Vulkan Ray Tracing – 5 New Shader Types!

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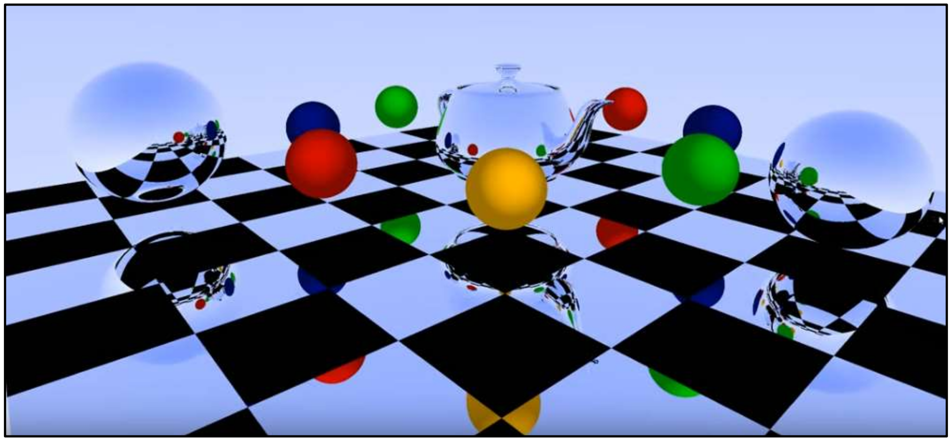

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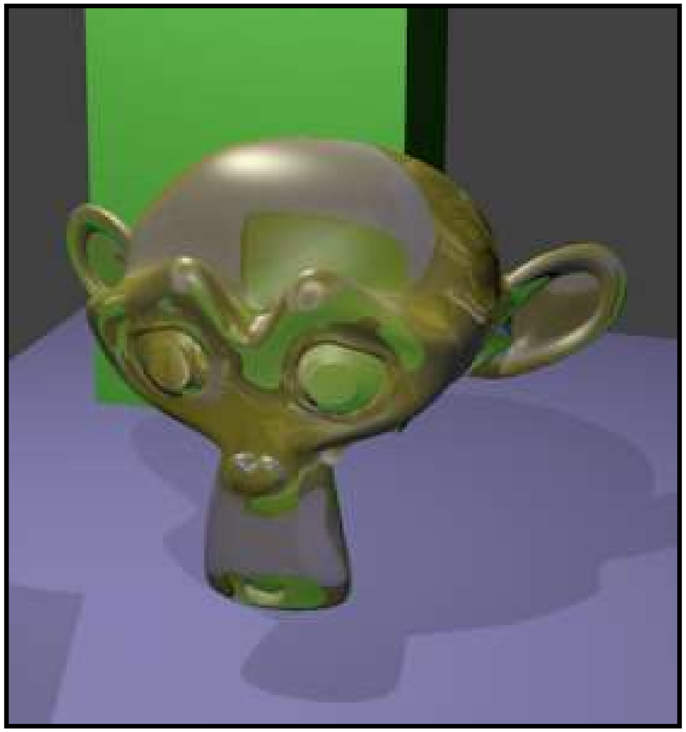
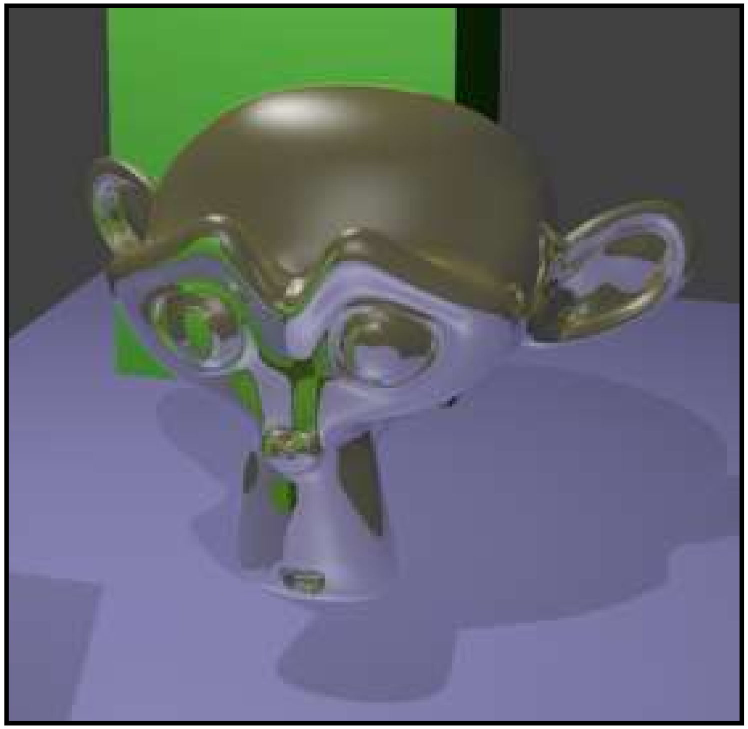
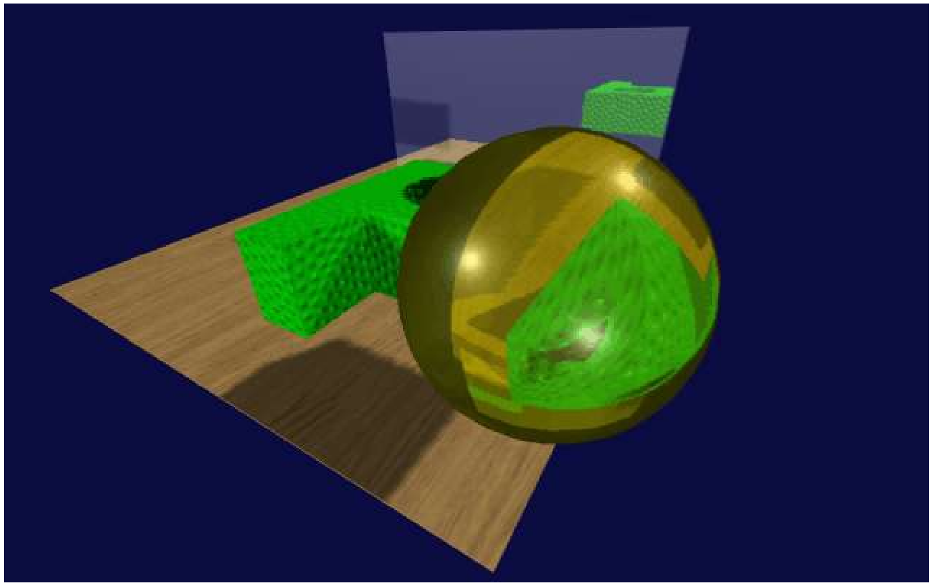
Analog Ray Tracing Example ☺

