Ray Tracing II
(Acceleration Structures)

Last Lecture

- Why ray tracing?
- Whitted-style ray tracing
- Ray-object intersections
  - Implicit surfaces
  - Triangles

Today

- Axis-Aligned Bounding Boxes (AABBs)
    - Understanding — pairs of slabs
    - Ray-AABB intersection
- Using AABBs to accelerate ray tracing
    - Uniform grids
    - Spatial partitions

Accelerating Ray-Surface Intersection

Ray Tracing – Performance Challenges

Simple ray-scene intersection

- Exhaustively test ray-intersection with **every triangle**
- Find the closest hit (i.e. minimum t)

Problem:

- Naive algorithm = #pixels × # traingles (× #bounces)
- Very slow!

Ray Tracing – Performance Challenges

Jun Yan, Tracy Renderer

San Miguel Scene, 10.7M triangles

Ray Tracing – Performance Challenges

Plant Ecosystem, 20M triangles

Bounding Volumes

Bounding Volumes

Quick way to avoid intersections: bound complex object with a simple volume

- Object is fully contained in the volume
- If it doesn't hit the volume, it doesn't hit the object
- So test BVol first, then test object if it hits

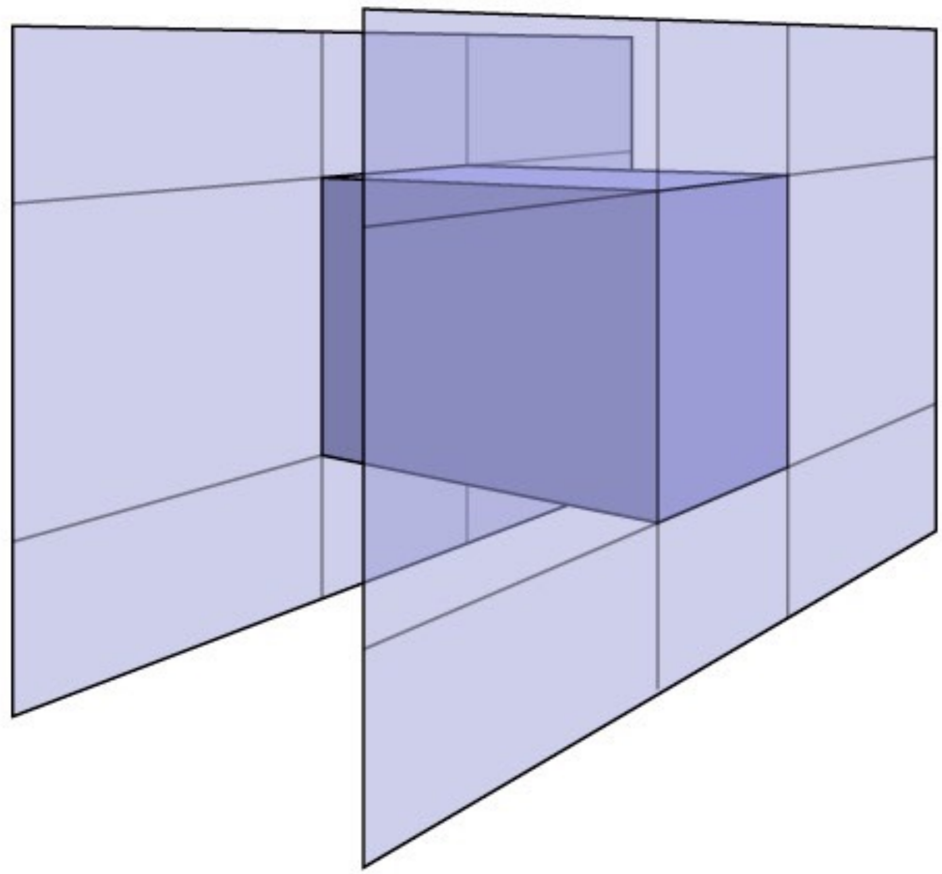
Ray-Intersection With Box

Understanding: **box is the intersection of 3 pairs of slabs**

Specifically:

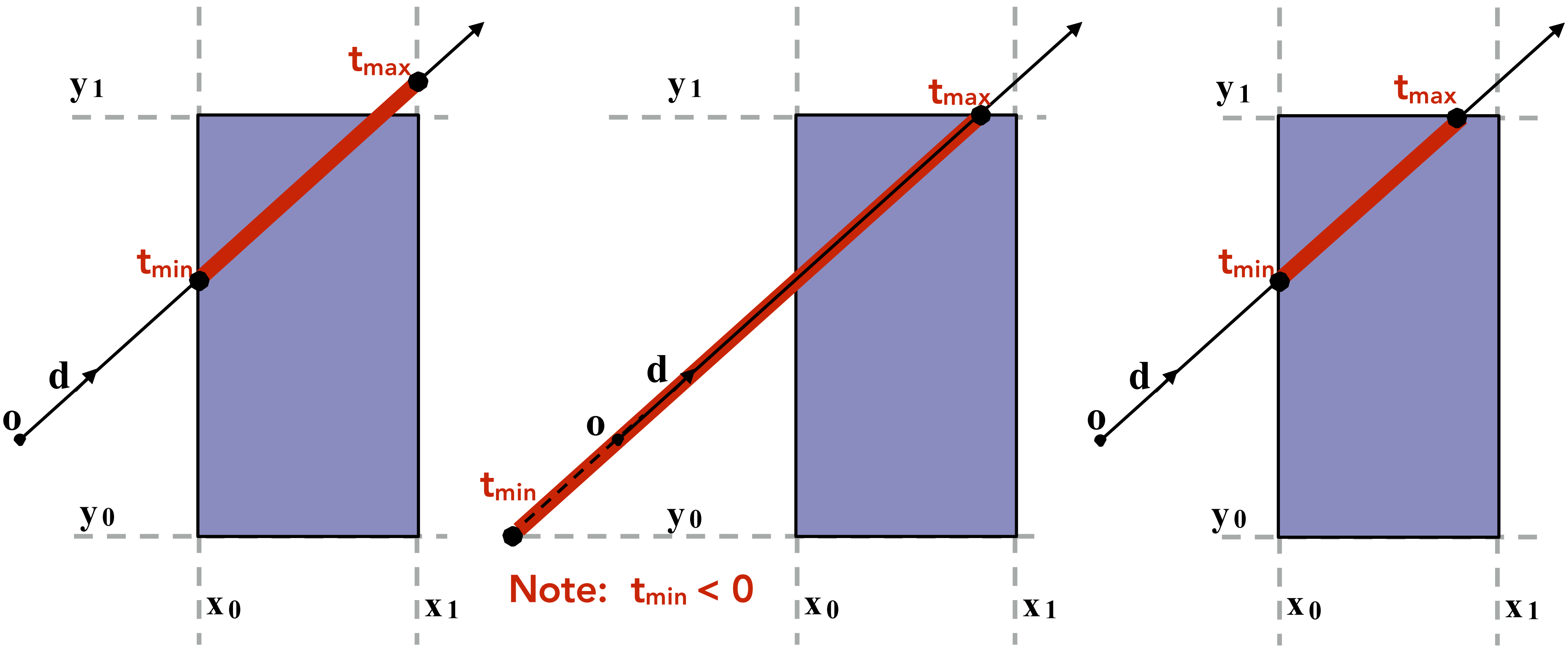
We often use an **Axis-Aligned Bounding Box (AABB)**

i.e. any side of the BB is along either x, y, or z axis



Ray Intersection with Axis-Aligned Box

2D example; 3D is the same! Compute intersections with slabs and take intersection of t_{min}/t_{max} intervals



Intersections with *x* planes **Intersections with *y* planes** **Final intersection result**

How do we know when the ray intersects the box?

Ray Intersection with Axis-Aligned Box

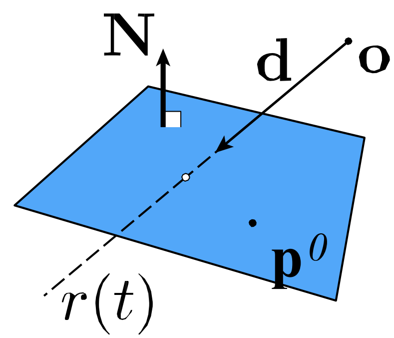
- Recall: a box (3D) = three pairs of infinitely large slabs
- Key ideas
  - The ray enters the box **only when** it enters all pairs of slabs
  - The ray exits the box **as long as** it exits any pair of slabs
- For each pair, calculate the t_{min} and t_{max} (negative is fine)
- For the 3D box, $t_{enter} = \textbf{max}\{t_{min}\}$, $t_{exit} = \textbf{min}\{t_{max}\}$
- If $t_{enter} < t_{exit}$, we know the ray **stays a while** in the box (so they must intersect!) (not done yet, see the next slide)

Ray Intersection with Axis-Aligned Box

- However, ray is not a line
  - Should check whether t is negative for physical correctness!
- What if $t_{exit} < 0$?
  - The box is “behind” the ray — no intersection!
- What if $t_{exit} >= 0$ and $t_{enter} < 0$?
  - The ray’s origin is inside the box — have intersection!
- In summary, ray and AABB intersect iff
  - $t_{enter} < t_{exit}$ && $t_{exit} >= 0$

Why Axis-Aligned?

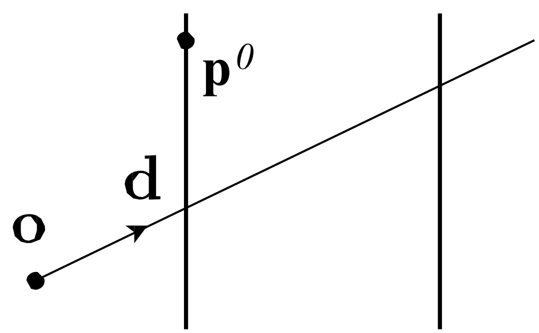
General



$$t = \frac{(\mathbf{p}^{0} - \ \mathbf{o}) \cdot \mathbf{N}}{\mathbf{d} \quad \mathbf{N}}$$

