

Ray Tracing Acceleration

CS 4620 Lecture 19

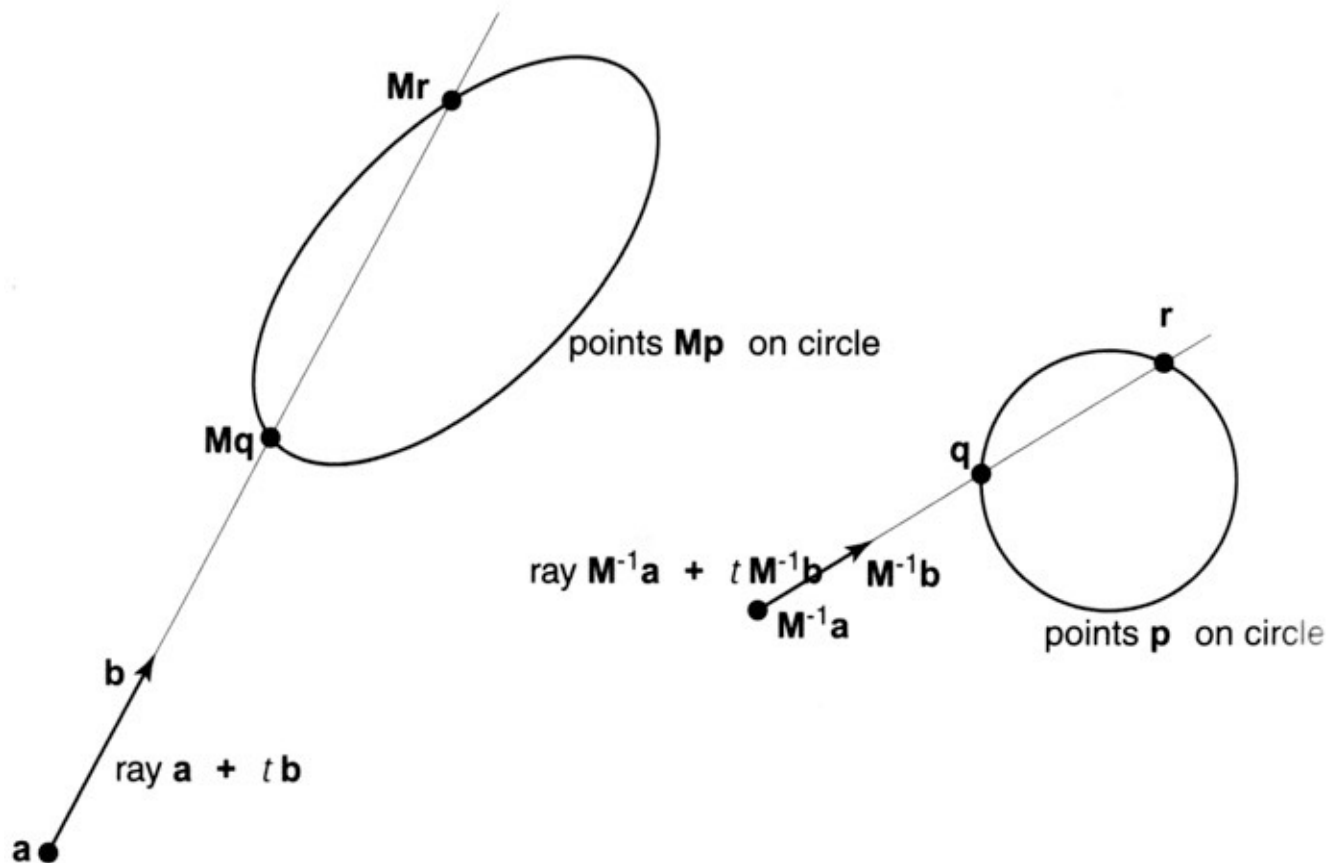
Topics

- Transformations in ray tracing
 - Transforming objects
 - Transformation hierarchies
- Ray tracing acceleration structures
 - Bounding volumes
 - Bounding volume hierarchies
 - Uniform spatial subdivision
 - Adaptive spatial subdivision

Transforming objects

- In modeling, we've seen the usefulness of transformations
 - How to do the same in RT?
- Take spheres as an example: want to support transformed spheres
 - Need a new Surface subclass
- Option 1: transform sphere into world coordinates
 - Write code to intersect arbitrary ellipsoids
- Option 2: transform ray into sphere's coordinates
 - Then just use existing sphere intersection routine

Intersecting transformed objects



Implementing RT transforms

- Create wrapper object “TransformedSurface”
 - Subclass of Surface
 - Has a transform T and a reference to a surface S
 - To intersect:
 - Transform ray to local coords (by inverse of T)
 - Call `surface.intersect`
 - Transform hit data back to global coords (by T)
 - Intersection point
 - Surface normal
 - Any other relevant data (maybe none)

```
class TransformedSurface : Surface {  
    Transform xf;  
    Surface s;  
    intersect(Ray r, tMin, tMax) {  
        (p, n, t) = s.intersect(xf-1 r, tMin, tMax);  
        return (xf p, xf-T n, t);  
    }  
}
```

Groups, transforms, hierarchies

- Often it's useful to transform several objects at once
 - Add “SurfaceGroup” as a subclass of Surface
 - Has a list of surfaces
 - Returns closest intersection
 - Opportunity to make Scene a single Surface to avoid duplication
- With TransformedSurface and SurfaceGroup you can put transforms below transforms
 - Voilà! A transformation hierarchy.

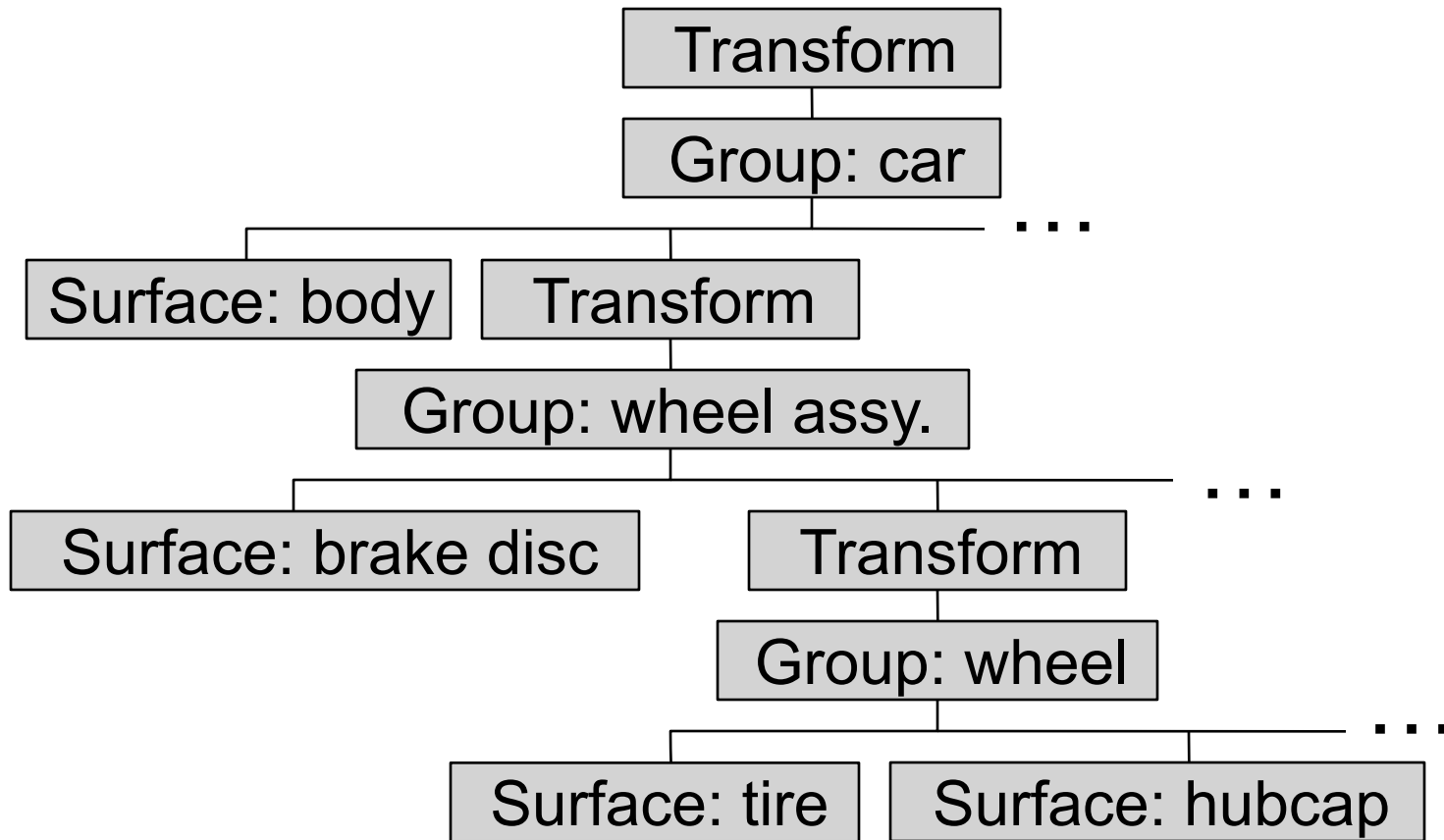
```

class SurfaceGroup : Surface {
    List<Surface> sList;
    intersect(Ray r, tMin, tMax) {
        hit = false;
        for (s in sList) {
            (p, n, t) = s.intersect(r, tMin, tMax);
            tMax = min(t, tMax);
            hit = true;
        }
        if (hit)
            return (p, n, tMax);
        else
            return false;
    }
}

```

Algorithm is quite familiar from Scene.intersect in Ray 1...

A transformation hierarchy

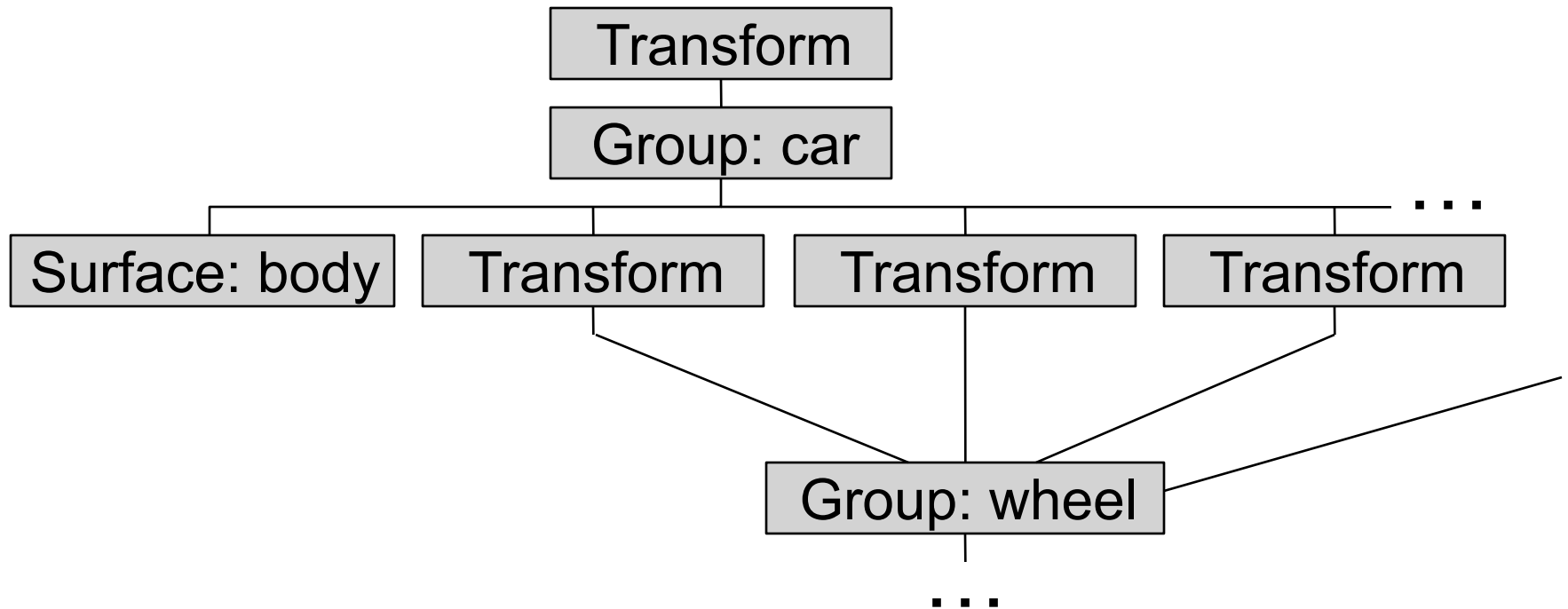


- Common optimization: merge transforms with groups

Instancing

- Anything worth doing is worth doing n times
- If we can transform objects, why not transform them several ways?
 - Many models have repeated subassemblies
 - Mechanical parts (wheels of car)
 - Multiple objects (chairs in classroom, ...)
 - Nothing stops you from creating two TransformedSurface objects that reference the same Surface
 - Allowing this makes the transformation tree into a DAG
 - (directed acyclic graph)
 - Mostly this is transparent to the renderer

Hierarchy with instancing



- Previous code still works just fine!

