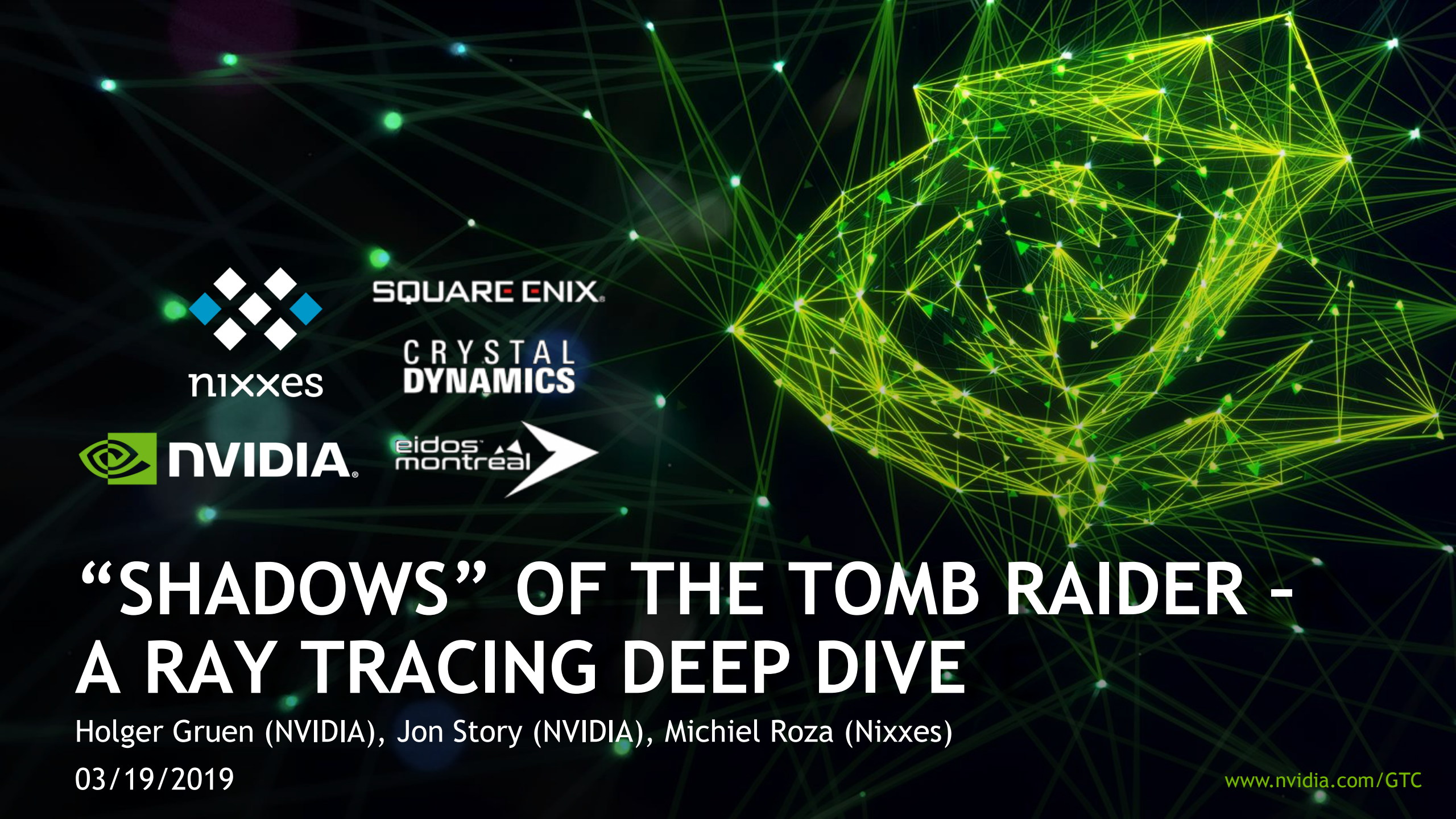

“SHADOWS” OF THE TOMB RAIDER – A RAY TRACING DEEP DIVE

Holger Gruen (NVIDIA), Jon Story (NVIDIA), Michiel Roza (Nixxes)

03/19/2019

AGENDA

- Shadow of the Tomb Raider
- Why ray traced shadows?
- DXR shaders (ray generation)
- GameWorks spatial denoiser
- DXR acceleration structure
- Integration in render pipeline
- Results
- Future work

AGENDA

Shadow of the Tomb Raider

Why ray traced shadows?

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SHADOW OF THE
TOMB RAIDER

AGENDA

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Shadow Mapped

Shadow Mapped

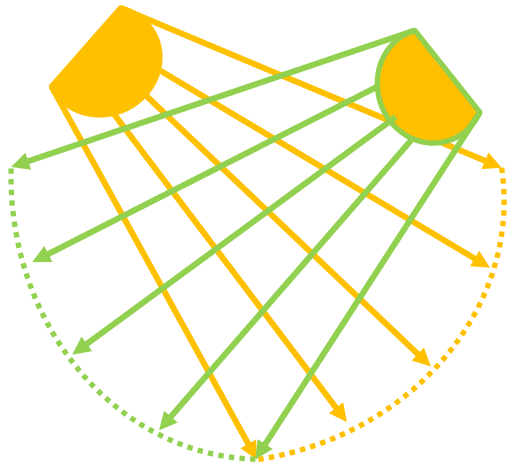

Shadow Mapped


Raytraced

WHY RAY TRACED SHADOWS?

There’s so much that shadow mapping can’t do!

- Pixel perfect shadows
- Translucent shadows
- Point lights
  - Currently faked by using two spot lights
- Area lights



AGENDA

Shadow of the Tomb Raider

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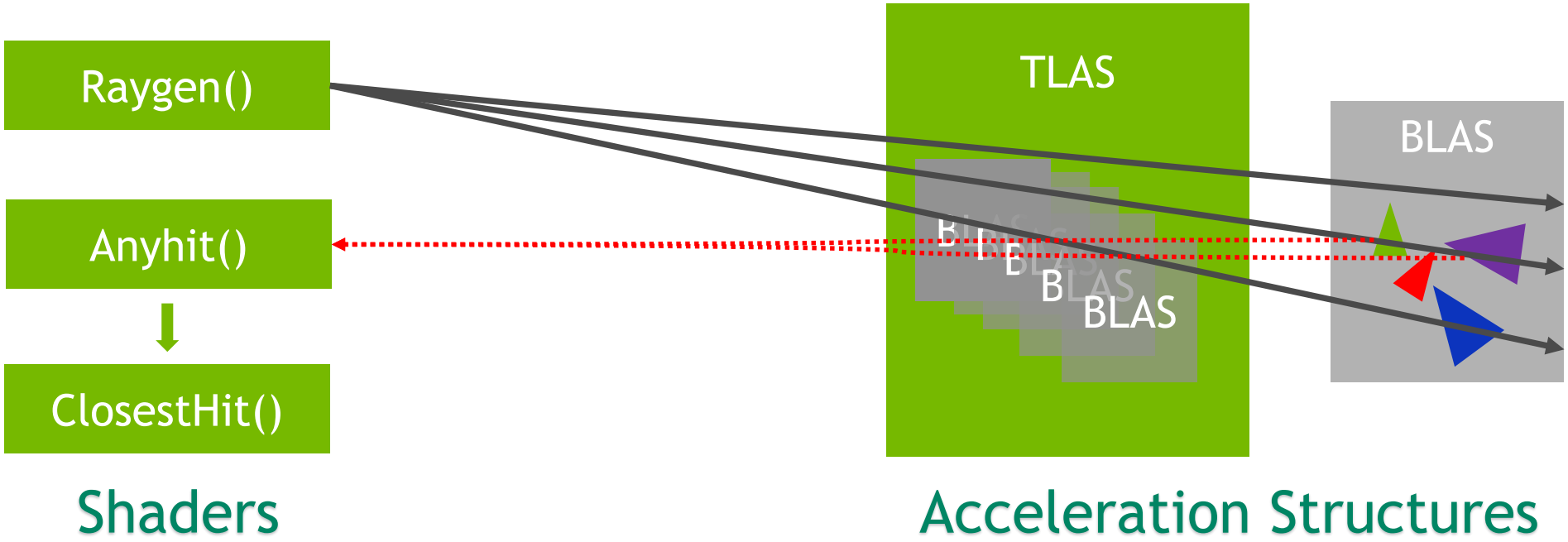
DXR SHADERS

Mini Agenda

- Noise / random number generation
- Ray generation
- Hit shaders
- Adaptive raytracing
- Translucency
- TAA and jittering

DXR SHADERS

DXR Mini intro



DXR SHADERS

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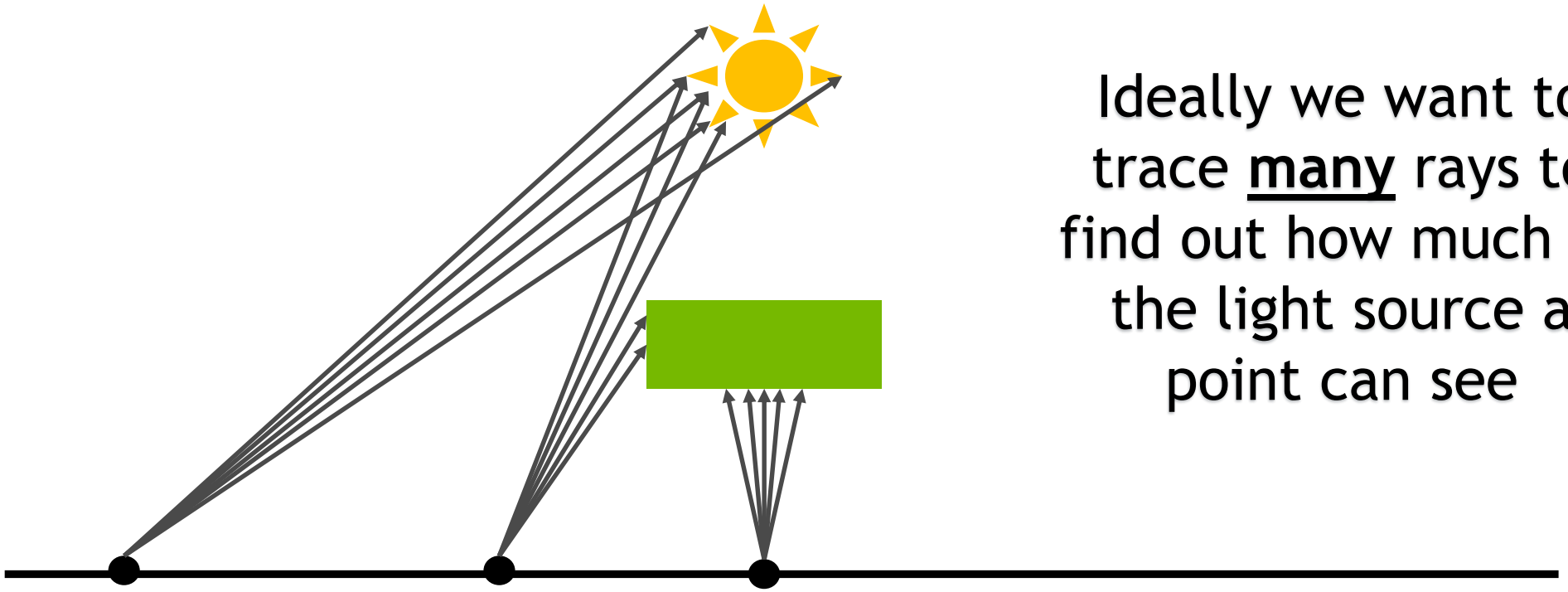
DXR SHADERS

Noise / random number generation



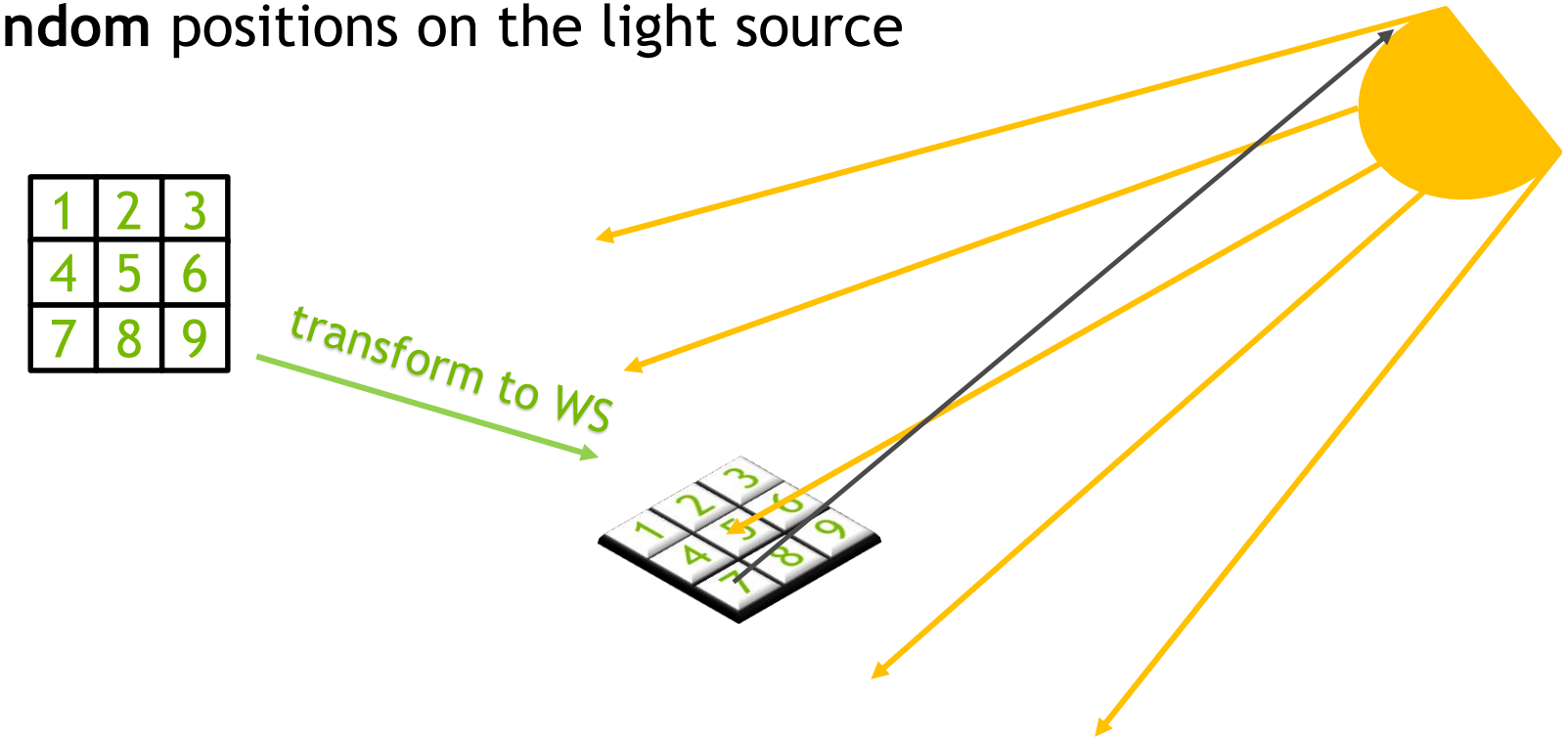
Ideally we want to trace **many** rays to find out how much of the light source a point can see

Full light Penumbra Umbra

DXR SHADERS

Noise / random number generation

- For great performance we want to shoot only 1 ray per pixel
- So instead of one pixel shooting many rays, a neighborhood of pixels samples ‘enough’ **random** positions on the light source



DXR SHADERS

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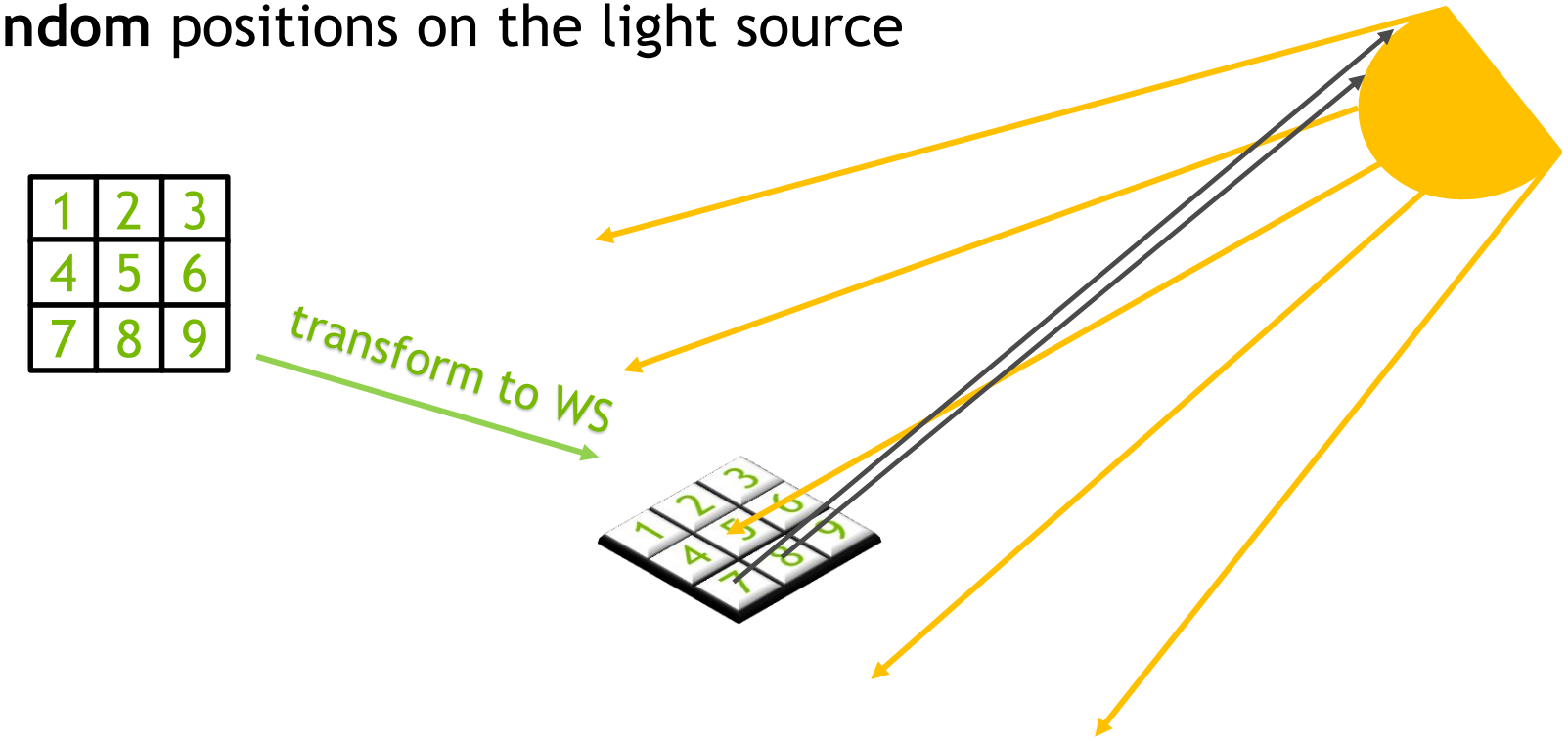