3 subtractions, 6 multiplies, 1 division

Slabs perpendicular to x-axis

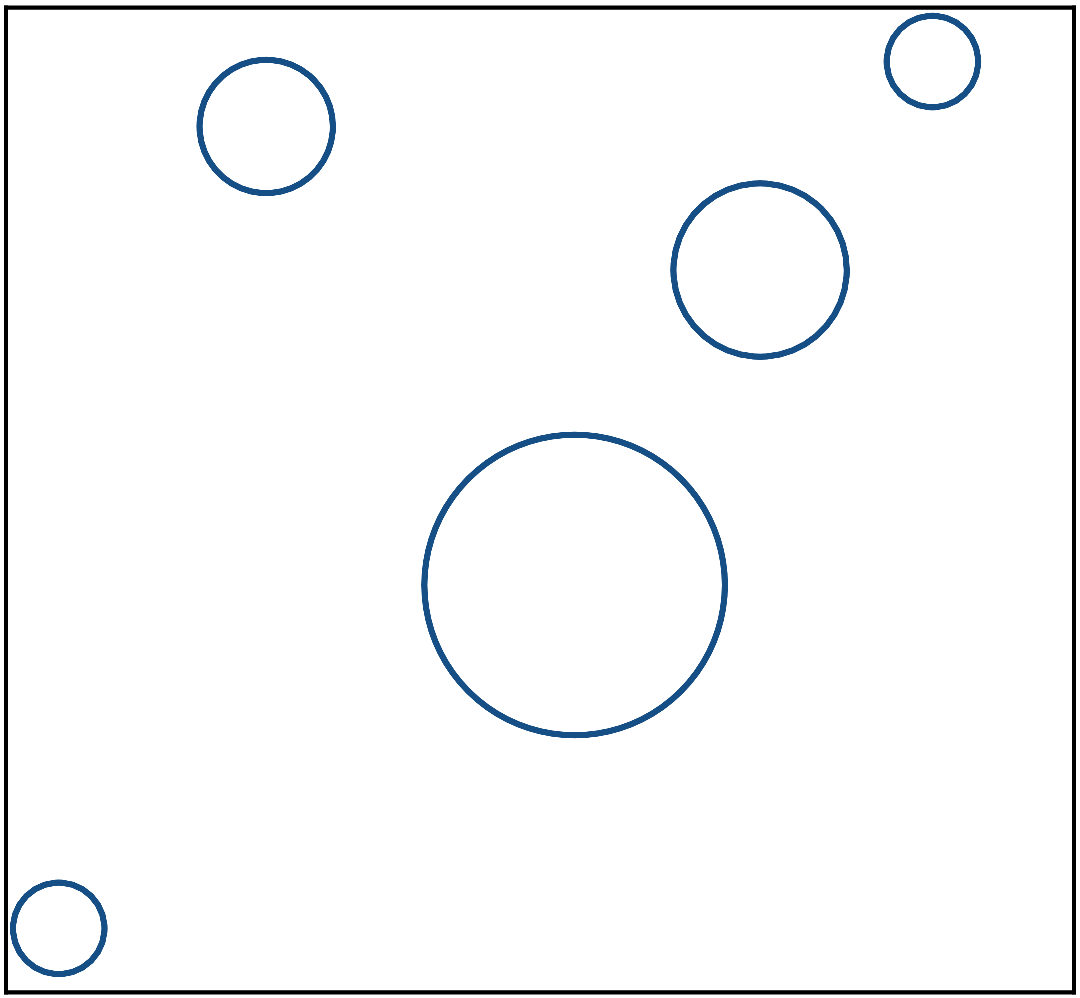


$$t = \frac{\mathbf{p}'_x - \mathbf{o}_x}{\mathbf{d}_x}$$

1 subtraction, 1 division

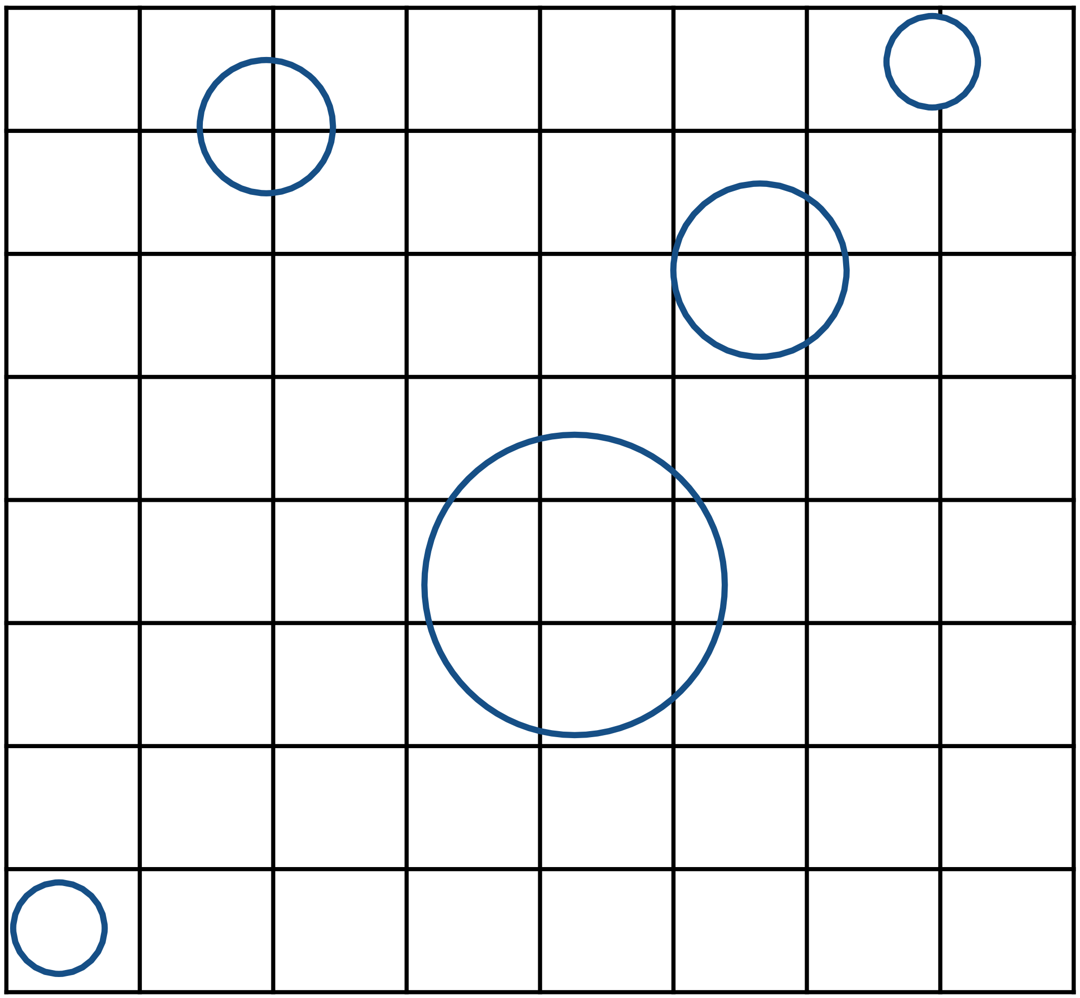
Uniform Spatial Partitions (Grids)

