Ray Tracing in Games with NVIDIA RTX

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Booth #223 - South Hall
www.nvidia.com/GDC
Agenda

Introduction to Ray Tracing for Games

RTX, DXR and GameWorks

Real-time Ray Tracing and Denoising

Path Tracing and Light Baking

Integrating Ray Tracing into your engine
Introduction to Ray Tracing for Games
Ray Tracing 101

What is Ray Tracing

- Ray Tracing: a primitive to query the intersections of rays against some geometry

Hit ‘t’ = ~1.8
Ray Tracing 101

Applications in Games

- Higher quality in-game rendering
  - Reflections
  - Ambient Occlusion
  - Shadows

- Content Creation Workflows
  - Light baking
  - Cinematic rendering
  - Path traced reference

- Non-rendering applications
  - Audio simulation in VR (VRWorks Audio)
  - Physics / Collision detection
  - AI
Ray Tracing 101

Applications in Games

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Ray Tracing 101

Rendering

- Commonly used to solve the **rendering equation** with Monte Carlo sampling

\[
L(\omega_o) = L_e(\omega_o) + \int_\delta L(\omega_i)f(\omega_o, \omega_i)|\omega_i \cdot n|d\omega_i
\]

- Natural solution for Shadows, AO, Reflections, Light Baking, Film Rendering
Ray Tracing 101

Ray Tracing in Rendering Today

- Similar primitives used today in games in real-time in various forms:
  - Screen space ray tracing, distance field ray tracing, voxel cone tracing

- In this talk: ray tracing against full scene geometry (mostly triangles)

- Rendering with Ray Tracing usually requires many samples for high quality results
  - From a few hundred to a few thousand
  - Depending on the complexity of the integrand (scene)
Ray Traced Shadows
Ray Traced Ambient Occlusion
Ray Traced Reflections
Ray Tracing 101

- 100s of samples per pixel are not practical in real time
- Small number of rays per pixel possible on current HW

- Is that useful enough?
Ray Tracing 101

- 100s of samples per pixel are not practical in real time
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- Is that useful enough?

- Previous images generated with 1-2 samples per pixel + real-time denoising
- Yes: high quality results possible with few samples per pixel + denoising
RTX, DXR and GameWorks
NVIDIA RTX & DirectX Raytracing (DXR)

Context

- NVIDIA® RTX™: ray-tracing technology for Volta GPUs
- The result of a decade of GPU ray tracing R&D at NVIDIA
- Exposed via Microsoft’s new DirectX Raytracing API (DXR) for DirectX 12
- New pipeline: the Ray Tracing Pipeline
RTX & DXR

Benefits

- Powerful and flexible programming model, similar to NVIDIA OptiX
- Easy to write efficient ray tracing algorithms
- DXR makes it easy to integrate into engines that already use DirectX 12
- DXR provides IHV-agnostic abstraction
- RTX provides an efficient implementation on NVIDIA Volta GPUs
- RTX on Volta delivers performance needed for real-time ray tracing
- For more DXR details see Matt Sandy’s talk at 3:30 pm, [http://aka.ms/DXR](http://aka.ms/DXR) and NVIDIA blog
GameWorks Ray Tracing

More context

- GameWorks: tools, simulation and rendering technology for developers

- Announcing GameWorks Ray Tracing Denoising modules

- Ray Traced Shadows, Ambient Occlusion and Reflections Denoising

- Available soon
Related Work at GDC

Be sure to check these out too

- Advanced Graphics Day (Monday): Microsoft, Futuremark and Remedy
- Epic-NVIDIA-ILMxLAB Reflections demo earlier today
- Additional talks later today in this room: NV Research, EA SEED, EA Frostbite
- Talk by Microsoft + EA about future of DirectX (DXR)
This Talk

What to expect

- A showcase of possibilities enabled by real-time ray tracing with RTX
- Details about NVIDIA’s new GameWorks Ray Tracing Denoising modules
- Our goal: inspire you to start experimenting with real-time ray tracing
Real-Time Ray Tracing and Denoising
Source of Noise in Ray Tracing

- The rendering equation is solved with Monte Carlo sampling

\[
L(\omega_o) = \int_\delta L(\omega_i)f(\omega_o, \omega_i)|\omega_i \cdot n|d\omega_i = \sum_{i=0}^{n} L(\omega_i)f(\omega_o, \omega_i)|\omega_i \cdot n|/p(\omega_i)
\]

- Every term in the estimator is a complicated function over the hemisphere
  - Incoming radiance, visibility, BRDF, and sampling Pdf
- Insufficient sampling leads to high variance in the estimator
Previous Denoising Work

