Tutorials: Build a Path Tracer Step-by-Step

(Or Learning DirectX HLSL by example)

More information: http://intro-to-dxr.cwyman.org

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- Abstract the GPU ↔ CPU communication

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  - High-level C++, using a render graph style
  - (Mostly) standard HLSL shaders

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Ask for textures managed by render graph resource manager

Here: We need to output to default output texture

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Setup a wrapper around our ray tracing GPU launch

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Our shader file where the HLSL code is located

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The names of our shader functions in the HLSL code

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Setup our miss shader

In HLSL, will be miss shader #0, since we declare it here first

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Setup our hit group (using default triangle intersector)

In HLSL, will be hit group #0, since we declare it here first

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Using no closest-hit shader? Skip it

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Compile shaders & build internal data structures

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Make sure we know what our scene includes

So the wrapper can build an acceleration structure

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    Texture::SharedPtr pOutTex = pRes->getTexture( ResourceManager::kOutputChannel );
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Get a pointer to the (managed) output texture

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Clear our output texture

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Send variable data down to our HLSL shader

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Variable named “gOutTex” in HLSL will be our output

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Launch our GPU-accelerated ray tracing work

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How many rays? # pixels on screen

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Quickly get going with GPU-accelerated ray tracing

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This wrapper:

Hides ugly host-side code

Gives an easy-to-use abstraction layer

Not designed to expose advanced functionality

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Don't like it?

Shawn will talk about raw host C++ API later

Want to use my abstractions?

Feel free to chat with me afterwards or online

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My focus for these tutorials

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[shader("raygeneration")]
void MyRayGen()  {
    uint2  curPixel    = DispatchRaysIndex().xy;
    float3 pixelRayDir = normalize( getRayDirFromPixelID( curPixel ) );

    RayDesc ray        = { gCamera.posW, 0.0f, pixelRayDir, 1e+38f };
    RayPayload payload = { float3(0, 0, 0) };

    TraceRay( gRtScene, RAY_FLAG_NONE, 0xFF, 0, 1, 0, ray, payload );

    outTex[curPixel]   = float4( payload.color, 1.0f );
}
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Same name specified in C++ code

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RWTexture<float4> gOutTex;
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Output texture specified in C++ code

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```

Scene specific globals provided by our tutorial wrapper

Tutorial Code Structure

- Two pieces:
  - High-level C++, using a render graph style
    - *Contains an* `initialize()` *callback*
    - *Contains an* `execute()` *callback*
  - (Mostly) standard HLSL shaders

```
RWTexture<float4> gOutTex;
struct RayPayload { float3 color; };
```

User-defined ray payload

```
[shader("raygeneration")]
void MyRayGen()  {
    uint2  curPixel    = DispatchRaysIndex().xy;
    float3 pixelRayDir = normalize( getRayDirFromPixelID( curPixel ) );

    RayDesc ray        = { gCamera.posW, 0.0f, pixelRayDir, 1e+38f };
    RayPayload payload = { float3(0, 0, 0) };

    TraceRay( gRtScene, RAY_FLAG_NONE, 0xFF, 0, 1, 0, ray, payload );

    outTex[curPixel]   = float4( payload.color, 1.0f );
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Utility function computes direction given:

3 camera vectors

2D pixel location on screen

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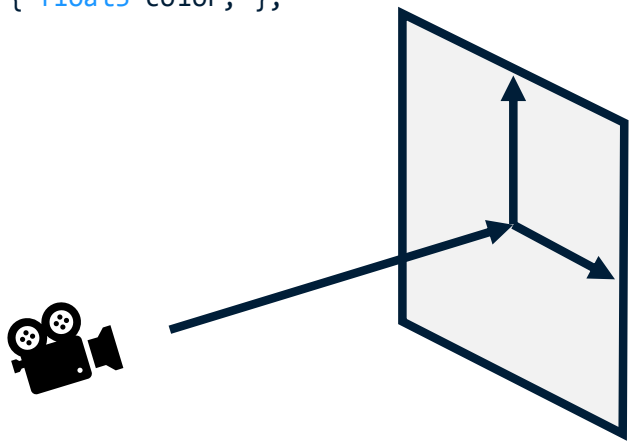
struct RayPayload { float3 color; };
```



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Min & max distance to search along ray

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     outTex[curPixel]   = float4( payload.color, 1.0f );
}
```

Which miss shader to use?

First one specified in C++ code

Tutorial Code Structure

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Which hit group to use?

First one specified in C++ code

May have 1 any hit, 1 closest hit, and 1 intersection shader

```
RWTexture<float4> gOutTex;
struct RayPayload { float3 color; };

[shader("miss")]
void MyMiss(inout RayPayload payload)  {
     payload.color = float3( 0, 0, 1 );
}

[shader("closesthit")]
void MyClosestHit(inout RayPayload data, BuiltinIntersectAttribs attribs)  {
     data.color = float3( 1, 0, 0 );
}

[shader("raygeneration")]
void MyRayGen()  {
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     TraceRay( gRtScene, RAY_FLAG_NONE, 0xFF, 0, 1, 0, ray, payload );

     outTex[curPixel]   = float4( payload.color, 1.0f );
}
```

Total number of hit groups

Tutorial Code Structure

Only non-standard shader code here

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     TraceRay( gRtScene, RAY_FLAG_NONE, 0xFF, 0, 1, 0, ray, payload );

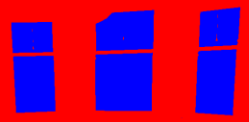
     outTex[curPixel]   = float4( payload.color, 1.0f );
}
```

Allows access to variables for our scene and geometry

(Any framework needs some similar mechanism)

Tutorial Code Structure

This code renders this



For this scene

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}
```

How to Read This Code, In English

This code renders this

For this scene


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     TraceRay( gRtScene, RAY_FLAG_NONE, 0xFF, 0, 1, 0, ray, payload );

     outTex[curPixel]   = float4( payload.color, 1.0f );
}
```

How to Read This Code, In English

This code renders this

For this scene

Given the current pixel ID, compute the direction through the center of the pixel

```
__import Raytracing;

RWTexture<float4> gOutTex;
struct RayPayload { float3 color; };

[shader("miss")]
void MyMiss(inout RayPayload payload)  {
     payload.color = float3( 0, 0, 1 );
}

[shader("closesthit")]
void MyClosestHit( RayPayload data, BuiltinTriangleAttribs attribs)  {
     data.color = float3( 1, 0, 0 );
}

[shader("raygeneration")]
void MyRayGen()  {
     uint2  curPixel    = DispatchRaysIndex().xy;
     float3 pixelRayDir = normalize( getRayDirFromPixelID( curPixel ) );

     RayDesc ray        = { gCamera.posW, 0.0f, pixelRayDir, 1e+38f };
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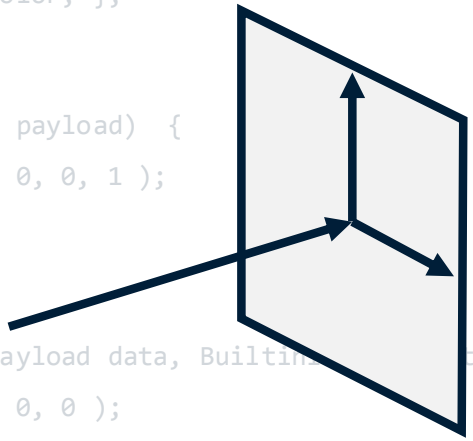
}
```



How to Read This Code, In English

This code renders this

For this scene

Given that direction, trace a ray from the camera out into the scene…

```
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RWTexture<float4> gOutTex;
struct RayPayload { float3 color; };

[shader("miss")]
void MyMiss(inout RayPayload payload)  {
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[shader("raygeneration")]
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     TraceRay( gRtScene, RAY_FLAG_NONE, 0xFF, 0, 1, 0, ray, payload );

     outTex[curPixel]   = float4( payload.color, 1.0f );
}
```

How to Read This Code, In English

This code renders this

If we hit something, return red…

For this scene


```
__import Raytracing;

RWTexture<float4> gOutTex;
struct RayPayload { float3 color; };

[shader("miss")]
void MyMiss(inout RayPayload payload)  {
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}
```

How to Read This Code, In English

This code renders this

If we miss everything, return blue…

For this scene


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How to Read This Code, In English

