Scan Conversion

COS 426, Spring 2018
Princeton University
3D Rendering Pipeline  (for direct illumination)

3D Primitives

  Modeling Transformation

    Lighting

      Viewing Transformation

        Projection Transformation

          Clipping

            Viewport Transformation

              Scan Conversion

                Image
Rasterization

• Scan conversion
  ◦ Determine which pixels to fill

• Shading
  ◦ Determine a color for each filled pixel

• Texture mapping
  ◦ Describe shading variation within polygon interiors

• Visible surface determination
  ◦ Figure out which surface is front-most at every pixel
Rasterization

- Scan conversion (last time)
  - Determine which pixels to fill

- Shading
  - Determine a color for each filled pixel

- Texture mapping
  - Describe shading variation within polygon interiors

- Visible surface determination
  - Figure out which surface is front-most at every pixel
Shading

- How do we choose a color for each filled pixel?

Emphasis on methods that can be implemented in hardware
Ray Casting

- Simplest shading approach is to perform independent lighting calculation for every pixel

\[ I = I_E + K_A I_{AL} + \sum_i \left( K_D (N \cdot L_i) I_i + K_S (V \cdot R_i)^n I_i \right) \]
Polygon Shading

- Can take advantage of spatial coherence
  - Illumination calculations for pixels covered by same primitive are related to each other

\[
I = I_E + K_A I_{AL} + \sum_i \left( K_D (N \cdot L_i) I_i + K_S (V \cdot R_i)^n I_i \right)
\]
Polygon Shading Algorithms

- Flat Shading
- Gouraud Shading
- Phong Shading
Flat Shading

- What if a faceted object is illuminated only by directional light sources and is either diffuse or viewed from infinitely far away

\[ I = I_E + K_A I_{AL} + \sum_i \left( K_D (N \cdot L_i) I_i + K_S (V \cdot R_i)^n I_i \right) \]
Flat Shading

- One illumination calculation per polygon
  - Assign all pixels inside each polygon the same color
Flat Shading

- Objects look like they are composed of polygons
  - OK for polyhedral objects
  - Not so good for smooth surfaces
Polygon Shading Algorithms

- Flat Shading
- **Gouraud Shading**
- Phong Shading
Gouraud Shading

- What if smooth surface is represented by polygonal mesh with a normal at each vertex?

\[ I = I_E + K_A I_{AL} + \sum_i \left( K_D (N \cdot L_i) I_i + K_S (V \cdot R_i)^n I_i \right) \]
Gouraud Shading

- Method 1: One lighting calculation per vertex
  - Assign pixels inside polygon by interpolating colors computed at vertices
Gouraud Shading

Bilinear interpolation of colors at vertices

• down and across scan lines = barycentric coords

\[ A = \alpha l_1 + (1-\alpha) l_3 \]
\[ B = \beta l_2 + (1-\beta) l_3 \]
\[ I = \phi A + (1-\phi) B \]
Gouraud Shading

- Smooth shading over adjacent polygons
  - Curved surfaces
  - Illumination highlights
  - Soft shadows

Mesh with shared normals at vertices
Gouraud Shading

- Produces smoothly shaded polygonal mesh
  - Piecewise linear approximation
  - Need fine mesh to capture subtle lighting effects
Polygon Shading Algorithms

• Flat Shading
• Gouraud Shading
• **Phong Shading** (≠ Phong reflectance model)
Phong Shading

- What if polygonal mesh is too coarse to capture illumination effects in polygon interiors?

\[ I = I_E + K_A I_{AL} + \sum_i \left( K_D (N \cdot L_i) I_i + K_S (V \cdot R_i)^n I_i \right) \]
Phong Shading

• One lighting calculation per pixel
  ◦ Approximate surface normals for points inside polygons by bilinear interpolation of normals from vertices
Phong Shading

Bilinear interpolation of surface normals at vertices

\[
A = \alpha N_1 + (1-\alpha)N_3
\]

\[
B = \beta N_2 + (1-\beta)N_3
\]

\[
I = \varphi A + (1-\varphi)B
\]
Polygon Shading Algorithms

Wireframe

Flat

Gouraud

Phong
Shading Issues

- Problems with interpolated shading:
  - Polygonal silhouettes still obvious
  - Perspective distortion (due to screen-space interpolation)
  - Problems computing shared vertex normals
  - Problems at T-junctions
Rasterization

