Embree Ray Tracing Kernels:
Overview and New Features

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Embree Overview

Embree API
Advanced Features
Embree Performance

Usage of Ray Tracing Today

- Special effects in movies (better image quality, faster feedback)
- High quality rendering for product visualization
- Provides higher fidelity for automotive rendering, architectural design, etc.
- Various kind of simulations (lighting, sound, particles, collision detection, etc.)
- Prebaked lighting in games

Fast Ray Tracing Challenges

Multi-threading

- Easy for rendering but difficult for hierarchy construction

Vectorization

- Efficient use of SIMD units, different ISAs (SSE, AVX, AVX2, AVX-512)

Domain knowledge

- Many different data structures and algorithms to choose from

Support for different CPUs

- Different ISAs/CPU types favor different data structures, data layouts, and algorithms

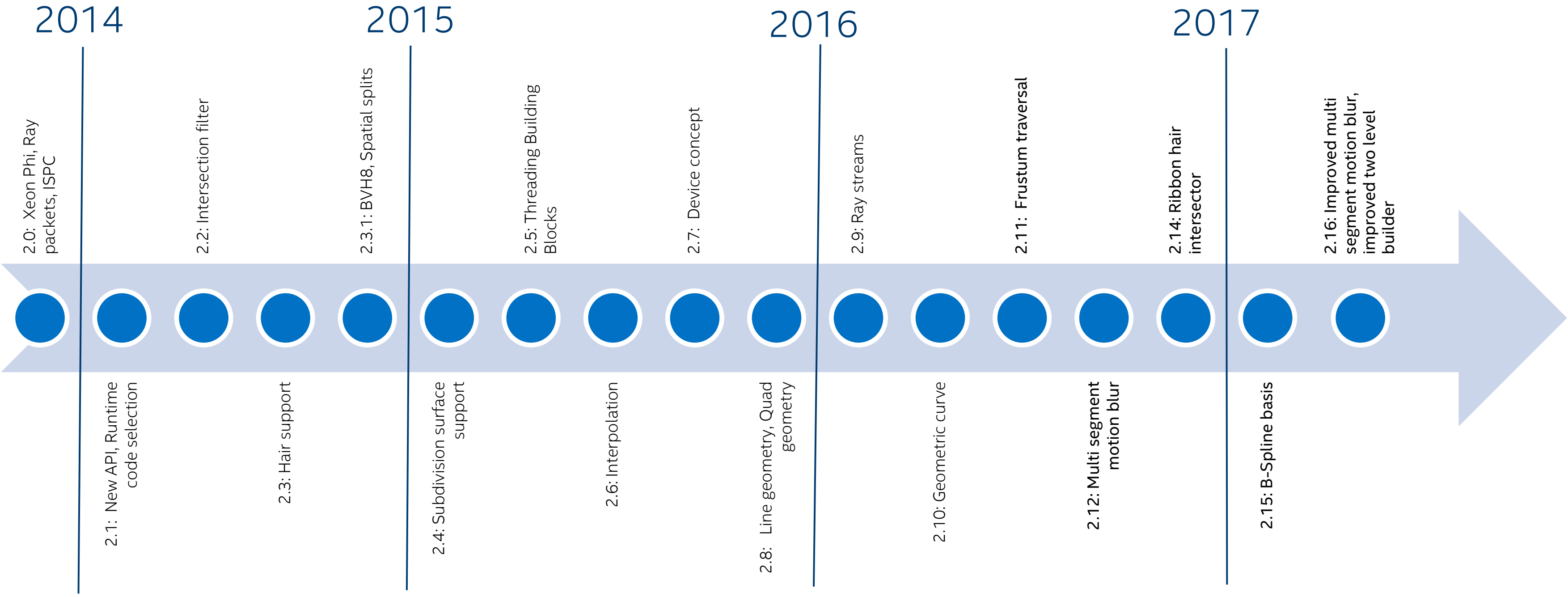
Different usage scenarios

- e.g. large model visualization favors memory conservative algorithms

Embree Ray Tracing Kernels

- Provides highly optimized and scalable ray tracing kernels
  - Focus on acceleration structure build and ray traversal
- Highest ray tracing performance on CPUs
  - 1.5–6× speedup reported by users
- Support for latest CPUs and ISAs (e.g. AVX-512)
- Targets professional rendering applications
- API for easy integration into applications
- Free and Open Source under Apache 2.0 license
  - http://embree.github.com

