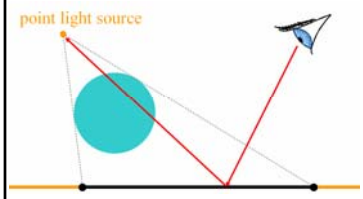
Acceleration Data Structures for Ray Tracing

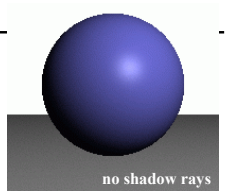
Today

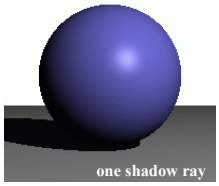
- Motivation – Distribution Ray Tracing
  - Soft shadows
  - Antialiasing (getting rid of jaggies)
  - Glossy reflection
  - Motion blur
  - Depth of field (focus)
- Bounding Boxes
- Spatial Acceleration Data Structures

Shadows

- one shadow ray per intersection per point light source







Shadows & Light Sources

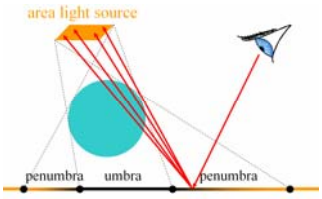
http://3media.initialized.org/photos/2000-10-18/index_gall.htm

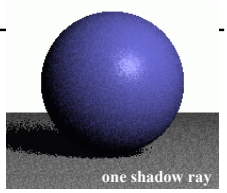
http://www.davidfay.com/index.php

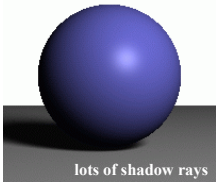
http://www.pa.uky.edu/~sciworks/light/preview/bulb2.htm