This code renders this

For this scene

Store the result out to texture ‘gOutTex’

```
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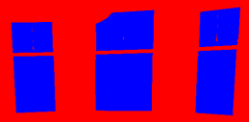

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Tutorial: Ray Traced G-Buffer

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- What is a G-Buffer?
  - Common in *deferred rendering*
  - Save visible geometry in first pass
  - Shade at visible geometry in subsequent pass

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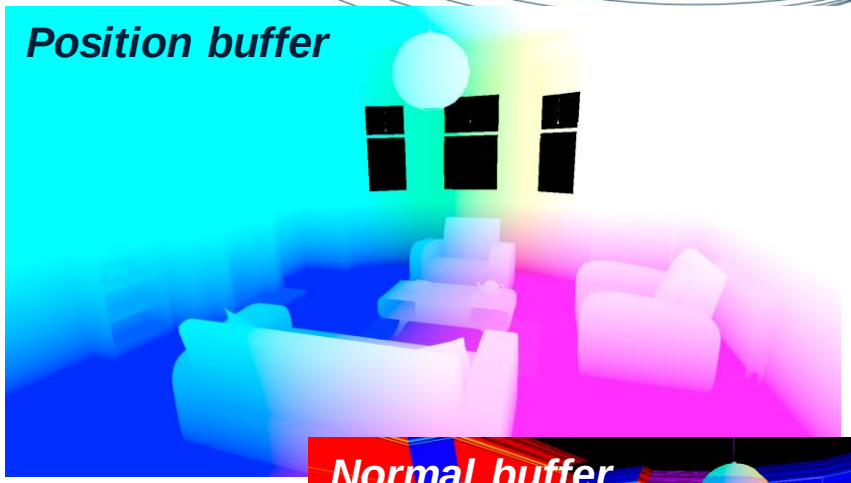

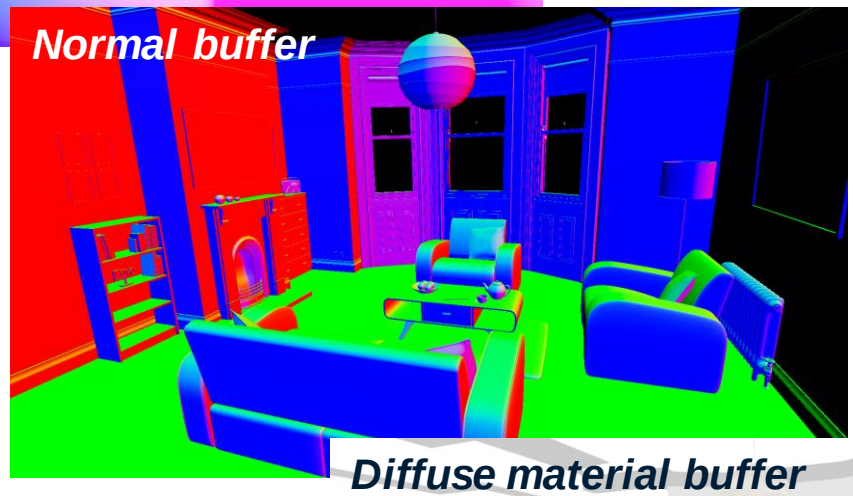

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- What is a G-Buffer?
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- What might shader code for this look like?

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RWTexture<float4> gPosOut, gNormOut, gMatlOut;
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[shader("closesthit")]
void MyClosestHit(inout Payload, BuiltinIntersectAttribs attribs)  {
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     ShadingData shade   = getShadingData( PrimitiveIndex(), attribs );

     gPosOut[launchIdx]  = float4( shade.posW, 1.0f );
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Tutorial: Ray Traced G-Buffer


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Write out geometry properties in closest hit shader

(Behaves a lot like pixel shader in raster)

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Tutorial-provided utility for accessing scene data

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To know what material & texture properties to return, need the triangle ID and hit location

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Ray generation shader similar to before

(except no writing to texture)

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     RayPayload payload = { false };

     TraceRay( gRtScene, RAY_FLAG_NONE, 0xFF, 0, 1, 0, ray, payload );
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```

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Currently: payload must be a struct

```
RWTexture<float4> gPosOut, gNormOut, gMatlOut;
struct Payload { bool dummyValue; };

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}
```

Assume the user clears G-buffer in C++

(So use an empty or null miss shader)

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```
__import Raytracing;

RWTexture<float4> gPosOut, gNormOut, gMatlOut;
struct Payload { bool dummyValue; };

[shader("miss")]
void MyMiss(inout Payload) { }

[shader("closesthit")]
void MyClosestHit(inout Payload, BuiltinIntersectAttribs attribs)  {
    uint2 launchIdx     = DispaychRaysIndex();
    ShadingData shade   = getShadingData( PrimitiveIndex(), attribs );

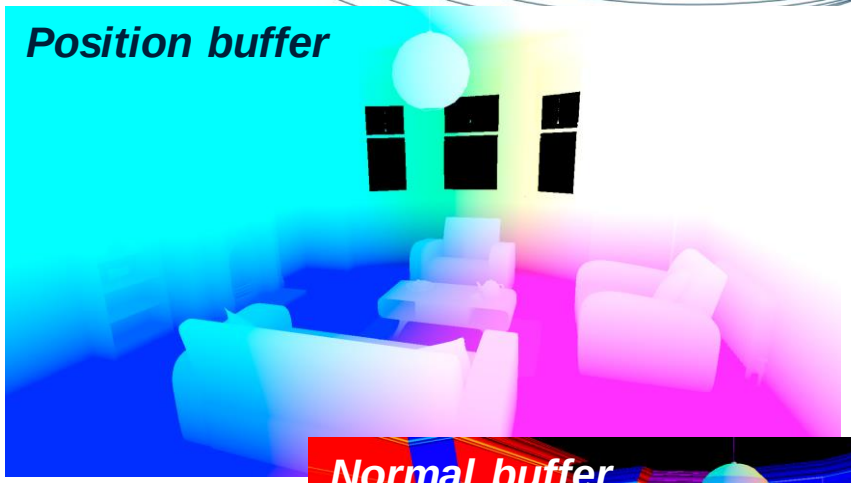
    gPosOut[launchIdx]  = float4( shade.posW, 1.0f );
    gNormOut[launchIdx] = float4( shade.N, 1.0f );
    gMatlOut[launchIdx] = float4( shade.diffuse, 1.0f );
}

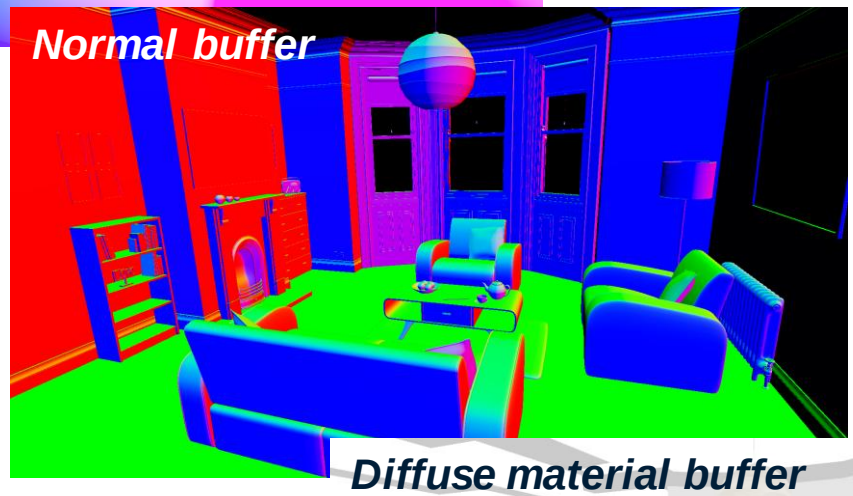
[shader("raygeneration")]
void MyRayGen()  {
    float3 pixelRayDir = normalize( getRayDirFromPixelID( DispatchRaysIndex() ) );
    RayDesc ray        = { gCamera.posW, 0.0f, pixelRayDir, 1e+38f };
    RayPayload payload = { false };

    TraceRay( gRtScene, RAY_FLAG_NONE, 0xFF, 0, 1, 0, ray, payload );
}
```

Tutorial: Ray Traced G-Buffer

- What is a G-Buffer?
  - Common in *deferred rendering*
  - Save visible geometry in first pass
  - Shade at visible geometry in subsequent pass
- What might shader code for this look like?





Tutorial: Ray Traced Ambient Occlusion

Tutorial: Ray Traced Ambient Occlusion

- What is ambient occlusion?
  - *Approximates incident light over hemisphere*
  - *Gives a (very) soft shadow*

Ambient occlusion with one shadow ray per pixel

Tutorial: Ray Traced Ambient Occlusion

- What is ambient occlusion?
  - *Approximates incident light over hemisphere*
  - *Gives a (very) soft shadow*

- Simplest implementation:
  - *Shoot random ray over hemisphere*
  - *See if any occluders within specified radius*
  - *No? Return 1*
  - *Yes? Return 0*

Ambient occlusion with one shadow ray per pixel

Tutorial: Ray Traced Ambient Occlusion

- How is this code different?

Tutorial: Ray Traced Ambient Occlusion

- How is this code different?
- Runs in two passes
  - *Generate a G-buffer (as last tutorial)*
  - *Spawn rays over hemisphere to compute AO*

Tutorial: Ray Traced Ambient Occlusion

- How is this code different?
- Runs in two passes
  - *Generate a G-buffer (as last tutorial)*
  - *Spawn rays over hemisphere to compute AO*

We just showed how to do this!

