Lecture 04

Rendering on Game Engine

Basics of Game Rendering

WANG XI

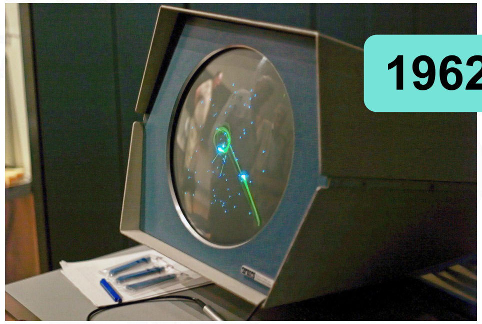
GAMES 104

2022

Rendering System in Games

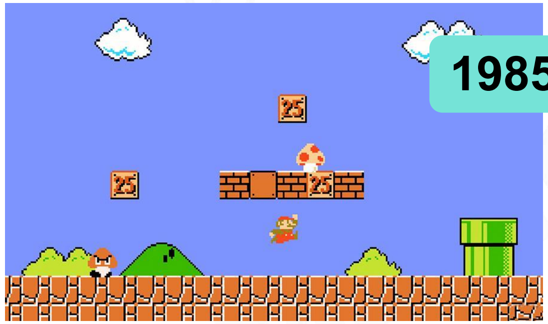
Q : **Is there any game without rendering?**

1962



SpaceWar!

1985



Super Mario

1993

Doom

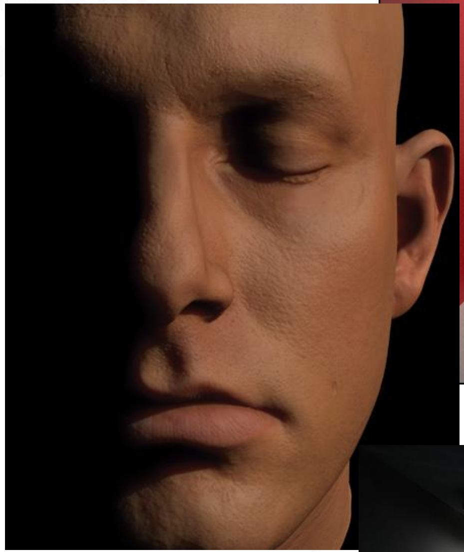
2022

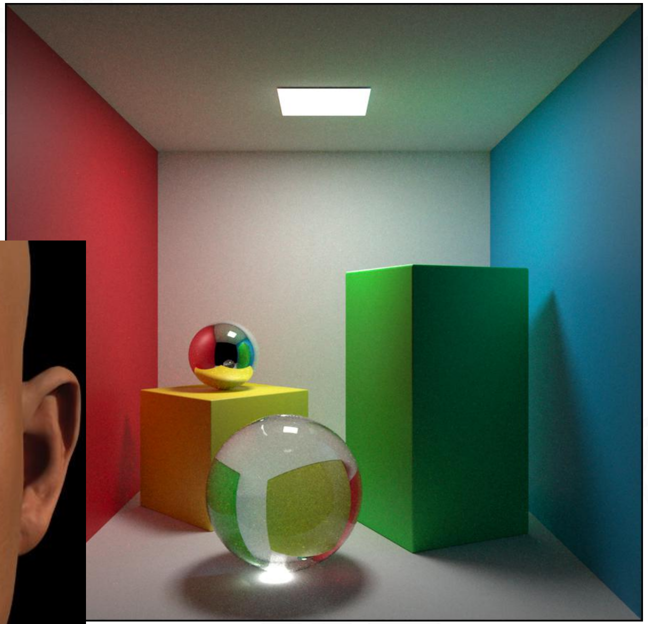
Horizon

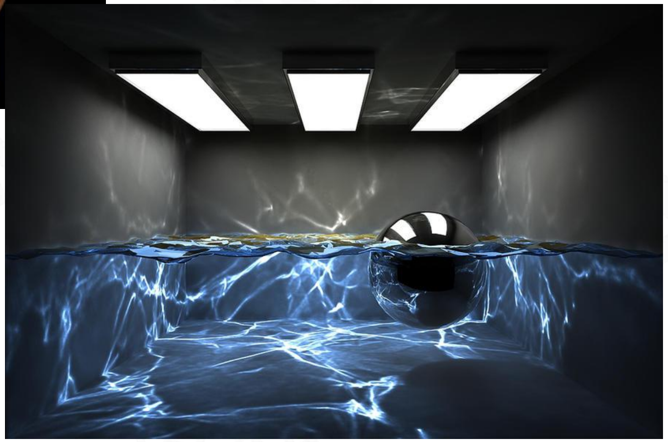
Rendering on Graphics Theory

- Objects with one type of effect
- Focus on representation and math correctness
- No strict performance requirement
  - Realtime (30FPS) / interactive (10FPS)
    offline rendering
  - Out-of-core rendering

Foundation of game engine rendering!





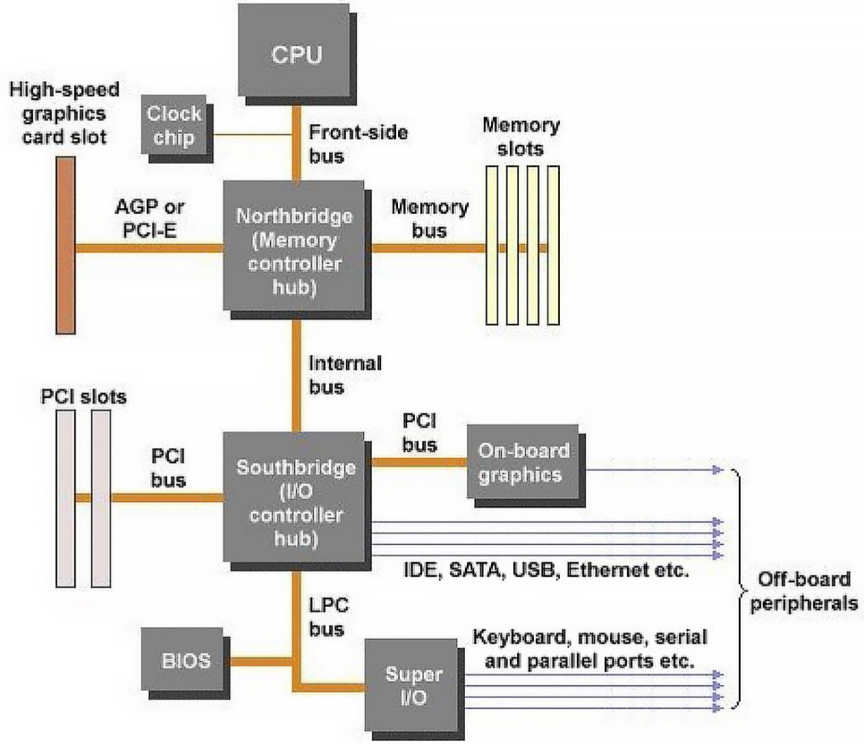


Challenges on Game Rendering (1/4)

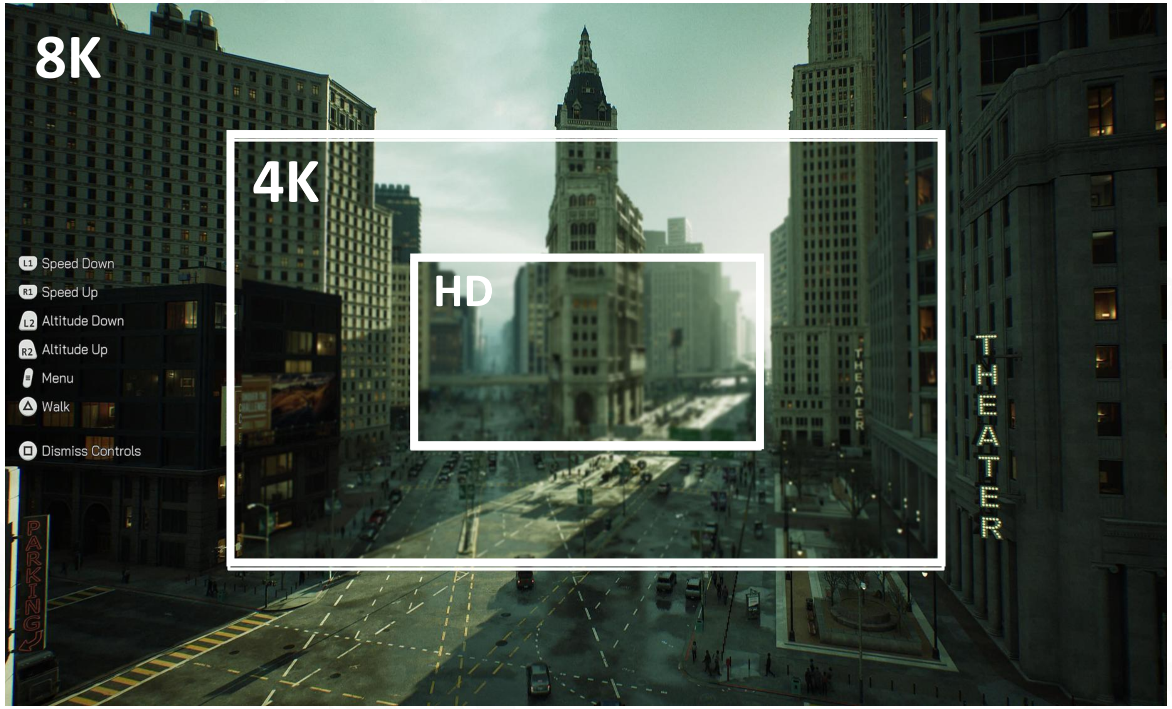
Tens of thousands of objects with dozens type of effects

Challenges on Game Rendering (2/4)

- Deal with architecture of modern computer with a complex combination of CPU and GPU



Challenges on Game Rendering (3/4)



Commit a bullet-proof framerate

- 30FPS (60FPS, 120FPS+VR)
- 1080P, 4K and 8K resolution

Challenges on Game Rendering (4/4)

- Limit access to CPU bandwidth and memory footprint
- Game logic, network, animation, physics and AI systems are major consumers of CPU and main memory

Rendering on Game Engine

A heavily optimized practical software framework to fulfill the critical rendering requirements of games on modern hardware (PC, console and mobiles)

Outline of Rendering

Rendering can be another 20+ lectures

01. Basics of Game Rendering

- Hardware architecture
- Render data organization
- Visibility

02. Materials, Shaders and Lighting

- PBR (SG, MR)
- Shader permutation
- Lighting
  - Point / Directional lighting
  - IBL / Simple GI

03. Special Rendering

- Terrain
- Sky / Fog
- Postprocess

04. Pipeline

- Forward, deferred rendering, forward plus
- Real pipeline with mixed effects
- Ring buffer and V-Sync
- Tiled-based rendering

What Is not Included

- Cartoon Rendering
- 2D Rendering Engine
- Subsurface
- Hair / Fur

Building Blocks of Rendering

Rendering Pipeline and Data

Vertex Data

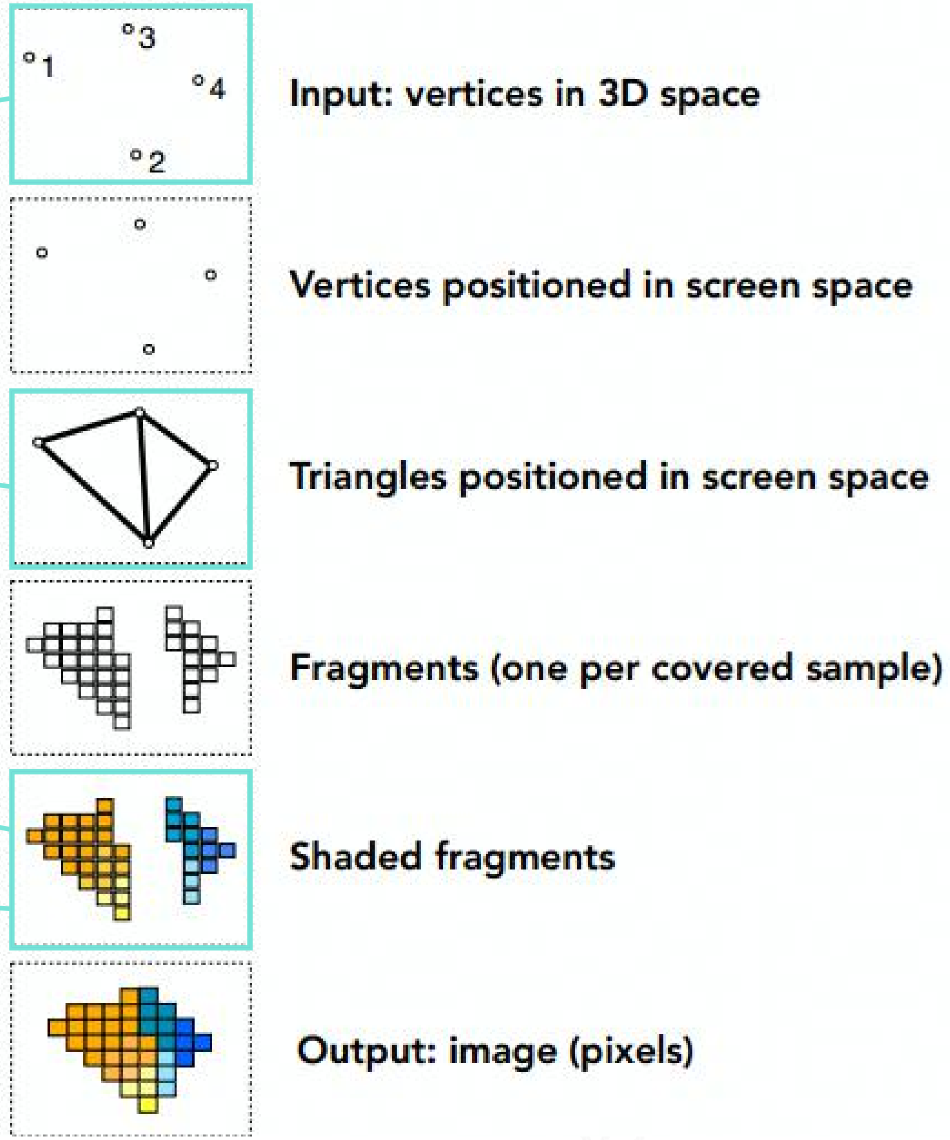
Triangle Data

Millions of vertices and triangles

Material Parameters

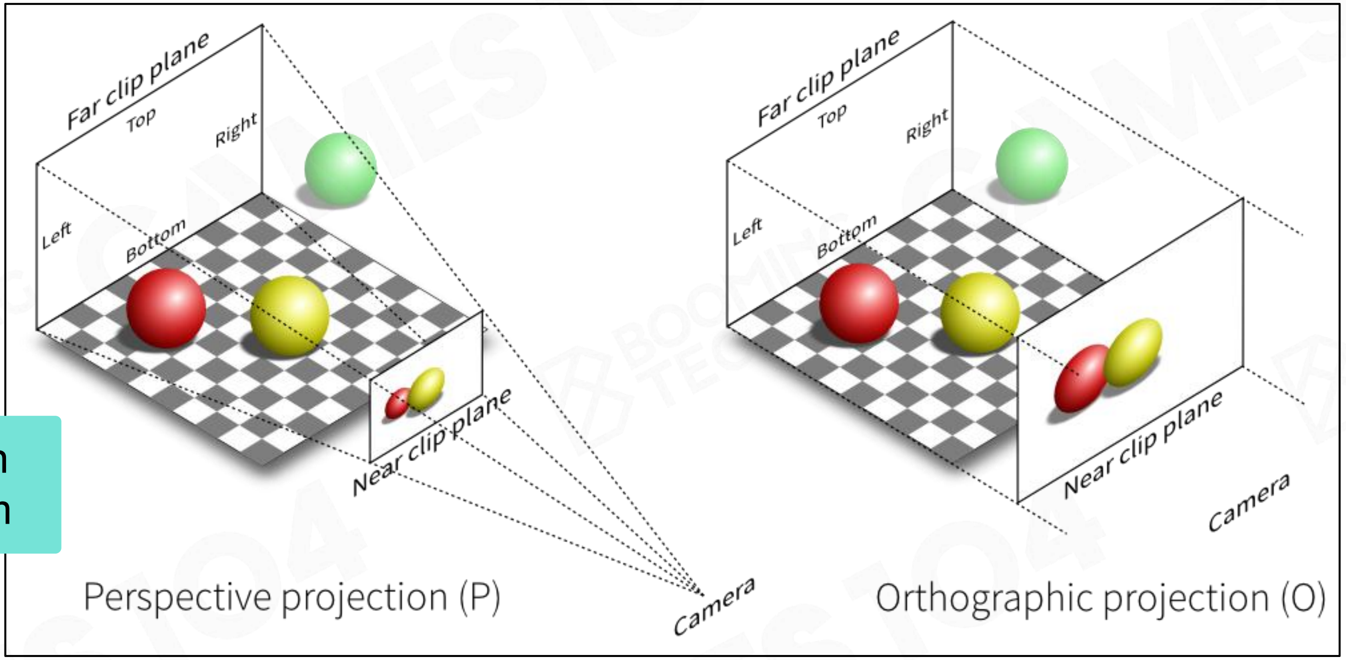
Textures

Tens of millions of pixels with hundreds ALU and dozen of texture samplings

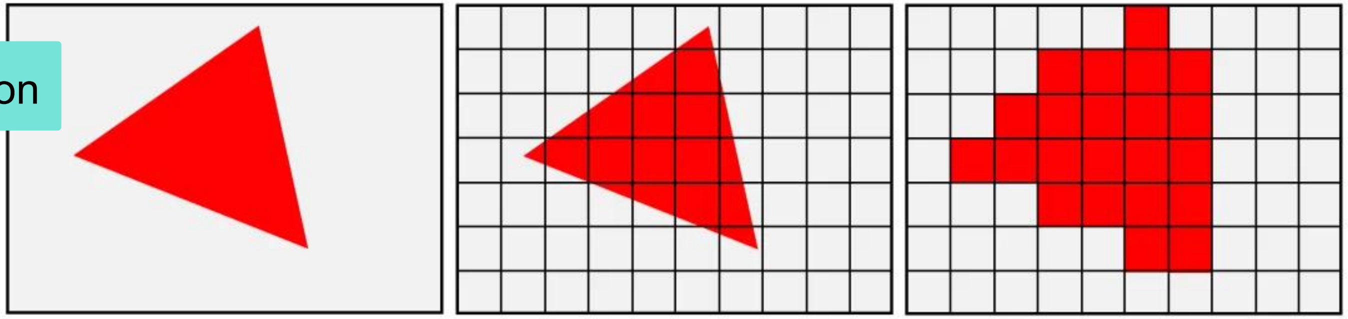


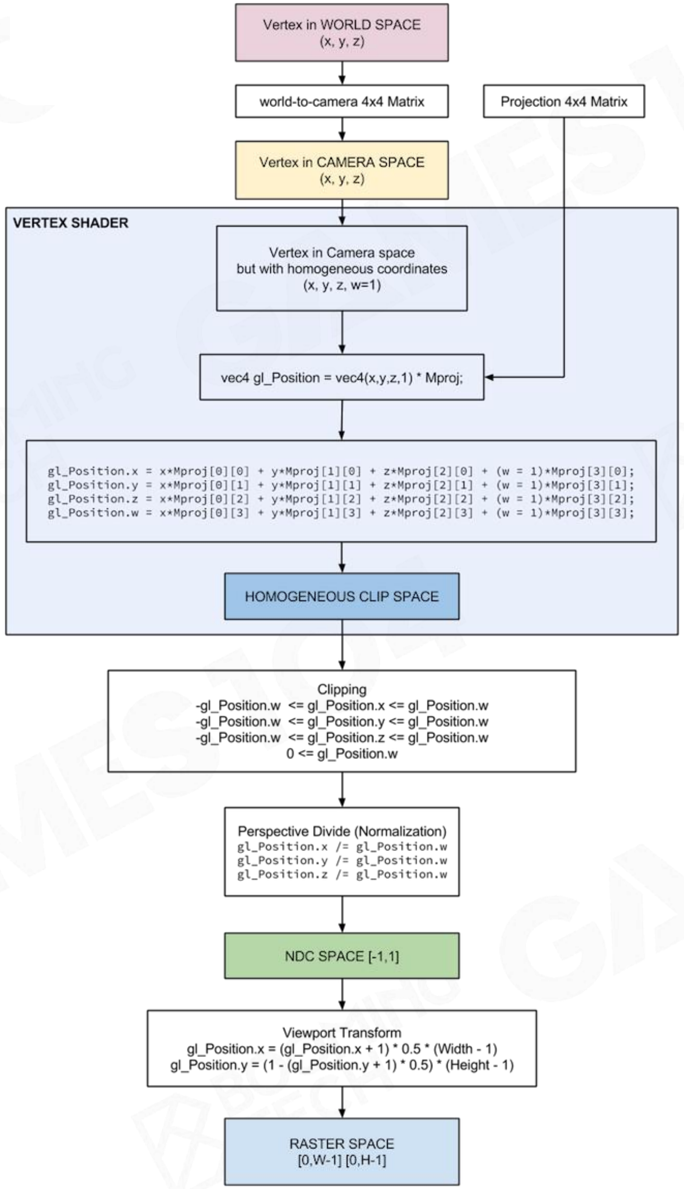
Computation - Projection and Rasterization

