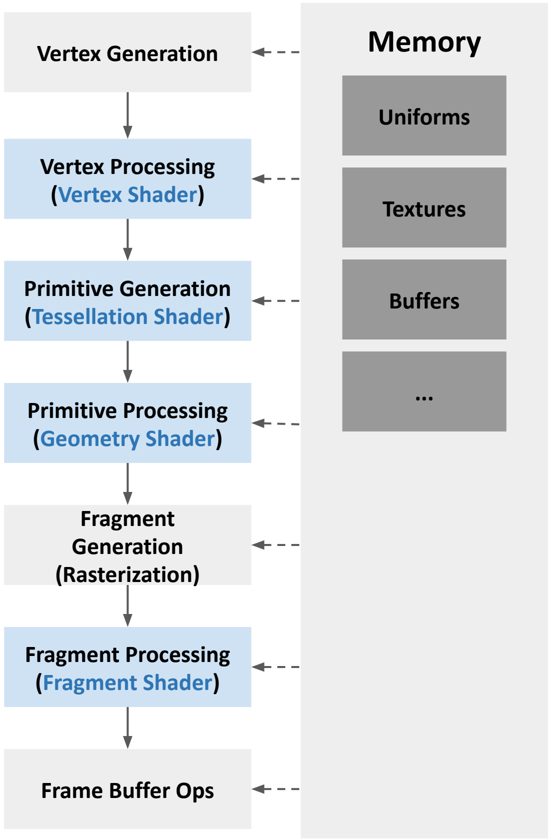
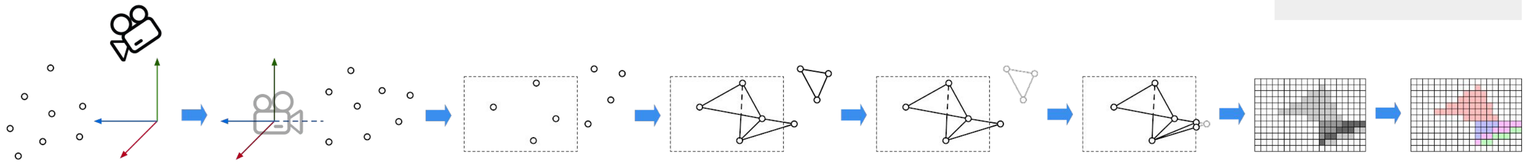
Prerequisite

Recap: Rasterization Pipeline

```
init frame buffer
init depth buffer
for each triangle t in scene {
   tp = project(t) // MVP
   for each pixel p in frame buffer {
       if tp covers p { // culling
           if z passes depth test at p { // depth-test
               update z buffer and frame buffer // interpolation & update
           }
       }
   }
}
flush frame buffer to monitor
```

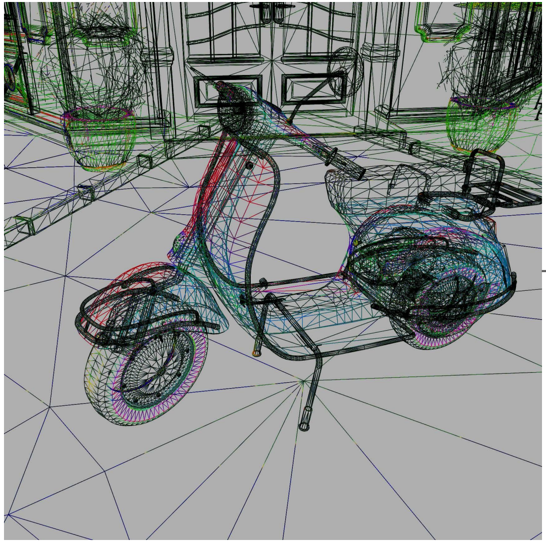


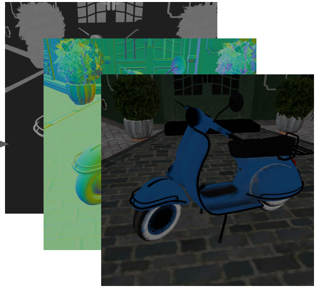


Deferred Rendering [Deering et al 1988]

Core idea: Two rendering pass! Use a geometry-buffer to store geometric information

Limitation: Screen-space information only





GBuffer: Depth, Albedo, Normal, Specular, Shadow, etc...

Deferred Rendering [Deering et al 1988]

Core idea: Two rendering pass! Use a geometry-buffer to store geometric information

Limitation: Screen-space information only

```
init frame buffer
init depth buffer
for each triangle t in scene {
   for each pixel p in frame buffer {
      if project(t) covers p {
         if z passes depth test at p {
            write(depth); shade(pixel)
         }
      }
   }
}
flush frame buffer to monitor
```

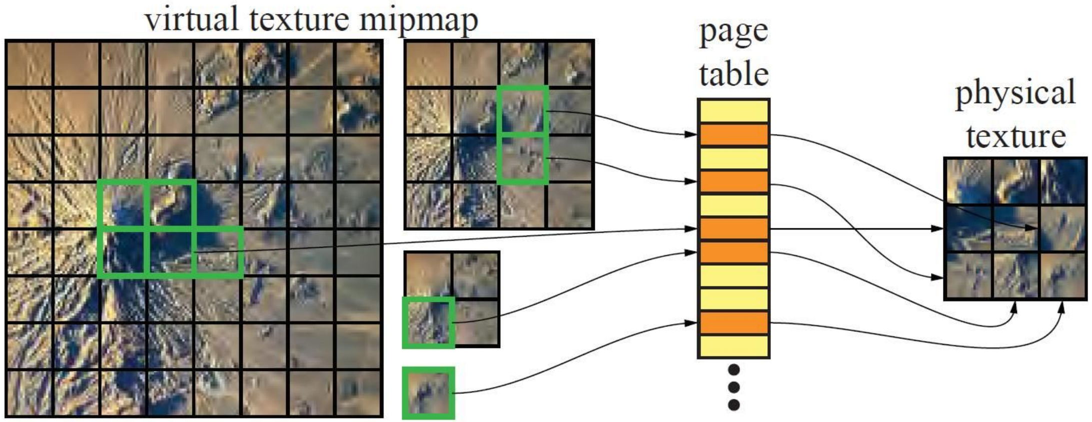
Forward Shading

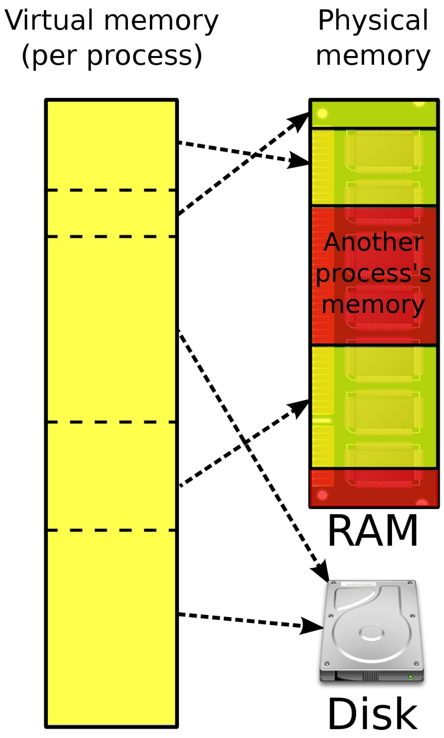
```
init frame buffer
init G    buffer
init depth buffer
for each triangle t in scene {
   for each pixel p in frame buffer {
      if project(t) covers p {
         if z passes depth test at p {
            write(z); write(G)
         }
      }
   }
}
for each pixel p in frame buffer {
   shade(p)
}
flush frame buffer to monitor
```

Deferred Shading

The Concept of "Virtual"

- Virtual *Memory*: allows transparent memory access to a larger address space than the physical memory.
- Virtual *Texture*: allows mip-mapped texture used as cache to allow a much higher resolution texture to be emulated for RTR, while only partly residing in texture memory
- Virtual *Geometry*: ???





