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Introduction to DirectX Raytracing:

Overview and Introduction to Ray Tracing Shaders

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Next Steps

- Pete gave a nice overview of basics:
  - *What is ray tracing? Why use ray tracing?*
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  - *How do I do it?*

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- Of course, you could start from scratch:
  - *Write a CPU ray tracer; plenty of resources*
  - *Write a GPU ray tracer; can be tricky & ugly*
- Use vendor-specific APIs
  - *Hide ugly, low-level implementation details*
  - *Poor scaling cross-vendor, interact w/ raster*

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Use Standardized API: DirectX Raytracing

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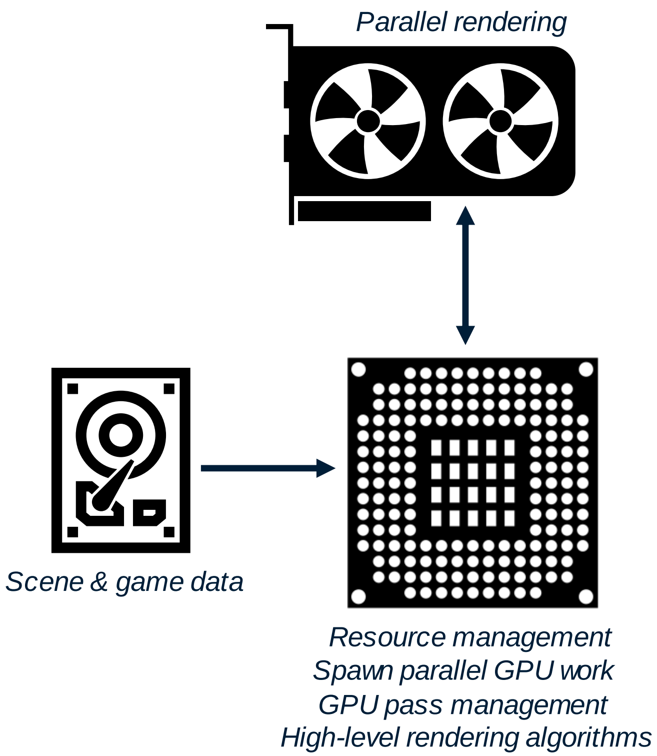
  - Today’s goal: show how to use DX Raytracing
- Part of a widely-used API, DirectX
- Shares resources:
  - *No data copying between raster and ray tracing*
- Works across multiple vendors, either:
  - *Via vendor-provided software or hardware*
  - *Via standardized compatibility layer (on DX12 GPUs)*

Overview: Modern Graphics APIs

- Two main parts:



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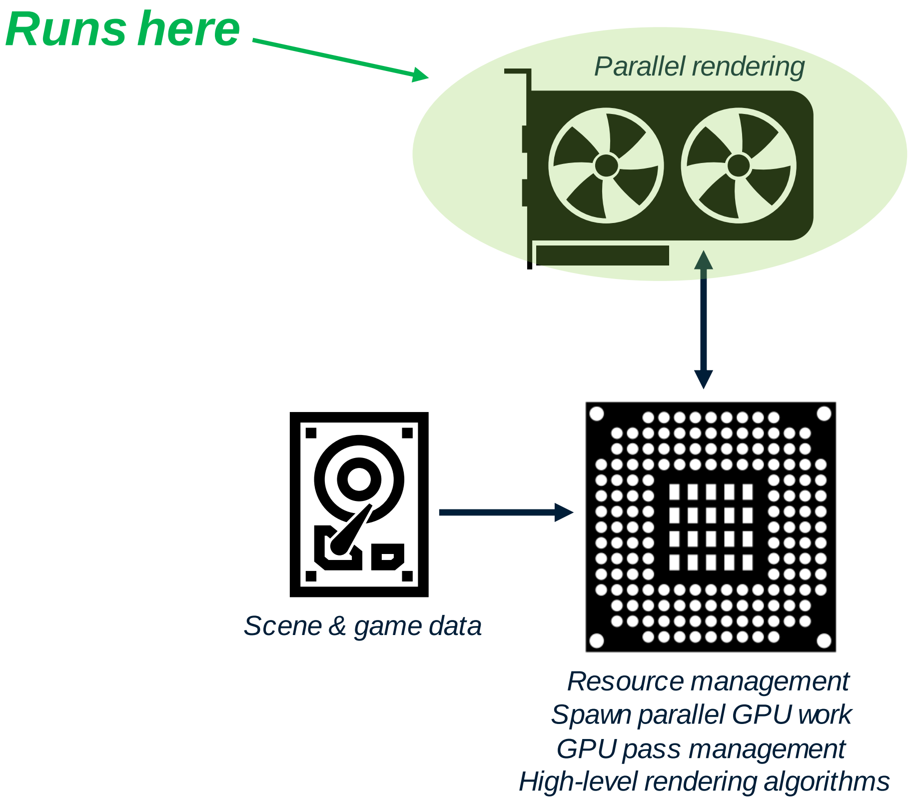

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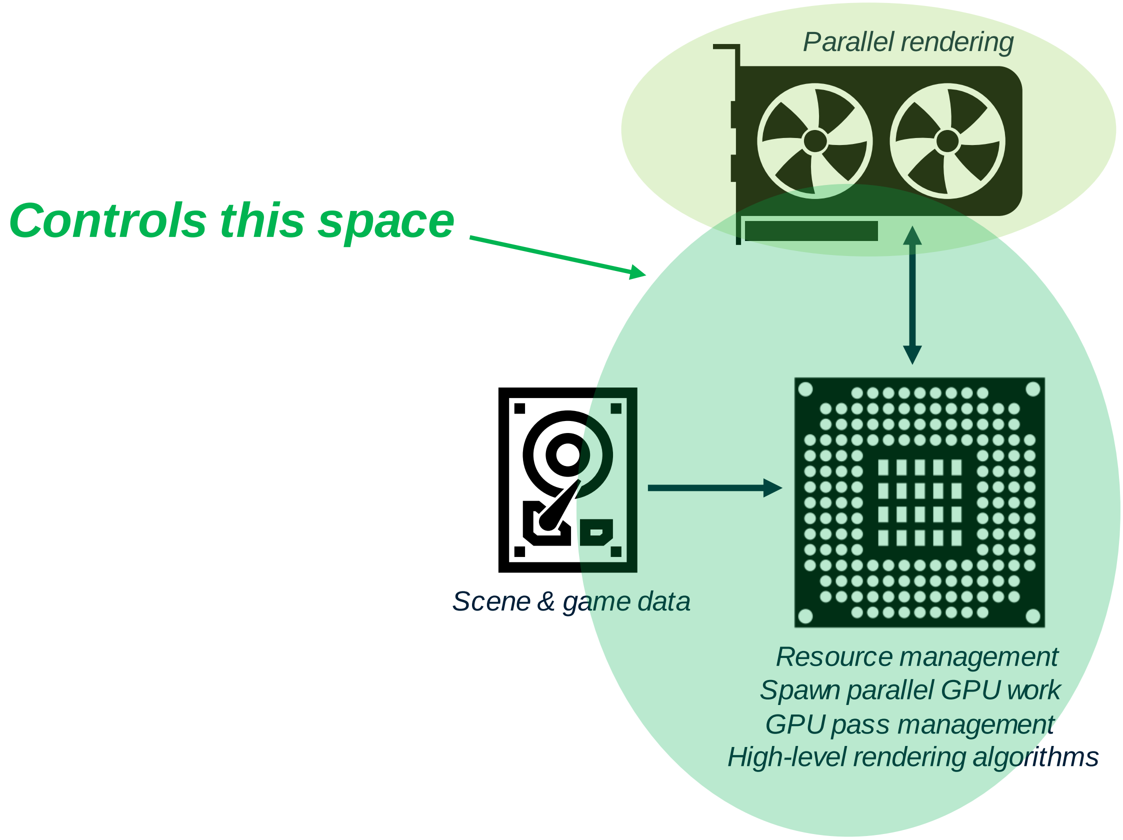

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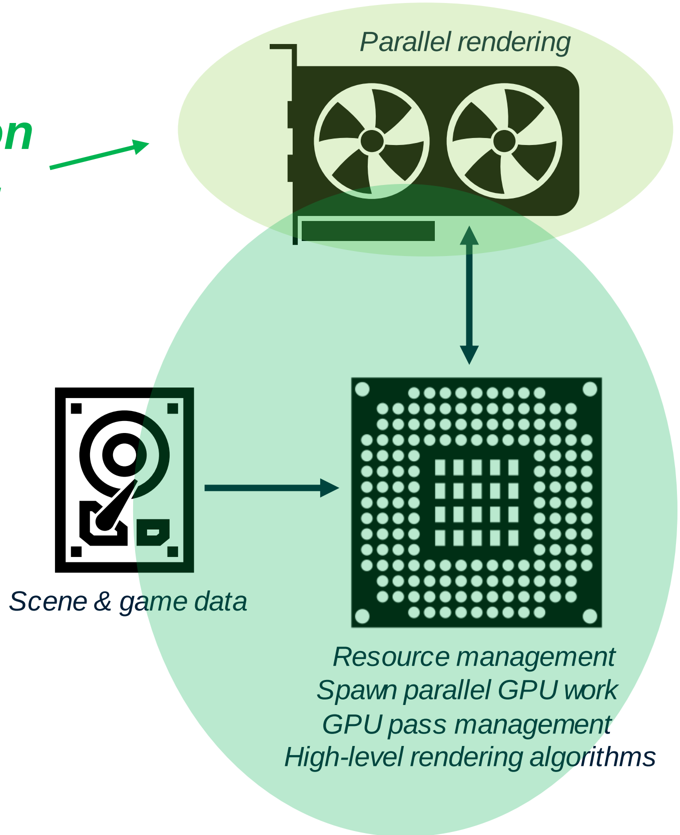
This rest of this talk focuses on DirectX Raytracing shaders!