• Scan conversion
  ◦ Determine which pixels to fill

• Shading
  ◦ Determine a color for each filled pixel

➢ Texture mapping
  ◦ Describe shading variation within polygon interiors

• Visible surface determination
  ◦ Figure out which surface is front-most at every pixel
Textures

- Describe color variation in interior of 3D polygon
  - When scan converting a polygon, vary pixel colors according to values fetched from a texture image

Angel Figure 9.3
Surface Textures

• Add visual detail to surfaces of 3D objects

Polygons model

With surface texture
Textures

- Add visual detail to surfaces of 3D objects

[Daren Horley]
Texture Mapping

- Steps:
  - Define texture
  - Specify mapping from texture to surface
  - Look up texture values during scan conversion

Texture Coordinate System

Modeling Coordinate System

Image Coordinate System
Texture Mapping

- When scan converting, map from …
  - image coordinate system \((x,y)\) to
  - modeling coordinate system \((u,v)\) to
  - texture image \((s,t)\)
Texture Mapping

- Texture mapping is a 2D projective transformation
  - texture coordinate system: \((s,t)\) to
  - image coordinate system \((x,y)\)
Texture Overview

• Texture mapping stages
  ◦ Parameterization
  ◦ Mapping
  ◦ Filtering

• Texture mapping applications
  ◦ Modulation textures
  ◦ Illumination mapping
  ◦ Bump mapping
  ◦ Environment mapping
  ◦ Image-based rendering
  ◦ Non-photorealistic rendering
Texture Overview

• Texture mapping stages
  ➢ Parameterization
    ○ Mapping
    ○ Filtering

• Texture mapping applications
  ○ Modulation textures
  ○ Illumination mapping
  ○ Bump mapping
  ○ Environment mapping
  ○ Image-based rendering
  ○ Non-photorealistic rendering
Texture Parameterization

geometry + image = texture map

• Q: How do we decide where on the geometry each color from the image should go?
Texture Parameterization
Texture Parameterization

Option 1: unfold the surface

[Ref: Piponi2000]
Texture Parameterization

Option 2: make an atlas

charts       atlas       surface

[Sander2001]
Texture Overview

• Texture mapping stages
  ◦ Parameterization
  ➢ Mapping
  ◦ Filtering

• Texture mapping applications
  ◦ Modulation textures
  ◦ Illumination mapping
  ◦ Bump mapping
  ◦ Environment mapping
  ◦ Image-based rendering
  ◦ Non-photorealistic rendering
Texture Mapping

• Scan conversion
  ◦ Interpolate texture coordinates down/across scan lines
  ◦ Distortion due to bilinear interpolation approximation
    › Cut polygons into smaller ones, or
    › Perspective divide at each pixel
Texture Mapping

Linear interpolation of texture coordinates

Correct interpolation with perspective divide

Hill Figure 8.42
Texture Overview

• Texture mapping stages
  ◦ Parameterization
  ◦ Mapping
  ➢ Filtering

• Texture mapping applications
  ◦ Modulation textures
  ◦ Illumination mapping
  ◦ Bump mapping
  ◦ Environment mapping
  ◦ Image-based rendering
  ◦ Non-photorealistic rendering
Texture Filtering

- Must **sample** texture to determine color at each pixel in image
Texture Filtering

- Aliasing is a problem

Point sampling

Area filtering
Texture Filtering

- Ideally, use elliptically shaped convolution filters

In practice, use rectangles or squares
Texture Filtering

• Size of filter depends on projective warp
  ◦ Compute prefILTERED images to avoid run-time cost
    » Mipmaps
    » Summed area tables
Mipmaps

- Keep textures prefILTERED at multiple resolutions
  - Usually powers of 2
  - For each pixel, linearly interpolate between two closest levels (i.e., trilinear filtering)
  - Fast, easy for hardware
Summed-area tables

- At each texel keep sum of all values down & right
  - To compute sum of all values within a rectangle, simply combine four entries: \( S_1 - S_2 - S_3 + S_4 \)
  - Better ability to capture oblique projections, but still not perfect

- (Mipmaps are more common.)
Texture Overview

• Texture mapping stages
  ◦ Parameterization
  ◦ Mapping
  ◦ Filtering

• Texture mapping applications
  ◦ Modulation textures
  ◦ Illumination mapping
  ◦ Bump mapping
  ◦ Environment mapping
  ◦ Image-based rendering
Modulation textures