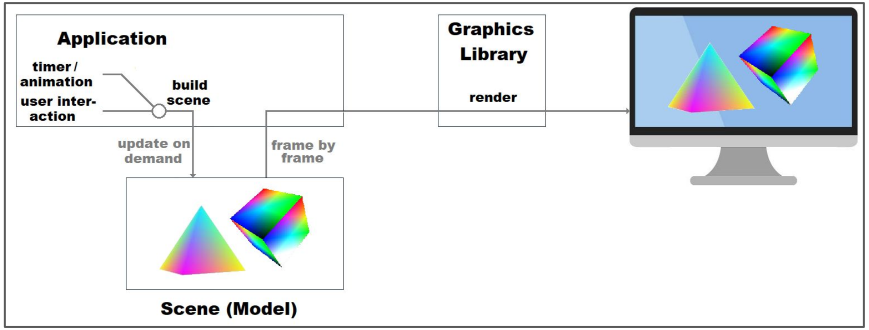
GPU Drawing Mode: Immediate vs. Retained Mode

Retained Mode: Scene representation ***persists between frames on GPU***

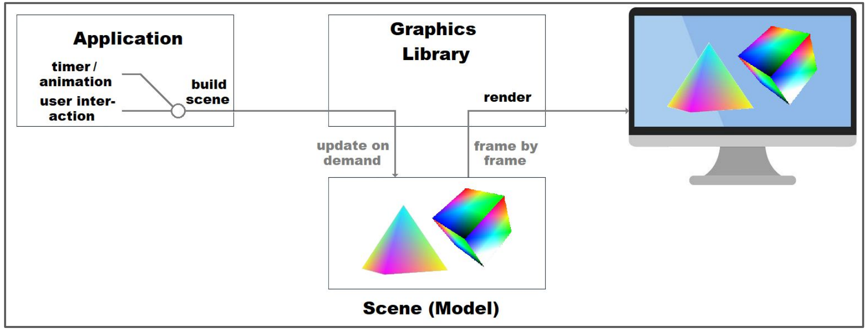
- All vertex/index data in single large resource

Immediate Mode: Primitive vertex attributes may inserted ***from CPU memory per frame***

- Vertex/index data are separately distributed



Immediate Mode



Retained Mode

Extra Session: The Nanite System in Unreal Engine 5

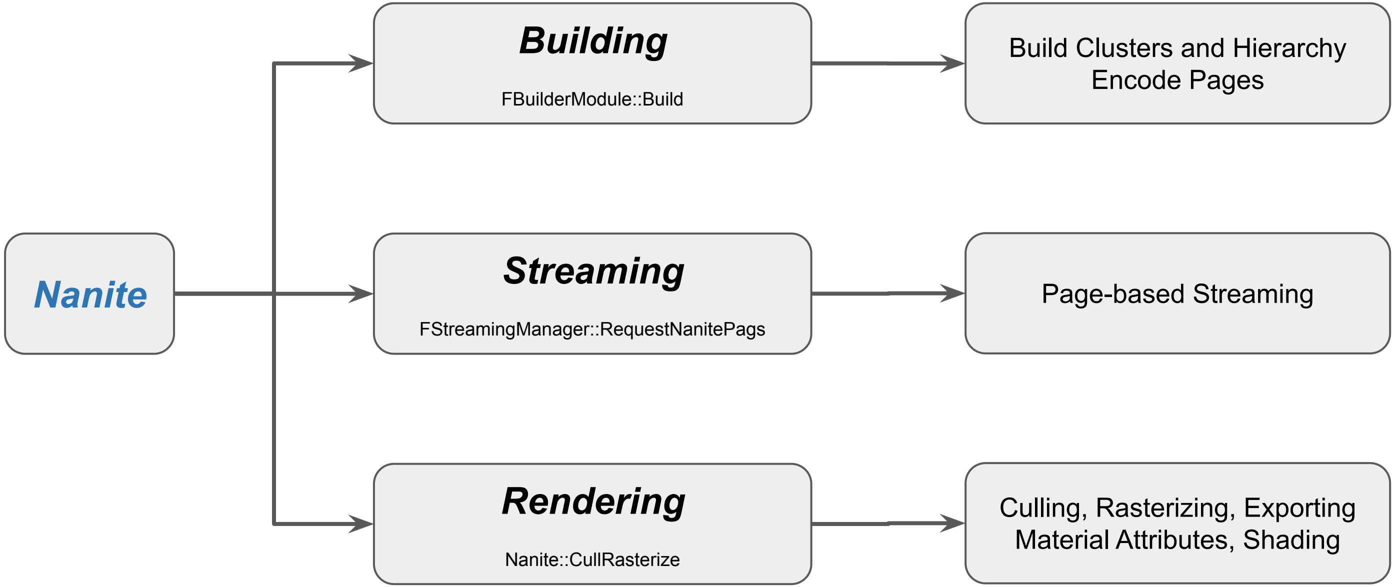
- An Overview of The Nanite System in UE5
- Mesh Building
  - Clustering Hierarchy
  - Culling, LOD, Visibility Buffer
- Mesh Rendering
  - Rasterization
  - Material, Shading, Shadowing
- Summary

What is *Nanite*?

Each statue has more than 33 million triangles

Nanite: An Overview

Nanite is a GPU-driven deferred rendering pipeline for rigid meshes.



Nanite: An Overview

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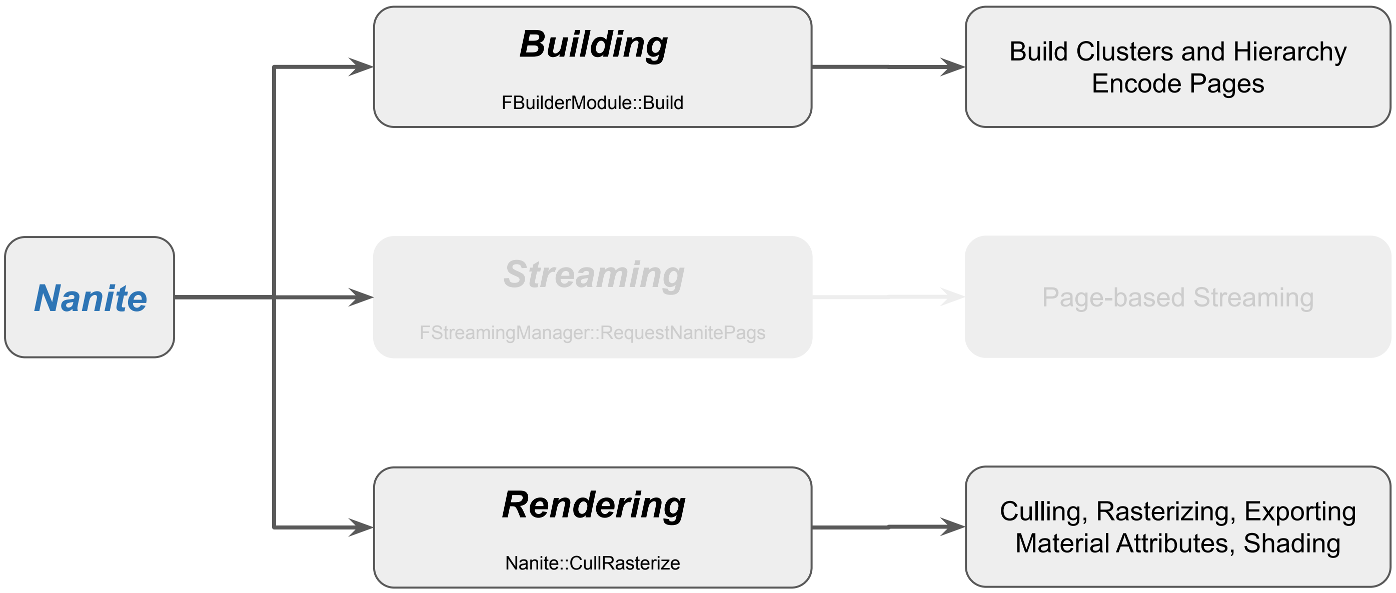

Key Challenges in Building Nanite: Data and Transfer

High-resolution models: 1M Triangles ≈ 140MB (including idx, pos, nor, uv, nor, and etc.)

