Welcome!

Lecture 2 - “Acceleration Structures”
Today’s Agenda:

- Problem Analysis
- Early Work
- BVH Up Close
Analysis

Just Cause 3
Avalanche Studios, 2015

World War Z
Paramount Pictures, 2013
Analysis

Characteristics

Rasterization:
- Games
- Fast
- Realistic
- Consumer hardware

Ray Tracing:
- Movies
- Slow
- Very Realistic
- Supercomputers

Characteristics

Advanced Graphics – Acceleration Structures

Heaven7, Exceed, 2000

LOTR: The Return of the King, 2003

Mirror’s Edge, DICE, 2008

Crysis, 2007
Analysis

Advanced Graphics – Acceleration Structures

Crysis, 2007
Analysis

Characteristics

Reality:

- everyone has a budget
- bar must be raised
- we need to optimize.

Cost Breakdown for Ray Tracing:

- Pixels
- Primitives
- Light sources
- Path segments

*Mind scalability as well as constant cost.*

Example: scene consisting of 1k spheres and 4 light sources, diffuse materials, rendered to 1M pixels:

\[ 1M \times 5 \times 1k = 5 \times 10^9 \text{ ray/prim intersections.} \]

(multiply by desired framerate for realtime)
Optimizing Ray Tracing

Options:

1. Faster intersections (reduce constant cost)
2. Faster shading (reduce constant cost)
3. Use more expressive primitives (trade constant cost for algorithmic complexity)
4. Fewer of ray/primitive intersections (reduce algorithmic complexity)

Note for option 1:

At 5 billion ray/primitive intersections, we will have to bring down the cost of a single intersection to 1 cycle on a 5Ghz CPU – if we want one frame per second.
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Complex Primitives

More expressive than a triangle:

- Sphere
- Torus
- Teapotahedron
- Bézier surfaces
- Subdivision surfaces*
- Implicit surfaces**
- Fractals***

**: Knoll et al., Interactive Ray Tracing of Arbitrary Implicits with SIMD Interval Arithmetic. RT'07 Proceedings, Pages 11-18
Rubin & Whitted*

"Hierarchically Structured Subspaces"

Proposed scheme:

- Manual construction of hierarchy
- Oriented parallelepipeds

A transformation matrix allows efficient intersection of the skewed / rotated boxes, which can tightly enclose actual geometry.

Amanatides & Woo*

“3DDD of a regular grid”

The grid can be automatically generated.

Considerations:

- Ensure that an intersection happens in the current grid cell
- Use mailboxing to prevent repeated intersection tests

Glassner*

"Hierarchical spatial subdivision"

Like the grid, octrees can be automatically generated.

Advantages over grids:

- Adapts to local complexity: fewer steps
- No need to hand-tune grid resolution

Disadvantage compared to grids:

- Expensive traversal steps.

Early Work

BSP Trees

root
BSP Tree*

“Binary Space Partitioning”

Split planes are chosen from the geometry.
A good split plane:

- Results in equal amounts of polygons on both sides
- Splits as few polygons as possible

The BSP tends to suffer from numerical instability (splinter polygons).

Early Work

**kD-Tree***

"Axis-aligned BSP tree"

---

Early Work

kD-Tree Construction*

Given a scene $S$ consisting of $N$ primitives:
A kd-tree over $S$ is a binary tree that recursively subdivides the space covered by $S$.

- The root corresponds to the axis aligned bounding box (AABB) of $S$;
- Interior nodes represent planes that recursively subdivide space perpendicular to the coordinate axis;
- Leaf nodes store references to all the triangles overlapping the corresponding voxel.

