Foundations of Computer Graphics (Fall 2012)
CS 184, Lectures 17, 18:
Nuts and bolts of Ray Tracing
http://inst.eecs.berkeley.edu/~cs184

Acknowledgements: Thomas Funkhouser and Greg Humphreys

Outline

- Camera Ray Casting (choose ray directions)
- Ray-object intersections
- Ray-tracing transformed objects
- Lighting calculations
- Recursive ray tracing

Ray Casting

Finding Ray Direction

- Goal is to find ray direction for given pixel i and j
- Many ways to approach problem
  - Objects in world coord, find dir of each ray (we do this)
  - Camera in canonical frame, transform objects (OpenGL)
- Basic idea
  - Ray has origin (camera center) and direction
  - Find direction given camera params and i and j
- Camera params as in gluLookAt
  - Lookfrom[3], LookAt[3], up[3], fov

Image Raytrace (Camera cam, Scene scene, int width, int height)
{
  Image image = new Image (width, height) ;
  for (int i = 0 ; i < height ; ++i) {
    for (int j = 0 ; j < width ; ++j) {
      Ray ray = RayThruPixel (cam, i, j) ;
      Intersection hit = Intersect (ray, scene) ;
      image[i][j] = FindColor (hit) ;
    }
  }
  return image ;
}
Similar to gluLookAt derivation

- `gluLookAt(eyex, eyey, eyez, centerx, centery, centerz, upx, upy, upz)`
- Camera at eye, looking at center, with up direction being up

From earlier lecture on deriving gluLookAt

Constructing a coordinate frame?

We want to associate `w` with `a`, and `v` with `b`
- But `a` and `b` are neither orthogonal nor unit norm
- And we also need to find `u`

\[
\begin{align*}
\mathbf{w} &= \frac{\mathbf{a}}{\|\mathbf{a}\|} \\
\mathbf{u} &= \frac{\mathbf{b} \times \mathbf{w}}{\|\mathbf{b} \times \mathbf{w}\|} \\
\mathbf{v} &= \mathbf{w} \times \mathbf{u}
\end{align*}
\]

From basic math lecture - Vectors: Orthonormal Basis Frames

Camera coordinate frame

\[
\mathbf{w} = \frac{\mathbf{a}}{\|\mathbf{a}\|} \quad \mathbf{u} = \frac{\mathbf{b} \times \mathbf{w}}{\|\mathbf{b} \times \mathbf{w}\|} \quad \mathbf{v} = \mathbf{w} \times \mathbf{u}
\]

- We want to position camera at origin, looking down –Z dim
- Hence, vector `a` is given by eye – center
- The vector `b` is simply the up vector

Canonical viewing geometry

\[
\begin{align*}
\alpha &= \tan \left( \frac{\text{fovx}}{2} \right) \times \left( \frac{j - \text{width} / 2}{\text{width} / 2} \right) \\
\beta &= \tan \left( \frac{\text{fovy}}{2} \right) \times \left( \frac{\text{height} / 2 - i}{\text{height} / 2} \right)
\end{align*}
\]

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```
Ray-Sphere Intersection

\[ \text{ray} = \vec{P} = \vec{P}_0 + \vec{P}_1 t \]
\[ \text{sphere} = (\vec{P} - \vec{C}) \cdot (\vec{P} - \vec{C}) - r^2 = 0 \]

Substitute

\[ \text{ray} = \vec{P} = \vec{P}_0 + \vec{P}_1 t \]
\[ \text{sphere} = (\vec{P}_0 + \vec{P}_1 t - \vec{C}) \cdot (\vec{P}_0 + \vec{P}_1 t - \vec{C}) - r^2 = 0 \]

Simplify

\[ t^2 (\vec{P}_1 \cdot \vec{P}_1) + 2 t \vec{P}_1 \cdot (\vec{P}_0 - \vec{C}) + (\vec{P}_0 - \vec{C}) \cdot (\vec{P}_0 - \vec{C}) - r^2 = 0 \]

Solve quadratic equations for \( t \)

