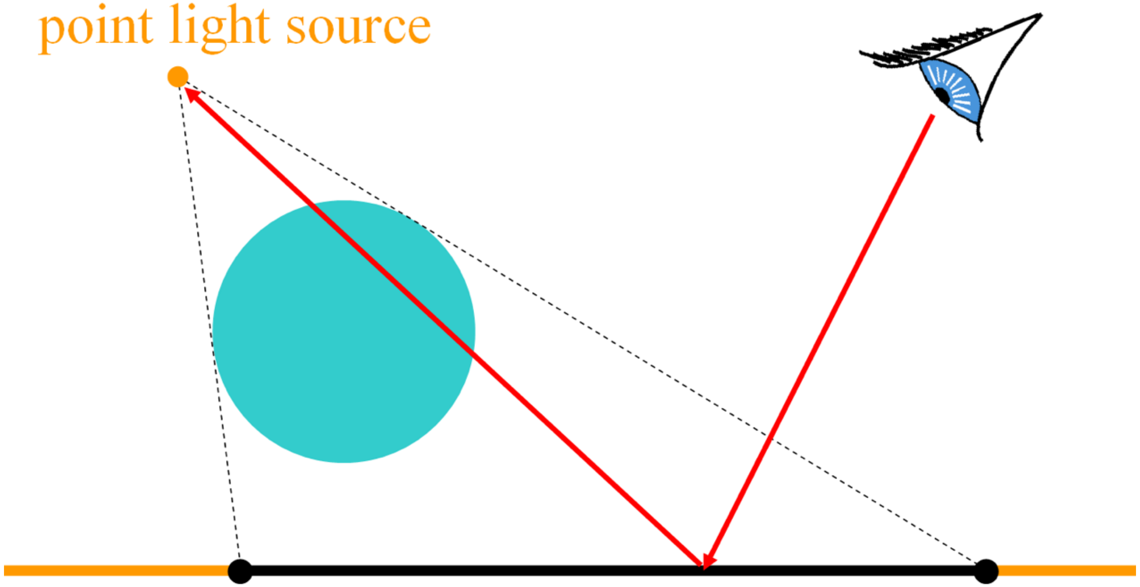
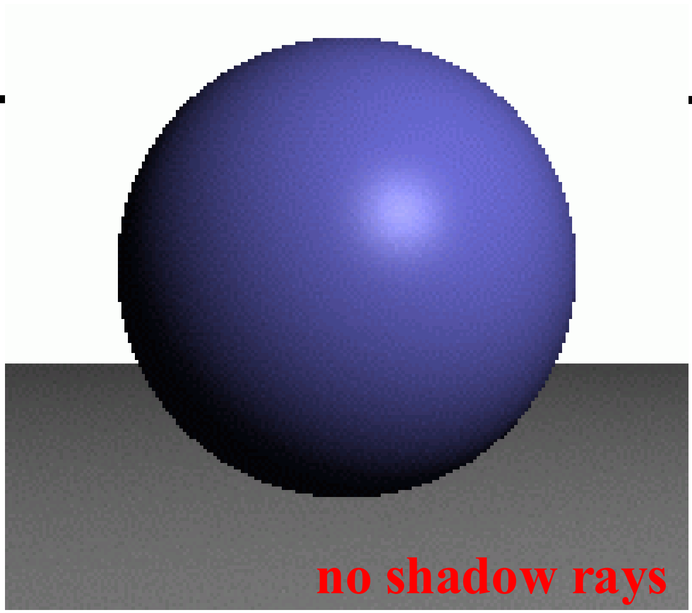
Acceleration Data Structures for Ray Tracing