Hierarchies and performance

- Transforming rays is expensive
 - minimize tree depth: flatten on input
 - push all transformations toward leaves
 - optional for triangle meshes
 - transform ray once, amortize cost over many intersections
 - internal group nodes still required for instancing
 - can't push two transforms down to same child!

```

TransformGroup {
  xf: A
  Mesh {
    v1, v2, v3, ...
  }
  TransformGroup {
    xf: B
    Sphere {
      radius: r
    }
  }
}

```



```

Mesh {
  xf: A
  v1, v2, v3, ...
}
Sphere {
  xf: BA
  radius: r
}

```



```

Mesh {
  Av1, Av2, Av3, ...
}
Sphere {
  xf: BA
  radius: r
}

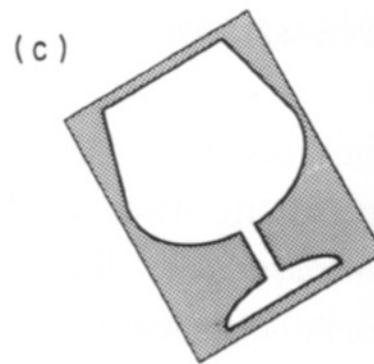
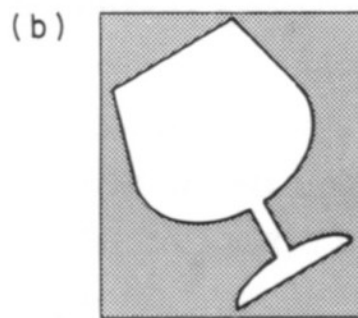
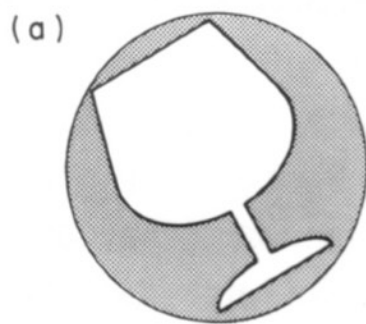
```

Ray tracing acceleration

- Ray tracing is slow. This is bad!
 - Ray tracers spend most of their time in ray-surface intersection methods
- Ways to improve speed
 - Make intersection methods more efficient
 - Yes, good idea. But only gets you so far
 - Call intersection methods fewer times
 - Intersecting every ray with every object is wasteful
 - Basic strategy: efficiently find big chunks of geometry that definitely do not intersect a ray

Bounding volumes

- Quick way to avoid intersections: bound 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



Bounding volumes

- Cost: more for hits and near misses, less for far misses
- Worth doing? It depends:
 - Cost of bvol intersection test should be small
 - Therefore use simple shapes (spheres, boxes, ...)
 - Cost of object intersect test should be large
 - Bvols most useful for complex objects
 - Tightness of fit should be good
 - Loose fit leads to extra object intersections
 - Tradeoff between tightness and bvol intersection cost

Implementing bounding volume

- Just add new Surface subclass, “BoundedSurface”
 - Contains a bounding volume and a reference to a surface
 - Intersection method:
 - Intersect with bvol, return false for miss
 - Return `surface.intersect(ray)`
 - Like transformations, common to merge with group
 - This change is transparent to the renderer (only it might run faster)
- Note that all Surfaces will need to be able to supply bounding volumes for themselves

```
class BoundedSurface : Surface {  
    BVol v;  
    Surface s;  
    intersect(Ray r, tMin, tMax) {  
        if (v.intersect(r, tMin, tMax))  
            return s.intersect(r, tMin, tMax);  
        else  
            return false;  
    }  
}
```

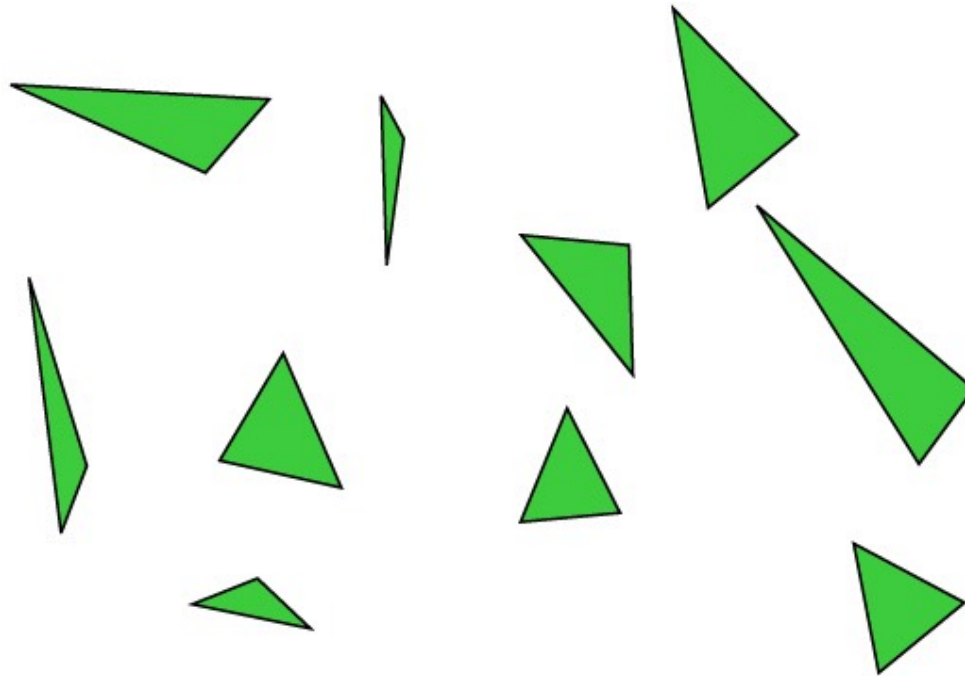
If it's worth doing, it's worth doing hierarchically!

- Bvols around objects may help
- Bvols around groups of objects will help
- Bvols around parts of complex objects will help
- Leads to the idea of using bounding volumes all the way from the whole scene down to groups of a few objects

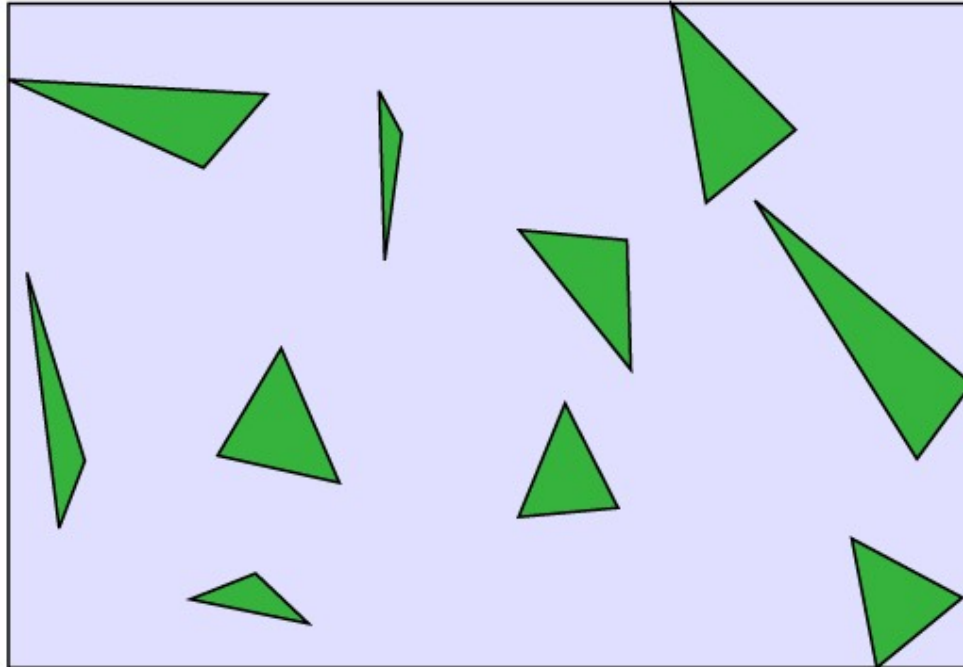
Implementing a bvol hierarchy

- A BoundedSurface can contain a list of Surfaces
- Some of those Surfaces might be more BoundedSurfaces
- Voilà! A bounding volume hierarchy
 - And it's all still transparent to the renderer