Preprocess – Build Acceleration Grid



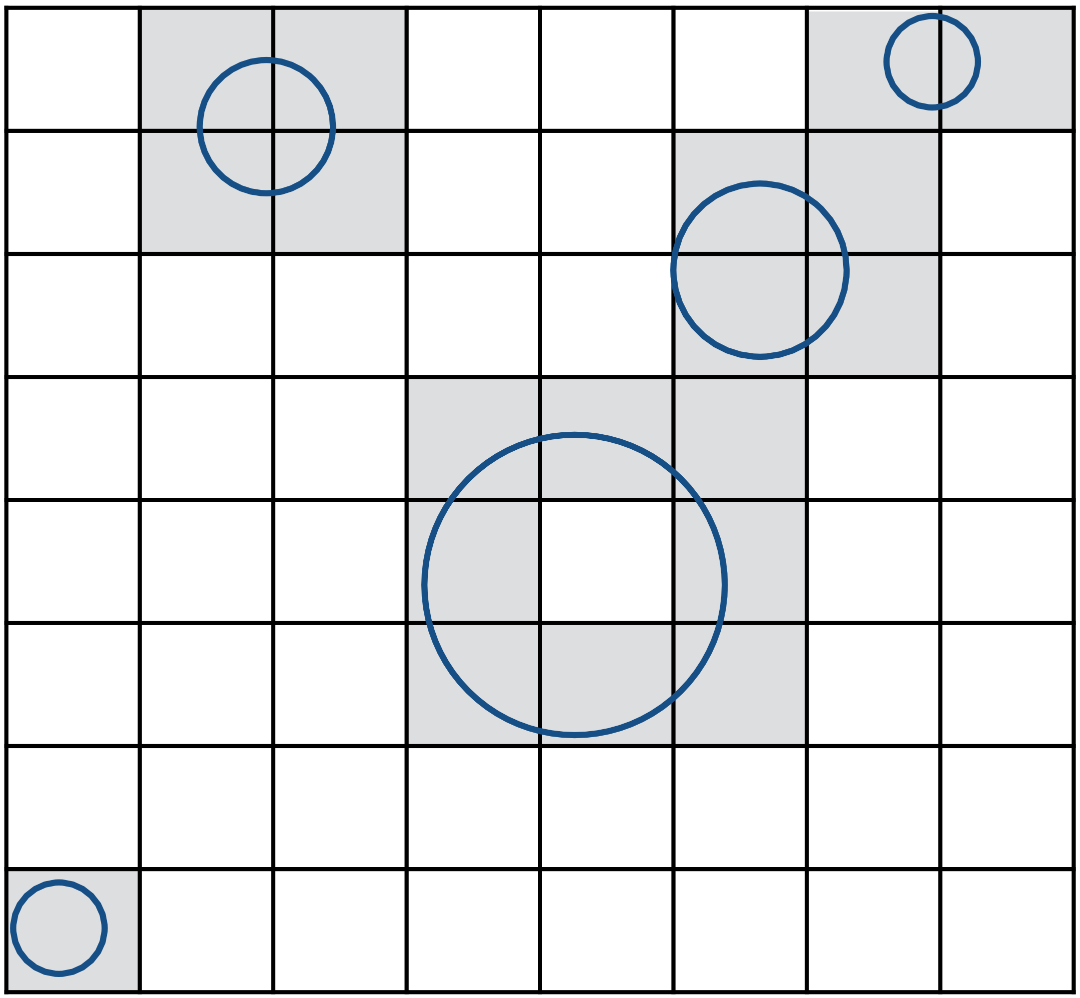
1. Find bounding box

Preprocess – Build Acceleration Grid



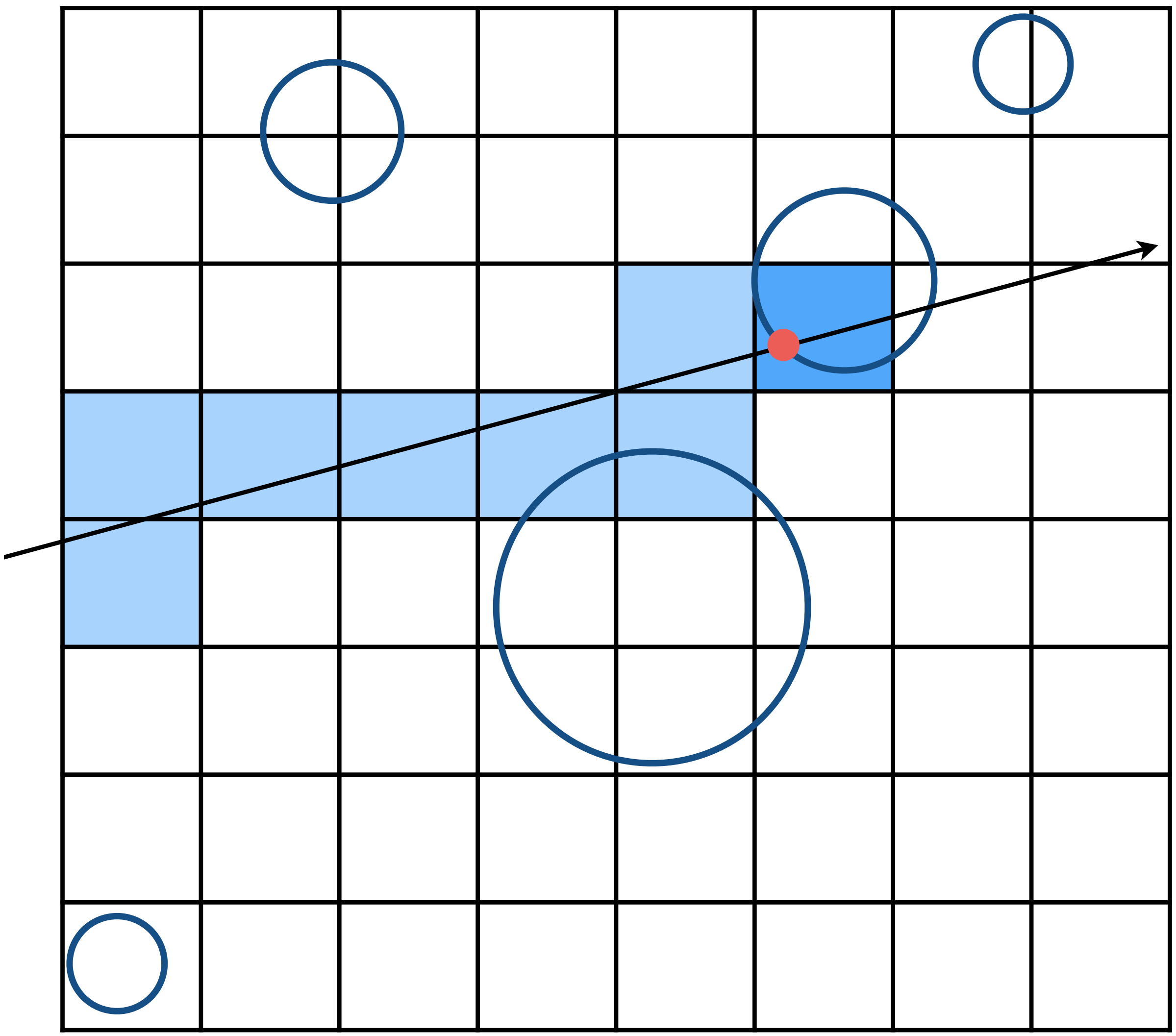
1. Find bounding box
2. Create grid

Preprocess – Build Acceleration Grid



1. Find bounding box
2. Create grid
3. Store each object in overlapping cells

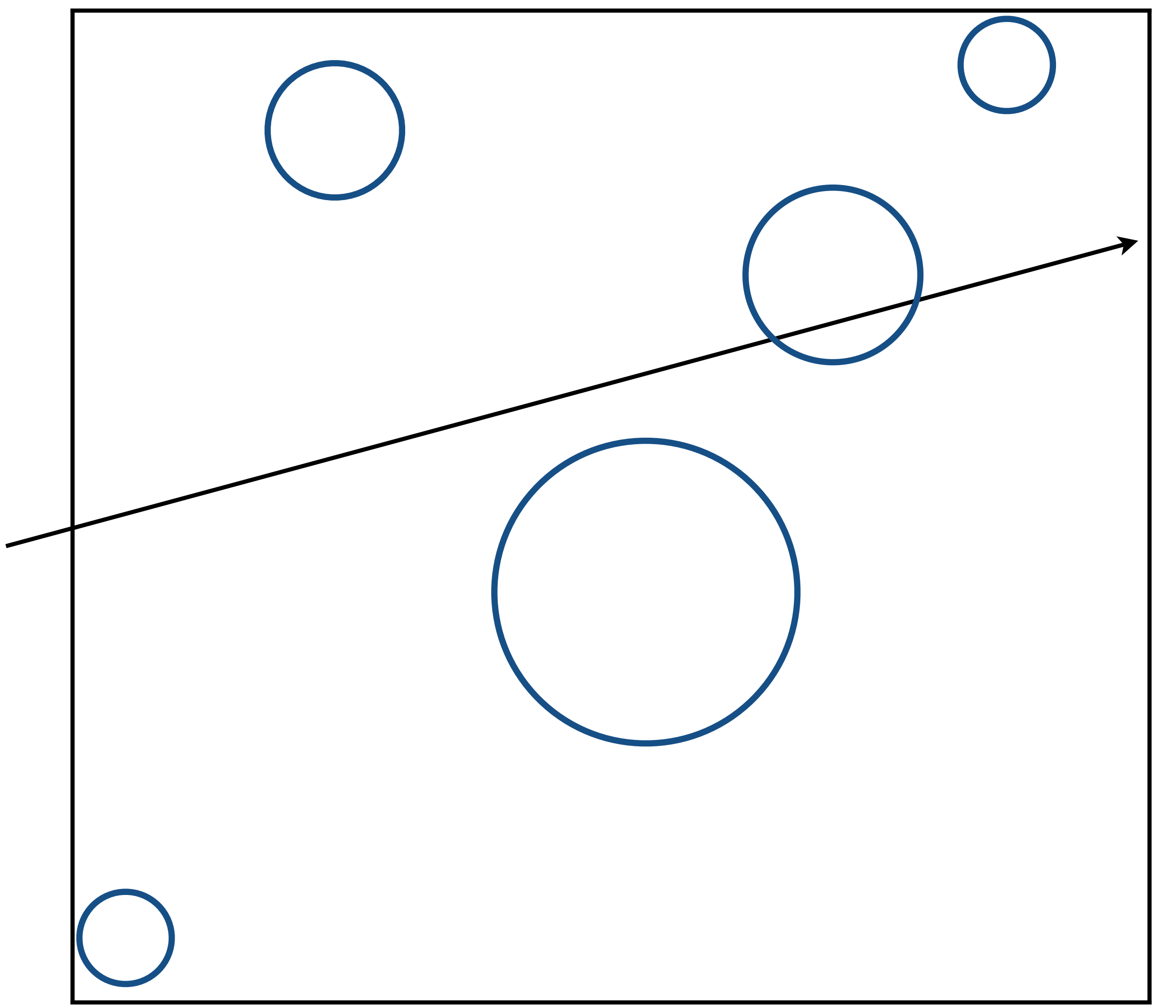
Ray-Scene Intersection



Step through grid in ray traversal order

For each grid cell Test intersection with all objects stored at that cell

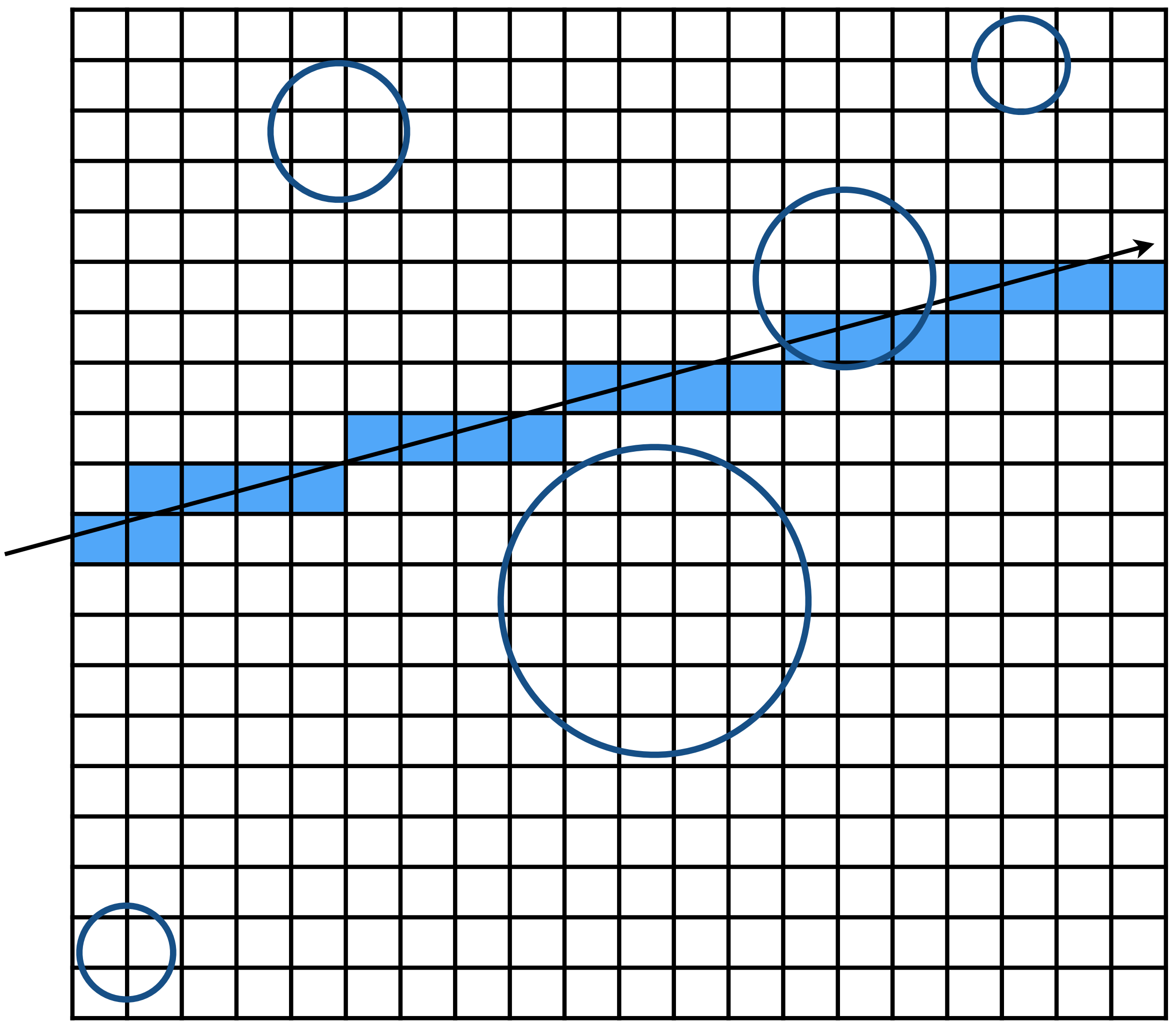
Grid Resolution?



One cell

- No speedup

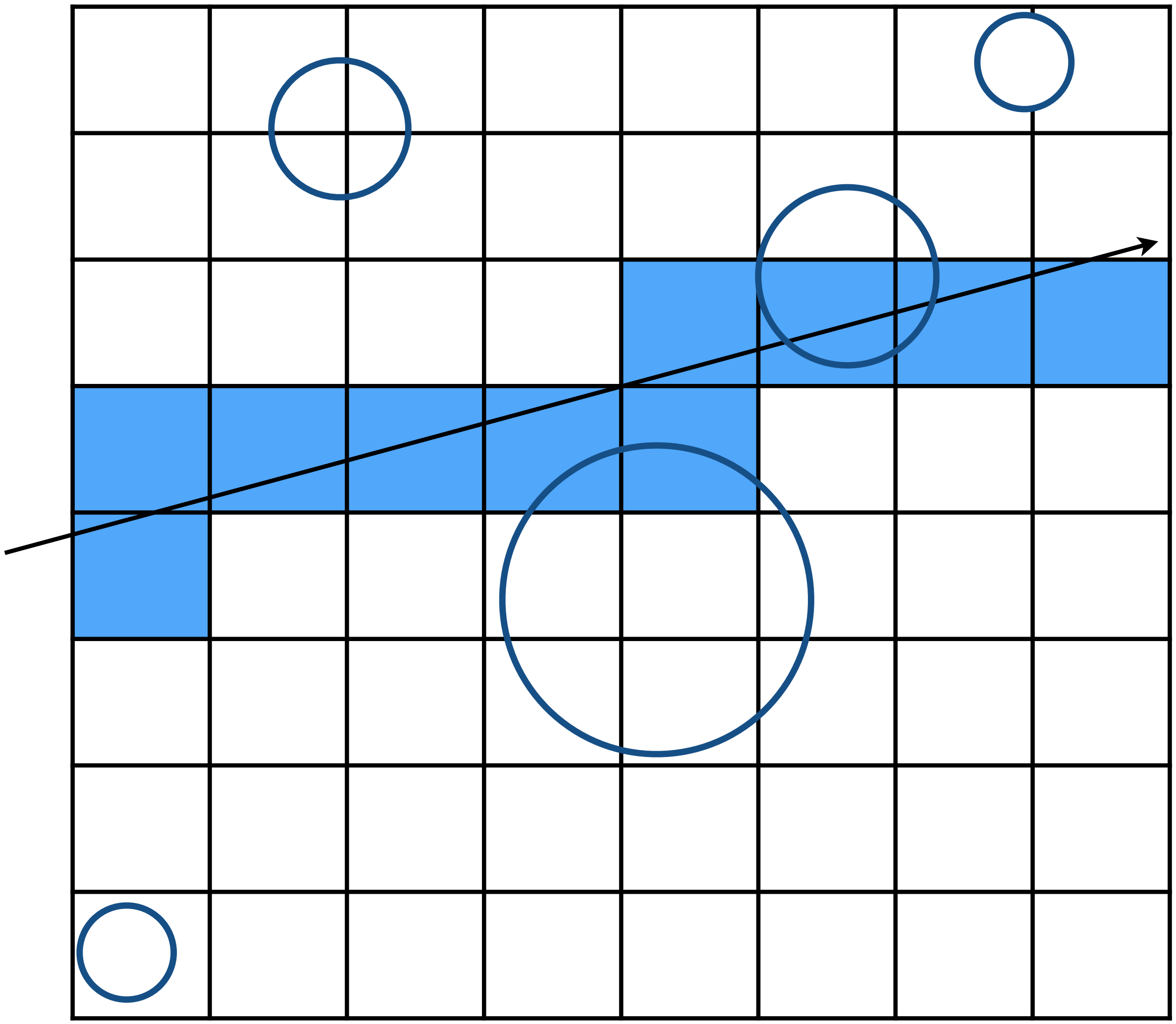
Grid Resolution?



Too many cells

- Inefficiency due to extraneous grid traversal

Grid Resolution?