Digital Ray Tracing Examples



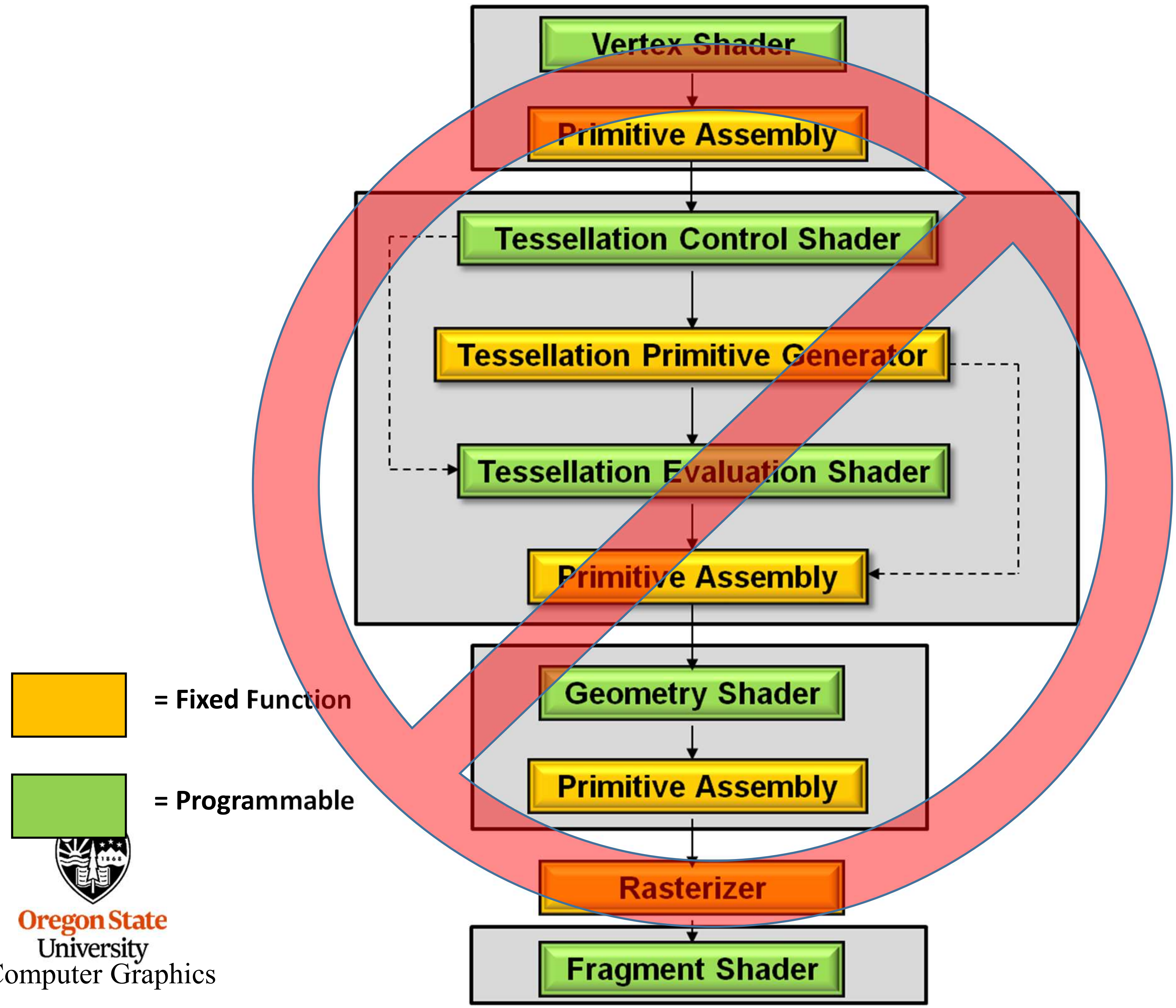


Blender



IronCad

The Rasterization Shader Pipeline That You Are used to Doesn't Apply to Vulkan Ray Tracing



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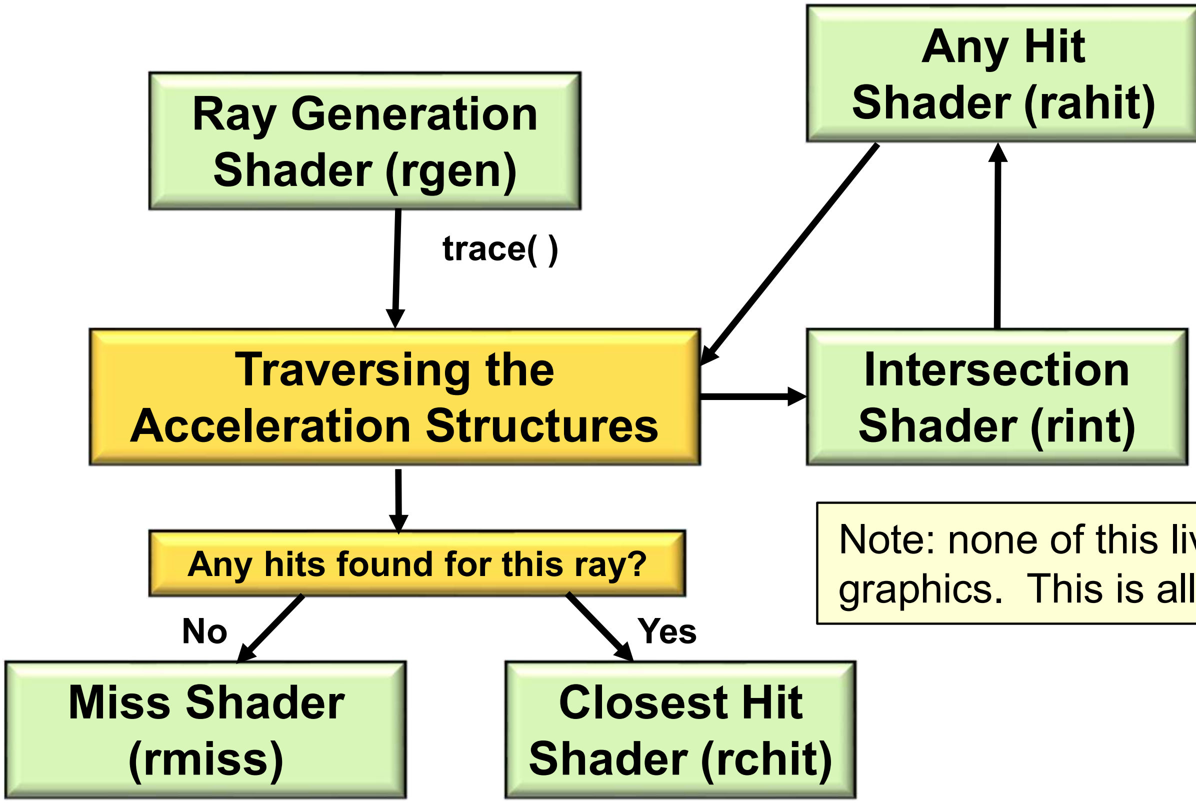
The Vulkan Ray Tracing Pipeline Involves Five New Shader Types



Unlike the rasterization pipeline, there is no constant flow from one shader to the next. Rather, particular shaders are called to respond to particular ***events***.

Note: none of this lives in the hardware meant for rasterization graphics. This is all built on top of the GPU *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. It decides if that intersection should be accepted or ignored.
- 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 shadows, reflections, and refractions.
- 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.

