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# Vulkan Ray Tracing – 5 New Shader Types!

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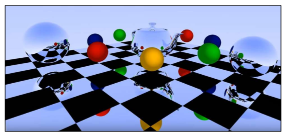



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## Analog Ray Tracing Example ☺



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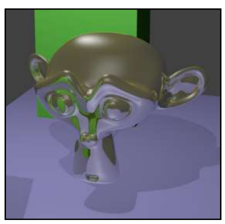
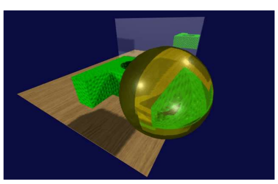
## Digital Ray Tracing Examples



Blender



IronCad



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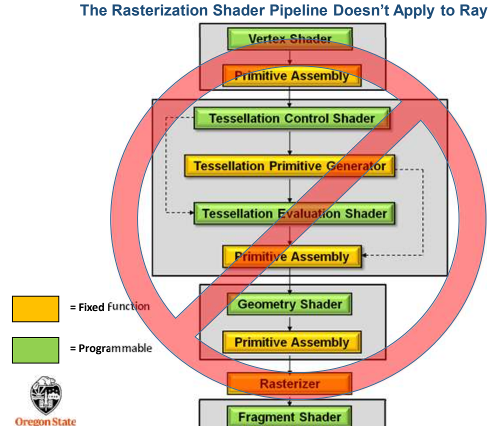
## The Rasterization Shader Pipeline Doesn't Apply to Ray Tracing



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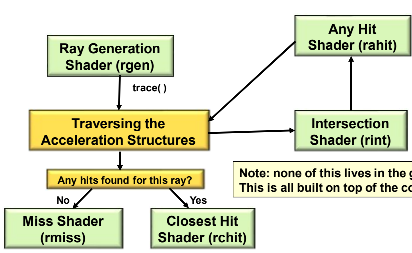
## The Ray-trace Pipeline Involves Five New Shader Types




**Note: none of this lives in the graphics hardware pipeline. This is all built on top of the compute functionality.**

- A **Ray Generation Shader** runs on a 2D grid of threads. It begins the entire ray-tracing operation.
- An **Intersection Shader** implements ray-primitive intersections.
- An **Any Hit Shader** is called when the Intersection Shader finds a hit.
- The **Closest Hit Shader** is called with the information about the hit that happened closest to the viewer. Typically lighting is done here, or firing off new rays to handle reflection and refraction.
- A **Miss Shader** is called when no intersections are found for a given ray. Typically it just sets its pixel color to the background color.



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## The Ray Intersection Process for a Sphere

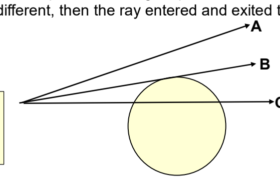
1. Sphere equation: $(x-x_c)^2 + (y-y_c)^2 + (z-z_c)^2 = R^2$

2. Ray equation: $(x,y,z) = (x_0,y_0,z_0) + t*(dx,dy,dz)$

Plugging (x,y,z) from the second equation into the first equation and multiplying-through and simplifying gives:

$At^2 + Bt + C = 0$
Solve for $t_1$, $t_2$

A. If both $t_1$ and $t_2$ are complex, then the ray missed the sphere.
B. If $t_1 == t_2$, then the ray brushed the sphere at a tangent point.
C. If both $t_1$ and $t_2$ are real and different, then the ray entered and exited the sphere.