Projection Transform



Rasterization



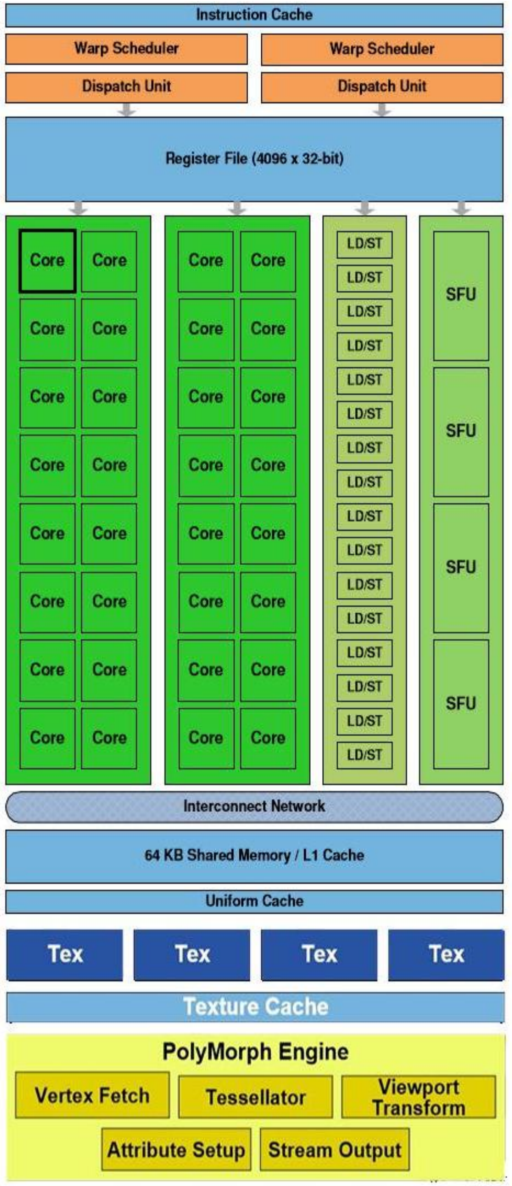


Computation - Shading

A shader sample code

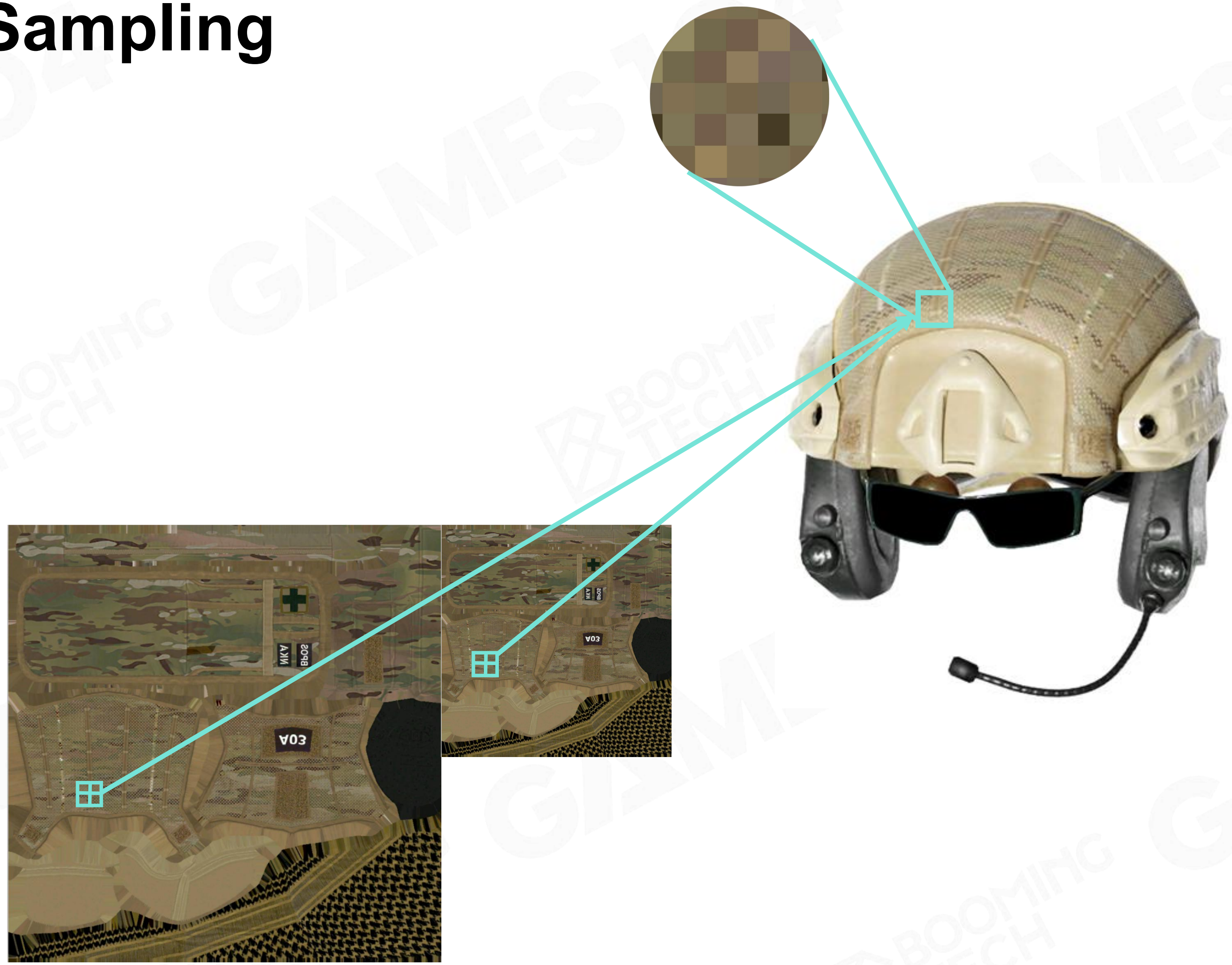
- Constants / Parameters
- ALU algorithms
- Texture Sampling
- Branches

```
struct PSInput
{
    float2 uv : TEXCOORD;
};

// constant buffer
cbuffer cbData
{
    float4 data;
}

Texture2D<float4> tex;
SamplerState samplerLinear;

float4 PSMain(PSInput input) : SV_TARGET
{
    // texture sample
    float4 result = tex.Sample(samplerLinear, input.uv);

    // logical operators
    float factor = data.x * data.y;

    // branch
    if (factor > 0)
        // logical operators
        return data.z * result;
    else
        // logical operators
        return data.w * result;
}
```



Computation - Texture Sampling

- **Step1**
  Use two nearest mipmap levels
- **Step2**
  Perform bilinear interpolation in both mip-maps
- **Step3**
  Linearly interpolate between the results

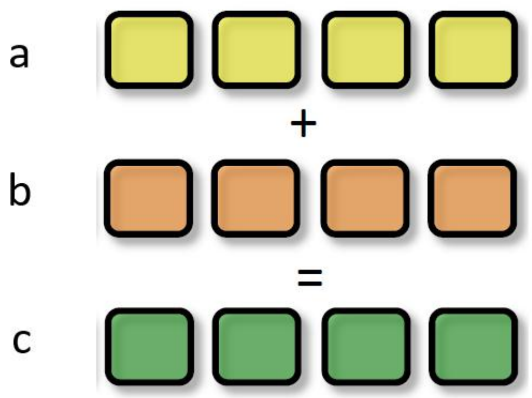


Understand the Hardware

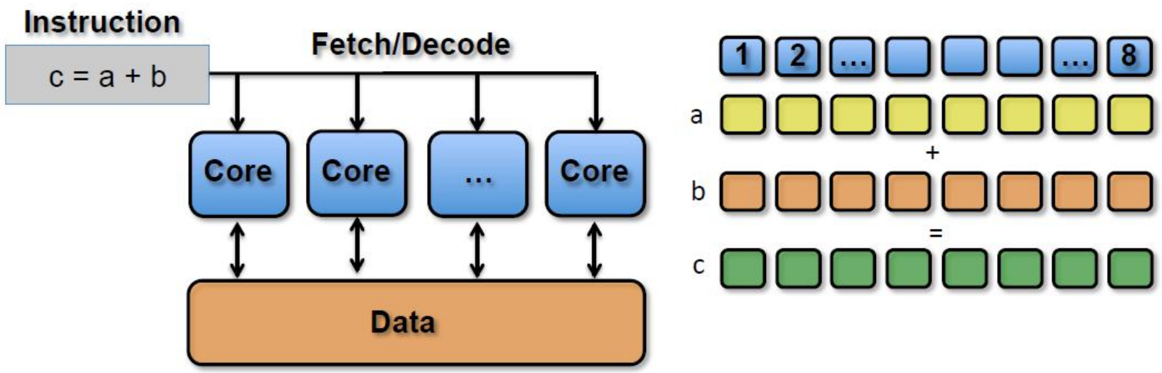
GPU

The dedicated hardware to solve massive jobs

SIMD and SIMT




```
SIMD_ADD c, a, b
```




```
SIMT_ADD c, a, b
```

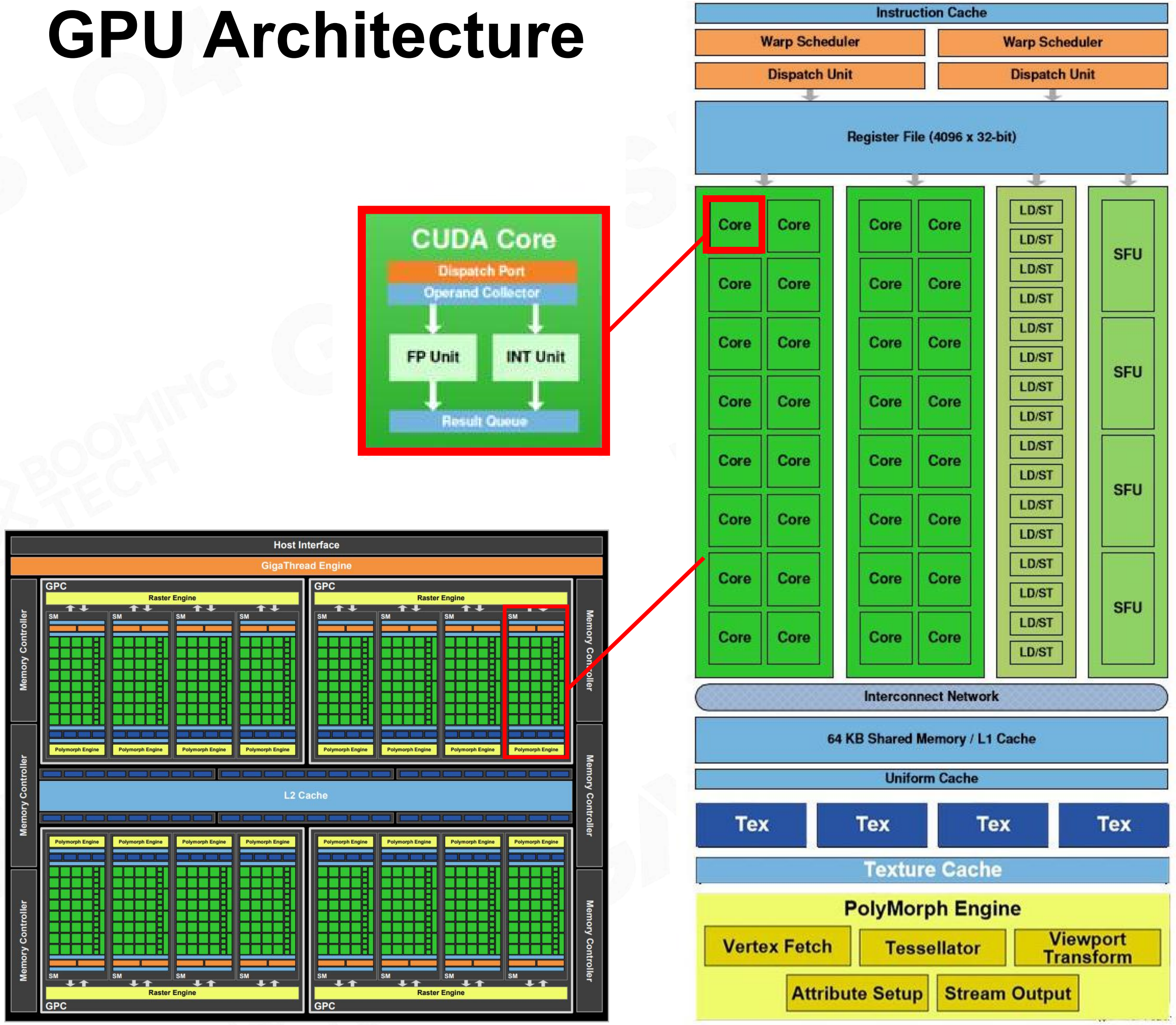
SIMD (Single Instruction Multiple Data)

- Describes computers with multiple processing elements that perform the same operation on multiple data points simultaneously

SIMT (Single Instruction Multiple Threads)

- An execution model used in parallel computing where single instruction, multiple data (SIMD) is combined with multithreading

GPU Architecture



GPC (Graphics Processing Cluster)

A dedicated hardware block for computing, rasterization, shading, and texturing

SM (Streaming Multiprocessor)

Part of the GPU that runs CUDA kernels

Texture Units

A texture processing unit, that can fetch and filter a texture

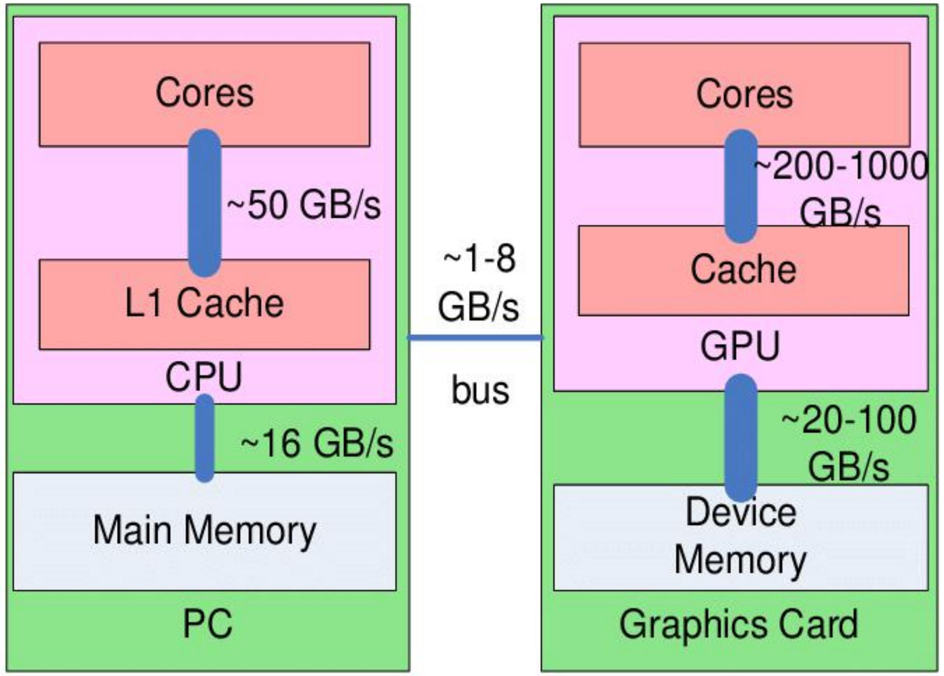
CUDA Core

Parallel processor that allow data to be worked on simultaneously by different processors

Warp

A collection of threads

Data Flow from CPU to GPU



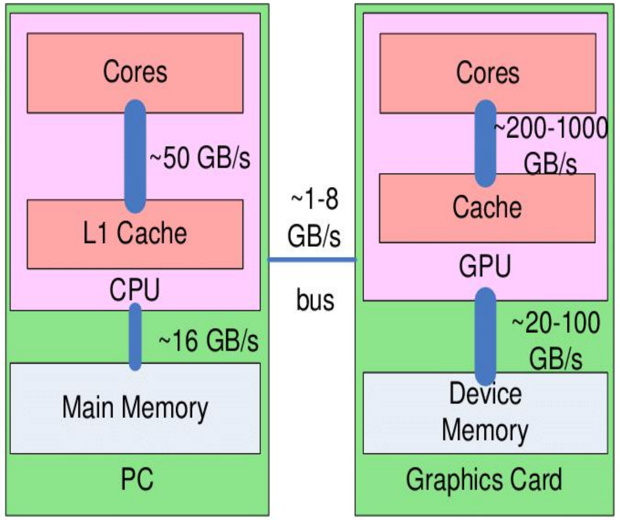
- **CPU and Main Memory**
  - Data Load / Unload
  - Data Preparation
- **CPU to GPU**
  - High Latency
  - Limited Bandwidth
- **GPU and Video Memory**
  - High Performance Parallel Rendering

Tips

Always minimize data transfer between CPU and GPU when possible

Be Aware of Cache Efficiency

- Take full advantage of hardware parallel computing
- Try to avoid the von Neumann bottleneck



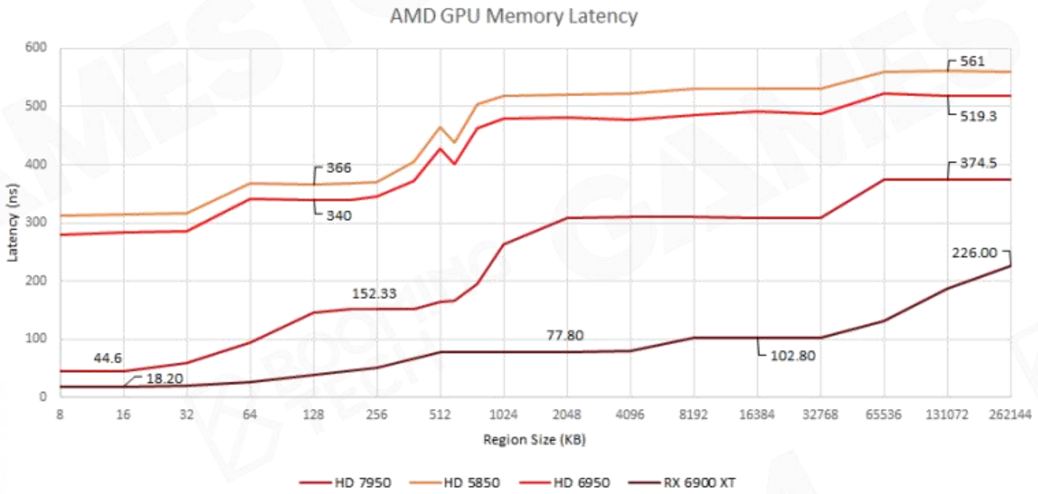
CPU Cache Access Latencies in Clock cycles

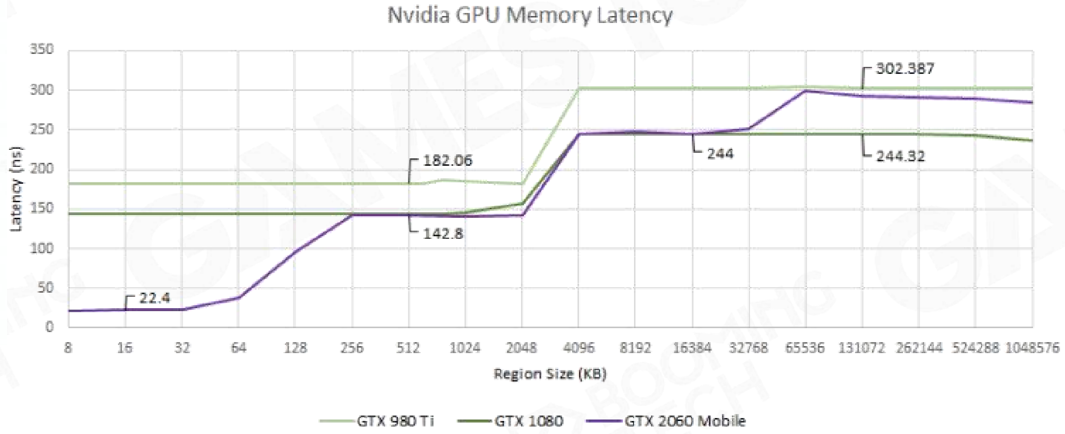
Mainmemory	167
L3 Cache	38
L2 Cache	11
L1 Cache	4

GPU L2 Cache Access Latencies (measured)

Amphere L2	100ns
RDNA L2	20ns

NVIDIA AMD





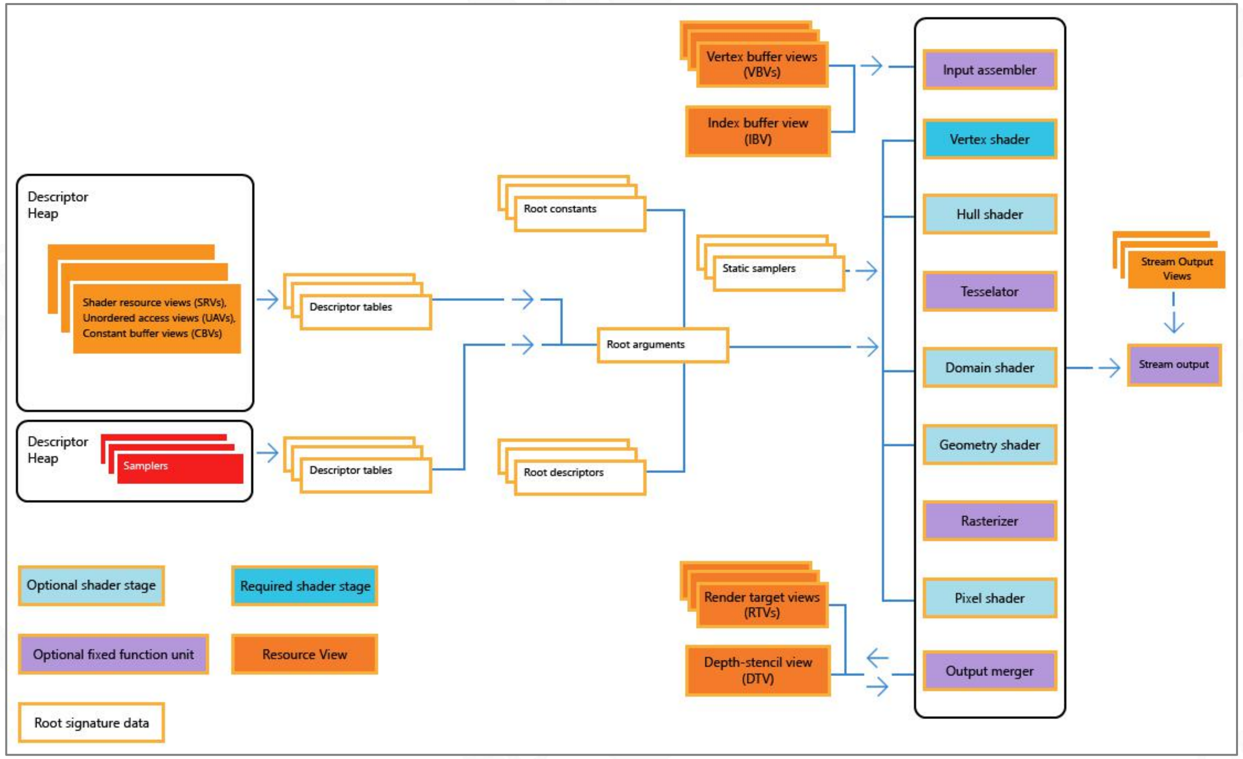
GPU Bounds and Performance

Application performance is limited by:

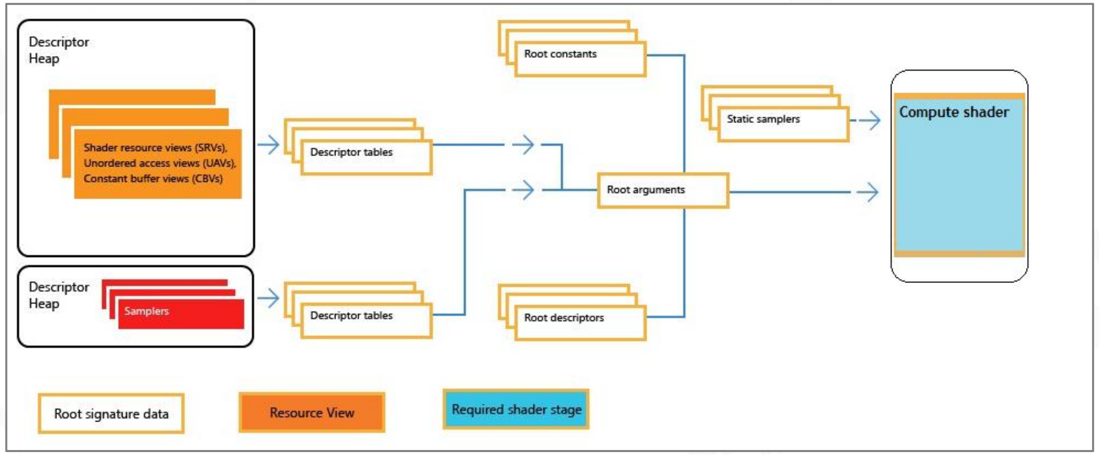
- Memory Bounds
- ALU Bounds
- TMU (Texture Mapping Unit) Bound
- BW (Bandwidth) Bound

Modern Hardware Pipeline

Direct3D 12 graphics pipeline



Mesh and amplification shaders



Direct3D 12 compute pipeline

Other State-of-Art Architectures

GPU:

1.825 GHz, 52CUs, 12 TFLOPS FP32, 3328 streaming processors

DRAM:

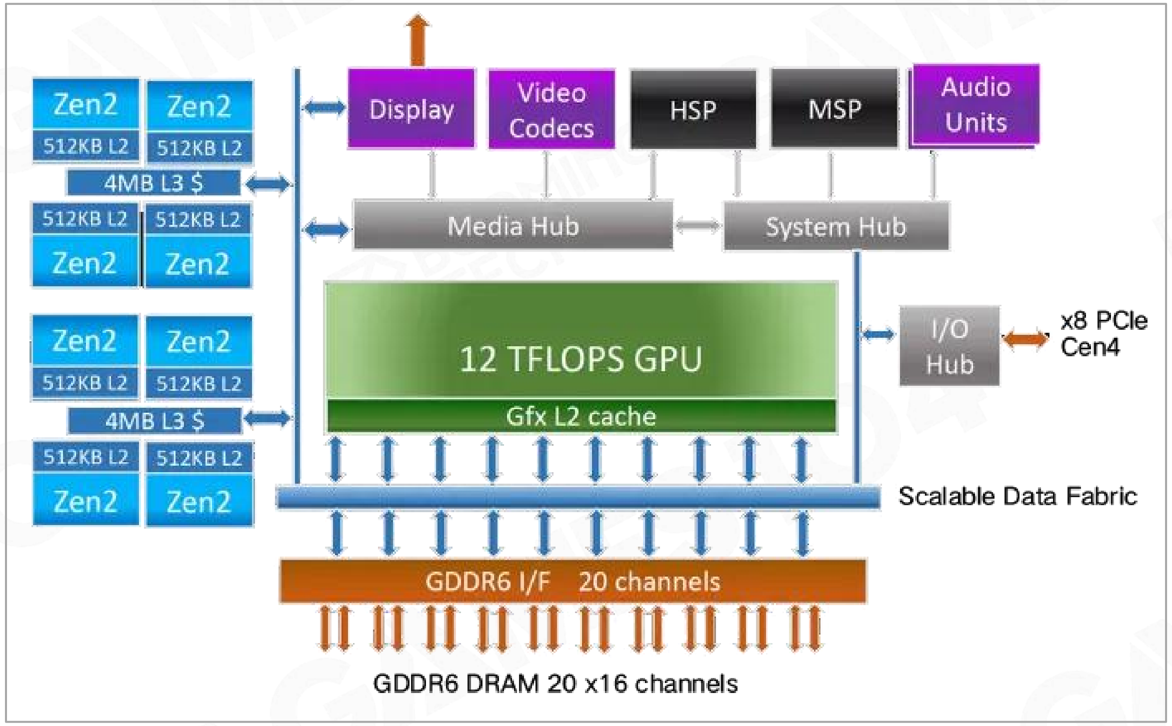
16 GB GDDR6, 10GB high memory interleave + 6GB low memory interleave

