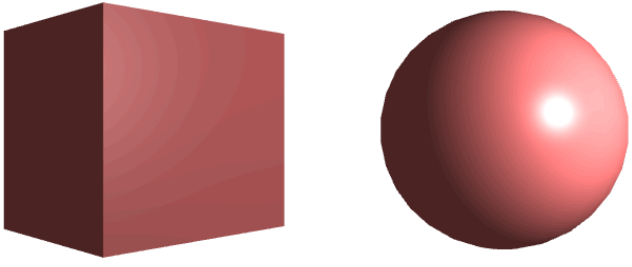


Computer Graphics

Lecture 21

The Graphics Pipeline

Announcements

- A2 artifact voting is open - see Canvas announcement; voting closes Monday night

~~Mid~~Lateterm Exam

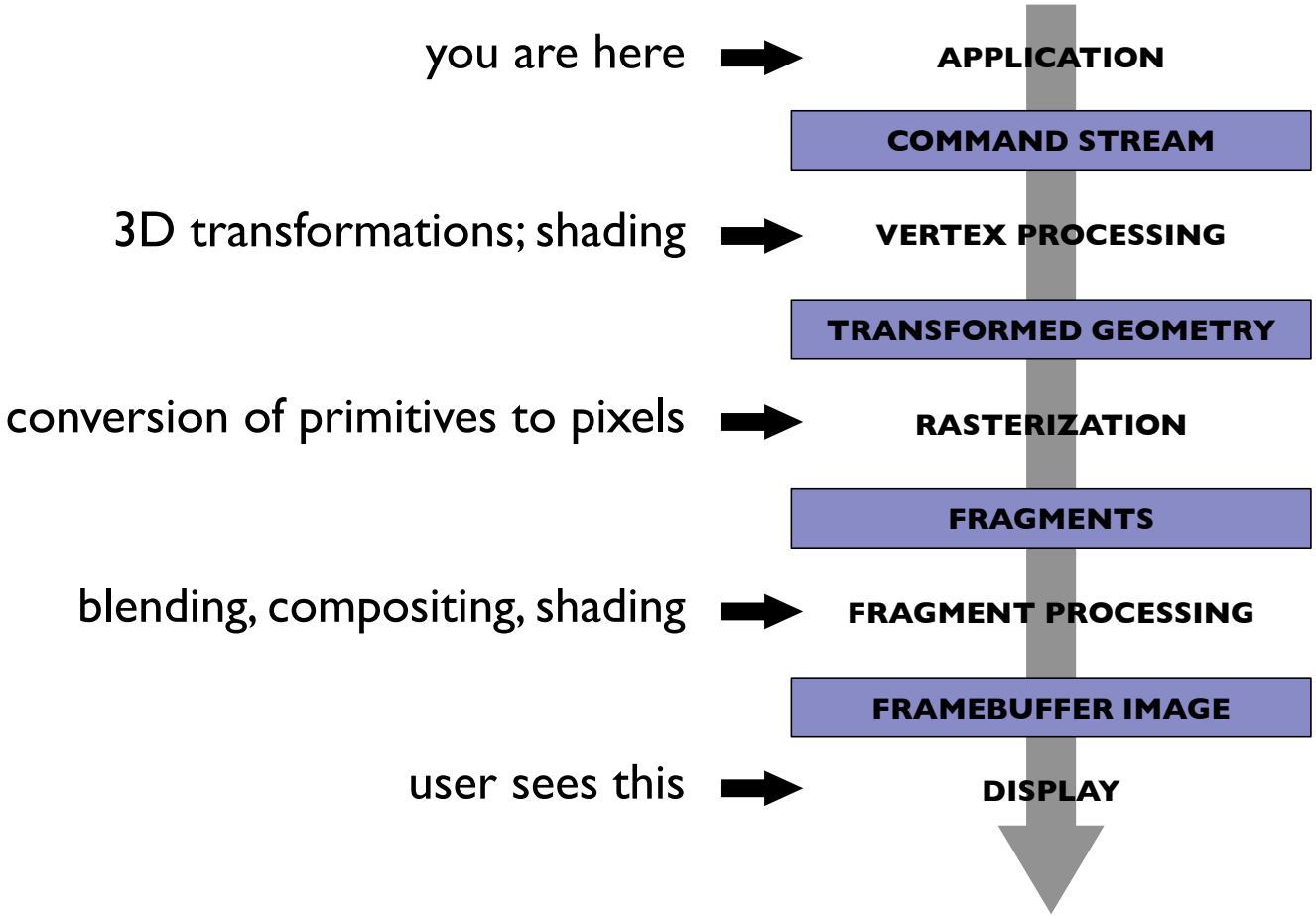
- Take-home exam out Friday 2/19
  Due Monday 2/22 at 10pm.
- Similar to the homeworks, but no collaboration and no google.
  - Book is ok. Writing code is ok.

