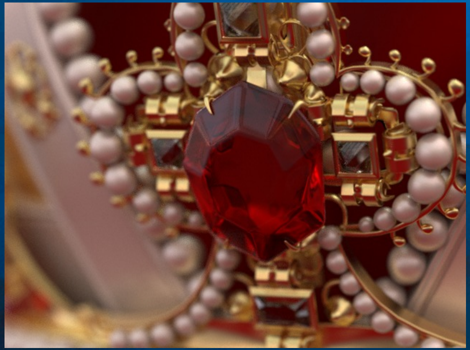
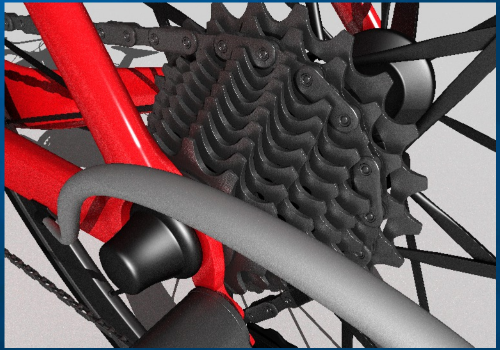
# Embree Ray Tracing Kernels

*Sven Woop*





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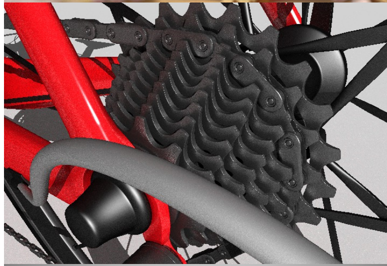
# Outline

- Embree Overview
- Embree Performance
- Embree API
- Catmull Clark Subdivision Surfaces

# 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.
- Provides higher fidelity for virtual design (automotive industry, architectural design, etc.)
- 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, KNCNI)
- **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

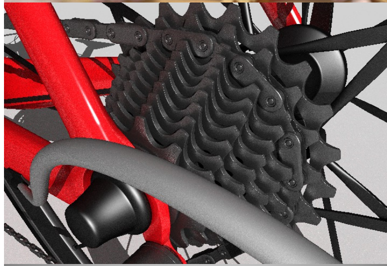
# Observations

- Ray tracers are often not sufficiently optimized
- Ray traversal consumes a lot of cycles of renderer (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 rendering applications**

# Embree Ray Tracing Kernels

- Provides highly optimized and scalable Ray Tracing Kernels (data structure build and ray traversal)
- Targets application developers in professional rendering environment
- Highest ray tracing performance on CPUs (1.5x – 6x speedup reported by users)
- Support for latest CPUs (e.g. AVX512 support)
- API for easy integration into applications
- Free and Open Source under Apache 2.0 license (http://embree.github.com)

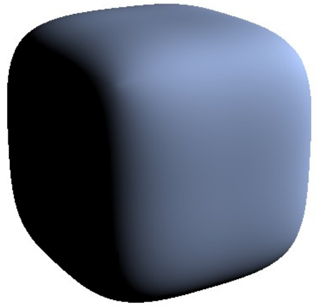


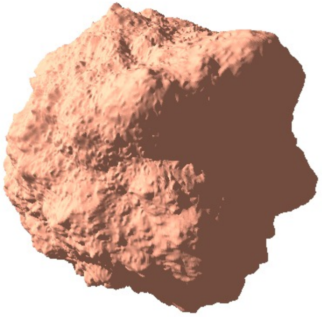
# Embree Features

- Find closest and any hit kernel (rtcIntersect, rtcOccluded)
- Single Rays and Ray Packets (4, 8, 16)
- High quality and high performance hierarchy builders
- Intel® SPMD Program Compiler (ISPC) supported
- Triangles, Instances, Hair, Linear Motion blur
- Extensible (User Defined Geometry, Intersection filter functions, Open Source)
- Support for Intel Threading Building Blocks (TBB)

# New Embree Features

- Catmull Clark Subdivision Surfaces
  – Smooth surface primitive
- Vector Displacement Mapping
  – Add geometric detai
- Interpolation
- Initial AVX512 support
  – 16 wide AVX512 traversal kernels
  – Full AVX512 optimizations will come when hardware available!