20 channels of x16 GDDR6 @ 14 Gbps->560GB

CPU:

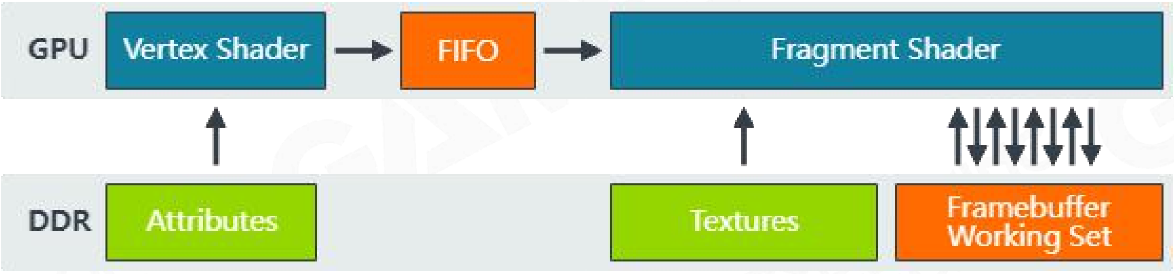
8x Zen2 CPU cores @ 3.8 GHz, 3.6 GHz w/SMT

32KB L1 I$,32KB L1 D$,512KB L2 per CPU core

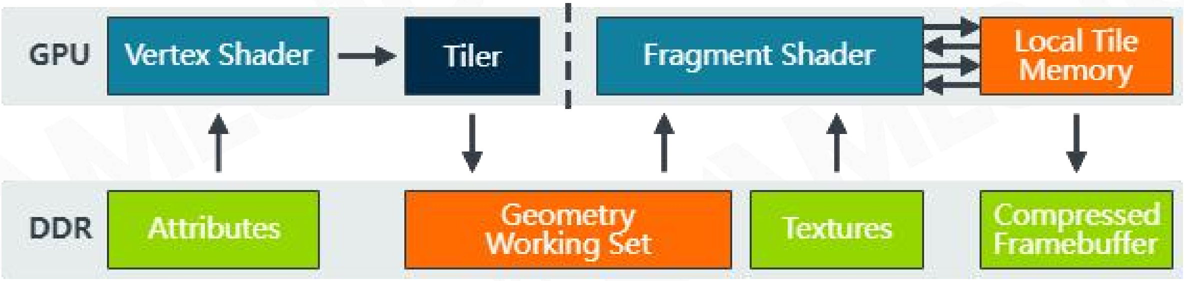


Xbox Series X SOC Unified Memory Architecture

Other State-of-Art Architectures



Immediate Mode GPUs



Tile-Based GPUs

```
# Pass one
for draw in renderPass:
    for primitive in draw:
        for vertex in primitive:
            execute_vertex_shader(vertex)
        if primitive not culled:
            append_tile_list(primitive)

# Pass two
for tile in renderPass:
    for primitive in tile:
        for fragment in primitive:
            execute_fragment_shader(fragment)
```

Renderable

Mesh Render Component

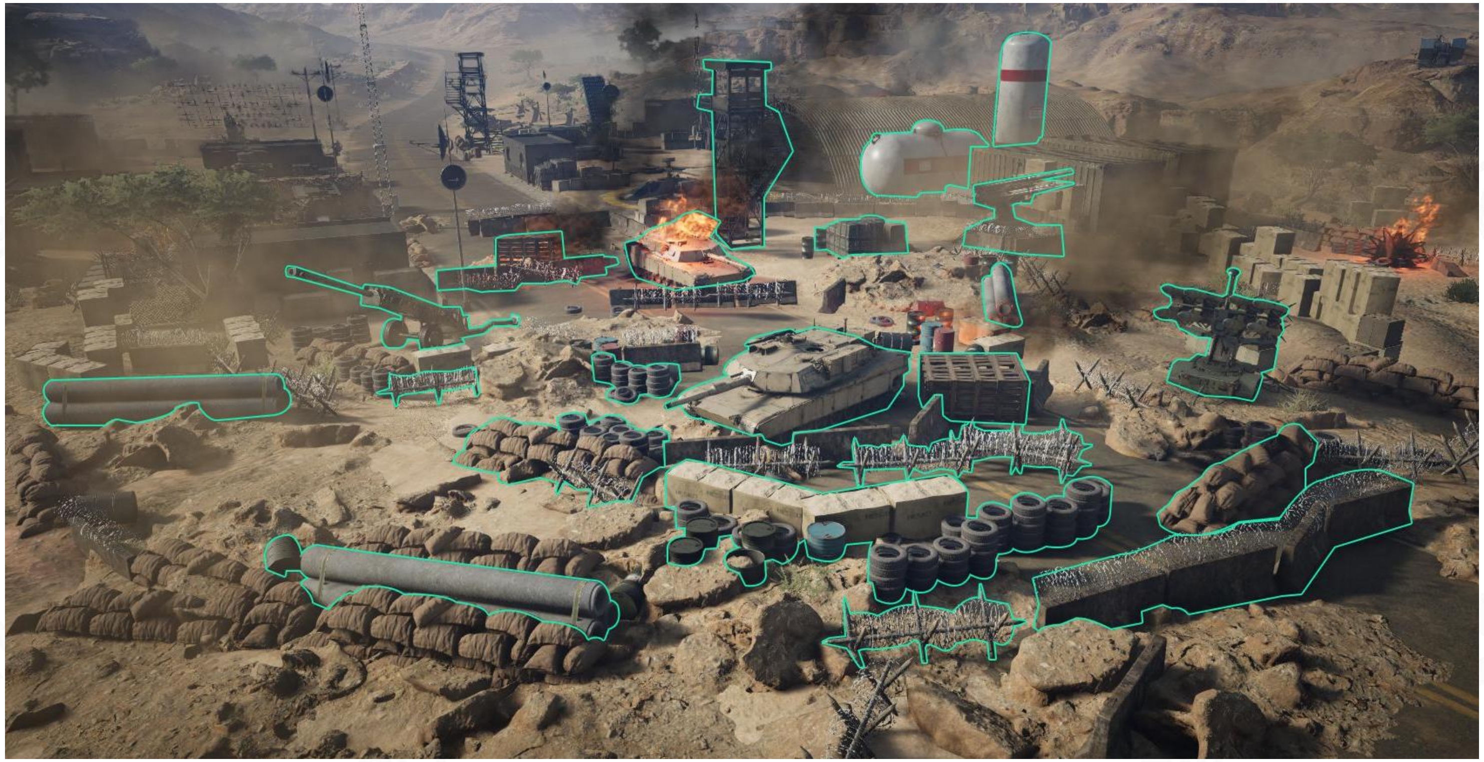
- Everything is a game object in the game world

- Game object could be described in the component-based way

Game Object

Components

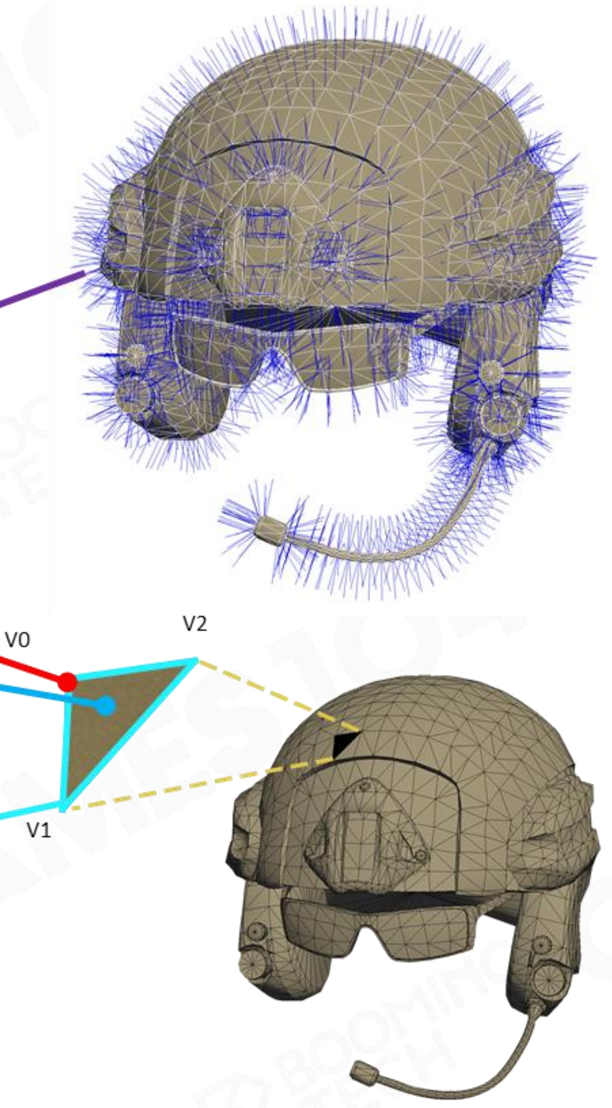
Mesh Render Component



Building Blocks of Renderable

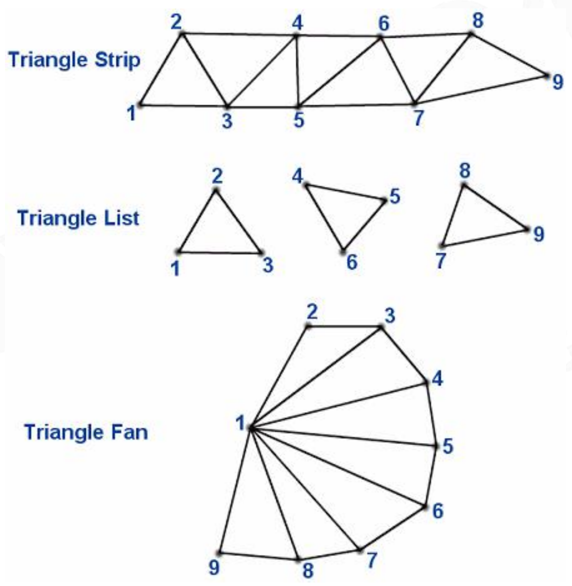
Mesh Primitive

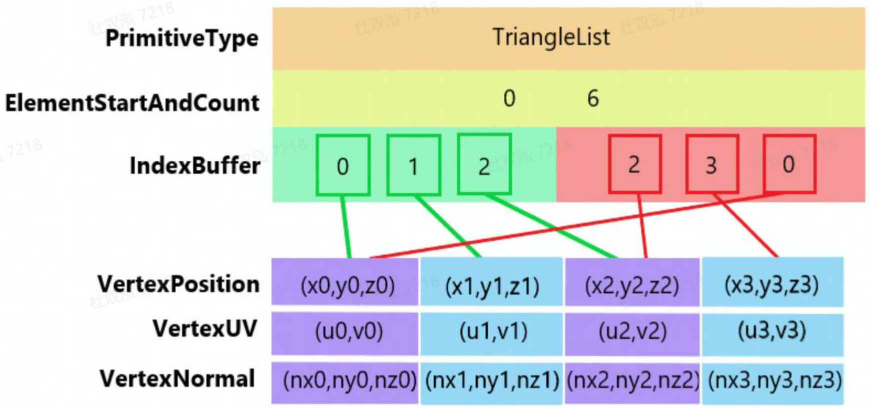
```
struct Vertex
{
    Vector3 m_position;
    // other data
    UByte4 m_color;
    Vector3 m_normal;
};

struct Triangle
{
    Vertex m_vertex[3]
};
```



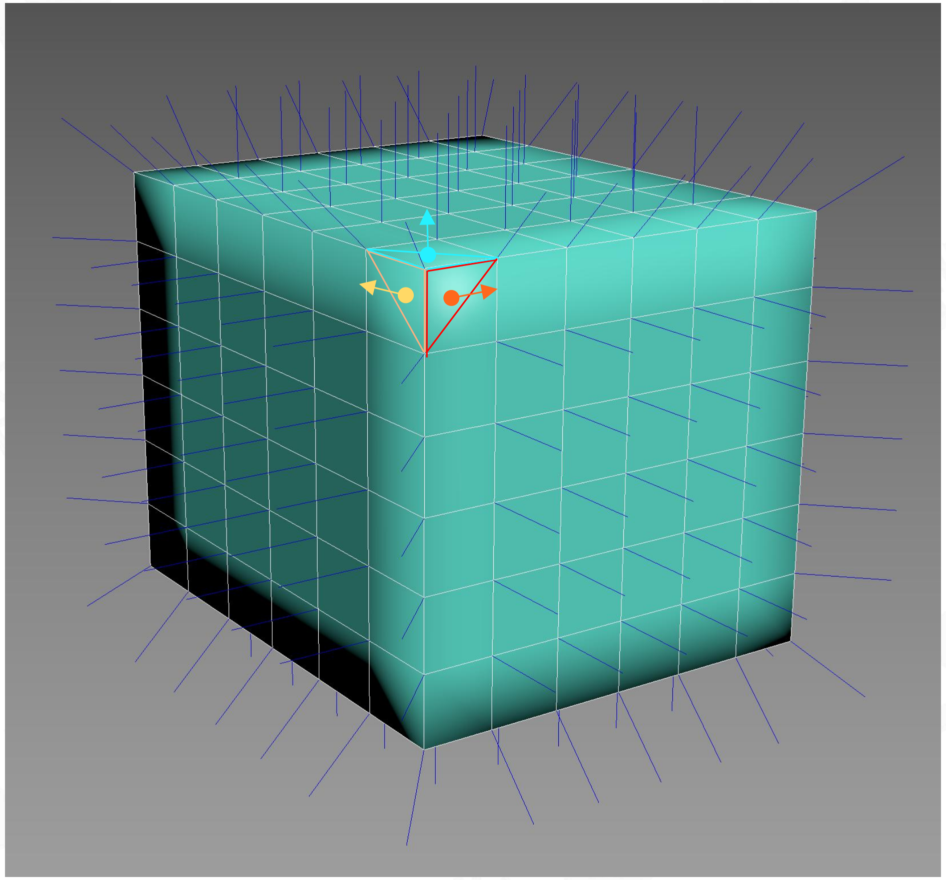
Vertex and Index Buffer

- **Vertex Data**
  - Vertex declaration
  - Vertex buffer
- **Index Data**
  - Index declaration
  - Index buffer

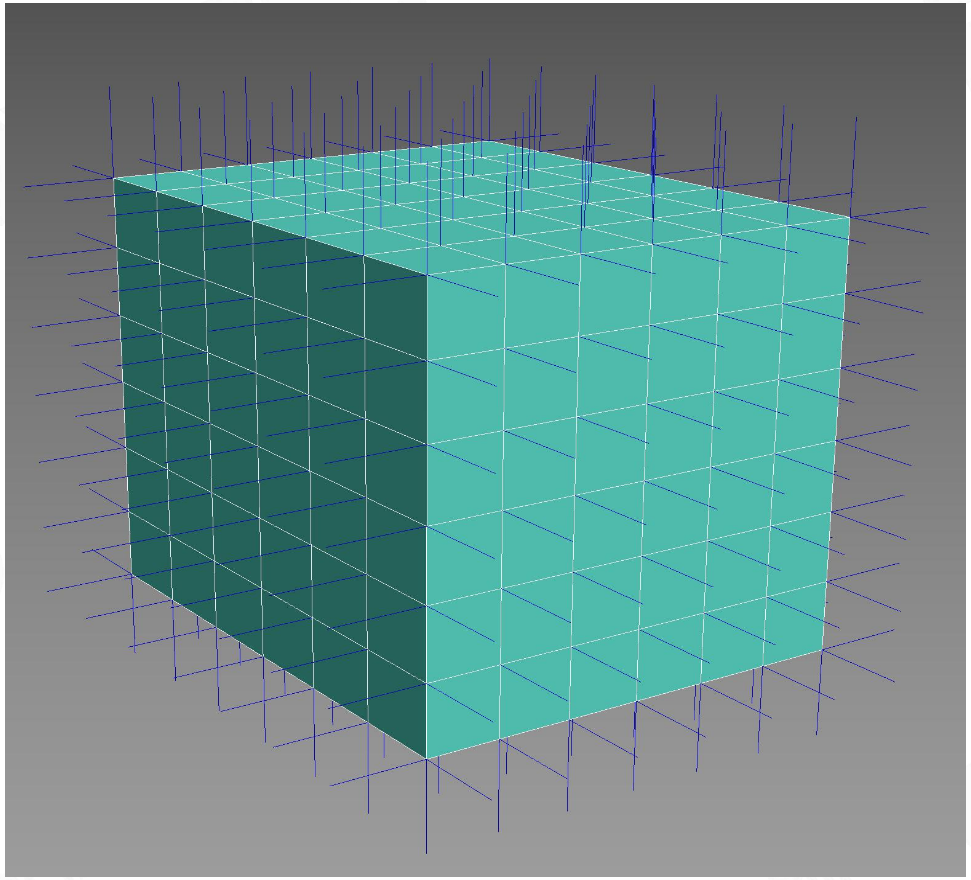




Why We Need Per-Vertex Normal



Interpolate vertex normal by triangle normal



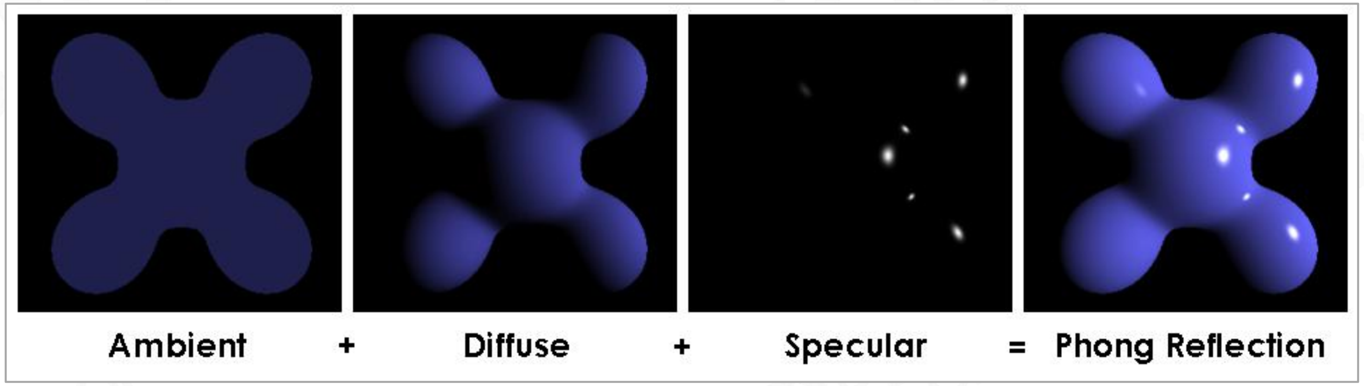
Per-Vertex normals necessary

Materials

Base | Smooth metal | Glossy paint | Rough stone | Transparent glass

Determine the appearance of objects, and how objects interact with light

Famous Material Models

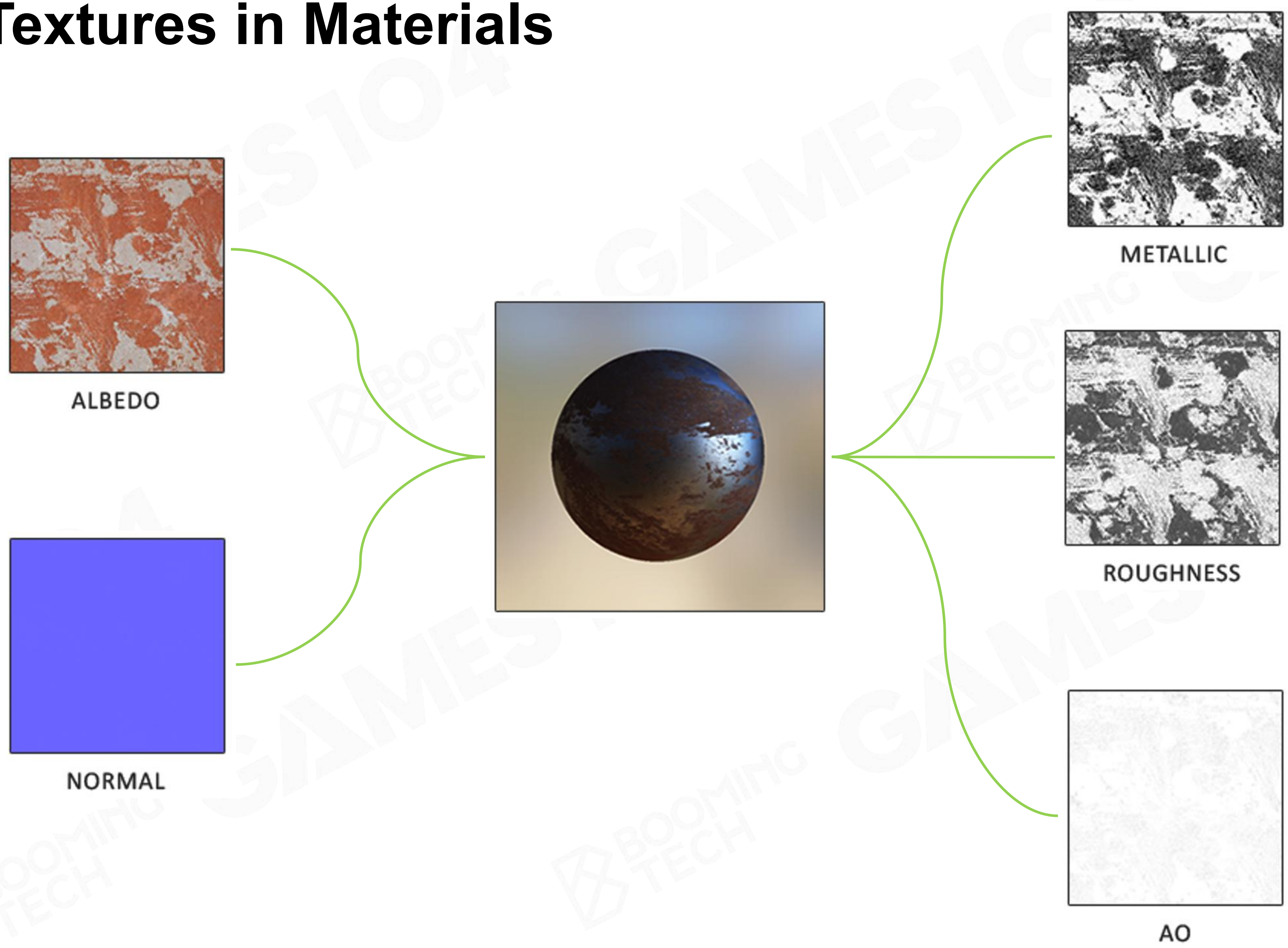


Phong Model

PBR Model - Physically based rendering

Subsurface Material - Burley SubSurface Profile

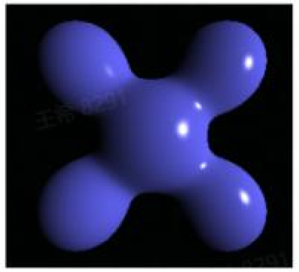
Various Textures in Materials



Variety of Shaders

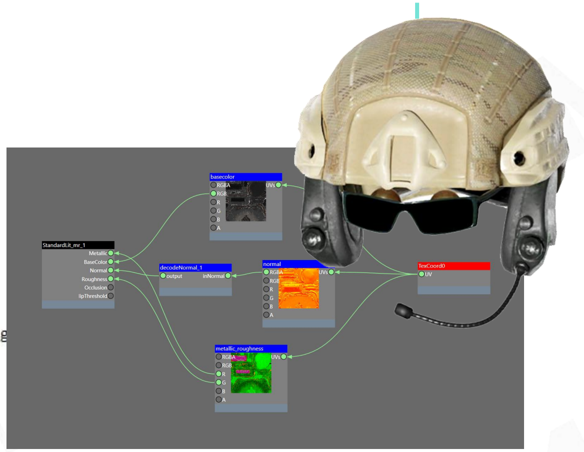
Fix Function Shading Shaders

```
float4 PSMain(PixelInput input) : SV_TARGET
{
    float3 world_normal = normalize(input.world_normal);

    float3 world_view_dir = normalize(world_space_camera_pos - input.world_pos);

    float3 world_light_reflection_dir = normalize(reflect(-world_light_dir, world_normal));

    float3 ambient = ambient_color * material.ambient;

    float3 diffuse = max(0, dot(world_normal, world_light_dir)) *
                     diffuse_color * material.diffuse;

    float3 specular = pow(max(0, dot(world_light_reflection_dir, world_view_dir)), shininess) *
                      specular_color * material.specular;

    float3 emissive = material.emissive;

    return float4(ambient + diffuse + specular  + emissive, 1.0f);
}
```