Example: The Ray Intersection Process for a Sphere

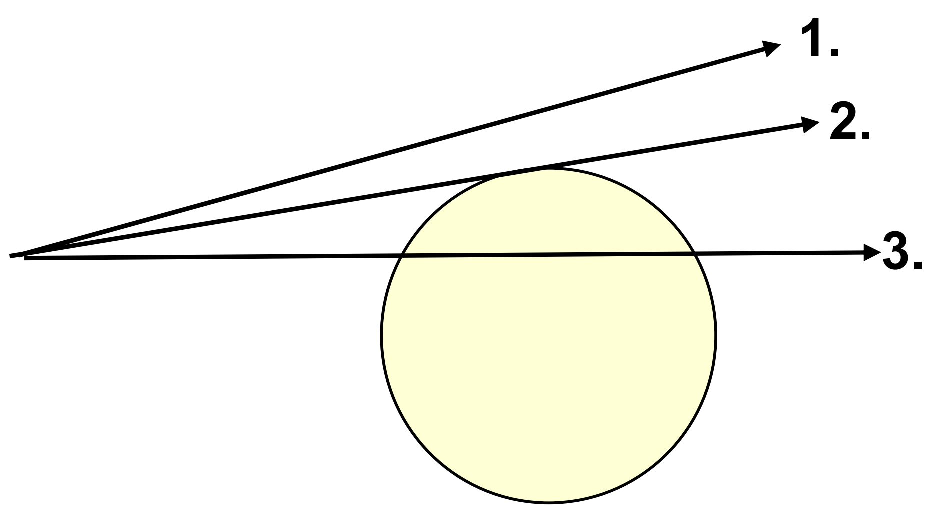
Sphere equation: $(x-x_c)^2 + (y-y_c)^2 + (z-z_c)^2 = R^2$
Ray equation: $(x,y,z) = (x_0,y_0,z_0) + t*(dx,dy,dz)$

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

$$At^2 + Bt + C = 0 \Rightarrow t_1, t_2 = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A}$$

Solve for t_1, t_2 and analyze the solution like this:

1. If both t_1 and t_2 are complex (i.e., have an imaginary component), then the ray missed the sphere completely.
2. If both t_1 and t_2 are real and identical, then the ray brushed the sphere at a tangent point.
3. If both t_1 and t_2 are real and different, then the ray entered and exited the sphere.



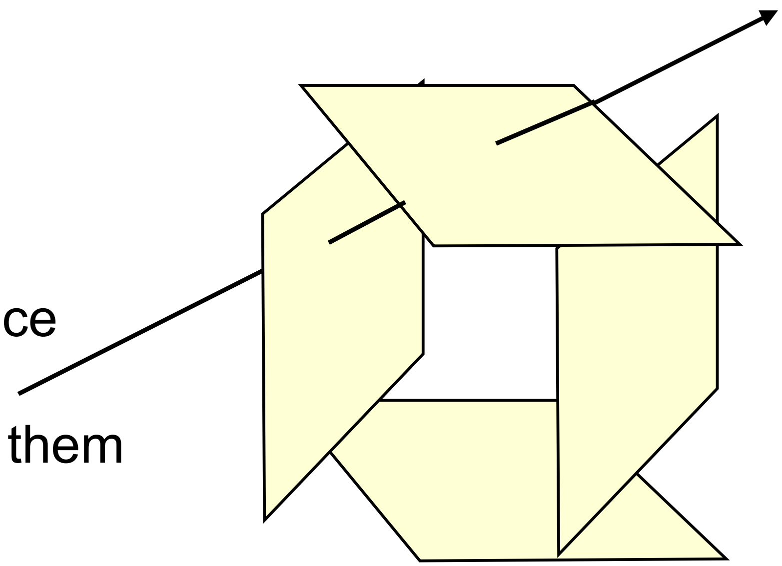
In Vulkan terms:
gl_WorldRayOrigin = (x_0,y_0,z_0)
gl_Hit = t
gl_WorldRayDirection = (dx,dy,dz)

Example: The Ray Intersection Process for a Cube

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

Qt + R = 0
Solve for t = -R/Q



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 cube 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 algorithm works for all convex solids (e.g., cylinder, cone)