Embree Timeline



Embree Features

- Find closest hit (rtcIntersect), find any hit (rtcOccluded)
- Single rays, ray packets (4, 8, 16), ray streams (N)
- High-quality and high-performance BVH builders
- Triangles, quads, subdivs + displacement, curves, instances, user defined geometries
- Multi segment motion blur
- Intel® SPMD Program Compiler (ISPC) support
- Intel® Threading Building Blocks (TBB) support

Embree System Overview

Embree API (C and ISPC)

Ray Tracing Kernel Selection

Acceleration Structures

bvh4.triangle4
bvh8.triangle4
bvh4.quad4v
...

Builders

SAH Builder
Spatial Split Builder
Morton Builder
BVH Refitter

Traversal

Single Ray
Packet/Hybrid
Ray Stream

Intersection

Möller-Trumbore
Plücker
Bézier Curve
Line Segment
Triangle Grid

Subdiv Engine

B-Spline Patch
Gregory Patch
Tessellation Cache
Displ. Mapping

Common Vector and SIMD Library
(Vec3f, Vec3fa, vfloat4, vfloat8, vfloat16, …, SSE2, SSE4.1, AVX, AVX2, AVX-512)

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Embree API Overview

- Version 2 of the Embree API (version 3 in progress)
- C and ISPC version
- Object oriented
- Easy to use
- Hides implementation details
- For details visit https://embree.github.io/api.html

Example: Scene creation

Scene is a container for a set of geometries

Scene flags passed at creation time

- Static scene
- Dynamic scene
- etc.

Scene geometry changes have to get commited (rtcCommit), which triggers BVH build

```
// include Embree headers
#include <embree2/rtcore.h>

int main()
{
  // create Embree device at application
    startup
  RTCDevice device = rtcNewDevice ();

  // create scene
  RTCScene scene = rtcDeviceNewScene
    (device, RTC_SCENE_STATIC,
    RTC_INTERSECT1);

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

  // commit changes
  rtcCommit(scene);

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

}
```

Example: Triangle Mesh creation

Triangle mesh contains vertex and index buffers

Number of triangles and vertices set at creation time

Shared buffers of flexible layout (offset + stride) supported

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

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

// set data buffers
rtcSetBuffer(scene, geomID, RTC_VERTEX_BUFFER,
  vertexPtr, 0, sizeof(Vertex));
rtcSetBuffer(scene, geomID, RTC_INDEX_BUFFER,
  indexPtr, 4, sizeof(Triangle));

// add more geometries
...

// commit changes
rtcCommit(scene);
```

Intel® SPMD Program Compiler (ISPC)

- C-based language plus vector extensions
- Simplifies writing vectorized renderer
- Scalar looking code that gets vectorized automatically
- Guaranteed vectorization
- Compilation to different vector ISAs (SSE, AVX, AVX2, AVX-512)
- Available as Open Source from http://ispc.github.com

Example: Rendering using ISPC

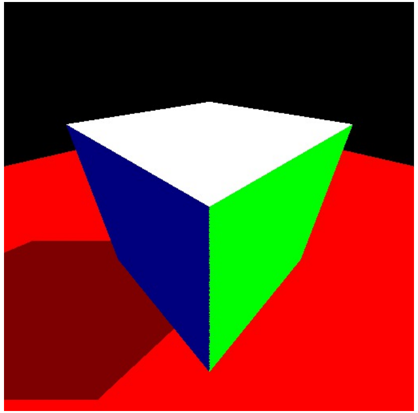
```
// loop over all screen pixels
foreach (y=0 ... screenHeight-1, x=0 ... screenWidth-1) {