Custom Shaders

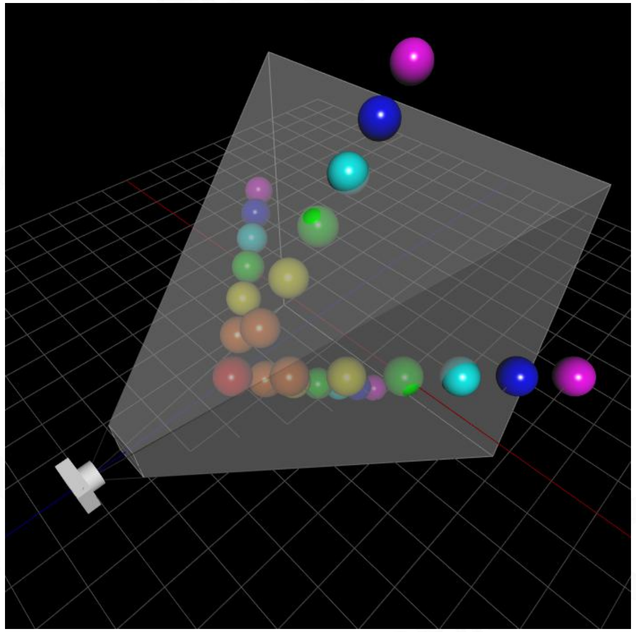
```
PixelOutGbuffer PS_Entry_deferred(PixelInput input)
{
    float3 T = input.world_tangent.xyz;
    float3 N = normalize(input.world_geo_normal);
    float3 B = cross(input.world_geo_normal, input.world_tangent.xyz)
        * input.world_tangent.w;

    T -= dot(T, N) * N;
    T = normalize(T);
    B -= dot(B, N) * N + dot(B, T) * T;
    B = normalize(B);

    float3x3 TBN; TBN[0] = T; TBN[1] = B; TBN[2] = N;

    GBufferData gbuffer_data;
    initializeGBufferData(gbuffer_data);

    //albedo
    float4 albedo_opacity_value = CHAOS_SAMPLE_TEX2D(albedo_opacity_map, input.tex0);
    gbuffer_data.albedo = albedo_opacity_value.rgb;

    //normal
    float3 normal_value = decodeNormalFromNormalMapValue(normal_map.rgba).rgb;
    gbuffer_data.world_normal =  normalize(mul(normal_value.rgb, TBN));

    //specular
    float4 specular_glossiness_value = CHAOS_SAMPLE_TEX2D(specular_glossiness_map, input.tex0);
    gbuffer_data.reflectance =  specular_glossiness_value.rgb;

    //smoothness
    gbuffer_data.smoothness =  specular_glossiness_value.r;

    //ao
    gbuffer_data.ao =  occlusion;

    //opacity
    float albedo_opacity_value = albedo_opacity_value.a;

    float  alpha_clip_value = alpha_clip;

    clip(albedo_opacity_value - alpha_clip_value);

    PixelOutGbuffer out_gbuffer = (PixelOutGbuffer)0;
    EncodeGBuffer(gbuffer_data, out_gbuffer.GBufferA, out_gbuffer.GBufferB, out_g

    return out_gbuffer;
}
```

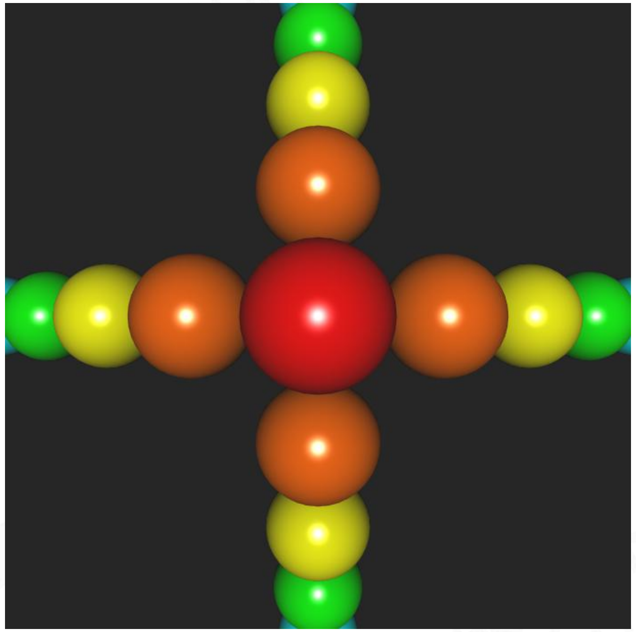


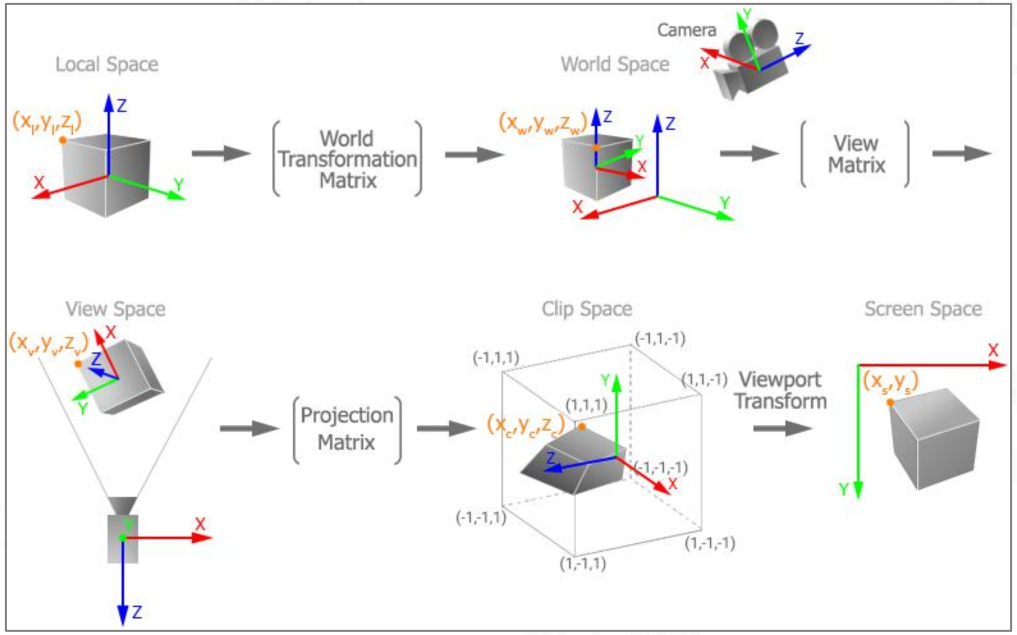
Render Objects in Engine

Coordinate System and Transformation

Model assets are made based on local coordinate systems, and eventually we need to render them into screen space

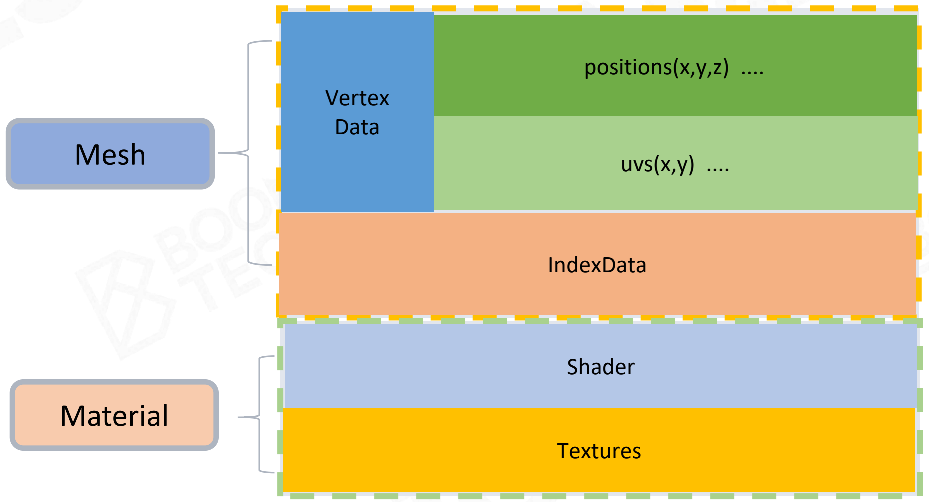


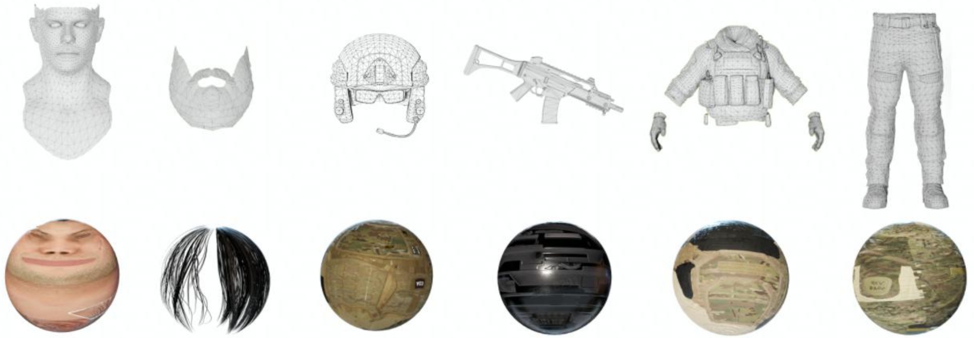




Object with Many Materials

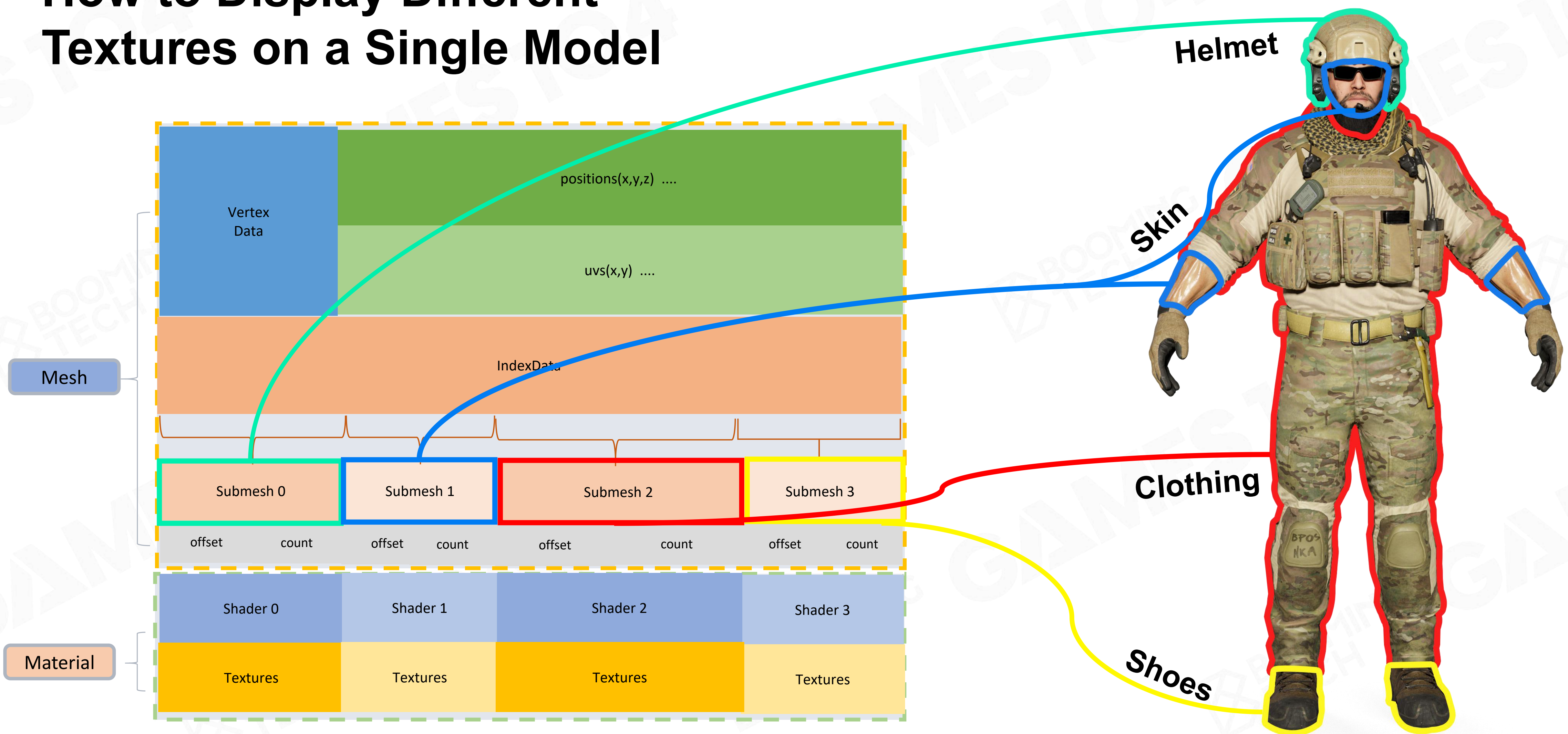
Expected

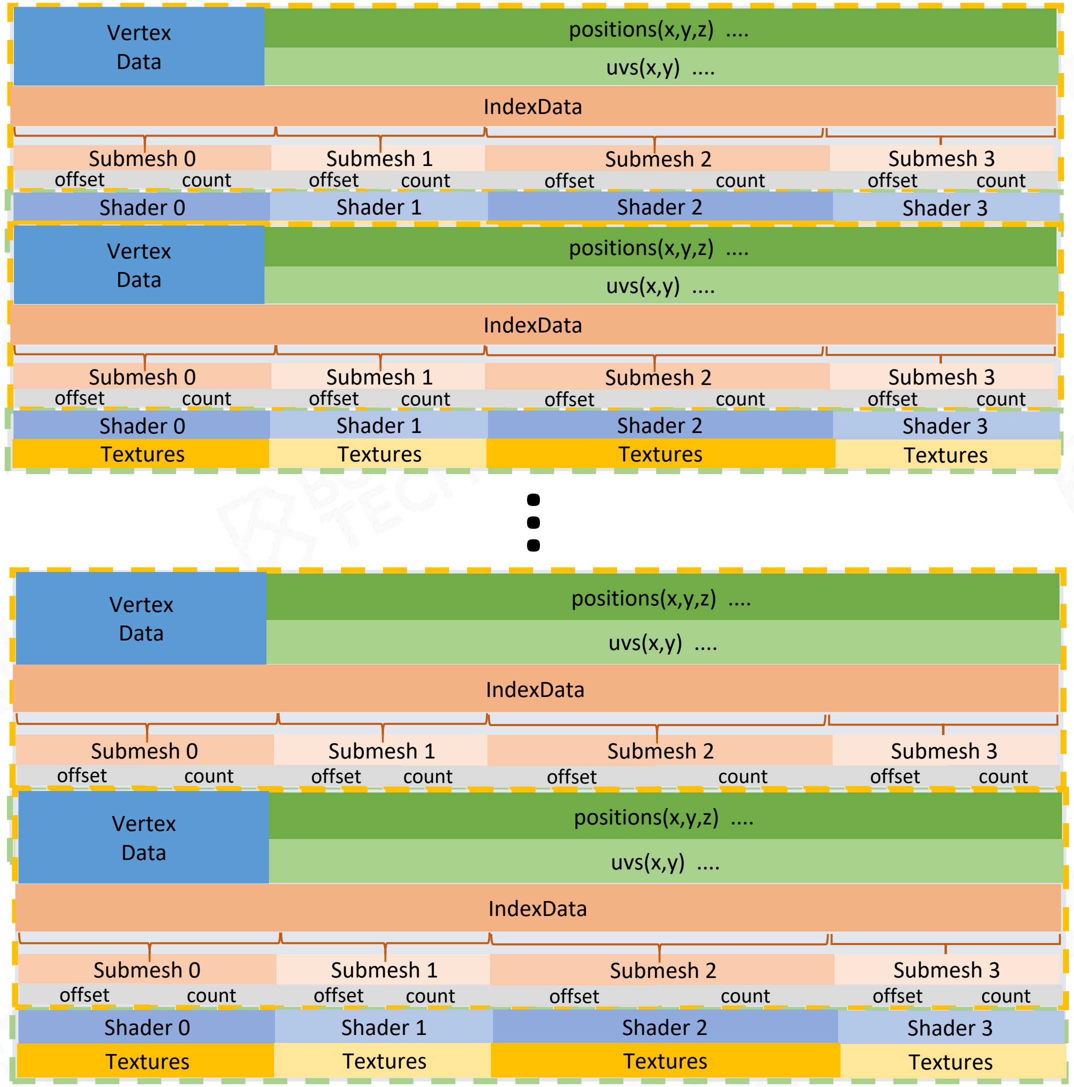




Actual

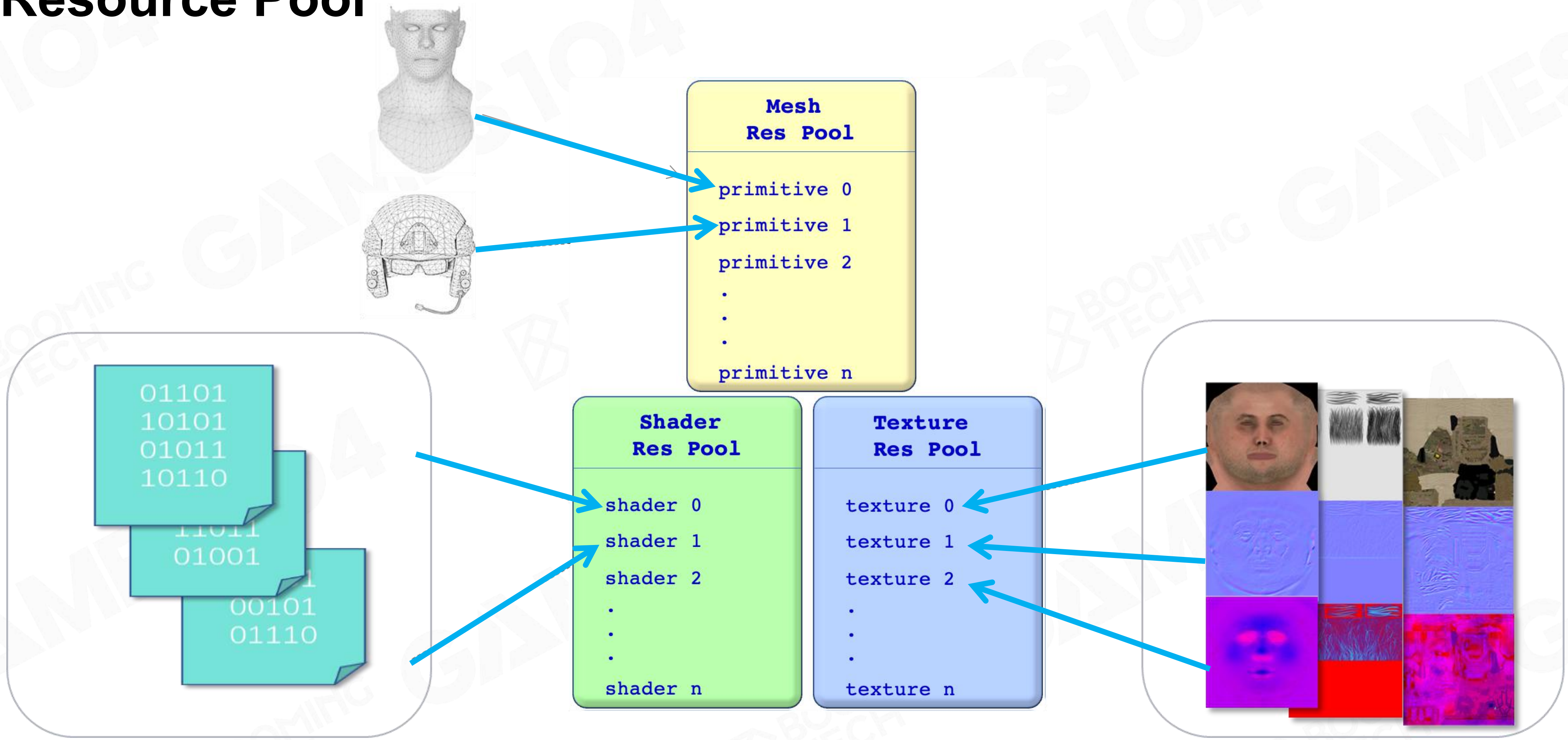
How to Display Different Textures on a Single Model