Heuristic:

- #cells = C * #objs
- C ≈ 27 in 3D

Uniform Grids – When They Work Well

Grids work well on large collections of objects
that are distributed evenly in size and space

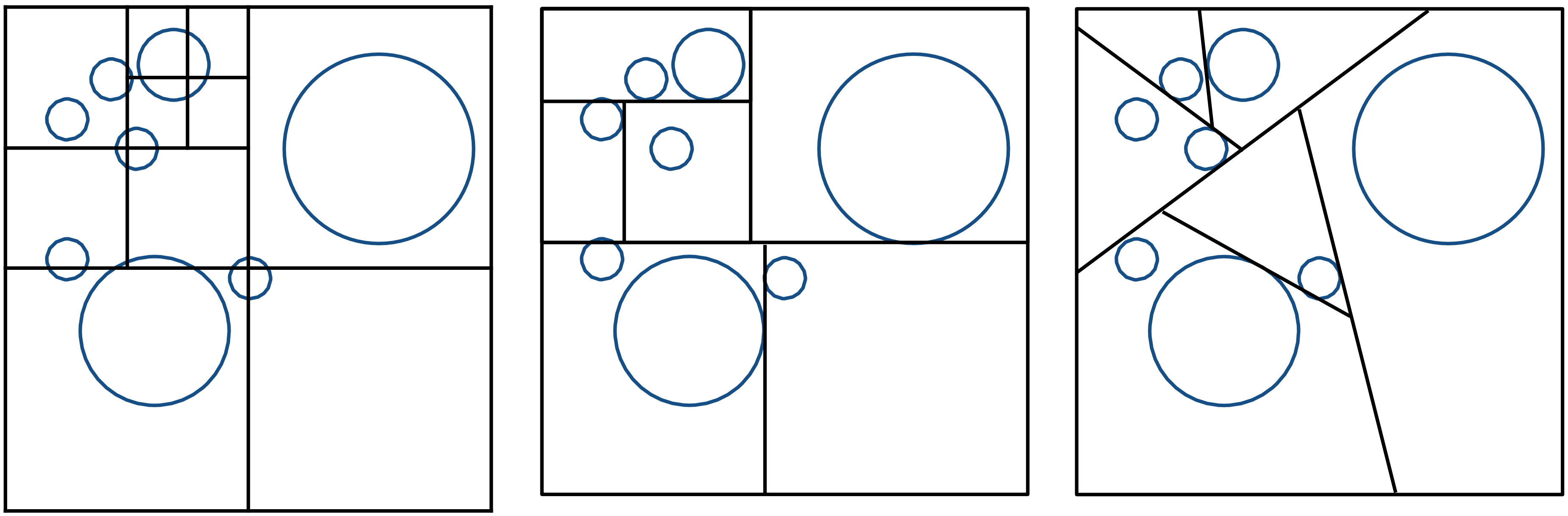
Uniform Grids – When They Fail


Jun Yan, Tracy Renderer

"Teapot in a stadium" problem

Spatial Partitions

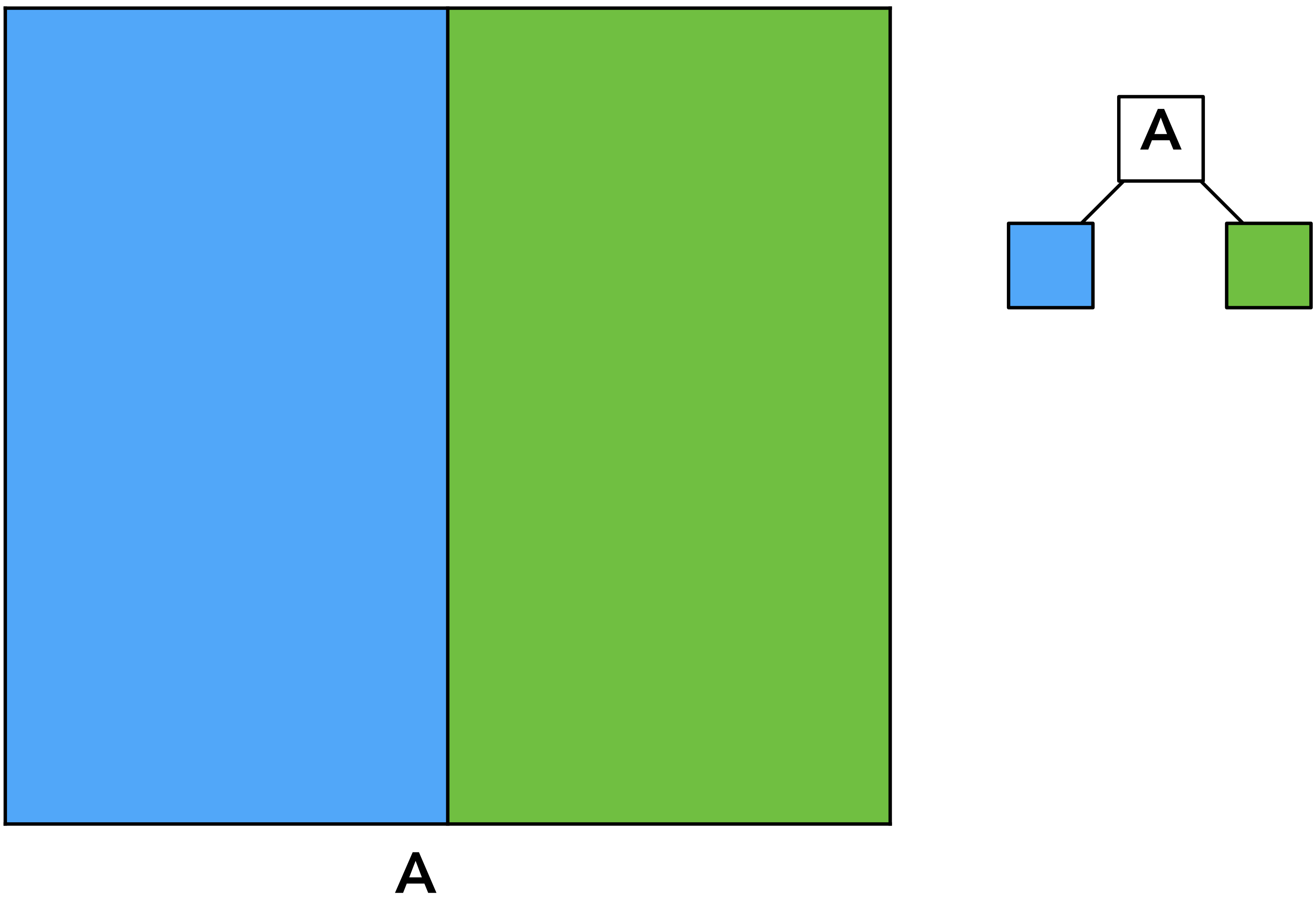
Spatial Partitioning Examples



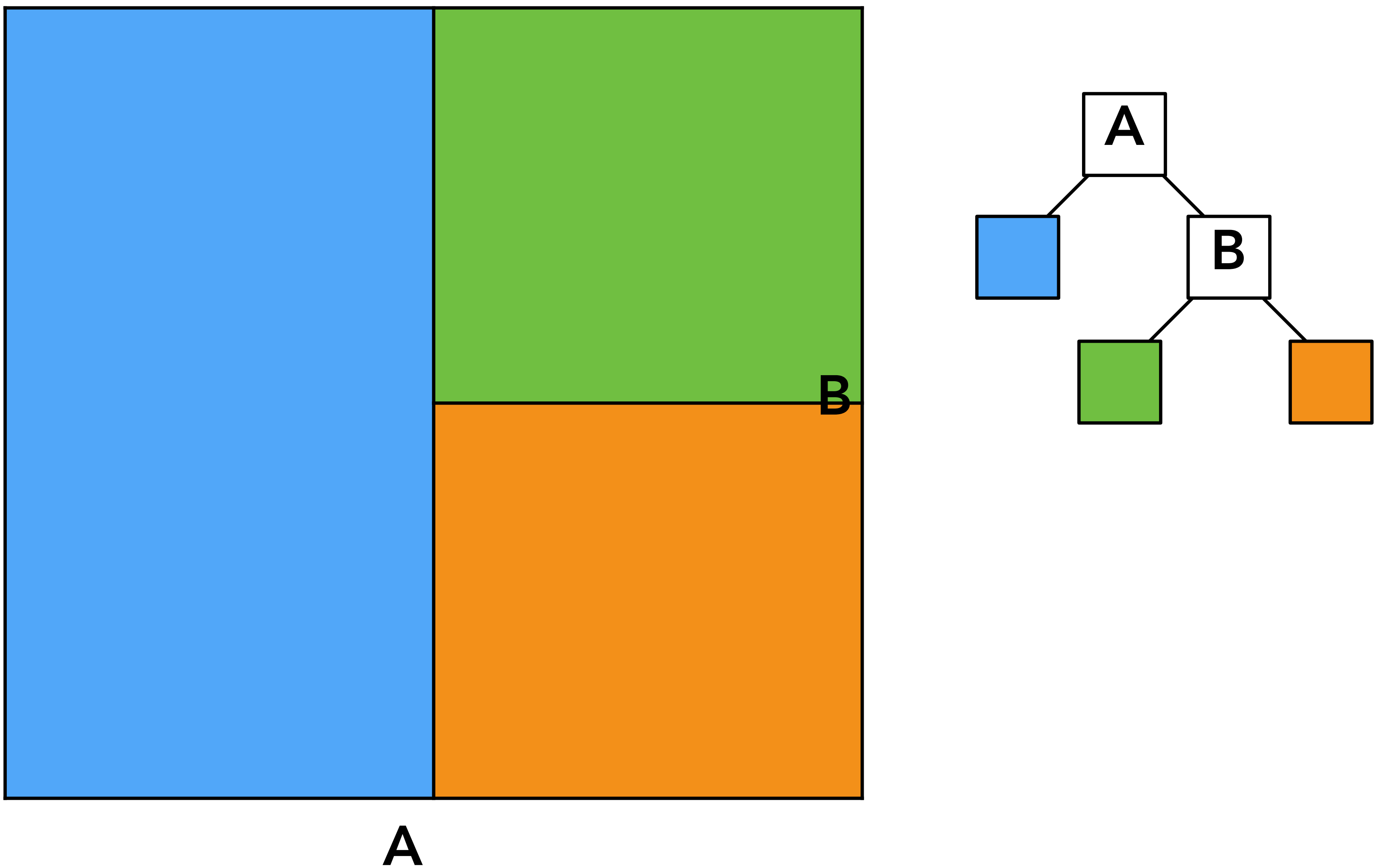
Oct-Tree **KD-Tree** BSP-Tree

Note: you could have these in both 2D and 3D. In lecture we will illustrate principles in 2D.

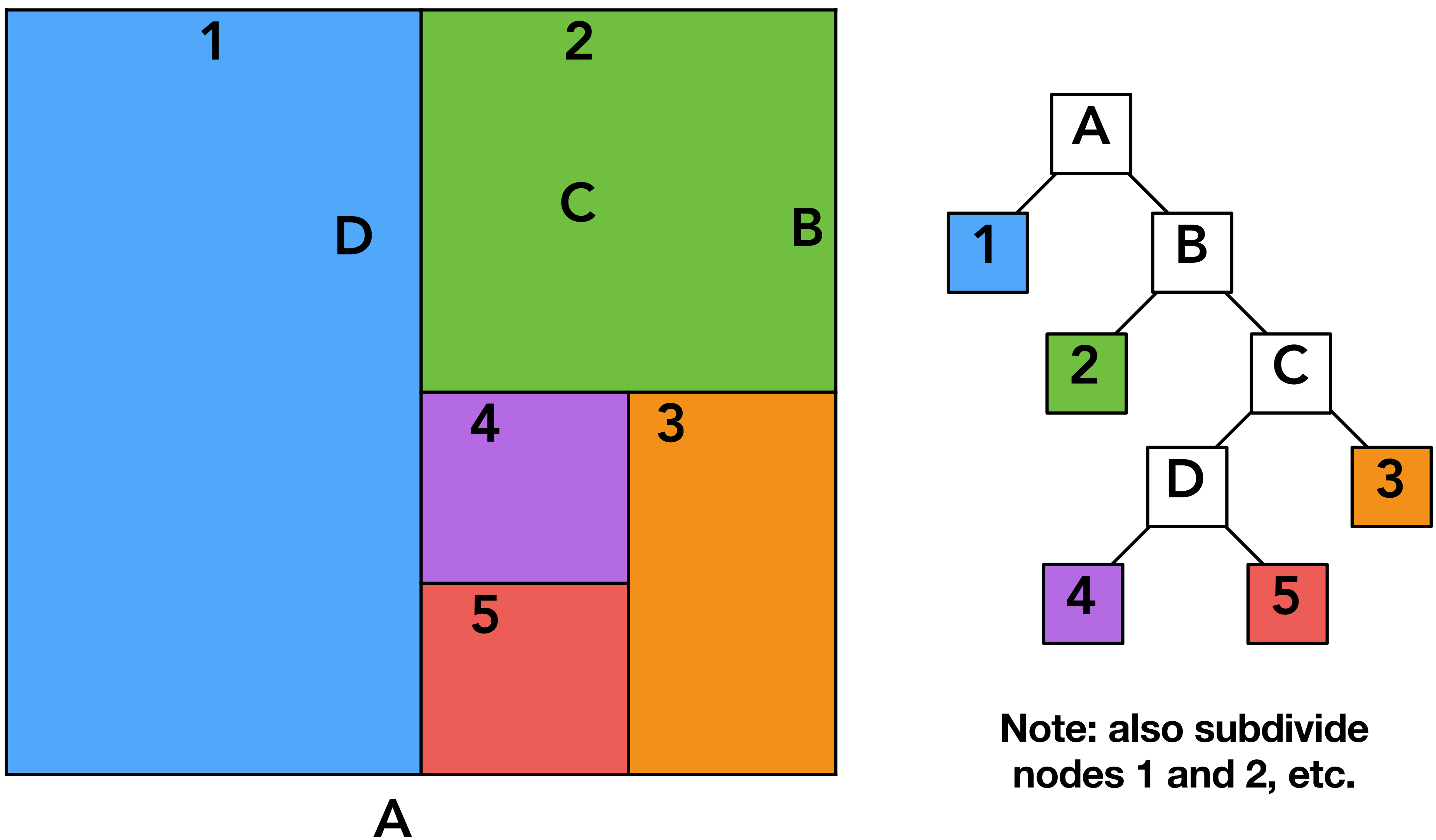
KD-Tree Pre-Processing



KD-Tree Pre-Processing



KD-Tree Pre-Processing



Note: also subdivide nodes 1 and 2, etc.