Final Project

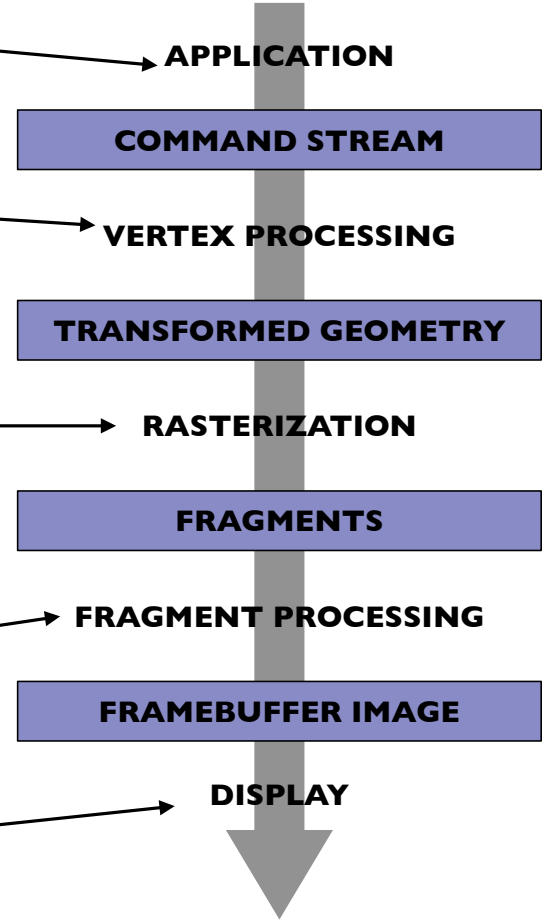
- Proposals due in **1 week**.

Questions?

Graphics Pipeline: Overview

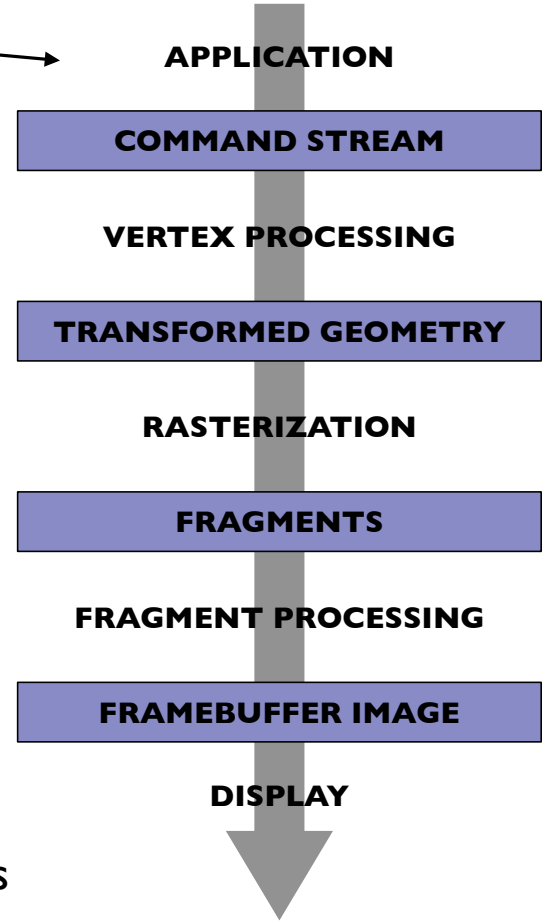


- Application sends geometric primitives to renderer (e.g., to GPU)
- Vertices are transformed to image space (we've done lots of this!)
- Primitives are converted into pixel-shaped "fragments"; values are interpolated across primitives.
- Fragments are shaded, blended, and composited to determine pixel colors.
- Pixel colors written to the framebuffer appear on the screen.