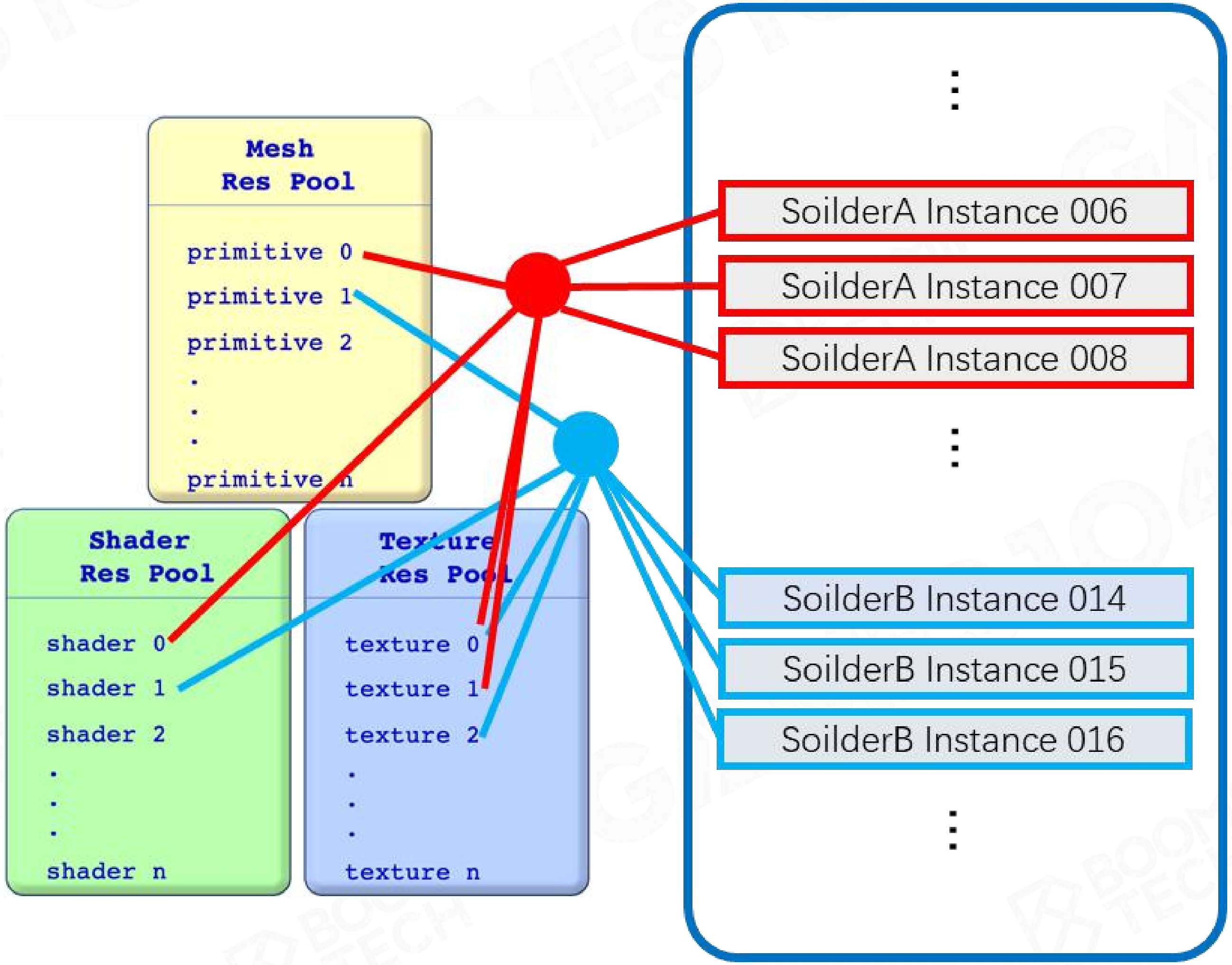


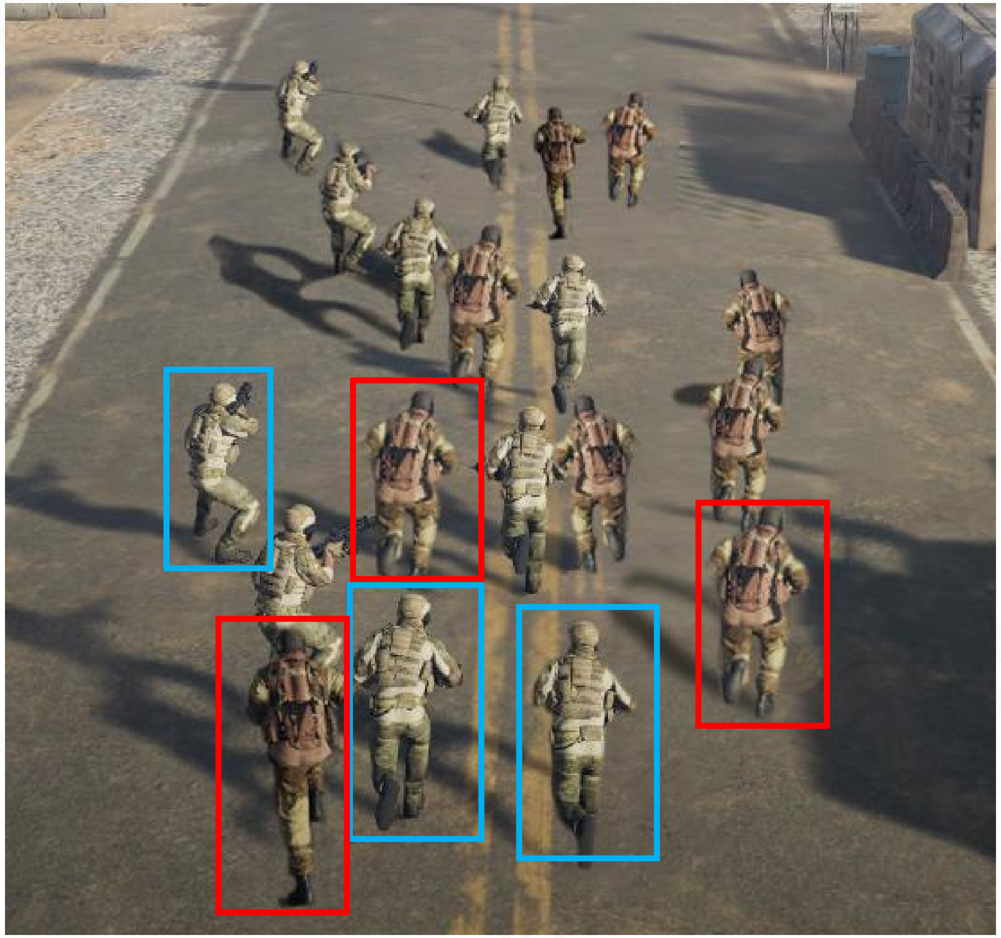
Wasting of memory

Resource Pool



Instance: Use Handle to Reuse Resources

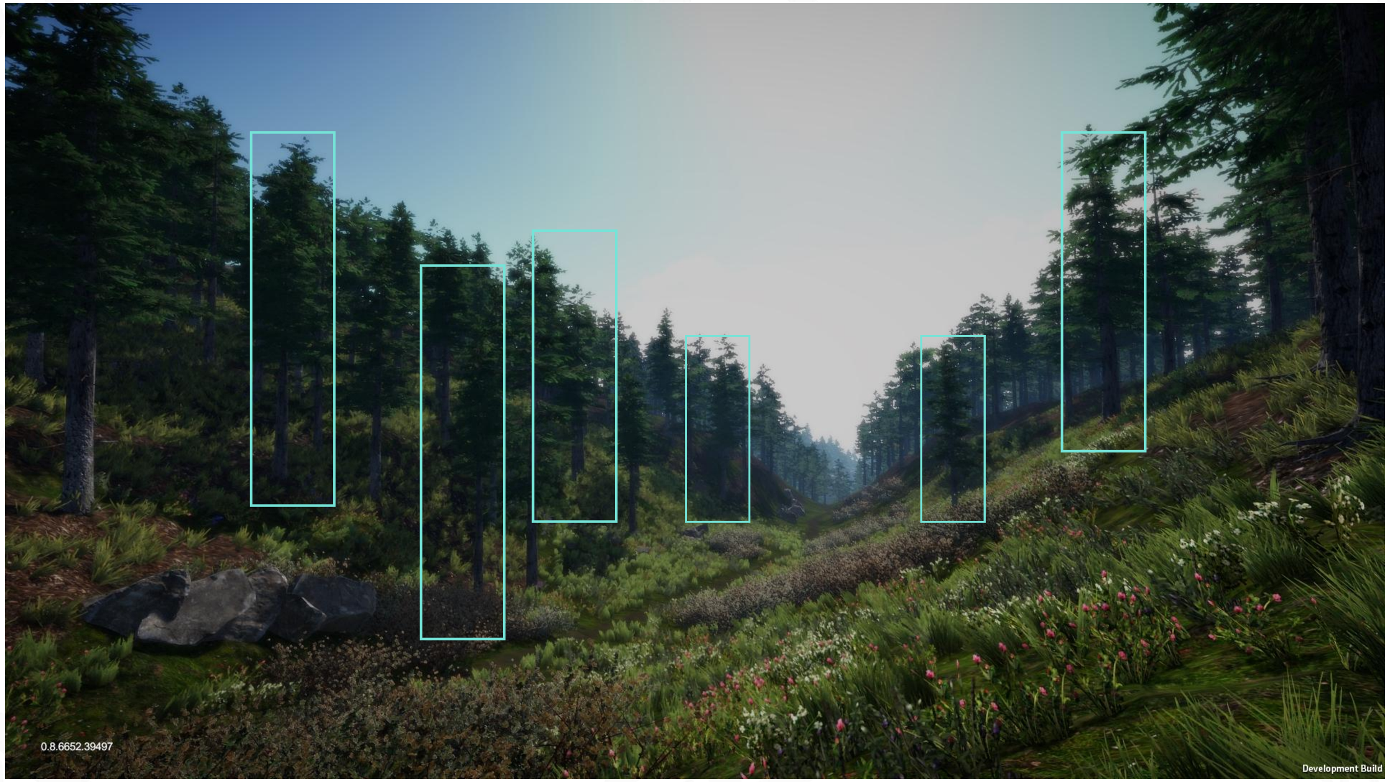




Sort by Material

```
Initialize Resource Pools
Load Resources

Sort all Submeshes by Materials

for each Materials
    Update Parameters
    Update Textures
    Update Shader
    Update VertexBuffer
    Update IndexBuffer
    for each Submeshes
        Draw Primitive
    end
end
```

GPU Batch Rendering



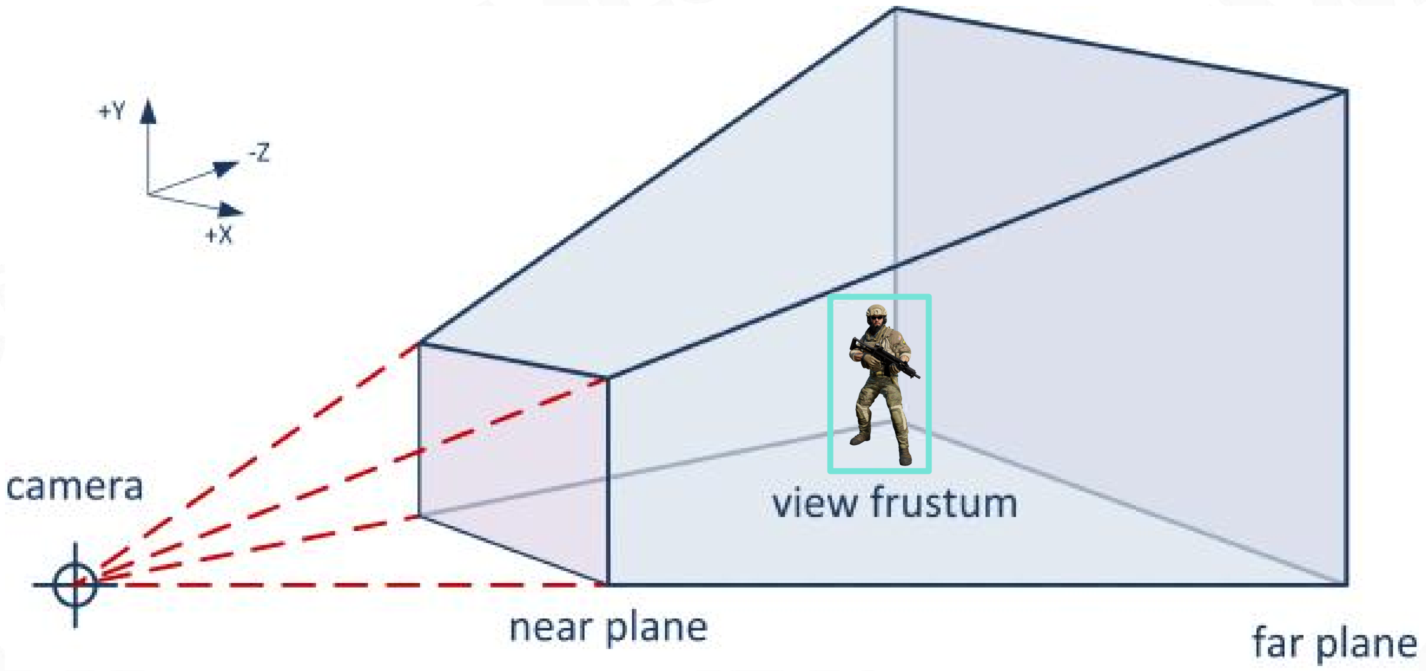

```
struct batchData
{
    SubmeshHandle m_submesh_handle;
    MaterialHandle m_material_handle;
    std::vector<PerInstanceData> m_per_instance_data;
    unsigned int m_instance_count;
};

Initialize Resource Pools
Load Resources

Collect batchData with same submesh and material

for each BatchData
    Update Parameters
    Update Textures
    Update Shader
    Update VertexBuffer
    Update IndexBuffer
        Draw Instance
end
```

Q : What if group rendering all instances with identical submeshes and materials together?

Visibility Culling

For each view, there are a lot of objects which aren't needed to be rendered.

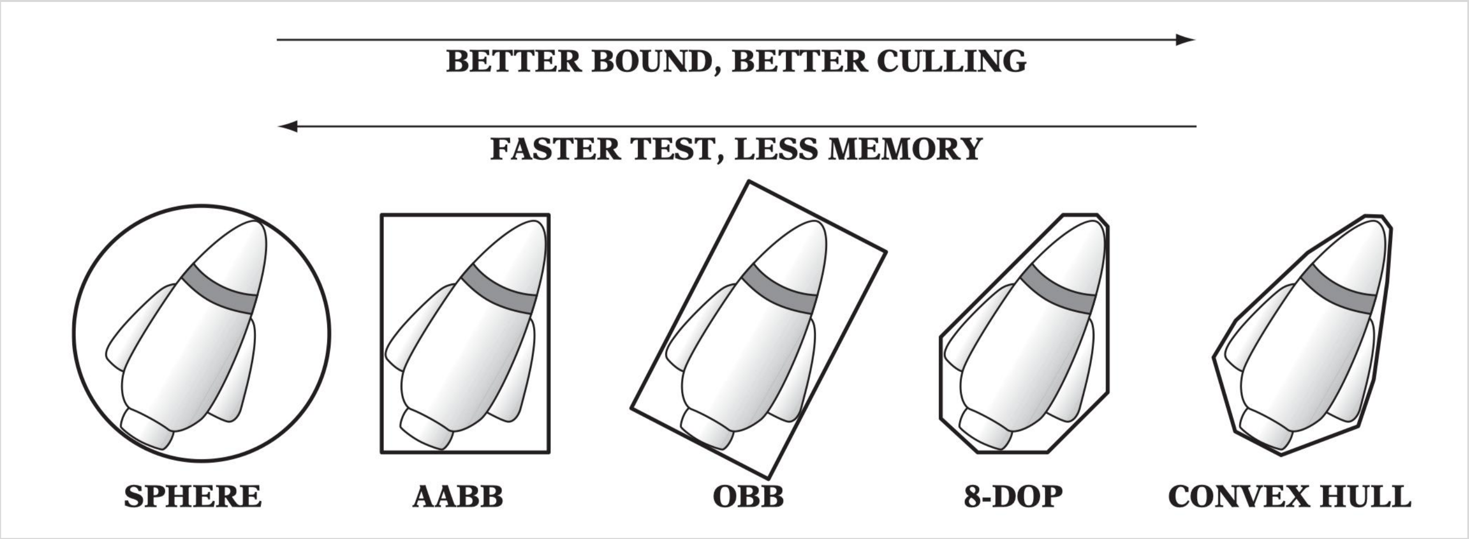
Culling One Object



View Frustum

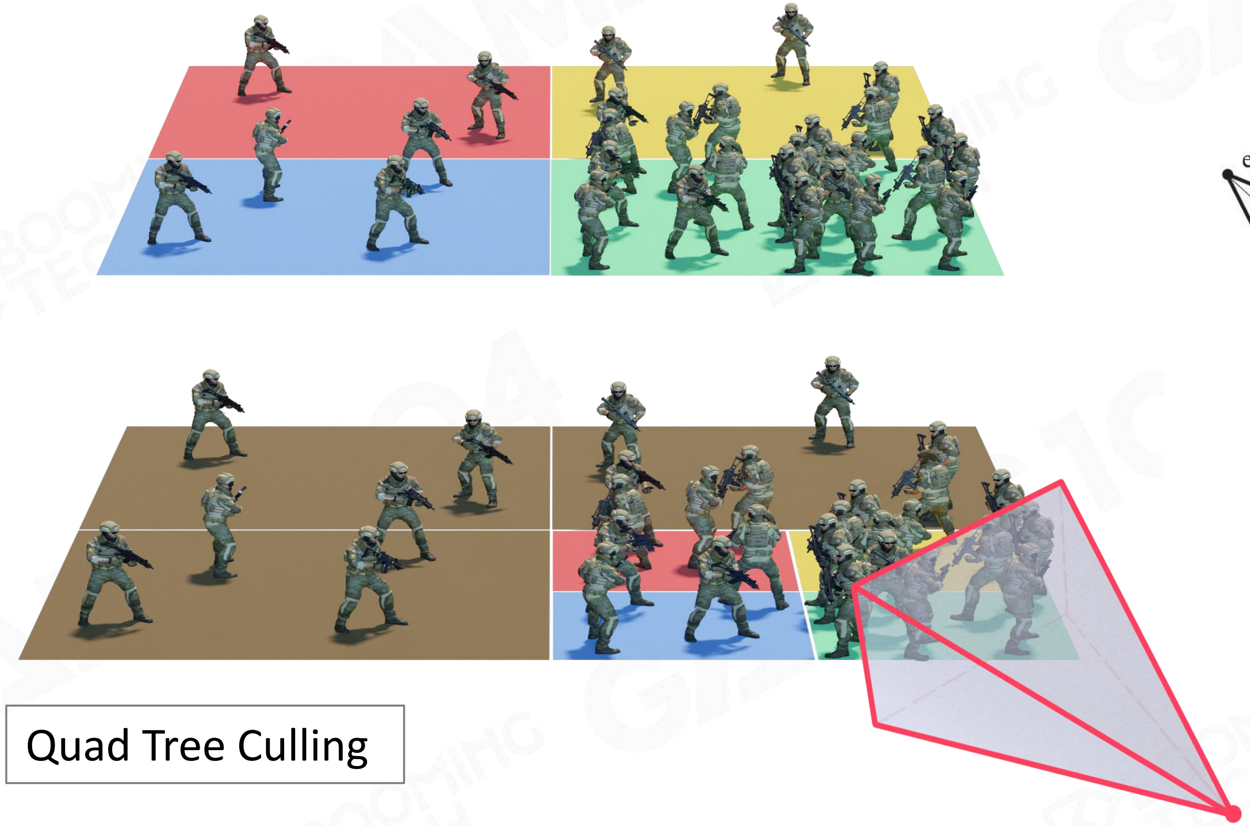
Solider Bounding Box

Using the Simplest Bound to Create Culling

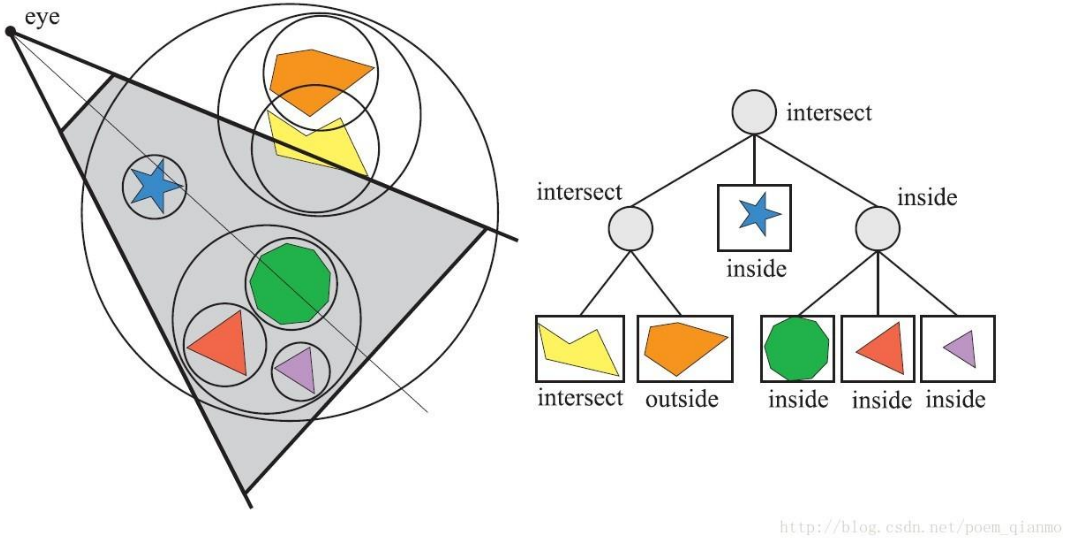


- Inexpensive intersection tests
- Tight fitting
- Inexpensive to compute
- Easy to rotate and transform
- Use little memory

Hierarchical View Frustum Culling



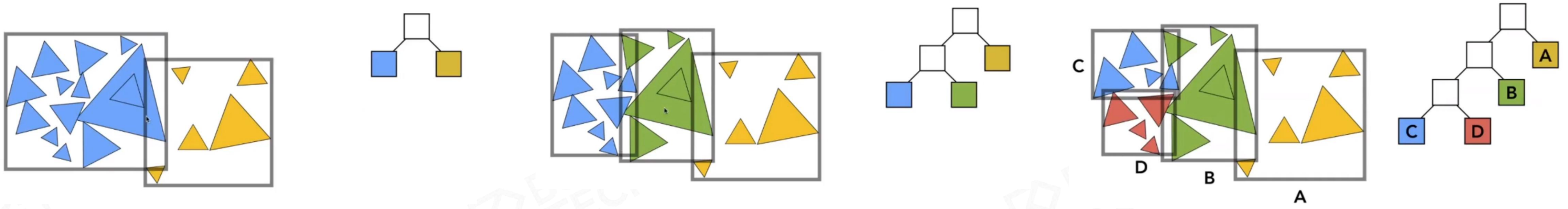
Quad Tree Culling



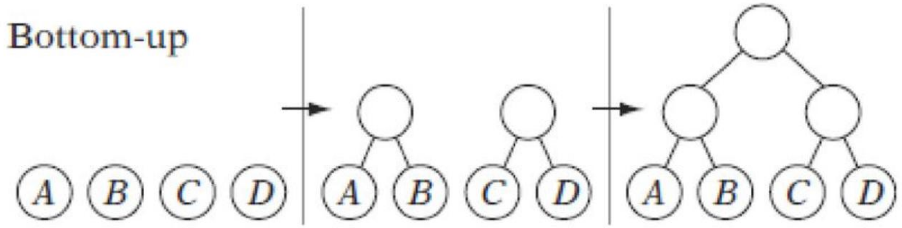
BVH (Bounding Volume Hierarchy) Culling

Construction and Insertion of BVH in Game Engine

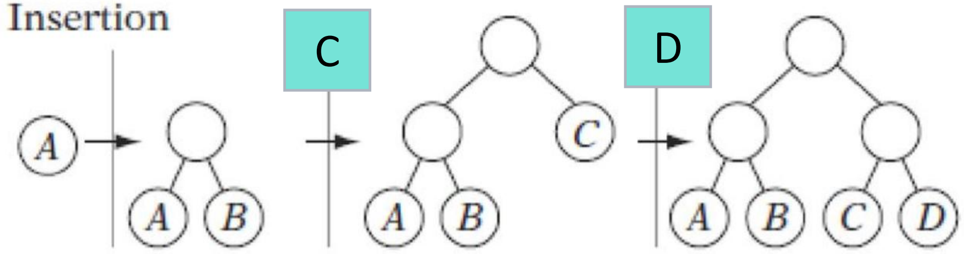
Top-down



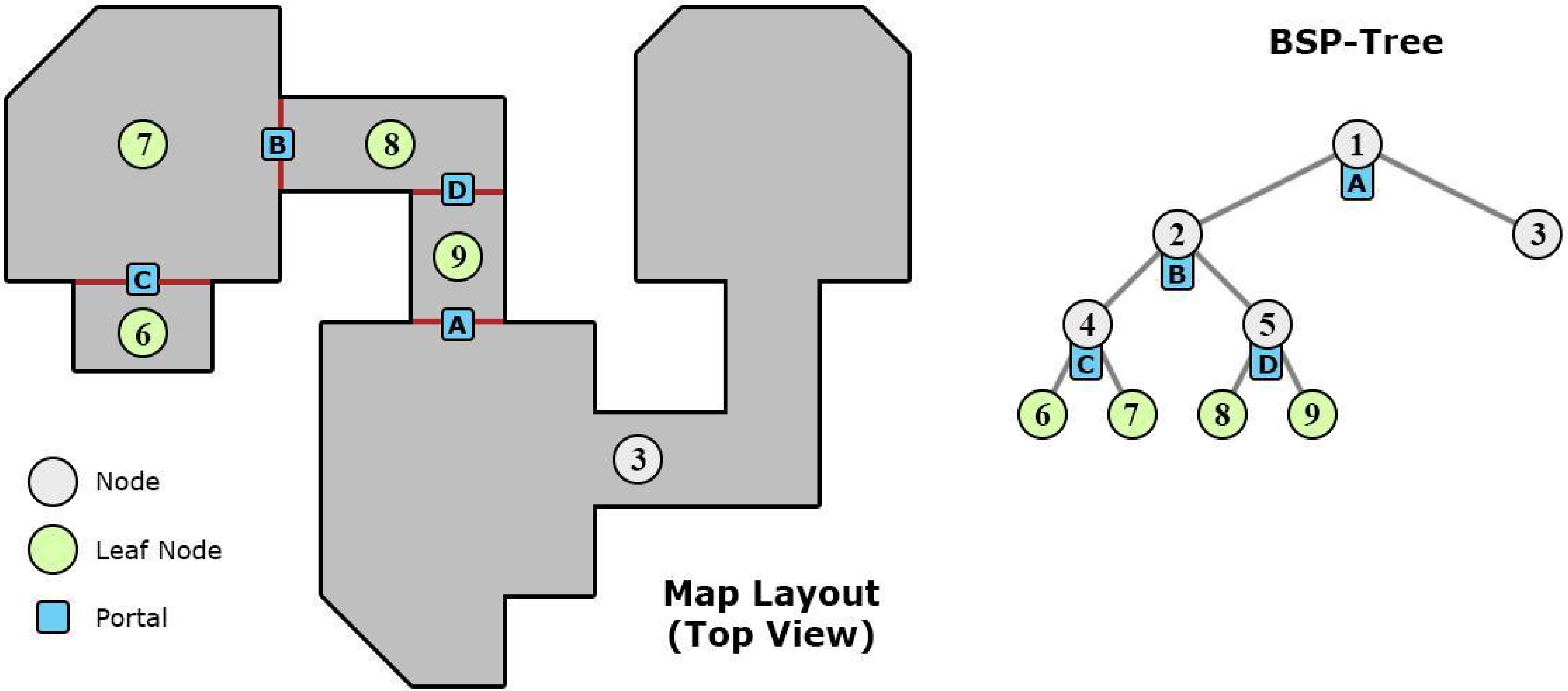
Bottom-up



Incremental tree-insertion



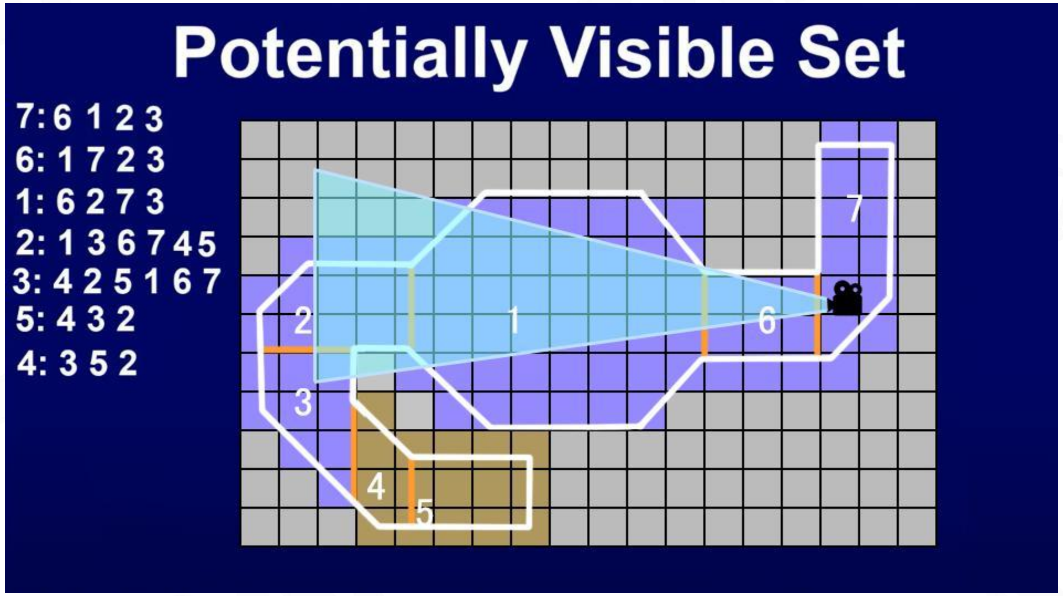
PVS (Potential Visibility Set)



Portal and PVS Data

Generate PVS data from portal:

```
for each portals
    getSamplingPoints();
    for each portal faces
        for each leaf
            do ray casting between portal face and leaf
        end
    end
end
```



Determine potentially visible leaf nodes immediately from portal

The Idea of Using PVS in Stand-alone Games

Green box:

The area to determine the potential visibility where you need.