Tutorial: Ray Traced Ambient Occlusion

- How is this code different?
- Runs in two passes
  - *Generate a G-buffer (as last tutorial)*
  - *Spawn rays over hemisphere to compute AO*

We now focus on this pass

Ambient Occlusion Shaders

```
__import Raytracing;
```

- Let’s look at our ray generation shader

```
[shader(“raygeneration”)]
void MyRayGen()  {
```

Ambient Occlusion Shaders

```
__import Raytracing;
```

- Let's look at our ray generation shader

```
[shader("raygeneration")]
void MyRayGen()  {
    uint2 launchIdx = DispatchRaysIndex();
    uint  randSeed  = initRand( launchIdx );
```

For current pixel, init random # generator

(Fairly standard; see code for details)

Ambient Occlusion Shaders

- Let's look at our ray generation shader

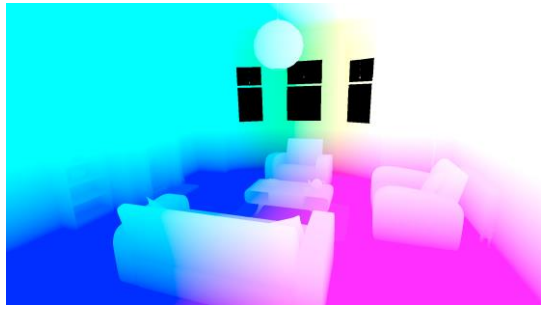
```
__import Raytracing;

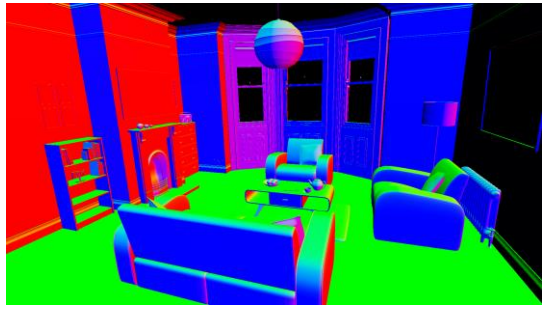
Texture<float4>   gPosition, gNormal;
```

```
[shader("raygeneration")]
void MyRayGen()  {
    uint2 launchIdx = DispatchRaysIndex();
    uint  randSeed  = initRand( launchIdx );

    float4 wsPos    = gPosition[launchIdx];
    float4 wsNorm   = gNormal[launchIdx];
```

Load pixel position and normal from G-buffer





Ambient Occlusion Shaders

- Let's look at our ray generation shader

```
__import Raytracing;

Texture<float4>   gPosition, gNormal;
RWTexture<float4> gOutColor;
```

```
[shader("raygeneration")]
void MyRayGen()  {
    uint2 launchIdx = DispatchRaysIndex();
    uint  randSeed  = initRand( launchIdx );

    float4 wsPos    = gPosition[launchIdx];
    float4 wsNorm   = gNormal[launchIdx];

    float  aoVal    = 1.0f;

    if ( !isBackgroundPixel( wsPos ) ) {



    }

    gOutColor[launchIdx] = float4( aoVal, aoVal, aoVal, 1.0f );
}
```

Set default AO value to output in background

Ambient Occlusion Shaders

- Let's look at our ray generation shader

```
__import Raytracing;

Texture<float4>   gPosition, gNormal;
RWTexture<float4> gOutColor;
```

```
[shader("raygeneration")]
void MyRayGen()  {
    uint2 launchIdx = DispatchRaysIndex();
    uint  randSeed  = initRand( launchIdx );

    float4 wsPos    = gPosition[launchIdx];
    float4 wsNorm   = gNormal[launchIdx];

    float  aoVal    = 1.0f;

    if ( !isBackgroundPixel( wsPos ) ) {
        float3 aoDir = getRandomDir( randSeed, wsNorm );

    }

    gOutColor[launchIdx] = float4( aoVal, aoVal, aoVal, 1.0f );
}
```

Elsewhere, pick a random direction for AO ray

See provided code for details

Should be a cosine-weighted random sample on the hemisphere

Ambient Occlusion Shaders

- Let's look at our ray generation shader

Shoot our AO ray

From our G-buffer location `wsPos` *in our random direction with minimum hit distance of 1e-4 and max of* `gMaxAO`

```
__import Raytracing;

Texture<float4>   gPosition, gNormal;
RWTexture<float4> gOutColor;

cbuffer ConstHostData {
     float gMaxAO;
};

[shader("raygeneration")]
void MyRayGen()  {
     uint2 launchIdx = DispatchRaysIndex();
     uint  randSeed  = initRand( launchIdx );

     float4 wsPos    = gPosition[launchIdx];
     float4 wsNorm   = gNormal[launchIdx];

     float  aoVal    = 1.0f;

     if ( !isBackgroundPixel( wsPos ) ) {
          float3 aoDir = getRandomDir( randSeed, wsNorm );
          aoVal = shootAoRay( wsPos.xyz, aoDir, 1.0e-4f, gMaxAO );
     }

     gOutColor[launchIdx] = float4( aoVal, aoVal, aoVal, 1.0f );
}
```

Ambient Occlusion Shaders

- Let's look at our ray generation shader

```
__import Raytracing;

Texture<float4>   gPosition, gNormal;
RWTexture<float4> gOutColor;

cbuffer ConstHostData {
     float gMaxAO;
};

[shader("raygeneration")]
void MyRayGen()  {
     uint2 launchIdx = DispatchRaysIndex();
     uint  randSeed  = initRand( launchIdx );

     float4 wsPos    = gPosition[launchIdx];
     float4 wsNorm   = gNormal[launchIdx];

     float  aoVal    = 1.0f;

     if ( !isBackgroundPixel( wsPos ) ) {
          float3 aoDir = getRandomDir( randSeed, wsNorm );
          aoVal = shootAoRay( wsPos.xyz, aoDir, 1.0e-4f, gMaxAO );
     }

     gOutColor[launchIdx] = float4( aoVal, aoVal, aoVal, 1.0f );
}
```

Constant buffer with data provided by our C++ program

Ambient Occlusion Shaders

- So how do we shoot our ambient occlusion ray?
  - *Note: In same shader file as last slide*

```
...
float shootAoRay(float3 orig, float3 dir, float minT, float maxT)  {

}
...
```

Ambient Occlusion Shaders

- So how do we shoot our ambient occlusion ray?
  - *Note: In same shader file as last slide*

```
...
struct AOPayload {
    float aoVal;  // 0.0 means 'hit', 1.0 means 'miss'
};
```

Setup our ray and payload

Trace the ray and return the result

```
float shootAoRay(float3 orig, float3 dir, float minT, float maxT)  {
    RayDesc   ray = { orig, minT, dir, maxT };
    AOPayload pay = { 0.0f };

    TraceRay( gRtScene, flags, 0xFF, 0, 1, 0, ray, pay );
    return pay.aoVal;
}
...
```

Ambient Occlusion Shaders

- So how do we shoot our ambient occlusion ray?
  - *Note: In same shader file as last slide*

Note: Assume the shadow ray *hits* unless otherwise told

```
...
struct AOPayload {
    float aoVal;  // 0.0 means 'hit', 1.0 means 'miss'
};
```

```
float shootAoRay(float3 orig, float3 dir, float minT, float maxT)  {
    RayDesc   ray = { orig, minT, dir, maxT };
    AOPayload pay = { 0.0f };

    TraceRay( gRtScene, flags, 0xFF, 0, 1, 0, ray, pay );
    return pay.aoVal;
}
...
```

Ambient Occlusion Shaders

- So how do we shoot our ambient occlusion ray?
  - *Note: In same shader file as last slide*

```
...
struct AOPayload {
    float aoVal;  // 0.0 means 'hit', 1.0 means 'miss'
};
```

```
float shootAoRay(float3 orig, float3 dir, float minT, float maxT)  {
    RayDesc   ray = { orig, minT, dir, maxT };
    AOPayload pay = { 0.0f };

    uint flags = RAY_FLAG_ACCEPT_FIRST_HIT_AND_END_SEARCH |
                 RAY_FLAG_SKIP_CLOSEST_HIT_SHADER;

    TraceRay( gRtScene, flags, 0xFF, 0, 1, 0, ray, pay );
    return pay.aoVal;
}
...
```

Our ray never executes closest hit

(Why? We assume rays hit, so no need)

Ambient Occlusion Shaders

- So how do we shoot our ambient occlusion ray?
  - *Note: In same shader file as last slide*

```
...
struct AOPayload {
    float aoVal;  // 0.0 means 'hit', 1.0 means 'miss'
};
```

```
float shootAoRay(float3 orig, float3 dir, float minT, float maxT)  {
    RayDesc   ray = { orig, minT, dir, maxT };
    AOPayload pay = { 0.0f };

    uint flags = RAY_FLAG_ACCEPT_FIRST_HIT_AND_END_SEARCH |
                 RAY_FLAG_SKIP_CLOSEST_HIT_SHADER;

    TraceRay( gRtScene, flags, 0xFF, 0, 1, 0, ray, pay );
    return pay.aoVal;
}
...
```

Once we find *any* hit, stop

(Why? We then know our assumption is true)

Ambient Occlusion Shaders

- So how do we shoot our ambient occlusion ray?
  - *Note: In same shader file as last slide*