Command Stream

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

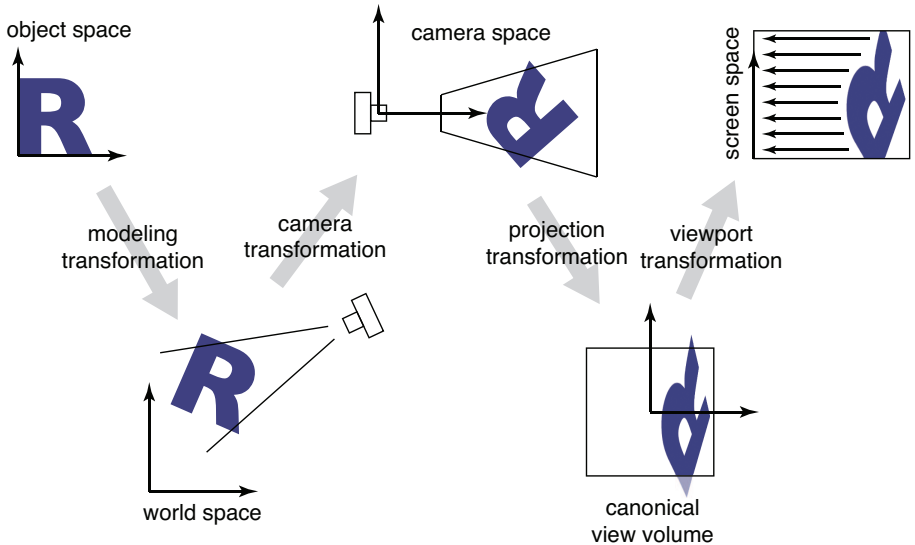


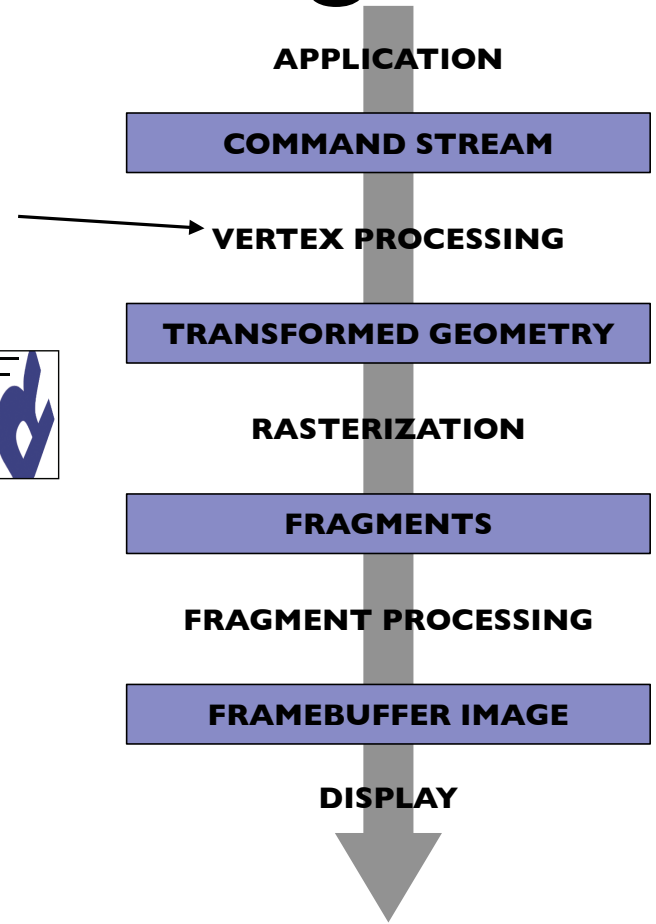
What primitives?

- 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!)