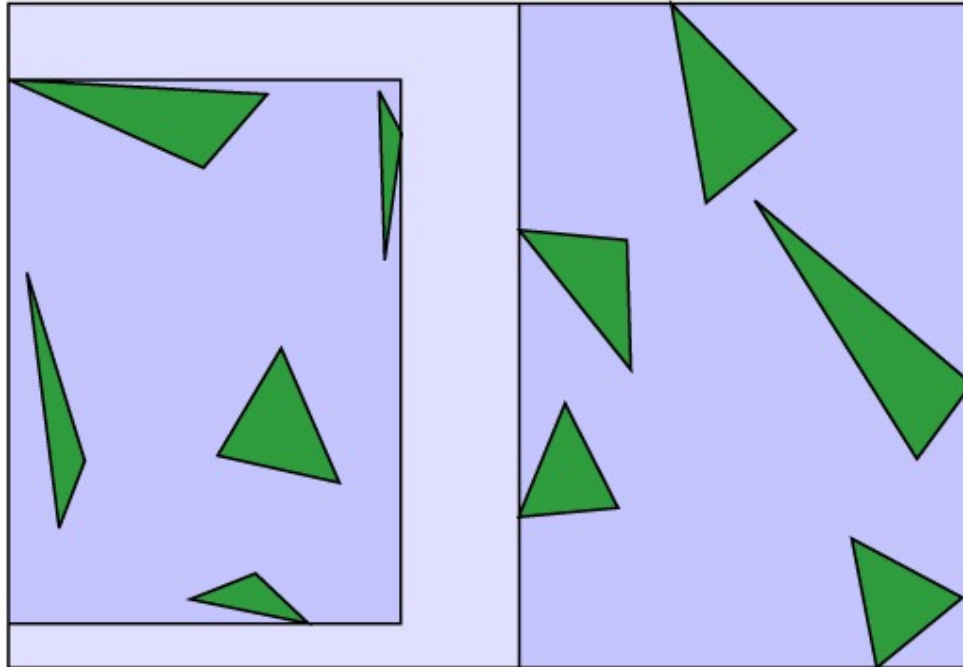
BVH construction example



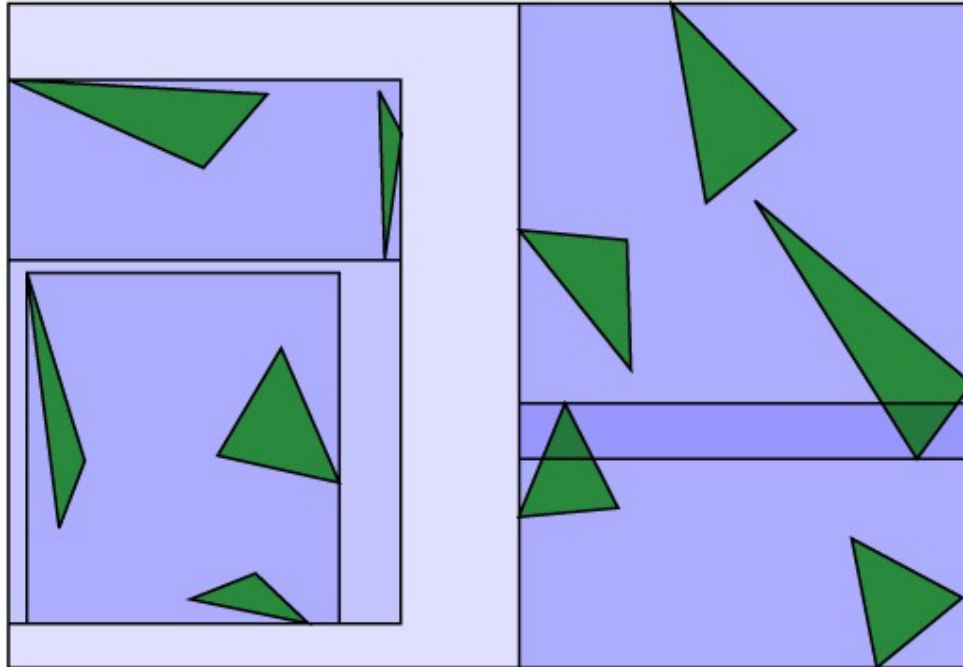
BVH construction example



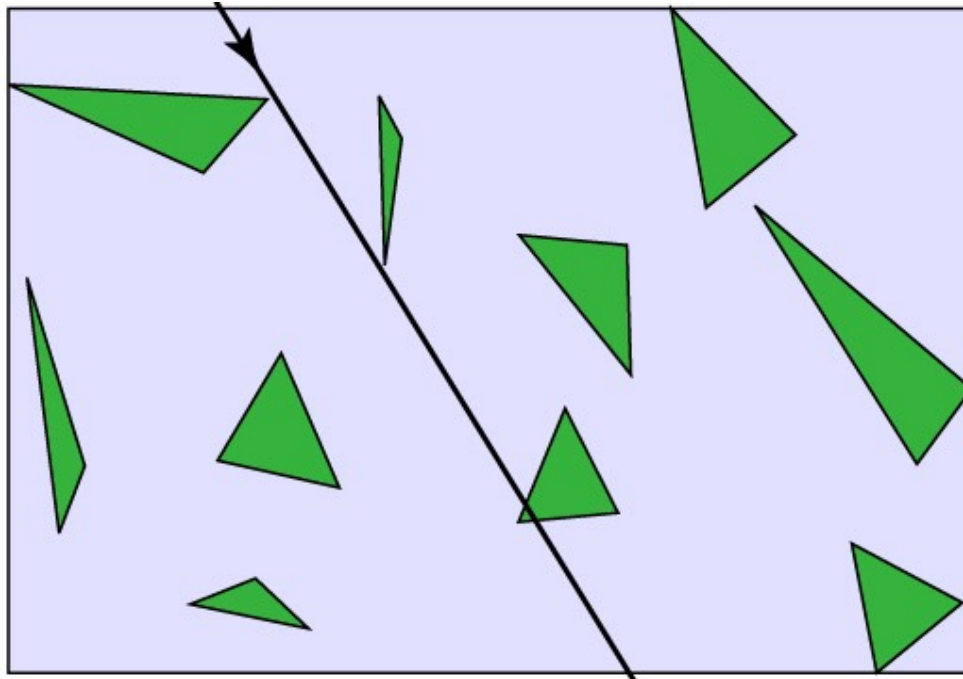
BVH construction example



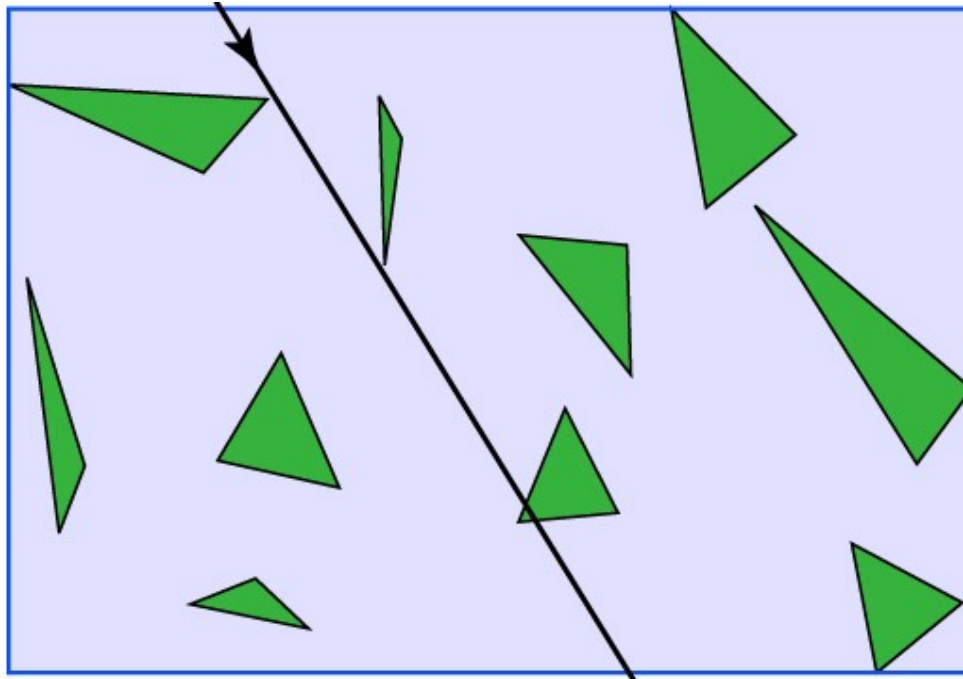
BVH construction example



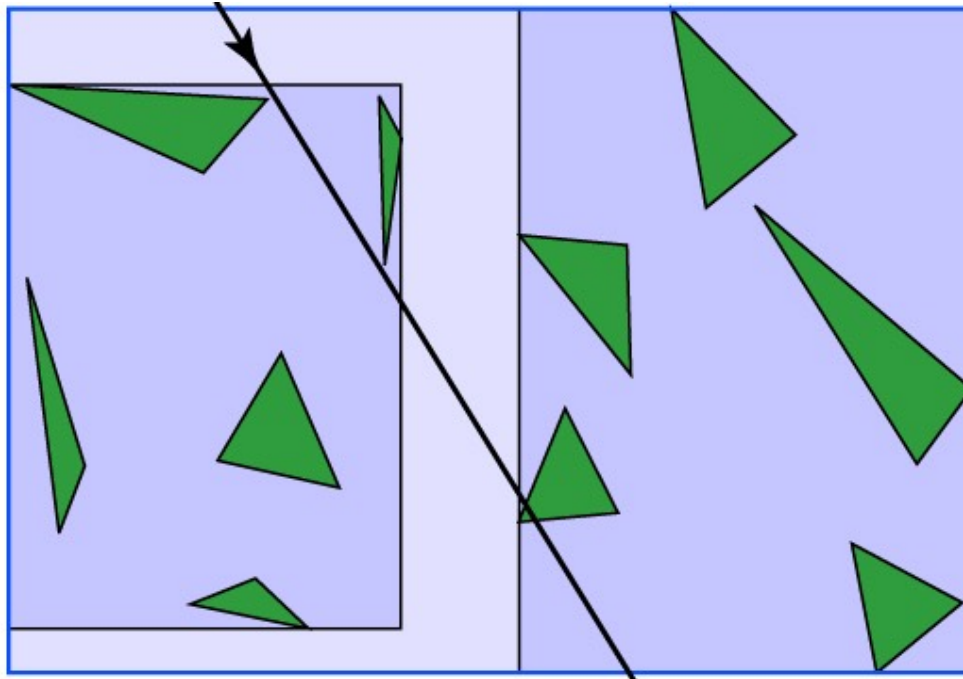
BVH ray-tracing example



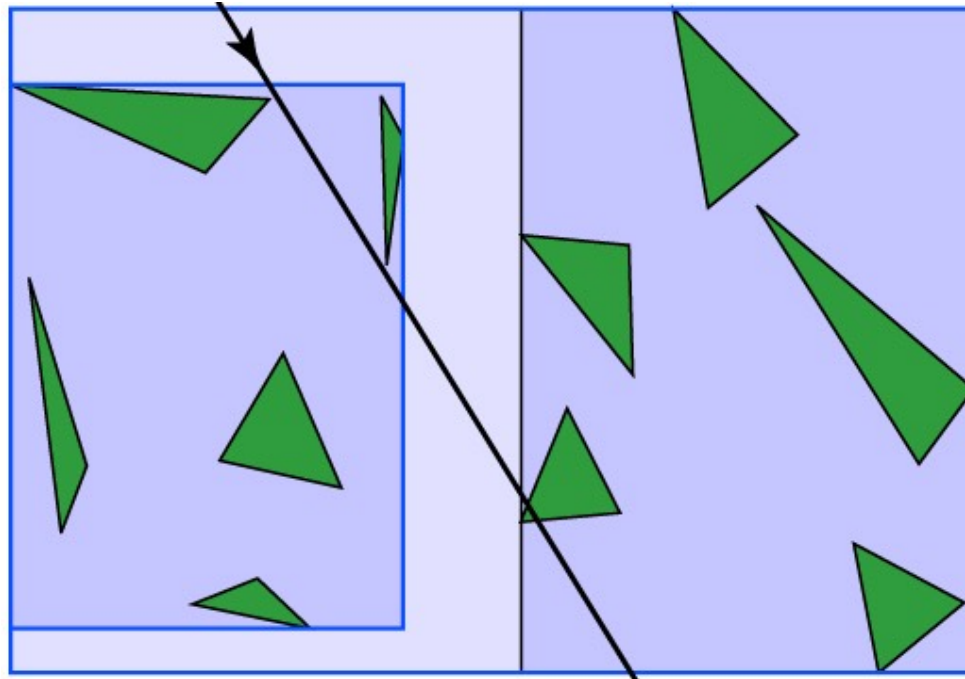
BVH ray-tracing example



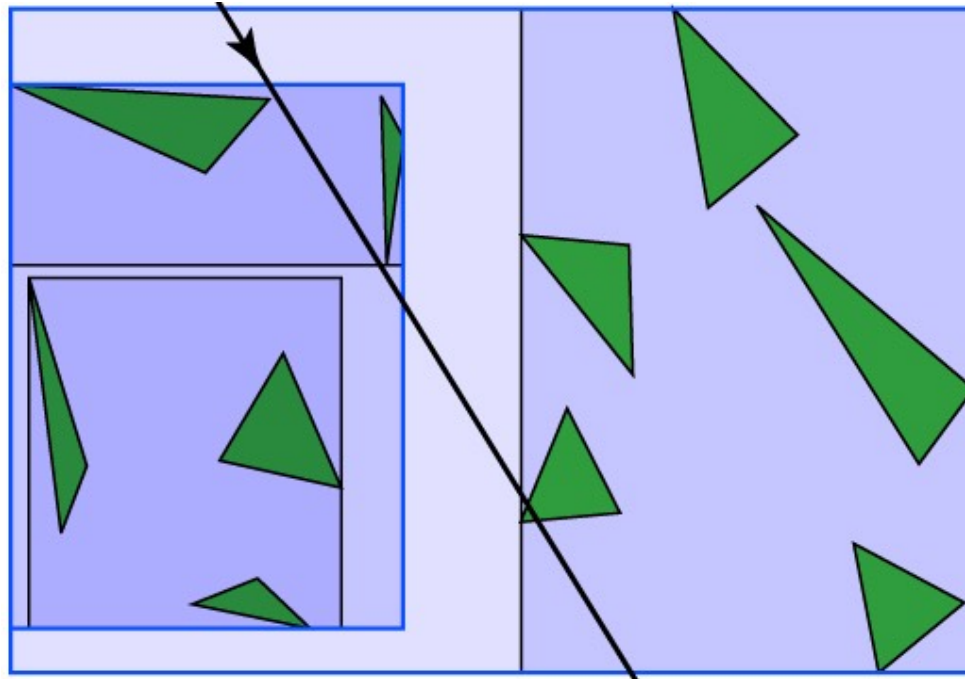
BVH ray-tracing example



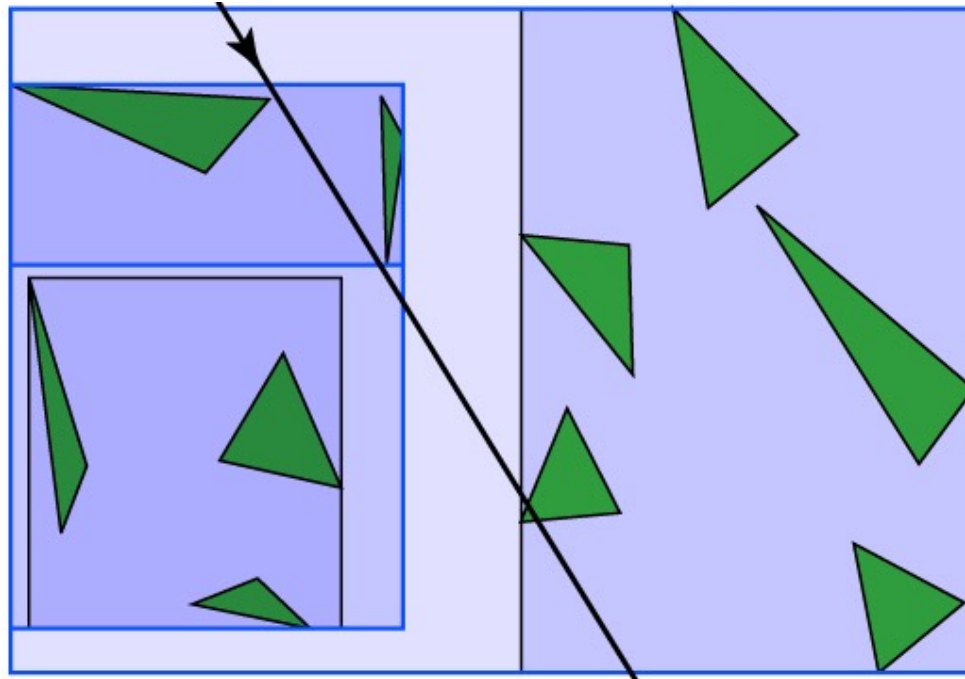
BVH ray-tracing example



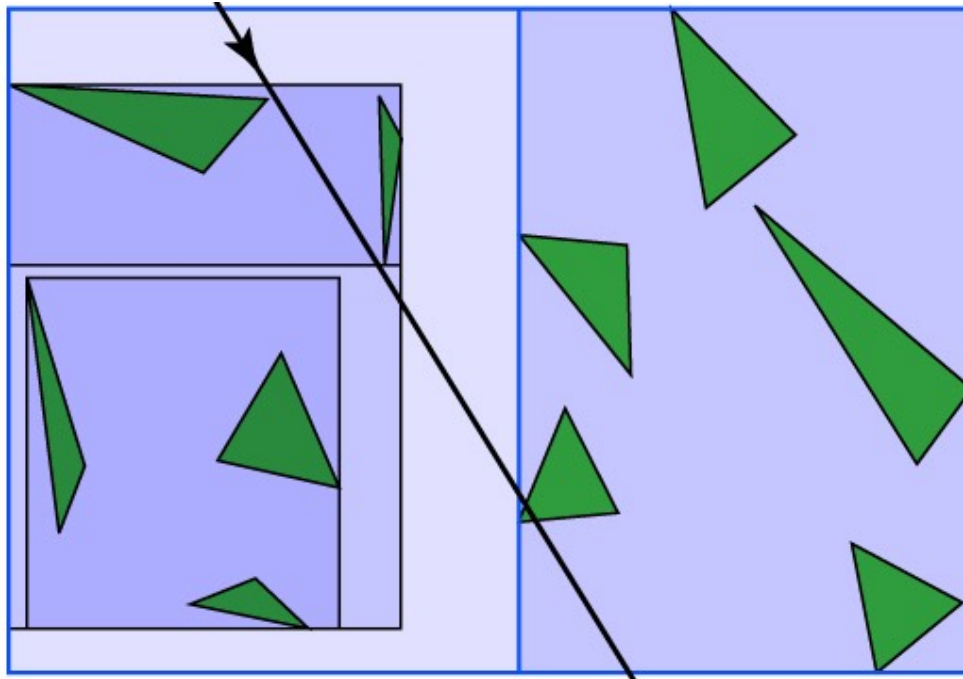
BVH ray-tracing example



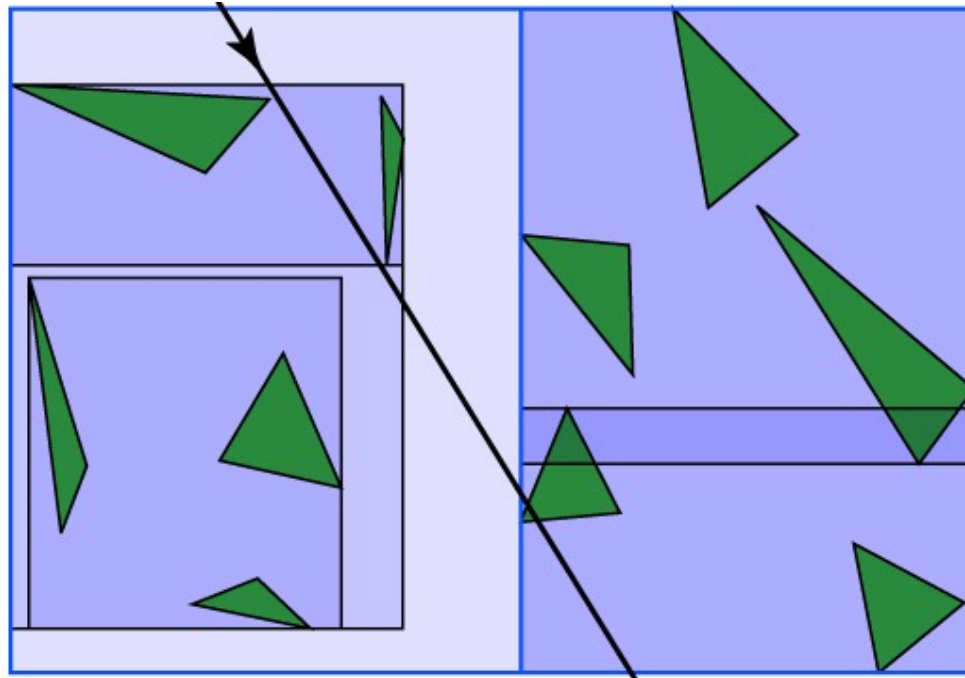
BVH ray-tracing example



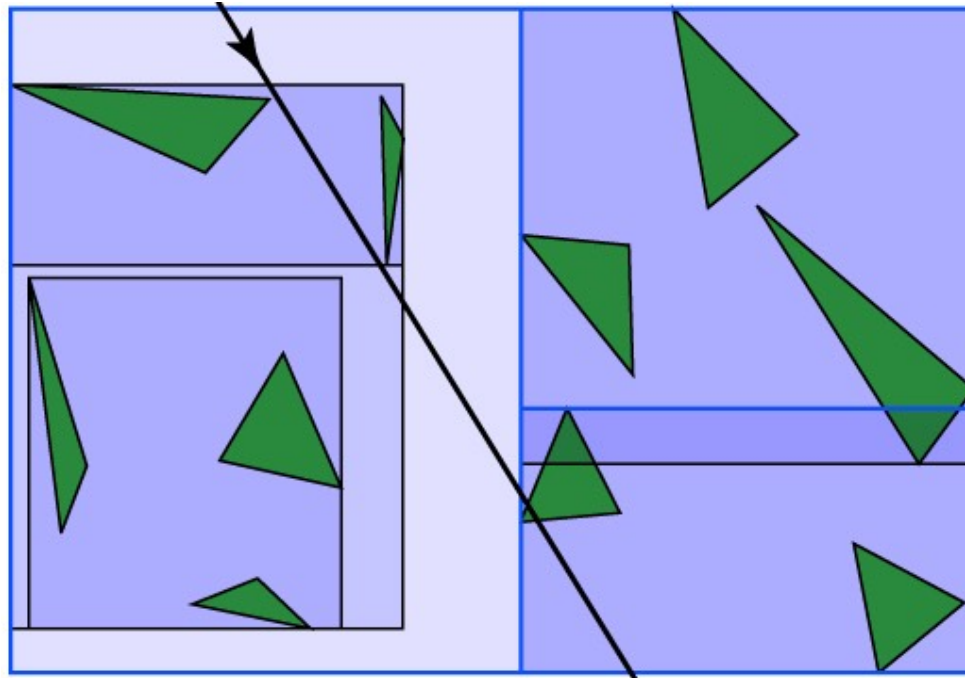
BVH ray-tracing example



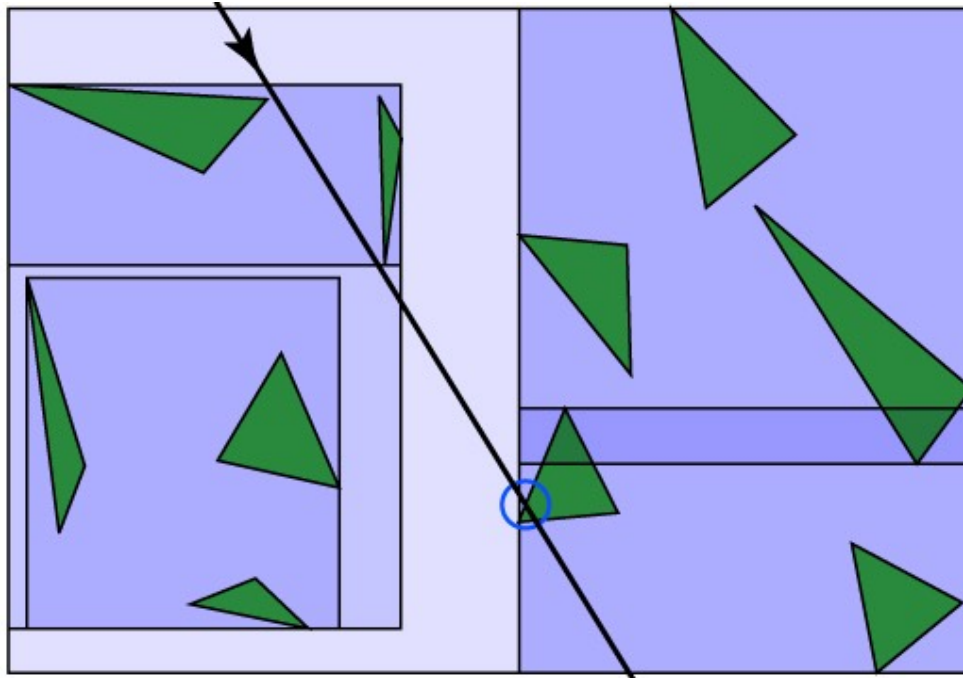
BVH ray-tracing example



BVH ray-tracing example