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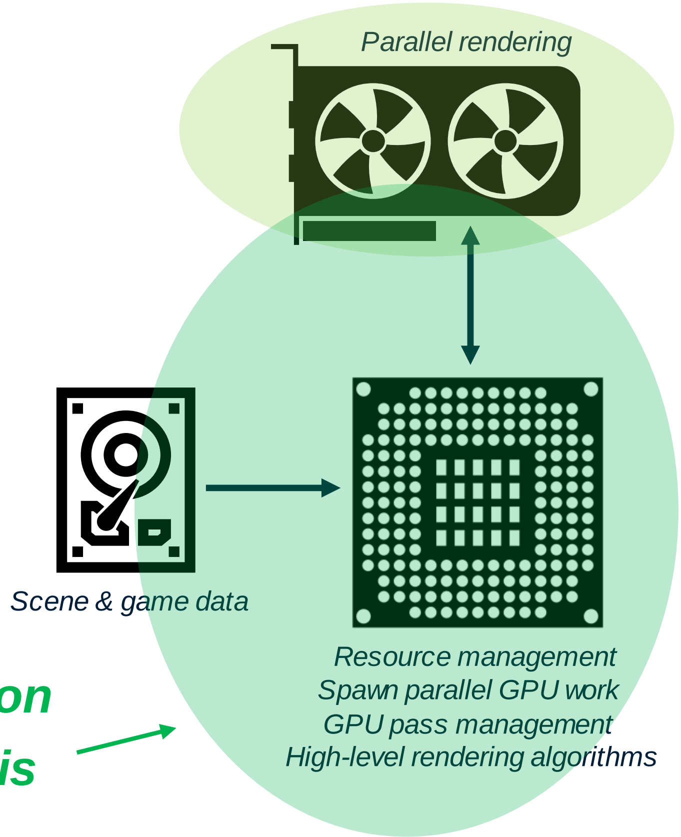
Shawn will focus on host code later this morning



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  - *The parts not automatically managed by the graphics API, driver, or hardware*
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- Individual shaders can represent instructions for complete GPU tasks
  - *E.g., DirectX's **compute shaders***
- Or they can represent a subset of a more complex pipeline
  - *E.g., transforming geometry to cover the right pixels in DirectX's **vertex shaders***

DirectX Rasterization Pipeline

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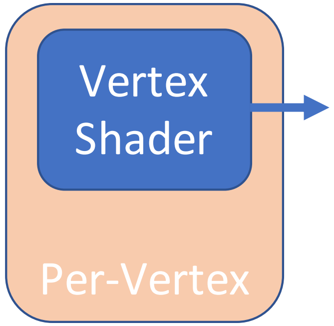

- Run a shader, the ***vertex shader***, on each vertex sent to the graphics card
  - *This usually transforms it to the right location relative to the camera*

DirectX Rasterization Pipeline

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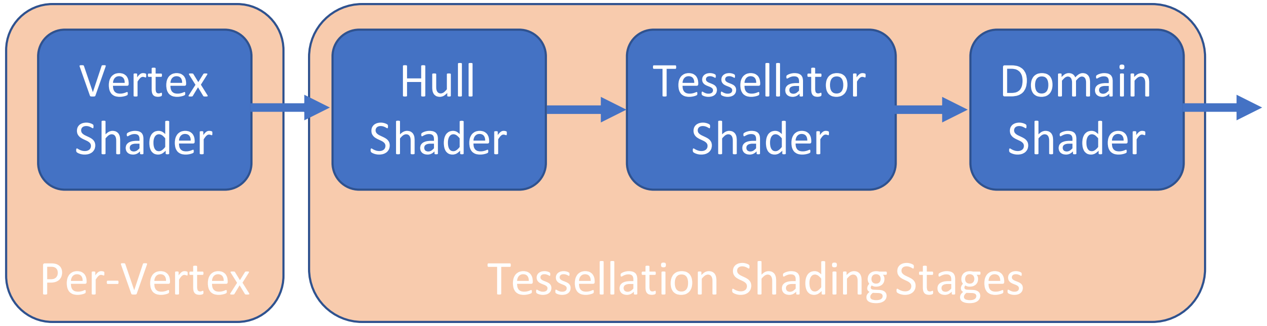

- Group vertices into triangles, then run *tessellation shaders* to allow GPU subdivision of geometry
  - Includes 3 shaders with different goals, the ***hull shader***, ***tessellator shader***, and ***domain shader***

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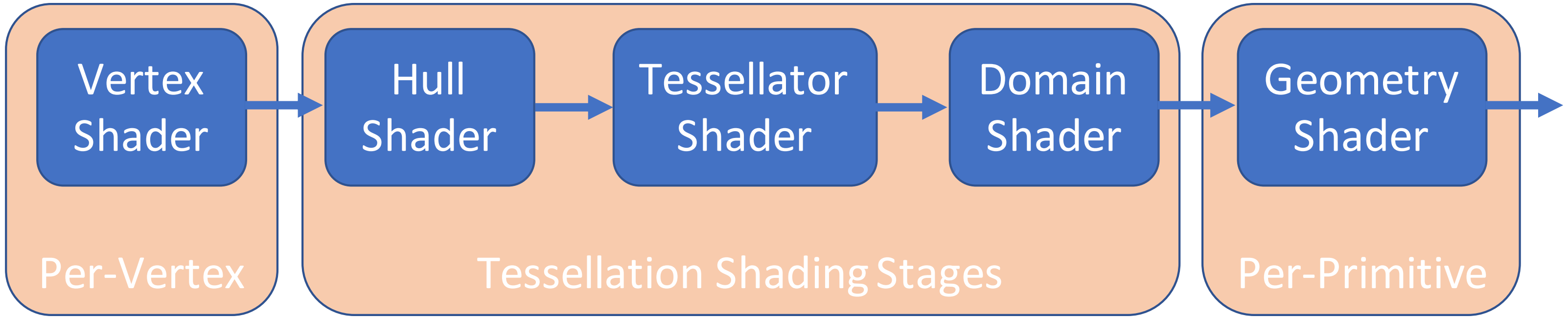

- Run a shader, the ***geometry shader***, on each tessellated triangle
  - *Allows computations that need to occur on a complete triangle, e.g., finding the geometric surface normal*

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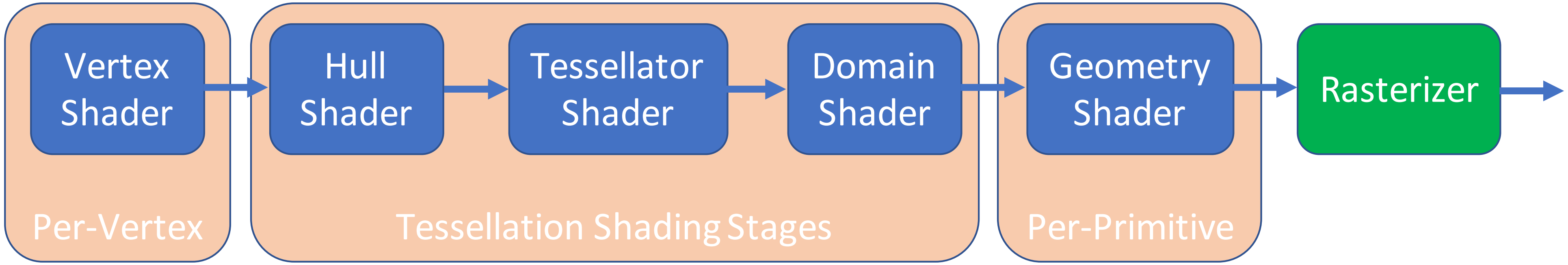

- Rasterize our triangles (i.e., determine the pixels they cover)
  - *Done by special-purpose hardware rather than user-software*
  - *Only a few developer controllable settings*

DirectX Rasterization Pipeline

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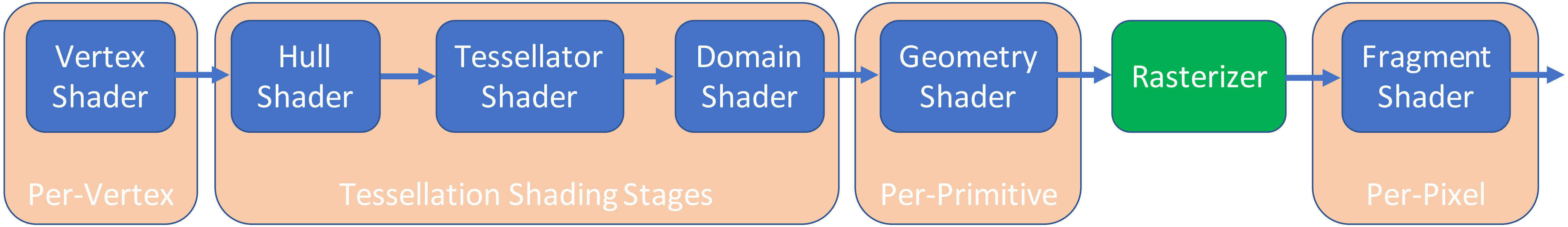
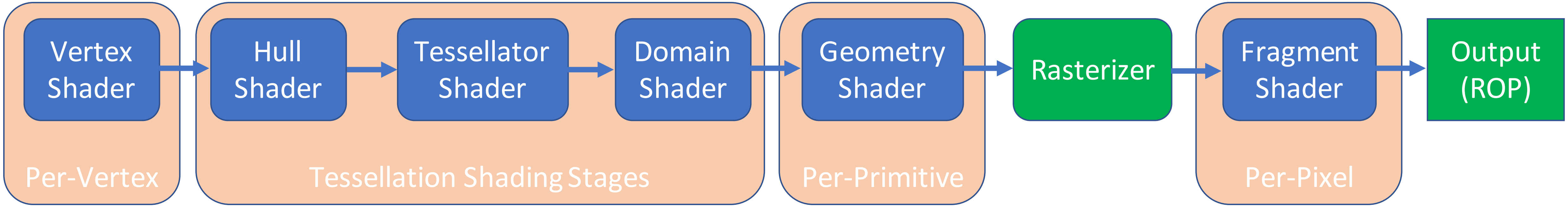


