Announcements

• Many people have not filled out A2 Hours. Please do so - there is no late penalty and I want the data.

• A2 Artifact voting is up: see the Canvas announcement from Wednesday night. Don't forget to vote for your favorite!

• A1 revisions: push revisions and submit by Sunday night for up to half of deducted points back.
MidLateterm Exam

• Take-home exam out Friday 2/21
  Due Monday 2/24 at 10pm.

• Similar to the homeworks, but no collaboration and no google.
  • Book is ok. Writing code is ok.

• HW1 and HW2 will be returned ASAP
It's final project time!

- Final Project proposal includes:
  - Group members; one assigned as project manager.
  - Milestone deliverable (progress made by Wed 3/4)
  - Final deliverable (finished product by 3/13)
  - Rough roadmap

- Due on paper(!) by 11am Friday 2/21.
What's a good final project?

• Substantial extensions to A1, A2, or A3: (mesh processing tools; raytracing enhancements; advanced WebGL/shaders)

• Implementation of a topic we talked about but didn't appear in an assignment: (acceleration structures; scene graphs)

• Explore a topic we haven't touched on (yet): (animation; spline curves; manipulation; particle systems; global illumination)

• Interactive educational demos: (transformation/change of basis playground, interactive visualizations for barycentric coordinates or ray tracing)
Questions?
Graphics Pipeline: Overview

- **APPLICATION**
- **COMMAND STREAM**
- **VERTEX PROCESSING**
- **TRANSFORMED GEOMETRY**
- **RASTERIZATION**
- **FRAGMENTS**
- **FRAGMENT PROCESSING**
- **FRAMEBUFFER IMAGE**
- **DISPLAY**

3D transformations; shading

currency of primitives to pixels

blending, compositing, shading

user sees this
Graphics Pipeline: Overview

- **Application**
  - Command Stream
  - Vertex Processing
  - Transformed Geometry
  - Rasterization
  - Fragments
  - Fragment Processing
  - Framebuffer Image
  - Display

- 3D transformations; shading
- Conversion of primitives to pixels
- Blending, compositing, shading
- User sees this
Application sends geometric primitives to renderer (e.g., to GPU)

Vertices are transformed to image space (we've done lots of this!)

Primitives are converted into pixel-shaped "fragments"; values are interpolated across primitives.

Fragments are shaded, blended, and composited to determine pixel colors.

Pixel colors written to the framebuffer appear on the screen.
Command Stream

Application sends geometric primitives to renderer (e.g., to GPU)

**What primitives?**

- Points
- Line segments
  - and chains of connected line segments
- Triangles
- And that’s all!
  - Curves? Approximate them with chains of line segments
  - Polygons? Break them up into triangles
  - Curved surfaces? Approximate them with triangles
- Trend over the decades: toward minimal primitives
  - simple, uniform, repetitive: good for parallelism
Vertex Processing

Vertices are transformed to clip space
Vertex values are computed (we've done much of this part!)
Rasterization

- First job: enumerate the pixels covered by a primitive
  - which pixels fall inside triangle?
  - includes "clipping" content outside view volume
- Second job: interpolate values across the primitive
  - e.g. colors computed at vertices
  - e.g. normals at vertices
  - e.g. texture coordinates
Rasterization

**Rasterization algorithms: next week**

- First job: enumerate the pixels covered by a primitive
  - which pixels fall inside triangle?
  - includes "clipping" content outside view volume
- Second job: interpolate values across the primitive
  - e.g. colors computed at vertices
  - e.g. normals at vertices
  - e.g. texture coordinates

Rasterization algorithms: next week
Fragment Processing

- Hidden surface removal (occlusion) - only the closest object is drawn
- Per-fragment shading:
  - determine color of the pixel based on a shading model
  - diffuse color might come from a texture
- Blending, compositing - e.g.:
  - anti-aliasing
  - transparency / alpha blending
Fragment Processing

*Painter's algorithm; Z buffering: today*

- Hidden surface removal (occlusion) - only the closest object is drawn
- Per-fragment shading:
  - determine color of the pixel based on a shading model
  - diffuse color might come from a texture
- Blending, compositing - e.g.:
  - anti-aliasing
  - transparency / alpha blending
Hidden Surface Removal

Two motivations: realism and efficiency
Back face culling

• For closed shapes you will never see the inside
  — therefore only draw surfaces that face the camera
  — implement by checking $\mathbf{n} \cdot \mathbf{v} > 0$
Handling Occlusion

• What if multiple triangles are facing the viewer at different depths?