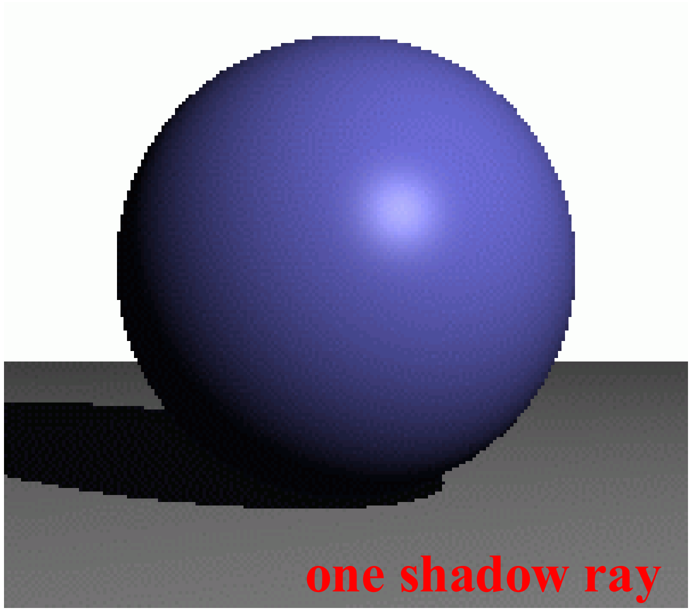
Most slides are taken from Fredo Durand

Shadows

- one shadow ray per intersection per point light source

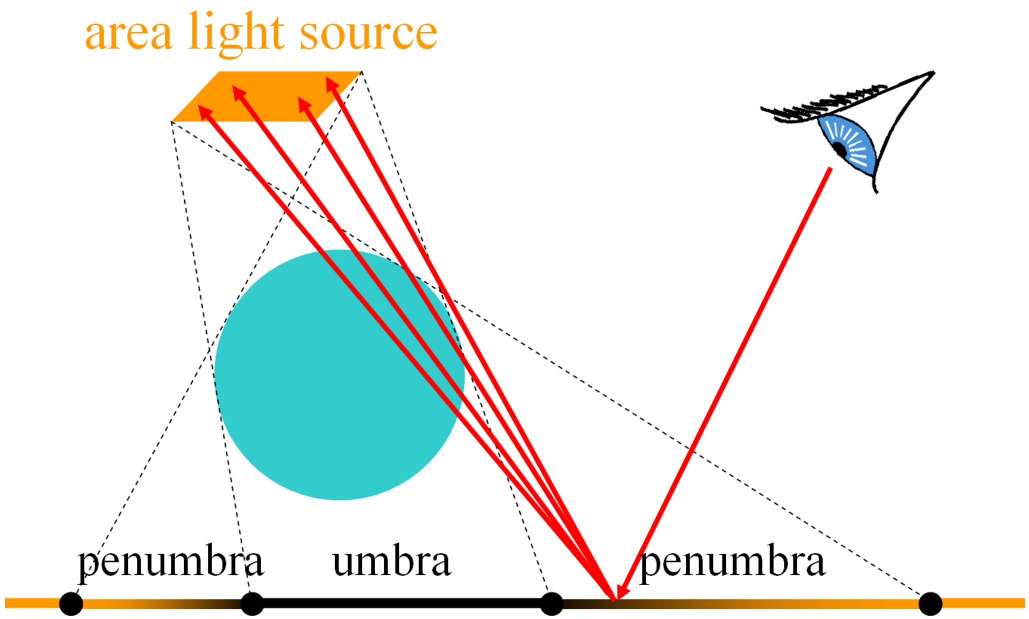


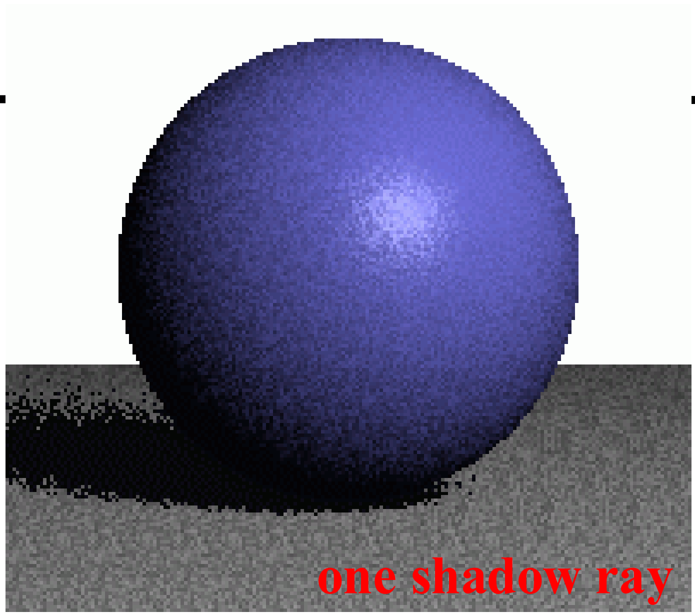


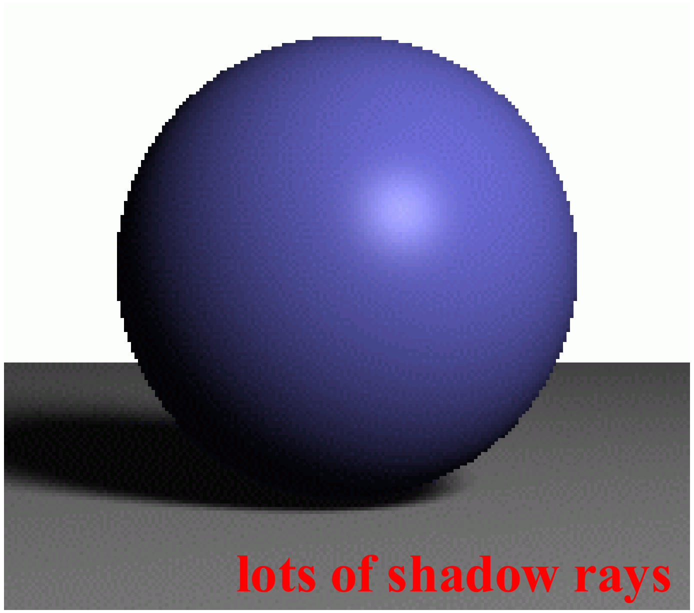


Soft Shadows

- multiple shadow rays to sample area light source







Antialiasing – Supersampling

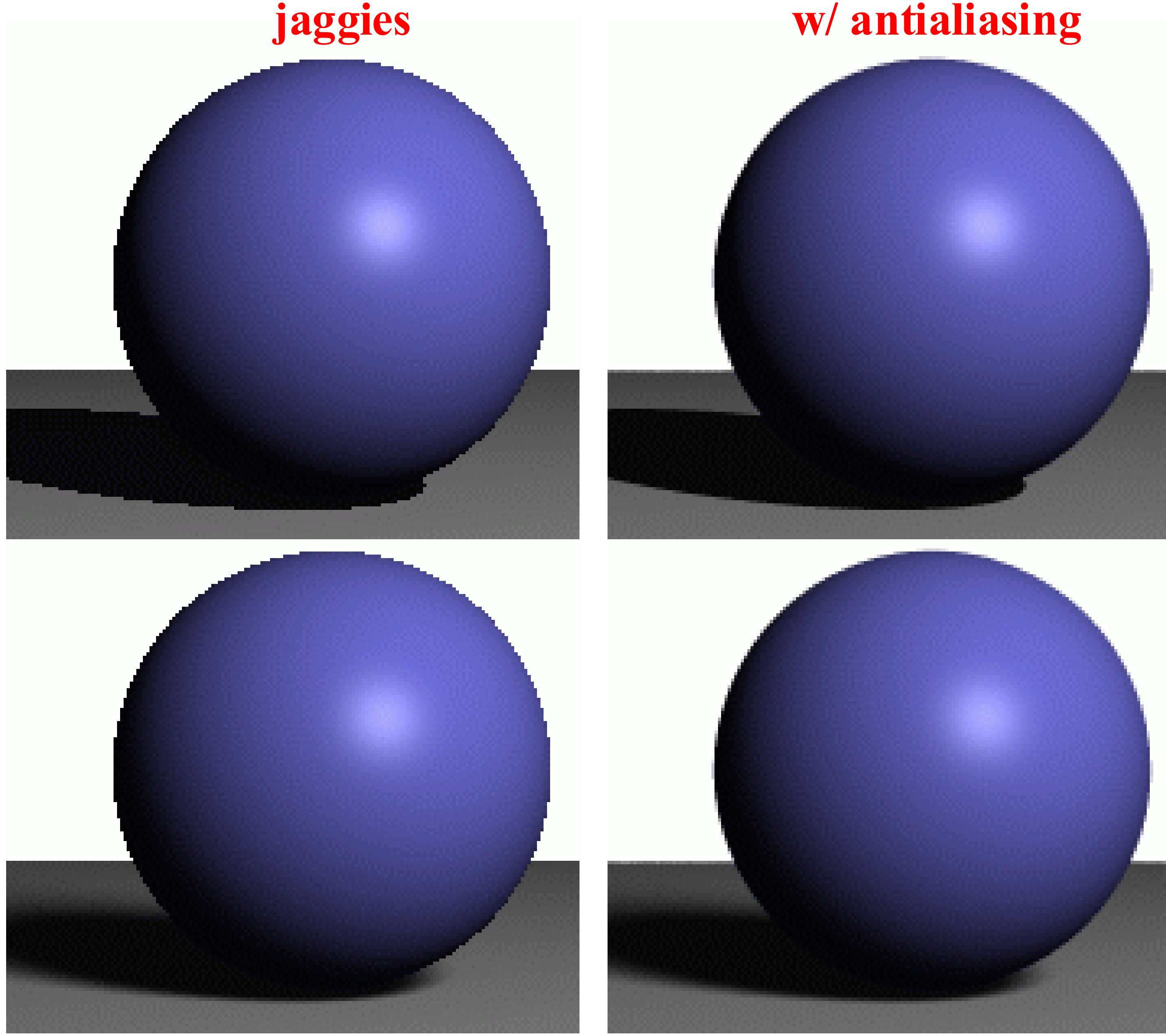
- multiple rays per pixel

jaggies

w/ antialiasing

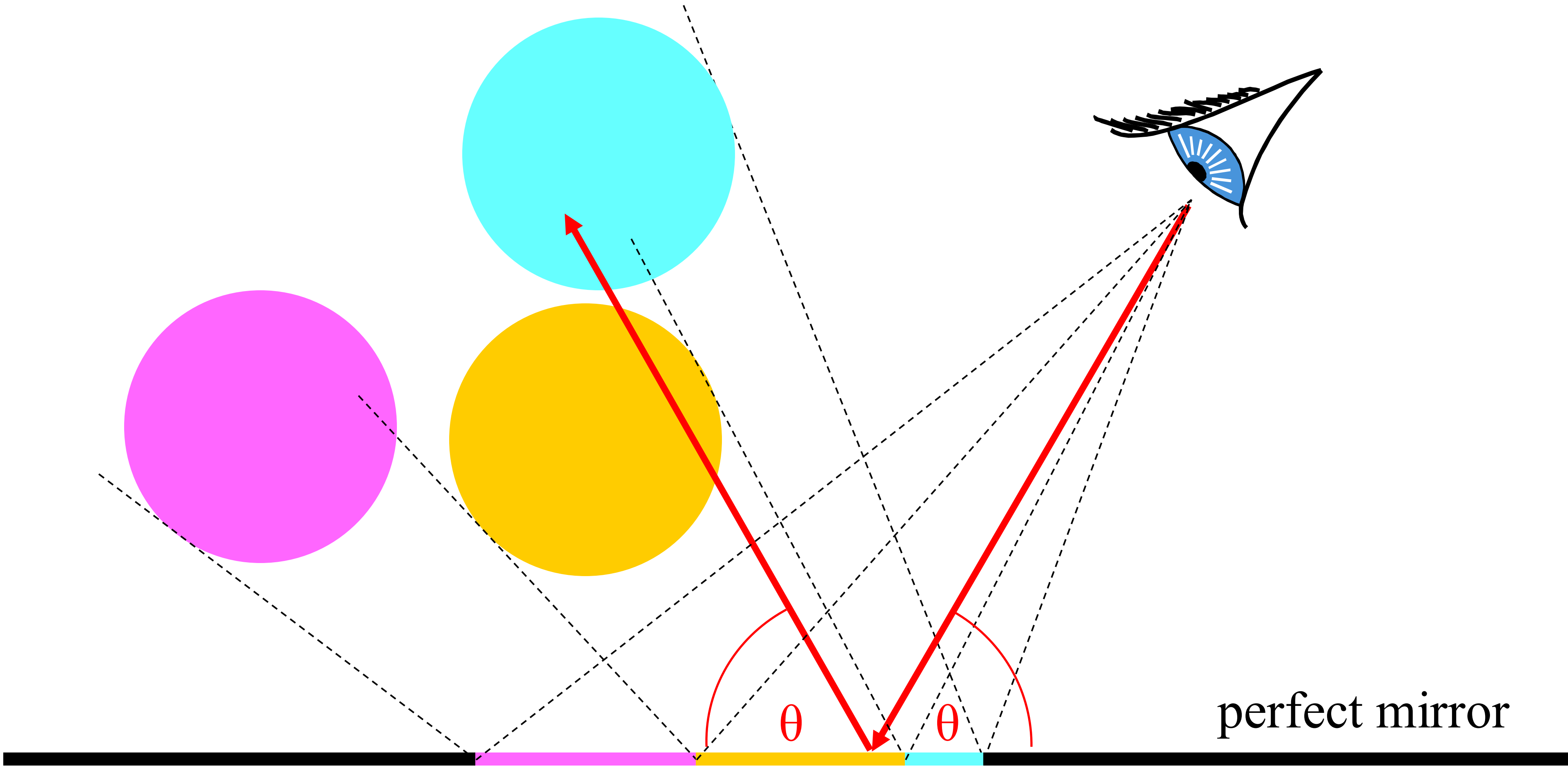
point light

area light



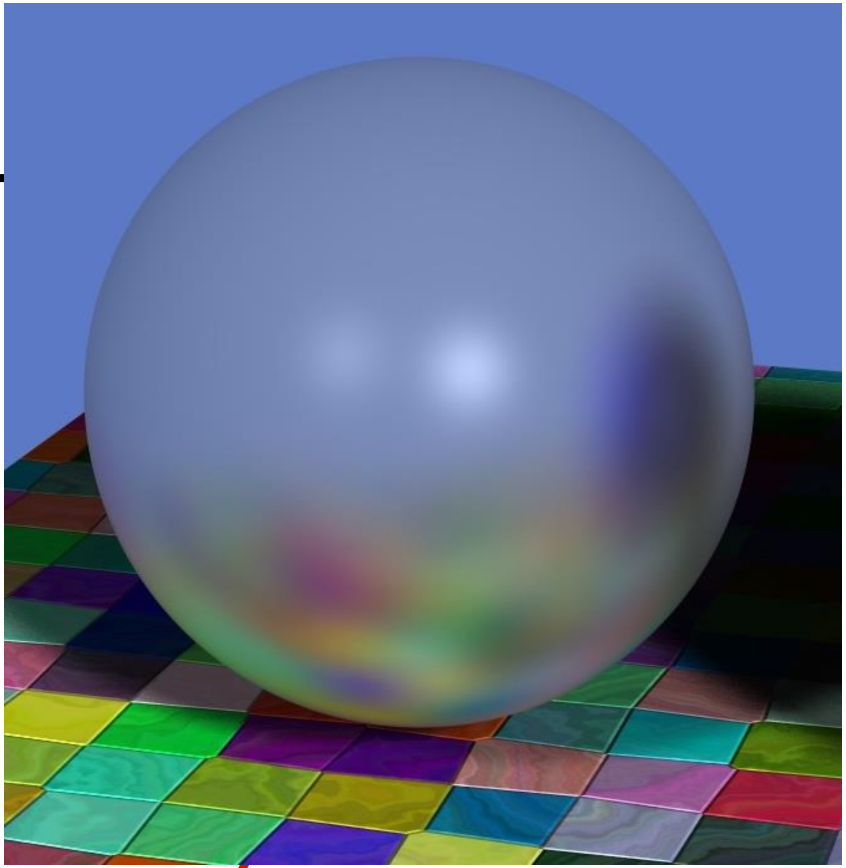
Reflection

- one reflection ray per intersection

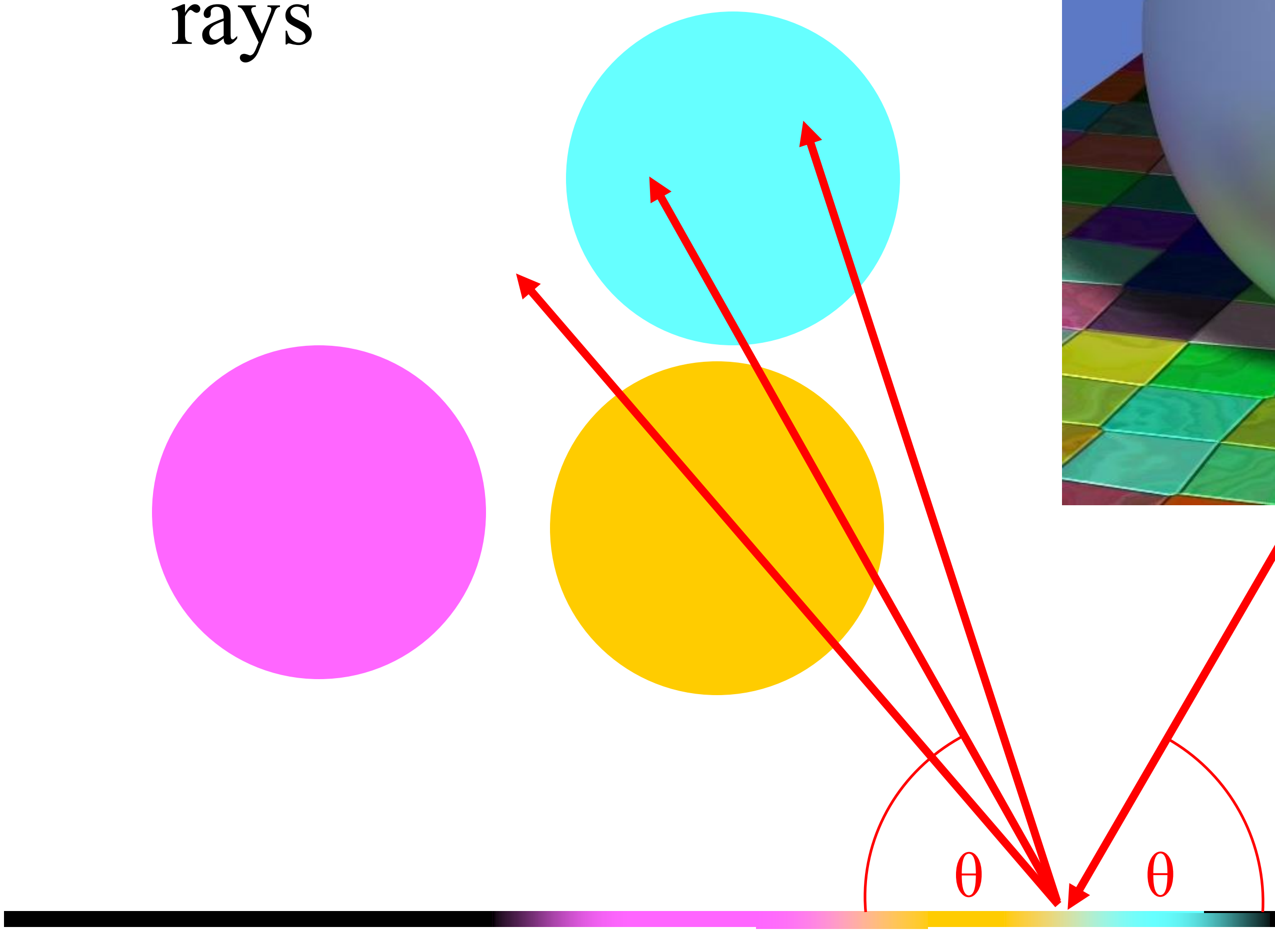


Glossy Reflection

- multiple reflection rays

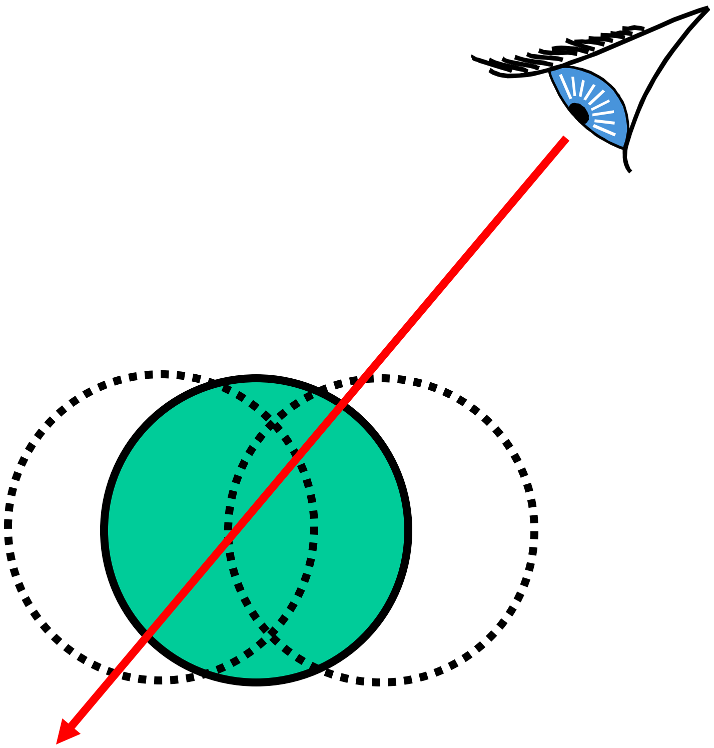


Justin Legakis



Motion Blur

- Sample objects temporally



Rob Cook

Algorithm Analysis

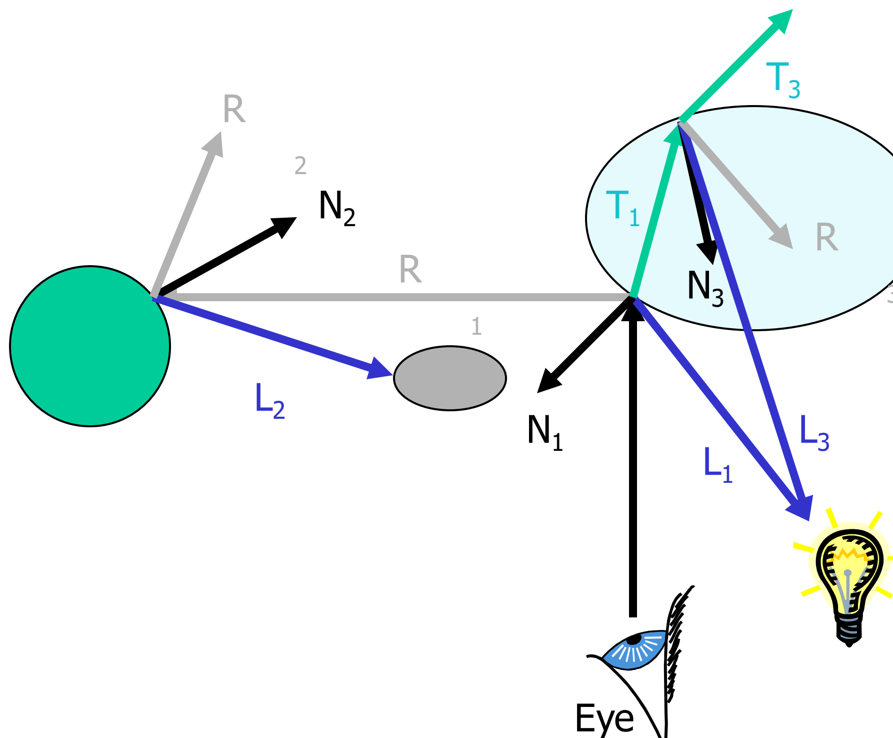
- Ray casting
- Lots of primitives
- Recursive
- Distributed Ray Tracing Effects
  - Soft shadows
  - Anti-aliasing
  - Glossy reflection
  - Motion blur
  - Depth of field

cost ≤ height * width *
$\boxed{\text{num primitives}}$ *
intersection cost *
num shadow rays *
super-sampling *
num glossy rays *
num temporal samples *
3^max recursion depth *
. . .

can we reduce this?

The cost of Ray Tracing

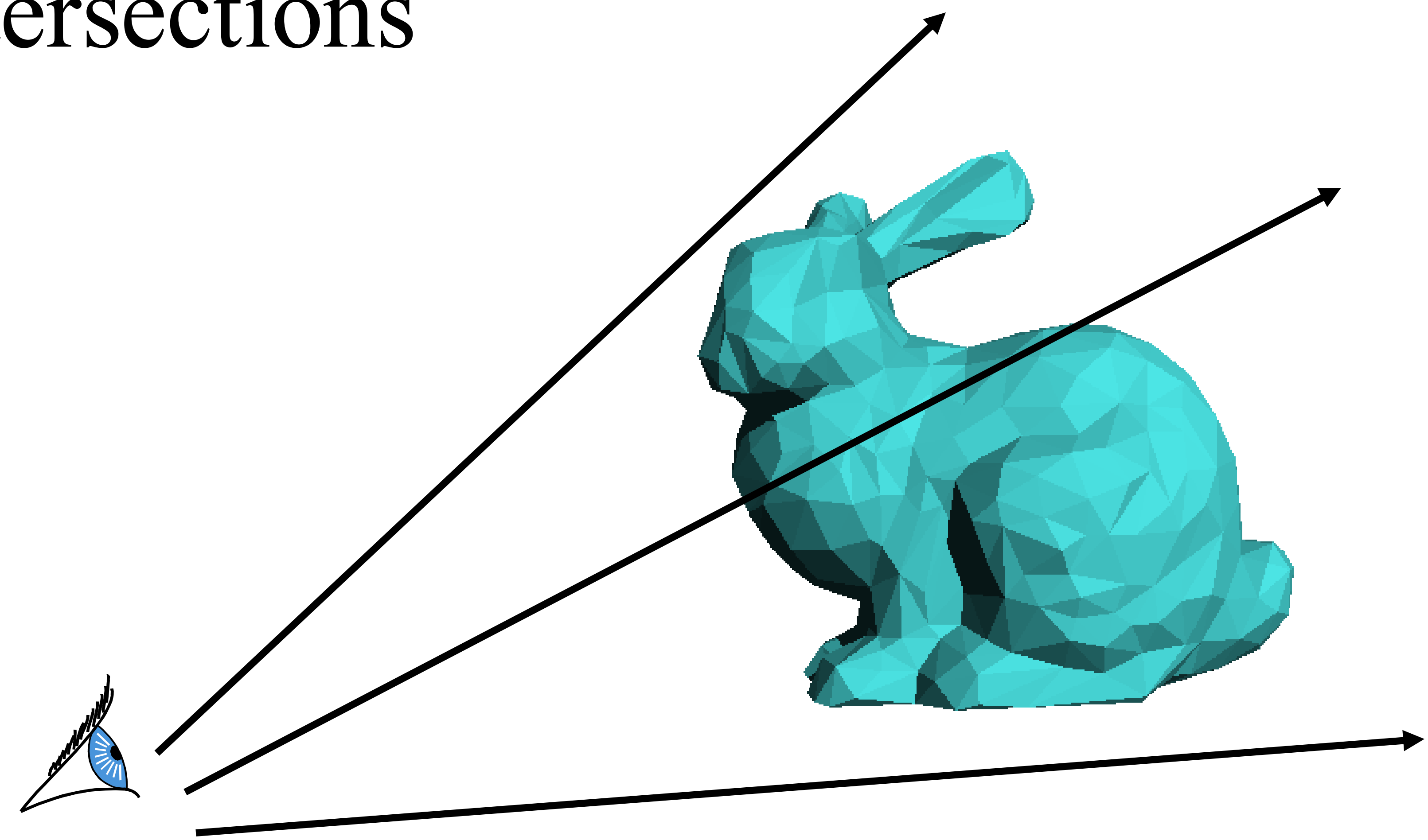
- Many Primitives
- Many Rays
- Expensive Intersections



Accelerating Ray Tracing

- Four main groups of acceleration techniques:
  - Reducing the average cost of intersecting a ray with a scene:
    - Faster intersection calculations
    - Fewer intersection calculations
  - Reducing the total number of rays that are traced
    - Adaptive recursion depth control
  - Parallelization, specialized hardware

Reduce the number of ray/primitive intersections



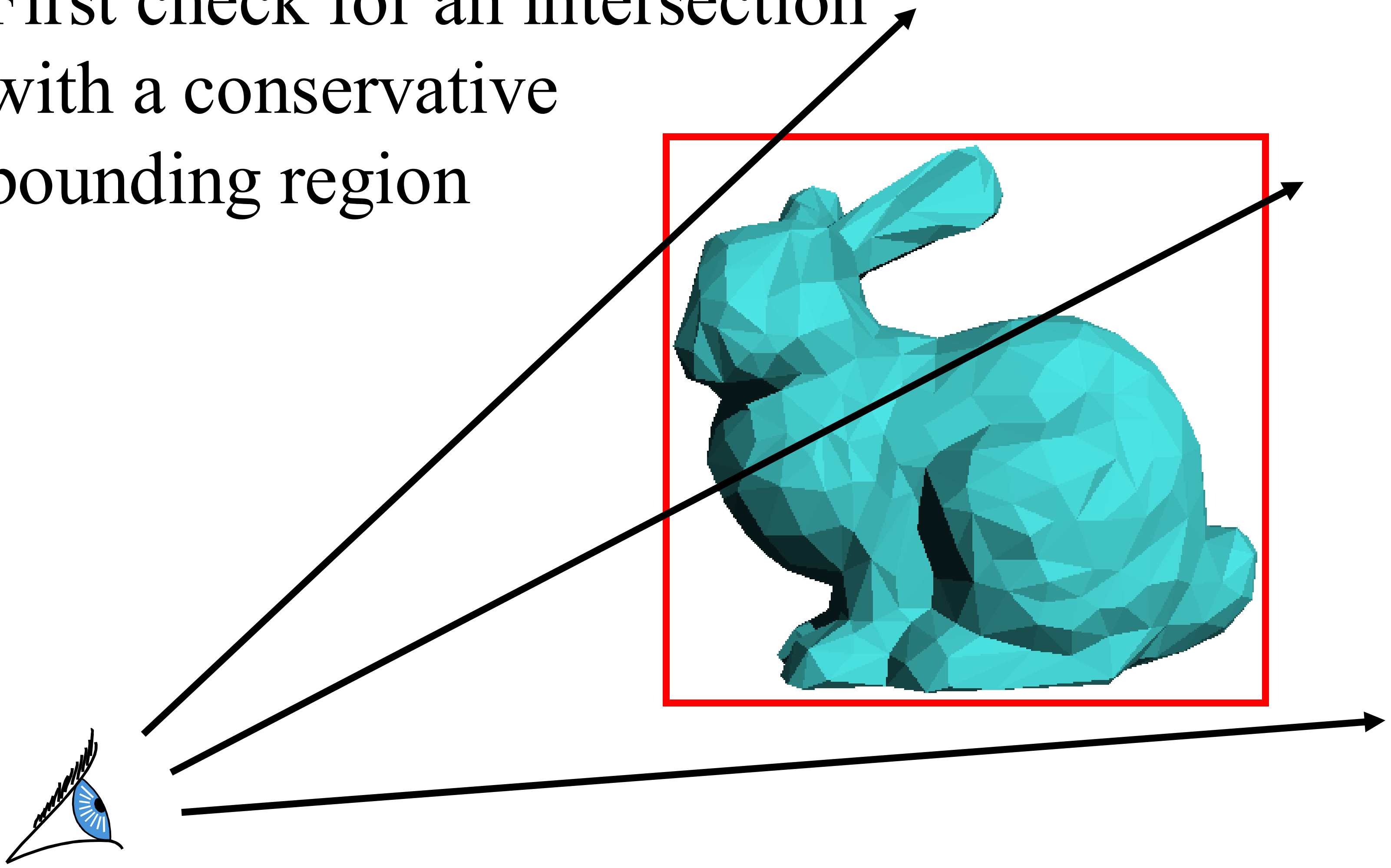
Bounding Volumes

- Idea: associate with each object a simple bounding volume. If a ray misses the bounding volume, it also misses the object contained therein.