Blue cells:

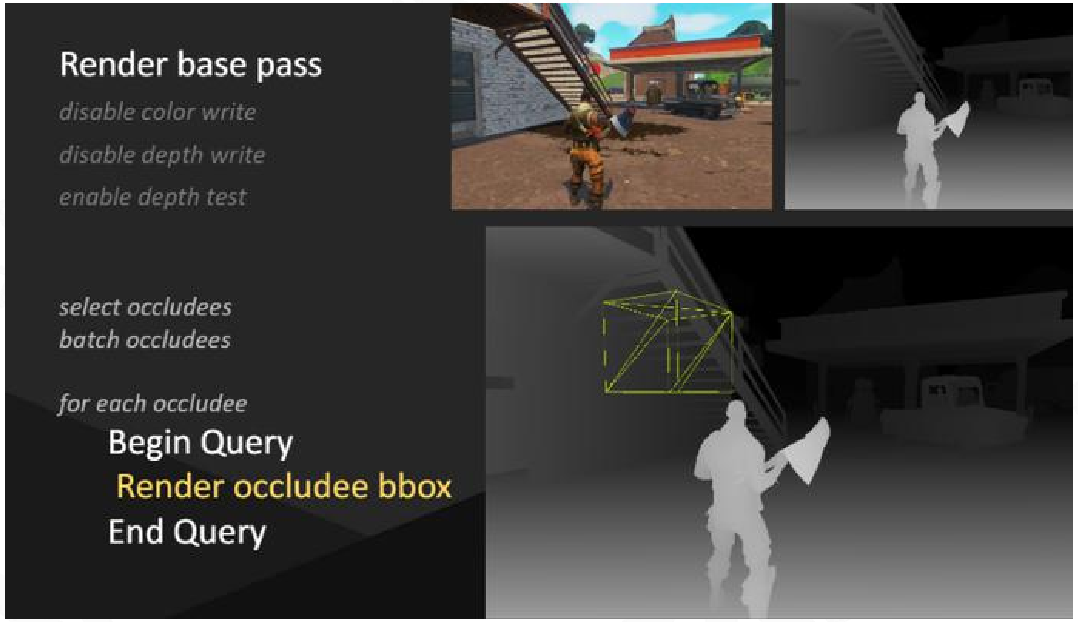
Auto generated smaller regions of each green box.

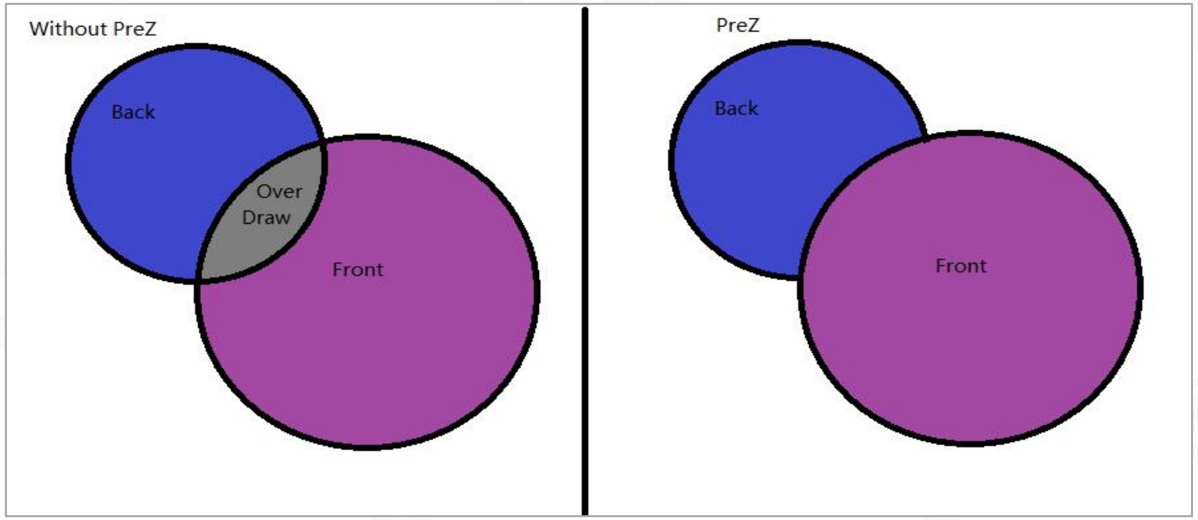
```
for each GreenBoxs
    for each BlueCells
        do ray casting between box and cell
    end
end
```

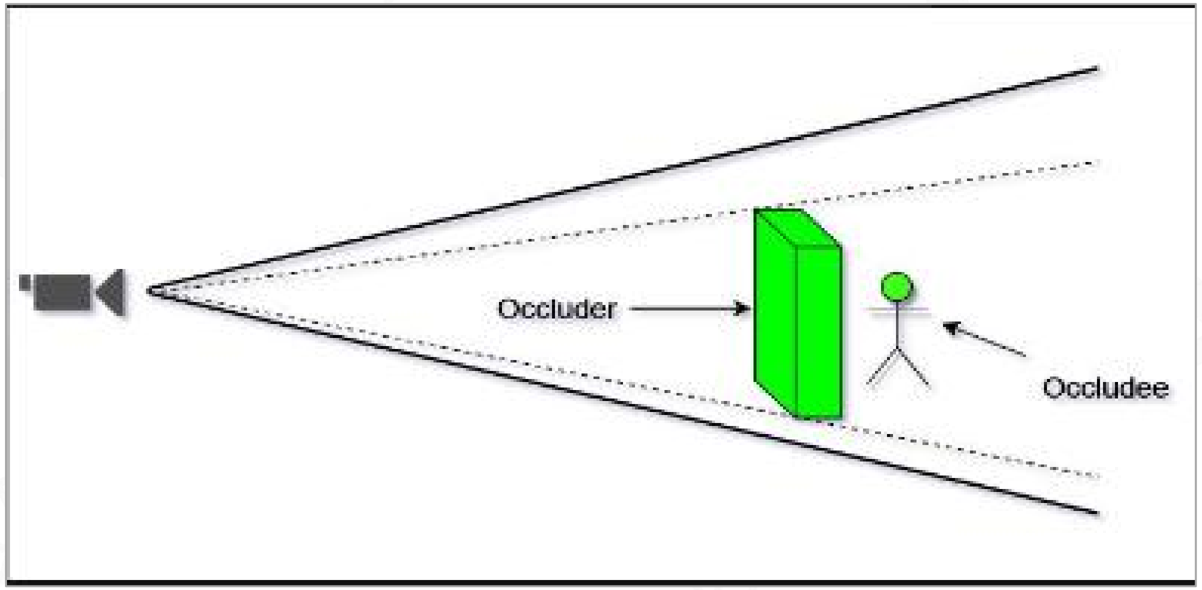
Pros

- Much faster than BSP / Octree
- More flexible and compatible
- Preload resources by PVS

GPU Culling


Render base pass
disable color write
disable depth write
enable depth test
select occludees
batch occludees
for each occludee
Begin Query
Render occludee bbox
End Query


Without PreZ
Back
Over Draw
Front
PreZ
Back
Front


Occluder
Occludee

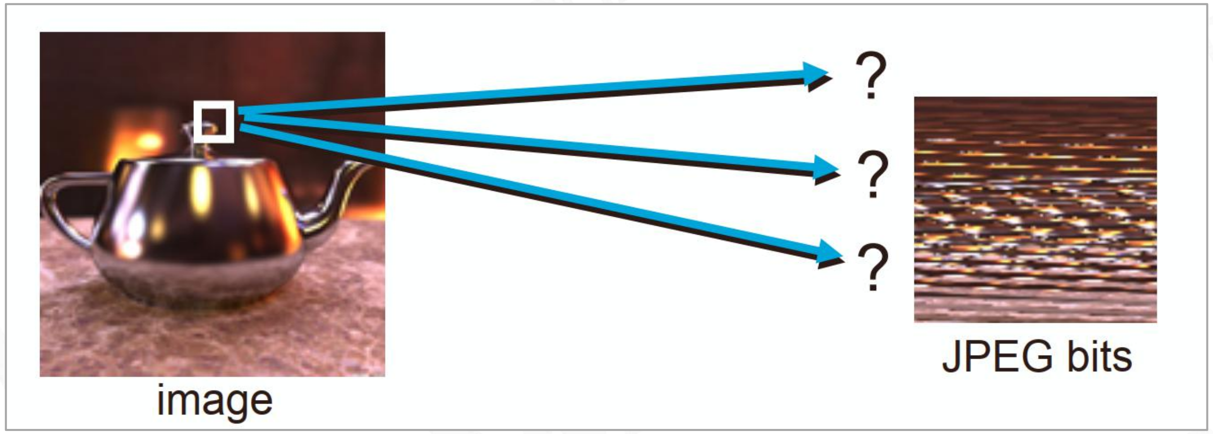
Texture Compression

A must-know for game engine

Texture Compression

- **Traditional image compression like JPG and PNG**
  - Good compression rates
  - Image quality
  - Designed to compress or decompress an entire image

- **In game texture compression**
  - Decoding speed
  - Random access
  - Compression rate and visual quality
  - Encoding speed

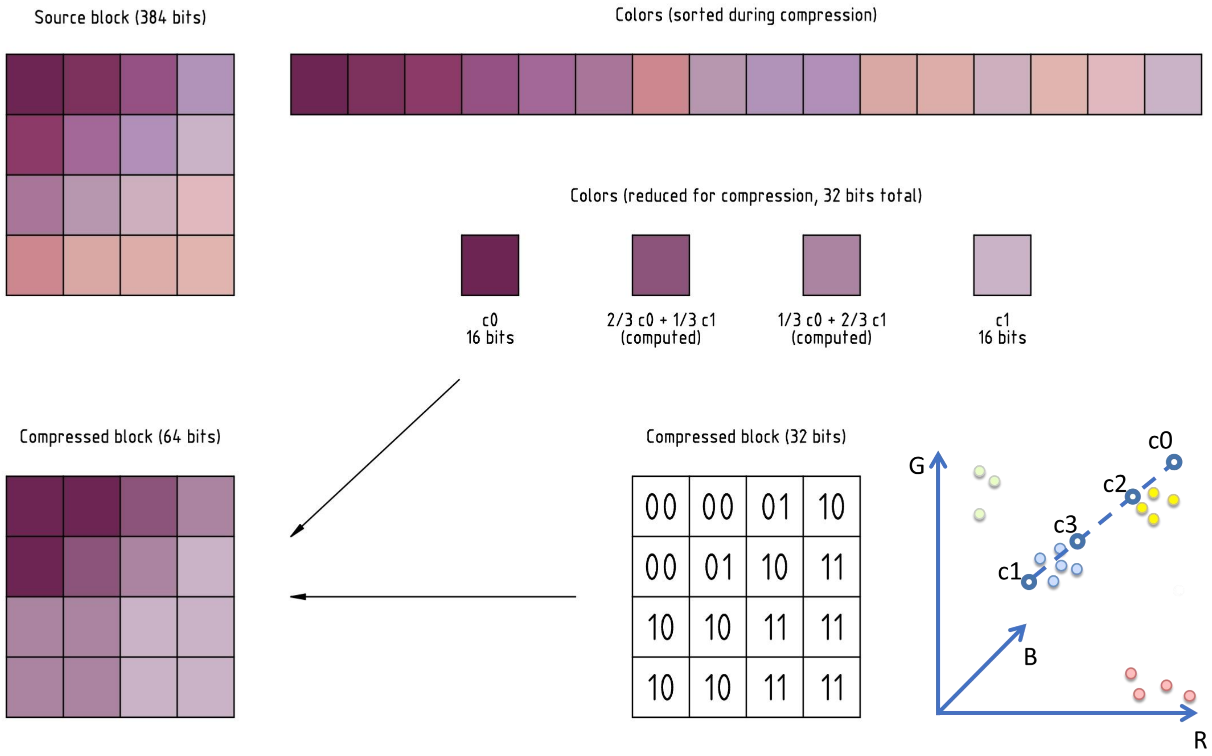


Sample JPEG format texture

Block Compression

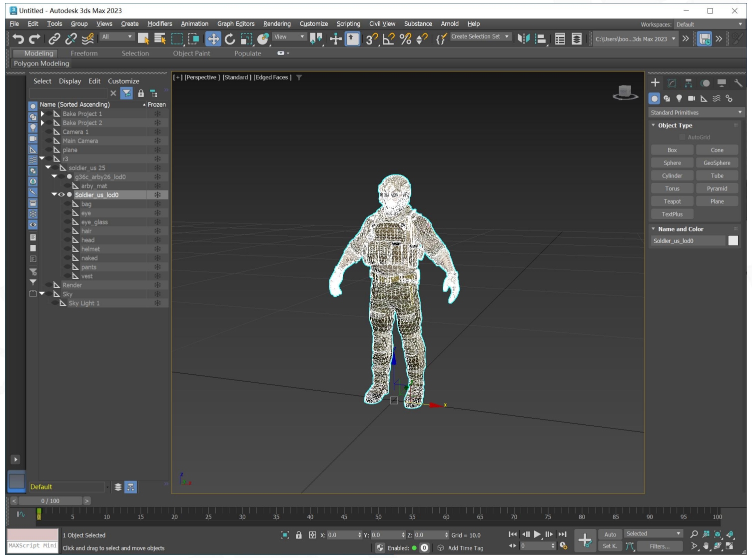
Common block-based compression format

- On PC, BC7 (modern) or DXTC (old) formats
- On mobile, ASTC (modern) or ETC / PVRTC (old) formats