BVH ray-tracing example



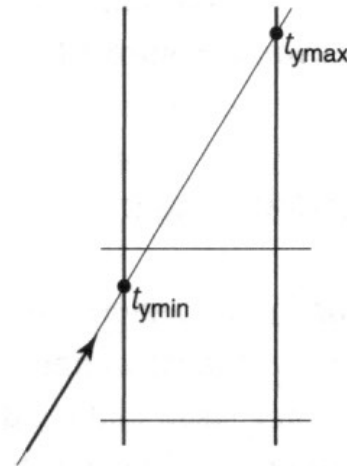
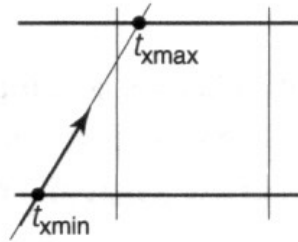
Choice of bounding volumes

- Spheres -- easy to intersect, not always so tight
- Axis-aligned bounding boxes (AABBs) -- easy to intersect, often tighter (esp. for axis-aligned models)
- Oriented bounding boxes (OBBs) -- easy to intersect (but cost of transformation), tighter for arbitrary objects
- Computing the bvols
 - For primitives -- generally pretty easy
 - For groups -- not so easy for OBBs (to do well)
 - For transformed surfaces -- not so easy for spheres

Axis aligned bounding boxes

- Probably easiest to implement
- Computing for (axis-aligned) primitives
 - Cube: duh!
 - Sphere, cylinder, etc.: pretty obvious
 - Groups or meshes: min/max of component parts
- AABBs for transformed surface