Ray misses? Set AO flag appropriately

```
...
struct AOPayload {
    float aoVal;  // 0.0 means 'hit', 1.0 means 'miss'
};

[shader("miss")]
void AoMiss(inout AOPayload pay) {
    pay.aoVal = 1.0f;
}
```

```
float shootAoRay(float3 orig, float3 dir, float minT, float maxT)  {
    RayDesc   ray = { orig, minT, dir, maxT };
    AOPayload pay = { 0.0f };

    uint flags = RAY_FLAG_ACCEPT_FIRST_HIT_AND_END_SEARCH |
                 RAY_FLAG_SKIP_CLOSEST_HIT_SHADER;

    TraceRay( gRtScene, flags, 0xFF, 0, 1, 0, ray, pay );
    return pay.aoVal;
}
...
```

Ambient Occlusion Shaders

- So how do we shoot our ambient occlusion ray?
  - *Note: In same shader file as last slide*

On any surface, check if alpha test passes

(If not, geometry is transparent here; ignore the hit)

```
...
struct AOPayload {
    float aoVal;  // 0.0 means 'hit', 1.0 means 'miss'
};

[shader("miss")]
void AoMiss(inout AOPayload pay) {
    pay.aoVal = 1.0f;
}

[shader("anyhit")]
void AoAnyHit(inout AOPayload pay, BuiltinIntersectAttribs attribs) {
    if (alphaTestFails(attribs))
        IgnoreHit();
}

float shootAoRay(float3 orig, float3 dir, float minT, float maxT)  {
    RayDesc   ray = { orig, minT, dir, maxT };
    AOPayload pay = { 0.0f };

    uint flags = RAY_FLAG_ACCEPT_FIRST_HIT_AND_END_SEARCH |
                 RAY_FLAG_SKIP_CLOSEST_HIT_SHADER;

    TraceRay( gRtScene, flags, 0xFF, 0, 1, 0, ray, pay );
    return pay.aoVal;
}
...
```

Ambient Occlusion Shaders

- So how do we shoot our ambient occlusion ray?
  - *Note: In same shader file as last slide*

A utility function queries scene textures

(See tutorial code for details)

```
...
struct AOPayload {
    float aoVal;  // 0.0 means 'hit', 1.0 means 'miss'
};

[shader("miss")]
void AoMiss(inout AOPayload pay) {
    pay.aoVal = 1.0f;
}

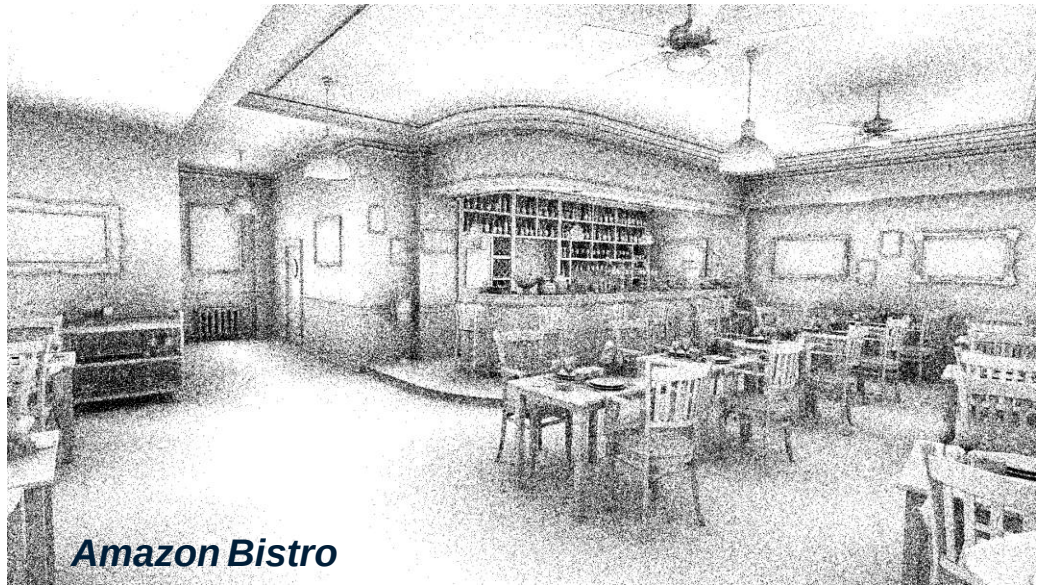
[shader("anyhit")]
void AoAnyHit(inout AOPayload pay, BuiltinIntersectAttribs attribs) {
    if (alphaTestFails(attribs))
        IgnoreHit();
}

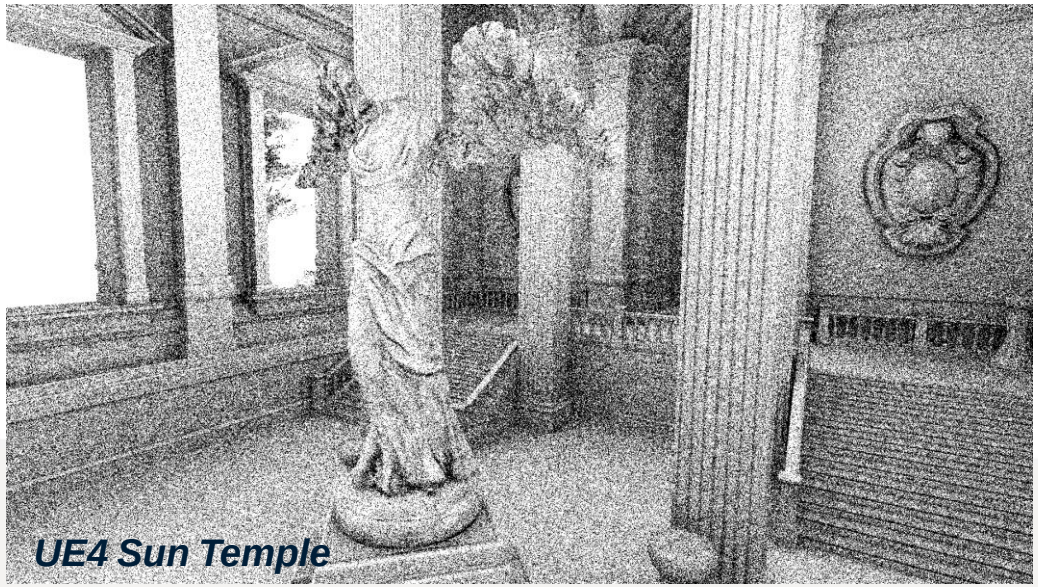
float shootAoRay(float3 orig, float3 dir, float minT, float maxT)  {
    RayDesc   ray = { orig, minT, dir, maxT };
    AOPayload pay = { 0.0f };

    uint flags = RAY_FLAG_ACCEPT_FIRST_HIT_AND_END_SEARCH |
                 RAY_FLAG_SKIP_CLOSEST_HIT_SHADER;

    TraceRay( gRtScene, flags, 0xFF, 0, 1, 0, ray, pay );
    return pay.aoVal;
}
...
```

Ambient Occlusion Results





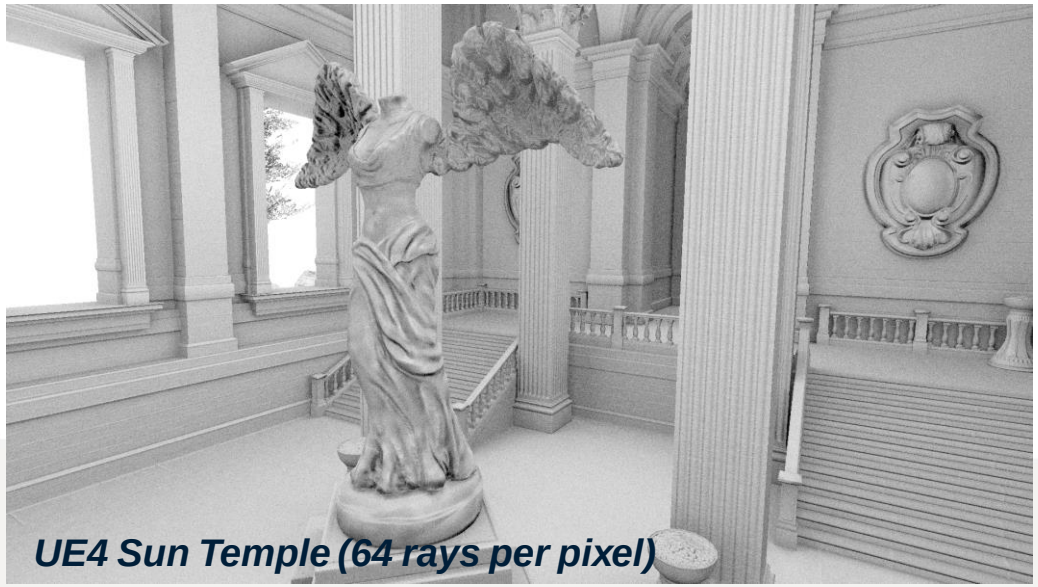

```
...
// Remember our shader's HLSL variables?
Texture<float4>   gPosition, gNormal;
RWTexture<float4> gOutColor;

cbuffer ConstHostData {
    float gMaxAO;
};
...
```

```
...
// Key differences in this tutorial's C++ code: sending data to HLSL
auto vars = mpRays->getRayGenVars();
vars["gPosition"] = pRes->getTexture( "GBufferPositions" );
vars["gNormal"]   = pRes->getTexture( "GBufferNormals" );
vars["gOutColor"] = pRes->getTexture( ResourceManager::kOutputChannel );
vars["ConstHostData"]["gMaxAO"] = float( myMaxAmbientOcclusionDistance );
...
```

Want Less Noise? Shoot More Rays!