DXR SHADERS

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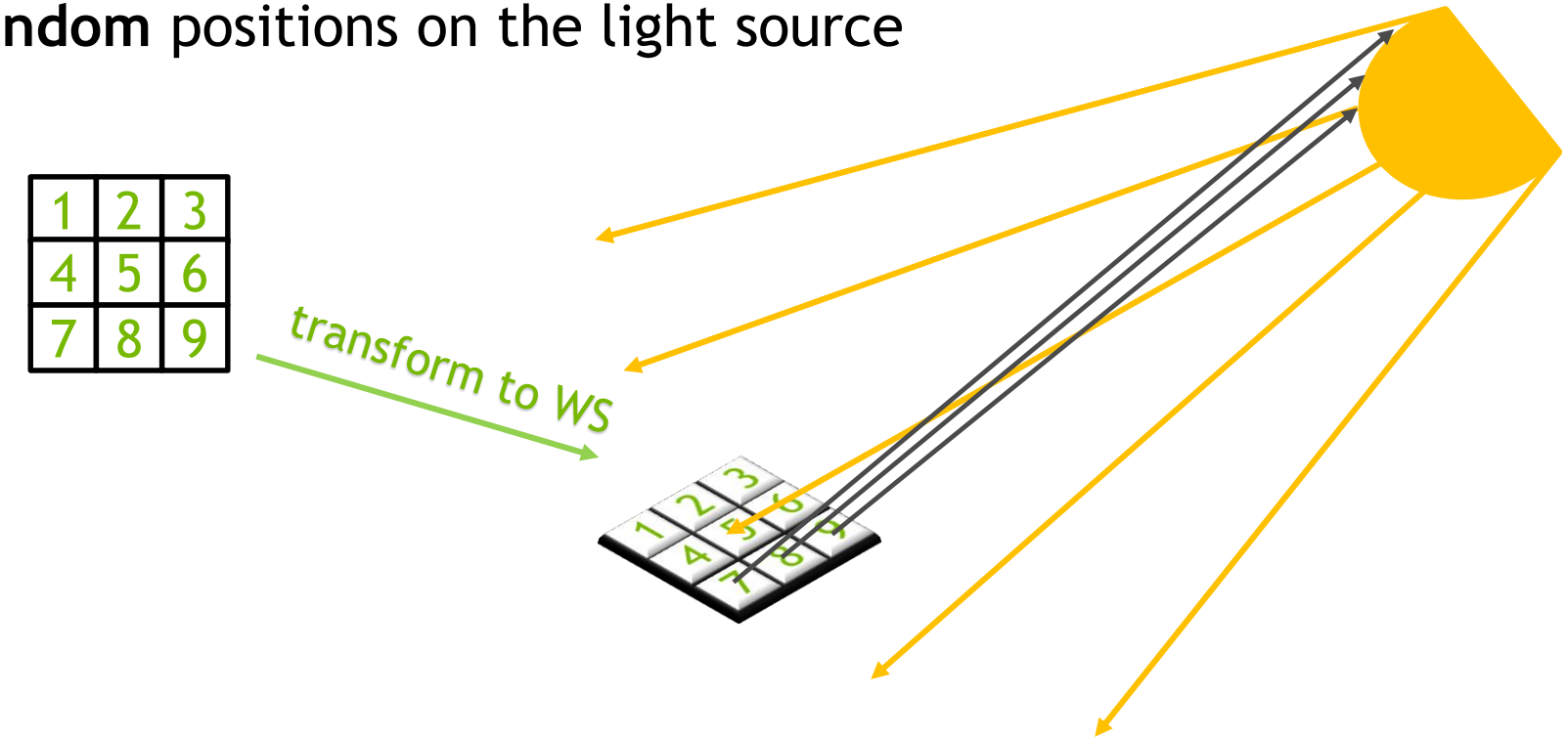

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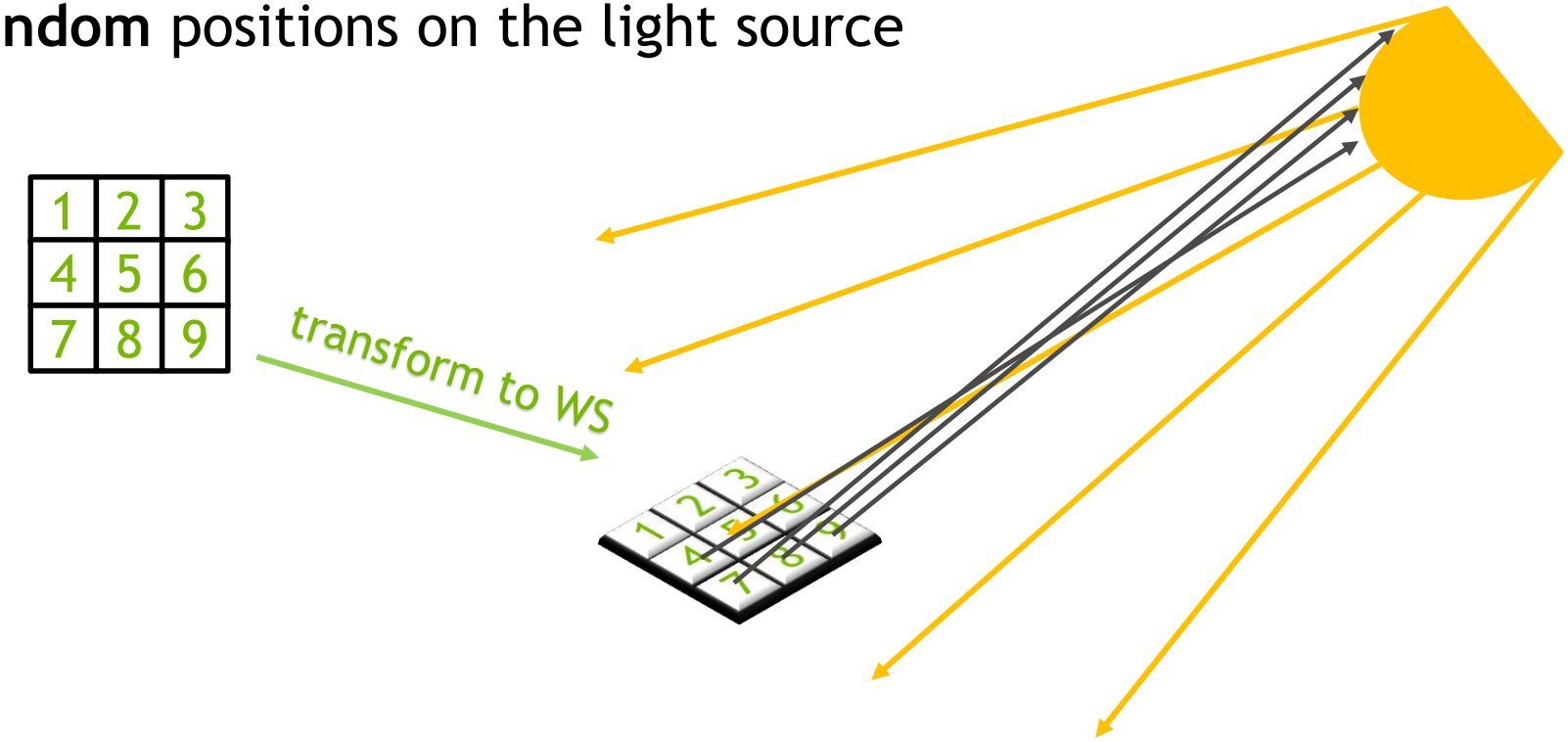

DXR SHADERS

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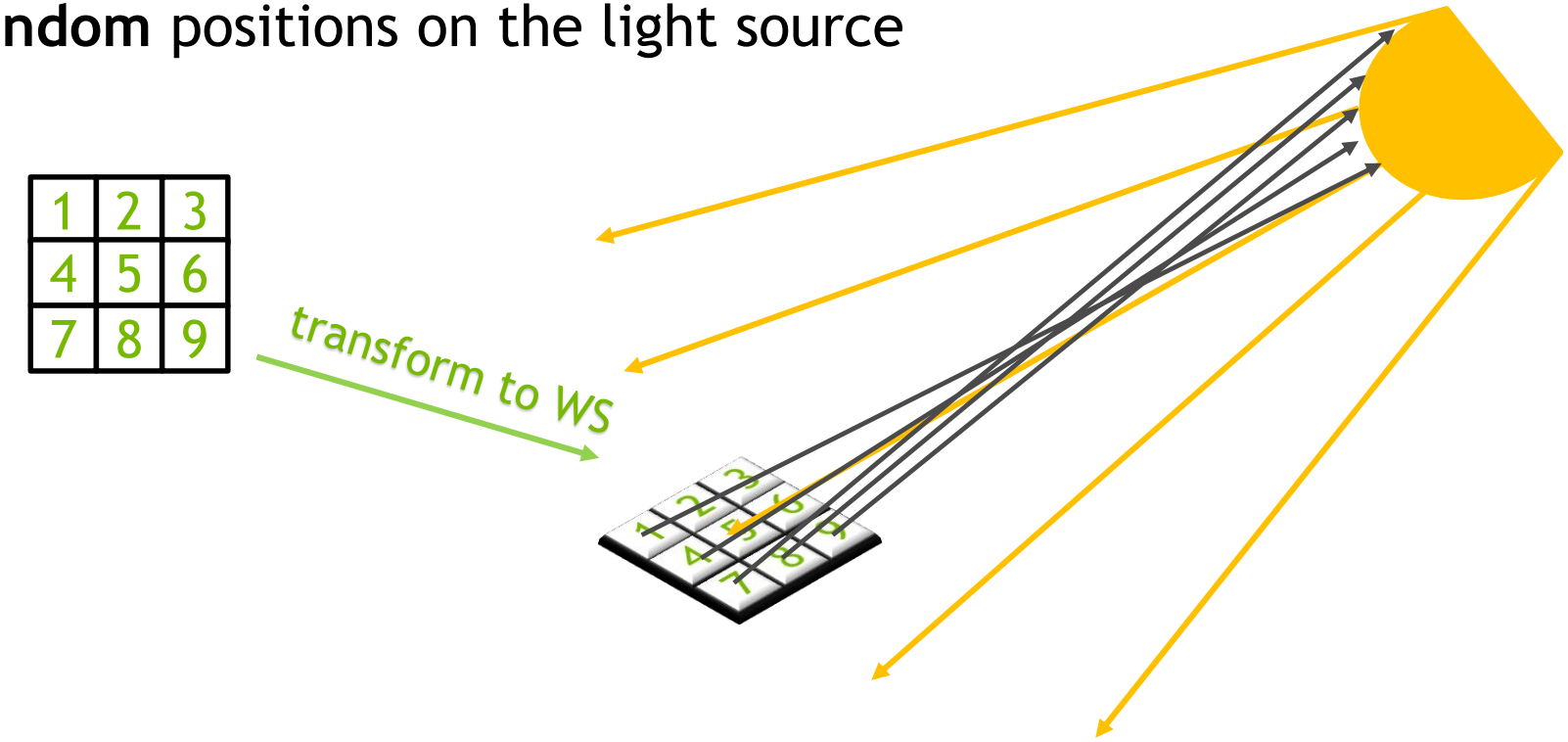

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DXR SHADERS

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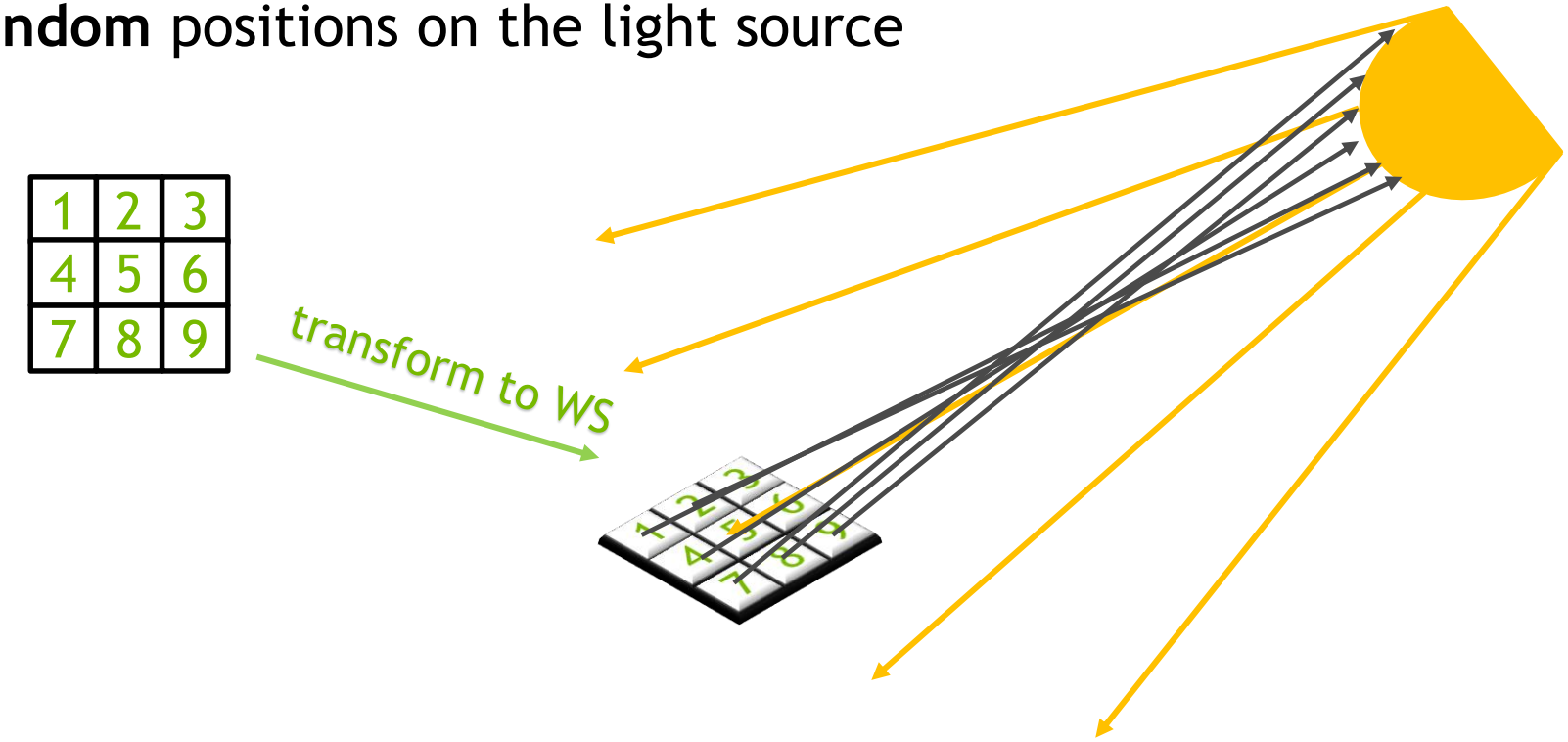

DXR SHADERS

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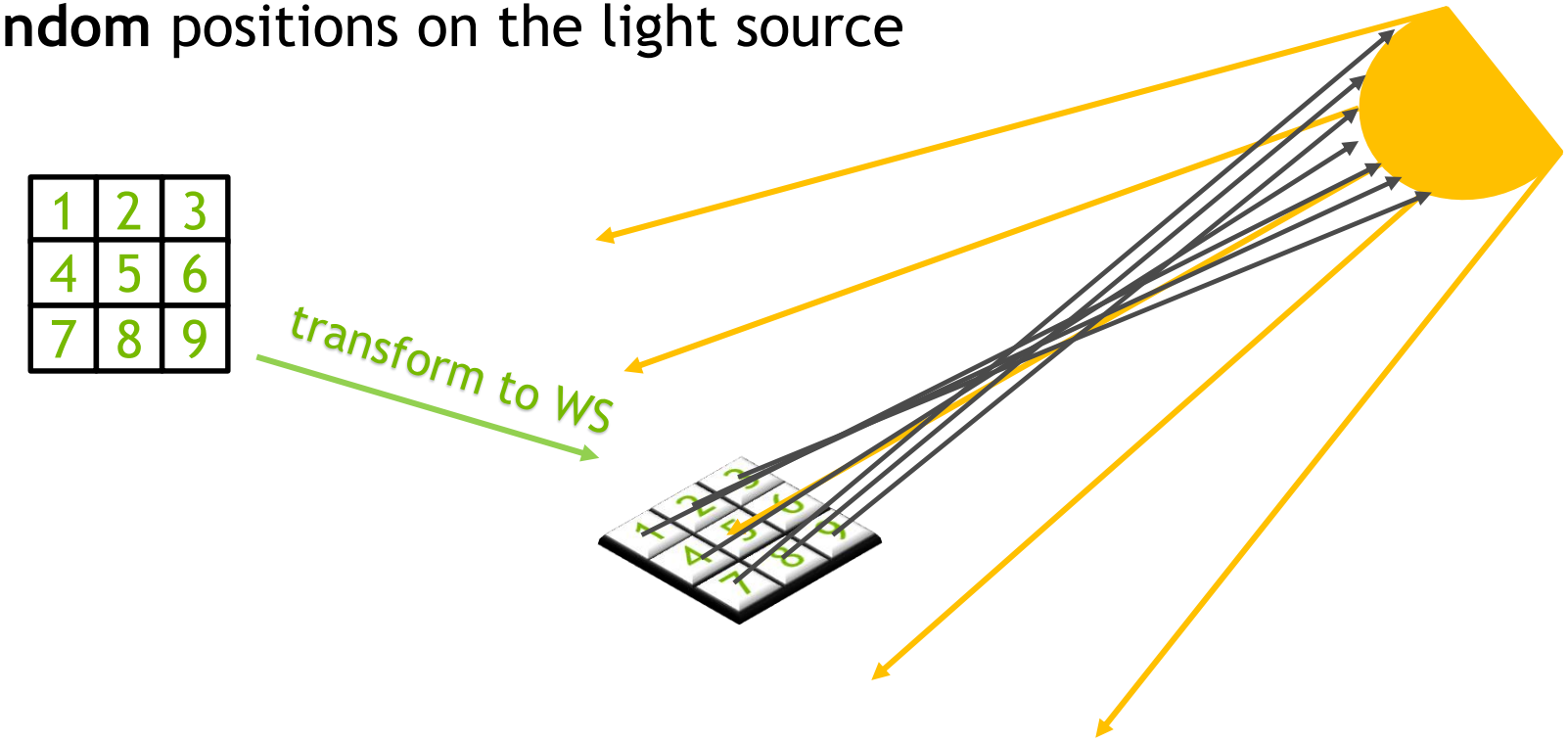

