The Traditional Graphics Pipeline

Last Time?
- Participating Media
- Measuring BRDFs
- 3D Digitizing & Scattering
- BSSRDFs
  - Monte Carlo Simulation
  - Dipole Approximation

Today
- Ray Casting / Tracing vs. Scan Conversion
- Traditional Graphics Pipeline
- Clipping
- Rasterization/Scan Conversion

Ray Casting / Tracing
- Advantages?
  - Smooth variation of normal, exact silhouettes
  - Generality: can render anything that can be intersected with a ray
  - Atomic operation, allows recursion
- Disadvantages?
  - Time complexity (N objects, R pixels)
  - Usually too slow for interactive applications
  - Hard to implement in hardware (lacks computation coherence, must fit entire scene in memory)

How Do We Render Interactively?
- Use graphics hardware (the graphics pipeline), via OpenGL, MesaGL, or DirectX
  - Most global effects available in ray tracing will be sacrificed, but some can be approximated

Ray Casting vs. Rendering Pipeline
Ray Casting
For each pixel
  For each object
Send pixels into the scene
Discretize first

Rendering Pipeline
For each pixel
For each triangle
Project scene to the pixels
Discretize last

"Inverse-Mapping" approach to Computer Graphics
"Forward-Mapping" approach to Computer Graphics
Scan Conversion (Rendering Pipeline)

- Given a primitive's vertices & the illumination at each vertex:
- Figure out which pixels to "turn on" to render the primitive
- Interpolate the illumination values to "fill in" the primitive
- At each pixel, keep track of the closest primitive (z-buffer)

Limitations of Scan Conversion

- Restricted to scan-convertible primitives
  - Must "polygonize" all objects
- Faceting, shading artifacts
- Effective resolution is hardware dependent
- No handling of shadows, reflection, transparency
- Problem of overdraw (high depth complexity)
- What if there are many more triangles than pixels?

Ray Casting vs. Rendering Pipeline

Ray Casting
For each pixel
  For each object
    • Whole scene must be in memory
    • Depth complexity: w/ spatial acceleration data structures no computation needed for hidden parts
    • Atomic computation
      - Primitives, lighting effects, adaptive antialiasing

Rendering Pipeline
For each triangle
  For each pixel
    • Primitives processed one at a time
    • Coherence: geometric transforms for vertices only
    • Early stages involve analytic processing
    • Computation increases with depth of the pipeline
      - Good bandwidth/computation ratio
    • Sampling occurs late in the pipeline
    • Minimal state required

Questions?

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The Graphics Pipeline

- Input:
  - Geometric model: Description of all object, surface, and light source geometry and transformations
  - Lighting model: Computational description of object and light properties, interaction (reflection)
- Synthetic Viewpoint (or Camera):
  - Eye position and viewing frustum
- Master Viewport
  - Pixel grid onto which image plane is mapped
- Output:
  - Colors/Intensities suitable for framebuffer display
  (For example: 24-bit RGB value at each pixel)
The Graphics Pipeline

- Primitives are processed in a series of stages
- Each stage forwards its result on to the next stage
- The pipeline can be drawn and implemented in different ways
- Some stages may be in hardware, others in software
- Optimizations & additional programmability are available at some stages

Modeling Transformations

- 3D models defined in their own coordinate system (object space)
- Modeling transforms orient the models within a common coordinate frame (world space)

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Illumination (Shading) (Lighting)

- Vertices lit (shaded) according to material properties, surface properties (normal) and light sources
- Local lighting model (Diffuse, Ambient, Phong, etc.)

Viewing Transformation

- Maps world space to eye space
- Viewing position is transformed to origin & direction is oriented along some axis (usually z)

Clipping

- Transform to Normalized Device Coordinates (NDC)
- Portions of the object outside the view volume (view frustum) are removed

Projection

- The objects are projected to the 2D image place (screen space)
Scan Conversion (Rasterization)

- Rasterizes objects into pixels
- Interpolate values as we go (color, depth, etc.)

Visibility / Display

- Each pixel remembers the closest object (depth buffer)
- Almost every step in the graphics pipeline involves a change of coordinate system. Transformations are central to understanding 3D computer graphics.

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  - Coordinate Systems in the Graphics Pipeline
- Rasterization/Scan Conversion

Clipping

- Eliminate portions of objects outside the viewing frustum
- View Frustum
  - boundaries of the image plane projected in 3D
  - a near & far clipping plane
- User may define additional clipping planes

What if the $p_z$ is $> eye_z$?
What if the $p_z$ is $< eye_z$?

What if the $p_z \approx eye_z$?

What if the $p_z \approx eye_z$?

Why Clip?