# Embree System Overview

Embree API (C++ and ISPC)

Ray Tracing Kernel Selection

| Accel. structure | Builders | Subdiv Engine | Traversal | Intersection |
|---|---|---|---|---|
| bvh4.triangle4, bvh8.triangle8, bvh4aos.triangle1, bvh4.grid … | SAH builder<br>Spatial split builder<br>Morton code builder<br>BVH Refitter | B-Spline Patch<br>Gregory Patch<br>TessellationCache<br>Displ. Mapping | Single ray (SSE2, AVX, AVX2), packet (SSE2), hybrid (SSE4.2), … | MöllerTrumbore, Plücker Variant, Bezier Curve, Triangle Grids |

Common Vector and SIMD Library
(Vec3f, Vec3fa, float4, float8, float16, SSE2, SSE4.1, AVX, AVX2, AVX512)

# Why Ray Tracing on CPUs?

- High ray tracing performance for photorealistic rendering
- Large memory capacity to render really complex models
- Runs on any CPU through well defined ISA
- No special hardware requirements
- Robust tools to develop and debug rendering application
- Large shading and rendering applications are executed efficiently

# Why should I use Embree?

- Hides complexity of writing high performance ray tracing kernels
  → gives you more time for innovation of your renderer
- High performance on latest Intel® Xeon® Processor family and Intel® Xeon Phi™ coprocessor products
- Embree always up to date with latest ISA instruction sets
- 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 to your code
  - However Embree internals change frequently!
- As a library through the Embree API (recommended)
  - Benefit from future Embree improvements!

# Embree v2.6.1 Performance

# Performance Methology

- Models and illumination effects representative for professional rendering environment
- Path tracer with different material types, different light types, about 2000 lines of code
- Evaluation on typical Intel® Xeon® rendering workstation* and Intel® Xeon Phi™ Coprocessor**
- Compare against state of the art GPU*** methods (using OptiX™ 3.8.0 and CUDA® 7.0.28)
- Identical implementations in ISPC (Xeon®), ISPC (Xeon Phi™), OptiX™ (GTX™ Titan X)

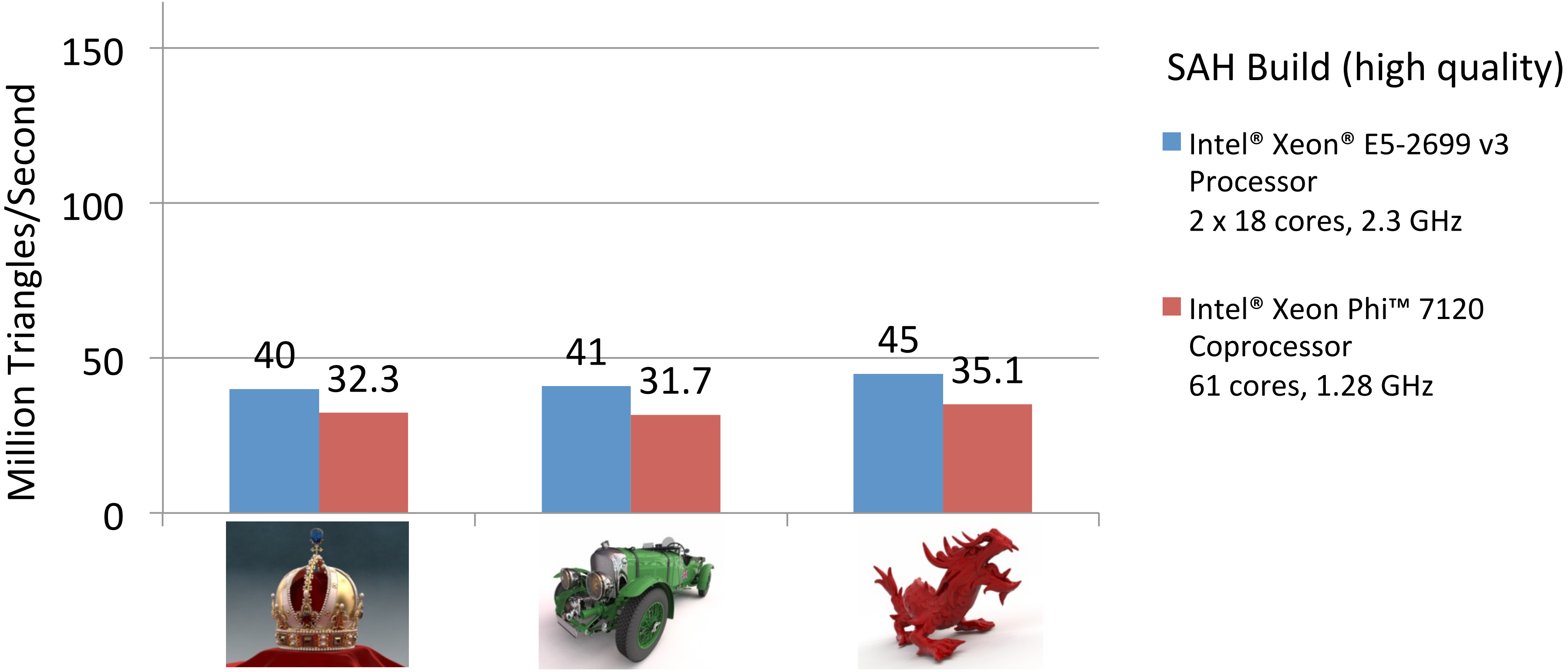
Imperial Crown of Austria
4.3M triangles

