Acceleration Structures

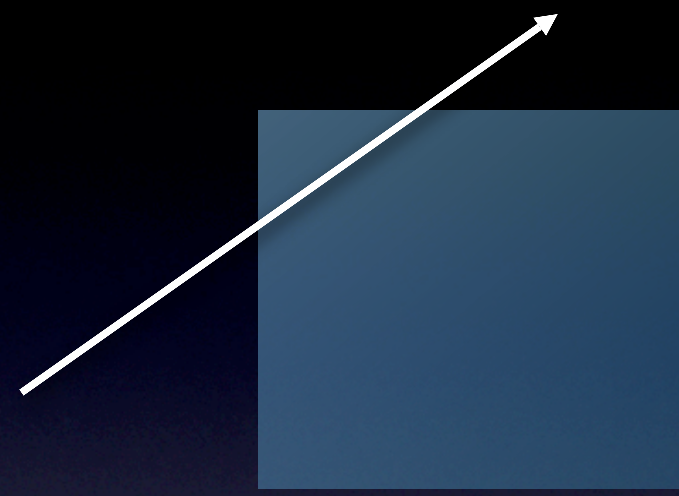
CS 6965 Fall 2011

Program 2

- Run Program 1 in simhwrt
  - Also run Program 2 and include that output
- Lab time?

- Inheritance probably doesn't work

Boxes



- Axis aligned boxes
- Parallelepiped

- 12 triangles?
- 6 planes with squares?

Ray-box intersection

$$\vec{N} \cdot \vec{P} - d = 0$$

$$t = \frac{d - \vec{N} \cdot \vec{O}}{\vec{N} \cdot \vec{V}}$$

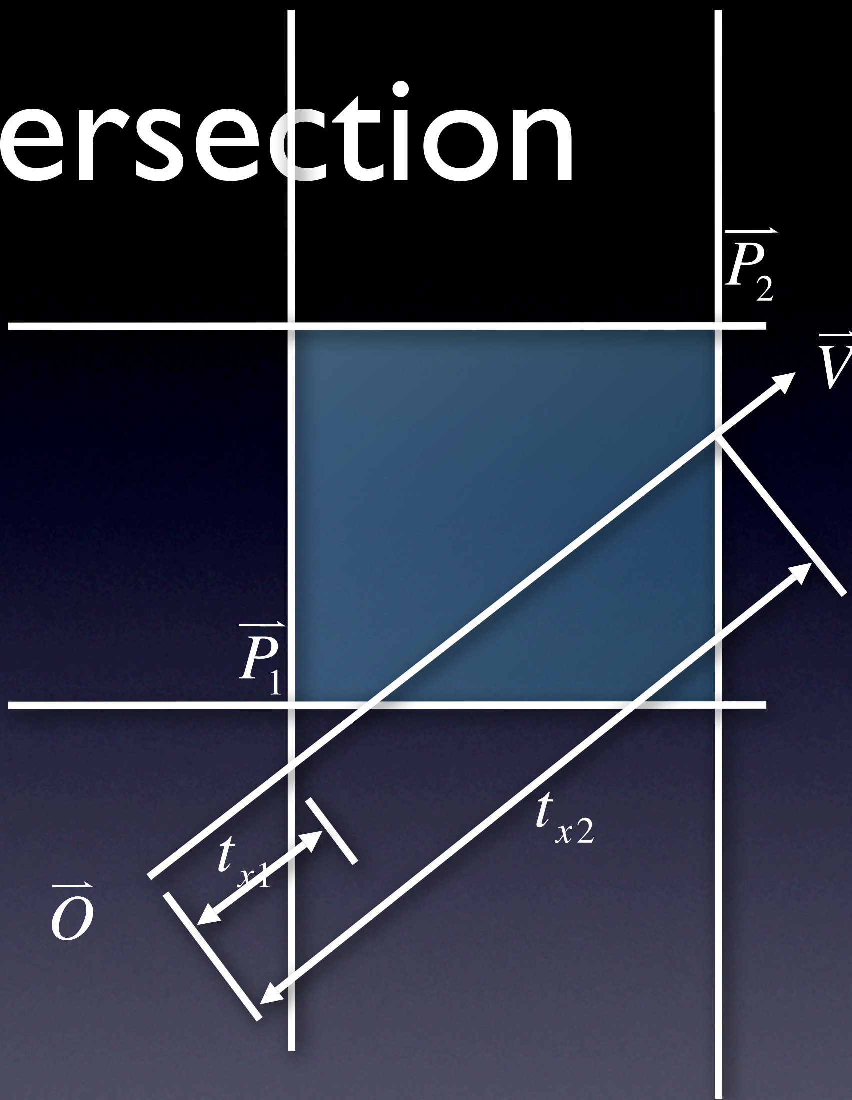
x plane: $\vec{\mathrm{N}} = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}$

$$t = \frac{d - O_x}{V_x}$$

$$d_1 = P_{1x}, d_2 = P_{2x}$$

$$t_{x1} = \frac{P_{1x} - O_x}{V_x}, t_{x2} = \frac{P_{2x} - O_x}{V_x}$$

Same for y, z planes



Intersection of intervals

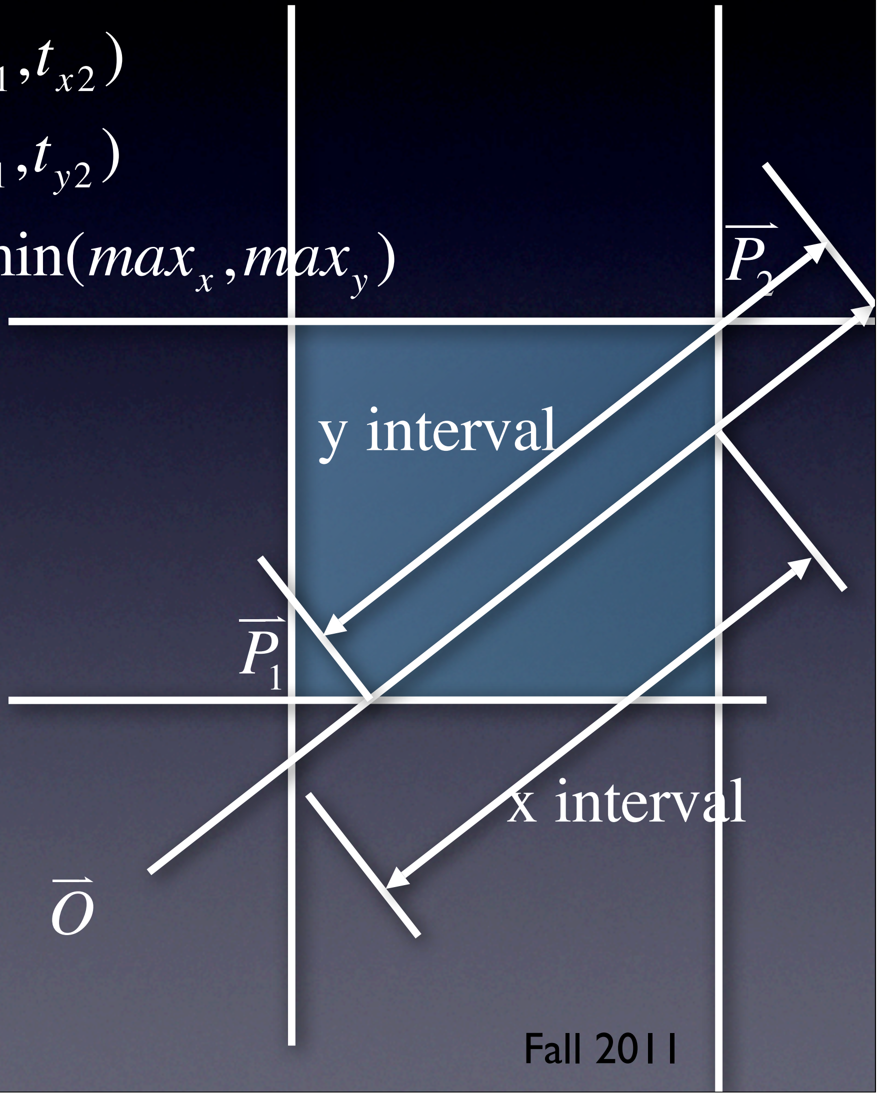
Intersection occurs where x interval overlaps y interval

x interval: $\min(t_{x1}, t_{x2}) \leq t \leq \max(t_{x1}, t_{x2})$

y interval: $\min(t_{y1}, t_{y2}) \leq t \leq \max(t_{y1}, t_{y2})$

intersection: $\max(min_x, min_y) \leq t \leq \min(max_x, max_y)$

In 3D also check z interval



Improved Box

- http://www.cs.utah.edu/~awilliam/box/

Ray tracing optimization

- Faster rays
  - CPU optimization techniques (CS6620 lecture)
- Fewer rays
  - Adaptive supersampling
  - Ray tree pruning
- Faster ray-object intersection tests
  - High-order surfaces
- Fewer ray-object intersection tests
  - Acceleration structures

Adapted from Arvo/Kirk “A survey of ray tracing acceleration techniques”

Acceleration structures

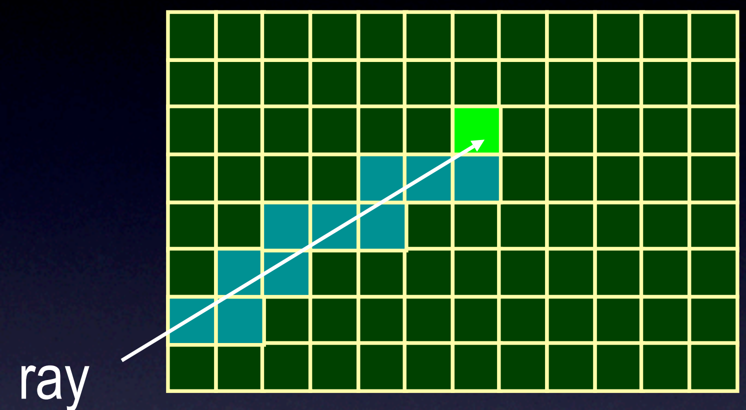
- Current ray tracer is O(# objects)
- Large # of objects can be SLOW

- Solution: intelligently determine which objects to intersect
- Good news: <<O(N) achievable!
- Real-time ray tracer exploits this to do very large models:
  - 262144x262144 heightfield (10+billion patches)
  - 35 million spheres
  - (1.1 million spheres + volume rendering) * 170 timesteps

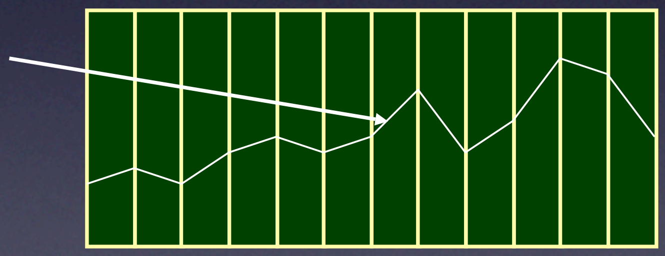
Acceleration structures

- Three main types
- Tree-based:
  - Binary Space Partitioning (BSP) tree
  - Bounding Volume Hierarchy
- Grid-based:
  - Uniform grid
  - Hierarchical grid
  - Octree
- Directional

Uniform grid

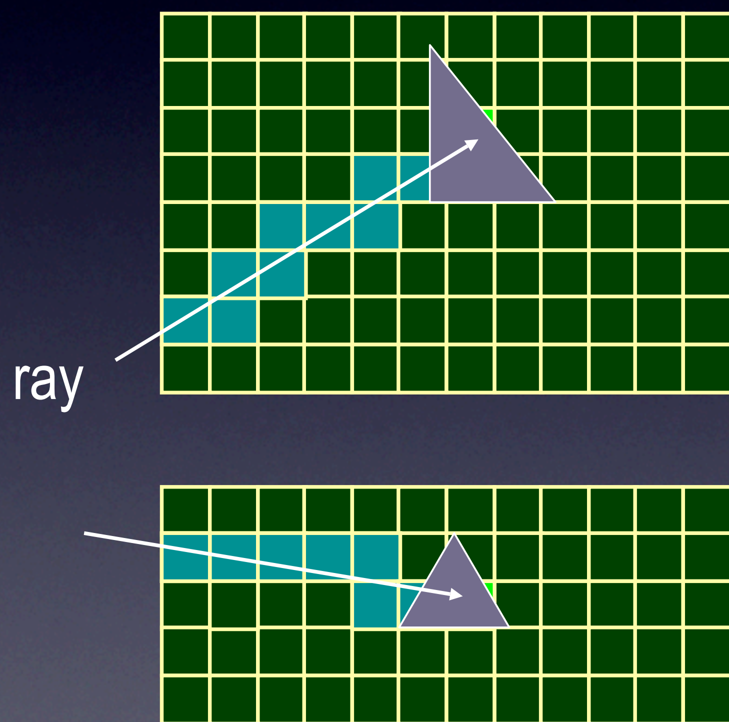


- Split space up in a grid
- A heightfield is a specialized acceleration structure
- A grid is more general



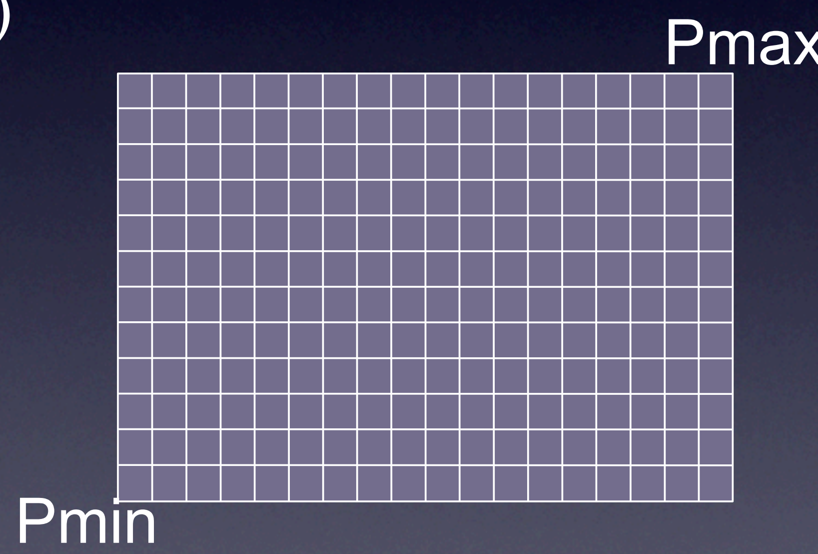
Grid traversal

- Just like a 2D Grid but in 3D



Heightfield traversal

- Step 1: Compute a few derived values
  - Diagonal: D = Pmax-Pmin
  - Cell Size: cellsize = D/(nx, ny, 1)
  - Data min, max: Zmin, Zmax
- Grid:
  - Add nz
  - Cell size 3D
  - Don't need Zmin/Zmax
  - Data located in cells, not at corners

