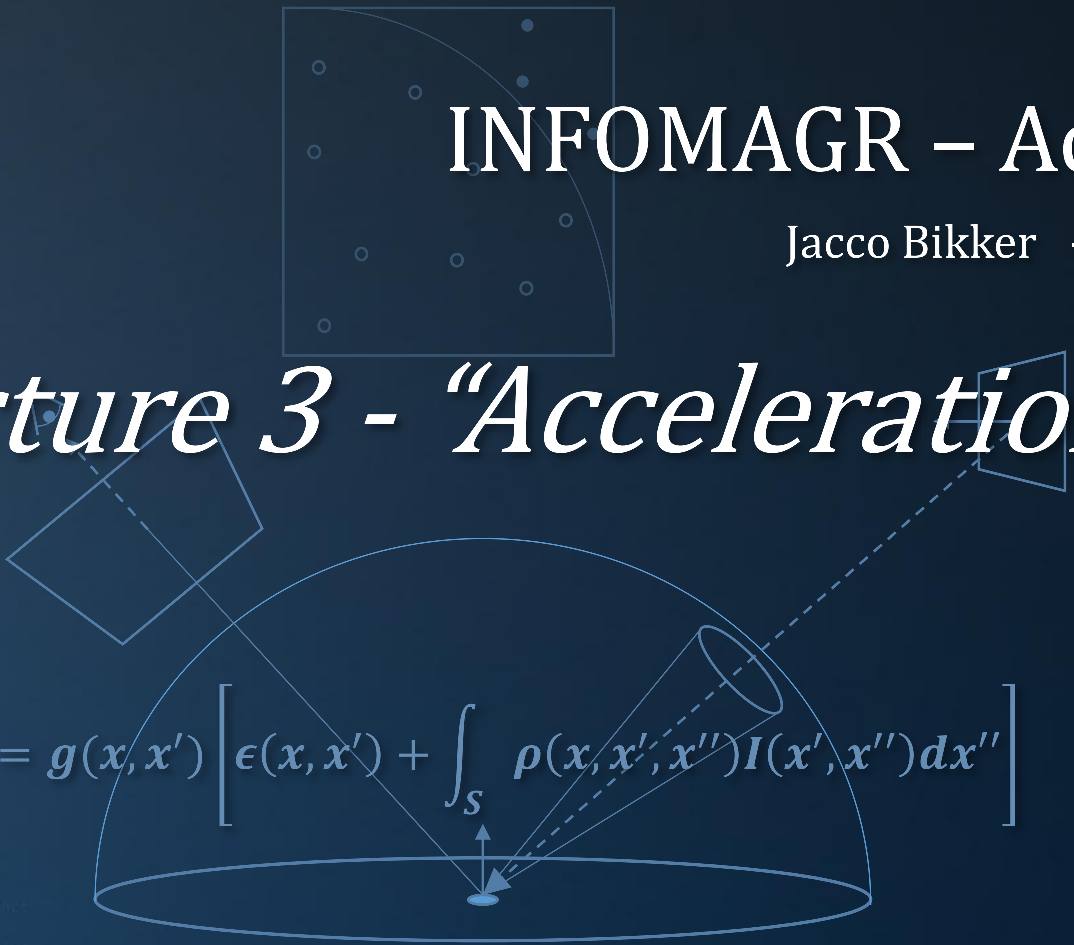
INFOMAGR – Advanced Graphics

Jacco Bikker - November 2021 - February 2022

Lecture 3 - “Acceleration Structures”

Welcome!

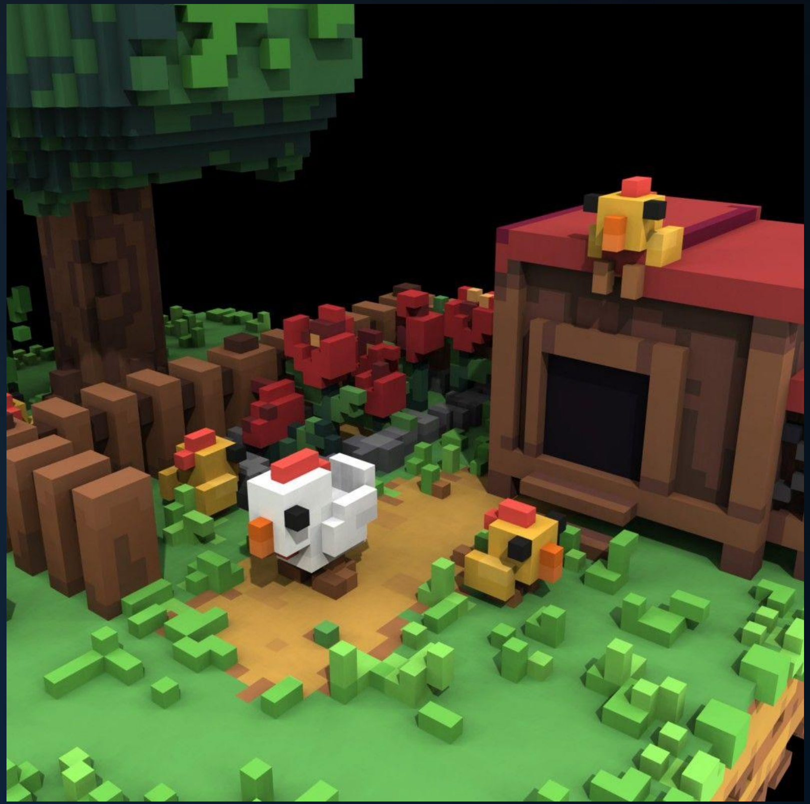


Today's Agenda:

- Problem Analysis
- Early Work
- BVH Up Close

Analysis

“Cornell Box”



Voxel game

Analysis

Unreal 5 Tech Demo

Avengers Endgame

Analysis

Characteristics

Rasterization:

- Games
- Fast
- Realistic
- Consumer hardware

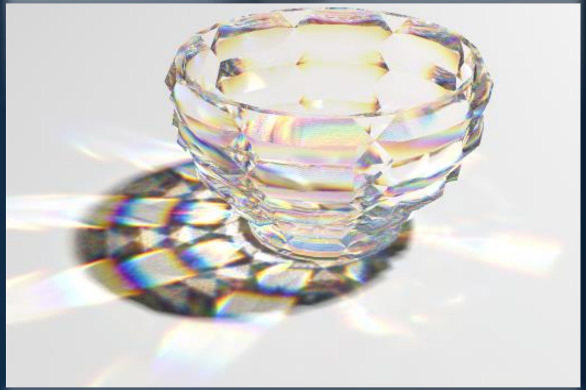
Ray Tracing:

- Movies
- Slow
- Very Realistic
- Supercomputers


Heaven7, Exceed, 2000


LOTR: The Return of the King, 2003


Mirror's Edge, DICE, 2008



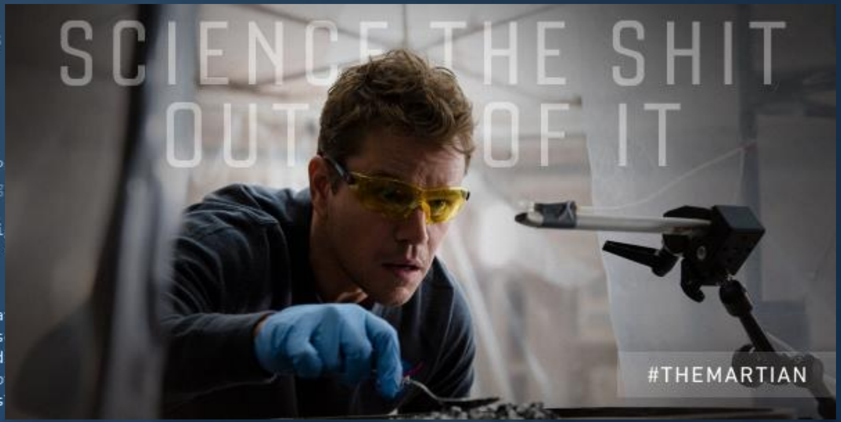

Crysis, 2007

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:

$1M \times 5 \times 1k = 5 \cdot 10^9$ 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.

