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Introduction to DirectX Raytracing

Part 2 – the API

How To Use DXR, In Three Easy Steps

Build geometry into acceleration structures

↓

Configure a raytracing pipeline state

↓

DispatchRays()

… backing up: D3D12 basics

- D3D12 is a low level API, so you control memory allocations, object lifespans, and synchronization
- Create resources in GPU memory (textures, vertices, constant buffers)
- Copy data into them
- Record GPU instructions into a command list

```
ID3D12GraphicsCommandList::Reset
ID3D12GraphicsCommandList::SetGraphicsRootSignature
ID3D12GraphicsCommandList::DrawInstanced
ID3D12GraphicsCommandList::Dispatch
```

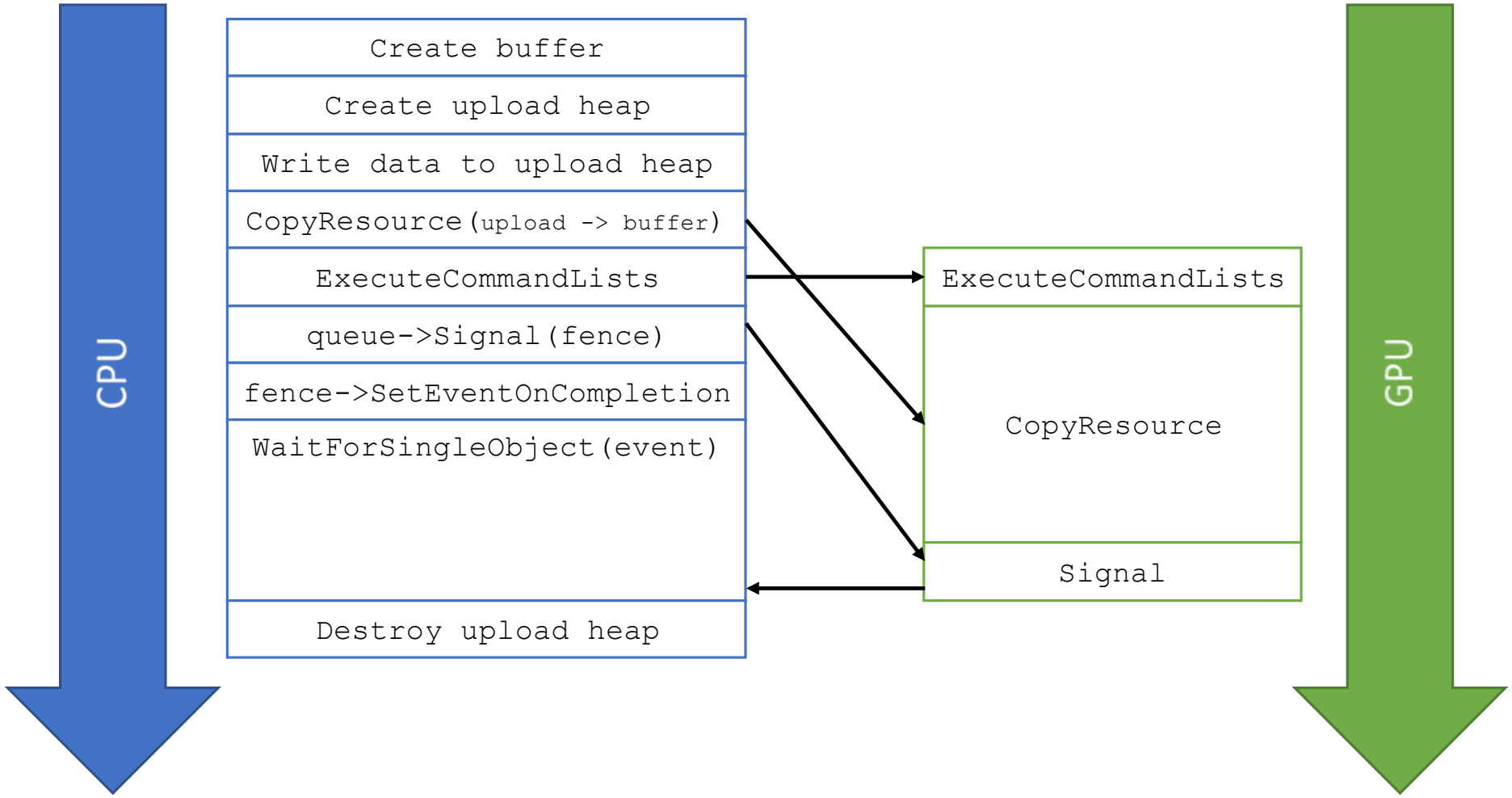
- Submit command lists to a queue for execution by the hardware

```
ID3D12CommandQueue::ExecuteCommandLists
```