- Run a shader, the ***pixel shader*** *(or* ***fragment shader****)*, on each pixel generated by rasterization
  - *This usually computes the surface's color*

DirectX Rasterization Pipeline

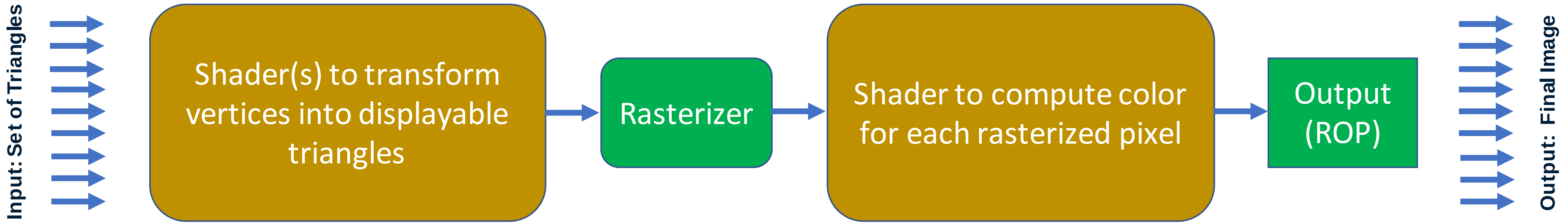
- What do shaders do in today's widely-used rasterization pipeline?



- Merge each pixel into the final output image (e.g., doing blending)
  - *Usually done with special-purpose hardware*
  - *Hides optimizations like memory compression and converting image formats*

DirectX Rasterization Pipeline

- Squint a bit, and that pipeline looks like:



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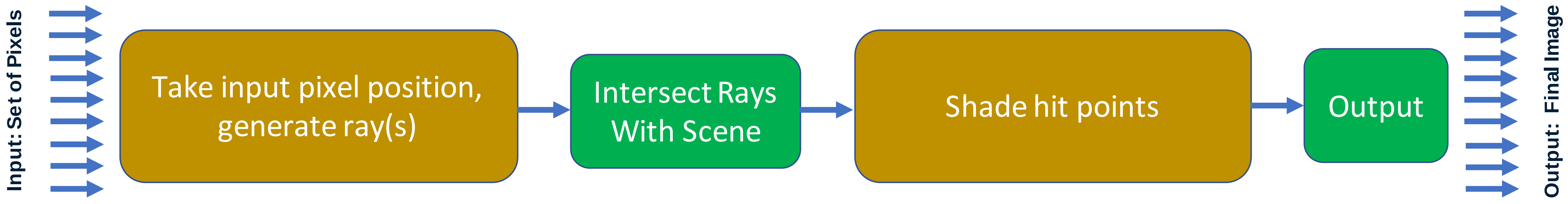

Please note:

A very simplified representation

DirectX Ray Tracing Pipeline

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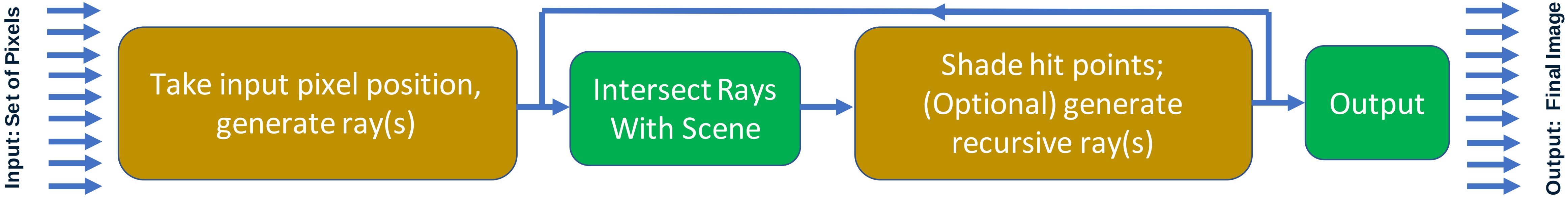

- One advantage of ray tracing:
  - *Algorithmically, much easier to add recursion*

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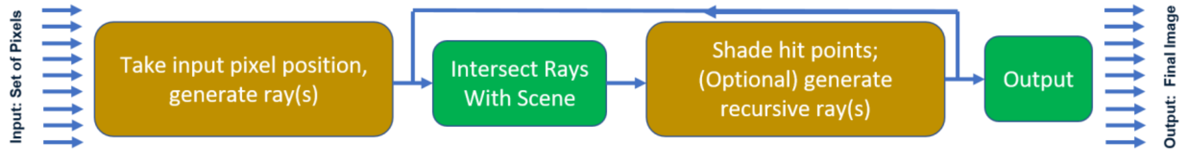
DirectX Ray Tracing Pipeline



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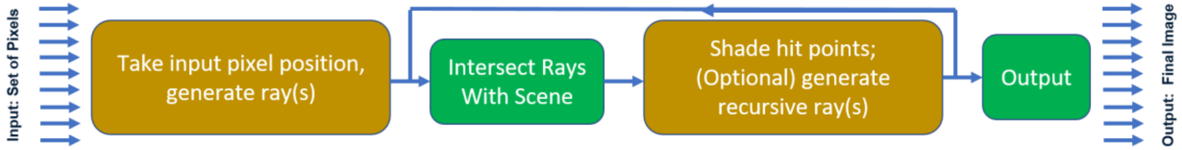
DirectX Ray Tracing Pipeline



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Runs once per algorithm (or per pass)

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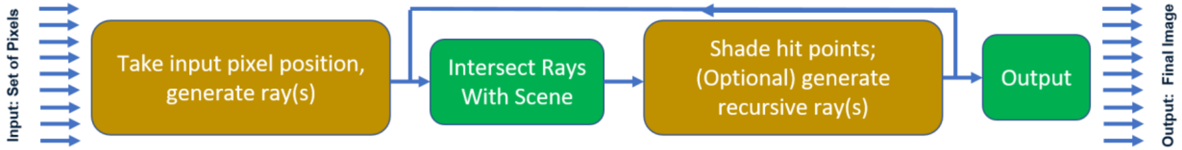

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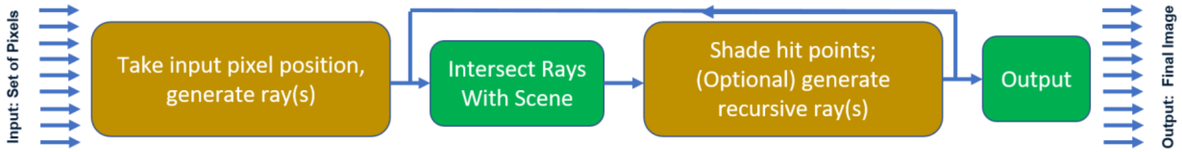

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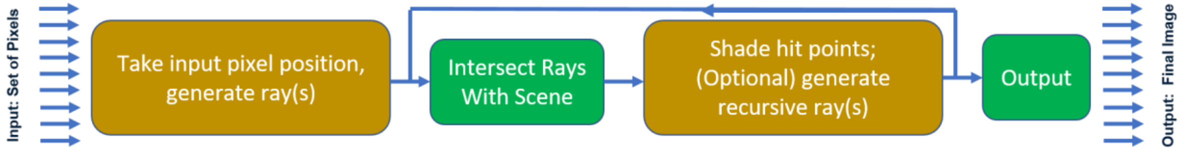

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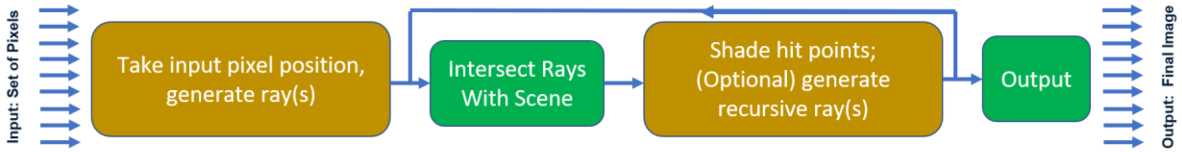

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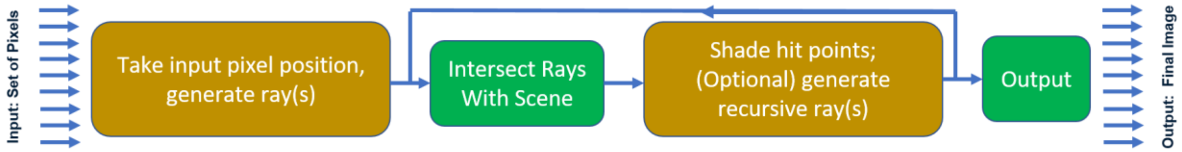

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Defines geometric shapes, widely reusable

Defines behavior of ray(s)