Crysis, 2007

Today's Agenda:

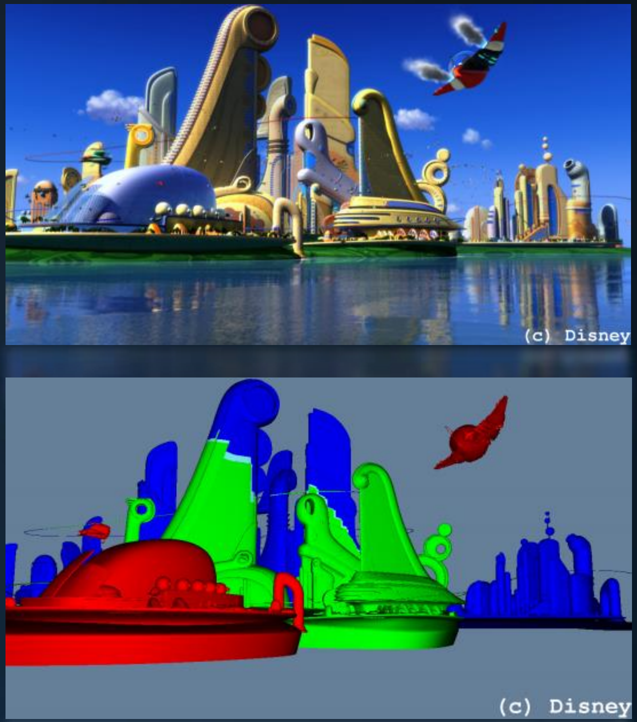
- Problem Analysis
- Early Work
- BVH Up Close

Early Work

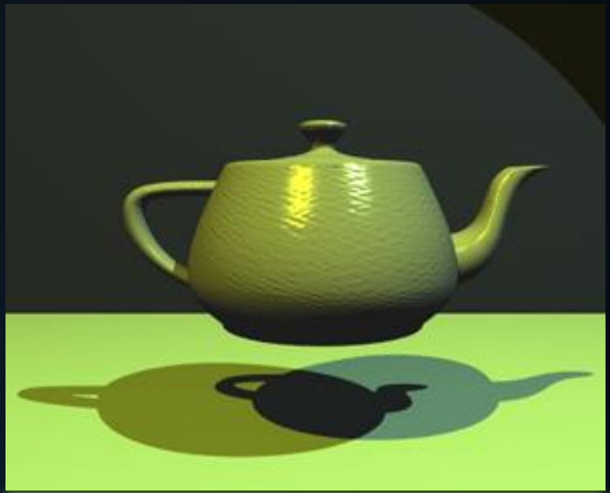
Complex Primitives

More expressive than a triangle:

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



Meet the Robinsons, Disney, 2007



Utah Teapot, Martin Newell, 1975

*: Benthin et al., Packet-based Ray Tracing of Catmull-Clark Subdivision Surfaces. 2007.
**: Knoll et al., Interactive Ray Tracing of Arbitrary Implicits with SIMD Interval Arithmetic. RT'07 Proceedings, Pages 11-18
***: Hart et al., Ray Tracing Deterministic 3-D Fractals. In Proceedings of SIGGRAPH '89, pages 289-296.

Early Work

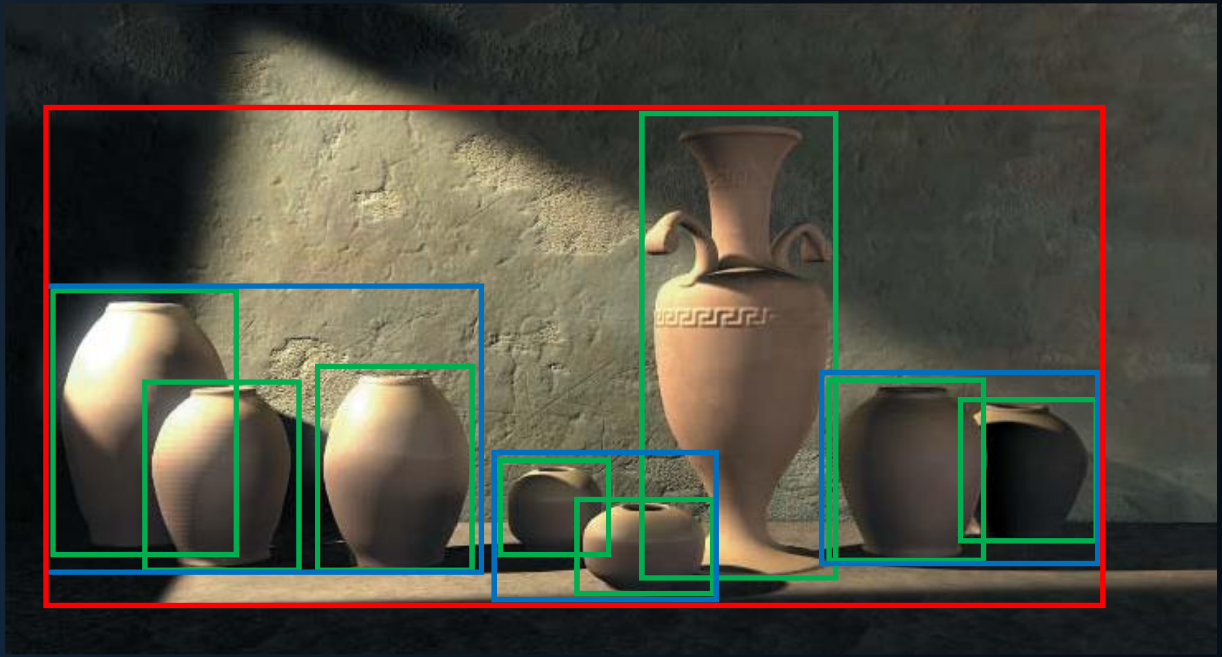
Rubin & Whitted*

"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.



*: S. M. Rubin and T. Whitted. A 3-Dimensional Representation for Fast Rendering of Complex Scenes. In: Proceedings of SIGGRAPH '*80*, pages 110–116.

Early Work

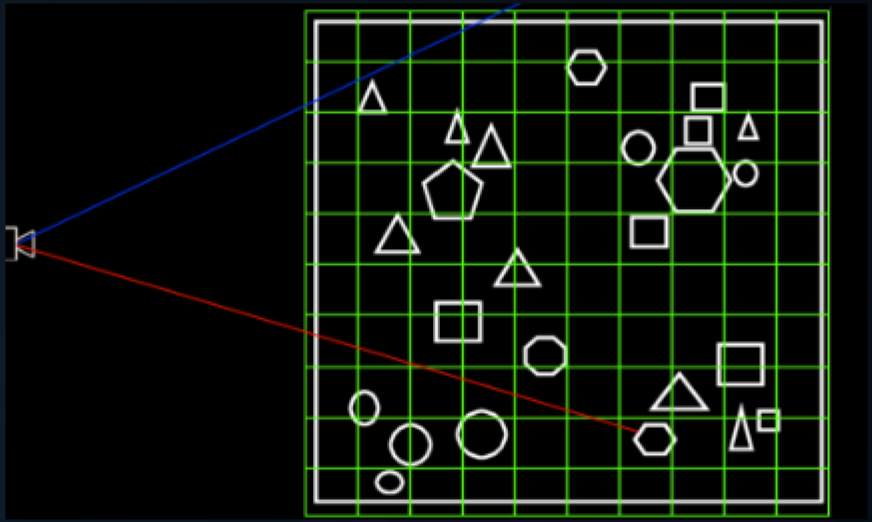
Amanatides & Woo*

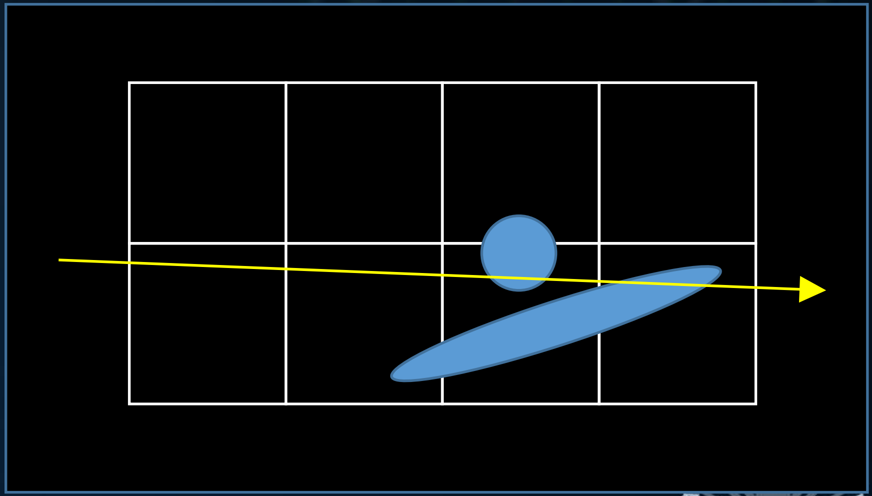
"3DDDA of a regular grid"

The grid can be automatically generated.

Considerations:

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





*: J. Amanatides and A. Woo. A Fast Voxel Traversal Algorithm for Ray Tracing. In Eurographics '*87*, pages 3–10, 1987.