Bentley 4.5l Blower (1927)
2.3M triangles

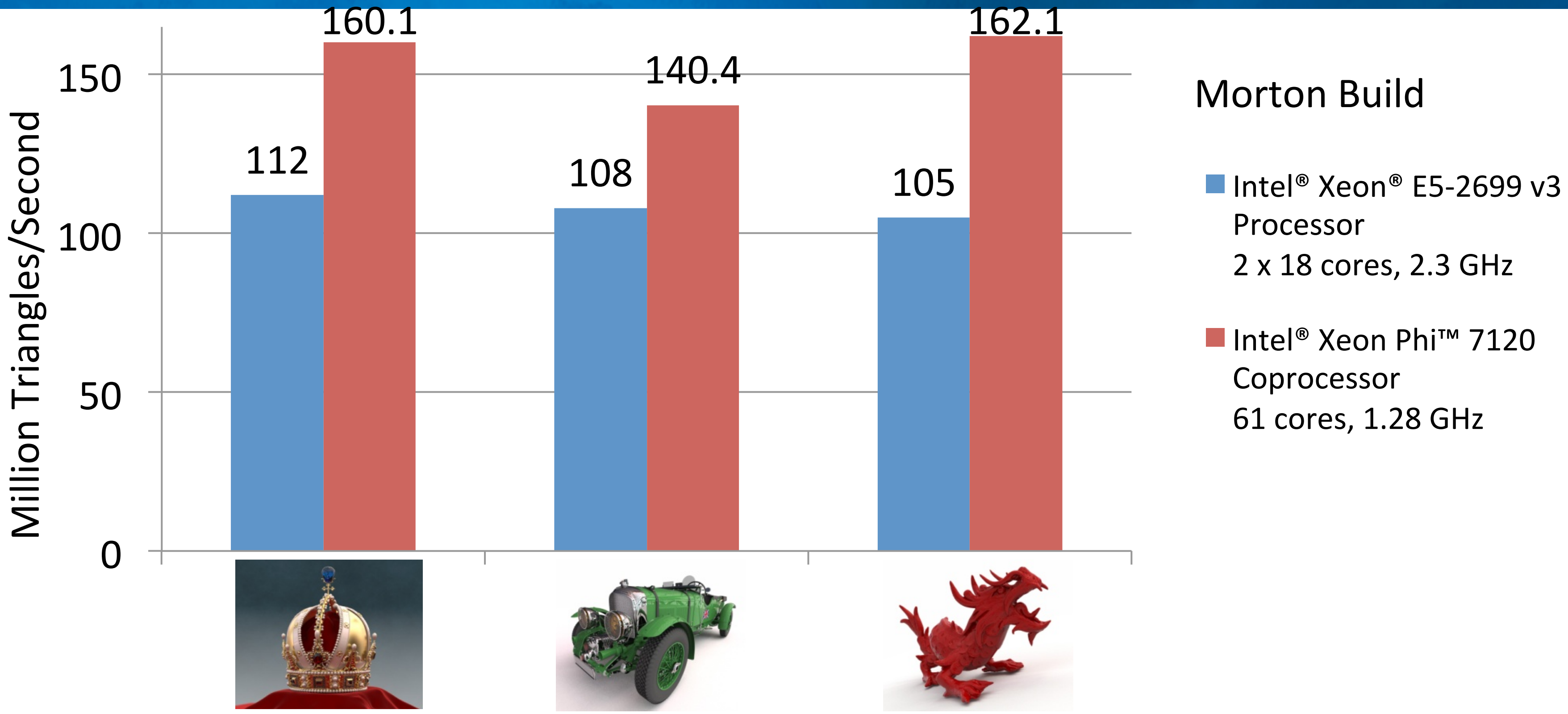
Asian Dragon
7.3M triangles

* Dual Socket Intel® Xeon® E5-2699 v3 2x18 cores @ 2.30GHz ** Intel® Xeon Phi™ 7120, 61 cores @ 1.238 GHz *** NVIDIA® GeForce® GTX™ Titan X