Different between shadow, primary, indirect rays

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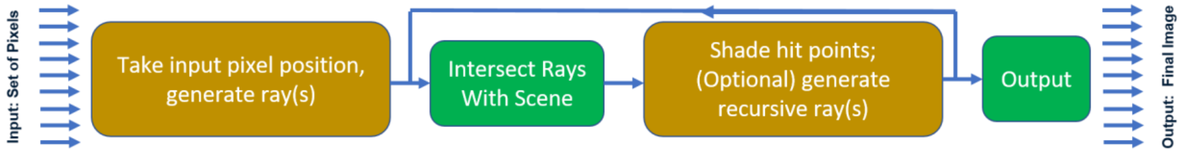

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- An new, unrelated ***sixth*** shader:
  - *A **callable shader** can be launched from another shader stage* — **Abstraction allows this; explicitly expose it**

  (Due to time limitations, see DXR spec for further details)

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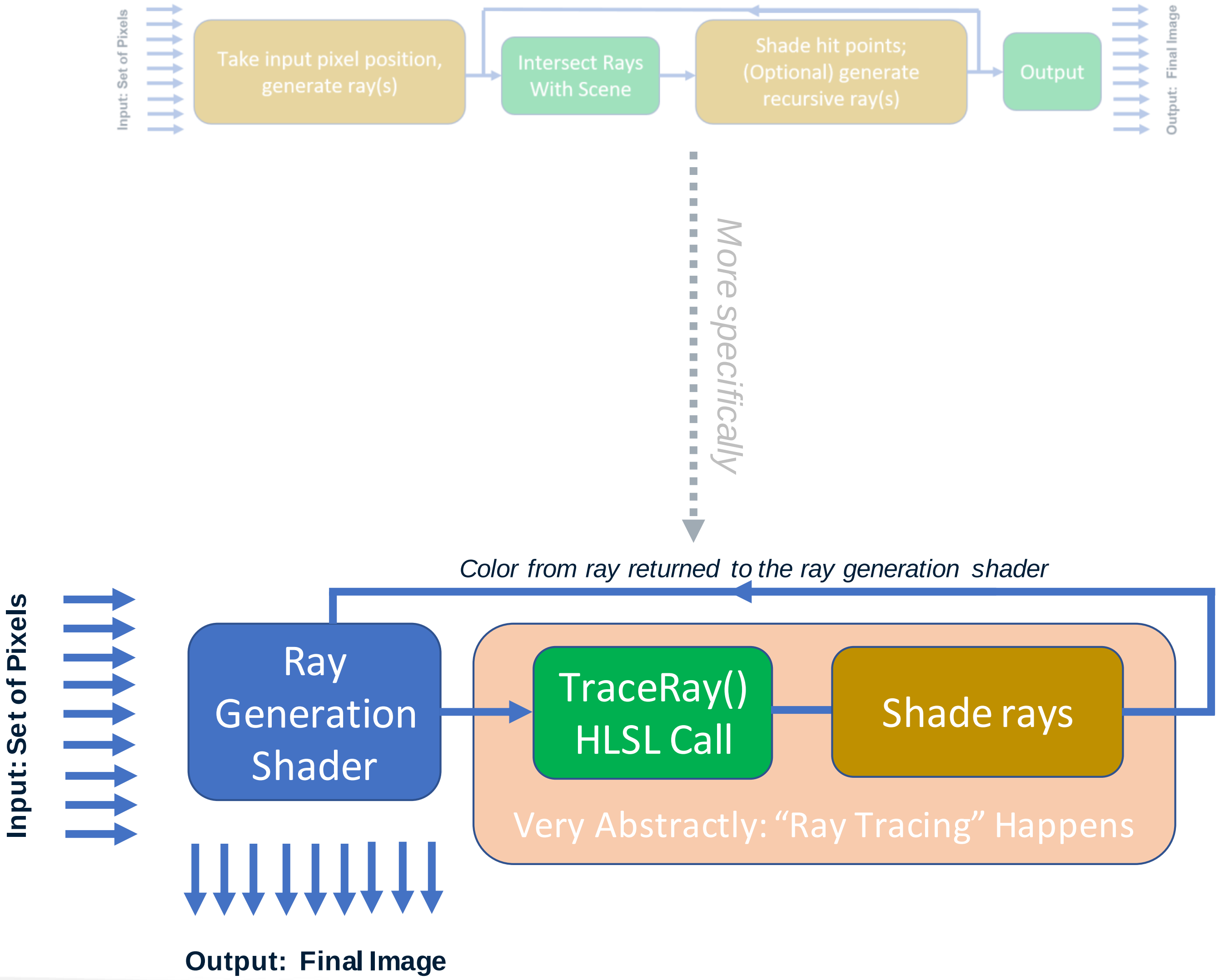
Ray Generation Shader

- Write code to:
  - *Specify what ray(s) to trace for each pixel*

- In particular:
  - *Launch ray(s) by calling new HLSL `TraceRay()` intrinsic*
  - *Accumulate ray color into image after ray tracing finishes*



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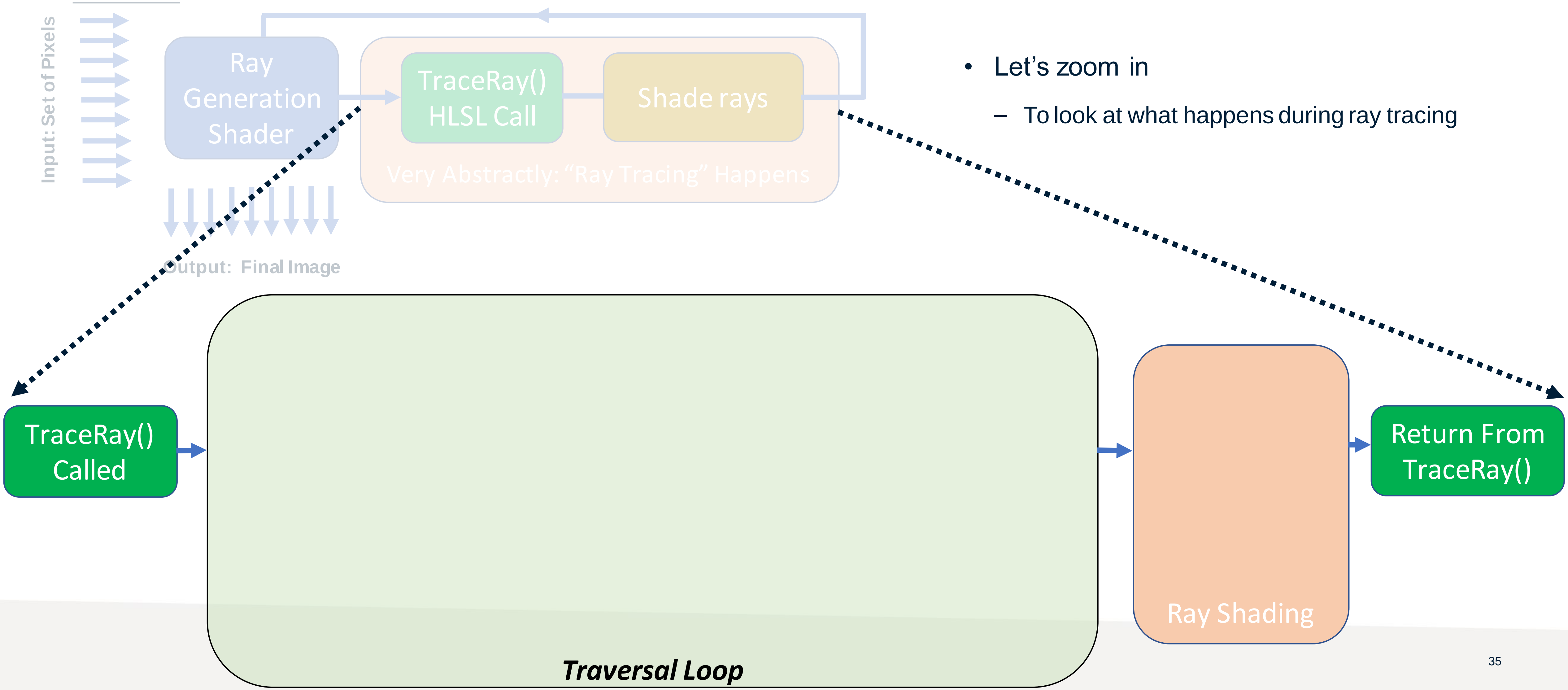

- Let's zoom in
  - To look at what happens during ray tracing

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What Happens When Tracing a Ray?

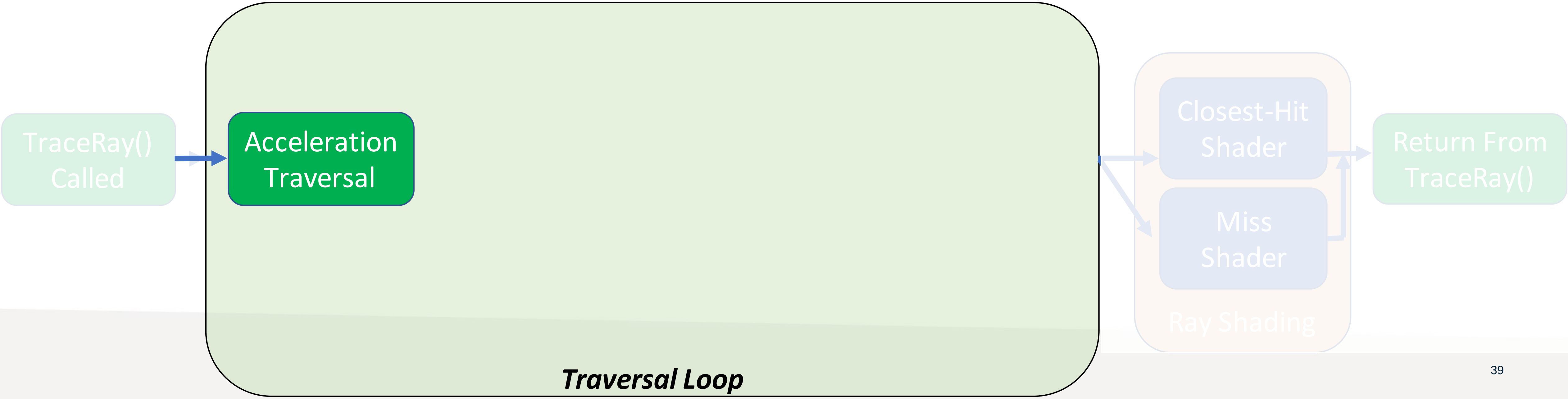
- A good mental model:
  - *First, we traverse our scene to find what geometry our ray hits*
  - *When we find the closest hit, shade at that point using the* ***closest-hit shader***
    - *This shader is a ray property; in theory, each ray can have a different closest-hit shader.*

What Happens When Tracing a Ray?