- consume large amounts of space (including disk and memory)
- read/write IO consumption between disk and memory
- bandwidths between CPU and GPU when copying memory

Solutions: Compression and Visibility buffer (optimized down to 13.8 MB on disk, not today's topic :(

Costs and Solutions in Nanite

When data is large, there will also be huge rendering costs:

- CPU processing cost: Entirely GPU driven, hence not much serious
- CPU-GPU communication cost: Parallel command buffer commit; GPU-Driven pipeline hence not much costs too
- **Vertex shader cost**: LOD clusters and Culling to remove non-visible clusters to reduce vertex shaders
- **Primitive rasterization cost**: sub-pixel primitives are rasterized using *software rasterization*

Nanite GPU Pipeline

Nanite::Streaming: Read cluster rendering information from last frame

Nanite::InitContext: Initialize Culling context

Nanite::CullRasterize: Execute culling and rasterization

- Nanite::InitArgs
- **Nanite::InstanceCull: Remove invisible instances**
- **Nanite::PersistentCull: Remove invisible clusters on BVH**
- Nanite::CalculateSafeRasterizerArgs: Sanity checks for SW/HW render regions
- **Rasterization (Hardware+Software, but all on GPU): Build visibility buffer**
- **Build HZB**

Nanite::EmitDeptTargets

Nanite::BasePass: Render G-Buffer

Nanite::Shadows: Render Shadow Maps

Nanite::Readback

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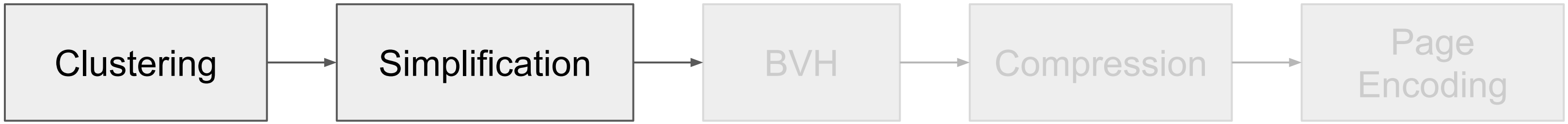
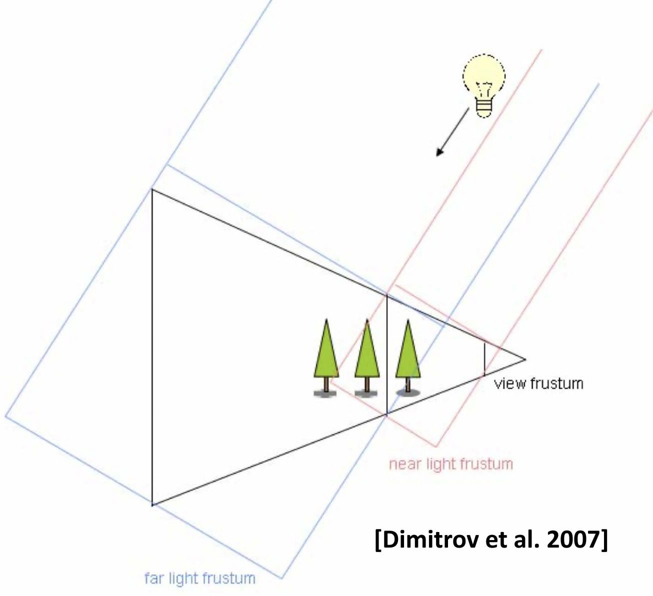
Nanite Mesh Preprocessing

Mesh process is computed offline, and triggered by any model update or activation.



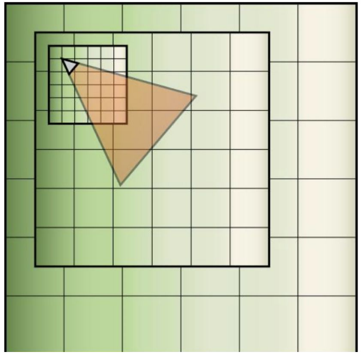
Levels of Detail (LOD) Solutions

- Level of Detail (LOD), a.k.a "Cascaded", is the key to performance
  - Recall: texture MipMapping
  - Choosing the right level of detail to use can speed up computation
- Multiple ways of applying levels of details. Examples:
  - Cascaded shadow maps **[Dimitrov et al. 2007]**
  - Cascaded light propagation volume **[Kaplanyan 2009]**
  - Progressive Meshes **[Hoppe 1996] [Garland et al 1997]**
- Key challenges
  - Transition between different levels: Handling discrete levels
  - Usually need some overlapping and blending near boundaries: Handling cracks



[Dimitrov et al. 2007]

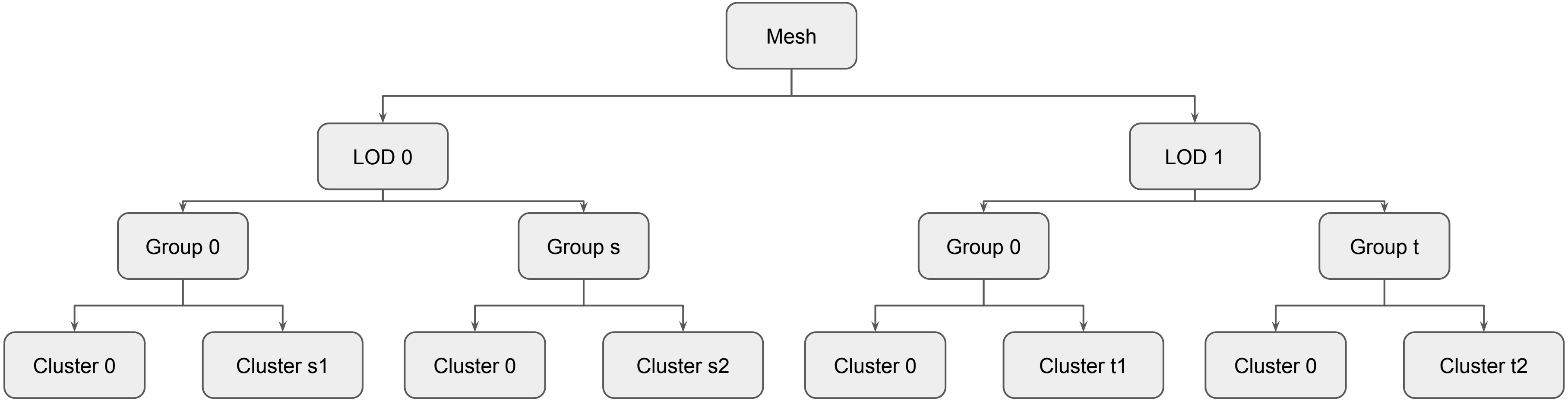
[Kaplanyan 2009]