Soft Shadows

- multiple shadow rays to sample area light source

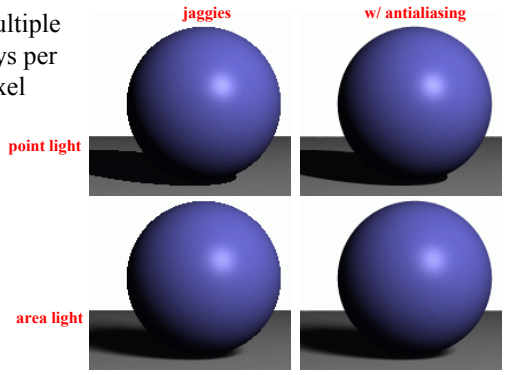






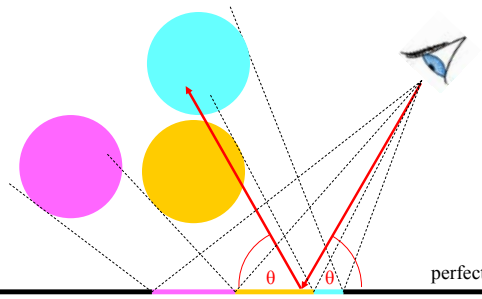
Antialiasing – Supersampling

- multiple rays per pixel



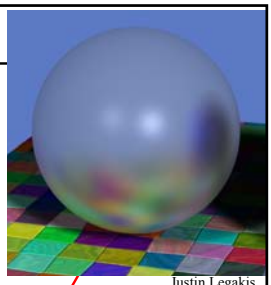
Reflection

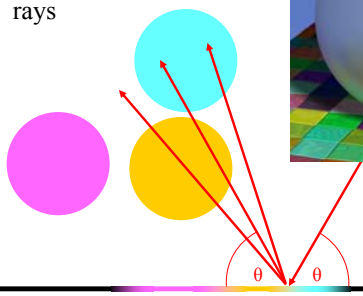
- one reflection ray per intersection



Glossy Reflection

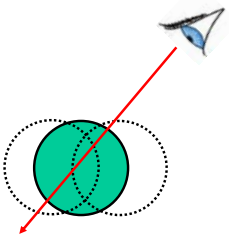
- multiple reflection rays


Justin Legakis



Motion Blur

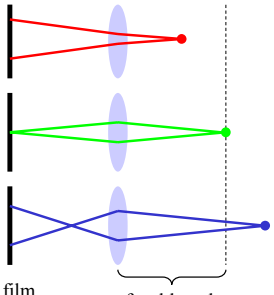
- Sample objects temporally

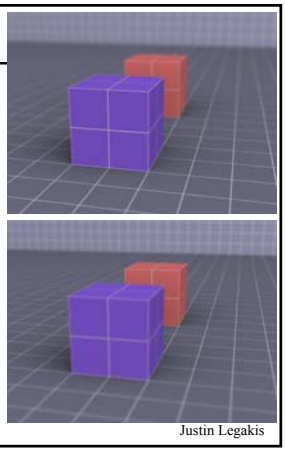



Rob Cook

Depth of Field

- multiple rays per pixel




Justin Legakis

Ray Tracing 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 *
num primitives *
intersection cost *
size of recursive ray tree *
num shadow rays *
num supersamples *
num glossy rays *
num temporal samples *
num aperture samples *
. . .

can we reduce this?

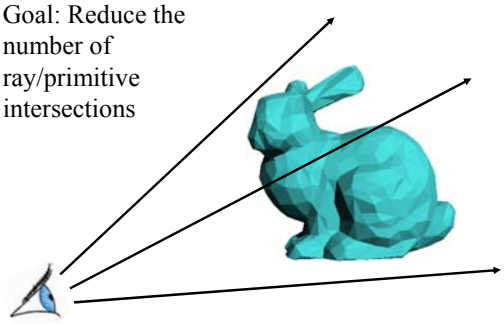
Questions?

Today

- Motivation – Distribution Ray Tracing
- Bounding Boxes
  - of each primitive
  - of groups
  - of transformed primitives
- Spatial Acceleration Data Structures
- Flattening the Transformation Hierarchy

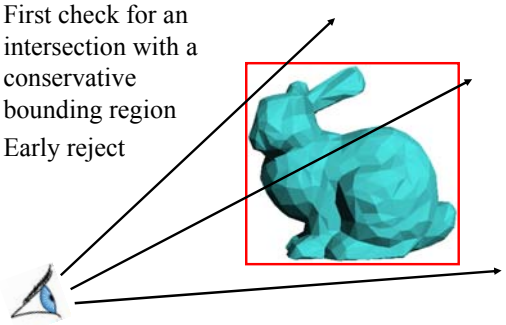
Acceleration of Ray Casting

- Goal: Reduce the number of ray/primitive intersections



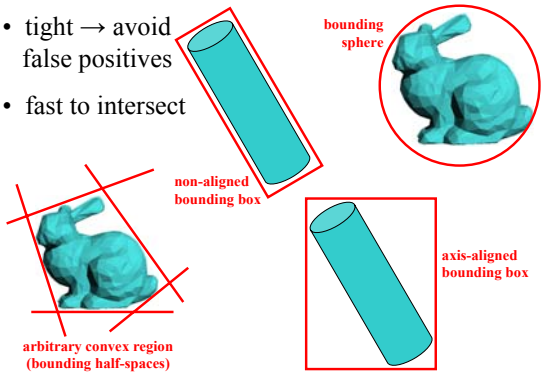
Conservative Bounding Region

- First check for an intersection with a conservative bounding region
- Early reject



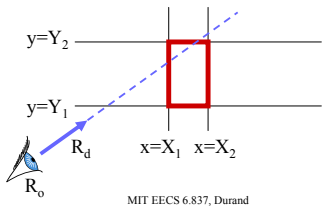
Conservative Bounding Regions

- tight → avoid false positives
- fast to intersect



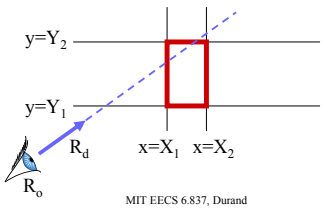
Ray-Box Intersection

- Axis-aligned
- Box: $(X_1, Y_1, Z_1) \rightarrow (X_2, Y_2, Z_2)$
- Ray: $P(t) = R_o + tR_d$



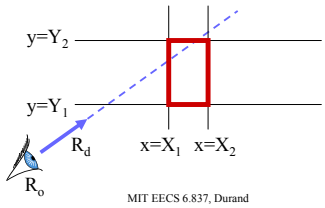
Naïve Ray-Box Intersection

- 6 plane equations: compute all intersections
- Return closest intersection inside the box
  - Verify intersections are on the correct side of each plane: $Ax+By+Cz+D < 0$