DXR SHADERS

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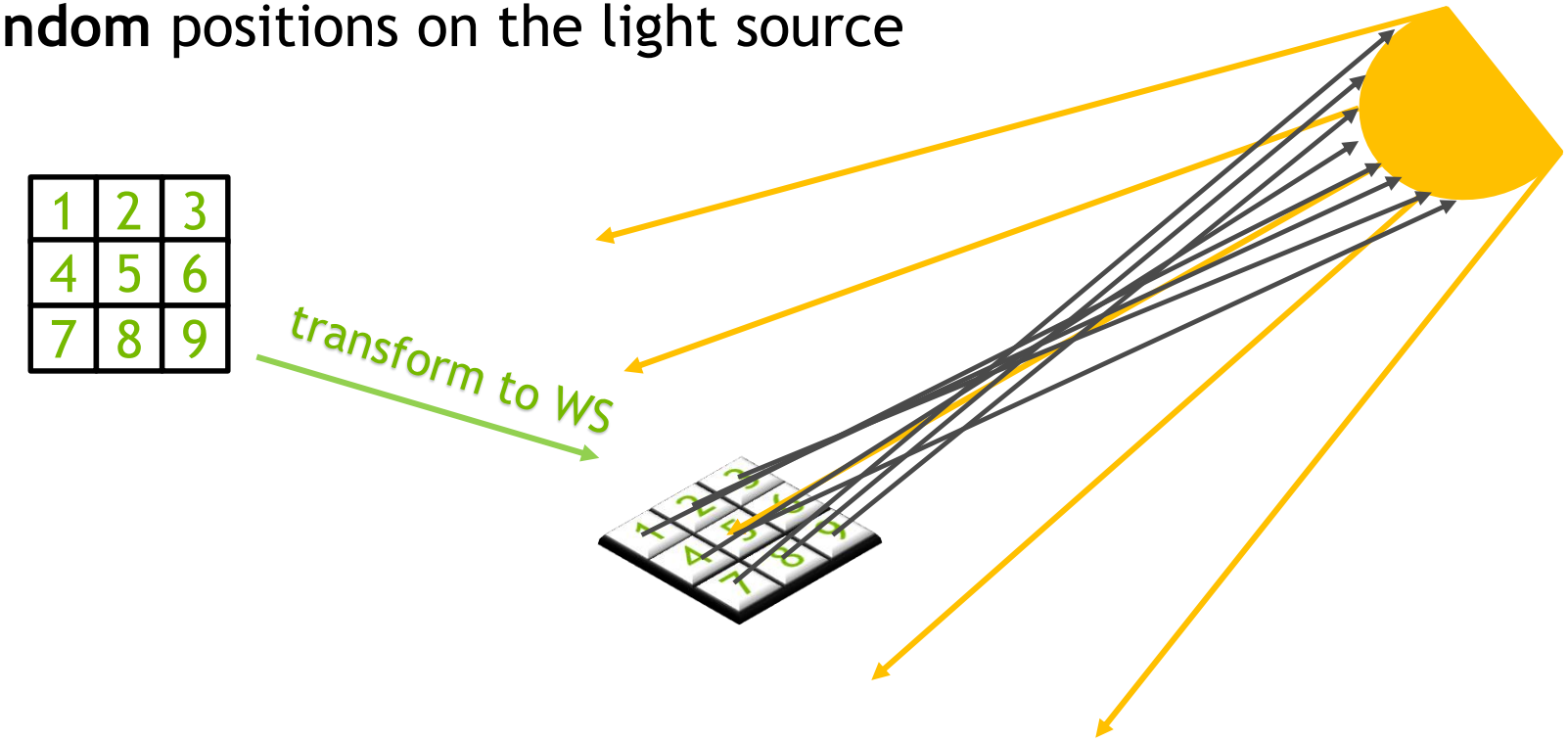

DXR SHADERS

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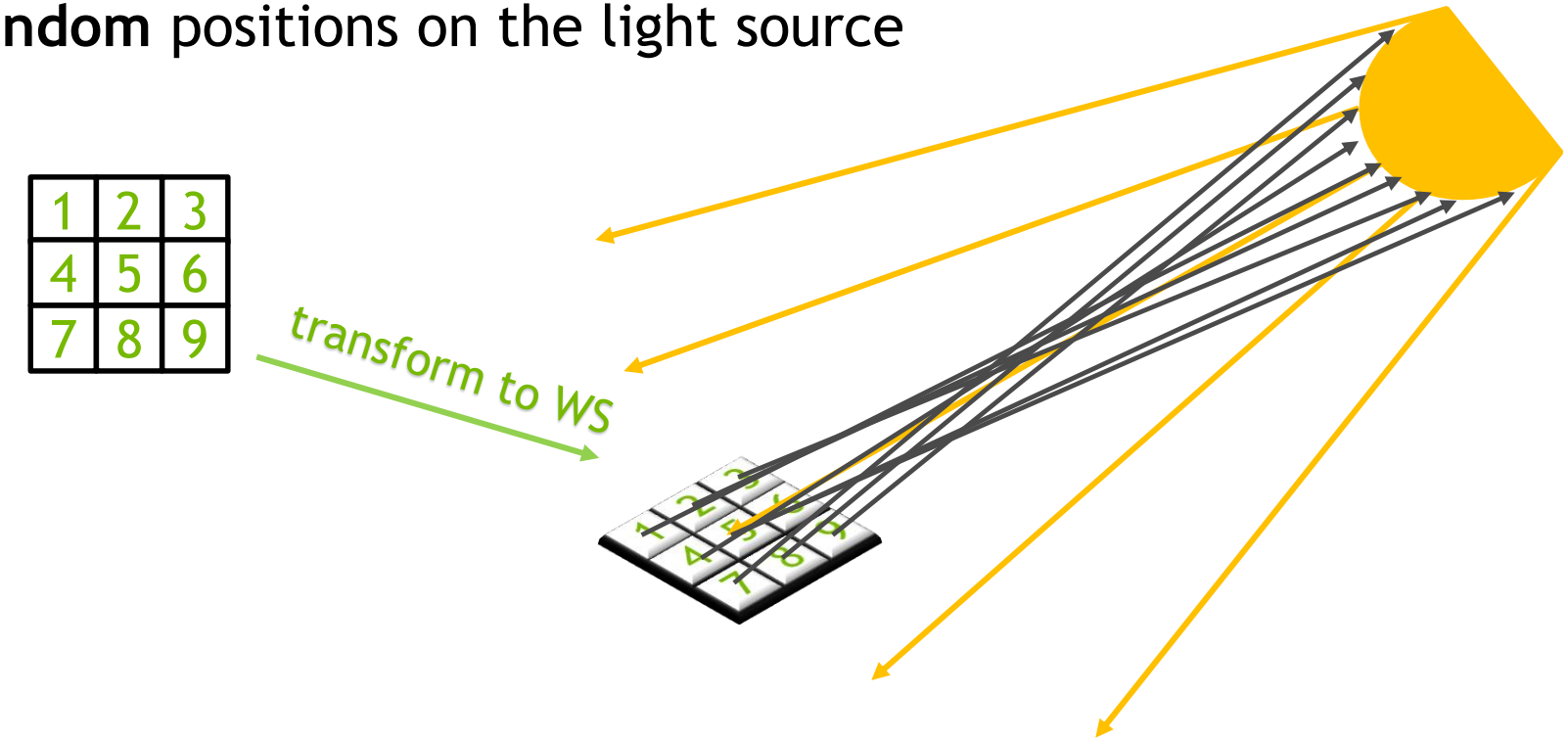

DXR SHADERS

Noise / random number generation

- Random positions on the light are based on generating pseudo random numbers

  http://www.reedbeta.com/blog/quick-and-easy-gpu-random-numbers-in-d3d11/

- The trick is to choose the right random seed for the generator

- We use a seed that is based on the 2D position of the pixel

```
Seed( ( pixel_2d_pos ) % TILE_SIZE_2D );
```

Noisy shadows

DXR SHADERS

Noise / random number generation

DXR SHADERS

Mini Agenda

- Noise / random number generation
- Ray generation
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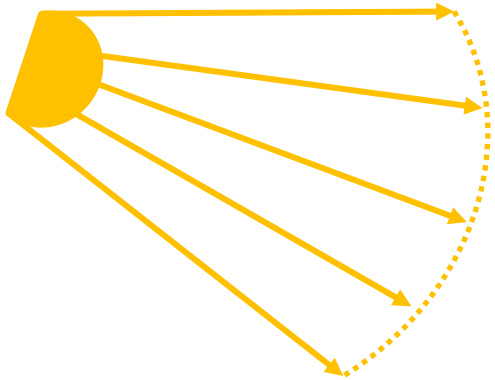
- Adaptive raytracing
- Translucency
- TAA and jittering

DXR SHADERS

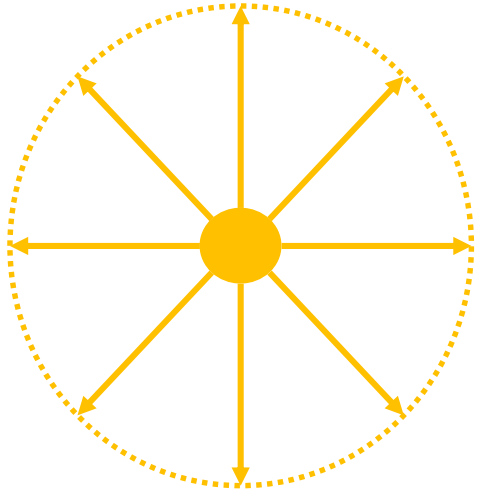
Ray generation

- We use specialized raygen shaders for each light type for optimal performance

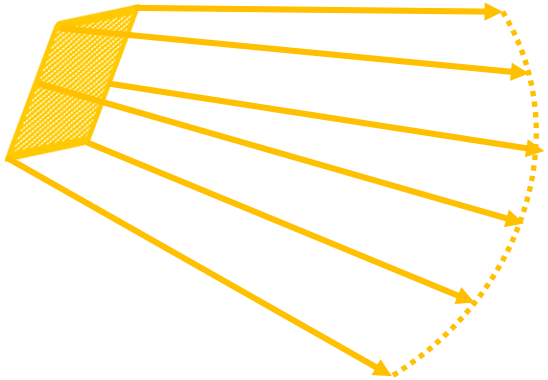
Directional light source with an angular extent



Area Cone light



Point light with a spherical area

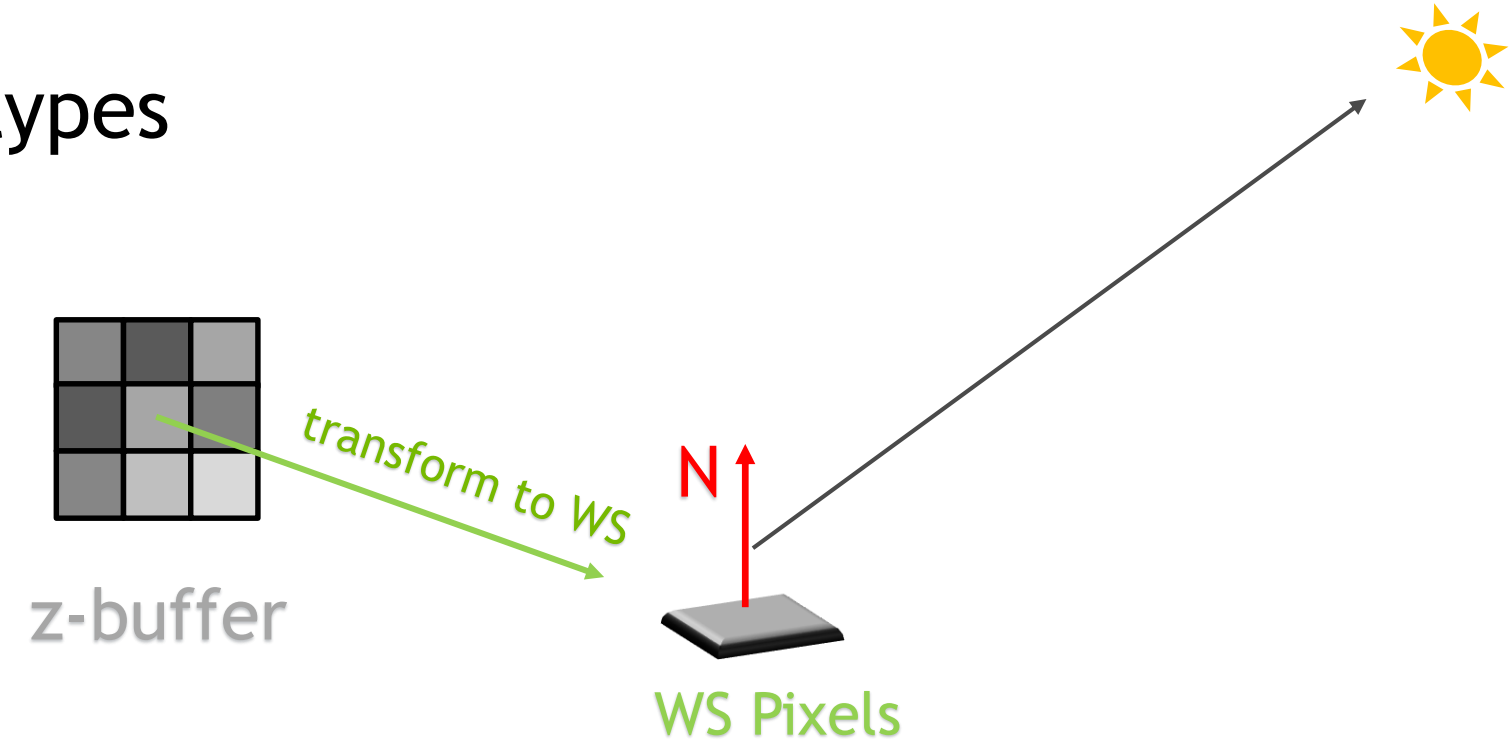


Rectangular area cone light

DXR SHADERS

Ray generation

All light types

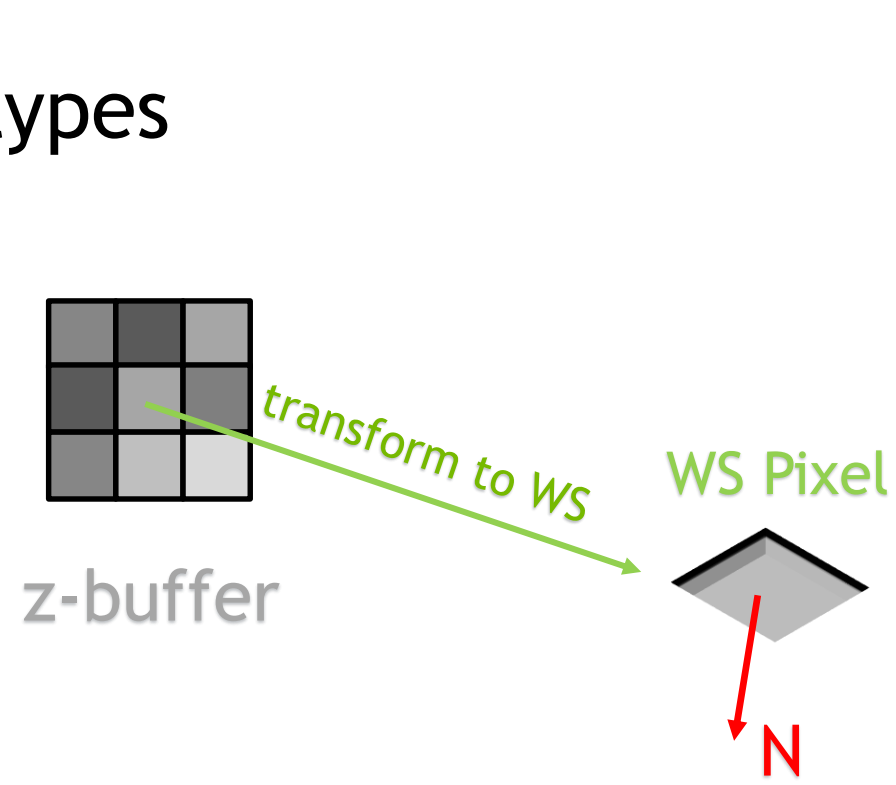


Move some small distance along the normal to prevent self-shadowing!

DXR SHADERS

Ray generation

All light types

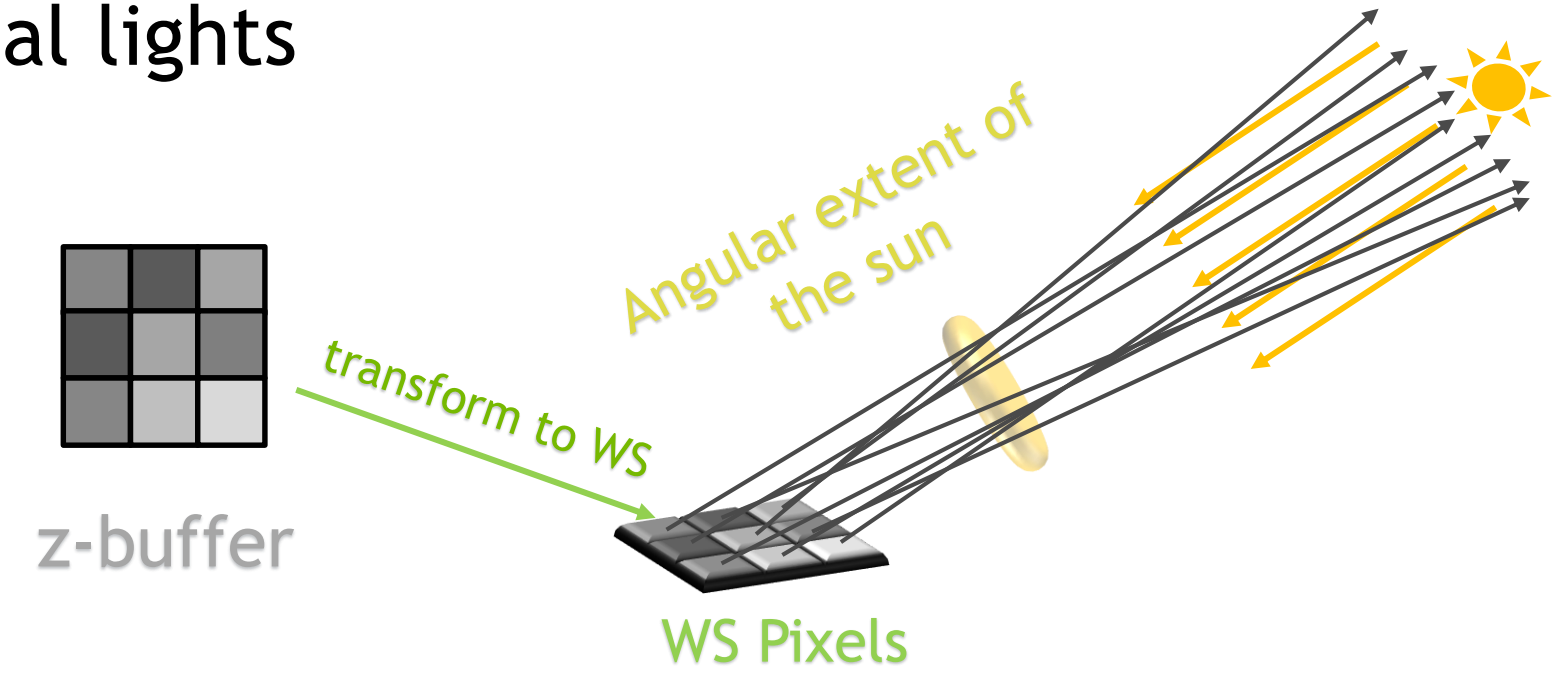


No rays for pixels that face away from the current light!