Data Structure for KD-Trees

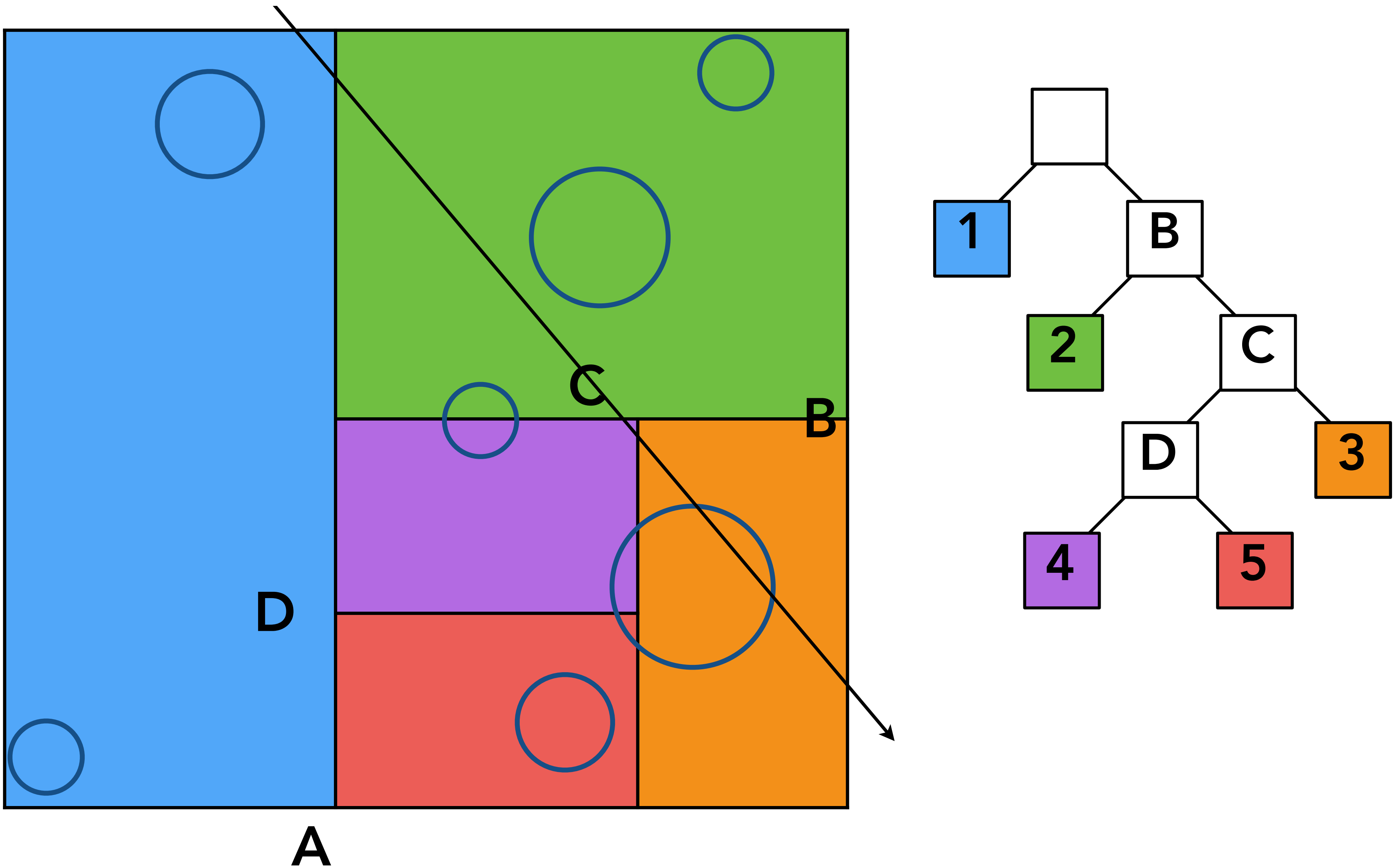
Internal nodes store

- split axis: x-, y-, or z-axis
- split position: coordinate of split plane along axis
- children: pointers to child nodes
- **No objects are stored in internal nodes**