In Vulkan terms:
**gl_WorldRayOrigin** = $(x_0,y_0,z_0)$
**gl_Hit** = t
**gl_WorldRayDirection** = (dx,dy,dz)



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## The Ray Intersection Process for a Cube

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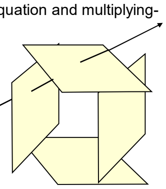
1. Plane equation: Ax + By + Cz + D = 0

2. Ray equation: $(x,y,z) = (x_0,y_0,z_0) + t^*(dx,dy,dz)$

Plugging (x,y,z) from the second equation into the first equation and multiplying-through and simplifying gives:

At + B = 0
Solve for t

A cube is actually the intersection of 6 half-space planes (just 4 are shown here). Each of these will produce its own t intersection value. Treat them as pairs: $(t_{x1},t_{x2})$ , $(t_{y1},t_{y2})$ , $(t_{z1},t_{z2})$



The ultimate entry and exit values are:

$$\left.\begin{aligned} t_{min} &= \max(\ \min(t_{x1},\ t_{x2}),\ \min(t_{y1},\ t_{y2}),\ \min(t_{z1},\ t_{z2})\ ) \\ t_{max} &= \min(\ \max(t_{x1},\ t_{x2}),\ \max(t_{y1},\ t_{y2}),\ \max(t_{z1},\ t_{z2})\ ) \end{aligned}\right\}$$

This works for all convex solids



## In a Raytracing, each ray typically hits a lot of Things

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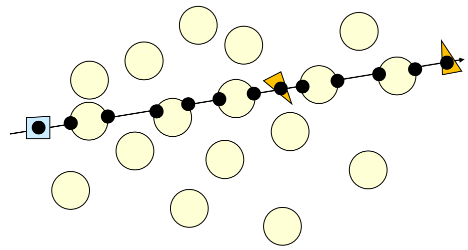



## Acceleration Structures

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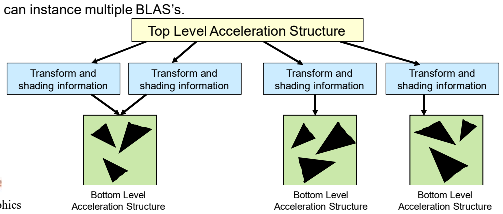
- Bottom-level Acceleration Structure (BLAS) holds the vertex data and is built from vertex and index VkBuffers
- The BLAS can also hold transformations, but it looks like usually the BLAS holds vertices in the original Model Coordinates.
- Top-level Acceleration Structure (TLAS) holds a pointer to elements of the BLAS and a transformation.
- The BLAS is used as a Model Coordinate bounding box.
- The TLAS is used as a World Coordinate bounding box.
- A TLAS can instance multiple BLAS's.






## Creating *Bottom* Level Acceleration Structures

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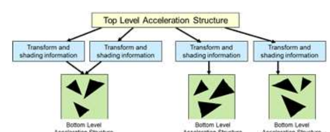
```
vkCreateAccelerationStructure                BottomLevelAccelerationStructure;

VkAccelerationStructureInfo                  vasi;
        vasi.sType = VK_ACCELERATION_STRUCTURE_TYPE_BOTTOM_LEVEL;
        vasi.flags = 0;
        vasi.pNext = nullptr;
        vasi.instanceCount = 0;
        vasi.geometryCount = << number of vertex buffers >>
        vasi.pGeometries   = << vertex buffer pointers >>

 VkAccelerationStructureCreateInfo           vasci;
        vasci.sType = VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_CREATE_INFO;
        vasci.pNext = nullptr;
        vasci.info = &vasi;
        vasci.compactedSize = 0;

result = vkCreateAccelerationStructure( LogicalDevice, IN &vasci, PALLOCATOR, OUT &BottomLevelAcceleraionrStructure );
```






## Creating *Top* Level Acceleration Structures

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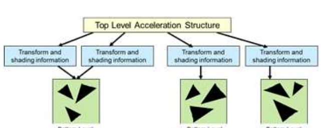
```
vkCreateAccelerationStructure                TopLevelAccelerationStructure;

VkAccelerationStructureInfo                  vasi;
        vasi.sType = VK_ACCELERATION_STRUCTURE_TYPE_TOP_LEVEL;
        vasi.flags = 0;
        vasi.pNext = nullptr;
        vasi.instanceCount = << number of bottom level acceleration structure instances >>;
        vasi.geometryCount = 0;
        vasi.pGeometries   = VK_NULL_HANDLE;

 VkAccelerationStructureCreateInfo           vasci;
        vasci.sType = VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_CREATE_INFO;
        vasci.pNext = nullptr;
        vasci.info = &vasi;
        vasci.compactedSize = 0;

result = vkCreateAccelerationStructure( LogicalDevice, &vasci, PALLOCATOR, &TopLevelAcceleraionrStructure );
```