DXR SHADERS

Ray generation

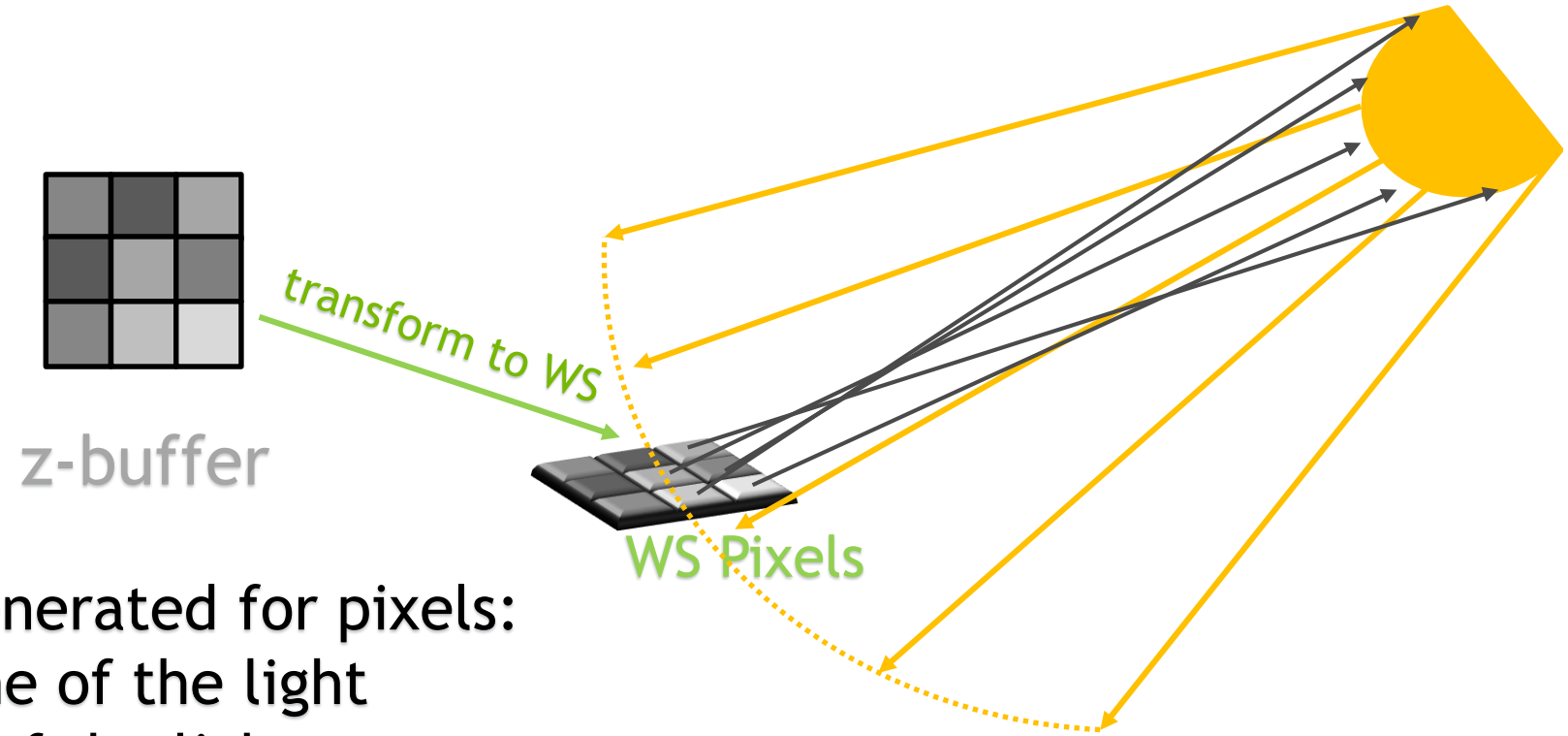
Directional lights



DXR SHADERS

Ray generation

Spot lights



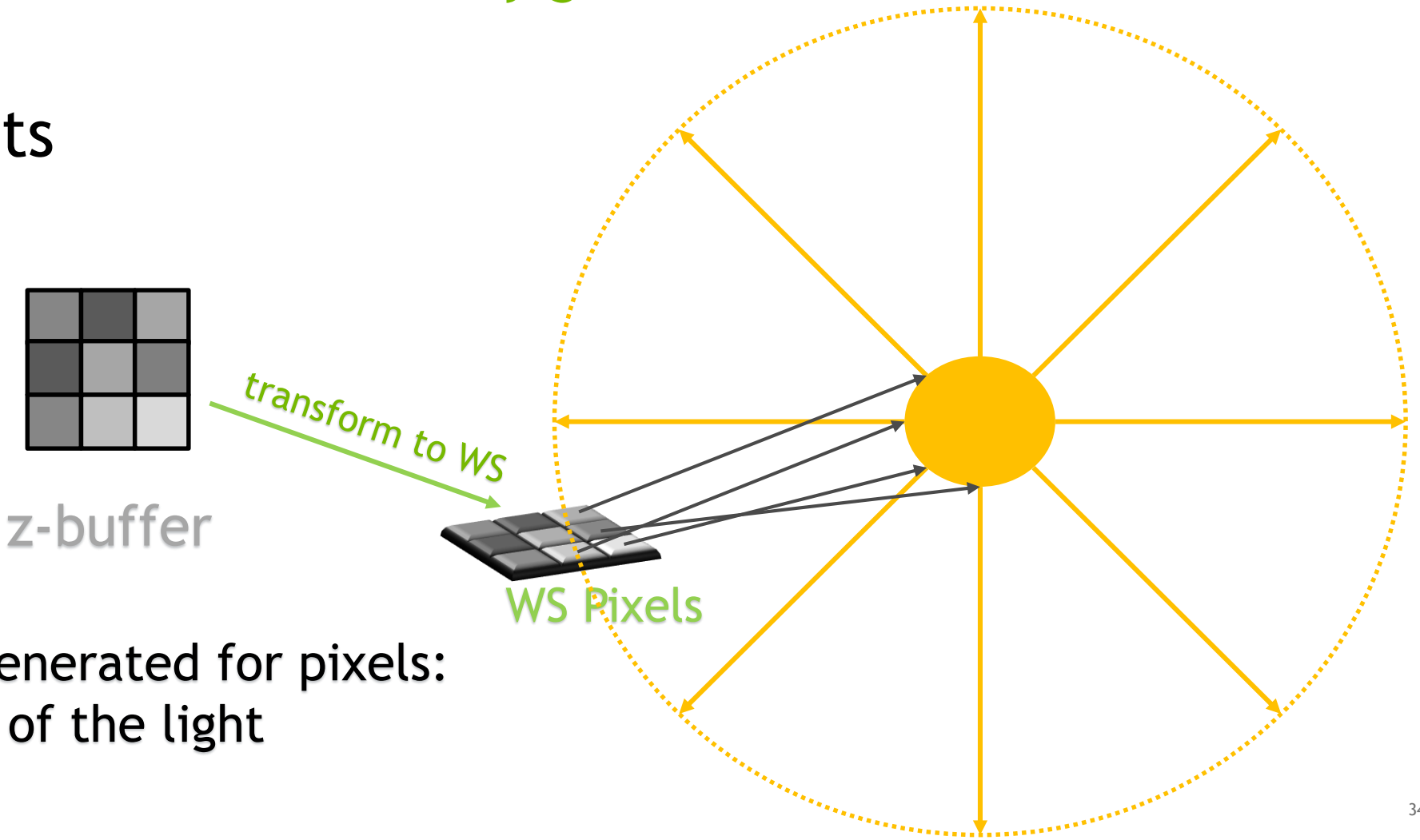
Rays only get generated for pixels:

- Inside the cone of the light
- Within reach of the light

DXR SHADERS

Ray generation

Point lights



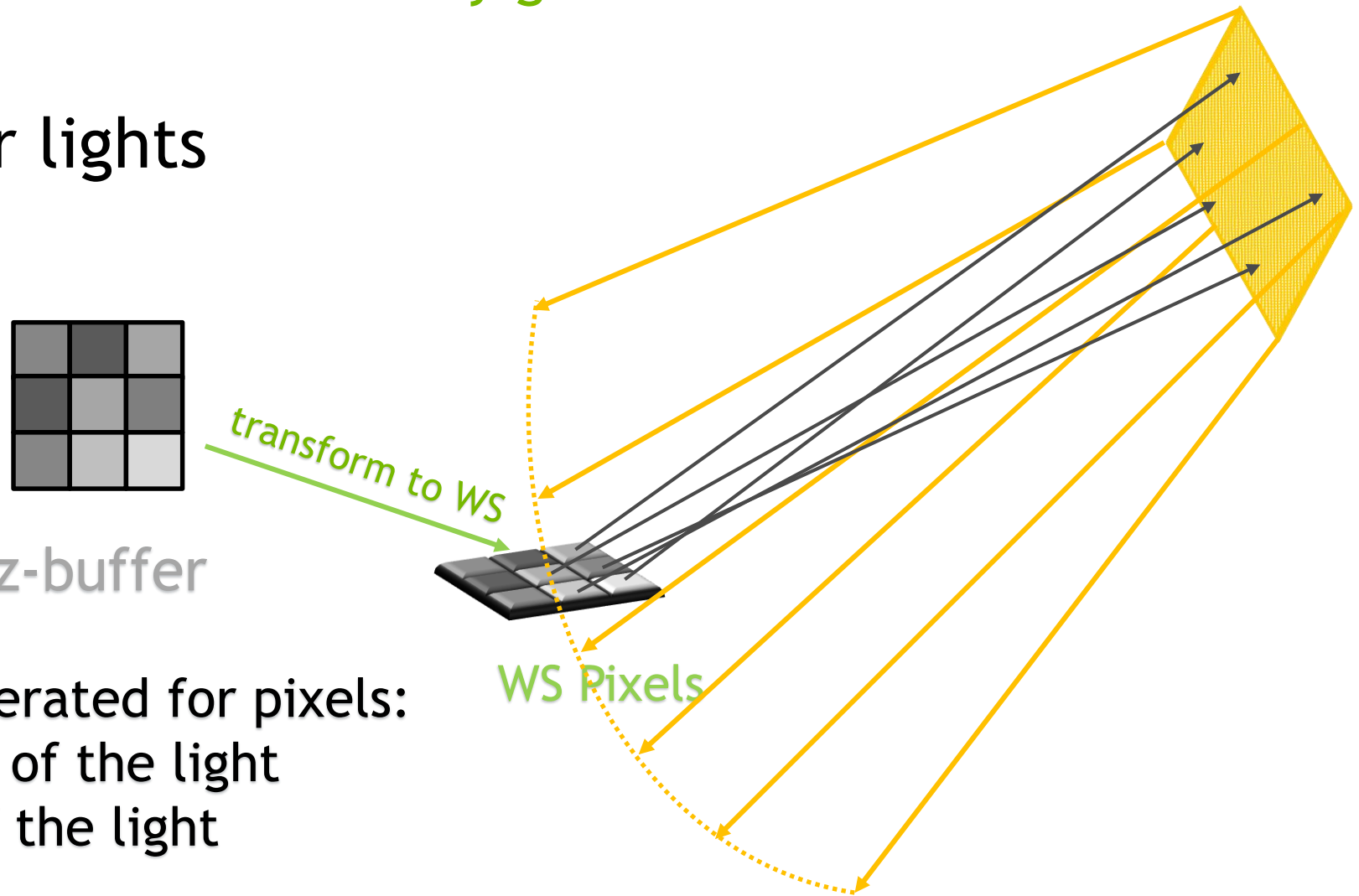
Rays only get generated for pixels:

- Within reach of the light

DXR SHADERS

Ray generation

Rectangular lights



Rays only get generated for pixels:

- Inside the cone of the light
- Within reach of the light

DXR SHADERS

Mini Agenda

- Noise / random number generation
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- Adaptive raytracing
- Translucency
- TAA and jittering

DXR SHADERS

Hit shaders

- We don‘t use the closest hit along the ray
- Instead we use the first opaque one that gets reported to anyhit()
  - Translucency for DXR ultra quality is an exception
- We fetch texture coords for alpha tested prims to carry out the alpha test

DXR SHADERS

Hit Shaders

- Opaque Geometry

```
void OpaqueClosestHit(…)
{
        payload.hitT = RayTCurrent();
        payload.visibility = 0.0f;
}
```

```
void OpaqueAnyHit(…)
{
        AcceptHitAndEndSearch();
}
```

- Alpha-tested Geometry

```
void AlphaClosestHit(…)
{
        payload.hitT = RayTCurrent();
}
```

```
void AlphaAnyHit(…)
{
        float  alpha = GetHitAlpha(bary);

        if( alpha < g_fAlphaThreshold )
                IgnoreHit();
        else {
                payload.visibility = 0.0f;
                AcceptHitAndEndSearch();
        }
}
```

DXR SHADERS

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DXR SHADERS

Adaptive raytracing

- Adaptive raytracing is only used for ultra DXR quality
- In this mode we cast more than 1 ray for some pixels
- Let’s dive into the details …

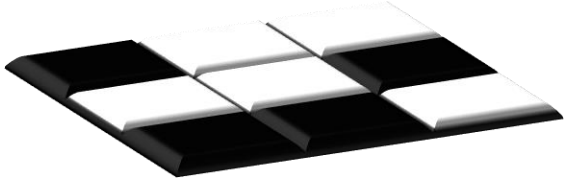
DXR SHADERS

Adaptive raytracing

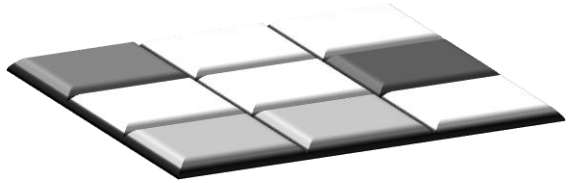
Phase 1 – Cast 1 ray per pixel

Phase 2 – Cast up to 2 more rays ‚where necessary‘

Visibility



hitT



Neighborhood of pixel

Visibility:

- Black => can’t see the light
- White => can see the light

hitT:

- Distance to blocker along ray
- White means ‘infinity’
- Dark means close-by blocker

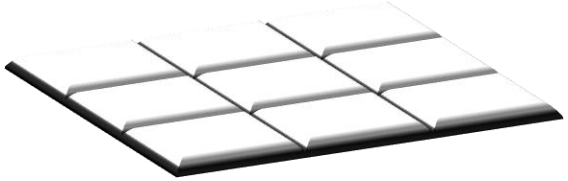
DXR SHADERS

Adaptive raytracing

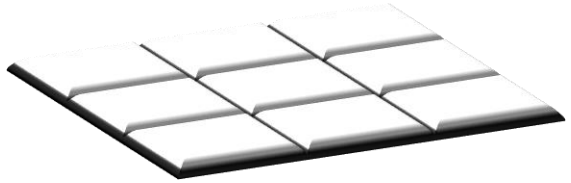
Phase 1 – Cast 1 ray per pixel

Phase 2 – Cast up to 2 more rays ‚where necessary‘

Visibility



hitT



No additional rays

Neighborhood of pixel

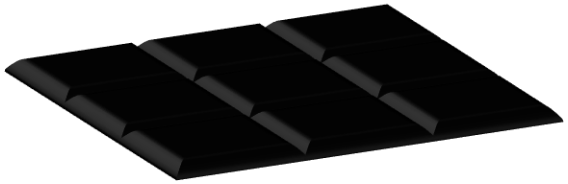
DXR SHADERS

Adaptive raytracing

Phase 1 – Cast 1 ray per pixel

Phase 2 – Cast up to 2 more rays ‚where necessary‘

Visibility



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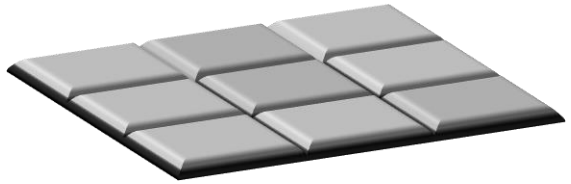

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DXR SHADERS

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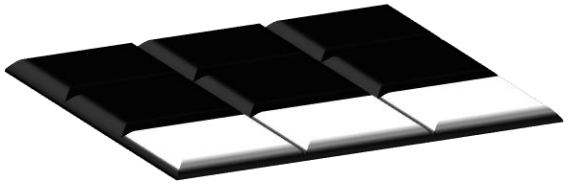
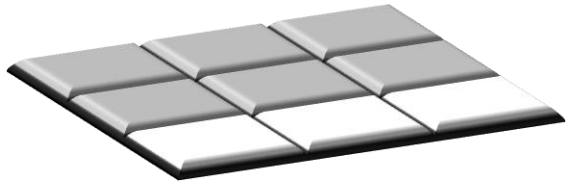


hitT



1 more ray

Visibility = (Visibility0+Visibility1)/2

Neighborhood of pixel

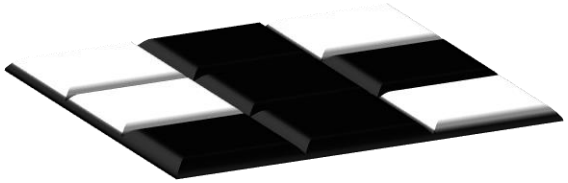
DXR SHADERS

Adaptive raytracing

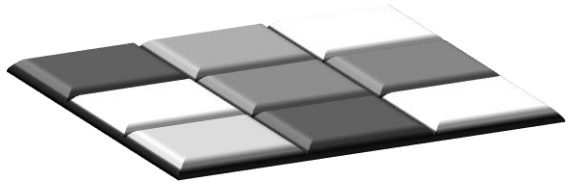
Phase 1 – Cast 1 ray per pixel

Phase 2 – Cast up to 2 more rays ‚where necessary‘

Visibility



hitT



Neighborhood of pixel

2 more rays

Visibility =
(Visibility0+Visibility1+Visibility2)/3

DXR SHADERS

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- Noise / random number generation
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- Translucency
- TAA and jittering

