Vulkan Ray Tracing

Mike Bailey
mjb@cs.oregonstate.edu

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License

The Ray-trace Pipeline Involves Five New Shader Types

- 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.

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:

\[Ax^2 + By + C = 0\]

Solve for \(t_1, t_2\)

If both \(t_1\) and \(t_2\) are complex, then the ray missed the sphere.
If \(t_1 = t_2\), then the ray brushes the sphere at a tangent point.
If both \(t_1\) and \(t_2\) are real and different, then the ray entered and exited the sphere.

In Vulkan terms:
- \(\text{gl}_\text{WorldRayOriginNV} = (x_0,y_0,z_0)\)
- \(\text{gl}_\text{WorldRayDirectionNV} = (dx,dy,dz)\)

The Ray Intersection Process for a Cube

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:

\[Ax + B = 0\]

Solve for \(t\)

A cube is actually the intersection of 8 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:

\(t_{\text{min}} = \max(\min(t_{x1}, t_{x2}), \min(t_{y1}, t_{y2}), \min(t_{z1}, t_{z2}))\)
\(t_{\text{max}} = \min(\max(t_{x1}, t_{x2}), \max(t_{y1}, t_{y2}), \max(t_{z1}, t_{z2}))\)
In a Raytracing, each ray typically hits a lot of Things

Acceleration Structures
- 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 TLAS is used as a Model Coordinate bounding box.
- A TLAS can instance multiple BLAS’s.

Creating Bottom Level Acceleration Structures
![Creating Bottom Level Acceleration Structures diagram]

Creating Top Level Acceleration Structures
![Creating Top Level Acceleration Structures diagram]

Ray Generation Shader
```glsl
layout( location = 1 ) rayPayloadNV myPayload
{
    vec4 color;
}

void main()
{
    traceNV( scene, …, 1 );
    imageStore( framebuffer, gl_GlobalInvocationIDNV.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.

New Built-In Functions
```glsl
void traceNV
{
    accelerationStructureNV topLevel,
    uint unit,
    uint cullMask,
    uint sbtRecordOffset,
    uint sbtRecordStride,
    uint missIndex,
    vec3 origin,
    float tmin,
    vec3 direction,
    float tmax,
    int payload
};
```

In Vulkan terms:
- `gl_WorldRayOriginNV` = \((x_0, y_0, z_0)\)
- `gl_HWNV` = \(r\)
- `gl_WorldRayDirectionNV` = \((dx, dy, dz)\)
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.

```glsl
hitAttributeNV vec3 attribs

void main( )
{
  SpherePrimitive sph = spheres[ gl_PrimitiveID ];
  vec3 orig = gl_WorldRayOriginNV;
  vec3 dir = normalize(gl_WorldRayDirectionNV);
  vec3 oc = orig - center;
  float discr = b*b - 4.*a*c;
  if( discr < 0. )
    return;
  float tmp = ( -b - sqrt(discr) ) / (2.*a);
  if( gl_RayTminNV < tmp &&  tmp < gl_RayTmaxNV )
  {
    vec3 p = orig + tmp * dir;
    attribs = p;
    reportIntersectionNV( tmp, 0 );
    return;
  }
  tmp = ( -b + sqrt(discr) ) / (2.*a);
  if( gl_RayTminNV < tmp &&  tmp < gl_RayTmaxNV )
  {
    vec3 p = orig + tmp * dir;
    attribs = p;
    reportIntersectionNV( tmp, 0 );
    return;
  }
}
```

Intersect a ray with an arbitrary 3D object. Passes data to the Any Hit shader.

Miss Shader

Handle a ray not hitting any 3D objects.

```glsl
rayPayloadNV myPayload
{
  vec4 color;
}

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

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

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

layout(location = 0) rayPayloadInNV uint outputId;
layout(location = 1) rayPayloadInNV uint hitCounter;

hitAttributeNV vec 3 attribs;

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

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

```glsl
rayPayloadNV myPayload
{
  vec4 color;
}

void main( )
{
  vec3 stp = gl_WorldRayOriginNV + gl_HitNV * gl_WorldRayDirectionNV;
  color = texture( MaterialUnit, stp ); // material properties lookup
}
```

New Built-in Functions

- `void ignoreIntersectionNV( )`;
- `void ignoreIntersectionNV( )`;
- `void reportIntersectionNV( float hit, uint hitKind )`;

Loosely equivalent to “discard”

Ray Trace Pipeline Data Structure

```glsl
int

result = vkCreateRayTracingPipelinesNV
( LogicalDevice, PALLOCATOR, 1, IN &rvrtpci, nullptr, OUT &RaytracePipeline);
```
The Trigger comes from the Command Buffer:

`vkCmdBindPipeline()` and `vkCmdTraceRaysNV()`

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

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

[Video: https://www.youtube.com/watch?v=QL7sXc2INJ8]