Real-Time Rendering

186.140, 2021W, VU, 4.5ECTS

Vulkan Lecture Series, Episode 6:

Real-Time Ray Tracing

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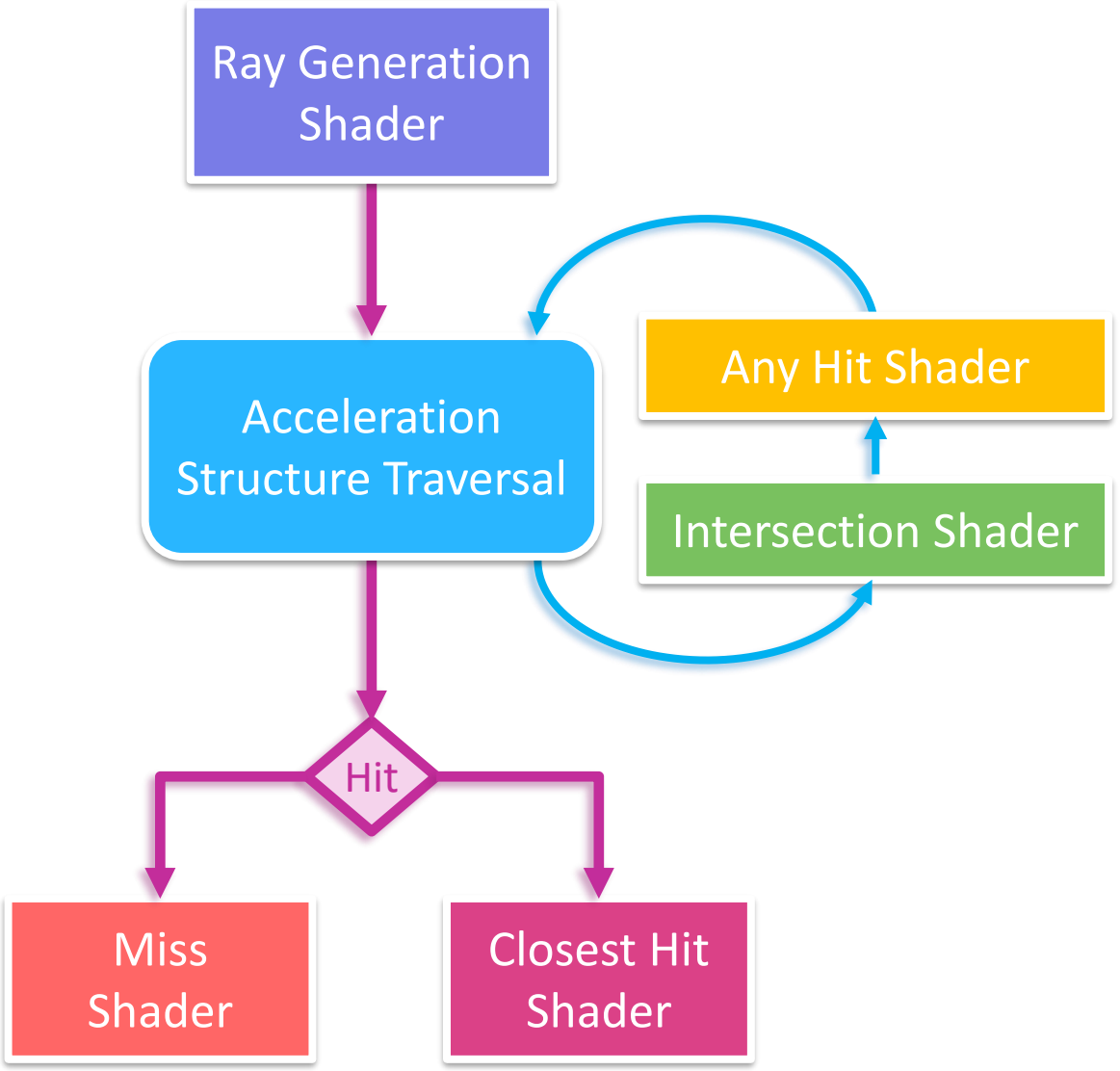
Institute of Visual Computing & Human-Centered Technology

TU Wien, Austria

Ray Tracing Pipeline



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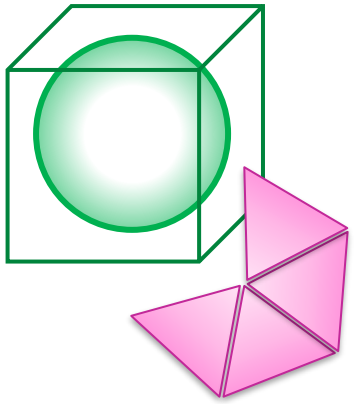

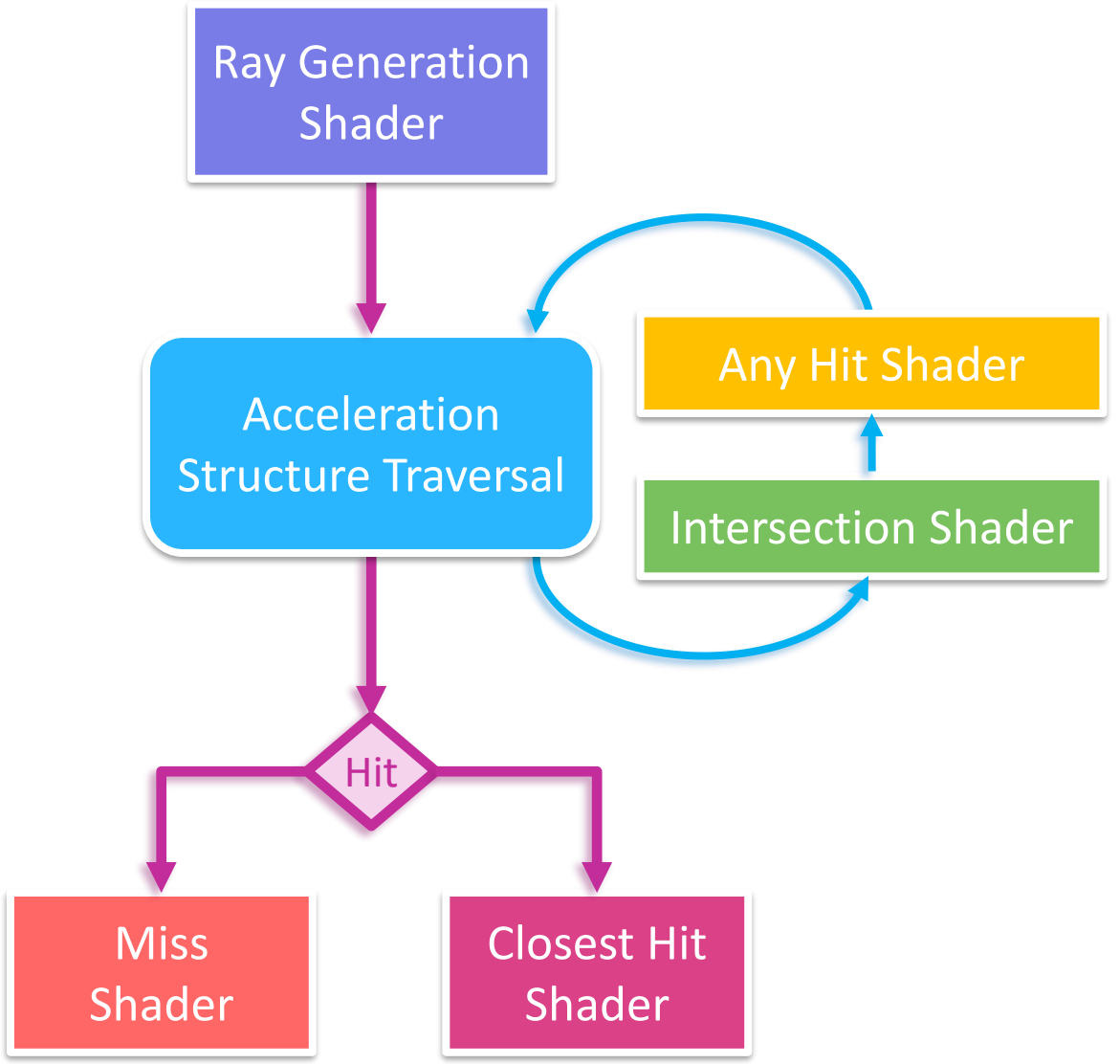

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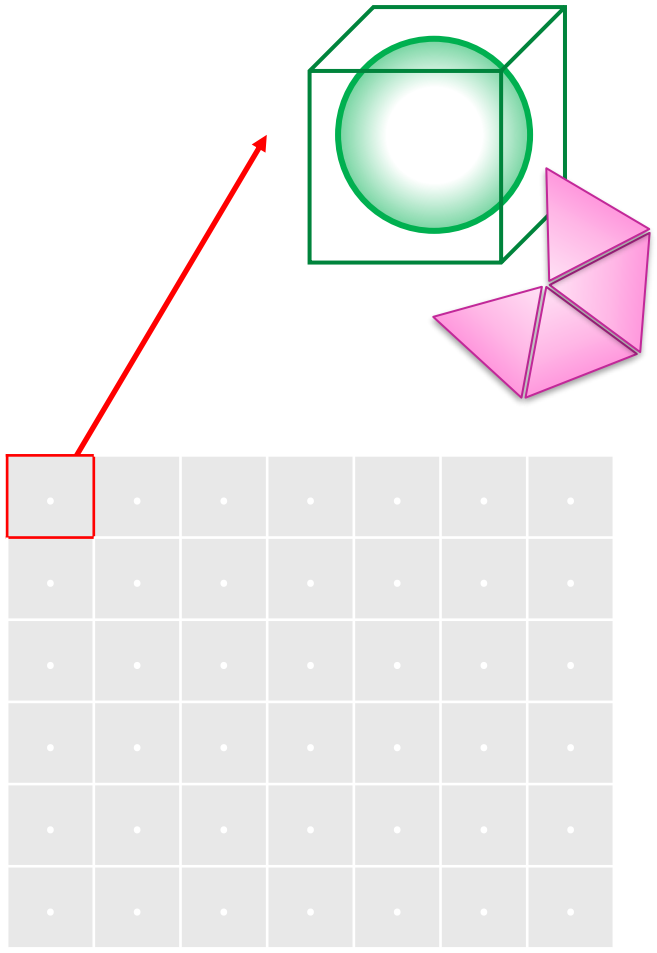

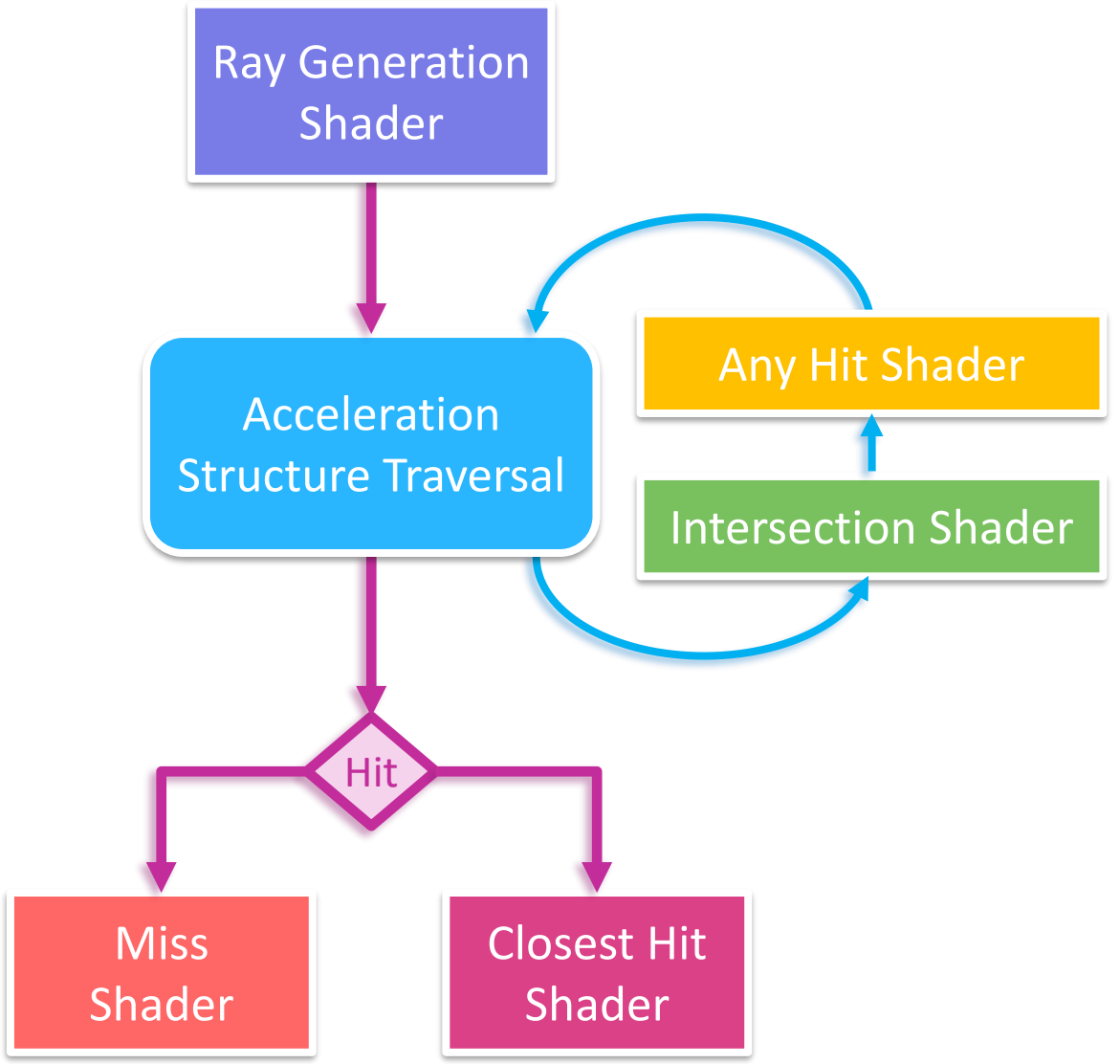

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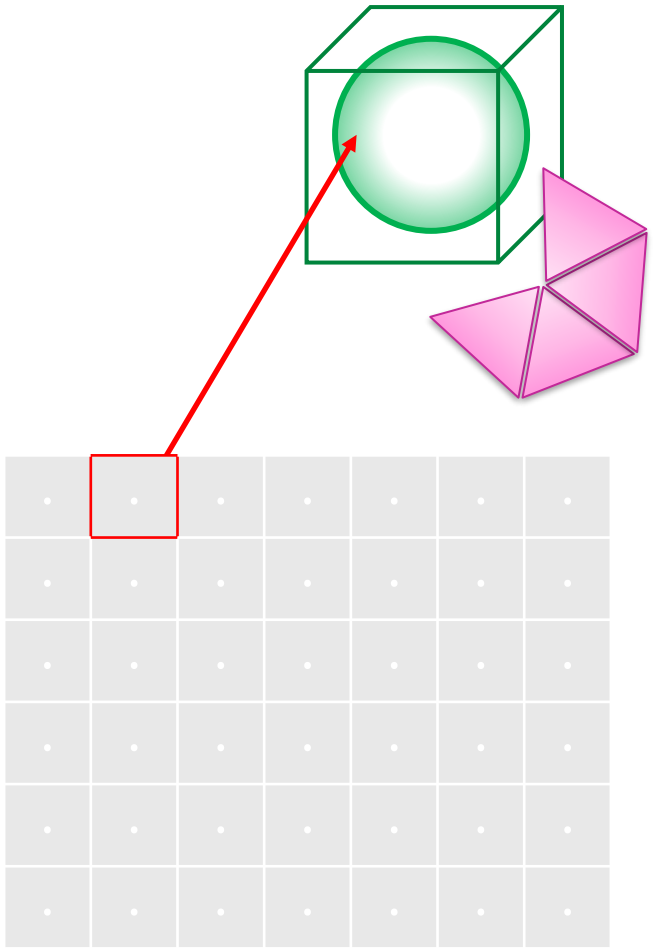

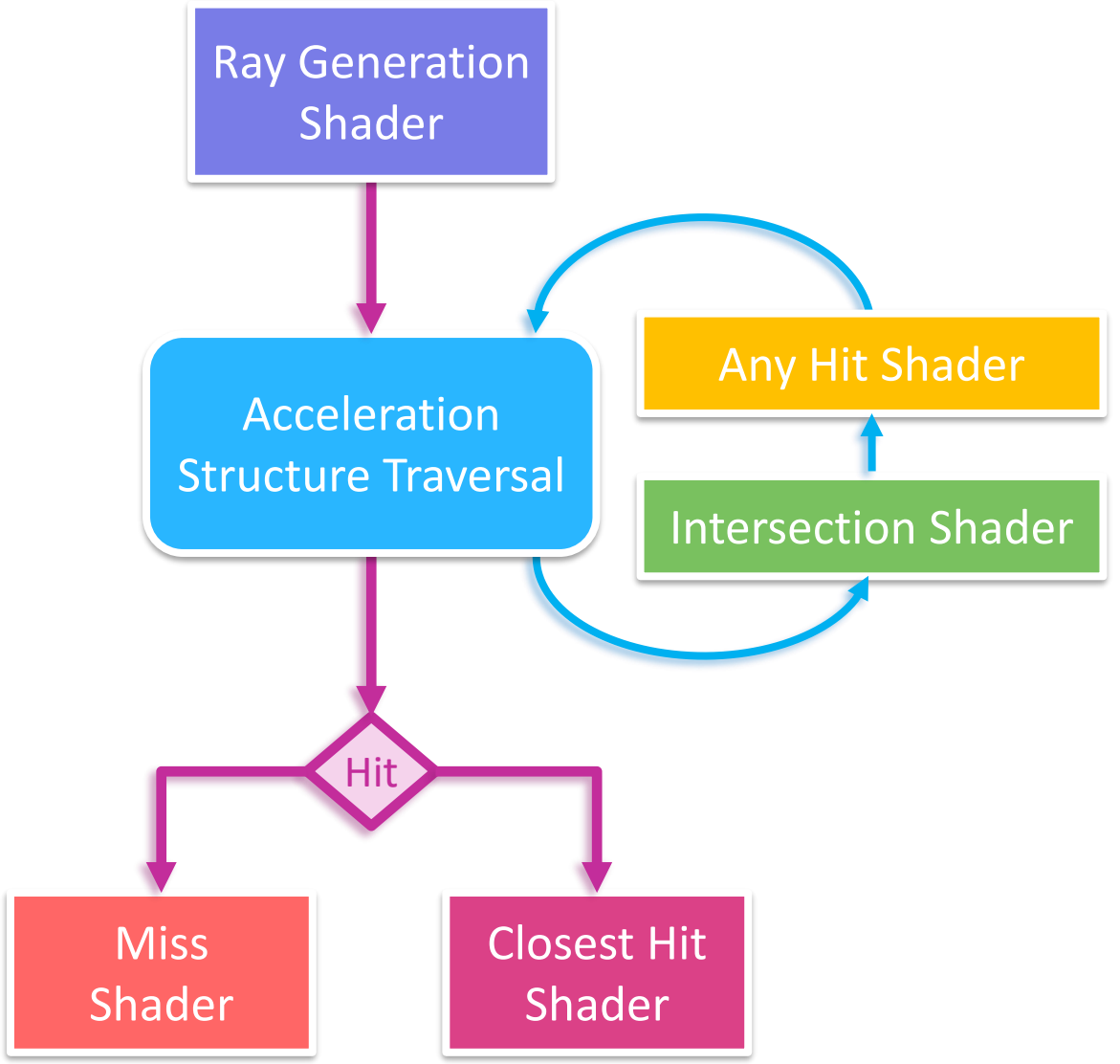

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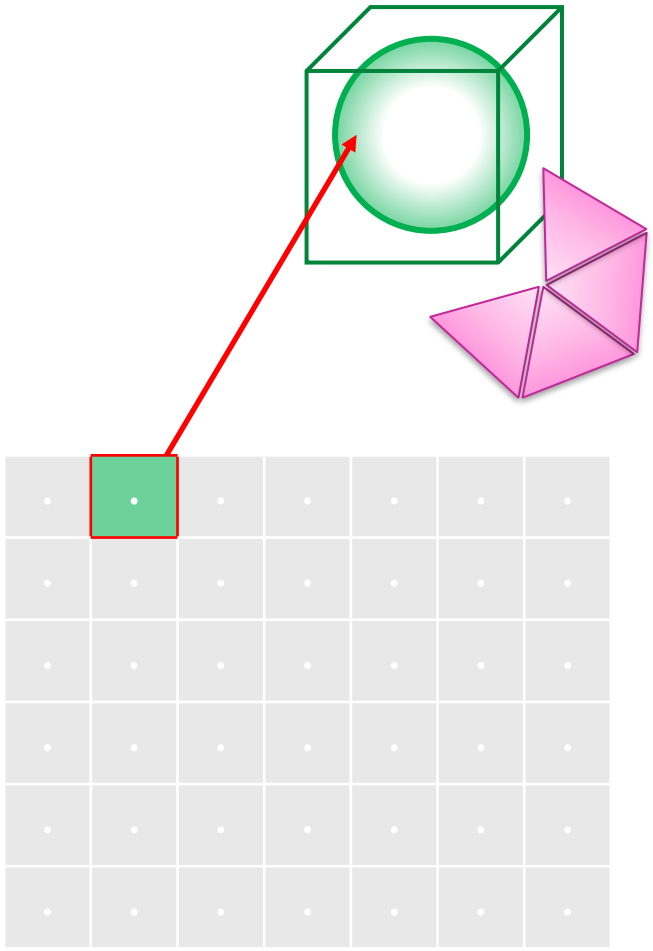

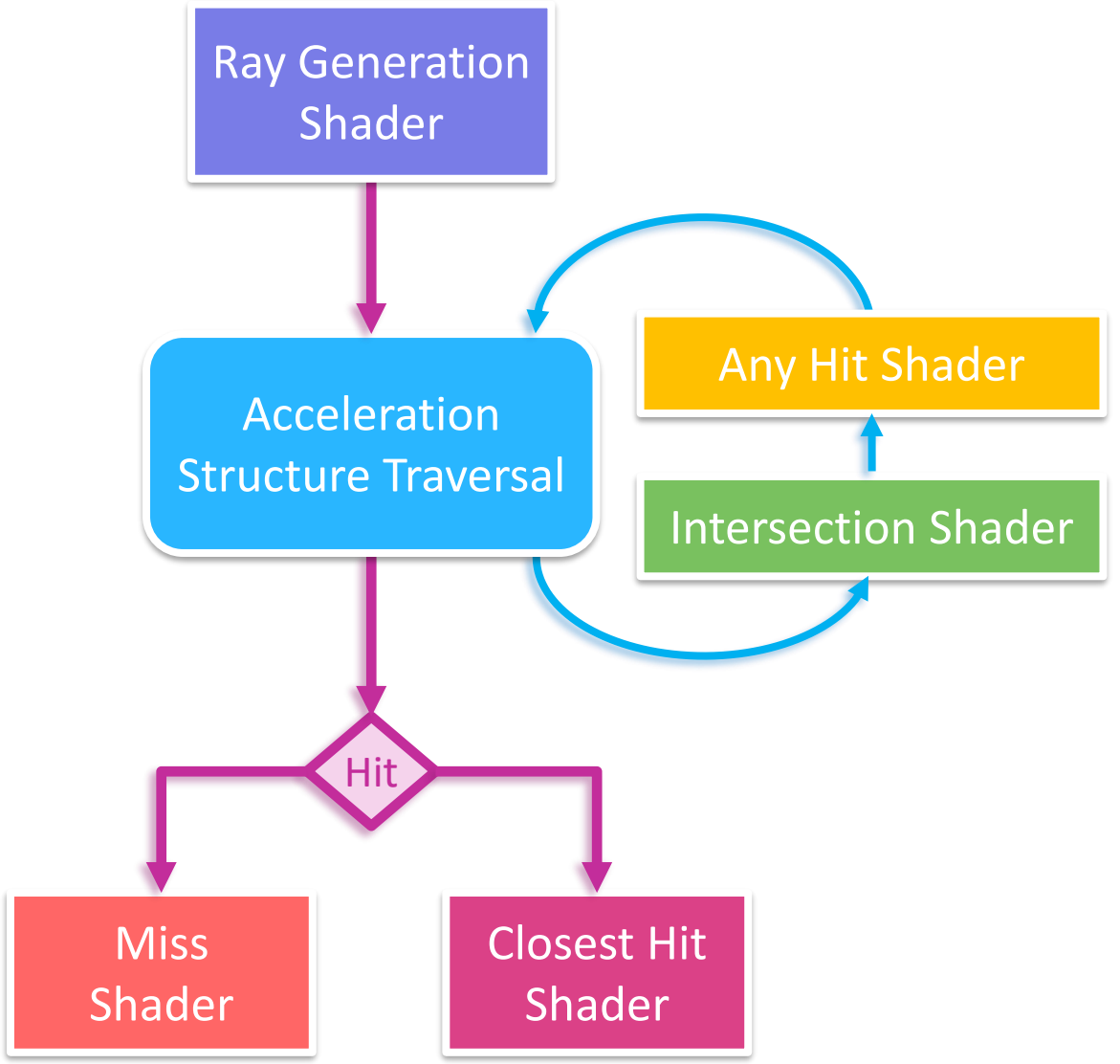

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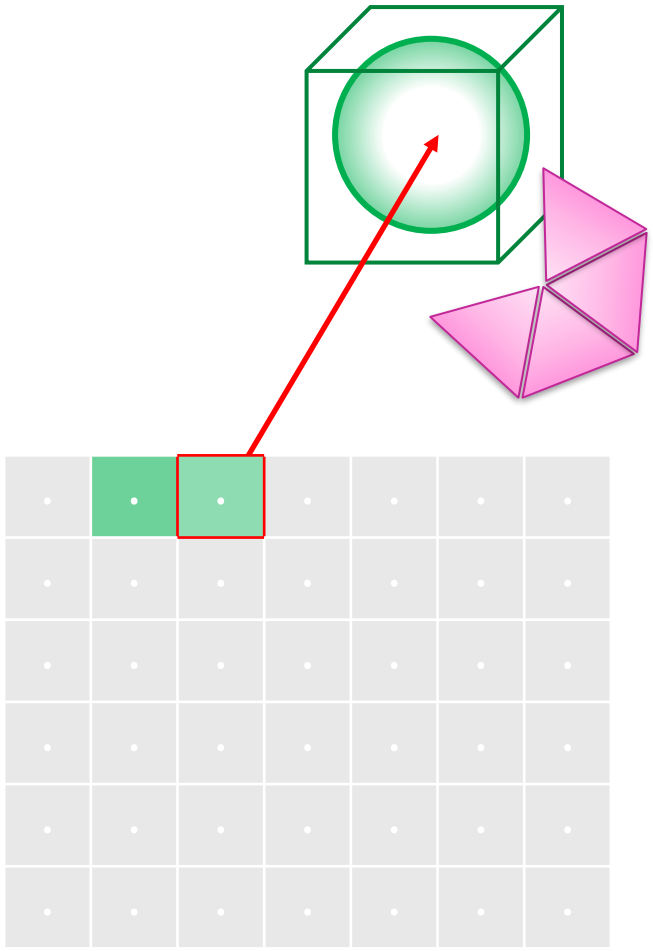

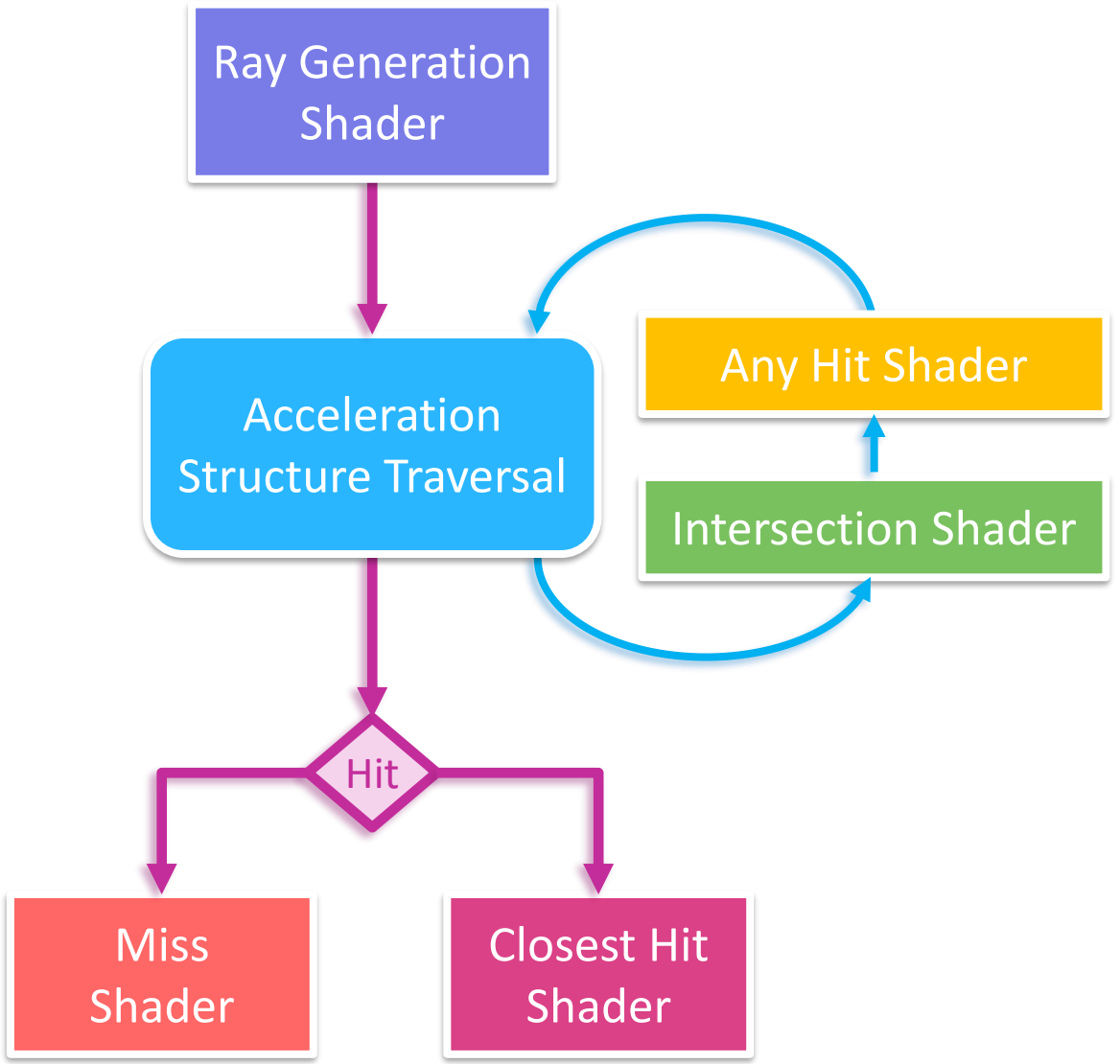

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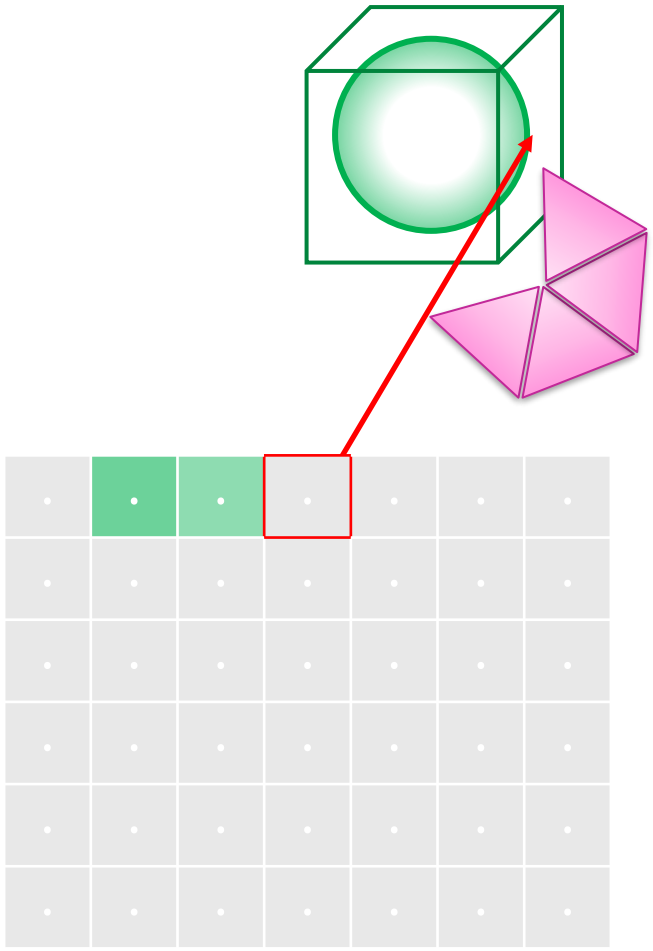

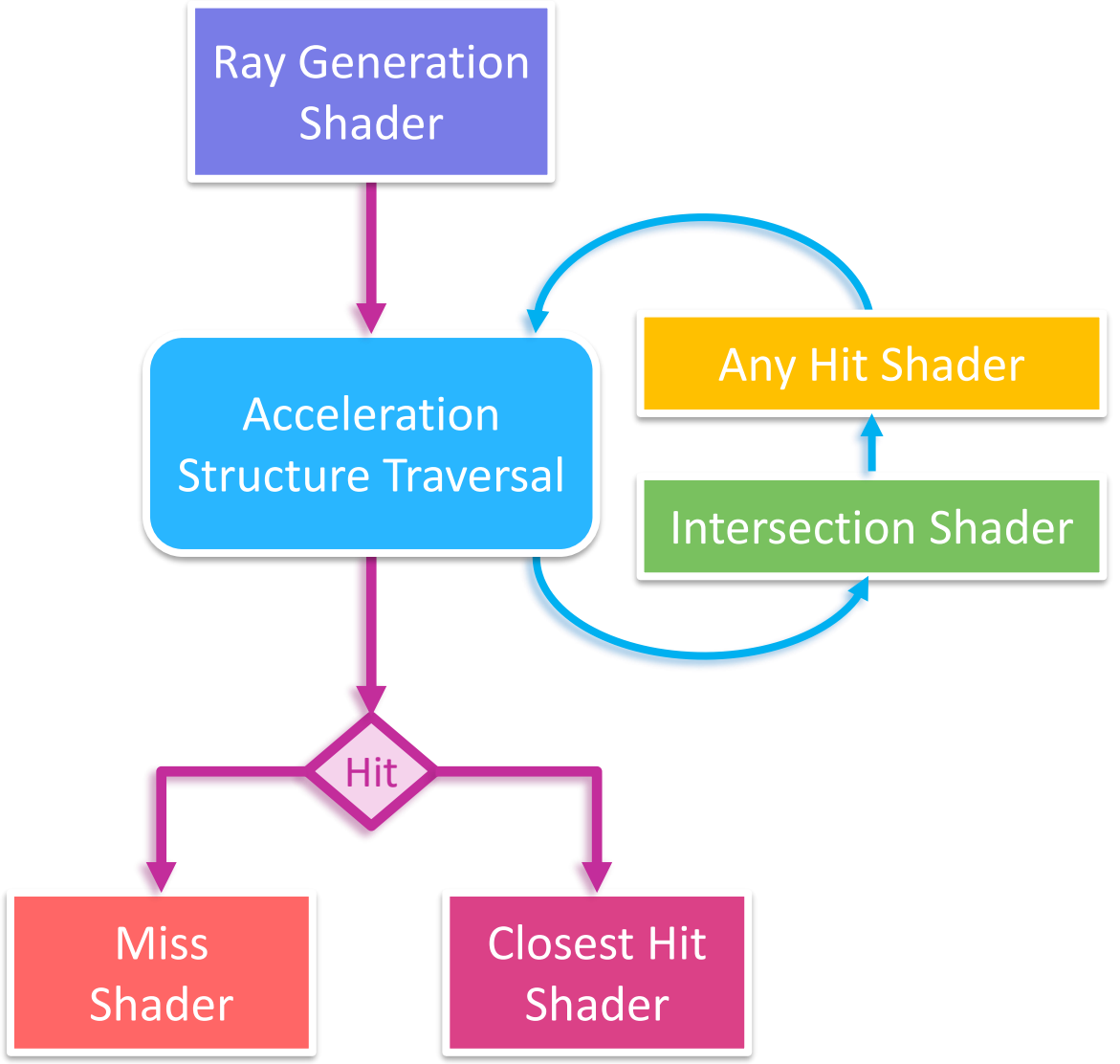

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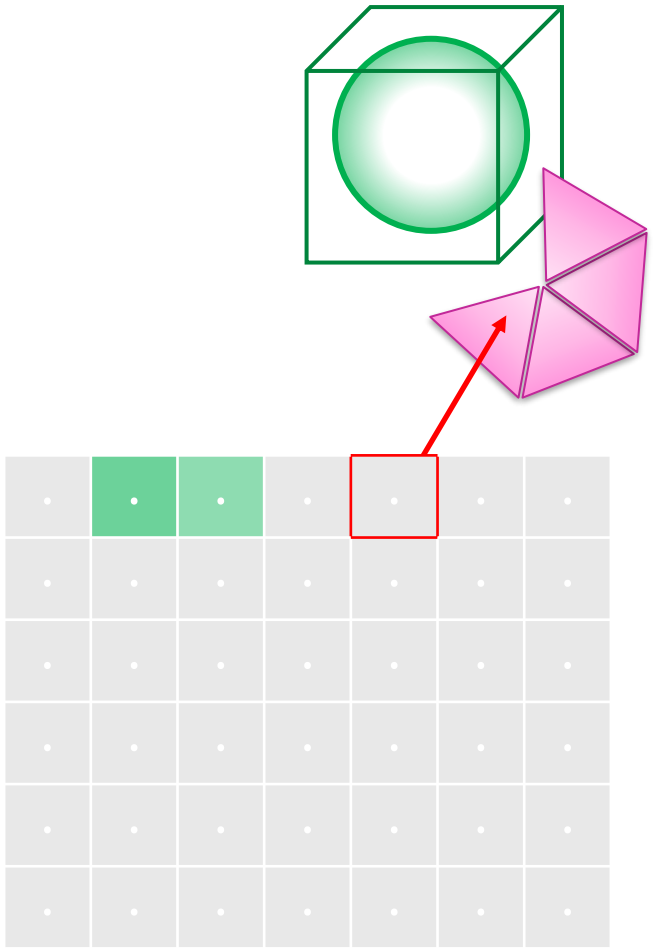

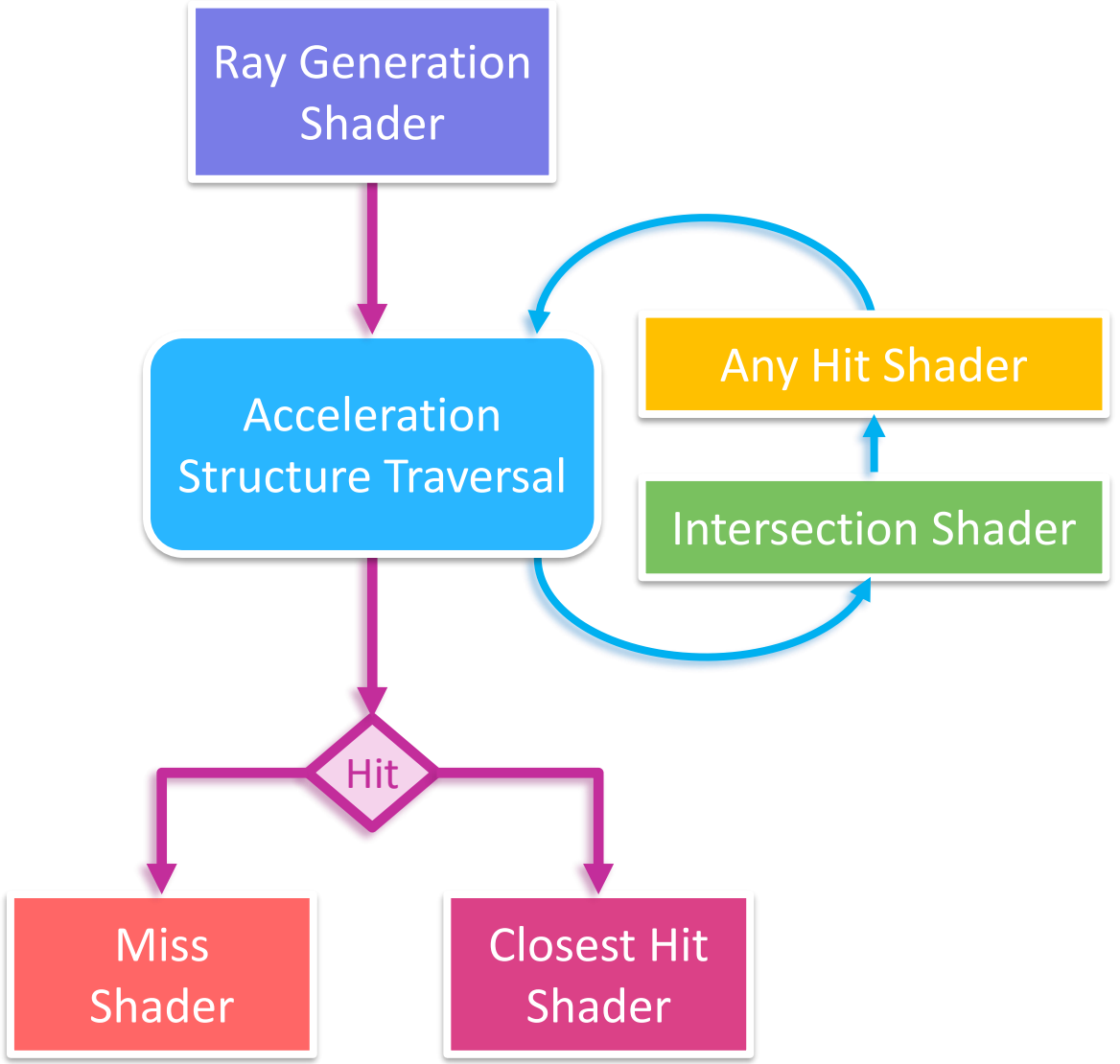

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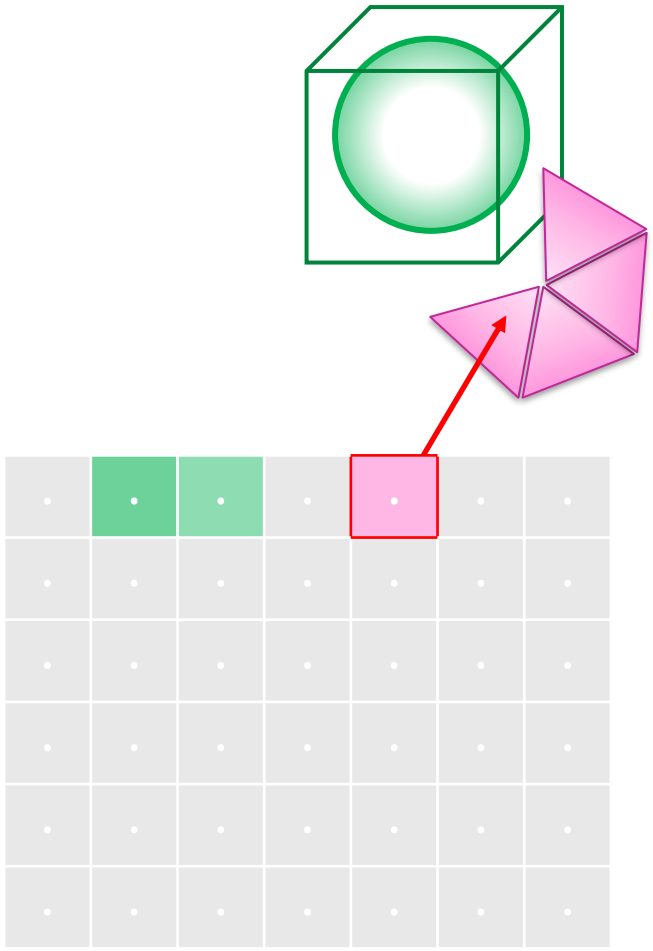

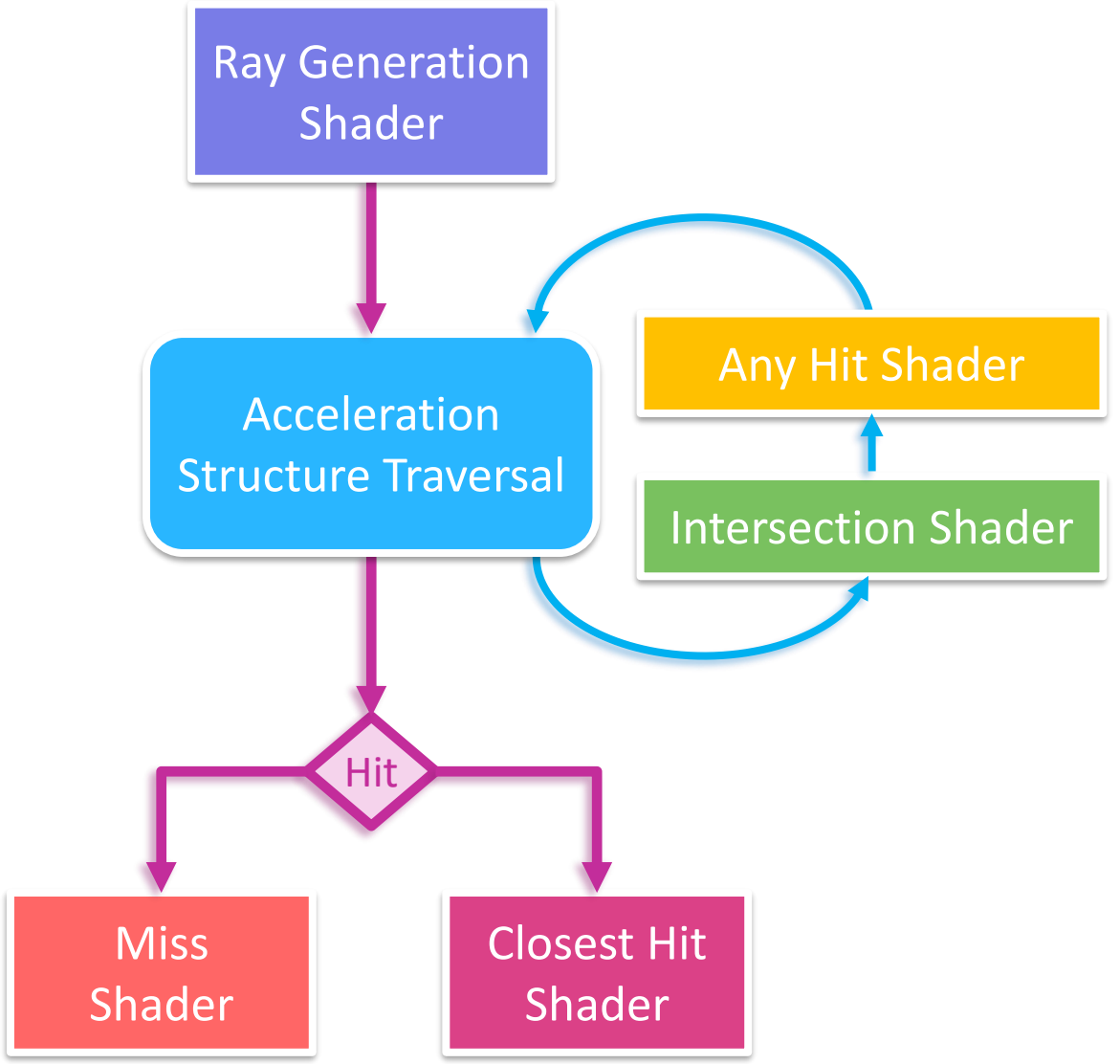

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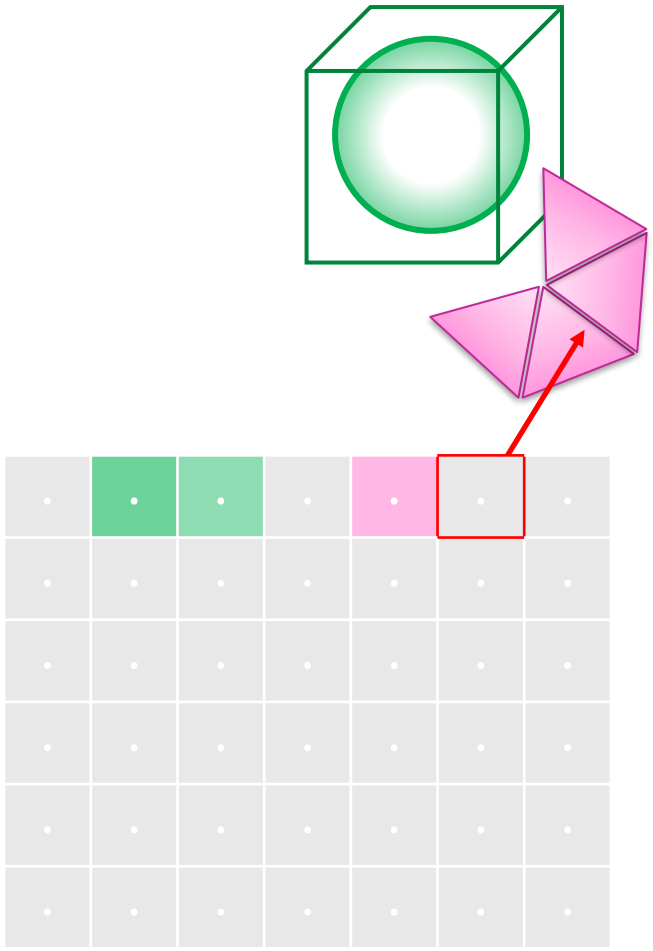