- If our ray misses all geometry, the **miss shader** gets invoked
  - *Can consider this a shading routine that runs when you see the background*
    - *Again, the miss shader is specified per-ray*

How Does Scene Traversal Happen?

- Traverse the scene acceleration structure to ignore trivially-rejected geometry
  - *An opaque process, with a few developer controls*
  - *Allows vendor-specific algorithms and updates without changing render code*



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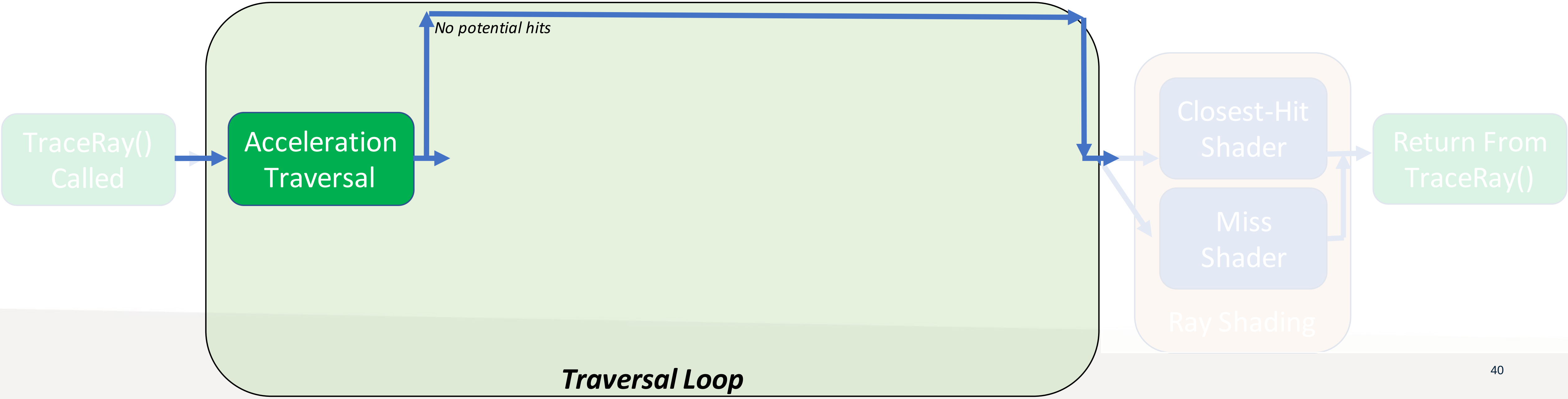
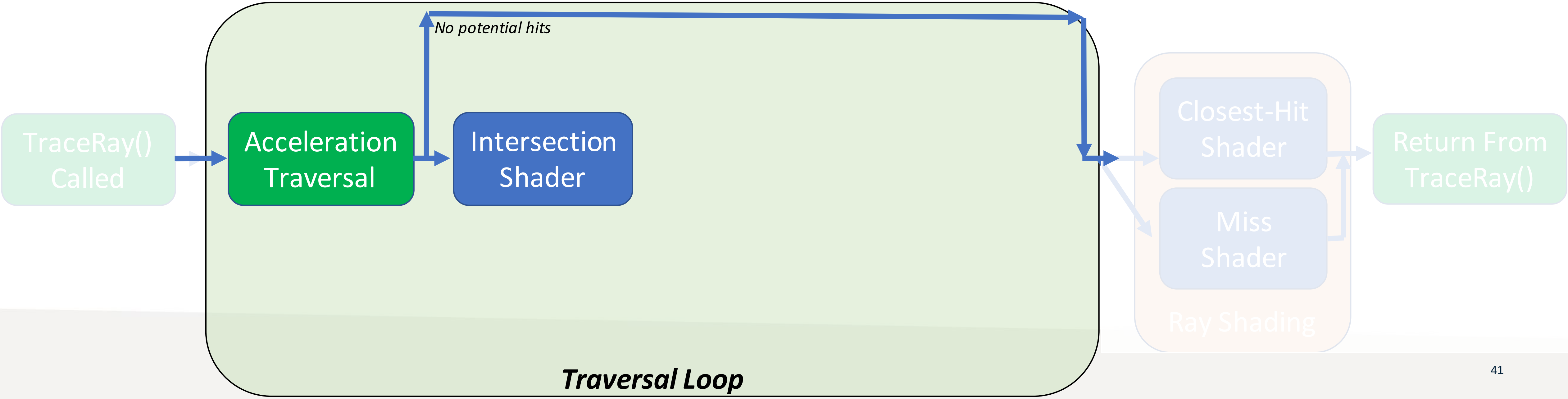


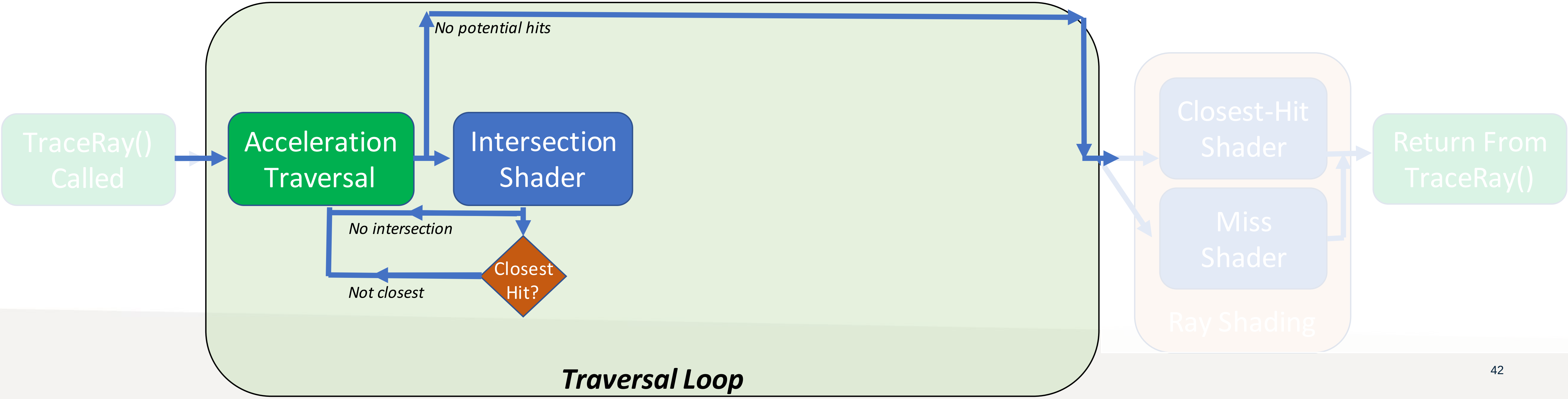
How Does Scene Traversal Happen?

- If all geometry trivially ignored, ray traversal ends
- For potential intersections, an **intersection shader** is invoked
  - *Specific to a particular geometry type (e.g., one shader for spheres, one for Bezier patches)*
  - *DirectX includes a default, optimized intersection for triangles*



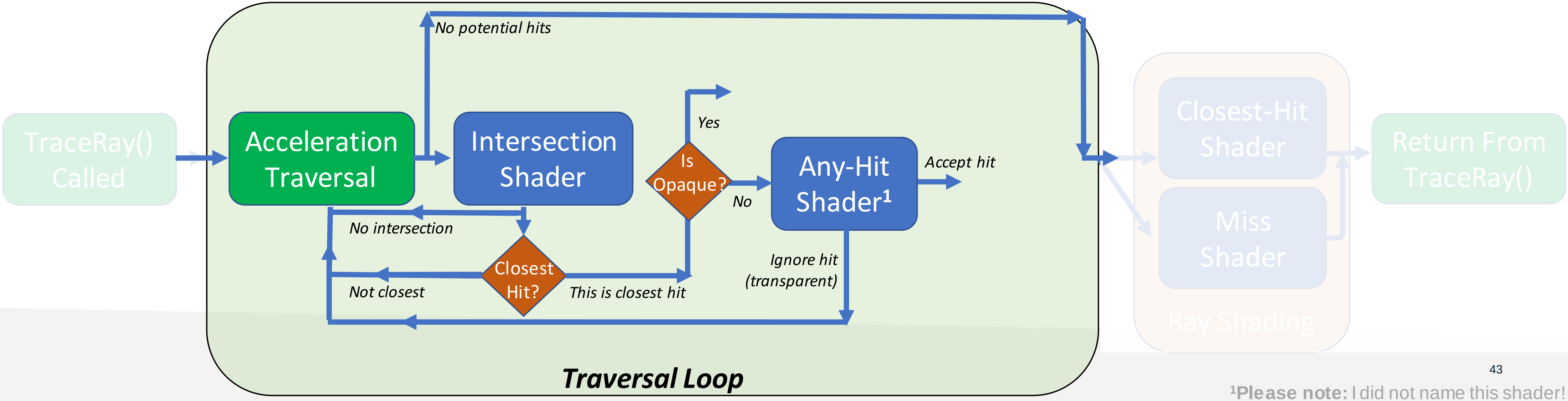
How Does Scene Traversal Happen?