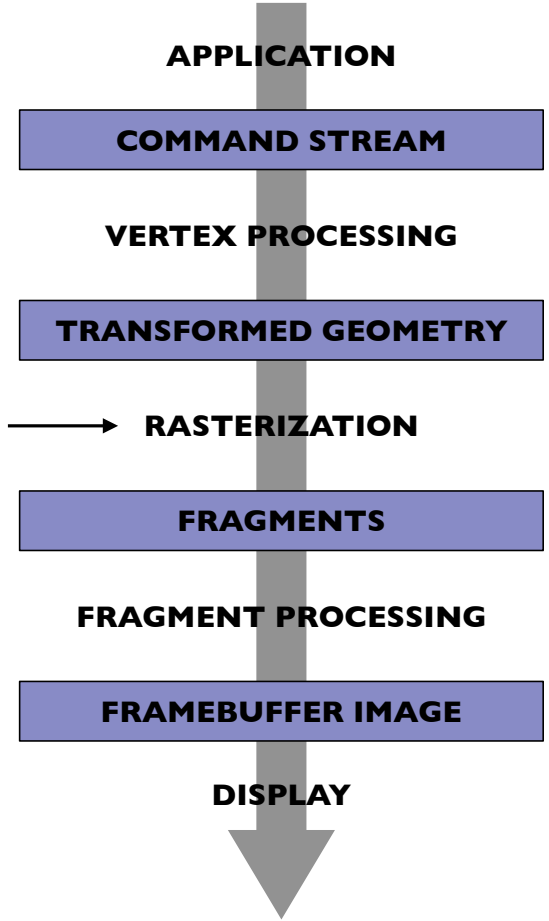


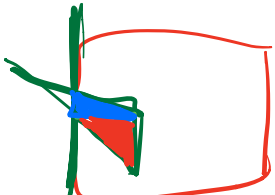


Rasterization

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

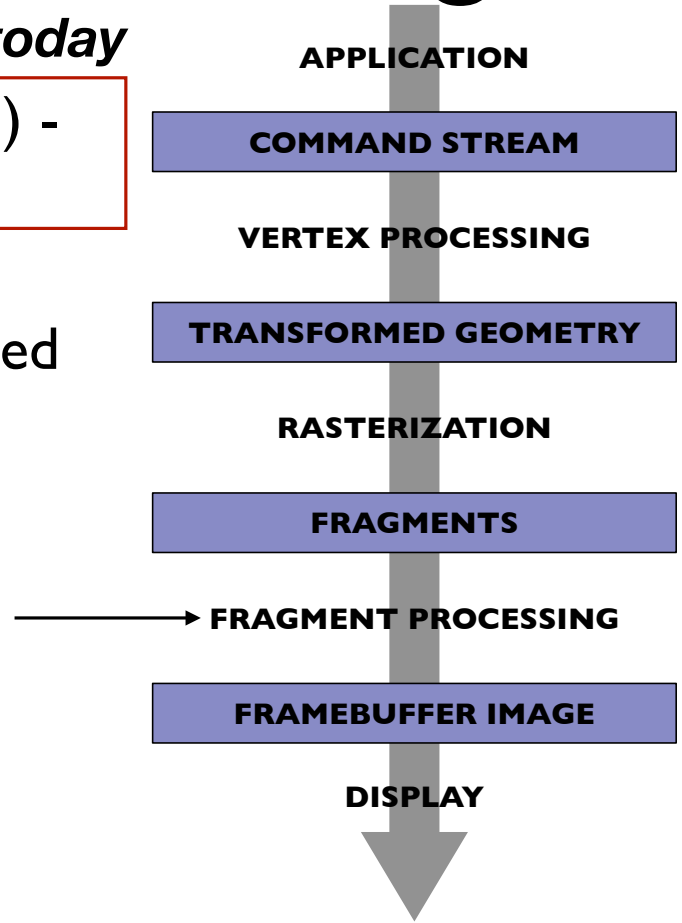




Fragment Processing

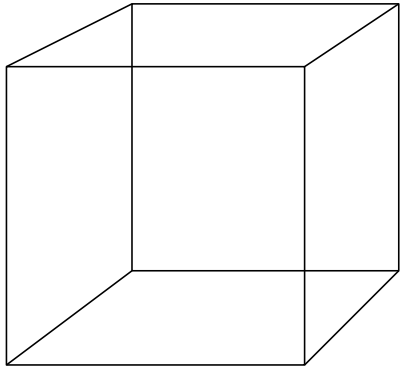
Painter's algorithm; Z buffering: today

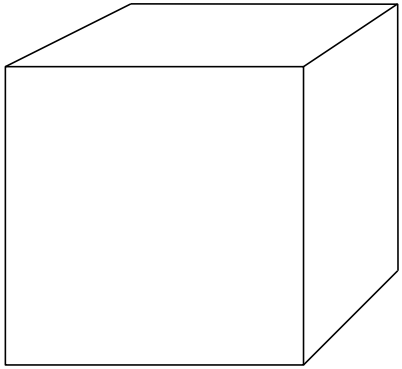
- Hidden surface removal (occlusion) - only the closest object is drawn
- Per-fragment shading:
  - determine color of the pixel based on a shading model
  - diffuse color might come from a texture
- Blending, compositing - e.g.:
  - anti-aliasing
  - transparency / alpha blending