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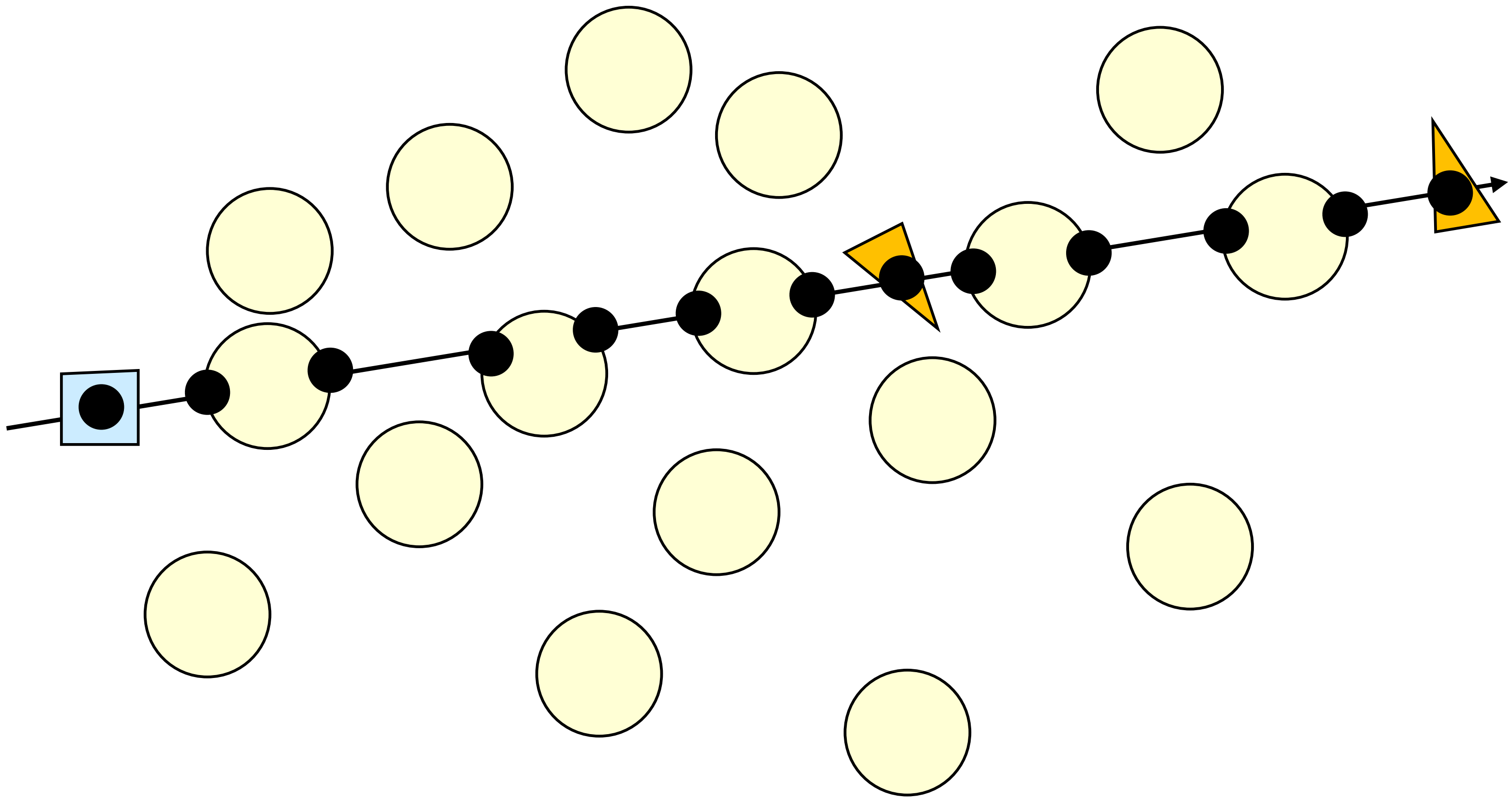
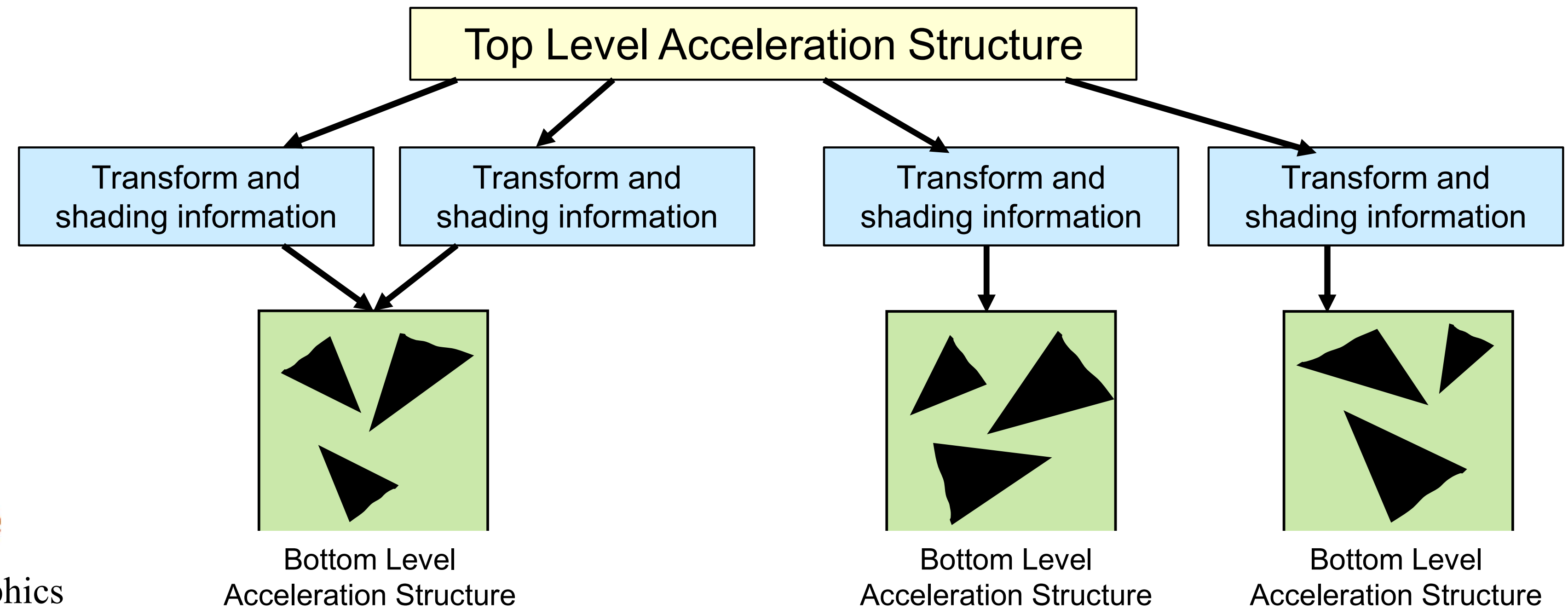
In a Raytracing, each ray typically hits a lot of Things



