Welcome!

Lecture 12 - “GPU Ray Tracing (2)"
Today's Agenda:

- Exam Questions: Sampler (2)
- State of the Art
- Wavefront Path Tracing
- Heterogeneous Architecture
- Random Numbers
Exam Questions

On Acceleration Structures:

a) Explain how a kD-tree can be traversed without using a stack, without adding data to the nodes (so, no ropes, no short stack).

b) Can the same approach be used to traverse a BVH?

c) What is the maximum size, in nodes, for a BVH over $N$ primitives, and why?
Exam Questions

When using *Next Event Estimation* in a path tracer, *implicit light connections* do not contribute energy to the path.

a) What is an ‘implicit light connection’?

b) Why do these connections not contribute energy to the path?
Exam Questions

The path tracing algorithm as described by Kajiya is a *unidirectional path tracer*: it traces paths from the camera back to the lights. It is therefore also known as *backward path tracing*. It is also possible to render a scene using *forward path tracing*, also known as *light tracing*. In this algorithm, paths start at the light sources, and explicit connections are made to the camera.

a) This algorithm is able to handle certain situations much better than a backward path tracer. Describe a scene that will have less variance when rendered forward rather than backward.

b) In a light tracer, pure specular objects show up black in the rendered image. Explain why.
Today's Agenda:

- Exam Questions: Sampler (2)
- State of the Art
- Wavefront Path Tracing
- Heterogeneous Architecture
- Random Numbers
Previously in Advanced Graphics

A Brief History of GPU Ray Tracing

2002: Purcell et al., multi-pass shaders with stencil, grid, low efficiency
2005: Foley & Sugerman, kD-tree, stack-less traversal with kdrestart
2007: Horn et al., kD-tree with short stack, single pass with flow control
2007: Popov et al., kD-tree with ropes
2007: Günther et al., BVH with packets.

- The use of BVHs allowed for complex scenes on the GPU (millions of triangles);
- CPU is now outperformed by the GPU;
- GPU compute potential is not realized;
- Aspects that affect efficiency are poorly understood.
Understanding the Efficiency of Ray Traversal on GPUs*

Observations on BVH traversal:

Ray/scene intersection consists of an unpredictable sequence of node traversal and primitive intersection operations. This is a major cause of inefficiency on the GPU.

Random access of the scene leads to high bandwidth requirement of ray tracing.

BVH packet traversal as proposed by Gunther et al. should alleviate bandwidth strain and yield near-optimal performance.

Packet traversal doesn’t yield near-optimal performance. Why not?

*: Understanding the Efficiency of Ray Tracing on GPUs, Aila & Laine, 2009.

Understanding the Efficiency of Ray Traversal on GPUs

Simulator:

1. Dump sequence of traversal, leaf and triangle intersection operations required for each ray.
2. Use generated GPU assembly code to obtain a sequence of instructions that need to be executed for each ray.
3. Execute this sequence assuming ideal circumstances:
   - Execute two instructions in parallel;
   - Make memory access instantaneous.

The simulator reports on estimated execution speed and SIMD efficiency.

→ The same program running on an actual GPU can never do better;
→ The simulator provides an upper bound on performance.
Understanding the Efficiency of Ray Traversal on GPUs

Test setup

Scene: “Conference”, 282K tris, 164K nodes

Ray distributions:

1. Primary: coherent rays
2. AO: short divergent rays
3. Diffuse: long divergent rays

Hardware: NVidia GTX285.
Understanding the Efficiency of Ray Traversal on GPUs

Simulator, results:

Packet traversal as proposed by Gunther et al. is a factor 1.7-2.4 off from simulated performance:

<table>
<thead>
<tr>
<th></th>
<th>Simulated</th>
<th>Actual</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>149.2</td>
<td>63.6</td>
<td>43</td>
</tr>
<tr>
<td>AO</td>
<td>100.7</td>
<td>39.4</td>
<td>39</td>
</tr>
<tr>
<td>Diffuse</td>
<td>36.7</td>
<td>16.6</td>
<td>45</td>
</tr>
</tbody>
</table>