• **Painter's algorithm:** draw them back-to-front

• Topological sort on the occlusion graph:
  • if A ever occludes B, it must come after B in the drawing order
Handling Occlusion

• What if multiple triangles are facing the viewer at different depths?

• **Painter's algorithm:** draw them back-to-front

• Topological sort on the occlusion graph:
  • if A ever occludes B, it must come after B in the drawing order
Handling Occlusion

• What if multiple triangles are facing the viewer at different depths?
• **Painter's algorithm:** draw them back-to-front
• Topological sort on the occlusion graph:
  • if A ever occludes B, it must come after B in the drawing order

Works great if the ordering is easy to find...
Handling Occlusion

- What if multiple triangles are facing the viewer at different depths?
- **Painter's algorithm:** draw them back-to-front
- Topological sort on the occlusion graph:
  - if A ever occludes B, it must come after B in the drawing order

Works great if the ordering is easy to find...

... but often it isn't.
The z buffer

- In many (most) applications maintaining a z sort is too expensive
  - changes all the time as the view changes
  - many data structures exist, but complex
- Solution: draw in any order, keep track of closest
  - allocate extra channel per pixel to keep track of closest depth so far
  - when drawing, compare object’s depth to current closest depth and discard if greater
  - this works just like any other compositing operation
The z buffer

- another example of a memory-intensive brute force approach that works and has become the standard
- store z as an integer for speed and memory efficiency (at the expense of precision!)
Precision in z buffer: Throwback

\[ P = \begin{bmatrix}
  n & 0 & 0 & 0 & 0 \\
  0 & n & 0 & 0 & 0 \\
  0 & 0 & n + f & -fn & 0 \\
  0 & 0 & 1 & 0 & 0 \\
\end{bmatrix} \]

- The precision is distributed between the near and far clipping planes
  - this is why these planes have to exist
  - also why you can’t always just set them to very small and very large distances
- Generally use z’ (not world z) in z buffer
Interpolating in projection

linear interp. in screen space ≠ linear interp. in world (eye) space
Interpolating in projection

linear interp. in screen space ≠ linear interp. in world (eye) space
Interpolating in projection

linear interp. in screen space ≠ linear interp. in world (eye) space
Interpolating in projection

linear interp. in screen space ≠ linear interp. in world (eye) space
Interpolating in projection

linear interp. in screen space ≠ linear interp. in world (eye) space
Interpolating in projection

linear interp. in screen space ≠ linear interp. in world (eye) space
Interpolating in projection

linear interp. in screen space ≠ linear interp. in world (eye) space
Interpolating in projection

linear interp. in screen space ≠ linear interp. in world (eye) space

instead of using the smallest z, use the largest 1/z
OpenGL: One implementation of the graphics pipeline.
OpenGL: One implementation of the graphics pipeline.

And now: a highly abridged and only somewhat accurate history of OpenGL.
OpenGL: The Bad Old Days

• OpenGL was (still is) a state machine.

• Basic usage:

  1. Set flags for shading mode (Lambertian or Blinn-Phong), interpolation methods, depth buffer, ...

  2. Set GL to triangle mode

  3. Send vertices to GPU one at a time.

  4. Call draw function to draw to the screen.
OpenGL: Nowadays
OpenGL: Nowadays

- Send buffers full of data to GPU up front.
OpenGL: Nowadays

- Send buffers full of data to GPU up front.
- Tell GL how to interpret them (triangles, line segments, ...)

