Advanced Rendering Techniques

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Online
Wednesday 6PM → 8:50PM

Presentation 4
4/20/22
Questions from Last Week?

- Color models
- Light models
- Phong shading model
- Assignment 2
Slide Credits

- Leonard McMillan, Seth Teller, Fredo Durand, Barb Cutler - MIT
- David Luebke - University of Virginia
- Matt Pharr - Stanford University
- Jonathan Cohen - Johns Hopkins U.
- Kevin Suffern - University of Technology, Sydney, Australia
Motivation
Extra rays needed for these effects

- Distributed Ray Tracing
  - Soft shadows
  - Anti-aliasing (getting rid of jaggies)
  - Glossy reflection
  - Motion blur
  - Depth of field (focus)
Shadows

- one shadow ray per intersection per point light source

point light source
Soft Shadows

- multiple shadow rays to sample area light source

- one shadow ray
- lots of shadow rays

area light source
penumbra
umbra
penumbra
Antialiasing – Supersampling

- multiple rays per pixel

- point light

- area light

- jaggies

- w/ antialiasing
Reflection

- one reflection ray per intersection

perfect mirror
Glossy Reflection

- multiple reflection rays

polished surface

Justin Legakis
Motion Blur

- Sample objects temporally

Rob Cook
Depth of Field

- multiple rays per pixel

film  focal length
Algorithm Analysis

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

\[
\text{cost} \leq \text{height} \times \text{width} \times \text{num primitives} \times \text{intersection cost} \times \text{num shadow rays} \times \text{supersampling} \times \text{num glossy rays} \times \text{num temporal samples} \times \text{max recursion depth} \times \ldots
\]

can we reduce this?
Ray Tracing Acceleration Techniques

Faster Intersections
- Object bounding volumes
- Efficient intersection routines

Fewer Rays
- Adaptive tree depth
- Statistical optimizations

Generalized Rays
- Beam tracing
- Cone tracing
- Pencil tracing

Bounding Regions
Acceleration of Ray Casting

- Goal: Reduce the number of ray/primitive intersection tests
Conservative Bounding Region

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

- tight $\rightarrow$ avoid false positives
- fast to compute
- fast to intersect

Arbitrary convex region (bounding half-spaces)

Bounding sphere

Non-aligned bounding box

Axis-aligned bounding box
What makes a “good” bounding volume?

- Tightness of fit (expressed how?)
- Easy to compute
- Simplicity of intersection

Total cost = b*B + i*I + S

- b: # times volume tested for intersection
- B: cost of ray-volume intersection test
- i: # times item is tested for intersection
- I: cost of ray-item intersection test
- S: cost to compute BV parameters
Bounding box speeds up rendering
Ray through this pixel tests the bounding box and intersects the object.

Bounding box slows down rendering.
Bounding Volumes

- Spheres
  - Cheap intersection test
  - Poor fit
  - Somewhat costly to fit to data
Bounding Volumes

- Axis-aligned bounding boxes (AABBs)
  - Relatively cheap intersection test
  - Usually better fit
  - Trivial to fit to data
Bounding Volumes

- Oriented bounding boxes (OBBs)
  - Medium-expensive intersection test
  - Very good fit (asymptotically better)
  - Medium-difficult to fit to data
Bounding Volumes

- Slabs (parallel planes)
  - Comparatively expensive
  - Very good fit
  - Very difficult to fit to data

arbitrary convex region (bounding half-spaces)
Intersection with Axis-Aligned Box

- For all 3 axes, calculate the intersection distances $t_1$ and $t_2$
  - $t_{\text{near}} = \max (t_{1x}, t_{1y}, t_{1z})$
  - $t_{\text{far}} = \min (t_{2x}, t_{2y}, t_{2z})$
- If $t_{\text{near}} > t_{\text{far}}$, box is missed
- If $t_{\text{far}} < 0$, box is behind
- If box survived tests, report intersection at $t_{\text{near}}$
Bounding Box of a Triangle

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

\[(x_{\text{max}}, y_{\text{max}}, z_{\text{max}}) = (\max(x_0, x_1, x_2), \max(y_0, y_1, y_2), \max(z_0, z_1, z_2))\]
Bounding Box of a Sphere

Let \( r = (x, y, z) \) be a sphere with center \( (x, y, z) \). The bounding box of this sphere is given by:

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

and

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

where \( x_{\text{min}}, y_{\text{min}}, z_{\text{min}} \) and \( x_{\text{max}}, y_{\text{max}}, z_{\text{max}} \) are the minimum and maximum coordinates along the x, y, and z axes, respectively.
Bounding Box of a Group

\[
(x_{\text{max}}, y_{\text{max}}, z_{\text{max}}) = (\max(x_{\text{max}_a}, x_{\text{max}_b}), \\
\max(y_{\text{max}_a}, y_{\text{max}_b}), \\
\max(z_{\text{max}_a}, z_{\text{max}_b}))
\]

\[
(x_{\text{min}}, y_{\text{min}}, z_{\text{min}}) = (\min(x_{\text{min}_a}, x_{\text{min}_b}), \\
\min(y_{\text{min}_a}, y_{\text{min}_b}), \\
\min(z_{\text{min}_a}, z_{\text{min}_b}))
\]
Acceleration Spatial Data Structures
Spatial Data Structures

- *Spatial partitioning* techniques classify all space into non-overlapping portions
  - Easier to generate automatically
  - Can “walk” ray from partition to partition
- *Hierarchical bounding volumes* surround objects in the scene with (possibly overlapping) volumes
  - Often tightest fit
Spatial Partitioning

- Some spatial partitioning schemes:
  - Regular grid (2-D or 3-D)
  - Octree
  - k-D tree
  - BSP-tree
Acceleration Spatial Data Structures

Regular Grid
Regular Grid
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
- Use algorithm to step through cells
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)
Where do we start?