- Very active area of research
  - Spatiotemporal Variance-Guided Filtering: Real-Time Reconstruction for Path-Traced Global Illumination [Schied, et al. 17]
  - Interactive Reconstruction of Monte Carlo Image Sequences using a Recurrent Denoising Autoencoder [CHAITANYA, el al. 17]
  - Multiple Axis-Aligned Filters for Rendering of Combined Distribution Effects [Wu, et al. 17]
  - Kernel-predicting Convolutional Networks for Denoising Monte Carlo Renderings [Bako, et al. 17]
  - ... And many others

- Also products like NVIDIA OptiX 5.0 AI Denoiser
Previous Denoising Work

- Input often contains 10s or hundreds of samples
  - Or rely on temporal reprojection (ghosting issue without correct motion vectors)
- Denoising cost from ~100ms to minutes
- Noisy primary visibility samples (DoF, Motion blur)
- Results often really close to ground truth, measured in rMSE
Real-Time Denoising Requirement

- Input image with extremely low sample count
  - We target 1 sample per pixel
- Ghosting free, temporally stable
- Denoising budget of ~1 ms for 1080p target resolution on gaming class GPU
- Perceptually close to ground truth, able to preserve:
  - physically correct contact hardening
  - Elongation and anisotropy
- Smooth G-Buffer (i.e.: no DOF, or motion blur, as common in film rendering)
Denoiser Design Choices

Many options

- Image space vs. Lightmap space vs. Path space vs. Light field space
- Temporal / history data vs. single-frame
- Image data vs. Scene data: ray hit distance, surface roughness, normal, light position, size etc.
- Denoising of individual terms separately vs. denoising all the lighting at once
- AI based vs. hand-crafted
State of the Art Real-Time Denoising

“One sample per pixel can achieve a lot!”

- Exciting results with glossy reflections, area light soft shadows, and AO
- Effect-specific denoising, using scene information to estimate optimal filter footprint
- State of the art quality at extremely low sample count
  - Works well with even 1spp
  - No temporal reprojection involved ➔ ghosting/lagging free
Ray Traced Shadows, 1spp Denoised
Ray Traced Ambient Occlusion, 2spp Denoised
Ray Traced Reflections, 1spp Denoised
RTX Demo Video for slides 31-70:
https://www.youtube.com/watch?v=tjf-1BxpR9c
Ray Traced Area Light Shadows and Denoising
Ray Traced Area Light Soft Shadow

Why Ray Traced Shadows?

- More physically correct soft shadow visuals
  - Higher quality contact hardening even for really large light source
    - Not possible with shadow mapping based algorithms
  - More accurate geometry than character capsule shadows
  - Supports non-rigid motion (skinning, etc) unlike Distance Field Shadows
  - Can be combined with analytical area lighting

- Eliminate common shadow mapping artifacts:
  - Sampling rate mismatch, shadow acne, peter panning, CSM seams, etc
Soft Shadows with 1spp
Soft Shadows Ground Truth
Shadow Mapping
Area Light Soft Shadow Denoising

Denoiser Overview

- Denoising only applied to visibility term (split sum approximation)
  
  \[ L(\omega_0) = \int_\delta f(\omega_o, \omega_i) L_d(\omega_i) V(\omega_i) |\omega_i \cdot n| d\omega_i \approx \int_\delta V(\omega_i) d\omega_i \int_\delta f(\omega_o, \omega_i) L_d(\omega_i) |\omega_i \cdot n| d\omega_i \]

  \[ \text{Denoised!} \quad \text{Analytical Approx.} \]

- Per light source denoising
- Inputs: Hit distance, Scene depth, Normal, Light size and direction
- Separated cross bilateral filter with variable filter radius and weights
- Different denoisers for radial lights, directional lights and rectangular lights
- Output: filtered visibility term
Ray Traced Ambient Occlusion and Denoising
Ray Traced Ambient Occlusion

Why Ray Tracing?

- Higher quality results compared with existing techniques
  - Physically correct ambient occlusion
  - SSAO leaves ‘dark halo’ around depth discontinuities
  - Screen Space techniques miss occlusion from geometry that is not visible:
    - Off screen boundaries
    - Behind the camera
    - Surfaces close to parallel to the view vector (e.g.: tables, chairs, very common)
Ambient Occlusion 2spp Denoised
Ambient Occlusion with 2spp
**Denoising Ray Traced Ambient Occlusion**