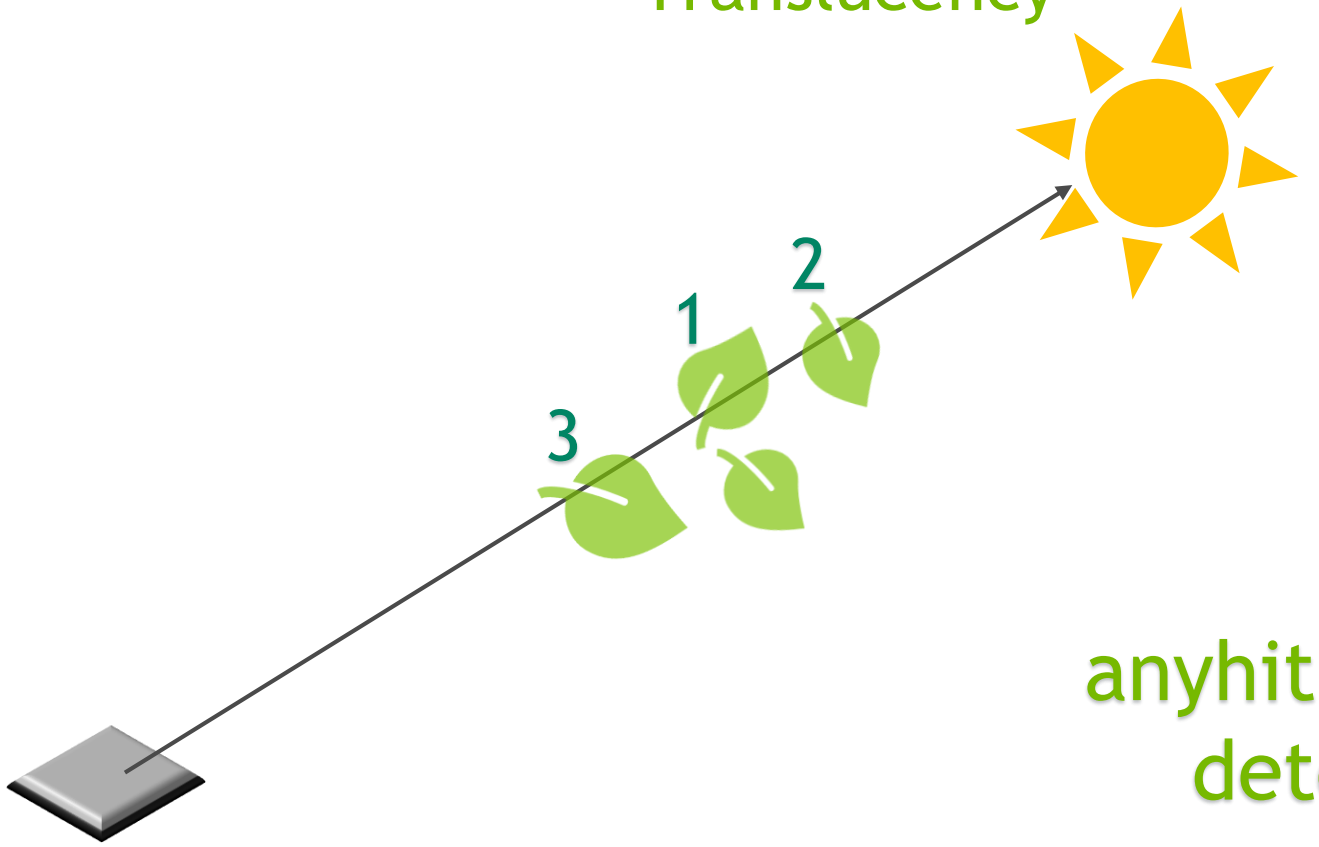
DXR SHADERS

Translucency

- Ultra DXR quality also features translucent shadows
- We support up to 3 layers of translucency
  - Mainly to keep performance at acceptable levels
- Translucency should be straightforward with DXR right?
  - Want to keep on using anyhit() instead of iterated closesthit()
  - Let’s look at the details …

DXR SHADERS

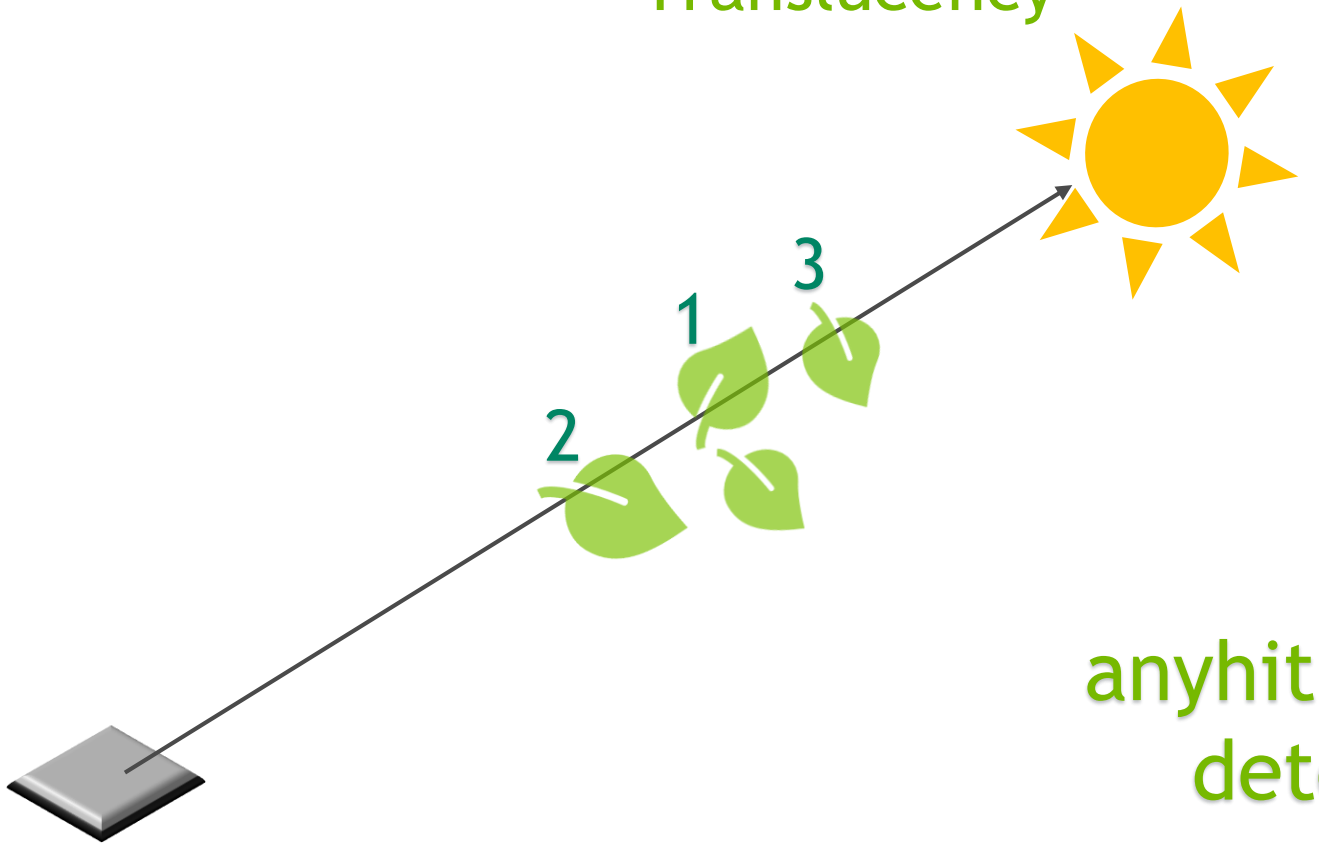
Translucency



anyhit() order non-deterministic

DXR SHADERS

Translucency



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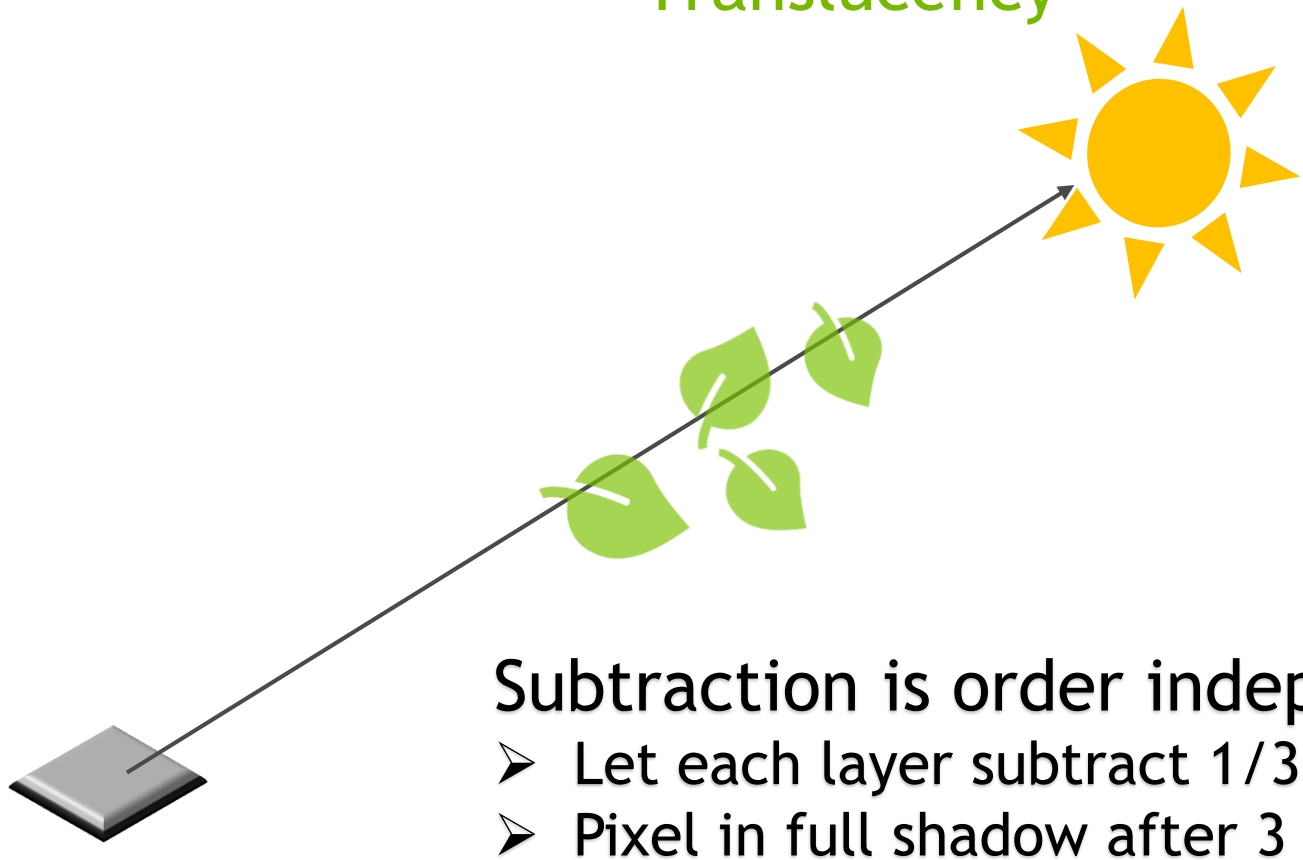
DXR SHADERS

Translucency



Subtraction is order independent:

- Let each layer subtract 1/3 of the light
- Pixel in full shadow after 3 order independent hits

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DXR SHADERS

Translucency

```
void TranslucentAnyHit(…)
{
      float alpha = GetHitAlpha(bary, PrimID);

      if( alpha >= g_fAlphaThreshold )
            payload.visibility -= ( 1.0f / 3.0f );

      if( payload.visibility < 0.01f ) {
            payload.visibility = 0.0f;
            AcceptHitAndEndSearch();
      }
      else
            IgnoreHit();
}
```

Opaque raytraced shadows

Translucent raytraced shadows

DXR SHADERS

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- Noise / random number generation
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DXR SHADERS

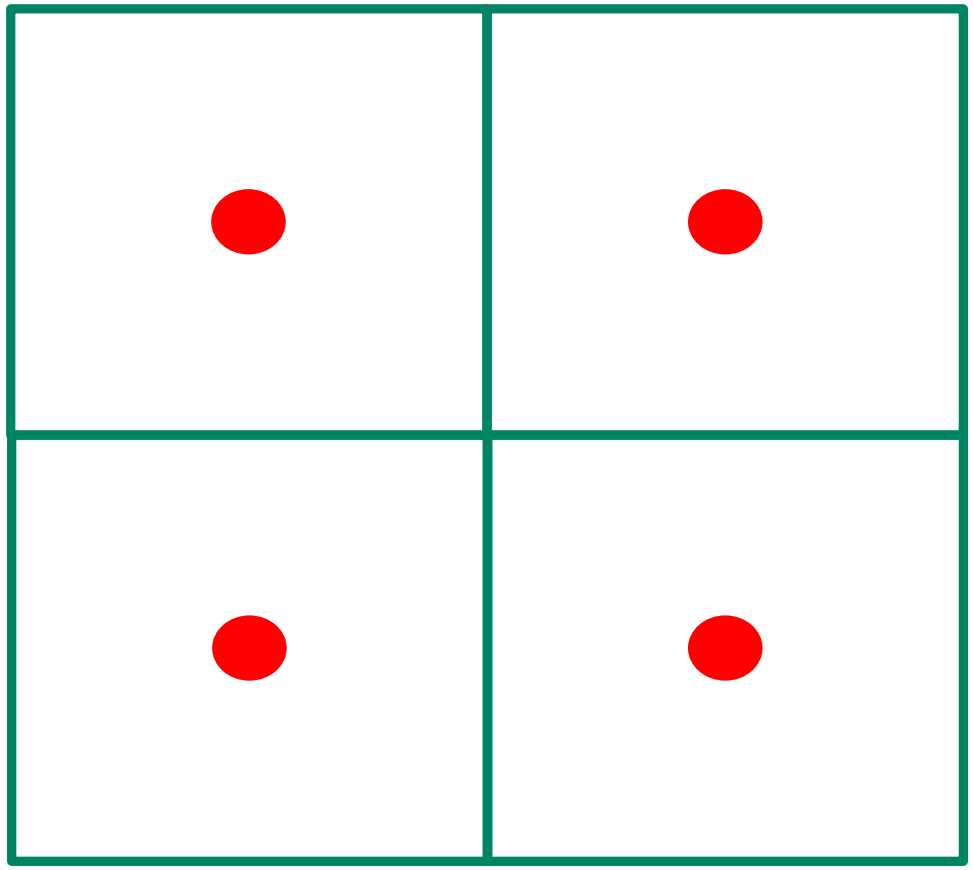
TAA + Jittering

- Like many games SotTR uses jittered TAA
- Each frame adds a ‘random’ subpixel offset to all geometry
- Surprisingly this creates problems with flickering shadows!

DXR SHADERS

TAA + Jittering

a 2x2 pixel grid

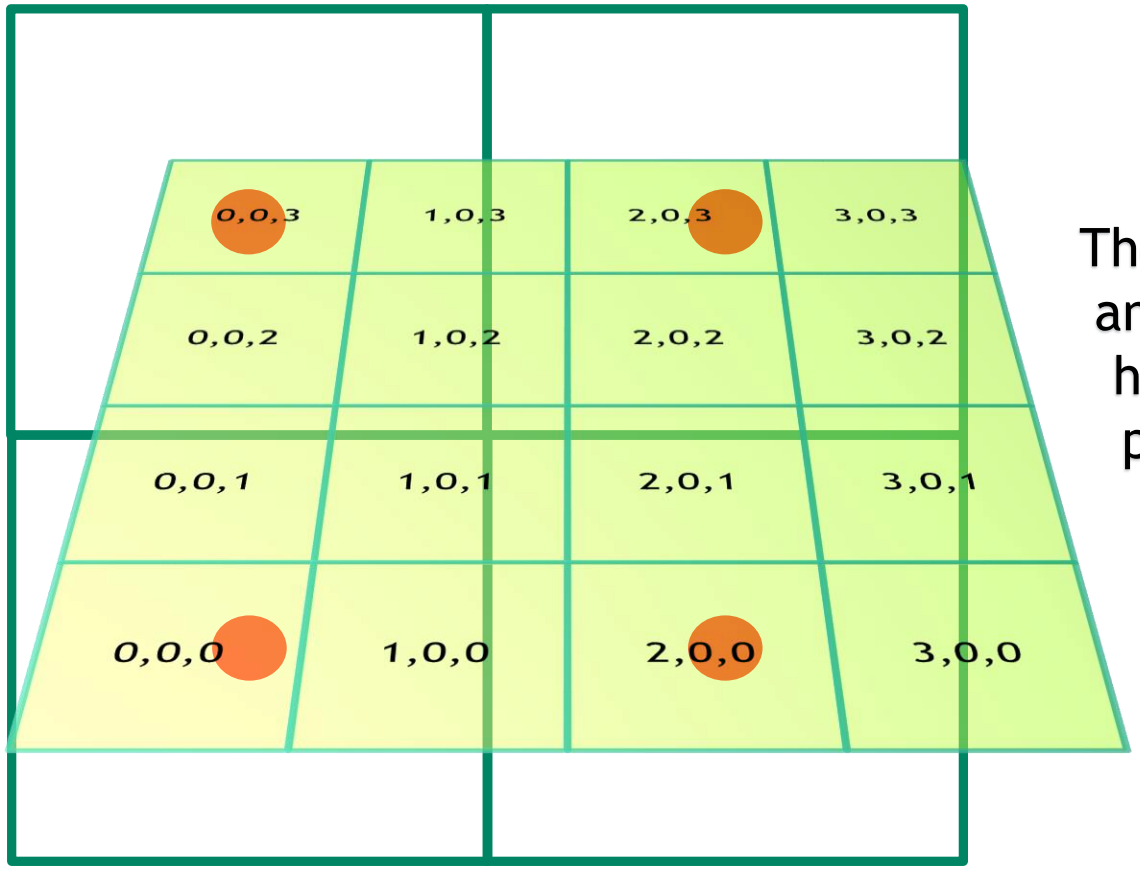


- The red dots are the pixel centers
- This is where rasterized geometry is sampled

DXR SHADERS

TAA + Jittering

Rasterizing a 3D quadrangle

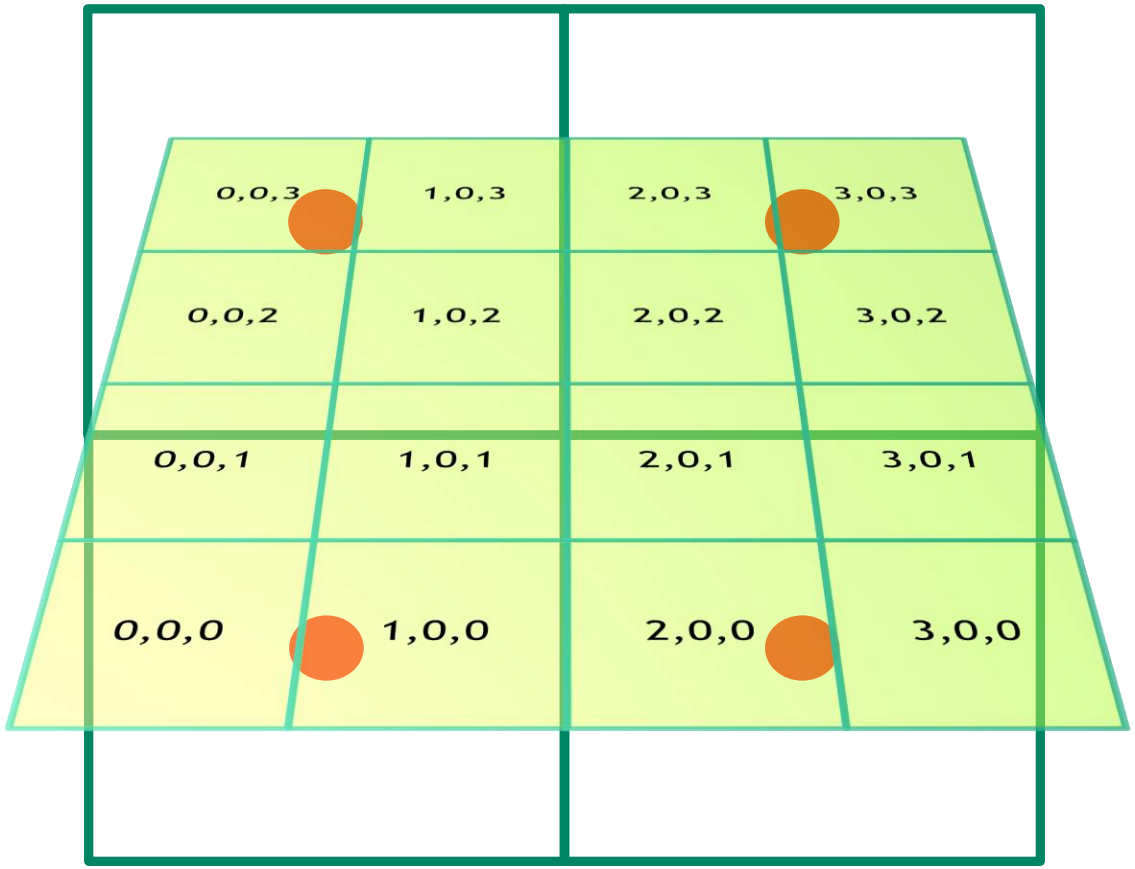


The intermediate positions and the grid are shown to help understand how 3D positions change across the quad

DXR SHADERS

TAA + Jittering

Jitter somewhat …



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DXR SHADERS

TAA + Jittering

- Jittering changes the WS position that is sampled at pixel centers
  - It also changes the depth values at the pixel centers
- Jittering changes the reconstructed world space positions

Shadow ray origins jitter as well

DXR SHADERS

TAA + Jittering

Jittered ray positions are not problematic in general, but:

- We typically shoot only one ray per pixel
  - Which is equivalent to ‘point sampling‘ of the visibility signal
- Large areas of flat ground are problematic
  - Vertical jittering leads to large differences in WS positions
  - Also visible with shadow maps but less because of SM filtering


53 FPS

DXR SHADERS

TAA + Jittering

Solutions:

1. Currently we render an extra depth pass without jittering
    - Use non-jittered depth to reconstruct WS ray origins
2. Future: Render ddx/ddy(1/z_buffer_depth) with depth pass
    - Reconstruct non-jittered depth
    - Use non-jittered depth to construct WS ray origins
    - 1/z-buffer-depth is linear in screen space

AGENDA

Shadow of the Tomb Raider

Why ray traced shadows?