Texture values scale result of lighting calculation

\[ I = T(s,t)(I_E + K_A I_A + \sum_L \left( K_D (N \cdot L) + K_S (V \cdot R)^n \right) S_L I_L + K_T I_T + K_S I_S) \]
Illumination Mapping

Map texture values to surface material parameter

- $K_A$
- $K_D$
- $K_S$
- $K_T$
- $n$

$$I = I_E + K_A I_A + \sum_L \left( K_D (s,t) (N \cdot L) + K_S (V \cdot R)^n \right) S_L I_L + K_T I_T + K_S I_S$$
Bump/Normal Mapping

Texture values perturb surface normals:

- Use gradient of grayscale image (“bump”)
- Encode normals (or offsets) in RGB
- Encode normal offsets in tangent space
Bump Mapping

H&B Figure 14.100
Normal Mapping

Original

Very many Polygons

Normal-Mapping

1 Polygon
Environment Mapping

Texture values are reflected off surface patch

H&B Figure 14.93

Gamer3D/Wikipedia
Image-Based Rendering

Map photographic textures to provide details for coarsely detailed polygonal model
Solid textures

Texture values indexed by 3D location (x,y,z)

• Expensive storage, or
• Compute on the fly, e.g. Perlin noise
Texture Summary

• Texture mapping stages
  ◦ Parameterization
  ◦ Mapping
  ◦ Filtering

• Texture mapping applications
  ◦ Modulation textures
  ◦ Illumination mapping
  ◦ Bump mapping
  ◦ Environment mapping
  ◦ Image-based rendering
  ◦ Volume textures
Rasterization

- **Scan conversion**
  - Determine which pixels to fill

- **Shading**
  - Determine a color for each filled pixel

- **Texture mapping**
  - Describe shading variation within polygon interiors

- **Visible surface determination**
  - Figure out which surface is front-most at every pixel
Visible Surface Determination

Make sure only front-most surface contributes to color at every pixel
Depth sort

“Painter’s algorithm”
- Sort surfaces in order of decreasing maximum depth
- Scan convert surfaces in back-to-front order, overwriting pixels

Diagram shows surfaces A, B, C, D, E sorted from front to back with respect to depth.
3D Rendering Pipeline

3D Primitives
  3D Modeling Coordinates
    Modeling Transformation
      3D World Coordinates
      Lighting
        3D World Coordinates
        Viewing Transformation
          3D Camera Coordinates
          Projection Transformation
            2D Screen Coordinates
            Clipping
              2D Screen Coordinates
              Viewport Transformation
                2D Image Coordinates
                Scan Conversion
                  Image
                  Depth sort

Depth sort comments
- O(n log n)
- Better with frame coherence?
- Implemented in software
- Render every polygon
- Often use BSP-tree or static list ordering
Z-Buffer

Maintain color & depth of closest object per pixel

- Framebuffer now RGBA\(_z\) – initialize \(z\) to far plane
- Update only pixels with depth closer than in \(z\)-buffer
- Depths are interpolated from vertices, just like colors
Z-Buffer comments

+ Polygons rasterized in any order
+ Process one polygon at a time
+ Suitable for hardware pipeline
- Requires extra memory for z-buffer
- Subject to aliasing (A-buffer)
  ○ Commonly in hardware
Hidden Surface Removal Algorithms

Figure 29. Characterization of ten opaque-object algorithms. A Comparison of the algorithms.

[Sutherland '74]
Rasterization Summary

• Scan conversion
  ◦ Sweep-line algorithm

• Shading algorithms
  ◦ Flat, Gouraud

• Texture mapping
  ◦ Mipmaps

• Visibility determination
  ◦ Z-buffer

This is all in hardware
GPU Architecture

GeForce 6 Series Architecture
Actually ...

- Graphics hardware is programmable

Device-level APIs:
- Applications Using DirectX
  - HLSL Compute Shaders
  - DirectX Compute
- Applications Using OpenCL
  - OpenCL C
  - OpenCL Driver
- Applications Using the CUDA Driver API
  - C for CUDA
  - C for CUDA Compute Kernels
  - C for CUDA Compute Functions
- Applications Using C, C++, Fortran, Java, Python, ...
  - C Runtime for CUDA

Language Integration:
- CUDA Driver
- PTX (ISA)

CUDA Support in OS Kernel

CUDA Parallel Compute Engines inside NVIDIA GPUs

www.nvidia.com/cuda
Trend ...

- GPU is general-purpose parallel computer

www.nvidia.com/cuda