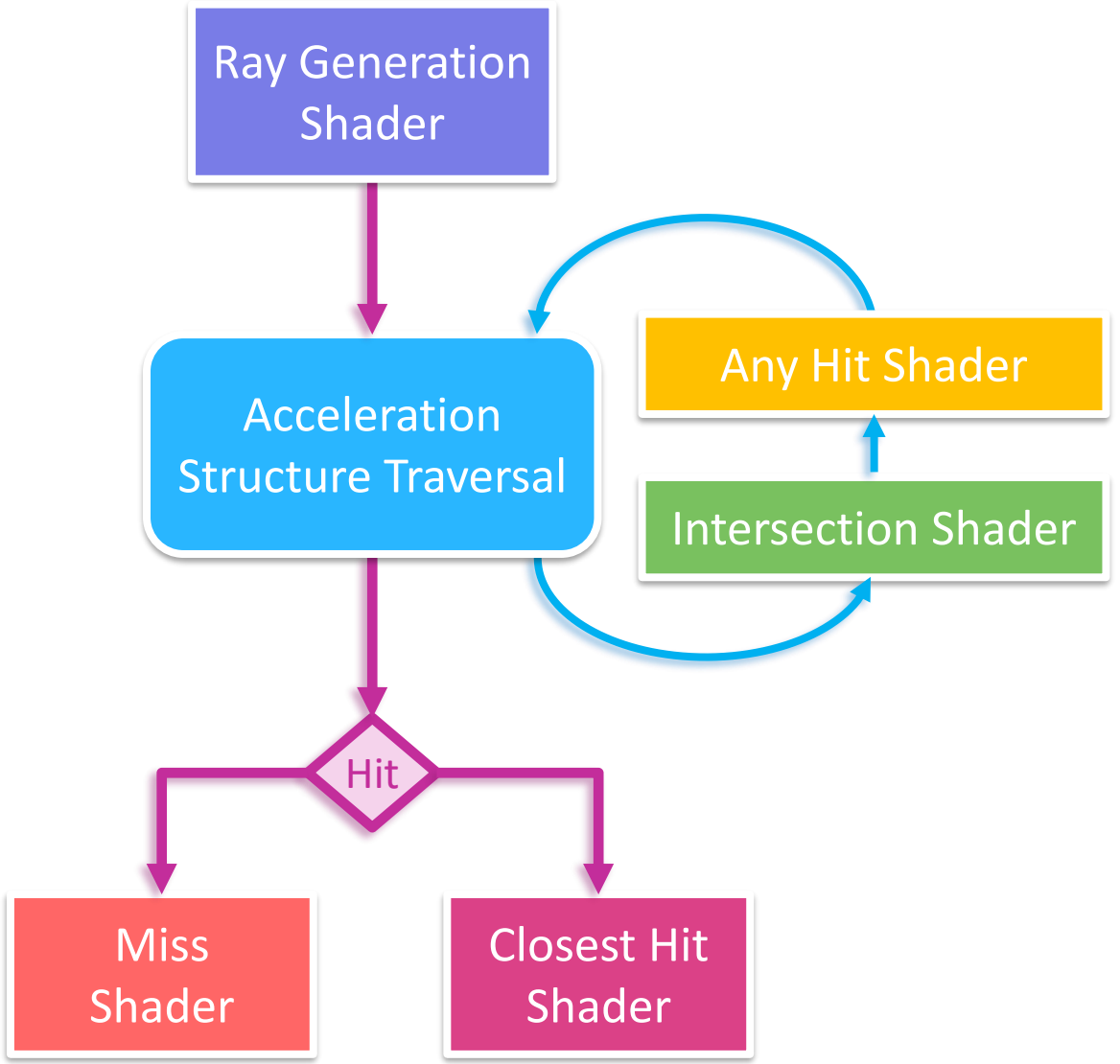

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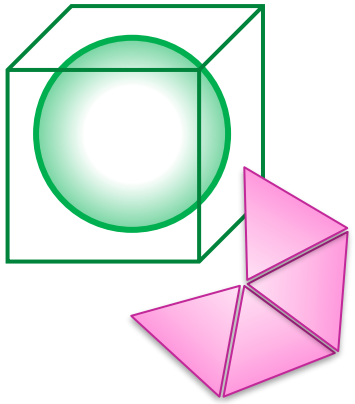

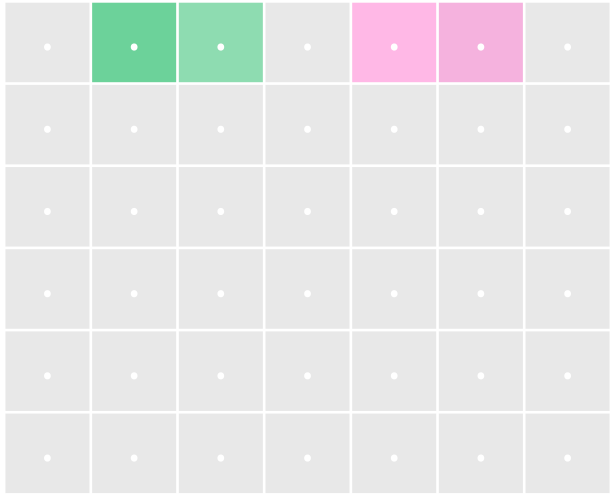

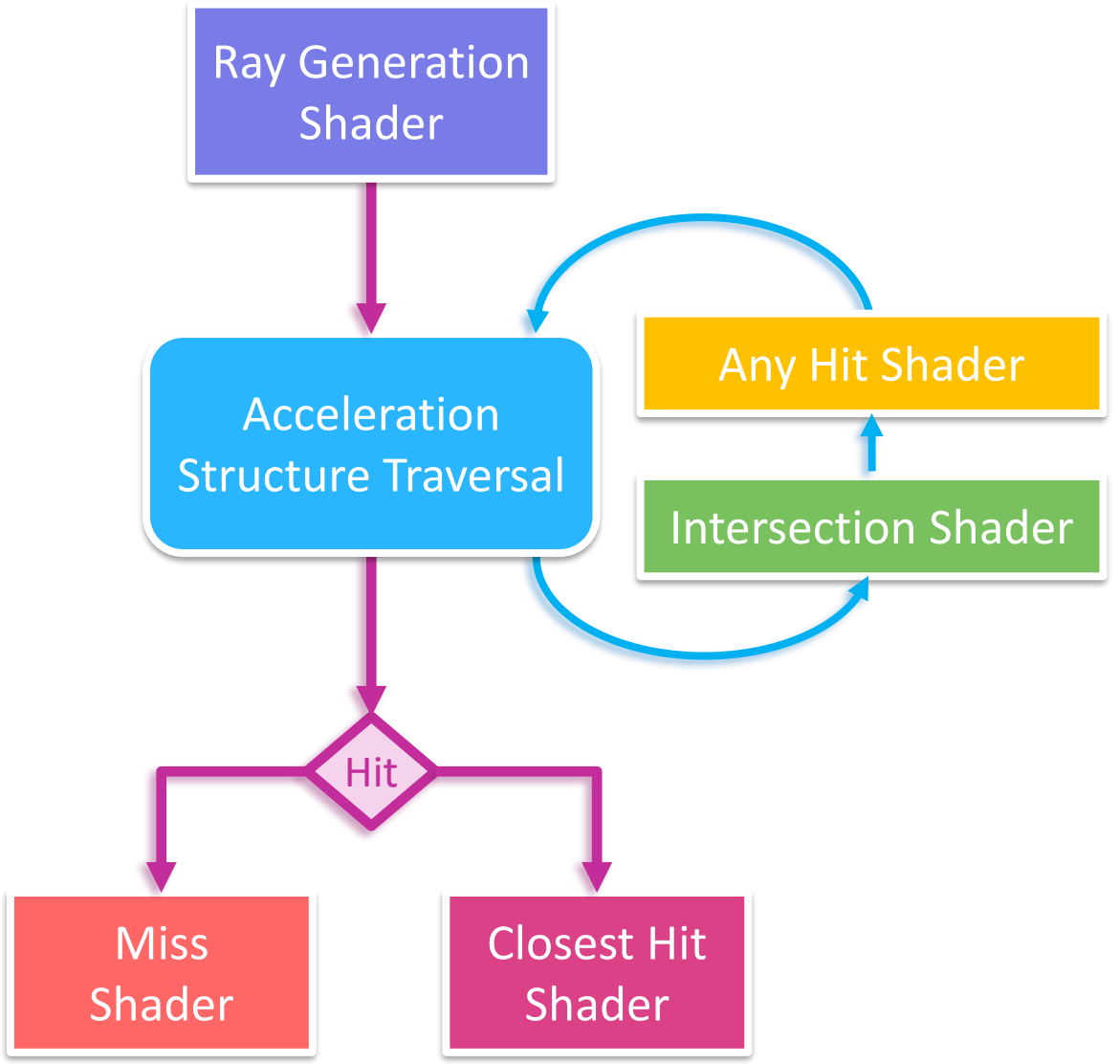

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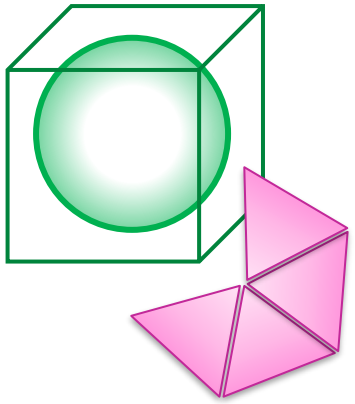

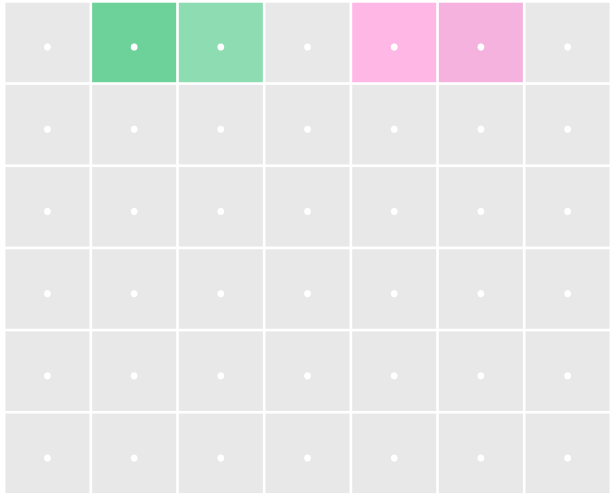

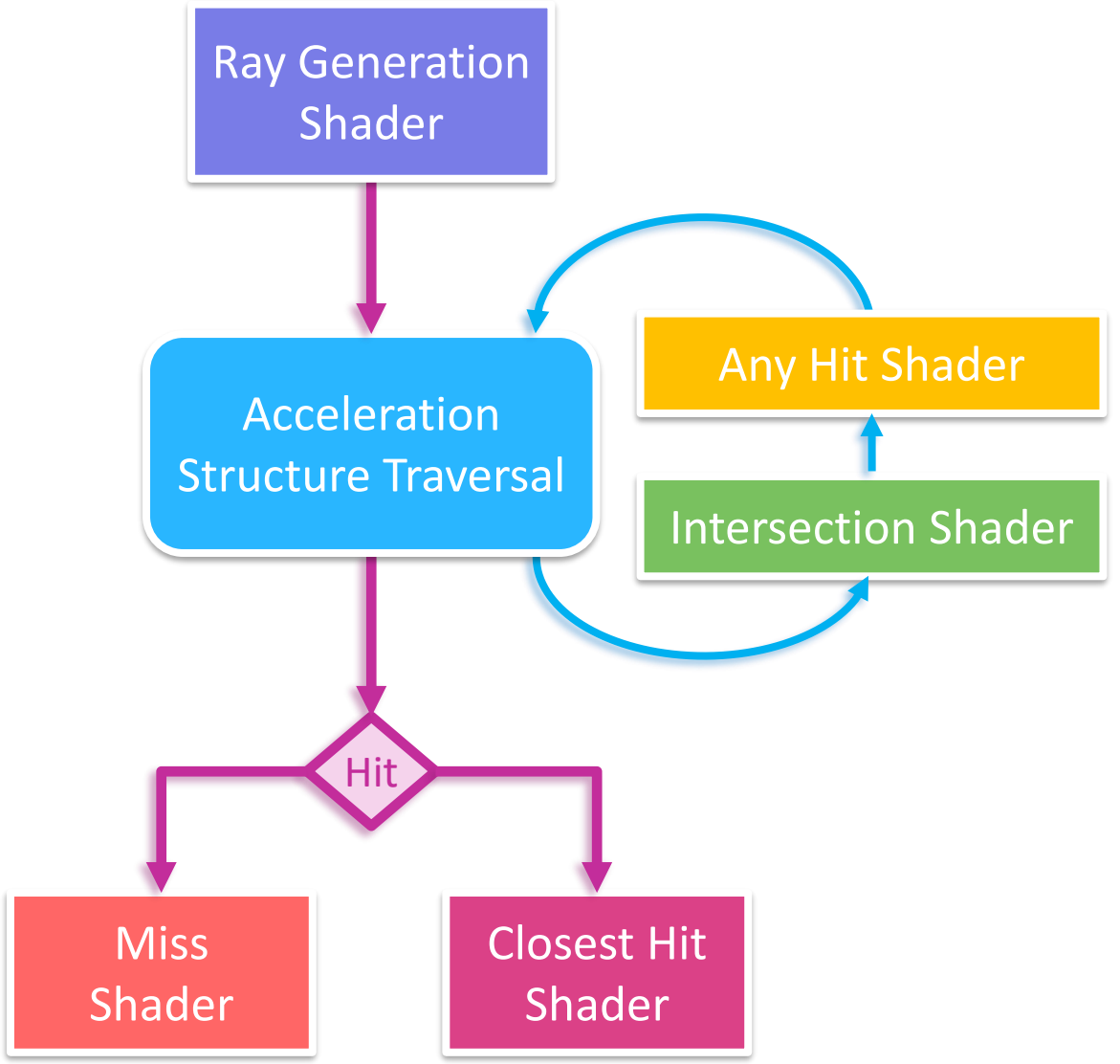

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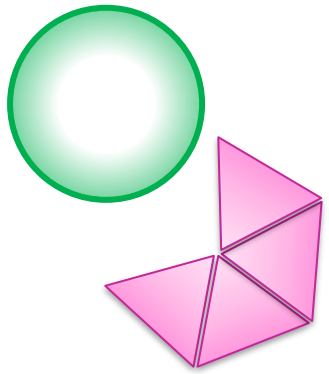
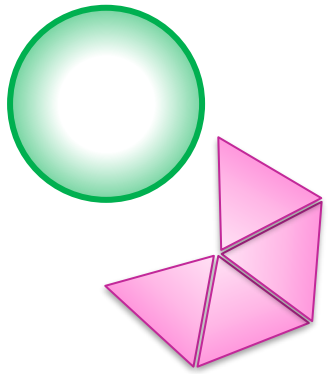


Acceleration Structure Traversal

Acceleration Structures

Acceleration Structures



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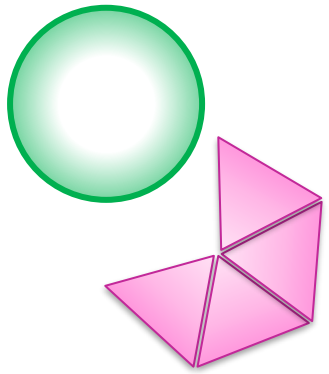
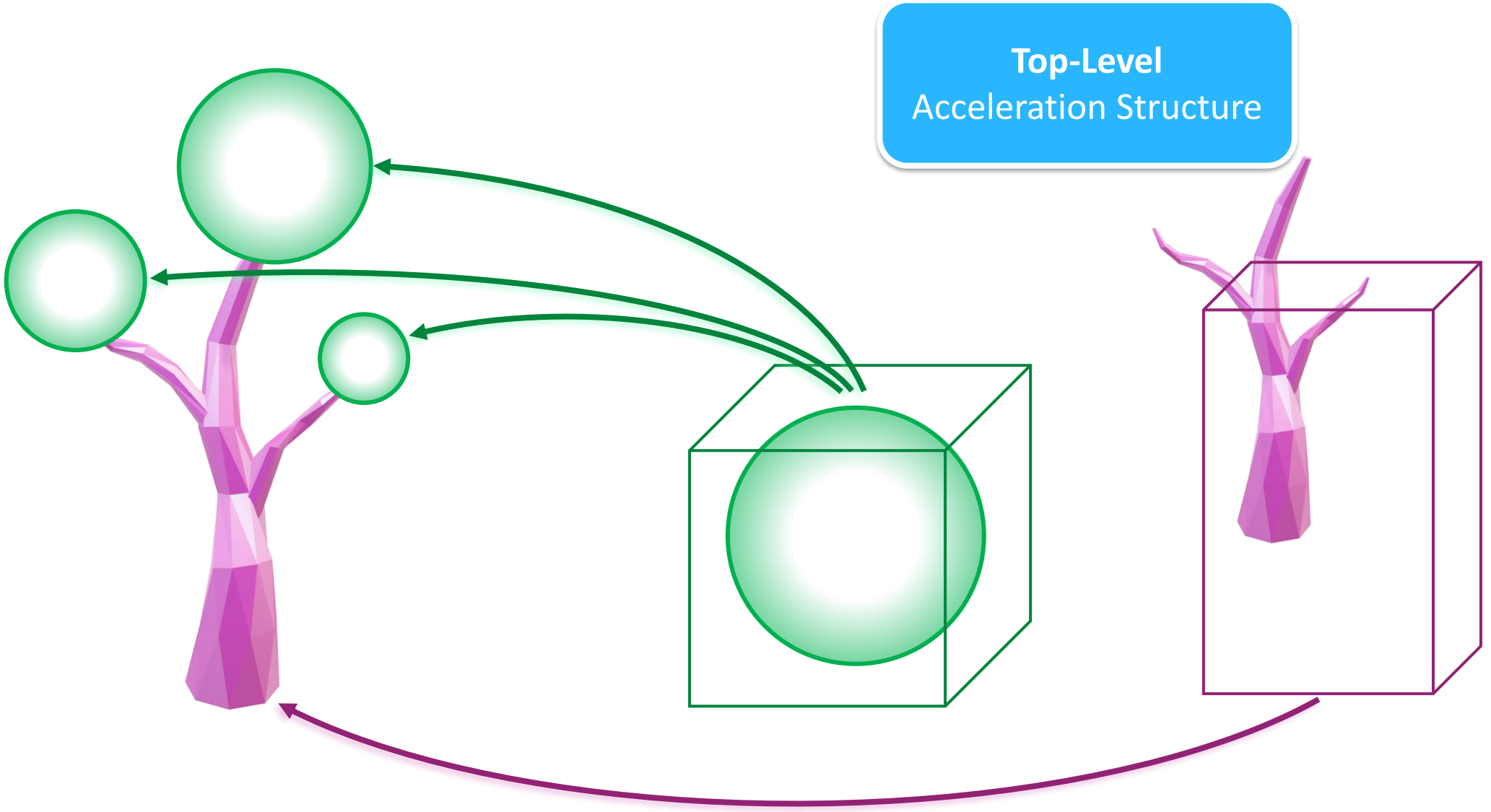


Top-Level
Acceleration Structure

Acceleration Structures



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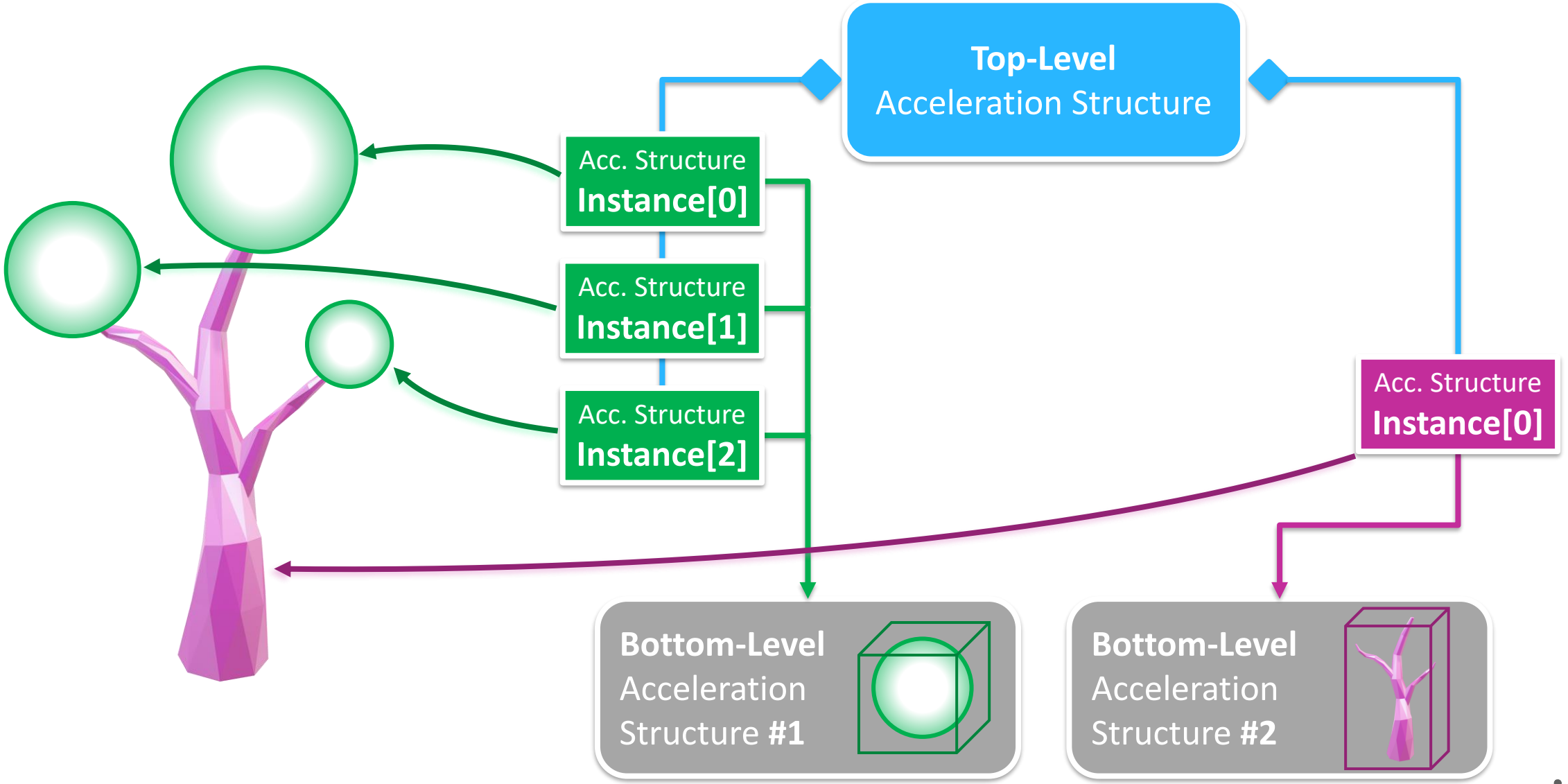

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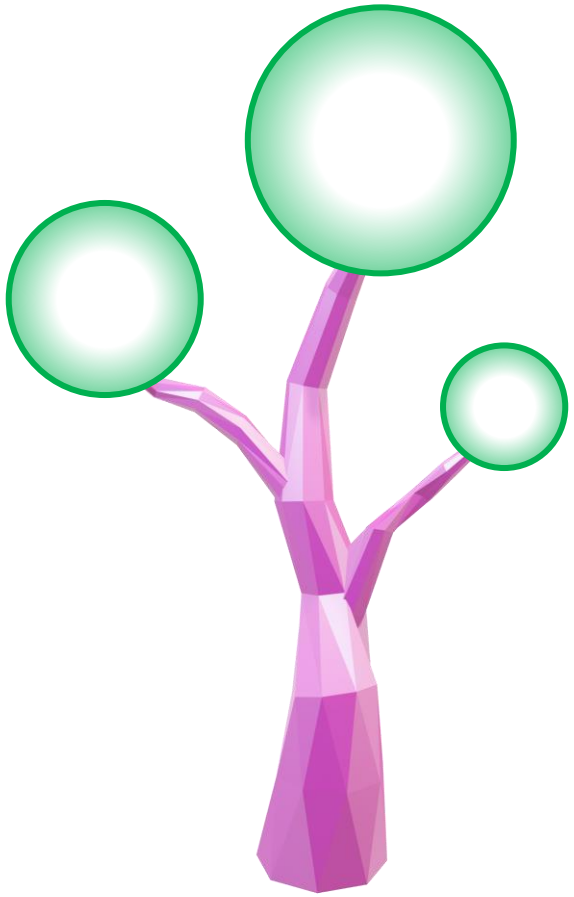


Top-Level
Acceleration Structure

Acc. Structure
Instance[0]

Acc. Structure
Instance[1]

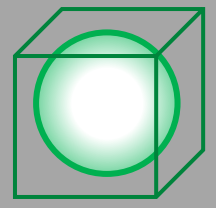
Acc. Structure
Instance[2]

Data per Instance

- Transformation Matrix
- Mask (include or exclude from tracing, e.g.: shadow pass)
- Flags (e.g.: winding order, back face culling on/off)
- Offset (for shader selection)
- Instance Custom Index (accessible in shaders)

Acc. Structure
Instance[0]

Bottom-Level
Acceleration
Structure **#1**



Bottom-Level
Acceleration
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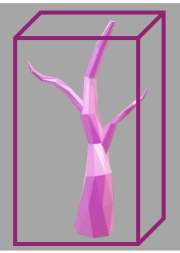
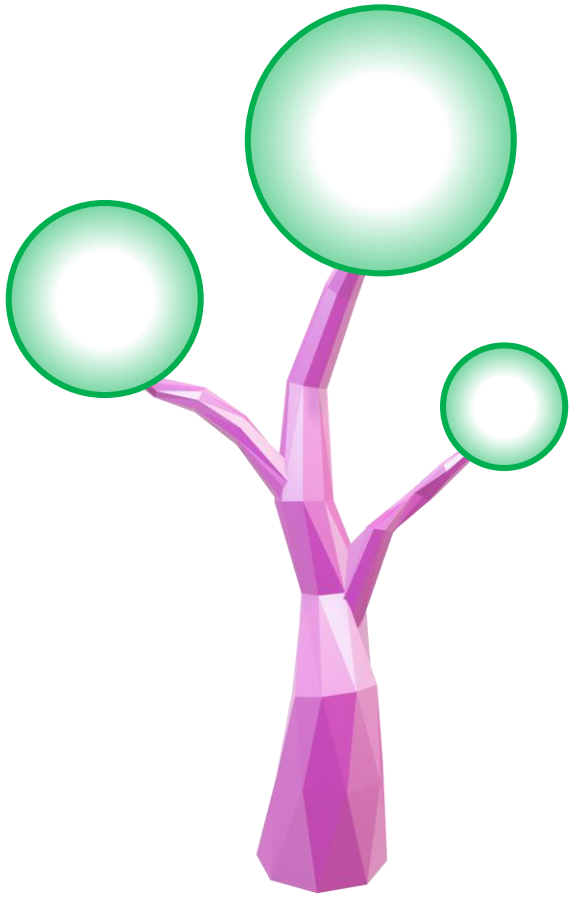


Acceleration Structures



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Acceleration
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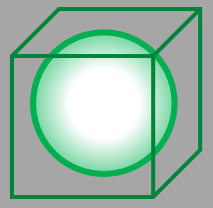

Bottom-Level
Acceleration
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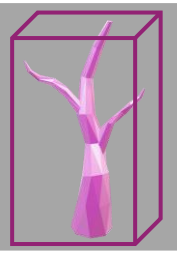

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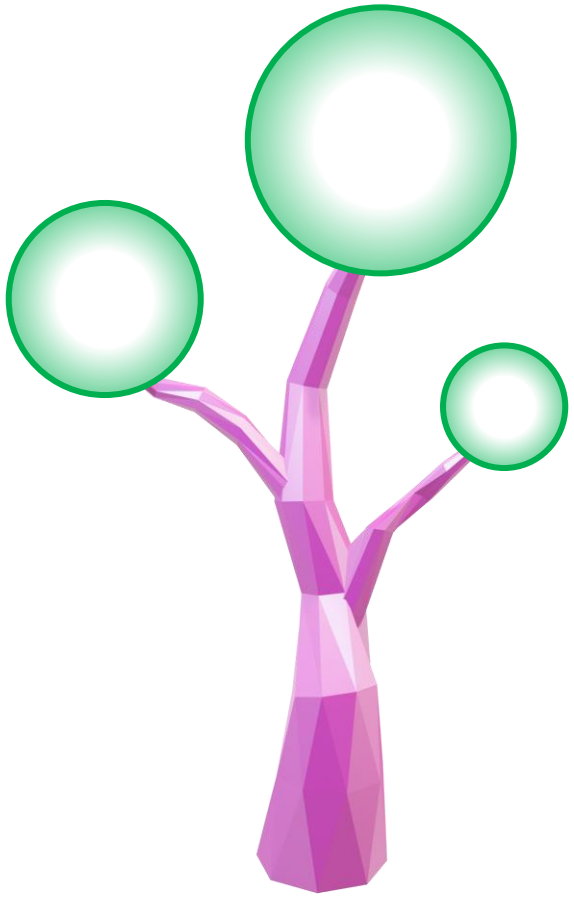

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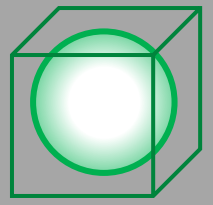

Bottom-Level
Acceleration
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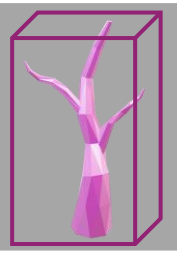

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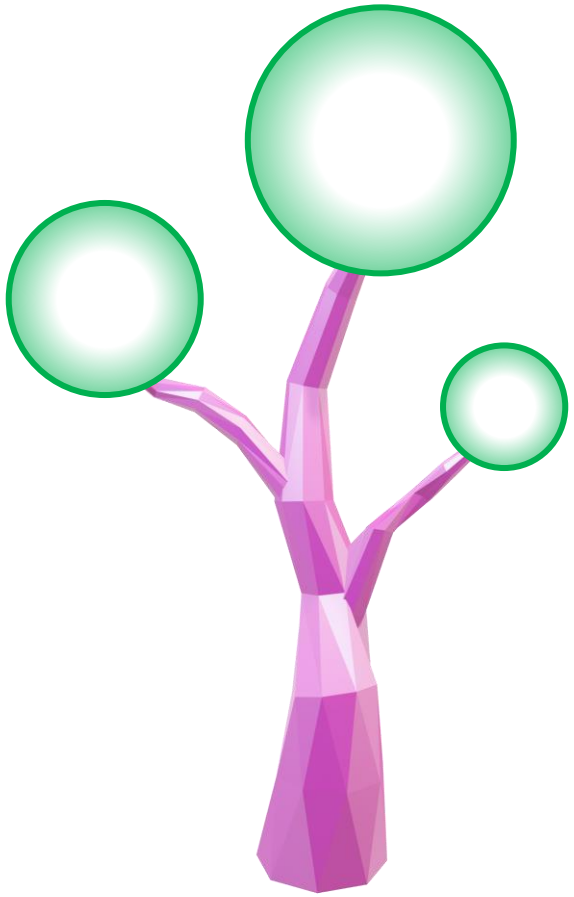

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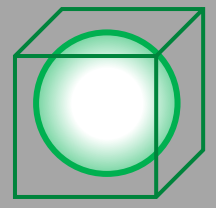

Bottom-Level
Acceleration
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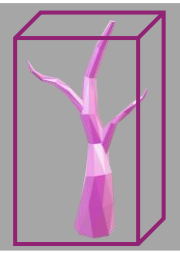

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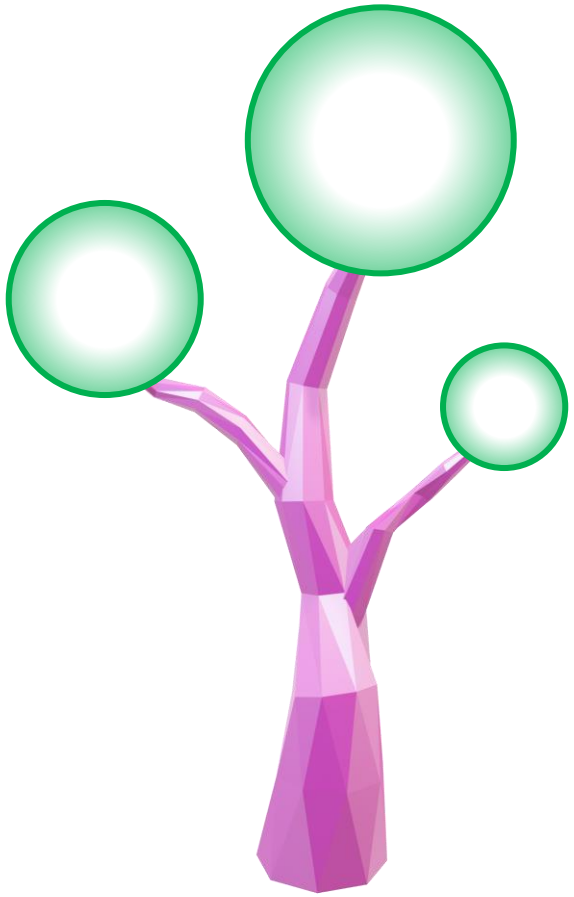

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Acceleration
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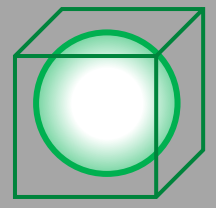

Bottom-Level
Acceleration
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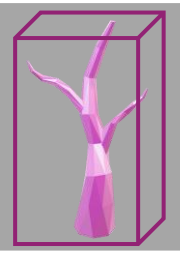

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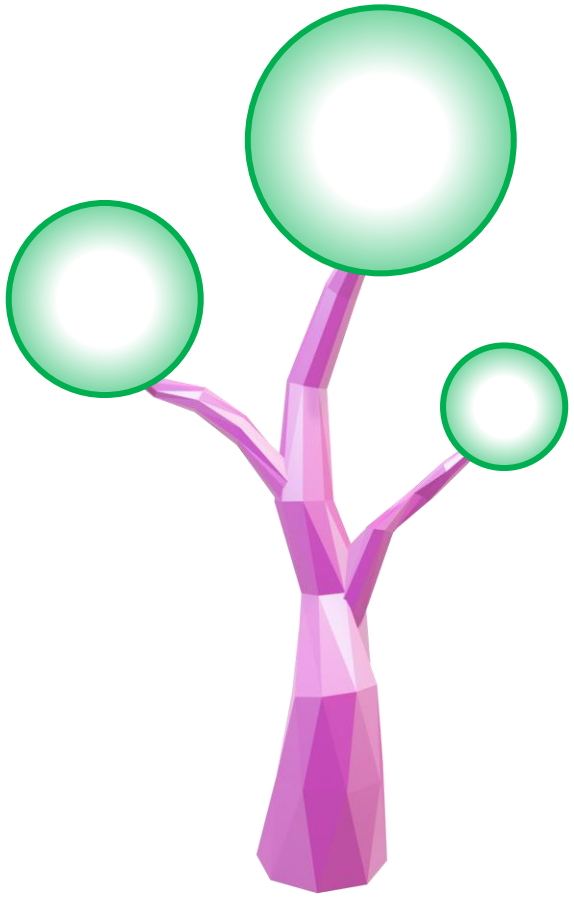

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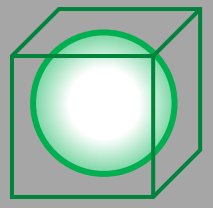
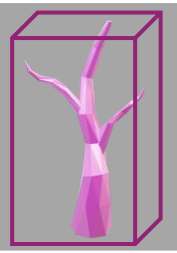
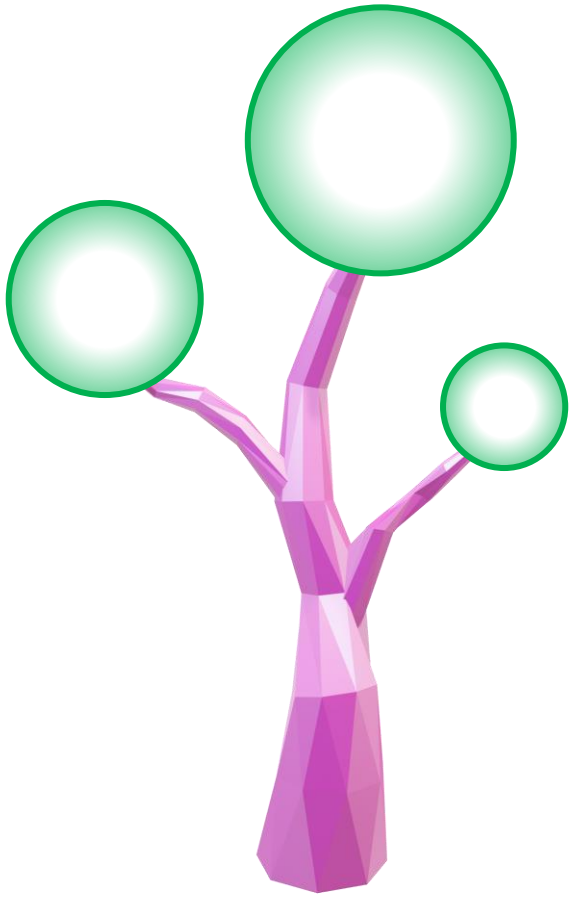
Acceleration
Structure **#1**

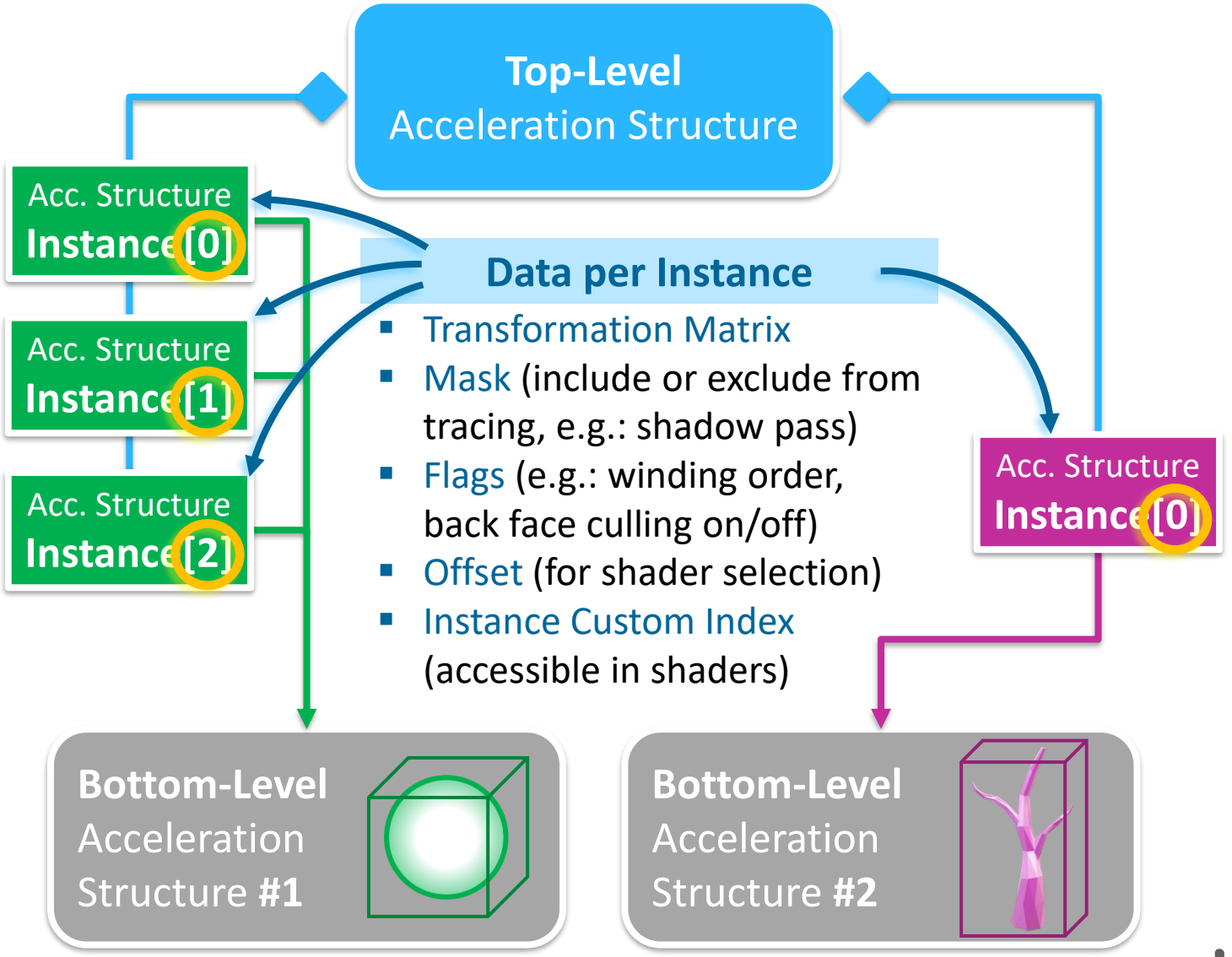


Bottom-Level
Acceleration
Structure **#2**



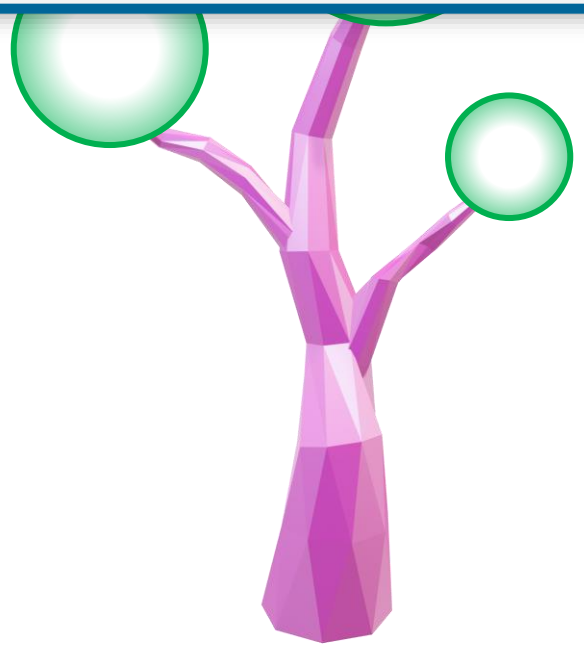
Acceleration Structures





Acceleration Structures

```
typedef struct VkAccelerationStructureInstanceKHR {
    VkTransformMatrixKHR           transform;
    uint32_t                       instanceCustomIndex:24;
    uint32_t                       mask:8;
    uint32_t                       instanceShaderBindingTableRecordOffset:24;
    VkGeometryInstanceFlagsKHR     flags:8;
    uint64_t                       accelerationStructureReference;
} VkAccelerationStructureInstanceKHR;
```



Top-Level
Acceleration Structure

Data per Instance

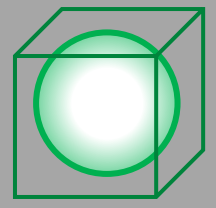
- Transformation Matrix
- Mask (include or exclude from tracing, e.g.: shadow pass)
- Flags (e.g.: winding order, back face culling on/off)
- Offset (for shader selection)
- Instance Custom Index (accessible in shaders)

Acc. Structure **Instance[0]**

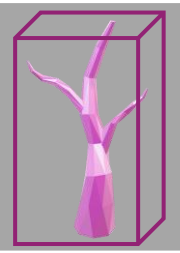
Acc. Structure **Instance[1]**

Acc. Structure **Instance[2]**

Bottom-Level Acceleration Structure **#1**



Bottom-Level Acceleration Structure **#2**



Acceleration Structures

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    VkGeometryInstanceFlagsKHR    flags:8;
    uint64_t                      accelerationStructureReference;
} VkAccelerationStructureInstanceKHR;


// Configure an instance:

uint64_t blasAddress = vkGetAccelerationStructureDeviceAddressKHR(...);

VkTransformMatrixKHR instanceTransform = {
    1.0f, 0.0f, 0.0f, 0.0f,
    0.0f, 1.0f, 0.0f, 0.0f,
    0.0f, 0.0f, 1.0f, 0.0f
};

VkAccelerationStructureInstanceKHR instance = {};
instance.transform = instanceTransform;
instance.instanceCustomIndex = 0;
instance.mask = 0xFF;
instance.instanceShaderBindingTableRecordOffset = 0;
instance.flags = VK_GEOMETRY_INSTANCE_TRIANGLE_FACING_CULL_DISABLE_BIT_KHR;
instance.accelerationStructureReference = blasAddress;
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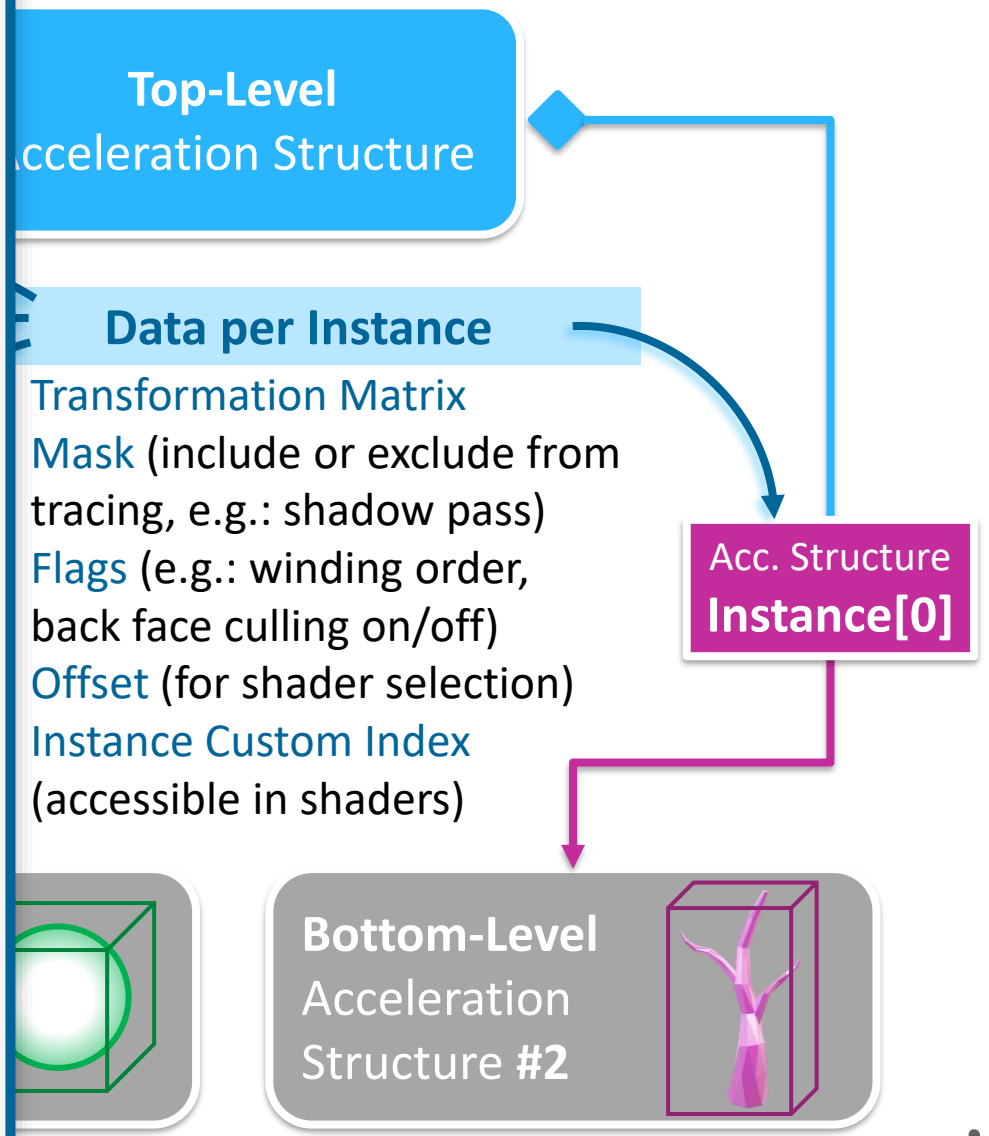