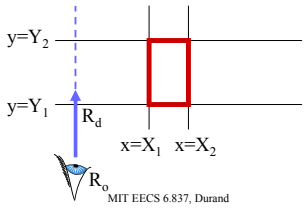
Reducing Total Computation

- Pairs of planes have the same normal
- Normals have only one non-0 component
- Do computations one dimension at a time



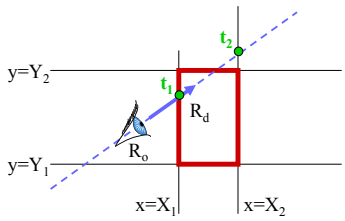
Test if Parallel

- If $R_{dx} = 0$ (ray is parallel) AND
  $R_{ox} < X_1$ or $R_{ox} > X_2$ → **no intersection**



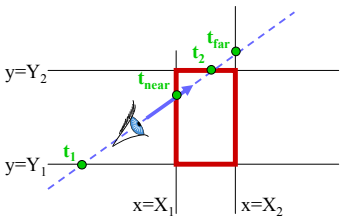
Find Intersections Per Dimension

- Calculate intersection distance t_1 and t_2
  - $t_1 = (X_1 - R_{ox}) / R_{dx}$
  - $t_2 = (X_2 - R_{ox}) / R_{dx}$



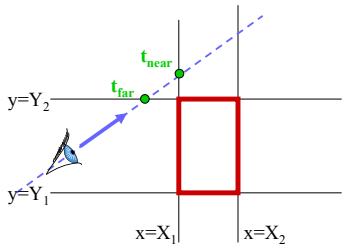
Maintain t_{near} & t_{far}

- Closest & farthest intersections *on the object*
  - If $t_1 > t_{near}$, $t_{near} = t_1$
  - If $t_2 < t_{far}$, $t_{far} = t_2$



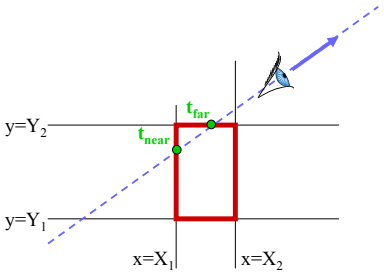
Is there an Intersection?

- If $t_{near} > t_{far}$ → **box is missed**



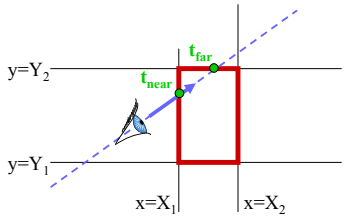
Is the Box Behind the Eyepoint?

- If $t_{far} < t_{min}$ → **box is behind**



Return the Correct Intersection

- If $t_{near} > t_{min}$ → **closest intersection at t_{near}**
- Else → **closest intersection at t_{far}**



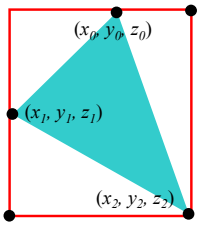
Ray-Box Intersection Summary

- For each dimension,
  - If $R_{dx} = 0$ (ray is parallel) AND $R_{ox} < X_1$ or $R_{ox} > X_2$ → **no intersection**
- For each dimension, calculate intersection distances t_1 and t_2
  - $t_1 = (X_1 - R_{ox}) / R_{dx}$ $\quad t_2 = (X_2 - R_{ox}) / R_{dx}$
  - If $t_1 > t_2$, swap
  - Maintain t_{near} and t_{far} (closest & farthest intersections so far)
  - If $t_1 > t_{near}$, $t_{near} = t_1$ $\quad$ If $t_2 < t_{far}$, $t_{far} = t_2$
- If $t_{near} > t_{far}$ → **box is missed**
- If $t_{far} < t_{min}$ → **box is behind**
- If $t_{near} > t_{min}$ → **closest intersection at t_{near}**
- Else → **closest intersection at t_{far}**

Efficiency Issues

- $1/R_{dx}$, $1/R_{dy}$ and $1/R_{dz}$ can be pre-computed and shared for many boxes
- Unroll the loop
  - Loops are costly (because of termination if)
  - Avoid the t_{near} & t_{far} comparison for first dimension