 - Easy to do conservatively: bbox of the 8 corners of the bbox of the untransformed surface
- How to intersect them
 - Treat them as an intersection of slabs (see Shirley)

Intersecting boxes



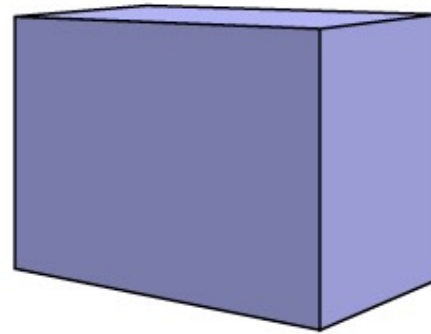
$$t \in [t_{xmin}, t_{xmax}]$$

$$t \in [t_{ymin}, t_{ymax}]$$

$$t \in [t_{xmin}, t_{xmax}] \cap [t_{ymin}, t_{ymax}]$$

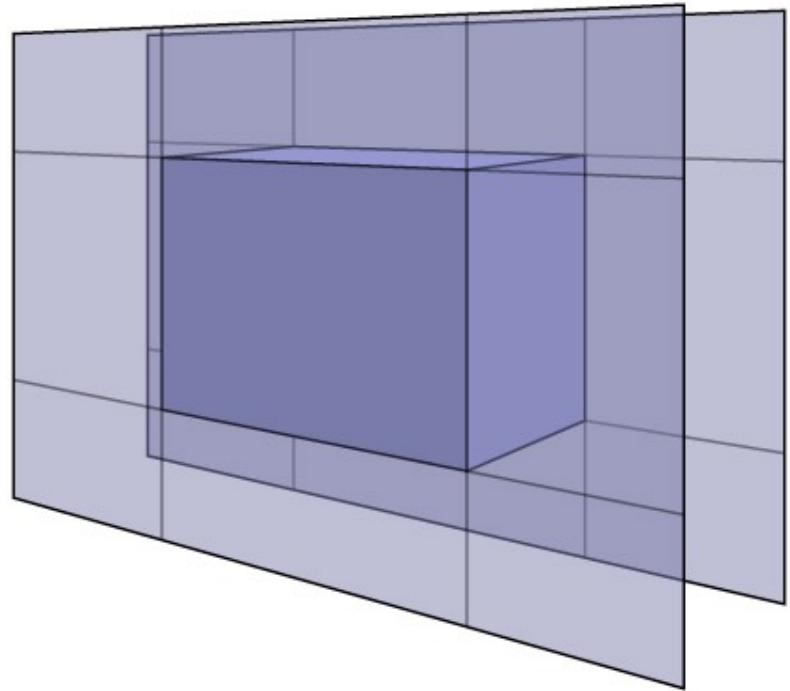
Ray-box intersection

- Could intersect with 6 faces individually
- Better way: box is the intersection of 3 slabs



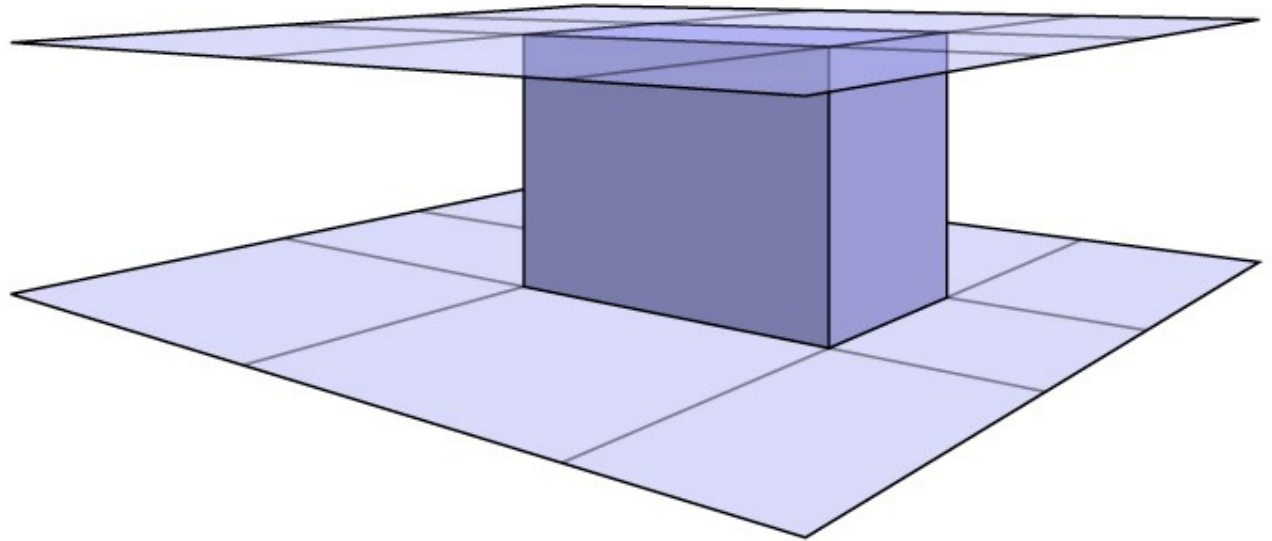
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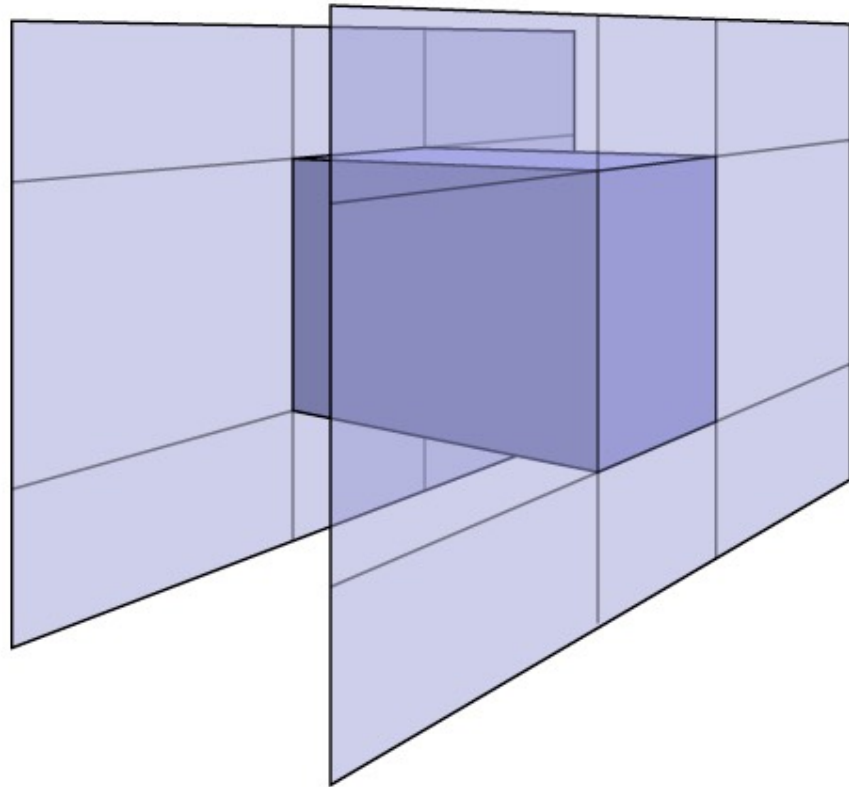
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Ray-box intersection

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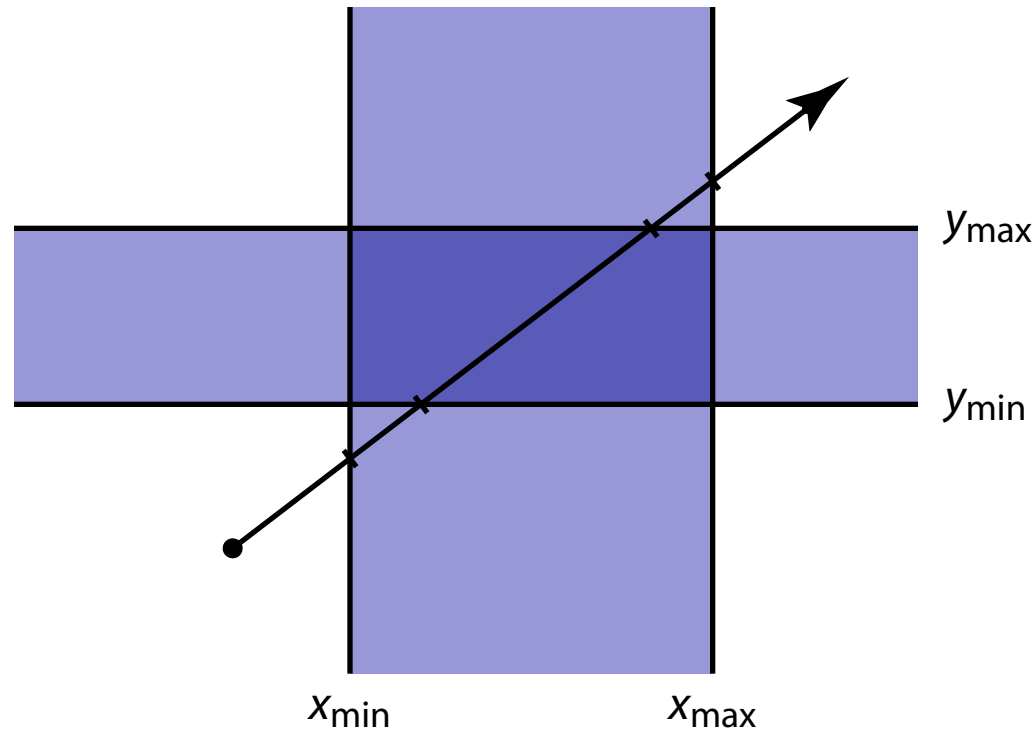
Ray-slab intersection

- 2D example
- 3D is the same!