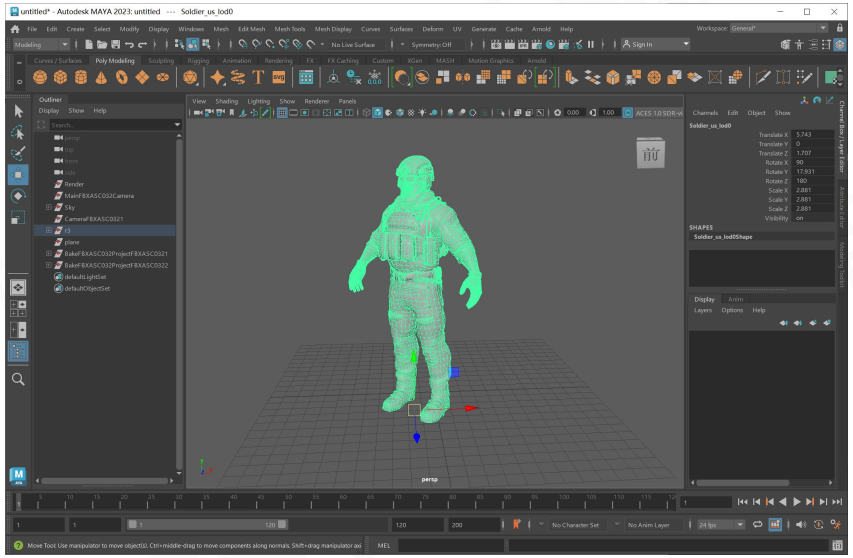


Authoring Tools of Modeling

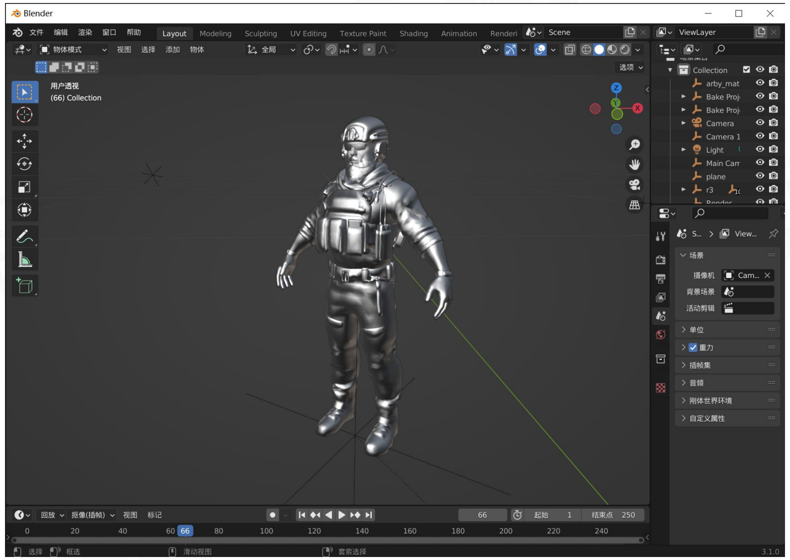
Modeling - Polymodeling



MAX

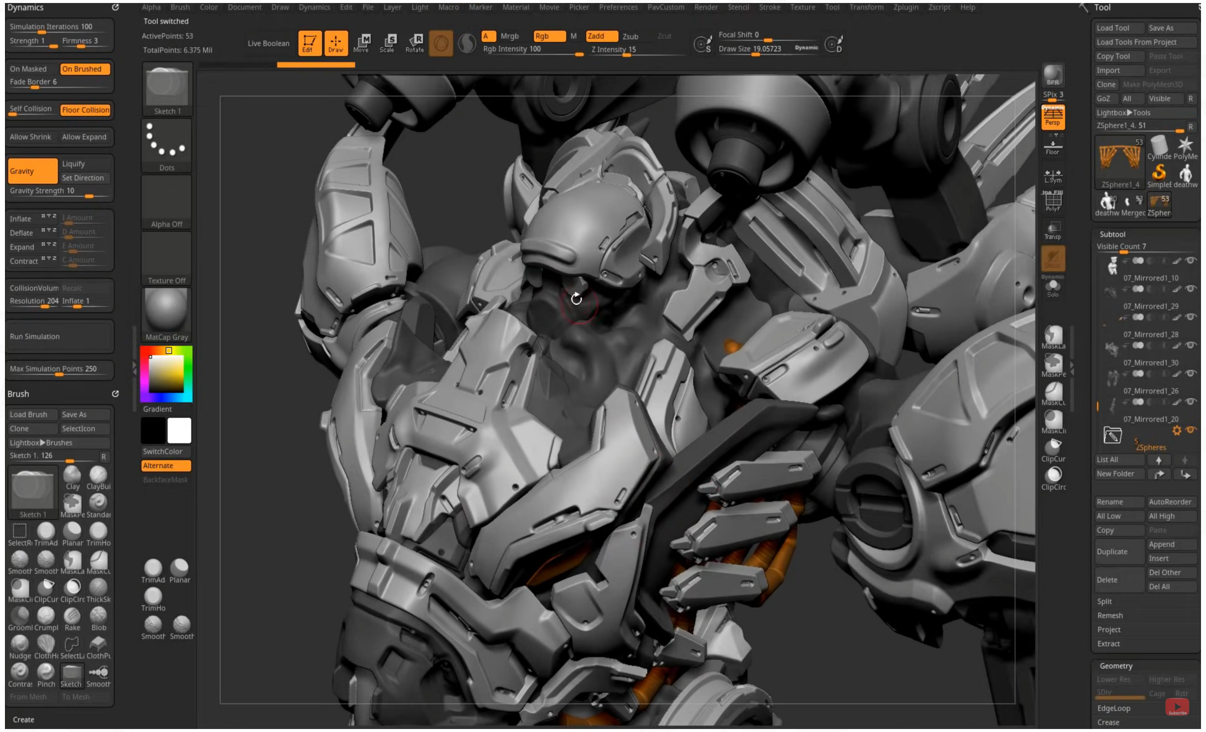


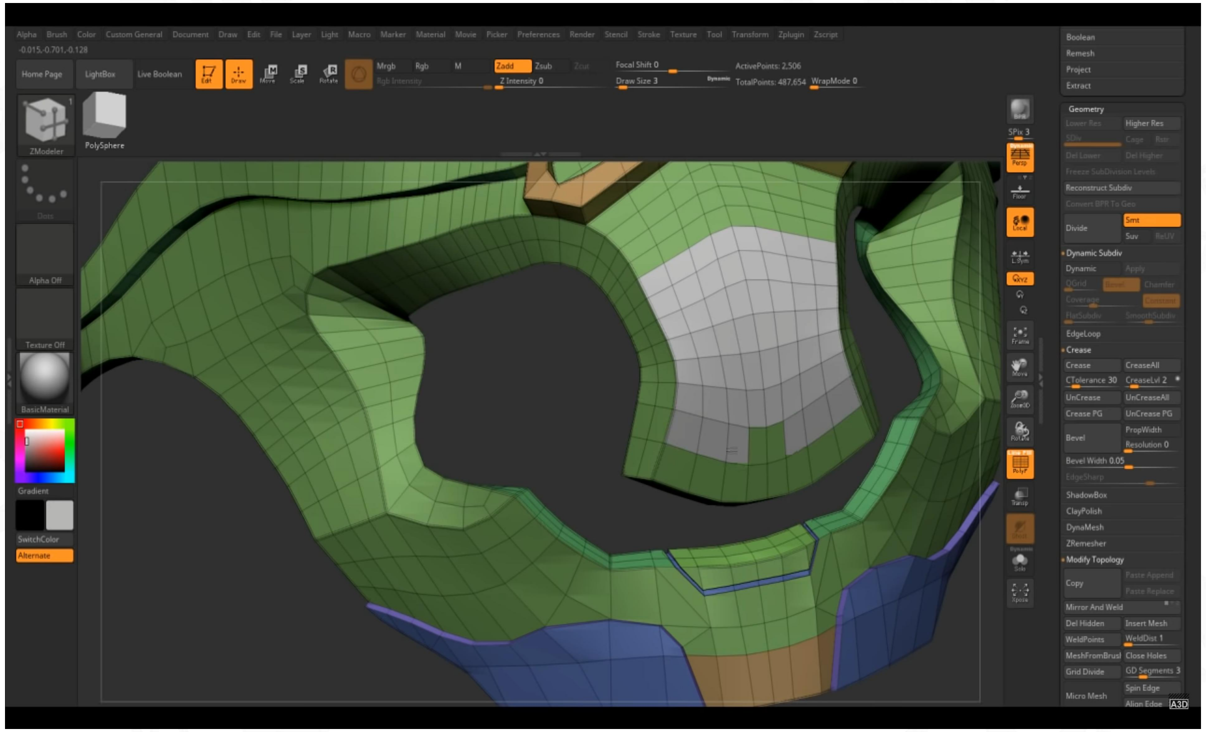
MAYA



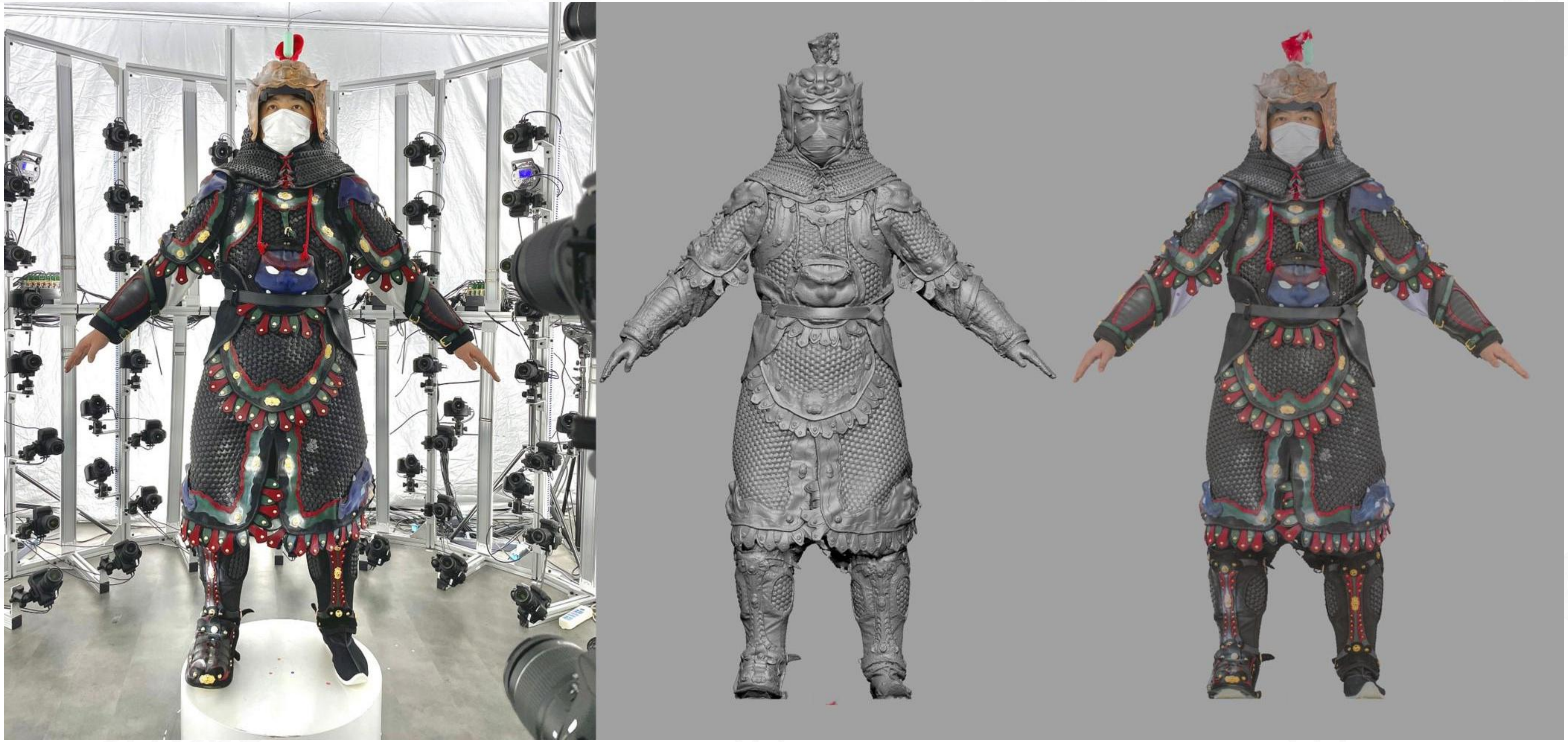
BLENDER

Modeling - Sculpting

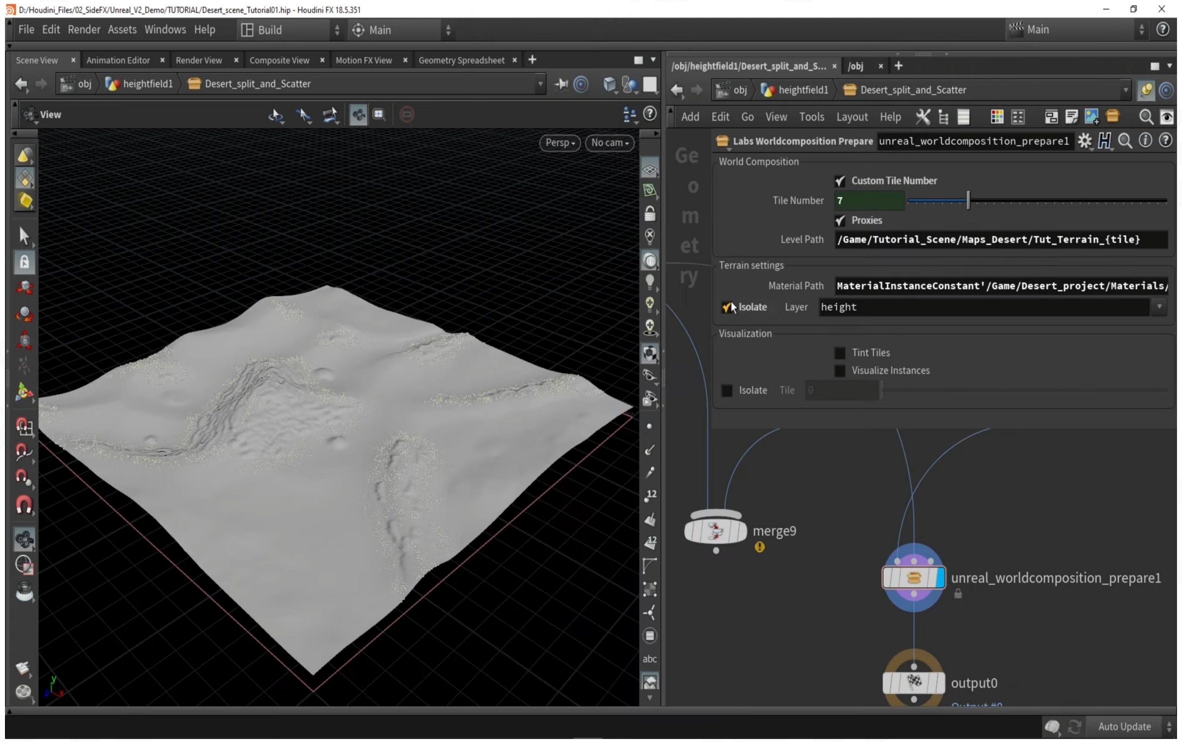




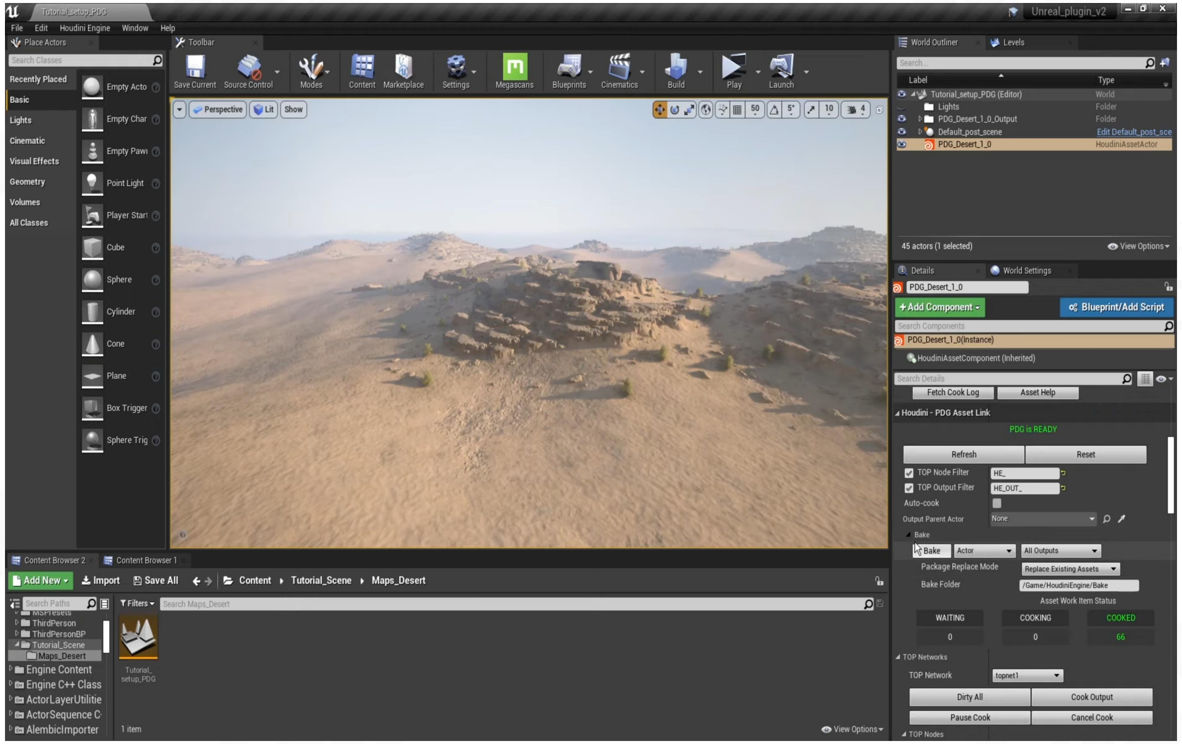
Modeling - Scanning



Modeling - Procedural Modeling

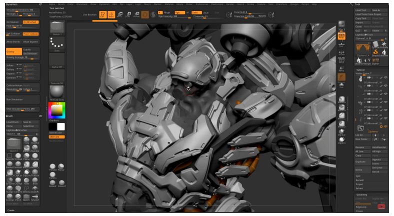
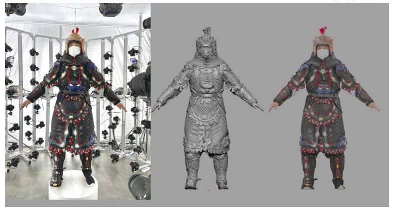
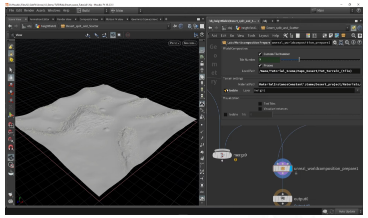


Houdini



Unreal

Comparison of Authoring Methods

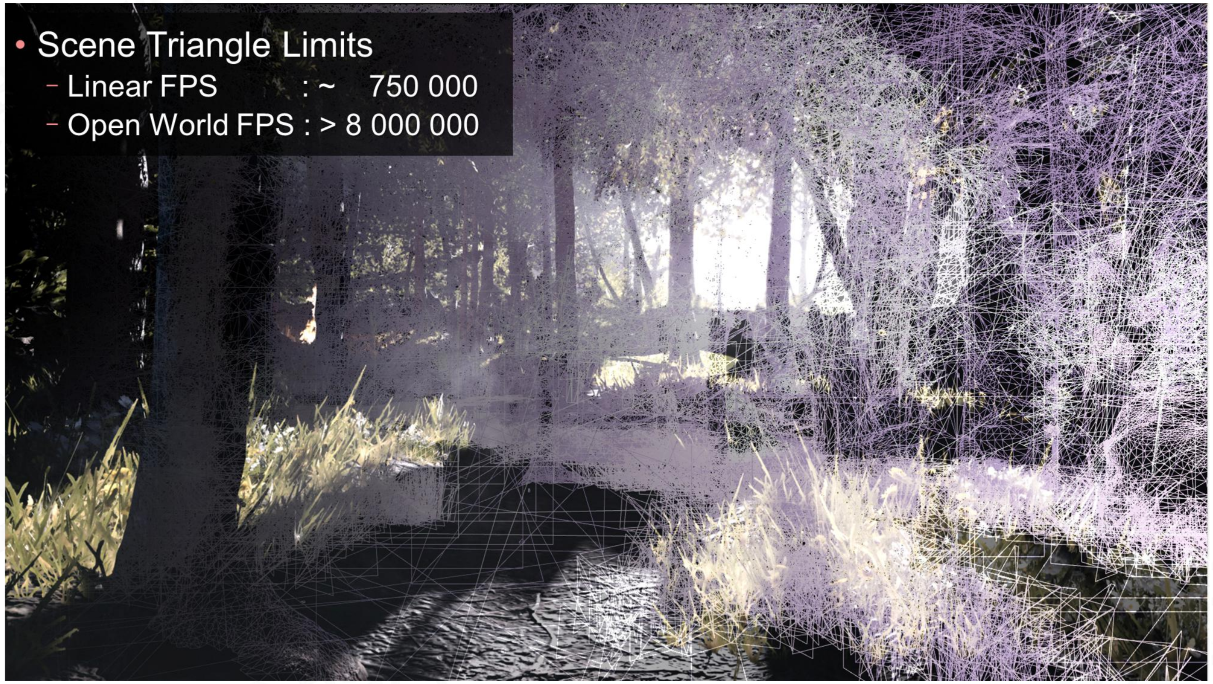
	Polymodeling	Sculpting	Scanning	Procedural modeling
Sample				
Advantage	Flexible	Creative	Realistic	Intelligent
Disadvantage	Heavy workload	Large volume of data	Large volume of data	Hard to achieve

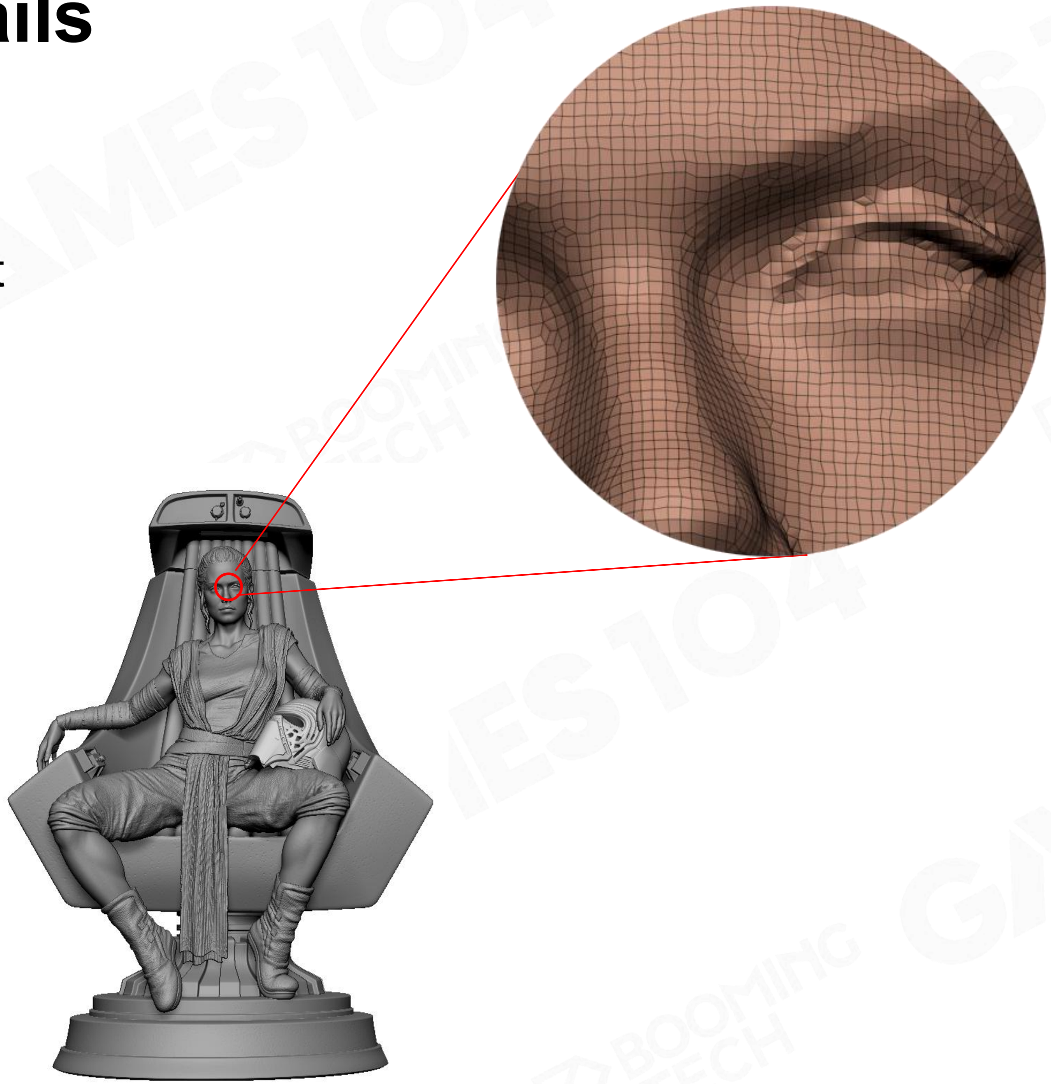
Cluster-Based Mesh Pipeline

Sculpting Tools Create Infinite Details

- Artists create models with infinite details
- From linear fps to open world fps, complex scene submit

  10 more times triangles to GPU per-frame





Cluster-Based Mesh Pipeline

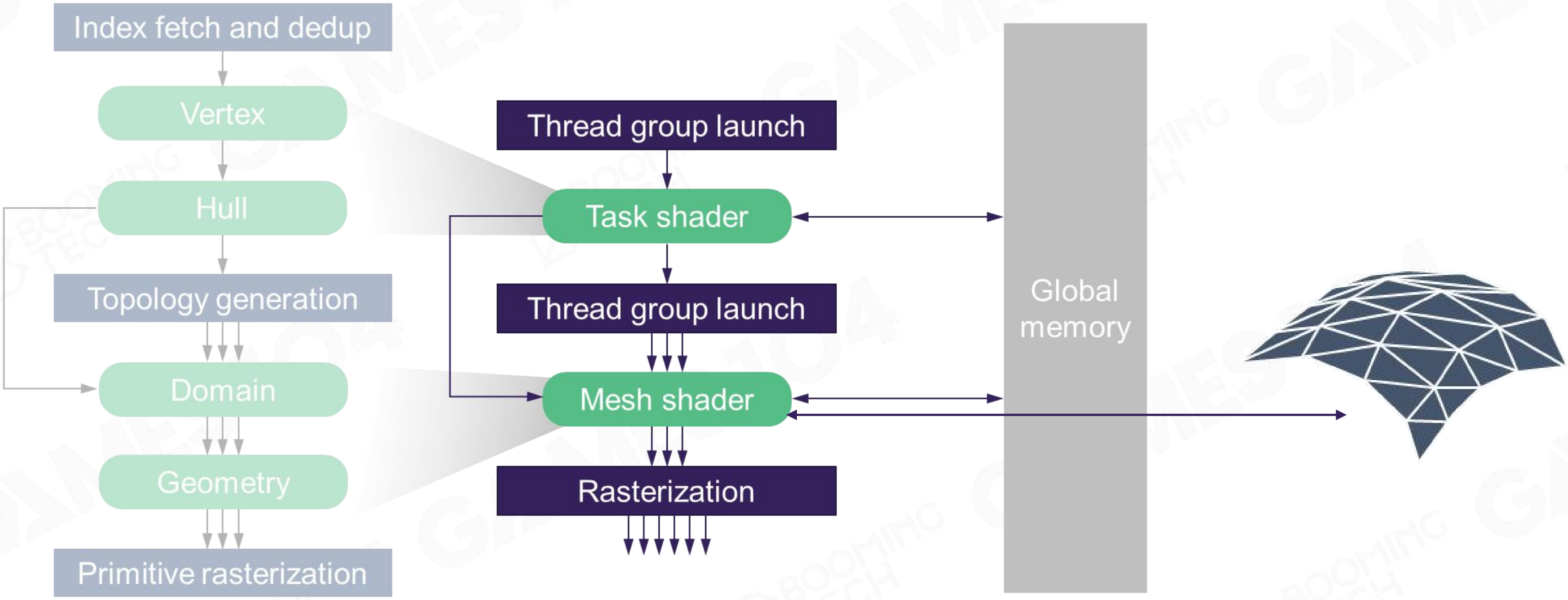
GPU-Driven Rendering Pipeline (2015)

- Mesh Cluster Rendering
  - Arbitrary number of meshes in single drawcall
  - GPU-culled by cluster bounds
  - Cluster depth sorting

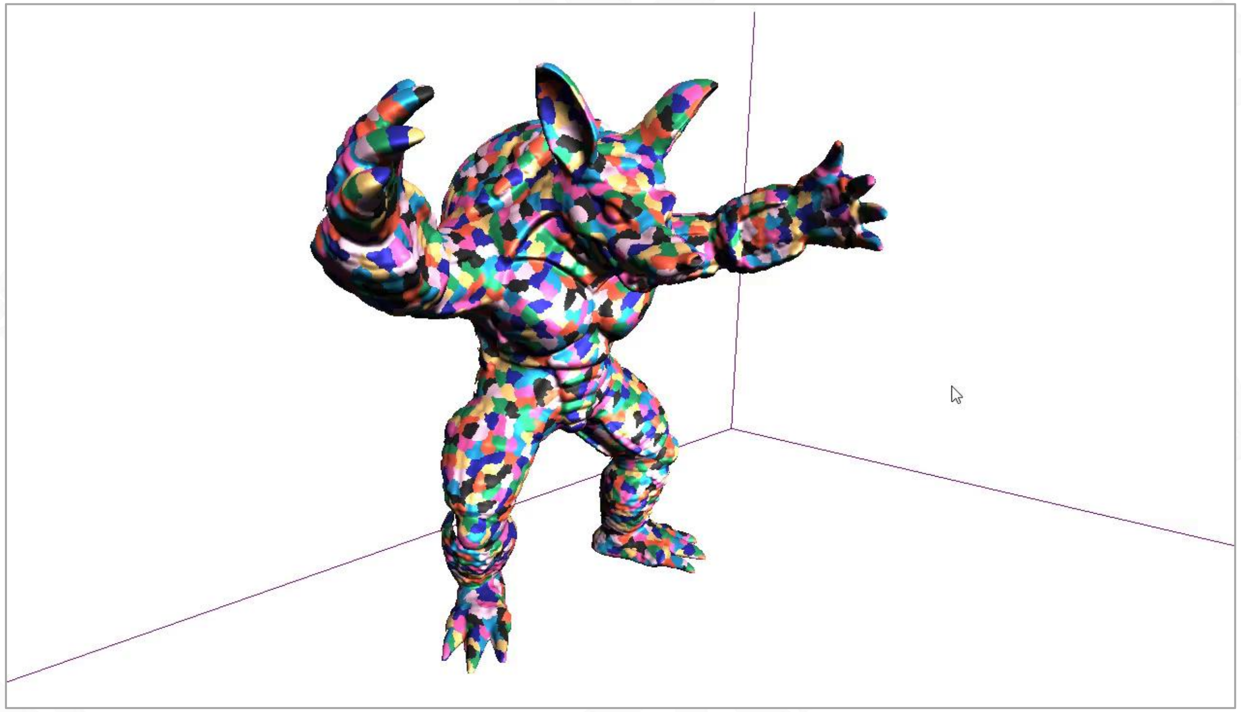
Geometry Rendering Pipeline Architecture (2021)

- Rendering primitives are divided as:
  - Batch: a single API draw (drawIndirect / drawIndexIndirect), composed of many Surfs
  - Surf: submeshes based on materials, composed of many Clusters
  - Cluster: 64 triangles strip