**Denoiser Overview**

- Separated cross bilateral filter
  - Estimate filter kernel size in world space based on hit $T$
- Using ideas from ‘Axis-Aligned Filtering for Interactive Physically-Based Diffuse Indirect Lighting’ [Mehta, el al. 13]
- Larger kernel size in open region, smaller in contact region
  - Visibility changes slower in open region, thus can share more spatially
  - Preserve contact darkening
- At 1spp, achieved smooth far field occlusion
- With 2-4 spp, can recover detailed occlusion in contact region
Ray Traced Reflections and Denoising
Ray Traced Reflections + Denoising

vs. Screen Space Reflections

- Screen Space Ray Traced Reflections
  - Missing data due to off screen ray hits
  - Incorrect specular on reflections
    - Specular of primary shading point being reused was computed with view direction instead of reflected ray direction
Ray Traced Reflections
Ray Traced Reflections + Denoising

vs. pre-integrated light probes

- Pre-integrated light probes / environment maps
  - Usually static. Dynamic is rarely practical
  - Can be very wrong if not placed correctly
  - Roughness range discretized into fixed number of levels
  - Pre-integration with view vector perpendicular to receiver plane misses NDF anisotropy
Ray Traced Reflections + Denoising

vs. Planar Reflections

- Planar reflections
  - Only works for planar surfaces
  - Does not scale to many of these
  - No correct glossy reflections
Glossy Reflections with 1spp. Roughness = 0.18
Glossy Reflections 1spp Denoised
Glossy Reflections Ground Truth
Stochastic Screen Space Reflections + Probe
Glossy Reflections Denoising

Denoiser overview

- Denoising applied only to the incoming radiance
  
  \[ L(\omega_o) = \int_\delta L(\omega_i) f(\omega_o, \omega_i) |\omega_i \cdot n| d\omega_i \approx \int_\delta L(\omega_i) d\omega_i \int_\delta f(\omega_o, \omega_i) |\omega_i \cdot n| d\omega_i \]

- Specular albedo included in pre-integration term so won’t be overblurred
- Denoising only the radiance term, no noise from BRDF sampling
- Cross bilateral filter with aniso kernel footprint estimated based on projecting the BRDF lobe footprint back to screen space
Limitations
of current denoising technology

- **Shadows** denoiser results can be of lower quality for overlapping penumbra from two occluders with very different distances from the receiver.
- **Reflections** denoiser is further from ground truth as roughness increases (e.g.: squared roughness > 0.4).
- **AO** denoiser may need at 2 or more rays to capture finer details.
- Expect to continue improving over time to match more closely ground truth with better performance.
Future Work

- Deep learning based denoisers
  - Using same input as these hand-crafted denoisers
  - Expect this could be the best solution

- Denoising all lighting component together to save time and memory

- Hybrid approaches combining screen space with world space tracing
Reference In-Engine Path Tracer
Path Traced Reference Image

Next Gen Rendering Work Flow

- Powerful tool to improve content creation pipeline
  - Render path traced image as target for tuning real-time rendering techniques
  - Material tuning, light probe placement, lighting setup, overall brightness...

- Extremely useful for rendering programmers too
  - Tuning and validating the look of real-time rendering algorithms
  - Adjusting shading of area lights
  - Tuning denoisers
  - Know what you are missing in your hacks
In-Engine Path Tracing
Easier today than it has ever been

- Powerful programming model in DXR abstracts all the complexity, making it easy to write light transport algorithms.
- RTX provides optimized implementations of Acceleration Structure build/update, as well as traversal and scheduling of ray tracing and shading.
- Ability to use HLSL means you can reuse much of your existing shading code.
- Physically based shading commonly used in game engines today makes building path tracer in game engine easier than it used to be.
In-Engine Path Tracing

What we did in UE4

- Experimental Path Tracer written by us as soon as DXR was integrated and working with ray traced reflections.
- Not production quality at this point
- Separate ray generation shader runs path tracing loop
- Simplified Pixel Shader that only evaluates the material graph, but no lighting
  - Output returned to path tracing ray gen shader via payload
  - Engine-generated material shaders can be used directly (except where using ddx/ddy)
In-Engine Path Tracing

What we did in UE4

- BRDF importance sampling on top of UE4’s shading model
- Light source sampling for all light types to do NEE
- Analytical ray-light intersection to support MIS initially
- Importance-sampled SkyLight cubemap
- Light culling when sampling from many light sources
DL Based Path Tracing Denoising

NVIDIA OptiX 5.0 AI Denoiser

- Integrated NVIDIA OptiX AI Denoiser, recently released in 5.0
- Improves quality of the rendered image from 0.8 ssim to 0.99 ssim (with respect to target reference image)
- Fast on Volta GPUs thanks to Tensor Cores
- Blend smoothly between noisy image and denoised image starting at some set number of iterations (depending on scene)
Light Baking
In-Engine Light Baking