Early Work

Glassner*

"Hierarchical spatial subdivision"

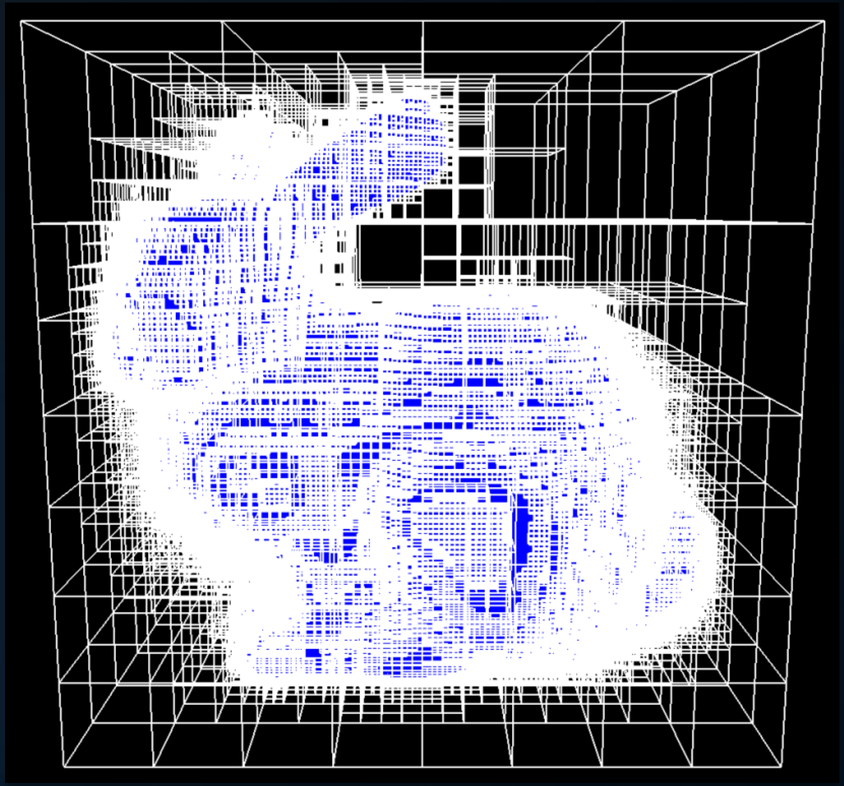
Like the grid, octrees can be automatically generated.

Advantages over grids:

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

Disadvantage compared to grids:

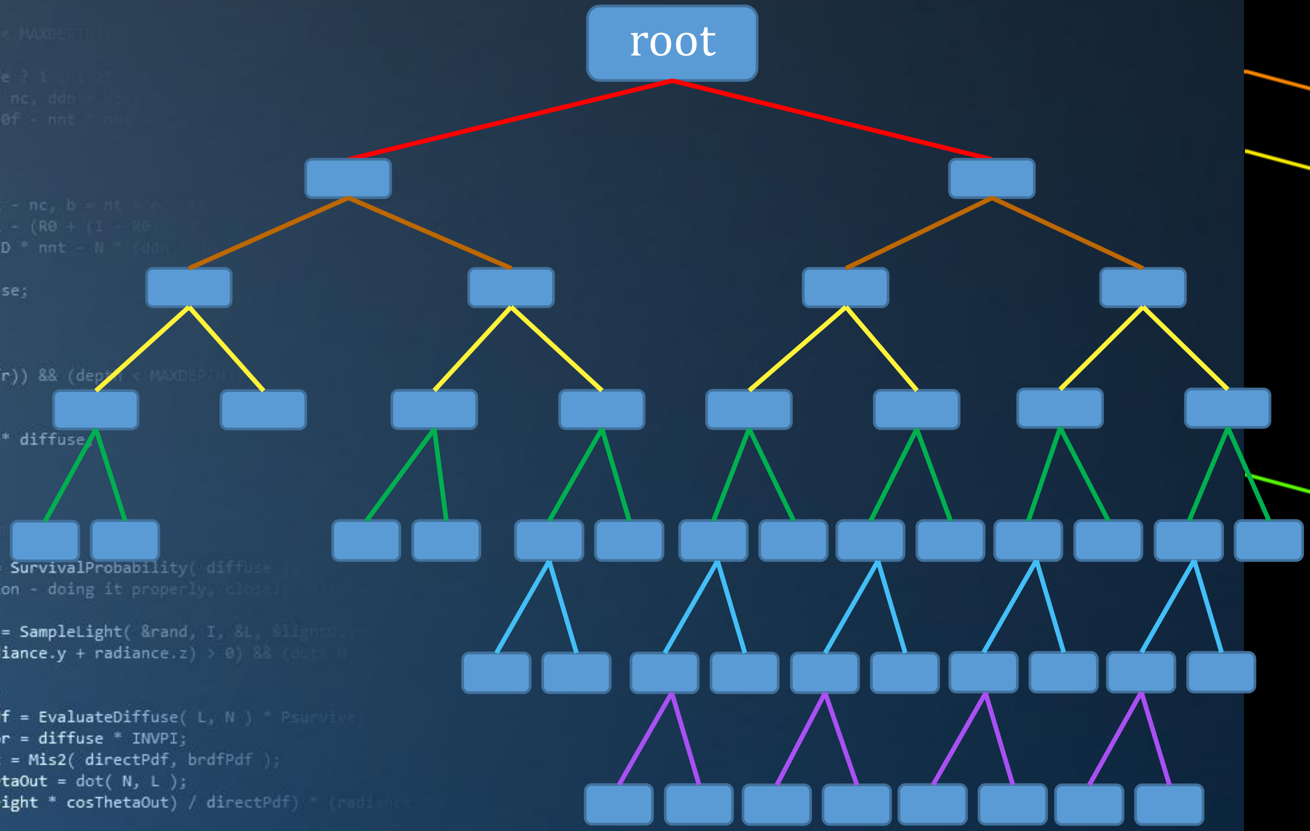
- Expensive traversal steps.

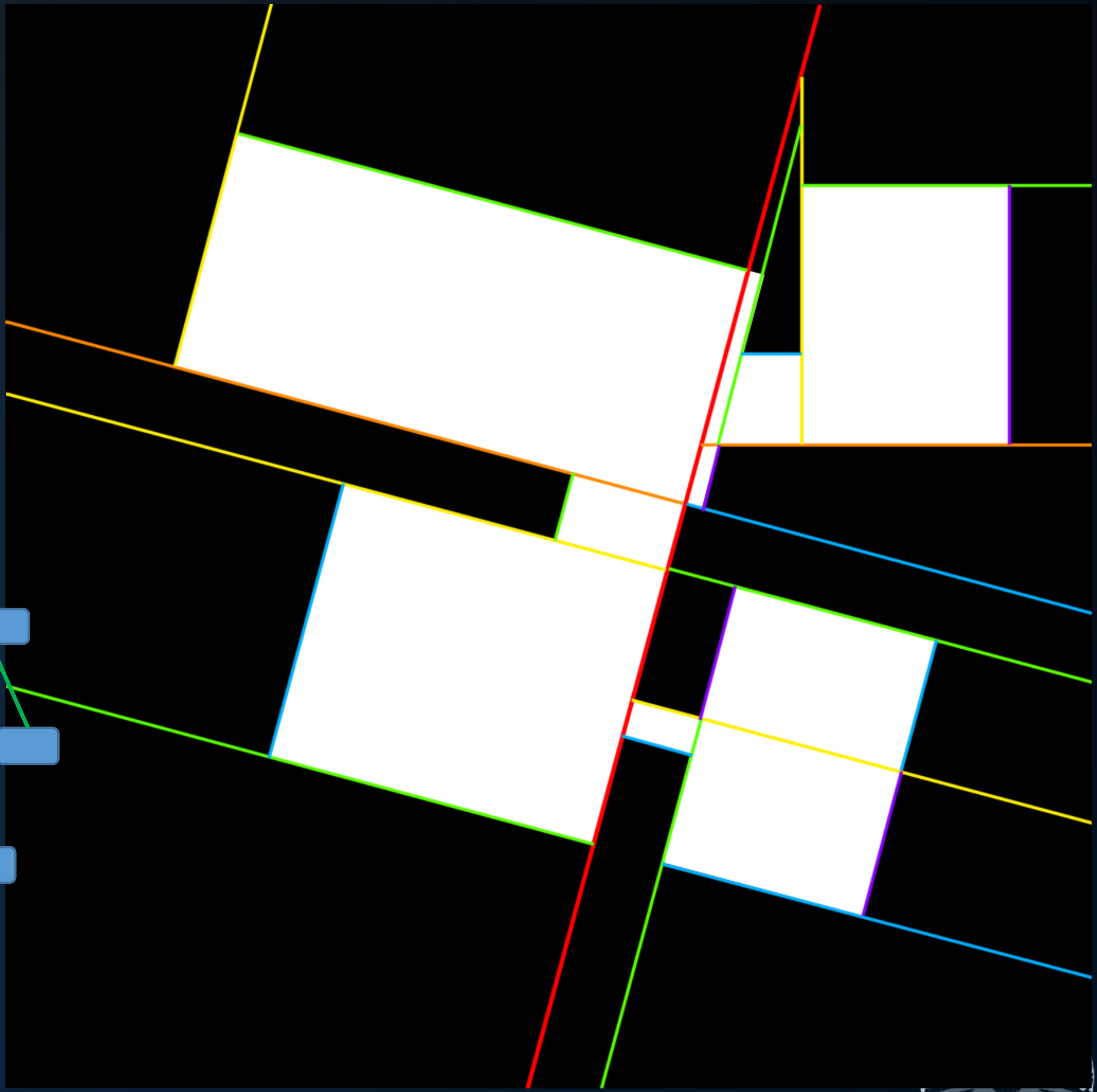


*: A. S. Glassner. Space Subdivision for Fast Ray Tracing. IEEE Computer Graphics and Applications, 4:15–22, 1984.