- 2 real positive roots: pick smaller root
- Both roots same: tangent to sphere
- One positive, one negative root: ray origin inside sphere (pick + root)
- Complex roots: no intersection (check discriminant of equation first)

Ray-Triangle Intersection

- One approach: Ray-Plane intersection, then check if inside triangle
- Plane equation:
  \[ \text{plane} = \vec{P} \cdot \hat{n} - \vec{A} \cdot \hat{n} = 0 \]

Ray-Triangle Intersection

- One approach: Ray-Plane intersection, then check if inside triangle
- Plane equation:
  \[ \text{plane} = \vec{P} \cdot \hat{n} - \vec{A} \cdot \hat{n} = 0 \]
- Combine with ray equation:
  \[ \vec{r} = \vec{P}_0 + \vec{P}_1 t \]
  \[ (\vec{P}_0 + \vec{P}_1 t) \cdot \hat{n} = \vec{A} \cdot \hat{n} \]
  \[ t = \frac{\vec{A} \cdot \hat{n} - \vec{P}_0 \cdot \hat{n}}{\vec{P}_1 \cdot \hat{n}} \]
Ray inside Triangle

- Once intersect with plane, still need to find if in triangle
- Many possibilities for triangles, general polygons (point in polygon tests)
- We find parametrically [barycentric coordinates]. Also useful for other applications (texture mapping)

\[ P = \alpha A + \beta B + \gamma C \]
\[ \alpha, \beta, \gamma \geq 0 \]
\[ \alpha + \beta + \gamma = 1 \]

Other primitives

- Much early work in ray tracing focused on ray-primitive intersection tests
- Cones, cylinders, ellipsoids
- Boxes (especially useful for bounding boxes)
- General planar polygons
- Many more
- Consult chapter in Glassner (handed out) for more details and possible extra credit

Ray Scene Intersection

Intersection (Ray ray, Scene scene)

```c
min_t = infinity
min_primitive = NULL
For each primitive in scene |
    t = Intersect(ray, primitive);
    if (t > 0 && t < min_t) then
        min_primitive = primitive
        min_t = t
    }
return Intersection(min_t, min_primitive)
```

Transformed Objects

- E.g. transform sphere into ellipsoid
- Could develop routine to trace ellipsoid (compute parameters after transformation)
- May be useful for triangles, since triangle after transformation is still a triangle in any case
- But can also use original optimized routines
Ray-Tracing Transformed Objects

We have an optimized ray-sphere test
- But we want to ray trace an ellipsoid...

Solution: Ellipsoid transforms sphere
- Apply inverse transform to ray, use ray-sphere
- Allows for instancing (traffic jam of cars)
- Same idea for other primitives

Transformed Objects

- Consider a general 4x4 transform $M$
  - Will need to implement matrix stacks like in OpenGL
- Apply inverse transform $M^{-1}$ to ray
  - Locations stored and transform in homogeneous coordinates
  - Vectors (ray directions) have homogeneous coordinate set to 0 (so there is no action because of translations)
- Do standard ray-surface intersection as modified
  - Transform intersection back to actual coordinates
    - Intersection point $p$ transforms as $Mp$
    - Distance to intersection if used may need recalculation
    - Normals $n$ transform as $M^{-1}n$. Do all this before lighting

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```

Shadows

- Virtual Viewpoint
- Virtual Screen
- Objects
- Light Source

Shadows: Numerical Issues

- Numerical inaccuracy may cause intersection to be below surface (effect exaggerated in figure)
- Causing surface to incorrectly shadow itself
- Move a little towards light before shooting shadow ray
Lighting Model

- Similar to OpenGL
- Lighting model parameters (global)
  - Ambient r g b
  - Attenuation constant linear quadratic
    \[ L = \frac{L_0}{\text{const} + \text{lin} \cdot d + \text{quad} \cdot d^2} \]
- Per light model parameters
  - Directional light (direction, RGB parameters)
  - Point light (location, RGB parameters)
  - Some differences from HW 2 syntax

Material Model

- Diffuse reflectance (r g b)
- Specular reflectance (r g b)
- Shininess s
- Emission (r g b)
- All as in OpenGL