(\textit{this does not take into account algorithmic inefficiencies})

Hardware: NVidia GTX285.
Simulating Alternative Traversal Loops

**Variant 1: ‘while-while’**

```plaintext
while ray not terminated
  while node is interior node
    traverse to the next node
  while node contains untested primitives
    perform ray/prim intersection
```

**Results:**

<table>
<thead>
<tr>
<th></th>
<th>Simulated</th>
<th>Actual</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary</strong></td>
<td>149.2</td>
<td>63.6</td>
<td>43</td>
</tr>
<tr>
<td><strong>AO</strong></td>
<td>100.7</td>
<td>39.4</td>
<td>39</td>
</tr>
<tr>
<td><strong>Diffuse</strong></td>
<td>36.7</td>
<td>16.6</td>
<td>45</td>
</tr>
</tbody>
</table>

Here, every ray has its own stack; This is simply a GPU implementation of typical CPU BVH traversal. Compared to packet traversal, memory access is less coherent. One would expect a larger gap between simulated and actual performance. However, this is not the case (not even for divergent rays).

**Conclusion:** bandwidth is not the problem.

Hardware: NVidia GTX285.
Simulating Alternative Traversal Loops

Variant 2: ‘if-if’

\[
\text{while ray not terminated} \quad \text{if node is interior node} \quad \text{traverse to the next node} \\
\text{if node contains untested primitives} \quad \text{perform a ray/prim intersection}
\]

Results:

<table>
<thead>
<tr>
<th></th>
<th>Simulated</th>
<th>Actual</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>166.7</td>
<td>129.3</td>
<td>80</td>
</tr>
<tr>
<td>AO</td>
<td>160.7</td>
<td>131.6</td>
<td>88</td>
</tr>
<tr>
<td>Diffuse</td>
<td>81.4</td>
<td>70.5</td>
<td>45</td>
</tr>
</tbody>
</table>

This time, each loop iteration either executes a traversal step or a primitive intersection.

Memory access is even less coherent in this case.

Nevertheless, it is faster than while-while. Why?

While-while leads to a small number of long-running warps. Some threads stall while others are still traversing, after which they stall again while others are still intersecting.

Hardware: NVidia GTX285.
Simulating Alternative Traversal Loops

Variant 3: ‘persistent while-while’

Idea: rather than spawning a thread per ray, we spawn the ideal number of threads for the hardware.

Each thread increases an atomic counter to fetch a ray from a pool, until the pool is depleted*.

Benefit: we bypass the hardware thread scheduler.

Results:

<table>
<thead>
<tr>
<th></th>
<th>Simulated</th>
<th>Actual</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>129.3</td>
<td>166.7</td>
<td>90.1</td>
</tr>
<tr>
<td></td>
<td>135.6</td>
<td>70</td>
<td>81</td>
</tr>
<tr>
<td>AO</td>
<td>131.6</td>
<td>160.7</td>
<td>88.8</td>
</tr>
<tr>
<td></td>
<td>130.7</td>
<td>67</td>
<td>81</td>
</tr>
<tr>
<td>Diffuse</td>
<td>70.5</td>
<td>81.4</td>
<td>45.3</td>
</tr>
<tr>
<td></td>
<td>62.4</td>
<td>64</td>
<td>77</td>
</tr>
</tbody>
</table>

*: In practice, this is done per warp: the first thread in the warp increases the counter by 32. This reduces the number of atomic operations.

This test shows what the limiting factor was: thread scheduling. By handling this explicitly, we get much closer to theoretical optimal performance.

Hardware: NVidia GTX285.
Simulating Alternative Traversal Loops

Variant 4: ‘speculative traversal’

Idea: while some threads traverse, threads that want to intersect prior to (potentially) continuing traversal may just as well traverse anyway – the alternative is idling.