Early Work

BSP Trees





Early Work

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

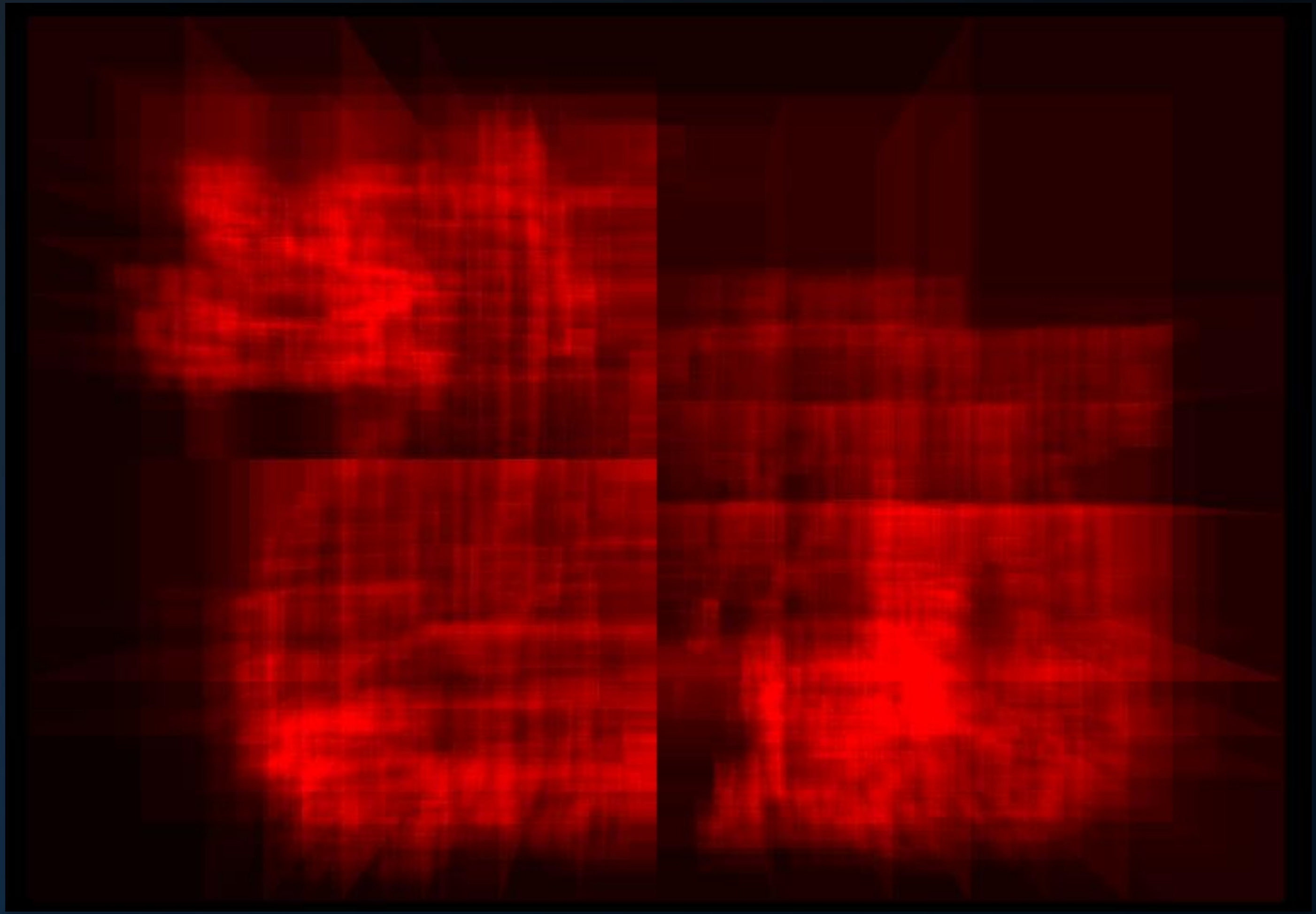
The BSP tends to suffer from numerical instability (splinter polygons).

*: K. Sung, P. Shirley. Ray Tracing with the BSP Tree. In: Graphics Gems III, Pages 271-274. Academic Press, 1992.

Early Work

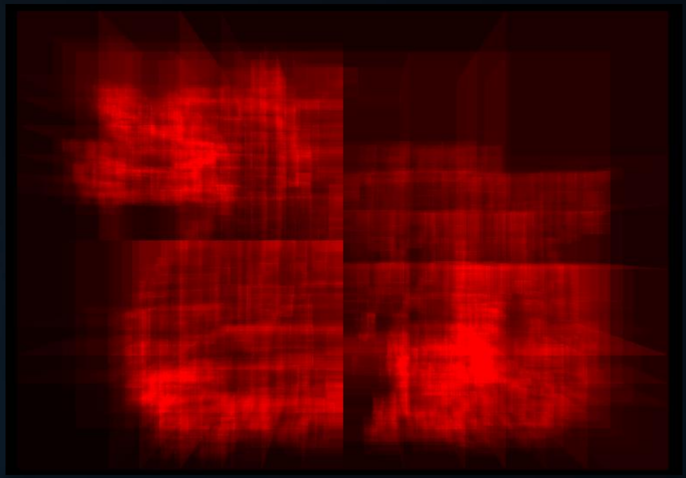
kD-Tree*

"Axis-aligned BSP tree"



*: V. Havran, Heuristic Ray Shooting Algorithms. PhD thesis, 2000.

