Chapter 10

Hidden Surface Removal/Depth Test

Rendering Pipeline

Geometry Processing

Geometric Content → Model/View Transform. → Lighting → Perspective Transform. → Clipping

Rasterization

Scan Conversion → Texturing → Depth Test → Blending → Frame-buffer

Fragment Processing

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For most interesting scenes, some polygons overlap.

To render the correct image, we need to determine which polygons occlude which.

Simple: render the polygons from back to front, “painting over” previous polygons.

Draw cyan, then green, then red.
Will this work in general?
Intersecting polygons present a problem
Even non-intersecting polygons can form a cycle with no valid visibility order:

Object Space Methods:
- Work in 3D before scan conversion
  - E.g. Painter’s algorithm
- Usually independent of resolution
  - Important to maintain independence of output device (screen/printer etc.)

Image Space Methods:
- Work on per-pixel/per fragment basis after scan conversion
  - Z-Buffer/Depth Buffer
- Much faster, but resolution dependent
The Z-Buffer Algorithm

- What happens if multiple primitives occupy the same pixel on the screen?
- Which is allowed to paint the pixel?

The Z-Buffer Algorithm

- Idea: retain depth after projection transform
  - Each vertex maintains z coordinate
    - Relative to eye point
    - To compute z per pixel use barycentric coordinates (next week)
## The Z-Buffer Algorithm

- Augment color framebuffer with Z-buffer
  - Also called depth buffer
  - Stores z value at each pixel
  - At frame beginning, initialize all pixel depths to $\infty$ (depth = far)
- When scan converting: interpolate depth (z) across polygon
- Check z-buffer before storing pixel color in framebuffer and storing depth in z-buffer
  - don’t write pixel if its z value is more distant than the z value already stored there

### Z-Buffer

- Store $(r,g,b,z)$ for each pixel
  - typically 8+8+8+24 bits, can be more

```plaintext
for all i,j {
    Depth[i,j] = MAX_DEPTH
    Image[i,j] = BACKGROUND_COLOUR
}
for all polygons P {
    for all pixels in P {
        if (Z_pixel < Depth[i,j]) {
            Image[i,j] = C_pixel
            Depth[i,j] = Z_pixel
        }
    }
}
```
Interpolating Z

- Use barycentric coordinates
  - Interpolate z like other parameters
    - E.g. color
    - Use one of three formulas shown
      - Plane/edge walk/barycentric

The Z-Buffer Algorithm (mid-70’s)

- History:
  - Object space algorithms were proposed when memory was expensive
  - First 512x512 framebuffer was >$50,000!

- Radical new approach at the time
  - The big idea:
    - Resolve visibility independently at each pixel
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Depth Test Precision

- Reminder: projective transformation maps eye-space z to generic z-range (NDC)
- Simple example:

\[
T \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & a & b \\ 0 & 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}
\]

- Thus:

\[
z_{NDC} = \frac{a \cdot z_{\text{eye}} + b}{z_{\text{eye}}} = a + \frac{b}{z_{\text{eye}}}
\]

- Therefore, depth-buffer essentially stores 1/z, rather than z!
- Issue with integer depth buffers
  - High precision for near objects
  - Low precision for far objects

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Depth Test Precision

- Low precision can lead to depth fighting for far objects
  - Two different depths in eye space get mapped to same depth in framebuffer
  - Which object “wins” depends on drawing order and scan-conversion
- Gets worse for larger ratios $f:n$
  - Rule of thumb: $f:n < 1000$ for 24 bit depth buffer
- With 16 bits cannot discern cm differences in objects at 1 km distance

Z-Buffer Algorithm Questions

- How much memory does the Z-buffer use?
- Does the image rendered depend on the drawing order?
- Does the time to render the image depend on the drawing order?
- How does Z-buffer load scale with visible polygons? with framebuffer resolution?
Z-Buffer Pros

- Simple!!
- Easy to implement in hardware
  - Hardware support in all graphics cards today
  - Polygons can be processed in arbitrary order
  - Easily handles polygon interpenetration

Z-Buffer Cons

- Poor for scenes with high depth complexity
  - Need to render all polygons, even if most are invisible
- Shared edges/overlaps handled inconsistently
  - Ordering dependent
Z-Buffer Cons

- Requires “lots” of memory
  - (e.g. 1280x1024x32 bits)
- Requires fast memory
  - Read-Modify-Write in inner loop
- Hard to simulate transparent polygons
  - We throw away color of polygons behind closest one
  - Works if polygons ordered back-to-front
    - Extra work throws away much of the speed advantage

Object Space Algorithms

- Determine visibility on object or polygon level
  - Using camera coordinates
- Resolution independent
  - Explicitly compute visible portions of polygons
- Early in pipeline
  - After clipping
- Requires depth-sorting
  - Painter’s algorithm
  - BSP trees
BSP Trees: Idea

- For any plane (3D) objects on the same side of plane as viewer CANNOT be occluded by objects on other side
- Idea:
  - Recursively split space by planes
  - Traverse resulting tree to establish rendering order
    - Test eye location w.r.t. each plane

Creating BSP Trees: Objects
**Splitting Objects**

- No bunnies were harmed in previous example
- But what if a splitting plane passes through an object?
  - Split the object; give half to each node

**Traversing BSP Trees**

- Tree creation independent of viewpoint
  - Preprocessing step
- Tree traversal uses viewpoint
  - Runtime, happens for many different viewpoints
BSP Trees: Viewpoint A

- decide independently at each tree vertex
- not just left or right child!
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BSP Trees: Viewpoint A

- Each plane divides world into near and far
  - For given viewpoint, decide which side is near and which is far
    - Check which side of plane viewpoint is on independently for each tree vertex
    - Tree traversal differs depending on viewpoint!
  - Recursive algorithm
    - Recurse on far side
    - Draw object
    - Recurse on near side
renderBSP(BSPtree *T)
    BSPtree *near, *far;
    if (eye on left side of T->plane)
        near = T->left; far = T->right;
    else
        near = T->right; far = T->left;
    renderBSP(far);
    if (T is a leaf node)
        renderObject(T)
    renderBSP(near);
BSP Trees: Viewpoint B

- Split along the plane defined by any polygon from scene
- Classify all polygons into positive or negative half-space of the plane
  - If a polygon intersects plane, split polygon into two and classify them both
- Recurse down the negative half-space
- Recurse down the positive half-space

BSP Tree Traversal: Polygons
BSP Demo

- Useful demo:
  - http://symbolcraft.com/graphics/bsp

Summary: BSP Trees

- Pros:
  - Simple, elegant scheme
  - Correct version of painter’s algorithm back-to-front rendering approach
  - Still very popular for video games

- Cons:
  - Slow(ish) to construct tree: $O(n \log n)$ to split, sort
  - Splitting increases polygon count: $O(n^2)$ worst-case
  - Computationally intense preprocessing stage restricts algorithm to static scenes

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In closed polyhedron you don’t see object “back” faces

Assumption
- Normals of faces point *out* from the object

Back Face Culling (object space)

Back Face Culling
- Determine back & front faces using sign of inner product \( n \cdot v \)
  \[ n \cdot v = n_x v_x + n_y v_y + n_z v_z = \|n\| \|v\| \cos \theta \]
- In a convex object:
  - Invisible back faces
  - All front faces entirely visible \( \Rightarrow \) solves hidden surfaces problem
- In non-convex object:
  - Invisible back faces
  - Front faces can be visible, invisible, or partially visible