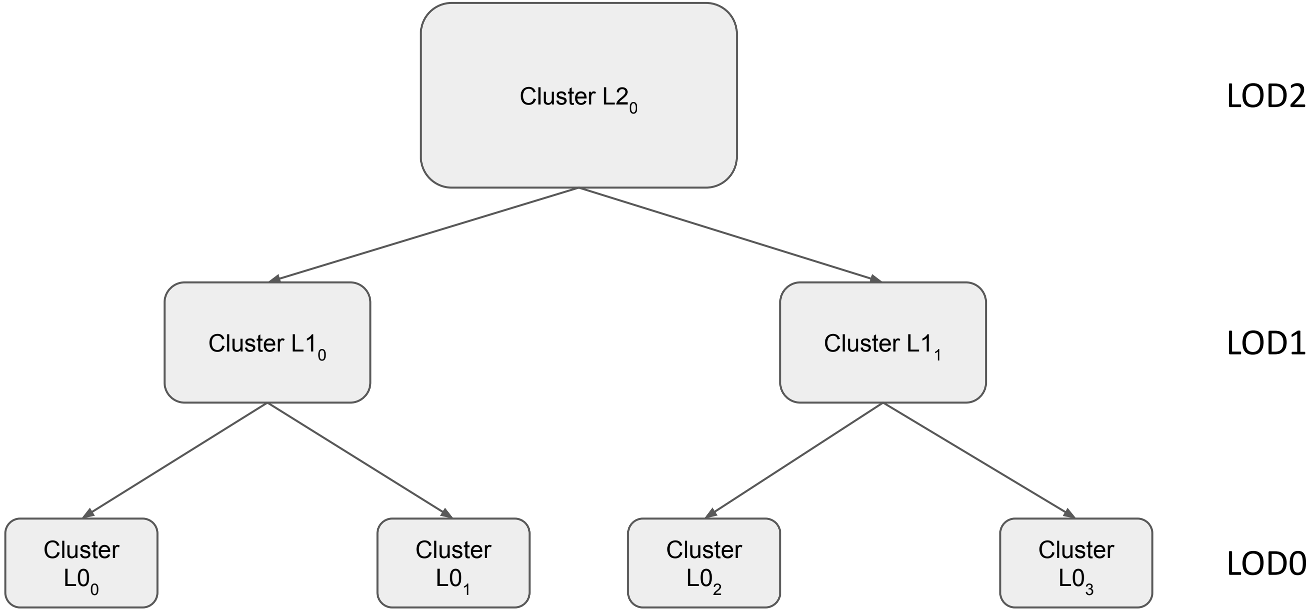
LODs, Groups, and Clusters

Nanite organizes a static mesh by the following hierarchy

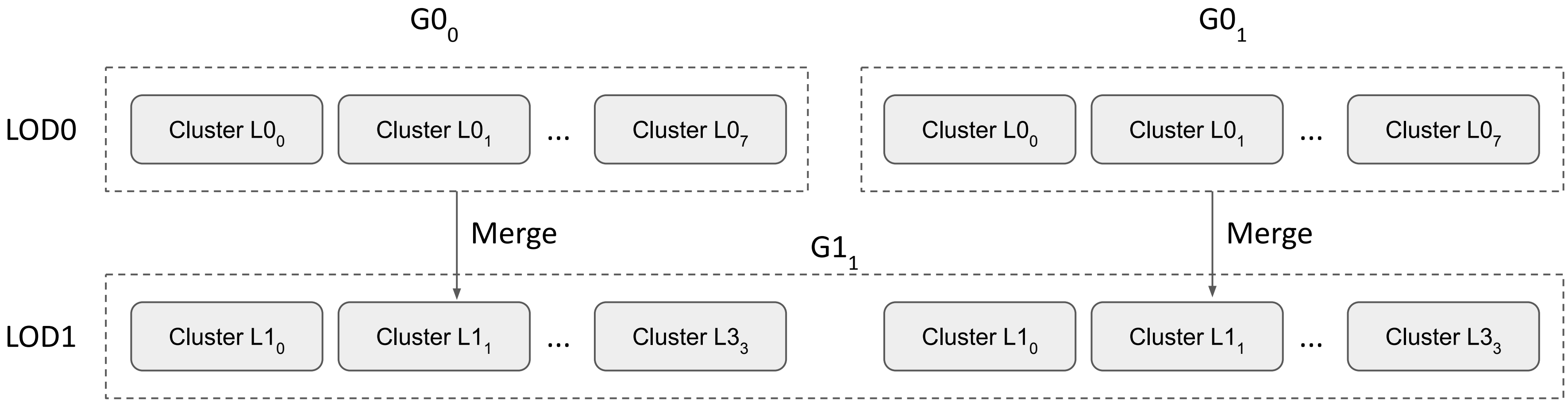
- Each mesh generates different LODs
- Each LOD points to different groups
- Each group is a collection of multiple clusters
- A cluster can only be in a single LOD



Cluster Hierarchy



Cluster Hierarchy

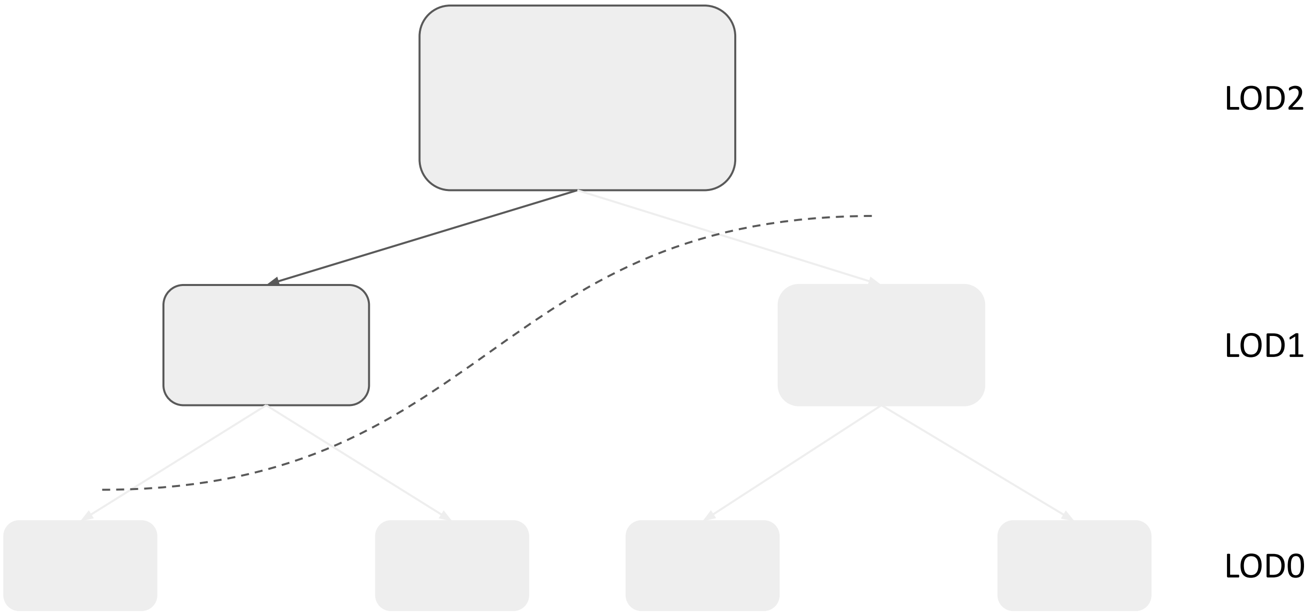


View-dependent Selection [Hoppe 1997]

Two submeshes contain same boundary but in different LOD

Choose between them based on screen-space error

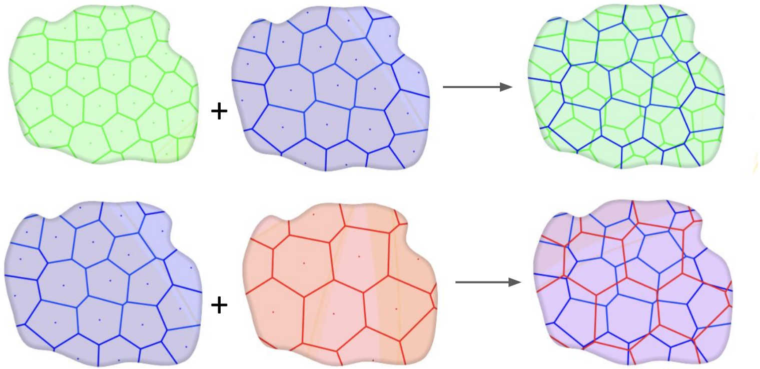
All clusters in group must make same LOD decision