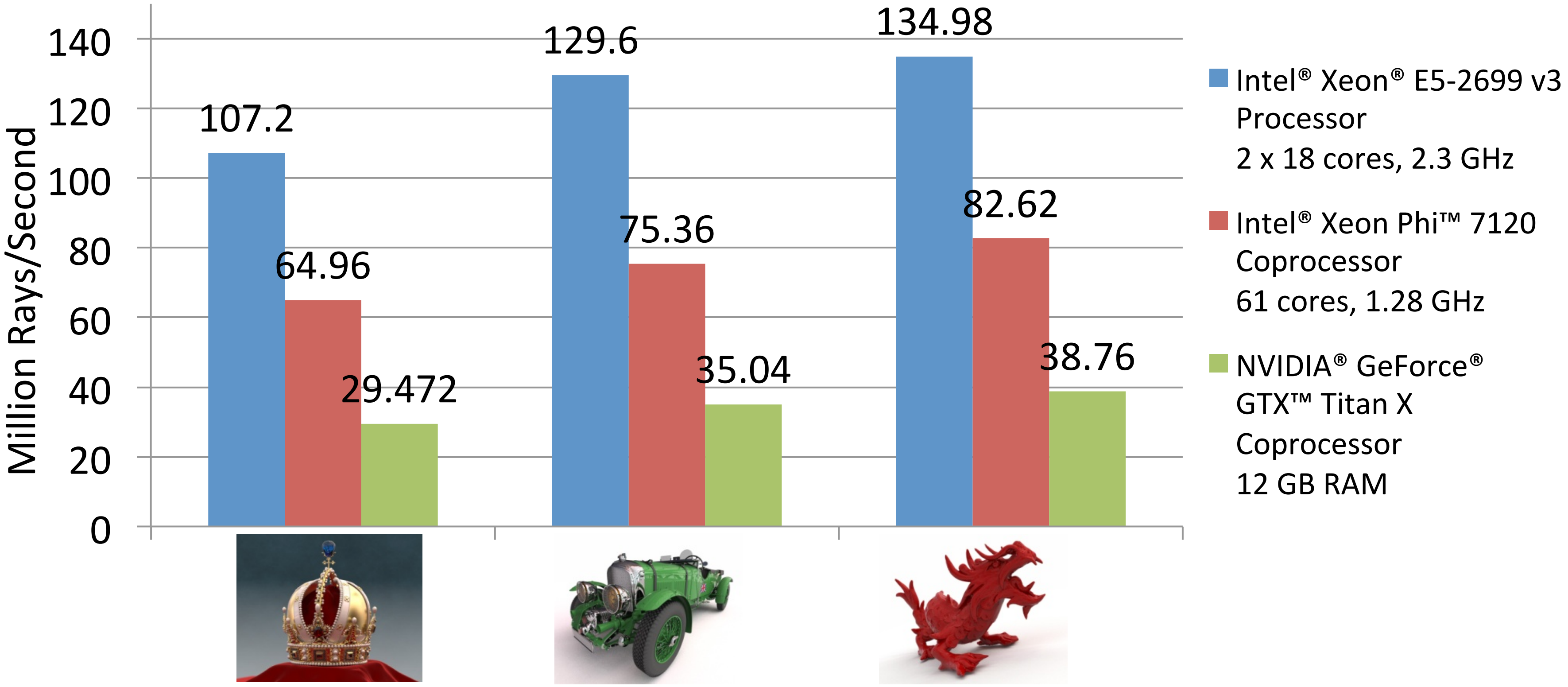
# Build Performance for Static Scenes



# Build Performance for Dynamic Scenes



# Ray Tracing Performance (incl. Shading)



# Embree API

# Scene Object

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

```
/* 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) ➔ faster ray traversal
  - For final frame rendering
- Dynamic Scenes
  - Geometries can get added, modified, and removed
  - Faster build (Morton) ➔ slower ray traversal
  - Preview mode during geometric modeling

# Triangle Mesh

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

```
/* 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 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; };

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

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

# Tracing Rays

- **rtcIntersect (scene, ray)** reports first intersection
- **rtcOccluded (scene, ray)** reports any intersection
- Packet versions for ray packets of size 4,8, and 16

# rtcIntersect: Ray Structure Inputs

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

```
struct RTCRay
{
  Vec3f org;
  Vec3f dir;
  float tnear;
  float tfar;
  float time;

  Vec3f Ng;
  float u;
  float v;
  int geomID;
  int primID;
  int instID;
}
```