Acceleration Structures

- A Bottom-level Acceleration Structure (BLAS) reads the vertex data from vertex and index VkBuffers to determine bounding boxes.
- You can also supply your own bounding box information to a BLAS.
- A Top-level Acceleration Structure (TLAS) holds transformations and pointers to multiple BLASes.
- The BLAS is essentially used as a Model Coordinate bounding box, while the TLAS is used as a World Coordinate bounding box.



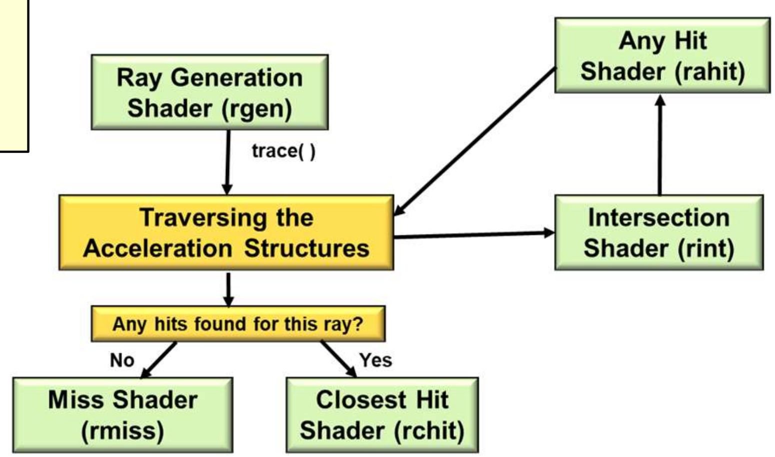
Ray Generation Shader

Gets each individual ray 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 processing of an individual ray. 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 GLSL Function

```
void trace
(
        VkAccelerationStructure      topLevel,          // TLAS
        uint                         rayFlags,
        uint                         cullMask,
        uint                         sbtRecordOffset,
        uint                         sbtRecordStride,
        uint                         missIndex,
        vec3                         origin,            // x0, y0, z0
        float                        tmin,              // minimum t to allow (near)
        vec3                         direction,         // dx, dy, dz
        float                        tmax,              // maximum t to allow (far)
        int                          payload
);
```

In Vulkan terms (these are built-ins accessible from GLSL):
gl_WorldRayOrigin = (x_0,y_0,z_0)
gl_Hit = t
gl_WorldRayDirection = (dx,dy,dz)