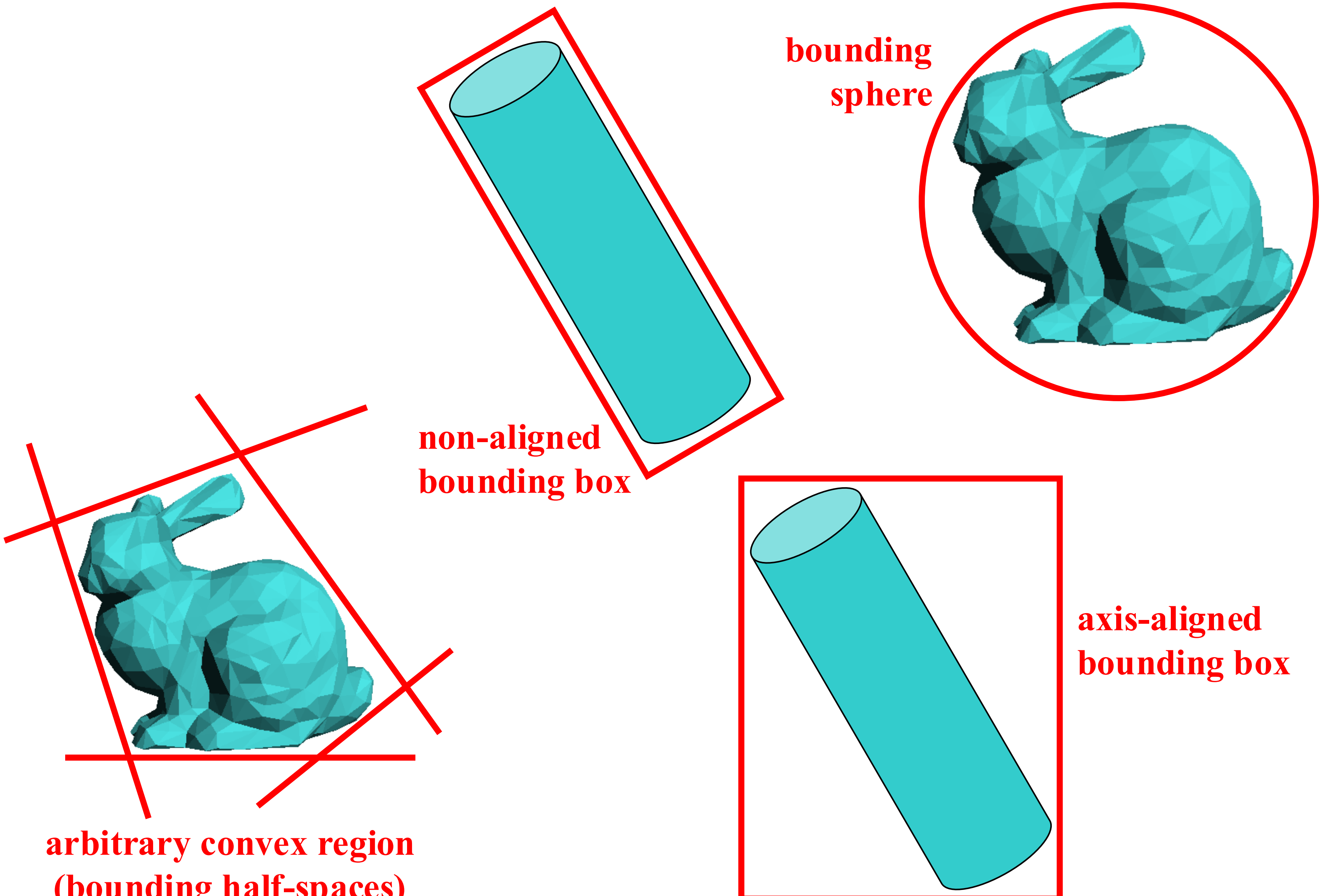
- Effective for additional applications:
  - Clipping acceleration
  - Collision detection

Early reject

- First check for an intersection with a conservative bounding region

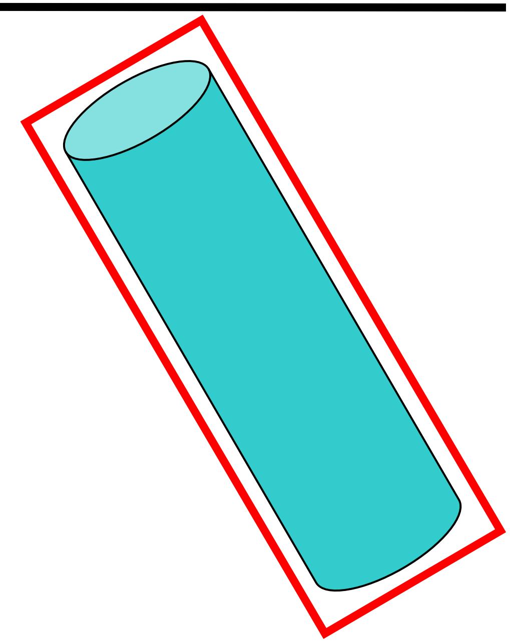


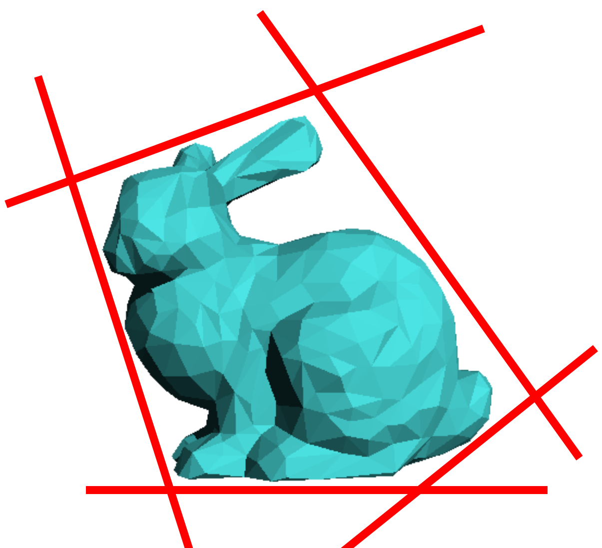
Conservative Bounding Regions



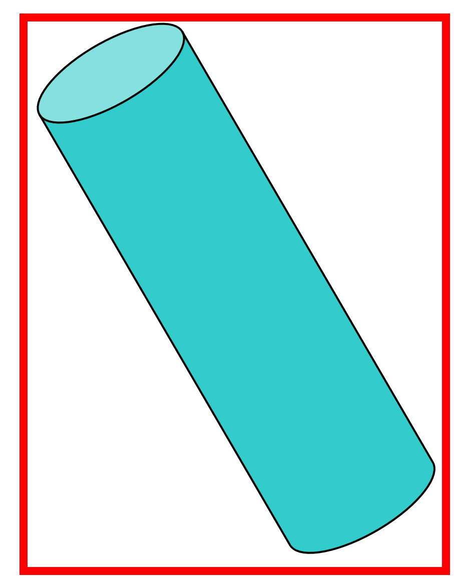
What is a good bounding volume?

- tight → avoid false positives
- fast to intersect
- easy to construct

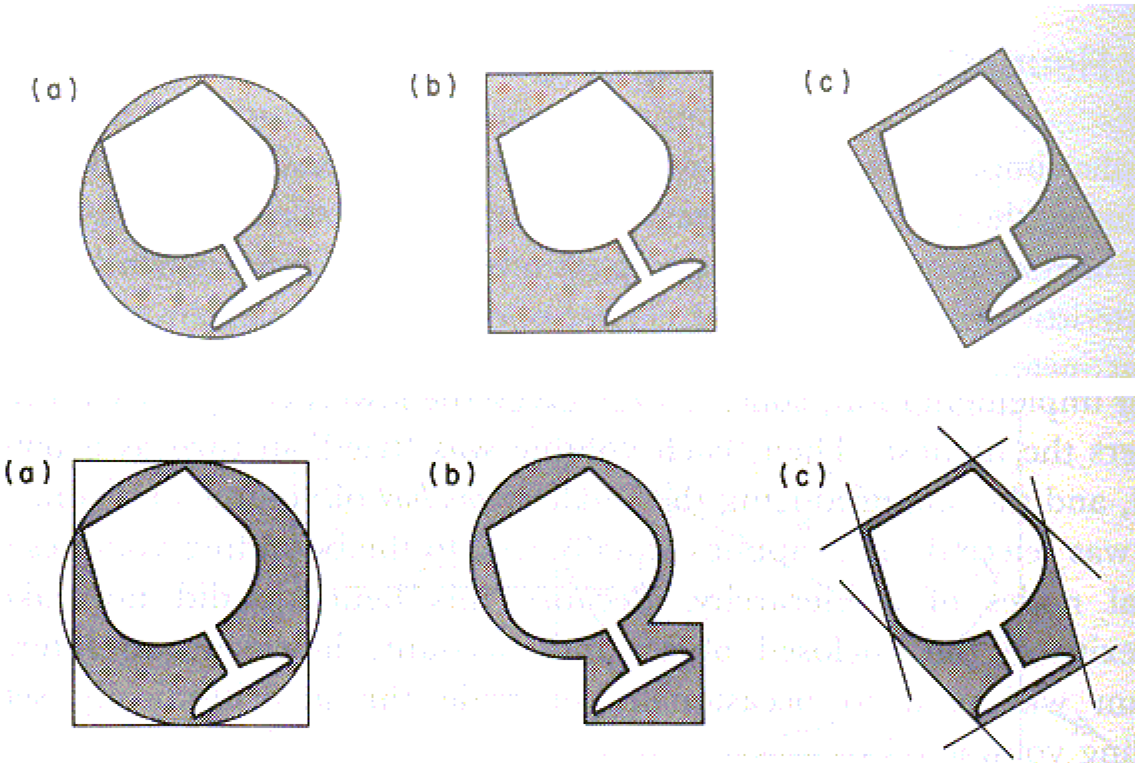




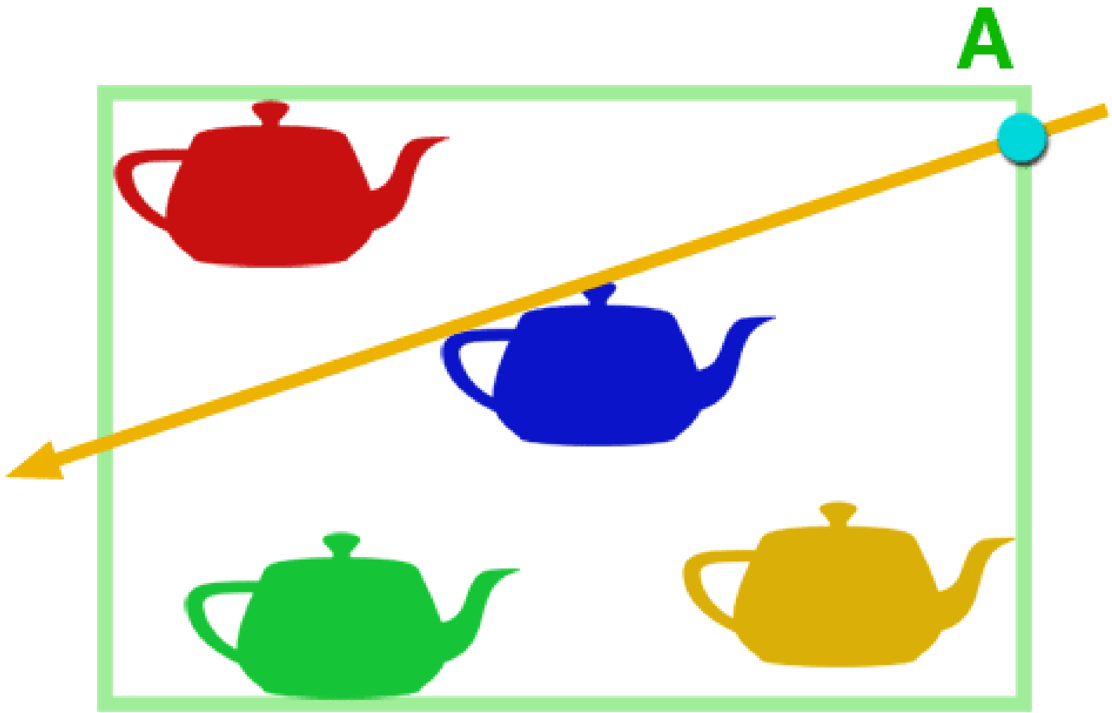
arbitrary convex region (bounding half-spaces)



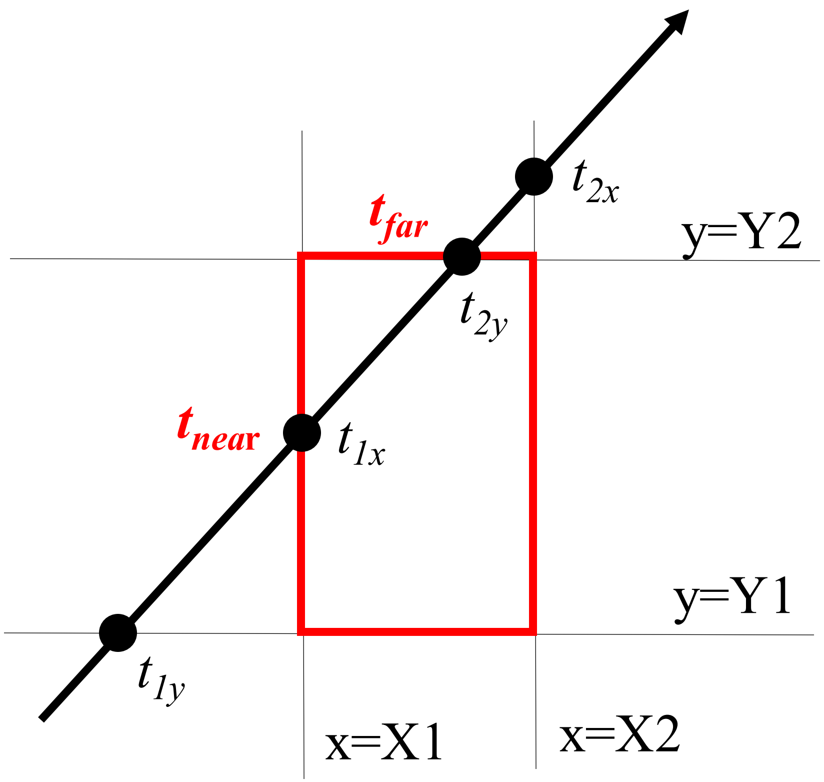
Bounding Volumes



Hierarchical Bounding Boxes



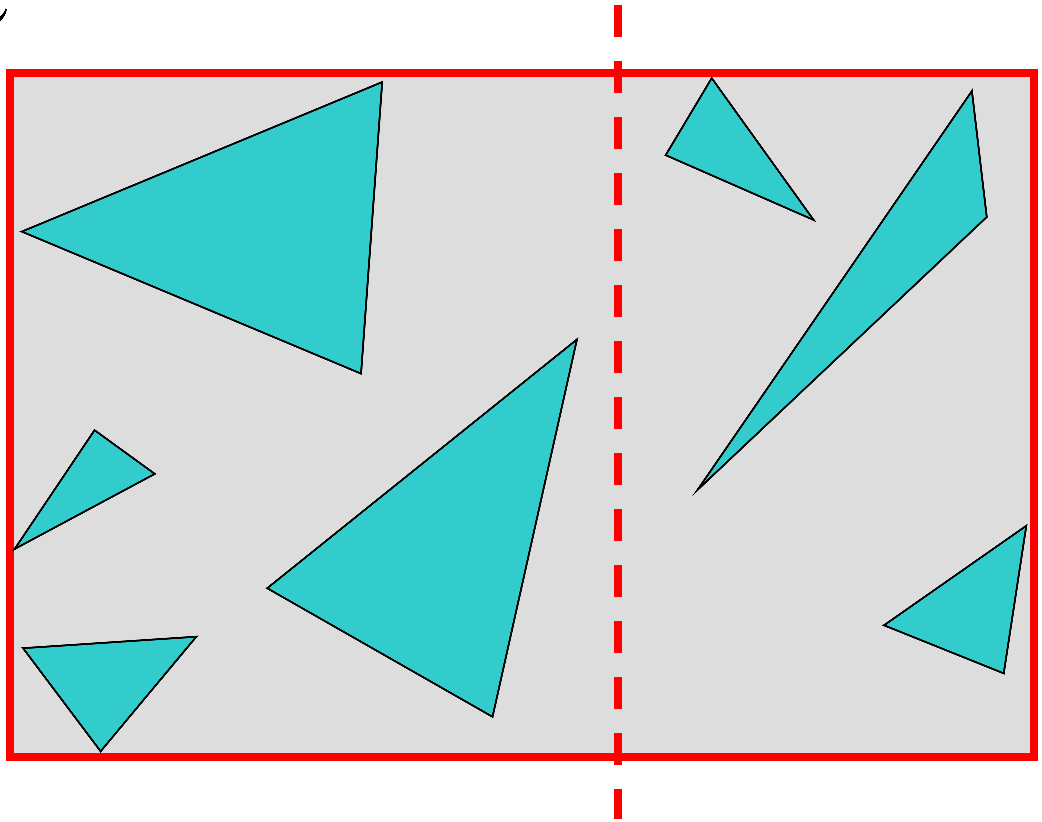
Intersection with Axis-Aligned Box



- For all 3 axes, calculate the intersection distances t_1 and t_2
- $t_{near} = \max(t_{1x}, t_{1y}, t_{1z})$
  $t_{far} = \min(t_{2x}, t_{2y}, t_{2z})$
- If $t_{near} > t_{far}$, box is missed
- If $t_{far} < t_{min}$, box is behind
- If box survived tests, report intersection at t_{near}