Drawback: these threads now fetch nodes that they may not need to fetch*. However, we noticed before that bandwidth is not the issue.

Results for persistent speculative while-while:

<table>
<thead>
<tr>
<th></th>
<th>Simulated</th>
<th>Actual</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>166.7</td>
<td>165.7</td>
<td>86</td>
</tr>
<tr>
<td>AO</td>
<td>160.7</td>
<td>169.1</td>
<td>80</td>
</tr>
<tr>
<td>Diffuse</td>
<td>81.4</td>
<td>92.9</td>
<td>77</td>
</tr>
</tbody>
</table>

For diffuse rays, performance starts to differ significantly from simulated performance. This suggests that we now start to suffer from limited memory bandwidth.

*: On a SIMT machine, we do not get redundant calculations using this scheme. We do however increase implementation complexity, which may affect performance.

Hardware: NVidia GTX285.
Understanding the Efficiency of Ray Traversal on GPUs

- Three years later*

In 2009, NVidia’s Tesla architecture was used (GTX285).

Results on Tesla (GTX285), Fermi (GTX480) and Kepler (GTX680):

<table>
<thead>
<tr>
<th></th>
<th>Tesla</th>
<th>Fermi</th>
<th>Kepler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>142.2</td>
<td>272.1</td>
<td>432.6</td>
</tr>
<tr>
<td>AO</td>
<td>134.5</td>
<td>284.1</td>
<td>518.2</td>
</tr>
<tr>
<td>Diffuse</td>
<td>60.9</td>
<td>126.1</td>
<td>245.4</td>
</tr>
</tbody>
</table>

*: Aila et al., 2012. Understanding the efficiency of ray traversal on GPUs - Kepler and Fermi Addendum.
Advanced Graphics – GPU Ray Tracing (2)

### GTX285
- 779 GFLOPS
- 159 GB/s

### GTX480
- 1344 GFLOPS
- 179 GB/s

### GTX680
- 3090 GFLOPS
- 192 GB/s
Latency Considerations of Depth-first GPU Ray Tracing*

A study of GPU ray tracing performance in the spirit of Aila & Laine has been published in 2014 by Guthe. Three optimizations are proposed:

1. Using a shallower hierarchy;
2. Loop unrolling for the while loops;
3. Loading data at once rather than scattered over the code.

<table>
<thead>
<tr>
<th></th>
<th>Titan (AL’09)</th>
<th>Titan (Guthe)</th>
<th>+%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>605.7</td>
<td>688.6</td>
<td>13.7</td>
</tr>
<tr>
<td>AO</td>
<td>527.2</td>
<td>613.3</td>
<td>16.3</td>
</tr>
<tr>
<td>Diffuse</td>
<td>216.4</td>
<td>254.4</td>
<td>17.6</td>
</tr>
</tbody>
</table>

*: Latency Considerations of Depth-first GPU Ray Tracing, Guthe, 2014
Shallow Bounding Volume Hierarchies*

Idea:

*We can cut the number of traversal steps in half if our BVH nodes have 4 instead of 2 child nodes.*

Additional benefits:
- A proper layout allows for SIMD intersection of all four child AABBs;
- We increase the arithmetic density of a single traversal step.

---

*: Shallow Bounding Volume Hierarchies for Fast SIMD Ray Tracing of Incoherent Rays, Dammertz et al., 2008
Getting Rid of Packets - Efficient SIMD Single-Ray Traversal using Multi-branching BVHs, Wald et al., 2008
Building the MBVH

*Collapsing a regular BVH*

For each node $n$: iterate over the children $c_i$:

1. See if we can ‘adopt’ the children of $c_i$:
   \[ N_n - 1 + N_{c_i} \leq 4; \]
2. Select the child with the greatest area;
3. Replace node $c_i$ with its children;
4. Repeat until no merge is possible.

Repeat this process for the children of $n$.