Ray-slab intersection

- 2D example
- 3D is the same!

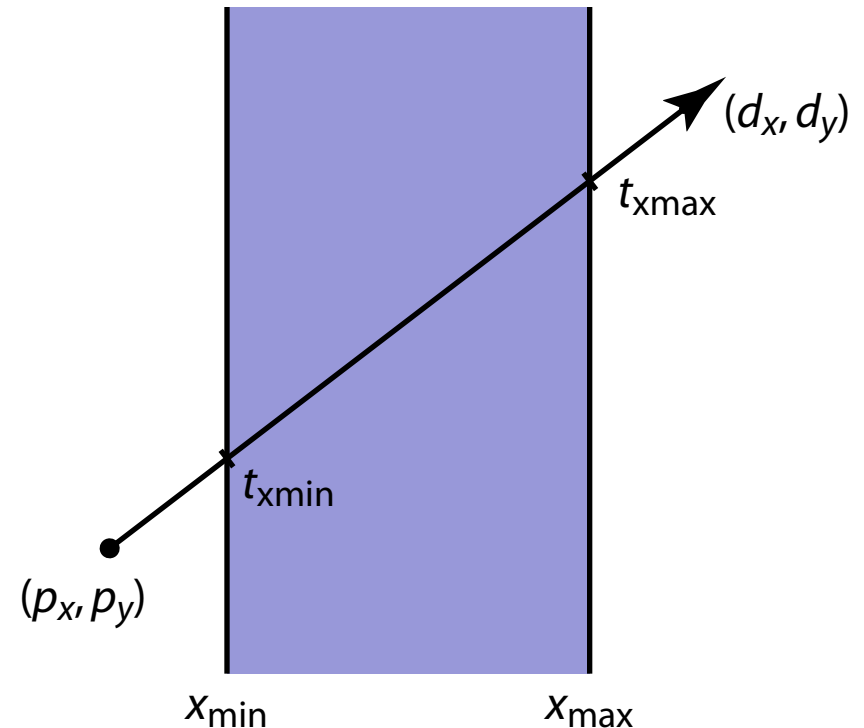


Ray-slab intersection

- 2D example
- 3D is the same!

$$p_x + t_{x\min} d_x = x_{\min}$$

$$t_{x\min} = (x_{\min} - p_x) / d_x$$



Ray-slab intersection

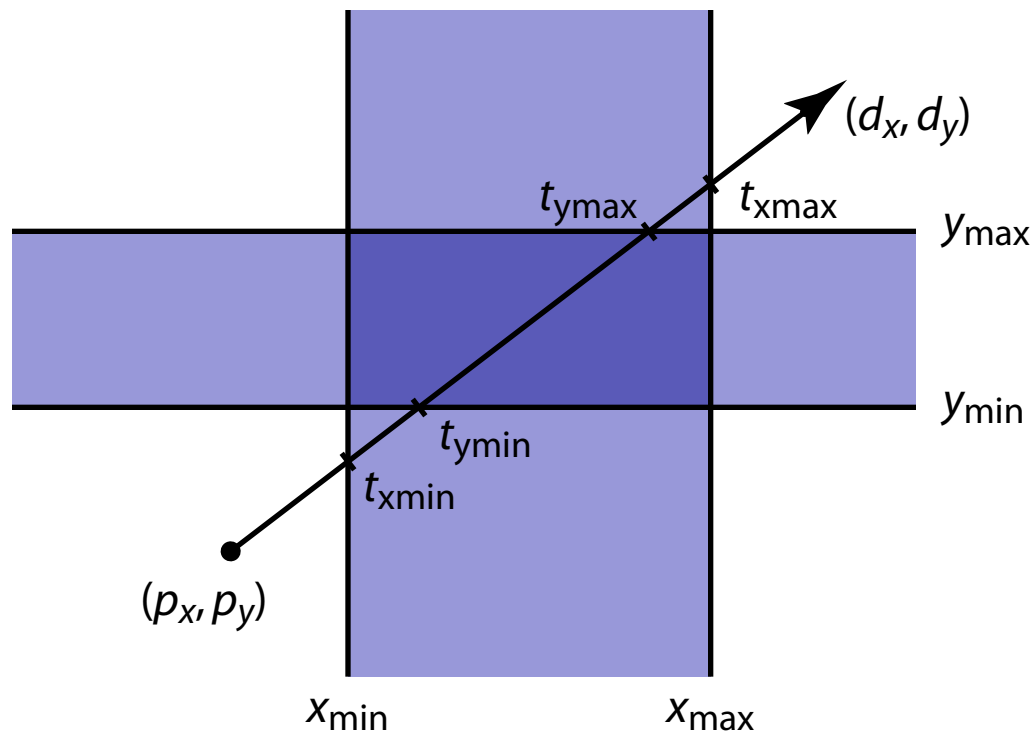
- 2D example
- 3D is the same!

$$p_x + t_{x\min} d_x = x_{\min}$$

$$t_{x\min} = (x_{\min} - p_x) / d_x$$

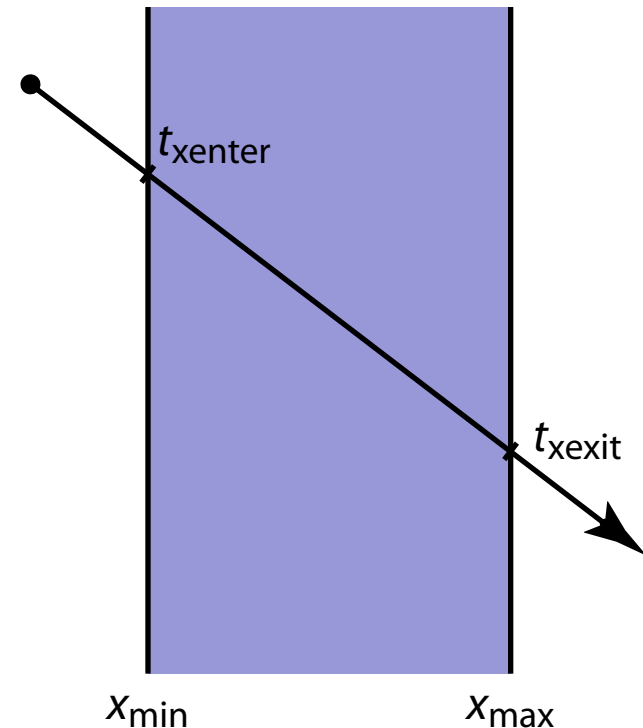
$$p_y + t_{y\min} d_y = y_{\min}$$

$$t_{y\min} = (y_{\min} - p_y) / d_y$$



Intersecting intersections

- Each intersection is an interval
- Want last entry point and first exit point

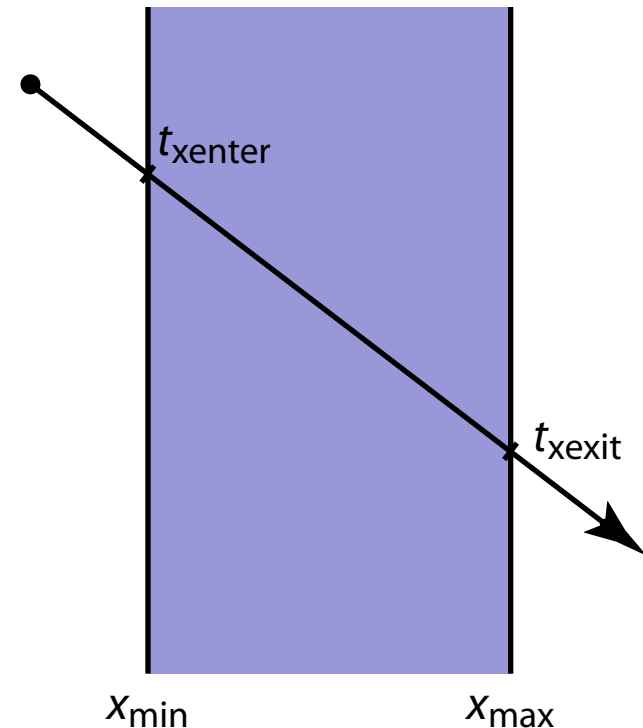


Intersecting intersections

- Each intersection is an interval
- Want last entry point and first exit point

$$t_{xenter} = \min(t_{xmin}, t_{xmax})$$

$$t_{xexit} = \max(t_{xmin}, t_{xmax})$$

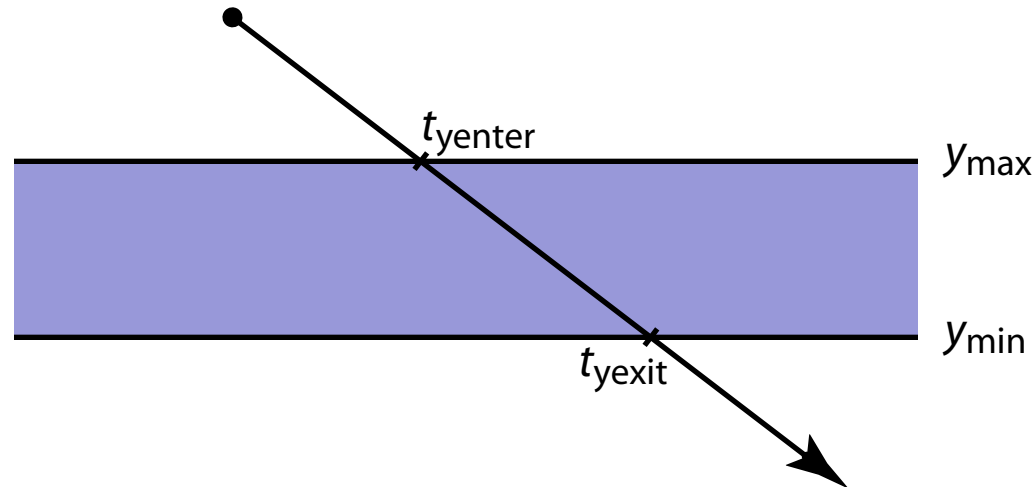


Intersecting intersections

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Intersecting intersections

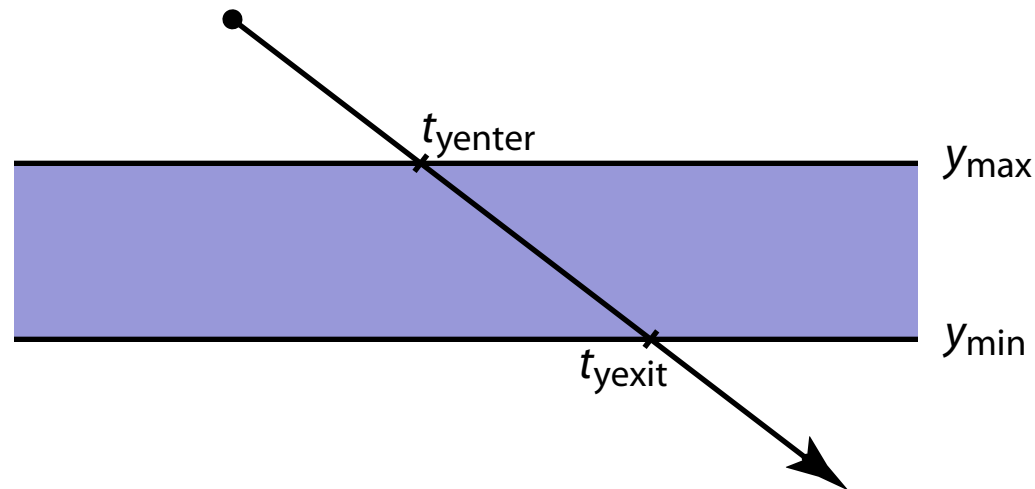
- Each intersection is an interval
- Want last entry point and first exit point