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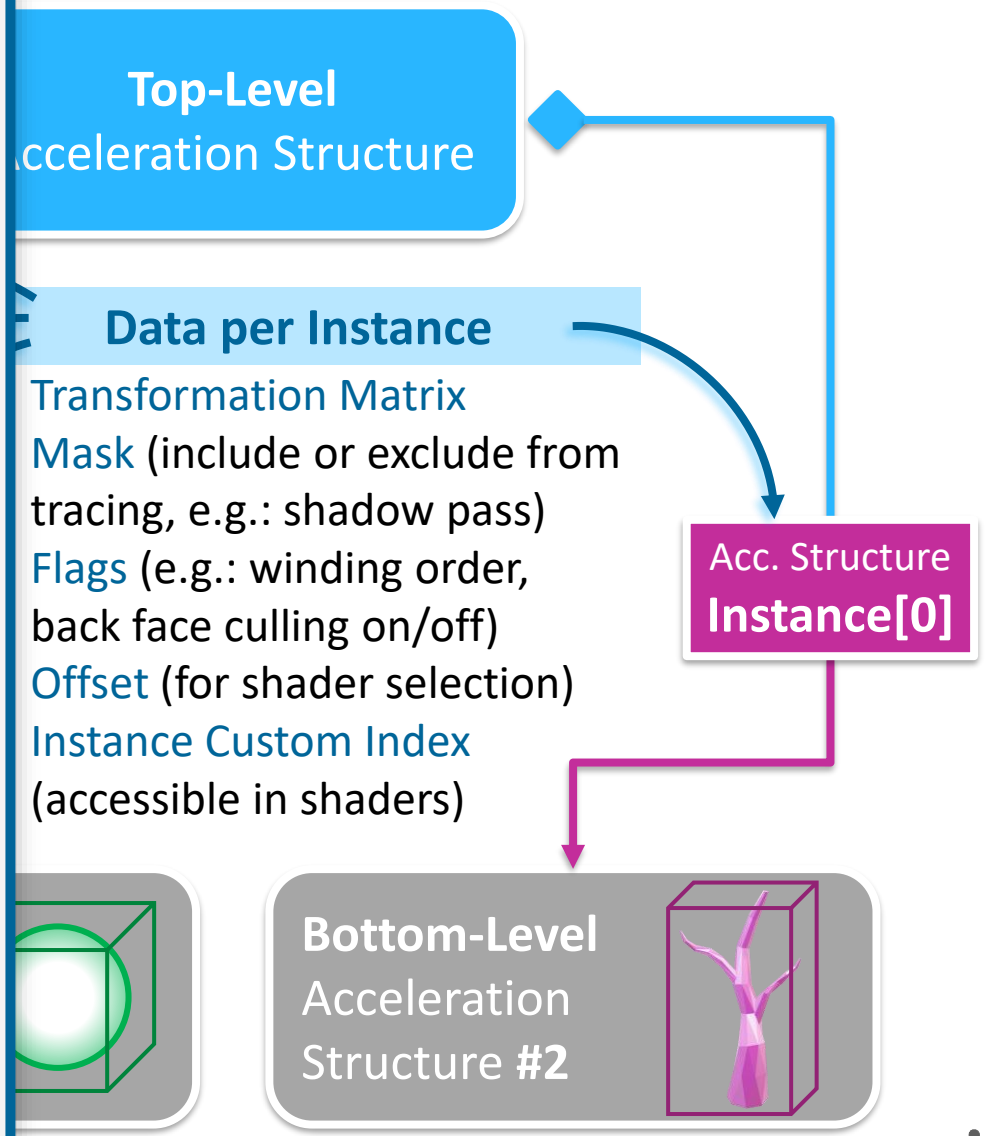

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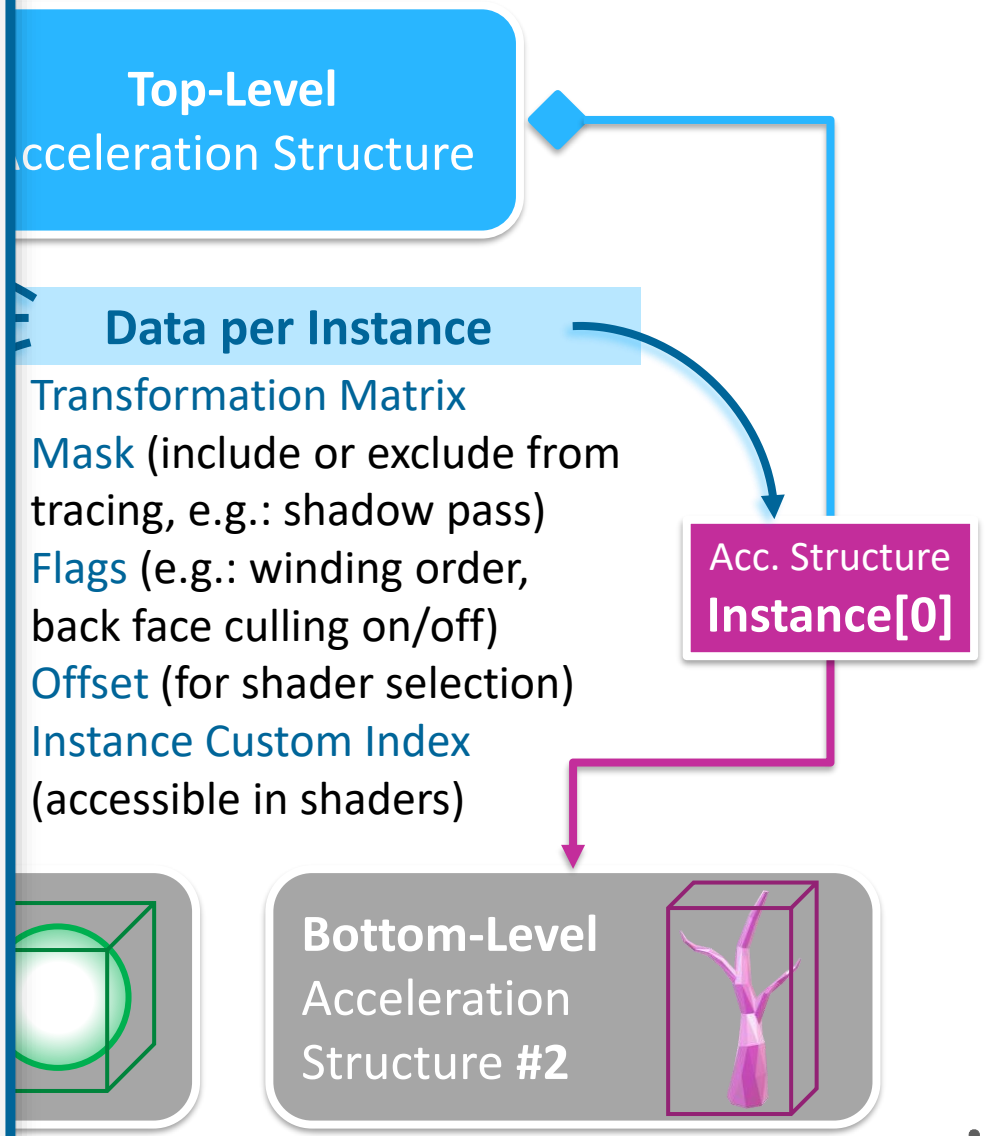

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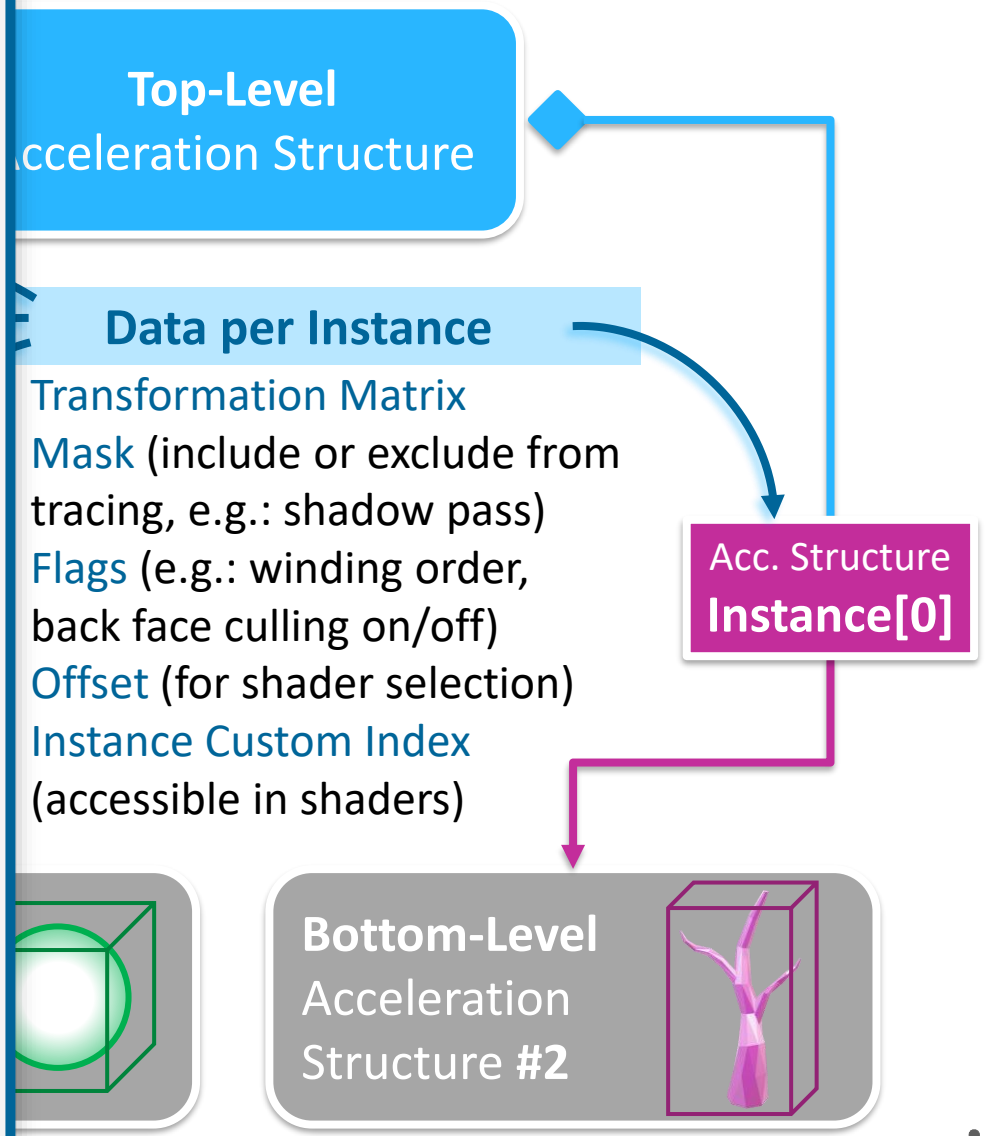

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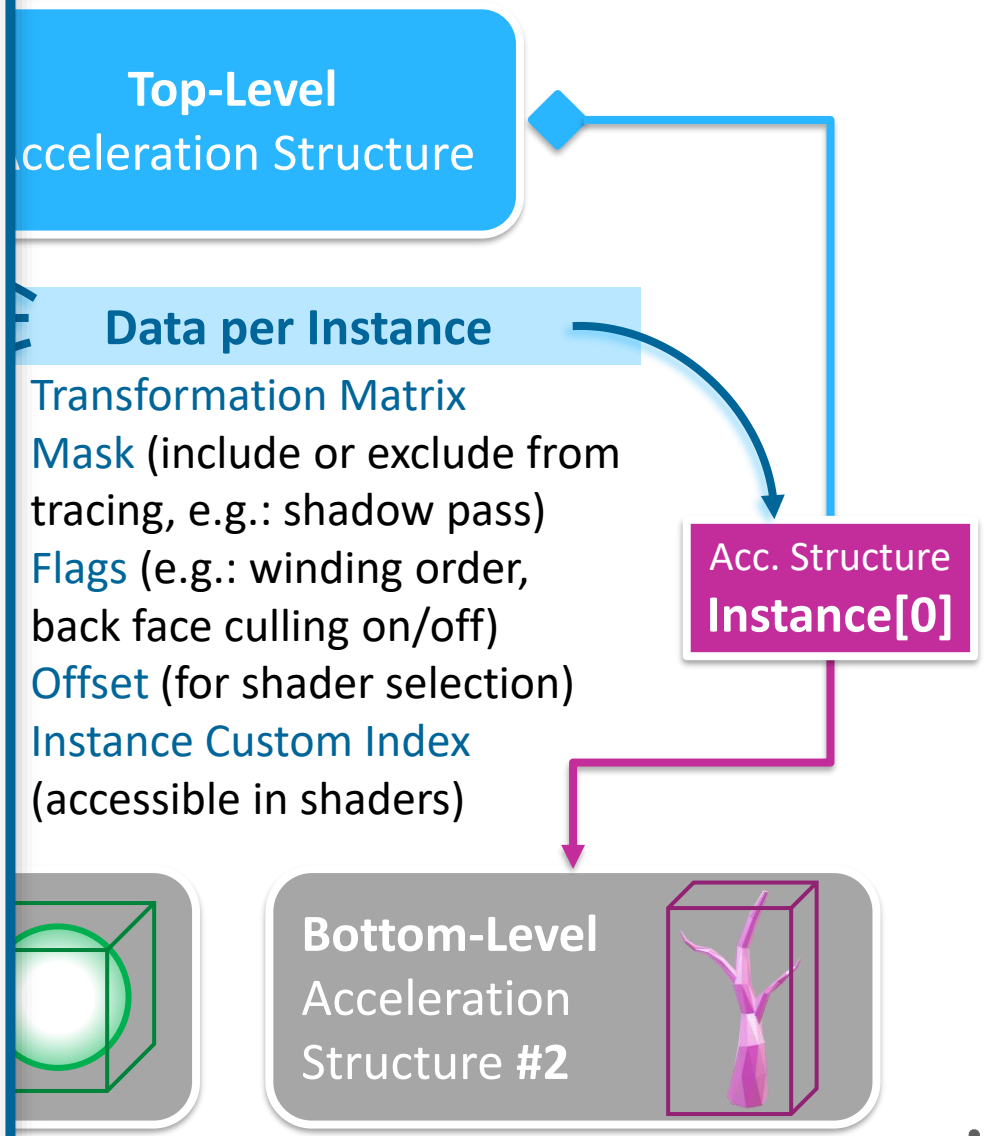

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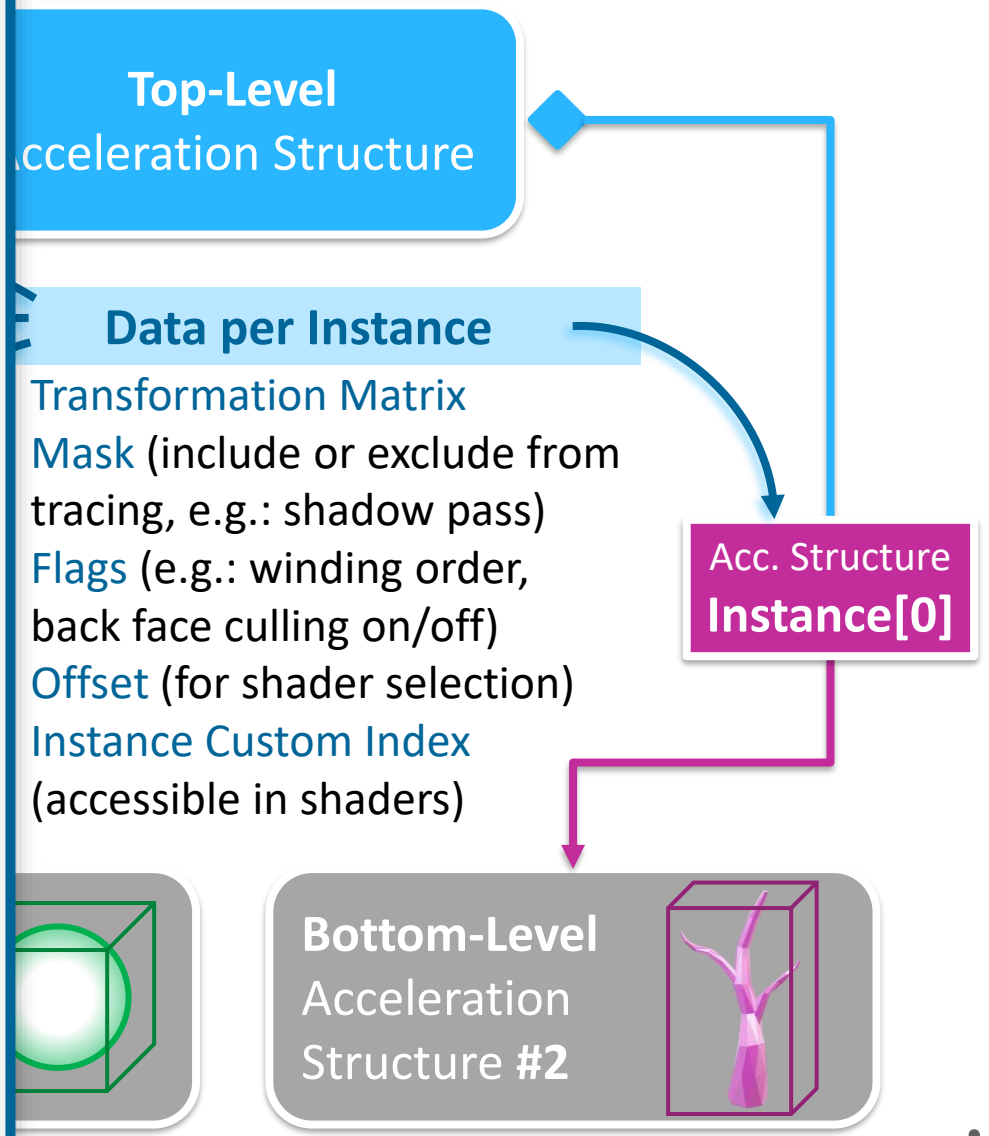

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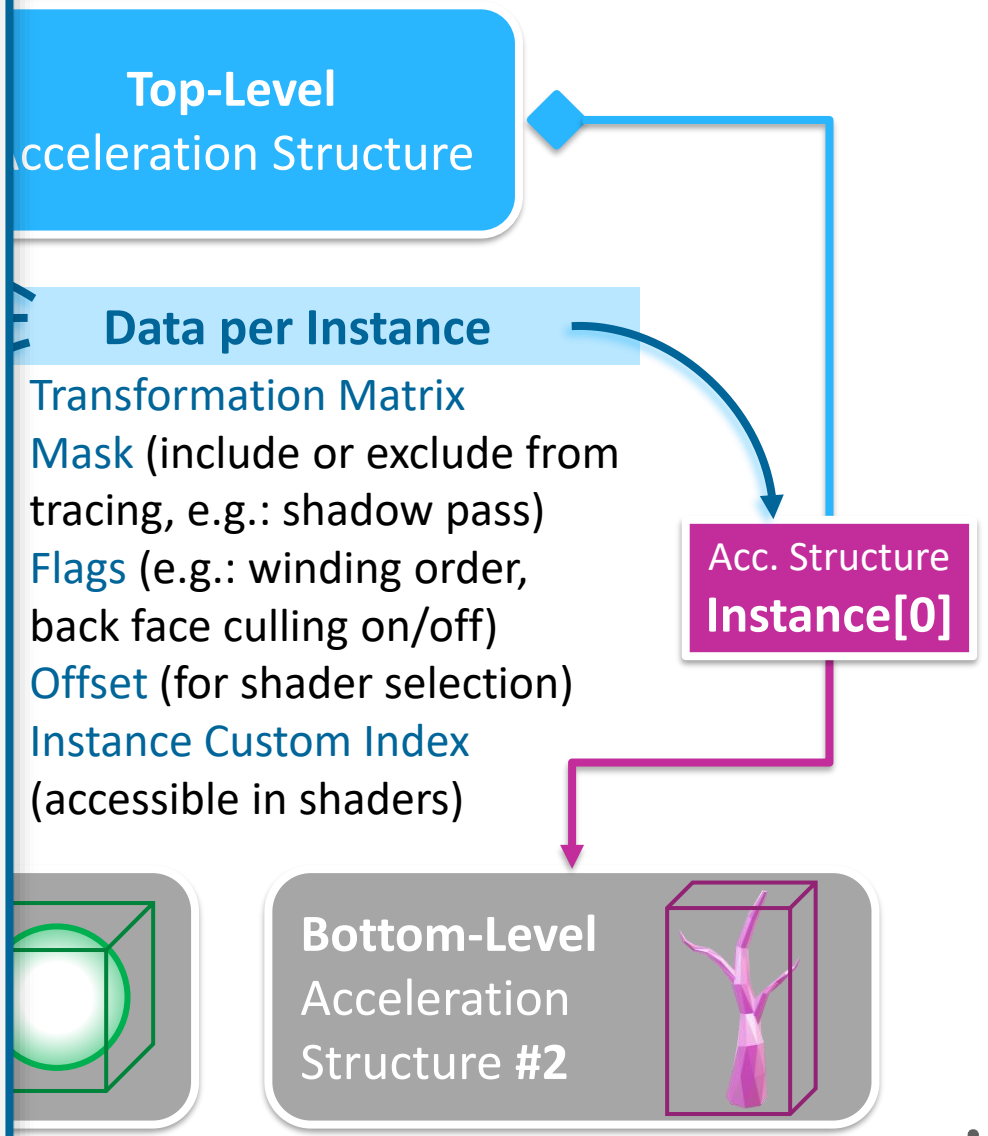
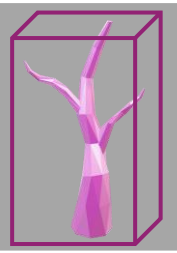


Acceleration Structures

```
VkAccelerationStructureGeometryKHR triangleGeometry = {};
triangleGeometry.sType = VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_GEOMETRY_KHR;
triangleGeometry.flags = VK_GEOMETRY_OPAQUE_BIT_KHR;
triangleGeometry.geometryType = VK_GEOMETRY_TYPE_TRIANGLES_KHR;
triangleGeometry.geometry.triangles.sType =
   VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_GEOMETRY_TRIANGLES_DATA_KHR;
triangleGeometry.geometry.triangles.vertexData = vertexBufferDeviceAddress;
triangleGeometry.geometry.triangles.indexData = indexBufferDeviceAddress;
triangleGeometry.geometry.triangles.vertexFormat = VK_FORMAT_R32G32B32_SFLOAT;
triangleGeometry.geometry.triangles.maxVertex = 100;
triangleGeometry.geometry.triangles.vertexStride = sizeof(MyVertexData);
triangleGeometry.geometry.triangles.indexType = VK_INDEX_TYPE_UINT32;
```

```
struct MyVertexData {
  float position[3];
  float normal[3];
  float texCoord[2];
};
```

Bottom-Level Acceleration Structure **#2**



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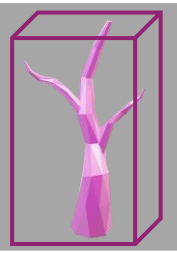

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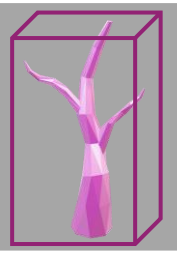
Bottom-Level Acceleration Structure **#2**



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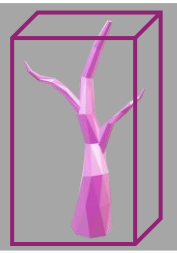

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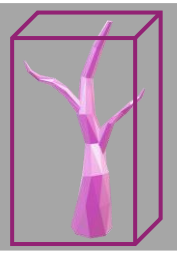

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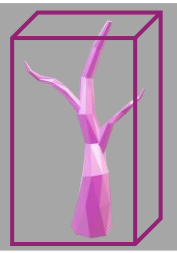

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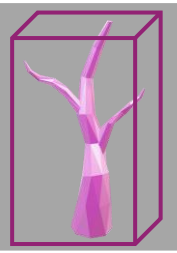

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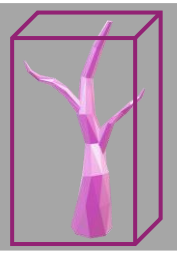
VkAccelerationStructureGeometryKHR triangleGeometry = {};
triangleGeometry.sType = VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_GEOMETRY_KHR;
triangleGeometry.flags = VK_GEOMETRY_OPAQUE_BIT_KHR;
triangleGeometry.geometryType = VK_GEOMETRY_TYPE_TRIANGLES_KHR;
triangleGeometry.geometry.triangles.sType =
   VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_GEOMETRY_TRIANGLES_DATA_KHR;
triangleGeometry.geometry.triangles.vertexData = vertexBufferDeviceAddress;
triangleGeometry.geometry.triangles.indexData = indexBufferDeviceAddress;
triangleGeometry.geometry.triangles.vertexFormat = VK_FORMAT_R32G32B32_SFLOAT;
triangleGeometry.geometry.triangles.maxVertex = 100;
triangleGeometry.geometry.triangles.vertexStride = sizeof(MyVertexData);
triangleGeometry.geometry.triangles.indexType = VK_INDEX_TYPE_UINT32;
```

```
struct MyVertexData {
  float position[3];
  float normal[3];
  float texCoord[2];
};
```

Bottom-Level Acceleration Structure **#2**

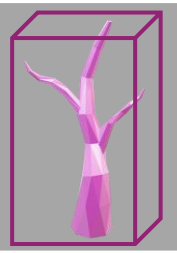


Acceleration Structures

```
VkAccelerationStructureGeometryKHR triangleGeometry = {};
triangleGeometry.sType = VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_GEOMETRY_KHR;
triangleGeometry.flags = VK_GEOMETRY_OPAQUE_BIT_KHR;
triangleGeometry.geometryType = VK_GEOMETRY_TYPE_TRIANGLES_KHR;
triangleGeometry.geometry.triangles.sType =
   VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_GEOMETRY_TRIANGLES_DATA_KHR;
triangleGeometry.geometry.triangles.vertexData = vertexBufferDeviceAddress;
triangleGeometry.geometry.triangles.indexData = indexBufferDeviceAddress;
triangleGeometry.geometry.triangles.vertexFormat = VK_FORMAT_R32G32B32_SFLOAT;
triangleGeometry.geometry.triangles.maxVertex = 100;
triangleGeometry.geometry.triangles.vertexStride = sizeof(MyVertexData);
triangleGeometry.geometry.triangles.indexType = VK_INDEX_TYPE_UINT32;
```

```
struct MyVertexData {
  float position[3];
  float normal[3];
  float texCoord[2];
};
```

Bottom-Level Acceleration Structure **#2**



Acceleration Structures

```
VkAccelerationStructureGeometryKHR triangleGeometry = {};
triangleGeometry.sType = VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_GEOMETRY_KHR;
triangleGeometry.flags = VK_GEOMETRY_OPAQUE_BIT_KHR;
triangleGeometry.geometryType = VK_GEOMETRY_TYPE_TRIANGLES_KHR;
triangleGeometry.geometry.triangles.sType =
   VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_GEOMETRY_TRIANGLES_DATA_KHR;
triangleGeometry.geometry.triangles.vertexData = vertexBufferDeviceAddress;
triangleGeometry.geometry.triangles.indexData = indexBufferDeviceAddress;
triangleGeometry.geometry.triangles.vertexFormat = VK_FORMAT_R32G32B32_SFLOAT;
triangleGeometry.geometry.triangles.maxVertex = 100;
triangleGeometry.geometry.triangles.vertexStride = sizeof(MyVertexData);
triangleGeometry.geometry.triangles.indexType = VK_INDEX_TYPE_UINT32;
```

```
struct MyVertexData {
  float position[3];
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};
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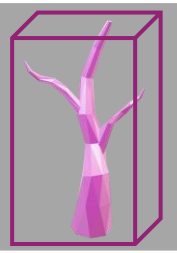
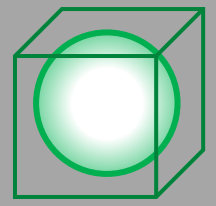
Bottom-Level Acceleration Structure **#2**



Acceleration Structures

```
VkAccelerationStructureGeometryKHR aabbGeometry = {};
aabbGeometry.sType = VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_GEOMETRY_KHR;
aabbGeometry.geometryType = VK_GEOMETRY_TYPE_AABBS_KHR;
aabbGeometry.geometry.aabbs.sType =
VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_GEOMETRY_AABBS_DATA_KHR;
aabbGeometry.geometry.aabbs.data = aabbsBufferDeviceAddress;
aabbGeometry.geometry.aabbs.stride = sizeof(VkAabbPositionsKHR);
```

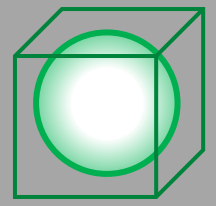
Bottom-Level Acceleration Structure **#1**



Acceleration Structures

```
VkAccelerationStructureGeometryKHR aabbGeometry = {};
aabbGeometry.sType = VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_GEOMETRY_KHR;
aabbGeometry.geometryType = VK_GEOMETRY_TYPE_AABBS_KHR;
aabbGeometry.geometry.aabbs.sType =
VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_GEOMETRY_AABBS_DATA_KHR;
aabbGeometry.geometry.aabbs.data = aabbsBufferDeviceAddress;
aabbGeometry.geometry.aabbs.stride = sizeof(VkAabbPositionsKHR);
```

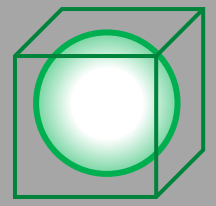
Bottom-Level Acceleration Structure **#1**



Acceleration Structures

```
VkAccelerationStructureGeometryKHR aabbGeometry = {};
aabbGeometry.sType = VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_GEOMETRY_KHR;
aabbGeometry.geometryType = VK_GEOMETRY_TYPE_AABBS_KHR;
aabbGeometry.geometry.aabbs.sType =
VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_GEOMETRY_AABBS_DATA_KHR;
aabbGeometry.geometry.aabbs.data = aabbsBufferDeviceAddress;
aabbGeometry.geometry.aabbs.stride = sizeof(VkAabbPositionsKHR);
```

Bottom-Level Acceleration Structure **#1**

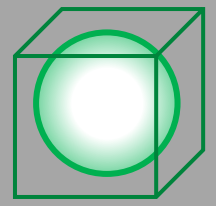


Acceleration Structures

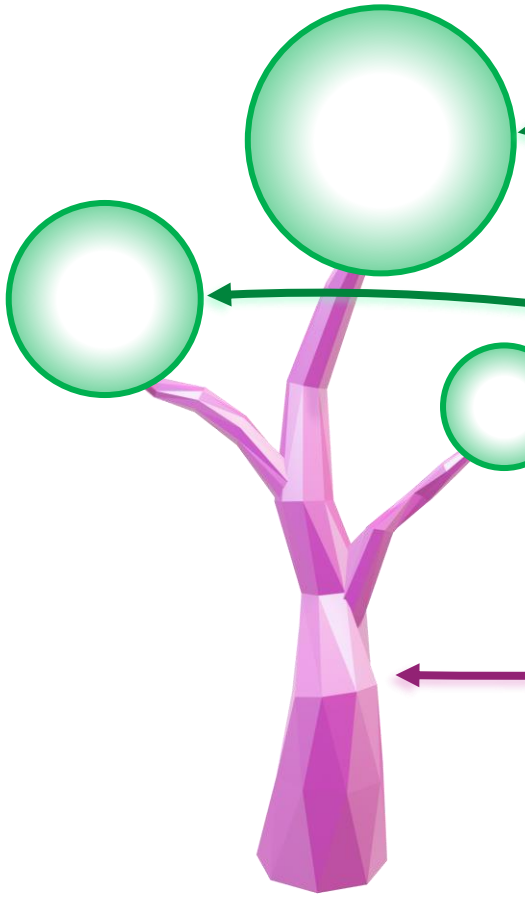
```
VkAccelerationStructureGeometryKHR aabbGeometry = {};
aabbGeometry.sType = VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_GEOMETRY_KHR;
aabbGeometry.geometryType = VK_GEOMETRY_TYPE_AABBS_KHR;
aabbGeometry.geometry.aabbs.sType =
VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_GEOMETRY_AABBS_DATA_KHR;
aabbGeometry.geometry.aabbs.data = aabbsBufferDeviceAddress;
aabbGeometry.geometry.aabbs.stride = sizeof(VkAabbPositionsKHR);
```

```
typedef struct VkAabbPositionsKHR {
    float minX;
    float minY;
    float minZ;
    float maxX;
    float maxY;
    float maxZ;
} VkAabbPositionsKHR;
```

Bottom-Level Acceleration Structure **#1**



Acceleration Structures



Top-Level Acceleration Structure

`vkCmdBuildAccelerationStructuresKHR`

Acc. Structure **Instance[0]**

Acc. Structure **Instance[1]**

Acc. Structure **Instance[2]**

Acc. Structure **Instance[0]**

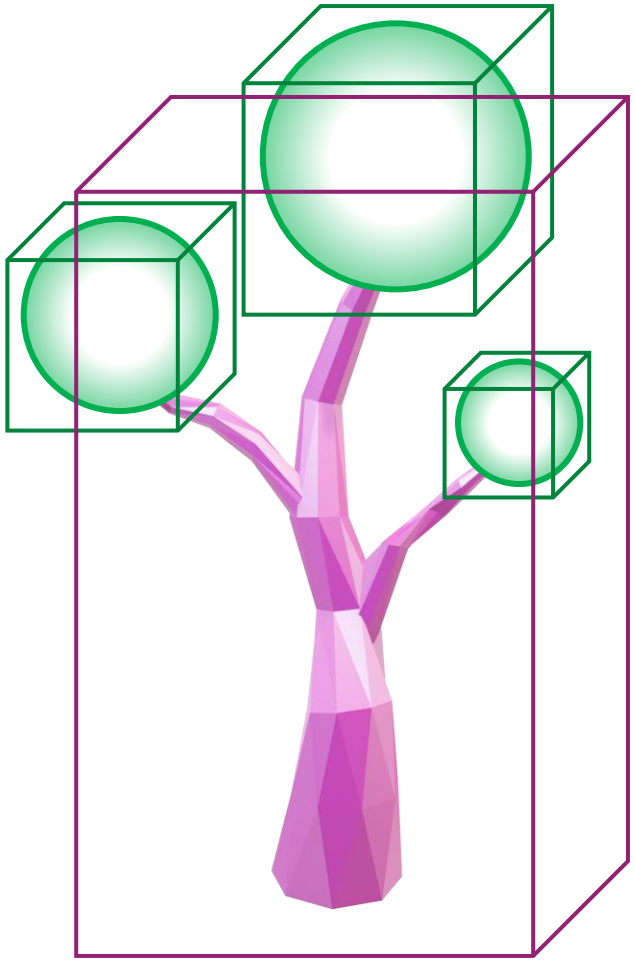
Bottom-Level Acceleration Structure **#1**