    // 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;
}
```



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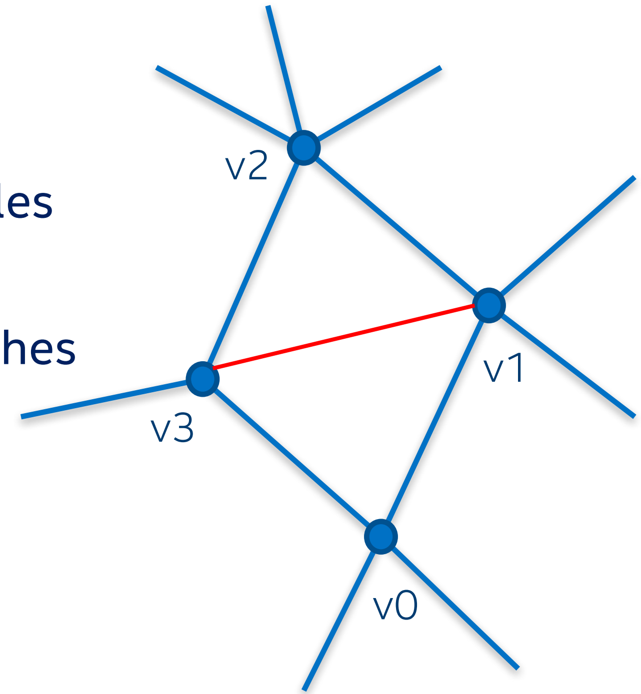
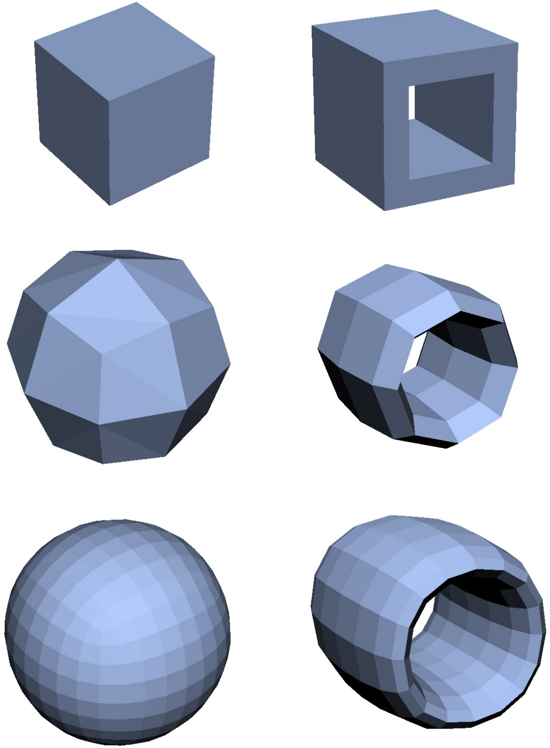
Quad Meshes

- Quad rendered as pairs of triangles (v0,v1,v3 and v2,v3,v1)
- Mixed Triangle/Quad mesh supported as triangles can also get encoded using quads (v0,v1,v3,v3)
- Most 3D modeling packages produce quad meshes
- Lower memory consumption
- Faster BVH building
- Ray Tracing slightly slower than for triangles

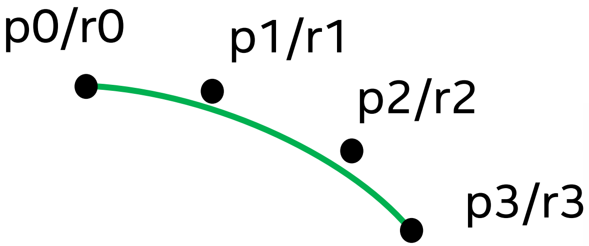


Catmull Clark Subdivision Surfaces

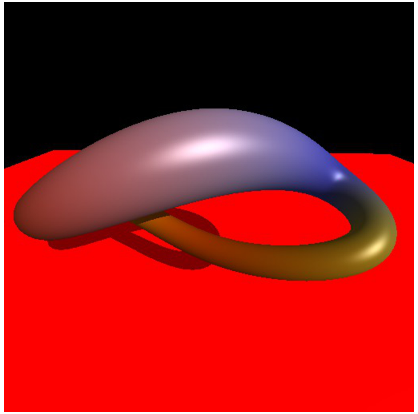
- Converts coarse mesh into smooth surface by subdivision (C2 continous almost everywhere)
- Support for arbitrary topology (generalization of B-spline surface, no trimming required as with NURBS)
- Established as standard in movie production
- Embree implementation compatible with OpenSubdiv 3.0 (creases, boundary modes, etc.)
- Vector displacement mapping supported



Cubic Spline Curves