Hidden Surface Removal

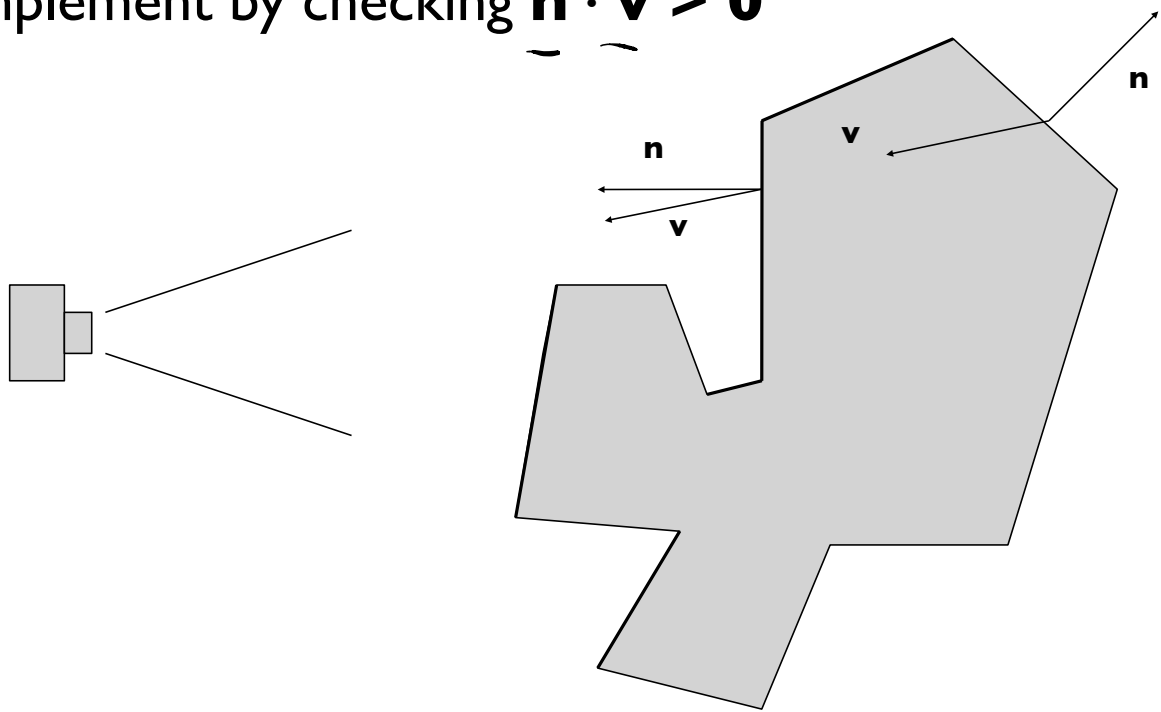
Two motivations: realism **and** efficiency