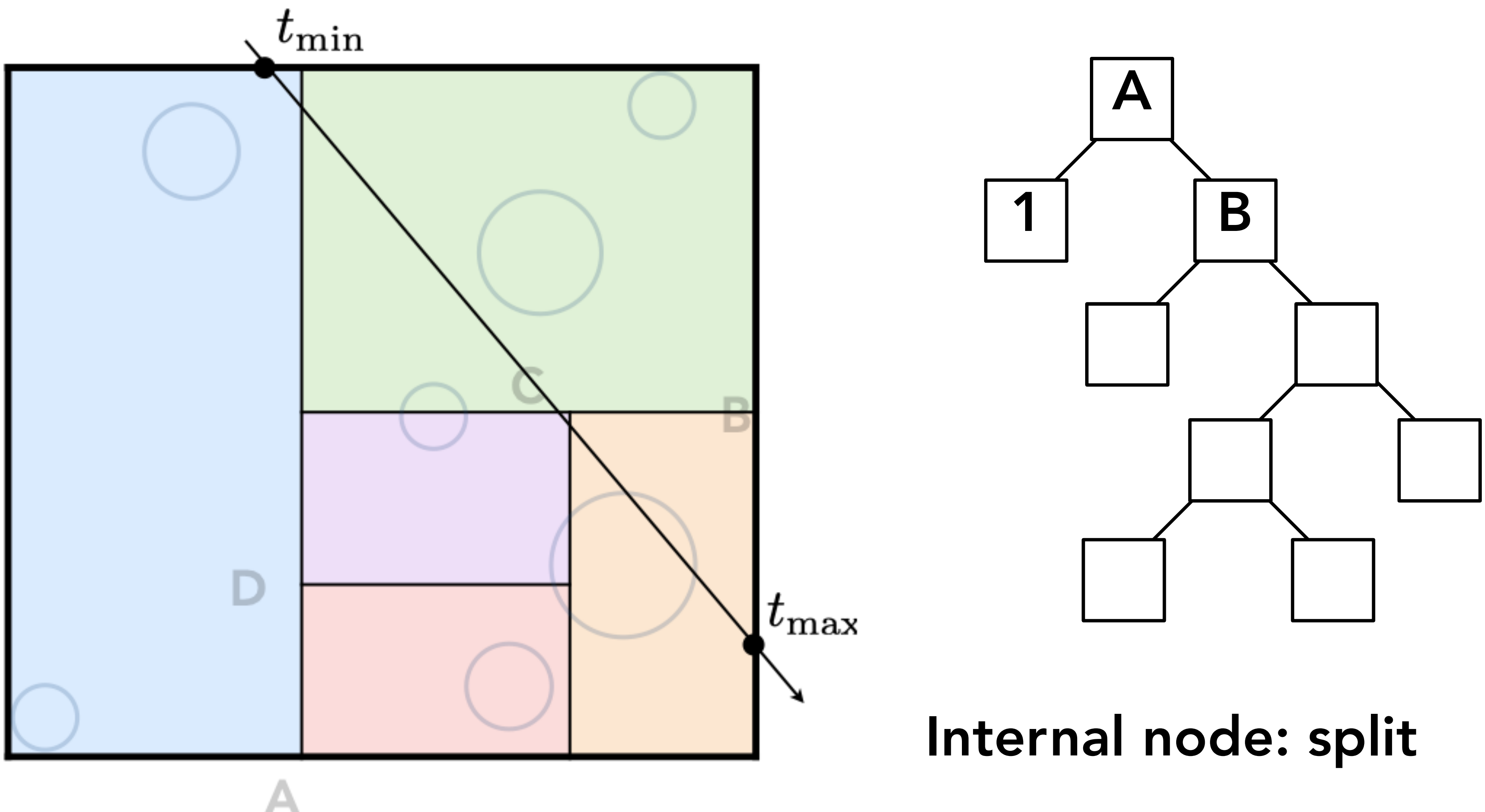
Leaf nodes store

- list of objects

Traversing a KD-Tree

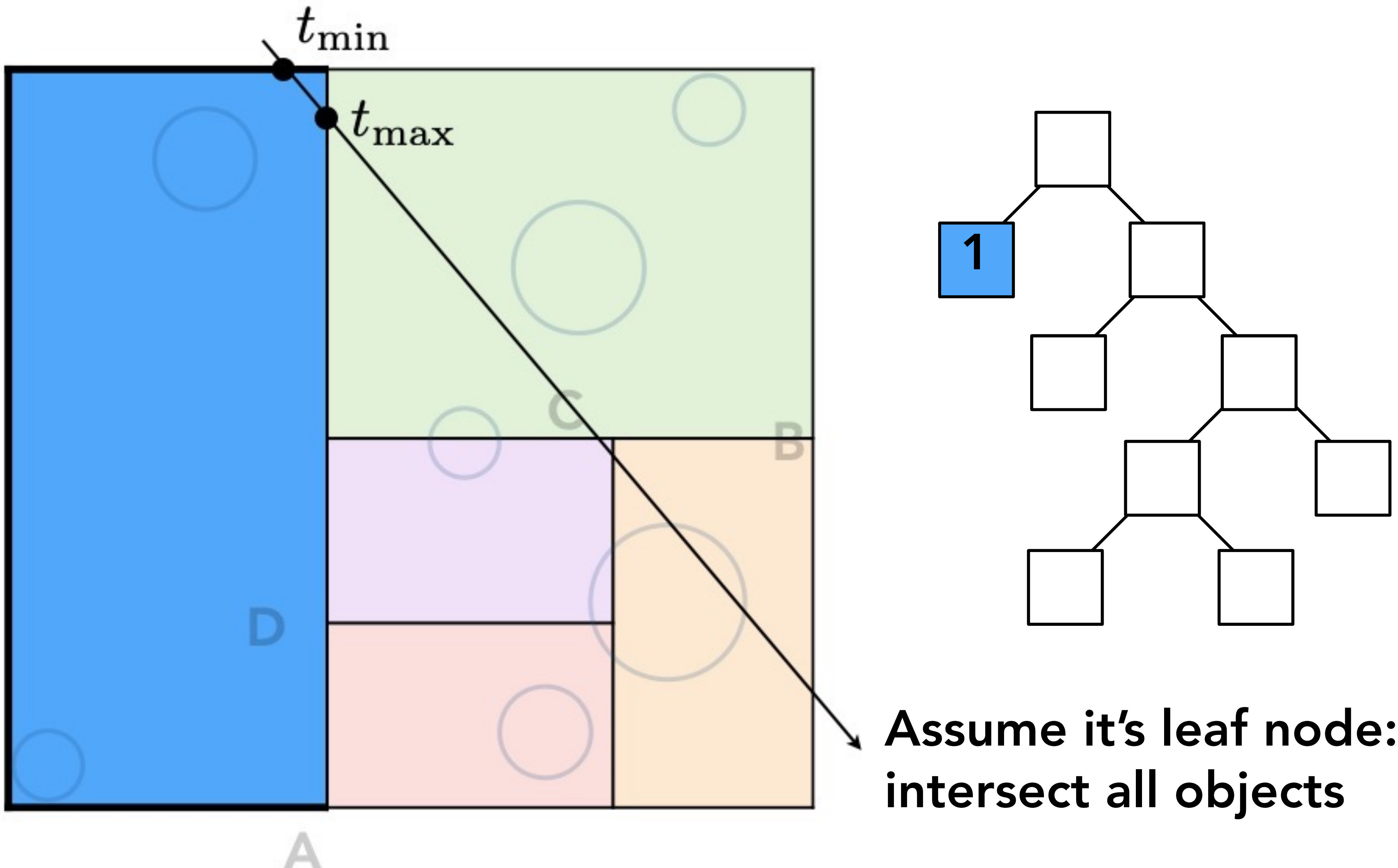


Traversing a KD-Tree



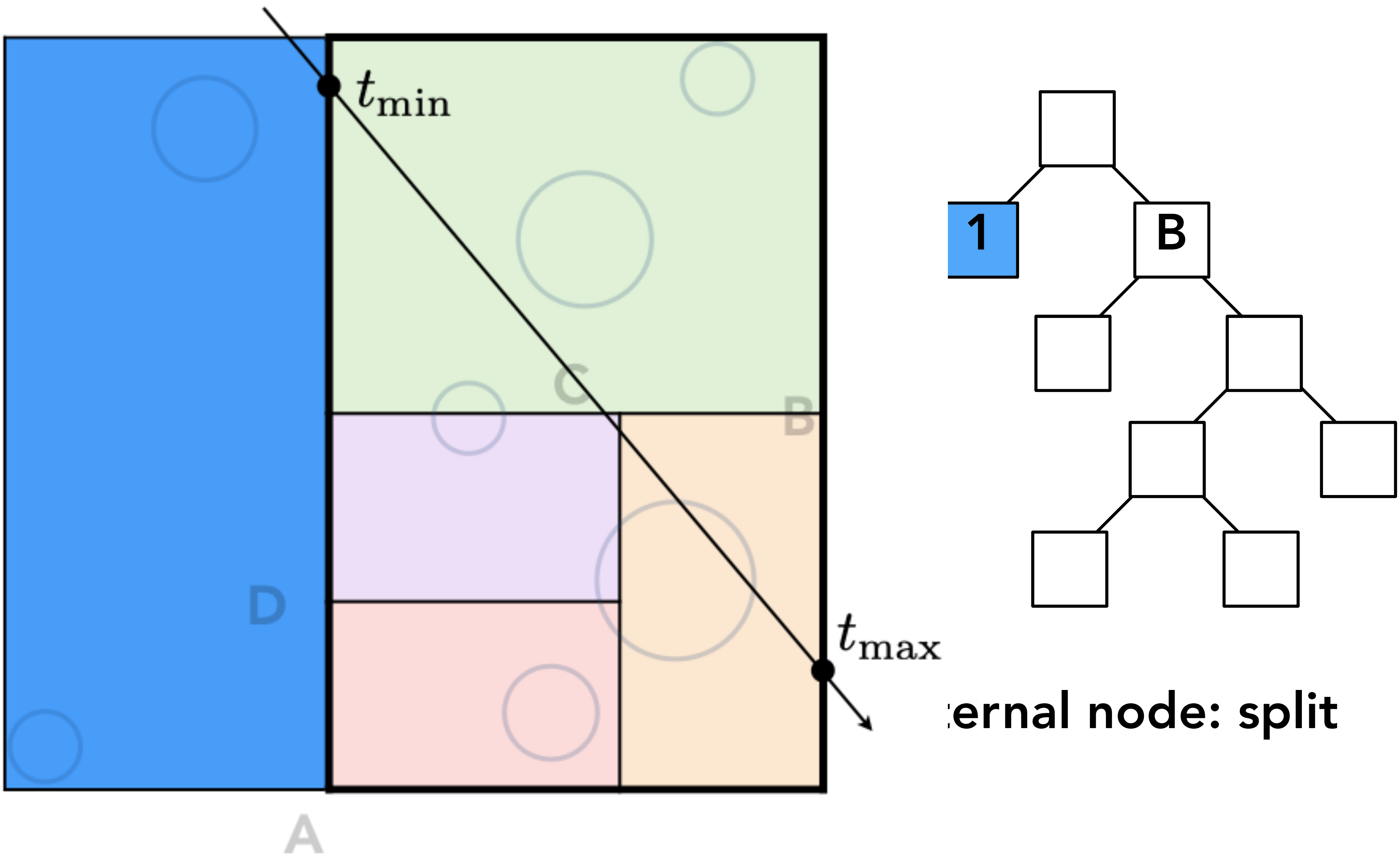
Internal node: split

Traversing a KD-Tree



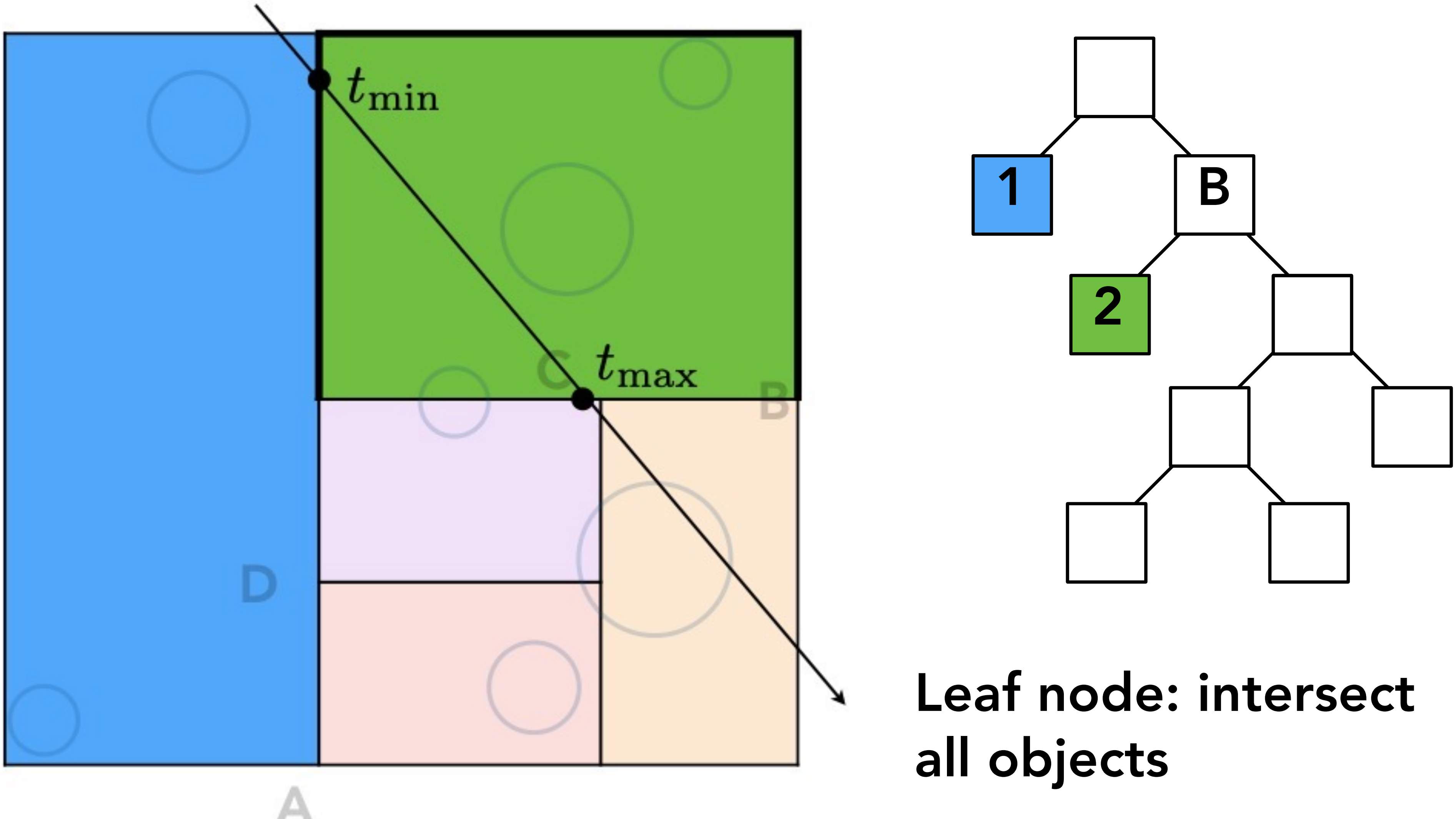
Assume it's leaf node: intersect all objects