*: On building fast kD-trees for ray tracing, and on doing that in $O(N \log N)$, Wald & Havran, 2006
function Build( triangles $T$, voxel $V$ )
{
  if (Terminate( $T$, $V$ )) return new LeafNode( $T$ )
  $p = \text{FindPlane}( T, V )$
  $V_L, V_R = \text{Split } V \text{ with } p$
  $T_L = \{ t \in T | (t \cap V_L) \neq \emptyset \}$
  $T_R = \{ t \in T | (t \cap V_R) \neq \emptyset \}$
  return new InteriorNode( $p$,
    Build( $T_L$, $V_L$ ),
    Build( $T_R$, $V_R$ )
  )
}

Function BuildKDTree( triangles $T$ )
{
  $V = \text{bounds}(T)$
  return Build( $T$, $V$ )
}
Considerations

- **Termination**
  
  *minimum primitive count, maximum recursion depth*

- **Storage**
  
  *primitives may end up in multiple voxels: required storage hard to predict*

- **Empty space**
  
  *empty space reduces probability of having to intersect primitives*

- **Optimal split plane position / axis**
  
  *good solutions exist – will be discussed later.*
**Traversal***

1. Find the point $P$ where the ray enters the voxel
2. Determine which leaf node contains this point
3. Intersect the ray with the primitives in the leaf
   If intersections are found:
   - Determine the closest intersection
   - If the intersection is inside the voxel: done
4. Determine the point $B$ where the ray leaves the voxel
5. Advance $P$ slightly beyond $B$

Note: step 2 traverses the tree repeatedly – inefficient.

Traversing – Alternative Method*

For interior nodes:
1. Determine ‘near’ and ‘far’ child node
2. Determine if ray intersects ‘near’ and/or ‘far’
   If only one child node intersects the ray:
     - Traverse the node (goto 1)
   Else (both child nodes intersect the ray):
     - Push ‘far’ node to stack
     - Traverse ‘near’ node (goto 1)

For leaf nodes:
1. Determine the nearest intersection
2. Return if intersection is inside the voxel.

Early Work

kD-Tree Traversal

Traversing a kD-tree is done in a strict order.

Ordered traversal means we can stop as soon as we find a valid intersection.
## Early Work

### Acceleration Structures

<table>
<thead>
<tr>
<th></th>
<th>Partitioning</th>
<th>Construction</th>
<th>Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid</td>
<td>space</td>
<td>O(n)</td>
<td>low</td>
</tr>
<tr>
<td>Octree</td>
<td>space</td>
<td>O(n log n)</td>
<td>medium</td>
</tr>
<tr>
<td>BSP</td>
<td>space</td>
<td>O(n^2)</td>
<td>good</td>
</tr>
<tr>
<td>kD-tree</td>
<td>space</td>
<td>O(n log n)</td>
<td>good</td>
</tr>
<tr>
<td>BVH</td>
<td>object</td>
<td>O(n log n)</td>
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<tr>
<td>Tetrahedralization</td>
<td>space</td>
<td>?</td>
<td>low</td>
</tr>
<tr>
<td>BIH</td>
<td>object</td>
<td>O(n log n)</td>
<td>medium</td>
</tr>
<tr>
<td>...</td>
<td></td>
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</tbody>
</table>
Today’s Agenda:

- Problem Analysis
- Early Work
- BVH Up Close
Automatic Construction of Bounding Volume Hierarchies

BVH: tree structure, with:

- a bounding box per node
- pointers to child nodes
- geometry at the leaf nodes
Automatic Construction of Bounding Volume Hierarchies

**BVH: tree structure, with:**

- a bounding box per node
- pointers to child nodes
- geometry at the leaf nodes

```c
struct BVHNode {
    AABB bounds;
    bool isLeaf;
    BVHNode*** child;
    Primitive*** primitive;
};
```
Automatic Construction of Bounding Volume Hierarchies
Automatic Construction of Bounding Volume Hierarchies

1. Determine AABB for primitives in array
2. Determine split axis and position
3. Partition
4. Repeat steps 1-3 for each partition

Note:

Step 3 can be done ‘in place’.
This process is identical to QuickSort: the split plane is The ‘pivot’.
Automatic Construction of Bounding Volume Hierarchies

```
struct BVHNode {
    AABB bounds;                // 24 bytes
    bool isLeaf;                // 4 bytes
    BVHNode* left, *right;     // 8 or 16 bytes
    Primitive** primList;      // ? bytes
};
```
Auto-aligned Construction of Bounding Volume Hierarchies

```c
struct BVHNode {
    AABB bounds; // 24 bytes
    bool isLeaf; // 4 bytes
    BVHNode* left, *right; // 8 or 16 bytes
    int first, count; // 8 bytes
};

// 24 bytes
// 4 bytes
// 8 or 16 bytes
// 8 bytes
```
Automatic Construction of Bounding Volume Hierarchies

void BVH::ConstructBVH( Primitive* primitives )
{
    // create index array
    indices = new uint[N];
    for( int i = 0; i < N; i++ ) indices[i] = i;

