Embree Ray Tracing Kernels
Tutorial and Application at Dreamworks Animation and in Autodesk Maya
Talks

- Building Ray Tracing Applications with Embree (40min)  
  **Sven Woop (Intel)**
- Interactive Light Transport Simulation at DreamWorks Animation (35min)  
  **Louis Feng (Intel), Evan Smyth (DreamWorks Animation)**
- Interactive Embree-Based Ray Tracing in Autodesk Maya (40min)  
  **Charles Congdon (Intel)**
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Notice revision #20110804
Outline

✦ Embree Overview
✦ Embree Performance
✦ Embree API Tutorial
After this talk you ...

... will be able to write high performance CPU ray tracing applications using Embree!
Embree Overview
Usage of Ray Tracing Today

- Movie industry transitioning to ray tracing (better image quality, faster feedback)
- High quality rendering for commercials, prints, etc.
- Virtual design in automotive industry, architectural design, ...
- Various kind of simulations (lighting, sound, particles, collision detection, etc.)
- Prebaked lighting in games
- etc.
Writing a Fast Ray Tracer is Difficult

- **Need to multi-thread:** easy for rendering but difficult for hierarchy construction
- **Need to vectorize:** efficient use of SIMD units, different ISAs (SSE, AVX, AVX2, AVX-512, Xeon Phi™)
- **Need deep domain knowledge:** many different data structures (kd-trees, octrees, grids, BVH2, BVH4, ..., hybrid structures) and algorithms (single rays, packets, large packets, stream tracing, ...) to choose
- **Need to support different CPUs:** Different ISAs/CPU types favor different data structures, data layouts, and algorithms
Observations

- Ray tracers are often not sufficiently optimized
- Ray traversal consumes a lot of cycles (often over 70%)
- Ray tracing can be expressed by small number of commonly used operations (build and traversal)
- Ray tracing kernel library has potential to speed up many applications
Embree

- Provides highly optimized and scalable Ray Tracing Kernels (data structure build and ray traversal)
- High performance on current (and future) CPUs (1.5x – 6x speedup reported by users)
- Targets application developers in professional rendering environment
- API for easy integration into applications
- Free and Open Source under Apache 2.0 license (http://embree.github.com)
Embree Features

- Find closest hit kernel (**rtcIntersect**)
- Find any hit kernel (**rtcOccluded**)
- Single Ray, Ray Packets (4, 8, 16)
- High quality and high performance hierarchy builders
- Intel® SPMD Program Compiler (ISPC) supported
- Triangles, Instances, Hair
- Extensible (User Defined Geometry, Intersection filter functions, Open Source)
## Embree System Overview

### Embree API (C++ and ISPC)

### Ray Tracing Kernel Selection

<table>
<thead>
<tr>
<th>Accel. structure</th>
<th>Builders</th>
<th>Traversal</th>
<th>Intersection</th>
</tr>
</thead>
<tbody>
<tr>
<td>bvh4.triangle4, bvh4.triangle8, bvh8.triangle8, bvh4aos.triangle1, ...</td>
<td>SAH builder, Spatial split builder, Morton code builder, BVH Refitter</td>
<td>Single ray (SSE2), single ray (SSE4.1), single ray (AVX), single ray (AVX2), packet (SSE2), hybrid (SSE4.2), ...</td>
<td>Möller Trumbore, Plücker Variant, Bezier Curve</td>
</tr>
</tbody>
</table>

### Common Vector and SIMD Library

(Vec3f, Vec3fa, ssef, avxf, SSE2, SSE4.1, AVX, AVX2)

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8/18/2014
Vectorized Ray Traversal in Embree

- Bounding Volume Hierarchy with fanout of 4 (BVH4) for fast single ray traversal

- Packets of rays for 2x faster coherent ray traversal

- Hybrid packet/single ray traversal also fast for incoherent rays
Why Ray Tracing on CPUs?

- High ray tracing performance for photorealistic rendering
- Large memory capacity to render really complex models
- Robust tools to develop and debug complex applications
- Complex shading and rendering applications are executed efficiently (e.g. light cuts with large per pixel state)
Why should I use Embree?

- Hides complexity of writing high performance ray tracing kernels, and gives you more time developing your renderer
- High performance on latest Intel® Xeon® Processor family and Intel® Xeon Phi™ coprocessor products
- High potential performance gain (1.5x – 6x rendering speedup reported by Embree users)
How can I use Embree?