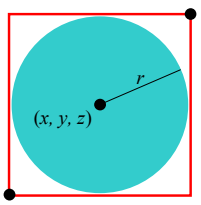
Bounding Box of a Triangle



$(x_{max}, y_{max}, z_{max})$
$= (\max(x_0,x_1,x_2),$
$\max(y_0,y_1,y_2),$
$\max(z_0,z_1,z_2))$

$(x_{min}, y_{min}, z_{min})$
$= (\min(x_0,x_1,x_2),$
$\min(y_0,y_1,y_2),$
$\min(z_0,z_1,z_2))$

Bounding Box of a Sphere

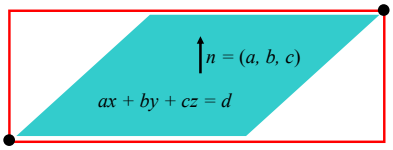


$(x_{max}, y_{max}, z_{max})$
$= (x+r,\ y+r,\ z+r)$

$(x_{min}, y_{min}, z_{min})$
$= (x-r,\ y-r,\ z-r)$

Bounding Box of a Plane

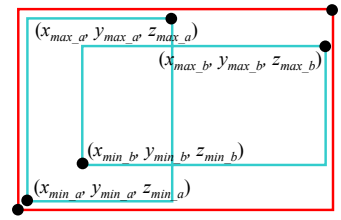
$(x_{max}, y_{max}, z_{max})$
$= (+\infty, +\infty, +\infty)^*$



$(x_{min}, y_{min}, z_{min})$
$= (-\infty, -\infty, -\infty)^*$

** unless n is exactly perpendicular to an axis*

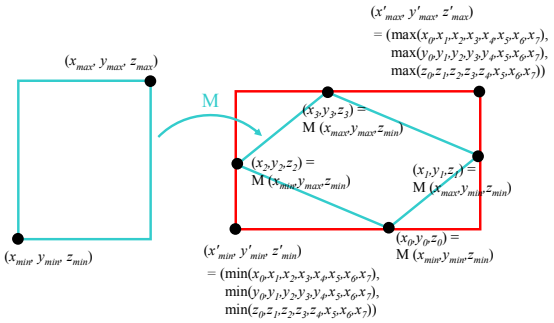
Bounding Box of a Group



$(x_{max}, y_{max}, z_{max})$
$= (\max(x_{max\_a}, x_{max\_b}),$
$\max(y_{max\_a}, y_{max\_b}),$
$\max(z_{max\_a}, z_{max\_b}))$

$(x_{min}, y_{min}, z_{min}) = (\min(x_{min\_a}, x_{min\_b}),$
$\min(y_{min\_a}, y_{min\_b}),$
$\min(z_{min\_a}, z_{min\_b}))$

Bounding Box of a Transform

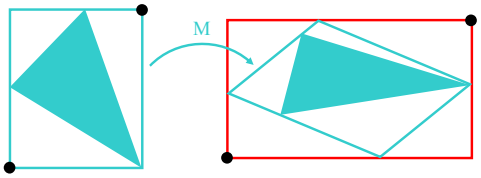


$(x'_{max}, y'_{max}, z'_{max})$
$= (\max(x_0,x_1,x_2,x_3,x_4,x_5,x_6,x_7),$
$\max(y_0,y_1,y_2,y_3,y_4,x_5,x_6,x_7),$
$\max(z_0,z_1,z_2,z_3,z_4,x_5,x_6,x_7))$

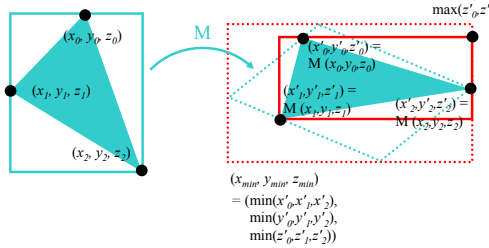
$(x'_{min}, y'_{min}, z'_{min})$
$= (\min(x_0,x_1,x_2,x_3,x_4,x_5,x_6,x_7),$
$\min(y_0,y_1,y_2,y_3,y_4,x_5,x_6,x_7),$
$\min(z_0,z_1,z_2,z_3,z_4,x_5,x_6,x_7))$

Special Case: Transformed Triangle

Can we do better?