Shading Model

\[ I = K_a + K_e + \sum_{i=1}^{n} L_i (K_d \max (l_i \cdot n, 0) + K_s (\max (h_i \cdot n, 0))^s) \]

- Global ambient term, emission from material
- For each light, diffuse specular terms
- Note visibility/shadowing for each light (not in OpenGL)
- Evaluated per pixel per light (not per vertex)

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Mirror Reflections/Refractions

- Virtual Viewpoint
- Virtual Screen
- Generate reflected ray in mirror direction
- Get reflections and refractions of objects

Turner Whitted 1980
Basic idea

For each pixel
- Trace Primary Eye Ray, find intersection
- Trace Secondary Shadow Ray(s) to all light(s)
  - Color = Visible ? Illumination Model : 0 ;
- Trace Reflected Ray
  - Color += reflectivity * Color of reflected ray

Recursive Shading Model

\[
l = K_a + K_p + \sum_{i=1}^{n} L_i (K_d (\mathbf{L_i} \cdot \mathbf{n_i}) + K_s (\max(\mathbf{h_i} \cdot \mathbf{n_i}, 0))^s) + K_sIR + K_tIT
\]

- Highlighted terms are recursive specularities [mirror reflections] and transmission (latter is extra credit)
- Trace secondary rays for mirror reflections and refractions, include contribution in lighting model
- GetColor calls RayTrace recursively (the I values in equation above of secondary rays are obtained by recursive calls)

Problems with Recursion

- Reflection rays may be traced forever
- Generally, set maximum recursion depth
- Same for transmitted rays (take refraction into account)

Effects needed for Realism

- (Soft) Shadows
- Reflections (Mirrors and Glossy)
- Transparency (Water, Glass)
- Interreflections (Color Bleeding)
- Complex Illumination (Natural, Area Light)
- Realistic Materials (Velvet, Paints, Glass)

Discussed in this lecture so far
Not discussed but possible with distribution ray tracing
Hard (but not impossible) with ray tracing: radiosity methods

Some basic add ons

- Area light sources and soft shadows: break into grid of n x n point lights
  - Use jittering: Randomize direction of shadow ray within small box for given light source direction
  - Jittering also useful for antialiasing shadows when shooting primary rays
- More complex reflectance models
  - Simply update shading model
  - But at present, we can handle only mirror global illumination calculations

Acceleration

Testing each object for each ray is slow
- Fewer Rays
  - Adaptive sampling, depth control
- Generalized Rays
  - Beam tracing, cone tracing, pencil tracing etc.
- Faster Intersections
  - Optimized Ray-Object Intersections
  - Fewer Intersections
**Acceleration Structures**

Bounding boxes (possibly hierarchical)
If no intersection bounding box, needn't check objects

**Bounding Volume Hierarchies 1**

- Build hierarchy of bounding volumes
  - Bounding volume of interior node contains all children

**Bounding Volume Hierarchies 2**

- Use hierarchy to accelerate ray intersections
  - Intersect node contents only if hit bounding volume

**Bounding Volume Hierarchies 3**

- Sort hits & detect early termination

```c
FindIntersection(Ray ray, Node node)
{
  // Find intersections with child node bounding volumes
  // Sort intersections front to back
  // Process intersections (checking for early termination)
  min_t = infinity;
  for each intersected child i {
    if (min_t > by_y) break;
    shape_t = FindIntersection(ray, child);
    if (shape_t == min_t) min_t = shape_t;
  }
  return min_t;
}
```

**Acceleration Structures: Grids**

**Uniform Grid: Problems**

- Potential problem:
  - How choose suitable grid resolution?

  - Too little benefit if grid is too coarse
  - Too much cost if grid is too fine
Octree

- Construct adaptive grid over scene
  - Recursively subdivide box-shaped cells into 8 octants
  - Index primitives by overlaps with cells

Octree traversal

- Trace rays through neighbor cells
  - Fewer cells
  - More complex neighbor finding

Other Accelerations

- Screen space coherence
  - Check last hit first
  - Beam tracing
  - Pencil tracing
  - Cone tracing
- Memory coherence
  - Large scenes
- Parallelism
  - Ray casting is “embarrassingly parallelizable”
- etc.