- Leverages a lot of the same code written for a reference path tracer
- Different types of light baking
  - 2D Lightmaps
  - Volumetric lightmaps
  - Environment capture cubemaps
- Different modes of baking
  - Preview mode
  - Batch mode
Lightmap Baking Preview Mode

- Focus on updating only the lightmap texels contributing to the current image.
- Enables quick iteration for artists & lighters.
  - Adjust lights, move objects and see results instantly.
- Our experience:
  - Tried approach that launches path tracing work in lightmap space
  - In the end found it easier to get good results by path tracing in screen space while accumulating output into lightmap texels using NvInterlockedAddFp32 (via NVAPI)
  - Progressive lightmap computation, combined with smart temporal reuse and lightmap space denoising allows near real-time updates
Lightmap Baking Batch Mode

- Utilize one or more GPUs to bake all the lightmaps in a level until converged
- Can dispatch a ray generation shader 2D grid per lightmap texture, or per lightmap atlas
- Two ways to get to object space data at a lightmap texel:
  - Traditional: conservative rasterization of interpolated vertex attributes in lightmap space
  - New: ray tracing an Acceleration Structure built over the 2D lightmap UVs
- Each has pros and cons. New approach is convenient but loses benefits of conservative raster
Game Engine Ray Tracing Integration
Game Engine Integration

High Level Plan

- Extend Graphics API abstraction with RT shader types and RT commands
- Build and Update Acceleration Structures
- Create shaders and create the Ray Tracing Pipeline State Object
- Update Shader Parameters
- Start experimenting with ray tracing techniques
Game Engine Integration

Build and Update Acceleration Structures

- Build Acceleration Structure for static geometry once
- Rebuild Top Level Acceleration Structure every frame
- Update Bottom Level Acceleration Structure for deforming geometry every frame
- Use Compute shader to process deformable geometry into a temporary buffer to use as input to Acceleration Structure Update and shaders
Game Engine Integration

Shaders and Shader Parameters

- Use dxcompiler utility function to convert VS+PS pair to Hit shaders
  - Supports generation of both Closest Hit and Any Hit shader (alpha-test only)

- Register shaders and create the Ray Tracing Pipeline State Object

- Update shader parameters:
  - Naïve approach: update shader parameters every frame for every object
  - Optimal: update only the shader parameters that changed
Game Engine Integration

Start Experimenting, then Optimize

- Replace existing deferred passes for shadows, AO and reflections with ray generation shaders + denoising
- Add new techniques such as path tracing and lightmap baking

Some optimization tips:
- Allow artists to create simplified materials for reflection shading
- Build a single bottom level Acceleration Structure for an object with multiple sub-objects with different materials overlapping spatially
- Use RAY_FLAG_ACCEPT_FIRST_HIT_AND_END_SEARCH for shadow and AO rays even if you need the hit distance for denoising purposes
Game Engine Integration

Challenges and solutions

- Decals: early prototype outside engine showed promise
- Tessellation: start by disabling it if possible, otherwise limit update rate, output tessellated geometry to buffers and provide as input to AS builder
- Texture LOD: tried approaches such as replicating part of the Pixel Shader code to compute UVs at two auxiliary points to be able to compute derivatives
  - Does not seem worth it in most scenes, unless tracing primary rays or flat mirror rays and texture has high frequencies
  - TAA can eliminate a lot of the aliasing
Wrapping Up
Takeways

RTX and DXR brings real-time ray tracing to developers

- Biggest change in Graphics APIs since programmable shaders
- A few rays per pixel practical today for lighter weight effects
- More expensive ones (path tracing) can provide useful workflow improvements
- We showed a few examples of what’s possible
- Expect you to come up with bright new ideas
- Hope this was inspiring and exciting
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Thank you!
Ray Tracing Gems

Call for Papers

▪ A new book series with focus on real-time and interactive ray tracing for game development using the DXR API.

▪ We invite articles on the following topics:
  Basic ray tracing algorithms, effects (shadows, reflections, etc), non-graphics applications, reconstruction, denoising, & filtering, efficiency and best practices, baking & preprocessing, ray tracing API & design, rasterization and ray tracing, global Illumination, BRDFs, VR, deep learning, etc.

▪ Important dates
  o 15th of October 2018: submission deadline for full papers
  o GDC 2019: publication of Ray Tracing Gems (paper version + e-book)

▪ Eric Haines and Tomas Akenine-Möller will lead the editorial team
http://developer.nvidia.com/raytracinggems/
Questions?
Ignacio Llamas, illamas AT nvidia.com
Edward Liu, edliu AT nvidia.com

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