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

Cell \((i, j)\)
Is there a pattern to cell crossings?

Yes, the horizontal and vertical crossings have regular spacing.

\[
dt_y = \frac{\text{grid}_y}{\text{dir}_y} \\
dt_h = \frac{\text{grid}_x}{\text{dir}_x}
\]
What's the next cell?

```plaintext
if \( t_{next\_v} < t_{next\_h} \)
\[
  i += \text{sign}_x
  
  t_{\min} = t_{next\_v}
  
  t_{next\_v} += dt_v
\]
else
\[
  j += \text{sign}_y
  
  t_{\min} = t_{next\_h}
  
  t_{next\_h} += dt_h
\]
```

if \((\text{dir}_x > 0)\) \(\text{sign}_x = 1\) else \(\text{sign}_x = -1\)
if \((\text{dir}_y > 0)\) \(\text{sign}_y = 1\) else \(\text{sign}_y = -1\)
What's the next cell?

- 3DDDA – Three Dimensional Digital Difference Analyzer
- 3D Bresenham Algorithm
Pseudo-code

create grid
insert primitives into grid
for each ray \( r \)
  find initial cell \( c(i,j) \), \( t_{\text{min}}, t_{\text{next}_v} \) & \( t_{\text{next}_h} \)
  compute \( dt_v, dt_h, \text{sign}_x \) and \( \text{sign}_y \)
  while \( c \neq \text{NULL} \)
    for each primitive \( p \) in \( c \)
      intersect \( r \) with \( p \)
      if intersection in range found
        return
    \( c = \text{find next cell} \)
Regular Grid Discussion

■ Advantages?
  ■ easy to construct
  ■ easy to traverse

■ Disadvantages?
  ■ may be only sparsely filled
  ■ geometry may still be clumped in a small number of cells
Acceleration Spatial Data Structures

Adaptive Grids
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

Octree/(Quadtree)
Adaptive Grid Discussion

- Advantages?
  - grid complexity matches geometric density

- Disadvantages?
  - more expensive to traverse (especially octree)
k-D Trees

- k-D tree pros:
  - Moderately simple to generate
  - More adaptive than octrees

- k-D tree cons:
  - Less efficient to trace rays across
  - Moderately complex data structure
BSP Trees

- **BSP tree pros:**
  - Extremely adaptive
  - Simple & elegant data structure

- **BSP tree cons:**
  - Very hard to create optimal BSP
  - Splitting planes can explode storage
  - Simple but slow to trace rays across
Acceleration Spatial Data Structures

Bounding Volume Hierarchy
What makes a “good” bounding volume hierarchy?

- Grouped objects (or volumes) should be near each other
- Volume should be minimal
- Sum of all volumes should be minimal
- Top of the tree is most critical
- Constructing the hierarchy should pay for itself!
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

- Find bounding box of objects
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Where to split objects?

- At midpoint
- Sort, and put half of the objects on each side
- Use modeling hierarchy
sort_axis = 0;
Make_BVH(object_list, sort_axis, ptr)
    struct.bbox = BoundingBox(object_list);
    If # of objects < Threshold
        struct.obj_list = object_list
    Else
        If ((sort_axis % 3) == 0) Sort object centroids in X
        ElseIf ((sort_axis % 3) == 1)
            Sort object centroids in Y
        Else
            Sort object centroids in Z
        Split sorted list into two halves
        Make_BVH(left_obj_list, sort_axis++, lptr)
        Make_BVH(right_obj_list, sort_axis++, rptr)
    struct.lptr = lptr; struct.rptr = rptr;
    ptr = &struct;
Return
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
Intersection Pseudo-code

Does ray intersect box?

\[ \text{intersect\_BVH}(\text{box, ray, xsect\_pt, t}) \]

If no more subboxes

Intersect geometry and return nearest xsect\_pt & t

Intersect ray with both subboxes

No hits: return xsect\_pt = Null;

Sort t’s

Call subbox of nearest t subbox1

\[ \text{intersect\_BVH}(\text{subbox1, ray, xsect\_pt, t}) \]

If hit_subbox2?

If xsect\_pt == Null || t_{2\text{near}} <= t_{1\text{far}}

\[ \text{intersect\_BVH}(\text{subbox2, ray, xsect\_pt, t}) \]

Set nearest xsect\_pt and t

Return
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

Hint
- Alternate sorting in X, Y & Z
Transformation Hierarchy

Group & Transformation hierarchy may not be a good spatial hierarchy

Flatten
What’s the best method?

- What kind of scene are you rendering?
  - Teapot in a stadium vs. uniform distribution
  - Impact on surface tessellation on distribution
- Parameter values are critical
Shoot Fewer Rays

- Adaptive depth control
  - Naïve ray tracer: spawn 2 rays per intersection until max recursion limit
  - In practice, few surfaces are transparent or reflective
  - Stop shadow ray at first intersection between start and light source
  - Just shoot the rays you need
  - Determine contribution of ray
    - Don’t shoot rays w/ contribution near 0%
Shoot Fewer Rays

- Adaptive sampling
  - Shoot rays coarsely, interpolating their values across pixels
  - Where adjacent rays differ greatly in value, sample more finely
  - Stop when some maximum resolution is reached
Generalized Rays

- Beams, cones, pencils
- Area sampling, rather than point sampling
- Geometric computations are tricky (expensive?)
- Problems with reflection/refractions
Wrap Up

- Discuss next programming assignment
  - Add an acceleration technique
    - Adaptive grid
    - Bounding volume hierarchy
  - Supersample image
- Discuss status/problems/issues with this week’s programming assignment