Bounding Volume Hierarchy

- Find bounding box of objects
- Split objects into two groups
- Recurse



Bounding Volume Hierarchy

- Find bounding box of objects
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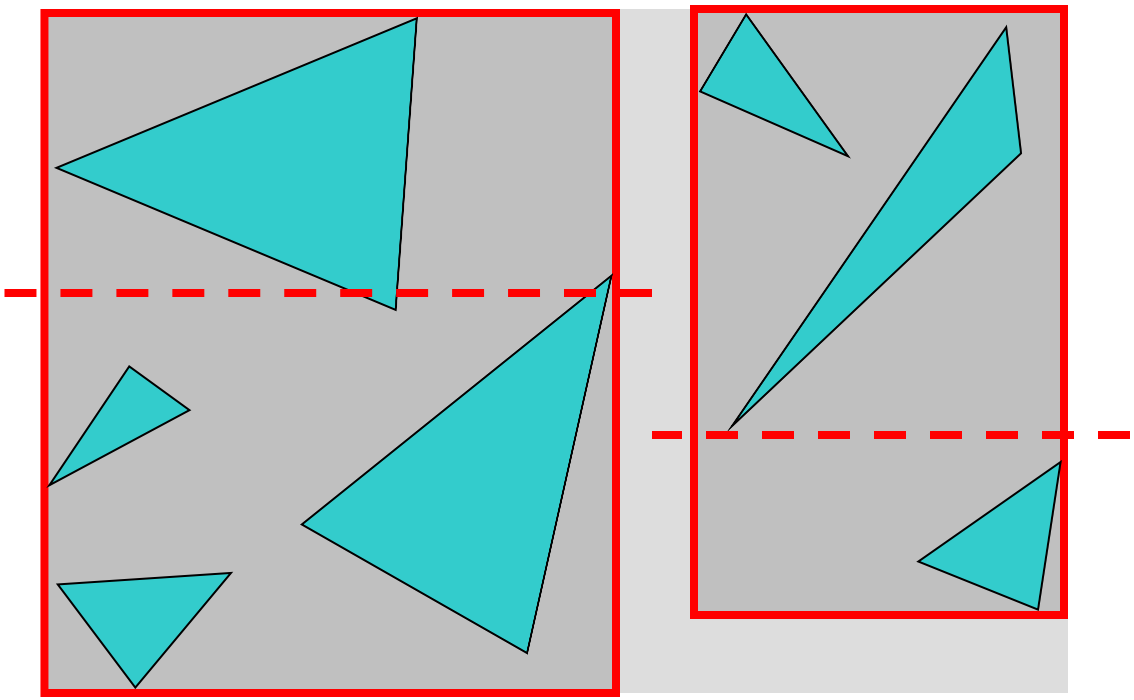
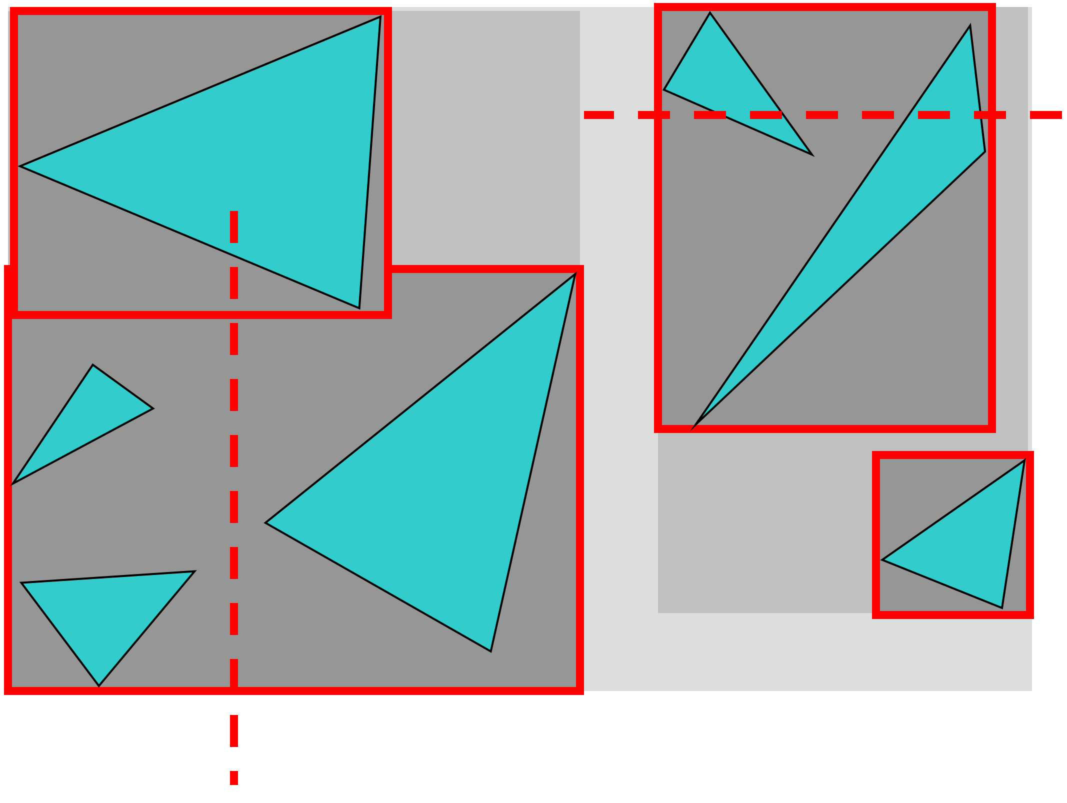
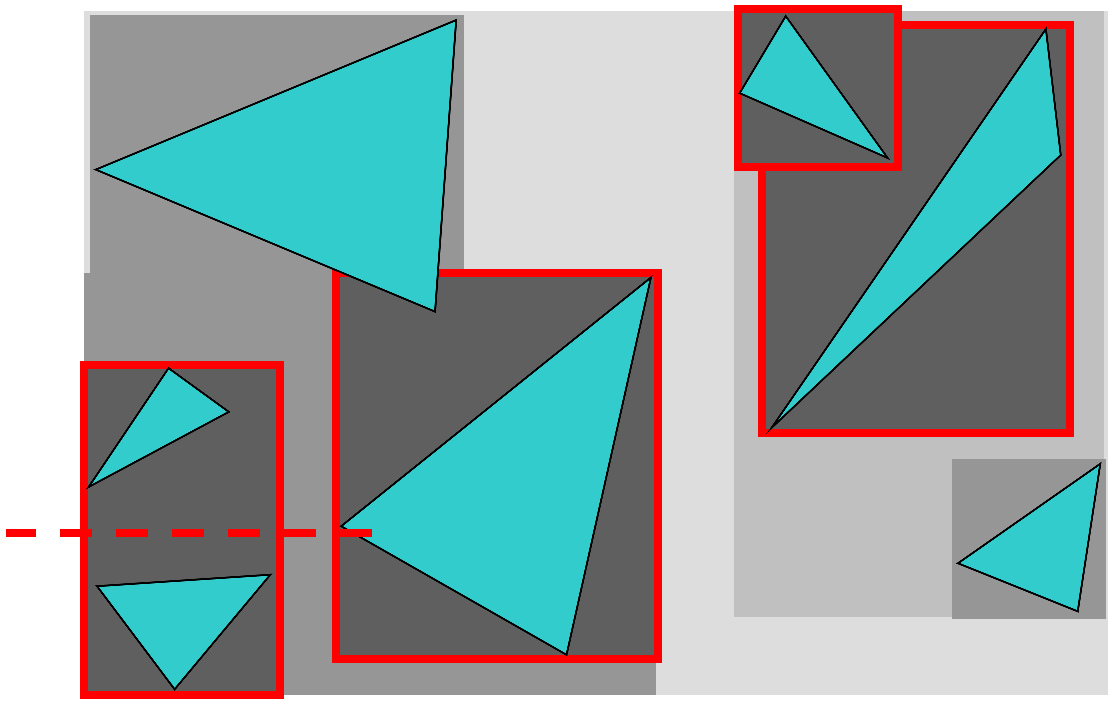


Bounding volumes can intersect

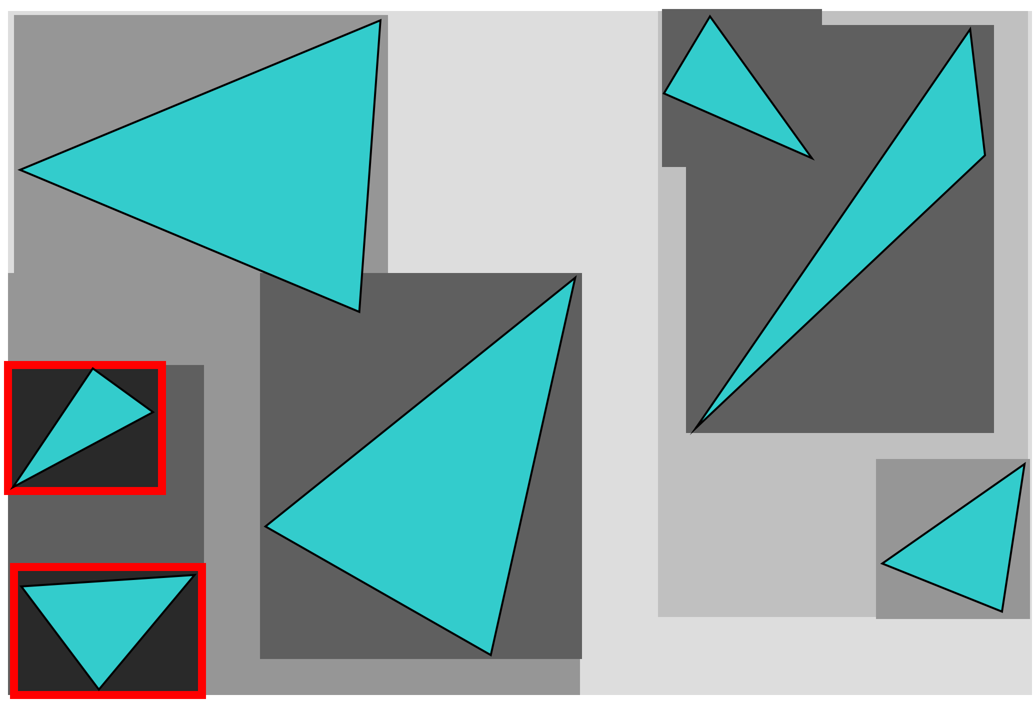
- Find bounding box of objects
- Split objects into two groups
- Recurse



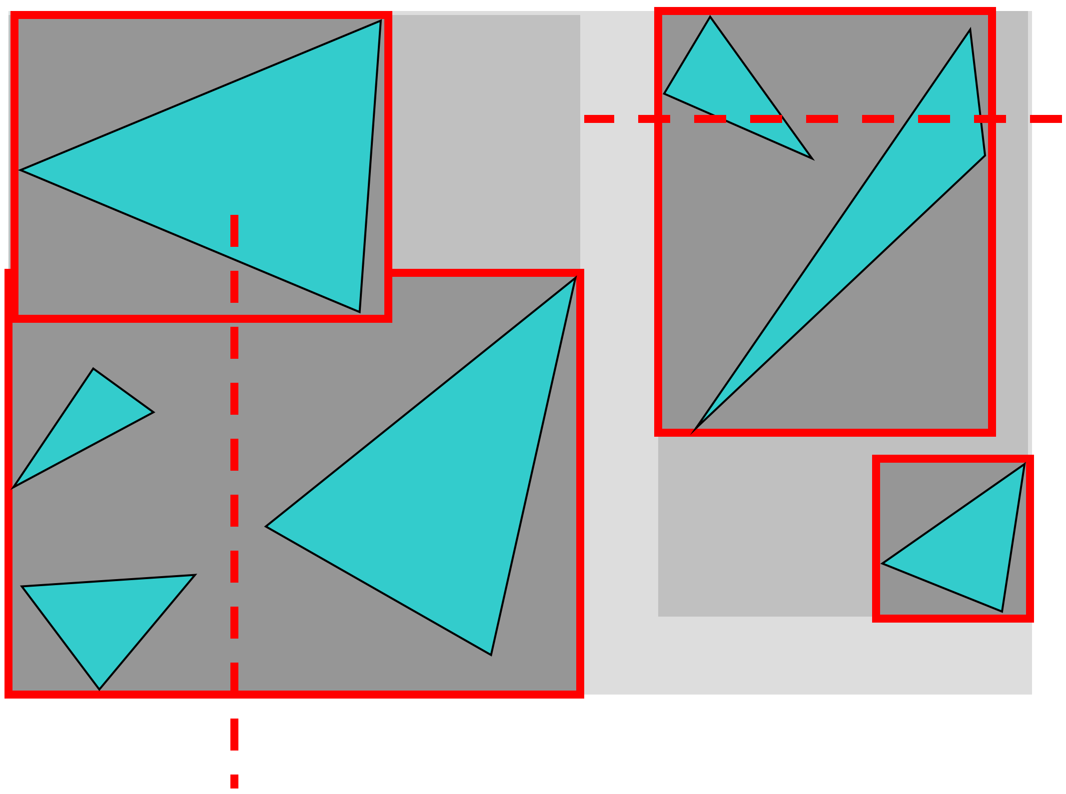
Bounding Volume Hierarchy



Bounding Volume Hierarchy

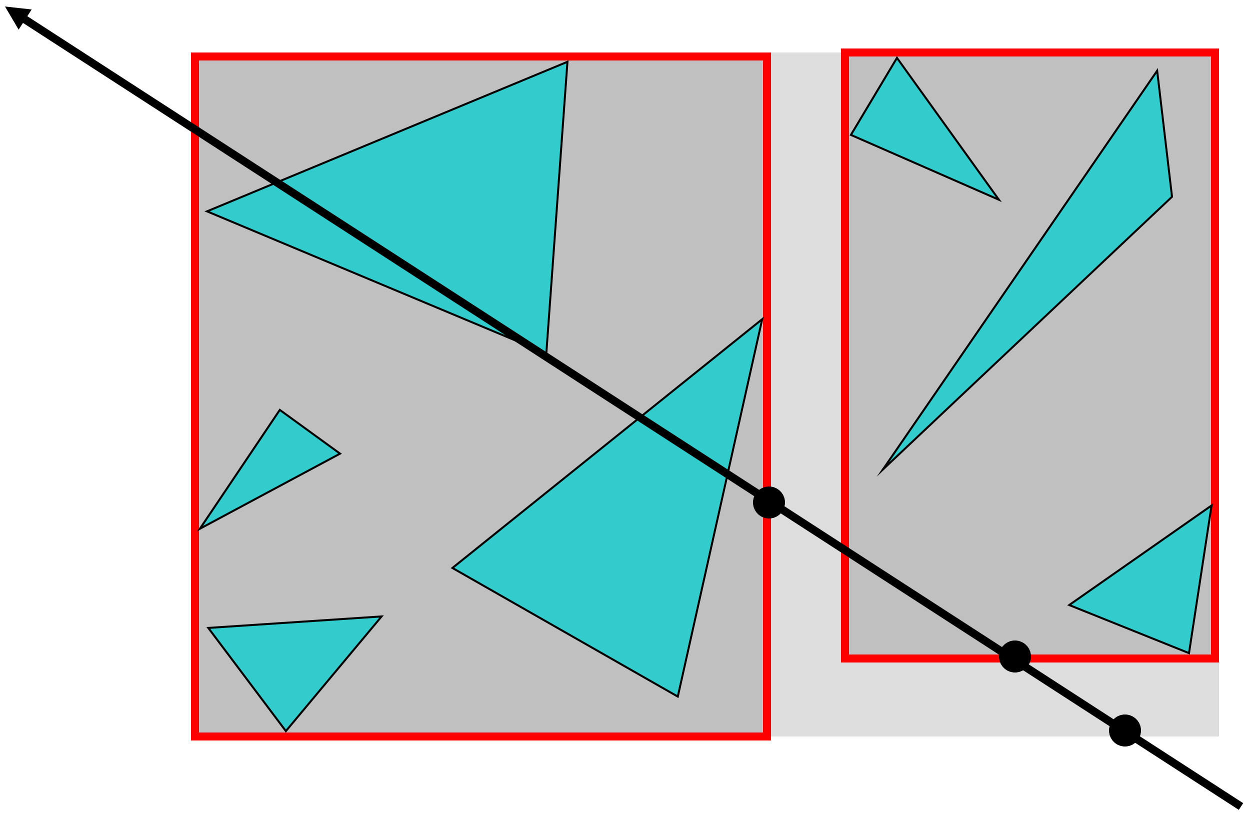


Where to split objects?