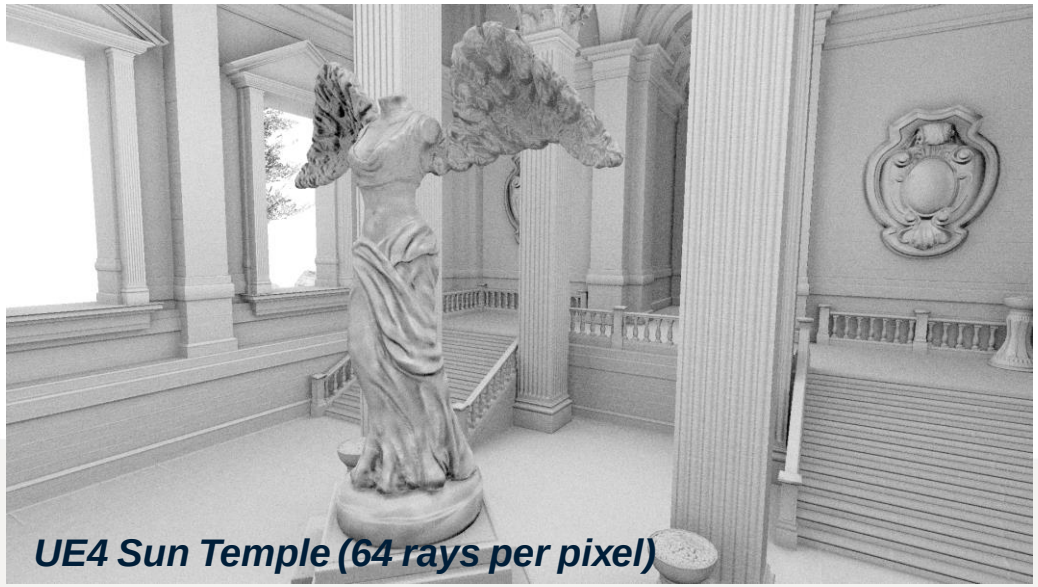
Amazon Bistro (64 rays per pixel)



UE4 Sun Temple (64 rays per pixel)

Shooting >1 Ray Per Pixel

Amazon Bistro (64 rays per pixel)



UE4 Sun Temple (64 rays per pixel)

```
...
cbuffer ConstHostData {
    float gMaxAO;

};

[shader("raygeneration")]
void AoRayGen()  {
    uint2 launchIdx = DispatchRaysIndex();
    uint  randSeed  = initRand( launchIdx );

    float4 wsPos    = gPosition[launchIdx];
    float4 wsNorm   = gNormal[launchIdx];

    float  aoVal    = 1.0f;

    if ( !isBackgroundPixel( wsPos ) ) {

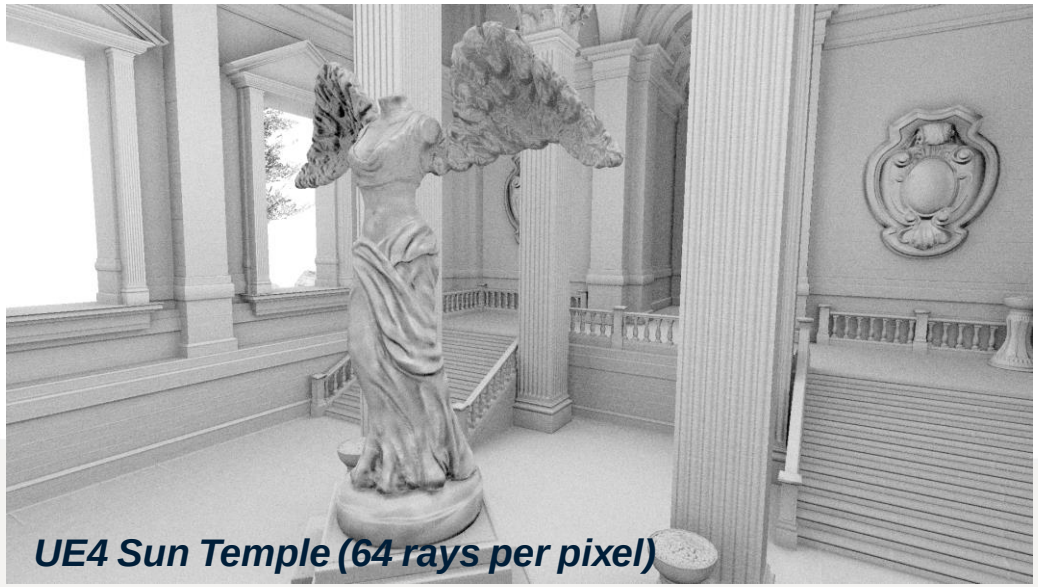

        float3 aoDir = getRandomDir( randSeed, wsNorm );
        aoVal = shootAoRay( wsPos.xyz, aoDir, 1.0e-4f, gMaxAO );

    }

    gOutColor[launchIdx] = float4( aoVal, aoVal, aoVal, 1.0f );
}
```

Shooting >1 Ray Per Pixel

Amazon Bistro (64 rays per pixel)



UE4 Sun Temple (64 rays per pixel)

```
...
cbuffer ConstHostData {
    float gMaxAO;
    uint  gNumRays;
};

[shader("raygeneration")]
void AoRayGen()  {
    uint2 launchIdx = DispatchRaysIndex();
    uint  randSeed  = initRand( launchIdx );

    float4 wsPos    = gPosition[launchIdx];
    float4 wsNorm   = gNormal[launchIdx];

    float  aoCount  = float( gNumRays );

    if ( !isBackgroundPixel( wsPos ) ) {
        aoCount = 0.0f;
        for (int i = 0; i < gNumRays; i++) {
            float3 aoDir = getRandomDir( randSeed, wsNorm );
            aoCount += shootAoRay( wsPos.xyz, aoDir, 1.0e-4f, gMaxAO );
        }
    }

    float aoVal = aoCount / float( gNumRays );
    gOutColor[launchIdx] = float4( aoVal, aoVal, aoVal, 1.0f );
}
```

Diffuse Lighting Only

Diffuse Plus Shadows

Diffuse, Shadows, 1 Bounce Global Illumination

Tutorial: Diffuse Shadows And Global Illumination

- How is this code different?

Tutorial: Diffuse Shadows And Global Illumination

- How is this code different?
- Shoots two ***types*** of rays:
  - *Shadow rays (test visibility only)*
  - *Indirect rays (return a color in selected direction)*

Tutorial: Diffuse, Shadows, & GI

- How is this code different?
- Shoots two ***types*** of rays:
  - *Shadow rays (test visibility only)*
  - *Indirect rays (return a color in selected direction)*
- Shadow rays ***identical*** to AO rays
  - *Both test visibility in a specified direction*

```
...
struct AOPayload {
    float aoVal;  // 0.0 means 'hit', 1.0 means 'miss'
};

[shader("miss")]
void AoMiss(inout AOPayload pay) {
    pay.aoVal = 1.0f;
}

[shader("anyhit")]
void AoAnyHit(inout AOPayload pay, BuiltinIntersectAttribs attribs) {
    if (alphaTestFails(attribs))
        IgnoreHit();
}

float shootAoRay(float3 orig, float3 dir, float minT, float maxT)  {
    RayDesc   ray = { orig, minT, dir, maxT };
    AOPayload pay = { 0.0f };

    uint flags = RAY_FLAG_ACCEPT_FIRST_HIT_AND_END_SEARCH |
                 RAY_FLAG_SKIP_CLOSEST_HIT_SHADER;

    TraceRay( gRtScene, flags, 0xFF, 0, 1, 0, ray, pay );
    return pay.aoVal;
}
...
```

Tutorial: Diffuse, Shadows, & GI

- How is this code different?
- Shoots two ***types*** of rays:
  - *Shadow rays (test visibility only)*
  - *Indirect rays (return a color in selected direction)*
- Shadow rays ***identical*** to AO rays
  - *Both test visibility in a specified direction*
  - *Unless you want to rename for clarity*

```
...
struct ShadowPayload {
    float visibility;  // 0.0 means 'shadowed', 1.0 means 'lit'
};

[shader("miss")]
void ShadowMiss(inout ShadowPayload pay) {
    pay.visibility = 1.0f;
}

[shader("anyhit")]
void ShadowAnyHit(inout ShadowPayload pay, BuiltinIntersectAttribs attribs) {
    if (alphaTestFails(attribs))
        IgnoreHit();
}

float shootShadowRay(float3 orig, float3 dir, float minT, float maxT)  {
    RayDesc       ray = { orig, minT, dir, maxT };
    ShadowPayload pay = { 0.0f };

    uint flags = RAY_FLAG_ACCEPT_FIRST_HIT_AND_END_SEARCH |
                 RAY_FLAG_SKIP_CLOSEST_HIT_SHADER;

    TraceRay( gRtScene, flags, 0xFF, 0, 1, 0, ray, pay );
    return pay.visibility;
}
...
```

