Scan Conversion

COS 426, Spring 2019
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
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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

![Diagram of Gouraud Shading](image)
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

Flat Shading  Gouraud Shading
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

Demo: https://threejs.org/docs/scenes/material-browser.html#MeshPhongMaterial
**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

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➤ Texture mapping
  ◦ Describe shading variation within polygon interiors

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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
Textures

- Add visual detail to surfaces of 3D objects
Texture Mapping

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

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

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  ○ 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

[Paul Bourke]
Texture Parameterization

Option 1: unfold the surface

[Piponi2000]
Texture Parameterization

Option 2: make an atlas

charts  atlas  surface

[Sander2001]
Texture Overview

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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

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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

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

Map texture values to surface material parameter

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

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

Texture value
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

Gamer3D/Wikipedia

H&B Figure 14.93
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

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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
3D Rendering Pipeline

3D Primitives

Modeling Transformation

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Viewport Transformation

Scan Conversion

Image

3D Modeling Coordinates

3D World Coordinates

3D Camera Coordinates

2D Screen Coordinates

2D Image Coordinates

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

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

Only z-buffer and ray tracing commonly used today.

[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 Compute Kernels
  - OpenCL Driver

- Applications Using the CUDA Driver API
  - C for CUDA Compute Kernels
  - CUDA Driver
  - PTX (ISA)

Language Integration

- Applications Using C, C++, Fortran, Java, Python, ...
  - C for CUDA Compute Functions
  - C Runtime for CUDA

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