OpenGL: Nowadays

- Send buffers full of data to GPU up front.
- Tell GL how to interpret them (triangles, line segments, ...)
- GL executes custom-written vertex shader program on each vertex (to determine is location in clip space)
OpenGL: Nowadays

• Send buffers full of data to GPU up front.

• Tell GL how to interpret them (triangles, line segments, ...)

• GL executes custom-written vertex shader program on each vertex (to determine is location in clip space) = normalized device coordinates
OpenGL: Nowadays

• Send buffers full of data to GPU up front.

• Tell GL how to interpret them (triangles, line segments, ...)

• GL executes custom-written vertex shader program on each vertex (to determine is location in clip space) = normalized device coordinates

• GL rasterizes primitives into pixel-shaped fragments
OpenGL: Nowadays

- Send buffers full of data to GPU up front.
- Tell GL how to interpret them (triangles, line segments, ...)
- GL executes custom-written **vertex shader** program on each vertex (to determine its location in clip space) = normalized device coordinates
- GL **rasterizes** primitives into pixel-shaped **fragments**
- Execute custom-written **fragment shader** program on each fragment to determine its color.
OpenGL: Nowadays

• Send buffers full of data to GPU up front.

• Tell GL how to interpret them (triangles, line segments, ...)

• GL executes custom-written **vertex shader** program on each vertex (to determine is **location in clip space**) = **normalized device coordinates**

• GL **rasterizes** primitives into pixel-shaped **fragments**

• Execute custom-written **fragment shader** program on each fragment to determine its color.

• GL writes fragment colors to framebuffer pixels; neat things appear on your screen.
You are a user of OpenGL

Your tasks are:

• Send geometry

• Write vertex shader

• Write fragment shader

• Sit back and watch the pretty pictures happen.
OpenGL: Nowadays
OpenGL: Nowadays

- Send buffers full of data to GPU up front.
OpenGL: Nowadays

• Send buffers full of data to GPU up front.
• Tell GL how to interpret them (triangles, line segments, ...)
OpenGL: Nowadays

- Send buffers full of data to GPU up front.
- Tell GL how to interpret them (triangles, line segments, ...)
- GL executes custom-written \textit{vertex shader} program on each vertex (to determine is \textit{location in clip space})
OpenGL: Nowadays

- Send buffers full of data to GPU up front.
- Tell GL how to interpret them (triangles, line segments, ...)
- GL executes custom-written vertex shader program on each vertex (to determine its location in clip space) = normalized device coordinates
OpenGL: Nowadays

- Send buffers full of data to GPU up front.
- Tell GL how to interpret them (triangles, line segments, ...)
- GL executes custom-written vertex shader program on each vertex (to determine is location in clip space) = normalized device coordinates
- GL rasterizes primitives into pixel-shaped fragments
OpenGL: Nowadays

- Send buffers full of data to GPU up front.
- Tell GL how to interpret them (triangles, line segments, ...)
- GL executes custom-written vertex shader program on each vertex (to determine its location in clip space) = normalized device coordinates
- GL rasterizes primitives into pixel-shaped fragments
- Execute custom-written fragment shader program on each fragment to determine its color.
OpenGL: Nowadays

- Send buffers full of data to GPU up front.
- Tell GL how to interpret them (triangles, line segments, ...)
- GL executes custom-written **vertex shader** program on each vertex (to determine its **location in clip space**) = normalized device coordinates
- GL **rasterizes** primitives into pixel-shaped **fragments**
- Execute custom-written **fragment shader** program on each fragment to determine its color.
- GL writes fragment colors to framebuffer pixels; neat things appear on your screen.
Pipeline for minimal operation

- **Vertex stage** (input: position / vtx; color / tri)
  - transform position (object to screen space)
  - pass through color
- **Rasterizer**
  - pass through color
- **Fragment stage** (output: color)
  - write to color planes
Result of minimal pipeline

https://facultyweb.cs.wwu.edu/~wehrwes/courses/csci480_20w/pipeline_demo/
Pipeline for basic z buffer