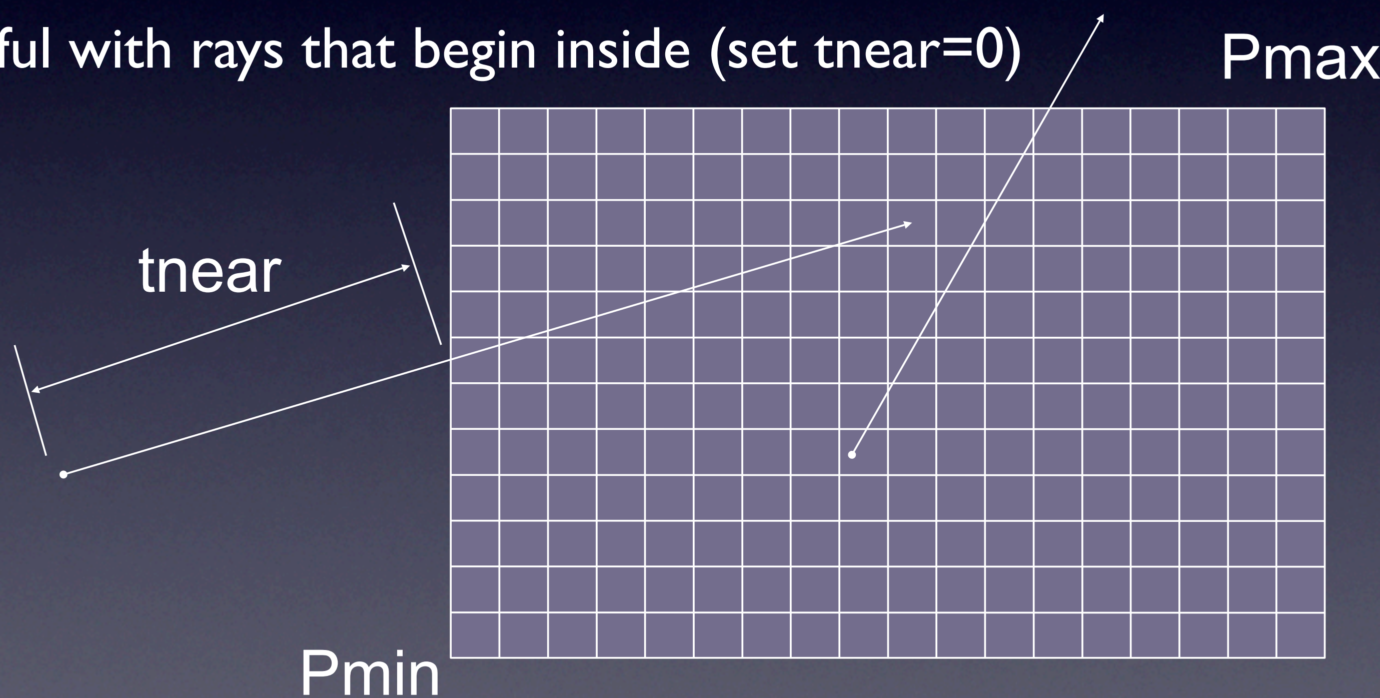


Grid traversal

- Step 2-8: straightforward extension to 3D

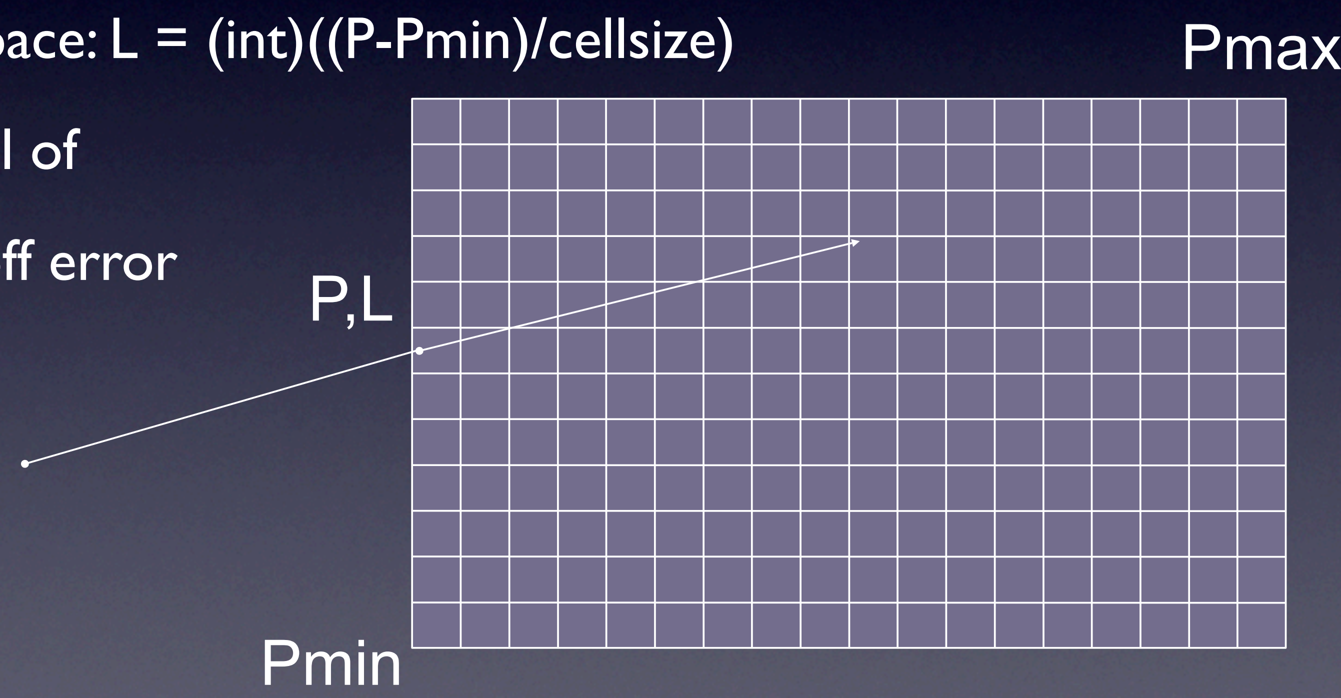
Heightfield traversal

- Step 2: Compute tnear
  - Use ray-box intersection
  - Be careful with rays that begin inside (set tnear=0)



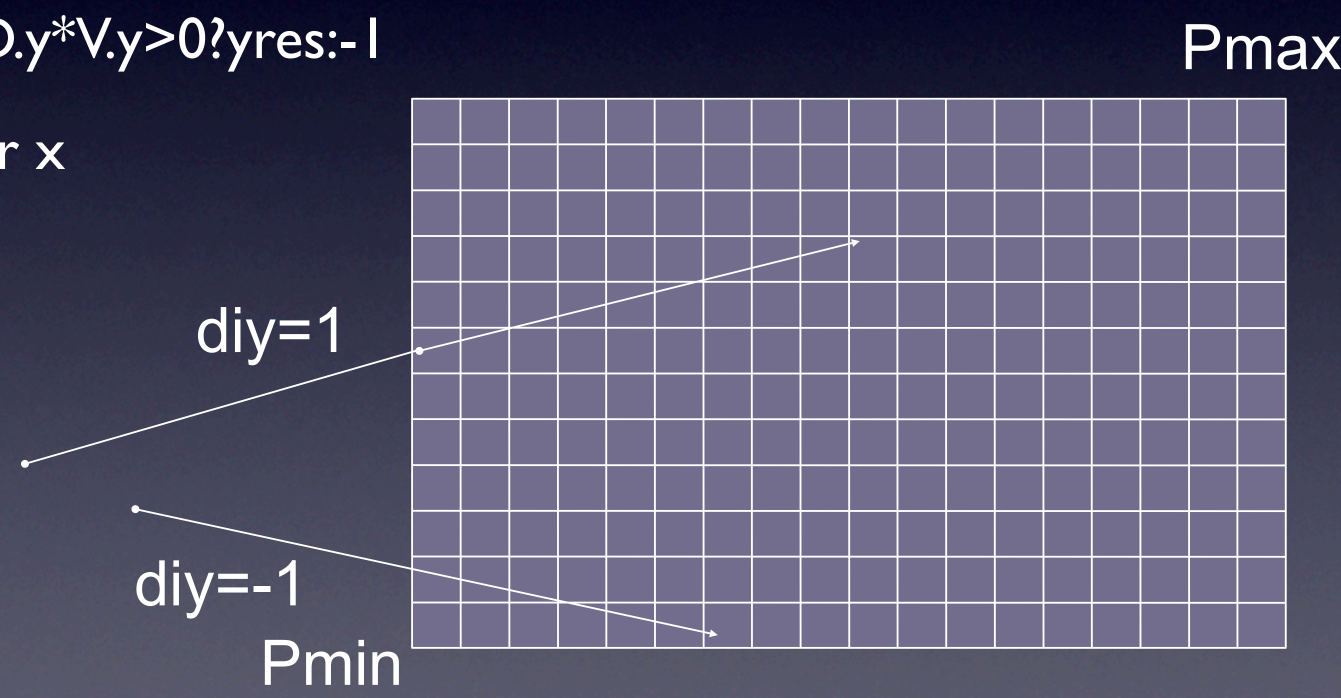
Heightfield traversal

- Step 3: Compute lattice coordinates of near point
  - World space: P = O+tnear V
  - Lattice space: L = (int)((P-Pmin)/cellsize)
  - Be careful of
  - roundoff error



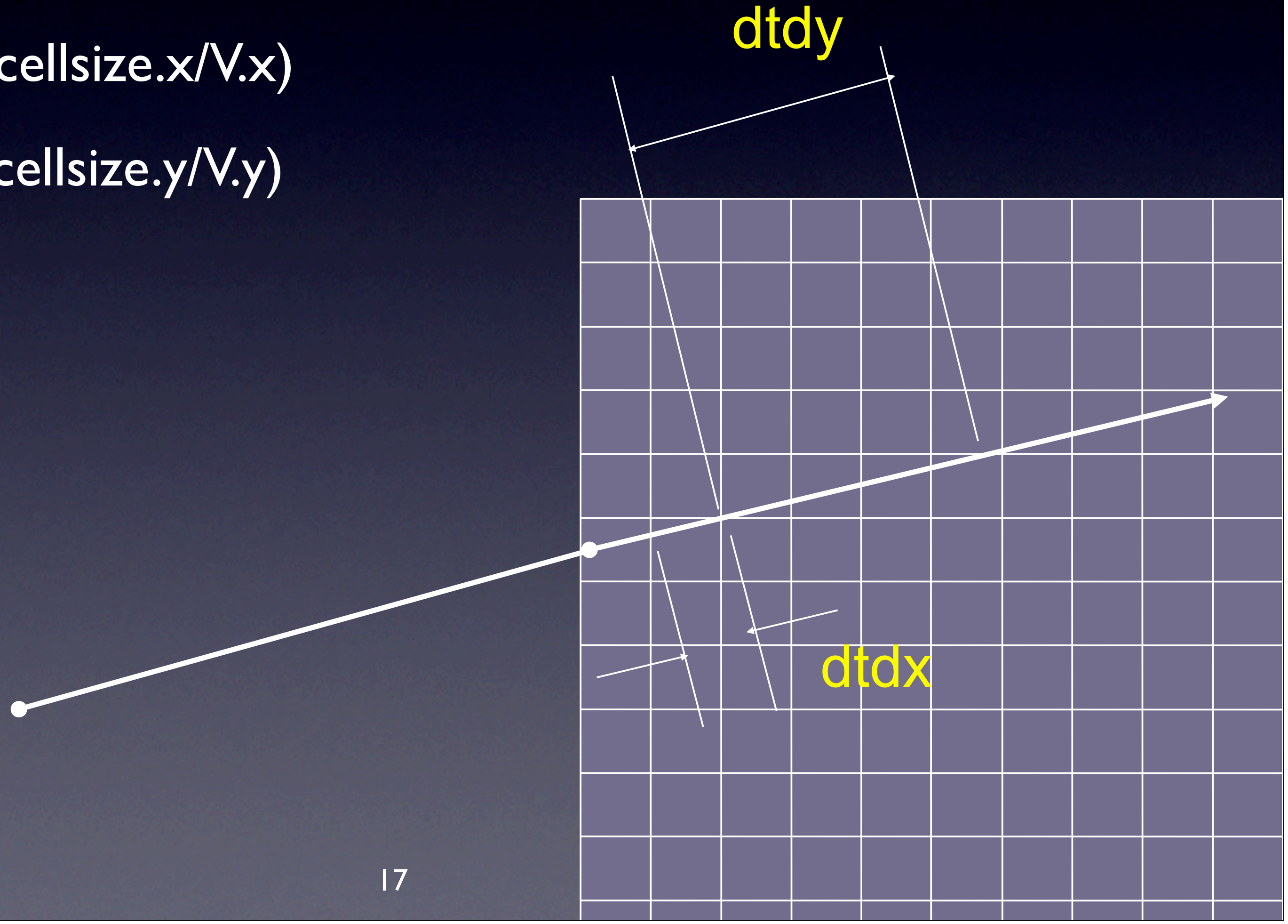
Heightfield traversal

- Step 4: Determine how ray marching changes index
  - diy = D.y*V.y>0?1:-1
  - stopy = D.y*V.y>0?yres:-1
  - similar for x



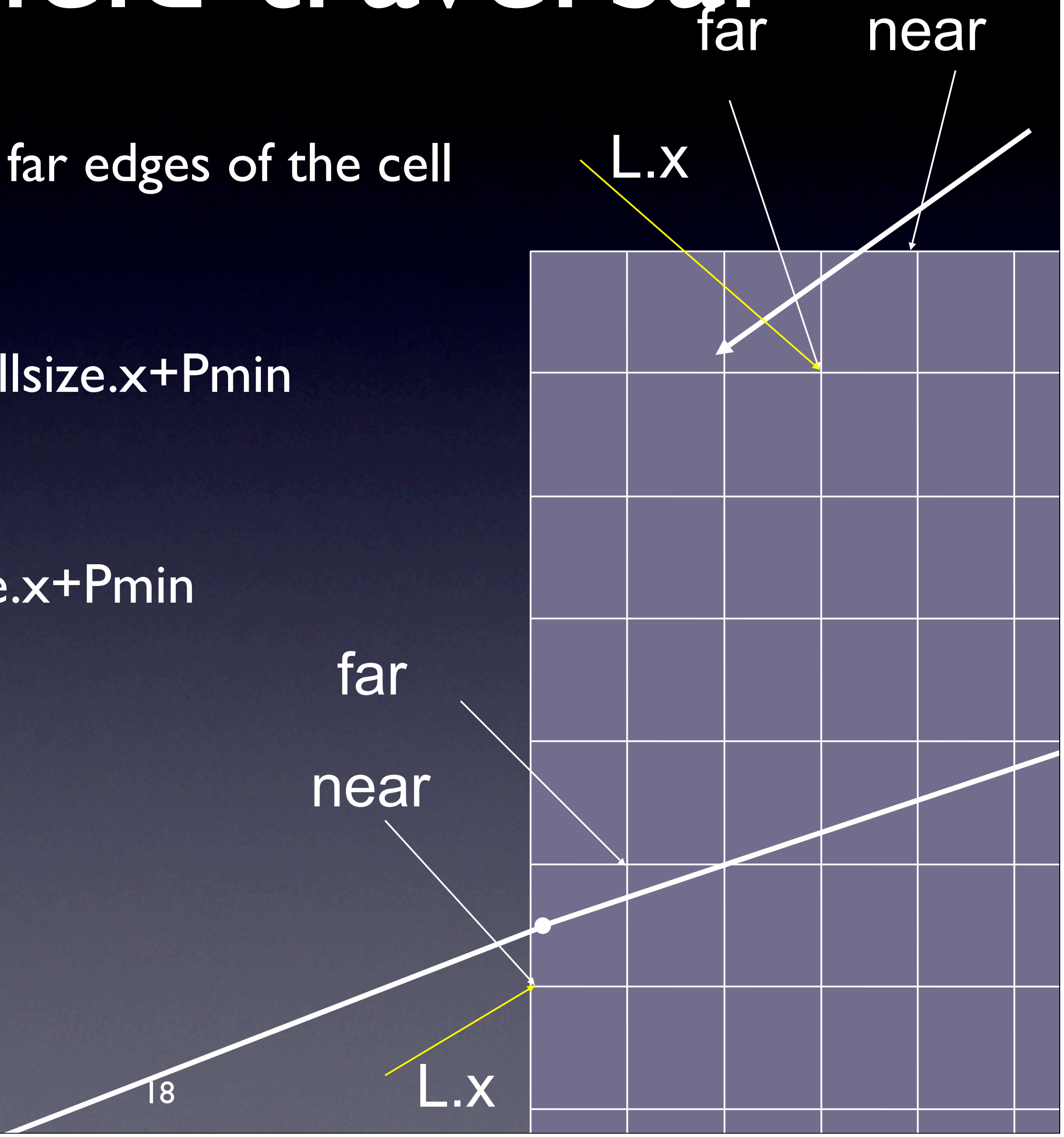
Heightfield traversal

- Step 5: Determine how t value changes with ray marching:
- dtdx = Abs(cellsize.x/V.x)
- dtdy = Abs(cellsize.y/V.y)