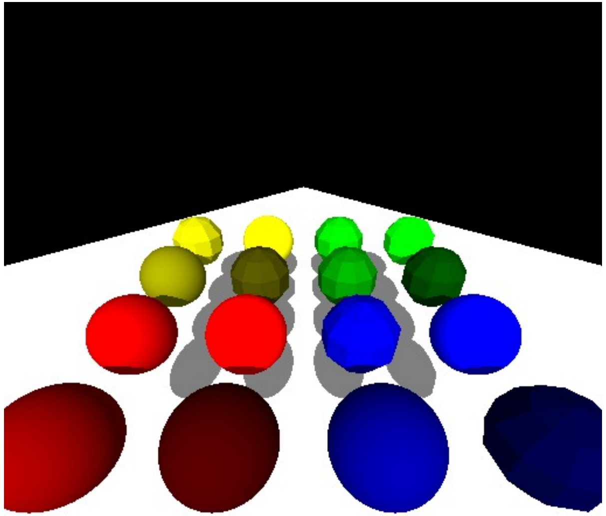


- Cubic polynomial curves
  - Bézier basis, B-spline basis, and line segments
  - Varying radius along the curve
- Two accuracies (close vs. distant curves):
  - Sweep surface of a circle along curve
  - Ray oriented ribbon primitive
- High performance through use of oriented bounding boxes [Woop et al. 2014]
- Low memory consumption through direct ray/curve intersection



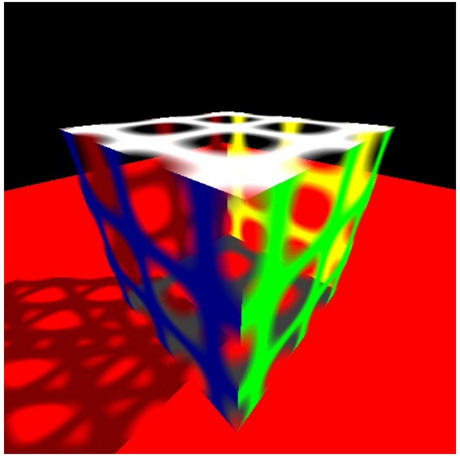
User Defined Geometries

- Enables implementing custom primitives and features not provided by Embree
  - e.g., sphere, disk, multi level instancing, rotation motion blur, etc.
- User provides:
  - Bounding function
  - Intersect and Occluded functions



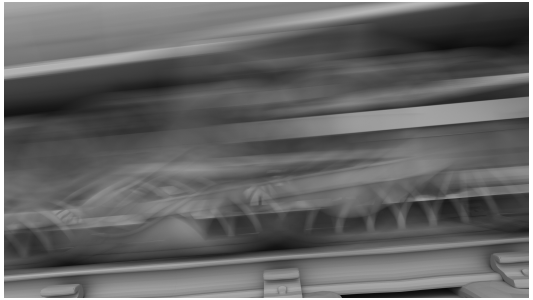
Intersection Filter Functions

- Per geometry callback that is called during traversal for each primitive intersection
- Callback can **accept** or **reject** hit
- Can be used for:
  - Trimming curves (e.g. modeling tree leaves)
  - Transparent shadows (reject and accumulate)