- As a benchmark to identify performance issues in existing applications
- Adopt algorithms from Embree into your code
  - However Embree internals change frequently!
- As a library through the Embree API (recommended)
  - Benefit from future Embree improvements!
Supported Software and Hardware

- Windows XP, Windows 7, Windows 8, Mac OS X 10.X, Linux
- 64 bit (recommended) and 32 bit
- SSE2, ..., AVX, AVX2, Xeon Phi™ Instructions
- Visual Studio 2010 - 2013
- ICC (recommended), GCC, CLANG, MSVC
Embree Performance
Performance Methodology

- Models and illumination effects representative for professional rendering environment
- Evaluation on typical Intel® Xeon® rendering workstation* and Intel® Xeon Phi™ Coprocessor**
- Compare against state of the art GPU*** methods (using OptiX™ 3.5.1 and CUDA® 5.5)
- Path tracer with different material types, different light types, about 2000 lines of code
- Identical implementations in C++ (Xeon®), ISPC (Xeon Phi™), OptiX™ (GTX™ Titan)

* Dual Socket Intel® Xeon® E5-2690, 2x 8 cores @ 2.9 GHz  ** Intel® Xeon Phi™ 7120, 61 cores @ 1.238 GHz  *** NVIDIA® GeForce® GTX™ Titan

Imperial Crown of Austria
4.3M triangles

Bentley 4.5l Blower (1927)
2.3M triangles

Asian Dragon
12.3M triangles
Build Performance for Static Scenes

![Graph showing build performance comparison between Xeon® and Xeon Phi™ for static scenes.]

- **Xeon®**: 32.3 Million Triangles/Second
- **Xeon Phi™**: 31.7 Million Triangles/Second
- **NVIDIA® GeForce® GTX™ Titan**: 35.1 Million Triangles/Second

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Build Performance for Dynamic Scenes

- **Dual Socket Intel® Xeon® E5-2690, 2x 8 cores @ 2.9 GHz**
- **Intel® Xeon Phi™ 7120, 61 cores @ 1.238 GHz**
- **NVIDIA® GeForce® GTX™ Titan**

**Million Triangles/Second**

<table>
<thead>
<tr>
<th></th>
<th>Xeon® * Single Ray (Morton)</th>
<th>Xeon Phi™ ** ISPC (Morton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>76.1</td>
<td>56.5</td>
</tr>
<tr>
<td>50</td>
<td>81.9</td>
<td>140.4</td>
</tr>
<tr>
<td>100</td>
<td>160.1</td>
<td>162.1</td>
</tr>
<tr>
<td>150</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Ray Tracing Performance (incl. Shading)

* Dual Socket Intel® Xeon® E5-2690, 2x 8 cores @ 2.9 GHz  
** Intel® Xeon Phi™ 7120, 61 cores @ 1.238 GHz  
*** NVIDIA® GeForce® GTX™ Titan

Million Rays/Second

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<th>Titan*** OptiX™</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ray Tracing</td>
<td>38.6</td>
<td>60.2</td>
<td>82.7</td>
</tr>
<tr>
<td>Performance</td>
<td>54.3</td>
<td>51.7</td>
<td>37.5</td>
</tr>
<tr>
<td>Million Rays/Second</td>
<td>28.3</td>
<td>32.3</td>
<td>76.8</td>
</tr>
</tbody>
</table>
Embree API Overview

- Version 2 of the Embree API
- Compact and easy to use
- C++ and ISPC version
- Hides implementation details (such as different spatial index structures)
Scene

- Scene is container for set of geometries
- Scene flags passed at creation time
- Scene geometry changes have to get committed (rtcCommit) which triggers BVH build

```c
/* include embree headers */
#include <embree2/rtcore.h>

int main ()
{
    /* initialize at application startup */
    rtcInit ();

    /* create scene */
    RTCScene scene = rtcNewScene
                       (RTC_SCENE_STATIC,RTC_INTERSECT1);

    /* add geometries */
    ... later slide ...

    /* commit changes */
    rtcCommit (scene);

    /* trace rays */
    ... later slide ...

    /* cleanup at application exit */
    rtcExit ();
}
```
Scene Types

✧ Static Scenes
  – Geometry cannot get changed
  – High quality BVH build (SAH), fast trace
  – For final frame rendering

✧ Dynamic Scenes
  – Geometries can get added, modified, and removed
  – Faster build (Morton), slower trace
  – Preview mode during geometric modeling
Geometries

- Geometries created inside a scene and always belong to that scene
- Geometries of scene can share the same or have separate spatial index structures internally
- Accessed via geometry identifier (geomID) of compact integer range
- Supported are: Triangle meshes, hair geometry, instances, and „user defined geometry“
Triangle Mesh