Special Case: Transformed Triangle



$(x_{max}, y_{max}, z_{max})$
$= (\max(x'_0,x'_1,x'_2),$
$\max(y'_0,y'_1,y'_2),$
$\max(z'_0,z'_1,z'_2))$

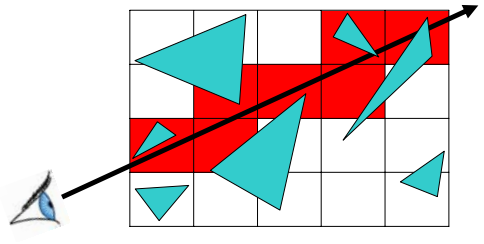
$(x_{min}, y_{min}, z_{min})$
$= (\min(x'_0,x'_1,x'_2),$
$\min(y'_0,y'_1,y'_2),$
$\min(z'_0,z'_1,z'_2))$

Questions?

Today

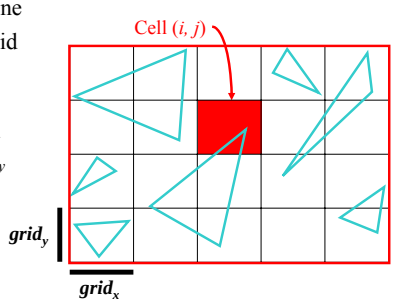
- Motivation – Distribution Ray Tracing
- Bounding Boxes
- Spatial Acceleration Data Structures
  - Regular Grid
  - Adaptive Grids
  - Hierarchical Bounding Volumes
- Flattening the Transformation Hierarchy

Regular Grid



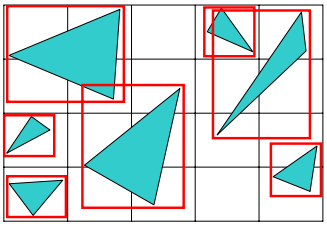
Create Grid

- Find bounding box of scene
- Choose grid resolution (n_x, n_y, n_z)
- $grid_x$ need not = $grid_y$



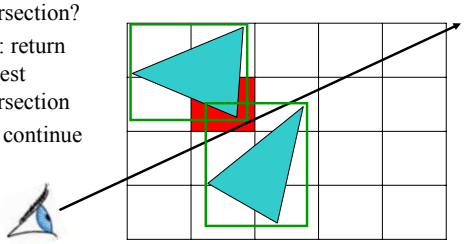
Insert Primitives into Grid

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



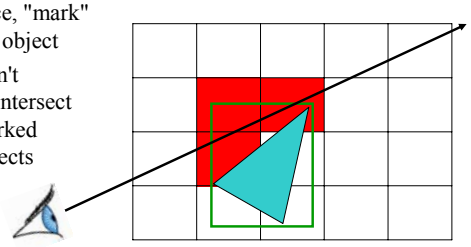
For Each Cell Along a Ray

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



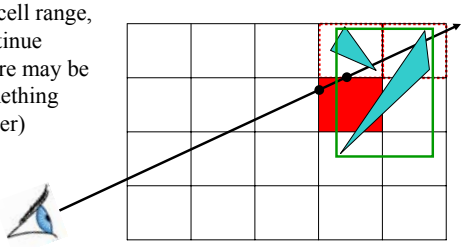
Preventing Repeated Computation

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



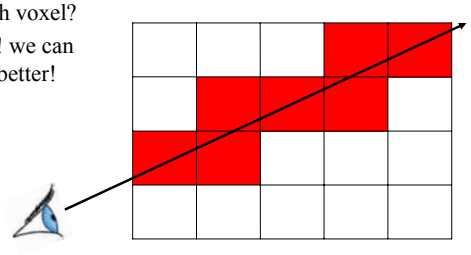
Don't Return Distant Intersections

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



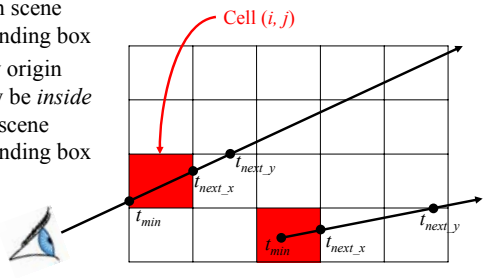
Which Cells Should We Examine?

- Should we intersect the ray with each voxel?
- No! we can do better!