- Synchronize to know when work has finished

```
ID3D12CommandQueue::Signal
ID3D12Fence::GetCompletedValue
ID3D12Fence::SetEventOnCompletion
```

Parallel Execution – Creating a Resource



D3D12 Binding Model (indirection ftw!)

- Descriptor = pointer to a GPU resource
- Descriptor table = indexable array of descriptors
- Descriptor heap = area of GPU memory containing multiple descriptor tables
- Root signature defines a binding convention, used by shaders to locate whatever data they need to access
  - Inlined root constants
  - Inlined root descriptors
  - Pointers to descriptor tables within the descriptor heap

New Requirements For Raytracing

- Acceleration structure format is opaque
  - Unlike traditional vertex data used for rasterization, there is no standard layout suitable for all implementations
- Rays can go anywhere
  - So all geometry and shaders must be simultaneously available
- Different shaders may want different resource bindings

More levels of indirection!

Build Acceleration Structures

Acceleration Structures

- Opaque geometry format optimized for ray traversal (e.g. BVH)
- Layout determined by driver and hardware
- Built at runtime on the GPU
- Immutable except for incremental in-place updates

Top vs. Bottom

- Bottom level acceleration structures
  - Contain triangles
  - Or procedural primitives defined by AABB plus intersection shader
  - Take time to build
- Top level acceleration structures
  - Point to one or more bottom level acceleration structures
  - Instancing = multiple references to the same bottom level structure
  - Fast to build
- Balance between:
  - Ray intersection performance: larger bottom level structures
  - Flexibility: more/smaller bottom level structures

Memory Management

- Because the format is implementation defined, you cannot know up front how big an acceleration structure will be

`GetRaytracingAccelerationStructurePrebuildInfo()`

- Runs on the CPU
- Returns a conservative estimate
- `D3D12_RAYTRACING_ACCELERATION_STRUCTURE_PREBUILD_INFO`
  - `.ResultDataMaxSizeInBytes`
  - `.ScratchDataSizeInBytes`

`BuildRaytracingAccelerationStructure()`

- Runs on the GPU
- Returns actual size, in GPU memory after the command list has finished executing
- `D3D12_RAYTRACING_ACCELERATION_STRUCTURE_POSTBUILD_INFO_TYPE`
  - `_CURRENT_SIZE`
  - `_COMPACTED_SIZE`

Acceleration Structure Build Flags

- D3D12_RAYTRACING_ACCELERATION_STRUCTURE_BUILD_FLAG
  - _PREFER_FAST_TRACE
  - _PREFER_FAST_BUILD
  - _MINIMIZE_MEMORY
  - _ALLOW_COMPACTION
  - _ALLOW_UPDATE
  - _PERFORM_UPDATE

Compaction

- Suballocate out of larger buffers
- Use conservative sizes while generating command list for initial build
- After real size data is available, perform a compaction pass
- Don’t compact things that animate…
- Beware CPU/GPU stalls!

No Compaction

1. `GetRaytracingAccelerationStructurePrebuildInfo()`
2. Allocate _PREBUILD_INFO.ResultDataMaxSizeInBytes
3. `BuildRaytracingAccelerationStructure()`

Wasted space:

_PREBUILD_INFO.ResultDataMaxSizeInBytes - _POSTBUILD_INFO_COMPACTED_SIZE

In-place Compaction

Allocate multiple acceleration structures at offsets within larger buffer:

1. `BuildRaytracingAccelerationStructure` to `(buffer + bufferOffset)`
2. Wait for build to finish executing
3. `bufferOffset += _POSTBUILD_INFO_CURRENT_SIZE`

Wasted space:

_POSTBUILD_INFO_CURRENT_SIZE - _POSTBUILD_INFO_COMPACTED_SIZE

Beware stalls!