DXR shaders (ray generation)

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DXR acceleration structure

Integration in render pipeline

Results

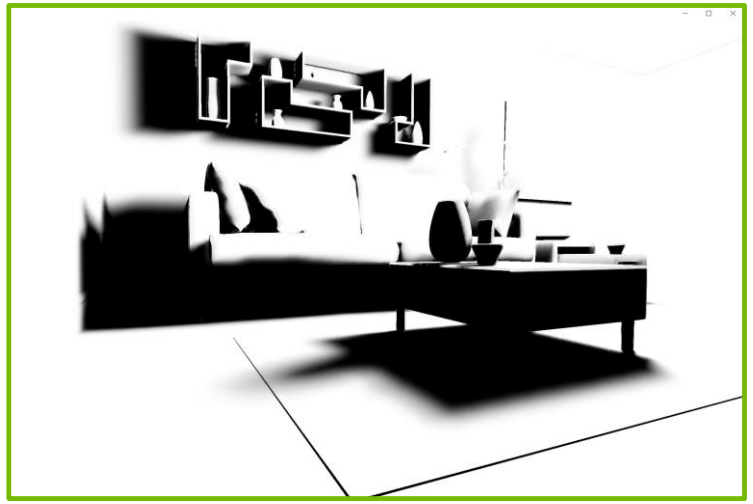
Future work

INPUT / OUTPUT

Light
Desc
Params

GameWorks Spatial
Denoiser

Edward Liu &
Jon Story



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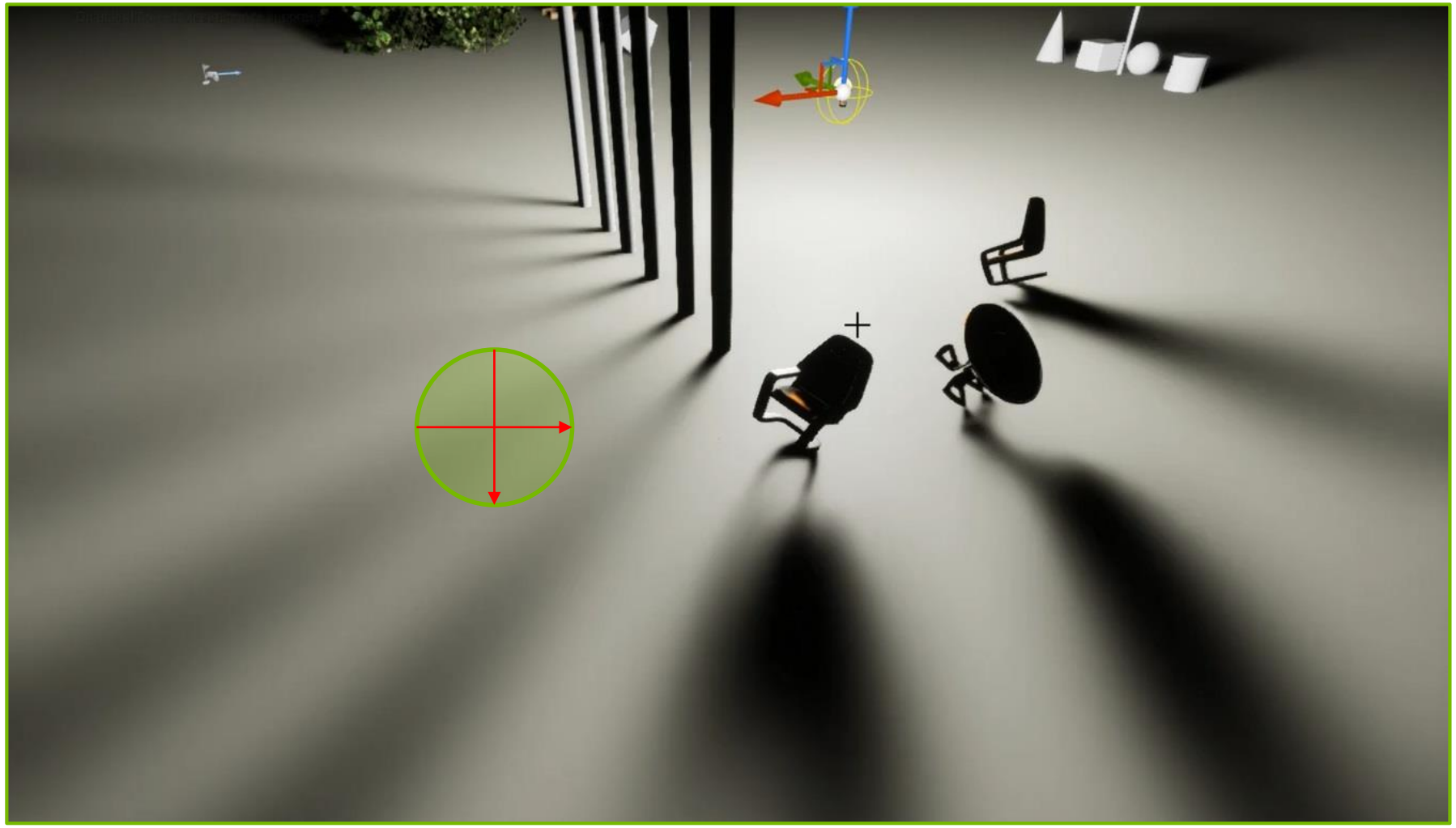
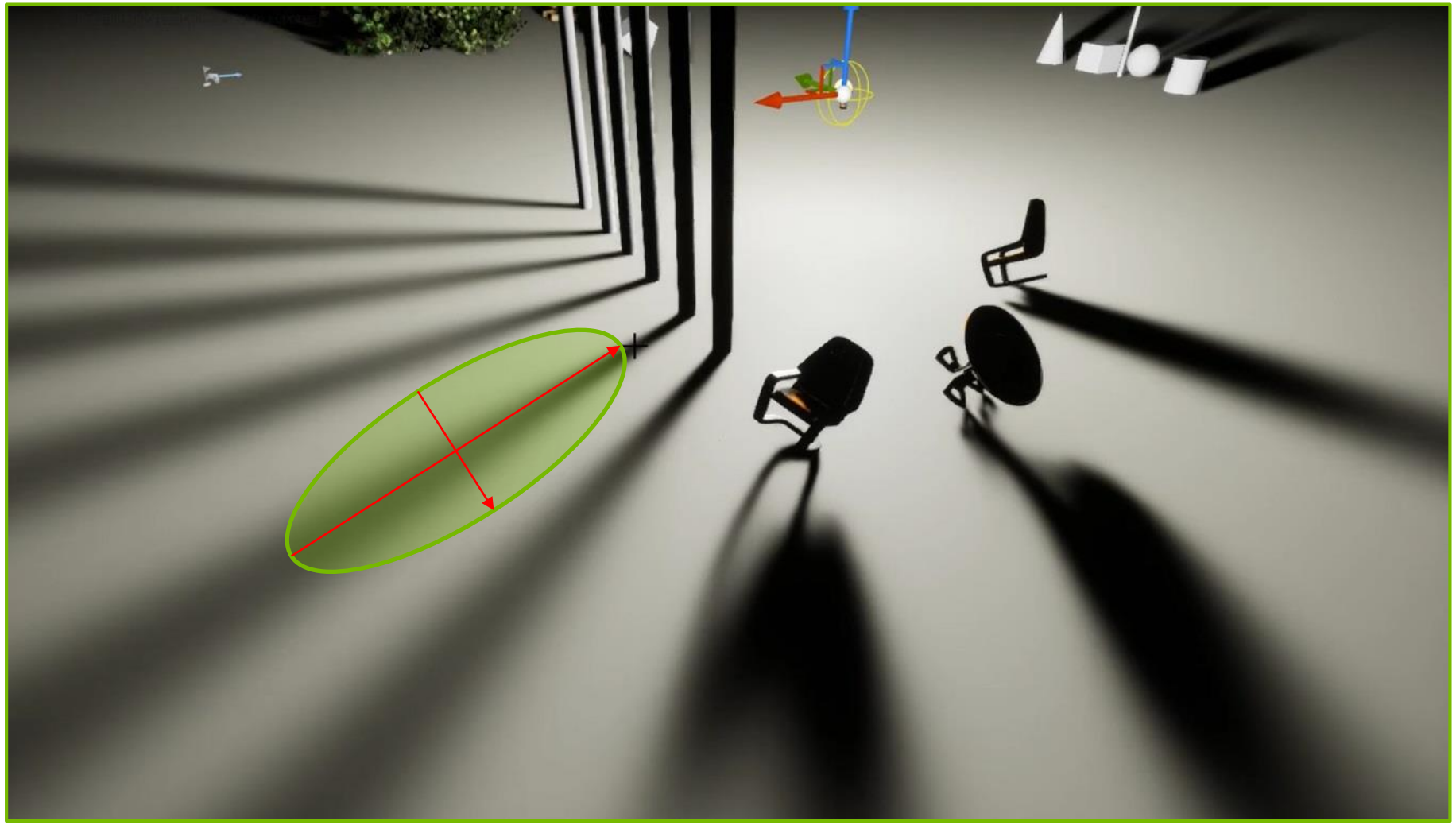
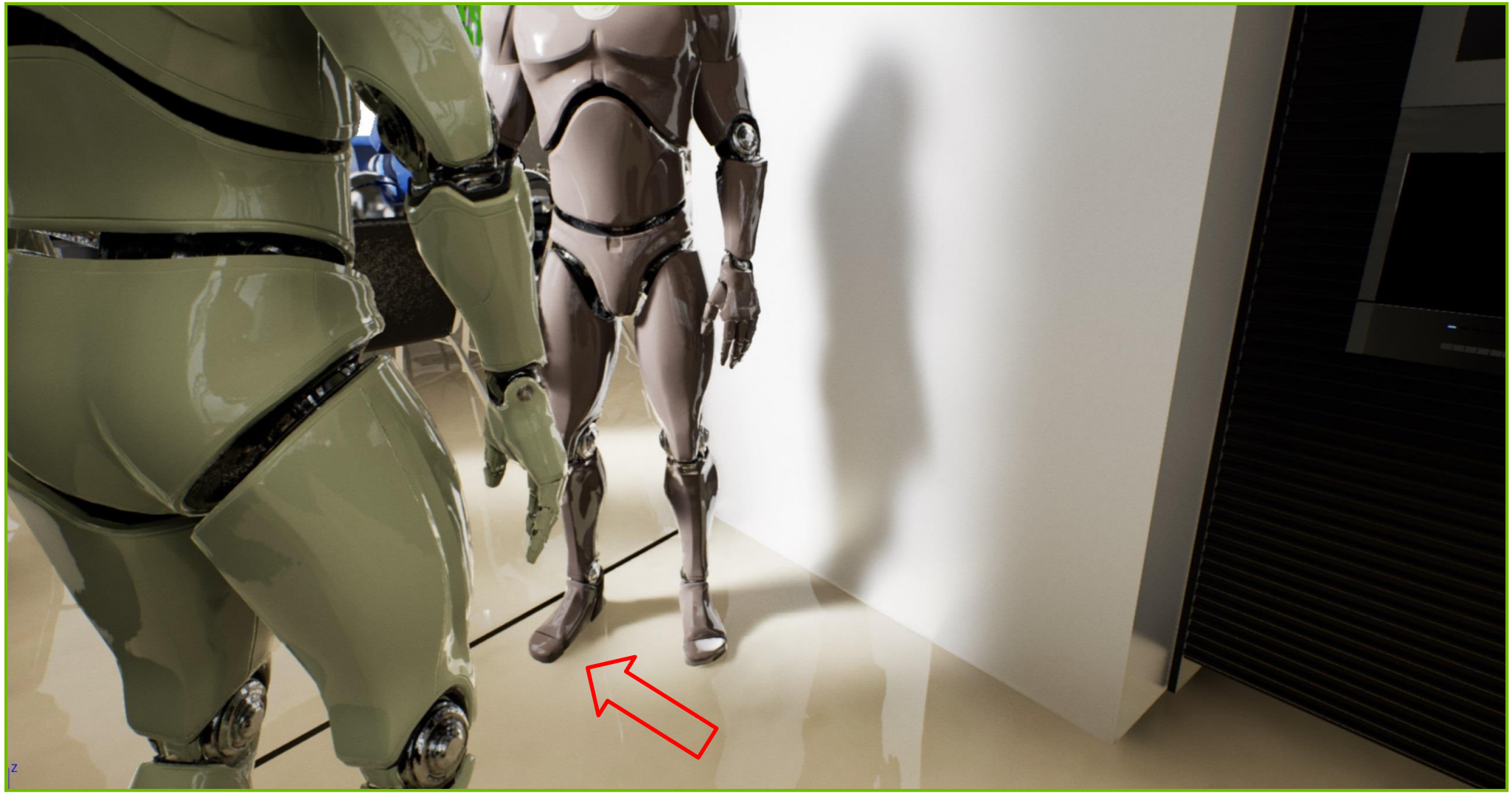
ISOTROPIC KERNEL