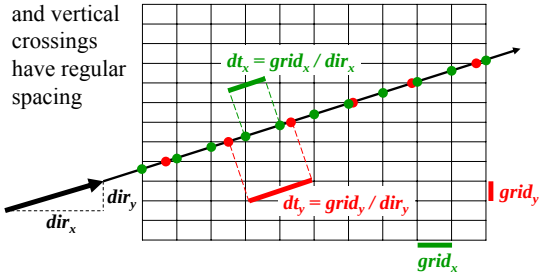
Where Do We Start?

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



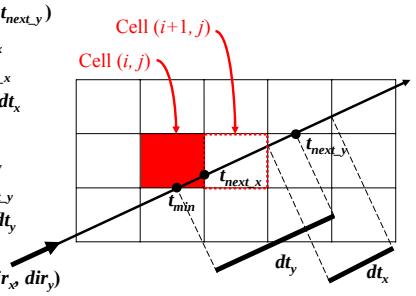
Is there a Pattern to Cell Crossings?

- Yes, the horizontal and vertical crossings have regular spacing



What's the Next Cell?

```
if ( t_next_x < t_next_y )
  i += sign_x
  t_min = t_next_x
  t_next_x += dt_x
else
  j += sign_y
  t_min = t_next_y
  t_next_y += dt_y
```

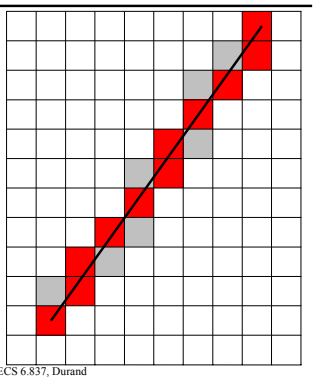


if $(dir_x > 0)$ $sign_x = 1$ *else* $sign_x = -1$

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

What's the Next Cell?

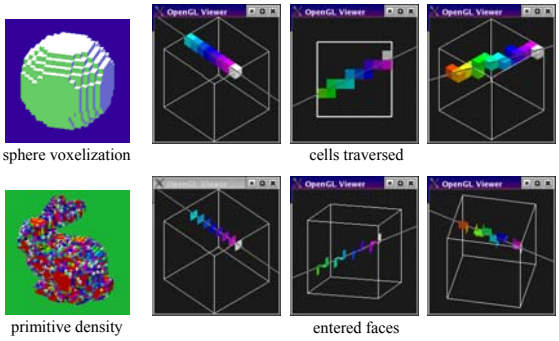
- 3DDDA – Three Dimensional Digital Difference Analyzer
- Similar to Line Rasterization



Pseudo-Code

```
create grid
insert primitives into grid
for each ray r
  find initial cell c(i,j), t_min, t_next_x & t_next_y
  compute dt_x, dt_y, sign_x and sign_y
  while c != NULL
    for each primitive p in c
      intersect r with p
      if intersection in range found
        return
    c = find next cell
```

Ray Marching Visualization



Regular Grid Discussion

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

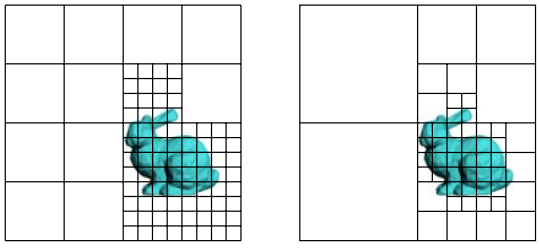
Questions?

Today

- Motivation – Distribution Ray Tracing
- Bounding Boxes
- Spatial Acceleration Data Structures
  - Regular Grid
  - Adaptive Grids
  - Hierarchical Bounding Volumes
- Flattening the Transformation Hierarchy

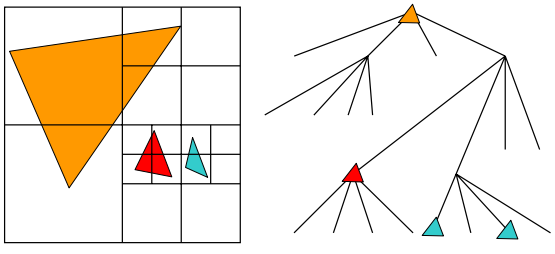
Adaptive Grids

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



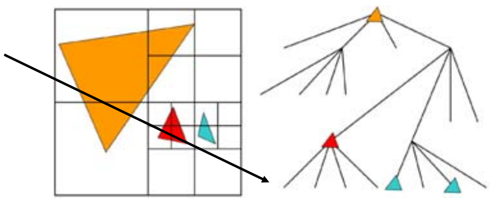
Primitives in an Adaptive Grid

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



Adaptive Grid Discussion

- Advantages?
  - grid complexity matches geometric density
- Disadvantages?
  - more expensive to traverse (especially octree)