# rtcIntersect: 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.

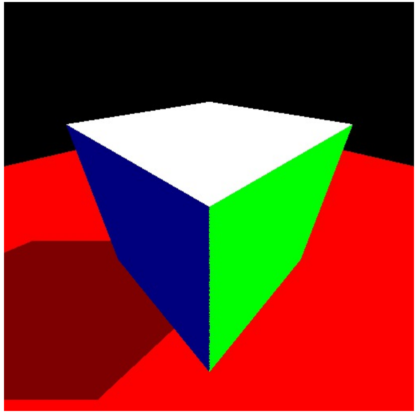
```
struct RTCRay
{
  Vec3f org;
  Vec3f dir;
  float tnear;
  float tfar;
  float time;

  Vec3f Ng;
  float u;
  float v;
  int geomID;
  int primID;
  int instID;
}
```

# Intel® SPMD Program Compiler (ISPC)

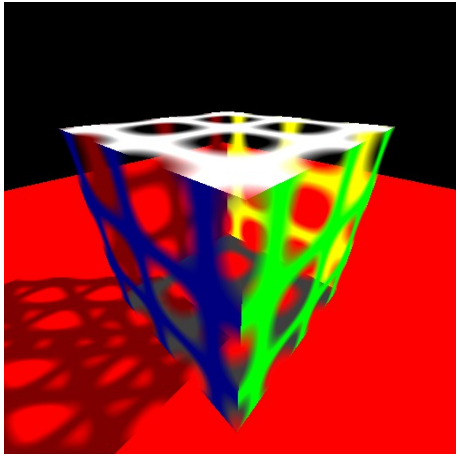
- Simplifies writing vectorized renderer
- C-based language plus vector extensions
- Scalar looking code that gets vectorized automatically
- Guaranteed vectorization
- Compilation to different vector ISAs (SSE, AVX, AVX2, AVX512, Xeon Phi™)
- Available as Open Source from http://ispc.github.com

# 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;
}
```



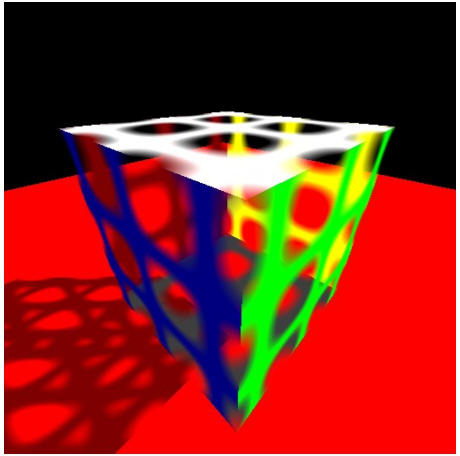
# Intersection Filter Functions



- 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)

# Filter Function Example

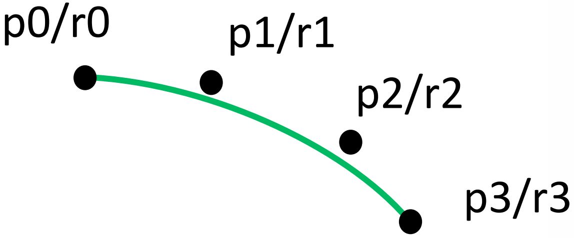
```
/* procedural intersection filter function */
void intersectionFilter(void* userPtr, RTCRay& ray)
{
    Vec3fa h = ray.org + ray.dir*ray.tfar;
    float v = abs(sin(4.0f*h.x)*cos(4.0f*h.y)*sin(4.0f*h.z));
    float T = clamp((v-0.1f)*3.0f,0.0f,1.0f);
    if (T > 1.0f) return;                    // 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

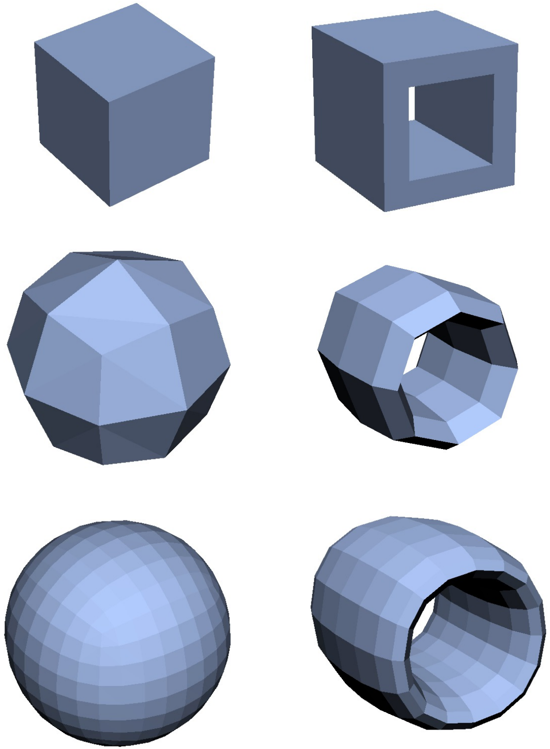
- Hair curves represented as cubic bezier curves with varying radius
- High performance through use of oriented bounding boxes
- Low memory consumption through direct ray/curve intersection