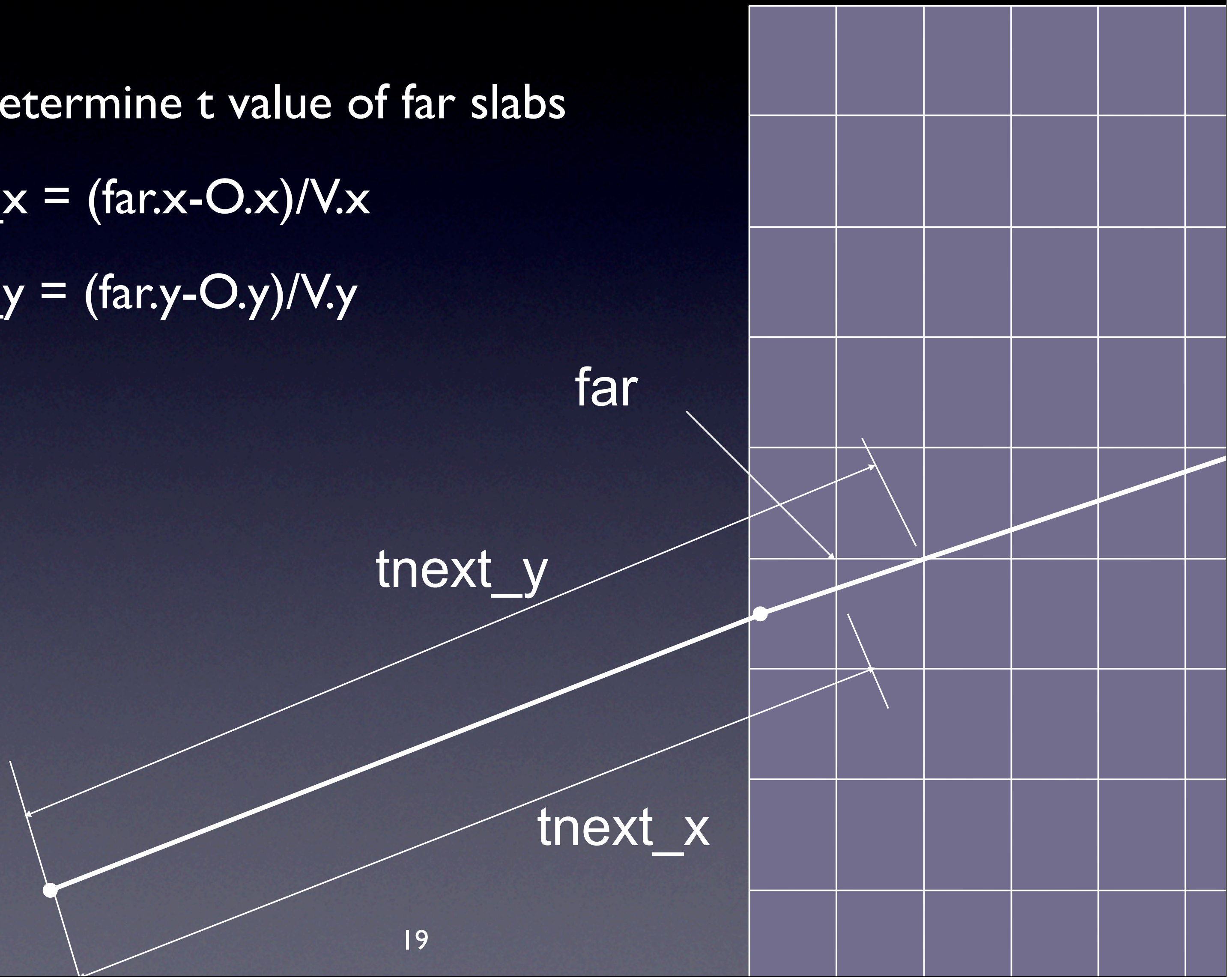
Heightfield traversal

- Step 6: Determine the far edges of the cell
  - if dix == 1:
  - far.x=(L.x+1)*cellsize.x+Pmin
  - if dix == -1:
  - far.x=L.x*cellsize.x+Pmin
  - Similar for y



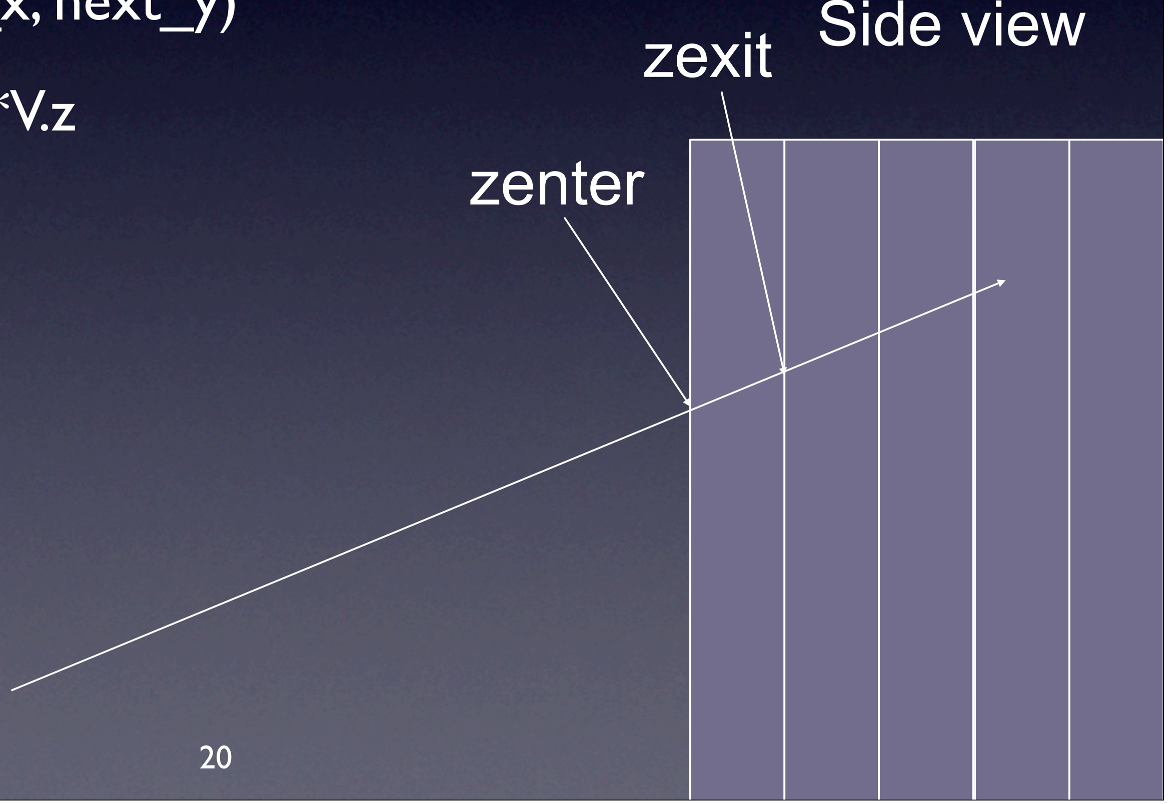
Heightfield traversal

- Step 7: Determine t value of far slabs
  - tnext_x = (far.x-O.x)/V.x
  - tnext_y = (far.y-O.y)/V.y



Heightfield traversal

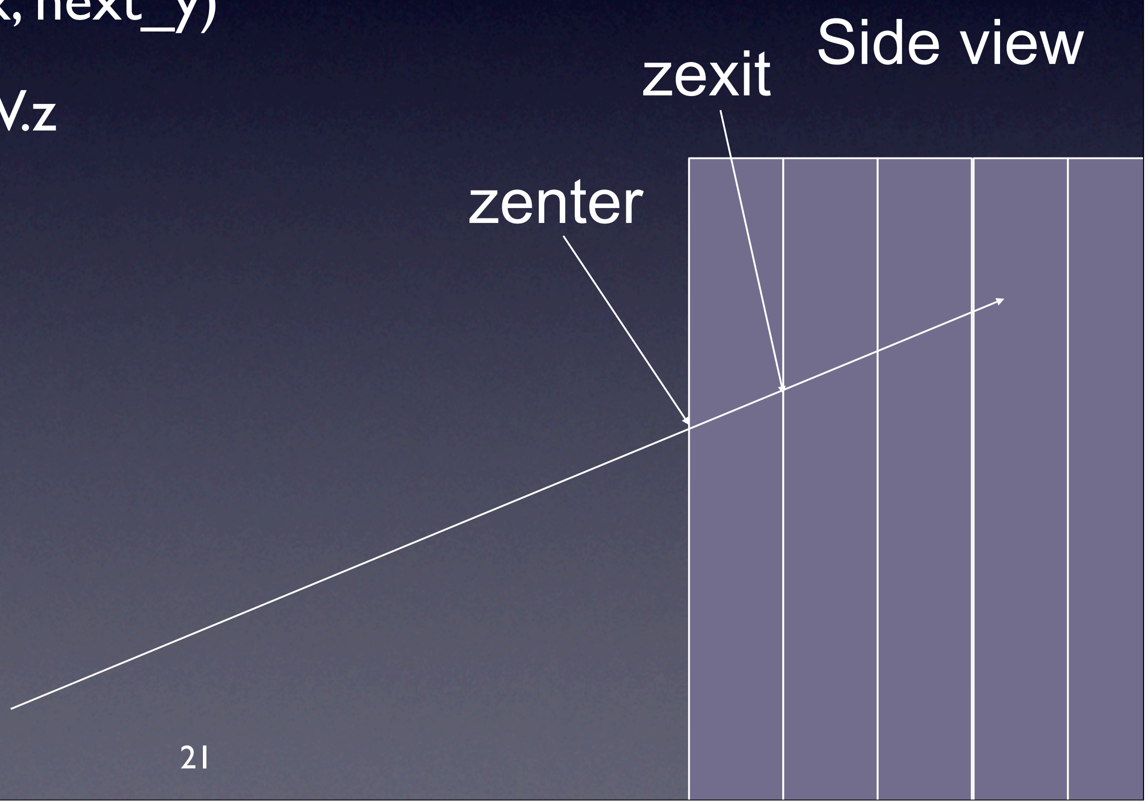
- Step 8: Beginning of loop Compute range of Z values
  - zenter = O.z+tnear*V.z
  - texit = Min(next_x, next_y)
  - zexit = O.z+texit*V.z



Heightfield traversal

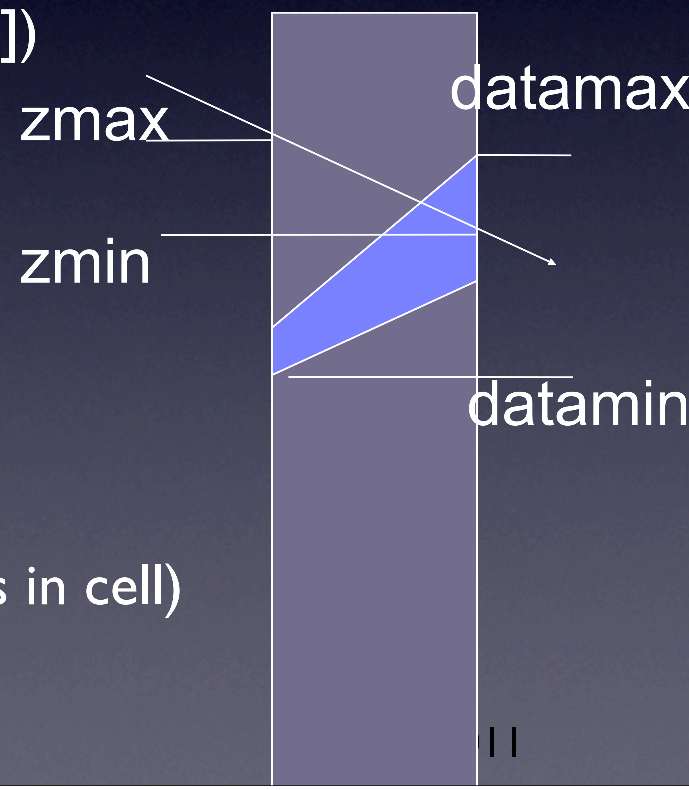
- Step 8: Beginning of loop Compute range of Z values
  - zenter = O.z+tnear*V.z
  - texit = Min(next_x, next_y)
  - zexit = O.z+texit*V.z

- Grid: not needed



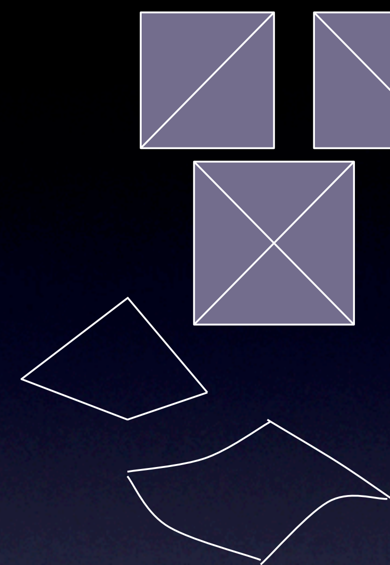
Heightfield traversal

- Step 9: Determine overlap of z range
  - datamin = Min(data[L.x][L.y],
  - data[L.x+1][L.y],
  - data[L.x][L.y+1],
  - data[L.x+1][L.y+1])
  - zmin = Min(zenter, zexit)
  - Similar for max
- if zmin > datamax || zmax<datamin
  - skip to step 11
- Grid: not needed (skip cell if no objects in cell)