`vkCmdBuildAccelerationStructuresKHR`

Bottom-Level Acceleration Structure **#2**

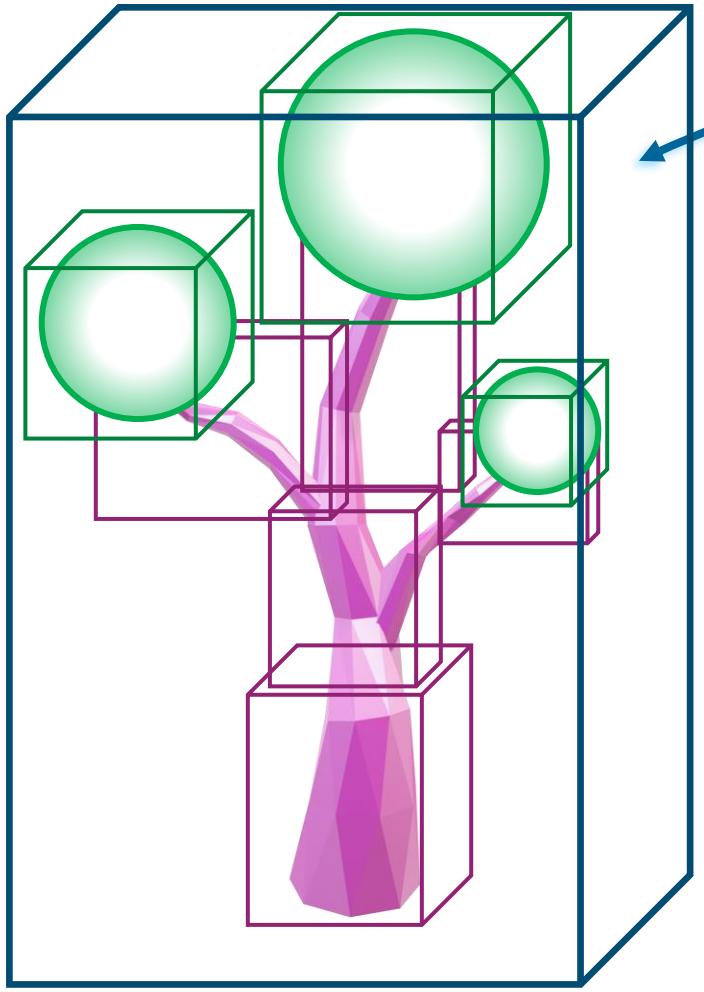
`vkCmdBuildAccelerationStructuresKHR`

Bounding Volume Hierarchy Traversal



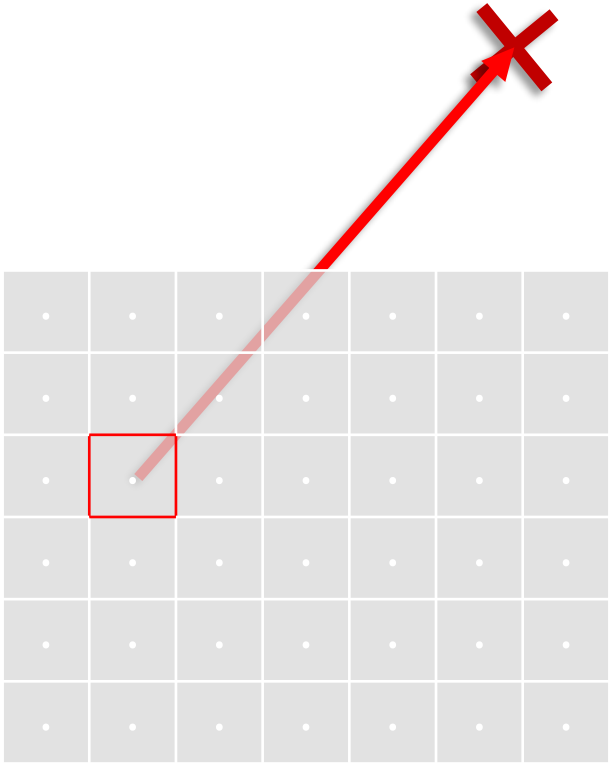
Top-Level
Acceleration Structure

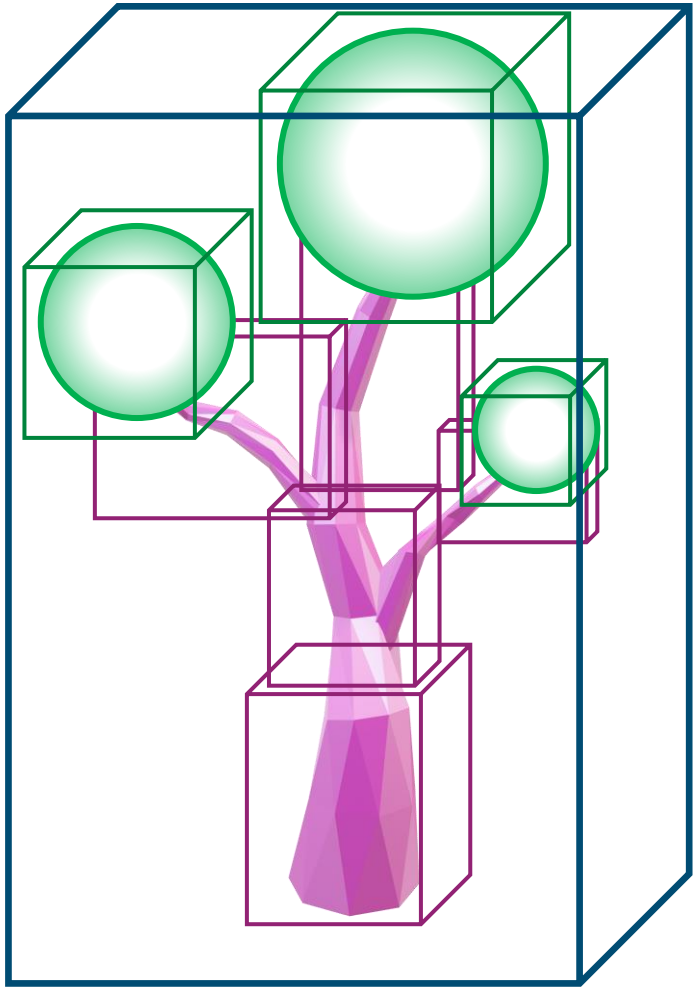
Bounding Volume Hierarchy Traversal



Top-Level
Acceleration Structure

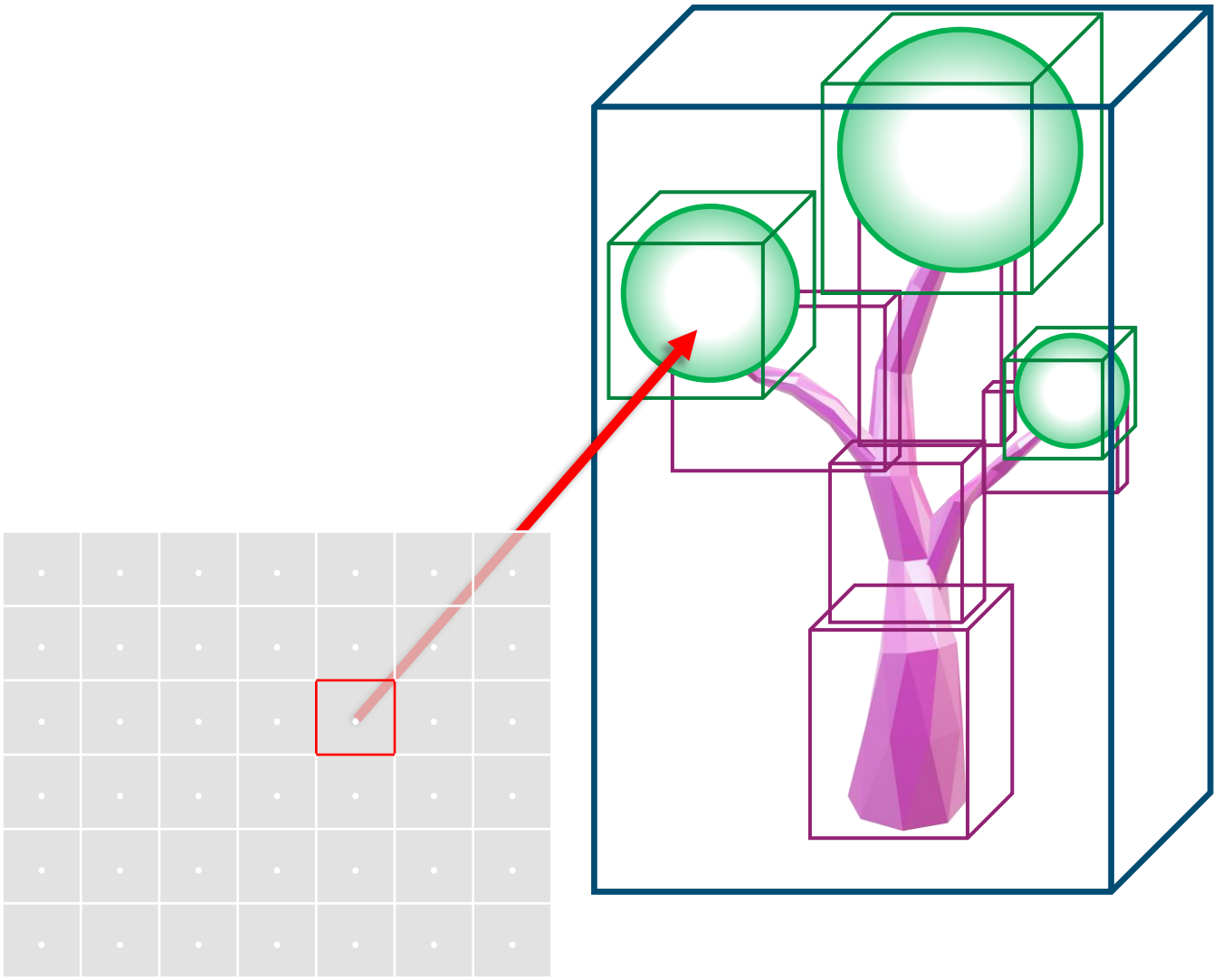
Bounding Volume Hierarchy Traversal





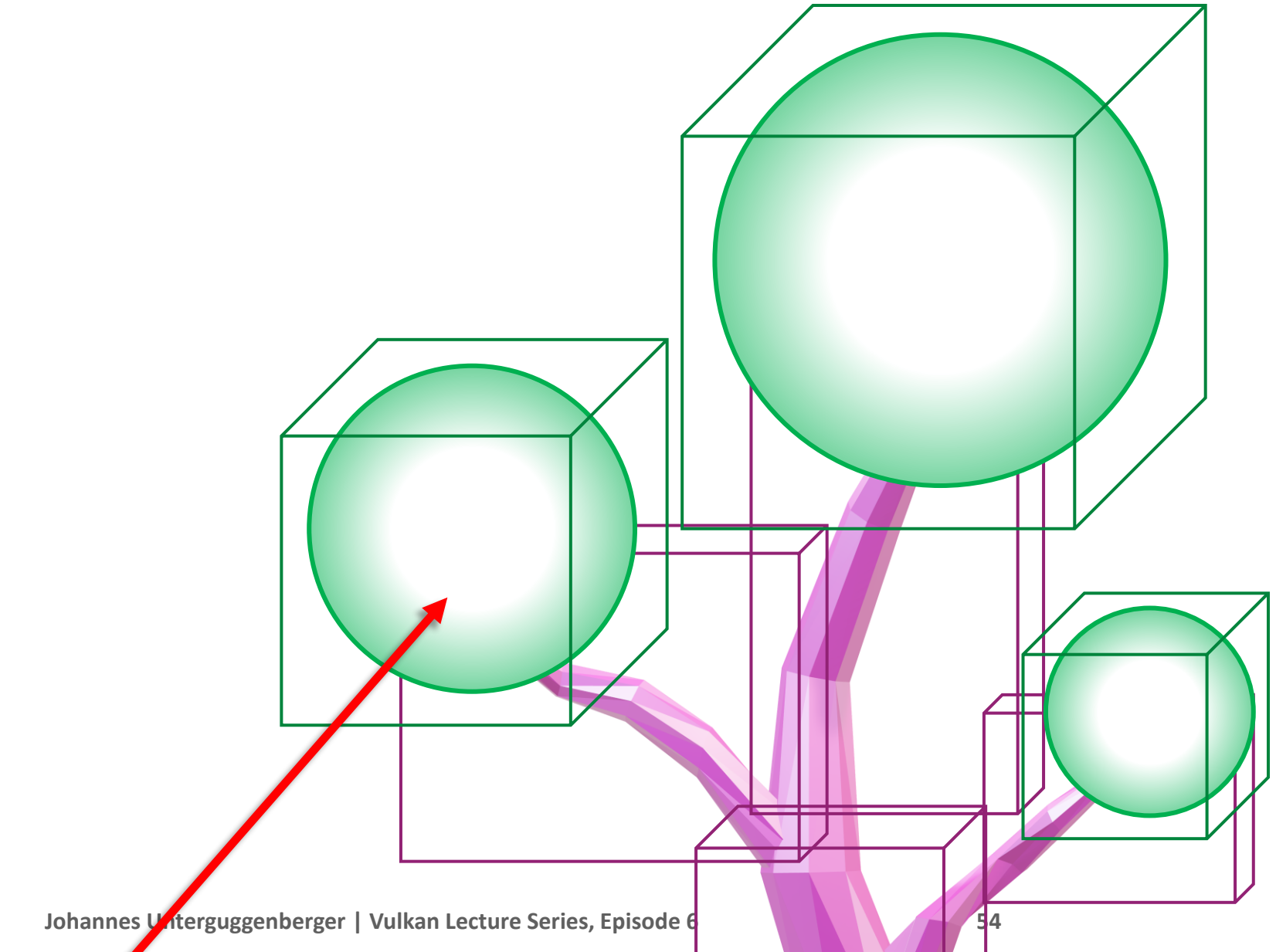
Top-Level
Acceleration Structure

Bounding Volume Hierarchy Traversal



Top-Level
Acceleration Structure

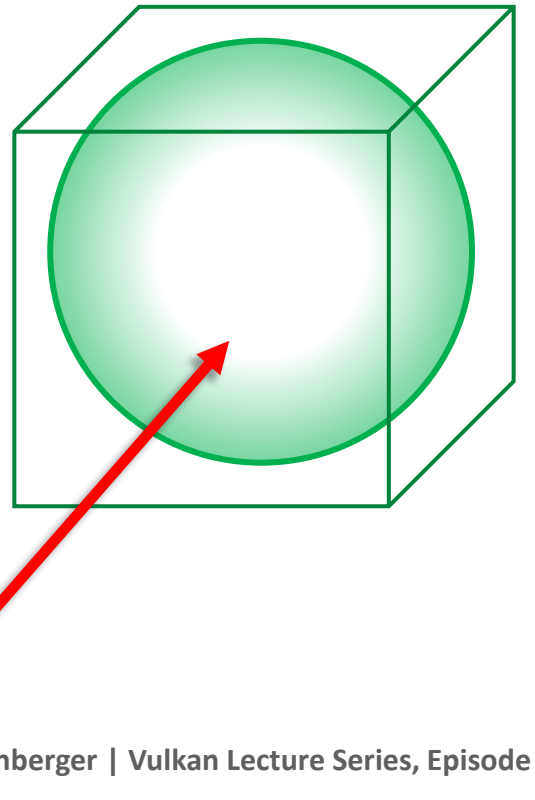
Bounding Volume Hierarchy Traversal



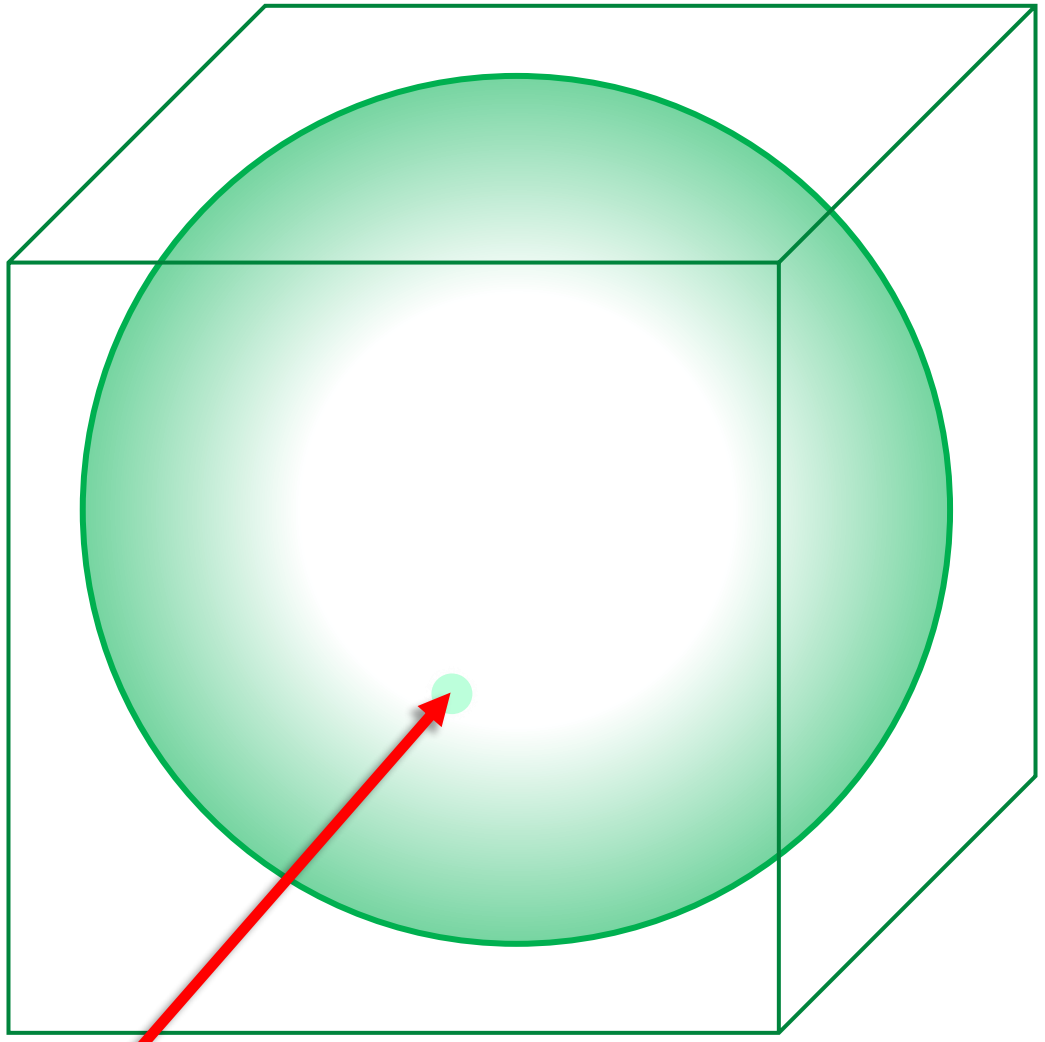
Top-Level
Acceleration Structure

Bounding Volume Hierarchy Traversal

Top-Level
Acceleration Structure



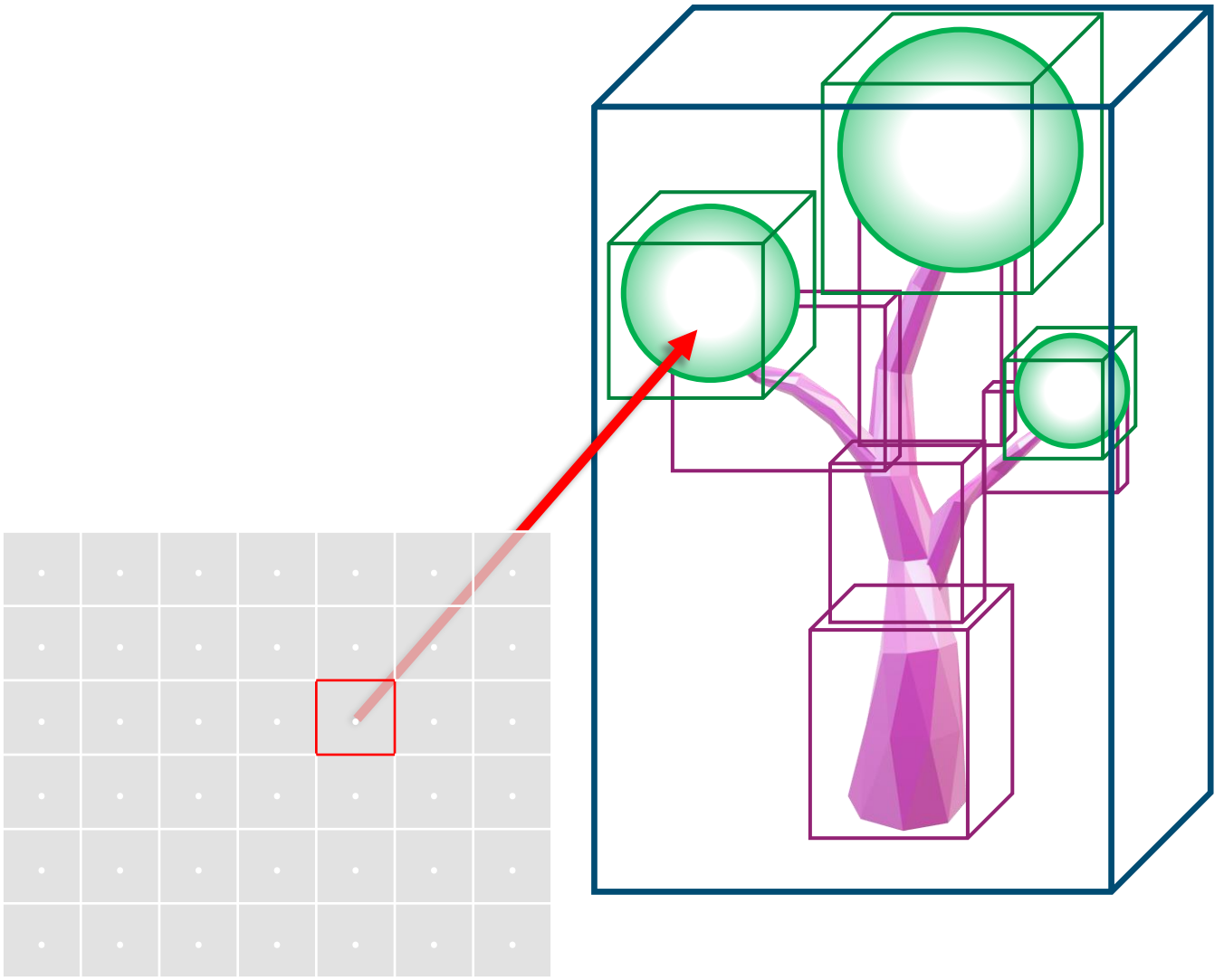
Bounding Volume Hierarchy Traversal



Top-Level
Acceleration Structure

Intersection Shader

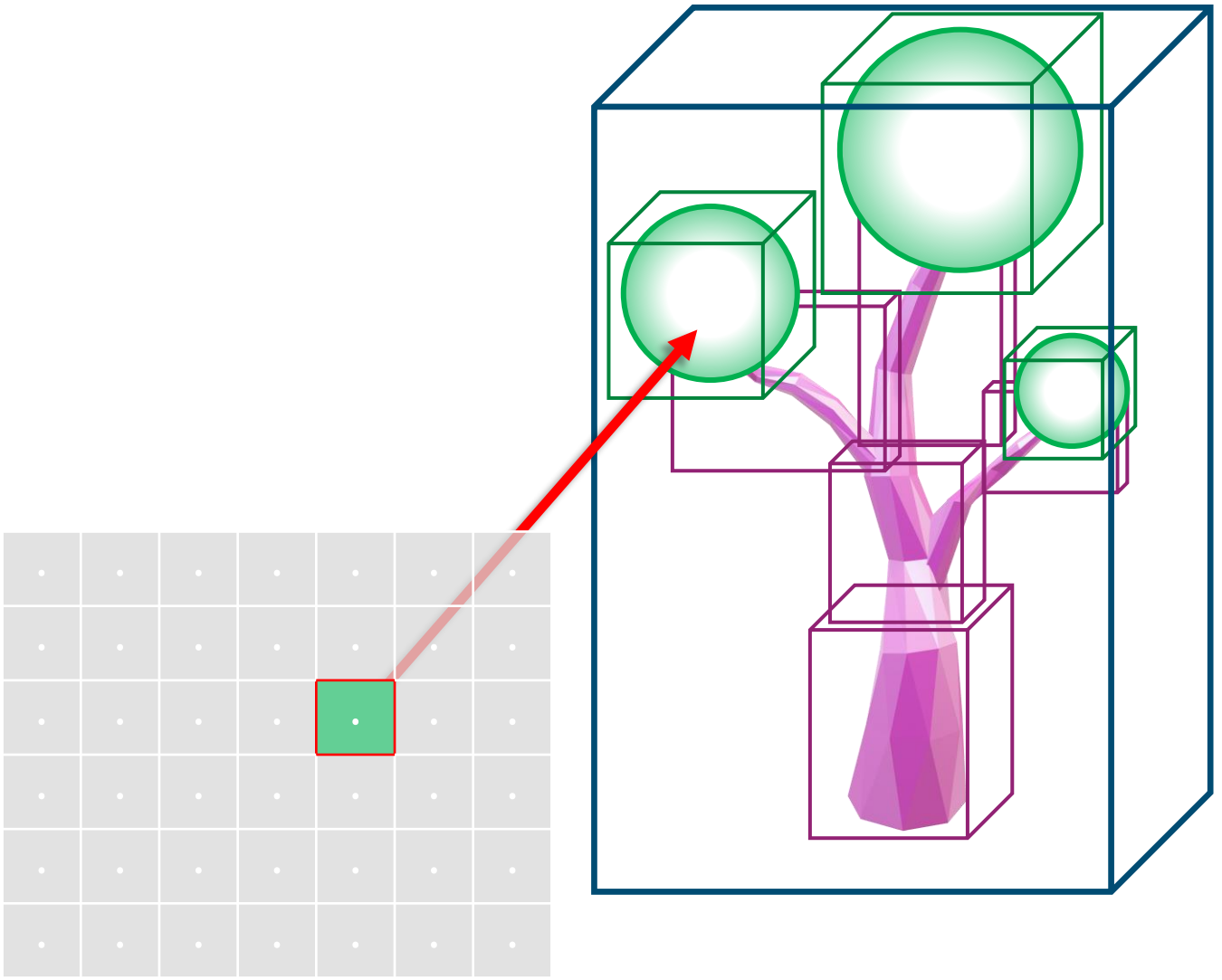
Bounding Volume Hierarchy Traversal



Top-Level
Acceleration Structure

Closest Hit Shader

Bounding Volume Hierarchy Traversal



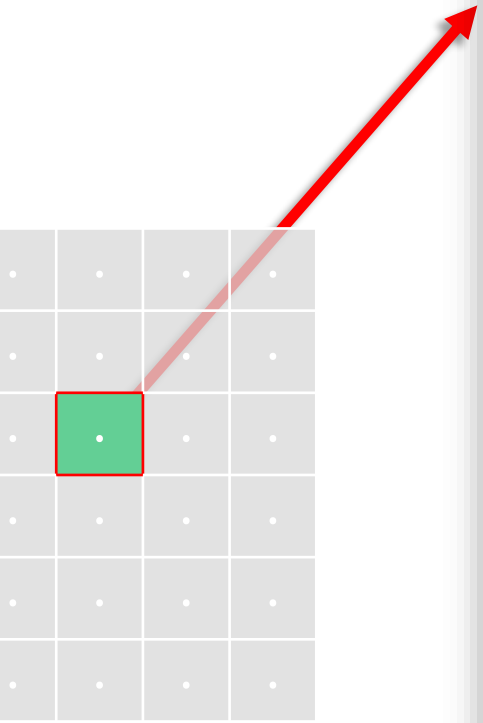
Top-Level
Acceleration Structure

Tracing One Ray

Tracing One Ray

Start ONE ray in a shader with traceRayEXT():

Top-Level
Acceleration Structure



Ray Generation Shader (GLSL)

```
#version 460
#extension GL_EXT_ray_tracing : require

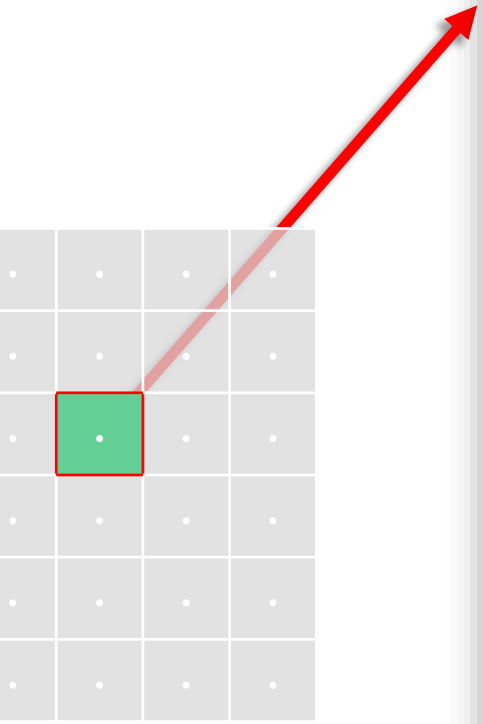
layout(set = 0, binding = 0) uniform accelerationStructureEXT topLevelAS;
layout(set = 0, binding = 1, rgba8) uniform image2D image;
layout(location = 0) rayPayloadEXT vec3 hitValue;

void main() {
    // ...
    // Compute ray parameters like origin and direction
    // ...
    traceRayEXT(topLevelAS,
        gl_RayFlagsOpaqueEXT /*ray flags*/, 0xff /*culling mask*/,
        0 /*sbtRecordOffset*/, 0 /*sbtRecordStride*/, 0 /*missIndex*/,
        origin, 0.1 /*min hit distance*/, direction, 100.0 /*max ray length*/,
        0 /*location of payload*/);
    imageStore(image, ivec2(gl_LaunchIDEXT.xy), vec4(hitValue, 0.0));
}
```

Tracing One Ray

Start ONE ray in a shader with traceRayEXT():

Top-Level Acceleration Structure



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    traceRayEXT(topLevelAS,
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Tracing One Ray

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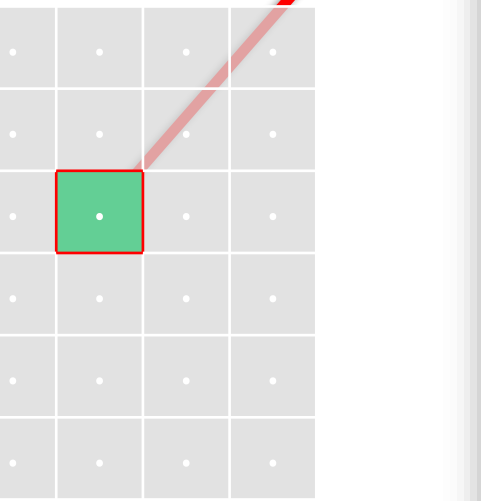

Top-Level
Acceleration Structure

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```

Tracing One Ray

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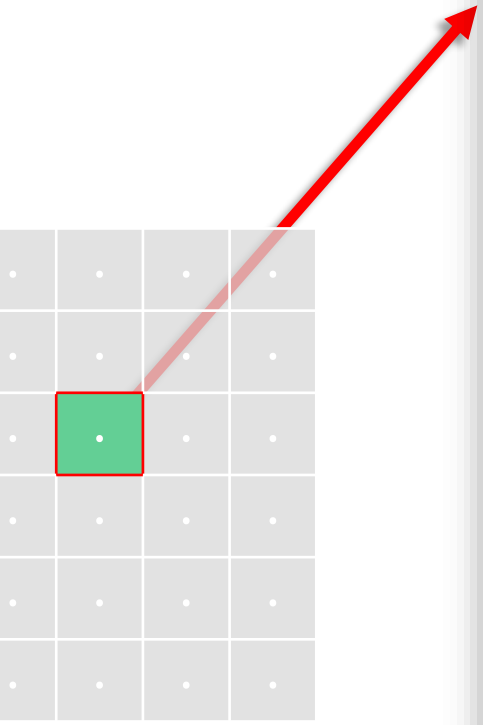

Top-Level
Acceleration Structure

Ray Generation Shader (GLSL)

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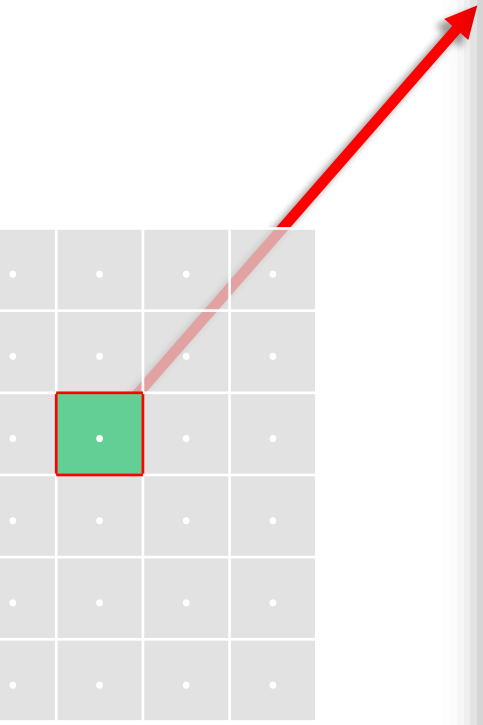

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Tracing One Ray

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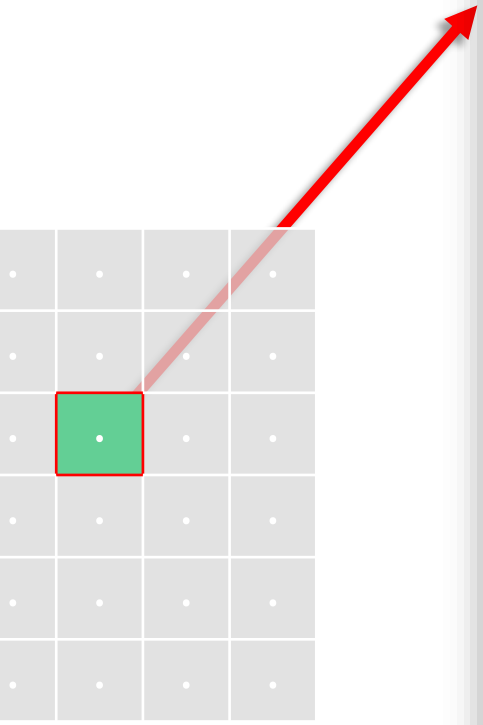

Top-Level
Acceleration Structure

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    // ...
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        0 /*sbtRecordOffset*/, 0 /*sbtRecordStride*/, 0 /*missIndex*/,
        origin, 0.1 /*min hit distance*/, direction, 100.0 /*max ray length*/,
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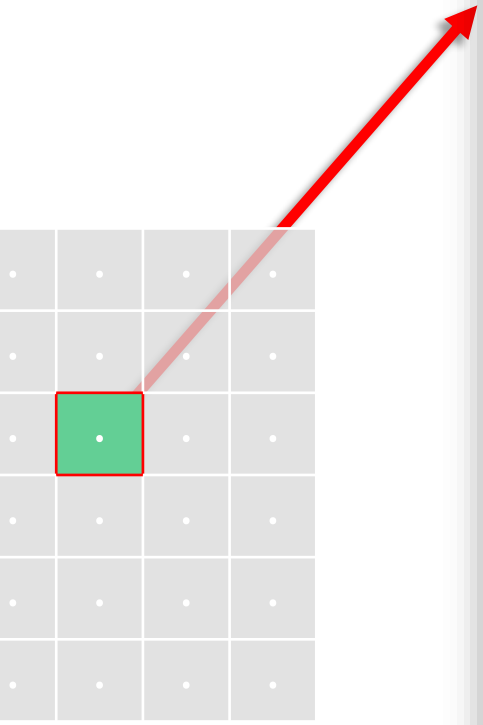
```

Tracing One Ray

Start ONE ray in a shader with traceRayEXT():



Top-Level
Acceleration Structure

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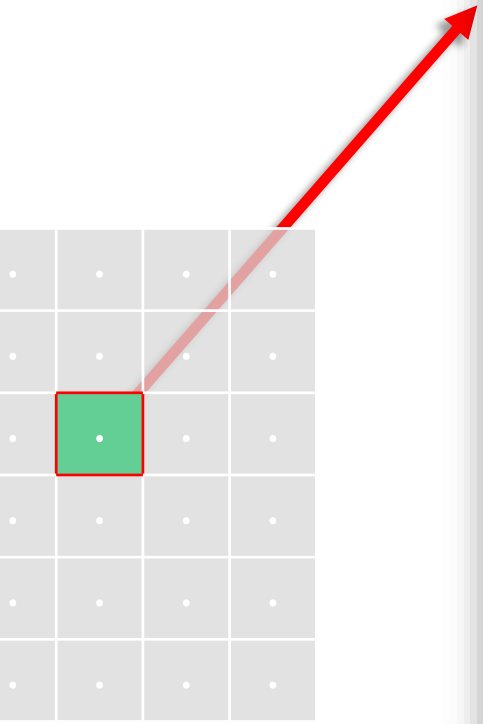
        0 /*sbtRecordOffset*/, 0 /*sbtRecordStride*/, 0 /*missIndex*/,
        origin, 0.1 /*min hit distance*/, direction, 100.0 /*max ray length*/,
        0 /*location of payload*/);
    imageStore(image, ivec2(gl_LaunchIDEXT.xy), vec4(hitValue, 0.0));
}
```

Tracing One Ray

Start ONE ray in a shader with traceRayEXT():



Ray Generation Shader (GLSL)

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#extension GL_EXT_ray_tracing : require

layout(set = 0, binding = 0) uniform accelerationStructureEXT topLevelAS;
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layout(location = 0) rayPayloadEXT vec3 hitValue;

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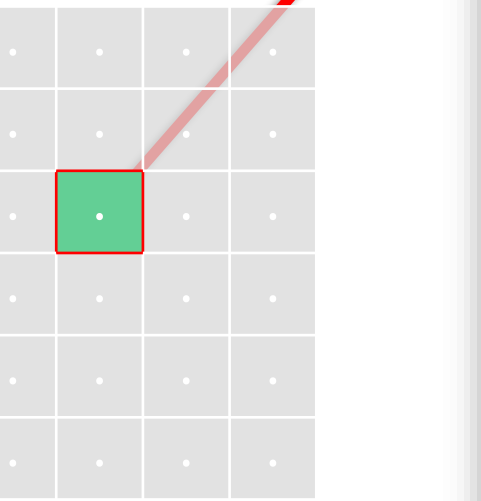
    // Compute ray parameters like origin and direction
    // ...
    traceRayEXT(topLevelAS,
        gl_RayFlagsOpaqueEXT /*ray flags*/, 0xff /*culling mask*/,
        0 /*sbtRecordOffset*/, 0 /*sbtRecordStride*/, 0 /*missIndex*/,
        origin, 0.1 /*min hit distance*/, direction, 100.0 /*max ray length*/,
        0 /*location of payload*/);
    imageStore(image, ivec2(gl_LaunchIDEXT.xy), vec4(hitValue, 0.0));
}
```

Top-Level Acceleration Structure

Tracing One Ray

Start ONE ray in a shader with traceRayEXT():



Ray Generation Shader (GLSL)

```
#version 460
#extension GL_EXT_ray_tracing : require

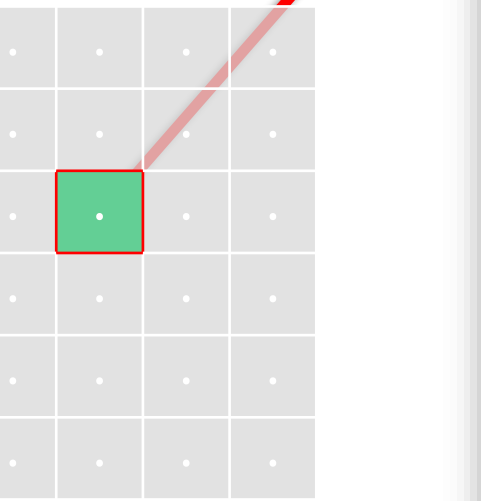
layout(set = 0, binding = 0) uniform accelerationStructureEXT topLevelAS;
layout(set = 0, binding = 1, rgba8) uniform image2D image;
layout(location = 0) rayPayloadEXT vec3 hitValue;

void main() {
    // ...
    // Compute ray parameters like origin and direction
    // ...
    traceRayEXT(topLevelAS,
        gl_RayFlagsOpaqueEXT /*ray flags*/, 0xff /*culling mask*/,
        0 /*sbtRecordOffset*/, 0 /*sbtRecordStride*/, 0 /*missIndex*/,
        origin, 0.1 /*min hit distance*/, direction, 100.0 /*max ray length*/,
        0 /*location of payload*/);
    imageStore(image, ivec2(gl_LaunchIDEXT.xy), vec4(hitValue, 0.0));
}
```

Top-Level Acceleration Structure

Tracing One Ray

Start ONE ray in a shader with traceRayEXT():



Top-Level
Acceleration Structure

Ray Generation Shader (GLSL)

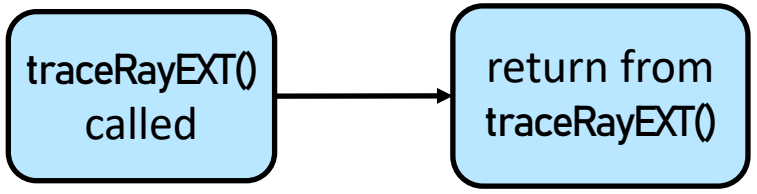
```
#version 460
#extension GL_EXT_ray_tracing : require

layout(set = 0, binding = 0) uniform accelerationStructureEXT topLevelAS;
layout(set = 0, binding = 1, rgba8) uniform image2D image;
layout(location = 0) rayPayloadEXT vec3 hitValue;

void main() {
    // ...
    // Compute ray parameters like origin and direction
    // ...
    traceRayEXT(topLevelAS,
        gl_RayFlagsOpaqueEXT /*ray flags*/, 0xff /*culling mask*/,
        0 /*sbtRecordOffset*/, 0 /*sbtRecordStride*/, 0 /*missIndex*/,
        origin, 0.1 /*min hit distance*/, direction, 100.0 /*max ray length*/,
        0 /*location of payload*/);
    imageStore(image, ivec2(gl_LaunchIDEXT.xy), vec4(hitValue, 0.0));
}
```

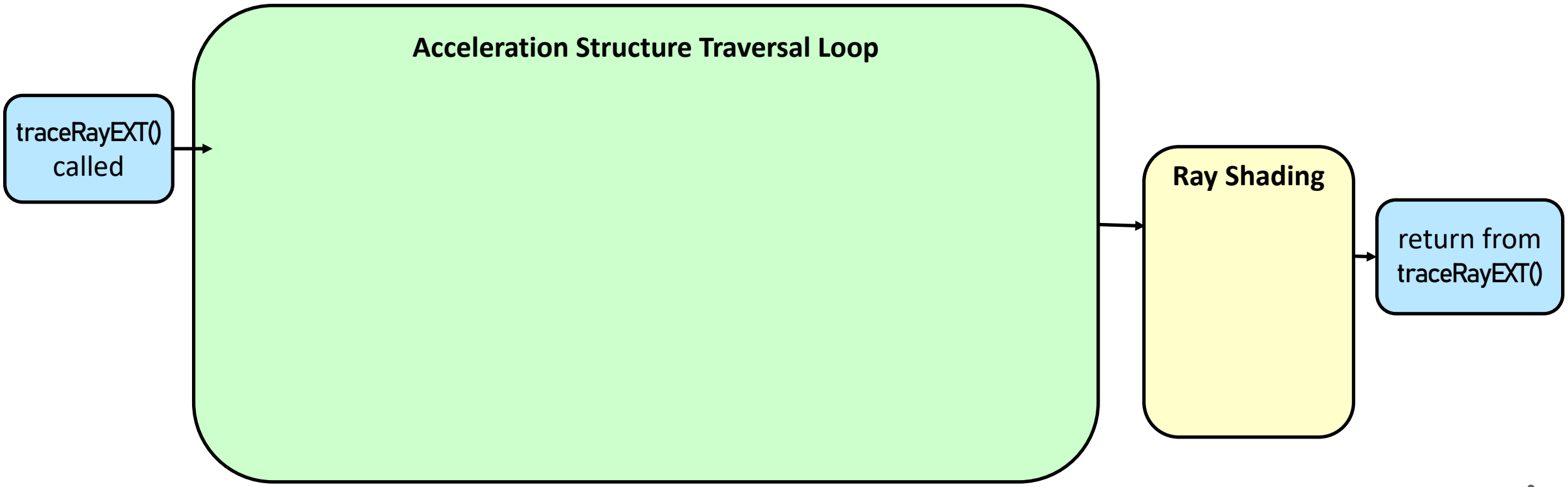
Ray Tracing Pipeline in Depth

- Ray Generation Shader
- Per pixel: traceRayEXT()



Ray Tracing Pipeline in Depth

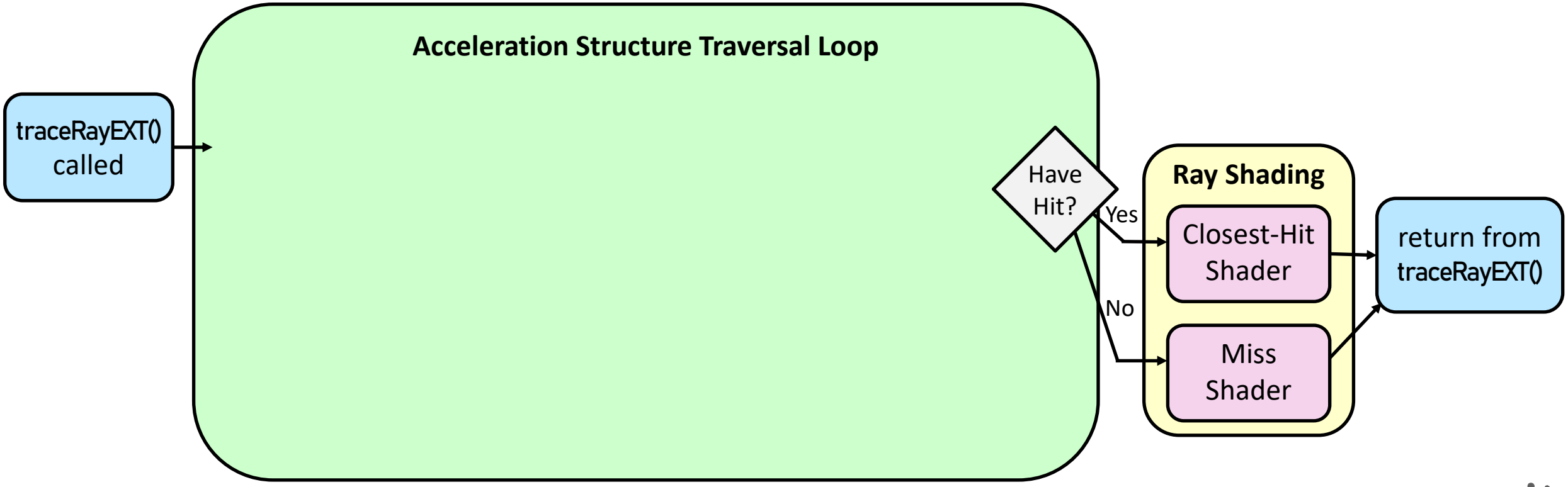
- Ray Generation Shader
- Per pixel: traceRayEXT()



Adapted from: Chris Wyman and Shawn Hargreaves and Peter Shirley and Colin Barré-Brisebois, Introduction to DirectX Raytracing, ACM SIGGRAPH 2018 Courses, https://intro-to-dxr.cwyman.org

Ray Tracing Pipeline in Depth

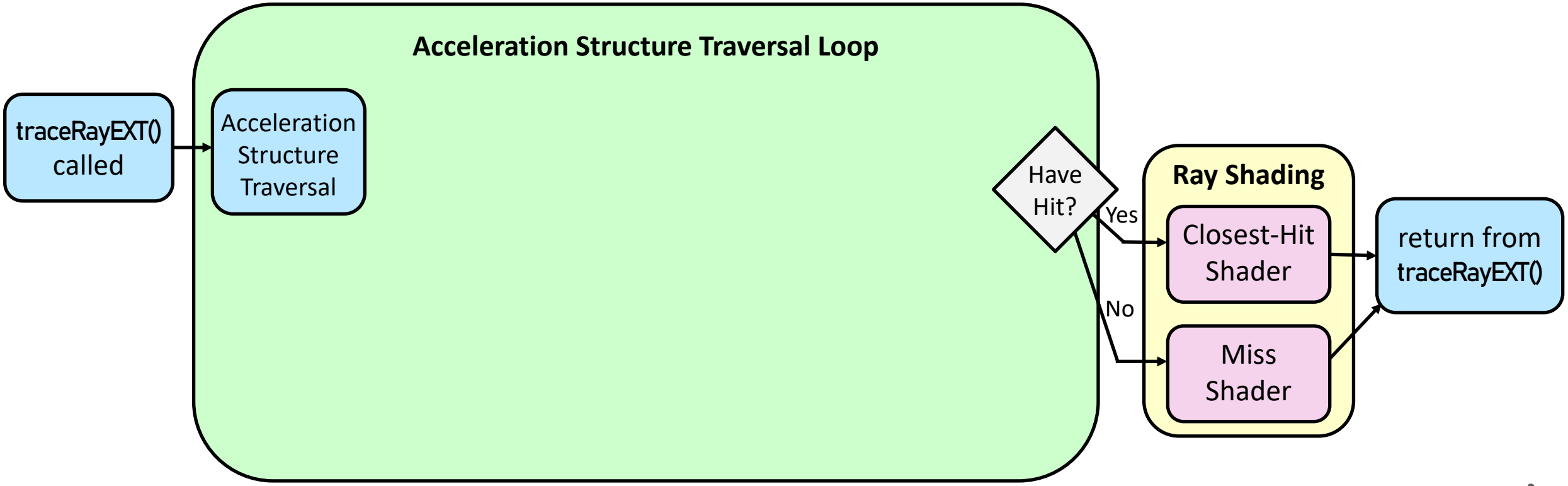
- Shading in Closest-Hit or in Miss Shader
  - If we had a valid hit => Closest-Hit Shader
  - If we didn't => Miss Shader



Adapted from: Chris Wyman and Shawn Hargreaves and Peter Shirley and Colin Barré-Brisebois, Introduction to DirectX Raytracing, ACM SIGGRAPH 2018 Courses, https://intro-to-dxr.cwyman.org

Ray Tracing Pipeline in Depth

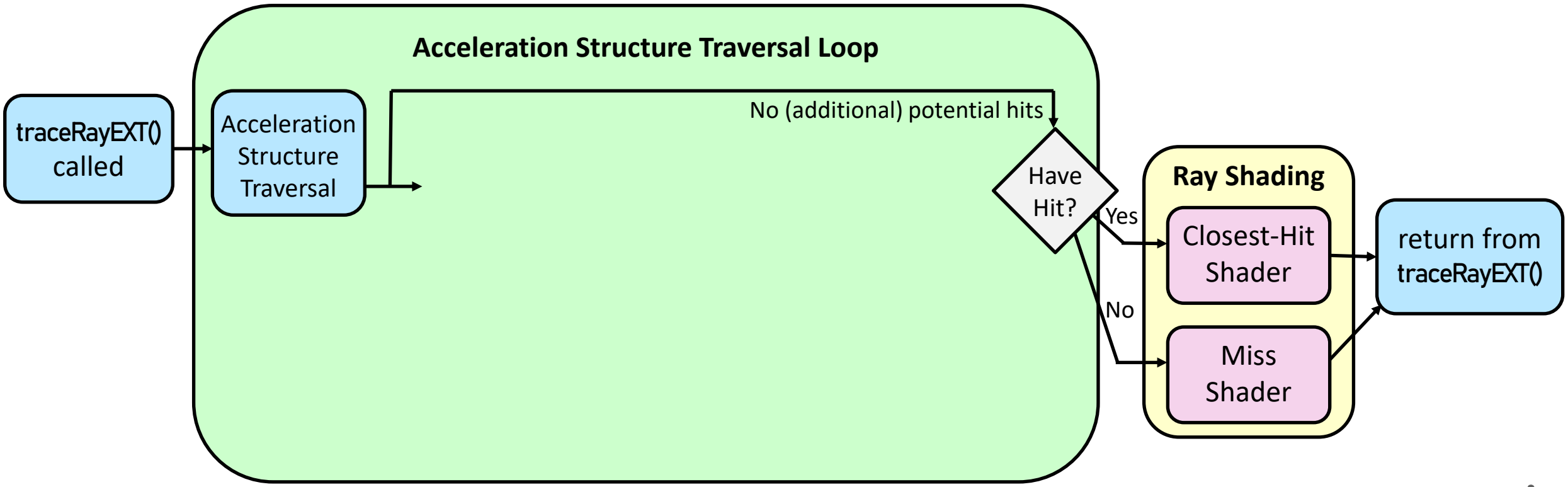
- Traverse the acceleration structure
  - Opaque process, configurable
  - Vendor-specific implementation



Adapted from: Chris Wyman and Shawn Hargreaves and Peter Shirley and Colin Barré-Brisebois, Introduction to DirectX Raytracing, ACM SIGGRAPH 2018 Courses, https://intro-to-dxr.cwyman.org

Ray Tracing Pipeline in Depth

- No hit => acceleration structure traversal ends

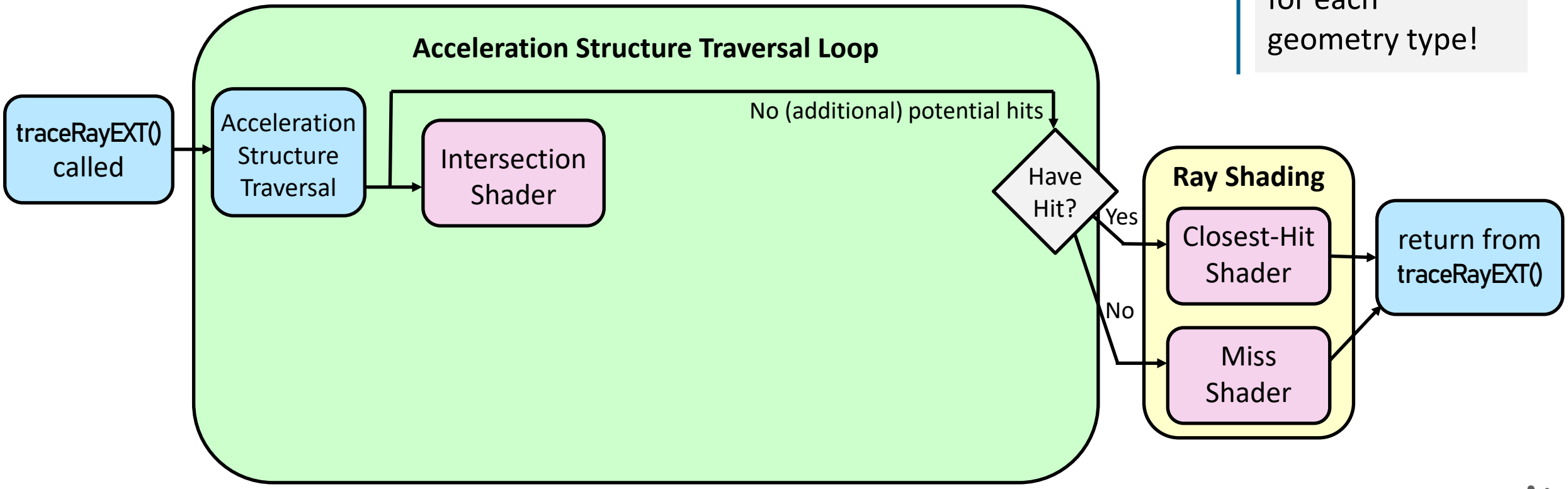


Adapted from: Chris Wyman and Shawn Hargreaves and Peter Shirley and Colin Barré-Brisebois, Introduction to DirectX Raytracing, ACM SIGGRAPH 2018 Courses, https://intro-to-dxr.cwyman.org

Ray Tracing Pipeline in Depth

- For potential intersections, Intersection Shader is invoked
  - Specific to a particular geometry type (spheres, Bezier patches, …)
  - Default, optimized intersection for triangles

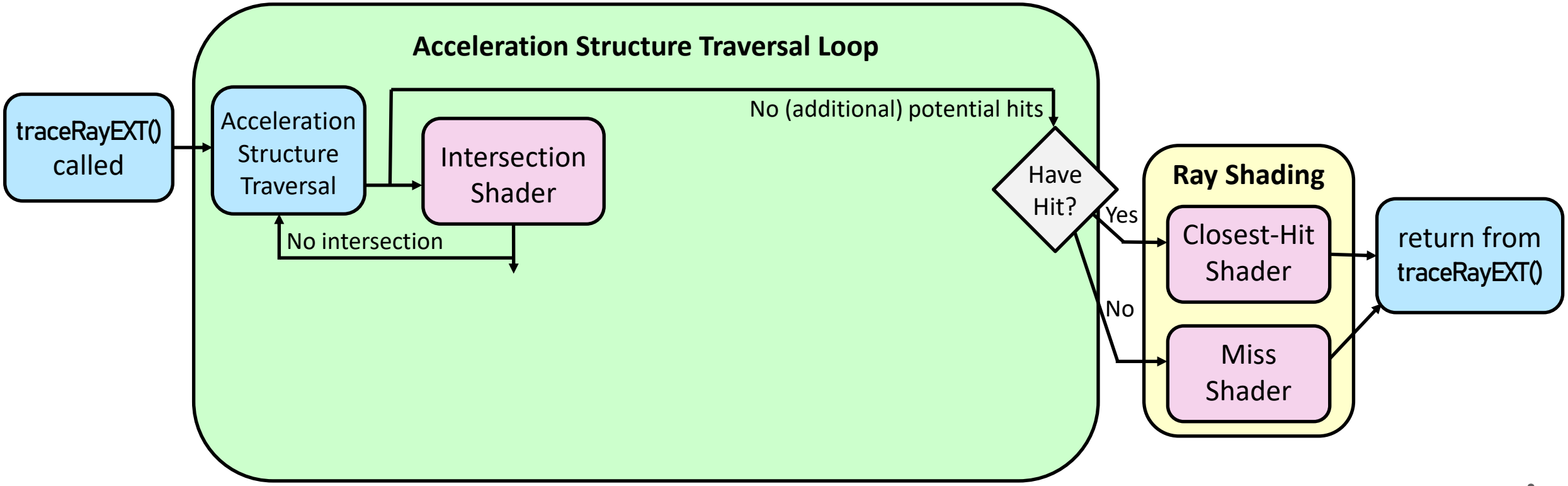
Different shader for each geometry type!



Adapted from: Chris Wyman and Shawn Hargreaves and Peter Shirley and Colin Barré-Brisebois, Introduction to DirectX Raytracing, ACM SIGGRAPH 2018 Courses, https://intro-to-dxr.cwyman.org

Ray Tracing Pipeline in Depth

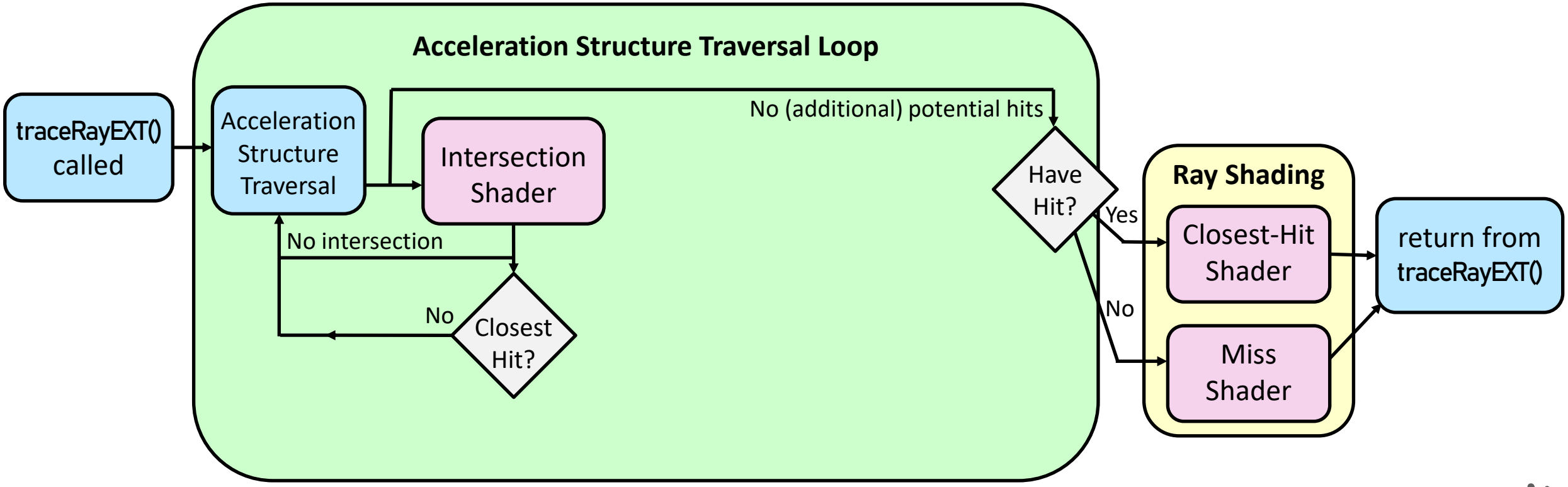
- No intersection from Intersection Shader?
- => Continue traversing the acceleration structure!



Adapted from: Chris Wyman and Shawn Hargreaves and Peter Shirley and Colin Barré-Brisebois, Introduction to DirectX Raytracing, ACM SIGGRAPH 2018 Courses, https://intro-to-dxr.cwyman.org

Ray Tracing Pipeline in Depth

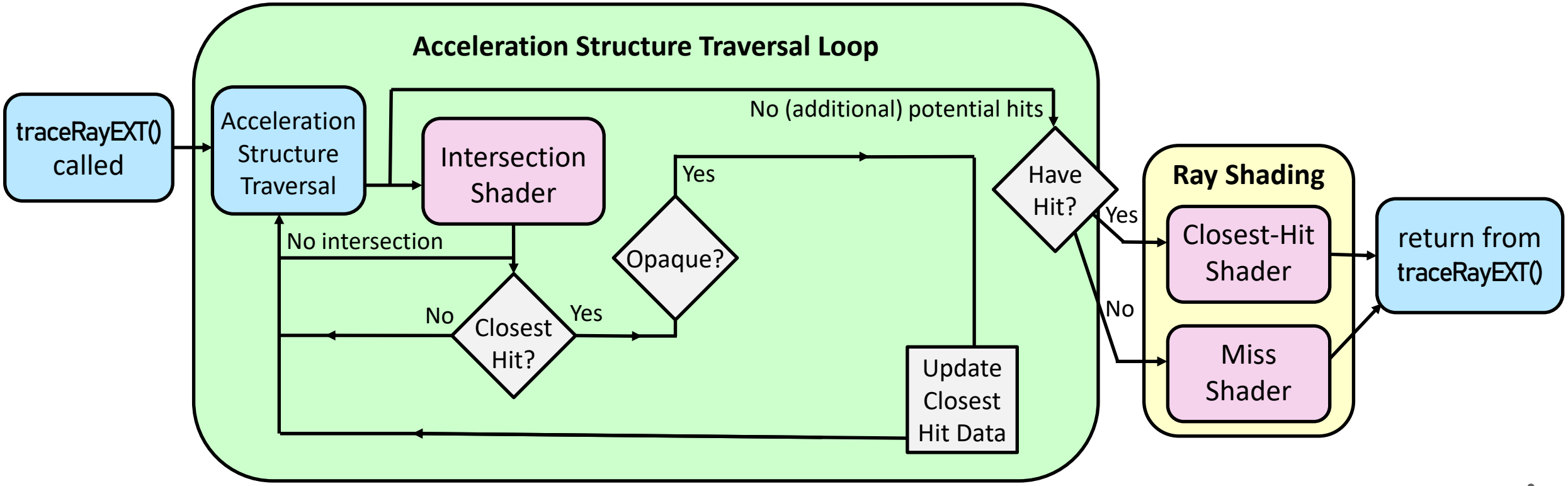
- We have detected an intersection, but:
- The intersection is not the closest hit (so far)
- => Continue traversing the acceleration structure!



Adapted from: Chris Wyman and Shawn Hargreaves and Peter Shirley and Colin Barré-Brisebois, Introduction to DirectX Raytracing, ACM SIGGRAPH 2018 Courses, https://intro-to-dxr.cwyman.org

Ray Tracing Pipeline in Depth

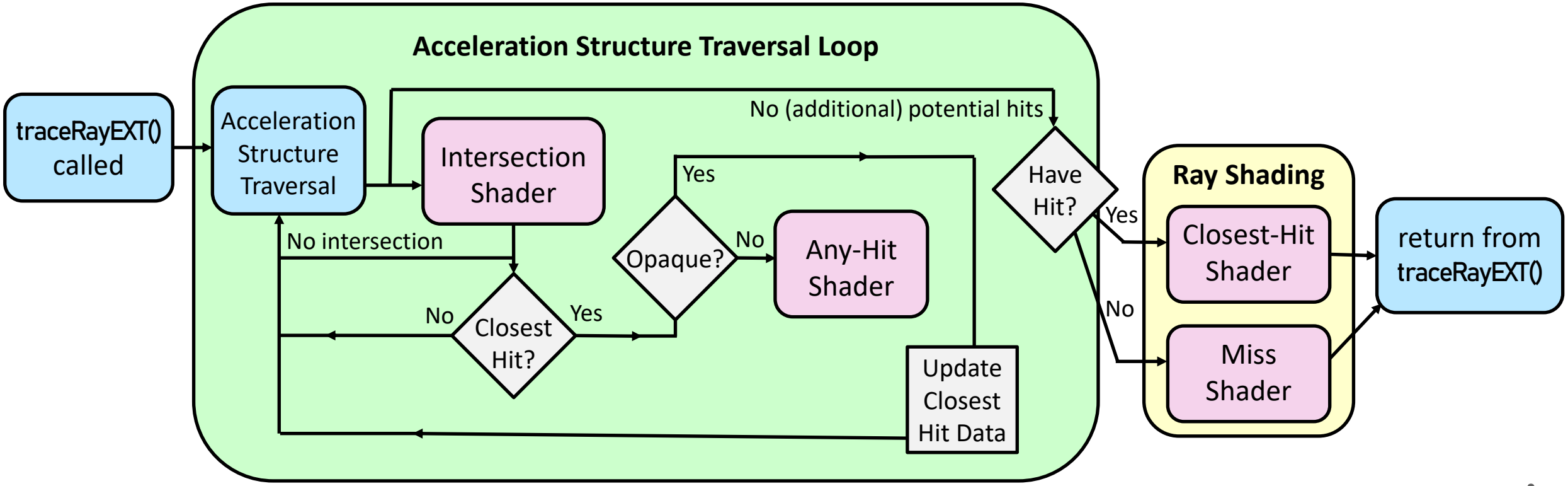
- Hit detected AND it is opaque
  - The new hit is our closest hit (so far!) => Update the closest hit data
  - Continue traversing the acceleration structure (search for closer hit)



Adapted from: Chris Wyman and Shawn Hargreaves and Peter Shirley and Colin Barré-Brisebois, Introduction to DirectX Raytracing, ACM SIGGRAPH 2018 Courses, https://intro-to-dxr.cwyman.org

Ray Tracing Pipeline in Depth

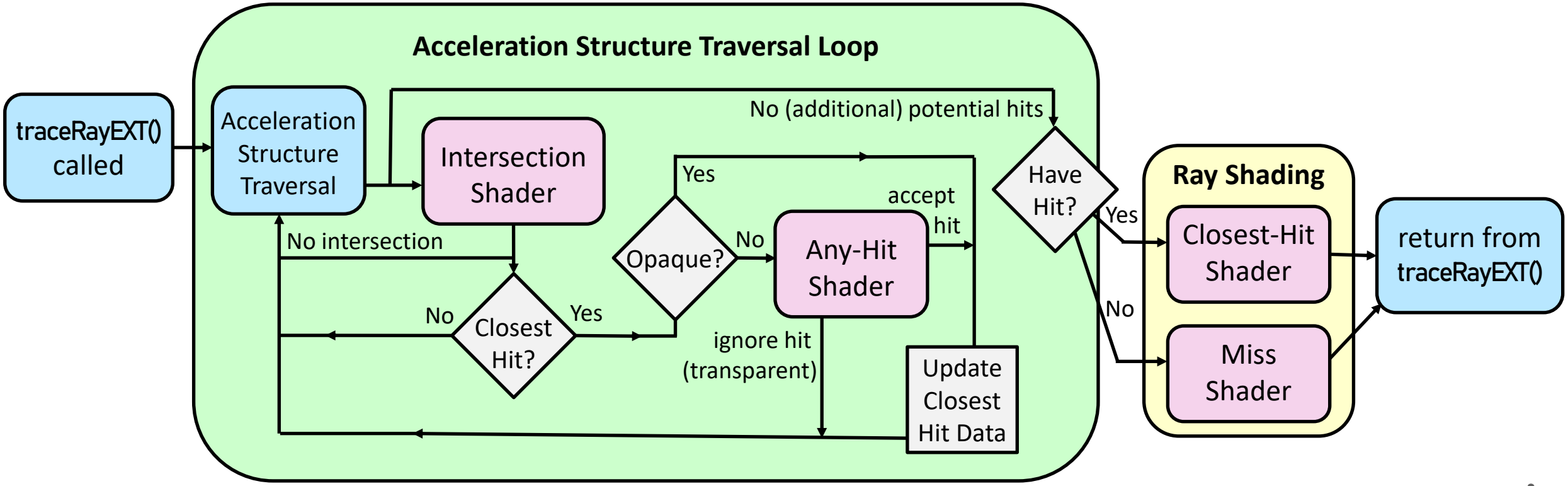
- Hit detected AND it is not opaque
  - => run the Any-Hit Shader



Adapted from: Chris Wyman and Shawn Hargreaves and Peter Shirley and Colin Barré-Brisebois, Introduction to DirectX Raytracing, ACM SIGGRAPH 2018 Courses, https://intro-to-dxr.cwyman.org

Ray Tracing Pipeline in Depth

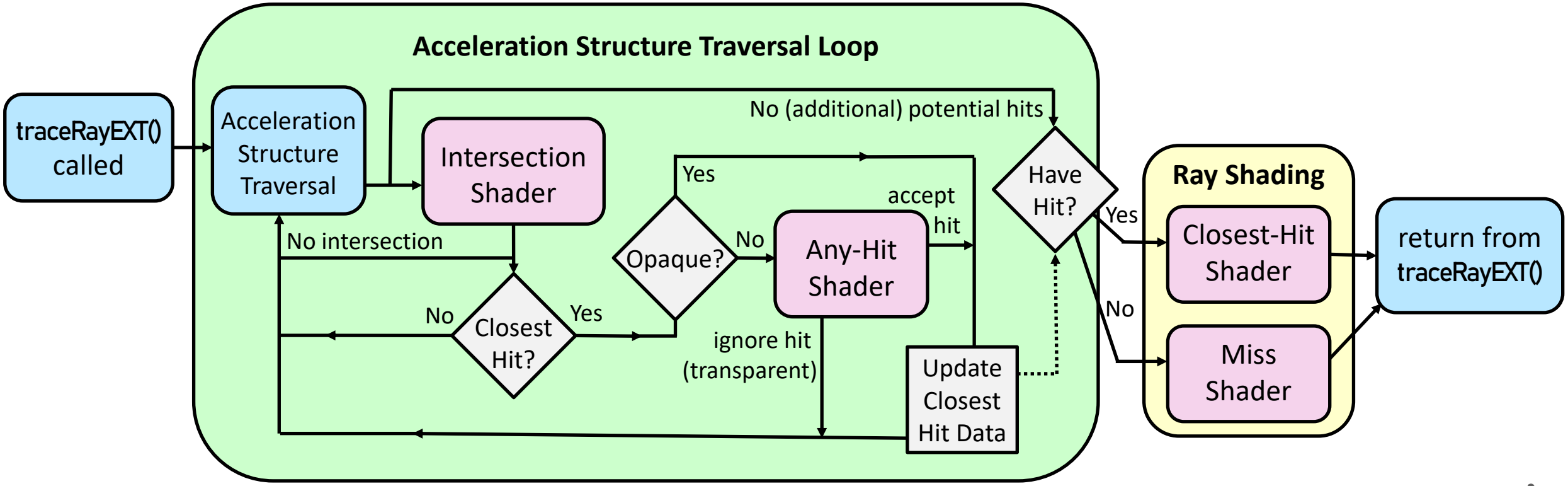
- In hit shader, accept or ignore the hit
  - Accept hit => Current hit becomes the new closest hit
  - In any case, continue traversing AS to look for closer intersections



Adapted from: Chris Wyman and Shawn Hargreaves and Peter Shirley and Colin Barré-Brisebois, Introduction to DirectX Raytracing, ACM SIGGRAPH 2018 Courses, https://intro-to-dxr.cwyman.org

Ray Tracing Pipeline in Depth

- Continue traversing AS until no closer hits discovered
  - Had a valid hit along the ray? => Shade via the Closest-Hit Shader
  - Didn't have valid hits? => Shade via the Miss Shader



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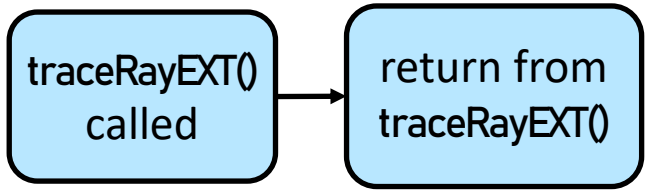
Ray Tracing Pipeline in Depth

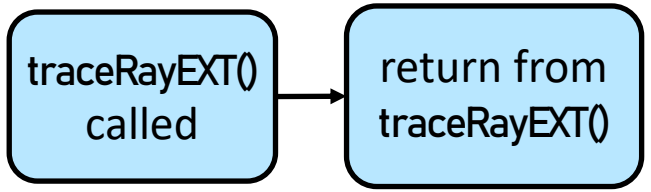
- Ray Generation Shader
- Per pixel: traceRayEXT()



Tracing All the Rays

Host-Side Code

- Ray Generation Shader
- Per pixel: traceRayEXT()



Ray Generation Shader (GLSL)

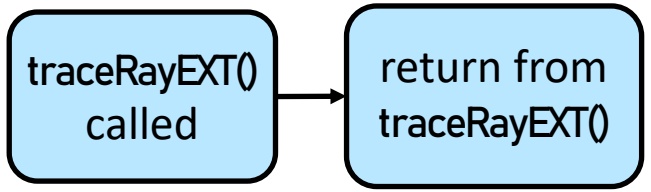
```
#version 460
#extension GL_EXT_ray_tracing : require