Traversing a KD-Tree



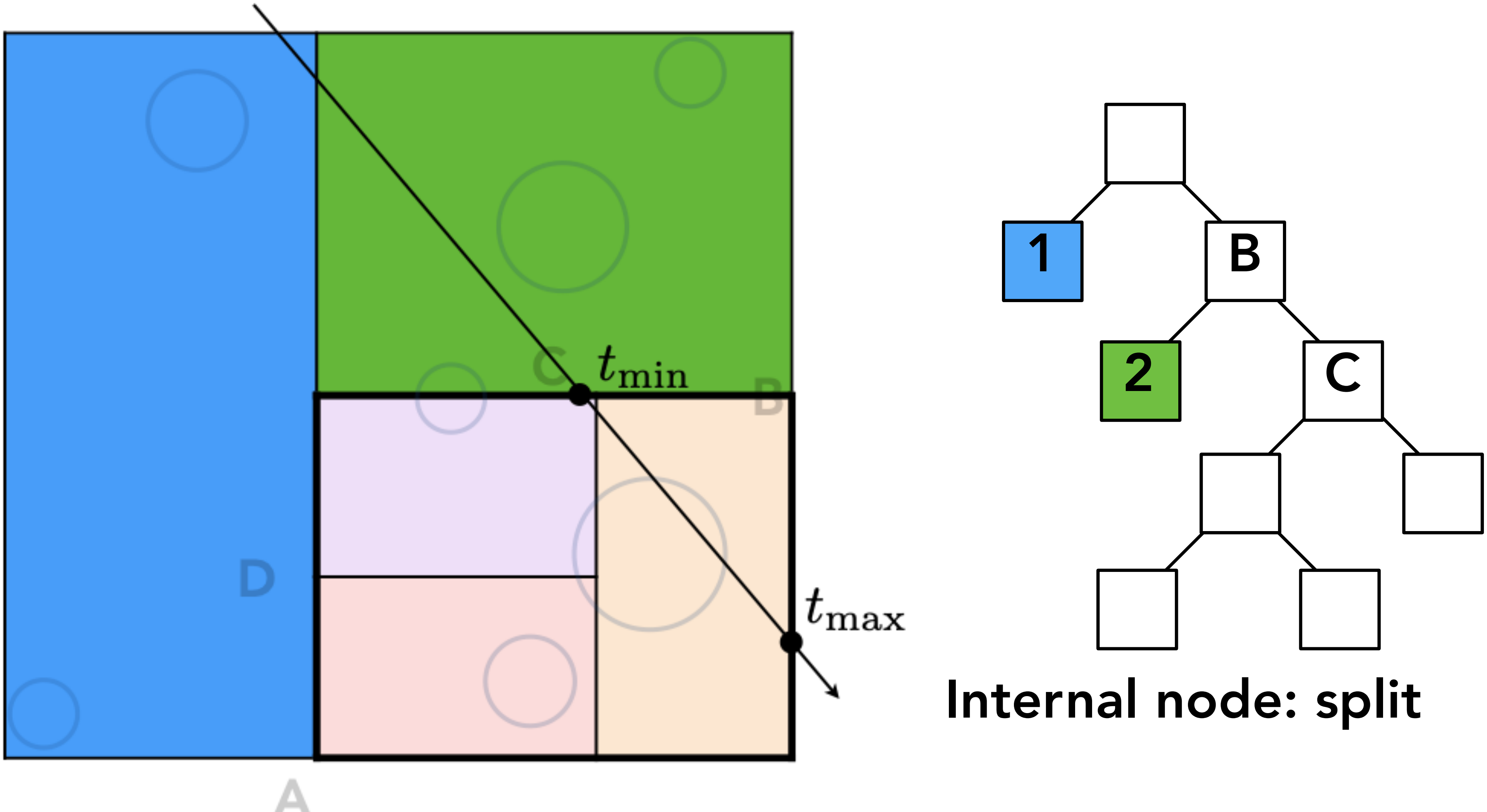
ernal node: split

Traversing a KD-Tree



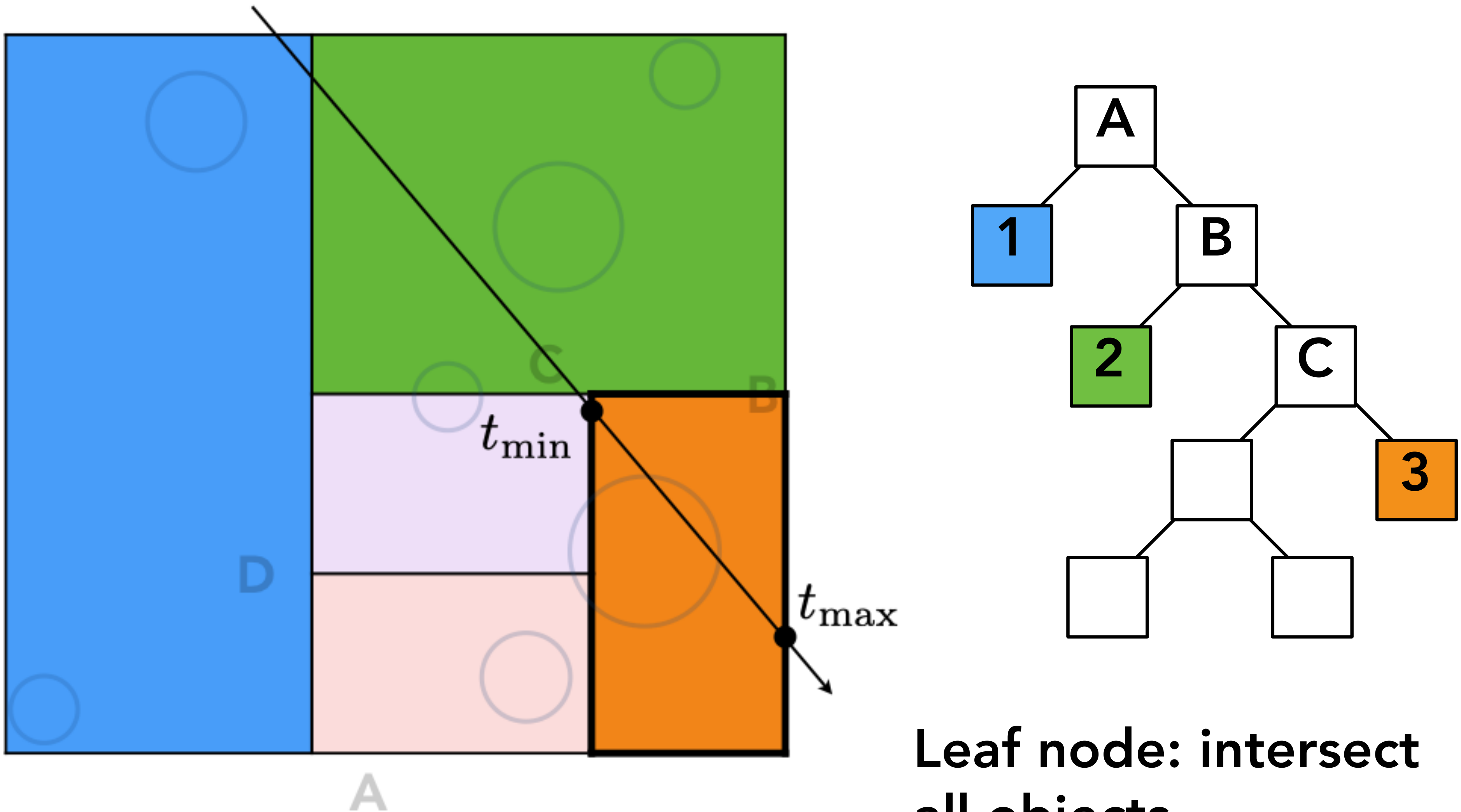
Leaf node: intersect all objects

Traversing a KD-Tree



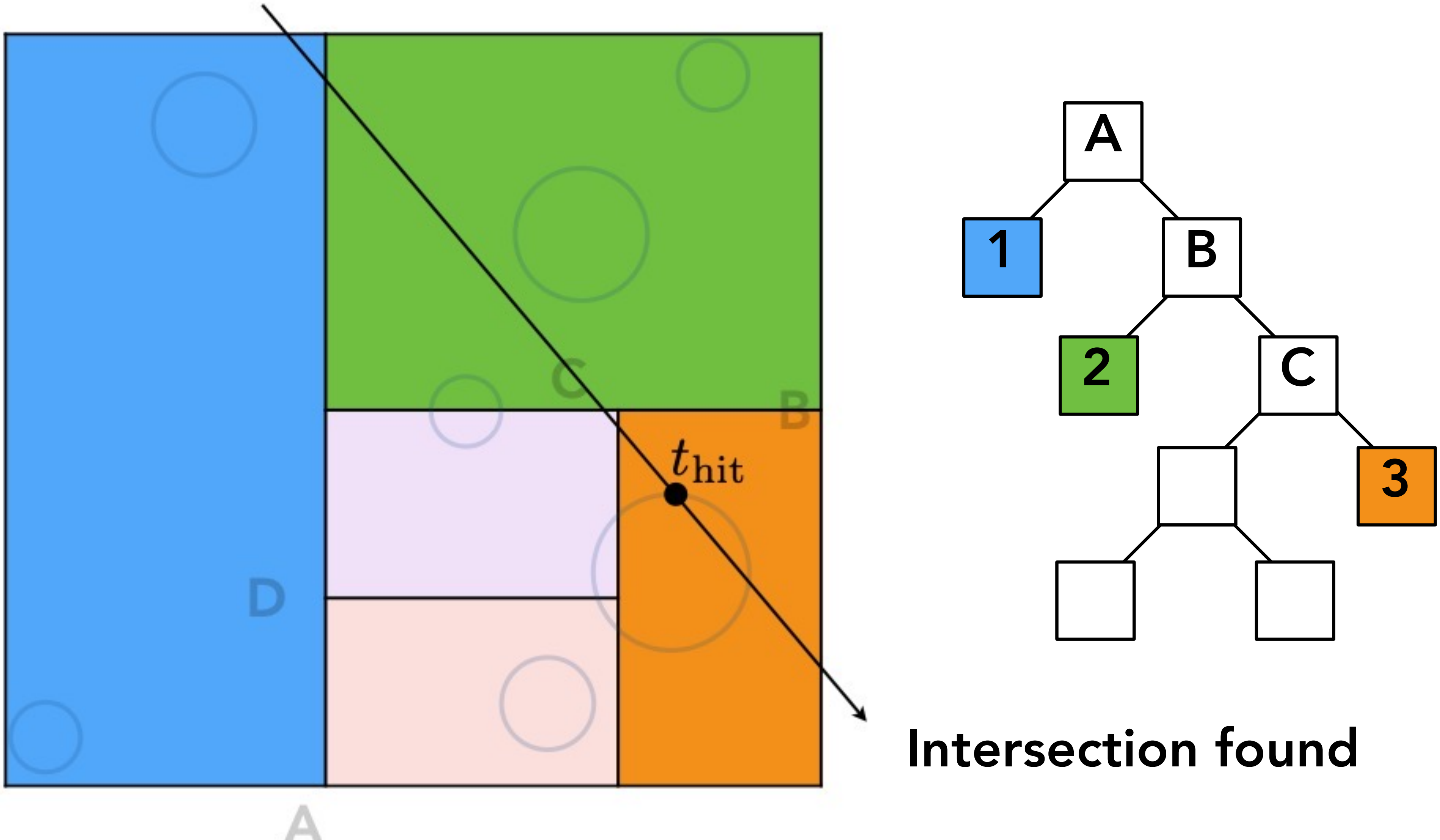
Internal node: split

Traversing a KD-Tree



Leaf node: intersect all objects

Traversing a KD-Tree



Intersection found

Object Partitions &

Bounding Volume Hierarchy (BVH)

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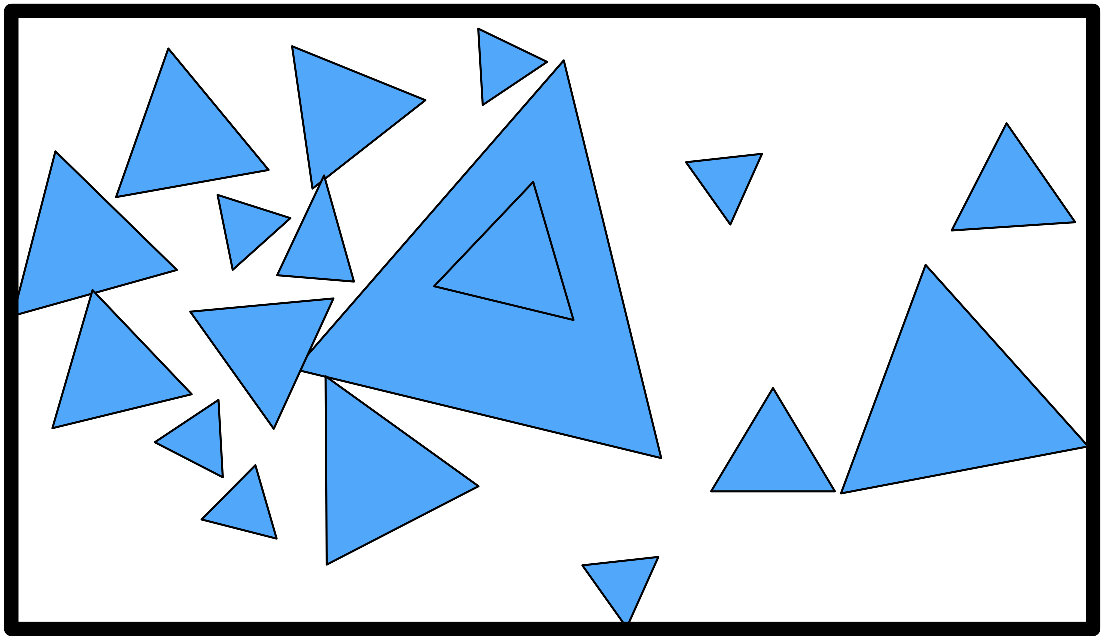
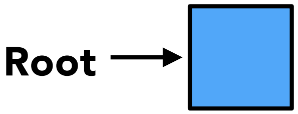
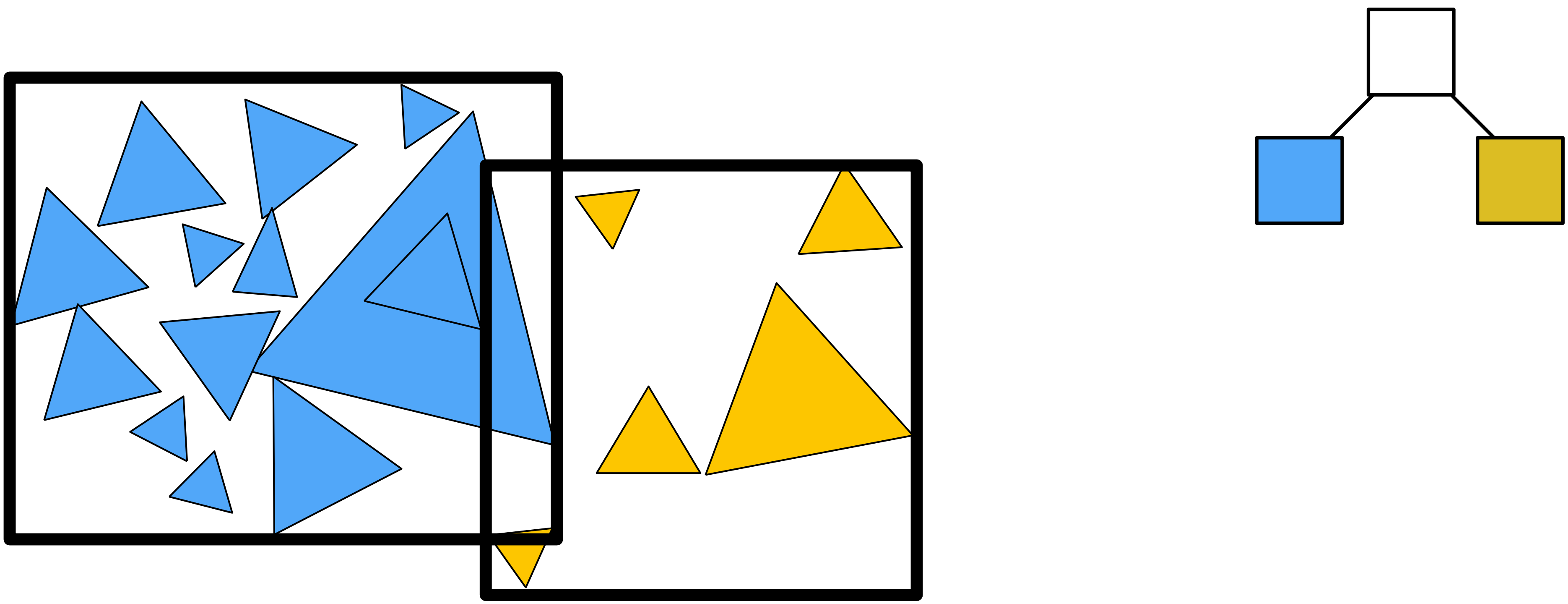




Bounding Volume Hierarchy (BVH)