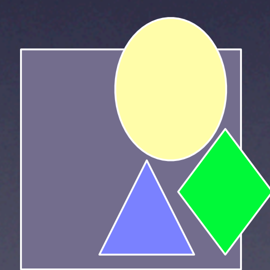


Step 10:

- Intersect ray with cell
  - 2 triangles, 4 triangles, Bilinear patch, Bicubic patch

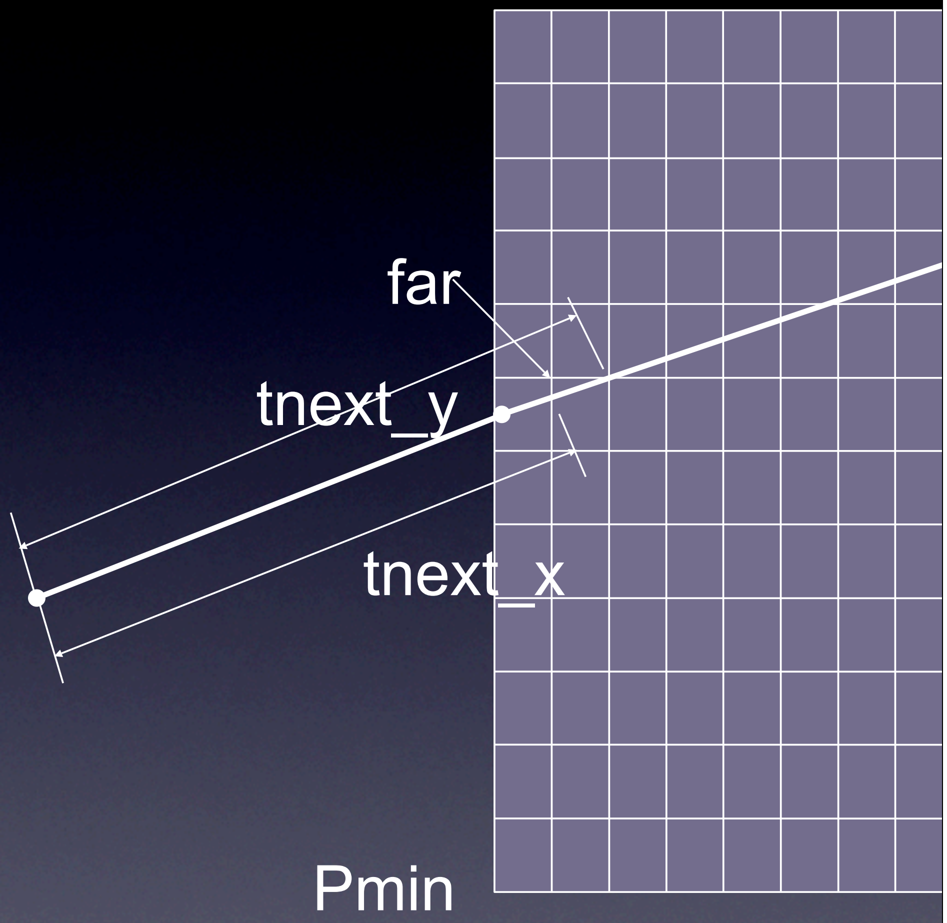


- Grid: intersect with list of objects that partially overlap cell



Heightfield traversal

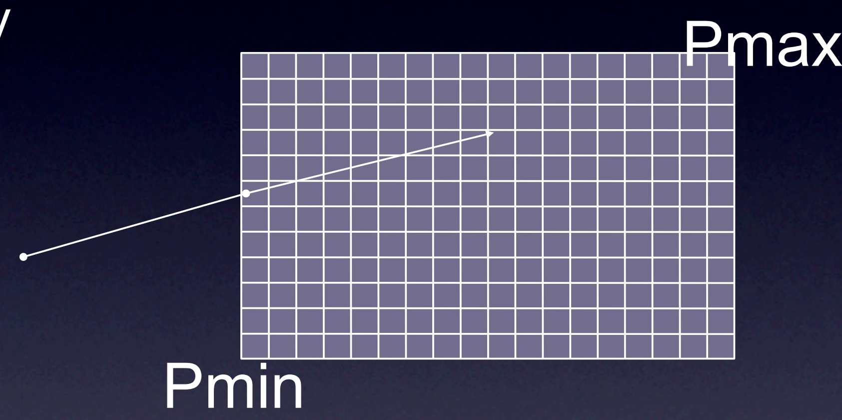
- Step 11: March to next cell
- if tnext_x < tnext_y
- tnear = tnext_x
- tnext_x += dtdx
- L.x += dix
- else
- Similar for y
- Grid: 3 way minimum



Heightfield traversal

- Step 12: Decide if it is time to stop
  - Stop if hit the surface at t>epsilon
  - Stop if L.x == stop_x or L.y == stop_y
  - Stop if tnear > tfar

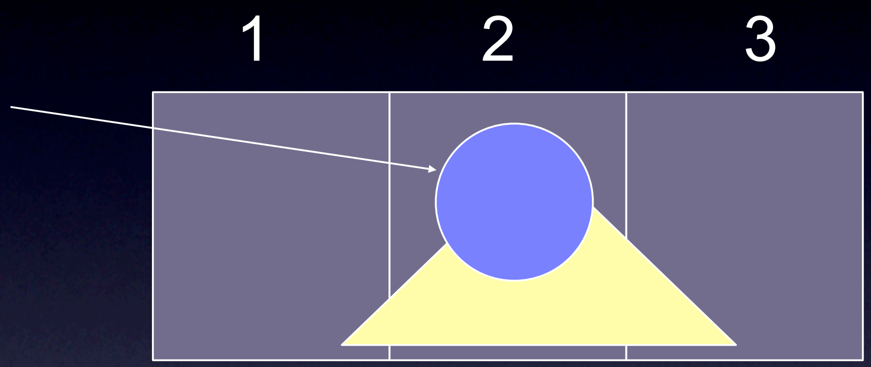
  - Otherwise, back to step 8

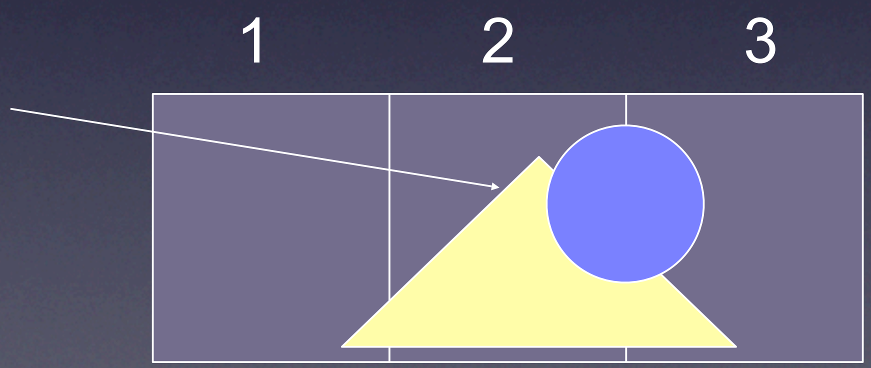


- Grid:
  - Cannot stop if you find a hit!
  - Stop if hit.minT < new tnear
  - Stop if L.x == stop_x or L.y == stop_y or L.z == stop_z
  - tnear > tfar condition is redundant

Stopping example

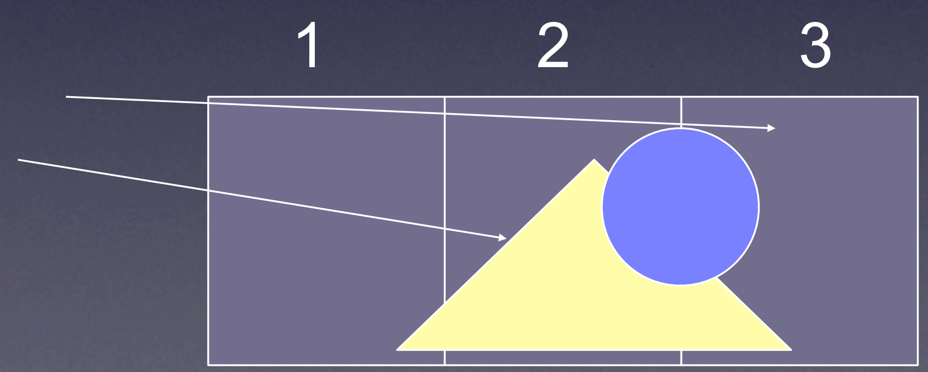
- When intersecting cell 1, ray finds yellow triangle, t outside of cell
- Proceed to next cell and intersect again, ray finds blue circle with smaller t
- Second example shows the opposite





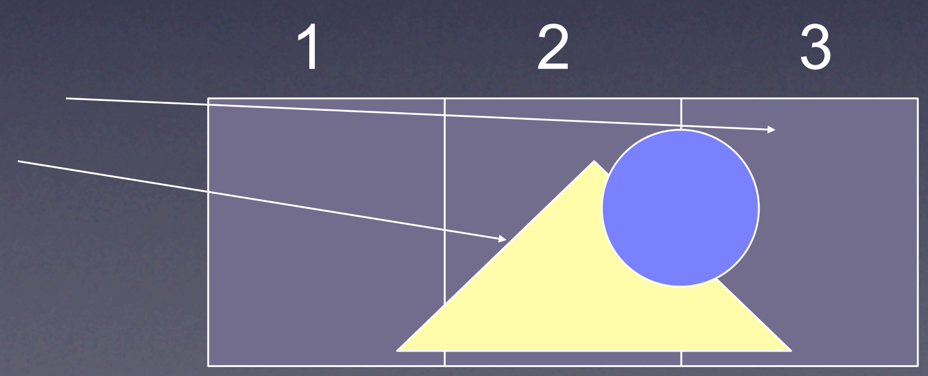
Extra work

- This example highlights a common grid problem: redundant intersections
- Ray can intersect yellow triangle up to three times!
- Worst case: ground polygon
- Gets worse with increased grid size



Avoiding extra work

- Don't worry about it? (not always effective)
- Mailbox: store unique ray ID with each object, don't call intersect if ray ID == last ray ID for object (NOT thread safe!)
- Remember last N intersected objects, don't re-intersect (extra overhead)
- Hierarchical grid



Building a Grid

Building a grid

- Add two methods to your object class:
  - Required:

```
// Get the bounding box for this object
// Expand the input bounding box
void getBounds(BoundingBox& bbox);
```

  - Optional:

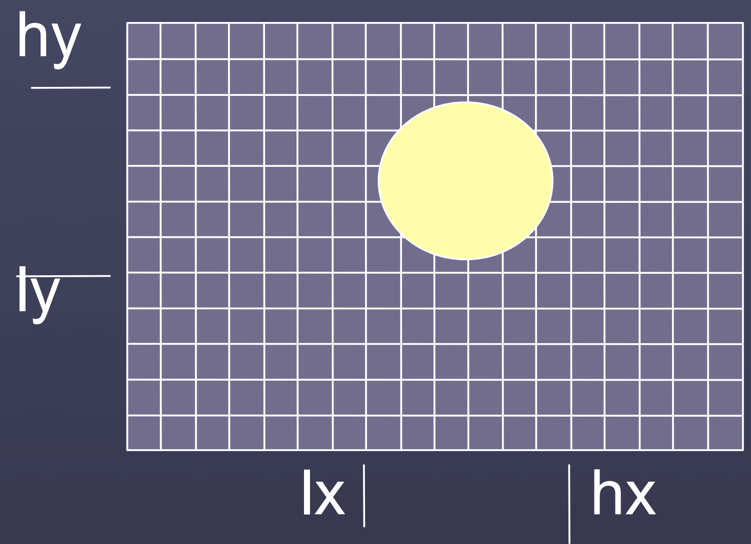
```
// Does the object intersect this box?
// always return true if you aren't sure
bool intersects(BoundingBox& cell_bbox);
```

- Methods to find these later

Building a grid

Foreach object:

- Compute bounding box
- Transform extents to index space (careful with rounding)

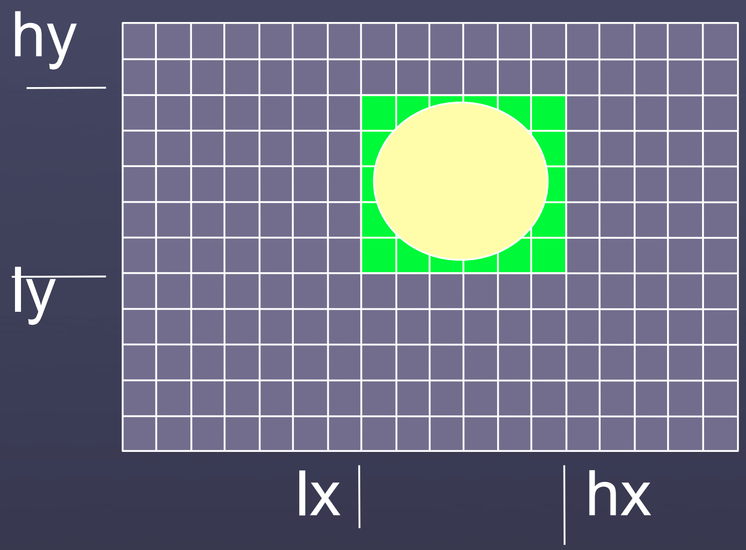


Rounding:
Lower: round down
Upper: round up

Building a grid

Foreach object:

- Compute bounding box
- Transform extents to index space (careful with rounding)
- 3D loop lx,ly,lz to hx,hy,hz:
  - Add object to each cell

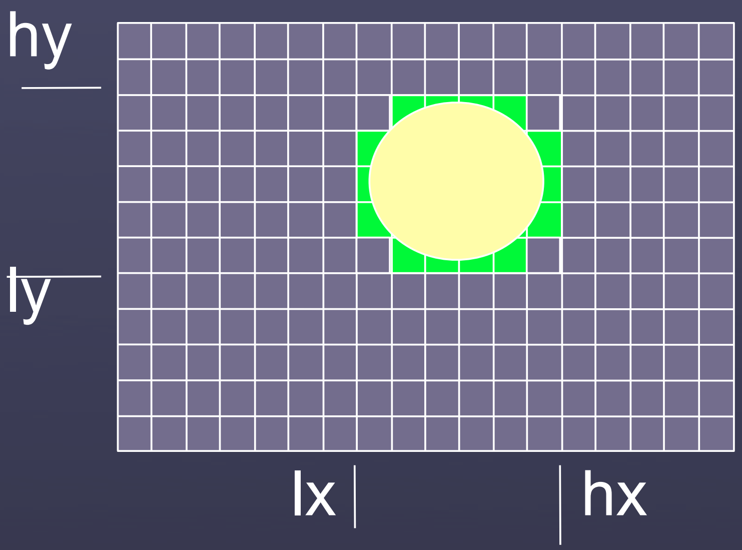


Loop over green area

More efficient

Foreach object:

- Compute bounding box
- Transform extents to index space (careful with rounding)
- 3D loop lx,ly,lz to hx,hy,hz:
  - If(object intersects cell boundary)
    - Add object to each cell