  - Find all hits (reject and collect)
  - Advanced self intersection avoidance



Multi Segment Motion Blur

- Important to render fast curved motion (e.g. rotating wheel, fight scenes, spinning dancer, etc.)
- Sequence of time steps to be linearly interpolated provided to renderer.
- Typically equidistant time steps and often different number of time steps per geometry.

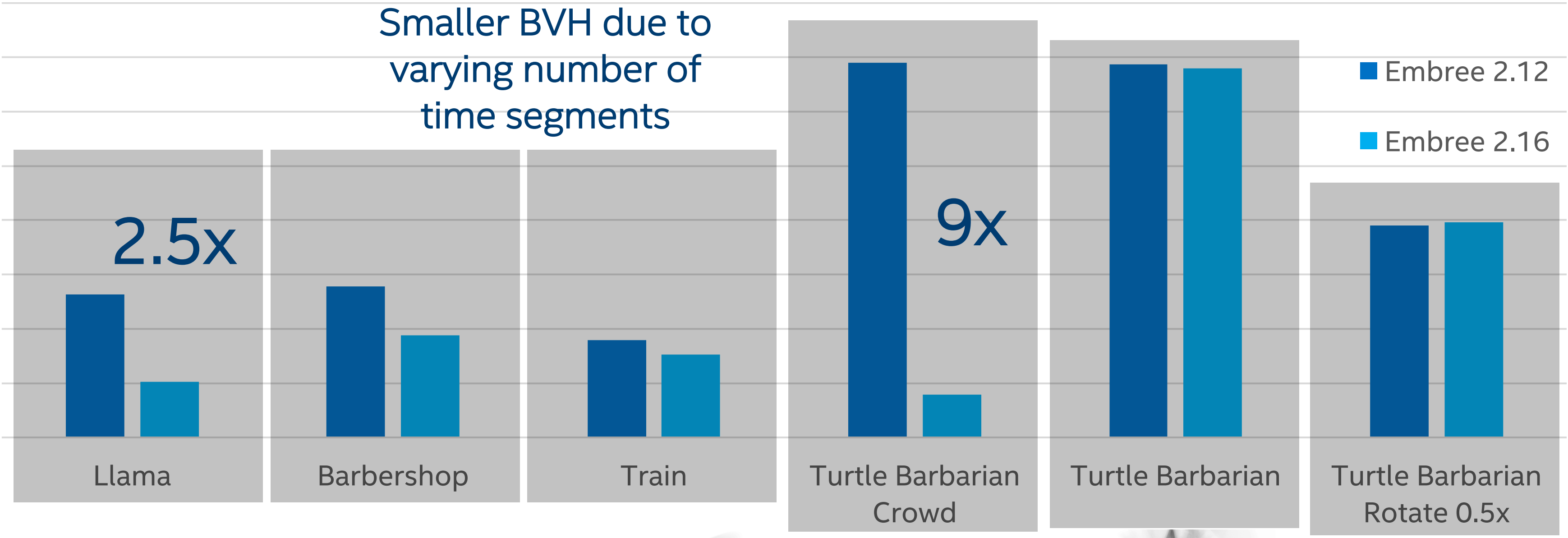


Multi Segment Motion Blur Implementation

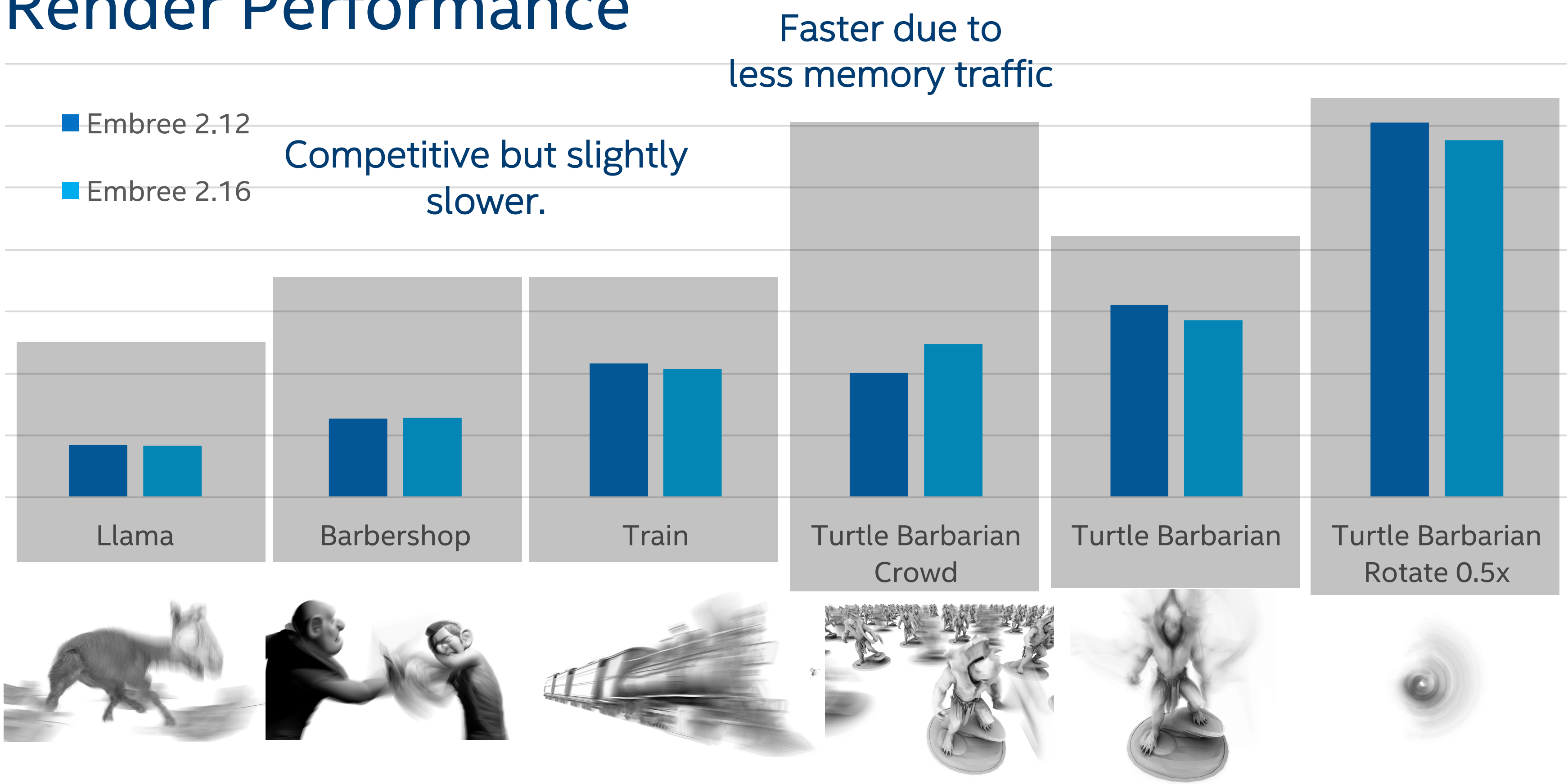
- 4D-BVH which stores linear spatial and temporal bounds
  - BVH can spatially separate geometries
  - BVH can reduce time ranges where required
- High temporal resolution for parts of the scene supported efficiently
- Longer animations efficiently supported, e.g. to render multiple frames using single geometry setup
- Large memory savings compared to Embree v2.12 implementation

Memory Consumption

Similar BVH size



Render Performance



Multi Segment Motion Blur Implementation