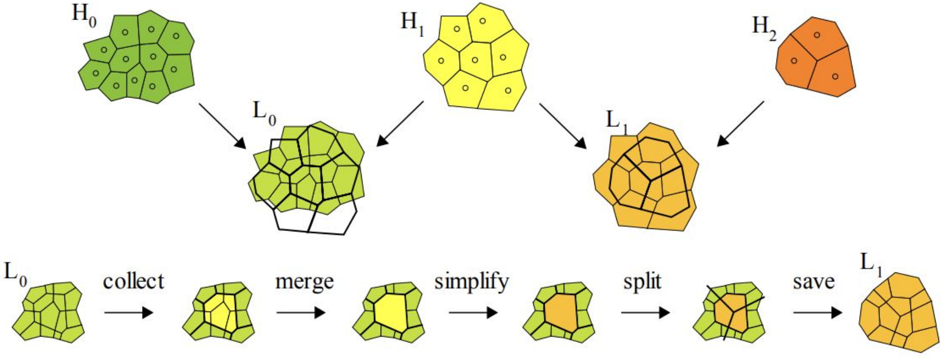


Cluster Generation

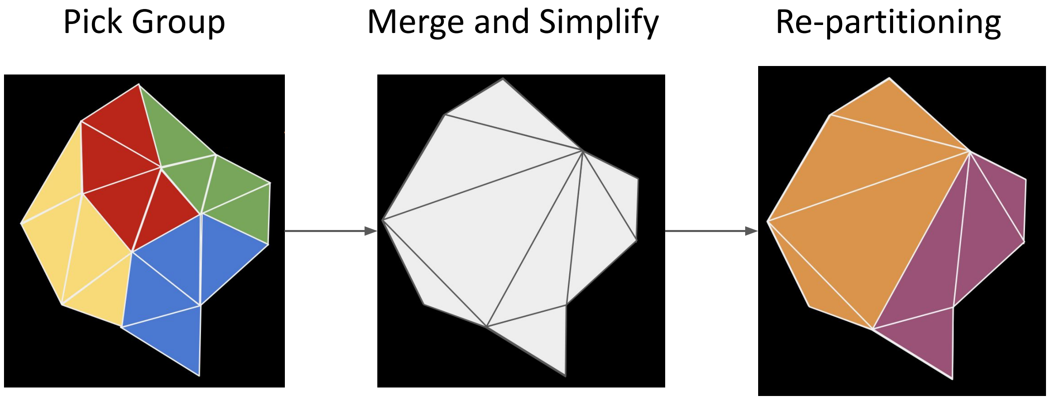
- Use original mesh (LOD 0) to generate graph partition
- Similar to Meshlets from NVIDIA
- Neighbor triangles are treat as a cluster, using ***Metis*** (cache-miss)
- Each cluster contains 128 triangles (to fit vertex processing memory cache)
- Cluster can be grouped together, each group contains 8~32 clusters
- Each LOD need to repeat this process and each group are belongs to one mesh

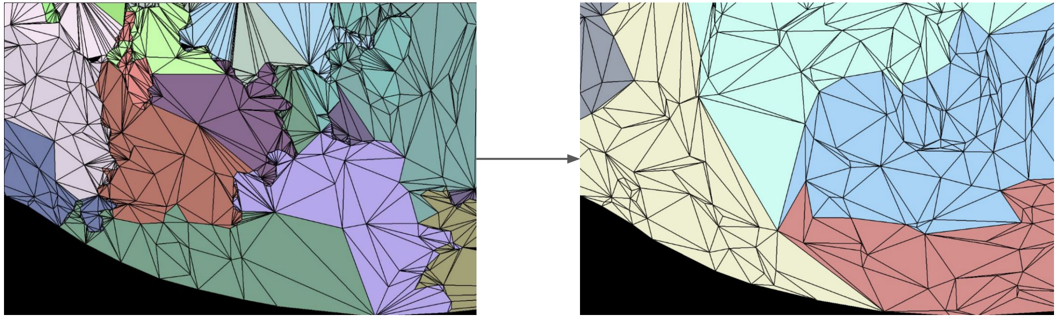
Handling LOD Cracks by Graph Partitioning [Ponchio 2009]





Handling LOD Cracks by Graph Partitioning in Nanite

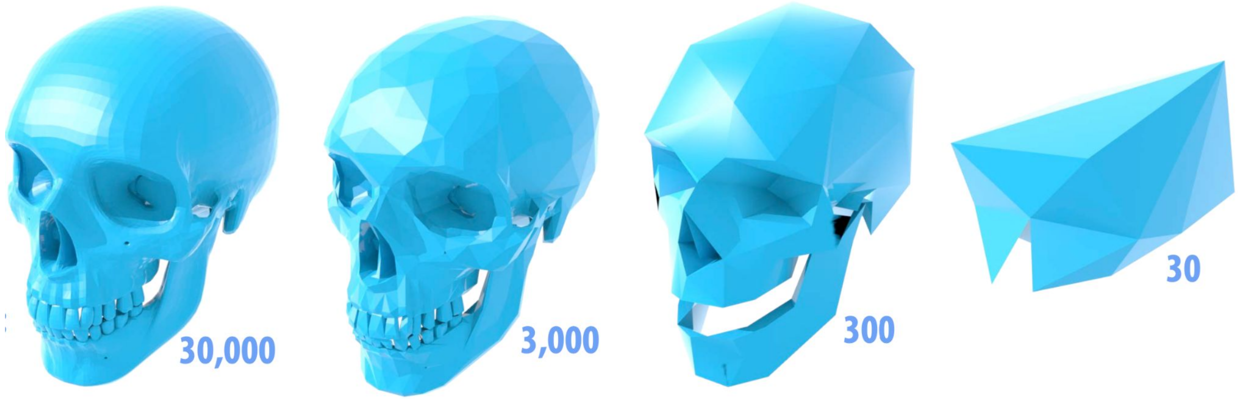




Mesh Simplification

Per Cluster Group Simplification

Simplification by QSim **[Garland 1997]** (discussed in Geometry Processing: 5 Remesh)



Nanite Mesh Build Process

Cluster original triangles

While NumCluster > 1, do:

- **Group** clusters to clean their shared boundary
- **Merge** triangles from group into shared list
- **Simplify** to 50% of triangles
- **Split** simplified triangle list into clusters (per 128 triangles)