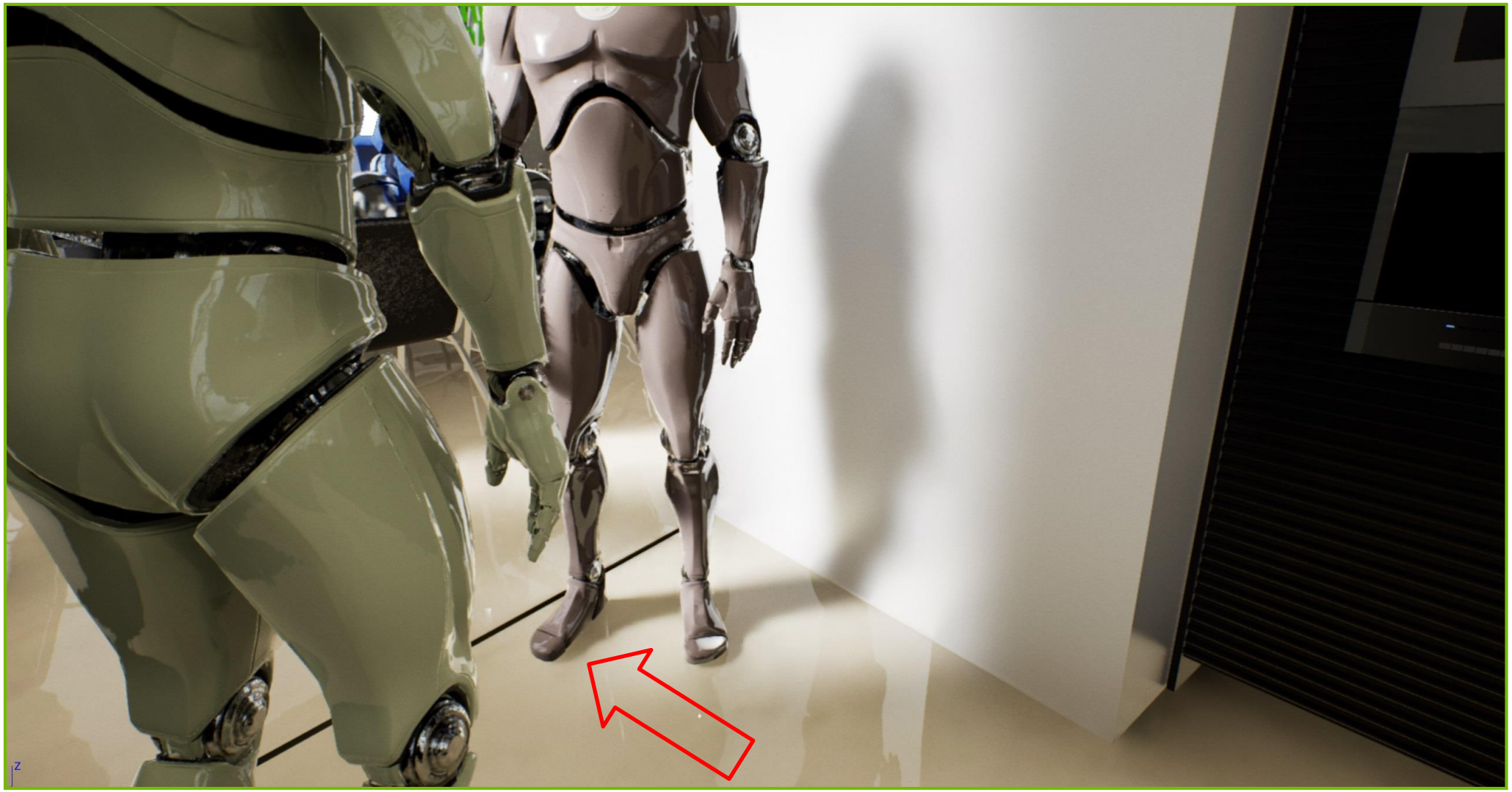
ANISOTROPIC KERNEL



OVERLAPPING PENUMBRA #1

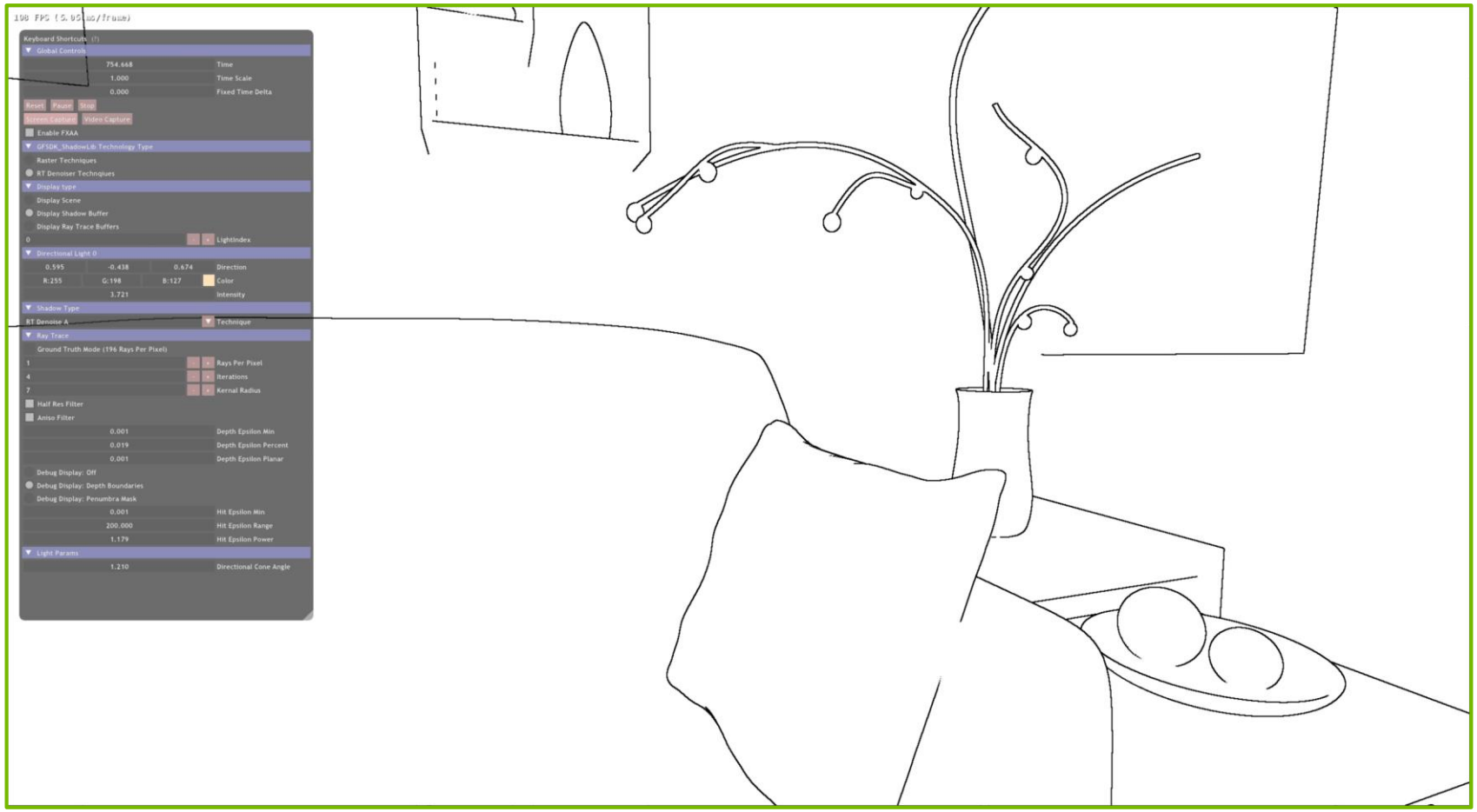


OVERLAPPING PENUMBRA #2



BLEEDING ARTIFACTS

CUSTOMIZED BOUNDARY DETECTION



COULD WE DO LESS WORK?

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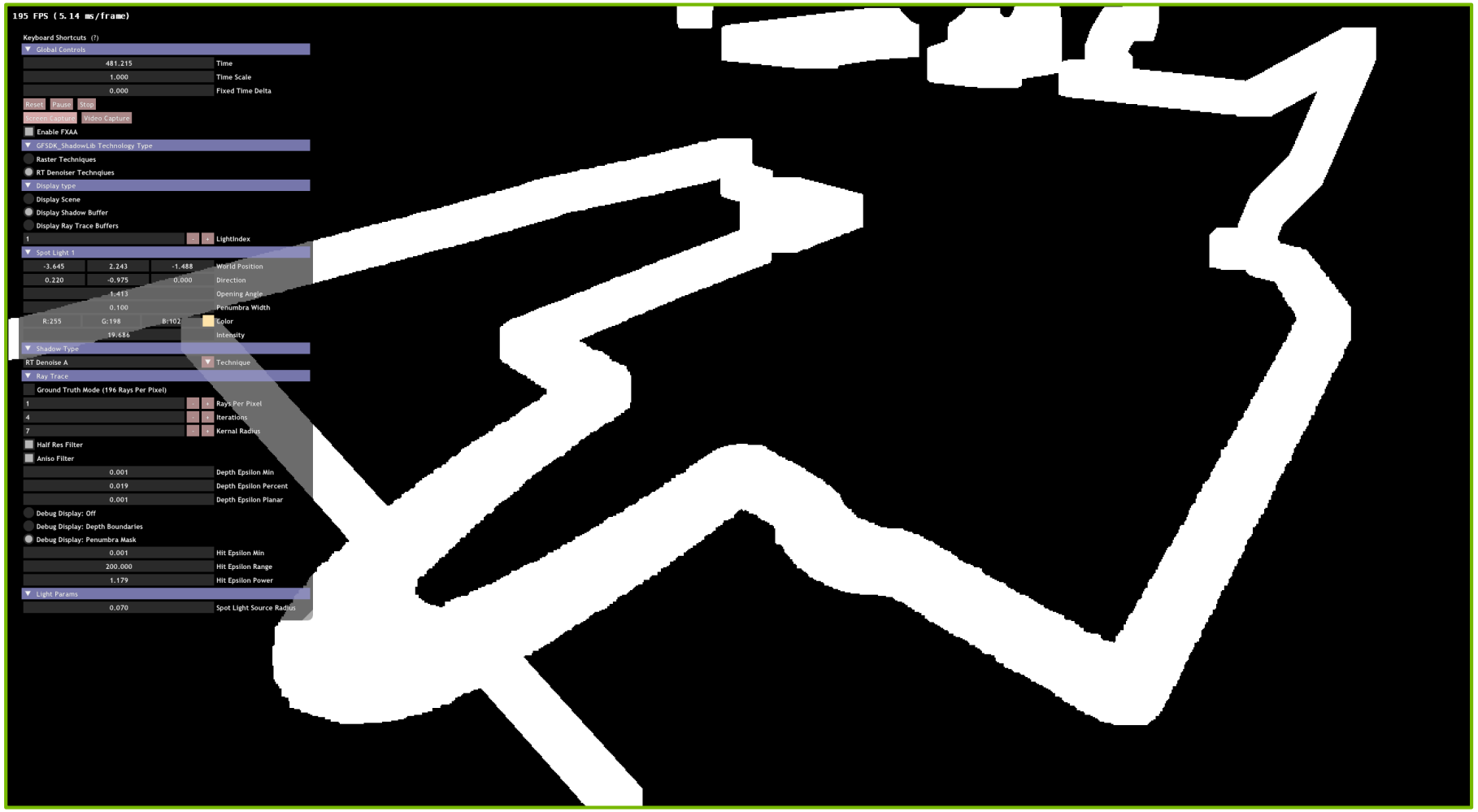
PENUMBRA MASK



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IMPORTANT FEATURES

- Half resolution denoising
  - Drastically improves performance
  - SOTTR uses this mode for ALL light types
- MSAA input Depth & Normal buffers supported
  - Still only requires single sample Visibility & HitT buffers
  - Produces MSAA shadow mask
- Sub-viewports supported for local light sources
  - Just need to figure out screen area affected

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BLAS

“a mesh”

- Vertex and index buffers for each geometry
- Straightforward for static geometry

```
struct D3D12_RAYTRACING_GEOMETRY_TRIANGLES_DESC
{
    DXGI_FORMAT IndexFormat;
    DXGI_FORMAT VertexFormat;
    UINT IndexCount;
    UINT VertexCount;
    D3D12_GPU_VIRTUAL_ADDRESS IndexBuffer;
    D3D12_GPU_VIRTUAL_ADDRESS VertexBuffer;
}
```

BLAS

What about skinned objects and vertex animations?

- Each vertex needs to be fully transformed!
- Foundation Engine uses shader graphs
- Added a shader permutation in VS template for exporting a transformed vertex buffer
- Run a pass for all dynamic objects before building

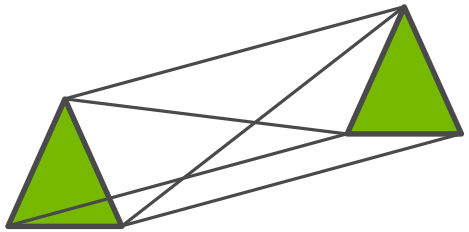
```
#if ExportVertexBuffer
            RWStructuredBuffer<float3> OutVertexBuffer;
#endif

VertexOutput main(
            in VertexInput vi,
            uint vertID : SV_VertexID)
{
            VertexOutput vo;

            %ShaderGraph%

#if ExportVertexBuffer
            OutVertexBuffer[vertID] = vo.OutPosition;
#endif

            return vo;
}
```

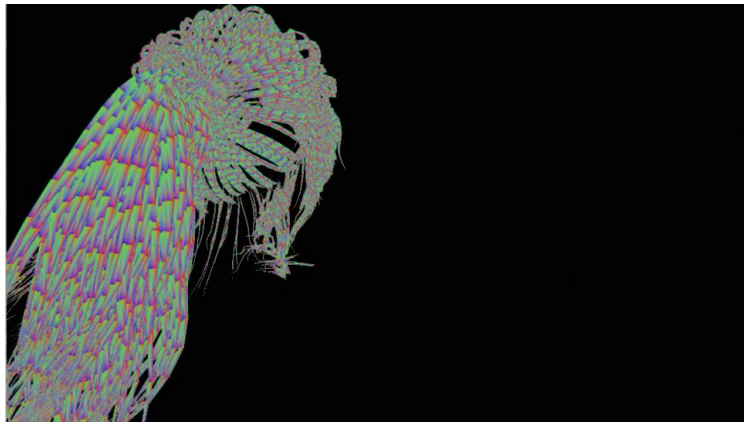
Skinning gone wrong: Inner demon ☺

BLAS

Lara's hair

- PureHair, an evolution of TressFX
  - Simulates control points
  - Renders strands of hair as camera facing quads
- Everything needs to be actual geometry in the AS
  - Make the simplest cylinder possible for every strand





BLAS
Rebuild/refit strategy

- Two modes of updating dynamic BLASes in DXR:
  - Rebuild, essentially “replacing” the old one (~100M tris/sec)
  - Refit, for “small” model changes (~1000M tris/sec, 10x as fast!)
    - Catch: ray trace performance might degrade!
    - Top refitting throughput only for large enough workloads
- We chose to always refit BLAS unless # vertices change

TLAS

"A scene"

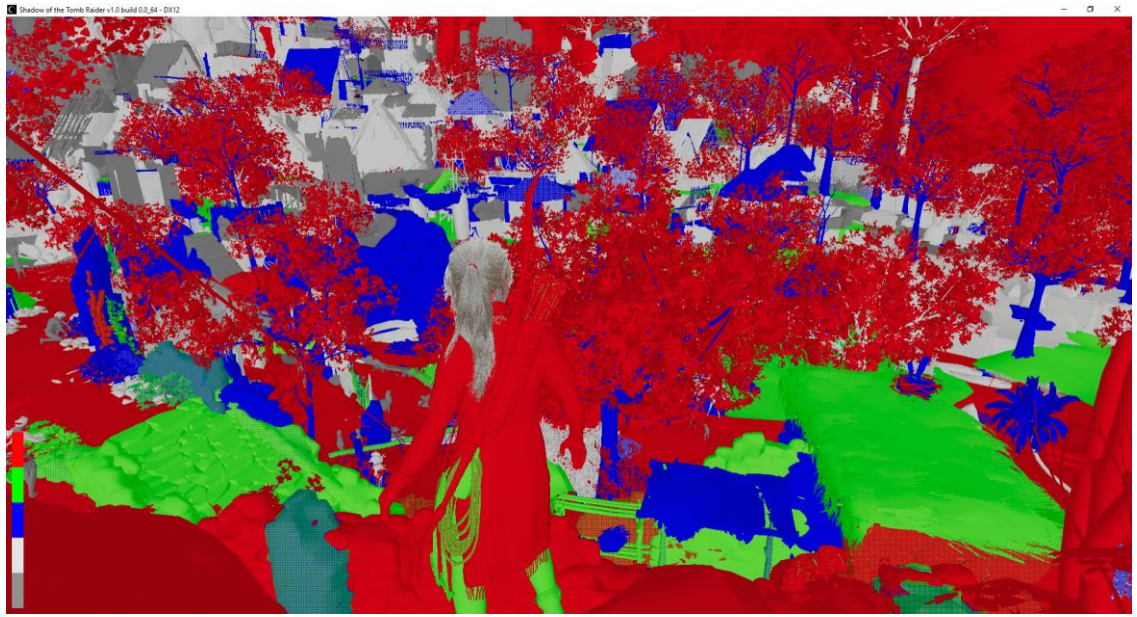
- Static BLASes can be instanced
- Always rebuilding TLAS seems to be fast enough (<1ms)

```
struct
D3D12_BUILD_RAYTRACING_ACCELERATION_STRUCTURE_INPUTS
{
    UINT NumDescs;
    D3D12_GPU_VIRTUAL_ADDRESS InstanceDescs;
}
```

ACCELERATION STRUCTURE

About LODs of meshes

- Every LOD level is stored in a separate BLAS
- Using LOD 0 for everything caused self-shadowing artifacts!
- Just use the same LOD we use for rendering
- What about LOD fading?
  - Use “most visible” LOD



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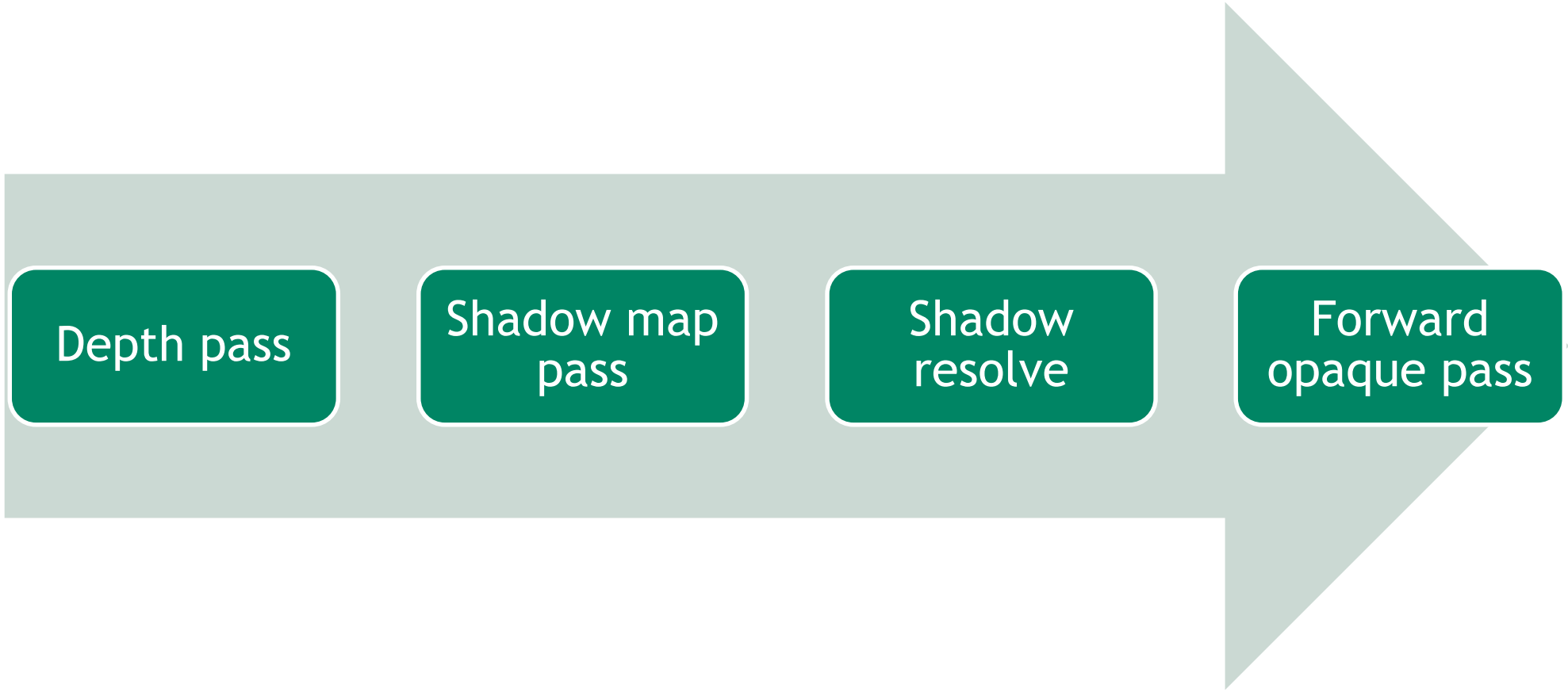
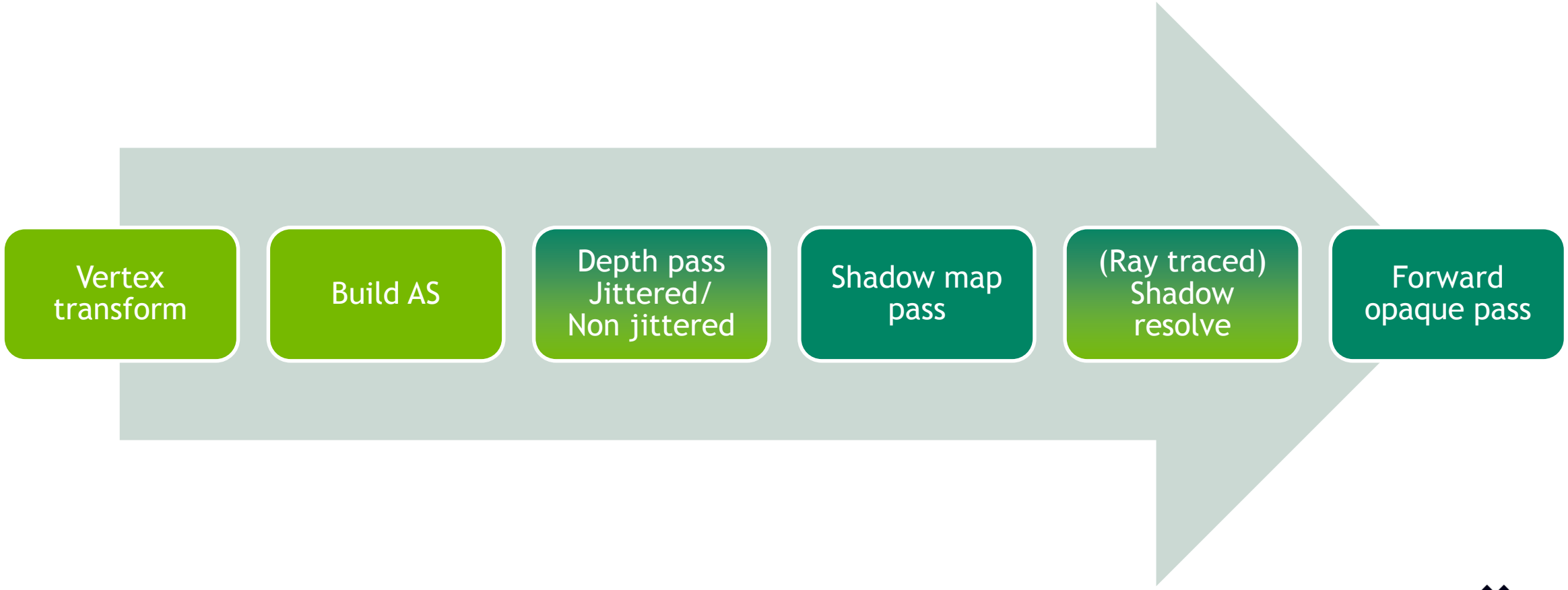
RENDER PIPELINE