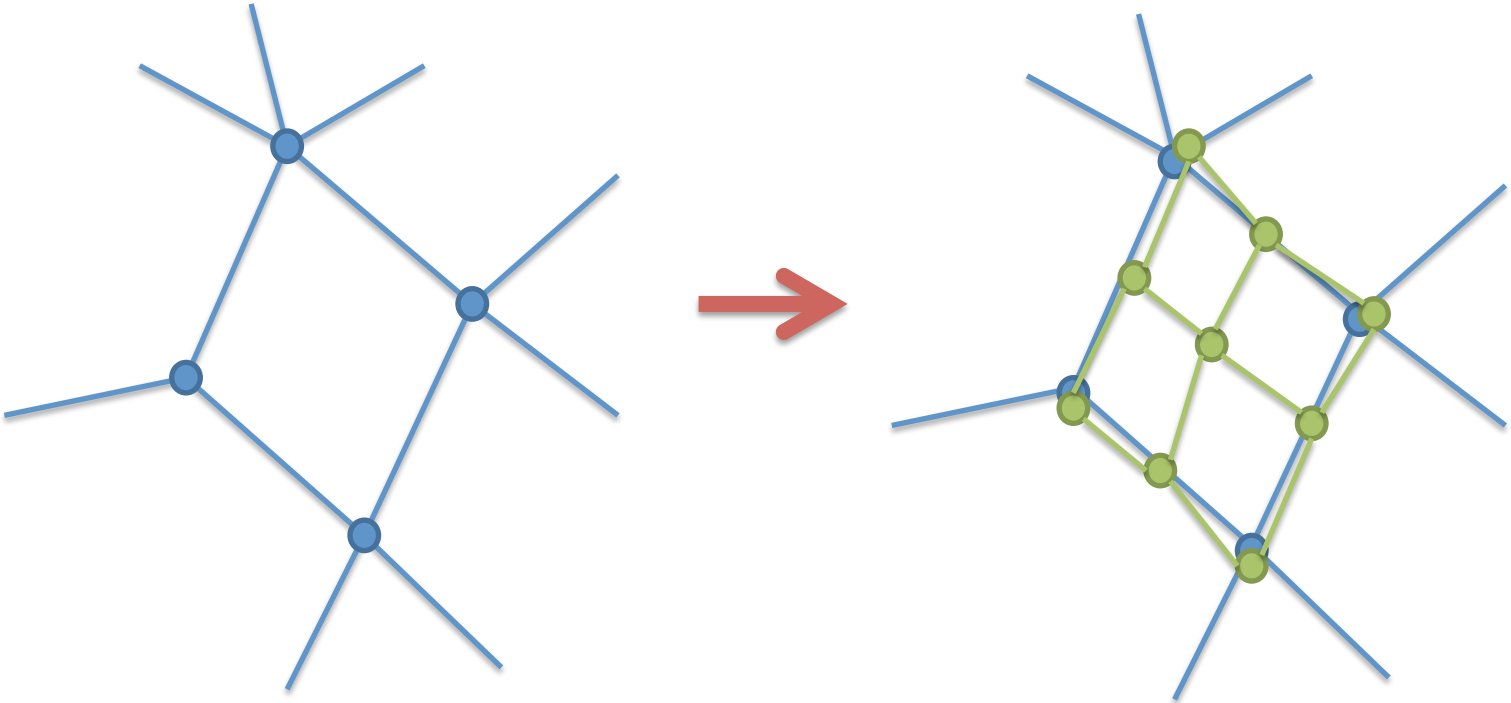

# Catmull Clark Subdivision Surfaces

# Catmull Clark Subdivision Surfaces

- Converts coarse mesh into smooth surface by subdivision
- Generalization of bi-cubic B-Spline surfaces to arbitrary topology
- Embree is compatible with OpenSubdiv 3.0