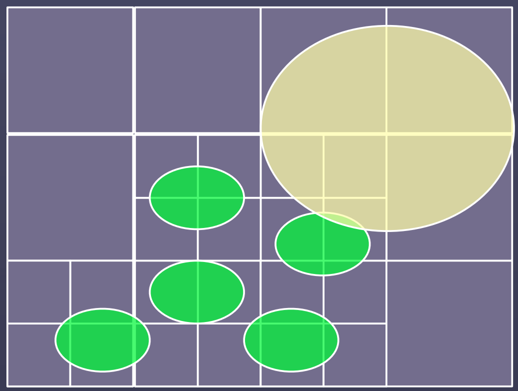
Blue cells won't get added with an additional check

Still more efficient

- Two pass algorithm:
  - –First pass: count objects in each cell
  - –Allocate memory all at once
  - –Second pass: insert objects into list
- Huge memory savings over linked lists (2X to 8X or more)
- Huge memory coherence improvement

Other improvements

- Memory tiling (or bricking in 3D)
- Pseudo-tiling of contiguous object lists
- Hierarchical:
  - Objects only at bottom levels
  - Objects mixed throughout the tree
  - Lots of variations
- Octree:
  - Theoretically optimal
  - BUT traversal across grid is much faster than up/down grid



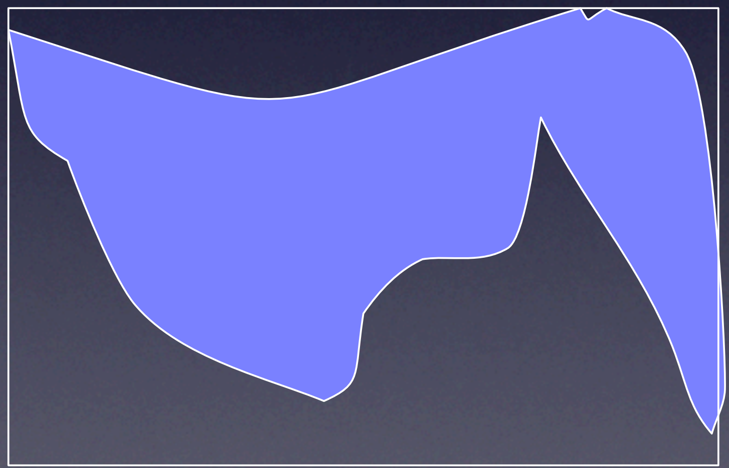
Grid summary

- Grids work very well for objects of uniform size
- Should be easy if you understood the heightfield traversal
- Build is straightforward

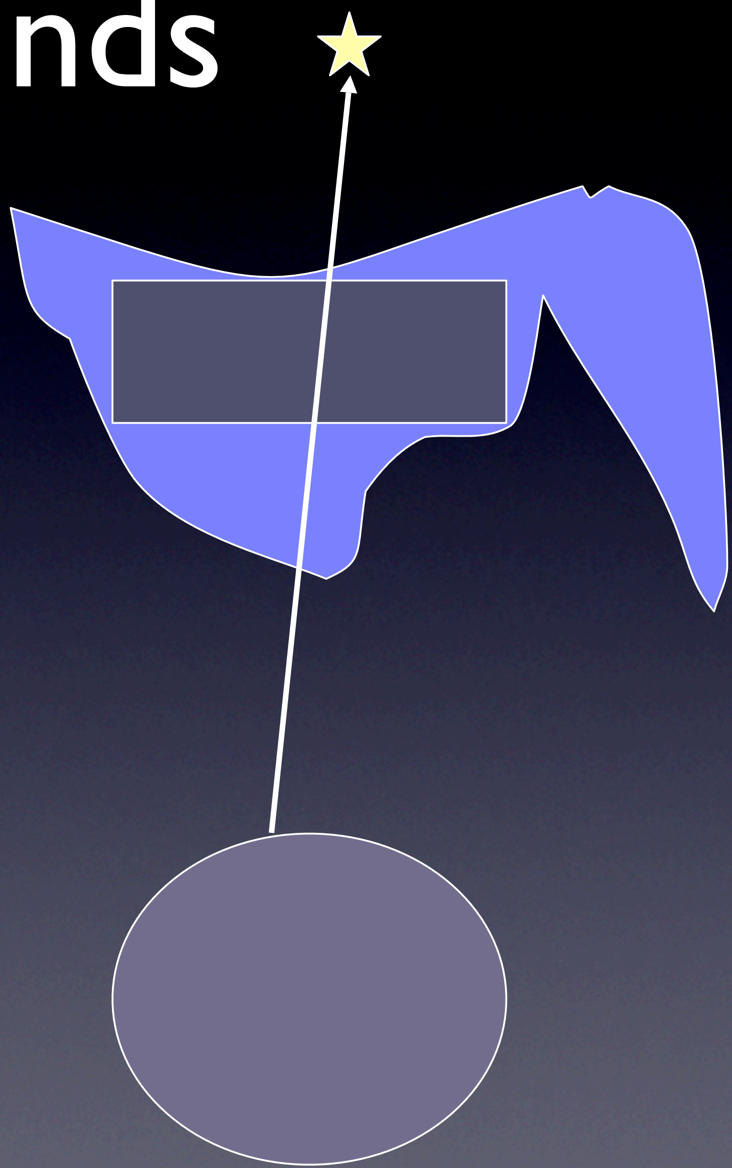
- Possibly large memory requirements
- Grid spacing requires tuning (tradeoff memory consumption and redundant intersections vs. efficiency)

Bounding primitives

- Optimize intersections
- Enclose expensive objects in a simpler primitive
- If a ray misses the bounds, it misses the object



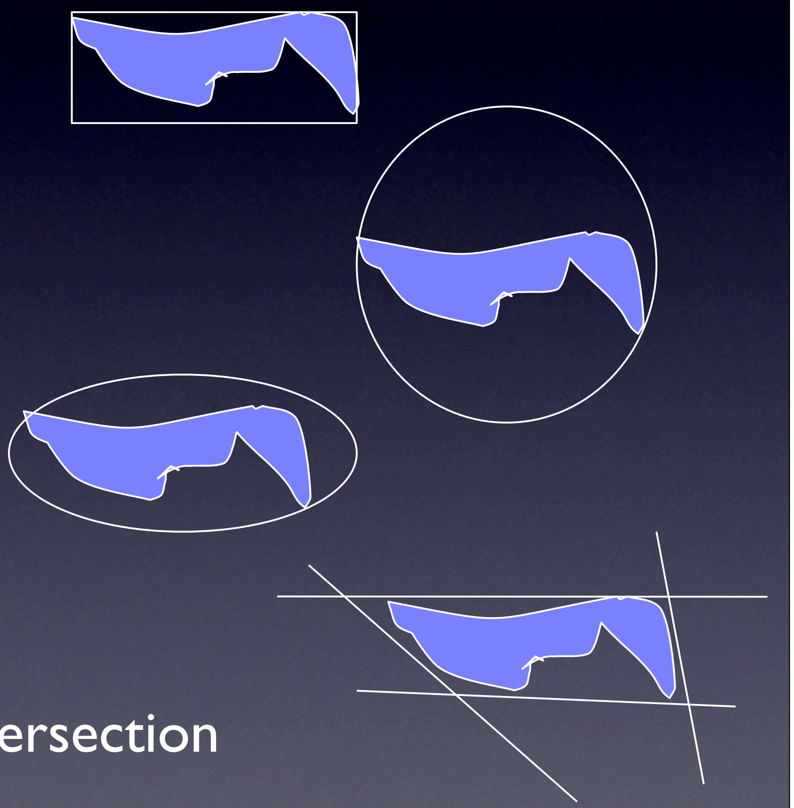
Inner bounds



- Can also be used to know that a ray hits a particular object
- Only good for shadows
- Rarely used

Bounding primitives

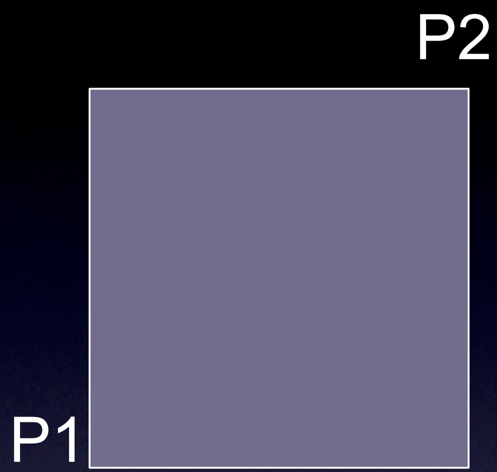
- Tradeoff: tight bounds vs. intersection speed
- Box
- Spheres
- Ellipsoids
- Slabs



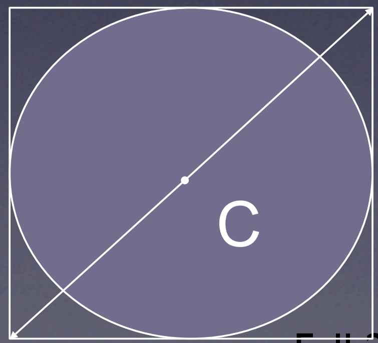
- Box is most common
- Depends on the relative costs of intersection

Bounding boxes

- Box: easy
- bounds = Min(p1, p2), Max(p1, p2)

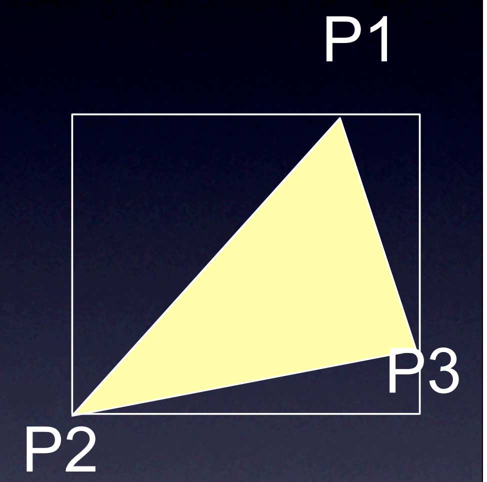


- Sphere:
- bounds = C-Vector(radius, radius,radius)
- C+Vector(radius, radius, radius)



Bounding Boxes

- Triangle:
  - bounds = Min(p1,p2,p3), Max(p1,p2,p3)



- Plane
  - infinite bounds
  - You may want to consider removing planes from your renderer at this point
  - Or keep them outside of your accel structures

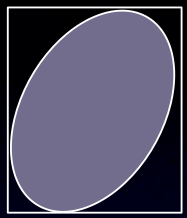
Bounding boxes

- Disc/Ring:

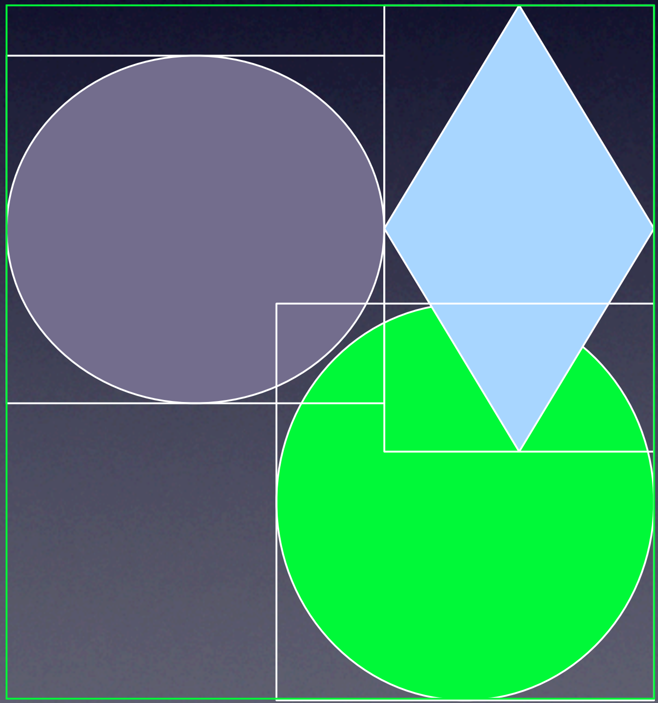
$$C_x \pm rad\sqrt{N_y^2 + N_z^2}$$

$$\left\|\overrightarrow{N}\right\| = 1$$

Similar for y/z



- Group:
- Union of object bounding boxes
- min of mins
- max of maxs

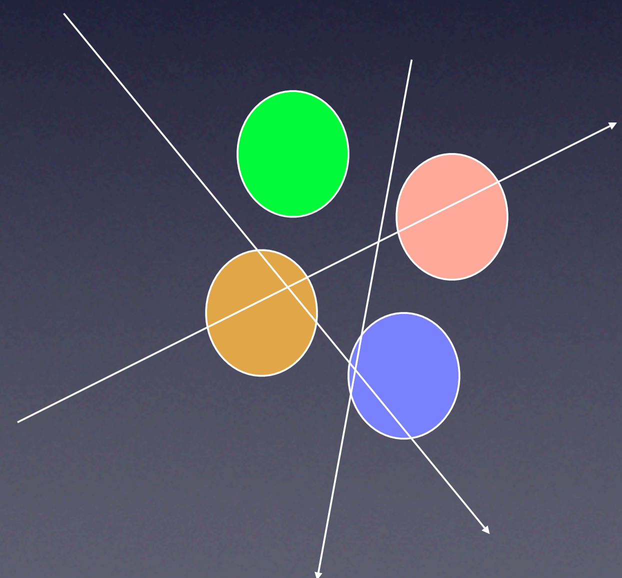


Uses for bounding boxes

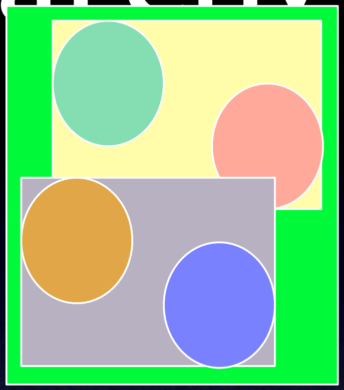
- Quick reject for expensive primitives
- To fill in grid cells
- Directly in Bounding Volume Hierarchy or similar

Bounding Volume Hierarchy

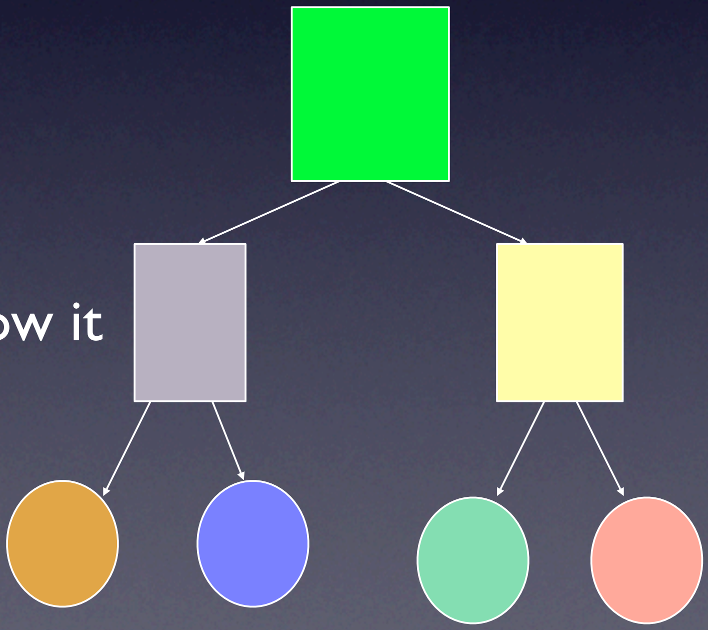
- Observe that intersection is like a search
- We know that searching is O(n) for unsorted lists but O(log n) for sorted lists
- How do we sort objects from all directions simultaneously?