Tutorial: Diffuse, Shadows, & GI

- How is this code different?
- Shoots two ***types*** of rays:
  - *Shadow rays (test visibility only)*
  - *Indirect rays (return a color in selected direction)*
- Shadow rays ***identical*** to AO rays
  - *Both test visibility in a specified direction*
  - *Unless you want to rename for clarity*
  - *And changes due to different number of ray shaders*
    - *For me, shadows are hit group #0, miss shader #0*
    - *For me, there are 2 hit groups (1 for shadows, 1 for color)*

```
...
struct ShadowPayload {
    float visibility;  // 0.0 means 'shadowed', 1.0 means 'lit'
};

[shader("miss")]
void ShadowMiss(inout ShadowPayload pay) {
    pay.visibility = 1.0f;
}

[shader("anyhit")]
void ShadowAnyHit(inout ShadowPayload pay, BuiltinIntersectAttribs attribs) {
    if (alphaTestFails(attribs))
        IgnoreHit();
}

float shootShadowRay(float3 orig, float3 dir, float minT, float maxT)  {
    RayDesc       ray = { orig, minT, dir, maxT };
    ShadowPayload pay = { 0.0f };

    uint flags = RAY_FLAG_ACCEPT_FIRST_HIT_AND_END_SEARCH |
                 RAY_FLAG_SKIP_CLOSEST_HIT_SHADER;

    TraceRay(gRtScene, flags, 0xFF, shadHitGrp, totalHitGrps, shadMiss, ray, pay);
    return pay.visibility;
}
...
```

Tutorial: Diffuse, Shadows, & GI

- How is this code different?
- Shoots two ***types*** of rays:
  - *Shadow rays (test visibility only)*
  - *Indirect rays (return a color in selected direction)*
- Shadow rays ***identical*** to AO rays
  - *Both test visibility in a specified direction*
  - *Unless you want to rename for clarity*
  - *And changes due to different number of ray shaders*
    - *For me, shadows are hit group #0, miss shader #0*
    - *For me, there are 2 hit groups (1 for shadows, 1 for color)*

```
...
struct ShadowPayload {
    float visibility;  // 0.0 means 'shadowed', 1.0 means 'lit'
};

[shader("miss")]
void ShadowMiss(inout ShadowPayload pay) {
    pay.visibility = 1.0f;
}

[shader("anyhit")]
void ShadowAnyHit(inout ShadowPayload pay, BuiltinIntersectAttribs attribs) {
    if (alphaTestFails(attribs))
        IgnoreHit();
}

float shootShadowRay(float3 orig, float3 dir, float minT, float maxT)  {
    RayDesc       ray = { orig, minT, dir, maxT };
    ShadowPayload pay = { 0.0f };

    uint flags = RAY_FLAG_ACCEPT_FIRST_HIT_AND_END_SEARCH |
                 RAY_FLAG_SKIP_CLOSEST_HIT_SHADER;

    TraceRay( gRtScene, flags, 0xFF, 0, 2, 0, ray, pay );
    return pay.visibility;
}
...
```

Tutorial: Diffuse, Shadows, & GI

- Color rays are a ***bit*** more complex. How?

Tutorial: Diffuse, Shadows, & GI

```
struct IndirectPayload {
    float3 color;    // will store ray color
    uint   rndSeed;  // current random seed
};
```

- Color rays are a ***bit*** more complex. How?
  - *Payload contains a color, per-pixel random seed*

Tutorial: Diffuse, Shadows, & GI

- Color rays are a ***bit*** more complex. How?
  - *Payload contains a color, per-pixel random seed*
  - *Miss shader needs to return the background color*

```
struct IndirectPayload {
    float3 color;    // will store ray color
    uint   rndSeed;  // current random seed
};

[shader("miss")]
void IndirectMiss(inout IndirectPayload pay) {
    pay.color = GetBackgroundColor( WorldRayDirection() );
}
```

Tutorial: Diffuse, Shadows, & GI

- Color rays are a ***bit*** more complex. How?
  - *Payload contains a color, per-pixel random seed*
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These routines are all specific to your material & shading system

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float3 shootColorRay(float3 orig, float3 dir, float minT, uint rndSeed )  {
    RayDesc         ray = { orig, minT, dir, 1.0e+38 };
    IndirectPayload pay = { float3(0.0f,0.0f,0.0f), rndSeed };
    TraceRay( gRtScene, RAY_FLAG_NONE, 0xFF, 1, 2, 1, ray, pay );
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Let's take a look at this function

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    // We will only shoot one shadow ray per frame, randomly to a light
    uint randomLight = uint( nextRand(seed) * gLightsCount );

    // What is the probability we picked that light?
    float sampleProb = 1.0f / float( gLightsCount );

}
```

Tutorial: Diffuse, Shadows, & GI

- What happens for our diffuse shading?
  - *Pick a random light, so we don't shoot one ray to each*
  - *Load information about the selected light*

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    float3 lightIntensity = gLights[randomLight].intensity;
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- What happens for our diffuse shading?
  - *Pick a random light, so we don't shoot one ray to each*
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As for most shading, go back to the rendering equation for clarity

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But we're actually sampling it randomly

(aka Monte Carlo Integration)

$$\int_{\Omega} f_r(\omega_i,\omega_o)L_i(\omega)(\omega_i\cdot\hat{\boldsymbol{n}})d\omega_i \approx \frac{1}{N}\sum_{j=1}^{N}\frac{f_r(\omega_i,\omega_o)L_i(\omega_i)(\omega_i\cdot\hat{\boldsymbol{n}})}{p(\omega_j)}$$

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With only N=1 shadow ray

$$\frac{1}{N}\sum_{j=1}^{N}\frac{f_r(\omega_i,\omega_o)L_i(\omega_i)(\omega_i\cdot\hat{\boldsymbol{n}})}{p(\omega_j)}$$

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[shader("raygeneration")]
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    uint2 launchIdx = DispatchRaysIndex();        // What pixel are we?
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    // Accumulate properly weighted result into final color
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void DiffuseGIRayGen()  {
    uint2 launchIdx = DispatchRaysIndex();        // What pixel are we?
    uint  randSeed  = initRand( launchIdx );      // Get RNG for this pixel

    float3 wsPos    = gPosition[launchIdx].xyz;   // Load position from G-buffer
    float3 wsNorm   = gNormal[launchIdx].xyz;     // Load normal from G-buffer
    float3 difColor = gDifColor[launchIdx].xyz;   // Load material from G-buffer

    // Do diffuse shading at the primary hit
    float3 color   = DiffuseShade( wsPos, wsNorm, difColor, randSeed );

    // Pick random direction for global illumination indirect ray; shoot ray
    float3 giDir   = getCosWeightedRandomDir( randSeed, wsNorm );
    float3 giColor = shootColorRay( wsPos, giDir, 1.0e-4f, randSeed );

    // Accumulate properly weighted result into final color
    //    Due to cosine-weighting, terms cancel, leaving simpler equation
    color += difColor * giColor;

    gOutColor[launchIdx] = float4( color, 1.0f );
}
```

Tutorial: Diffuse, Shadows, & GI

- Our ray generation shader, pretty straightforward:
  - *Initialize random seed for current pixel*
  - *Load pixel data from our G-buffer*
  - *Do our diffuse shade & shadows at this point*
  - *Shoot our global illum query; accumulate the result*
  - *Save to the output buffer*

$$\frac{1}{N}\sum_{j=1}^{N}\frac{f_r(\omega_j,\omega_o)L_i(\omega_j)(\omega_j\cdot\hat{\boldsymbol{n}})}{p(\omega_j)}$$

Key… For cos-weighted samples:

$$p(\omega_j)=\frac{(\omega_j\cdot\hat{\boldsymbol{n}})}{\pi}$$

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```

Diffuse Global Illumination Results

Tutorial: Adding Multiple Bounces

Direct Lighting Only

Direct + 1 Bounce Diffuse GI

Direct + 2 Bounces Diffuse GI

Tutorial: Adding Multiple Bounces

- Adding extra bounces can have big impact!

Tutorial: Adding Multiple Bounces

- Adding extra bounces can have big impact!
- No huge code change with recursive ray tracing

Tutorial: Adding Multiple Bounces

Remember our closest hit shader?

```
[shader("closesthit")]
void IndirectClosestHit(inout IndirectPayload pay, BuiltinIntersectAttribs attribs) {
    ShadingData hit = getHitShadingData( attribs );

    pay.color = DiffuseShade( hit.pos, hit.norm, hit.difColor, pay.rndSeed );
}
```

Tutorial: Adding Multiple Bounces

Remember our closest hit shader?