## Ray Generation Shader

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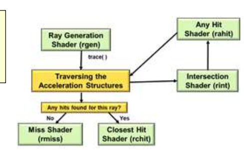
Gets all of the rays going and writes the final color to the pixel

```
layout( location = 1 ) rayPayload  myPayLoad
{
        vec4 color;
};

void
main( )
{
        trace( topLevel, …, 1 );
        imageStore( framebuffer, gl_GlobalInvocationID.xy, color );
}
```

A "payload" is information that keeps getting passed through the process. Different stages can add to it. It is finally consumed at the very end, in this case by writing *color* into the pixel being worked on.



## A New Built-in Function



```
void trace
(
        accelerationStructure     topLevel,
        uint                      rayFlags,
        uint                      cullMask,
        uint                      sbtRecordOffset,
        uint                      sbtRecordStride,
        uint                      missIndex,
        vec3                      origin,
        float                     tmin,
        vec3                      direction,
        float                     tmax,
        int                       payload
);
```

In Vulkan terms:
**gl_WorldRayOrigin** = ($x_0$,$y_0$,$z_0$)
**gl_Hit** = t
**gl_WorldRayDirection** = (dx,dy,dz)



## Intersection Shader

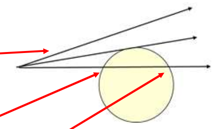


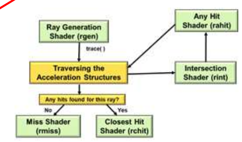
Intersect a ray with an arbitrary 3D object.
Passes data to the Any Hit shader.
There is a built-in ray-triangle Intersection Shader.

```
hitAttribute vec3 attribs

void main( )
{
        SpherePrimitive sph = spheres[ gl_PrimitiveID ];
        vec3 orig = gl_WorldRayOrigin;
        vec3 dir = normalize( gl_WorldRayDirection );
          . . .
        float discr = b*b – 4.*a*c;
        if( discr < 0. )
                return;

        float tmp = ( -b - sqrt(discr) ) / (2.*a);
        if( gl_RayTmin < tmp && tmp < gl_RayTmax )
        {
                vec3 p = orig + tmp * dir;
                attribs = p;
                reportIntersection( tmp, 0 );
                return;
        }
        tmp = ( -b + sqrt(discr) ) / (2.*a);
        if( gl_RayTmin < tmp && tmp < gl_RayTmax )
        {
                vec3 p = orig + tmp * dir;
                attribs = p;
                reportIntersection( tmp, 0 );
                return;
        }
}
```







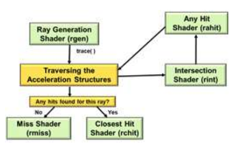

## Miss Shader



Handle a ray that doesn't hit *any* objects

```
rayPayload myPayLoad
{
        vec4 color;
};

void
main( )
{
        color = vec4( 0., 0., 0., 1. );
}
```






## Any Hit Shader

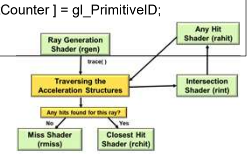


Handle a ray that hits *anything.*
Store information on each hit.
Can reject a hit.

```
layout( binding = 4, set = 0) buffer outputProperties
{
        float outputValues[ ];
} outputData;

layout(location = 0) rayPayloadIn uint outputId;
layout(location = 1) rayPayloadIn uint hitCounter;
hitAttribute vec3 attribs;

void
main( )
{
        outputData.outputValues[ outputId + hitCounter ] = gl_PrimitiveID;
        hitCounter = hitCounter + 1;
}
```