- Contains vertex and index buffers
- Number of triangles and vertices set at creation time
- Linear motion blur supported (2 vertex buffers)

```c
/* add mesh to scene */
unsigned int geomID = rtcNewTriangleMesh
    (scene, numTriangles, numVertices, 1);

/* fill data buffers */
... later slide ...

/* add more geometries */
...

/* commit changes */
rtcCommit (scene);
```
Buffer Sharing

- Recommended to use buffer sharing
- Reduces memory consumption
- Application manages buffers (buffer has to stay alive during rendering and as long as geometry is alive)
- Support for stride and offset allows application flexibility in its data layout
Buffer Sharing Example

/* application vertex and index layout */
struct Vertex { float x, y, z, s, t; };
struct Triangle { int materialID, v0, v1, v2; };

/* share buffers with application */
rtcSetBuffer(scene, geomID, RTC_VERTEX_BUFFER, vertexPtr, 0, sizeof(Vertex));
rtcSetBuffer(scene, geomID, RTC_INDEX_BUFFER, indexPtr, 4, sizeof(Triangle));
Ray Structure: Inputs

- Ray origin and direction (org, dir)
- Ray interval (tnear, tfar)
- Time used for motion blur [0,1]

```c
struct RTCRay
{
    Vec3f org;
    Vec3f dir;
    float tnear;
    float tfar;
    float time;
    Vec3f Ng;
    float u;
    float v;
    int geomID;
    int primID;
    int instID;
}
```
Ray Structure: Outputs

- Hit distance (tfar)
- Unnormalized geometry normal (Ng)
- Local hit coordinates (u,v)
- Geometry identifier of hit geometry (geomID)
- Index of hit primitive of geometry (primID)
- Geometry identifier of hit instance (instID)
- No shading normals, texture coordinates, etc.

```c
struct RTCRay {
    Vec3f org;
    Vec3f dir;
    float tnear;
    float tfar;
    float time;
    Vec3f Ng;
    float u;
    float v;
    int geomID;
    int primID;
    int instID;
};
```
Tracing Rays

- **rtcIntersect** reports first intersection in tfar, Ng, u, v, geomID, primID, (instID)

- **rtcOccluded** reports any intersection by setting geomID to 0
Intel® SPMD Program Compiler (ISPC)

- Simplifies writing vectorized renderer
- C-based language plus vector extensions
- Scalar looking code that gets vectorized automatically
- Compilation to different vector ISAs (SSE, AVX, AVX2, Xeon Phi™)
- Available as Open Source from http://ispc.github.com
Embree Rendering: ISPC Example

/* loop over all screen pixels */
foreach (y=0 ... screenHeight-1, x=0 ... screenWidth-1)
{
 /* create and trace primary ray */
 RTCRay ray = make_Ray(p,normalize(x*vx + y*vy + vz),eps,inf);
 rtcIntersect(scene,ray);

 /* environment shading */
 if (ray.geomID == RTC_INVALID_GEOMETRY_ID) {
   pixels[y*screenWidth+x] = make_Vec3f(0.0f); continue;
 }

 /* calculate hard shadows */
 RTCRay shadow = make_Ray(ray.org+ray.tfar*ray.dir,neg(lightDir),eps,inf);
 rtcOccluded(scene,shadow);

 if (shadow.geomID == RTC_INVALID_GEOMETRY_ID)
   pixels[y*width+x] = colors[ray.primID]*(0.5f + clamp(-dot(lightDir,normalize(ray.Ng)),0.0f,1.0f));
 else
   pixels[y*width+x] = colors[ray.primID]*0.5f;
}
Dynamic Scenes

- Create scene with RTC_SCENE_DYNAMIC flag
- Report modified meshes with rtcUpdate call
- Possibly enable (rtcEnable), disable (rtcDisable), add (rtcNewXX), and delete (rtcDeleteGeometry) geometries

```c
for each frame {
    for each dynamic mesh {
        /* modify shared buffers */
        modify mesh->indices
        modify mesh->vertices

        /* signal that mesh got updated */
        rtcUpdate(scene, mesh);
    }

    /* commit changes */
    rtcCommit(scene);

    /* trace rays */
    ...
}
```
User Defined Geometry