Two steps:

- *Load data to shade*
- *Do direct lighting*

```
[shader("closesthit")]
void IndirectClosestHit(inout IndirectPayload pay, BuiltinIntersectAttribs attribs) {
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}
```

Tutorial: Adding Multiple Bounces

Let's add a third step…

Two steps:

- *Load data to shade*
- *Do direct lighting*
- *Add additional bounces*

```
[shader("closesthit")]
void IndirectClosestHit(inout IndirectPayload pay, BuiltinIntersectAttribs attribs) {
    ShadingData hit = getHitShadingData( attribs );

    pay.color = DiffuseShade( hit.pos, hit.norm, hit.difColor, pay.rndSeed );

    if (pay.rayDepth < gMaxRayDepth)
    {
        float3 giDir   = getCosWeightedRandomDir( randSeed, wsNorm );
        float3 giColor = shootColorRay( wsPos, giDir, 1.0e-4f, randSeed );
        pay.color     += hit.difColor * giColor;
    }
}
```

Tutorial: Adding Multiple Bounces

Requires a new shader parameter

*(Note this a hit shader variable, which is specified **separately** from a ray gen variable)*

Requires remembering current ray depth

```
cbuffer HitShaderCB {
    uint   gMaxRayDepth;  // Specify your max ray depth
};

struct IndirectPayload {
    float3 color;    // will store ray color
    uint   rndSeed;  // current random seed
    uint   rayDepth; // increment by 1 every time you bounce
};

[shader("closesthit")]
void IndirectClosestHit(inout IndirectPayload pay, BuiltinIntersectAttribs attribs) {
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    }
}
```


Love

Want a Different Material Model?

Want a Different Material Model?

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```

Want a Different Material Model?

Write a new function to do direct shading

(See tutorial code for GGX model)

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        float3 giColor = shootColorRay( wsPos, giDir, 1.0e-4f, randSeed );
        pay.color     += hit.difColor * giColor;
    }
}
```

Want a Different Material Model?

Write new sampling code to do indirect light

(See tutorial code for GGX model)

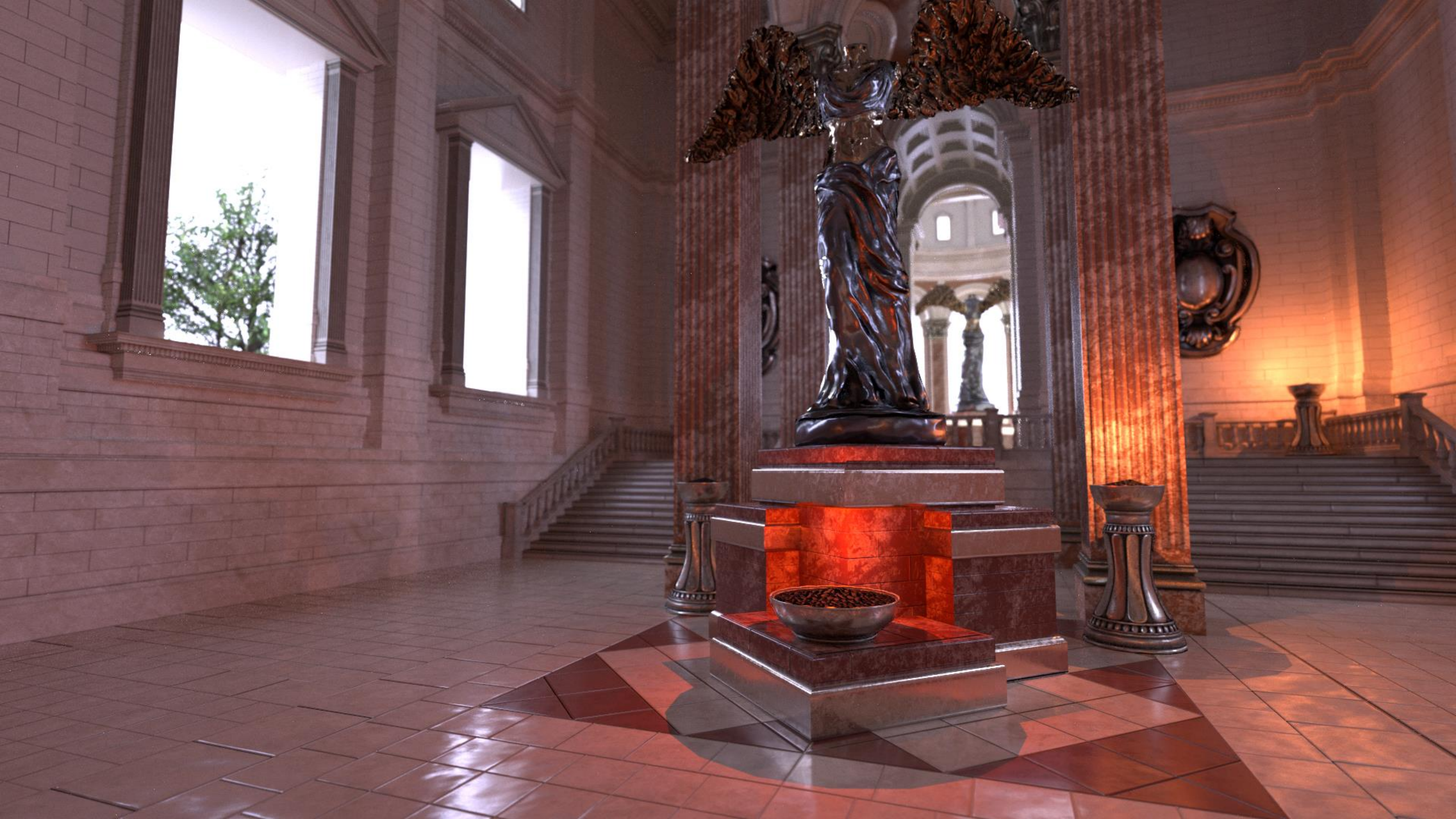
```
cbuffer HitShaderCB {
    uint   gMaxRayDepth;  // Specify your max ray depth
};

struct IndirectPayload {
    float3 color;    // will store ray color
    uint   rndSeed;  // current random seed
    uint   rayDepth; // increment by 1 every time you bounce
};

[shader("closesthit")]
void IndirectClosestHit(inout IndirectPayload pay, BuiltinIntersectAttribs attribs) {
    ShadingData hit = getHitShadingData( attribs );

    pay.color = DiffuseShade( hit.pos, hit.norm, hit.difColor, pay.rndSeed );

    if (pay.rayDepth < gMaxRayDepth)
    {
        float3 giDir   = getCosWeightedRandomDir( randSeed, wsNorm );
        float3 giColor = shootColorRay( wsPos, giDir, 1.0e-4f, randSeed );
        pay.color     += hit.difColor * giColor;
    }
}
```



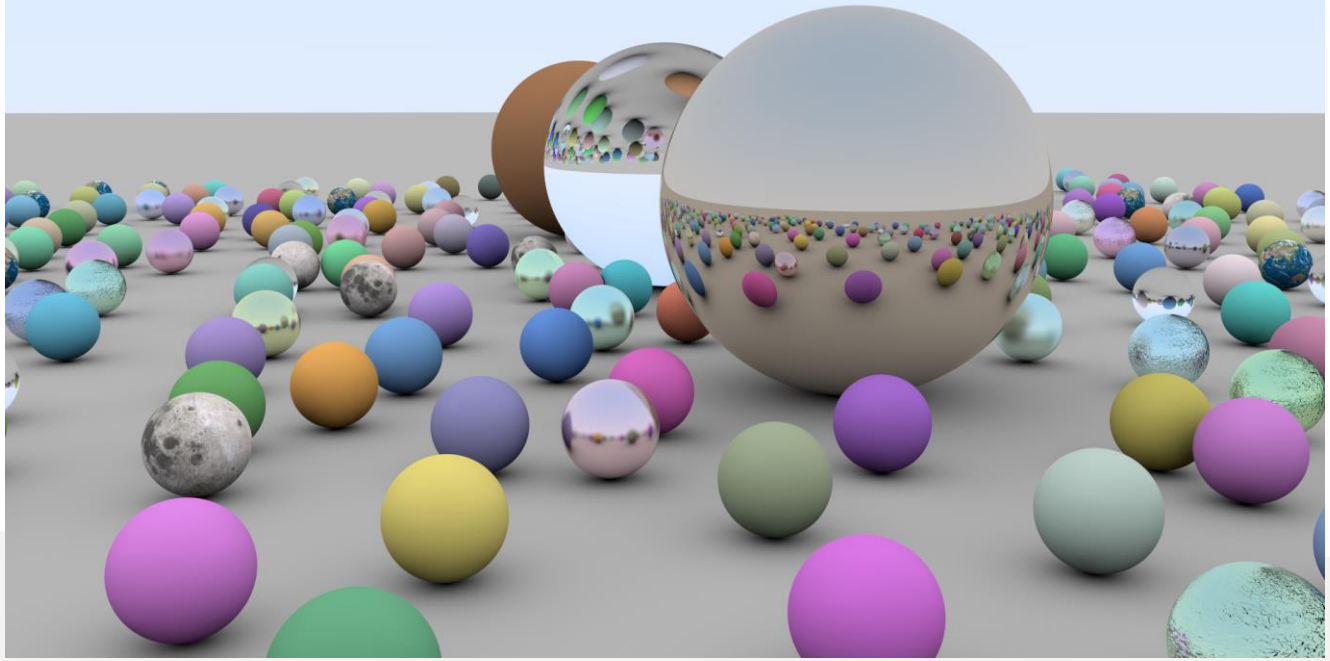
One Last Example: Sphere Rendering

- All examples have used raster scenes: i.e., only triangles

One Last Example: Sphere Rendering

- All examples have used raster scenes: i.e., only triangles
- But one advantage of ray tracing: arbitrary shapes!

Final example from Pete's "Ray Tracing in One Weekend"



One Last Example: Sphere Rendering

- Need: define how rays intersect a sphere
  - Plenty of documentation on required mathematics