Back face culling

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

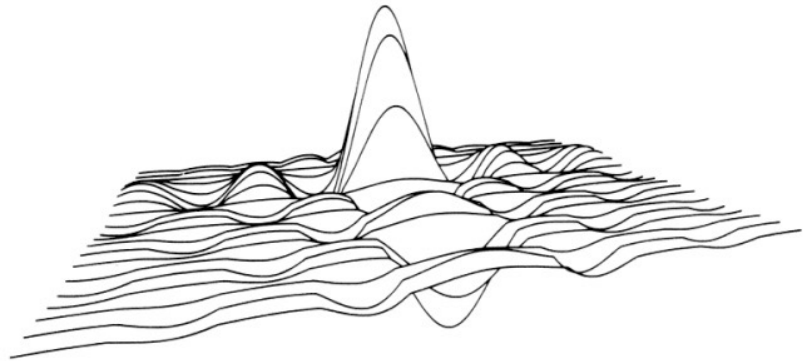


Handling Occlusion

- 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

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

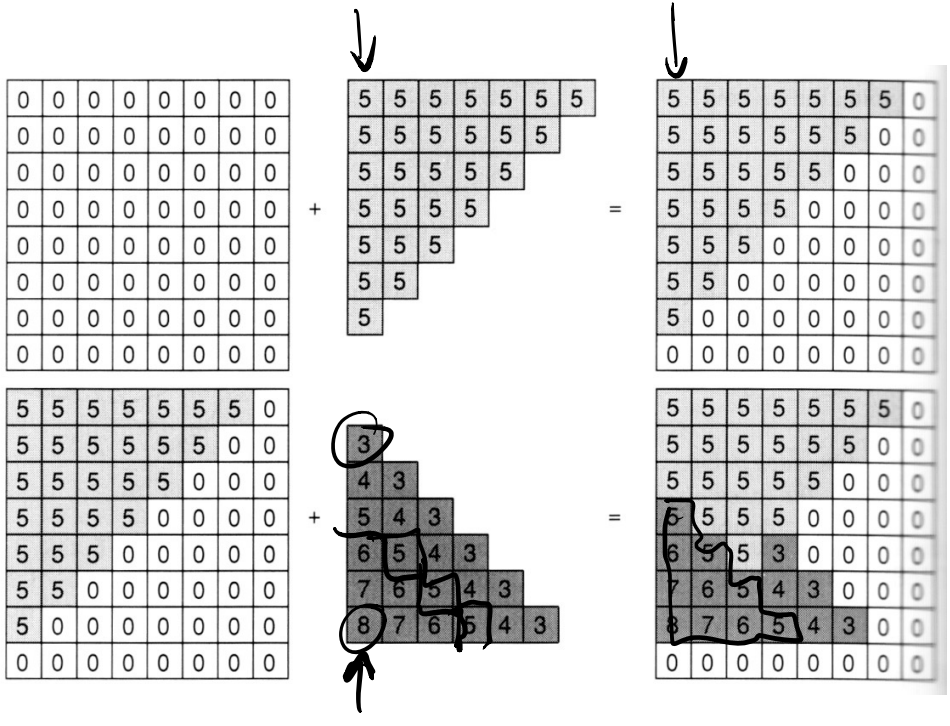
... but often it isn't.
Example: z.obj



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

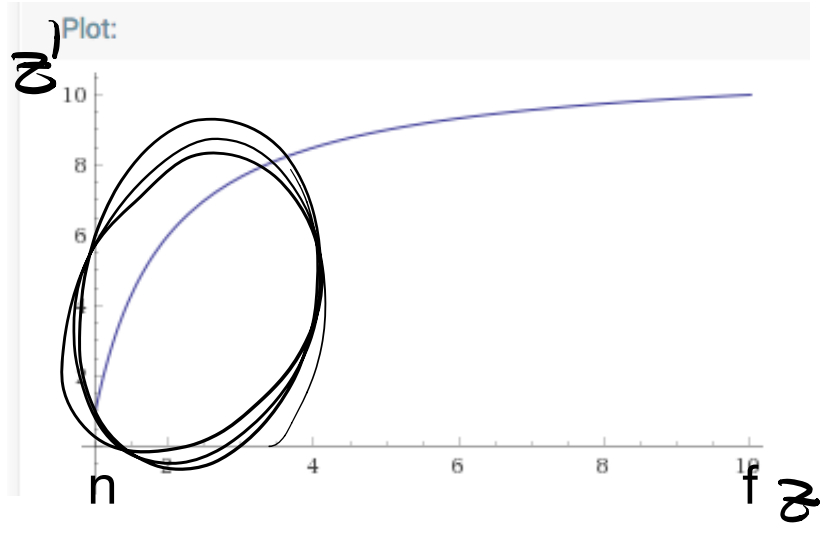


[Foley et al.]

- 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!)