*Note that for this tree, the end result has one interior node with only 2 children, and one with only 3 children.*
Building the MBVH

Data structure:

```c
struct SIMD_BVH_Node {
    __m128 bminx4, bmaxx4;
    __m128 bminy4, bmaxy4;
    __m128 bminz4, bmaxz4;
    int child[4], count[4];
};
```

To traverse a regular BVH front-to-back, we can use a single comparison to find the nearest child. For an MBVH, this is not as trivial.

Pragmatic solution:

1. Obtain the four intersection distances in t4;
2. Overwrite the lowest bits of each float in t4 with binary 00, 01, 10 and 11;
3. Use a small sorting network to sort t4;
4. Extract the lowest bits to obtain the correct order in which the nodes should be processed.
Today's Agenda:

- Exam Questions: Sampler (2)
- State of the Art
- Wavefront Path Tracing
- Heterogeneous Architecture
- Random Numbers
Mapping Path Tracing to the GPU

The modified loop from lecture 8 is straight-forward to implement on the GPU.

However:

- Terminated paths become idling threads;
- A significant number of paths will not trace a shadow ray.

(Exam question: show how IS invalidates the second statement.)

(Also note that Russian roulette amplifies the first problem.)

Color Sample( Ray ray )
{
    T = ( 1, 1, 1 ), E = ( 0, 0, 0 );
    while (1)
    {
        I, N, material = Trace( ray );
        BRDF = material.albedo / PI;
        if (ray.NOHIT) break;
        if (material.isLight) break;
        // sample a random light source
        L, NL, dist, A = RandomPointOnLight();
        Ray lr( I, L, dist );
        if (N∙L > 0 && NL∙-L > 0) if (!Trace( lr ))
        {
            solidAngle = ((NL∙-L) * A) / dist^2;
            lightPDF = 1 / solidAngle;
            E += T * (N∙L / lightPDF) * BRDF * lightColor;
        }
        // continue random walk
        R = DiffuseReflection( N );
        hemiPDF = 1 / (PI * 2.0f);
        ray = Ray( I, R );
        T *= (N∙R) / hemiPDF;  
    }
    return E;
}
Megakernels Considered Harmfull*

Naïve path tracer:

KernelFunction

- Generate primary ray
- Intersect
- Shade
- Trace shadow ray
- Finalize

terminate? yes

no

shadow? yes

Translating this to CUDA or OpenCL code yields a single kernel: individual functions are still compiled to one monolithic chunk of code.

Resource requirements (registers) - and thus parallel slack - are determined by ‘weakest link’, i.e. the functional block that requires most registers.

* Wavefront Path Tracing on GPUs, Laine et al., 2013
Megakernels Considered Harmful

Solution: *split the kernel.*

Example:

Kernel 1: Generate primary rays.

Kernel 2: Trace paths.

Kernel 3: Accumulate, gamma correct, convert to ARGB32.

Consequence:

Kernel 1 generates *all* primary rays, and stores the result. Kernel 2 takes this buffer and operates on it.

> Massive memory I/O.
Wavefront

Megakernels Considered Harmful

Taking this further: streaming path tracing*. 

Kernel 1: generate primary rays.
Kernel 2: extend.
Kernel 3: shade.
Kernel 4: connect.
Kernel 5: finalize.

Here, kernel 2 traces a set of rays to find the next path vertex (the random walk).

Kernel 3 processes the results and generates new path segments and shadow rays (2 separate buffers).

Kernel 4 traces the shadow ray buffer.

Kernel 1, 2, 3 and 4 are executed in a loop until no rays remain.

*: Improving SIMD Efficiency for Parallel Monte Carlo Light Transport on the GPU, van Antwerpen, 2011
Finally, the `connect` kernel traces shadow rays. The `extend` kernel traces extension rays and produces intersections.* The `shade` kernel processes intersections, and produces new extension paths as well as shadow rays: Buffer 1: path segments \((N \text{ times } O,D,t)\)

Buffer 2: generated path segments \((N \text{ times } O,D,t)\)

Buffer 3: generated shadow rays \((N \text{ times } O,D,E)\)

Note: here, the loop is implemented on the host. Each block is a separate kernel invocation.