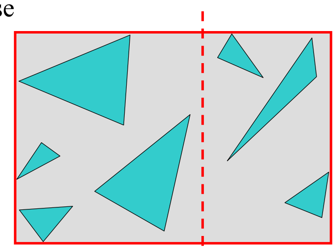


Today

- Motivation – Distribution Ray Tracing
- Bounding Boxes
- Spatial Acceleration Data Structures
  - Regular Grid
  - Adaptive Grids
  - Hierarchical Bounding Volumes
- Flattening the Transformation Hierarchy

Bounding Volume Hierarchy

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



Bounding Volume Hierarchy

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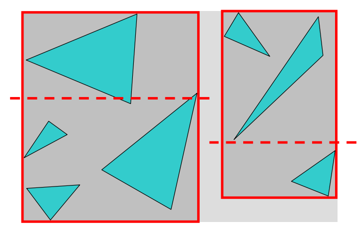

Bounding Volume Hierarchy

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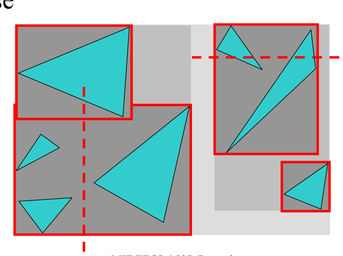

Bounding Volume Hierarchy

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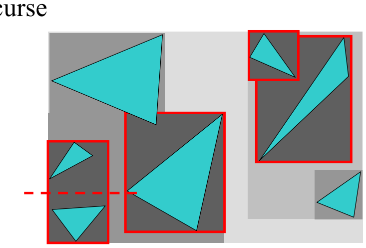

Bounding Volume Hierarchy

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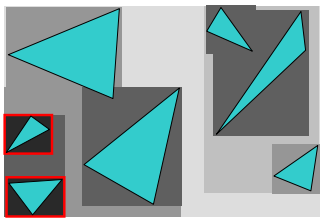
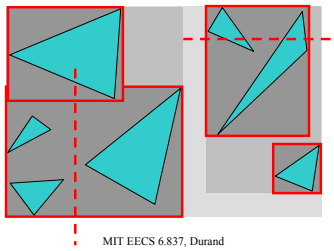


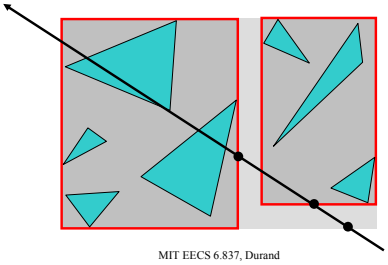
Where to split objects?

- At midpoint *OR*
- Sort, and put half of the objects on each side *OR*
- Use modeling hierarchy



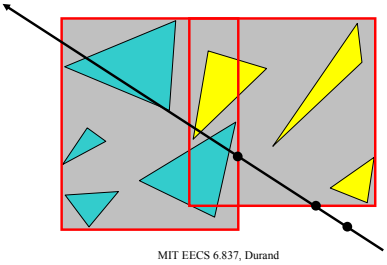
Intersection with BVH

- Check sub-volume with closer intersection first



Intersection with BVH

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

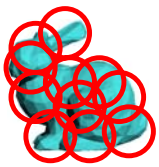


Bounding Volume Hierarchy Discussion

- Advantages
  - easy to construct
  - easy to traverse
  - binary
- Disadvantages
  - may be difficult to choose a good split for a node
  - poor split may result in minimal spatial pruning

Assignment 5

- Bounding spheres → reuse sphere intersection
- Bounding spheres given by parser
- Marco implemented a simple preprocess to decompose a mesh into clusters of triangles and compute their bounding spheres
  - Flat hierarchy, just one level of bounding spheres



Next Time:

Texture Mapping