# Catmull Clark Subdivision



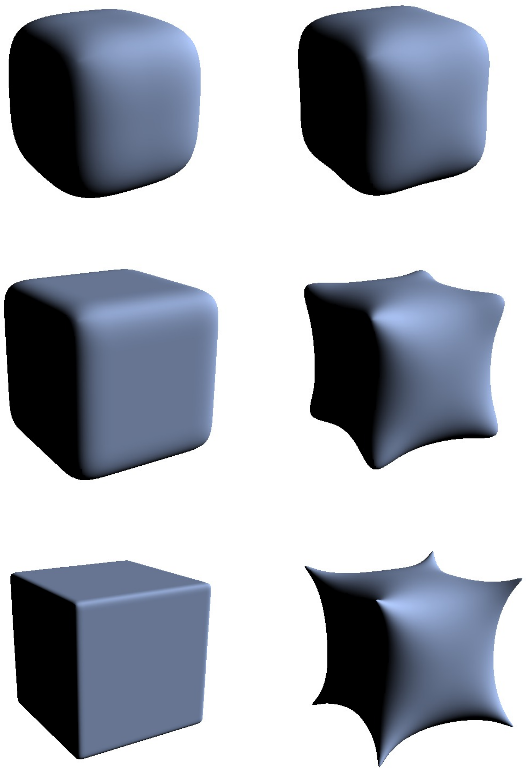
# CC Subdivision Surface Advantages

- Low resolution base mesh controls high resolution surface
- Smoothness always guaranteed (C2 continous almost everywhere)
- Support for arbitrary topology (no trimming required as with NURBS)
- Creases allow introducing sharp features
- Support in most modeling tools

→ Established as standard in movie production

# Embree Subdivision Features

- Semi-sharp edge creases
- Semi-sharp vertex creases
- Vertex attribute interpolation
- Tessellation level per edge
- Non-manifolds and holes
- Boundary modes
- Triangles, Quads, Pentagons, …
- Vector Displacement mapping



# Embree Subdivision Example

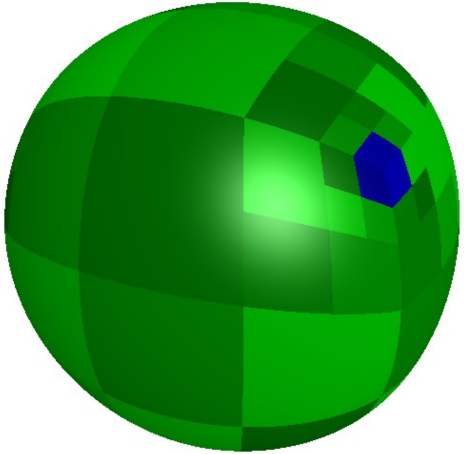
```
unsigned geomID = rtcNewSubdivisionMesh (scene, RTC_GEOMETRY_STATIC,
  numFaces, numIndices, numVertices,
  numEdgeCreases, numVertexCreases, numHoles);
```

```
rtcSetBuffer (scene,geomID,RTC_VERTEX_BUFFER, vertices, 0, sizeof(float3));
rtcSetBuffer (scene,geomID,RTC_INDEX_BUFFER , indices,  0, sizeof(int));
rtcSetBuffer (scene,geomID,RTC_FACE_BUFFER  , faces,    0, sizeof(int));
rtcSetBuffer (scene,geomID,RTC_LEVEL_BUFFER , levels,   0, sizeof(float));
```

```
rtcSetBuffer (scene,geomID,RTC_EDGE_CREASE_INDEX_BUFFER,...);
rtcSetBuffer (scene,geomID,RTC_EDGE_CREASE_WEIGHT_BUFFER,...);

rtcSetBuffer (scene,geomID,RTC_VERTEX_CREASE_INDEX_BUFFER,...);
rtcSetBuffer (scene,geomID,RTC_VERTEX_CREASE_WEIGHT_BUFFER,...);

rtcSetBuffer (scene,geomID,RTC_HOLE_BUFFER,holes,0,sizeof(char));
```

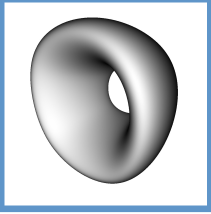
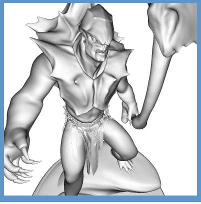
# Embree Subdivision Implemention

- Tessellate and Cache
  - limited memory consumption
  - trade memory for performance
- Parallel Shared Tessellation Cache
- Grid evaluation through feature adaptive subdivision into B-Spline patches and Gregory patches



Feature adaptive subdivision into B-Spline patches (green) and Gregory Patches (blue)

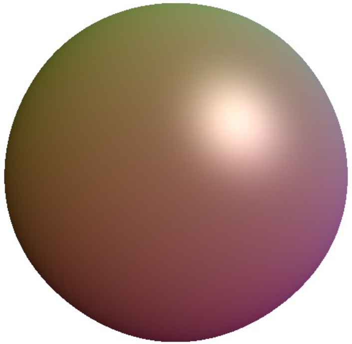
# Embree Subdivision Performance

| |  |  |  |
|---|---|---|---|
| Patches | 16 | 52k | 53k |
| Edge Creases | 0 | 0 | 30k |
| Micro Quads | 1048k | 831k | 837k |
| Same View | 105 fps | 84 fps | 100 fps |
| Walkthrough | 40 fps | 72 fps | 80 fps |