- No shader-detected intersection? Detected intersection not the closest hit so far?
  - *Continue traversing through our scene*



How Does Scene Traversal Happen?

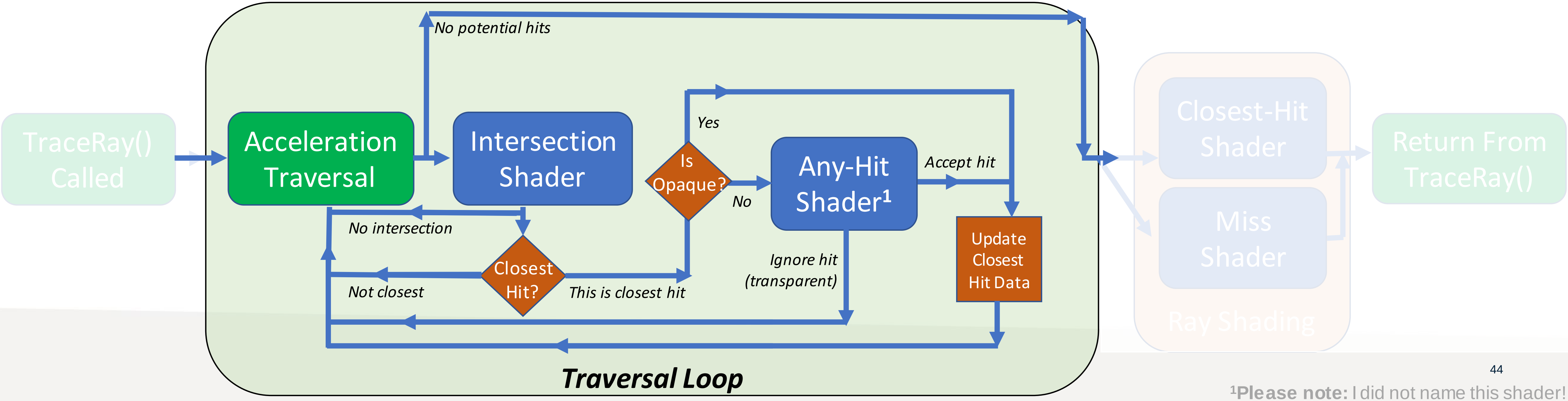
- Detected hit might be transparent? Run the **any-hit shader**[1]
  - *A ray-specific shader, specified in conjunction with the closest-hit shader*
  - *Shader can call* `IgnoreHit()` *to continue traversing, ignoring this surface*



[1]**Please note:** I did not name this shader!

How Does Scene Traversal Happen?

- Update the closest hit point with newly discovered hit
- Continue traversing to look for closer intersections



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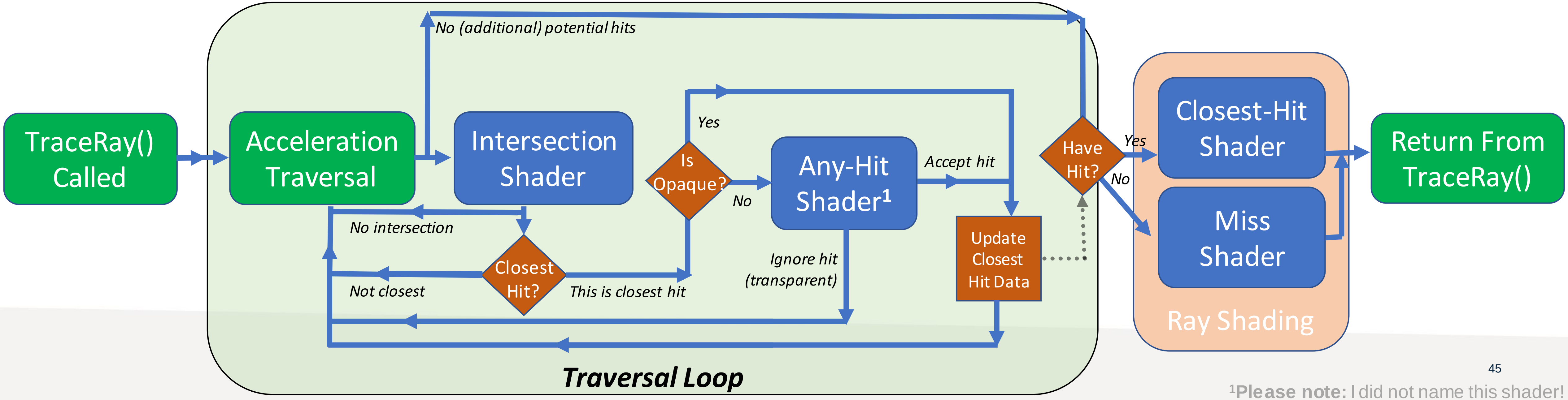
Ray Traversal Pipeline

- Continue traversing scene until no closer hits discovered
  - *Had a valid hit along the ray? Shade via the closest-hit shader*
  - *No valid hits? Shade via the miss shader*



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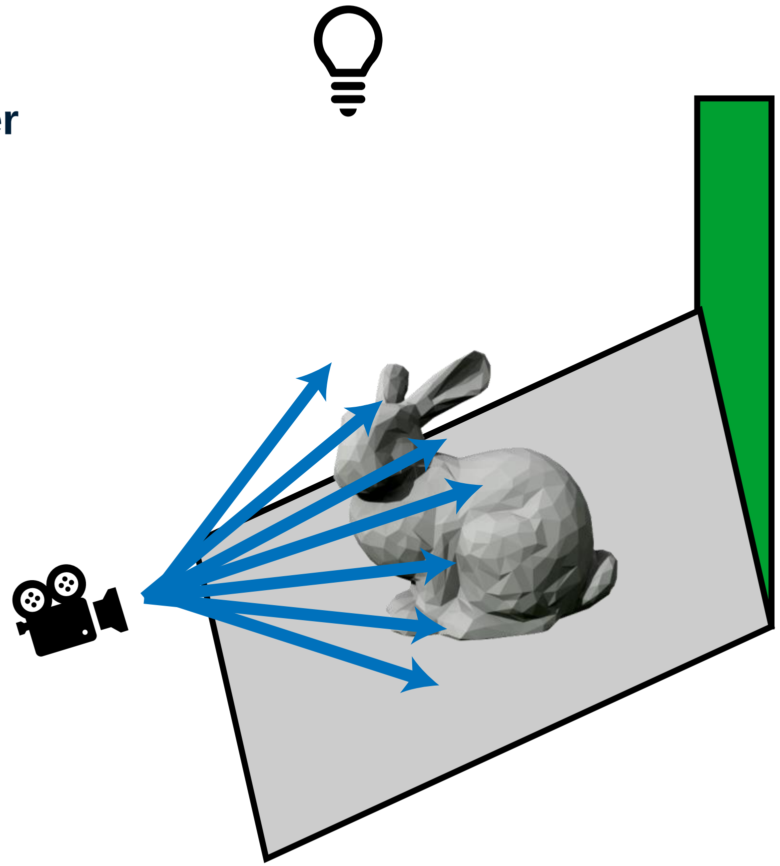
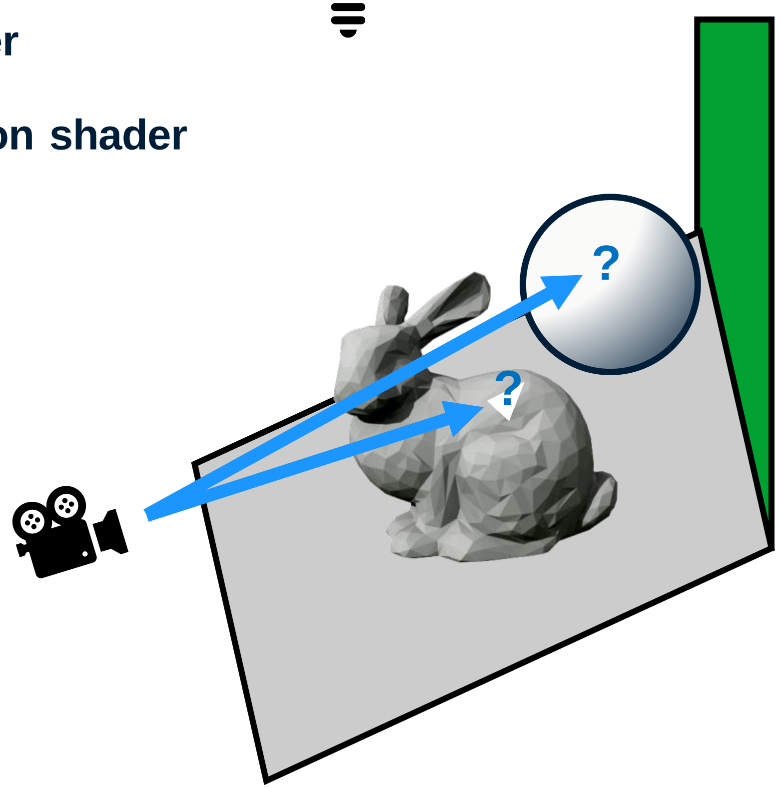


Summary: DirectX Ray Tracing Shaders

- Control where your rays start? See the **ray generation shader**
- Control when your rays intersect geometry? See the geometry's **intersection shader**