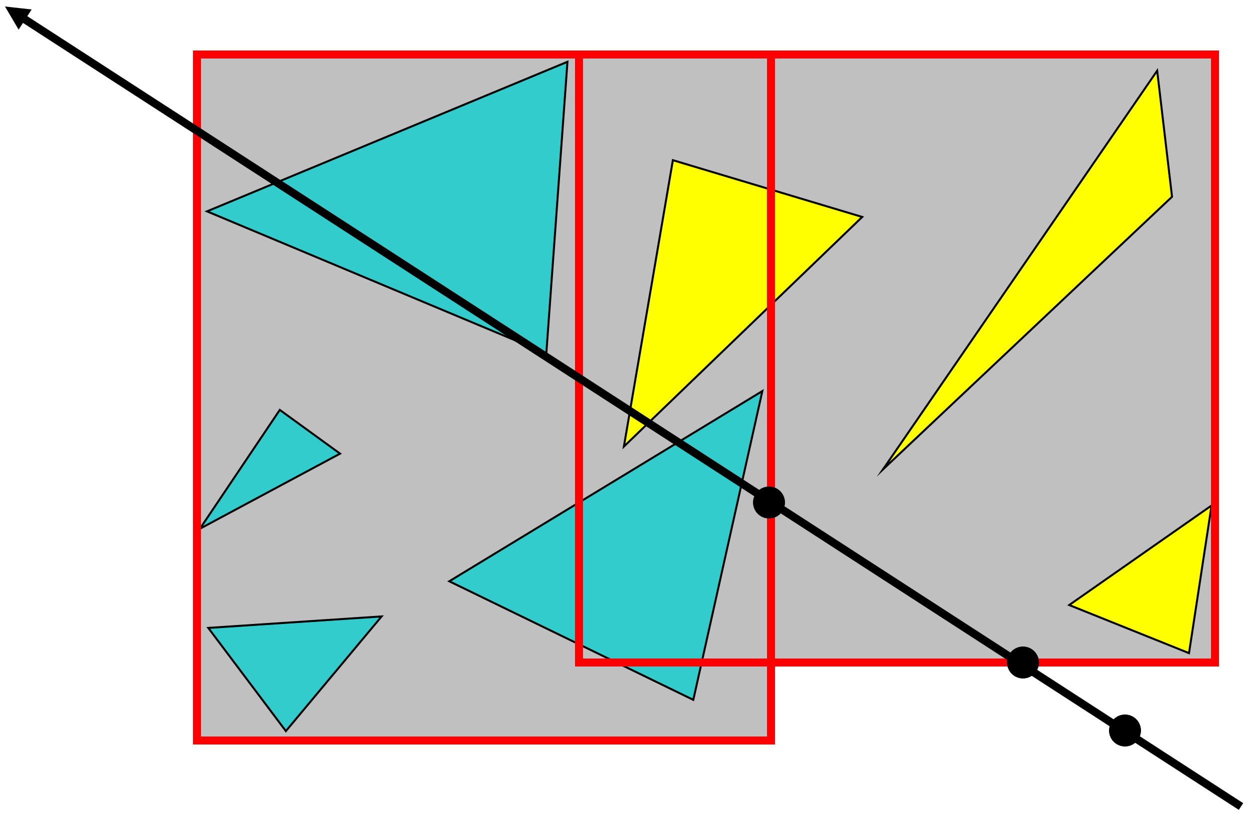
Intersection with BVH

- Check subvolume with closer intersection first

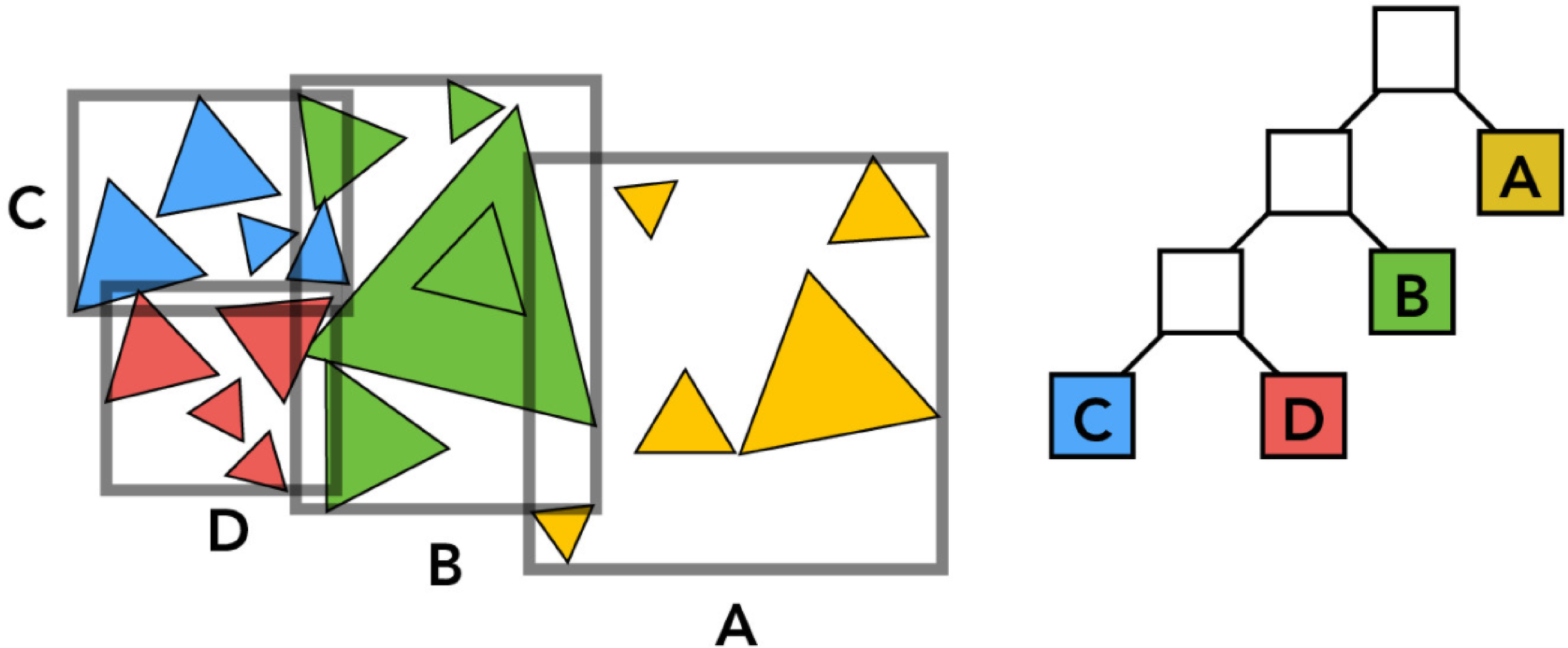


Intersection with BVH

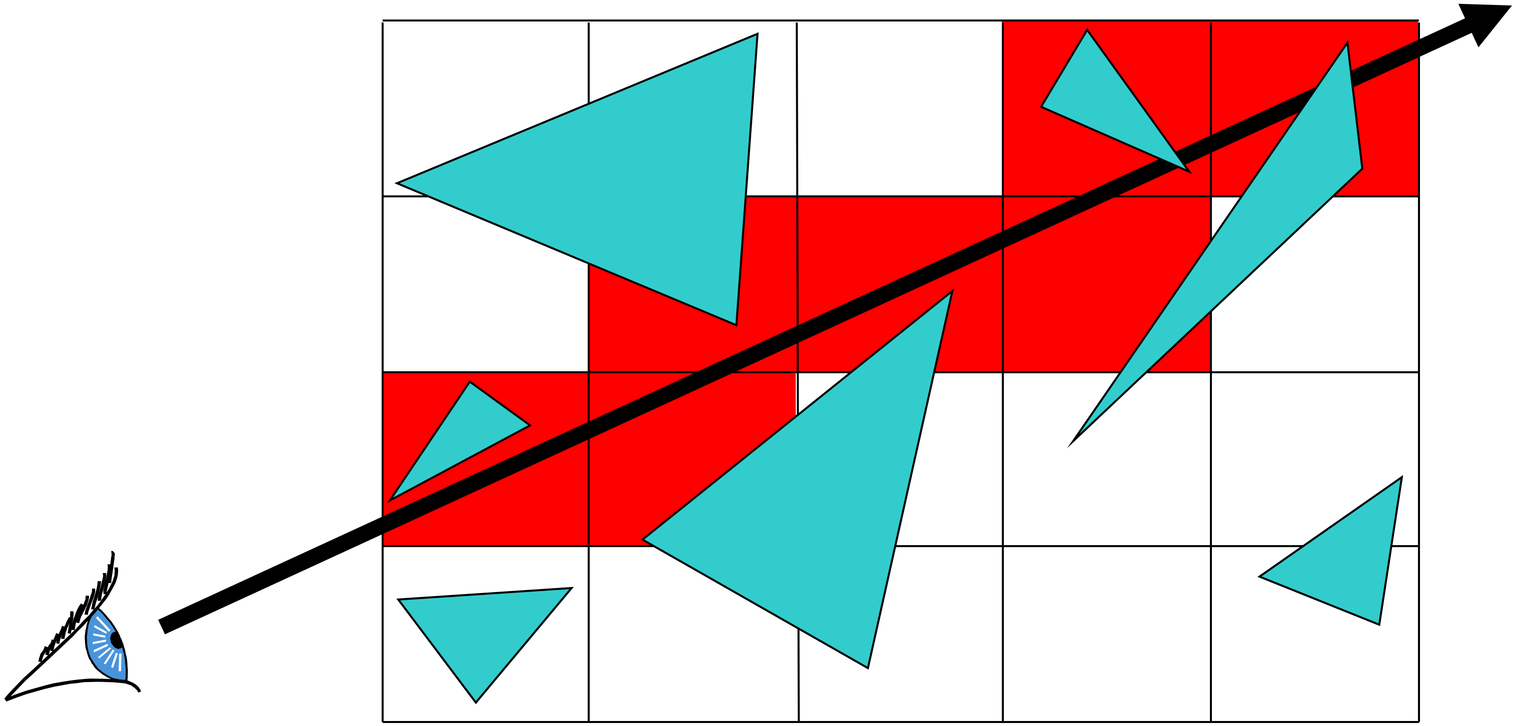
- Don't return intersection immediately if the other subvolume may have a closer intersection



Bounding Volume Hierarchy (BVH)



Spatial Subdivision

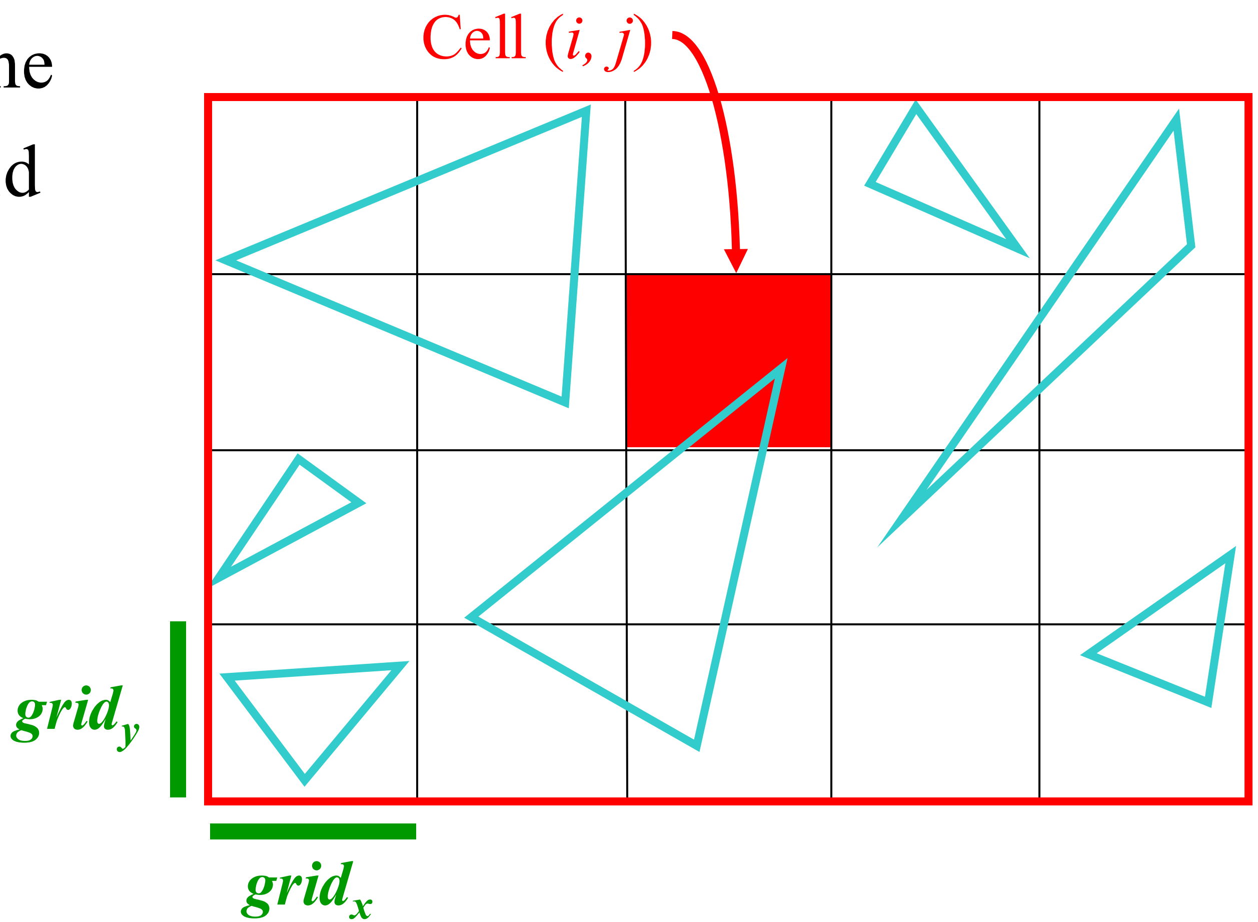


Spatial Subdivision

- Uniform spatial subdivision:
  - The space containing the scene is subdivided into a uniform grid of cubes “voxels”.
  - Each voxel stores a list of all objects at least partially contained in it.
  - Given a ray, voxels are traversed using a 3D variant of the 2D line drawing algorithms.
  - At each voxel the ray is tested for intersection with the primitives stored therein
  - Once an intersection has been found, there is no need to continue to other voxels.

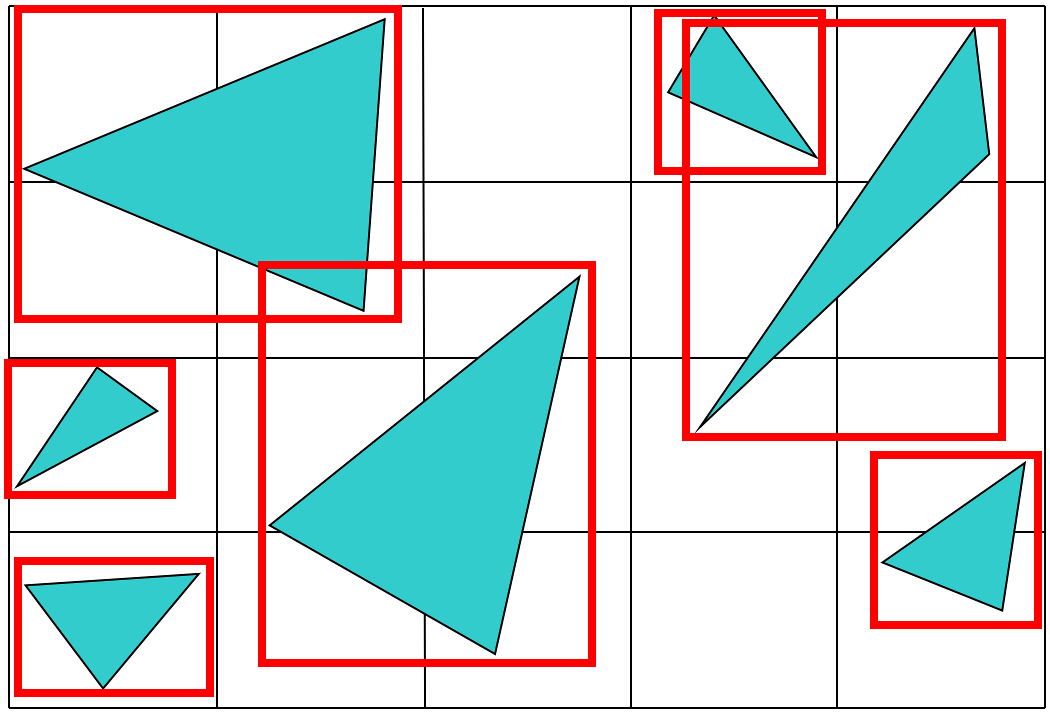
Create grid

- Find bounding box of scene
- Choose grid spacing
- $grid_x$ need not = $grid_y$



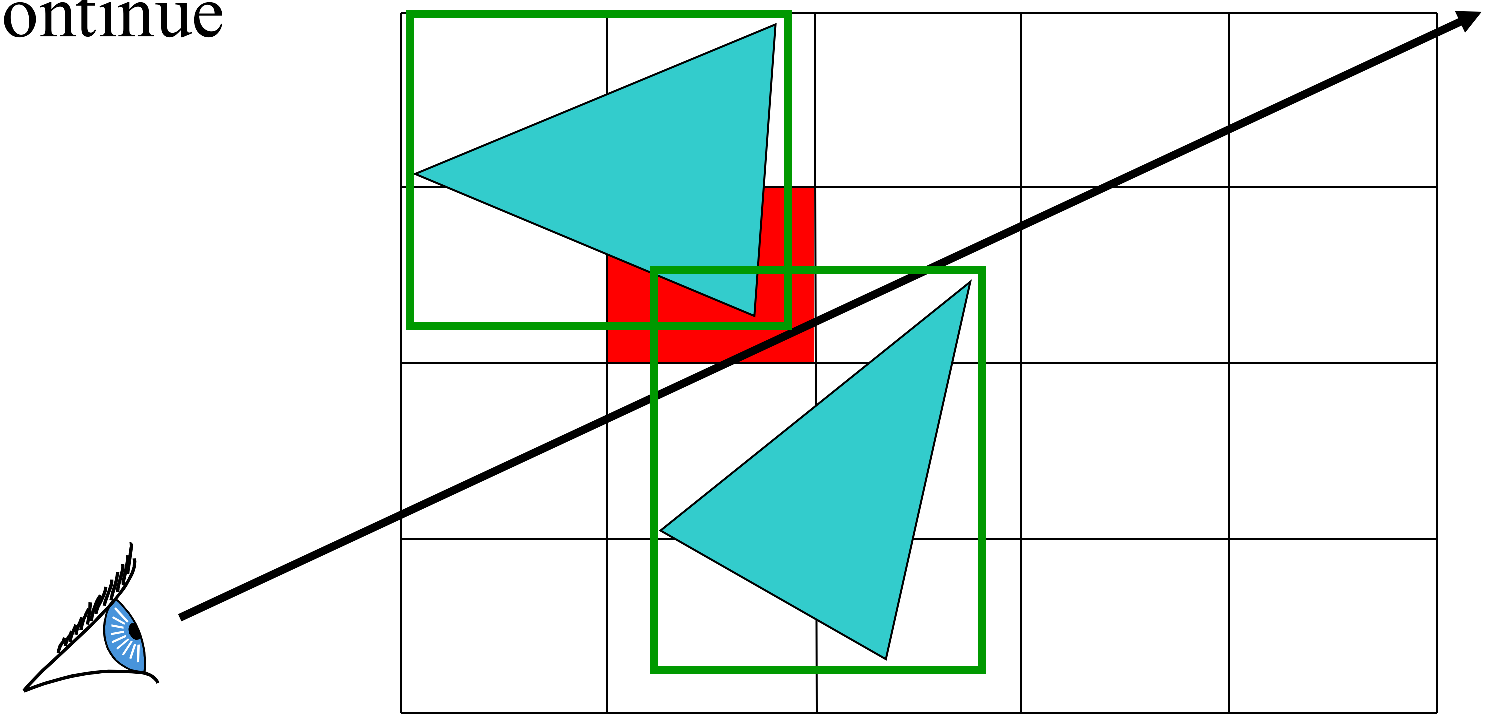
Insert primitives into grid

- Primitives that overlap multiple cells?
- Insert into multiple cells (use pointers)



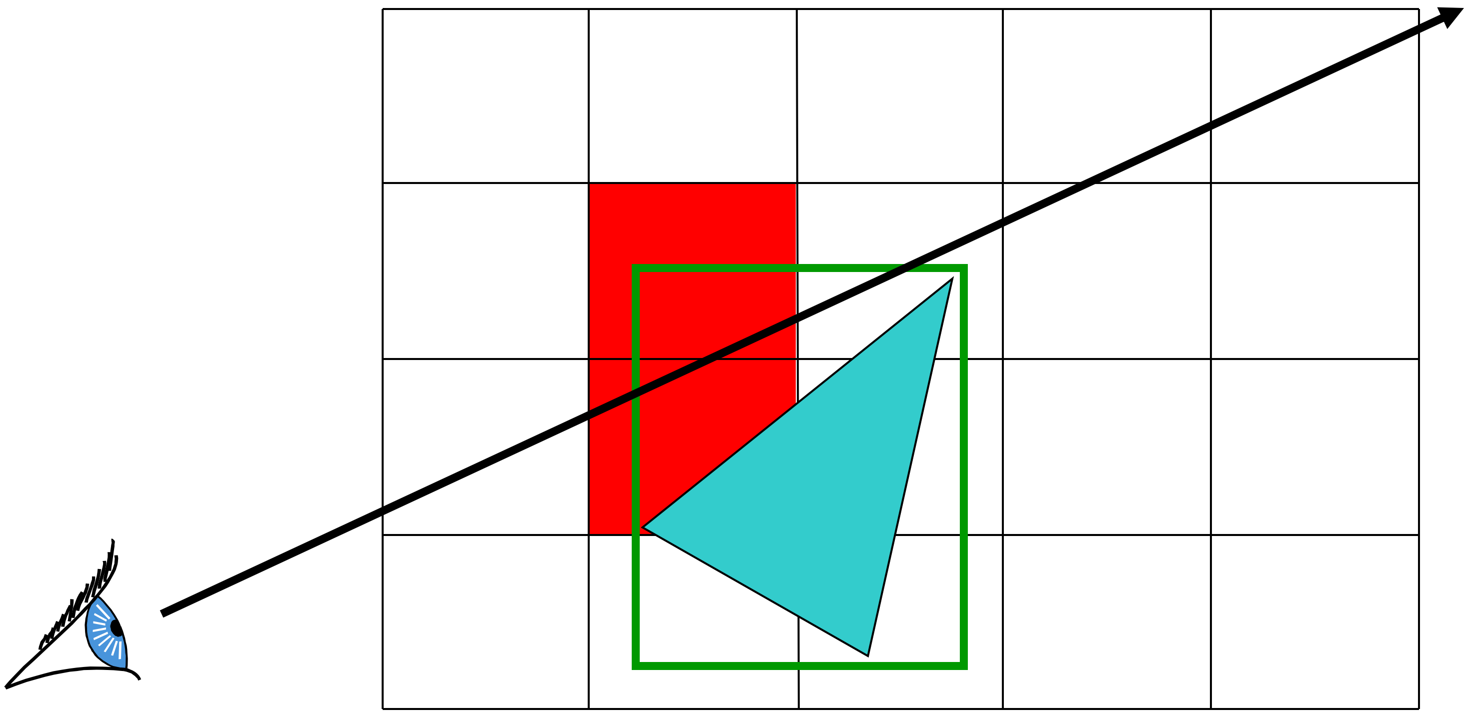
For each cell along a ray

- Does the cell contain an intersection?
- Yes: return closest intersection
- No: continue