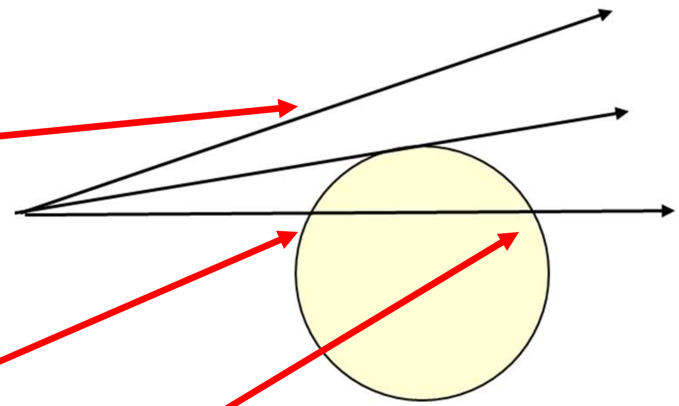
Sample Intersection Shader Code

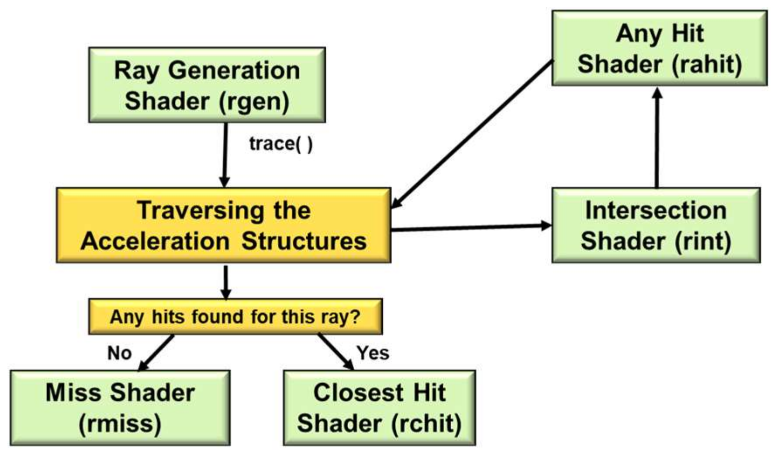
Intersect a ray with an arbitrary 3D object.
Passes data to the **Any Hit** shader.
There is a built-in ray-triangle **Intersection Shader**.

```
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;
        }
}
```



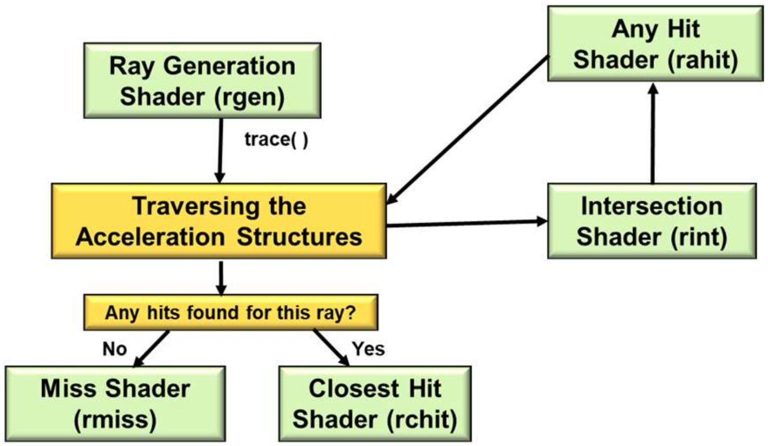


Sample Miss Shader Code

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

```
Layout( location=0 ) rayPayload
{
        vec4 color;
} myPayLoad;

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



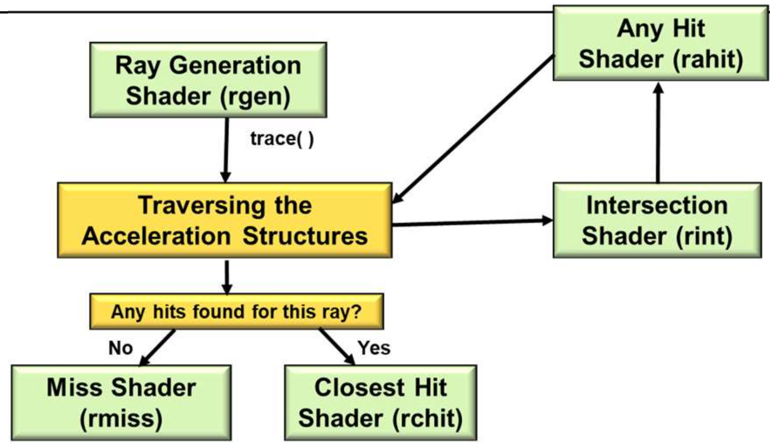
Sample Any Hit Shader Code

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;
}
```