Ray Tracing Acceleration Structures

- Bounding Volume Hierarchies (BVH)
- Uniform Spatial Subdivision (Grids)
- Binary Space Partitioning (BSP Trees)
  - Axis-aligned often for ray tracing: kd-trees
- Conceptually simple, implementation a bit tricky
- Lecture relatively high level: Start early, go to section
- Remember that acceleration a small part of grade
- See 12.3, 12.4 in book

Math of 2D Bounding Box Test

- Can you find a \( t \) in range
  - \( t > 0 \)
  - \( t_{\text{min}} \leq t \leq t_{\text{max}} \)
  - \( t_{\text{min}} \leq t \leq t_{\text{max}} \)

\[
\text{if } t_{\text{min}} > t_{\text{max}} \text{ OR } t_{\text{min}} > t_{\text{max}} \\
\text{return false;}
\]

\[
\text{else return true;}
\]

No intersection if x and y ranges don’t overlap

Bounding Box Test

- Ray-Intersection is simple coordinate check
- Intricacies with test, see book
- Hierarchical Bounding Boxes
Hierarchical Bounding Box Test

- If ray hits root box
  - Intersect left subtree
  - Intersect right subtree
  - Merge intersections (find closest one)
- Standard hierarchical traversal
  - But caveat, since bounding boxes may overlap
- At leaf nodes, must intersect objects

Creating Bounding Volume Hierarchy

```
function bvh-node::create (object array A, int AXIS)
N = A.length();
if (N == 1) {left = A[0]; right = NULL; bbox = bound(A[0]);}
else if (N == 2) {
  left = A[0]; right = A[1];
  bbox = combine(bound(A[0]),bound(A[1]));
} else
  Find midpoint m of bounding box of A along AXIS
  Partition A into lists of size k and N-k around m
  left = new bvh-node (A[0…k],(AXIS+1) mod 3);
  right = new bvh-node(A[k+1…N-1],(AXIS+1) mod 3);
  bbox = combine (left -> bbox, right -> bbox);
```

Uniform Spatial Subdivision

- Different idea: Divide space rather than objects
- In BVH, each object is in one of two sibling nodes
  - A point in space may be inside both nodes
- In spatial subdivision, each space point in one node
  - But object may lie in multiple spatial nodes
- Simplest is uniform grid (have seen this already)
- Challenge is keeping all objects within cell
- And in traversing the grid

Traversal of Grid High Level

- Next Intersect Pt?
- Irreg. samp. pattern?
- But regular in planes
- Fast algo. possible
  - (more on board)
- See figs 12.29,30

BSP Trees

- Used for visibility and ray tracing
  - Book considers only axis-aligned splits for ray tracing
  - Sometimes called kd-tree for axis aligned
- Split space (binary space partition) along planes
- Fast queries and back-to-front (painter’s) traversal
- Construction is conceptually simple
  - Select a plane as root of the sub-tree
  - Split into two children along this root
  - Random polygon for splitting plane (may need to split polygons that intersect it)

BSP slides courtesy Prof. O’Brien
First Split

Second Split

Third Split

Fourth Split

Final BSP Tree

BSP Trees Cont’ d

- Continue splitting until leaf nodes
- Visibility traversal in order
  - Child one
  - Root
  - Child two
- Child one chosen based on viewpoint
  - Same side of sub-tree as viewpoint
- BSP tree built once, used for all viewpoints
- More details in book
Interactive Raytracing

- Ray tracing historically slow
- Now viable alternative for complex scenes
  - Key is sublinear complexity with acceleration; need not process all triangles in scene
- Allows many effects hard in hardware
- OpenRT project real-time ray tracing (http://www.openrt.de)

Raytracing on Graphics Hardware

- Modern Programmable Hardware general streaming architecture
- Can map various elements of ray tracing
- Kernels like eye rays, intersect etc.
- In vertex or fragment programs
- Convergence between hardware, ray tracing
  [Purcell et al. 2002, 2003]
  http://graphics.stanford.edu/papers/photongfx