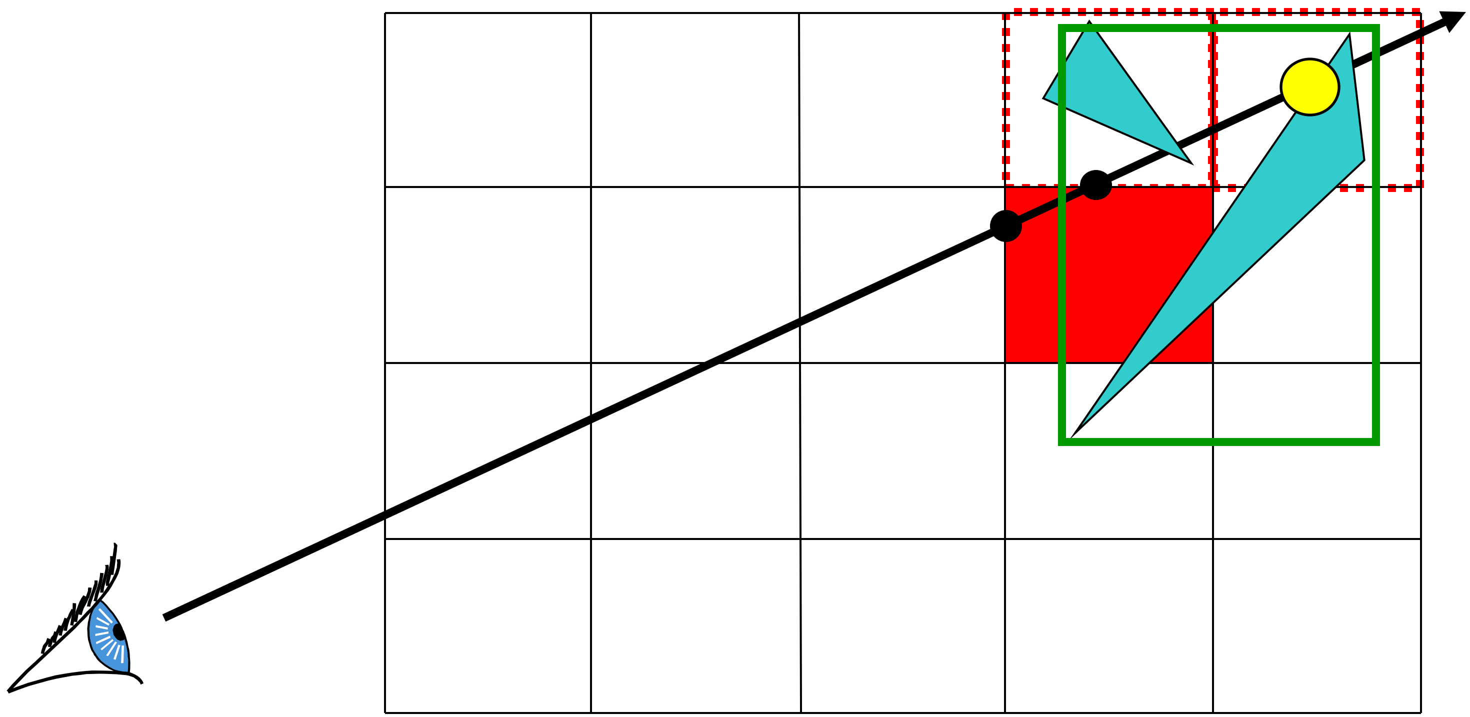
Preventing repeated computation

- Perform the computation once, "mark" the object
- Don't re-intersect marked objects



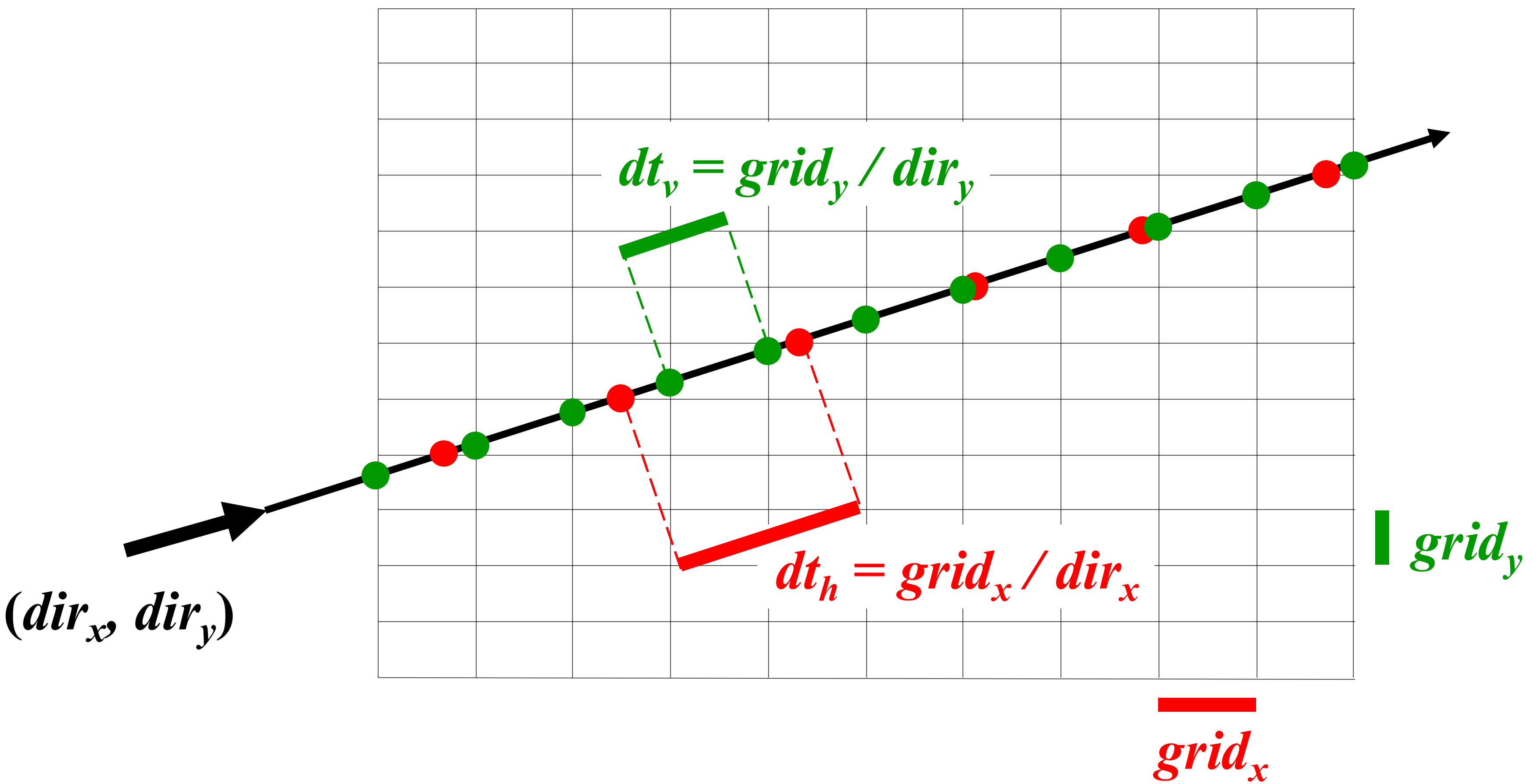
Don't return distant intersections

- If intersection t is not within the cell range, continue (there may be something closer)



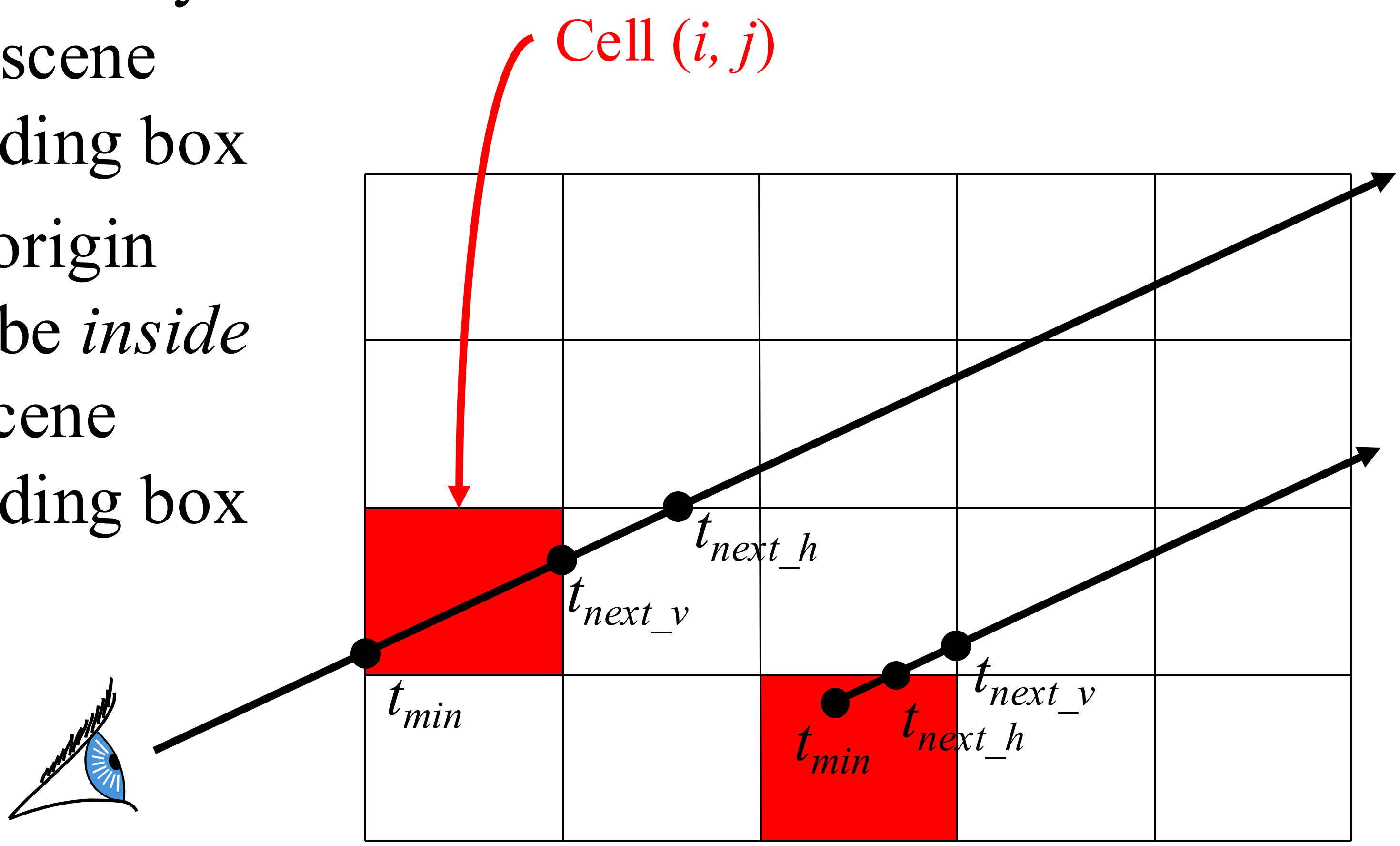
Is there a pattern to cell crossings?

- Yes, the horizontal and vertical crossings have regular spacing



Where do we start?

- Intersect ray with scene bounding box
- Ray origin may be *inside* the scene bounding box



What's the next cell?

