The Traditional Graphics Pipeline

Facade, Debevec et al. 1997

Modeling and Rendering Architecture from Photographs
Debevec, Taylor, and Malik 1996

Original photograph with marked edges
Recovered model
Model edges projected onto photograph
Synthetic rendering

“Oh, lovely—just the hundredth time you’ve managed to cut everyone’s head off.”
Facade, Debevec et al. 1997

Belvedere
M.C. Escher
1958

“Combining Deep Learning and Active Contours Opens The Way to Robust, Automated Analysis of Brain Cytoarchitecture”, Thierbach et al, 2018
Escher’s Belvedere, Sachiko Tsuruno, 1997

Last Time?

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

- Worksheet
- Ray Casting / Tracing vs. Scan Conversion
- Traditional Graphics Pipeline
- Clipping
- Rasterization/Scan Conversion
- Readings for Today
- Papers for Next Time

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

"Inverse-Mapping" approach

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

"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)

```markdown
glBegin(GL_TRIANGLES)
  glNormal3f(...)  
  glVertex3f(...)  
  glVertex3f(...)  
  glVertex3f(...)  
glEnd();
```

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

<table>
<thead>
<tr>
<th>Ray Casting</th>
<th>Rendering Pipeline</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>For each pixel</strong></td>
<td><strong>For each triangle</strong></td>
</tr>
<tr>
<td><strong>For each object</strong></td>
<td><strong>For each pixel</strong></td>
</tr>
<tr>
<td>• Whole scene must be in memory</td>
<td>• Primitives processed one at a time</td>
</tr>
<tr>
<td>• Depth complexity: w/ spatial acceleration data structures no computation needed for hidden parts</td>
<td>• Coherence: geometric transforms for vertices only</td>
</tr>
<tr>
<td>• Atomic computation</td>
<td>• Early stages involve analytic processing</td>
</tr>
<tr>
<td>• More general, more flexible</td>
<td>• Computation increases with depth of the pipeline</td>
</tr>
<tr>
<td>– Primitives, lighting effects, adaptive antialiasing</td>
<td>– Good bandwidth/computation ratio</td>
</tr>
<tr>
<td></td>
<td>• Sampling occurs late in the pipeline</td>
</tr>
<tr>
<td></td>
<td>• Minimal state required</td>
</tr>
</tbody>
</table>

### Questions?
Today

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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
- **Raster 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)
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

<table>
<thead>
<tr>
<th>Modeling Transformations</th>
<th>Transform to Normalized Device Coordinates (NDC)</th>
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</thead>
<tbody>
<tr>
<td>Illumination (Shading)</td>
<td></td>
</tr>
<tr>
<td>Viewing Transformation (Perspective / Orthographic)</td>
<td>Portions of the object outside the view volume (view frustum) are removed</td>
</tr>
<tr>
<td>Clipping</td>
<td></td>
</tr>
<tr>
<td>Projection (to Screen Space)</td>
<td></td>
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<tr>
<td>Scan Conversion (Rasterization)</td>
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<td>Visibility / Display</td>
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Eye space $\rightarrow$ NDC

## Projection

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<tr>
<th>Modeling Transformations</th>
<th>The objects are projected to the 2D image place (screen space)</th>
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<td>Illumination (Shading)</td>
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NDC $\rightarrow$ 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.
Questions?

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• Clipping
  – Coordinate Systems in the Graphics Pipeline
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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 $>$ $e_y$?
What if the $p_z$ is $< \text{eye}_z$?

(eye_x, eye_y, eye_z)

image plane

What if the $p_z$ $\approx \text{eye}_z$?

(eye_x, eye_y, eye_z)

???

image plane
What if the $p_z \approx \text{eye}_z$?

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)
Constructive Solid Geometry

Clipping Strategies

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

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] → [1,1,1]
- Screen space
  - indexed according to hardware attributes
Coordinate Systems in the Pipeline

1. Modeling Transformations
2. Illumination (Shading)
3. Viewing Transformation (Perspective / Orthographic)
4. Clipping
5. Projection (to Screen Space)
6. Scan Conversion (Rasterization)
7. Visibility / Display

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

Normalized Device Coordinates

- Clipping is more efficient in a rectangular, axis-aligned volume: \((-1,-1,-1) \rightarrow (1,1,1)\)  OR \((0,0,0) \rightarrow (1,1,1)\)
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  – Line Rasterization
  – Triangle Rasterization
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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 $x_1, y_1; x_2, y_2$)
- 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, round (y(x)))

\[
y = y1 + \frac{x - x1}{x2 - x1} (y2 - y1)
\]

\[
= y1 + m(x - x1)
\]

\[
m = \frac{dy}{dx}
\]

Efficiency

- Computing y value is expensive
  \[y = y1 + m(x - x1)\]
- Observe: \(y += m\) at each x step (\(m = dy/dx\))
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
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 \[// \text{pixel } [x,y] \text{ in triangle}\]
    framebuffer\[x,y\] = triangleColor
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Reading for Today: (pick one)

"The Reyes Image Rendering Architecture", Cook, Carpenter, and Catmull, SIGGRAPH 1987
Young Sherlock Holmes 1985 (Lucasfilm / ILM)

Reading for Today: *(pick one)*

- "RenderMan: An Advanced Path Tracing Architecture for Movie Rendering", Christensen et al., TOG 2018

Fig. 8. Complex illumination in *Coco*: 8 million lights (© 2017 Disney•Pixar).
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Reading for Next Time: *pick one*

- "Rendering Fake Soft Shadows with Smoothies", Chan & Durand, EGSR 2003
Reading for Next Time: (pick one)

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