* An intersection is at least the t value, plus a primitive identifier.

Buffer 0, 1, \(\ldots\), \(N-1\)

Buffer 0, 1, \(\ldots\), \(N-1\)

Buffer 0, 1, \(\ldots\), \(N-1\)

Buffer 0, 1, \(\ldots\), \(N-1\)

The generate kernel produces \(N\) primary rays.

The extend kernel produces \(N\) primary rays.

Megakernels Considered Harmful.
Wavefront

Megakernels Considered Harmful

Notes:

- We do not have to generate all primary rays at once. Instead, we chose $N$ to match hardware capabilities.
- After each loop iteration, we add sufficient primary rays to fill up the extension ray buffer.
- Full buffers are not guaranteed, especially not for shadow rays. We need to inform the host about ray counts.

Also note:

- Rays are automatically sorted.
- At the start of each kernel, occupancy is 100%.
- We can also separate rays to handle each material using its own kernel.
Megakernels Considered Harmful

Digest:

Streaming path tracing introduces seemingly costly operations:

- Repeated I/O to/from large buffers;
- A significant number of kernel invocations per frame;
- Communication with the host.

The Wavefront paper claims that this is beneficial for complex shaders. In practice, this also works for (very) simple shaders.

Also note that the megakernel paper (2013) presents an idea already presented by Dietger van Antwerpen (2011).
Today's Agenda:

- Exam Questions: Sampler (2)
- State of the Art
- Wavefront Path Tracing
- Heterogeneous Architecture
- Random Numbers
Heterogeneous

The Brigade Project*

The Brigade Project

Research questions:

1. How close are we to path tracing for games?
2. How does path tracing affect game production?

And a related project goal:

Produce an experimentation platform for interactive / game-oriented path tracing.

Design considerations:

- Interactive performance (~20fps)
- Consumer hardware (1 CPU, 1 GPU, high-end)
- Game-style scene complexity (~100k – 500k triangles, basic shading)
Heterogeneous architecture:

- one or several CPUs;
- one or several GPUs;
- networked peers;
- DSPs, audio processors, physics processors;
- ...

Ray tracing on a heterogeneous system:

1. render using CPU or GPU;
2. full implementation on CPU as well as GPU;
3. distribute tasks over CPU and GPU;
4. blend between 2 and 3.
Heterogeneous

Starcraft 2

Borderlands 2

Deus Ex: Human Revolution
Advanced Graphics – GPU Ray Tracing (2)

Heterogeneous

Architecture

application

physics

AI

scene abstraction

audio

scene data &
scene graph

core

accstruc
updater

tracer

OpenGL

BRIGADE
Advanced Graphics – GPU Ray Tracing (2)

Heterogeneous

Architecture

- application
- physics
- AI
- scene
- audio
- scene graph
- core
- accstruc updater
- tracer
- OpenGL
Advanced Graphics – GPU Ray Tracing (2)

Heterogeneous

architecture

application

physics

AI

scene

audio

scene graph

core

accstruc updater

tracer

OpenGL

tracer

tracer

tracer
Heterogeneous

in:
camera, scene

core
SyncScene()
UpdateAccStruc()
SyncAccStruc()
Render()
Combine()
Present()

tracer

Render
▪ GenerateRay()
▪ Intersect()
▪ Shade()
▪ TraceShadow()
Heterogeneous

Advanced Graphics – GPU Ray Tracing (2)

Architecture

CPU
- Update AccStruc()
- Sync()
- Render()

GPU 1
- Render()

GPU 2
- Render()

Combine
- Present

frame
Heterogeneous

Architecture

CPU
- Update AccStruc()
- Sync(n)
- Render(n-1)
- Combine/Present

GPU 1
- Render(n-1)

GPU 2
- Render(n-1)

Sync(n)
Update AccStruc()
Sync(n+1)
Render(n)
Combine/Present

Advanced Graphics – GPU Ray Tracing (2)