“STBVH: A Spatial-Temporal BVH for Efficient Multi-Segment Motion Blur” Sven Woop, Attila T. Afra, Carsten Benthin, High Performance Graphics 2017

“High Performance Rendering Appliance” demo at Intel booth #807

Embree Dynamic Scene Support

- Two level BVH for optimal build performance
  - only changed geometries have to get updated
- Traditional two level build causes suboptimal render performance
  - multiple geometries traversed at overlapping region
  - wrong traversal order at overlapping region

Embree Improved Top Level Build

- Top level BVH built using novel approach
  - Exploit available BVH of geometries
  - Open large BVH nodes of geometries during build
  - Disable opening when single object isolated
- Slightly more expensive BVH build
- Up to 2x improvement of render performance of dynamic BVH

Embree Improved Top Level Build

"Improved Two-Level BVHs using Partial Re-Braiding", Carsten Benthin, Sven Woop, Ingo Wald, Attila T. Afra, High Performance Graphics 2017

"Embree Ray Tracing" demo at Intel booth #807

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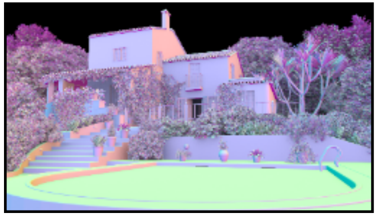
Diffuse Path Tracing Performance

- Simple illumination effect to measure pure ray tracing performance
- Highest quality BVH build for all platforms
- Embree v2.16.0 performance measured on:
  - Dual socket Intel® Xeon® Platinum 8180 Processor (2x28 cores @ 2.5 GHz, AVX-512)
  - Intel® Xeon Phi™ 7250 Processor (68 cores @ 1.4 GHz, AVX-512)
- Comparing against state of the art GPU methods using:
  - OptiX™ Prime 4.0.2 and CUDA® 8.0.44
  - NVIDIA Tesla P100 Coprocessor (3584 CUDA cores @ 1.175 GHz, Pascal)

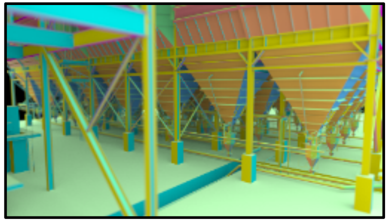
3D Models used for Benchmarking

Mazda
5.7M triangles



Villa
37.7M triangles

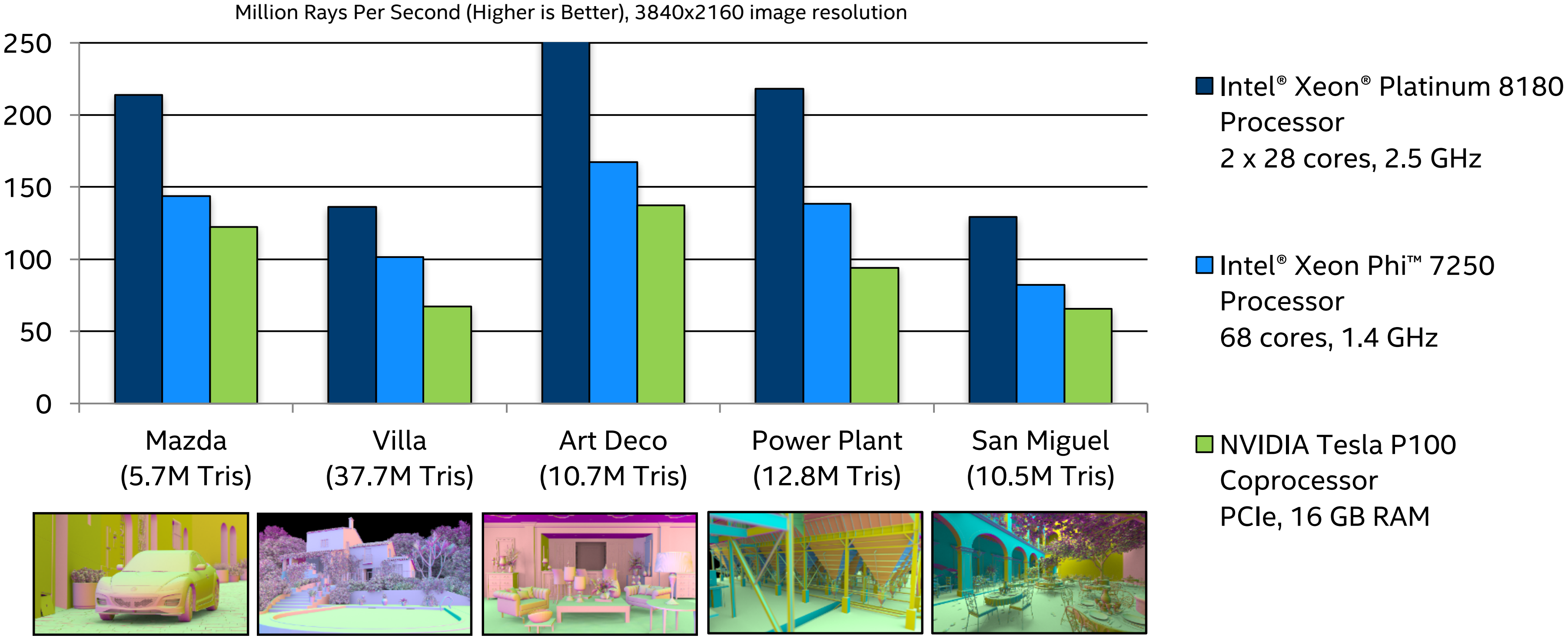
Art Deco
10.7M triangles



Power Plant
12.8M triangles

San Miguel
10.5M triangles

Diffuse Path Tracing Performance



Questions?

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

Visit the Intel booth #807 for a live Embree demo!

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