$$t_{x\text{enter}} = \min(t_{x\text{min}}, t_{x\text{max}})$$

$$t_{x\text{exit}} = \max(t_{x\text{min}}, t_{x\text{max}})$$

$$t_{y\text{enter}} = \min(t_{y\text{min}}, t_{y\text{max}})$$

$$t_{y\text{exit}} = \max(t_{y\text{min}}, t_{y\text{max}})$$



Intersecting intersections

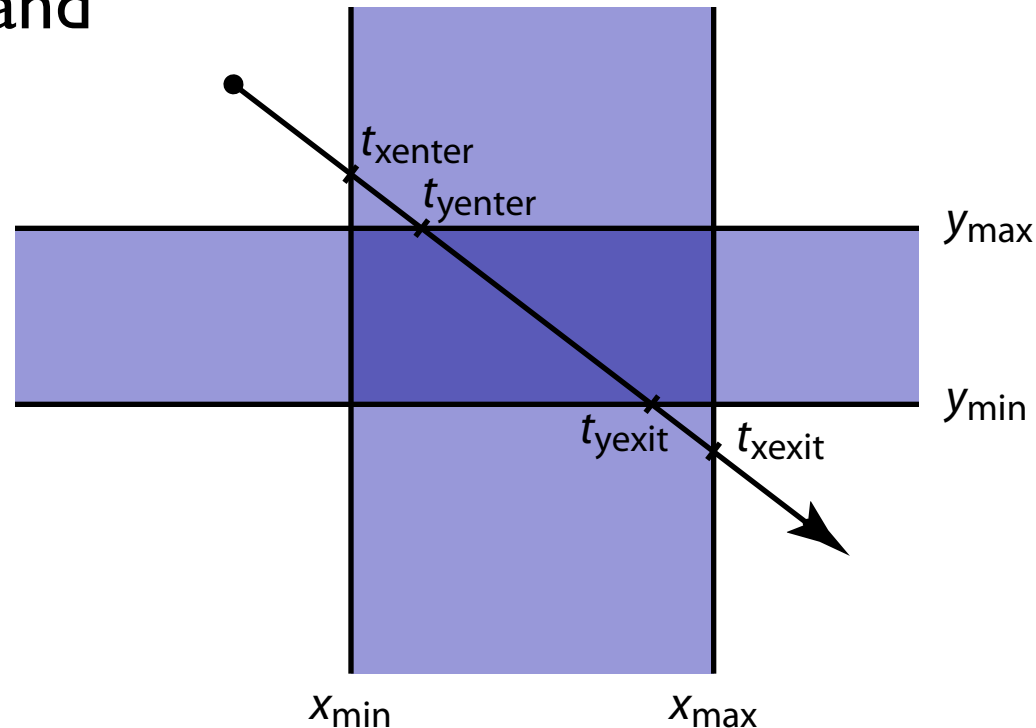
- Each intersection is an interval
- Want last entry point and first exit point

$$t_{xenter} = \min(t_{xmin}, t_{xmax})$$

$$t_{xexit} = \max(t_{xmin}, t_{xmax})$$

$$t_{yenter} = \min(t_{ymin}, t_{ymax})$$

$$t_{yexit} = \max(t_{ymin}, t_{ymax})$$



Intersecting intersections

- Each intersection is an interval
- Want last entry point and first exit point

$$t_{xenter} = \min(t_{xmin}, t_{xmax})$$

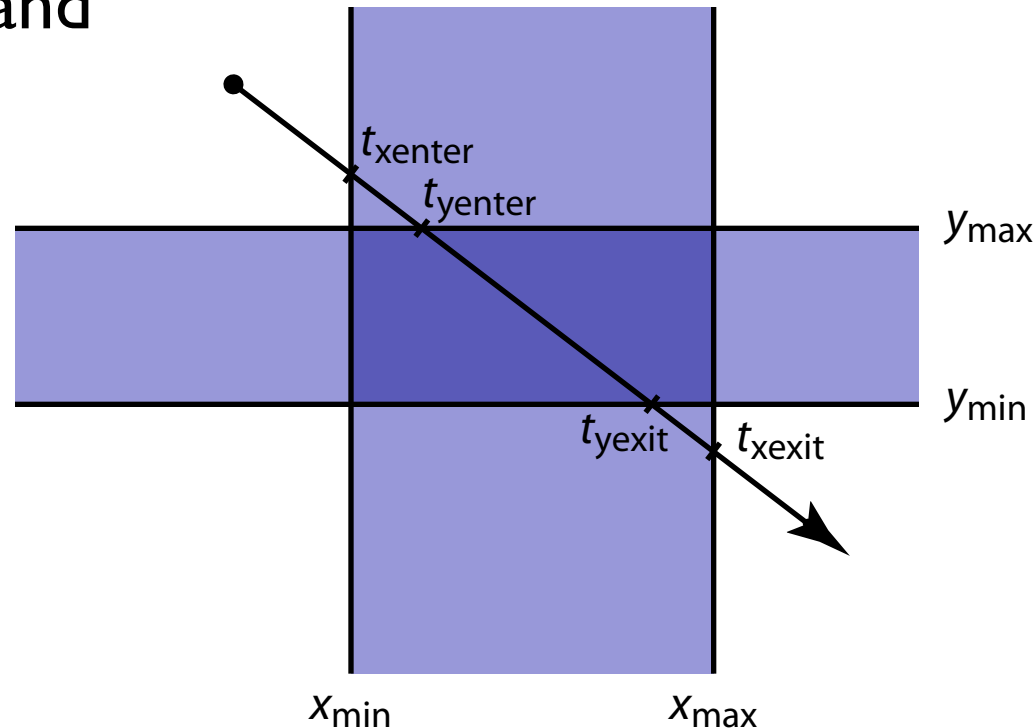
$$t_{xexit} = \max(t_{xmin}, t_{xmax})$$

$$t_{yenter} = \min(t_{ymin}, t_{ymax})$$

$$t_{yexit} = \max(t_{ymin}, t_{ymax})$$

$$t_{enter} = \max(t_{xenter}, t_{yenter})$$

$$t_{exit} = \min(t_{xexit}, t_{yexit})$$



Building a hierarchy

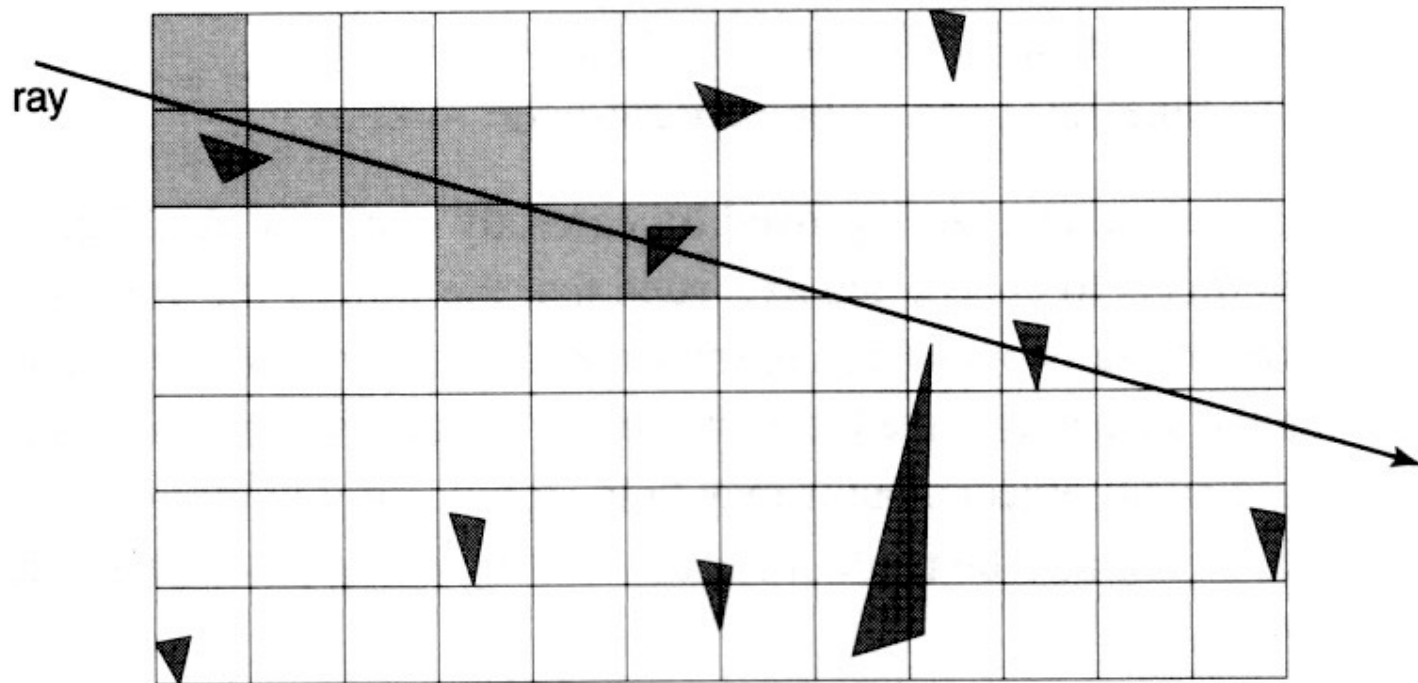
- Usually do it top-down
- Make bbox for whole scene, then split into (maybe 2) parts
 - Recurse on parts
 - Stop when there are just a few objects in your box

Building a hierarchy

- How to partition?
 - Ideal: clusters
 - Practical: partition along axis
 - Center partition
 - Less expensive, simpler
 - Unbalanced tree (but may sometimes be better)
 - Median partition
 - More expensive
 - More balanced tree
 - Surface area heuristic
 - Model expected cost of ray intersection
 - Generally produces best-performing trees