Early Work



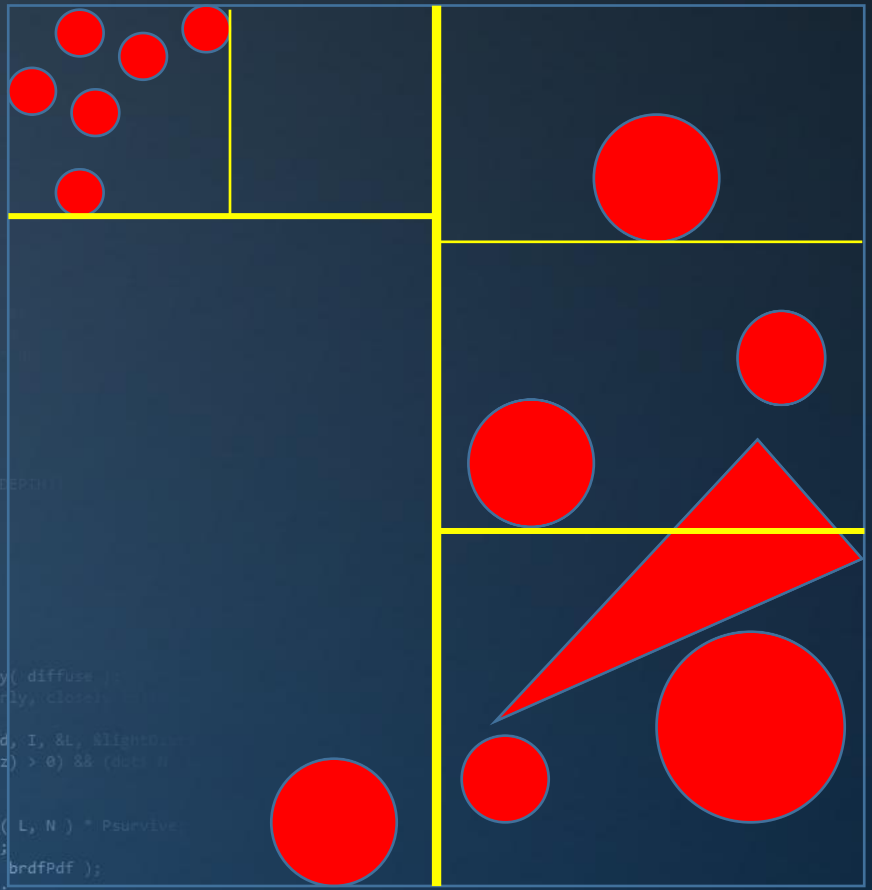
kD-Tree Construction*

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

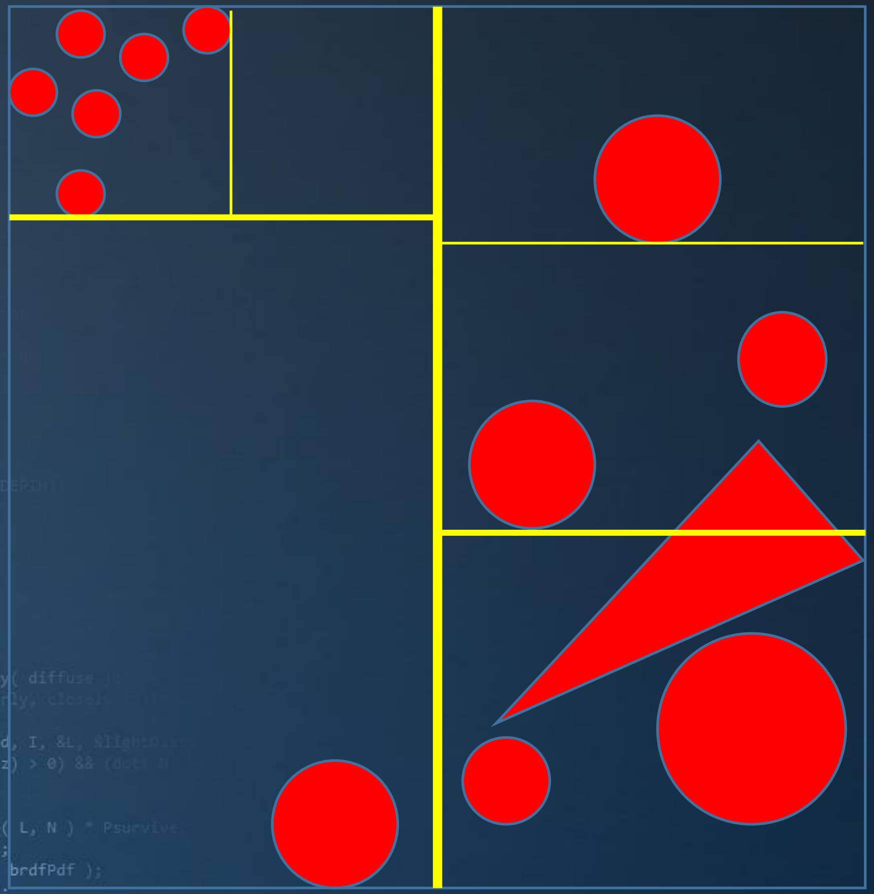
Early Work



```
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 ∈ T | (t ∩ V_L) ≠ 0
   triangles T_R = { t ∈ T | (t ∩ V_R) ≠ 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

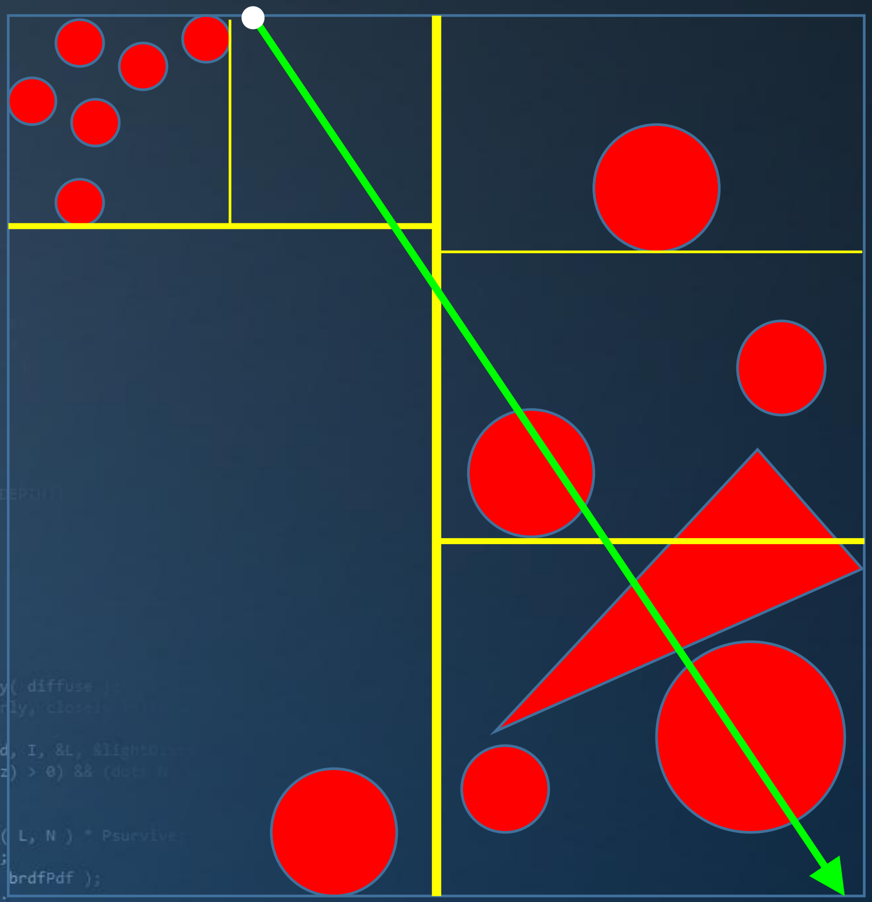
- Empty space

empty space reduces probability of having to intersect primitives

- Optimal split plane position / axis

good solutions exist – will be discussed later.

Early Work

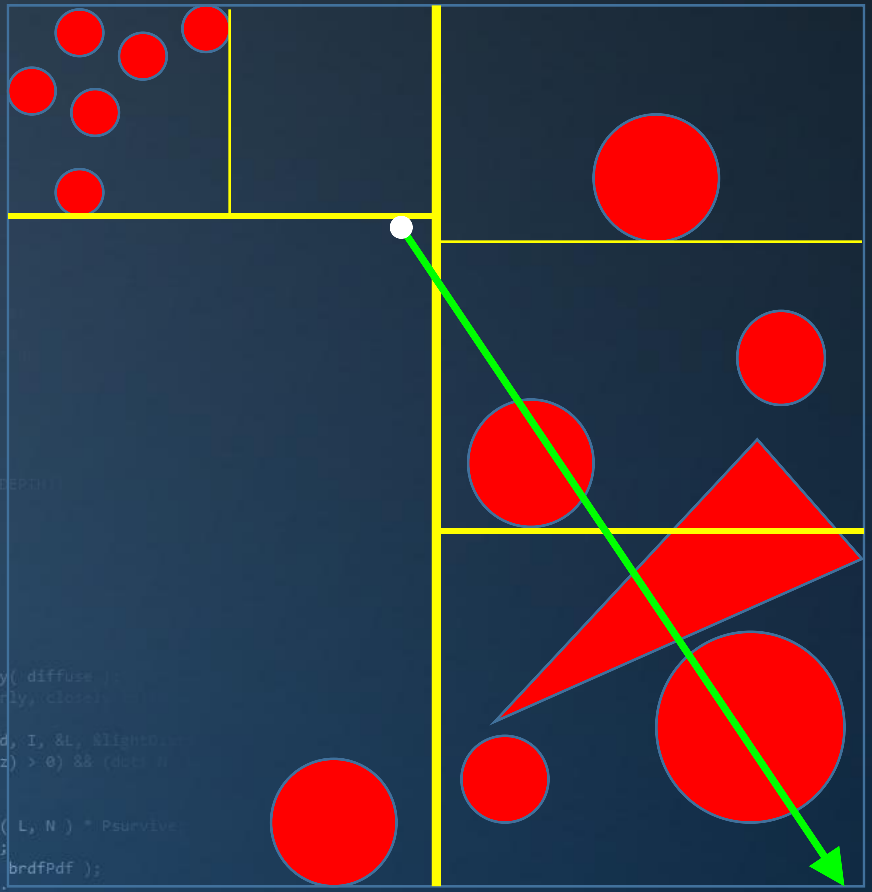


Traversal*

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

*: Space-Tracing: a Constant Time Ray-Tracer, Kaplan, 1994

Early Work



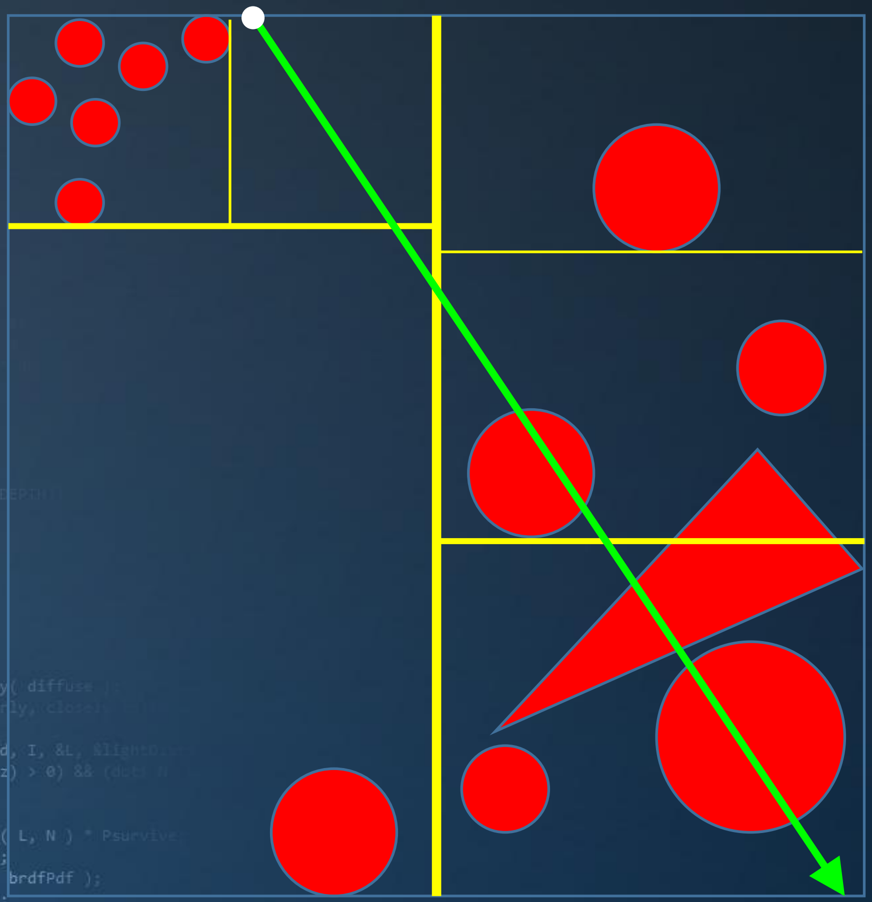
Traversal*

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
4. Determine the point B where the ray leaves the voxel
5. Advance P slightly beyond B
6. Goto 1.

Note: step 2 traverses the tree repeatedly – inefficient.

