Rendering: Spatial Acceleration Structures

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With slides based on material by Jaakko Lehtinen, used with permission
What we have and what we want

- Larger images, more geometry!

32 triangles

500k+ triangles
How do we resolve visibility right now?

- A good image needs both realistic **intensity** and **visibility**
  - **Intensity** taken care of by simulating correct light transport
  - **Visibility** makes sure that objects adhere to depth
    How would you process the scene on the right to make sure the rendered output image is correct?

- (Naïve) Ray Casting-based Visibility
  - Shoot a ray through **each** pixel into the scene
  - Test against **all** objects for intersection
  - Record the **closest** intersection, use for intensity computations

Source: Wojciech Mula, Wikipedia “Painter’s algorithm”
for (i = 0; i < N; i++)
    v_inv = camera.gen_ray(px, py)
    pixel_color += Li(v_inv, 0)
pixel_color /= N

function Li(v_inv, D)
    x = scene.trace(v_inv)
    ...

method trace(Ray ray)
    x_min(t = INF);
    for (i = 0; i < scene.num_triangles; i++)
        x = ray.intersect(scene.triangles[i])
        if (x.t < x_min.t)
            x_min = x
    return x_min
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    v_inv = camera.gen_ray(px, py)
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    return x_min

This is $\mathcal{O}(N \cdot \#\Delta)$, but even worse, it’s $\Omega(N \cdot \#\Delta)$!
Is that actually a problem?

- Run time complexity quickly becomes a limiting factor
- High-quality scenes can have several million triangles per object
- Current screens and displays are moving towards 4k resolution

What if this thing had 1B triangles and your ray tracer just walked through all of them?
Amazon Lumberyard “Bistro”
3,780,244 triangles
1200x675 pixels
32 samples p.p.?

100 trillion ray/triangle intersection tests?

At 10M per second, one frame will take ~120 days.

Good luck with your movie!
What can we do about it?

- Find ways to speed up the basic loop for visibility resolution
- Enter “spatial acceleration structures”
- Essentially, pre-process the scene geometry into a structure that reduces expected traversal time to something more reasonable
- Pick smart traversal strategies to further raise performance
## Spatial Acceleration Structures

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<th>Traversal Time</th>
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Rendering – Spatial Acceleration Structures
Today’s Roadmap

- **Spatial Acceleration Unlocked!**
- **BVH Building and Traversal**
- **BVHs**
- **QuadTree/Octree**
- **Regular Grids**
- **BSP and k-d Trees**

**Questions:**
- What is an Octree?
- What is a k-d Tree?
- What are BVHs?
- When to choose which?
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  - What is a k-d Tree?
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Consider a group of triangles

Which ones should we test?
Regular Grids

- Overlay scene with regular grid
- Sort triangles into cells
- Traverse cells and test against their contents
Regular Grids

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- Geometry is usually not uniform

- Comes in clusters (buildings, characters, vegetation...)

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- Almost all triangles in one cell!
  Hitting this cell will be costly!
Regular Grids

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  - Almost all triangles in one cell! Hitting this cell will be costly!
- Using a finer grid works
- Geometry is usually not uniform

- Comes in clusters (buildings, characters, vegetation...)

  - Almost all triangles in one cell! Hitting this cell will be costly!

- Using a finer grid works, but most of its cells are unused!
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What is an Octree?
What is a k-d Tree?
What are BVHs?
When to choose which?
Quadtrees and Octrees

- Start with scene bounds, do finer subdivisions only if needed
- Define parameters $S_{max}, N_{leaf}$
- Recursively split bounds into quadrants (2D) or octants (3D)
- Stop after $S_{max}$ subdivisions or if no cell has $> N_{leaf}$ triangles
Quad and Octrees: $N_{leaf} = 4$

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- Triangles may not be contained within a quadrant or octant
- Triangles must be referenced in all overlapping cells or split at the border into smaller ones
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- Triangles must be referenced in all overlapping cells or *split* at the border into smaller ones

- Can drastically increase memory consumption!
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BSP Trees & k-d Trees

- Binary Space Partition Tree
  - Recursive split via hyperplanes
  - Left/right child nodes treat objects in each half-space
  - Splits can be arbitrary!
BSP Trees & k-d Trees, $N_{leaf} = 4$

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![BSP Tree Diagram]
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  - Every hyperplane must be perpendicular to a base axis
  - Limits search space for splits
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What is an Octree?
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Bounding Volumes

- Find enclosing ("conservative") volumes that are easier to test

- Ideally: tight, but easy to check for intersection with ray

- Common choices:
  - Bounding Spheres
  - Bounding Boxes
    - Axis-aligned (AABB)
    - Oriented (OBB)

- Saves on computational effort if reject
Axis-Aligned Bounding Boxes (AABBs)