Sample Closest Hit Shader

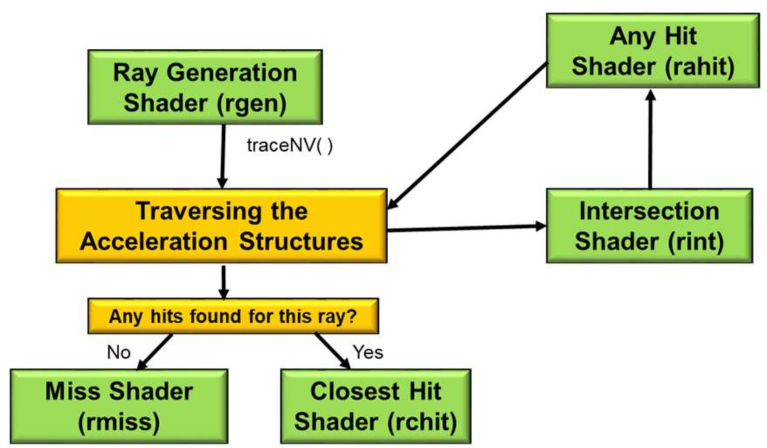
Handle the intersection closest to the viewer.
Collects data from calls to the Any Hit shader.
This shader can spawn more rays to handle shadows, reflections, and refractions.

```
uniform sampler2D uTexUnit;

rayPayload myPayLoad
{
        vec4 color;
};

void
main( )
{
        vec3 stp = gl_WorldRayOrigin + gl_Hit * gl_WorldRayDirection;
        color = texture( uTexUnit, 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"

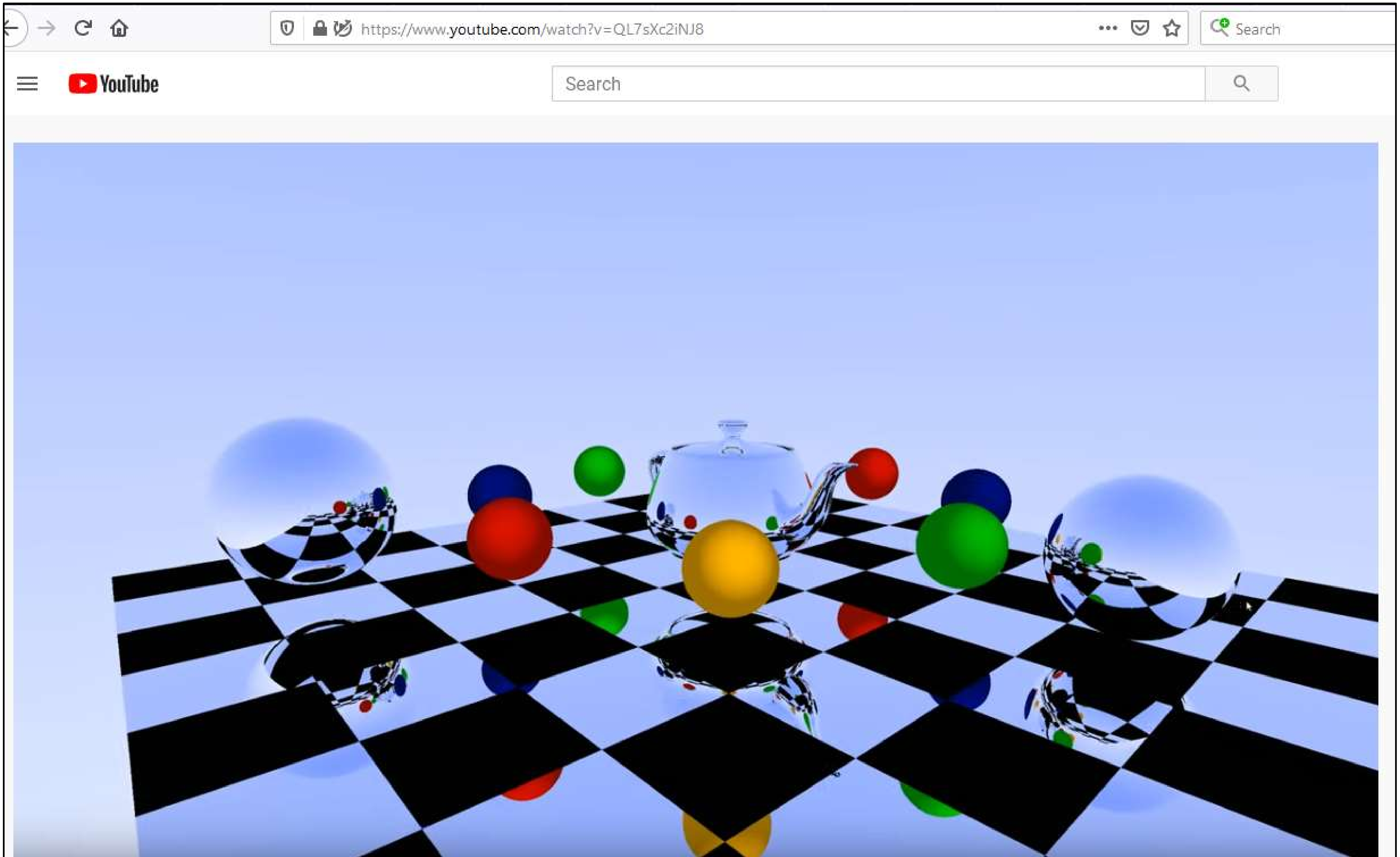
void **reportIntersection**(float hit, uint hitKind);

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

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


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

Check This Out!



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