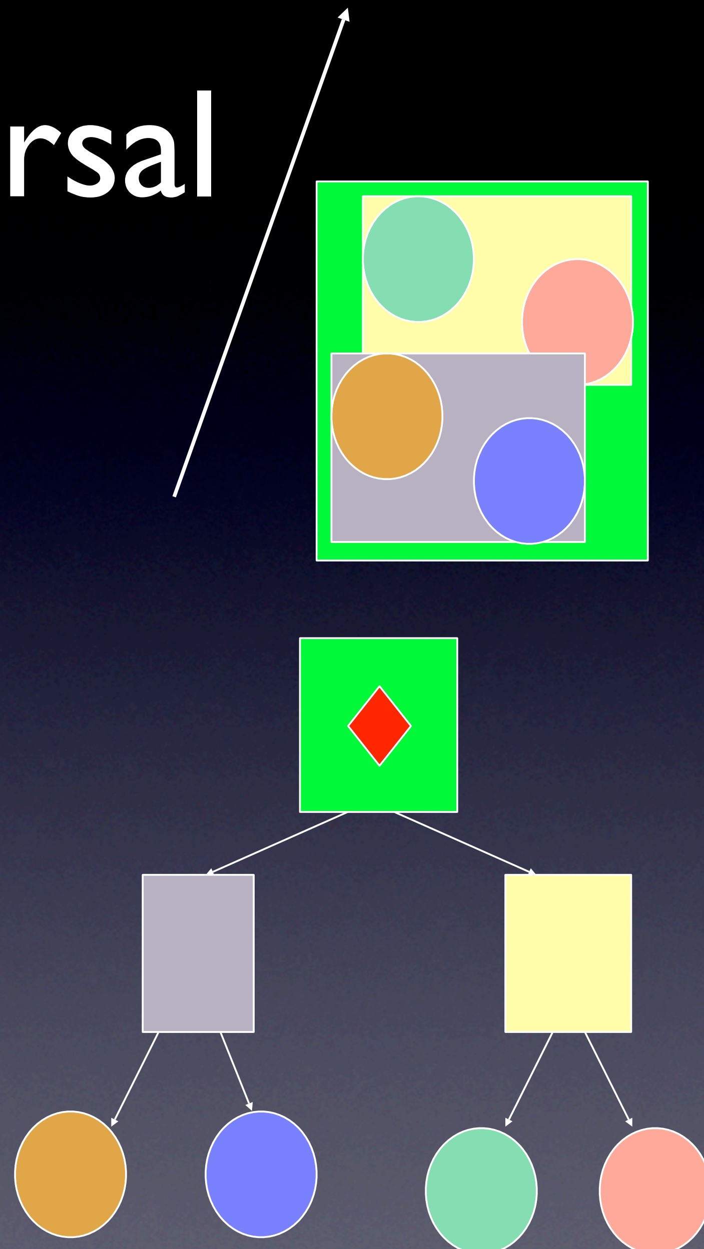
Bounding volume hierarchy



- Organize objects into a tree
- Group objects in the tree based on spatial relationships
- Each node in the tree contains a bounding box of all the objects below it

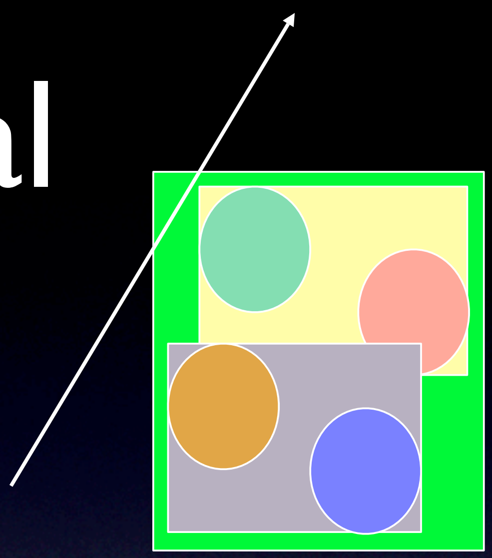


BVH traversal



- At each level of the tree, intersect the ray with the bounding box
  - miss: ray misses the entire subtree
  - hit: recurse to both children

BVH traversal



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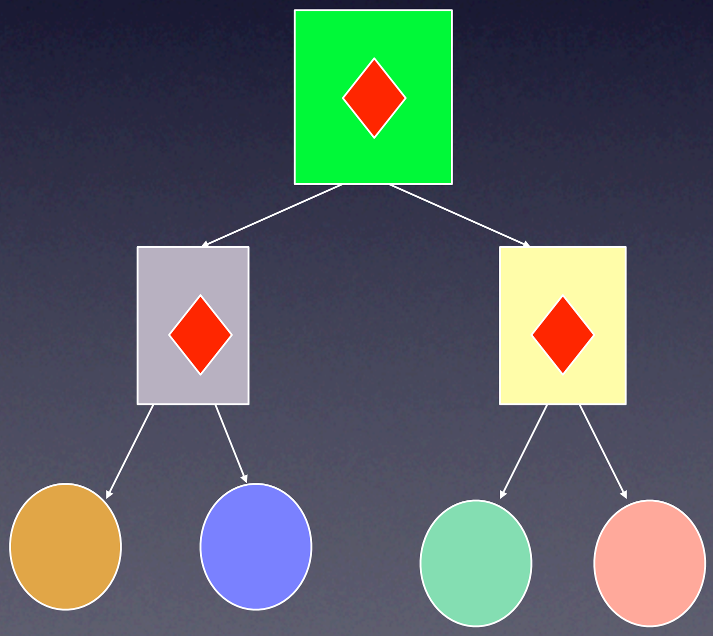

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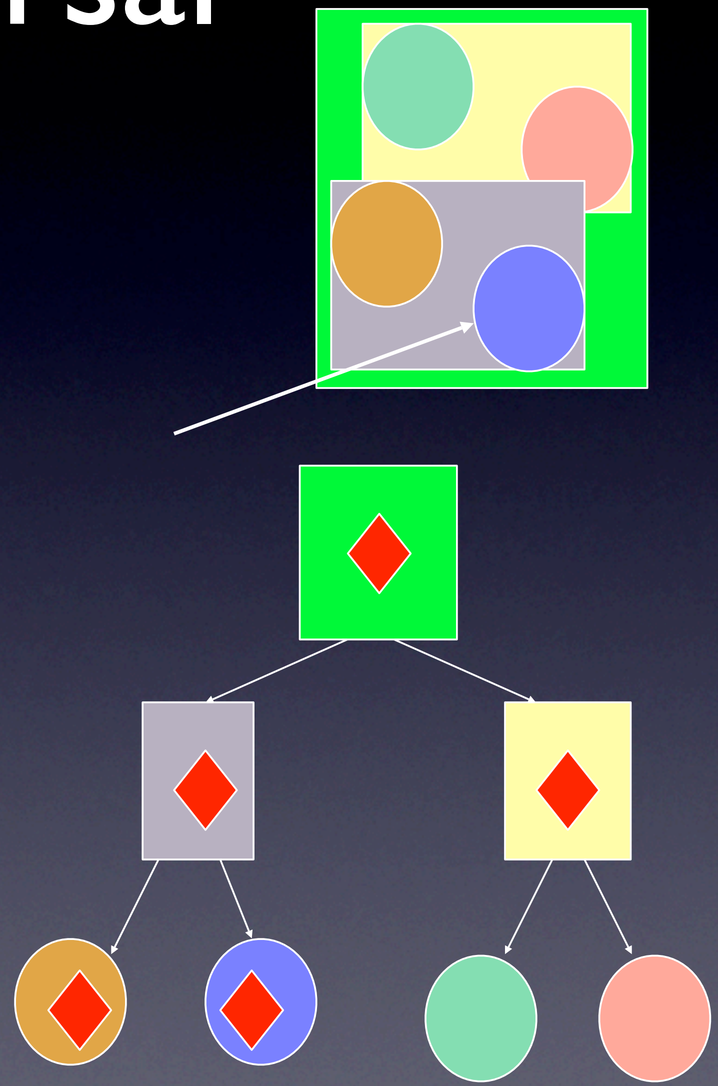

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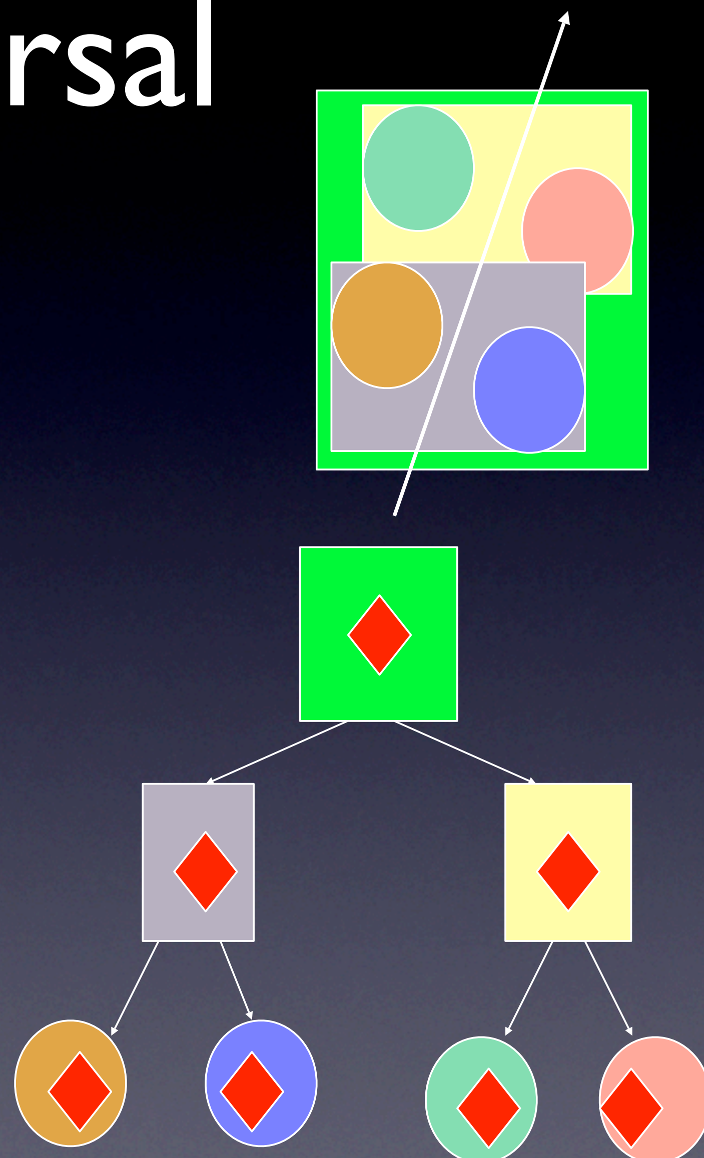
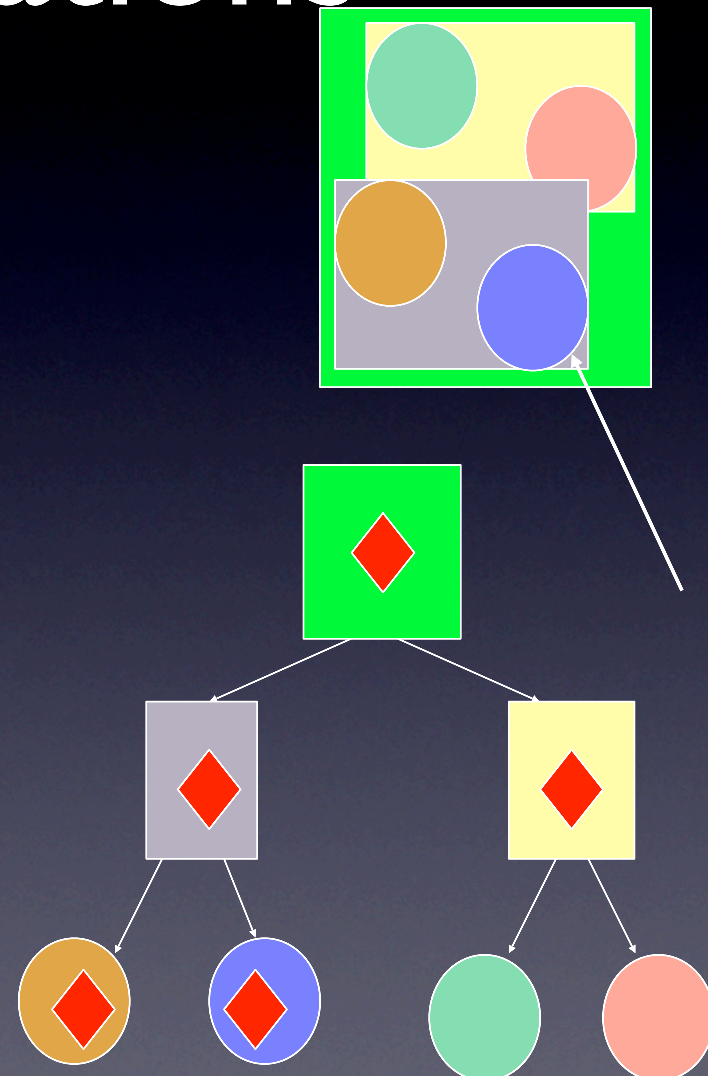
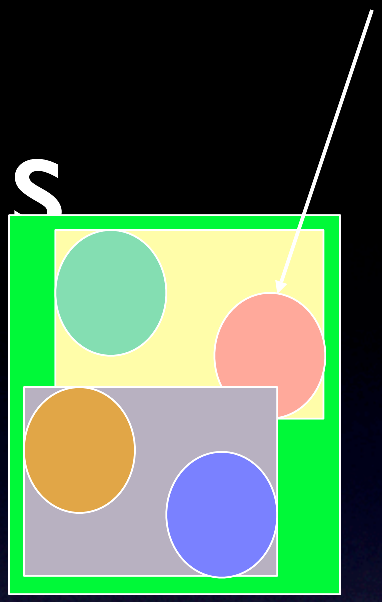