- AABBs are defined by their two extrema (min/max)
- Linear run time to compute
  - Iterate over all vertices
  - Keep min/max values for each dimension
  - Done!

\[
(x_{\text{min}}, y_{\text{min}}, z_{\text{min}}) = \left(\min(x_0, x_1, x_2), \min(y_0, y_1, y_2), \min(z_0, z_1, z_2)\right)
\]

\[
(x_{\text{max}}, y_{\text{max}}, z_{\text{max}}) = (\max(x_0, x_1, x_2), \max(y_0, y_1, y_2), \max(z_0, z_1, z_2))
\]
Merging AABBs

- Find the AABB that encloses multiple, smaller AABBs
- Operates only on extrema of each smaller AABB
- Merging process is commutative
Bounding Spheres

- Bounding spheres need a center $\hat{c}$ and a radius $r$

- For $\hat{c}$, can pick the mean vertex position or center of AABB

- Once center is chosen, find vertex position $\hat{v}_{max}$ farthest from it

- $r = |\hat{c} - \hat{v}_{max}|$

Rendering – Spatial Acceleration Structures
How to Use Bounding Volumes

- Can also be applied to entire objects

- Reject entire object if volume is not hit

- Good start, but what if...
  - ...scene is not partitioned into objects?
  - ...objects are extremely large (terrain)?
  - ...objects are extremely detailed (characters)?
  - ...there are millions of objects with ~ 2 triangles each (leaves)?
Bounding Volume Hierarchy (BVH)

- Each node of the hierarchy has its own bounding volume

- Every node can be
  - An inner node: references child nodes
  - A leaf node: references triangles

- Each node’s bounding volume is a subset of its parent’s bounding volume (i.e., child nodes are spatially contained by their parents)
The final hierarchy is (again) a tree structure with $N$ leaf nodes.

Leaf nodes can be:
- Individual triangles
- Clusters (e.g., $\leq 10\Delta$)

Total number of nodes for a binary tree: $2N - 1$
- If balanced, it takes $\sim \log N$ steps to reach a leaf from the root
- If trees have more than 2 branches, they require fewer nodes

Source: Schreiber, Wikipedia “Bounding Volume Hierarchy”
What makes BVHs special?

- Important feature: bounding volumes can **overlap**!

- No duplicate references or split triangles necessary!

- Implicitly limits the amount of memory required
BVH Building

- Generating BVH and tree for input triangle geometry

- CPU: usually top-down
  GPU: usually bottom-up

- From here on out, we will consider box BVHs only
Define $N_{leaf}$ for leaves

For each node, do the following:

- Compute bounding box that fully encloses triangles & store
- Holds $\leq N_{leaf}$ triangles? Stop.
- Else, split into child groups
- Make one new node per group
- Set them as children of current
- Repeat with child nodes
BVH Building, Top-Down, $N_{leaf} = 4$

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**BVH Building, Top-Down, \( N_{\text{leaf}} = 4 \)**

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Rendering – Spatial Acceleration Structures
How to split a node?

- Which axes to consider for building bounding boxes/splitting?
  - Basis vectors (1,0,0), (0,1,0), (0,0,1) only
  - Oriented basis vectors only
  - Arbitrary

- Where to split?
  - Spatial median
  - Object median
  - Something more elaborate...
How to split a node?

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  - Arbitrary

  Algorithms exist (e.g. “separating axis theorem”), but usually very slow!

- Where to split?
  - Spatial median
  - Object median
  - Something more elaborate...
Splitting at spatial median

- Pick the longest axis (X/Y/Z) of current node bounds
- Find the midpoint on that axis
- Assign triangles to A/B based on which side of the midpoint each triangle’s centroid lies on
- Continue recursion with A/B
Splitting at spatial median

- Careful: can result in infinite recursion!

- All triangles are assigned again to one node, none in the other

- Can guard against it in several ways
  - Limit max. number of split attempts
  - Try other axes if one node is empty
  - Compute box over triangle centroids and split that on longest axis instead
Pick an axis. Can try them all, don’t pick the same every time.

Sort triangles according to their centroid’s position on that axis.

Assign first half of the sorted triangles to A, the second to B.

Continue recursion with A/B.
BVH Traversal

0. Set $t_{\text{min}} = \infty$. Start at root node, return if it doesn’t intersect ray.

1. Process node if its closest intersection with ray is closer than $t_{\text{min}}$

2. If it’s an inner node, run from 1. for child nodes that intersect ray
   - Process the closest node first
   - Keep others on stack to process further ones later (recursion works)

3. If it’s a leaf, check triangles and update $t_{\text{min}}$ in case of closer hit
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The Surface Area Heuristic [1]