- **Vertex stage** (input: position / vtx; color / tri)
  - transform position (object to screen space)
  - pass through color

- **Rasterizer**
  - interpolated parameter: \( z' \) (screen \( z \))
  - pass through color

- **Fragment stage** (output: color, \( z' \))
  - write to color planes only if interpolated \( z' < \) current \( z' \)
Result of z-buffer pipeline
Flat shading

- Shade using the real normal of the triangle
  - same result as ray tracing a bunch of triangles
- Leads to constant shading and faceted appearance
  - truest view of the mesh geometry

Plate II.29 Shutterbug. Individually shaded polygons with diffuse reflection (Sections 14.4.2 and 16.2.3). (Copyright © 1990, Pixar. Rendered by Thomas Williams and H.B. Siegel using Pixar’s PhotoRealistic RenderMan™ software.)
Pipeline for flat shading

• Vertex stage (input: position / vtx; color and normal / tri)
  – transform position and normal (object to eye space)
  – compute shaded color per triangle using normal
  – transform position (eye to screen space)

• Rasterizer
  – interpolated parameters: $z'$ (screen $z$)
  – pass through color

• Fragment stage (output: color, $z'$)
  – write to color planes only if interpolated $z' <$ current $z'$
Result of flat-shading pipeline
Gouraud shading

- Often we’re trying to draw smooth surfaces, so facets are an artifact
  - compute colors at vertices using vertex normals
  - interpolate colors across triangles
  - “Gouraud shading”
  - “Smooth shading”
Gouraud shading

- Often we’re trying to draw smooth surfaces, so facets are an artifact
  - compute colors at vertices using vertex normals
  - interpolate colors across triangles
  - “Gouraud shading”
  - “Smooth shading”
Pipeline for Gouraud shading

- **Vertex stage** (input: position, color, and normal / vtx)
  - transform position and normal (object to eye space)
  - compute shaded color per vertex
  - transform position (eye to screen space)

- **Rasterizer**
  - interpolated parameters: \( z' \) (screen \( z \)); \( r, g, b \) color

- **Fragment stage** (output: color, \( z' \))
  - write to color planes only if interpolated \( z' < \) current \( z' \)
Result of Gouraud shading pipeline
Some possible efficiency hacks:

- Blinn-Phong model requires knowing
  - normal
  - light direction
  - view direction

- Hack: use directional lights so \( L \) doesn't change

- Hack: pretend viewer is infinitely distant so view direction doesn't change either.
Some possible efficiency hacks:

• Blinn-Phong model requires knowing
  – normal
  – light direction
  – view direction

• Hack: use directional lights so $\mathbf{l}$ doesn't change

• Hack: pretend viewer is infinitely distant so view direction doesn't change either.
Non-diffuse Gouraud shading

- Can apply Gouraud shading to any illumination model
  - it’s just an interpolation method
- Results are not so good with fast-varying models like specular ones
  - problems with any highlights smaller than a triangle
  - (demo)
Per-pixel (Phong) shading

• Get higher quality by interpolating the normal
  – just as easy as interpolating the color
  – but now we are evaluating the illumination model per pixel rather than per vertex (and normalizing the normal first)
  – in pipeline, this means we are moving illumination from the vertex processing stage to the fragment processing stage
Per-pixel (Phong) shading

• Bottom line: produces much better highlights
Pipeline for per-pixel shading

- **Vertex stage** (input: position, color, and normal / vtx)
  - transform position and normal (object to eye space)
  - transform position (eye to screen space)
  - pass through color

- **Rasterizer**
  - interpolated parameters: \( z' \) (screen \( z \)); \( r, g, b \) color; \( x, y, z \) normal

- **Fragment stage** (output: color, \( z' \))
  - compute shading using interpolated color and normal
  - write to color planes only if interpolated \( z' < \) current \( z' \)
Result of per-pixel shading pipeline