Full Compaction

1. For each acceleration structure:
   - `BuildRaytracingAccelerationStructure` to `(tempBuffer + tempOffset)`
   - `tempOffset += _PREBUILD_INFO.ResultDataMaxSizeInBytes`
2. Wait for builds to finish executing
3. For each acceleration structure:
   - `CopyRayTracingAccelerationStructure(buffer + bufferOffset, tempBufferLocation, _ACCELERATION_STRUCTURE_COPY_MODE_COMPACT)`
   - `bufferOffset += _POSTBUILD_INFO_COMPACTED_SIZE`

- No wasted space
- Starting point for more sophisticated dynamic allocation schemes

Animation

- Rigid body animation
  - Update just the top level structure
  - Change transform matrices
  - Add or remove bottom level references as required

- Skinned animation
  - Transform vertices into a buffer (e.g. using compute shader)
  - Apply new positions as an incremental update to an existing bottom level acceleration structure
  - Performance degrades the more things have moved
    - Skin in object space, not world space!
    - Periodic full rebuild after significant deformations?

Instance Masking

- 8 bit mask per top level acceleration structure entry
- TraceRay intrinsic takes an instance mask parameter
- Intersection only processed if

```
(TraceRay mask & acceleration structure mask) != 0
```

- For all rays to intersect everything, set both masks to 0xFF
- Allows different rays to process different geometry, without having to build entirely separate top level acceleration structures
- e.g. one of the bits could represent “casts shadow”

Configure Raytracing Pipeline State

Shader Tables

- Rays can go anywhere and hit anything
- Different objects can have different materials
- Need to run different shaders depending on which object a ray hit

- Solution:
  - Array of pointers to shaders
  - Index into the array is determined by which object was hit

Arrays of Pointers to Shaders

- Shader Identifier = ‘pointer’ to a shader (32 byte blob)
- Hit Group = { intersection shader, any hit shader, closest hit shader }
- Shader Record = { shader identifier, local root arguments }
- Shader Table = { shader record A }, { shader record B }, …

- No dedicated API for creating shader tables
  - These are just memory that can be filled however you like

Example – HitGroup Shader Table

	Shader Identifer (*32 bytes*)	Root Arguments	Pad to 32 byte alignment
Shader Record #1 - Terrain	Hit Group Identifier Intersection = null Any hit = null Closest hit = shadeTerrain	DescriptorHandle terrainTextureTable; *(8 bytes)* DescriptorHandle lightmapTable; *(8 bytes)* RootDescriptor constantBuffer; *(8 bytes)* float fogDistance; *(4 bytes)*	4 bytes
Shader Record #2 - Water	Hit Group Identifier Intersection = null Any hit = waterAny Closest hit = waterClosest	DescriptorHandle animTexTable; *(8 bytes)* int currentTextureFrame; *(4 bytes)*	20 bytes
Shader Record #3 - Volumetric Clouds	Hit Group Identifier Intersection = cloudIntersection Any hit = cloudAny Closest hit = null	RootDescriptor constantBuffer; *(8 bytes)* RootDescriptor volumeTexture; *(8 bytes)*	16 bytes

Shader Table Indexing

- DispatchRays provides base address and stride for each of:
  - `MissShaderTable`
  - `HitGroupTable`
  - `CallableShaderTable`
- TraceRay intrinsic parameters:
  - `RayContributionToHitGroupIndex`
  - `MultiplierForGeometryContributionToHitGroupIndex`
  - `MissShaderIndex`
- Top level acceleration structure provides:
  - `D3D12_RAYTRACING_INSTANCE_DESC.InstanceContributionToHitGroupIndex`

Miss Shader Indexing

MissShaderRecordAddress =

```
start + stride * index
```

where:

- start = `D3D12_DISPATCH_RAYS_DESC.MissShaderTable.StartAddress`
- stride = `D3D12_DISPATCH_RAYS_DESC.MissShaderTable.StrideInBytes`
- index = `MissShaderIndex` (TraceRay parameter)

Hit Group Indexing

HitGroupRecordAddress =

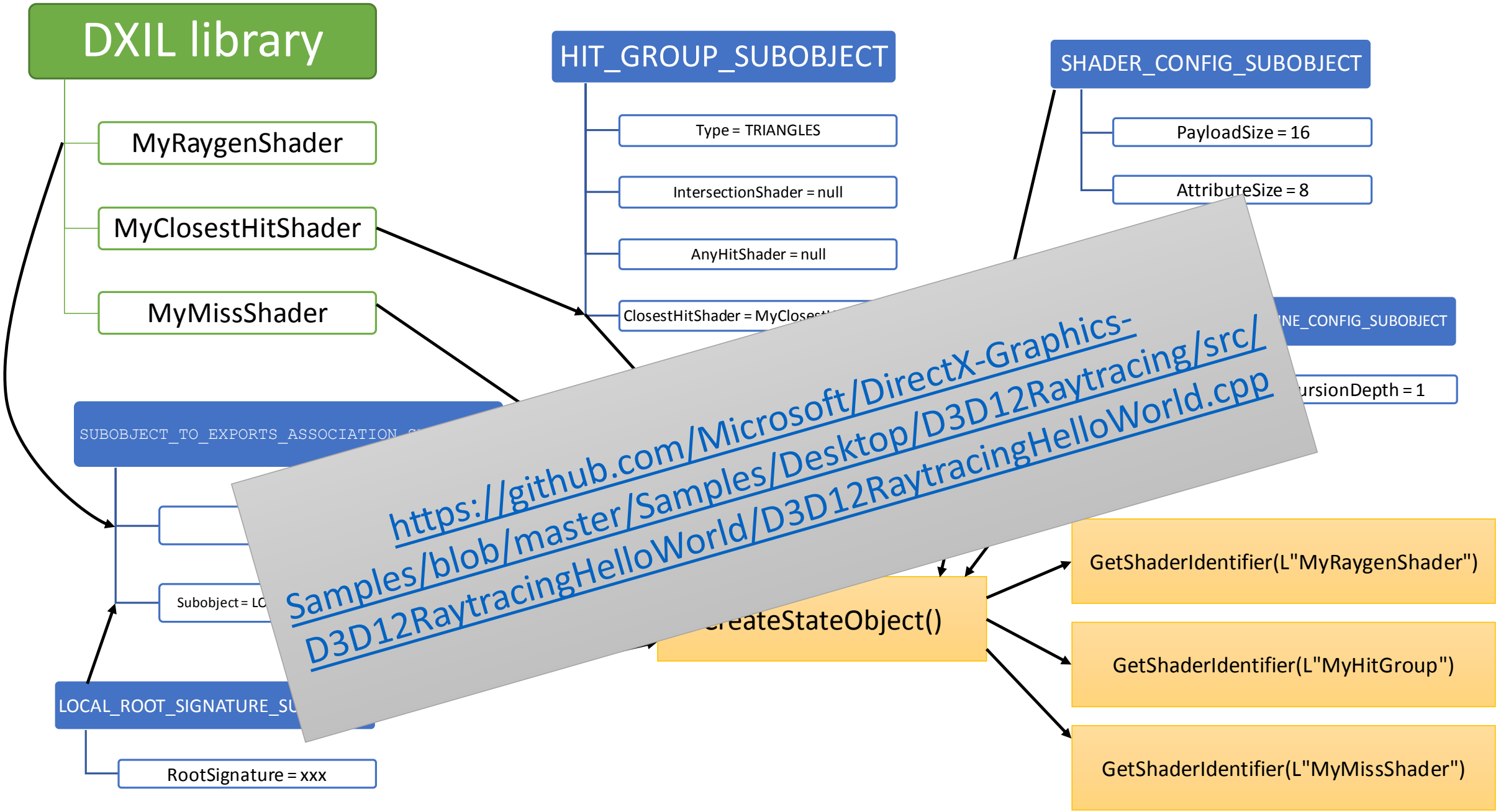
```
start + stride * (rayContribution +
                  (geometryMultiplier * geometryContribution) +
                  instanceContribution)
```

where:

- start = `D3D12_DISPATCH_RAYS_DESC.HitGroupTable.StartAddress`
- stride = `D3D12_DISPATCH_RAYS_DESC.HitGroupTable.StrideInBytes`
- rayContribution = `RayContributionToHitGroupIndex` (TraceRay parameter)
- geometryMultiplier = `MultiplierForGeometryContributionToHitGroupIndex` (TraceRay parameter)
- geometryContribution = index of geometry in bottom-level acceleration structure (0,1,2,3..)
- instanceContribution = `D3D12_RAYTRACING_INSTANCE_DESC.InstanceContributionToHitGroupIndex`

Compile and Link Shaders

- Offline
  - HLSL -> dxc.exe -> DXIL library
- At runtime
  - Load DXIL library code
  - Create subobjects and set associations
  - CreateStateObject(D3D12_STATE_OBJECT_TYPE_RAYTRACING_PIPELINE)
  - Look up shader identifiers


DXIL library
MyRaygenShader
MyClosestHitShader
MyMissShader
HIT_GROUP_SUBOBJECT
Type = TRIANGLES
IntersectionShader = null
AnyHitShader = null
SHADER_CONFIG_SUBOBJECT
PayloadSize = 16
AttributeSize = 8
NE_CONFIG_SUBOBJECT
ursionDepth = 1
SUBOBJECT_TO_EXPORTS_ASSOCIATION
Subobject = LO
LOCAL_ROOT_SIGNATURE_SU
RootSignature = xxx
reateStateObject()
GetShaderIdentifier(L"MyRaygenShader")
GetShaderIdentifier(L"MyHitGroup")
GetShaderIdentifier(L"MyMissShader")
https://github.com/Microsoft/DirectX-Graphics-Samples/blob/master/Samples/Desktop/D3D12Raytracing/src/D3D12RaytracingHelloWorld/D3D12RaytracingHelloWorld.cpp

DispatchRays()

Making It Happen

```
void DispatchRays(D3D12_DISPATCH_RAYS_DESC* pDesc);


struct D3D12_DISPATCH_RAYS_DESC
{
    D3D12_GPU_VIRTUAL_ADDRESS_RANGE RayGenerationShaderRecord;
    D3D12_GPU_VIRTUAL_ADDRESS_RANGE_AND_STRIDE MissShaderTable;
    D3D12_GPU_VIRTUAL_ADDRESS_RANGE_AND_STRIDE HitGroupTable;
    D3D12_GPU_VIRTUAL_ADDRESS_RANGE_AND_STRIDE CallableShaderTable;
    UINT Width;
    UINT Height;
    UINT Depth;
};


struct D3D12_GPU_VIRTUAL_ADDRESS_RANGE
{
    D3D12_GPU_VIRTUAL_ADDRESS StartAddress;
    UINT64                    SizeInBytes;
};

struct D3D12_GPU_VIRTUAL_ADDRESS_RANGE_AND_STRIDE
{
    D3D12_GPU_VIRTUAL_ADDRESS StartAddress;
    UINT64                    SizeInBytes;
    UINT64                    StrideInBytes;
};
```

Other Things You Should Know

Can haz plz? (for developers)

Experimental Preview	• Requires Windows 10 April 2018 update with suitable hardware and drivers • Minor differences from final design • http://forums.directxtech.com/index.php?topic=5860.0
Official Release	• Coming in the next version of Windows (RS5)
Raytracing Fallback Layer	• https://github.com/Microsoft/DirectX-Graphics-Samples/tree/master/Libraries/D3D12RaytracingFallback
Sample code	• https://github.com/Microsoft/DirectX-Graphics-Samples/blob/master/Samples/Desktop/D3D12Raytracing/readme.md