CPU
- Update AccStruc()
- Sync(n)
- Render(n-1)
- Combine/Present

GPU 1
- Render(n-1)

GPU 2
- Render(n-1)

Sync(n)
Update AccStruc()
Sync(n+1)
Render(n)
Combine/Present

Advanced Graphics – GPU Ray Tracing (2)
Heterogeneous

CPU
Update AccStruc() → Sync → Render(n-1) → Sync → Update AccStruc() → Sync → Render(n-1) → Sync

GPU 1
Render(n-1) → Sync → Render(n-1) → Sync

GPU 2
Render(n-1) → Sync → Render(n-1) → Sync

Architecture
Heterogeneous

CPU + GPU in Real-time

Host to device communication is slow:

- copy overhead is \(~7500\) cycles;
- bandwidth: \(31\)GB/s (PCIe 4.0).

However:

- we can transfer data asynchronously (while the GPU renders);
- this barely affects rendering performance.

Device-to-device communication is fast:

- \(336\)GB/s (on Titan X; GTX980: \(224\)GB/s; GTX580: \(192\)GB/s).
Heterogeneous

**CPU memory**

- Game objects
- Meshes
- Acceleration structure, under construction

**GPU memory**

- Triangle data
- Textures
- Acceleration structure
- Pixel buffer
- Commit buffer
Heterogeneous

Heterogeneous: guidelines

- only transfer data that actually changed
- send data in a single batch, if possible
- send minimal data
  
  *e.g.*
  - pack on CPU, unpack on GPU
  - recalculate triangle normals on GPU

Don’t make the GPU wait for the CPU

- Operate on data while transferring.
Today’s Agenda:

- Exam Questions: Sampler (2)
- State of the Art
- Wavefront Path Tracing
- Heterogeneous Architecture
- Random Numbers
Generating Random Numbers on the GPU

Random numbers are simulated using pseudo random number generators (PNRGs).

Basic concept:

- keep a state (e.g., a single 32-bit unsigned integer);
- modify this state for each query, so that it appears to be random.

Example:

- start with a prime;
- multiply this prime by a large 32-bit prime for each query;
- integer overflow ensures that successive numbers appear random.
Generating Random Numbers on the GPU

Good RNGs have the following properties:

- Must produce uniformly distributed numbers;
- Must not repeat the same sequence;
- Must not exhibit correlation between successive numbers.

An excellent PRNG is the Mersenne Twister.

For path tracing, we need a pretty decent PRNG – our entire algorithm is based on randomness. Question is: *how good does it have to be?*
Xor32*

Consider the following PRNG:

```c
float Xor32( uint& seed )
{
    seed ^= seed << 13;
    seed ^= seed >> 17;
    seed ^= seed << 5;
    return seed * 2.3283064365387e-10f;
}
```

Complexity: 6 (cheap) operations.

In practice, we get away with this in a path tracer.

*: Marsaglia, Xorshift RNGs, 2003.
Seeding the PRNG

When running thousands of threads, we must be careful to avoid correlation between pixels. This requires careful selection of the seed for the PRNG.

On top of this, we do not want to keep the state of the RNG from frame to frame; it must be seeded for each invocation.

- A thread is uniquely identified by it’s thread ID.
- Combining this with the frame number ensures different sequences over time.

Initializing the seed:

```c
uint seed = (threadID + frameID * largePrime1) * largePrime2;
```

For a list of 9-digit primes (will fit in 32-bit) see: [http://www.rsok.com/~jrm/9_digit_palindromic_primes.html](http://www.rsok.com/~jrm/9_digit_palindromic_primes.html)
Today’s Agenda:

- Exam Questions: Sampler (2)
- State of the Art
- Wavefront Path Tracing
- Heterogeneous Architecture
- Random Numbers
INFOMAGR – Advanced Graphics

Jacco Bikker - November 2017 - February 2018

END of “GPU Ray Tracing (2)”

next lecture: “BRDFs”