BVH optimizations

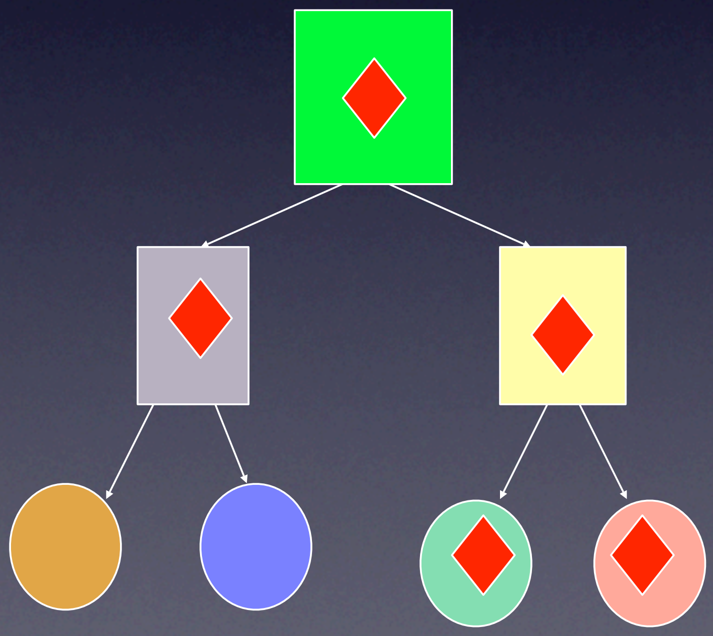
- Stop if the current T value is closer than the BVH node



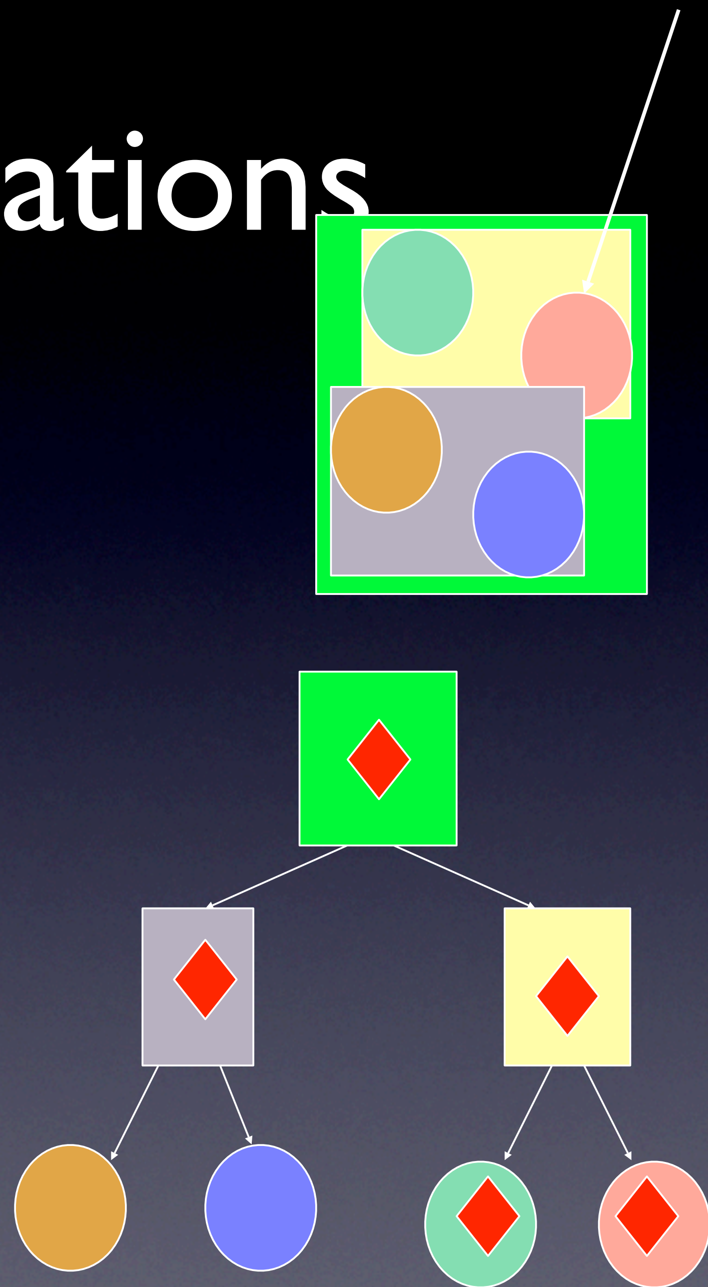
BVH optimizations



- Stop if the current T value is closer than the BVH node
- Traverse down side of tree that is closer to origin of the ray first



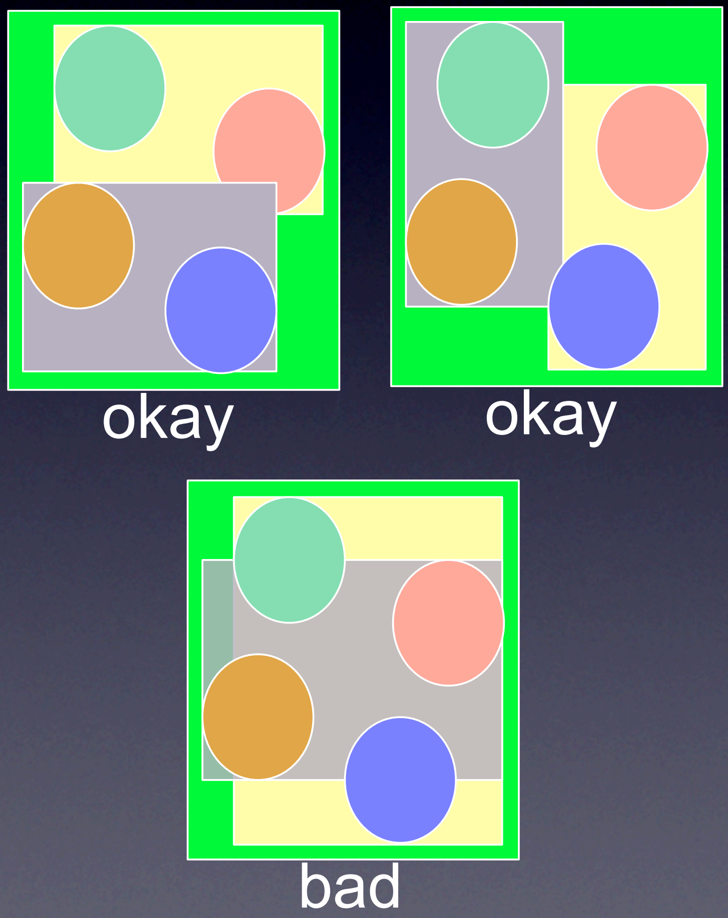
BVH optimizations



- Stop if the current T value is closer than the BVH node
- Traverse down side of tree that is closer to origin of the ray first
- Three or more way split

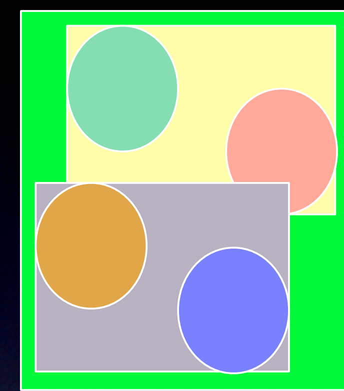
Building a BVH

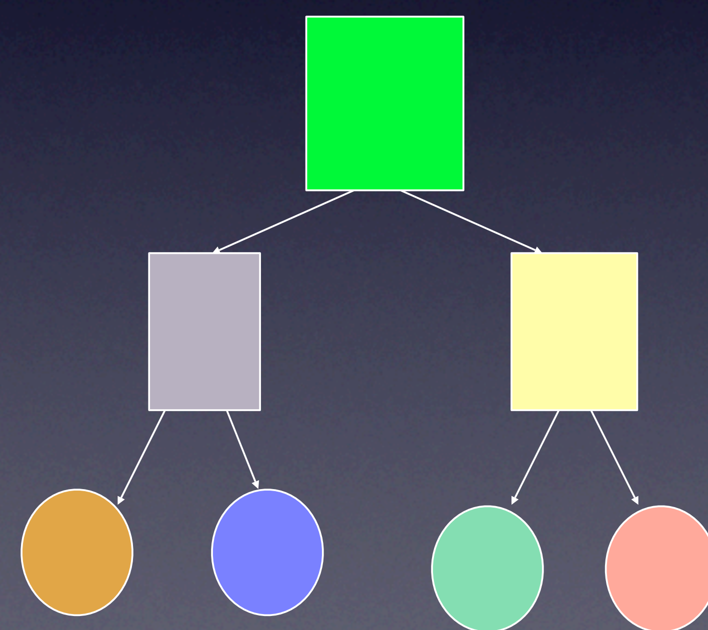
- Determining optimal BVH structure is NP-hard problem
- Heuristic approaches:
  - Cost models (minimize volume or surface area)
  - Spatial models
- Categories of approaches:
  - Top down
  - Bottom up



Median cut BVH construction

- Top down approach:
- Sort objects by position on axis
    - cycle through x,y,z
    - use center of bounding box
- Insert tree node with half of objects on left and half on right

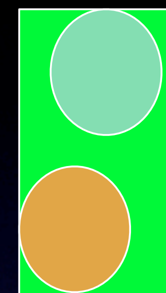




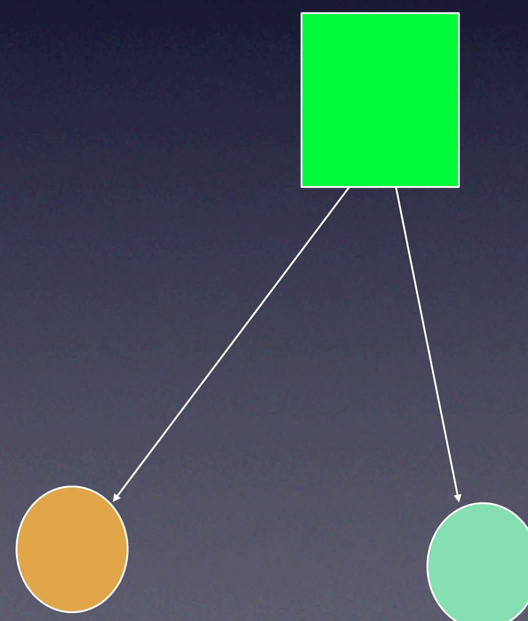
Weghorst BVH construction

- Bottom up construction
- Add objects one at a time to tree
- Insert to subtree that would cause smallest increase to area

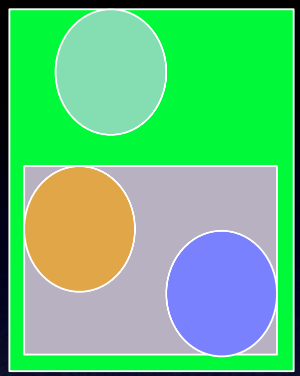
Weghorst BVH construction



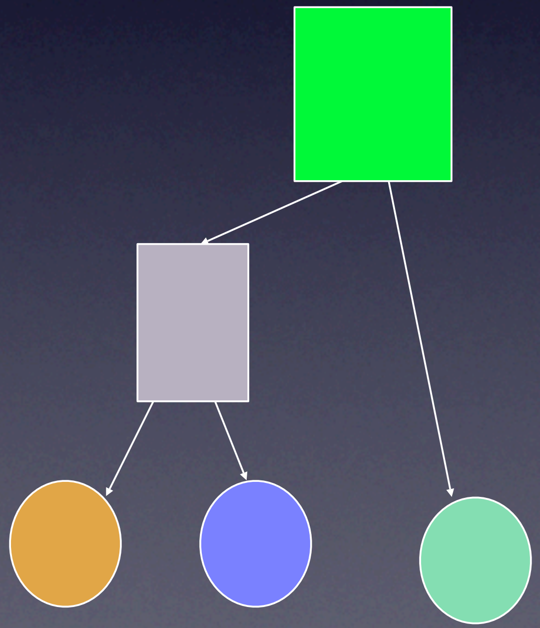
- Bottom up construction
- Add objects one at a time to tree
- Insert to subtree that would cause smallest increase to area



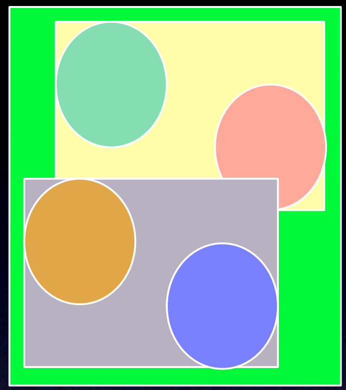
Weghorst BVH construction



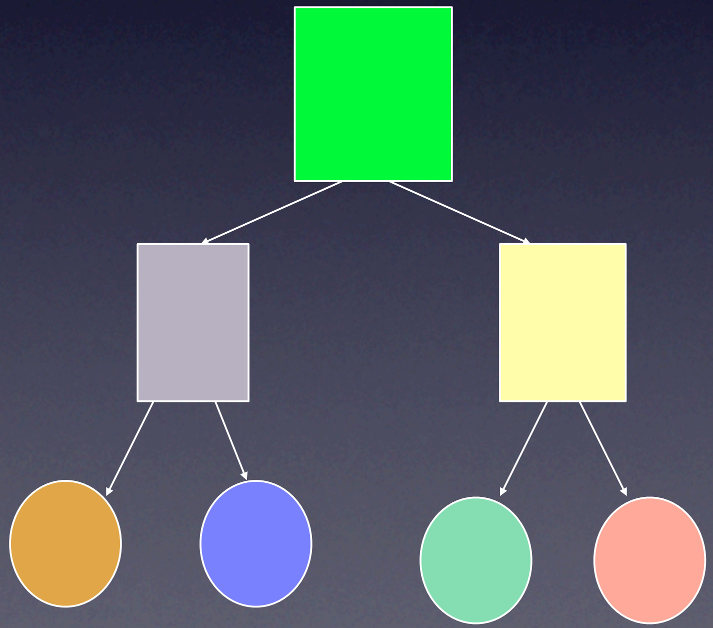
- Bottom up construction
- Add objects one at a time to tree
- Insert to subtree that would cause smallest increase to area



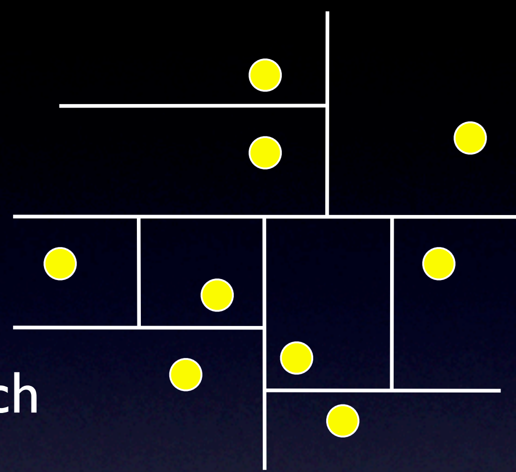
Weghorst BVH construction



- Bottom up construction
- Add objects one at a time to tree
- Insert to subtree that would cause smallest increase to area



k-d tree

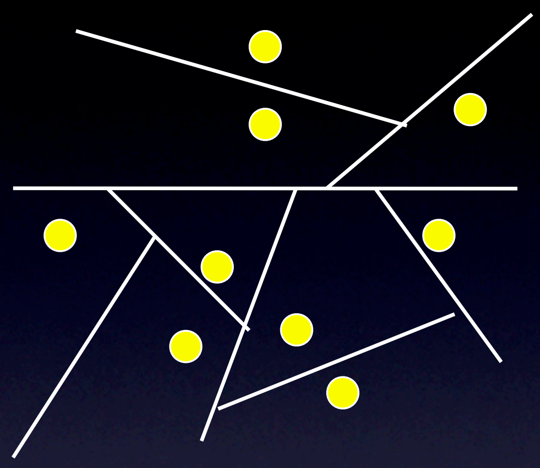


- Recursively divide space in half
- Alternate coordinate axes
- Cycle through axes or store axis split in each node

- What do you do with objects split by the plane?
- Hard part: where do you split in each dimension?