*: Space-Tracing: a Constant Time Ray-Tracer, Kaplan, 1994

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 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.

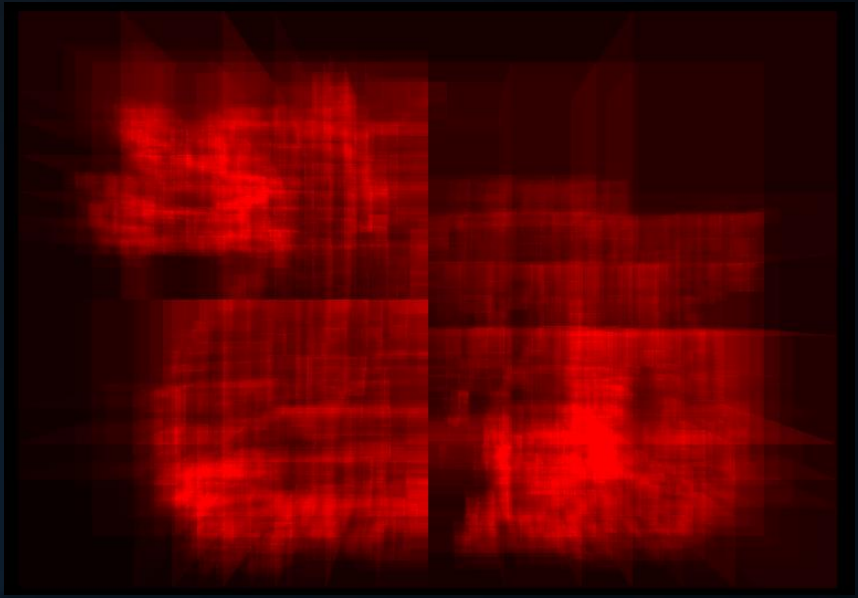
*: Data Structures for Ray Tracing, Jansen, 1986.

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

	Partitioning	Construction	Quality
▪ Grid	space	O(n)	low
▪ Octree	space	O(n log n)	medium
▪ BSP	space	O(n^2)	good
▪ kD-tree	space	O(n log n)	good
▪ BVH	object	O(n log n)	good
▪ Tetrahedralization	space	?	low
▪ BIH	object	O(n log n)	medium
▪ …			

Today's Agenda:

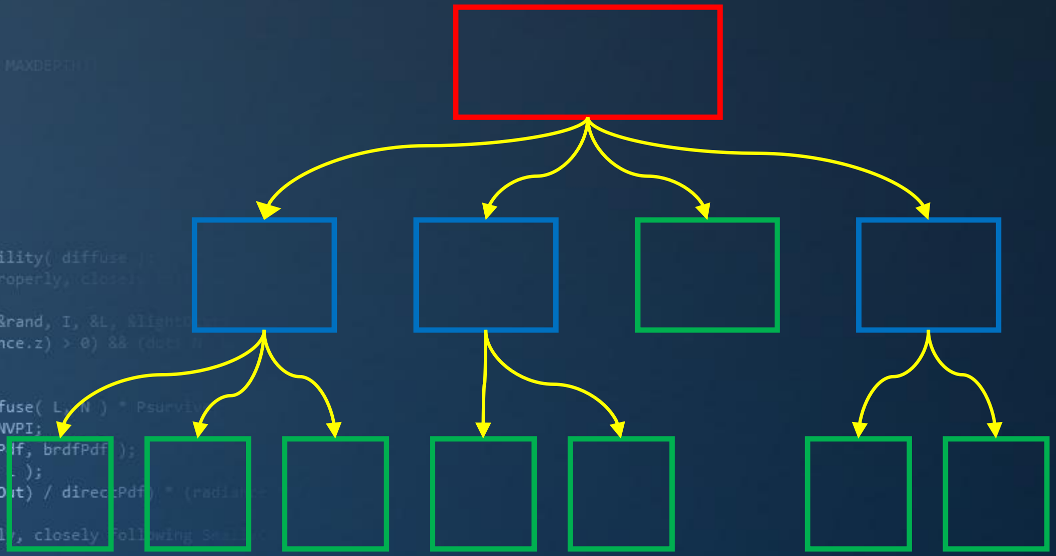
- Problem Analysis
- Early Work
- BVH Up Close

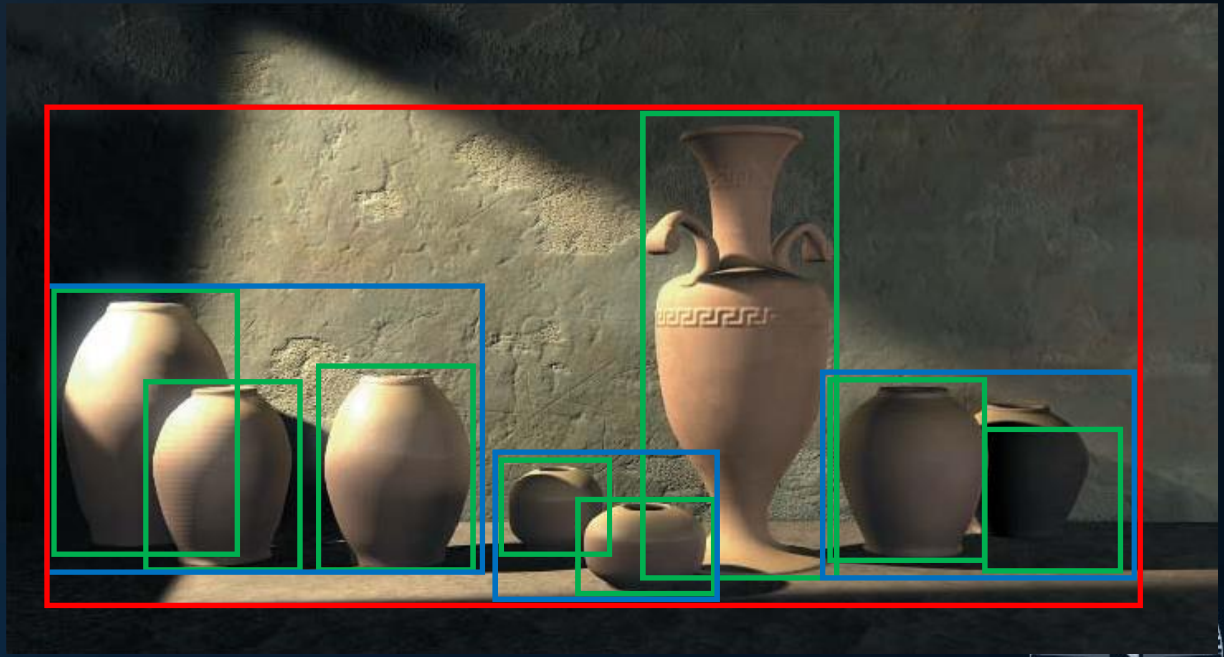
BVH

Automatic Construction of Bounding Volume Hierarchies

BVH: tree structure, with:

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





BVH

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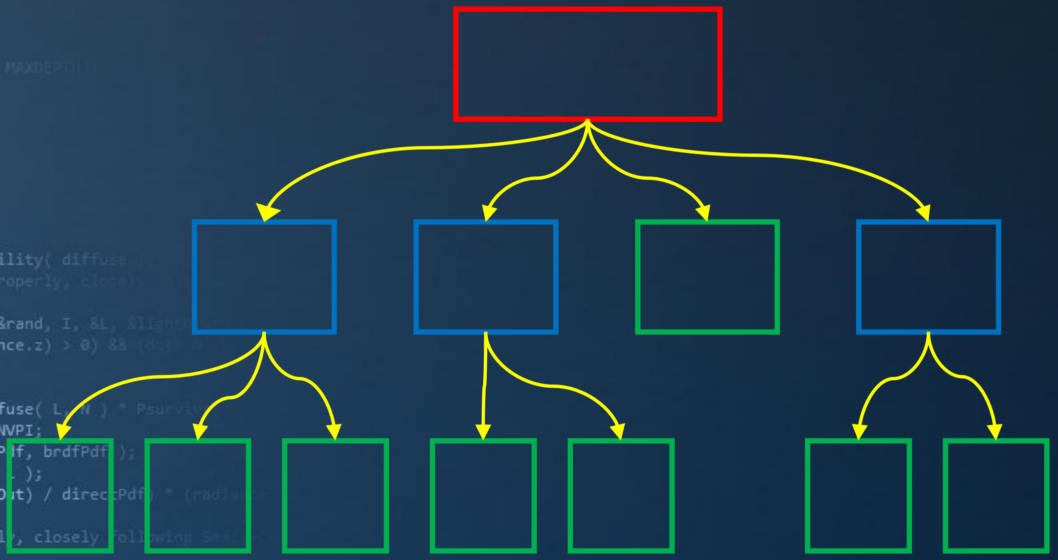
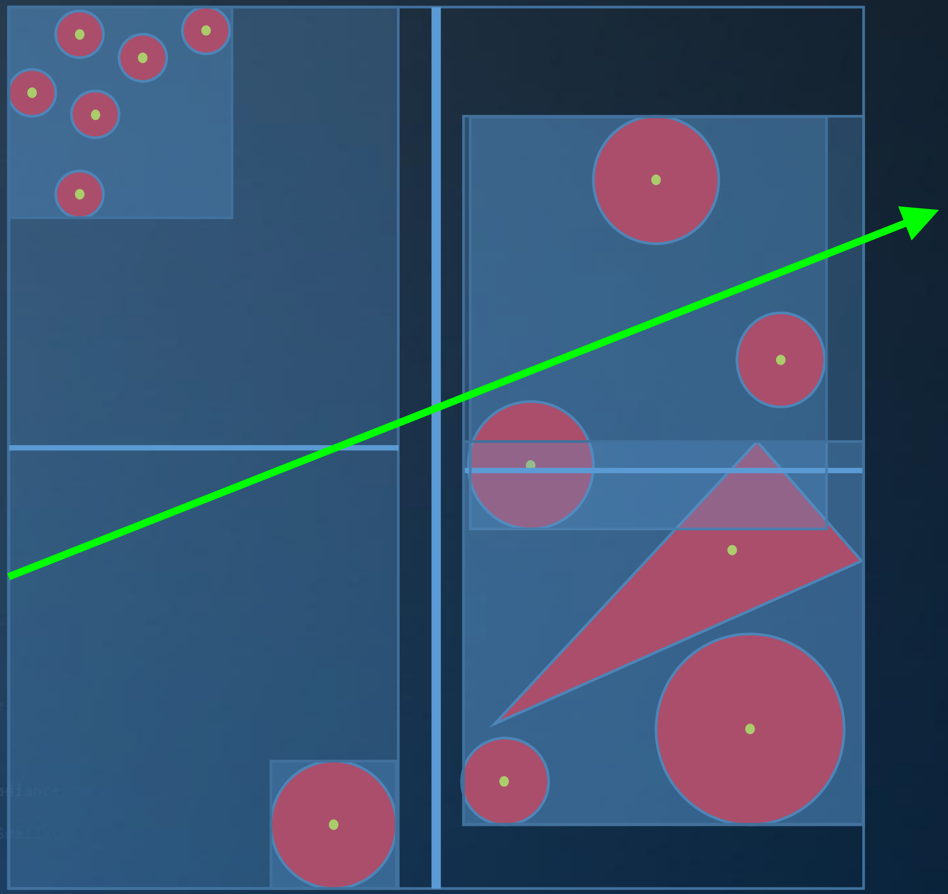
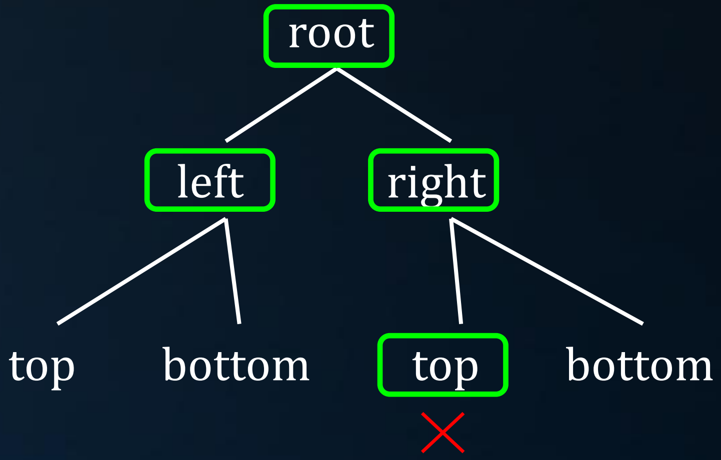