```
[shader("intersection")]
void SphereIntersect() {

}
```

One Last Example: Sphere Rendering

- Need: define how rays intersect a sphere
  - Plenty of documentation on required mathematics
- Custom intersection shaders:
  - You are responsible for sending data
  - I pass an array of sphere radii and centers

```
Buffer<float4> gSphereData;

[shader("intersection")]
void SphereIntersect() {
    float4 sphData = gSphereData[ PrimitiveIndex() ];
    float3 sphCenter = sphData.xyz;
    float  sphRadius = sphData.w;

}
```

One Last Example: Sphere Rendering

- Need: define how rays intersect a sphere
  - Plenty of documentation on required mathematics
- Custom intersection shaders:
  - You are responsible for sending data
  - I pass an array of sphere radii and centers
- Plug in center, radius, ray origin and direction
  - To standard intersection math

```
Buffer<float4> gSphereData;

[shader("intersection")]
void SphereIntersect() {
    float4 sphData = gSphereData[ PrimitiveIndex() ];
    float3 sphCenter = sphData.xyz;
    float  sphRadius = sphData.w;

    float3 toCenter = WorldRayOrigin() - sphCenter;
    float  a = dot( WorldRayDirection(), WorldRayDirection() );
    float  b = 2.0f * dot( WorldRayDirection(), toCenter );
    float  c = dot( toCenter, toCenter ) - sphRadius * sphRadius;

    if (b * b >= 4.0f * a * c) {



    }
}
```

One Last Example: Sphere Rendering

- Need: define how rays intersect a sphere
  - Plenty of documentation on required mathematics
- Custom intersection shaders:
  - You are responsible for sending data
  - I pass an array of sphere radii and centers
- Plug in center, radius, ray origin and direction
  - To standard intersection math
- `ReportHit()` at all possible hit points
  - Attribute is whatever data you need to shade

```
struct SphereAttribs {
    float3 sphCenter;
};

Buffer<float4> gSphereData;

[shader("intersection")]
void SphereIntersect() {
    float4 sphData = gSphereData[ PrimitiveIndex() ];
    float3 sphCenter = sphData.xyz;
    float  sphRadius = sphData.w;

    float3 toCenter = WorldRayOrigin() - sphCenter;
    float  a = dot( WorldRayDirection(), WorldRayDirection() );
    float  b = 2.0f * dot( WorldRayDirection(), toCenter );
    float  c = dot( toCenter, toCenter ) - sphRadius * sphRadius;

    if (b * b >= 4.0f * a * c) {
        float sqrtVal = sqrt( b * b - 4.0f * a * c );
        SphereAttribs sphAttr = { sphCenter };
        ReportHit( (-b - sqrtVal) / (2.0f * a), 0, sphAttr );
        ReportHit( (-b + sqrtVal) / (2.0f * a), 0, sphAttr );
    }
}
```

Distance to hit

User definable hit type

Intersection attribute

One Last Example: Sphere Rendering

- Your hit shaders use this attribute for shading

Get material information

Find sphere normal from attributes

Shade

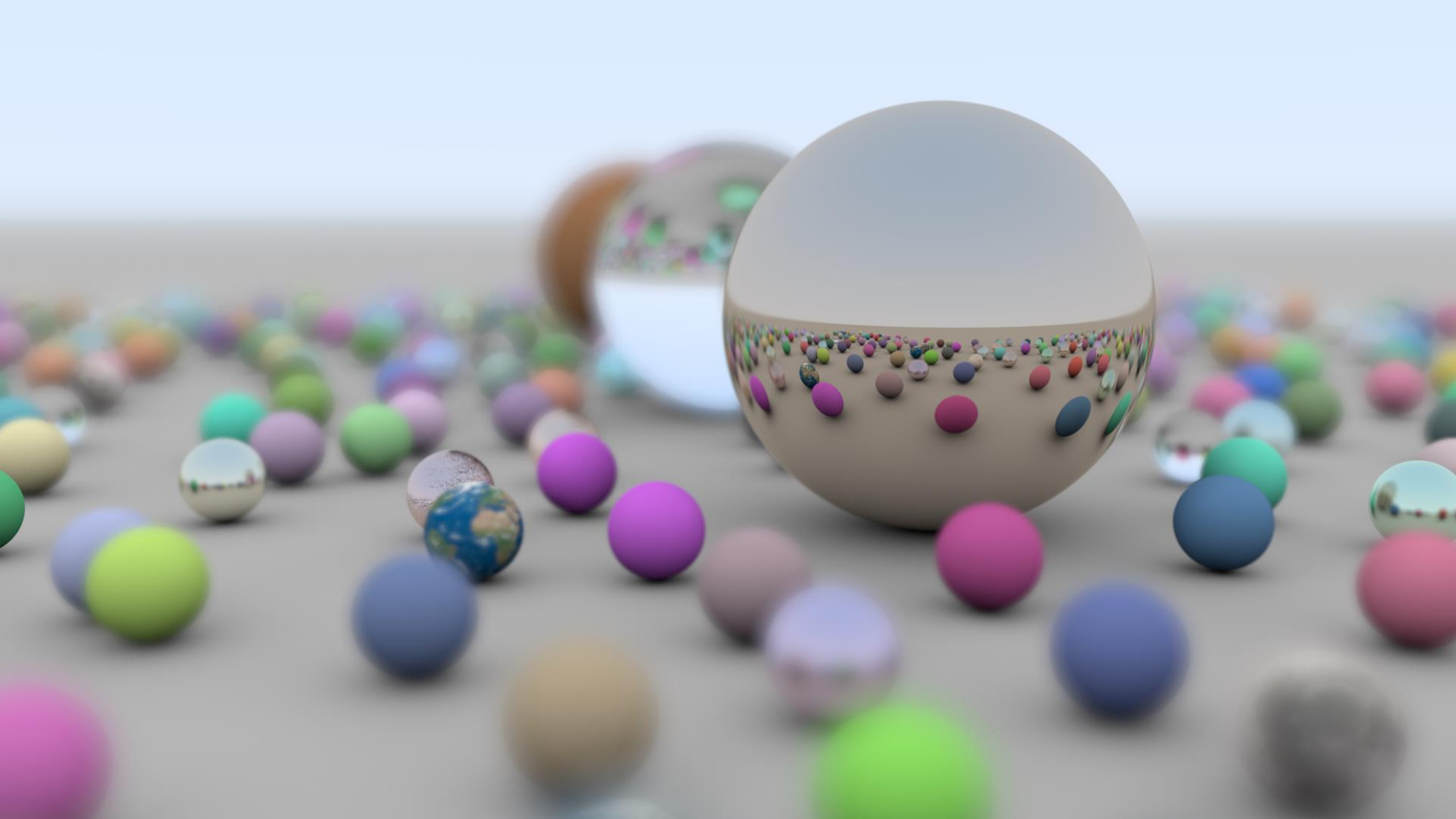
(see tutorial code for details)

```
Buffer<float4> gSphereMatls;

[shader("closesthit")]
void SphereClosestHit(inout Payload pay, SphereAttribs attribs)
{
    float4 sphMatl = gSphereMatls[ PrimitiveIndex() ];

    float3 hitPt   = WorldRayOrigin() + RayTCurrent() * WorldRayDirection();
    float3 sphNorm = normalize( hitPt - attribs.sphCenter );

    if ( isDiffuseMaterial( sphMatl ) )
        pay.color = ...
    else if ( isMetalMaterial( sphMatl ) )
        pay.color = ...
    else if ( isGlassMaterial( sphMatl ) )
        pay.color = ...
}
```



Summary

Image: My Tutorial 14 running on freely available Amazon Bistro scene

Summary

- Overview of DirectX Raytracing shaders
  - *Five new stages: ray generation, intersection, miss, closest-hit, and any-hit shaders*
  - *New builtin HLSL functions for ray tracing*
- Walked through a number of samples demonstrating their use
  - *Full code, additional tutorials, and runnable executables available online (intro-to-dxr.cwyman.org)*
- I hope your takeaway:
  - *The shader side of DirectX Raytracing: very similar to coding serial ray tracing in C++*
  - *The ugly API code can be encapsulated to allow for fast prototyping in a GPU-accelerated path tracer*

Image: My Tutorial 14 running on freely available Amazon Bistro scene

Questions?