Welcome!

Lecture 3 - “Acceleration Structures”

\[ I(x, x') = g(x, x') \left[ \epsilon(x, x') + \int_I \rho(x, x', x'') I(x', x'') dx'' \right] \]
Today's Agenda:

- Problem Analysis
- Early Work
- BVH Up Close
Analysis

“Cornell Box”

Voxel game
Advanced Graphics – Acceleration Structures

Analysis

Unreal 5 Tech Demo

Avengers Endgame
Analysis

Characteristics

Rasterization:
- Games
- Fast
- Realistic
- Consumer hardware

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

Advanced Graphics – Acceleration Structures
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:

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

(multiply by desired framerate for realtime)
Analysis

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.
Today's Agenda:

- Problem Analysis
- Early Work
- BVH Up Close
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 Implicit Surfaces 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*

"3DDDA 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($T$)
    Plane $p = $FindPlane($T$, $V$)
    Voxel $V_L, V_R = $Split $V$ with $p$
    triangles $T_L = \{t \in T | (t \cap V_L) \neq 0\}$
    triangles $T_R = \{t \in T | (t \cap V_R) \neq 0\}$
    return new InteriorNode($p$,
        Build($T_L$, $V_L$),
        Build($T_R$, $V_R$)
    )
}

Function BuildKDTree( triangles $T$ )
{
    Voxel $V = bounds(T)$
    return Build($T$, $V$)
}
Early Work

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.*
Early Work

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

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.

Early Work

Traversal – 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 ‘near’ and/or ‘far’
   - 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>
<td>good</td>
</tr>
<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>
<td></td>
<td></td>
</tr>
</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
};
Automatic Construction of Bounding Volume Hierarchies

\[
\begin{array}{cccccccccccc}
0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12
\end{array}
\]

\[
\begin{array}{cccccccccccc}
\text{primitives} & \text{primitive indices}
\end{array}
\]

\[
\text{struct BVHNode}
\]

- AABB bounds; // 24 bytes
- bool isLeaf; // 4 bytes
- BVHNode* left, *right; // 8 or 16 bytes
- int first, count; // 8 bytes
Automatic Construction of Bounding Volume Hierarchies

```cpp
void 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

```c++
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();
}
```
Automatic Construction of Bounding Volume Hierarchies

```c
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
}
```

BVH nodes
Automatic Construction of Bounding Volume Hierarchies

```c
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 );
    }
}
```
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**

**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.
Today's Agenda:

- Problem Analysis
- Early Work
- BVH Up Close
INFOMAGR – Advanced Graphics
Jacco Bikker - November 2021 - February 2022

END of “Acceleration Structures”
next lecture: “Light Transport”