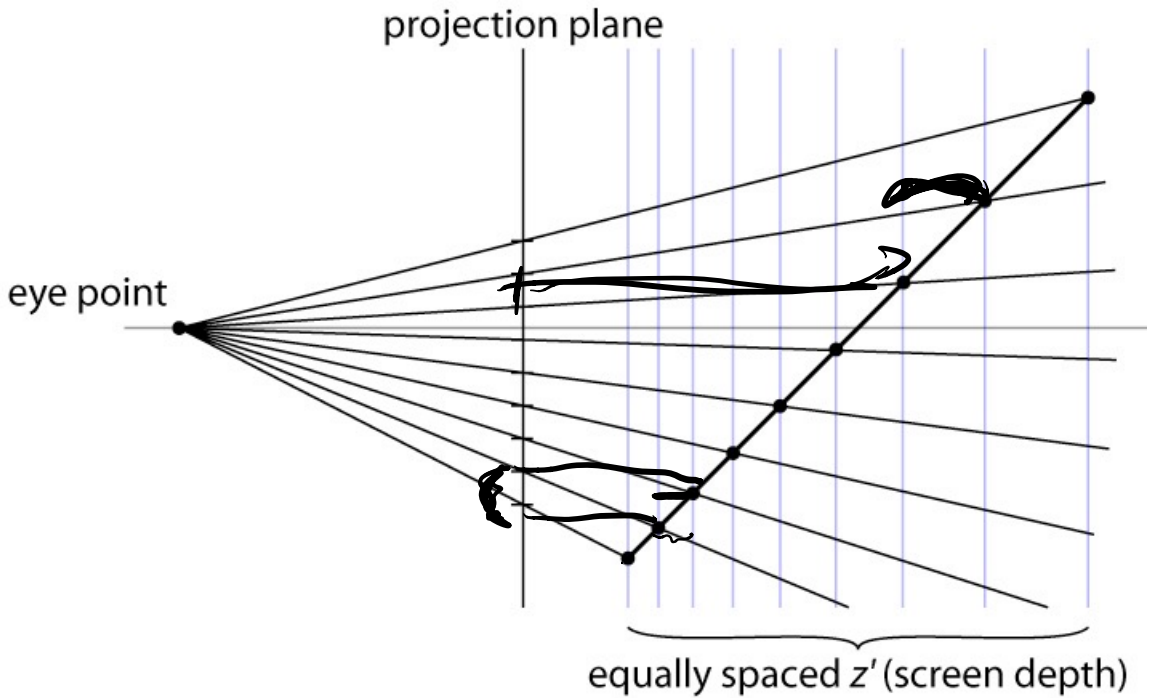
Precision in z buffer: Throwback

$$\mathbf{P} = \begin{bmatrix} n & 0 & 0 & 0 \\ 0 & n & 0 & 0 \\ 0 & 0 & \boxed{n+f} & \boxed{-fn} \\ 0 & 0 & 1 & 0 \end{bmatrix}$$



- 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

instead of using the smallest z, use the largest 1/z

$$\mathbf{P} = \begin{bmatrix} n & 0 & 0 & 0 \\ 0 & n & 0 & 0 \\ 0 & 0 & n+f & -fn \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix}$$