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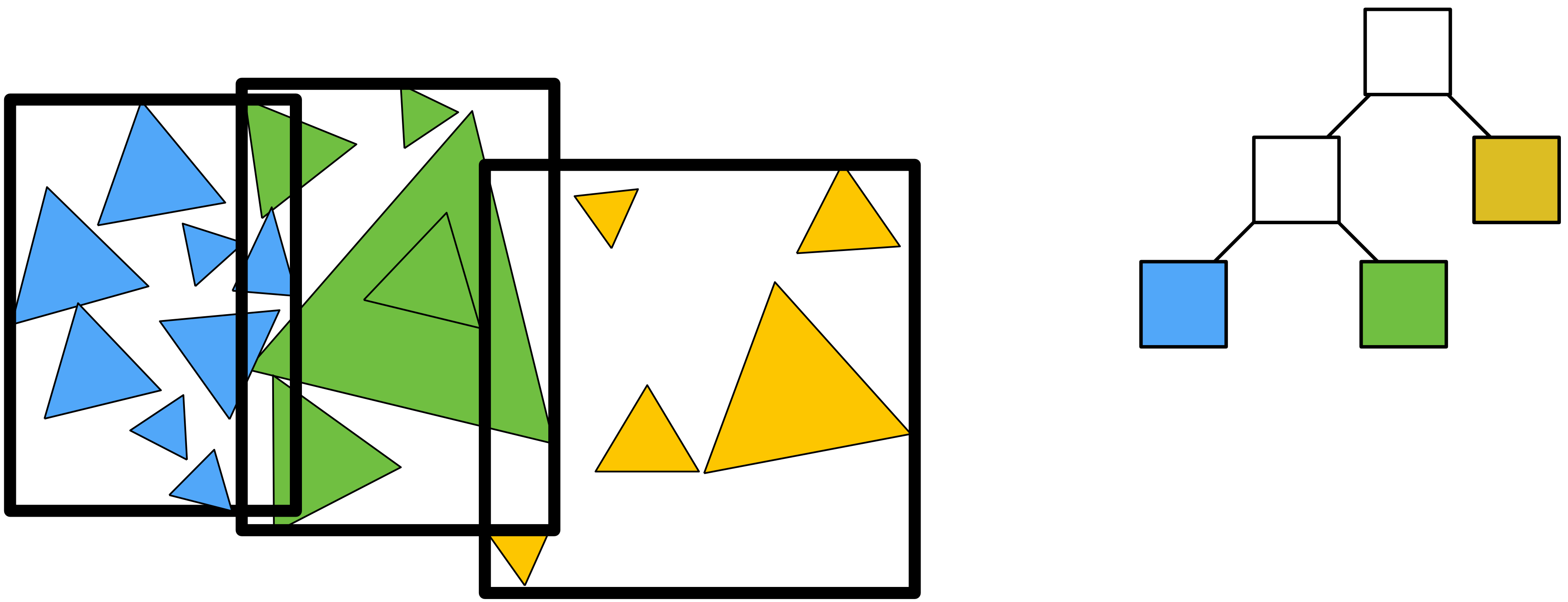
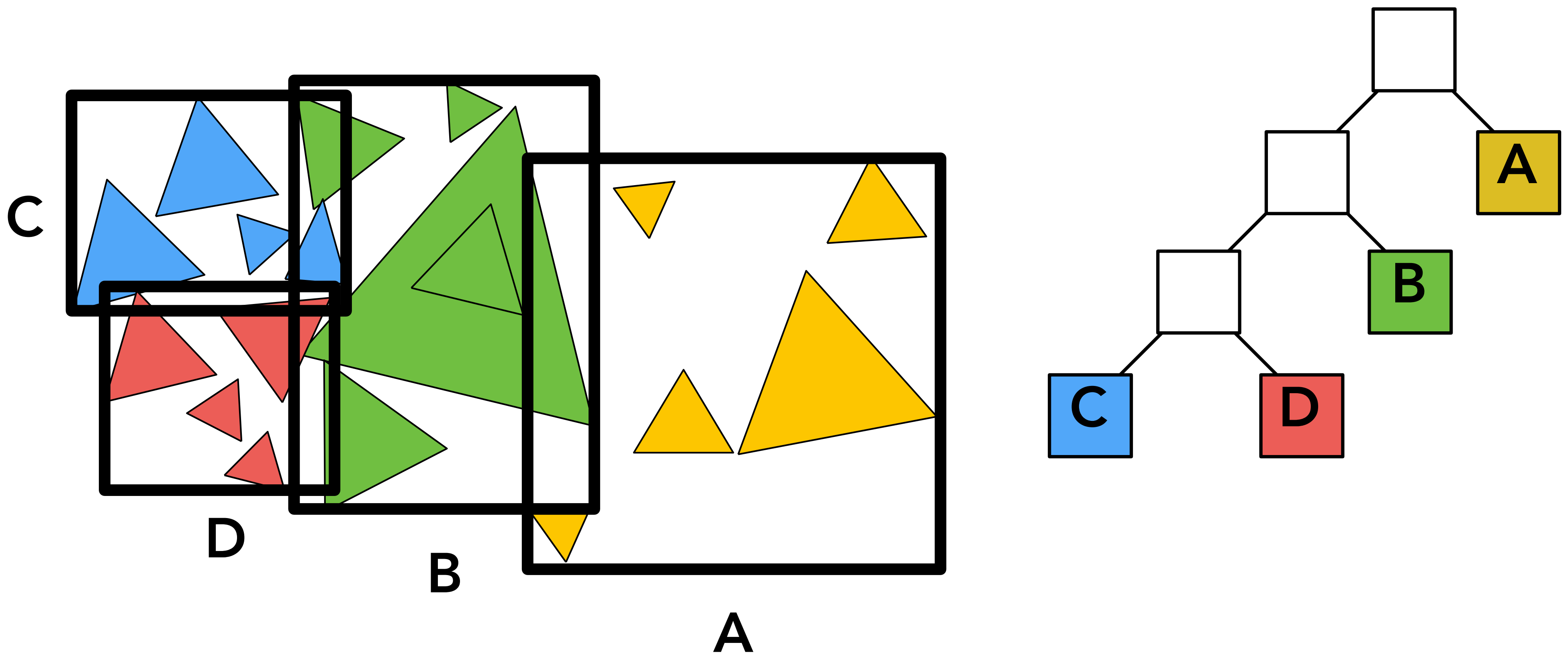
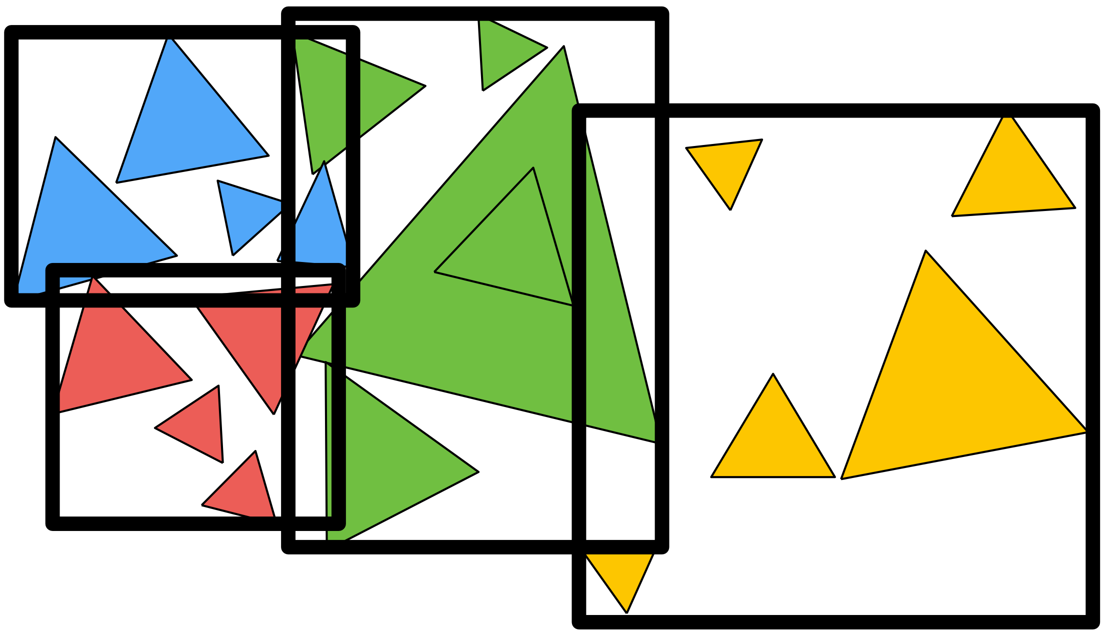


Bounding Volume Hierarchy (BVH)



Summary: Building BVHs



- Find bounding box
- Recursively split set of objects in two subsets
- **Recompute** the bounding box of the subsets
- Stop when necessary
- Store objects in each leaf node

Building BVHs

How to subdivide a node?

- Choose a dimension to split
- Heuristic #1: Always choose the longest axis in node
- Heuristic #2: Split node at location of **median** object

Termination criteria?

- Heuristic: stop when node contains few elements (e.g. 5)

Data Structure for BVHs

Internal nodes store

- Bounding box
- Children: pointers to child nodes

Leaf nodes store

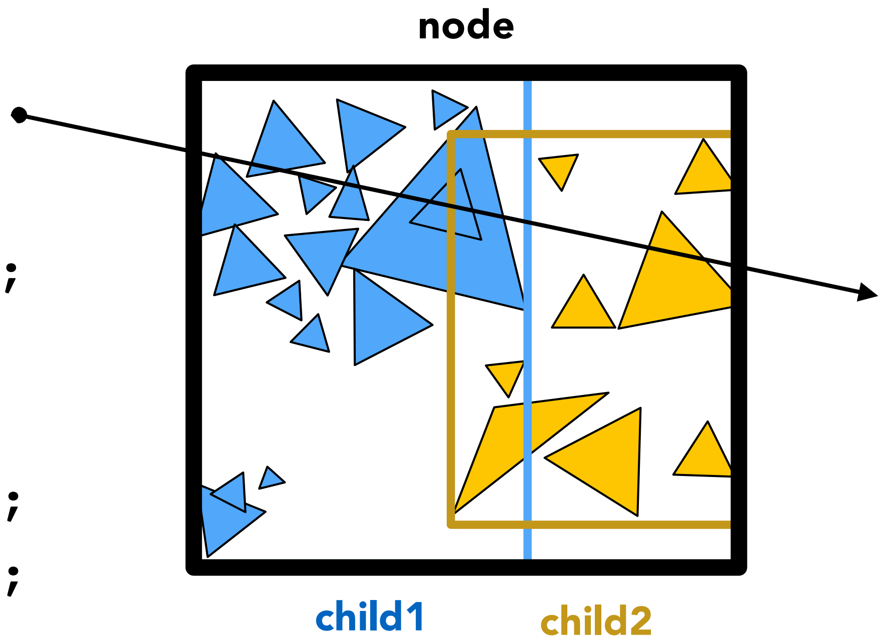
- Bounding box
- List of objects

Nodes represent subset of primitives in scene

- All objects in subtree

BVH Traversal

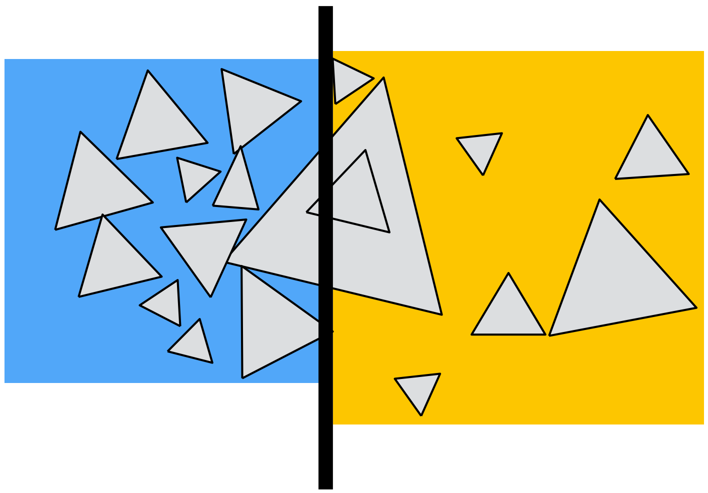
```
Intersect(Ray ray, BVH node) {
  if (ray misses node.bbox) return;

  if (node is a leaf node)
     test intersection with all objs;
     return closest intersection;

  hit1 = Intersect(ray, node.child1);
  hit2 = Intersect(ray, node.child2);

  return the closer of hit1, hit2;
}
```



Spatial vs Object Partitions

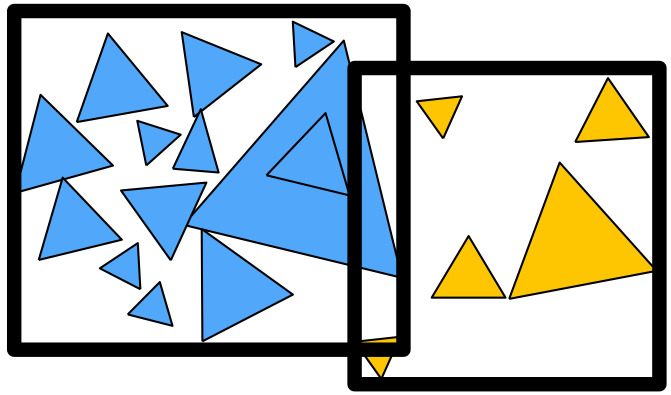
Spatial partition (e.g.KD-tree)

- Partition space into non-overlapping regions
- An object can be contained in multiple regions



Object partition (e.g. BVH)

- Partition set of objects into disjoint subsets
- Bounding boxes for each set may overlap in space



Thank you!

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