layout(set = 0, binding = 0) uniform accelerationStructureEXT as;
// ...
void main() {
  // ...
  traceRayEXT(as,
    gl_RayFlagsOpaqueEXT, 0xff,
    0 /*sbtRecordOffset*/, 0 /*sbtRecordStride*/, 0 /*missIndex*/,
    origin, 0.1, direction, 100.0,
    0 /*location of payload*/);
  // ...
}
```

```
vkCmdTraceRaysKHR(/* Record into this command buffer: */ commandBuffer,
    // Pass all the offsets for:
    // ray gen. shaders,   miss shaders,     and   hit groups (i.e. tuples of [closest hit], [any hit], [intersection])
    &rayGenStartAddr,     &missShaderStartAddr,   &hitGroupsStartAddr,
    &callableShadersStartAddr,
    // Specify ray tracing resolution of 1920 x 1080 x 1:
    1920, 1080, 1);
```

Host-Side Code

- Ray Generation Shader
- Per pixel: traceRayEXT()



Ray Generation Shader (GLSL)

```
#version 460
#extension GL_EXT_ray_tracing : require

layout(set = 0, binding = 0) uniform accelerationStructureEXT as;
// ...
void main() {
  // ...
  traceRayEXT(as,
    gl_RayFlagsOpaqueEXT, 0xff,
    0 /*sbtRecordOffset*/, 0 /*sbtRecordStride*/, 0 /*missIndex*/,
    origin, 0.1, direction, 100.0,
    0 /*location of payload*/);
  // ...
}
```

```
vkCmdTraceRaysKHR(/* Record into this command buffer: */ commandBuffer,
    // Pass all the offsets for:
    // ray gen. shaders,   miss shaders,     and   hit groups (i.e. tuples of [closest hit], [any hit], [intersection])
    &rayGenStartAddr,     &missShaderStartAddr,   &hitGroupsStartAddr,
    &callableShadersStartAddr,
    // Specify ray tracing resolution of 1920 x 1080 x 1:
    1920, 1080, 1);
```

Shader Binding Table

Shader Binding Table

Shader Binding Table		

Ray Generation Shader (GLSL)

```
#version 460
#extension GL_EXT_ray_tracing : require

layout(set = 0, binding = 0) uniform accelerationStructureEXT as;
// ...
void main() {
  // ...
  traceRayEXT(as,
    gl_RayFlagsOpaqueEXT, 0xff,
    0 /*sbtRecordOffset*/, 0 /*sbtRecordStride*/, 0 /*missIndex*/,
    origin, 0.1, direction, 100.0,
    0 /*location of payload*/);
  // ...
}
```

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    // Pass all the offsets for:
    // ray gen. shaders,   miss shaders,     and   hit groups (i.e. tuples of [closest hit], [any hit], [intersection])
    &rayGenStartAddr,     &missShaderStartAddr,   &hitGroupsStartAddr,
    &callableShadersStartAddr,
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    1920, 1080, 1);
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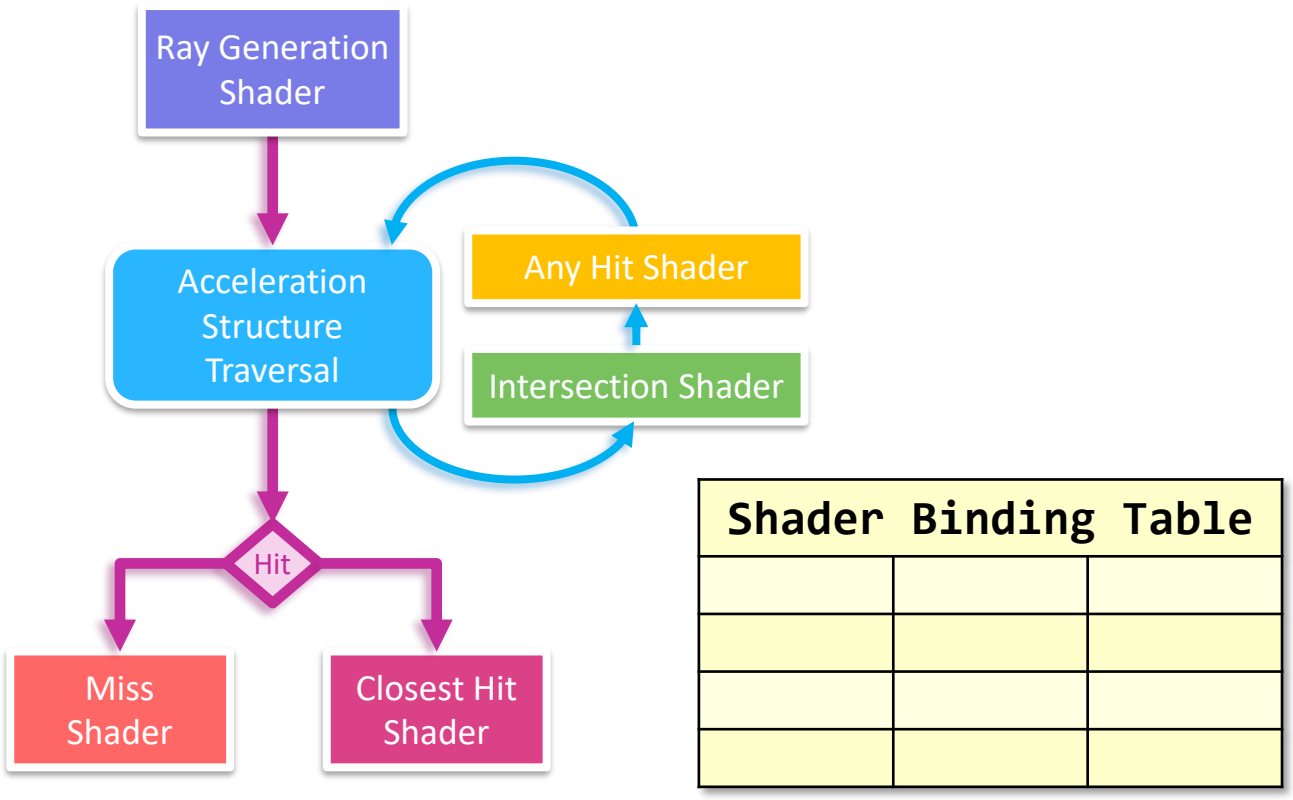
Shader Binding Table

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vkCmdTraceRaysKHR(/* Record into this command buffer: */ commandBuffer,
    // Pass all the offsets for:
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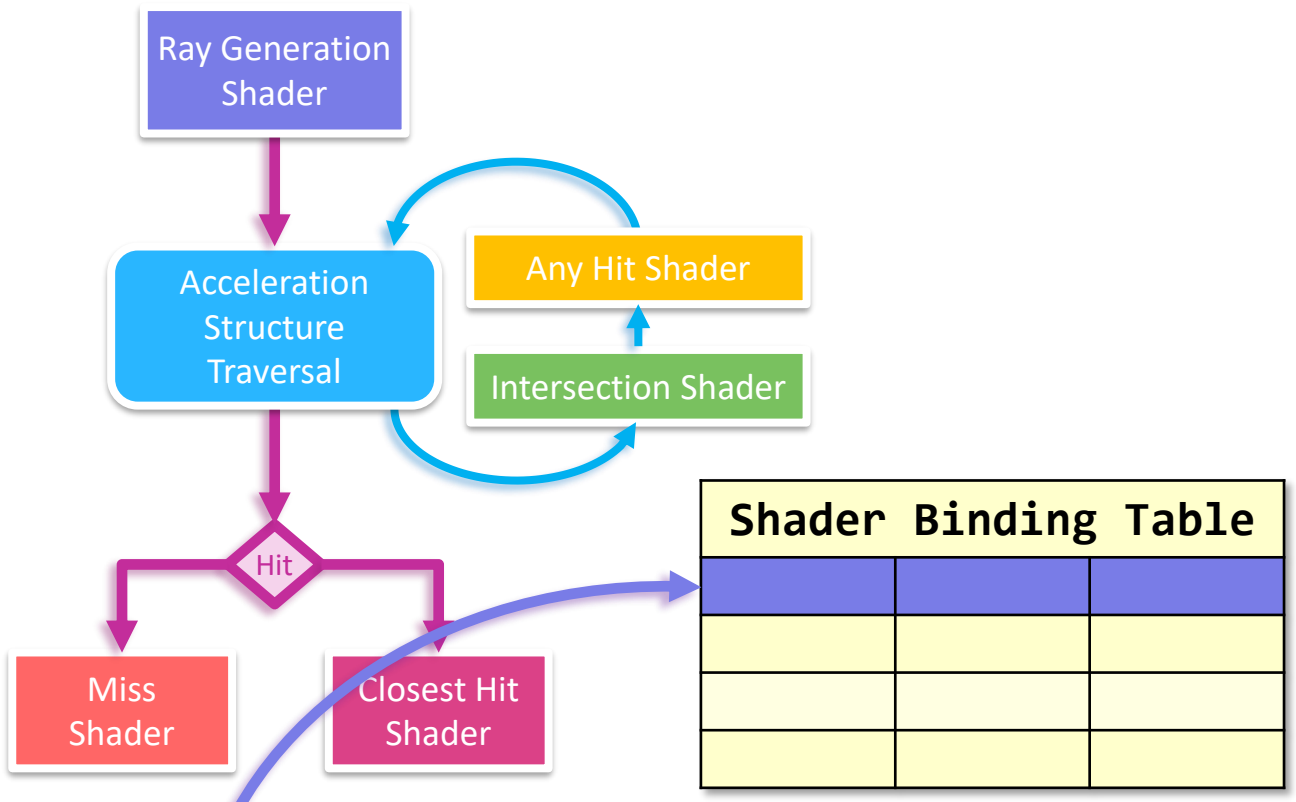
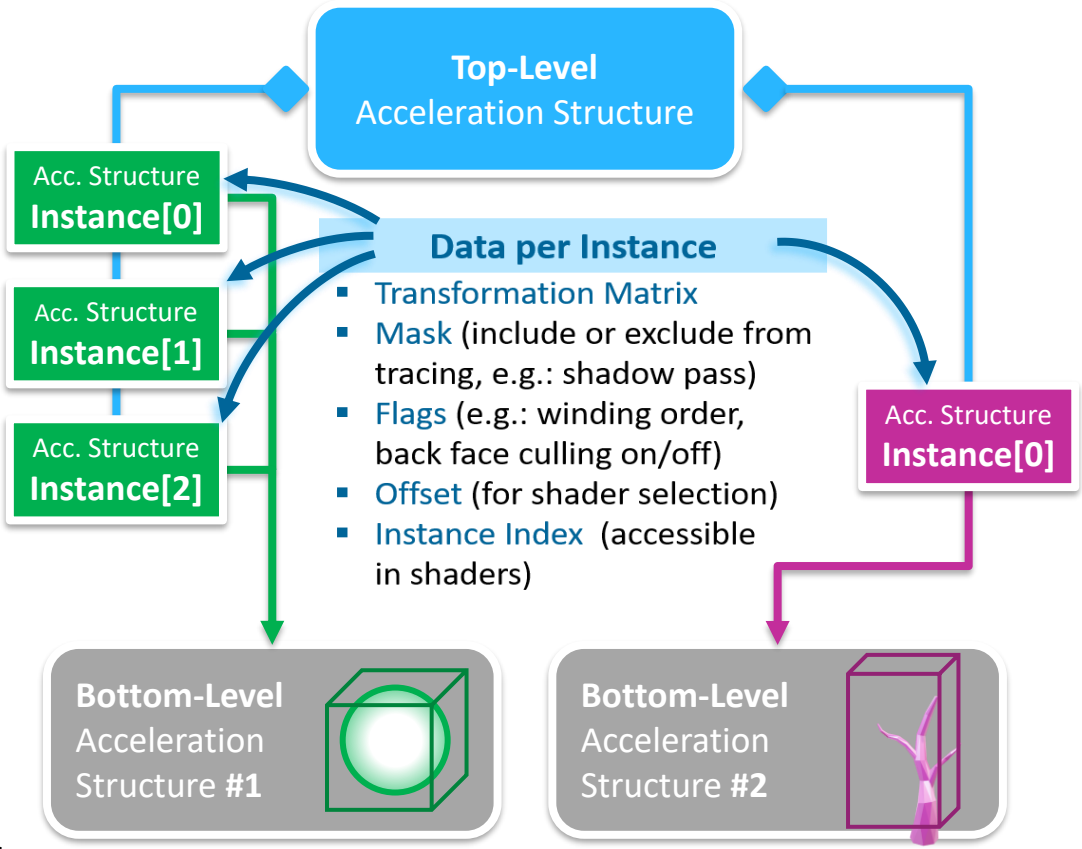
Shader Binding Table



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vkCmdTraceRaysKHR(/* Record into this command buffer: */ commandBuffer,
    // Pass all the offsets for:
    // ray gen. shaders,   miss shaders,     and   hit groups (i.e. tuples of [closest hit], [any hit], [intersection])
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    &callableShadersStartAddr,
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    1920, 1080, 1);
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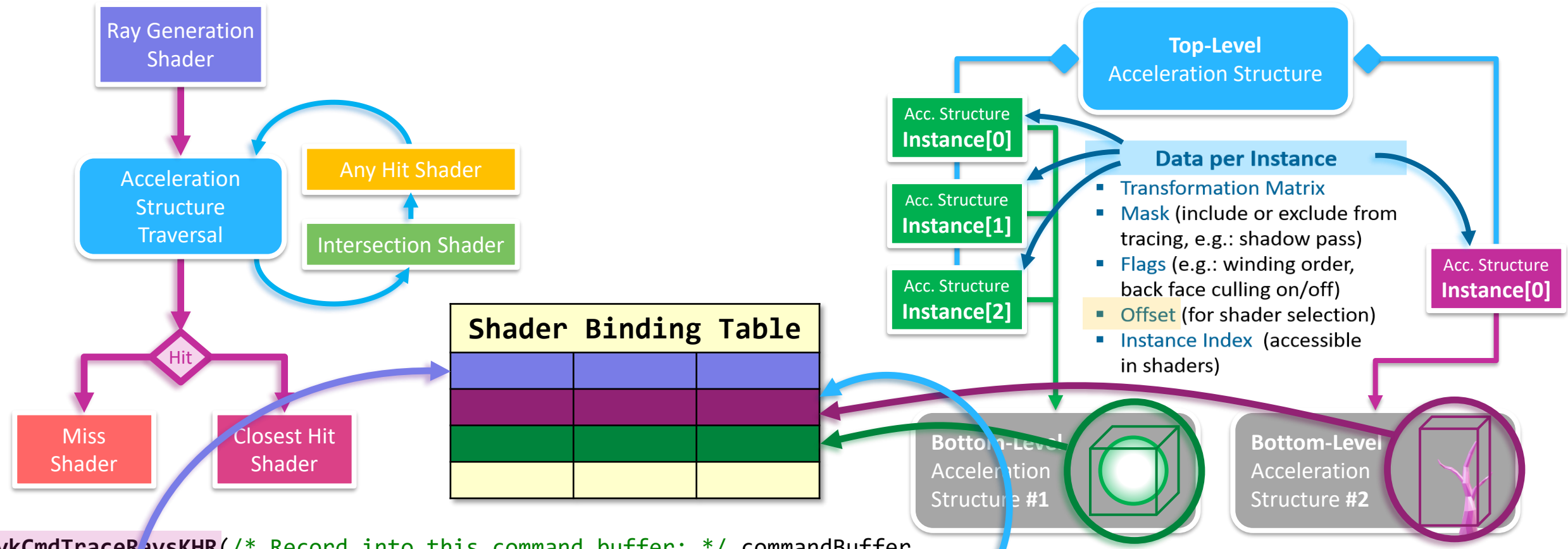
Shader Binding Table




```
vkCmdTraceRaysKHR(/* Record into this command buffer: */ commandBuffer,
    // Pass all the offsets for:
    // ray gen. shaders,   miss shaders,     and   hit groups (i.e. tuples of [closest hit], [any hit], [intersection])
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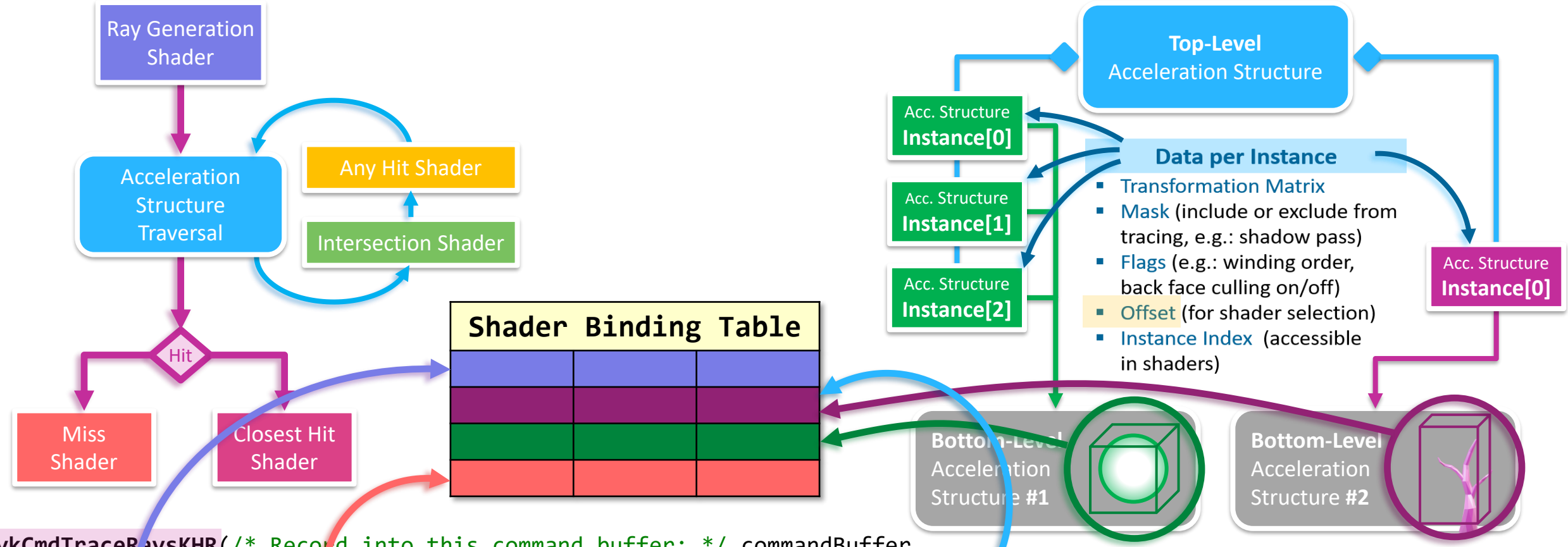
Shader Binding Table




```
vkCmdTraceRaysKHR(/* Record into this command buffer: */ commandBuffer,
    // Pass all the offsets for:
    // ray gen. shaders,  miss shaders,  and  hit groups (i.e. tuples of [closest hit], [any hit], [intersection])
    &rayGenStartAddr,  &missShaderStartAddr,  &hitGroupsStartAddr,
    &callableShadersStartAddr,
    // Specify ray tracing resolution of 1920 x 1080 x 1:
    1920, 1080, 1);
```

Shader Binding Table

```
VkStridedDeviceAddressRegionKHR rayGenOffsets{ rayGenBufferDeviceAddress };
rayGenOffsets.stride = 32;        // <-- TODO: query via VkPhysicalDeviceRayTracingPipelinePropertiesKHR
rayGenOffsets.size = rayGenOffsets.stride * numberOfRayGenShaders;

VkStridedDeviceAddressRegionKHR missShaderOffsets{ rayMissBufferDeviceAddress };
missShaderOffsets.stride = 32;    // <-- TODO: query via VkPhysicalDeviceRayTracingPipelinePropertiesKHR
missShaderOffsets.size = missShaderOffsets.stride * numberOfMissShaders;

VkStridedDeviceAddressRegionKHR hitGroupsOffsets{ rayHitBufferDeviceAddress };
hitGroupsOffsets.stride = 32;     // <-- TODO: query via VkPhysicalDeviceRayTracingPipelinePropertiesKHR
hitGroupsOffsets.size = hitGroupsOffsets.stride * numberOfHitGroups;

VkStridedDeviceAddressRegionKHR callableShaderOffsets{};

vkCmdTraceRaysKHR(/* Record into this command buffer: */ commandBuffer,
    // Pass all the offsets for:
    // ray gen. shaders,   miss shaders,     and   hit groups (i.e. tuples of [closest hit], [any hit], [intersection])
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    &callableShadersStartAddr,
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Shader Binding Table

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VkStridedDeviceAddressRegionKHR missShaderOffsets{ rayMissBufferDeviceAddress };
missShaderOffsets.stride = 32;   // <-- TODO: query via VkPhysicalDeviceRayTracingPipelinePropertiesKHR
missShaderOffsets.size = missShaderOffsets.stride * numberOfMissShaders;

VkStridedDeviceAddressRegionKHR hitGroupsOffsets{ rayHitBufferDeviceAddress };
hitGroupsOffsets.stride = 32;    // <-- TODO: query via VkPhysicalDeviceRayTracingPipelinePropertiesKHR
hitGroupsOffsets.size = hitGroupsOffsets.stride * numberOfHitGroups;

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vkCmdTraceRaysKHR(/* Record into this command buffer: */ commandBuffer,
    // Pass all the offsets for:
    // ray gen. shaders,   miss shaders,     and   hit groups (i.e. tuples of [closest hit], [any hit], [intersection])
    &rayGenStartAddr,     &missShaderStartAddr,   &hitGroupsStartAddr,
    &callableShadersStartAddr,
    // Specify ray tracing resolution of 1920 x 1080 x 1:
    1920, 1080, 1);
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Shader Binding Table

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rayGenOffsets.stride = 32;        // <-- TODO: query via VkPhysicalDeviceRayTracingPipelinePropertiesKHR
rayGenOffsets.size = rayGenOffsets.stride * numberOfRayGenShaders;

VkStridedDeviceAddressRegionKHR missShaderOffsets{ rayMissBufferDeviceAddress };
missShaderOffsets.stride = 32;    // <-- TODO: query via VkPhysicalDeviceRayTracingPipelinePropertiesKHR
missShaderOffsets.size = missShaderOffsets.stride * numberOfMissShaders;

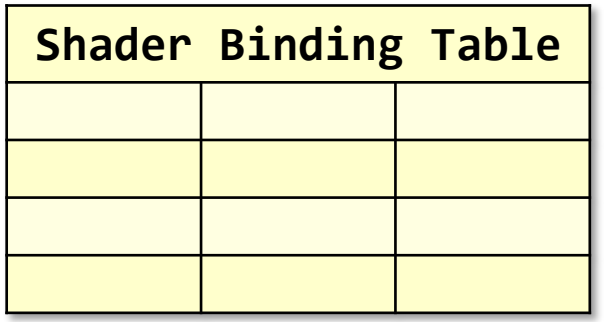
VkStridedDeviceAddressRegionKHR hitGroupsOffsets{ rayHitBufferDeviceAddress };
hitGroupsOffsets.stride = 32;     // <-- TODO: query via VkPhysicalDeviceRayTracingPipelinePropertiesKHR
hitGroupsOffsets.size = hitGroupsOffsets.stride * numberOfHitGroups;

VkStridedDeviceAddressRegionKHR callableShaderOffsets{};

vkCmdTraceRaysKHR(/* Record into this command buffer: */ commandBuffer,
    // Pass all the offsets for:
    // ray gen. shaders,   miss shaders,     and   hit groups (i.e. tuples of [closest hit], [any hit], [intersection])
    &rayGenStartAddr,     &missShaderStartAddr,   &hitGroupsStartAddr,
    &callableShadersStartAddr,
    // Specify ray tracing resolution of 1920 x 1080 x 1:
    1920, 1080, 1);
```

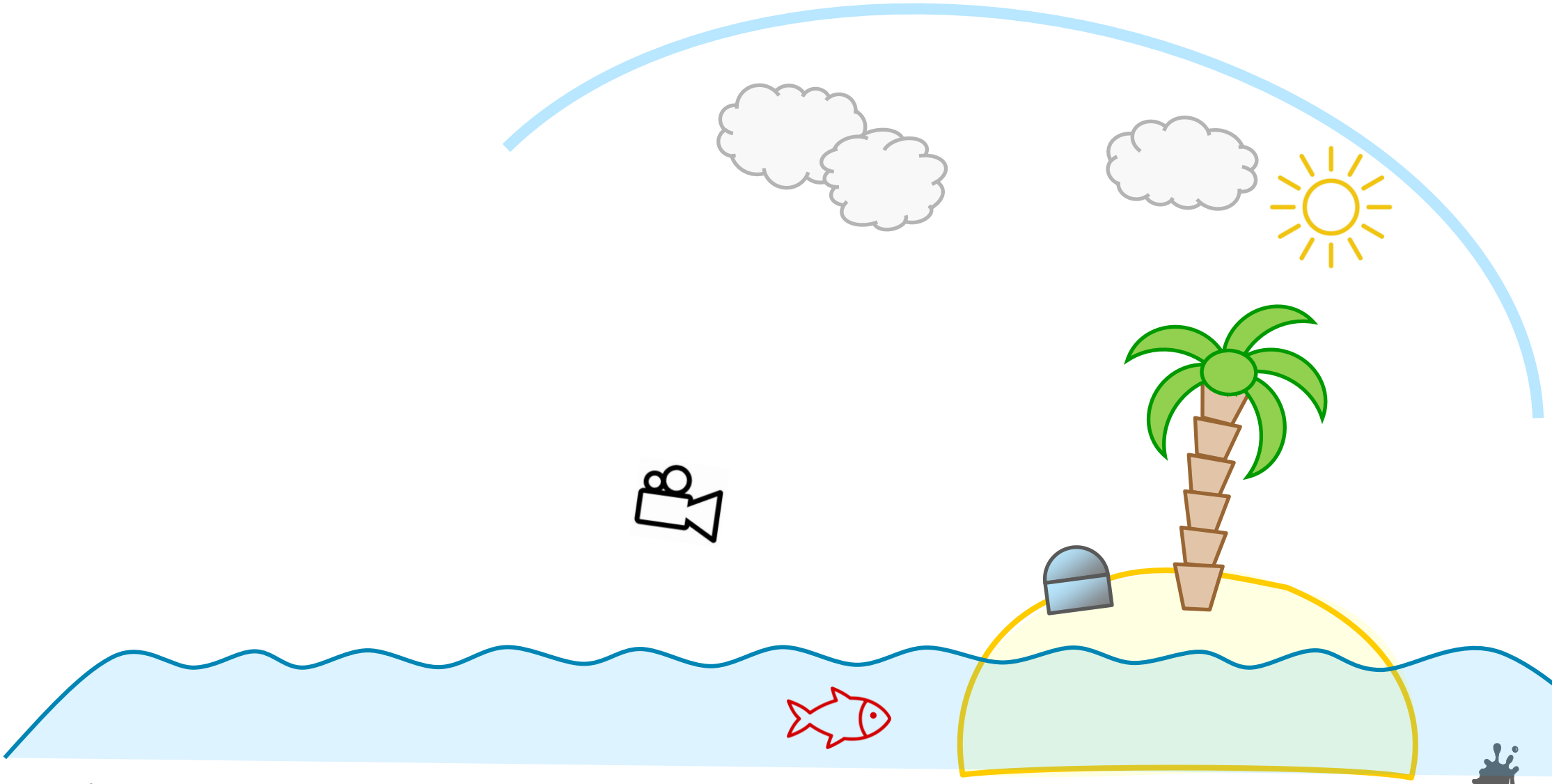

Shader Binding Table

- Shader Binding Table is a buffer
  - VK_BUFFER_USAGE_SHADER_BINDING_TABLE_BIT_KHR
  - VK_BUFFER_USAGE_SHADER_DEVICE_ADDRESS_BIT
  - Addresses are passed to vkCmdTraceRaysKHR()



- **One** shader binding table **entry** refers to 1, 2, or 3 shaders ("**Shader Group**")
  - E.g.: One specific **ray generation** shader (**"General Group"**)
  - E.g.: One specific **miss** shader (**"General Group"**)
  - E.g.: A group of shaders for when geometry was **hit** ("**Hit Group**")
    - E.g.: Closest hit shader only for opaque triangle mesh (**"Triangle Hit Group"**)
    - E.g.: Closest hit + any hit for a transparent triangle mesh (^ same ^)
    - E.g.: Closest hit + any hit + intersection for a **"Procedural Hit Group"**

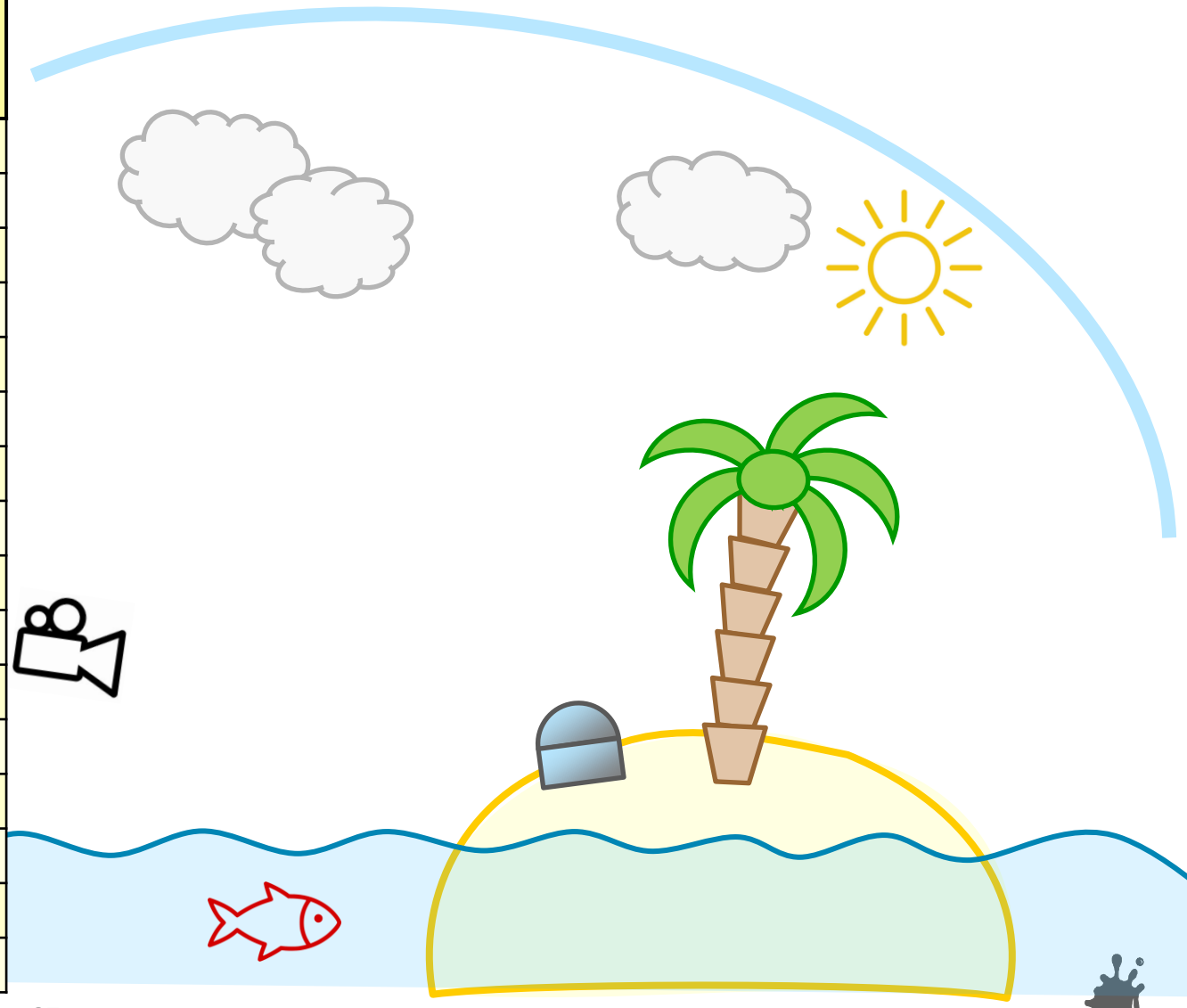
Shader Binding Table Example



Shader Binding Table Example

vkCmdTraceRaysKHR with rayGenAddr = start + 0 * stride, missAddr = start + 14 * stride, hitGroupsAddr = start + 1 * stride;

Shader Binding Table			
Idx	*[Closest Hit Shader]*	*[Any Hit Shader]*	*[Intersection Shader]*
0			
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			