Intel® Xeon® E5-2690
2.9 GHz
2x 8 cores
1024 x 1024 pixels

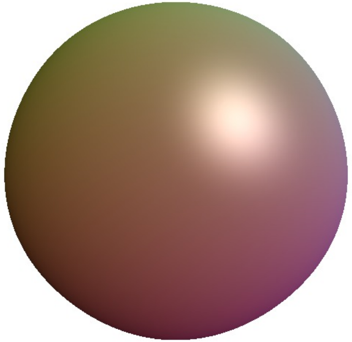
# Vertex Data Interpolation

- Interpolates arbitrary user data over geometries (non-trivial for subdivision geometries)
- Interpolated data P as well as dPdu and dPdv can be calculated at arbitrary location
- Enables smooth normals and anisotropic texture lookups
- Different rules for interpolation of texture coordinates supported (by evaluation of second subdiv mesh)



# Vertex Data Interpolation Example

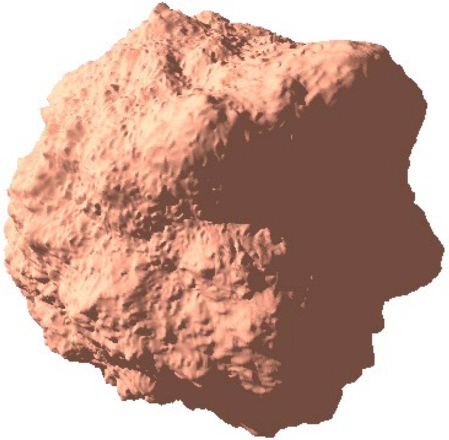
```
rtcNewScene (RTC_STATIC, RTC_INTERSECT1 | RTC_INTERPOLATE);
...
unsigned geomID = rtcNewSubdivisionMesh (...);
rtcSetBuffer (scene,geomID,RTC_INDEX_BUFFER,  indices,  0, sizeof(int));
rtcSetBuffer (scene,geomID,RTC_VERTEX_BUFFER, vertices, 0, sizeof(float3));
rtcSetBuffer (scene,geomID,RTC_USER_VERTEX_BUFFER, vertex_colors, 0, sizeof(float3));
...
rtcCommit (scene);
...
rtcIntersect (scene, ray);
...
float3 P, dPdu, dPdv;
rtcInterpolate (scene, ray.geomID, ray.primID, ray.u,ray.v, RTC_VERTEX_BUFFER, &P, &dPdu, &dPdv, 3);

float3 color;
rtcInterpolate (scene, ray.geomID, ray.primID, ray.u,ray.v, RTC_USER_VERTEX_BUFFER, &color, 0,0, 3);
```



# Displaced Subdivision Surface

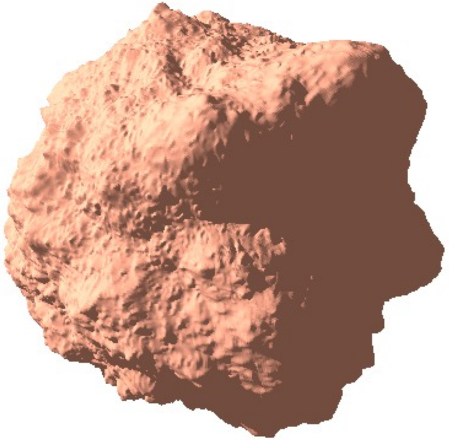
- Support for vector displacement
- Tessellation approach enables displacements
- Callback function displaces vertex positions
- Smooth normals possible through approximation

```
Q = P + D*Ng
dQdu ≈ dPdu + dDdu*Ng
dQdv ≈ dPdv + dDdv*Ng
```



# Displaced Subdivision Surface Example

```
void displacementFunction(
   void* ptr, int geomID, int primID,
   const float* u,  const float* v,
   const float* nx,  const float* ny, const float* nz,
   float* px, float* py, float* pz,
   size_t N)
{
   for (size_t i = 0; i<N; i++) {
      float D = displacement(...);
      px[i] += D*nx[i];
      py[i] += D*ny[i];
      pz[i] += D*nz[i];
   }
}
```



```
BBox3fa bounds(...);
rtcSetDisplacementFunction (scene,geomID,displacementFunction,&bounds);
```

# Demo

# Summary

- Embree delivers highest ray tracing performance on CPUs
- Embree is easy to use through its API
- Subdivision surface support compatible to OpenSubdiv 3.0
- Free and Open Source (https://embree.github.com)

# Questions?

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