- Allows to extend Embree with new primitives types (spheres, subdivision surfaces, etc.)
- User has to provide bounding, intersect, and occluded functions
- User Geometry represents array of primitives (to reduce memory overheads)
- Maintains fast path for natively supported primitives
/* user defined sphere representation */
struct Sphere {
    Vec3f p;  // position of the sphere
    float r;  // radius of the sphere
};

/* create application representation of spheres */
Sphere* spheres = new Sphere[N];
for (int i=0; i<N; i++) spheres[i] = createSphere(i);

/* add user geometry to scene */
unsigned int geomID = rtcNewUserGeometry(scene,N);
rtcSetBoundsFunction (scene,geomID,(RTCBoundsFunc) &sphereBoundsFunc);
rtcSetIntersectFunction (scene,geomID,(RTCIntersectFunc)&sphereIntersectFunc);
rtcSetOccludedFunction (scene,geomID,(RTCOccludedFunc )&sphereOccludedFunc);
rtcSetUserData (scene,geomID, spheres);
User Defined Geometry Bounds

```c
void sphereBoundsFunc(const Sphere* spheres,
                       uniform size_t N,
                       RTCBounds* bounds_o)
{
    const Sphere& sphere = spheres[N];
    bounds_o->lower_x = sphere.p.x-sphere.r;
    bounds_o->lower_y = sphere.p.y-sphere.r;
    bounds_o->lower_z = sphere.p.z-sphere.r;
    bounds_o->upper_x = sphere.p.x+sphere.r;
    bounds_o->upper_y = sphere.p.y+sphere.r;
    bounds_o->upper_z = sphere.p.z+sphere.r;
}
```
void sphereOccludedFunc(const Sphere* spheres, RTCRay& ray, size_t N) {
    const Sphere& sphere = spheres[N];
    const Vec3fa v = ray.org - sphere.p;
    const float A = dot(ray.dir, ray.dir);
    const float B = 2.0f * dot(v, ray.dir);
    const float C = dot(v, v) - sqr(sphere.r);
    const float D = B*B - 4.0f*A*C;
    if (D < 0.0f) return; // reports miss
    const float Q = sqrt(D);
    const float rcpA = rcp(A);
    const float t0 = 0.5f * rcpA * (-B - Q);
    const float t1 = 0.5f * rcpA * (-B + Q);
    if ((ray.tnear < t0) && (t0 < ray.tfar)) {
        ray.geomID = 0; // report hit
    }
    if ((ray.tnear < t1) && (t1 < ray.tfar)) {
        ray.geomID = 0; // report hit
    }
}
Intersection Filter Functions

- Per geometry callback that is called during traversal for each primitive intersection
- Can accept or reject hit (by setting geomID to -1)
- Can be used for:
  - Trimming curves (e.g. modeling tree leaves)
  - Transparent shadows (reject and accumulate)
  - Find all hits (reject and collect)
/* procedural intersection filter function */
void intersectionFilter(void* userPtr, RTCRay& ray)
{
    Vec3fa h = ray.org + ray.dir*ray.tfar;
    float v = abs(sin(4.0f*h.x)*cos(4.0f*h.y)*sin(4.0f*h.z));
    float T = clamp((v-0.1f)*3.0f,0.0f,1.0f);
    if (T > 1.0f) return;      // accept hit
    ray.geomID = RTC_INVALID_GEOMETRY_ID;   // reject hit
}

/* set intersection filter for the cube */
rtcSetIntersectionFilterFunction(scene, geomID, (RTCFilterFunc)&intersectionFilter);
rtcSetOcclusionFilterFunction    (scene, geomID, (RTCFilterFunc)&intersectionFilter);
rtcSetUserData                  (scene, geomID, NULL);
Hair Geometry

- Hair curves represented as cubic bezier curves with varying radius
- High performance through use of oriented bounding boxes
- Low memory consumption through direct ray/curve intersection
Summary

- Embree delivers high ray tracing performance on CPUs
- Embree has potential to speed up many ray tracing applications
- Embree is easy to use through its API
- Free and Open Source (https://embree.github.com)
Embree at Siggraph

- **Embree Ray Tracing Kernels: Tutorial and Application at Dreamworks Animation and in Autodesk Maya**
  Wednesday 2pm – 4:15pm (West Building, Rooms 208-209)

- **Embree – A Ray Tracing Kernel Framework for Efficient CPU Ray Tracing**
  Thursday 9am - 10:30am (East Building, Ballroom B-C)

- **Embree Demo at Exhibition**
  Tuesday – Thursday, Intel® Booth 1001 (West Building, Hall B/C)
Questions?

https://embree.github.io
embree@googlegroups.com