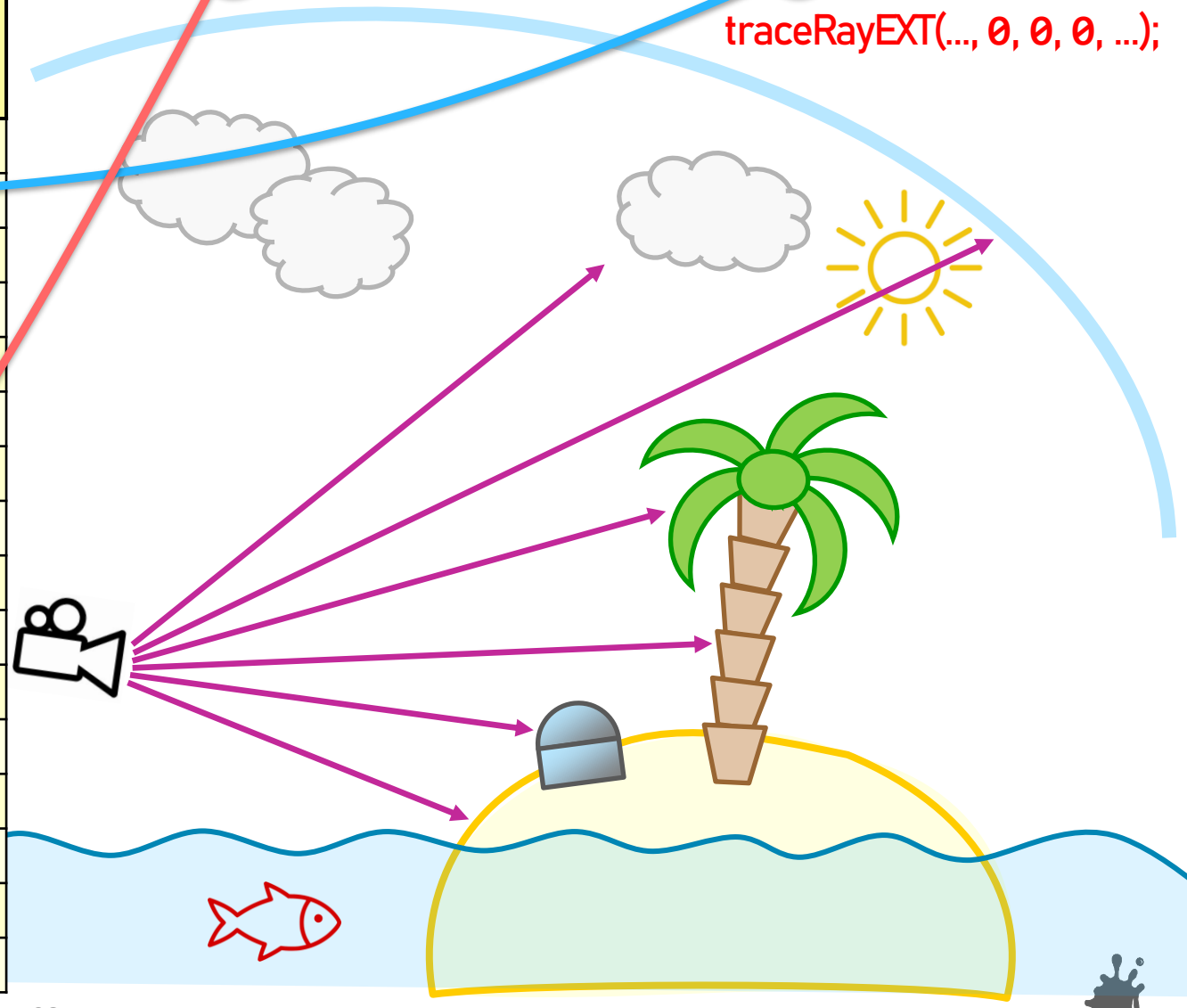


Shader Binding Table Example

vkCmdTraceRaysKHR with rayGenAddr = start + 0 * stride, missAddr = start + 14 * stride, hitGroupsAddr = start + 1 * stride;

traceRayEXT(..., 0, 0, 0, ...);

Shader Binding Table			
Idx	*[Closest Hit Shader]*	*[Any Hit Shader]*	*[Intersection Shader]*
0	*Ray Generation Shader:* GenerateRaysAndStoreResults		
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			

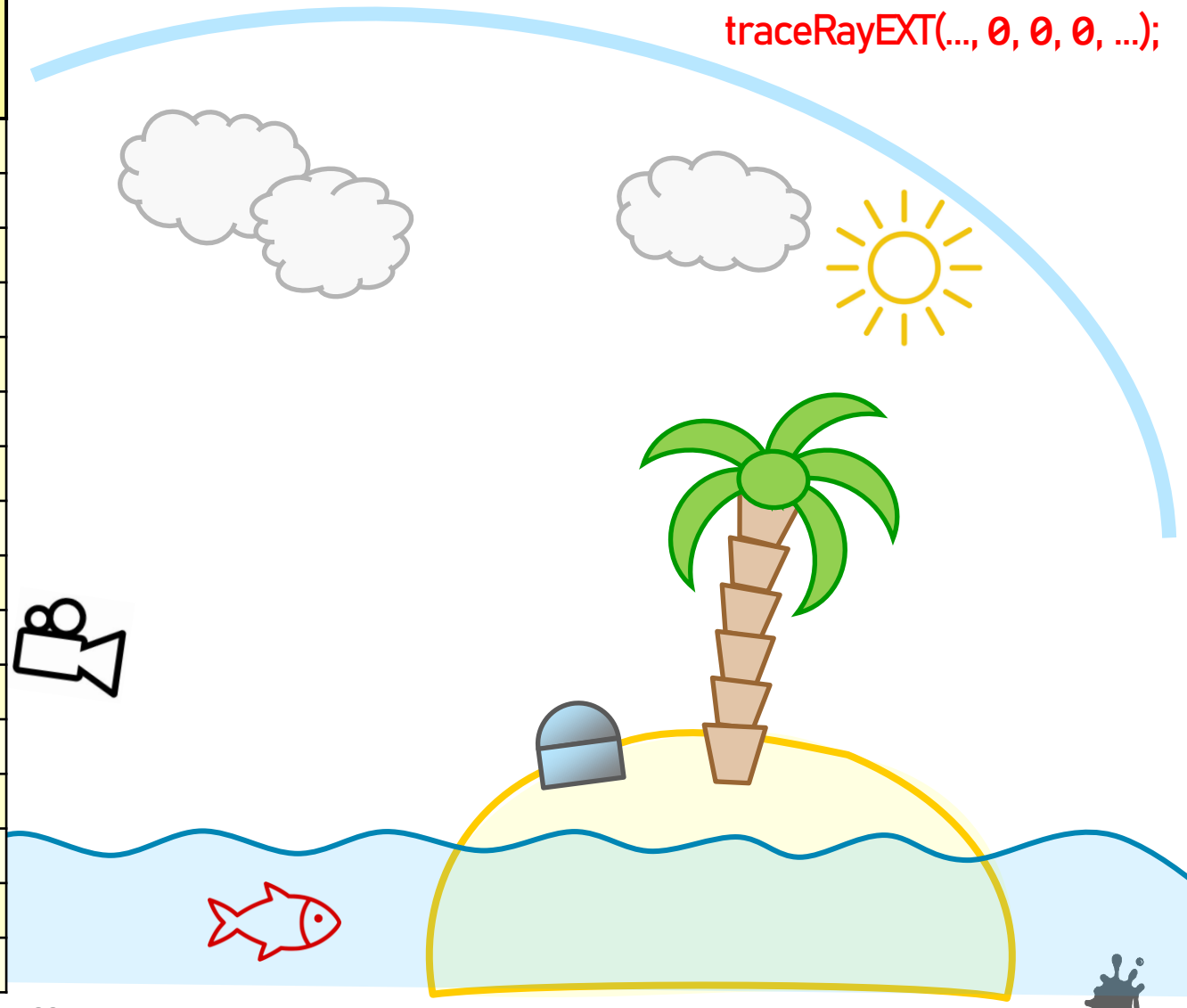


Shader Binding Table Example

vkCmdTraceRaysKHR with rayGenAddr = start + 0 * stride, missAddr = start + 14 * stride, hitGroupsAddr = start + 1 * stride;

Shader Binding Table			
Idx	*[Closest Hit Shader]*	*[Any Hit Shader]*	*[Intersection Shader]*
0	*Ray Generation Shader:* GenerateRaysAndStoreResults		
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			

traceRayEXT(..., 0, 0, 0, ...);

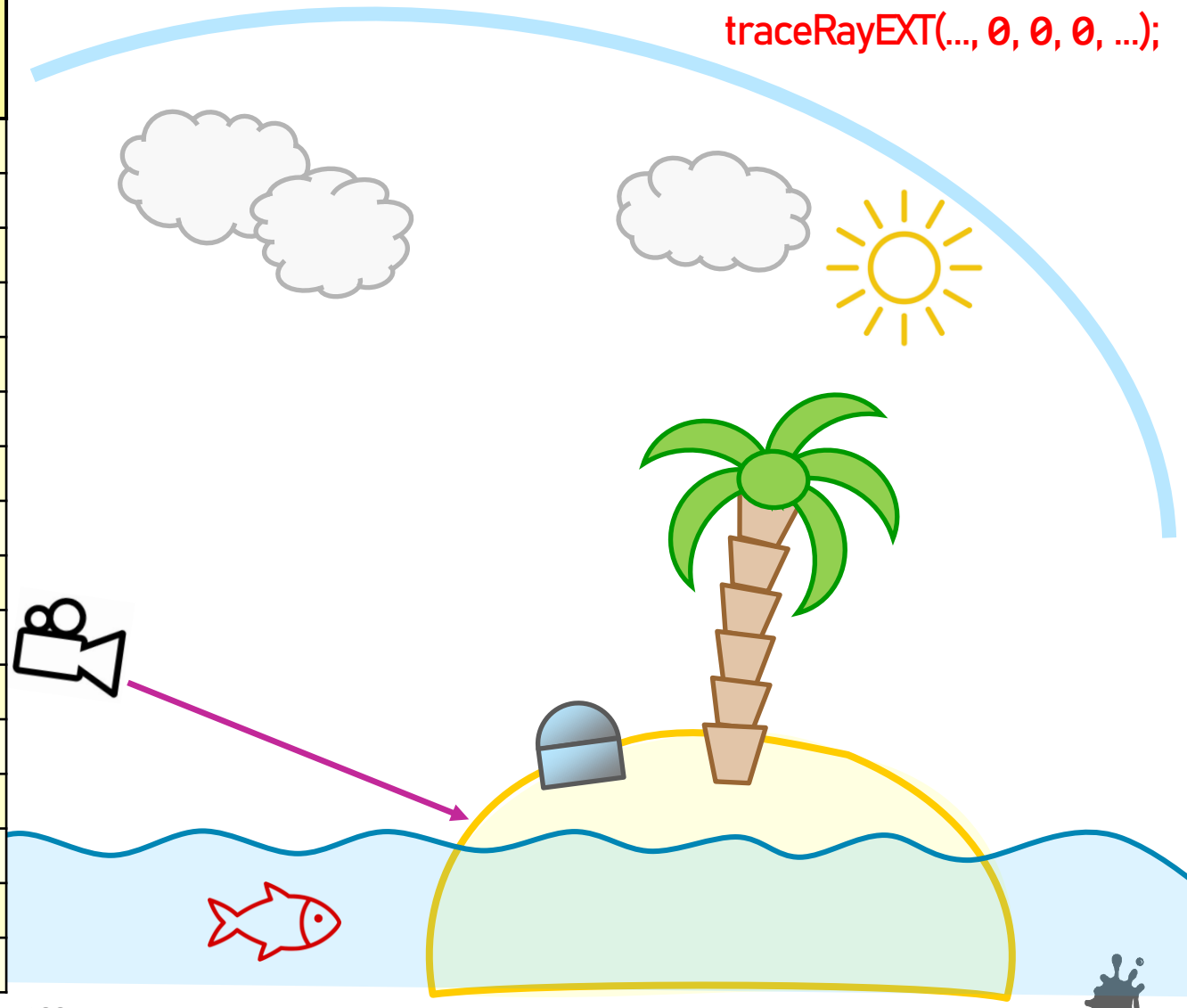


Shader Binding Table Example

vkCmdTraceRaysKHR with rayGenAddr = start + 0 * stride, missAddr = start + 14 * stride, hitGroupsAddr = start + 1 * stride;

Shader Binding Table			
Idx	*[Closest Hit Shader]*	*[Any Hit Shader]*	*[Intersection Shader]*
0	*Ray Generation Shader:* GenerateRaysAndStoreResults		
1	ShadeTerrain	-	Triangles (built-in)
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			

traceRayEXT(..., 0, 0, 0, ...);

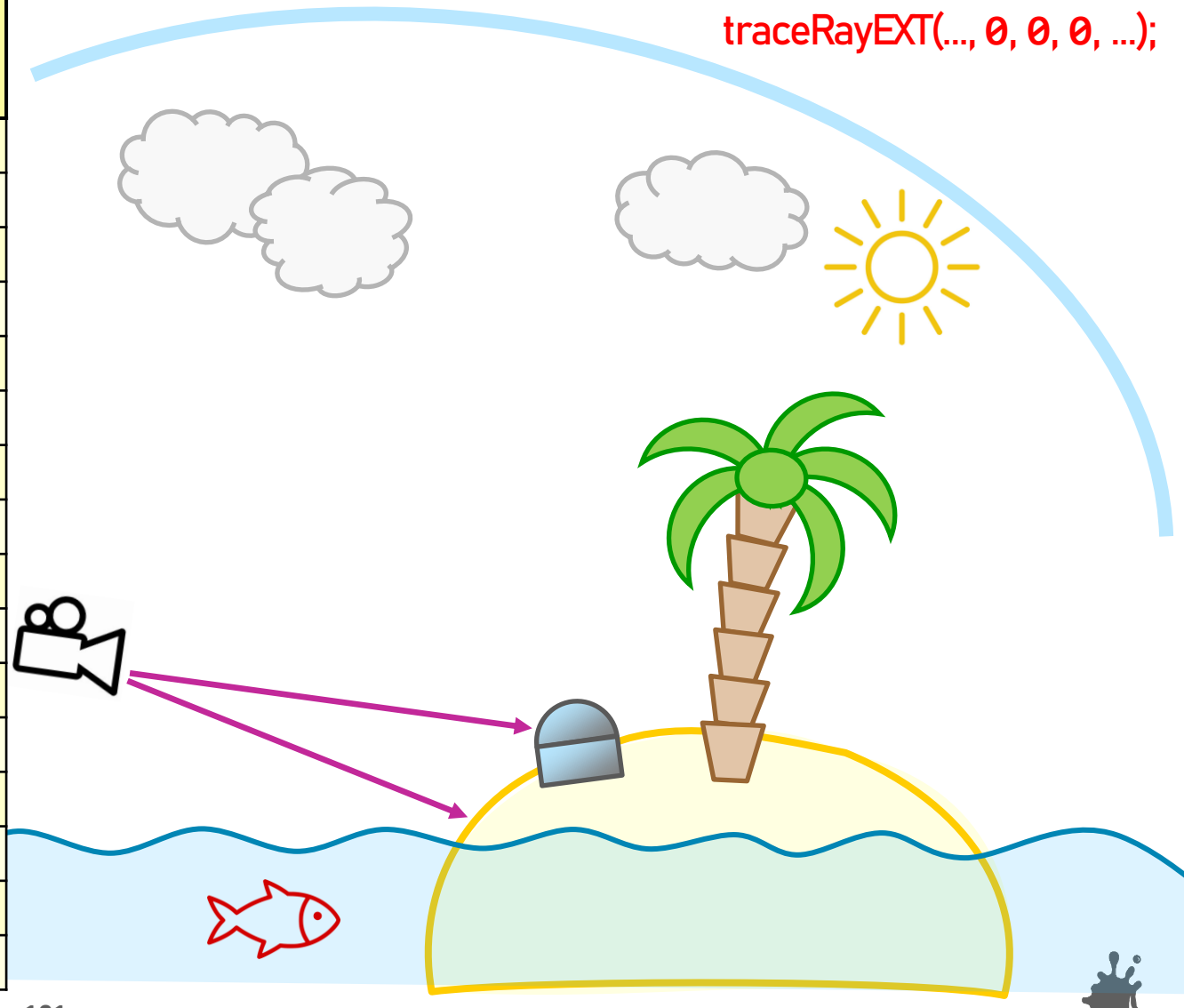


Shader Binding Table Example

vkCmdTraceRaysKHR with rayGenAddr = start + 0 * stride, missAddr = start + 14 * stride, hitGroupsAddr = start + 1 * stride;

Shader Binding Table			
Idx	*[Closest Hit Shader]*	*[Any Hit Shader]*	*[Intersection Shader]*
0	*Ray Generation Shader:* GenerateRaysAndStoreResults		
1	ShadeTerrain	-	Triangles (built-in)
2	ShadeTreasure	-	Triangles (built-in)
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			

traceRayEXT(..., 0, 0, 0, ...);

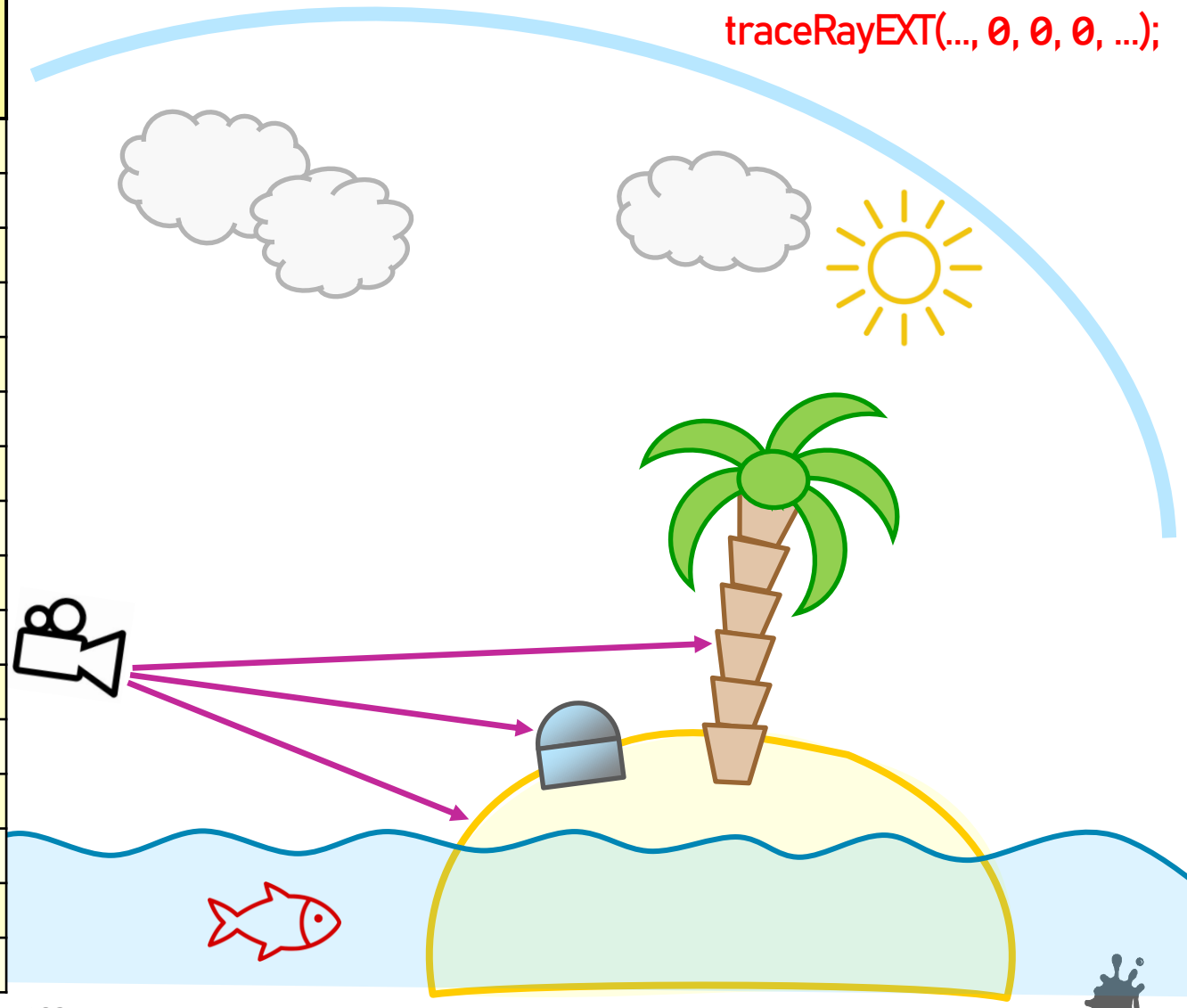


Shader Binding Table Example

vkCmdTraceRaysKHR with rayGenAddr = start + 0 * stride, missAddr = start + 14 * stride, hitGroupsAddr = start + 1 * stride;

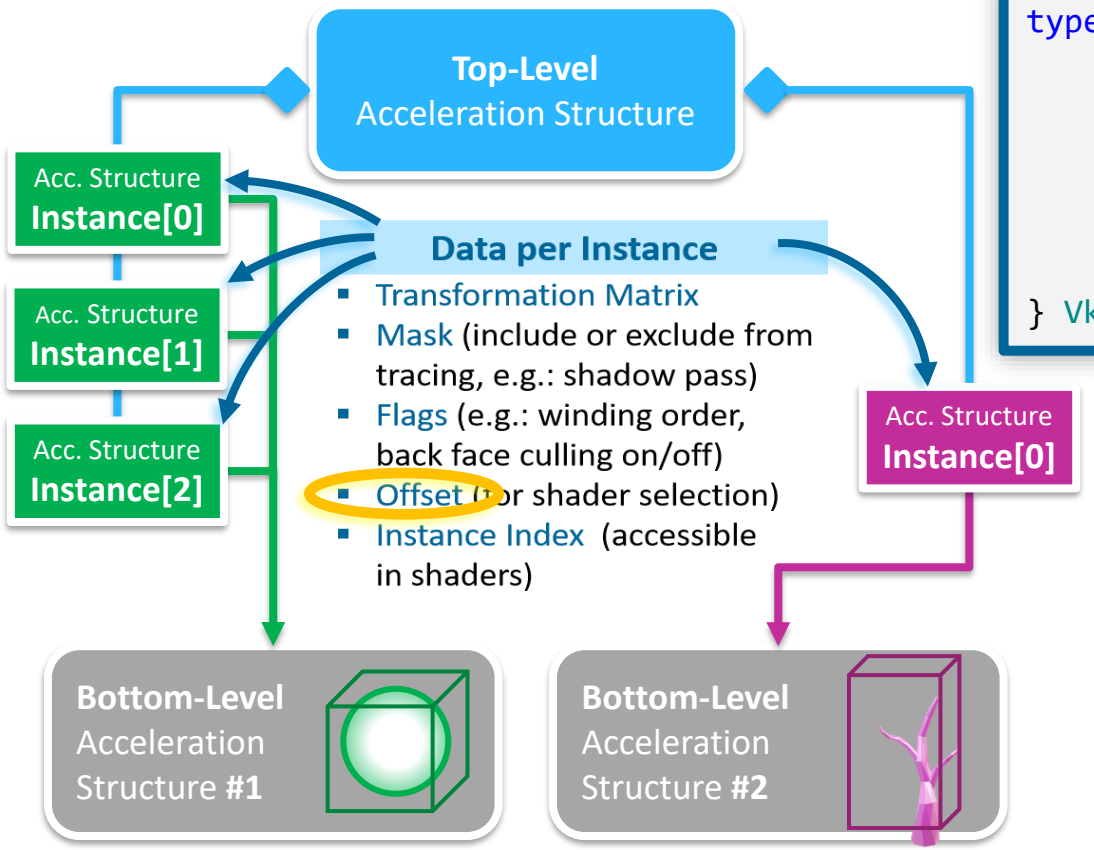
Shader Binding Table			
Idx	*[Closest Hit Shader]*	*[Any Hit Shader]*	*[Intersection Shader]*
0	*Ray Generation Shader:* GenerateRaysAndStoreResults		
1	ShadeTerrain	-	Triangles (built-in)
2	ShadeTreasure	-	Triangles (built-in)
3	ShadePalmTreeTrunk	-	Triangles (built-in)
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			

traceRayEXT(..., 0, 0, 0, ...);

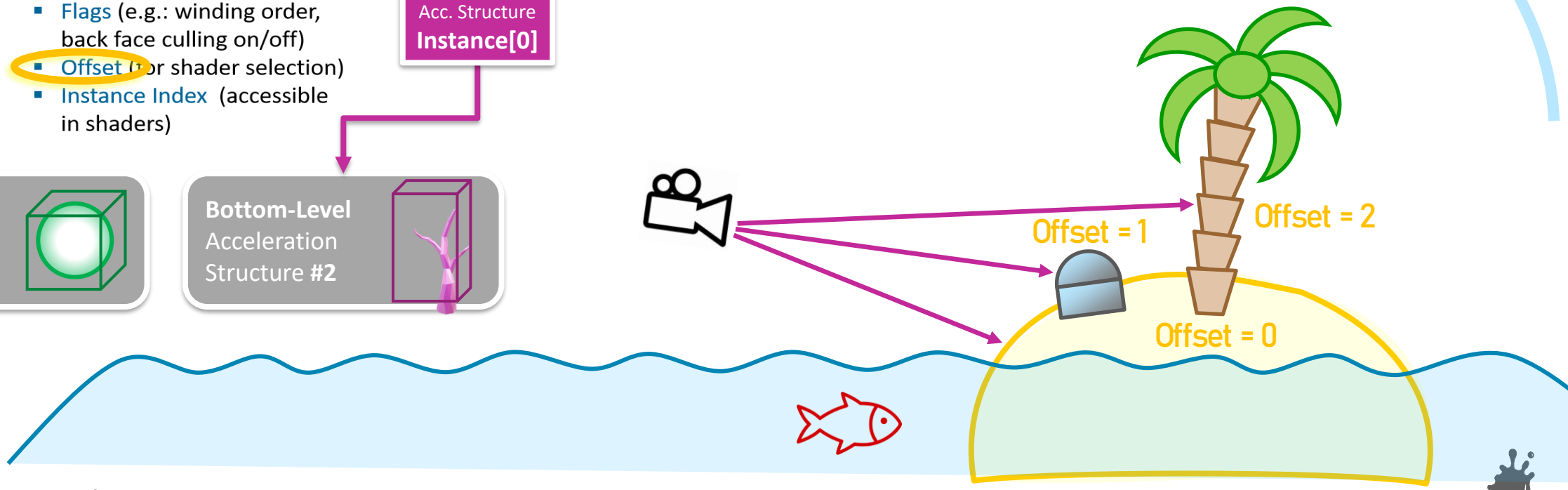


Shader Binding Table Example

vkCmdTraceRaysKHR with rayGenAddr = start + 0 * stride, missAddr = start + 14 * stride, hitGroupsAddr = start + 1 * stride;



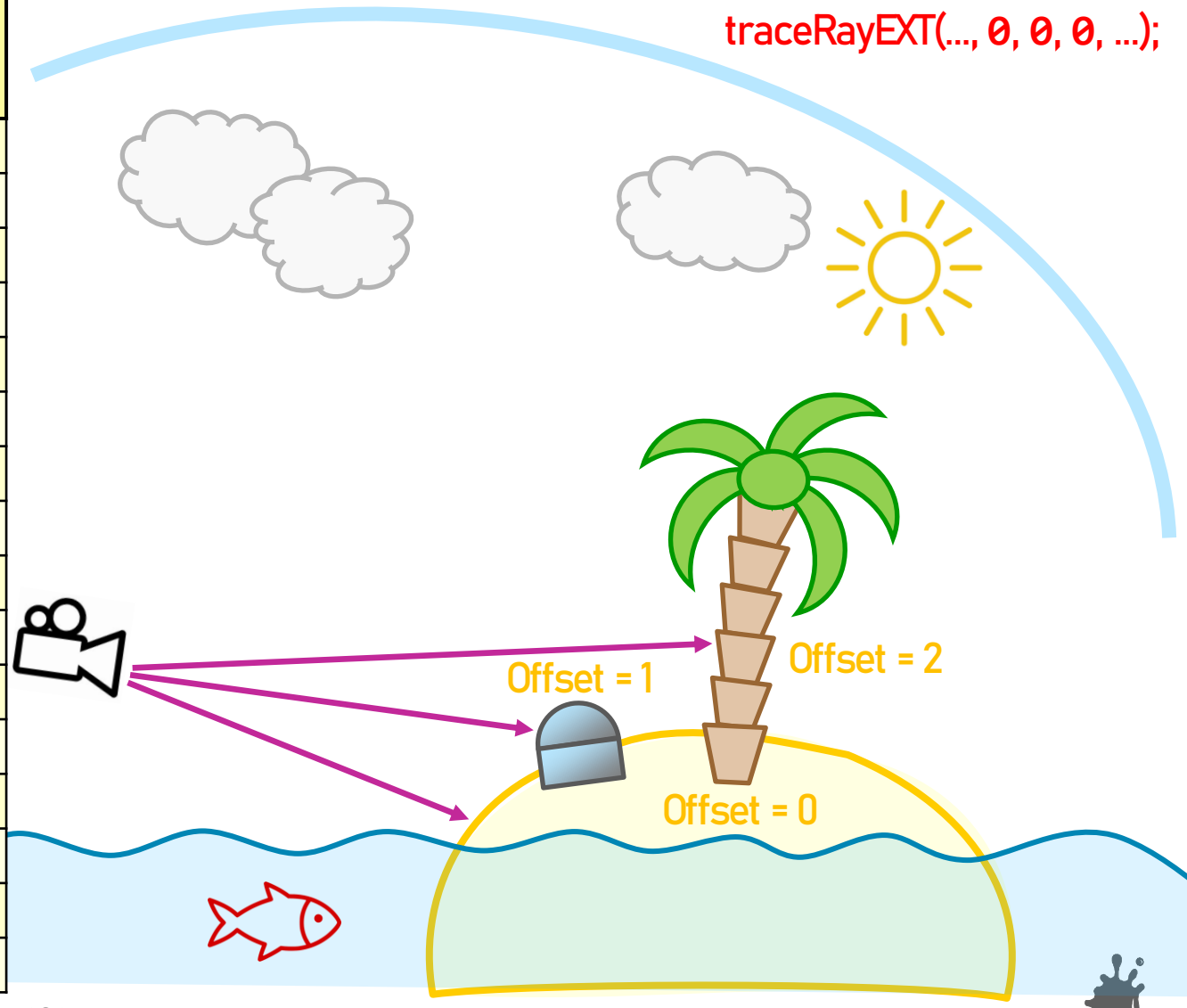

```
typedef struct VkAccelerationStructureInstanceKHR {
    VkTransformMatrixKHR          transform;
    uint32_t                      instanceCustomIndex:24;
    uint32_t                      mask:8;
    uint32_t                      instanceShaderBindingTableRecordOffset:24;
    VkGeometryInstanceFlagsKHR    flags:8;
    uint64_t                      accelerationStructureReference;
} VkAccelerationStructureInstanceKHR;
```



Shader Binding Table Example

vkCmdTraceRaysKHR with rayGenAddr = start + 0 * stride, missAddr = start + 14 * stride, hitGroupsAddr = start + 1 * stride;

Shader Binding Table			
Idx	*[Closest Hit Shader]*	*[Any Hit Shader]*	*[Intersection Shader]*
0	*Ray Generation Shader:* GenerateRaysAndStoreResults		
1	ShadeTerrain	-	Triangles (built-in)
2	ShadeTreasure	-	Triangles (built-in)
3	ShadePalmTreeTrunk	-	Triangles (built-in)
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			



Shader Binding Table Example

vkCmdTraceRaysKHR with rayGenAddr = start + 0 * stride, missAddr = start + 14 * stride, hitGroupsAddr = start + 1 * stride;

Shader Binding Table			
Idx	*[Closest Hit Shader]*	*[Any Hit Shader]*	*[Intersection Shader]*
0	*Ray Generation Shader:* GenerateRaysAndStoreResults		
1	ShadeTerrain	-	Triangles (built-in)
2	ShadeTreasure	-	Triangles (built-in)
3	ShadePalmTreeTrunk	-	Triangles (built-in)
4			
5			
6			
7			
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12			
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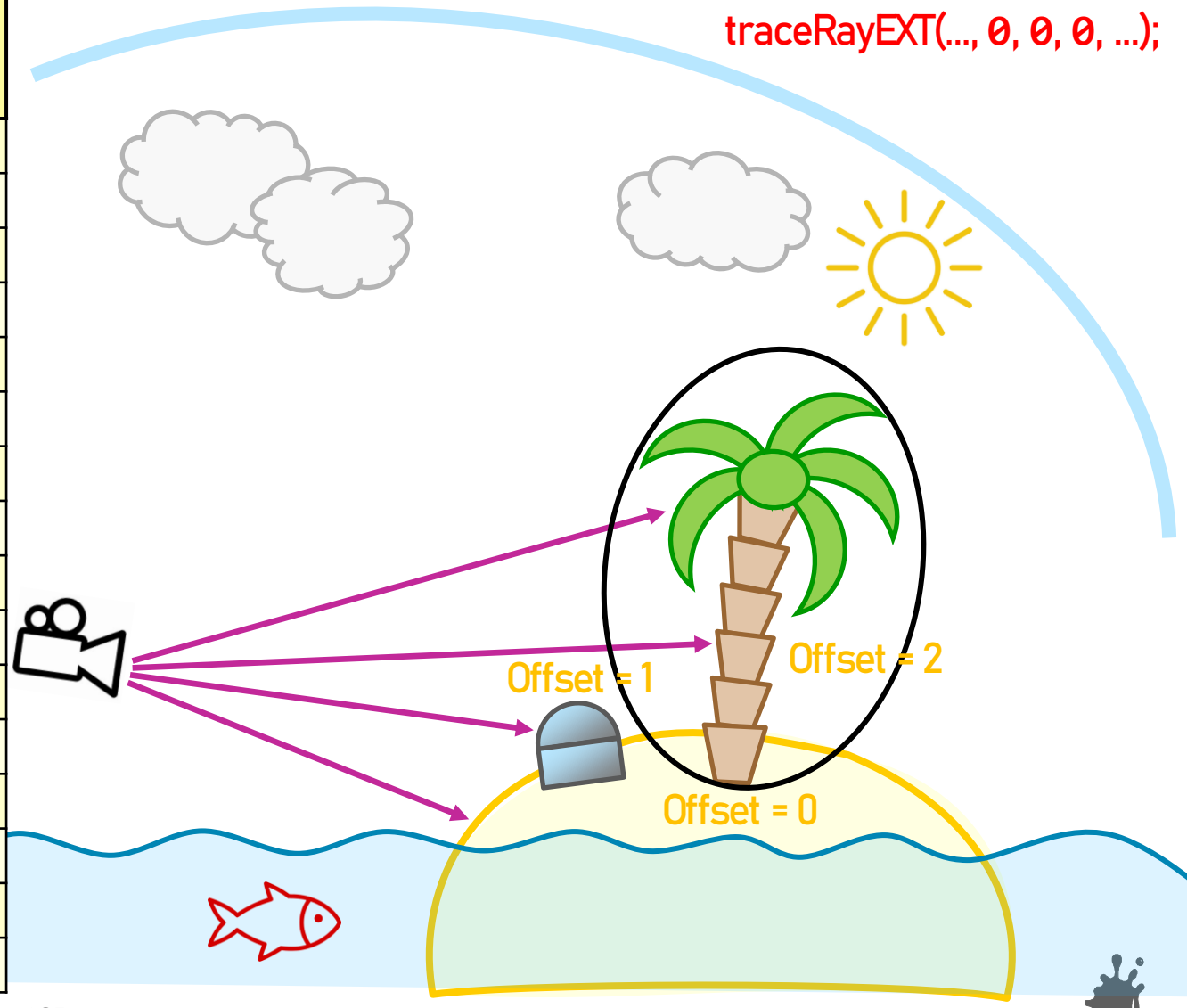
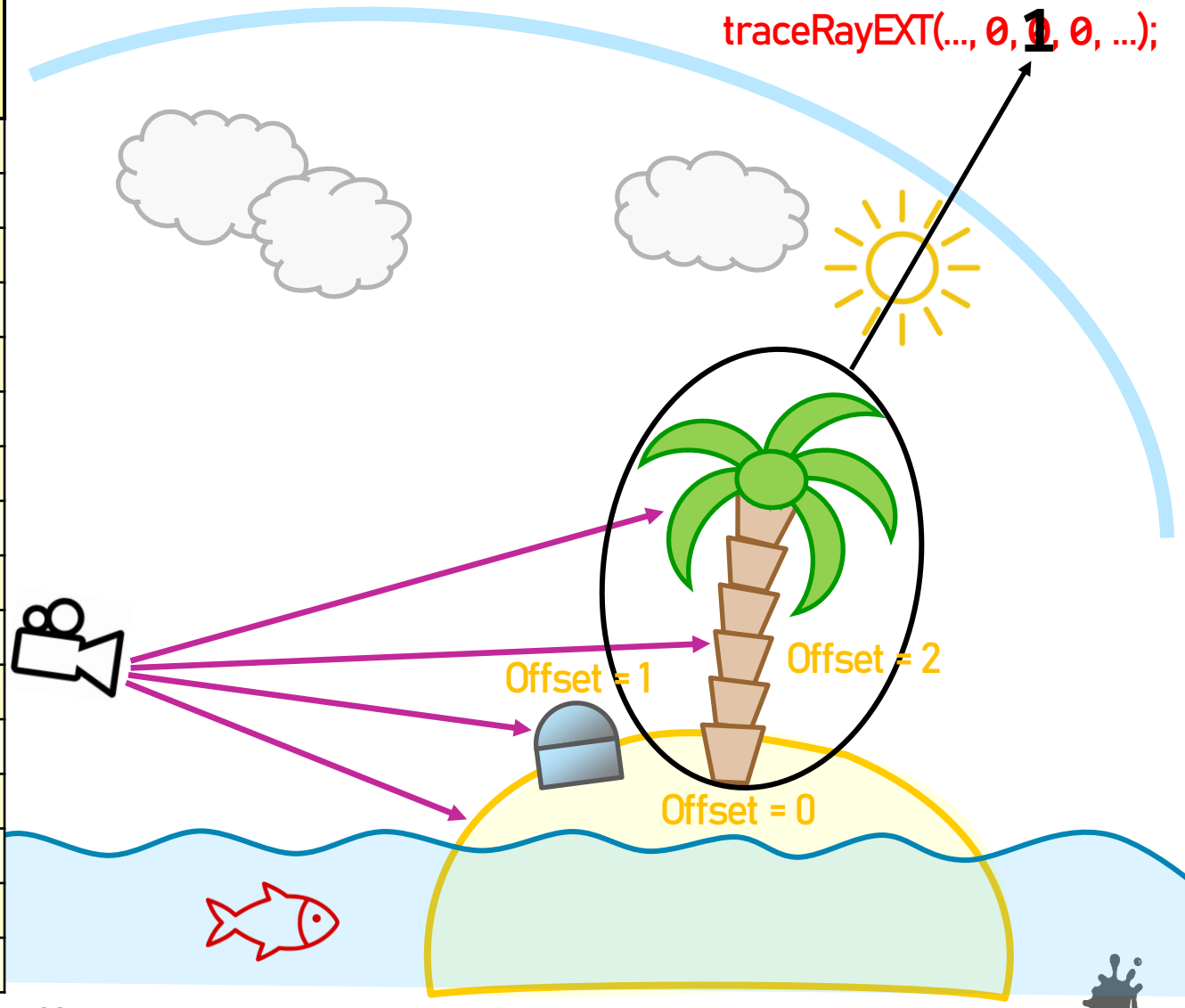
14			
15			



Shader Binding Table Example

vkCmdTraceRaysKHR with rayGenAddr = start + 0 * stride, missAddr = start + 14 * stride, hitGroupsAddr = start + 1 * stride;

Shader Binding Table			
Idx	*[Closest Hit Shader]*	*[Any Hit Shader]*	*[Intersection Shader]*
0	*Ray Generation Shader:* GenerateRaysAndStoreResults		
1	ShadeTerrain	-	Triangles (built-in)
2	ShadeTreasure	-	Triangles (built-in)
3	ShadePalmTreeTrunk	-	Triangles (built-in)
4	ShadePalmTreeLeaves	CheckAlphaTexture	Triangles (built-in)
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			



Indexing for Hit Groups

- Computing a Hit Shader Binding Table Record Address:

traceRayEXT(..., 0, 1, 0, ...);

```
hitGroupRecordAddress =
    start + stride * ( offset
                     + sbtRecordOffset
                     + (geometryIndex * sbtRecordStride)
                     )
```

where:

- `start` = `VkStridedDeviceAddressRegionKHR::deviceAddress` parameter of vkCmdTraceRaysKHR
- `stride` = `VkStridedDeviceAddressRegionKHR::stride` parameter of vkCmdTraceRaysKHR
- `offset` = `VkAccelerationStructureInstanceKHR::instanceShaderBindingTableRecordOffset` member, passed through acceleration structure instance data for top-level acceleration structure build
- `geometryIndex` = index of geometry in Bottom-Level Acceleration Structure (0,1,2,3,..)
- `sbtRecordOffset` = offset parameter of traceRayEXT GLSL function (index-offset, not byte-offset)
- `sbtRecordStride` = stride parameter of traceRayEXT GLSL function (index-stride, not byte-stride)

Indexing for Hit Groups

- Computing a H

```
hitGroupReco
    start +
```

```
VkAccelerationStructureGeometryKHR triangleGeometry = {};
triangleGeometry.sType = VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_GEOMETRY_KHR;
triangleGeometry.flags = VK_GEOMETRY_OPAQUE_BIT_KHR;
triangleGeometry.geometryType = VK_GEOMETRY_TYPE_TRIANGLES_KHR;
triangleGeometry.geometry.triangles.sType =
   VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_GEOMETRY_TRIANGLES_DATA_KHR;
triangleGeometry.geometry.triangles.vertexData = vertexBufferDeviceAddress;
triangleGeometry.geometry.triangles.indexData = indexBufferDeviceAddress;
triangleGeometry.geometry.triangles.vertexFormat = VK_FORMAT_R32G32B32_SFLOAT;
triangleGeometry.geometry.triangles.maxVertex = 100;
triangleGeometry.geometry.triangles.vertexStride = sizeof(MyVertexData);
triangleGeometry.geometry.triangles.indexType = VK_INDEX_TYPE_UINT32;

// ...
```

where:

- start = VkStri
- stride = VkStr
- offset = VkAccelerationStructureInstanceKHR::instanceShaderBindingTableRecordOffset member, passed through acceleration structure instance data for top-level acceleration structure build
- geometryIndex = index of geometry in Bottom-Level Acceleration Structure (0,1,2,3,..)
- sbtRecordOffset = offset parameter of traceRayEXT GLSL function (index-offset, not byte-offset)
- sbtRecordStride = stride parameter of traceRayEXT GLSL function (index-stride, not byte-stride)

Indexing for Hit Groups

- Computing a H

```
hitGroupReco
    start +
```

where:

- start = VkStri
- stride = VkStr
- offset = VkAcc
  passe
- geometryInde
- sbtRecordOff
- sbtRecordStr

```
VkAccelerationStructureGeometryKHR triangleGeometry = {};
triangleGeometry.sType = VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_GEOMETRY_KHR;
triangleGeometry.flags = VK_GEOMETRY_OPAQUE_BIT_KHR;
triangleGeometry.geometryType = VK_GEOMETRY_TYPE_TRIANGLES_KHR;
triangleGeometry.geometry.triangles.sType =
   VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_GEOMETRY_TRIANGLES_DATA_KHR;
triangleGeometry.geometry.triangles.vertexData = vertexBufferDeviceAddress;
triangleGeometry.geometry.triangles.indexData = indexBufferDeviceAddress;
triangleGeometry.geometry.triangles.vertexFormat = VK_FORMAT_R32G32B32_SFLOAT;
triangleGeometry.geometry.triangles.maxVertex = 100;
triangleGeometry.geometry.triangles.vertexStride = sizeof(MyVertexData);
triangleGeometry.geometry.triangles.indexType = VK_INDEX_TYPE_UINT32;

// ...

VkAccelerationStructureBuildGeometryInfoKHR geometryInfos = {};
geometryInfos.sType =
              VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_BUILD_GEOMETRY_INFO_KHR;
geometryInfos.type = VK_ACCELERATION_STRUCTURE_TYPE_BOTTOM_LEVEL_KHR;
geometryInfos.flags = VK_BUILD_ACCELERATION_STRUCTURE_PREFER_FAST_TRACE_BIT_KHR;
geometryInfos.geometryCount = 1;
geometryInfos.pGeometries = &triangleGeometry;
```

Indexing for Hit Groups

- Computing a H

```
hitGroupReco
    start +
```

where:

- start = VkStri
- stride = VkStr
- offset = VkAcc
  passe
- geometryInde
- sbtRecordOff
- sbtRecordStr

```
VkAccelerationStructureGeometryKHR triangleGeometry = {};
triangleGeometry.sType = VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_GEOMETRY_KHR;
triangleGeometry.flags = VK_GEOMETRY_OPAQUE_BIT_KHR;
triangleGeometry.geometryType = VK_GEOMETRY_TYPE_TRIANGLES_KHR;
triangleGeometry.geometry.triangles.sType =
   VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_GEOMETRY_TRIANGLES_DATA_KHR;
triangleGeometry.geometry.triangles.vertexData = vertexBufferDeviceAddress;
triangleGeometry.geometry.triangles.indexData = indexBufferDeviceAddress;
triangleGeometry.geometry.triangles.vertexFormat = VK_FORMAT_R32G32B32_SFLOAT;
triangleGeometry.geometry.triangles.maxVertex = 100;
triangleGeometry.geometry.triangles.vertexStride = sizeof(MyVertexData);
triangleGeometry.geometry.triangles.indexType = VK_INDEX_TYPE_UINT32;

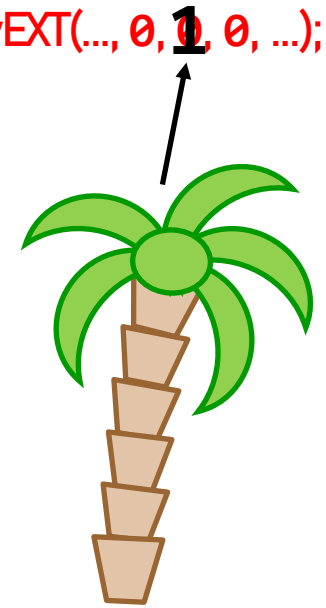
// ...

VkAccelerationStructureBuildGeometryInfoKHR geometryInfos = {};
geometryInfos.sType =
              VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_BUILD_GEOMETRY_INFO_KHR;
geometryInfos.type = VK_ACCELERATION_STRUCTURE_TYPE_BOTTOM_LEVEL_KHR;
geometryInfos.flags = VK_BUILD_ACCELERATION_STRUCTURE_PREFER_FAST_TRACE_BIT_KHR;
geometryInfos.geometryCount = 100;
geometryInfos.pGeometries = ...;
```

Indexing for Hit Groups

- Computing a Hit Shader Binding Table Record Address:

```
hitGroupRecordAddress =
    start + stride * ( offset
                     + sbtRecordOffset
                     + (geometryIndex * sbtRecordStride)
                     )
```