BSP tree

- Like a k-d tree where splitting planes can be arbitrarily located

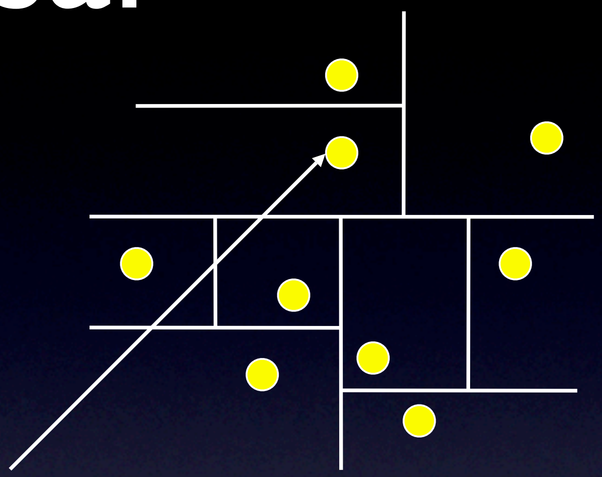


- Hard part: where do you split in each dimension?
- Harder part: how do you orient each plane?
- More storage/computation, tighter bounds

BSP/k-d tree tradeoffs

- Build is NP-hard problem
- Heuristic approaches are always used
- Traversal is quick
- Storage can be lower than BVH or grid

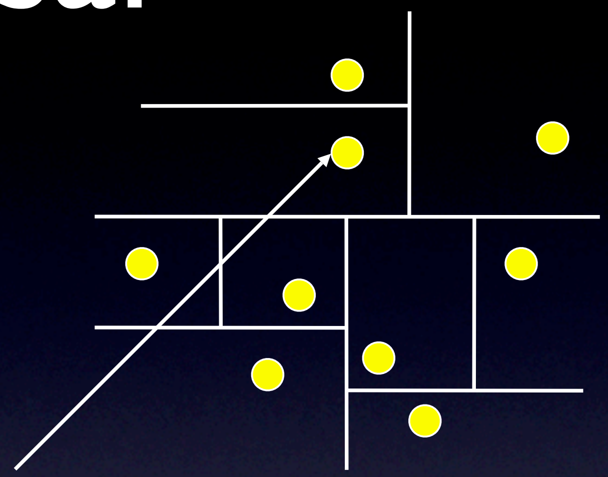
K-d traversal



- Keep track of intervals on ray:
  - min: 0
  - max: ∞
  - Compute t of split plane
  - If t > max: goto near child
  - If t < min: goto far child
  - Otherwise: goto both children with updated intervals

K-d traversal

- Keep track of intervals on ray:

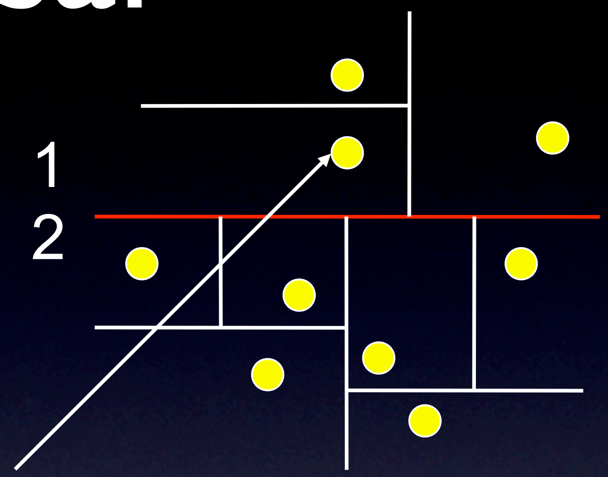


Min: 0
Max: ∞

- Compute t of split plane
- If t > max: goto near child
- If t < min: goto far child
- Otherwise: goto both children with updated intervals

K-d traversal

- Keep track of intervals on ray:



  - Compute t of split plane
  - If t > max: goto near child
  - If t < min: goto far child
  - Otherwise: goto both children with updated intervals

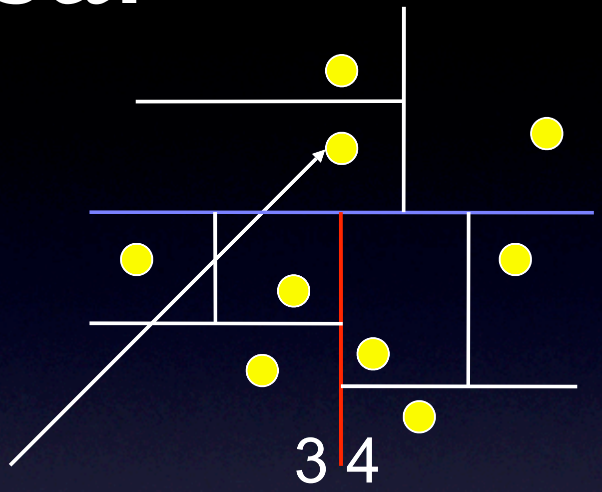
Min: 0
Max: ∞

Split: 1.0
Stack: 1

New min: 0
New max: 1.0

K-d traversal

- Keep track of intervals on ray:
    - Compute t of split plane
    - If t > max: goto near child
    - If t < min: goto far child
    - Otherwise: goto both children with updated intervals



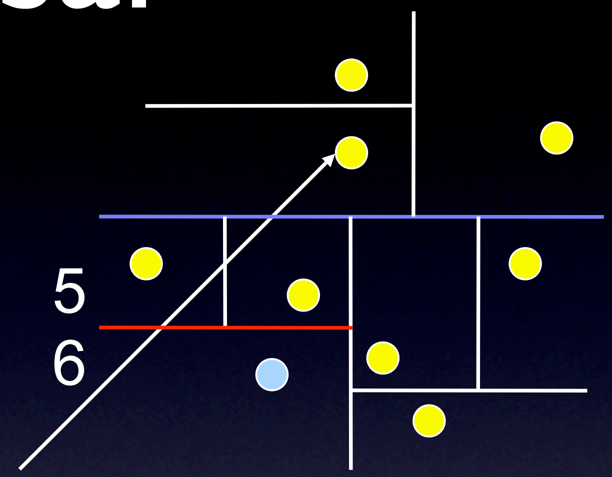
Min: 0
Max: 1.0

Split: 1.3
Stack: 1

New min: 0
New max: 1.0

K-d traversal

- Keep track of intervals on ray:



  - Compute t of split plane
  - If t > max: goto near child
  - If t < min: goto far child
  - Otherwise: goto both children with updated intervals

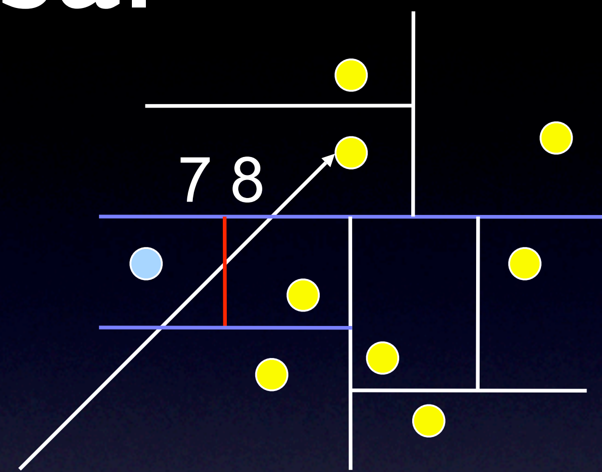
Min: 0
Max: 1.0

Split: 0.4
Stack: 1 5

New min: 0
New max: 0.4

K-d traversal

- Keep track of intervals on ray:



  - Compute t of split plane
  - If t > max: goto near child
  - If t < min: goto far child
  - Otherwise: goto both children with updated intervals

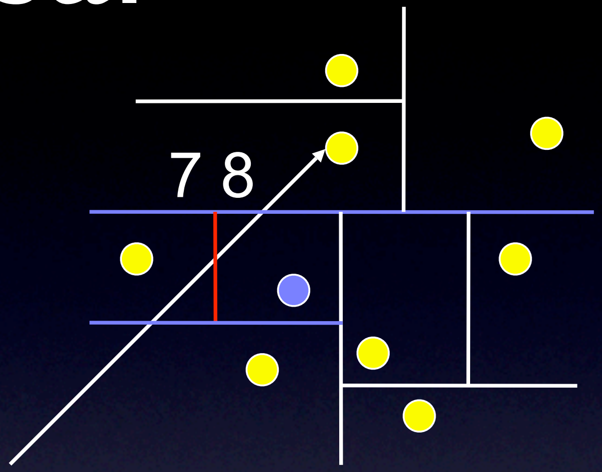
Min: 0.4
Max: 1.0

Split: 0.7
Stack: 1 8

New min: 0.4
New max: 0.6

K-d traversal

- Keep track of intervals on ray:



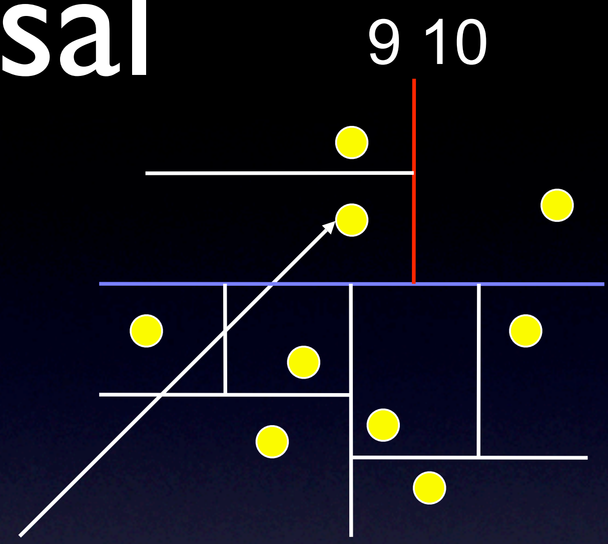
  - Compute t of split plane
  - If t > max: goto near child
  - If t < min: goto far child
  - Otherwise: goto both children with updated intervals

Min: 0.7
Max: 1.0

Split:
Stack: 1

New min: 0.4
New max: 0.6

K-d traversal



- Keep track of intervals on ray:
  - Compute t of split plane
  - If t > max: goto near child
  - If t < min: goto far child
  - Otherwise: goto both children with updated intervals

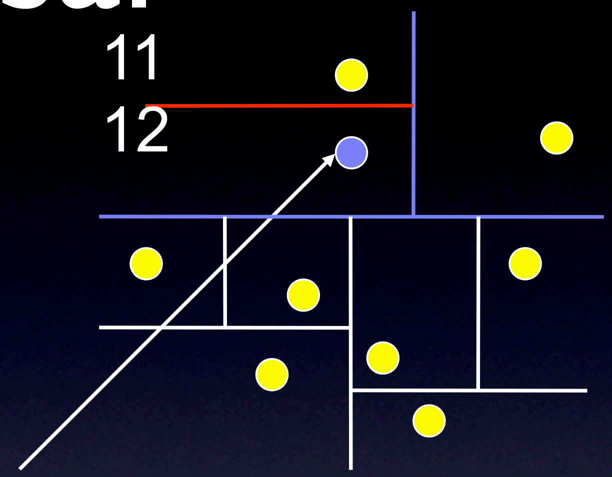
Min: 1.0
Max: ∞

Split: 1.5
Stack: 10

New min: 1.0
New max: 1.5

K-d traversal

- Keep track of intervals on ray:



  - Compute t of split plane
  - If t > max: goto near child
  - If t < min: goto far child
  - Otherwise: goto both children with updated intervals

Min: 1.0
Max: 1.5

Split: 1.4
Stack: 10 11

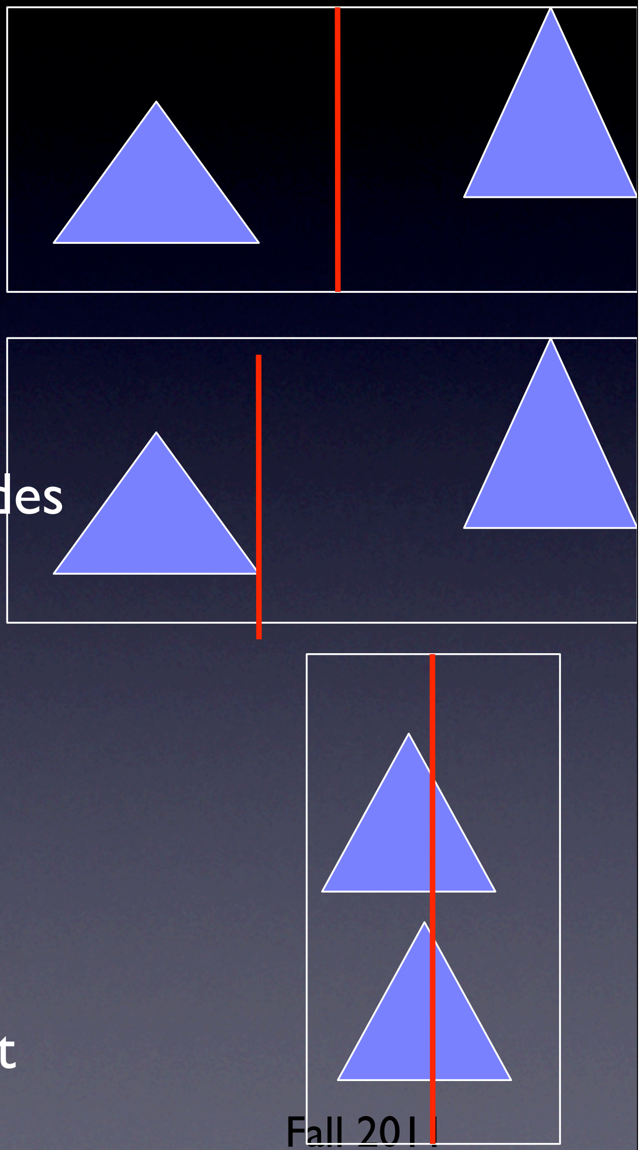
New min: 1.0
New max: 1.4

K-d tree build

- Optimal solution is NP-hard
- Spatial median split (a little like octree)
- Object median split (makes balanced trees)
- Cost model based (better)
  - Cost of traversal
  - Cost of intersection
  - Probability of hit

K-d tree build

- Havran '01:
- Start with bounding box of scene
- Select split plane along each axis
  - Start with spatial median
  - Move toward bounding box of child nodes
- Recurse
  - Stop if node contains 2-3 objects
  - Stop if depth > max (20-30)
- Backtrack
  - Combine children with identical content



Acceleration Structure Summary

- Most common: Grid, Hierarchical Grid, k-d tree, BVH
- Grid based:
  - P time deterministic build
  - Grid resolution tradeoff
- Tree based:
  - NP hard build
  - Heuristic approaches