if $t_{next\_v} < t_{next\_h}$

$i \mathrel{+}= sign_x$

$t_{min} = t_{next\_v}$

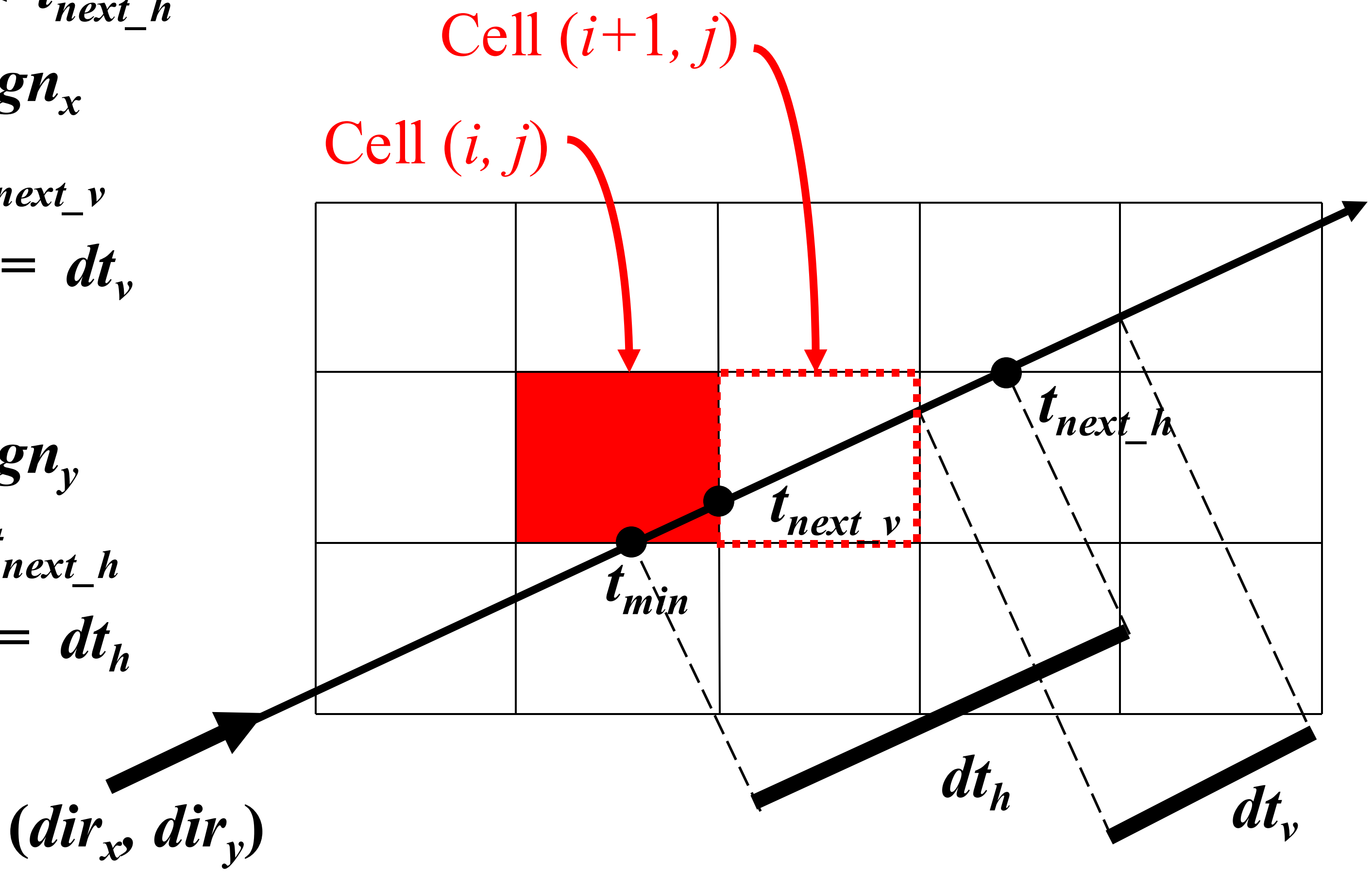
$t_{next\_v} \mathrel{+}= dt_v$

else

$j \mathrel{+}= sign_y$

$t_{min} = t_{next\_h}$

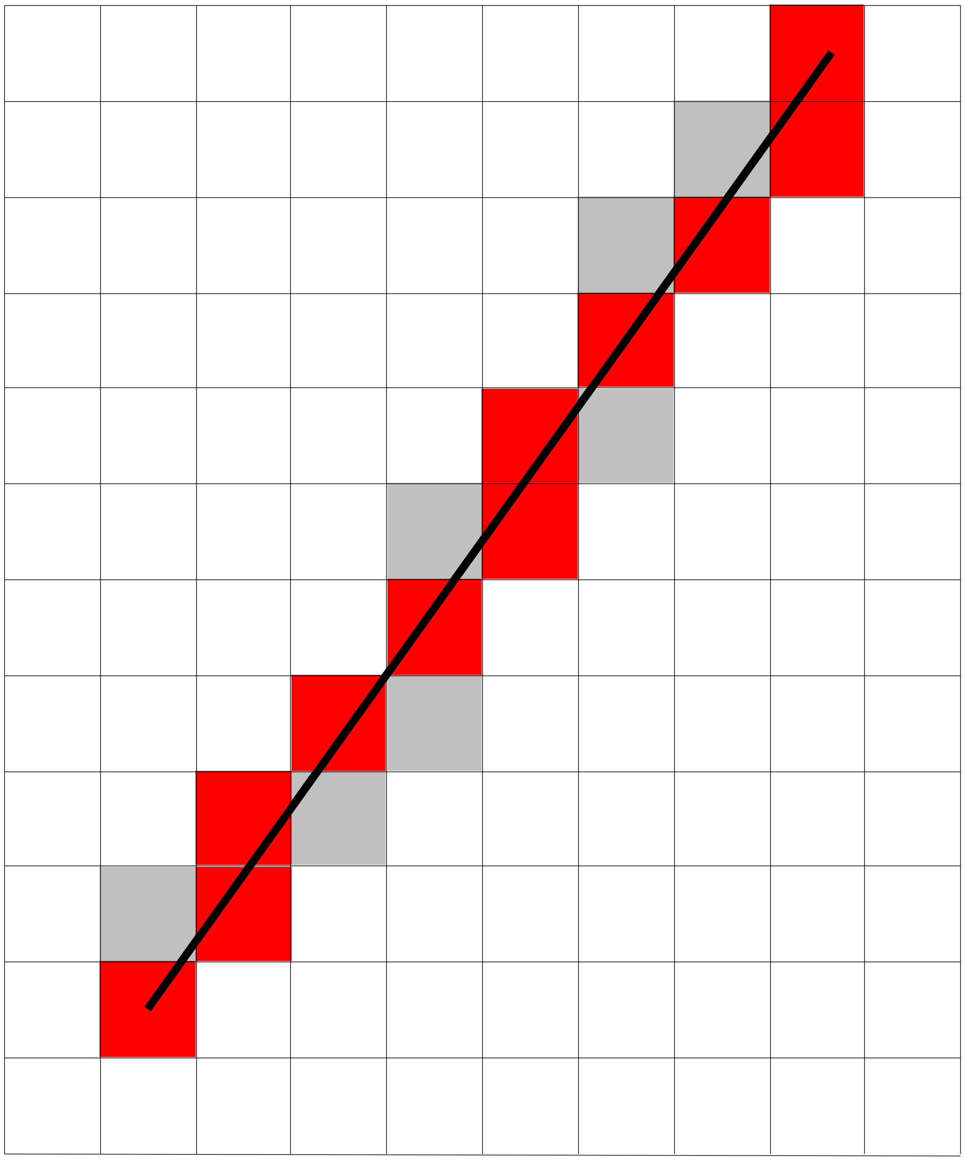
$t_{next\_h} \mathrel{+}= dt_h$



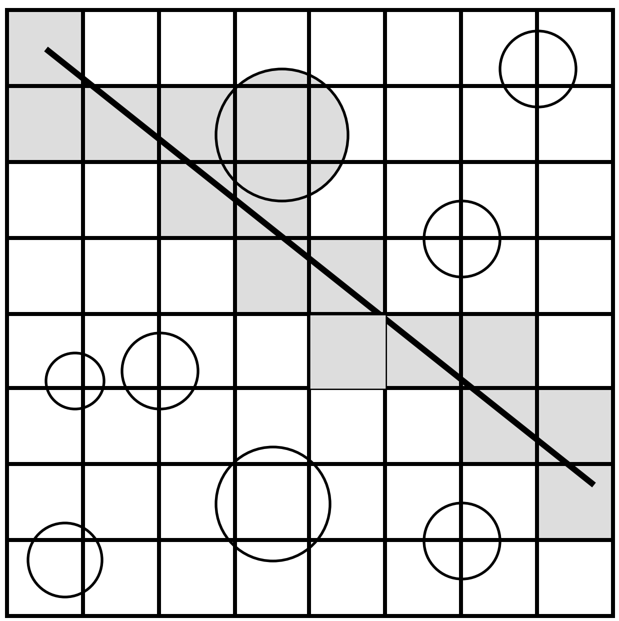
if $(dir_x > 0)$ $sign_x = 1$ *else* $sign_x = -1$

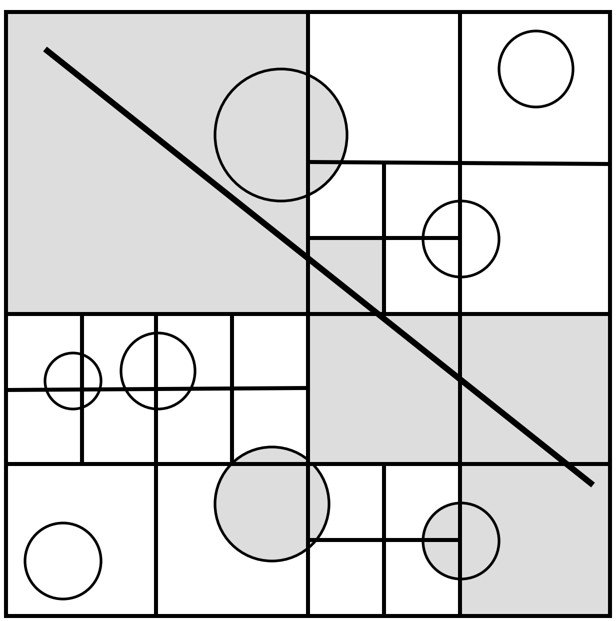
if $(dir_y > 0)$ $sign_y = 1$ *else* $sign_y = -1$

What's the next cell?



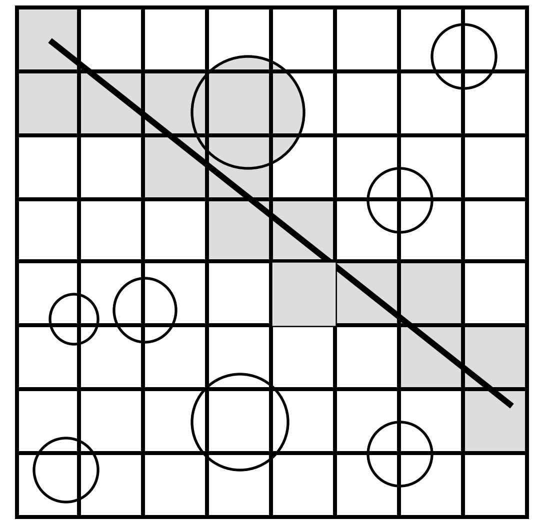
Uniform vs. Adaptive Subdivision





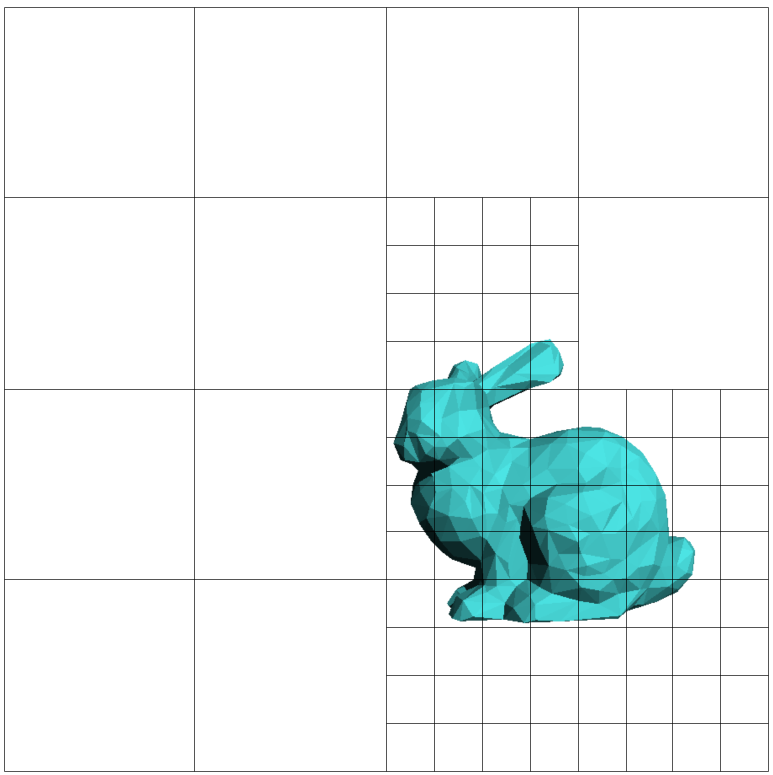
Regular Grid Discussion

- Advantages?
  - easy to construct
  - easy to traverse
- Disadvantages?
  - may be only sparsely filled
  - geometry may still be clumped

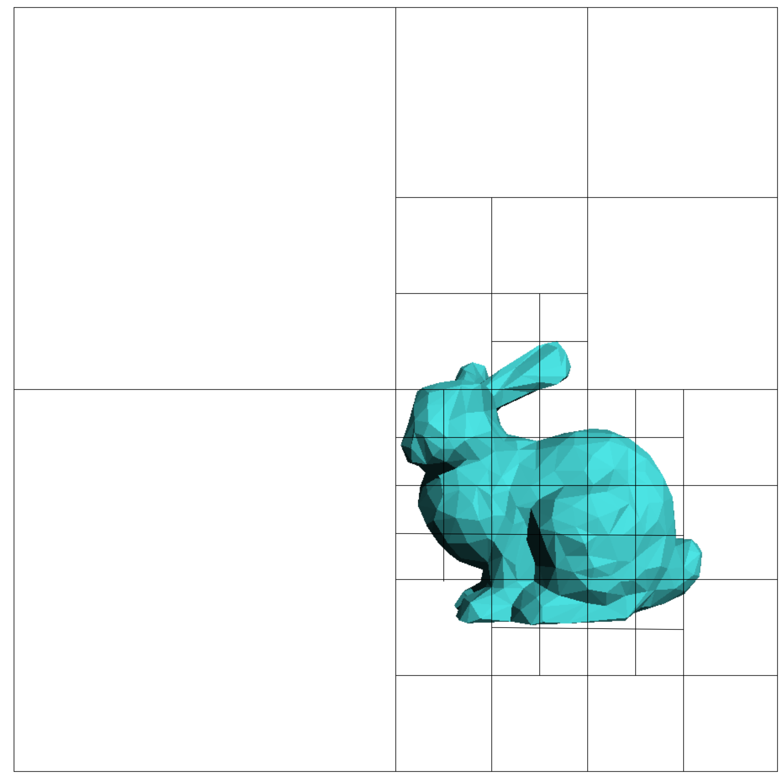


Adaptive Grids

- Subdivide until each cell contains no more than *n* elements, or maximum depth *d* is reached



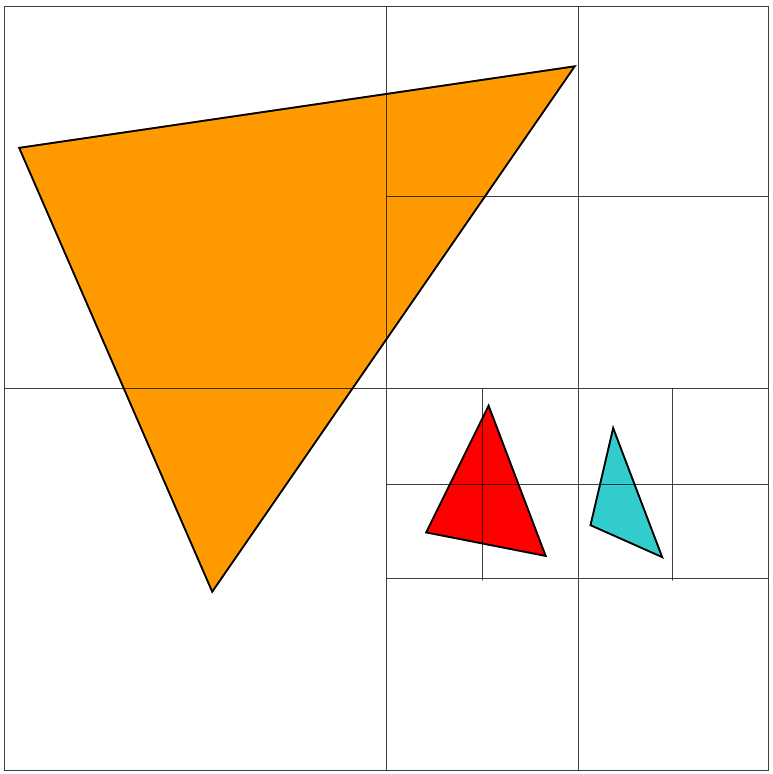
Nested Grids



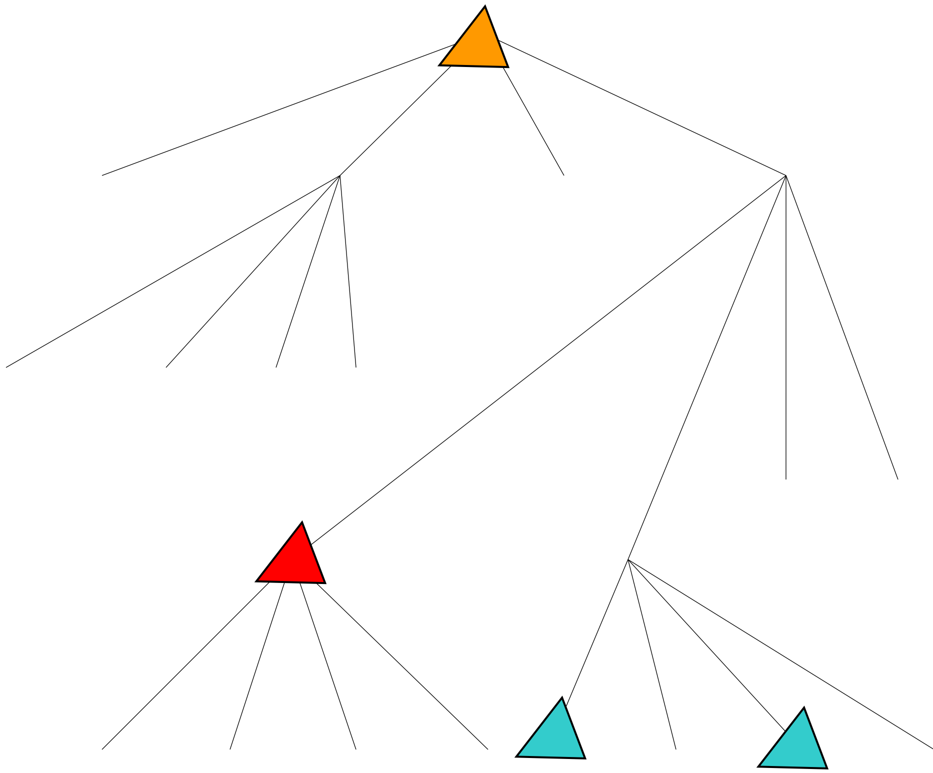
Octree/(Quadtree)

Primitives in an Adaptive Grid

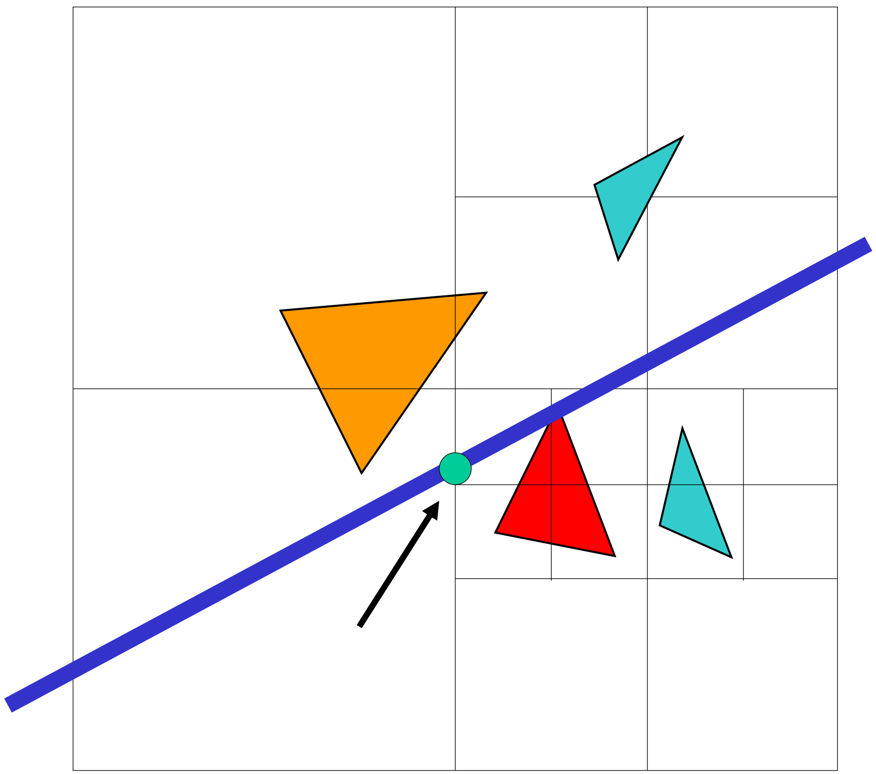
- Can live at intermediate levels, or be pushed to lowest level of grid



Octree/(Quadtree)



Bottom Up traversal



Step from cell to cell.

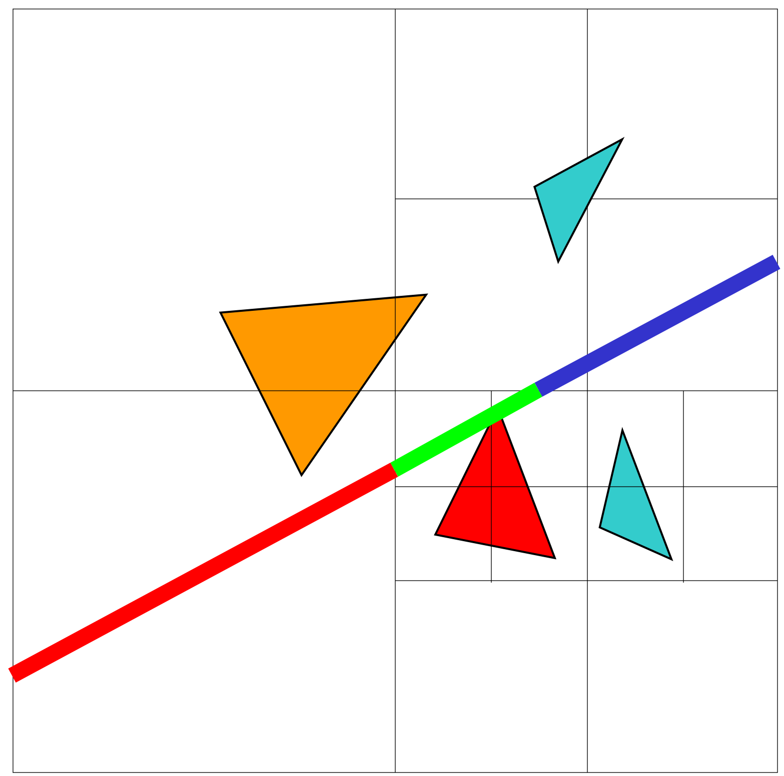
Intersect current cell and add an epsilon into the next cell.