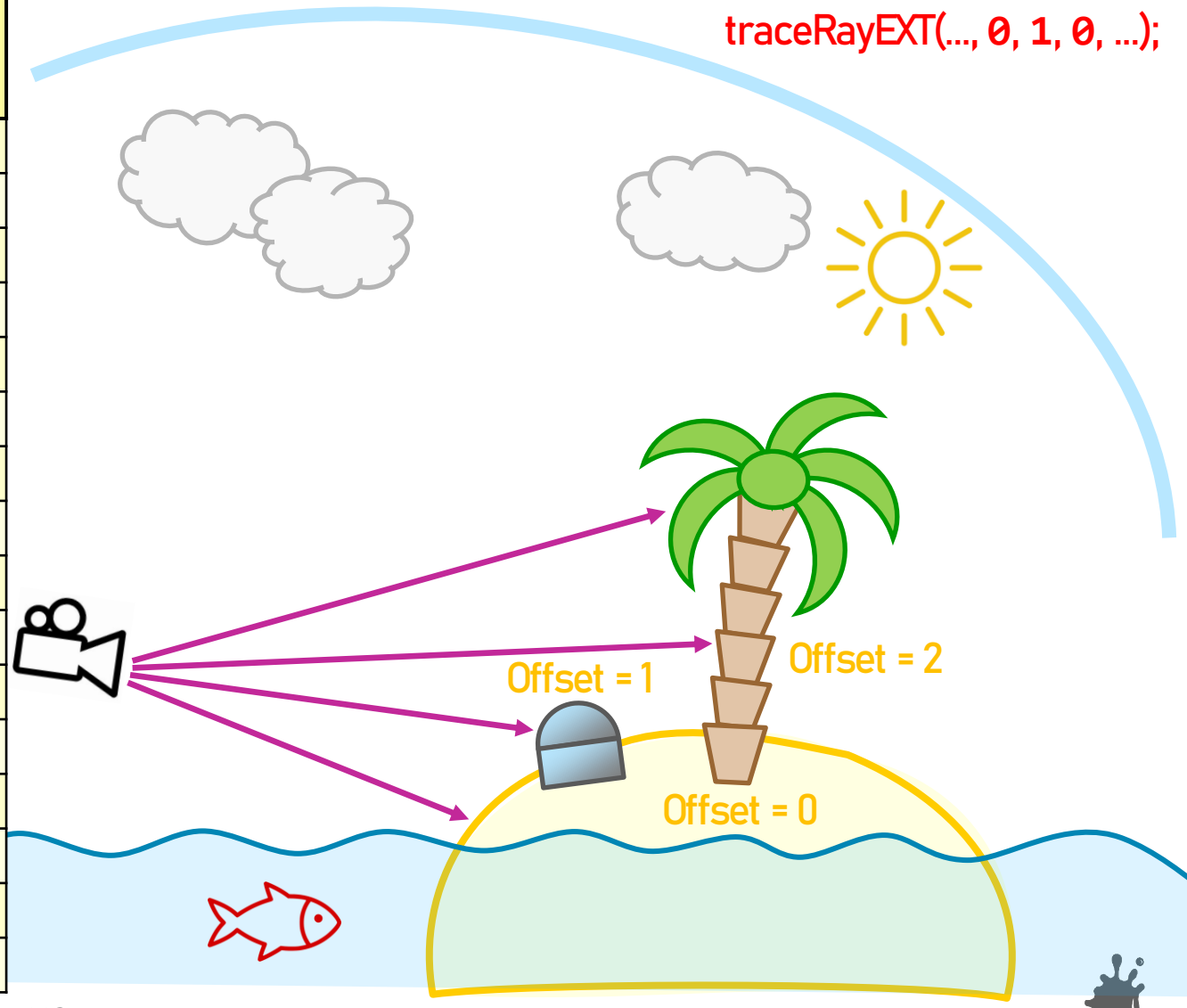
where:

- `start` = `VkStridedDeviceAddressRegionKHR::deviceAddress` parameter of vkCmdTraceRaysKHR
- `stride` = `VkStridedDeviceAddressRegionKHR::stride` parameter of vkCmdTraceRaysKHR
- `offset` = `VkAccelerationStructureInstanceKHR::instanceShaderBindingTableRecordOffset` member, passed through acceleration structure instance data for top-level acceleration structure build
- `geometryIndex` = index of geometry in Bottom-Level Acceleration Structure (0,1,2,3,..)
- `sbtRecordOffset` = offset parameter of traceRayEXT GLSL function (index-offset, not byte-offset)
- `sbtRecordStride` = stride parameter of traceRayEXT GLSL function (index-stride, not byte-stride)

Shader Binding Table Example

vkCmdTraceRaysKHR with rayGenAddr = start + 0 * stride, missAddr = start + 14 * stride, hitGroupsAddr = start + 1 * stride;

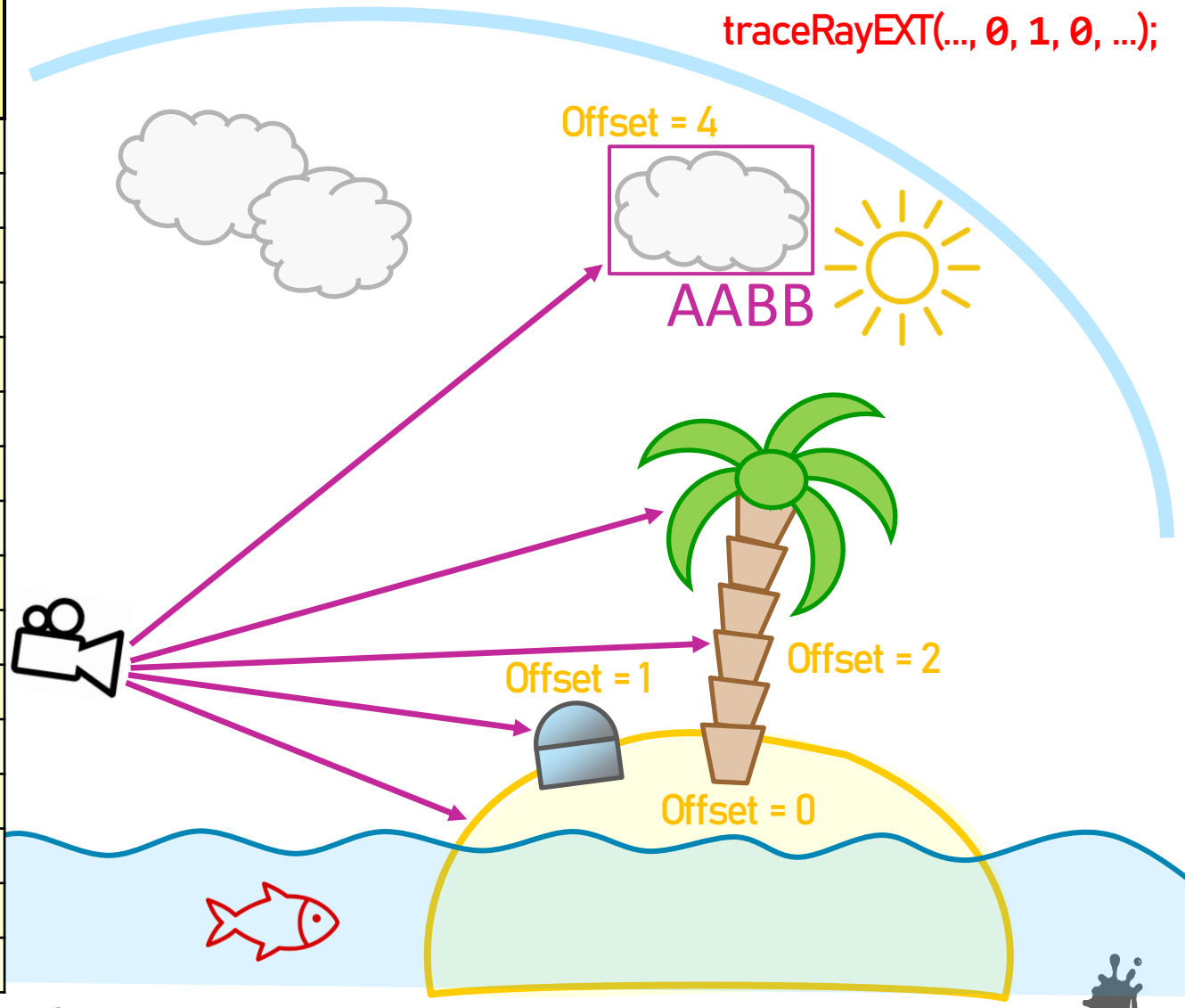
Shader Binding Table			
Idx	*[Closest Hit Shader]*	*[Any Hit Shader]*	*[Intersection Shader]*
0	*Ray Generation Shader:* GenerateRaysAndStoreResults		
1	ShadeTerrain	-	Triangles (built-in)
2	ShadeTreasure	-	Triangles (built-in)
3	ShadePalmTreeTrunk	-	Triangles (built-in)
4	ShadePalmTreeLeaves	CheckAlphaTexture	Triangles (built-in)
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			



Shader Binding Table Example

vkCmdTraceRaysKHR with rayGenAddr = start + 0 * stride, missAddr = start + 14 * stride, hitGroupsAddr = start + 1 * stride;

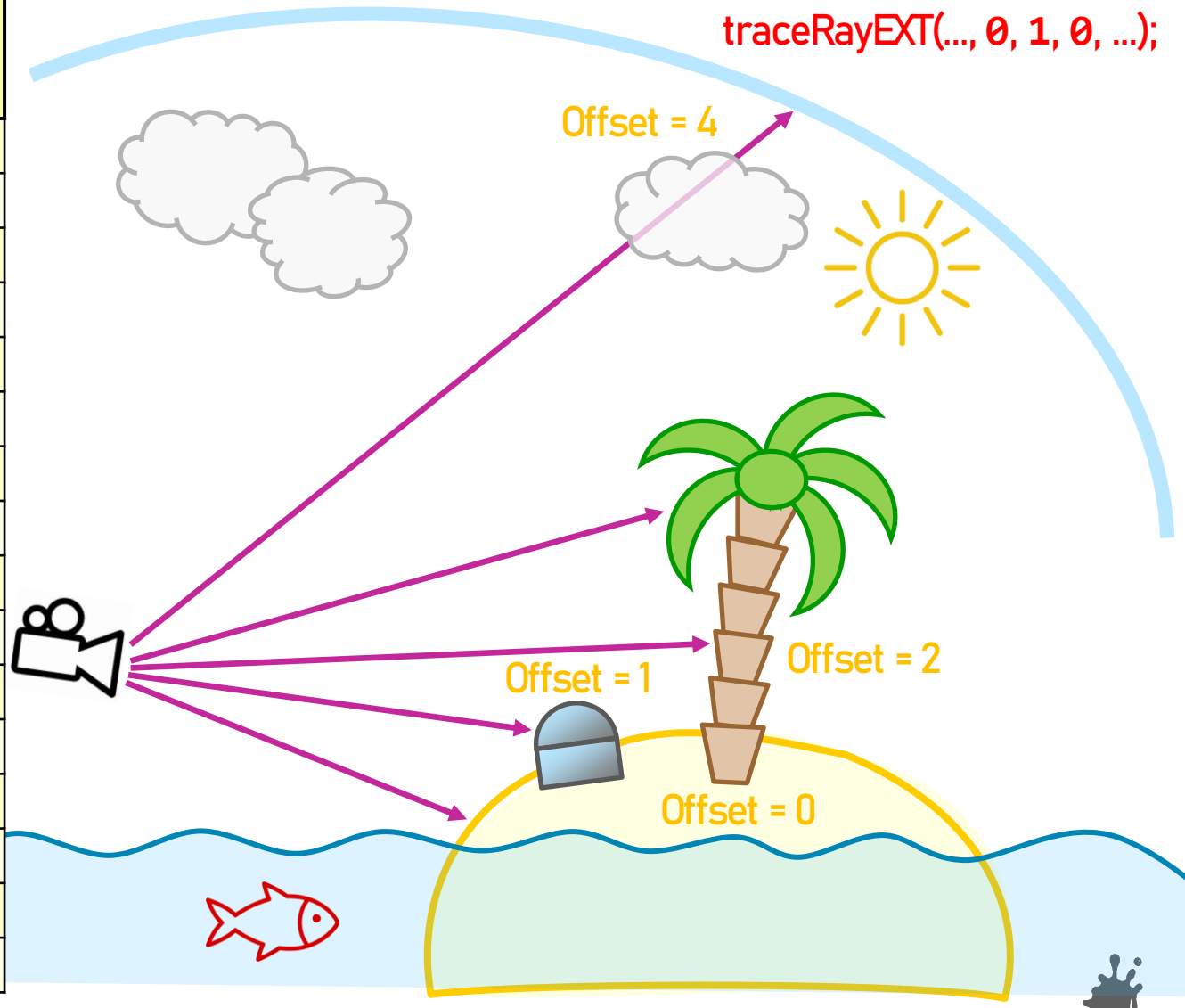
Shader Binding Table			
Idx	*[Closest Hit Shader]*	*[Any Hit Shader]*	*[Intersection Shader]*
0	*Ray Generation Shader:* GenerateRaysAndStoreResults		
1	ShadeTerrain	-	Triangles (built-in)
2	ShadeTreasure	-	Triangles (built-in)
3	ShadePalmTreeTrunk	-	Triangles (built-in)
4	ShadePalmTreeLeaves	CheckAlphaTexture	Triangles (built-in)
5	-	HandleClouds	ProceduralClouds
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			



Shader Binding Table Example

vkCmdTraceRaysKHR with rayGenAddr = start + 0 * stride, missAddr = start + 14 * stride, hitGroupsAddr = start + 1 * stride;

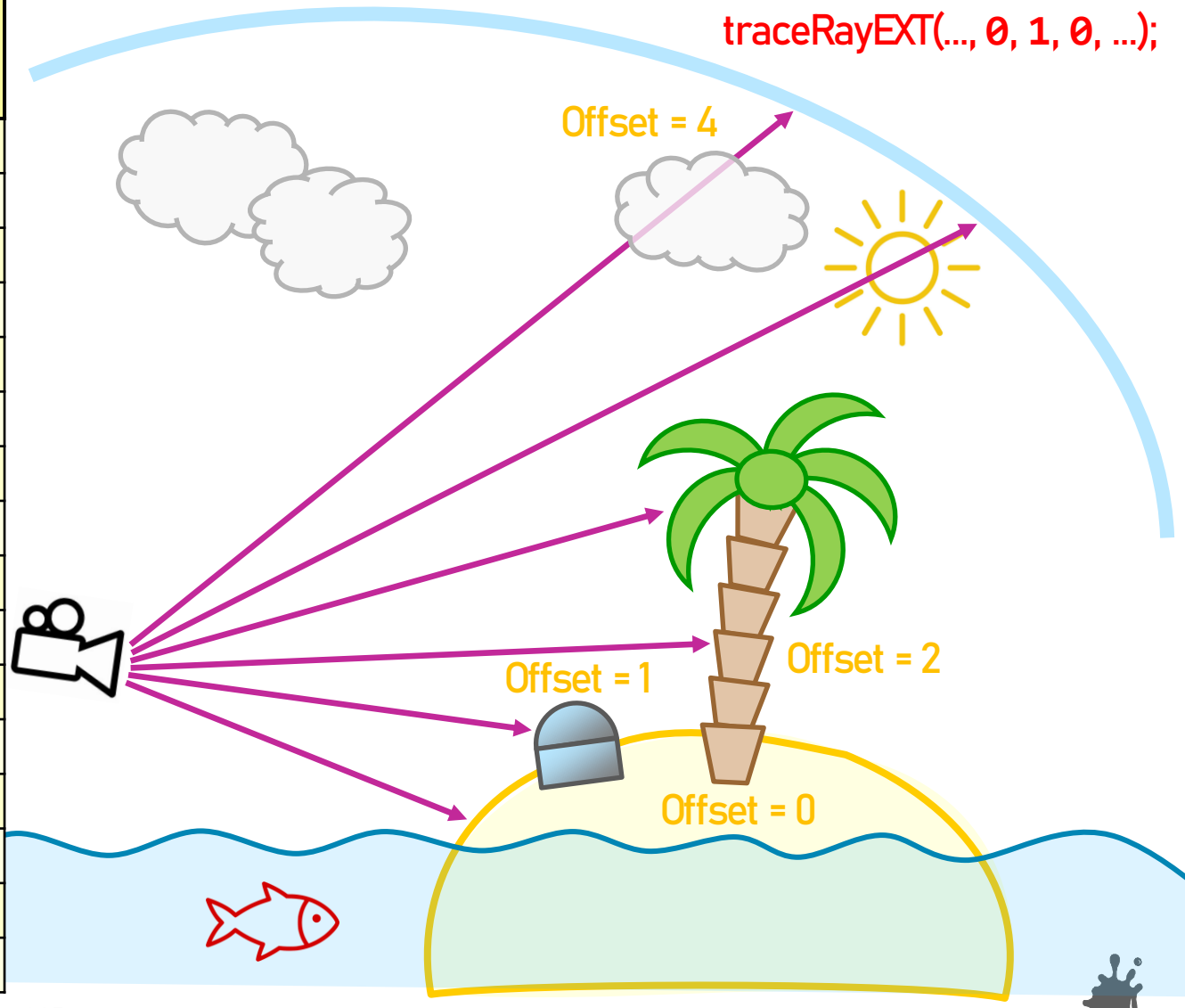
Shader Binding Table			
Idx	*[Closest Hit Shader]*	*[Any Hit Shader]*	*[Intersection Shader]*
0	*Ray Generation Shader:* GenerateRaysAndStoreResults		
1	ShadeTerrain	-	Triangles (built-in)
2	ShadeTreasure	-	Triangles (built-in)
3	ShadePalmTreeTrunk	-	Triangles (built-in)
4	ShadePalmTreeLeaves	CheckAlphaTexture	Triangles (built-in)
5	-	HandleClouds	ProceduralClouds
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			



Shader Binding Table Example

vkCmdTraceRaysKHR with rayGenAddr = start + 0 * stride, missAddr = start + 14 * stride, hitGroupsAddr = start + 1 * stride;

Shader Binding Table			
Idx	*[Closest Hit Shader]*	*[Any Hit Shader]*	*[Intersection Shader]*
0	*Ray Generation Shader:* GenerateRaysAndStoreResults		
1	ShadeTerrain	-	Triangles (built-in)
2	ShadeTreasure	-	Triangles (built-in)
3	ShadePalmTreeTrunk	-	Triangles (built-in)
4	ShadePalmTreeLeaves	CheckAlphaTexture	Triangles (built-in)
5	-	HandleClouds	ProceduralClouds
6			
7			
8			
9			
10			
11			
12			
13			
14	*Miss Shader:* SetSkyboxColor		
15			

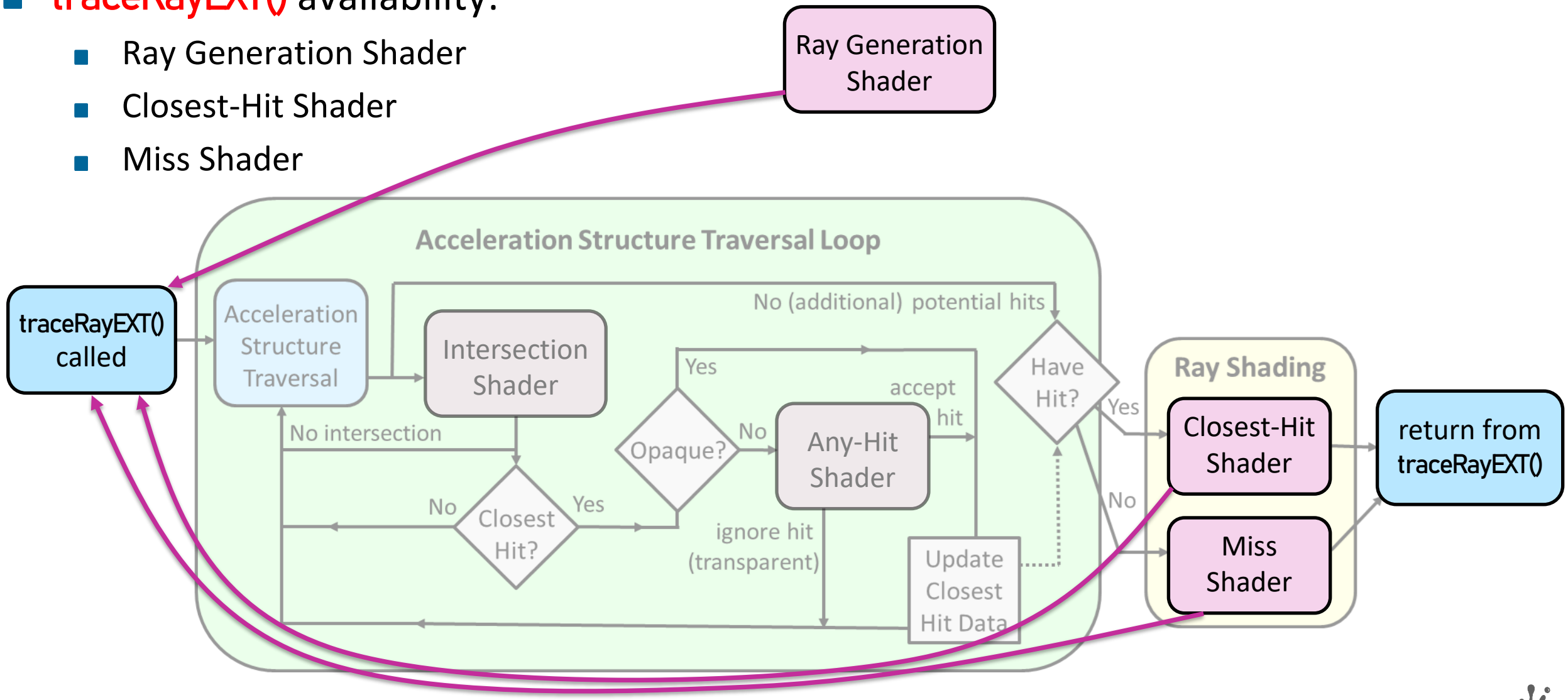


Recursive Rays

- So far:
  - Only evaluating first hit
  - Actually, this is "Ray Casting"
- Now:
  - Recursive rays
  - I.e., spawn more rays via traceRayEXT() within ray tracing pipeline traversal

Recursive Rays

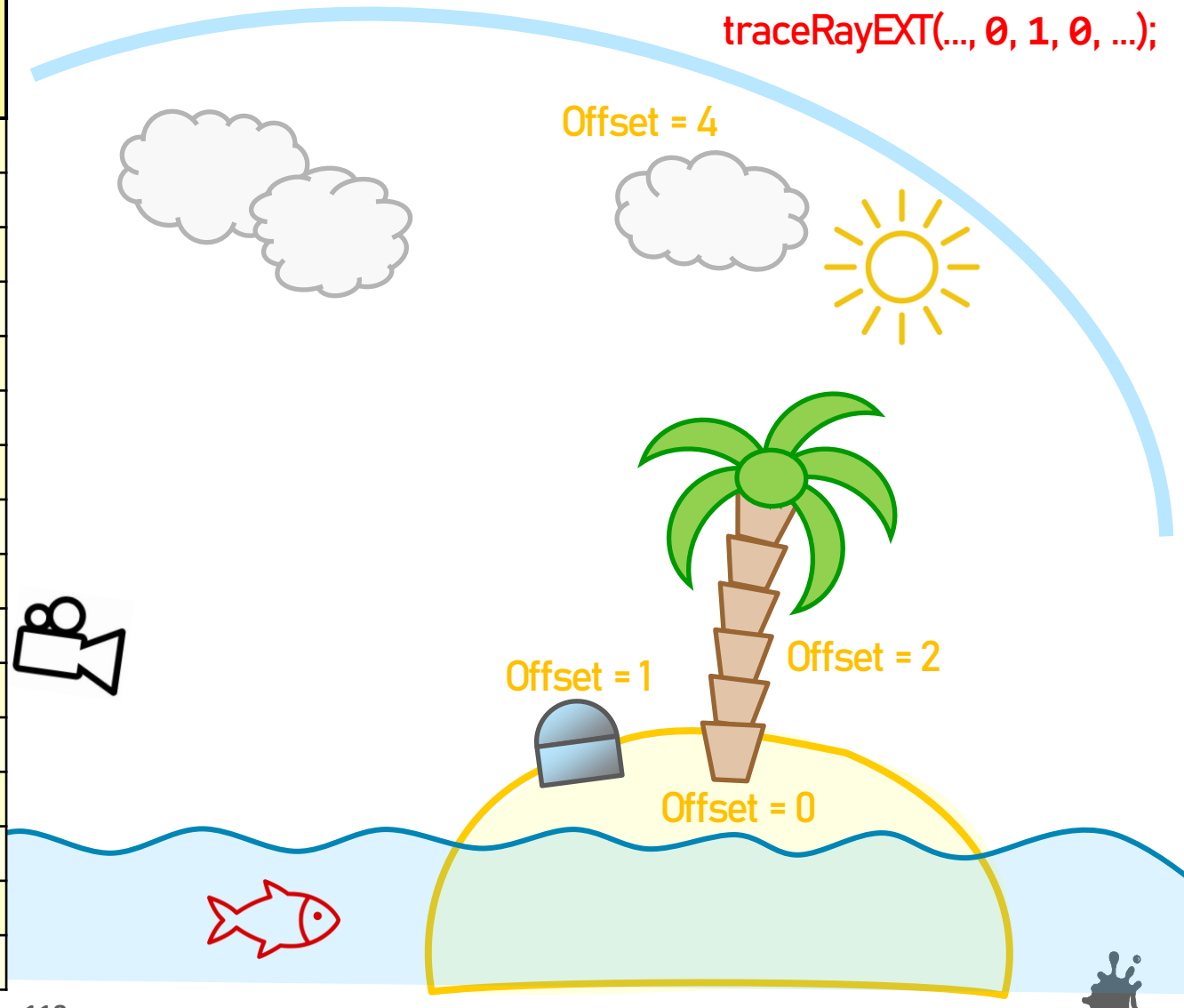
- traceRayEXT() availability:
  - Ray Generation Shader
  - Closest-Hit Shader
  - Miss Shader



Shader Binding Table Example + Reflection/Refraction

vkCmdTraceRaysKHR with rayGenAddr = start + 0 * stride, missAddr = start + 14 * stride, hitGroupsAddr = start + 1 * stride;

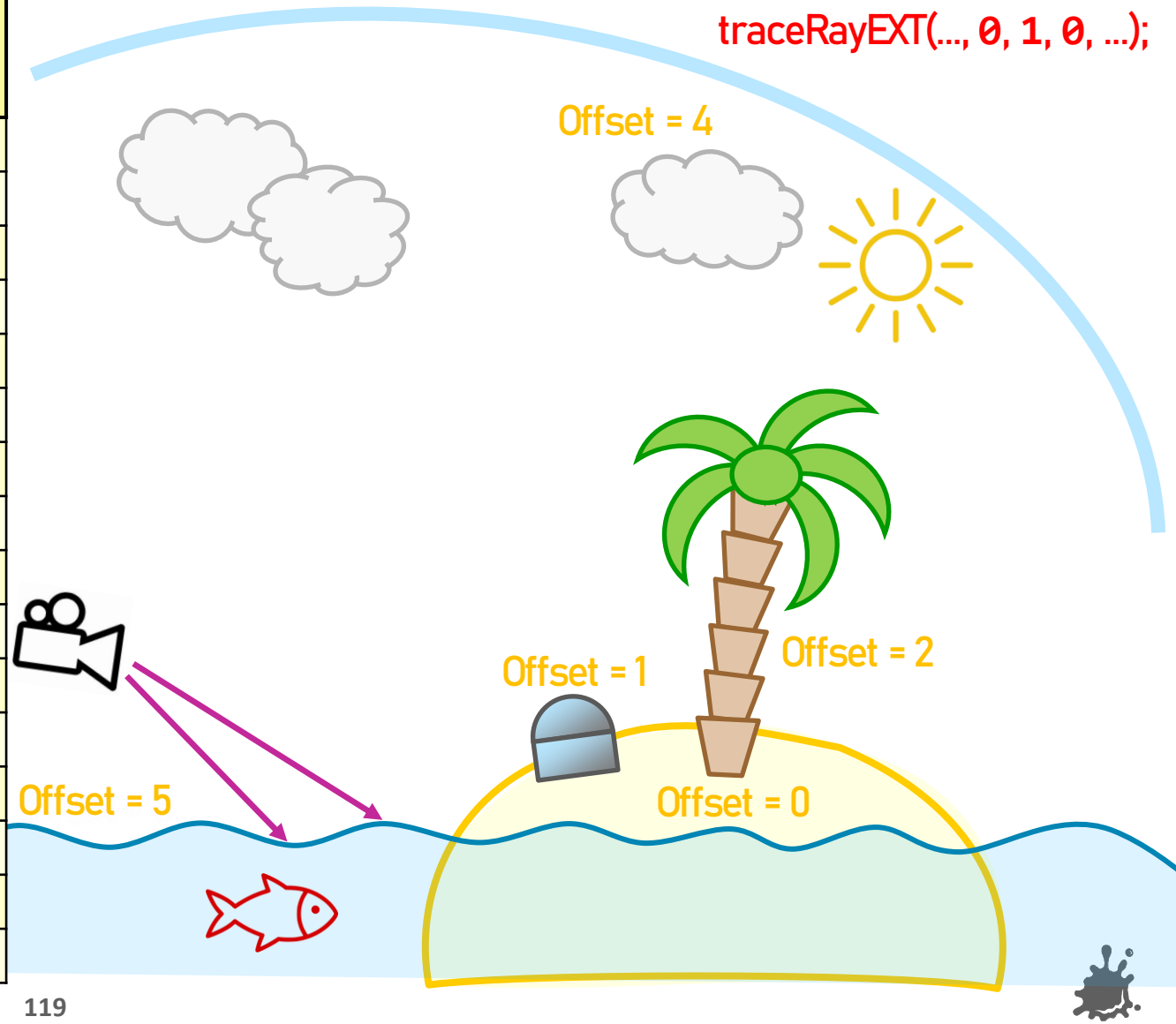
Shader Binding Table			
Idx	*[Closest Hit Shader]*	*[Any Hit Shader]*	*[Intersection Shader]*
0	*Ray Generation Shader:* GenerateRaysAndStoreResults		
1	ShadeTerrain	-	Triangles (built-in)
2	ShadeTreasure	-	Triangles (built-in)
3	ShadePalmTreeTrunk	-	Triangles (built-in)
4	ShadePalmTreeLeaves	CheckAlphaTexture	Triangles (built-in)
5	-	HandleClouds	ProceduralClouds
6			
7			
8			
9			
10			
11			
12			
13			
14	*Miss Shader:* SetSkyboxColor		
15			



Shader Binding Table Example + Reflection/Refraction

vkCmdTraceRaysKHR with rayGenAddr = start + 0 * stride, missAddr = start + 14 * stride, hitGroupsAddr = start + 1 * stride;

Shader Binding Table			
Idx	*[Closest Hit Shader]*	*[Any Hit Shader]*	*[Intersection Shader]*
0	*Ray Generation Shader:* GenerateRaysAndStoreResults		
1	ShadeTerrain	-	Triangles (built-in)
2	ShadeTreasure	-	Triangles (built-in)
3	ShadePalmTreeTrunk	-	Triangles (built-in)
4	ShadePalmTreeLeaves	CheckAlphaTexture	Triangles (built-in)
5	-	HandleClouds	ProceduralClouds
6	ShadeWaterSurface	-	ProceduralWater
7			
8			
9			
10			
11			
12			
13			
14	*Miss Shader:* SetSkyboxColor		
15			

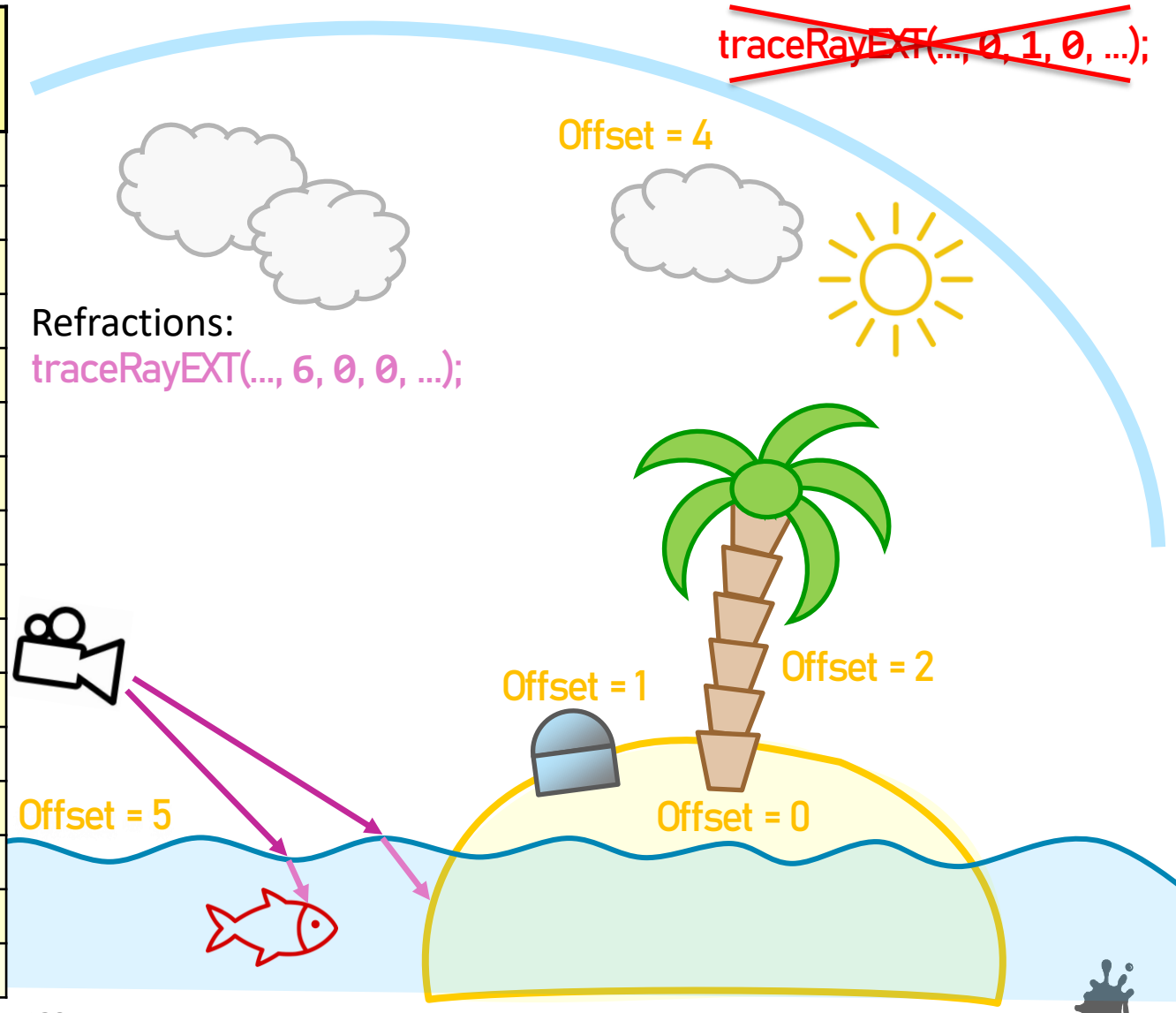


Shader Binding Table Example + Reflection/Refraction

vkCmdTraceRaysKHR with rayGenAddr = start + 0 * stride, missAddr = start + 14 * stride, hitGroupsAddr = start + 1 * stride;

Shader Binding Table			
Idx	*[Closest Hit Shader]*	*[Any Hit Shader]*	*[Intersection Shader]*
0	*Ray Generation Shader:* GenerateRaysAndStoreResults		
1	ShadeTerrain	-	Triangles (built-in)
2	ShadeTreasure	-	Triangles (built-in)
3	ShadePalmTreeTrunk	-	Triangles (built-in)
4	ShadePalmTreeLeaves	CheckAlphaTexture	Triangles (built-in)
5	-	HandleClouds	ProceduralClouds
6	ShadeWaterSurface	-	ProceduralWater
7	ShadeTerrainUnderwater	-	Triangles (built-in)
8	ShadeFishUnderwater	-	Triangles (built-in)
9			
10			
11			
12			
13			
14	*Miss Shader:* SetSkyboxColor		
15			

~~traceRayEXT(..., 0, 1, 0, ...);~~



Indexing for Hit Groups

- Computing a Hit Shader Binding Table Record Address:

~~traceRayEXT(..., 0, 1, 0, ...);~~

traceRayEXT(..., 6, 0, 0, ...);

```
hitGroupRecordAddress =
    start + stride * ( offset
                     + sbtRecordOffset
                     + (geometryIndex * sbtRecordStride)
                     )
```

where:

- `start` = `VkStridedDeviceAddressRegionKHR::deviceAddress` parameter of vkCmdTraceRaysKHR
- `stride` = `VkStridedDeviceAddressRegionKHR::stride` parameter of vkCmdTraceRaysKHR
- `offset` = `VkAccelerationStructureInstanceKHR::instanceShaderBindingTableRecordOffset` member, passed through acceleration structure instance data for top-level acceleration structure build
- `geometryIndex` = index of geometry in Bottom-Level Acceleration Structure (0,1,2,3,..)
- `sbtRecordOffset` = offset parameter of traceRayEXT GLSL function (index-offset, not byte-offset)
- `sbtRecordStride` = stride parameter of traceRayEXT GLSL function (index-stride, not byte-stride)

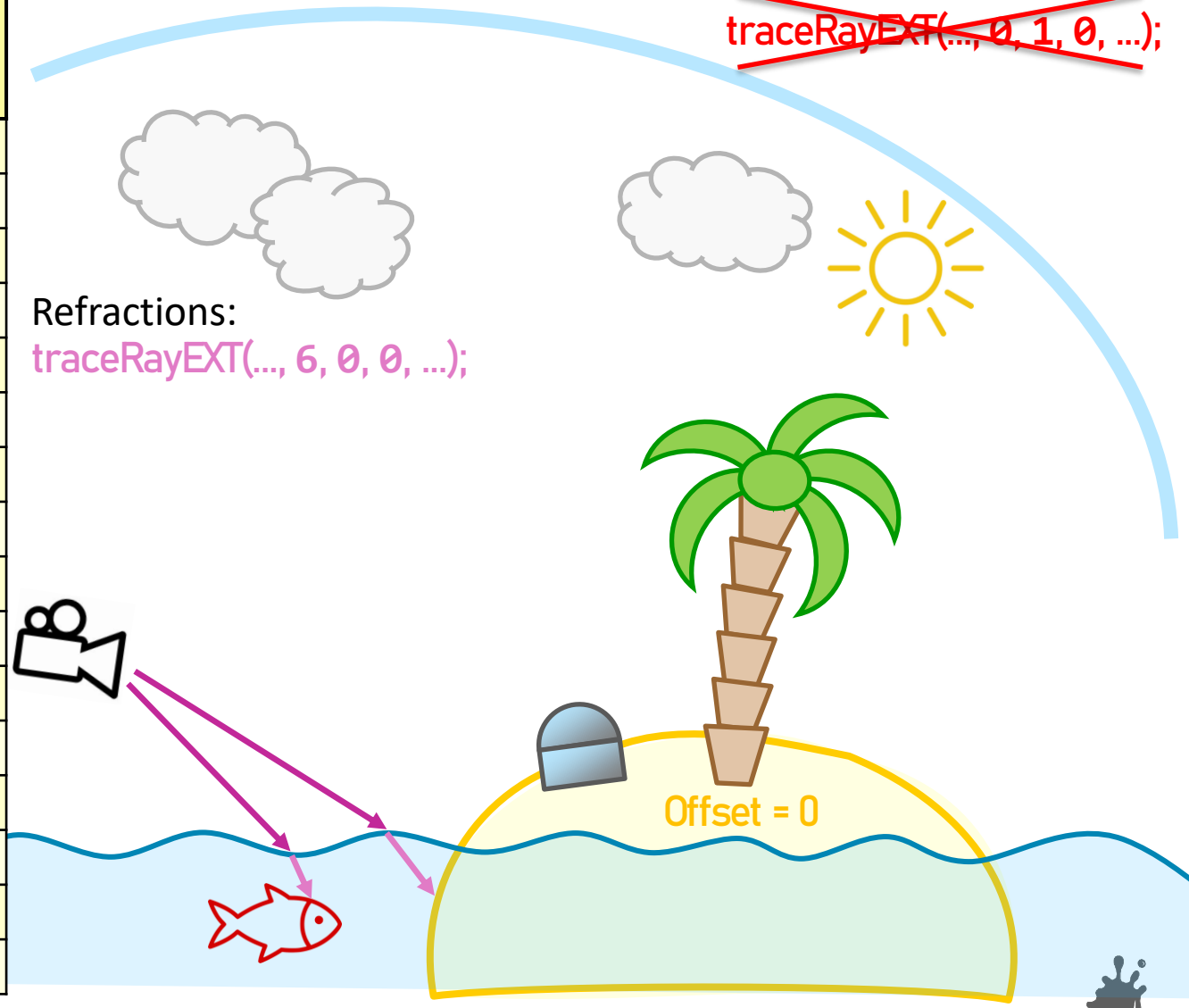
Shader Binding Table Example + Reflection/Refraction

`vkCmdTraceRaysKHR with rayGenAddr = start + 0 * stride, missAddr = start + 14 * stride, hitGroupsAddr = start + 1 * stride;`

Shader Binding Table			
Idx	*[Closest Hit Shader]*	*[Any Hit Shader]*	*[Intersection Shader]*
0	*Ray Generation Shader:* GenerateRaysAndStoreResults		
1	ShadeTerrain	-	Triangles (built-in)
2	ShadeTreasure	-	Triangles (built-in)
3	ShadePalmTreeTrunk	-	Triangles (built-in)
4	ShadePalmTreeLeaves	CheckAlphaTexture	Triangles (built-in)
5	-	HandleClouds	ProceduralClouds
6	ShadeWaterSurface	-	ProceduralWater
7	ShadeTerrainUnderwater	-	Triangles (built-in)
8	ShadeFishUnderwater	-	Triangles (built-in)
9			
10			
11			
12			
13			
14	*Miss Shader:* SetSkyboxColor		
15			

~~traceRayEXT(..., 0, 1, 0, ...);~~

Refractions:
`traceRayEXT(..., 6, 0, 0, ...);`

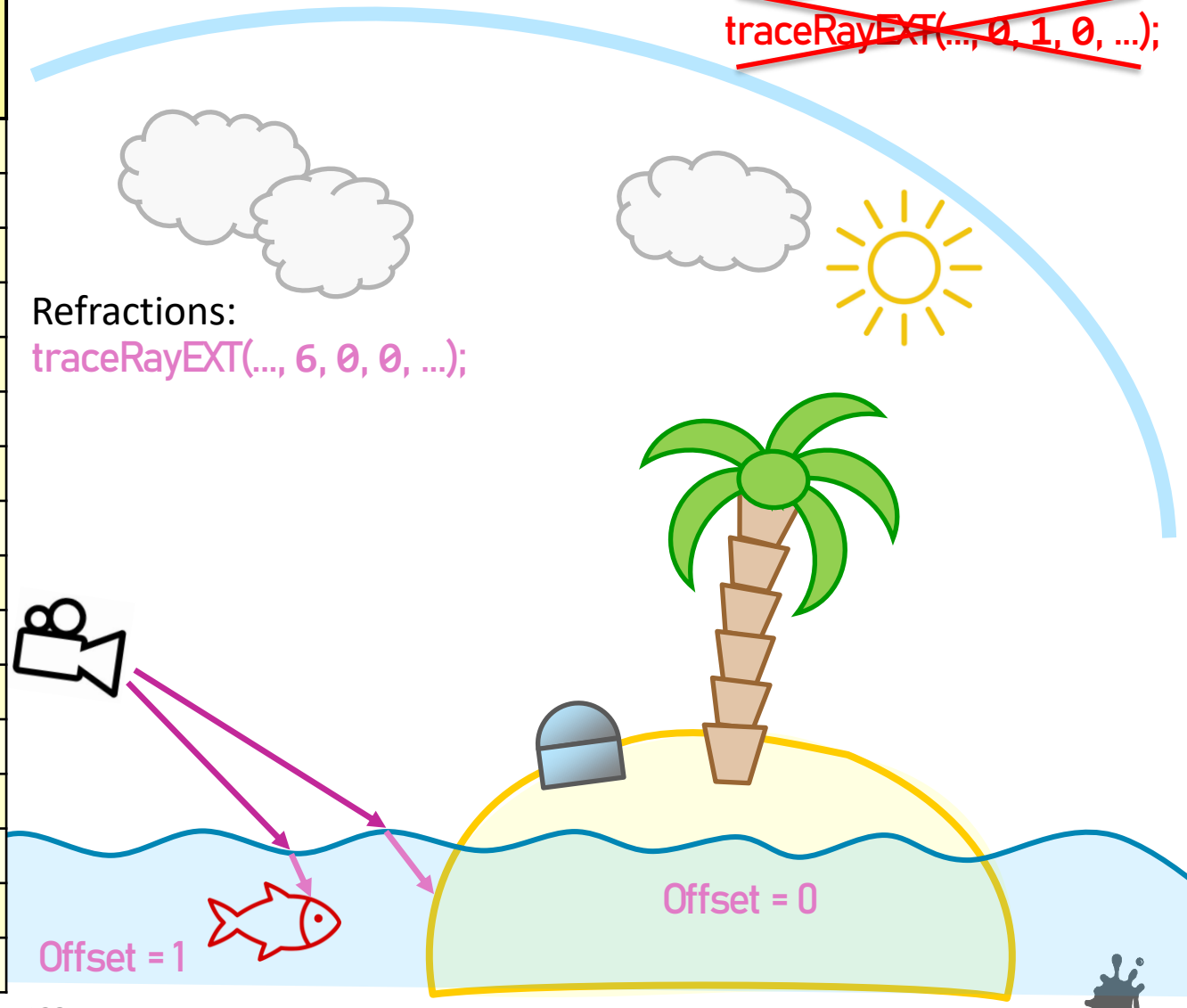


Shader Binding Table Example + Reflection/Refraction

vkCmdTraceRaysKHR with rayGenAddr = start + 0 * stride, missAddr = start + 14 * stride, hitGroupsAddr = start + 1 * stride;

~~traceRayEXT(..., 0, 1, 0, ...);~~

Shader Binding Table			
Idx	*[Closest Hit Shader]*	*[Any Hit Shader]*	*[Intersection Shader]*
0	*Ray Generation Shader:* GenerateRaysAndStoreResults		
1	ShadeTerrain	-	Triangles (built-in)
2	ShadeTreasure	-	Triangles (built-in)
3	ShadePalmTreeTrunk	-	Triangles (built-in)
4	ShadePalmTreeLeaves	CheckAlphaTexture	Triangles (built-in)
5	-	HandleClouds	ProceduralClouds
6	ShadeWaterSurface	-	ProceduralWater
7	ShadeTerrainUnderwater	-	Triangles (built-in)
8	ShadeFishUnderwater	-	Triangles (built-in)
9			
10			
11			
12			
13			
14	*Miss Shader:* SetSkyboxColor		
15			

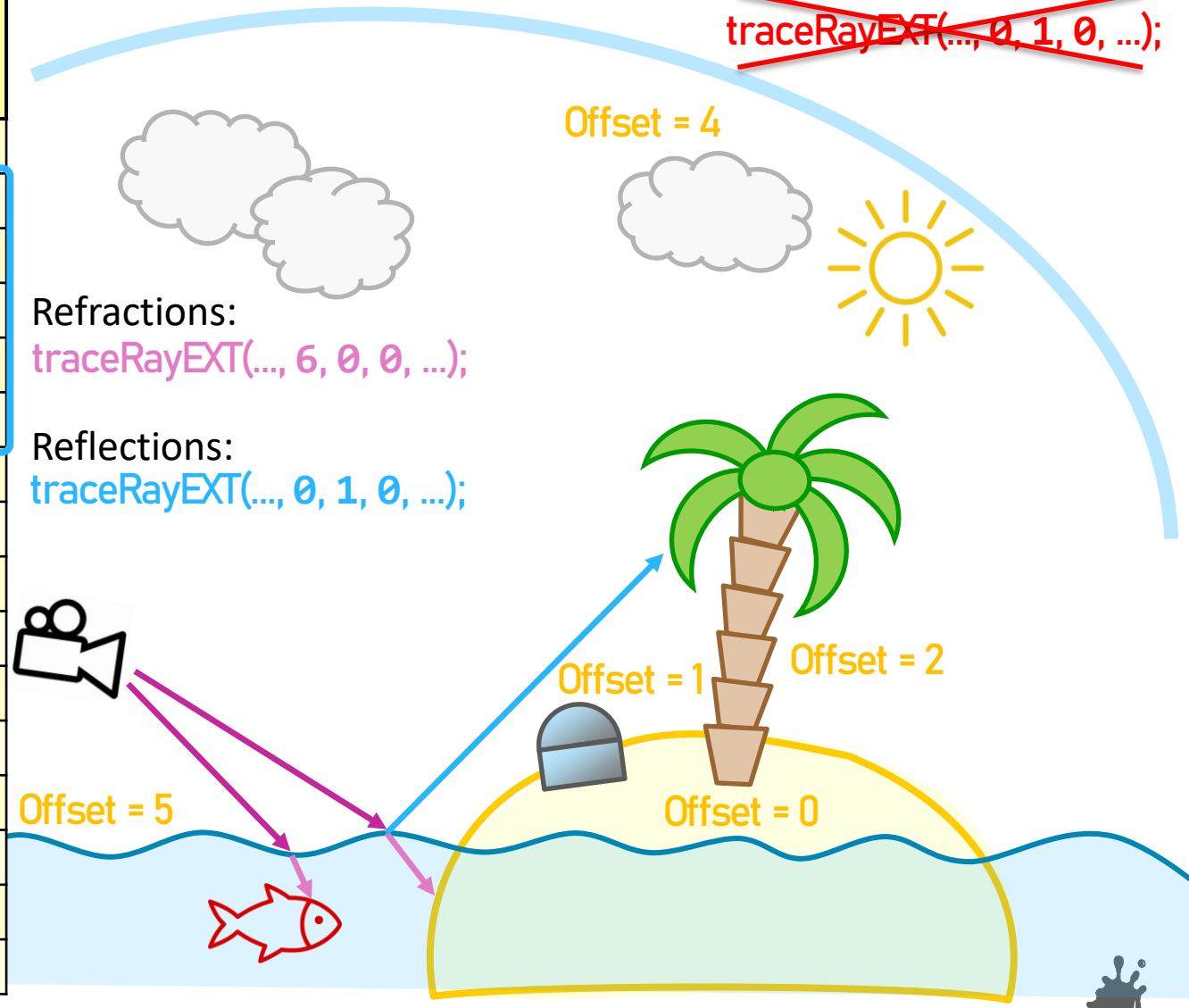


Shader Binding Table Example + Reflection/Refraction

vkCmdTraceRaysKHR with rayGenAddr = start + 0 * stride, missAddr = start + 14 * stride, hitGroupsAddr = start + 1 * stride;