- Simple, but powerful heuristic for choosing splits

- Created with traversal in mind, based on the following ideas:
  - Assume rays are uniformly distributed in space
  - Probability of a ray hitting a node is proportional to its surface area
  - Cost of traversing it depends on the number of triangles in its leaves
  - Hence, avoid large nodes with many triangles, because:
    - They have a tendency to get checked often
    - Getting a definite result (reject or closest hit) is likely to be expensive
Applying the Surface Area Heuristic

**Goal**: To split a node, find the hyperplane \( b \) that minimizes

\[
f(b) = LSA(b) \cdot L(b) + RSA(b) \cdot (N - L(b)),
\]

where

- \( LSA(b) / RSA(b) \) are the **surface area** of the nodes that enclose the triangles whose centroid is on the “left”/“right” of the split plane \( b \)

- \( L(b) \) is the **number of primitives on the “left”** of \( b \)

- \( N \) is the **total number of primitives** in the node
We want to constrain the search space for a good split

Pick a set of axes to test (e.g., 3D basis vectors X/Y/Z)

When splitting a node with $N$ triangles, for each axis
  - Sort all triangles by their centroid’s position on that axis
  - Find the index $i$ that minimizes

$$f(i) = LSA(i) \cdot i + RSA(i) \cdot (N - i),$$

where

- $LSA(i)$ is the surface area of the AABB over sorted triangles $[0, i)$
- $RSA(i)$ is the surface area of the AABB over sorted triangles $[i, N)$

Select the axis and index $i$ with the best $f(i)$ for the split overall!
Important trade-off: building time vs. traversal time
- Given the same tracing/traversal code, the quality of a BVH tree may have a big impact on performance!
- Can be as high as 2x compared to naïve splitting

Benefits depend on the parameters of your rendering scenario
- How big is your scene and how are triangles distributed?
- How long will your BVH be valid?
- What are the quality requirements for your images?
Evaluation of Combined Building + Traversal [2]

Efficiency measured as a function of TOTAL WALLCLOCK TIME PER RAY, taking into account both BVH construction and actual tracing.

Check out the paper this comparison came from https://users.aalto.fi/~ailat1/publications/karras2013hpg_paper.pdf
If you don’t have too many rays to trace, it probably pays off to construct BVH really quickly, even if tracing wasn’t as fast per ray.
Evaluation of Combined Building + Traversal [2]

After some point a faster but slower-to-build BVH’s increased tracing speed starts to pay off

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**BVH Building Hints**

- For each split, sort the node’s portion of the triangle list $L$ in-place.

- When constructing child nodes, pass them $L$ and *start/end* indices.

---

**List L**

- **Purple**: Primitive that lands in left child
- **Red**: Primitive that lands in right child
For each split, sort the node’s portion of the triangle list $L$ in-place.

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BVH Building Hints

- For each split, sort the node’s portion of the triangle list $L$ in-place.

- When constructing child nodes, pass them $L$ and `start/end` indices.
SAH Coding Hints

- Don’t loop over triangles at each \( i \) to get \( LSA(i) \) and \( RSA(i) \)!

- Precompute them once per node and axis instead
  - Create two 0-volume bounding boxes \( BB_L, BB_R \)
  - Allocate N+1 entries for \( LSA/RSA \), set \( LSA(0) = RSA(N) = 0 \)
  - Iterate \( i \) over range \([1, N]\), for each \( i \):
    - Merge \( BB_L \) with the AABB of sorted triangle with index \( (i - 1) \)
    - Store surface area of \( BB_L \) as value for \( LSA(i) \)
    - Merge \( BB_R \) with the AABB of sorted triangle with index \( (N - i) \)
    - Store surface area of \( BB_R \) as value for \( RSA(N - i) \)
BVH Building Hints (C++)

- Consider using `stdlib` container (e.g., `vector`)
- Try to avoid dynamic memory allocation
- $2N - 1$ is an upper bound for the total number of nodes you need
- `std::sort(<first>, <last>, <predicate>)`
- `std::nth_element(<first>, <nth>, <last>, <predicate>)`
  - Can be used for splitting if you don’t need exact sorting
  - Reorders the $N$-sized vector such that:
    - $n$ smallest elements are on the left
    - $N - n$ biggest are on the right
  - Faster than sorting!
BVH vs k-d Tree vs Others

- Each have their specializations, strengths and weaknesses

- E.g., k-d Trees with ropes do not require a stack for traversal [5]

- Which acceleration structure is the best is contentious

- Currently, BVHs are extremely widespread and well-understood
State-of-the-Art Variants and Trends

- Higher child counts (>2) per node, mixed nodes (children + triangles)

- Actually DO split triangles sometimes to get maximal performance

- Build BVHs bottom-up in parallel on the GPU [3]

- In animated scenes, reuse BVHs, update those parts that change

- Actually use built-in traversal logic of GPU hardware (NVIDIA RTX!)
References and Further Reading

- Interesting topics: BVHs for animation, LBVH, SIMD/packet/stackless traversal, Turing RTX architecture