Then search for the cell in the tree.

A naïve search starts from the root.

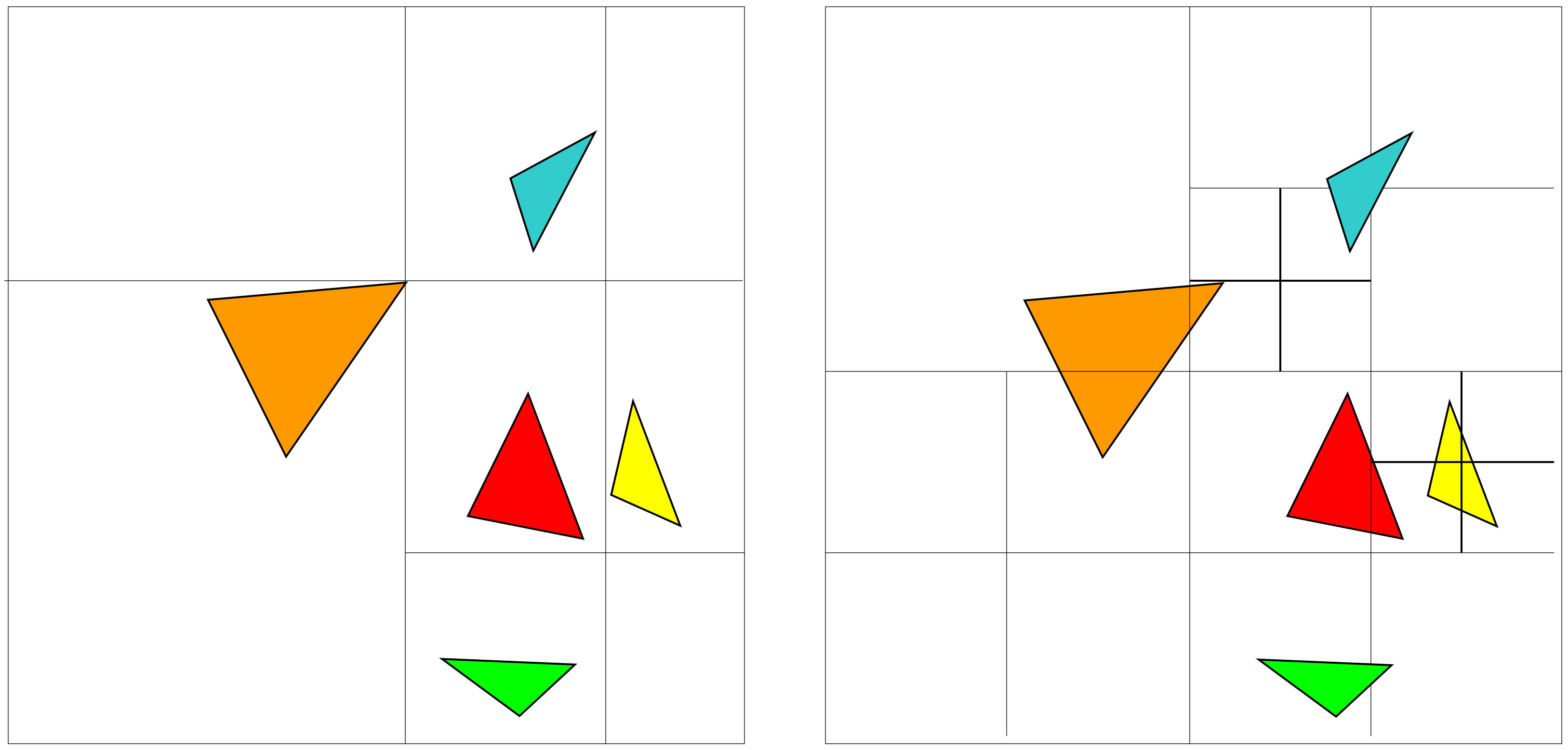
Otherwise, try an intelligent guess…

Top down traversal

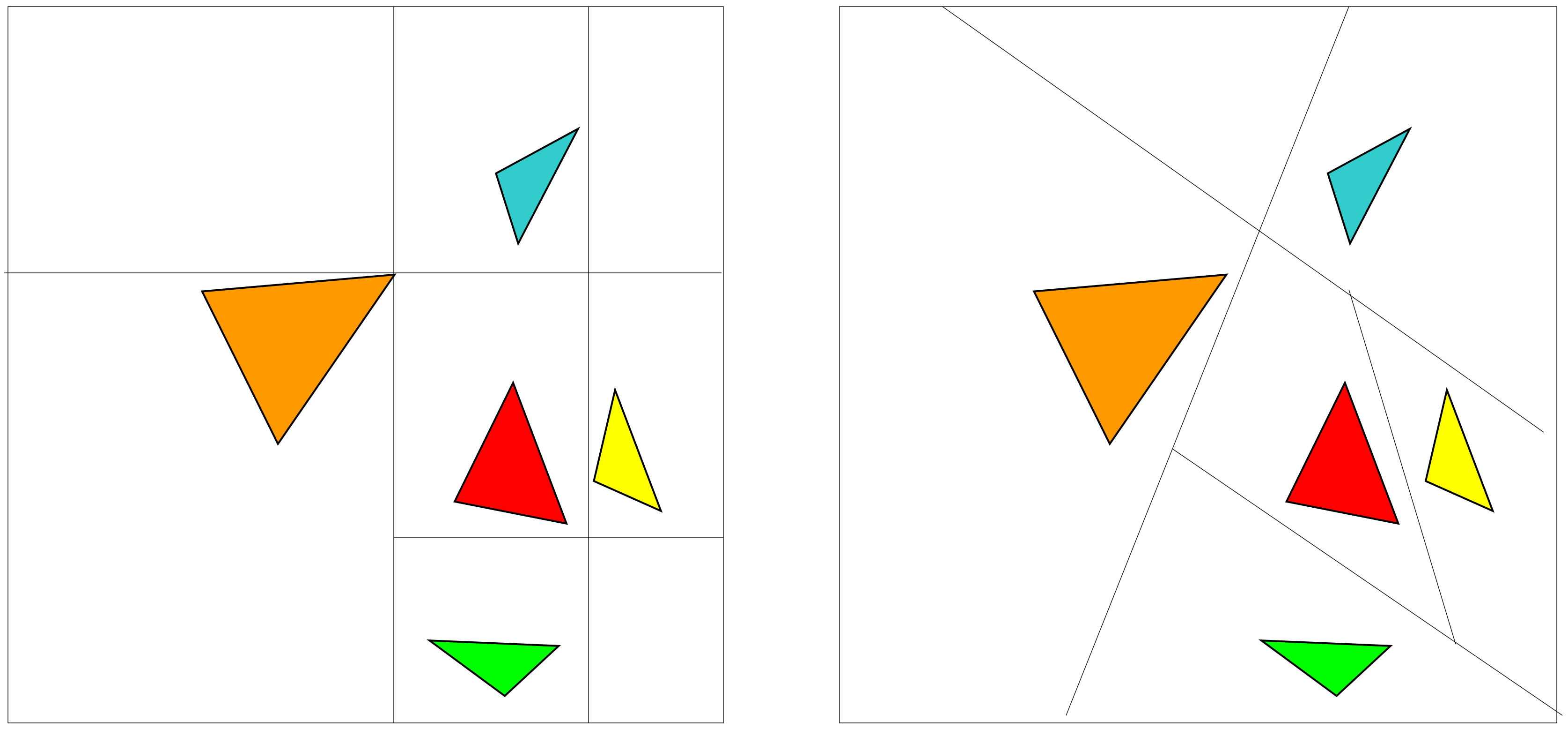


Split ray into sub-segments and traverse each segment recursively.

Kd-trees vs. Quad-tree



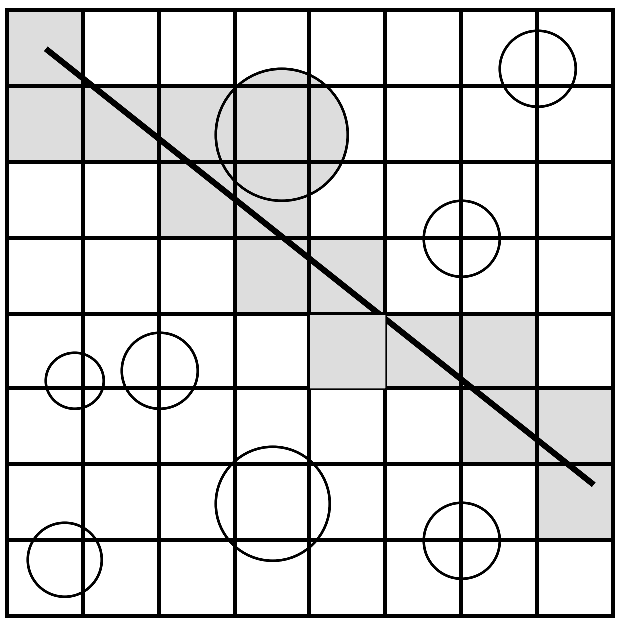
Kd-trees vs. BSP-tree

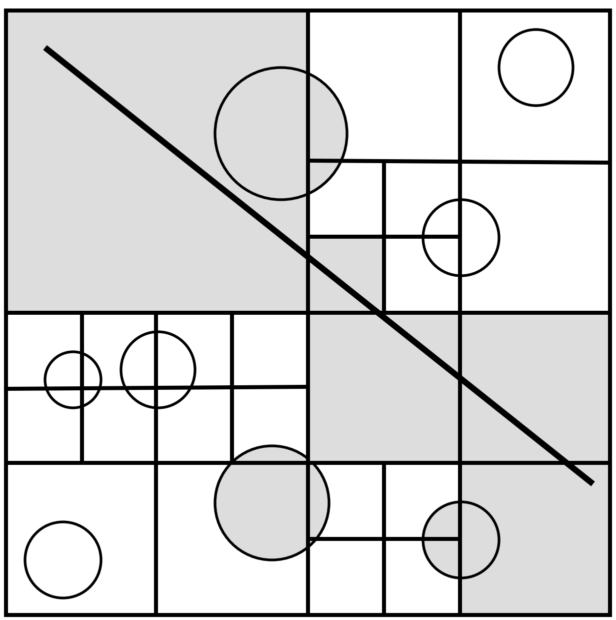


Adaptive Spatial Subdivision

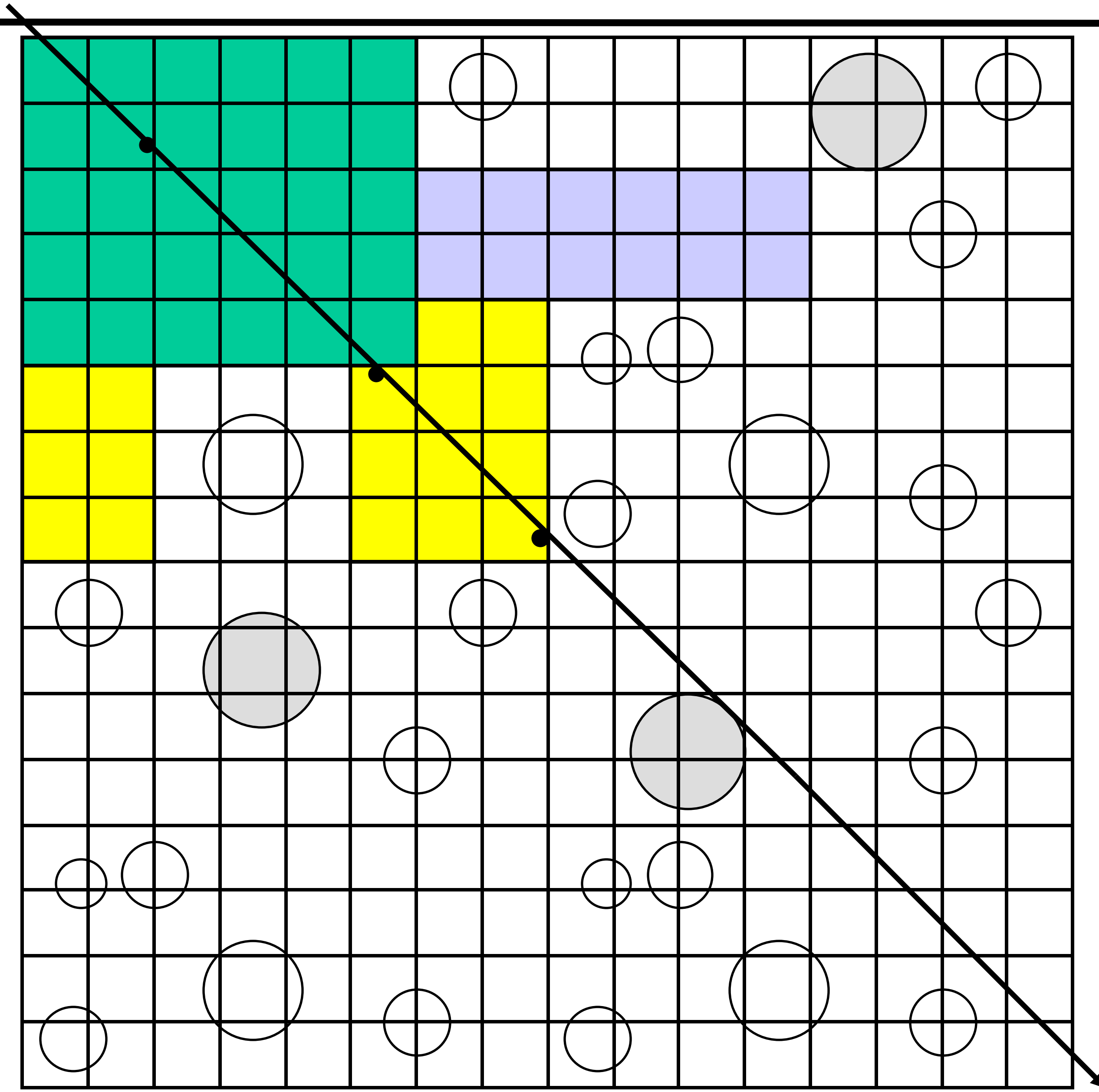
- Disadvantages of uniform subdivision:
  - requires a lot of space
  - traversal of empty regions of space can be slow
  - not suitable for “teapot in a stadium” scenes
- Solution: use a hierarchical adaptive spatial subdivision data structure
  - octrees
  - BSP-trees
- Given a ray, perform a depth-first traversal of the tree. Again, can stop once an intersection has been found.

Uniform vs. Adaptive Subdivision

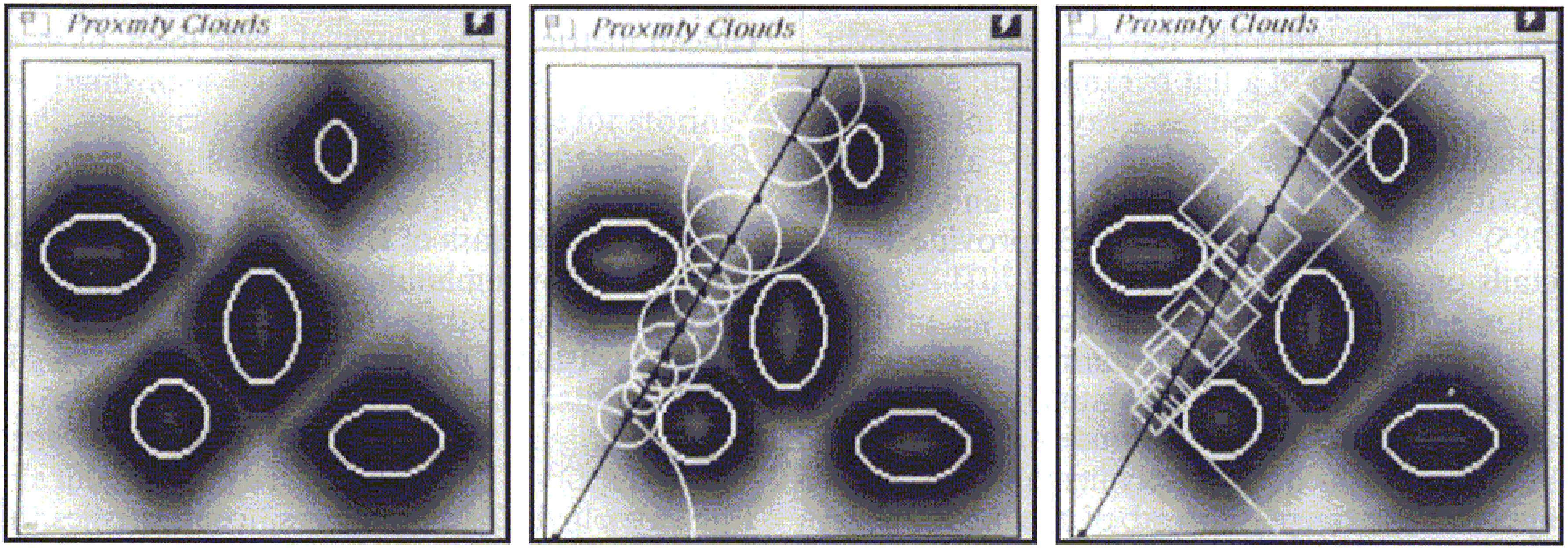




Macro-regions



Proximity Clouds



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Parallel/Distributed RT

- Two main approaches:
  - Each processor is in charge of tracing a subset of the rays. Requires a shared memory architecture, replication of the scene database, or transmission of objects between processors on demand.
  - Each processor is in charge of a subset of the scene (either in terms of space, or in terms of objects). Requires processors to transmit rays among themselves.

Directional Techniques

- Light buffer: accelerates shadow rays.
  - Discretize the space of directions around each light source using the *direction cube*
  - In each cell of the cube store a sorted list of objects visible from the light source through that cell
  - Given a shadow ray locate the appropriate cell of the direction cube and test the ray with the objects on its list

Directional Techniques

- Ray classification (Arvo and Kirk 87):
  - Rays in 3D have 5 degrees of freedom: (x,y,z,θ,ϕ)
  - Rays coherence: rays belonging to the same small 5D neighborhood are likely to intersect the same set of objects.
  - Partition the 5D space of rays into a collection of 5D hypercubes, each containing a list of objects.
  - Given a ray, find the smallest containing 5D hypercube, and test the ray against the objects on the list.
  - For efficiency, the hypercubes are arranged in a hierarchy: a 5D analog of the 3D octree. This data structure is constructed in a lazy fashion.