Shader Binding Table			
Idx	*[Closest Hit Shader]*	*[Any Hit Shader]*	*[Intersection Shader]*
0	*Ray Generation Shader:* GenerateRaysAndStoreResults		
1	ShadeTerrain	-	Triangles (built-in)
2	ShadeTreasure	-	Triangles (built-in)
3	ShadePalmTreeTrunk	-	Triangles (built-in)
4	ShadePalmTreeLeaves	CheckAlphaTexture	Triangles (built-in)
5	-	HandleClouds	ProceduralClouds
6	ShadeWaterSurface	-	ProceduralWater
7	ShadeTerrainUnderwater	-	Triangles (built-in)
8	ShadeFishUnderwater	-	Triangles (built-in)
9			
10			
11			
12			
13			
14	*Miss Shader:* SetSkyboxColor		
15			

~~traceRayEXT(..., 0, 1, 0, ...);~~



Shader Binding Table Example + Shadow Rays

vkCmdTraceRaysKHR with rayGenAddr = start + 0 * stride, missAddr = start + 14 * stride, hitGroupsAddr = start + 1 * stride;

Shader Binding Table			
Idx	*[Closest Hit Shader]*	*[Any Hit Shader]*	*[Intersection Shader]*
0	*Ray Generation Shader:* GenerateRaysAndStoreResults		
1	ShadeTerrain	-	Triangles (built-in)
2	ShadeTreasure	-	Triangles (built-in)
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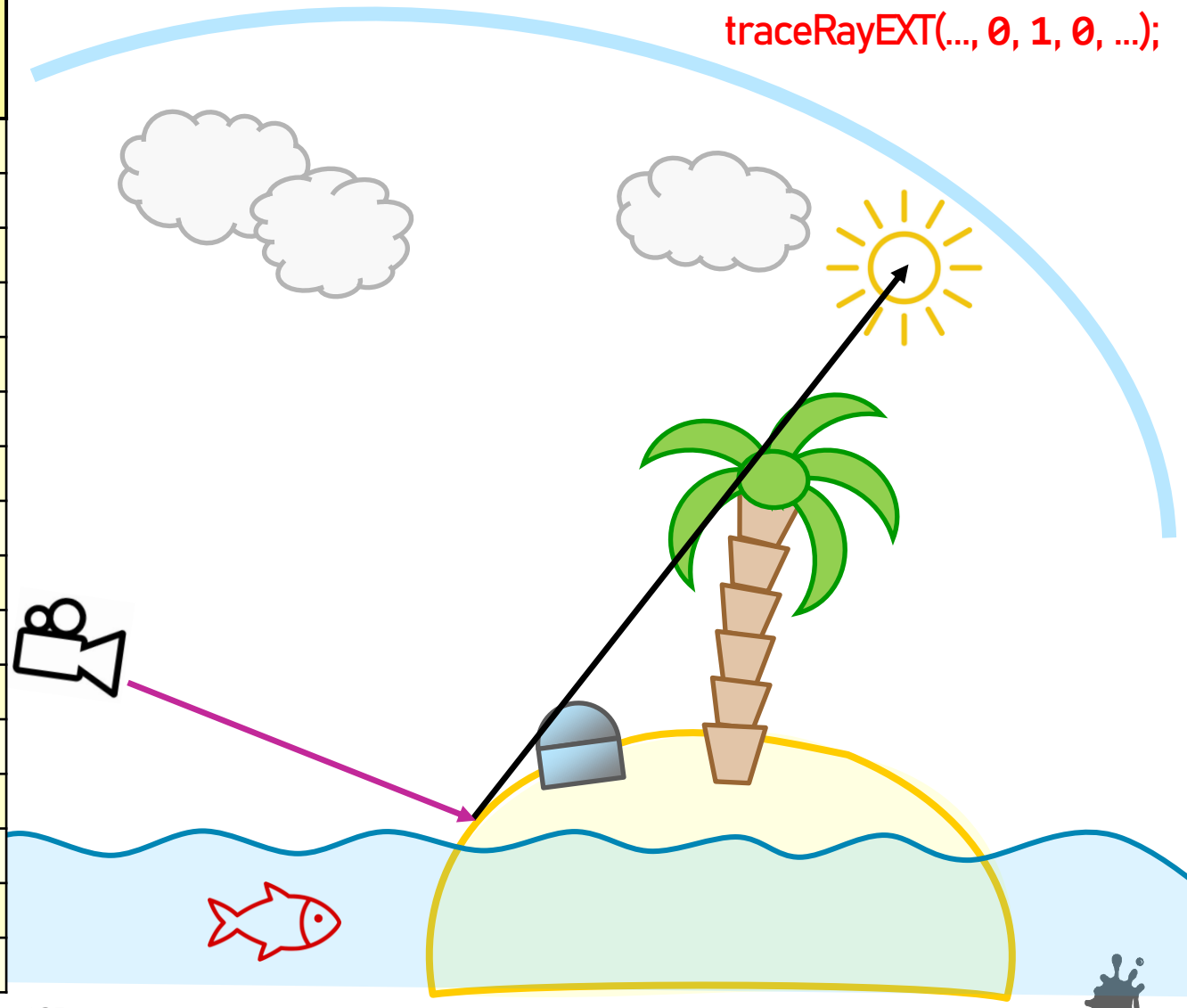
4	ShadePalmTreeLeaves	CheckAlphaTexture	Triangles (built-in)
5	-	HandleClouds	ProceduralClouds
6	ShadeWaterSurface	-	ProceduralWater
7	ShadeTerrainUnderwater	-	Triangles (built-in)
8	ShadeFishUnderwater	-	Triangles (built-in)
9			
10			
11			
12			
13			
14	*Miss Shader:* SetSkyboxColor		
15			



Shader Binding Table Example + Shadow Rays

vkCmdTraceRaysKHR with rayGenAddr = start + 0 * stride, missAddr = start + 14 * stride, hitGroupsAddr = start + 1 * stride;

Shader Binding Table			
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4	ShadePalmTreeLeaves	CheckAlphaTexture	Triangles (built-in)
5	-	HandleClouds	ProceduralClouds
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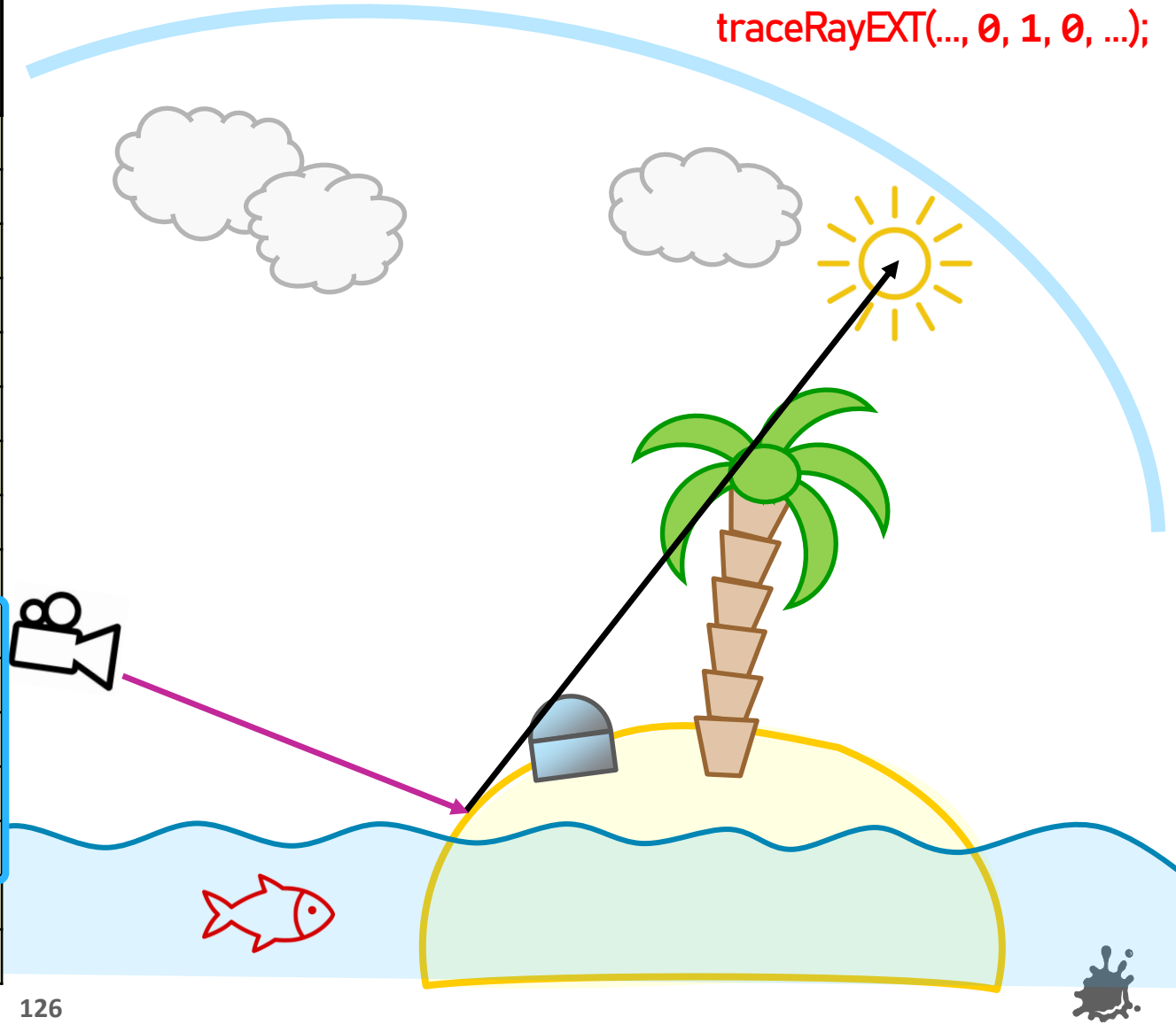
7	ShadeTerrainUnderwater	-	Triangles (built-in)
8	ShadeFishUnderwater	-	Triangles (built-in)
9	AddShadow	-	Triangles (built-in)
10	AddShadow	-	Triangles (built-in)
11	AddShadow	-	Triangles (built-in)
12	AddShadow	CheckAlphaTexture	Triangles (built-in)
13	-	AddSomeShadow	ProceduralClouds
14	*Miss Shader:* SetSkyboxColor		
15	*Miss Shader:* NoShadowAdded		



Shader Binding Table Example + Shadow Rays

vkCmdTraceRaysKHR with rayGenAddr = start + 0 * stride, missAddr = start + 14 * stride, hitGroupsAddr = start + 1 * stride;

Shader Binding Table			
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3	ShadePalmTreeTrunk	-	Triangles (built-in)
4	ShadePalmTreeLeaves	CheckAlphaTexture	Triangles (built-in)
5	-	HandleClouds	ProceduralClouds
6	ShadeWaterSurface	-	ProceduralWater
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8	ShadeFishUnderwater	-	Triangles (built-in)
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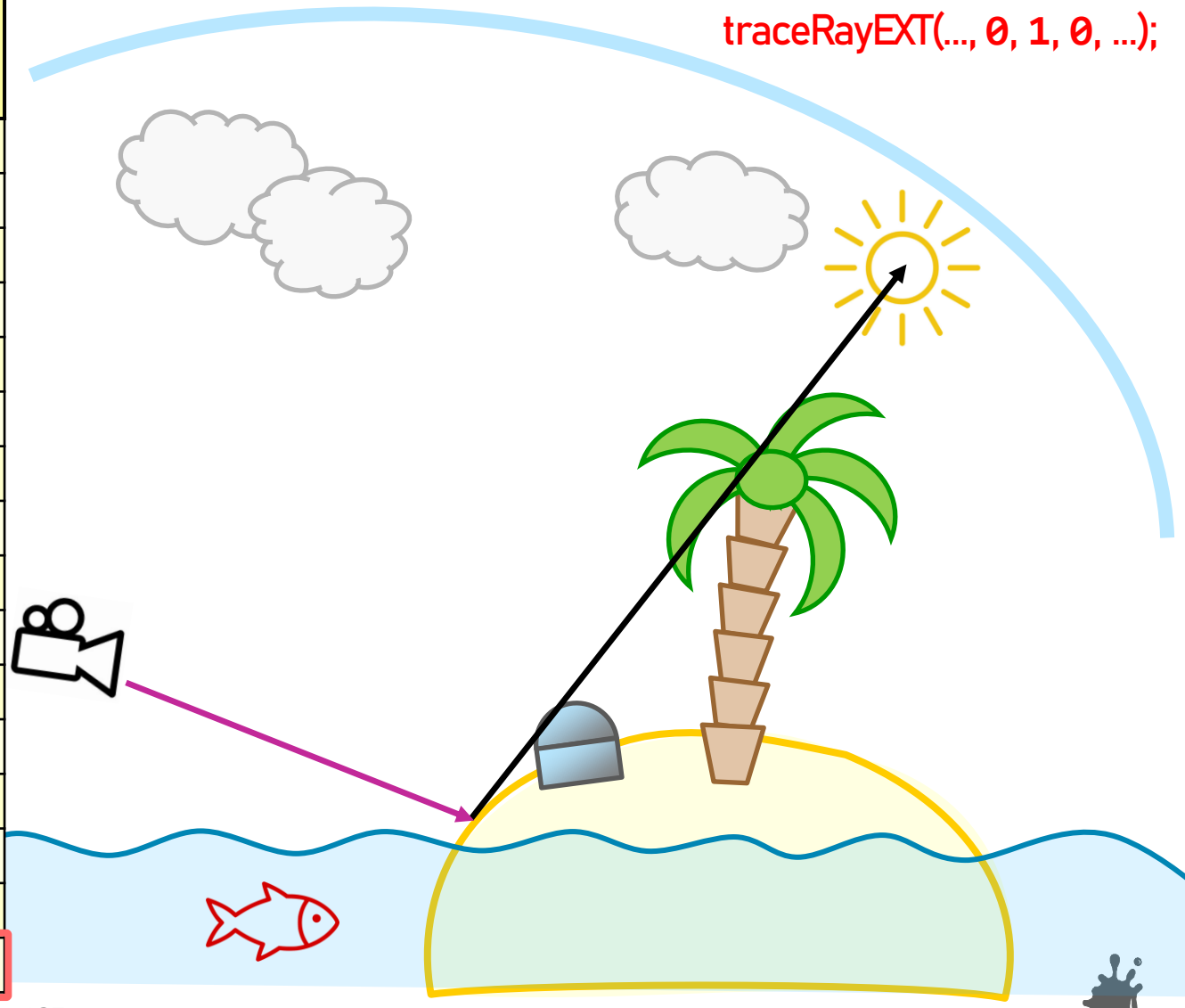
14	*Miss Shader:* SetSkyboxColor		
15	*Miss Shader:* NoShadowAdded		



Shader Binding Table Example + Shadow Rays

vkCmdTraceRaysKHR with rayGenAddr = start + 0 * stride, missAddr = start + 14 * stride, hitGroupsAddr = start + 1 * stride;

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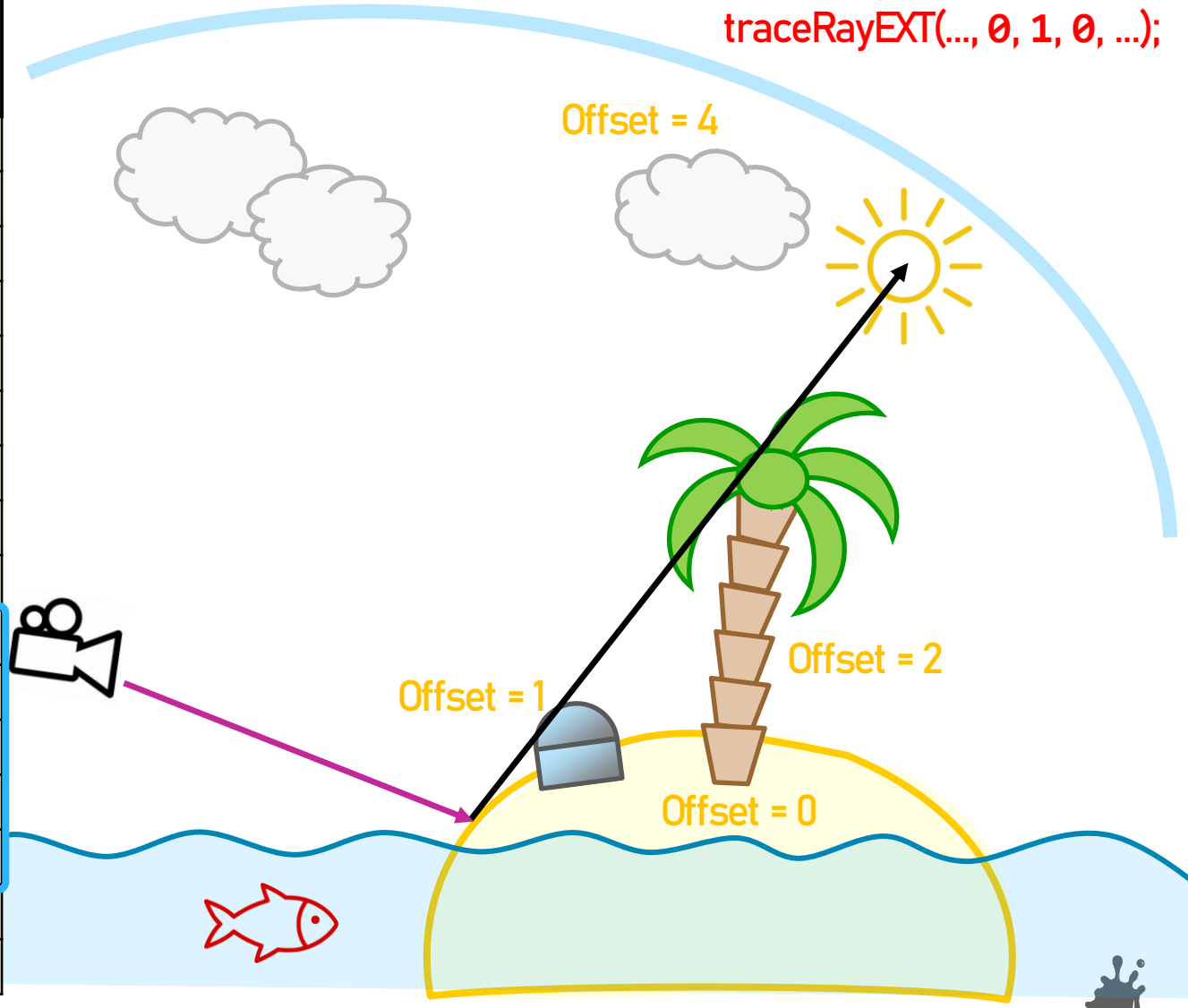

Shader Binding Table Example + Shadow Rays

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Shader Binding Table			
Idx	*[Closest Hit Shader]*	*[Any Hit Shader]*	*[Intersection Shader]*
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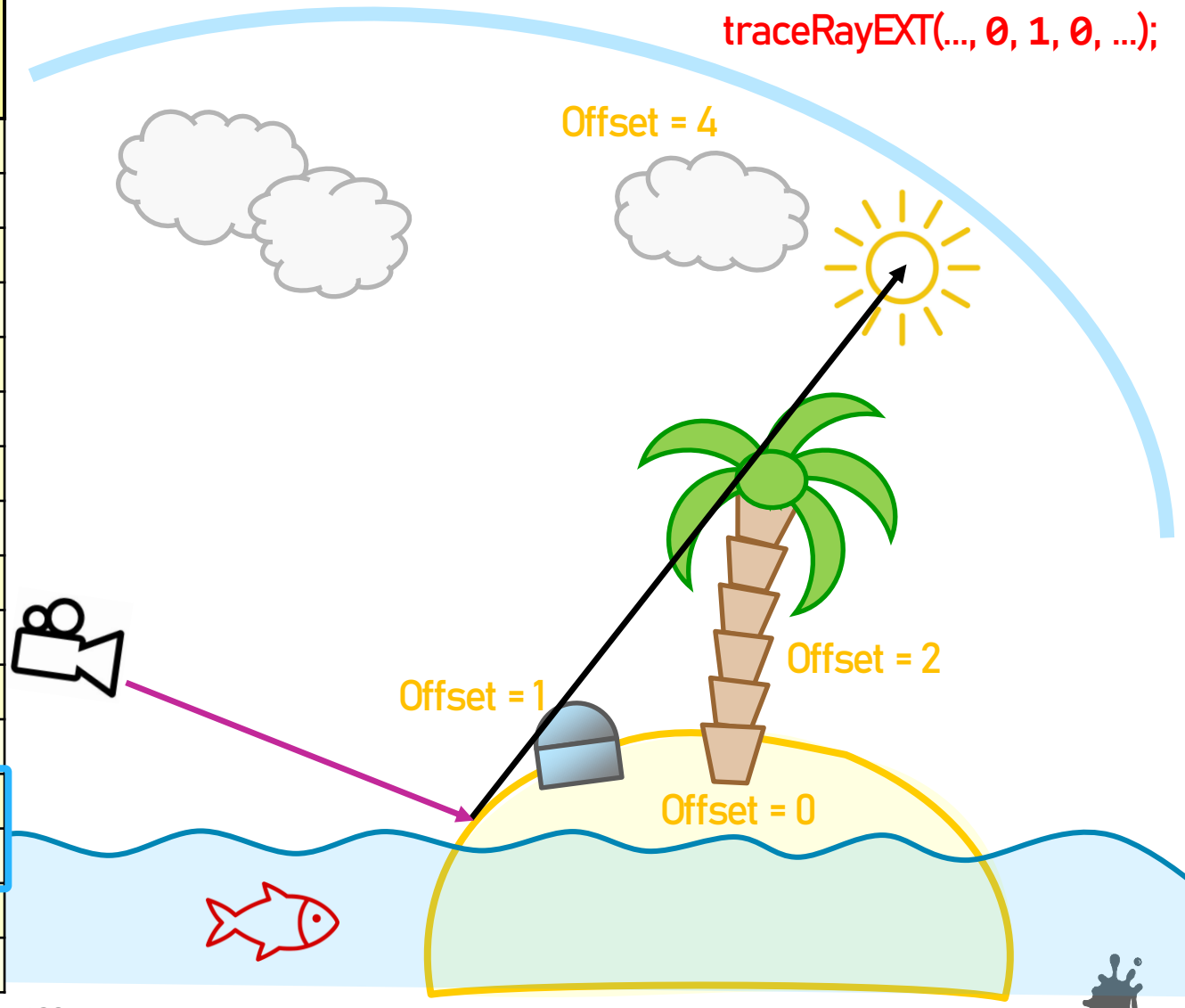

Shader Binding Table Example + Shadow Rays

vkCmdTraceRaysKHR with rayGenAddr = start + 0 * stride, missAddr = start + 14 * stride, hitGroupsAddr = start + 1 * stride;

Shader Binding Table			
Idx	*[Closest Hit Shader]*	*[Any Hit Shader]*	*[Intersection Shader]*
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14	*Miss Shader:* SetSkyboxColor		
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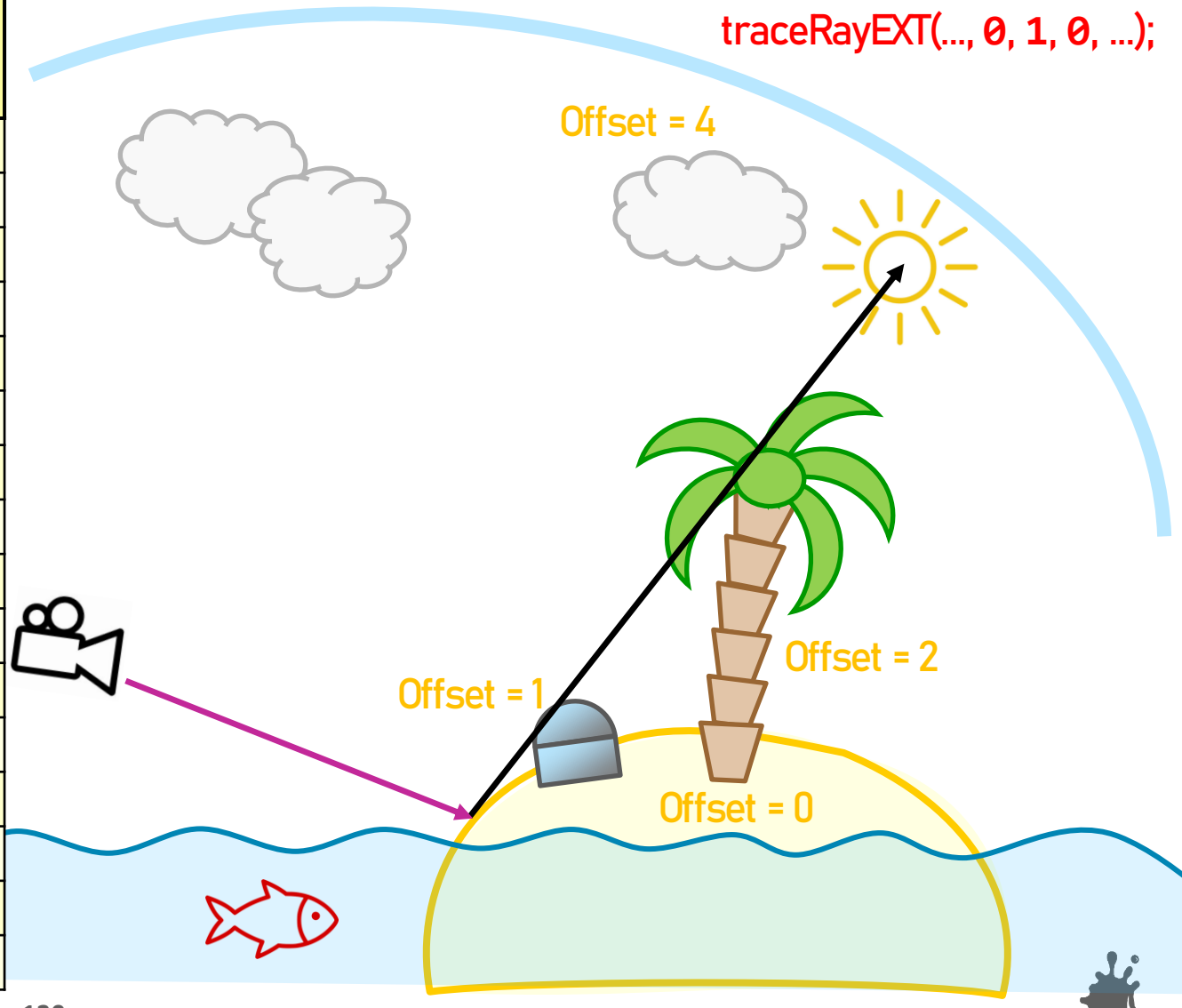
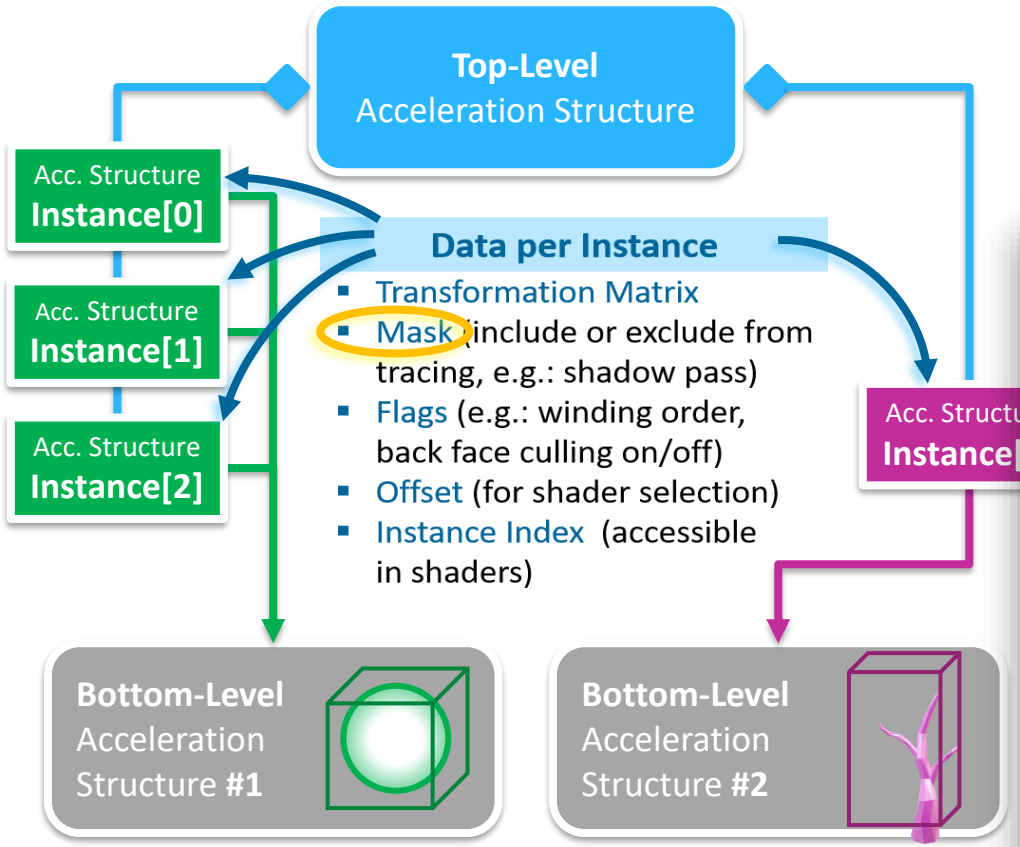


Shader Binding Table Example + Shadow Rays

vkCmdTraceRaysKHR with rayGenAddr = start + 0 * stride, missAddr = start + 14 * stride, hitGroupsAddr = start + 1 * stride;

traceRayEXT(..., 0, 1, 0, ...);



Offset = 4

GLSL

```
#version 460
#extension GL_EXT_ray_tracing : require

layout(set = 0, binding = 0) uniform accelerationStructureEXT as;
// ...
void main() {
  // ...
  traceRayEXT(as,
    gl_RayFlagsOpaqueEXT, 0xF0,
    0 /*sbtRecordOffset*/, 0 /*sbtRecordStride*/, 0 /*missIndex*/,
    origin, 0.1, direction, 100.0,
    0 /*location of payload*/);
  // ...
}
```

Shader Binding Table Example + Shadow Rays

vkCmdTraceRaysKHR with rayGenAddr = start + 0 * stride, missAddr = start + 14 * stride, hitGroupsAddr = start + 1 * stride;

Shader Binding Table			
Idx	*[Closest Hit Shader]*	*[Any Hit Shader]*	*[Intersection Shader]*
0	*Ray Generation Shader:* GenerateRaysAndStoreResults		
1	ShadeTerrain	-	Triangles (built-in)
2	ShadeTreasure	-	Triangles (built-in)
3	ShadePalmTreeTrunk	-	Triangles (built-in)
4	ShadePalmTreeLeaves	CheckAlphaTexture	Triangles (built-in)
5	-	HandleClouds	ProceduralClouds
6	ShadeWaterSurface	-	ProceduralWater
7	ShadeTerrainUnderwater	-	Triangles (built-in)
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11	AddShadow	-	Triangles (built-in)
12	AddShadow	CheckAlphaTexture	Triangles (built-in)
13	-	AddSomeShadow	ProceduralClouds
14	*Miss Shader:* SetSkyboxColor		
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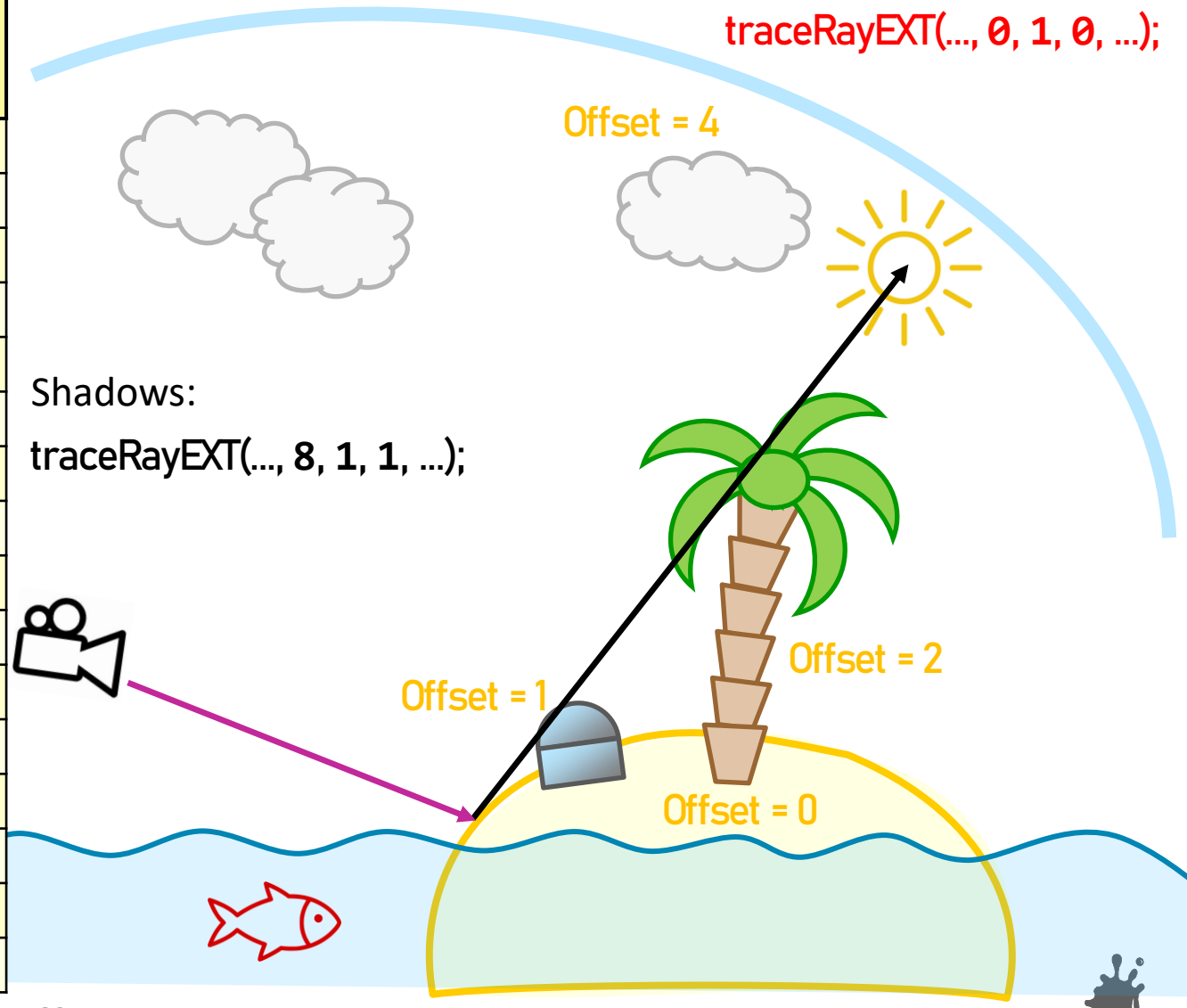


Indexing for Miss Shaders

- Computing a Miss Shader Binding Table Record Address:

```
missRecordAddress = start + stride * missIndex
```

where:

- `start` = `VkStridedDeviceAddressRegionKHR::deviceAddress` parameter of vkCmdTraceRaysKHR
- `stride` = `VkStridedDeviceAddressRegionKHR::stride` parameter of vkCmdTraceRaysKHR
- `missIndex` = parameter of traceRayEXT GLSL function (index-offset, not byte-offset)

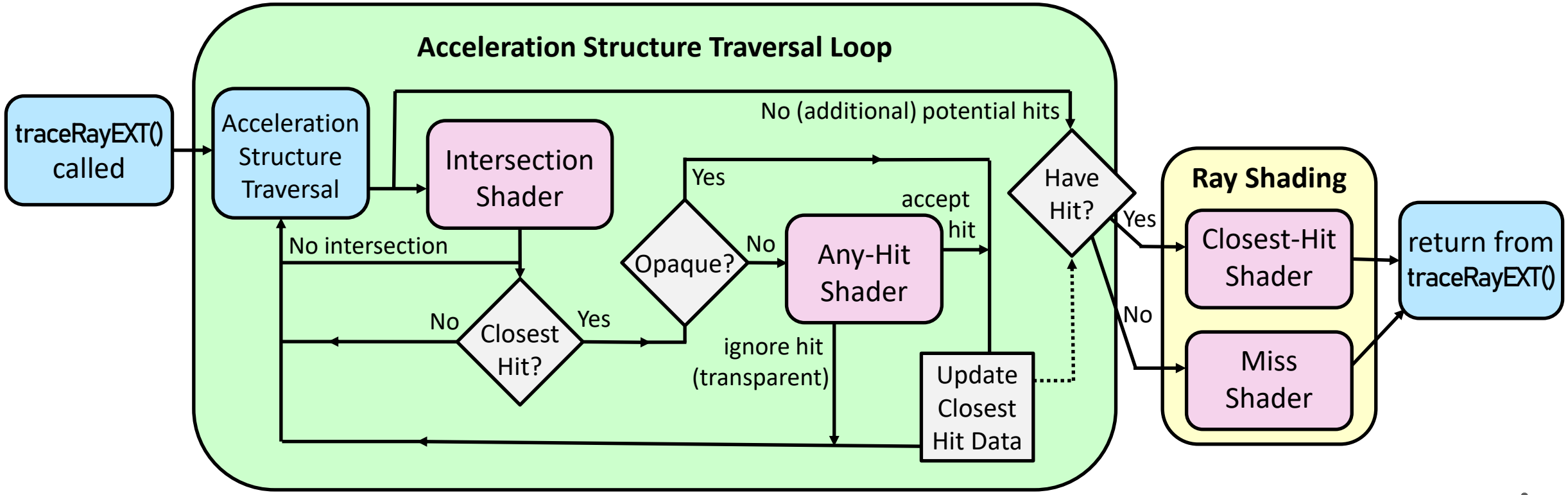
Ray Query

Ray Query

- Ray Query requires
  - Vulkan 1.1
  - VK_KHR_spirv_1_4
  - VK_KHR_acceleration_structure
  - VK_KHR_ray_query
- Access an acceleration structure from **any(!!)** shader
  (i.e., from compute shaders, fragment shaders, intersection shaders, …)
- Not the full ray tracing pipeline runs
- Only the fixed function ray -> bounding volume hierarchy intersection is performed

Ray Query

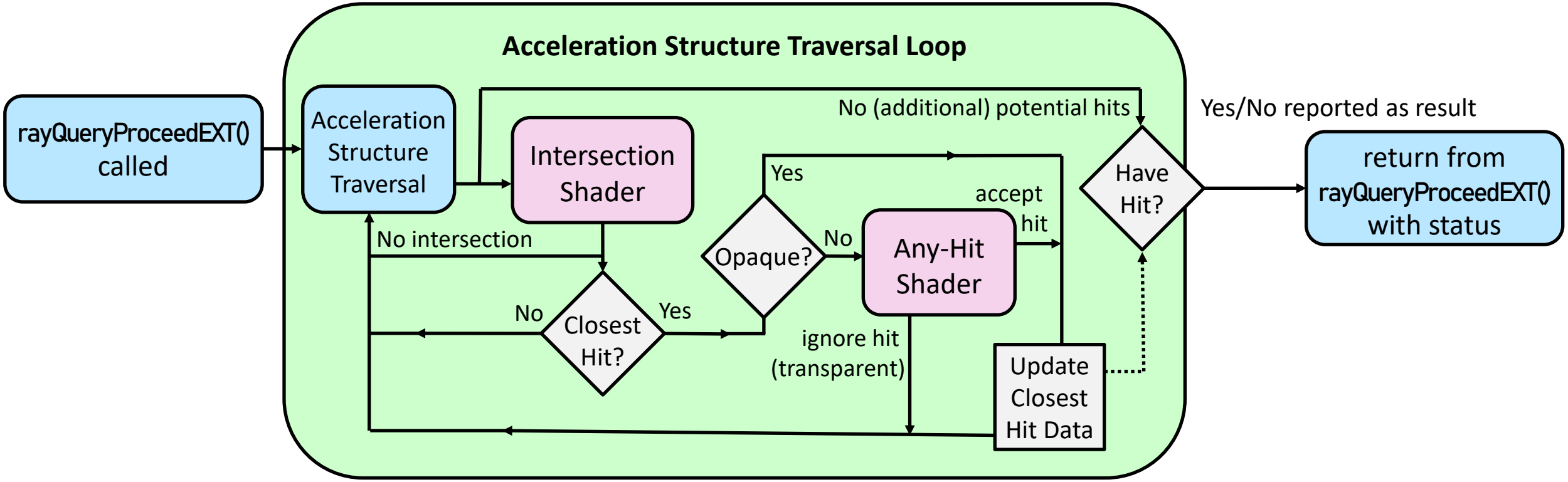
- Compared to **traceRayEXT()**, most notably, **no custom shaders** are executed during a Ray Query



Adapted from: Chris Wyman and Shawn Hargreaves and Peter Shirley and Colin Barré-Brisebois, Introduction to DirectX Raytracing, ACM SIGGRAPH 2018 Courses, https://intro-to-dxr.cwyman.org

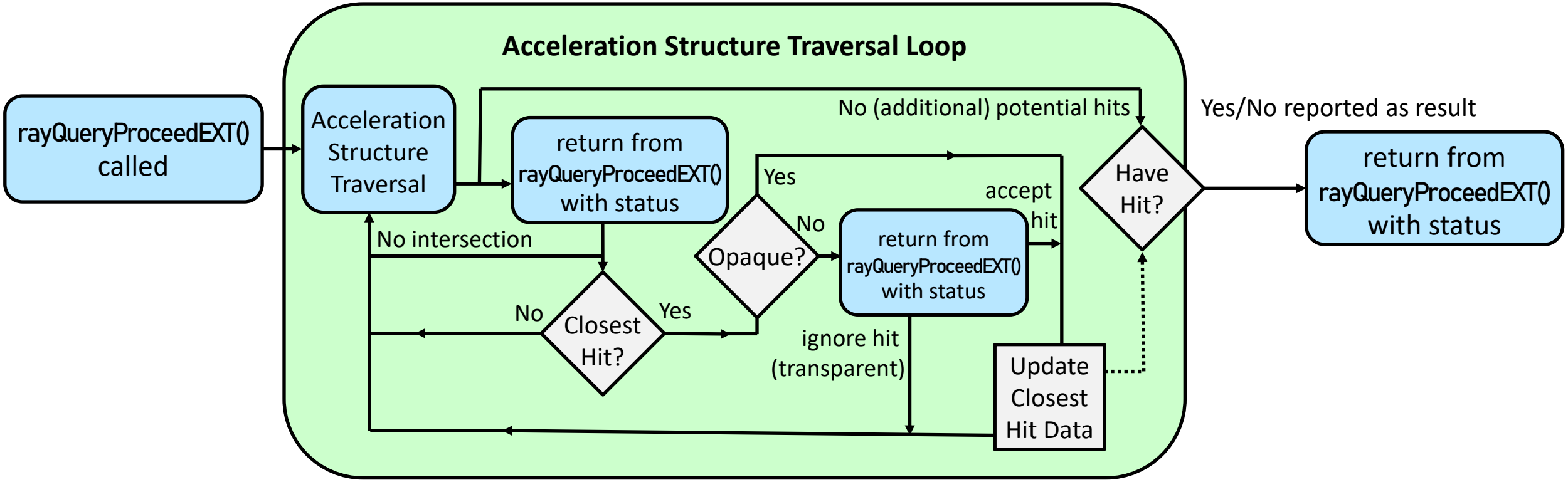
Ray Query

- Compared to **traceRayEXT()**, most notably, **no custom shaders** are executed during a Ray Query
- Call **rayQueryProceedEXT()** in a loop



Ray Query

- Compared to **traceRayEXT()**, most notably, **no custom shaders** are executed during a Ray Query
- Call **rayQueryProceedEXT()** in a loop



Ray Query

```
rayQueryEXT rayQuery;
rayQueryInitializeEXT(rayQuery, topLevelAS,
                      gl_RayFlagsTerminateOnFirstHitEXT,
                      0xFF, origin, 0.1 /*min hit distance*/, direction, 100.0 /*max ray length*/);

while(rayQueryProceedEXT(rayQuery)) {
    if (rayQueryGetIntersectionTypeEXT(rayQuery, false) == gl_RayQueryCandidateIntersectionTriangleEXT) {
        ... // Determine if an opaque triangle hit occurred
        if (opaqueHit) {
            rayQueryConfirmIntersectionEXT(rayQuery);
        }
    }
    else if (rayQueryGetIntersectionTypeEXT(rayQuery, false) == gl_RayQueryCandidateIntersectionAABBEXT) {
        ... // Determine if an opaque hit occurred in an AABB
        if (opaqueHit) {
            rayQueryGenerateIntersectionEXT(rayQuery, ...);
        }
    }
}

if (rayQueryGetIntersectionTypeEXT(rayQuery, true) == gl_RayQueryCommittedIntersectionNoneEXT) {
    // Not shadow!
} else {
    // Shadow!
}
```


Adapted from: The Khronos® Group Inc., Ray Tracing In Vulkan, 2020, https://www.khronos.org/blog/ray-tracing-in-vulkan

Ray Query

```
rayQueryEXT rayQuery;
rayQueryInitializeEXT(rayQuery, topLevelAS,
                      gl_RayFlagsTerminateOnFirstHitEXT,
                      0xFF, origin, 0.1 /*min hit distance*/, direction, 100.0 /*max ray length*/);

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    if (rayQueryGetIntersectionTypeEXT(rayQuery, false) == gl_RayQueryCandidateIntersectionTriangleEXT) {
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        if (opaqueHit) {
            rayQueryConfirmIntersectionEXT(rayQuery);
        }
    }
    else if (rayQueryGetIntersectionTypeEXT(rayQuery, false) == gl_RayQueryCandidateIntersectionAABBEXT) {
        ... // Determine if an opaque hit occurred in an AABB
        if (opaqueHit) {
            rayQueryGenerateIntersectionEXT(rayQuery, ...);
        }
    }
}

if (rayQueryGetIntersectionTypeEXT(rayQuery, true) == gl_RayQueryCommittedIntersectionNoneEXT) {
    // Not shadow!
} else {
    // Shadow!
}
```

Call it in a loop

Provide intersection information manually

Evaluate if hit or miss

Adapted from: The Khronos® Group Inc., Ray Tracing In Vulkan, 2020, https://www.khronos.org/blog/ray-tracing-in-vulkan

Real-Time Rendering

186.140, 2021W, VU, 4.5ECTS

Thank you for your attention!

Johannes Unterguggenberger

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TU Wien, Austria