- Avoid degeneracies
  - Don’t draw stuff behind the eye
  - Avoid division by 0 and overflow
- Efficiency
  - Don’t waste time on objects outside the image boundary
- Other graphics applications (often non-convex)
  - Hidden-surface removal, Shadows, Picking, Binning, CSG (Boolean) operations (2D & 3D)

Clipping Strategies

- Don’t clip (and hope for the best)
- Clip on-the-fly during rasterization
- Analytical clipping: alter input geometry

Common Coordinate Systems

- Object space
  - local to each object
- World space
  - common to all objects
- Eye space / Camera space
  - derived from view frustum
- Clip space / Normalized Device Coordinates (NDC)
  - $[-1,-1,-1] \rightarrow [1,1,1]$
- Screen space
  - indexed according to hardware attributes
Coordinate Systems in the Pipeline

#### Modeling Transformations

- Object space
- World space
- Eye Space / Camera Space
- Clip Space (NDC)

#### Viewing Transformation

- Projection (Perspective / Orthographic)
- Scan Conversion (Rasterization)

#### Clipping

- Visibility / Display

Normalized Device Coordinates

- Clipping is more efficient in a rectangular, axis-aligned volume: \((-1,-1,-1) \rightarrow (1,1,1)\) OR \((0,0,0) \rightarrow (1,1,1)\)

Clipping in the Graphics Pipeline

- Former hardware relied on full clipping
- Modern hardware mostly avoids clipping
  - Only with respect to plane \(z=0\)
- In general, it is useful to learn clipping because it is similar to many geometric algorithms

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  - Rasterization/Scan Conversion
    - Line Rasterization
    - Triangle Rasterization

2D Scan Conversion

- Geometric primitives
  - (point, line, polygon, circle, polyhedron, sphere...)
- Primitives are continuous; screen is discrete
- Scan Conversion: algorithms for efficient generation of the samples comprising this approximation
Scan Converting 2D Line Segments

- Given:
  - Segment endpoints (integers x1, y1; x2, y2)
- Identify:
  - Set of pixels (x, y) to display for segment

Line Rasterization Requirements

- Transform continuous primitive into discrete samples
- Uniform thickness & brightness
- Continuous appearance
- No gaps
- Accuracy
- Speed

Algorithm Design Choices

- Assume:
  - $m = \frac{dy}{dx}$, $0 < m < 1$
- Exactly one pixel per column
  - fewer → disconnected, more → too thick

Naive Line Rasterization Algorithm

- Simply compute y as a function of x
  - Conceptually: move vertical scan line from x1 to x2
  - What is the expression of y as function of x?
- Set pixel $(x, \text{round}(y(x)))$

Efficiency

- Computing y value is expensive
  - $y = y1 + m(x - x1)$
- Observe: $y + = m$ at each x step ($m = \frac{dy}{dx}$)

Bresenham's Algorithm (DDA)

- Select pixel vertically closest to line segment
  - intuitive, efficient, pixel center always within 0.5 vertically
- Generalize to handle all eight octants using symmetry
- Can be modified to use only integer arithmetic
Line Rasterization & Grid Marching
• Can be used for ray-casting acceleration
• March a ray through a grid
• Collect all grid cells, not just 1 per column (or row)

Questions?

Brute force solution for triangles
• For each pixel
  – Compute line equations at pixel center
  – “clip” against the triangle
Problem?

Brute force solution for triangles
• For each pixel
  – Compute line equations at pixel center
  – “clip” against the triangle
Problem?
  If the triangle is small, a lot of useless computation

Brute force solution for triangles
• Improvement: Compute only for the screen bounding box of the triangle
• How do we get such a bounding box?
  – Xmin, Xmax, Ymin, Ymax of the triangle vertices

Can we do better? Kind of!
• We compute the line equation for many useless pixels
• What could we do?
Scan-line Rasterization

- Compute the boundary pixels
- Fill the spans
- Interpolate vertex color along the edges & spans!

But These Days…

- Triangles are usually very small
- Setup costs are becoming more troublesome
- Clipping is annoying
- Brute force is tractable

Modern Rasterization

For every triangle
ComputeProjection
Compute bbox, clip bbox to screen limits
For all pixels in bbox
  Compute line equations
  If all line equations > 0 (pixel [x,y] in triangle
    Framebuffer[x,y] = triangleColor

Questions?

Reading for Today:

- “Ray Tracing on Programmable Graphics Hardware Purcell”, Buck, Mark, & Hanrahan SIGGRAPH 2002

Reading for Tuesday:

Reading for HW4: (start reading this weekend)

- “Improving Shadows and Reflections via the Stencil Buffer”, Mark Kilgard, NVIDIA