Can haz plz? (runtime check)

```
D3D12_FEATURE_DATA_D3D12_OPTIONS5 featureData{};

if (SUCCEEDED(CheckFeatureSupport(D3D12_FEATURE_D3D12_OPTIONS5, &featureData, sizeof(featureData))))
{
    if (featureData.RaytracingTier >= D3D12_RAYTRACING_TIER_1_0)
    {
        ...
    }
}
```

Raytracing Fallback Layer

Emulates the DXR API via compute shaders

- Runs on systems without native DXR driver support
- Requires Win10 Fall Creators Update (2017) and a GPU with retail DXIL capability

Standalone static lib

Redirects to the real DXR implementation if driver support exists

Good way to get started, but limited substitute for a DXR driver in terms of performance

Fallback Layer – Emulated GPU Pointers

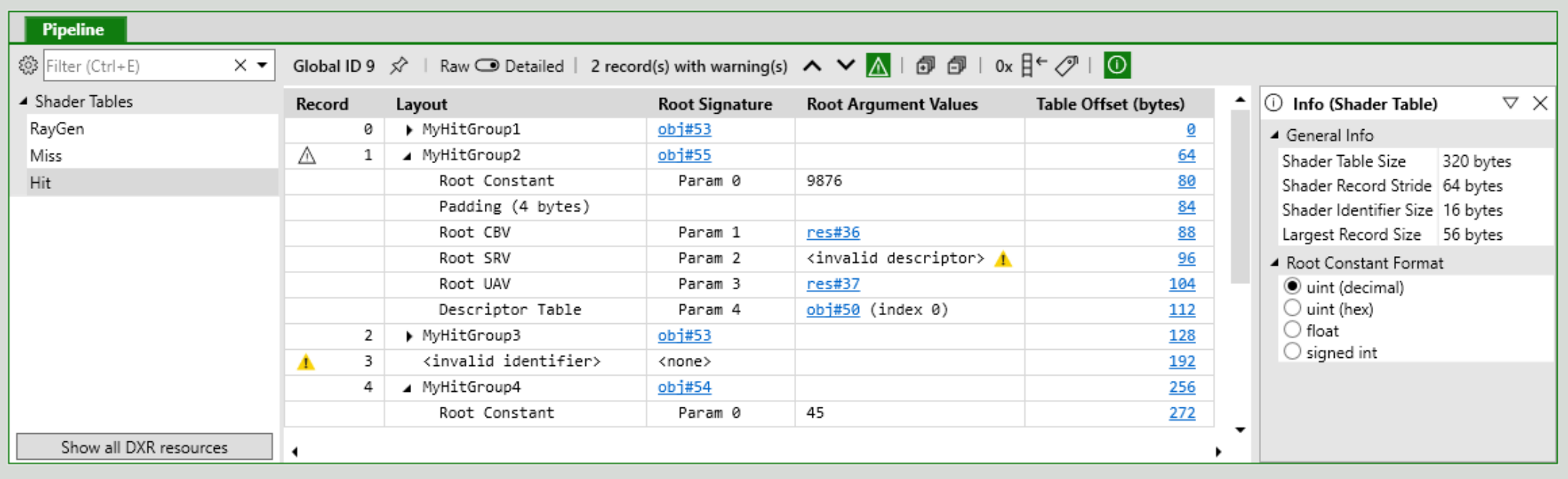
- Compute shaders do not support raw GPU memory pointers
- But the BuildRaytracingAccelerationStructure input structures are full of pointers…
- Emulated GPU Pointers replace a GPU VA with descriptor heap index and byte offset pair
- Apps must create views around memory they will access for raytracing

```
UINT descriptorHeapIndex = 0;

if (!fallbackDevice->UsingRaytracingDriver())
{
    D3D12_CPU_DESCRIPTOR_HANDLE descriptorHeapHandle;
    descriptorHeapIndex = AllocateDescriptor(&descriptorHeapHandle);
    device->CreateUnorderedAccessView(resource, nullptr, desc,
                                      descriptorHeapHandle);
}

WRAPPED_GPU_POINTER ptr = fallbackDevice->GetWrappedPointerSimple(
                                      descriptorHeapIndex,
                                      resource->GetGPUVirtualAddress());
```

Debugging DXR – http://blogs.msdn.com/pix



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