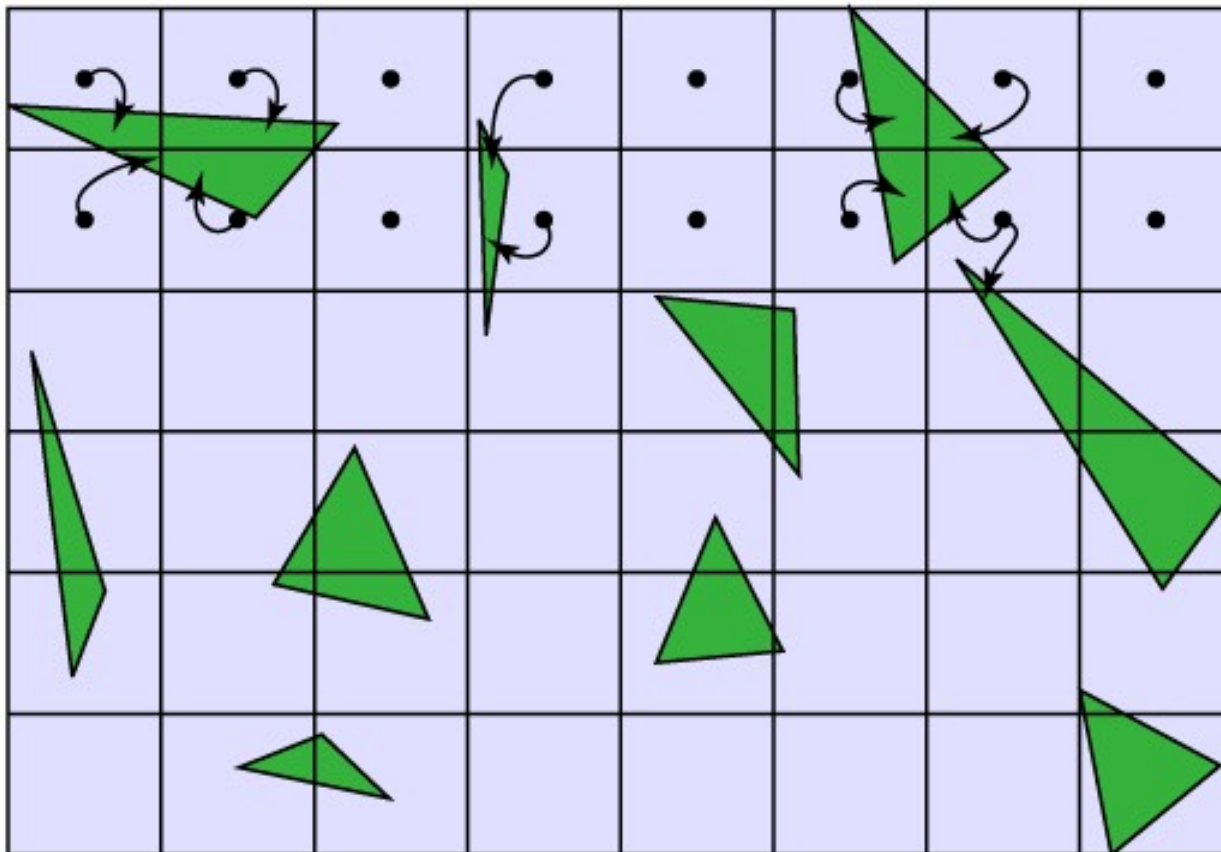
Regular space subdivision

- An entirely different approach: uniform grid of cells

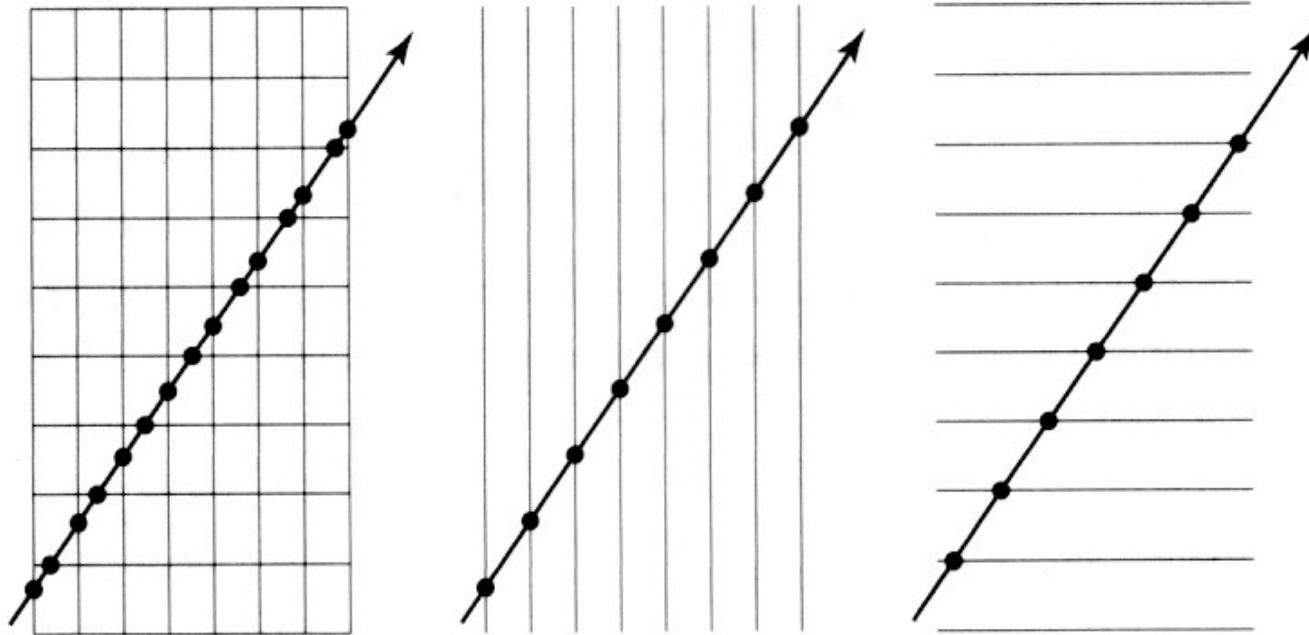


Regular grid example

- Grid divides space, not objects

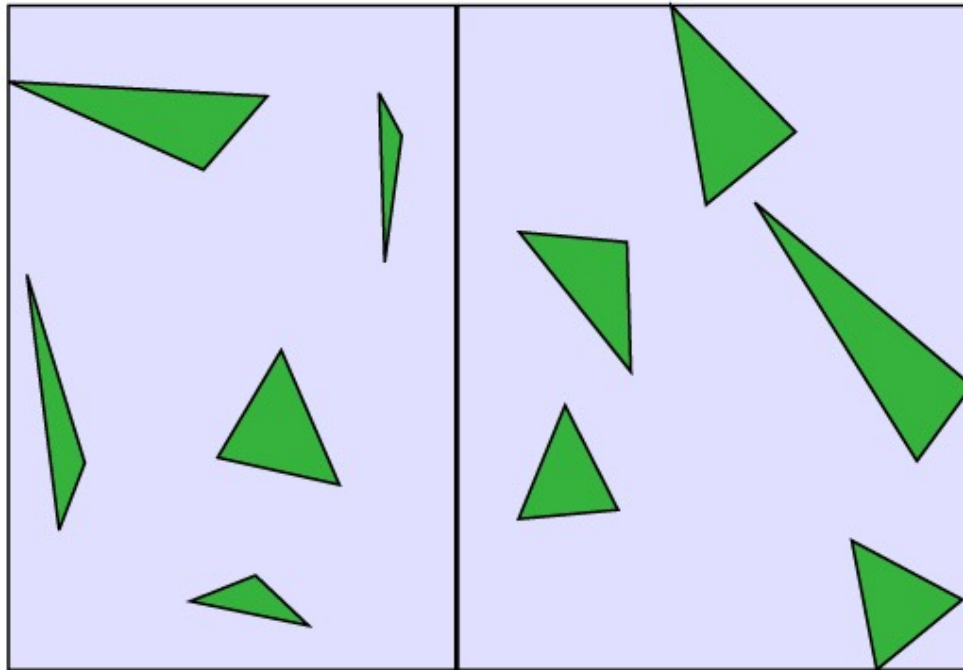


Traversing a regular grid



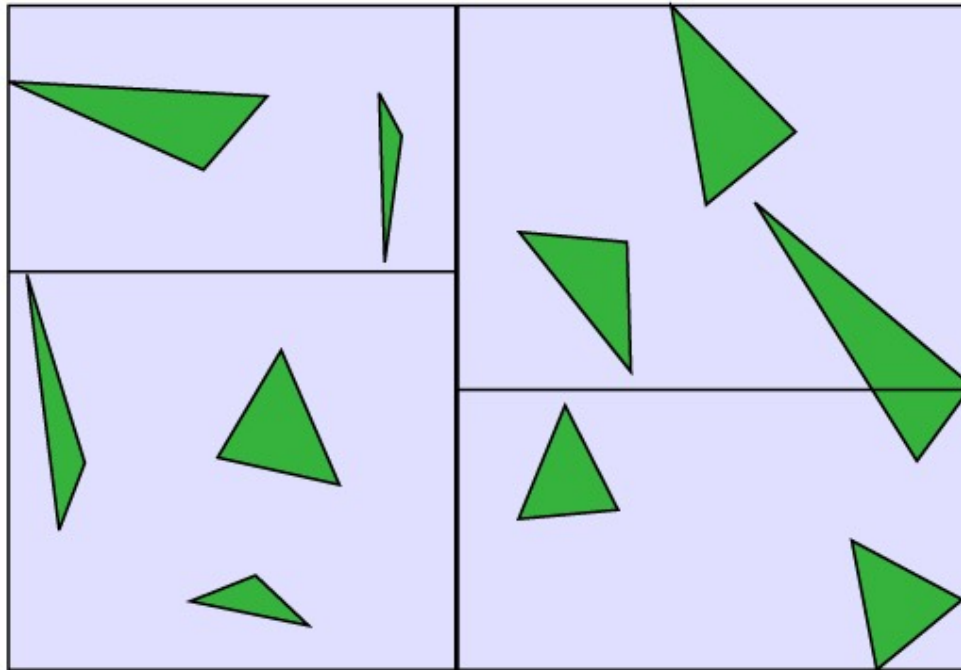
Non-regular space subdivision

- *k*-d Tree
 - subdivides space, like grid
 - adaptive, like BVH



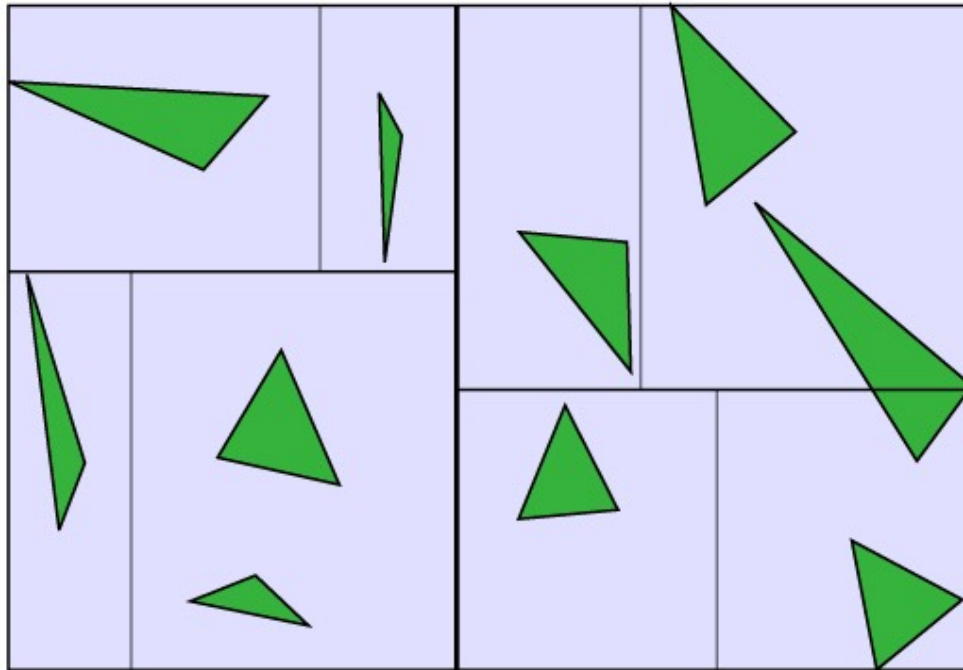
Non-regular space subdivision

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Non-regular space subdivision

- *k*-d Tree
 - subdivides space, like grid
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Implementing acceleration structures

- Conceptually simple to build acceleration structure into scene structure
 - what we sketched out earlier
- Better engineering decision to separate them
 - plug and play different acceleration structures
 - keep representation of scene itself simple