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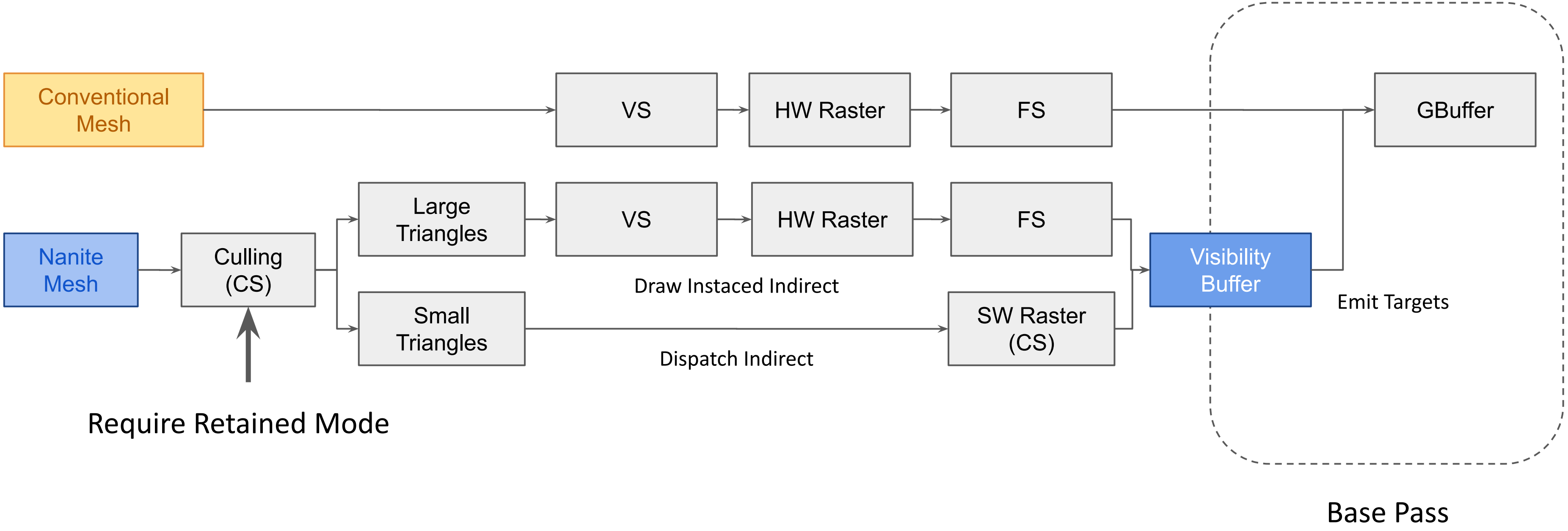
  - Culling, LOD, Visibility Buffer
- **Mesh Rendering**
  - Rasterization
  - Emit Targets and Material Classification
- Summary

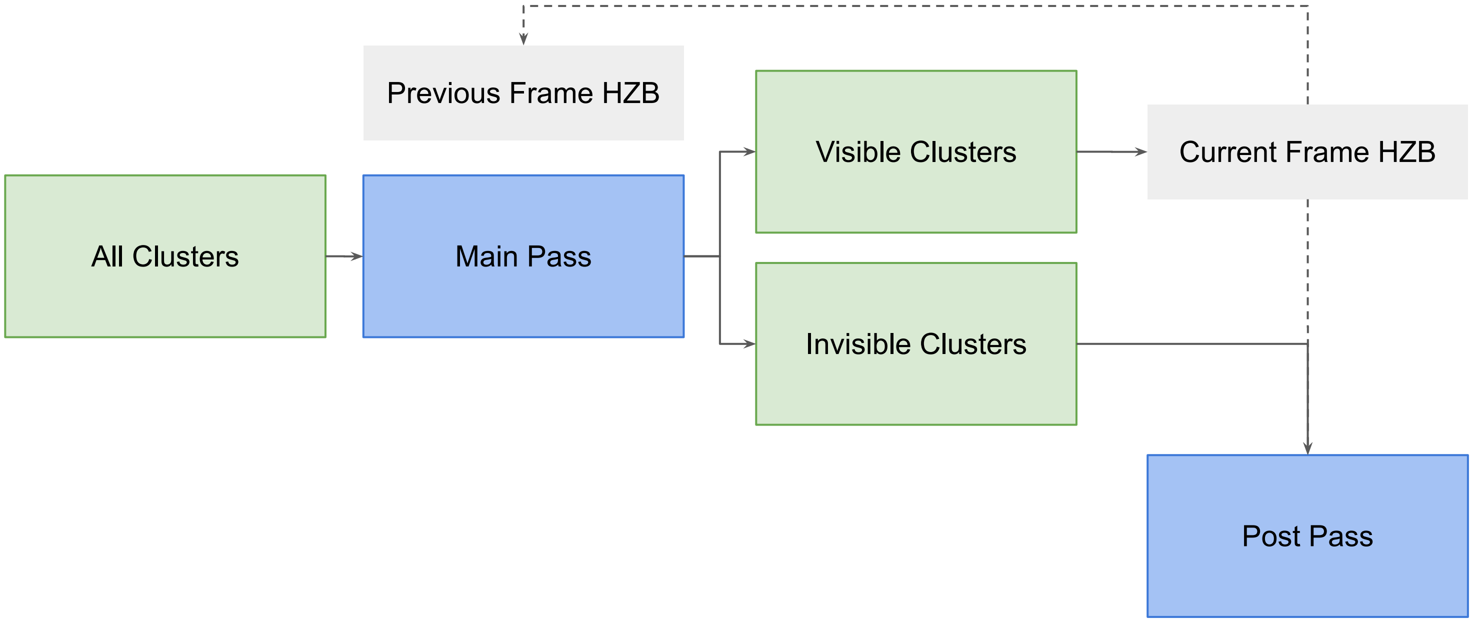
The Rendering Pipeline with Nanite

Conventional mesh can went through the traditional pipeline to render a GBuffer, whereas a nanite mesh is using a compute shader for culling then clustering triangles to do either HW or SW rasterization

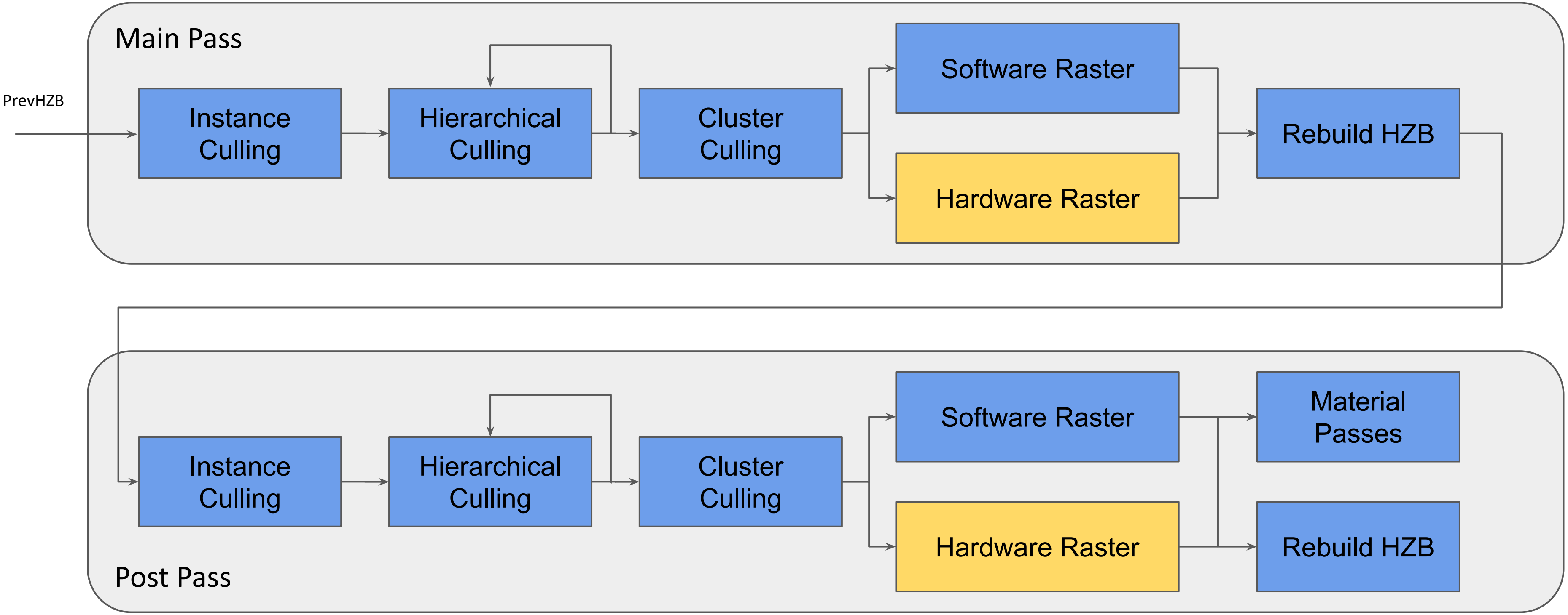


Culling Pipeline

A culling pipeline require two passes. The first pass requires Hierarchical Z-Buffer (HZB) from last frame.