    // allocate BVH root node
    root = new BVHNode();

    // subdivide root node
    root->first = 0;
    root->count = N;
    root->bounds = CalculateBounds( primitives, root->first, root->count );
    root->Subdivide();
}

void BVHNode::Subdivide()
{
    if (count < 3) return;
    this.left = new BVHNode();
    this.right = new BVHNode();
    Partition();
    this.left->Subdivide();
    this.right->Subdivide();
    this.isLeaf = false;
}
Automatic Construction of Bounding Volume Hierarchies

```cpp
void BVH::ConstructBVH( Primitive* primitives )
{
    // create index array
    indices = new uint[N];
    for( int i = 0; i < N; i++ ) indices[i] = i;

    // allocate BVH root node
    pool = new BVHNode[N * 2 - 1];
    root = pool[0];
    poolPtr = 2;

    // subdivide root node
    root->first = 0;
    root->count = N;
    root->bounds = CalculateBounds( primitives, root->first, root->count );
    root->Subdivide();
}

void BVHNode::Subdivide()
{
    if (count < 3) return;
    this.left = pool[poolPtr++];
    this.right = pool[poolPtr++];
    Partition();
    this.left->Subdivide();
    this.right->Subdivide();
    this.isLeaf = false;
}
```
Automatic Construction of Bounding Volume Hierarchies

```
struct BVHNode {
    AABB bounds; // 24 bytes
    bool isLeaf; // 4 bytes
    int left, right; // 8 bytes
    int first, count; // 8 bytes, total 44 bytes
};
```
Automatic Construction of Bounding Volume Hierarchies

```c
struct BVHNode {
    AABB bounds;       // 24 bytes
    int left;          // 4 bytes
    int first, count;  // 8 bytes, total 36
};
```
Automatic Construction of Bounding Volume Hierarchies

struct BVHNode {
  AABB bounds;  // 24 bytes
  int leftFirst; // 4 bytes
  int count;    // 4 bytes, total 32 😊
};
Automatic Construction of Bounding Volume Hierarchies

Optimal BVH representation:

- Partitioning of array of indices pointing to original triangles
- Using indices of BVH nodes, and assuming right = left + 1
- BVH nodes use exactly 32 bytes (2 per cache line)
- BVH node pool allocated in cache aligned fashion
- AABB splitted in 2x 12 bytes; 1st followed by ‘leftFirst’, 2nd by ‘count’.

Note: the BVH is now ‘relocatable’ and thus ‘serializable'.
BVH Traversal

root

left

right

top - bottom - top - bottom
BVH Traversal

Basic process:

```cpp
BVHNode::Traverse( Ray r )
{
    if (!r.Intersects( bounds )) return;
    if (isleaf())
    {
        IntersectPrimitives();
    }
    else
    {
        pool[left].Traverse( r );
        pool[left + 1].Traverse( r );
    }
}
```

Ray: vec3 O, D float t
BVH

**BVH Traversal**

**Ordered traversal, option 1:**

- Calculate distance to both child nodes
- Traverse the nearest child node first

**Ordered traversal, option 2:**

- For each BVH node, store the axis along which it was split
- Use ray direction sign for that axis to determine near and far

**Ordered traversal, option 3:**

- Determine the axis for which the child node centroids are furthest apart
- Use ray direction sign for that axis to determine near and far.
BVH Traversal

Ordered traversal of a BVH is approximative.

- Nodes may overlap.

And:

- We may find a closer intersection in a node that we visit later.

However:

- We do not have to visit nodes beyond an already found intersection distance.
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INFOMAGR – Advanced Graphics
Jacco Bikker - November 2017 - February 2018

END of “Acceleration Structures”
next lecture: “The Perfect BVH”