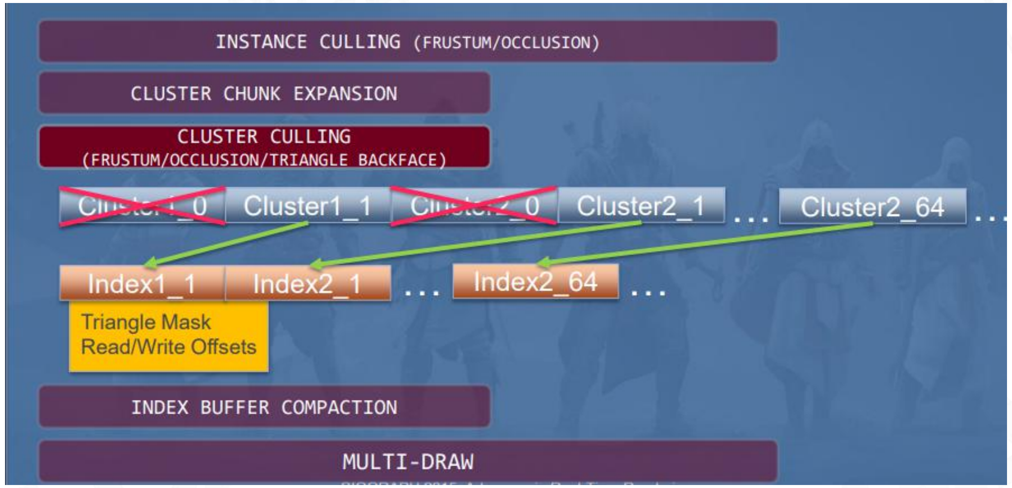
Programmable Mesh Pipeline



GPU Culling in Cluster-Based Mesh



350k triangles to 2791 clusters



GPU Pipeline

Nanite

- Hierarchical LOD clusters with seamless boundary
- Don’t need hardware support, but using a hierarchical cluster culling on the precomputed BVH tree by persistent threads (CS) on GPU instead of task shader

Take Away

1. The design of game engine is deeply related to the hardware architecture design

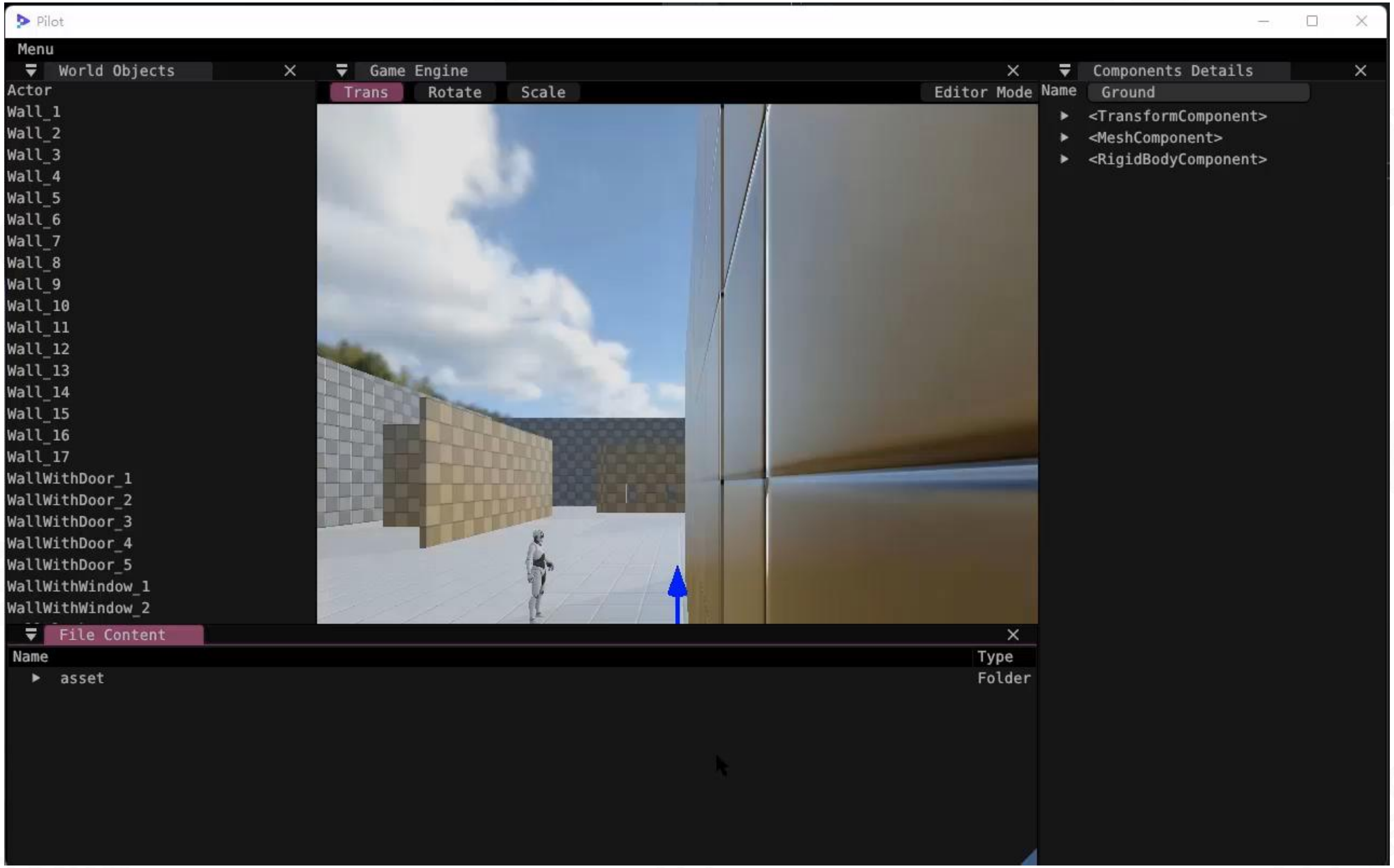
2. A submesh design is used to support a model with multiple materials

3. Use culling algorithms to draw as few objects as possible

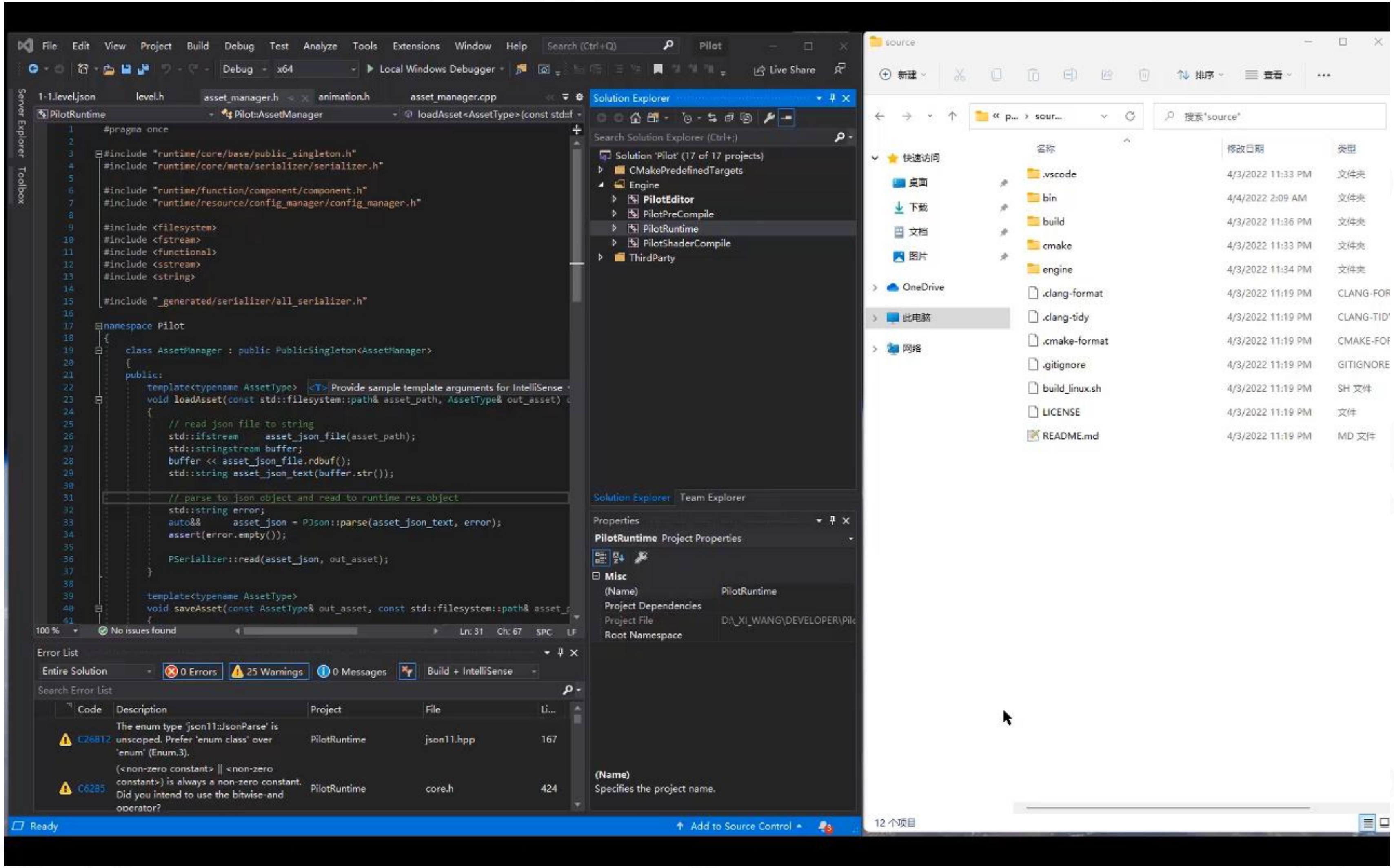
4. As GPU become more powerful, more and more work are moved into GPU, which called GPU Driven

PILOT
Game engine

Pilot Engine – Editor and Game



Pilot Engine – Source Code



1st release (4/4/2022)

- **Editor**
  - load / save level
  - add/delete/move/rotate/scale objects
  - Play In Editor (PIE)
- **Renderer**
  - forward shading
  - shadow
- **Animation**
  - simple skeleton animation
- **Collision**
  - sphere and box
- **Character/Camera**
  - first / third-person camera
- **Motor**
  - eight-direction moving + sprinting
- **Single-threaded object-based ticking**
- **Resource manager**
- **Windows and Linux compatible**

To be released with upcoming lectures

- **More graphics features**
  - fbx format support
  - submesh
- **More animation features**
  - animation blending
- **Gameplay and script systems**
- **MacOS compatible**
- And more…

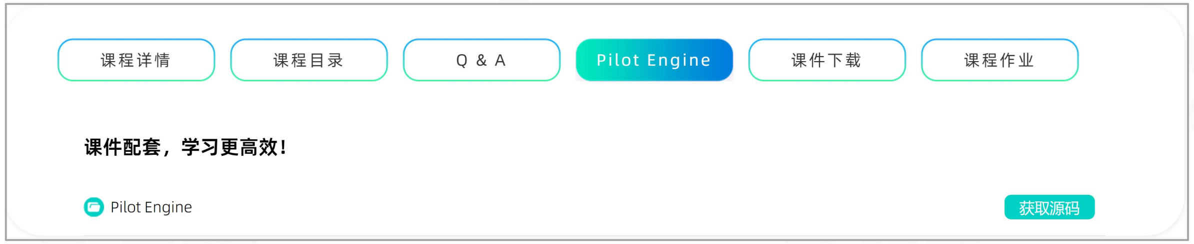
Not implemented

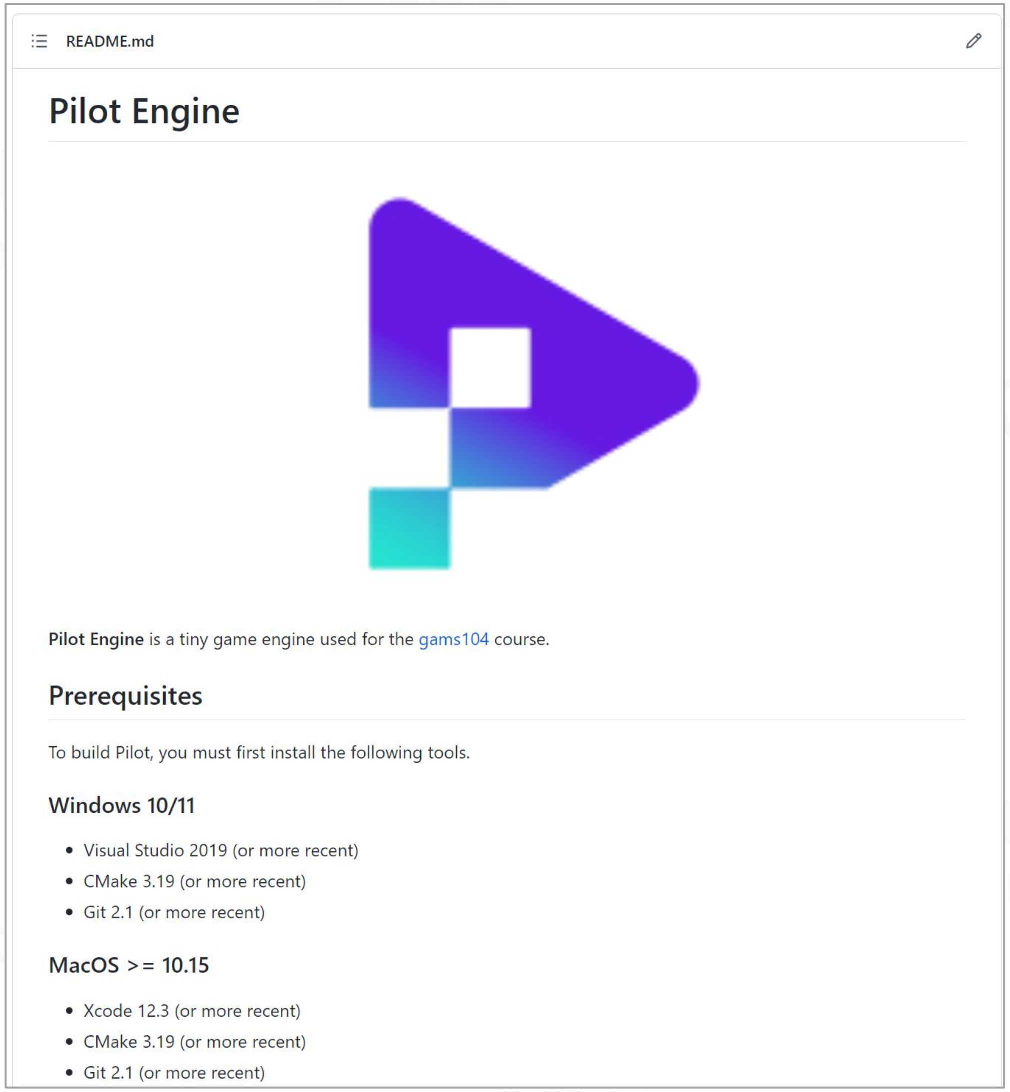
- **Multi-threaded framework**
- **Entity-Component-System (ECS)**
- **Space Partitioning**

Pilot Engine Download

Games104 Official WebSite:
https://cdn.boomingtech.com/games104_static/upload/Pilot.zip

GitHub： https://github.com/BoomingTech/Pilot




README.md

Pilot Engine

Pilot Engine is a tiny game engine used for the gams104 course.

Prerequisites

To build Pilot, you must first install the following tools.

Windows 10/11

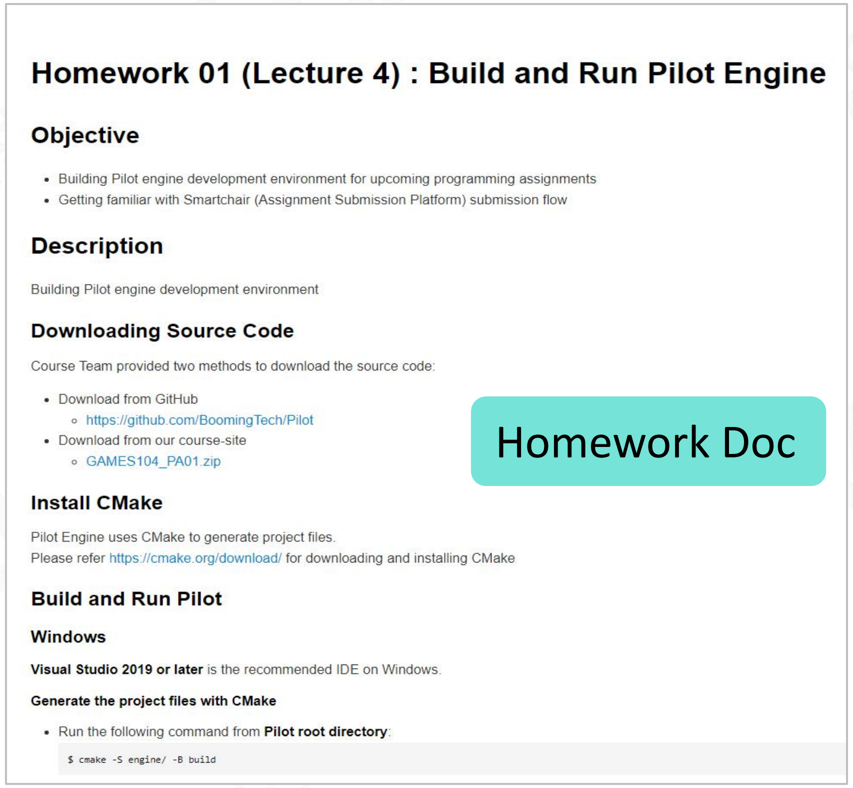
- Visual Studio 2019 (or more recent)
- CMake 3.19 (or more recent)
- Git 2.1 (or more recent)

MacOS >= 10.15

- Xcode 12.3 (or more recent)
- CMake 3.19 (or more recent)
- Git 2.1 (or more recent)

Homework

- Build and run Pilot Engine
- Take a screenshot and upload
- Please refer to homework document for details



Homework 01 (Lecture 4) : Build and Run Pilot Engine

Objective

- Building Pilot engine development environment for upcoming programming assignments
- Getting familiar with Smartchair (Assignment Submission Platform) submission flow

Description

Building Pilot engine development environment

Downloading Source Code

Course Team provided two methods to download the source code:

- Download from GitHub
  - https://github.com/BoomingTech/Pilot
- Download from our course-site
  - GAMES104_PA01.zip

Install CMake

Pilot Engine uses CMake to generate project files.
Please refer https://cmake.org/download/ for downloading and installing CMake

Build and Run Pilot

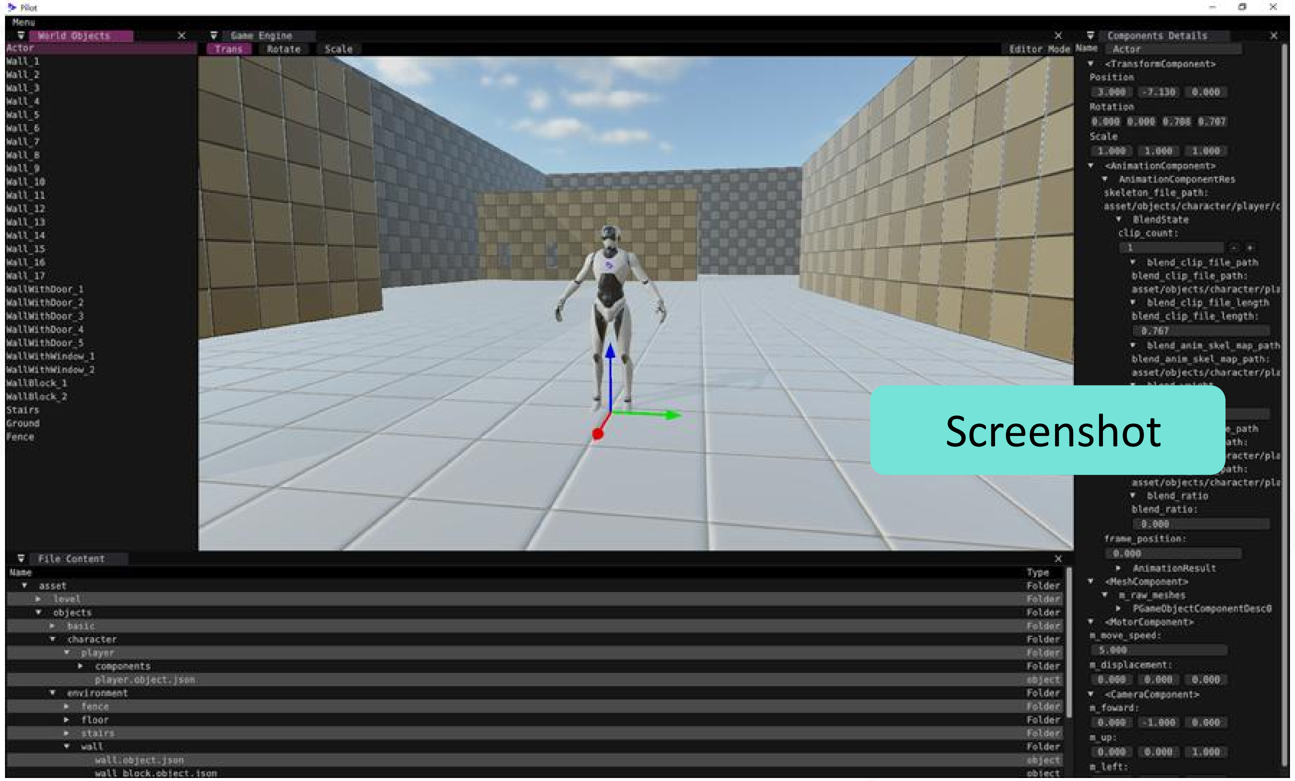
Windows

Visual Studio 2019 or later is the recommended IDE on Windows.

Generate the project files with CMake

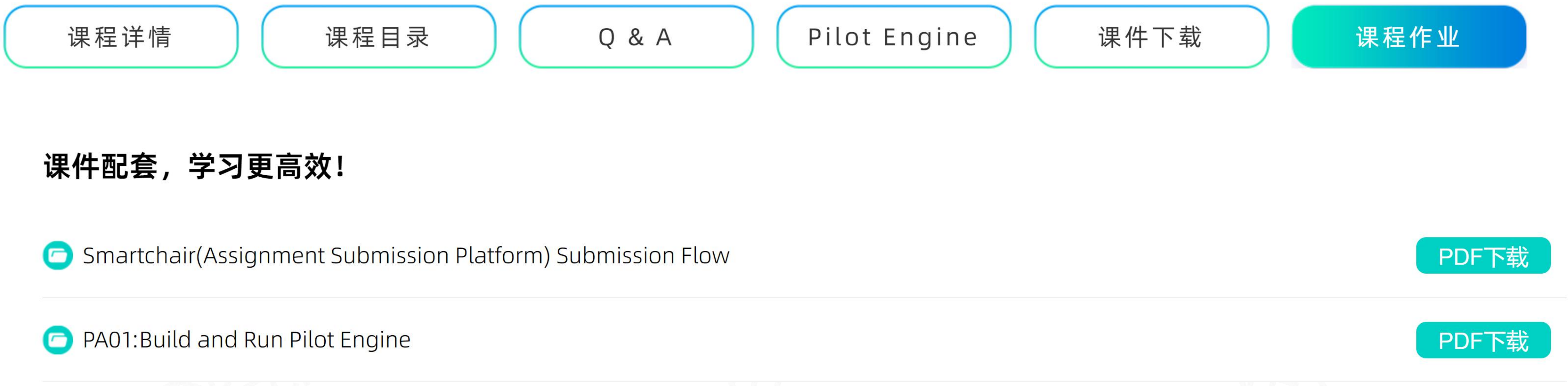
- Run the following command from **Pilot root directory**:

```
$ cmake -S engine/ -B build
```

Homework

- Homework information can be found on the course-site:
  http://games104.boomingtech.com/sc/course-list/
- Download the homework materials for details.



Q&A

Lecture 04 Contributor

- 一将
- 光哥
- 炯哥
- 玉林
- 小老弟
- 建辉
- 爵爷
- Jason
- 砚书
- BOOK
- MANDY
- 俗哥
- 金大壮
- Leon
- 梨叔
- Shine
- 邓导
- Judy
- QIUU
- C佬
- 阿乐
- 阿熊
- CC
- 大喷

Enjoy ;) Coding

Course Wechat

Follow us for further information