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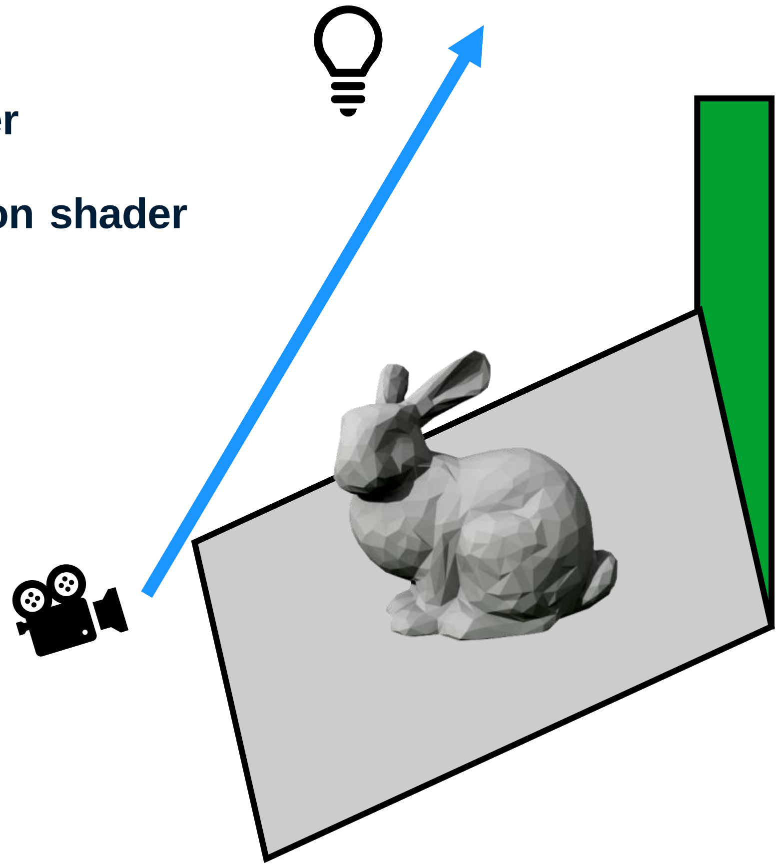
- Control when your rays intersect geometry? See the geometry's **intersection shader**
- Control what happens when rays miss? See your ray's **miss shader**



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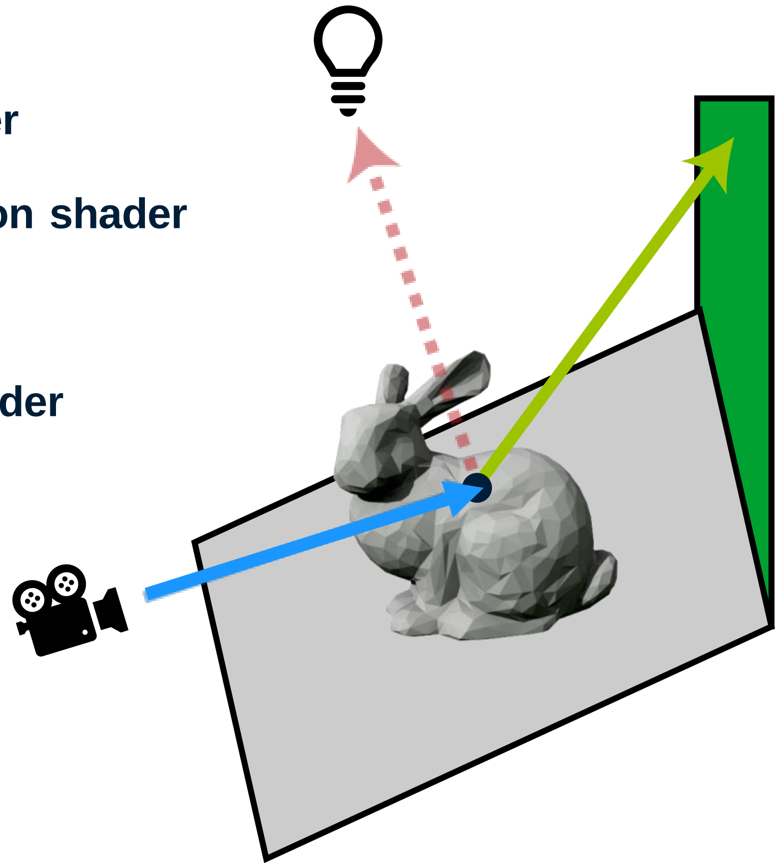
- Control how to shade your final hit points? — See your ray's **closest-hit shader**



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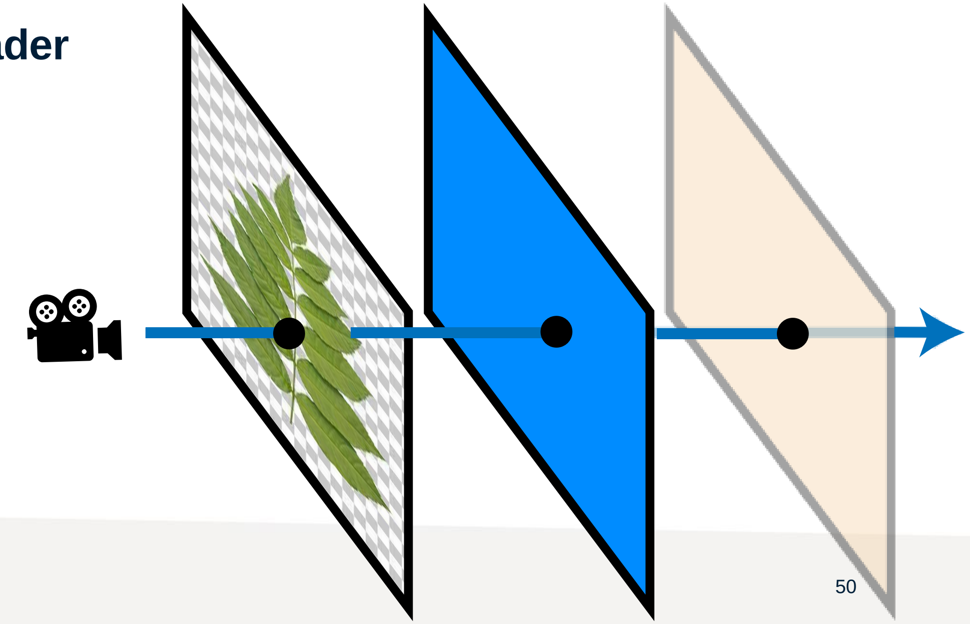
Control what happens when rays miss?	See your ray's **miss shader**
Control how to shade your final hit points?	See your ray's **closest-hit shader**
Control how transparency behaves?	See your ray's **any-hit shader**



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What Goes Into a DirectX Ray Tracing Shader?

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

Starting a DXR Shader

- As any program, need an entry point where execution starts
  - *Think* `main()` *in C/C++*

Starting a DXR Shader

```
[shader("raygeneration")]
void PinholeCameraRayGen()   // No parameters required
{ ... <Place code here> ... }
```

- As any program, need an entry point where execution starts
  - *Think* `main()` *in C/C++*
- Shader entry points can be *arbitrarily named*

Starting a DXR Shader


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[shader("raygeneration")]
void PinholeCameraRayGen()    // No parameters required
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- Starting other shader types look like this:
  - `RayPayload` *is a user-defined (and arbitrarily named structure)*
  - `IntersectAttribs` *has data reported on hits (by intersection shader)*

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What is a Ray Payload?

- Ray payload is an arbitrary user-defined, user-named structure
  - *Contains intermediate data needed during ray tracing*

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    float3 rayColor;
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Not familiar with HLSL?

Built-in types include scalar types: **bool**, **int**, **uint**, **float**

Also vectors of up to 4 components: **bool1**, **int2**, **uint3**, **float4**

And matrices up to 4x4 size: **uint1x4**, **float2x2**, **int3x2**, **float4x4**

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    - *Large payloads will reduce performance; spill registers into memory*

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What is a Ray Payload?

- Ray payload is an arbitrary user-defined, user-named structure
  - *Contains intermediate data needed during ray tracing*
  - ***Note**: Keep ray payload as small as possible*
    - *Large payloads will reduce performance; spill registers into memory*
- A simple ray might look like this:
  - *Sets color to blue when the ray misses*
  - *Sets color to red when the ray hits an object*

```
struct SimpleRayPayload
{
    float3 rayColor;
};

[shader("miss")]
void RayMiss(inout SimpleRayPayload data)
{
    data.rayColor = float3( 0, 0, 1 );
}

[shader("closesthit")]
void RayClosestHit(inout SimpleRayPayload data,
                   IntersectAttribs attribs)
{
    data.rayColor = float3( 1, 0, 0 );
}
```

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  - *E.g., how do you look up textures for your primitive?*

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  - *One structure for triangles, one for spheres, one for Bezier patches*
  - *DirectX provides a built-in for the fixed function triangle intersector*

```
struct BuiltinIntersectionAttribs
{                                 // Barycentric coordinates of hit in
    float2 barycentrics;  // the triangle are: (1-x-y, x, y)
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What are the Intersection Attributes?

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  - *Could imagine custom intersection attribute structures like:*

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struct BuiltinIntersectionAttribs
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```

```
struct PossibleSphereAttribs
{                          // Giving (theta,phi) of the hit on
    float2 thetaPhi;   // the sphere (thetaPhi.x, thetaPhi.y)
}

struct PossibleVolumeAttribs
{                     // Doing volumetric ray marching?  Maybe
    float3 vox;   // return voxel coord: (vox.x, vox.y, vox.z)
}
```

What are the Intersection Attributes?

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- Communications intersection information needed for shading
  - *E.g., how do you look up textures for your primitive?*
- Specific to each intersection type
  - *One structure for triangles, one for spheres, one for Bezier patches*
  - *DirectX provides a built-in for the fixed function triangle intersector*
  - *Could imagine custom intersection attribute structures like:*
- Limited attribute structure size: max 32 bytes

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struct BuiltinIntersectionAttribs
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- We need somewhere to write our output

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RWTexture<float4> outTex;
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A Simple Example

- Besides our shader, what data is needed on the GPU to shoot rays?
- We need somewhere to write our output
- Where are we looking? We need camera data

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RWTexture<float4> outTex;

// An HLSL “constant buffer”, to be populated from your host C++ code
cbuffer RayGenData {
    float3 wsCamPos;                  // World space camera position
    float3 wsCamU, wsCamV, wsCamW;    // Camera right, up, and forward vectors
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A Simple Example

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- Need to know about our scene geometry

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RaytracingAccelerationStructure sceneAccelStruct;
```

A Simple Example

- Besides our shader, what data is needed on the GPU to shoot rays?
- We need somewhere to write our output
- Where are we looking? We need camera data
- Need to know about our scene geometry
- Also need information on how to shade the scene
  - *More complex topic*
  - *Depends on your program's or engine's material format*
  - *Depends on your shading models*
  - *Leave for later, see full tutorial code for examples*

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A Simple Example – Code

CPU → GPU data declarations

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```

```
[shader("raygeneration")]
void PinholeCamera() {
     uint2 curPixel     = DispatchRaysIndex().xy;
     uint2 totalPixels  = DispatchRaysDimensions().xy;

     ...
}
```

What pixel are we currently computing?