```
struct BVHNode
{
    AABB bounds;
    bool isLeaf;
    BVHNode*[] child;
    Primitive*[] primitive;
};
```

BVH

Automatic Construction of Bounding Volume Hierarchies

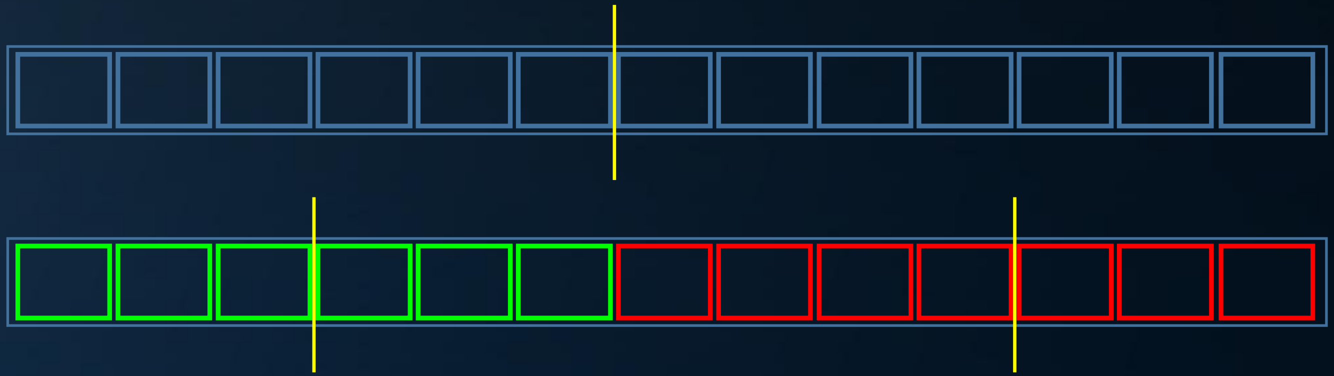




BVH

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



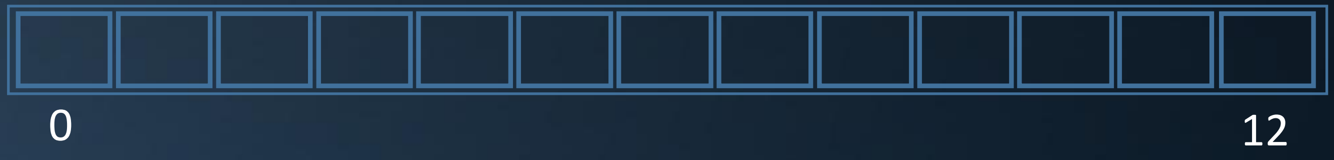
Note:

Step 3 can be done ‘in place’.

This process is identical to QuickSort: the split plane is The ‘pivot’.

BVH

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
};
```

BVH

Automatic Construction of Bounding Volume Hierarchies

primitives

0 12

primitive indices

0	1	2	3	4	5	6	7	8	9	10	11	12

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

BVH

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;
}
```

BVH

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
   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;
}
```

BVH

Automatic Construction of Bounding Volume Hierarchies

primitives

0 12

0	1	2	3	4	5	6	7	8	9	10	11	12

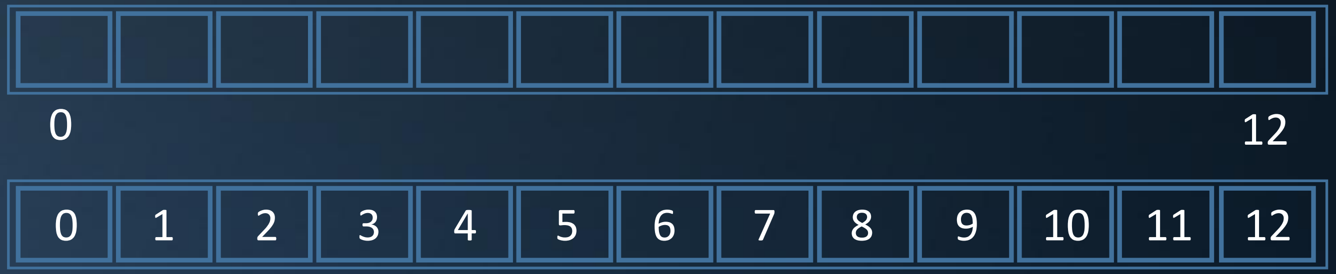
primitive indices

```
struct BVHNode
{
    AABB bounds;                    // 24 bytes
    bool isLeaf;                    // 4 bytes
    int left, right;                // 8 bytes
    int first, count;               // 8 bytes, total 44 bytes
};
```

BVH nodes

BVH

Automatic Construction of Bounding Volume Hierarchies



primitives

primitive indices

```
struct BVHNode
{
    AABB bounds;                 // 24 bytes
    int left;                    // 4 bytes
    int first, count;            // 8 bytes, total 36
};
```

BVH nodes

BVH

Automatic Construction of Bounding Volume Hierarchies

0 12

primitives

0	1	2	3	4	5	6	7	8	9	10	11	12

primitive indices

```
struct BVHNode
{
   AABB bounds;                   // 24 bytes
   int leftFirst;                 // 4 bytes
   int count;                     // 4 bytes, total 32  ☺
};
```