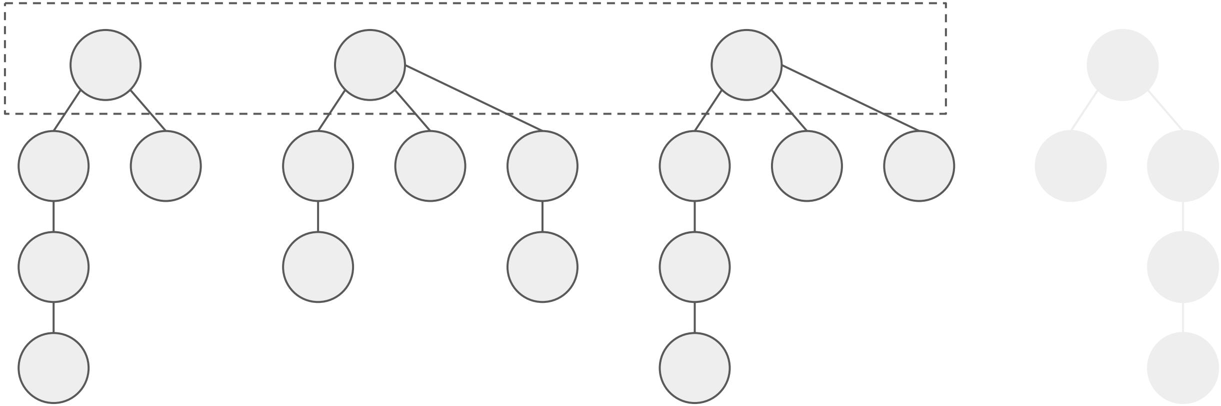
(Two-Pass) Culling Pipeline



Instance Culling

Instance culling removes invisible instances

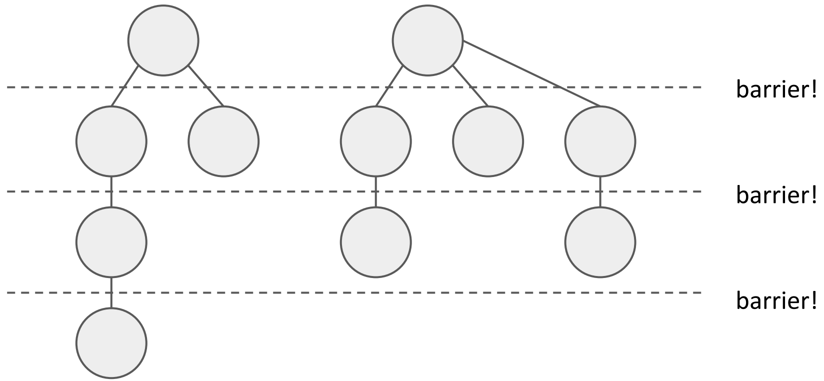
Visible instances are stored in a candidate BVH node list for persistent cull



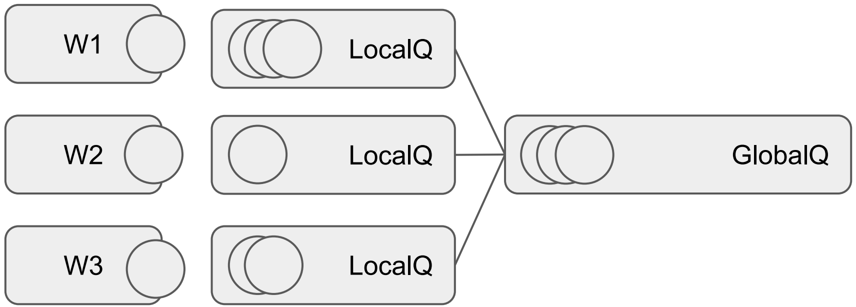
Hierarchical (Persistent) Culling

Each level of BVH is depending on its parents, the naive approach by dispatch per level is slow (obviously)

Using a persistent thread to consume all dispatched tasks (work-stealing algorithm)



Per-level Scheduling



Work-steal Scheduling

Sub-pixel Triangle Rasterization [Kenzel et al 2018]

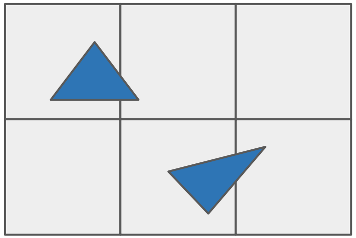
After culling, depending on the screen space size, each cluster will be dispatched to different SW rasterizers.

Large triangles are sent into HW rasterizer

Sub-pixel triangles are send to SW rasterizer that runs on compute shader

The rasterizer is based on Scanline algorithm (discussed in Computer Graphics 1: Rasterization I)

- Each cluster run an individual compute shader, and cache all clip space vertex position to shared memory
- Each thread reads index buffer and transformed vertex position, run backface culling and write depth atomically into **visibility buffer.**



Visibility Buffer

A general visibility buffer is similar to GBuffer but stores much less information on memory

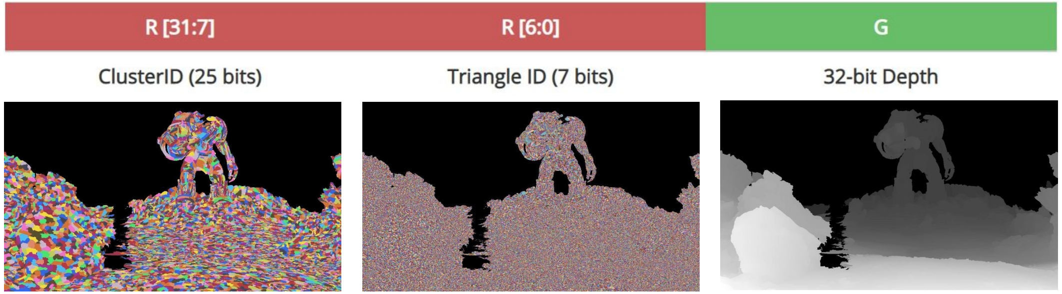
1. Instance ID
2. Primitive ID
3. Barycentric coordinates (for interpolation)
4. Depth buffer
5. Material ID (for shading)

Except screen resolution buffer data, visibility buffer require two additional structure

1. Global vertex buffer
2. Global material map

But Nanite is different:

Visibility Buffer



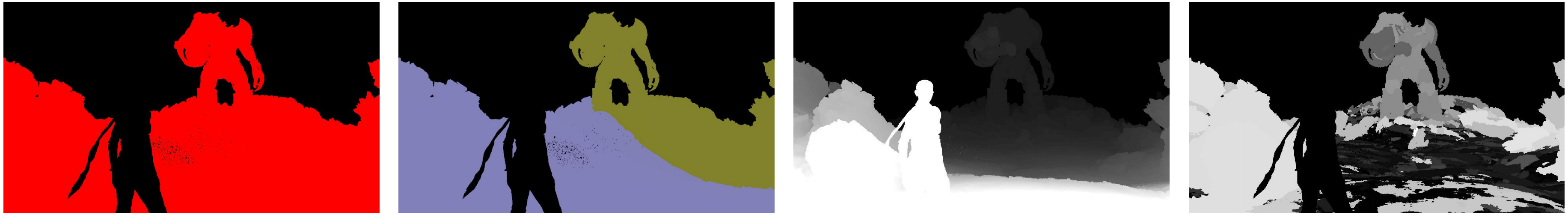
Cluster ID | Triangle ID | Depth

Emit Targets

When visibility buffer is prepared, all information will be write into depth/stencil buffer and motion vector buffer.