## Closest Hit Shader

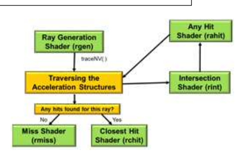


Handle the intersection closest to the viewer.
Collects data from the Any Hit shader.
Can spawn more rays.

```
rayPayload myPayLoad
{
        vec4 color;
};

void
main( )
{
        vec3 stp = gl_WorldRayOrigin + gl_Hit * gl_WorldRayDirection;
        color = texture( MaterialUnit, stp );         // material properties lookup
}
```

In Vulkan terms:
**gl_WorldRayOrigin** = ($x_0$,$y_0$,$z_0$)
**gl_Hit** = t
**gl_WorldRayDirection** = (dx,dy,dz)






## Other New Built-in Functions



void **terminateRay**( );

void **ignoreIntersection**( );

Loosely equivalent to "discard"

void **reportIntersection**( float hit, uint hitKind );

## Ray Trace Pipeline Data Structure

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```
VkPipeline                 RaytracePipeline;
VkPipelineLayout           PipelineLayout;

VkPipelineLayoutCreateInfo              vplci;
        vplci.sType                     = VK_STRUCTURE_TYPE_PIPELINE_LAYOUT_CREATE_INFO;
        vplci.pNext                     = nullptr;
        vplci.flags                     = 0;
        vplci.setLayoutCount            = 1;
        vplci.pSetLayouts               = &descriptorSetLayout;
        vplci.pushConstantRangeCount    = 0;
        vplci.pPushConstantRanges       = nullptr;

result = vkCreatePipelineLayout( LogicalDevice, IN &vplci, nullptr, OUT &PipelineLayout);


VkRayTracingPipelineCreateInfo          vrtpci;
        vrtpci.sType                    = VK_STRUCTURE_TYPE_RAY_TRACING_PIPELINE_CREATE_INFO;
        vrtpci.pNext                    = nullptr;
        vrtpci.flags                    = 0;
        vrtpci.stageCount               = << # of shader stages in the ray-trace pipeline >>
        vrtpci.pStages                  = << what those shader stages are >>
        vrtpci.groupCount               = << # of shader groups >>
        vrtpci.pGroups                  = << pointer to the groups (a group is a combination of shader programs >>
        vrtpci.maxRecursionDepth        = << how many recursion layers deep the ray tracing is allowed to go >>;
        vrtpci.layout                   = PipelineLayout;
        vrtpci.basePipelineHandle       = VK_NULL_HANDLE;
        vrtpci.basePipelineIndex        = 0;

result = vkCreateRayTracingPipelines( LogicalDevice, PALLOCATOR, 1, IN &rvrtpci, nullptr, OUT &RaytracePipeline);
```

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## The Trigger comes from the Command Buffer: vlCmdBindPipeline( ) and vkCmdTraceRays( )

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```
vkCmdBindPipeline( CommandBuffer, VK_PIPELINE_BIND_POINT_RAYTRACING, RaytracePipeline  );


vkCmdTraceRays(     CommandBuffer.
                    raygenShaderBindingTableBuffer, raygenShaderBindingOffset,
                    missShaderBindingTableBuffer,     missShaderBindingOffset,     missShaderBindingStride,
                    hitShaderBindingTableBuffer,      hitShaderBindingOffset,      hitShaderBindingStride,
                    callableShaderBindingTableBuffer, callableShaderBindingOffset, callableShaderBindingStride
                    width, height, depth );,
```

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## Check This Out!

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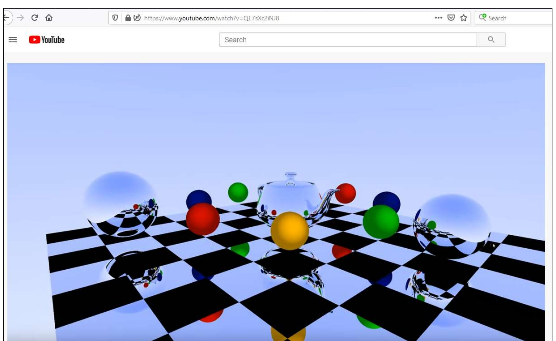

https://www.youtube.com/watch?v=QL7sXc2iNJ8

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