BVH nodes

BVH

Automatic Construction of Bounding Volume Hierarchies

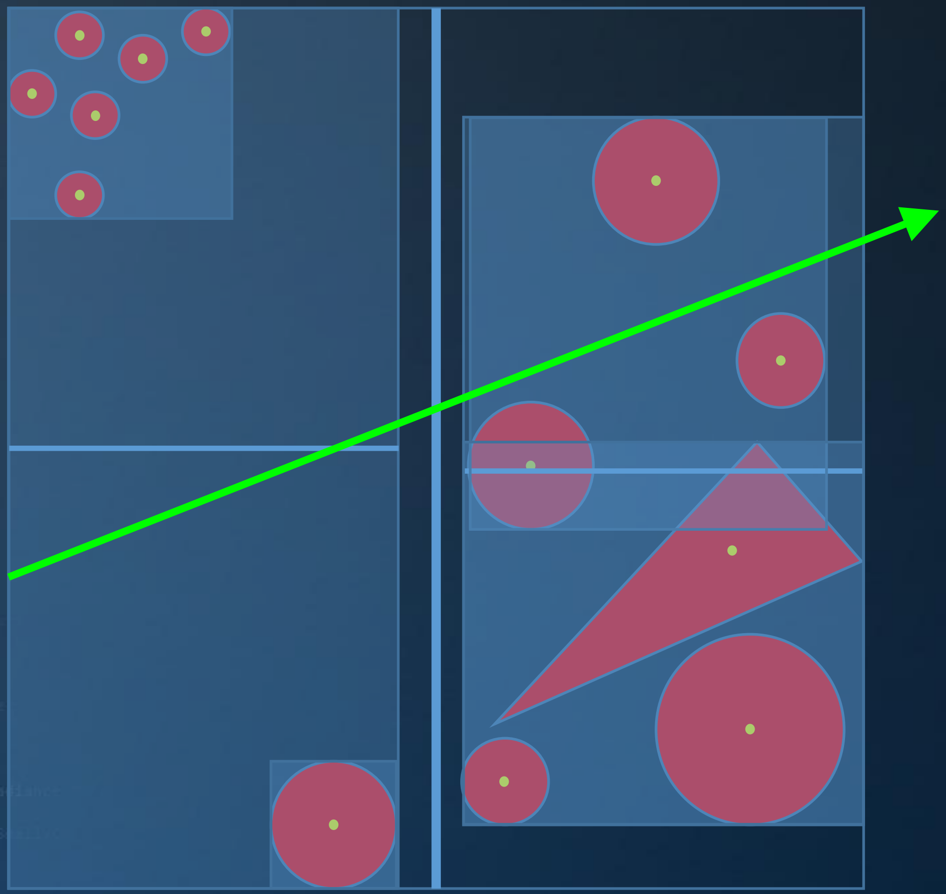
Optimal BVH representation:

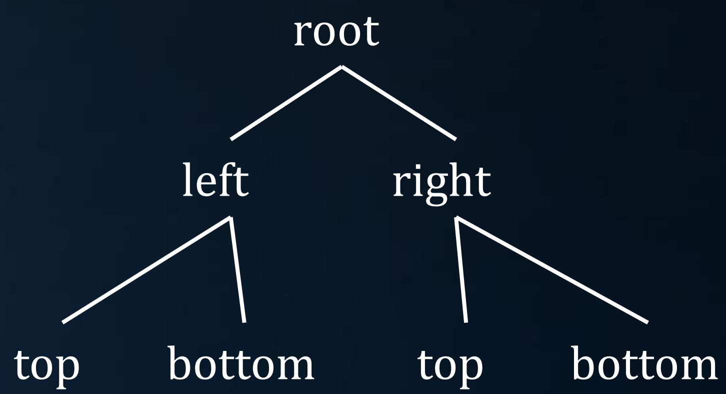
- Partitioning of array of indices pointing to original triangles
- Using indices of BVH nodes, and assuming right = left + 1
- BVH nodes use exactly 32 bytes (2 per cache line)
- BVH node pool allocated in cache aligned fashion
- AABB splitted in 2x 12 bytes; 1st followed by ‘leftFirst’, 2nd by ‘count’.

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

BVH

BVH Traversal





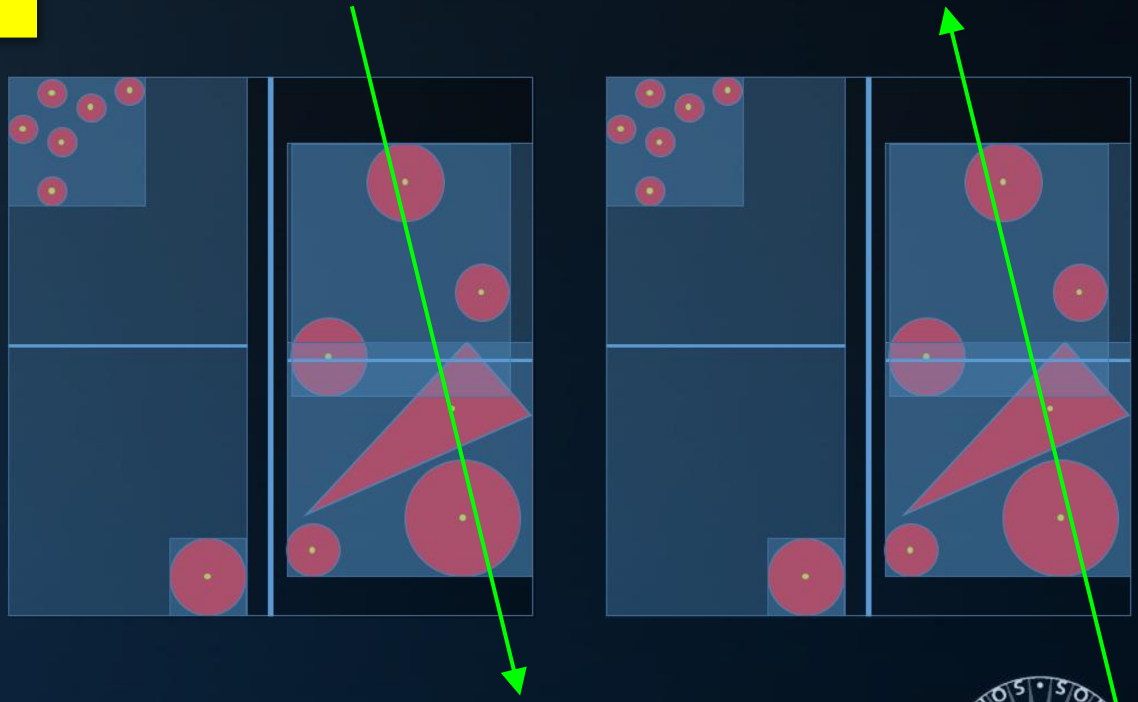
BVH

BVH Traversal

Basic process:

```
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:

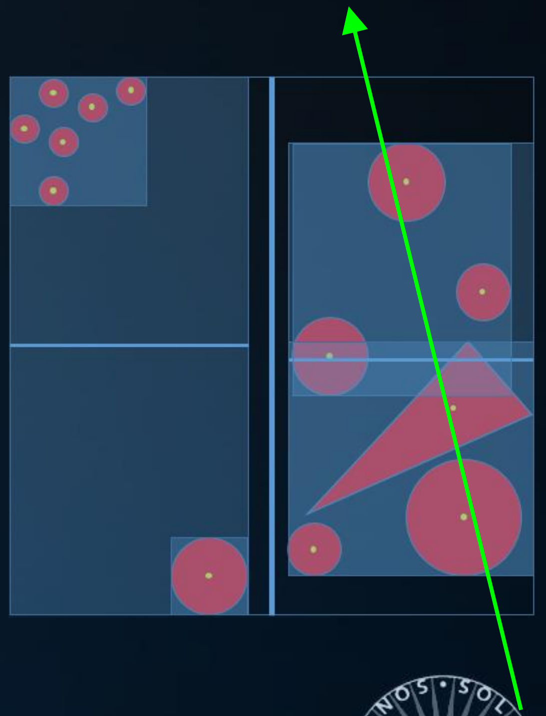
- Calculate distance to both child nodes
- Traverse the nearest child node first

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

BVH Traversal

Ordered traversal of a BVH is approximative.

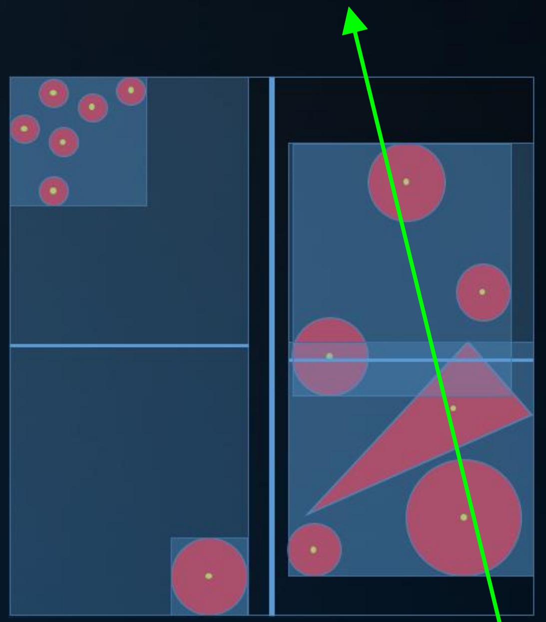
- Nodes may overlap.

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”