This consists of multiple screen-passes:

1. Emit scene depth/stencil/nanite mask/velocity buffer
    - Nanite Mask: 0/1 to indicate if mesh is conventional or nanite
    - Scene Depth Buffer: converted from Visibility buffer
    - Velocity buffer: for motion vectors
2. Emit Material Depth



Nanite Mask | Velocity Buffer | Scene Depth/Stencil Buffer | Material Depth Buffer

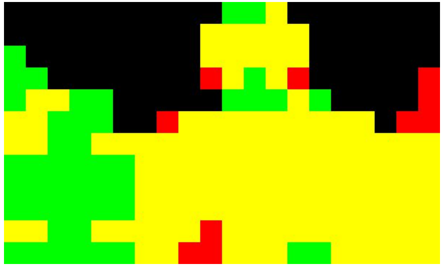
Classify Materials && Emit G-Buffer

In the shading phase, visibility buffer maintains a global material table that stores material parameters and texture index

Each pixel uses material ID to find the material, and parse material information then work with virtual texturing

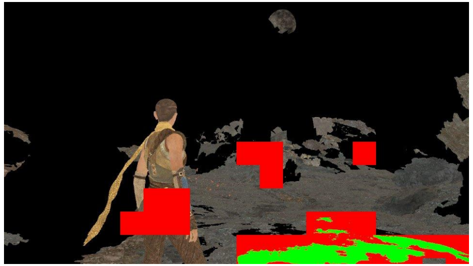
In a complex scene, the number of materials are huge and searching a correct material is costly

In the base pass, screen space is splited into 8x8 segments, each segment counts material depths range



Material Classification

Triangle ID



Material Depth Test

Performance

- Average ~2496x1404 upsampling to 4K
- Culling => Rasterizer => Visibility Buffer **~2.5ms**
- Visibility Buffer => GBuffer **~2ms**

Nanite::CullRasterize

Clear VisBuf	66us
InstanceCull	108ms
PersistentCull	406us
Rasterize	1148us
Build HZB	99us
Post InstanceCull	125us
Post PersistentCull	102us
Post Rasterize	183us

Nanite::BasePass

DepthExport	217us
Emit GBuffer	2084us

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Summary

- Nanite is a a extreme clever engineering that utilizes large amounts of research from 2000s
- The key engineering insights from Nanite
  - Software rasterization is powerful in processing subpixel triangles (but it is likely that future hardware will add additional support for this :)
  - "Perceptually lossless" real-time rendering on large high-resolution rigid models made possible (no more polygon budgets)
- Limitations
  - No Forward Rendering
  - No Alpha Blending/Mask Textures
  - No Deformable Meshes (including skinning, etc)
  - …
- Future Work
  - Non-rigid models?
  - Tessellation and displacement?
- Uncovered topics: **Virtual shadow map (VSM), paging, streaming, disk compression, TAA, etc.**

Nanite Source Code

- Search Strategy: "namespace Nanite"
- https://github.com/EpicGames/UnrealEngine/tree/ue5-main/Engine/Source/Developer/NaniteBuilder
- https://github.com/EpicGames/UnrealEngine/tree/ue5-main/Engine/Source/Runtime/Renderer/Private/Nanite
- https://github.com/EpicGames/UnrealEngine/blob/ue5-main/Engine/Source/Runtime/Engine/Private/Rendering/NaniteStreamingManager.cpp

Further Readings: *Geometry*

[Garland et al 1997] Garland, Michael et al. *Surface simplification using quadric error metrics*. SIGGRAPH' 97, 1997.

[Garland and Heckbert 1998] Garland et al. *Simplifying Surface with Color and Texture using quadric error metrics*. SIGGRAPH'98, 1998.

[Hoppe 1999] Hoppe. *New quadric metric for simplifying meshes with appearance attributes*. IEEE Visualization'99, 1999

[Hoppe et al. 2000] Hoppe and Marschner. *Efficient minimization of new quadric metric for simplifying meshes with appearance attributes*, IEEE Visualization'00, 2000.

[Christopher et al 1998] Christopher C. et al. *The clipmap: a virtual mipmap*. SIGGRAPH '98. 1998.

[Dimitrov et al. 2007] Dimitrov, Rouslan. *Cascaded shadow maps*. Developer Documentation, NVIDIA Corp. 2007.

[Hoppe 1996] Hoppe, Hugues. *Progressive meshes*. SIGGRAPH' 96, 1996.

[Hoppe 1997] Hoppe, Hugues. *View-dependent refinement of progressive meshes*. SIGGRAPH'97. 1997.

[Ponchio 2009] Ponchio, Federico. *Multiresolution structures for interactive visualization of very large 3D datasets*. Univ.-Bibliothek, 2009.

Further Readings: *Rendering*

[Kenzel 2018] Kenzel et al. *A high-performance software graphics pipeline architecture for the GPU*. ACM Trans. Graph. 37, 4, Article 140. August 2018.

Further Readings: *Official Sources from EpicGames*

[Karis et al 2021] Karis, Brian et al. *A Deep Dive into Nanite Virtualized Geometry*. ACM SIGGRAPH Courses, 2021. YouTube.

[Wright 2021] Wright, Daniel. *Radiance Caching for Real-Time Global Illumination*. ACM SIGGRAPH Courses, 2021.

[Unreal 2021] Unreal Engine Channel. Nanite | Inside Unreal. *YouTube*. Jun 4, 2021.

Additional Slides

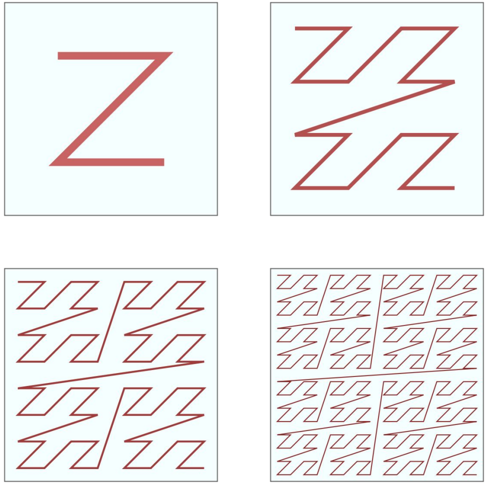
Compression and Encoding

Compression: Memory & disk representations

- High-resolution cluster use high-precision floating numbers
- Low resolution cluster uses low-precision floating numbers
- Cracks between clusters can align high precision to low precision

Page Encoding:

- 128kb size page
- Each page stores multiple groups
- Spatial neighbors are stored in the same page, and use Moton Code to order cluster groups then use LZ4 compression



More about Virtual Texture

Hardware Virtual Texture: Hardware sampling, address mapping, no more runtime memory costs, etc.

- Direct X: Tiled Resource
- Vulkan: Sparse Partially-Resident Images
- OpenGL: ARB_sparse_texutre
- Metal: Sparse Texture

Global Illumination Solutions

When would screen space ray tracing (SSR) fail?

No single GI solution that is perfect for all cases, except RTRT

But complexity using RTRT is still costly in the current generation

Therefore industry trends to use hybrid solutions

A possible solution:

SSR for a rough GI approximation

Upon SSR failure, switch to more complex ray tracing

Either hardware (RTRT) or software (?)

Global Illumination Solutions

Software ray tracing

- **HQ SDF for individual objects that are close-by**
- **LQ SDF for the entire scene**
- **RSM if there are strong directional / point lights**
- Probes that stores irradiance in a 3D grid (Dynamic Diffuse GI, or DDGI)

Hardware ray tracing

- **Doesn't have to use the original geometry, but low-poly proxies**
- Probes (RTXGI)

Highlighted solutions are mixed to get Lumen in UE5