How many rays, in total, are we generating?

A Simple Example – Code


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    float2 ndc         = float2(2,-2) * pixelCenter + float2(-1,1);
    float3 pixelRayDir = ndc.x * wsCamU + ndc.y * wsCamV + wsCamZ;

    ...
}
```

Find pixel center in [0..1] x [0..1]

Compute normalized device coordinate (as in raster)

Convert NDC into pixel's ray direction (using camera inputs)

A Simple Example – Code


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```

Collectively: Turn pixel ID into a ray direction

A Simple Example – Code

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    RayDesc ray;
    ray.Origin    = wsCamPos;
    ray.Direction = normalize( pixelRayDir );
    ray.TMin      = 0.0f;
    ray.TMax      = 1e+38f;

    ...
}
```

Setup our ray

A Simple Example – Code

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    ...
}
```

`RayDesc` is a new HLSL built-in type:

```
struct RayDesc {
    float3 Origin;    // Where the ray starts
    float  TMin;      // Min distance for a valid hit
    float3 Direction; // Direction the ray goes
    float  TMax;      // Max distance for a valid hit
};
```

A Simple Example – Code

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```
struct SimpleRayPayload {
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Setup our ray's payload

A Simple Example – Code

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    TraceRay( sceneAccelStruct, RAY_FLAG_NONE, 0xFF,
              HIT_GROUP, NUM_HIT_GROUPS, MISS_SHADER,
              ray, payload );

    ...
}
```

Trace our ray

```
RWTexture<float4> outTex;   // Output texture
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A Simple Example – Code

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A new intrinsic function in HLSL

Can call from ray generation, miss, and closest-hit shaders

A Simple Example – Code


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Our scene acceleration structure

A Simple Example – Code


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Special traversal behavior for this ray? (Here: No)

A Simple Example – Code

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```

Instance mask; 0xFF → test all geometry

This allows us to ignore some geometry via a mask

A Simple Example – Code

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    uint2 curPixel     = DispatchRaysIndex().xy;
    uint2 totalPixels  = DispatchRaysDimensions().xy;
    float2 pixelCenter = (curPixel + float2(0.5,0.5)) / totalPixels;
    float2 ndc         = float2(2,-2) * pixelCenter + float2(-1,1);
    float3 pixelRayDir = ndc.x * wsCamU + ndc.y * wsCamV + wsCamZ;

    RayDesc ray;
    ray.Origin    = wsCamPos;
    ray.Direction = normalize( pixelRayDir );
    ray.TMin      = 0.0f;
    ray.TMax      = 1e+38f;

    SimpleRayPayload payload = { float3(0, 0, 0) };

    TraceRay( sceneAccelStruct, RAY_FLAG_NONE, 0xFF,
              HIT_GROUP, NUM_HIT_GROUPS, MISS_SHADER,
              ray, payload );

    ...
}
```

Which intersection, any-hit, closest-hit, and miss shaders to use?

Known from C++ API setup & total number of shaders. This case: 0, 1, 0

A Simple Example – Code

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              ray, payload );

    ...
}
```

```
RWTexture<float4> outTex;    // Output texture
cbuffer RayGenData {         // World-space camera data
    float3 wsCamPos;
    float3 wsCamU, wsCamV, wsCamW;
};
RaytracingAccelerationStructure sceneAccelStruct;

struct SimpleRayPayload {
    float3 color;
};
```

What ray are we shooting?

A Simple Example – Code

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void PinholeCamera() {
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What is the ray payload? Stores intermediate, per-ray data

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              HIT_GROUP, NUM_HIT_GROUPS, MISS_SHADER,
              ray, payload );

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

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```

Write ray query result into our output texture

Combine With Simple Ray Type


```
RWTexture<float4> outTex;
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}
```

```
[shader("miss")]
void RayMiss(inout SimpleRayPayload data)
{
    data.color = float3( 0, 0, 1 );
}

[shader("closesthit")]
void RayClosestHit(inout SimpleRayPayload data,
                   BuiltinIntersectionAttribs attribs)
{
    data.color = float3( 1, 0, 0 );
}
```

- Now you have a complete DirectX Raytracing shader
  – *(Both intersection shader and any-hit shader are optional)*
- Shoots rays from app-specified camera
- Returns red if rays hit geometry, blue on background

What Can DXR HLSL Shaders Do?

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- All the standard HLSL data types, texture resources, user-definable structures and buffers
  - *See Microsoft documentation for more details and course tutorials for more examples*

What Can DXR HLSL Shaders Do?

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- Numerous standard HLSL intrinsic or built-in functions useful for graphics, spatial manipulation, and 3D mathematics
  - *Basic math* (`sqrt`, `clamp`, `isinf`, `log`), *trigonometry* (`sin`, `acos`, `tanh`), *vectors* (`normalize`, `length`), *matrices* (`mul`, `transpose`)
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  - *See Microsoft documentation for full list and course tutorials for more examples*
- New intrinsic functions for ray tracing
  - *Functions related to ray traversal:* `TraceRay()`, `ReportHit()`, `IgnoreHit()`, *and* `AcceptHitAndEndSearch()`
  - *Functions for ray state, e.g.:* `WorldRayOrigin()`, `RayTCurrent()`, `InstanceID()`, *and* `HitKind()`

New Ray Tracing Built-in Functions

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Ray Traversal Functions	**Ray Gen**	**Intersect**	**Any Hit**	***Closest***	***Miss***	***Summary***
`TraceRay()`	✓			✓	✓	Launch a new ray
`ReportHit()`		✓				Found a hit; test it; function returns true if hit accepted
`IgnoreHit()`			✓			Hit point should be ignored, traversal continues
`AcceptHitAndEndSearch()`			✓			Hit is good; stop search immediately, execute closest hit

New Ray Tracing Built-in Functions

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Ray Launch Details	Ray Gen	Intersect	Any Hit	*Closest*	*Miss*	***Summary***
`DispatchRaysDimensions()`	✓	✓	✓	✓	✓	How many rays were launched (e.g., 1920 × 1080)
`DispaychRaysIndex()`	✓	✓	✓	✓	✓	Why ray (in that range) is the shader currently processing

New Ray Tracing Built-in Functions

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Ray Launch Details	Ray Gen	Intersect	Any Hit	*Closest*	*Miss*	*Summary*
`DispatchRaysDimensions()`	✓	✓	✓	✓	✓	How many rays were launched (e.g., 1920 × 1080)
`DispaychRaysIndex()`	✓	✓	✓	✓	✓	Why ray (in that range) is the shader currently processing

Hit Specific Details	Ray Gen	Intersect	Any Hit	*Closest*	*Miss*	*Summary*
`HitKind()`			✓	✓		Information about what kind of hit we're processing

(Developer data specified by your intersection shader. For triangles can be: HIT_KIND_TRIANGLE_FRONT_FACE or HIT_KIND_TRIANGLE_BACK_FACE)

New Ray Tracing Built-in Functions

Ray Introspection	Ray Gen	Intersect	Any Hit	*Closest*	*Miss*	*Summary*
`RayTCurrent()`		✓	✓	✓	✓	Current distance along the ray
`RayTMin()`		✓	✓	✓	✓	Min ray distance, as passed to this ray's `TraceRay()`
`RayFlags()`		✓	✓	✓	✓	The flags passed to this ray's `TraceRay()`
`WorldRayOrigin()`		✓	✓	✓	✓	The ray origin passed to this ray's `TraceRay()`
`WorldRayDirection()`		✓	✓	✓	✓	The ray direction passed to this ray's `TraceRay()`

New Ray Tracing Built-in Functions

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Current Object Introspection	Ray Gen	Intersect	Any Hit	*Closest*	*Miss*	*Summary*
`InstanceIndex()`		✓	✓	✓		Instance index in acceleration structure (generated)
`InstanceID()`		✓	✓	✓		Instance identifier in acceleration struct (user-provided)
`PrimitiveIndex()`		✓	✓	✓		Index of primitive in geometry instance (generated)
`ObjectToWorld()`		✓	✓	✓		Matrix to transform object-space to world-space
`WorldToObject()`		✓	✓	✓		Matrix to transform world-space to object-space
`ObjectRayOrigin()`		✓	✓	✓		Essentially: `WorldToObject(WorldRayOrigin())`
`ObjectRayDirection()`		✓	✓	✓		Essentially: `WorldToObject(WorldRayDirection())`