Forward+ renderer



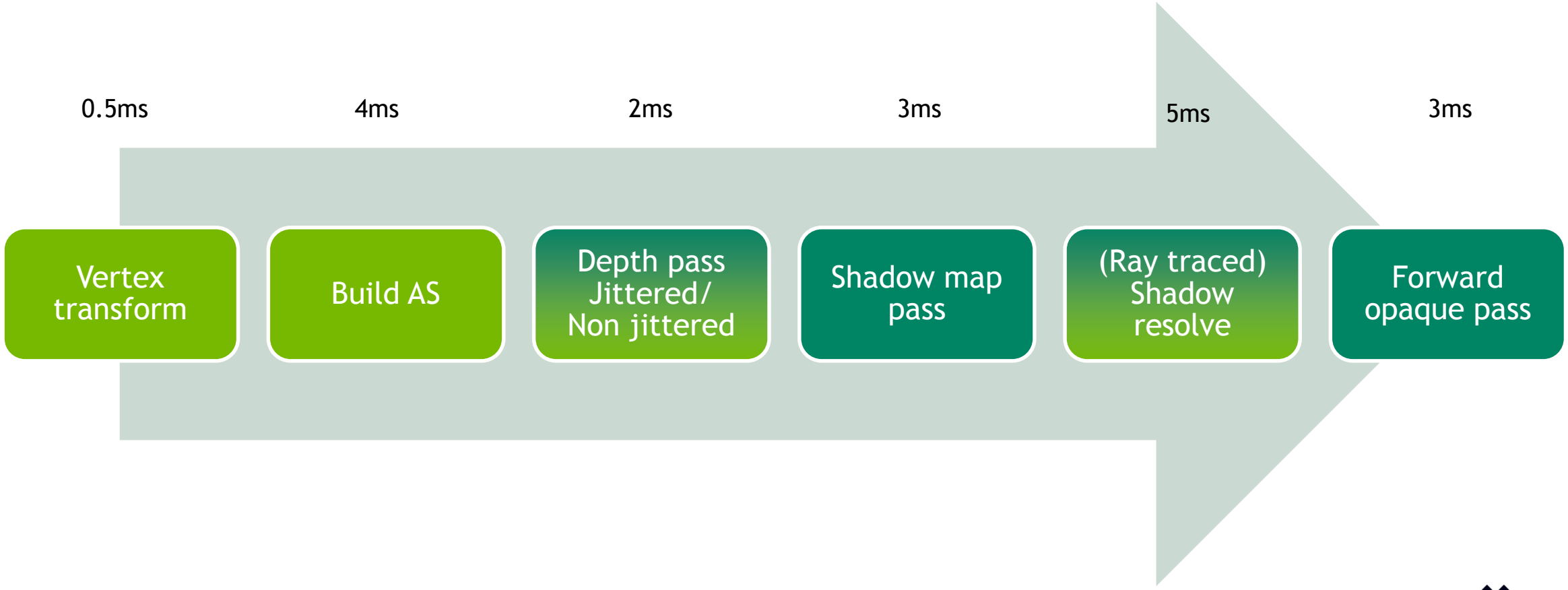
RENDER PIPELINE

Now with ray traced shadows!

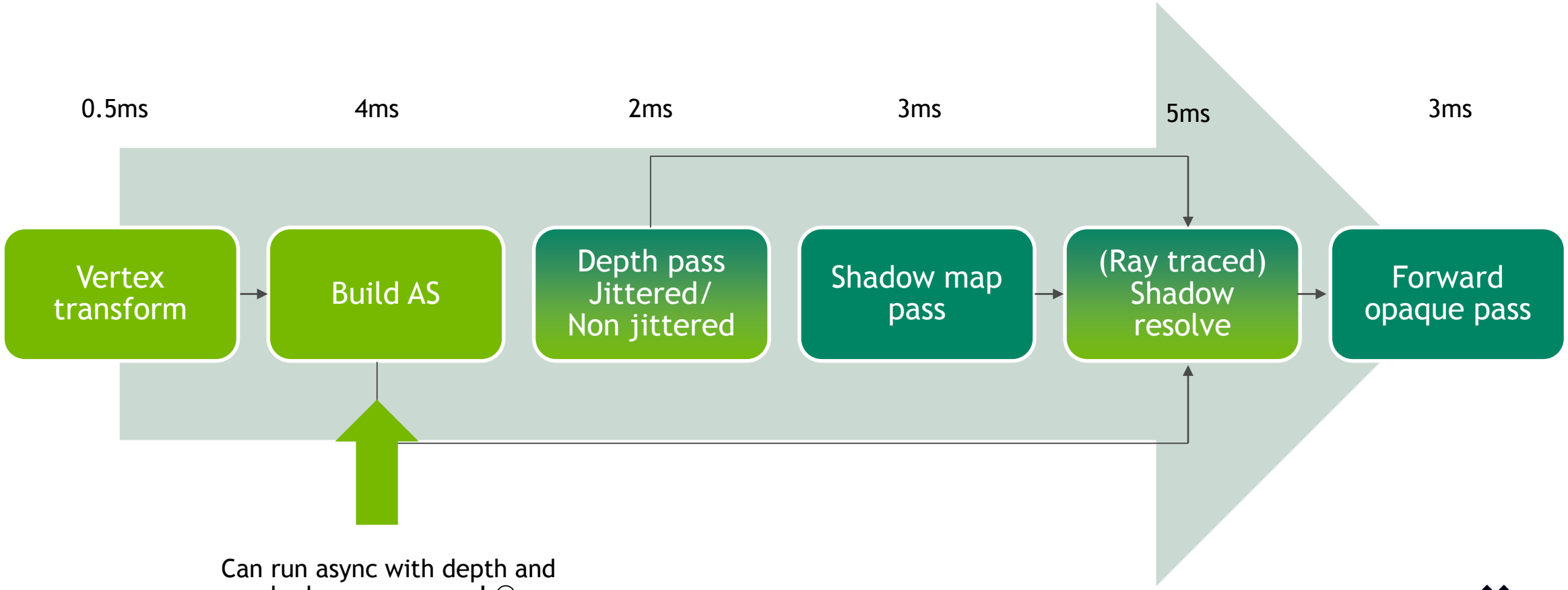


RENDER PIPELINE

Now with ray tracing!

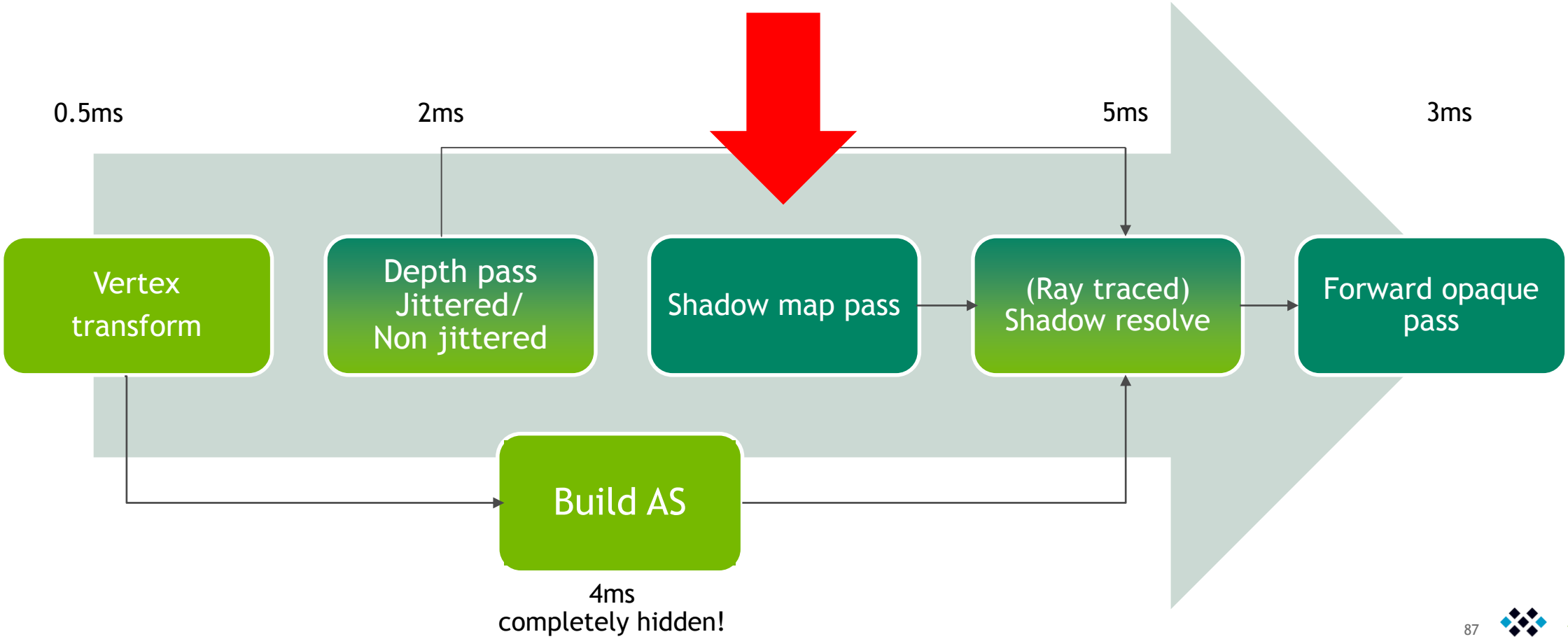


RENDER PIPELINE



RENDER PIPELINE

Async compute



WHY DO WE STILL NEED SHADOW MAPPING?

Translucent rendering

- Translucent rendering has no depth write
- Can’t use shadow resolve pass!
- We cannot shoot rays from pixel shaders

WHY DO WE STILL NEED SHADOW MAPPING?

Performance!

- Updating entire scene full of dynamic objects costs up to 20ms of BLAS refits ☹
- AS culling using existing shadow map culling

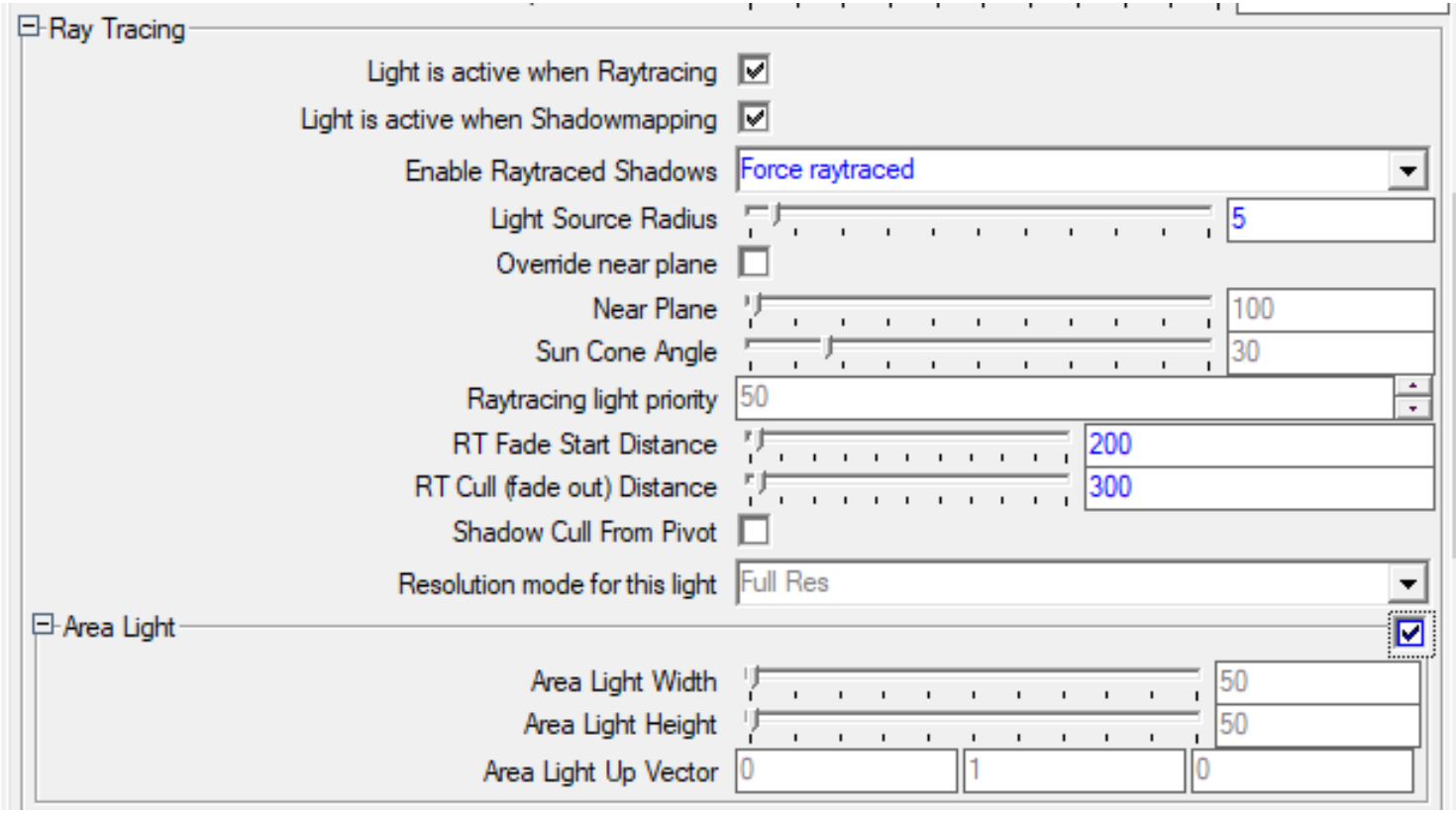
WHY DO WE STILL NEED SHADOW MAPPING?

Performance!

- For directional lights:
  - Replace only nearest cascades with ray traced shadows
- For local lights:
  - Distance based fade to shadow map
- How do we choose these distances?

ARTIST TOOLS

Let lighting artists decide!



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AGENDA

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No point light shadows

Raytraced point light shadows

Shadow mapped area light shadows

Raytraced area light shadows

Shadow mapped sun light shadows

Raytraced sun light shadows

AGENDA

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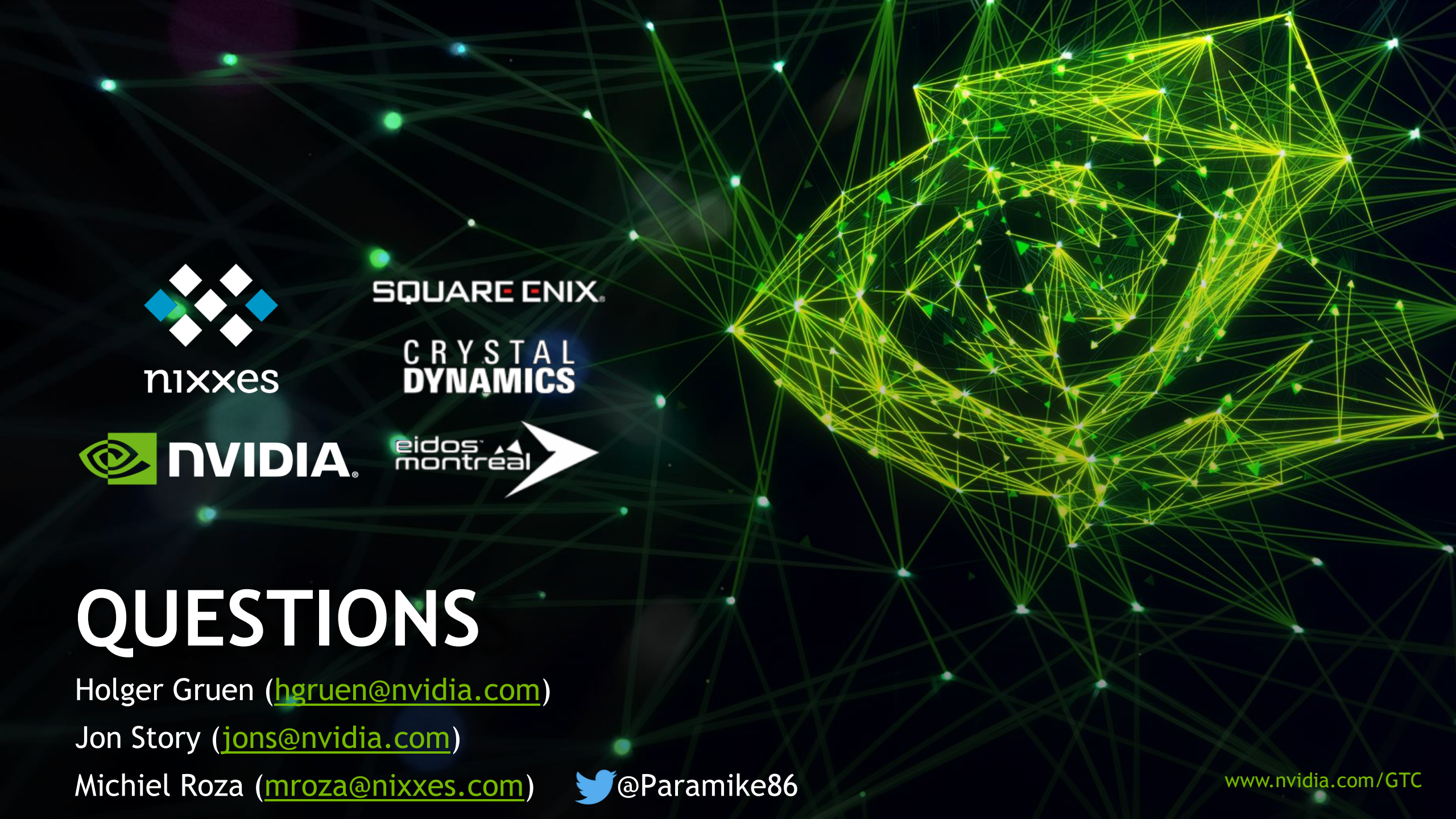
FUTURE WORK

- Reconstruct non-jittered depth
- Ray traced shadows on translucent geometry
- Tessellation
- Content authoring with ray tracing in mind
- Use vertex transform pass for rasterization as well
- GI / Reflections / AO / … ?



QUESTIONS

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