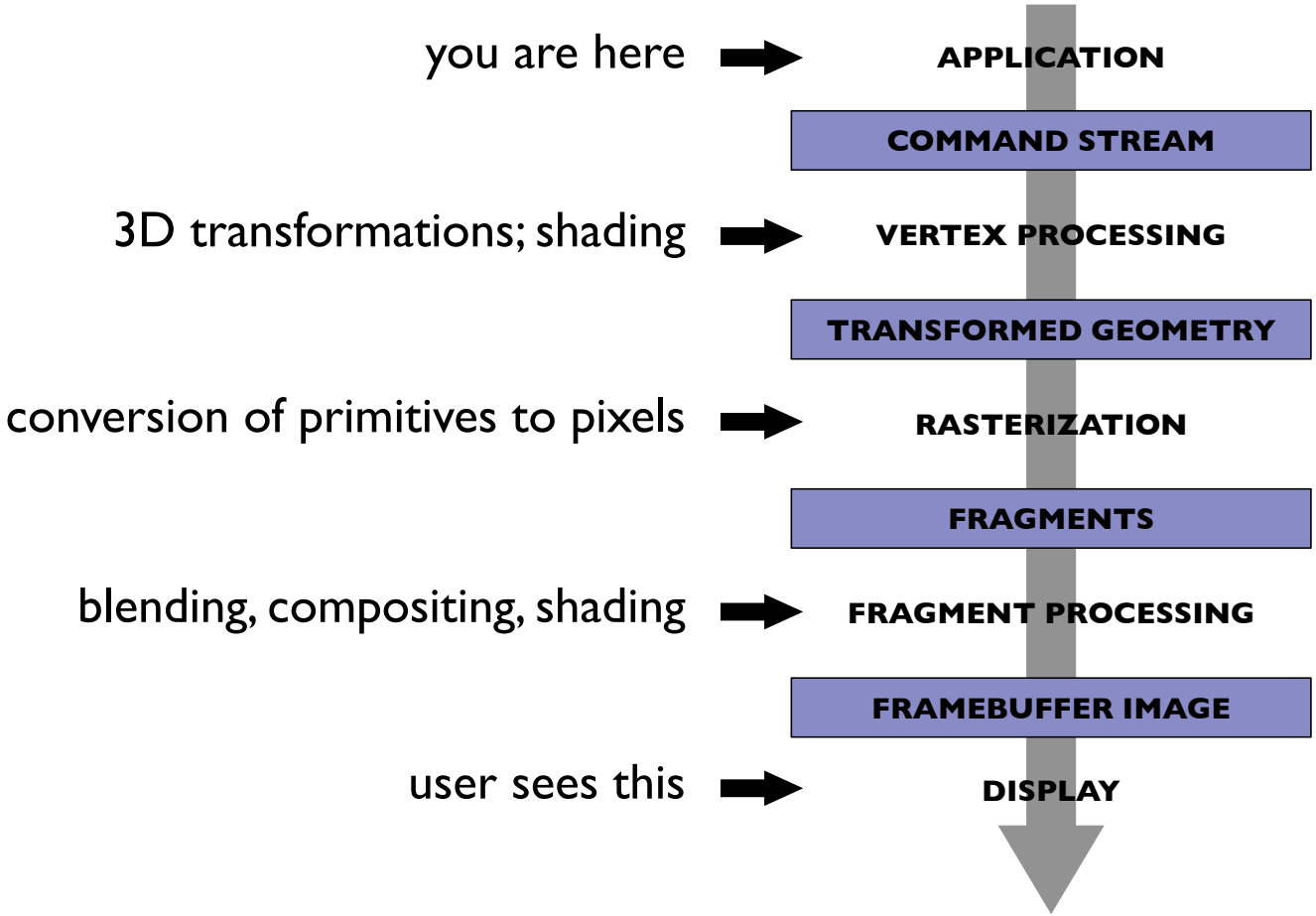
$z = 1$

$$z' = n + f - \frac{fn}{z}$$

$$= k_1 - k\frac{1}{z}$$

$\frac{-1}{z'} \propto z$ $\quad z' \propto \frac{-1}{z}$

Graphics Pipeline: Overview



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

- 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: Your job, conceptually

(send geometry)

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

(write vertex shader)

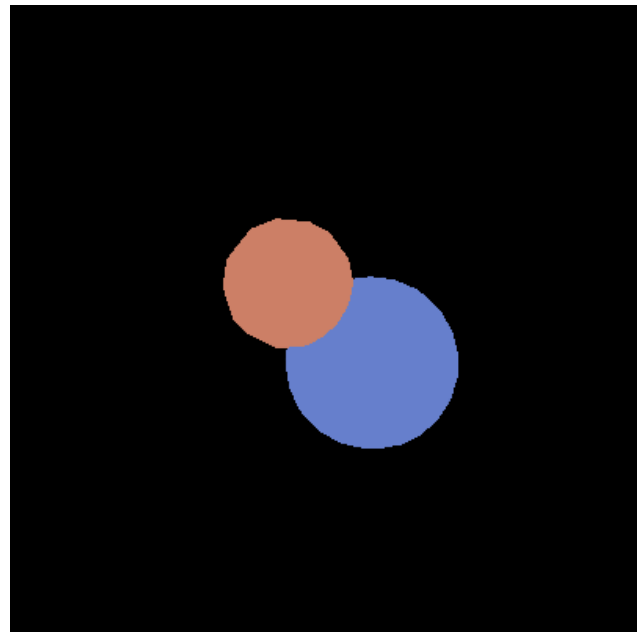
- GL executes custom-written **vertex shader** program on each vertex (to determine is **location in clip space**) *= normalized device coordinates*
- GL **rasterizes** primitives into pixel-shaped **fragments**

(write fragment shader)

- 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.

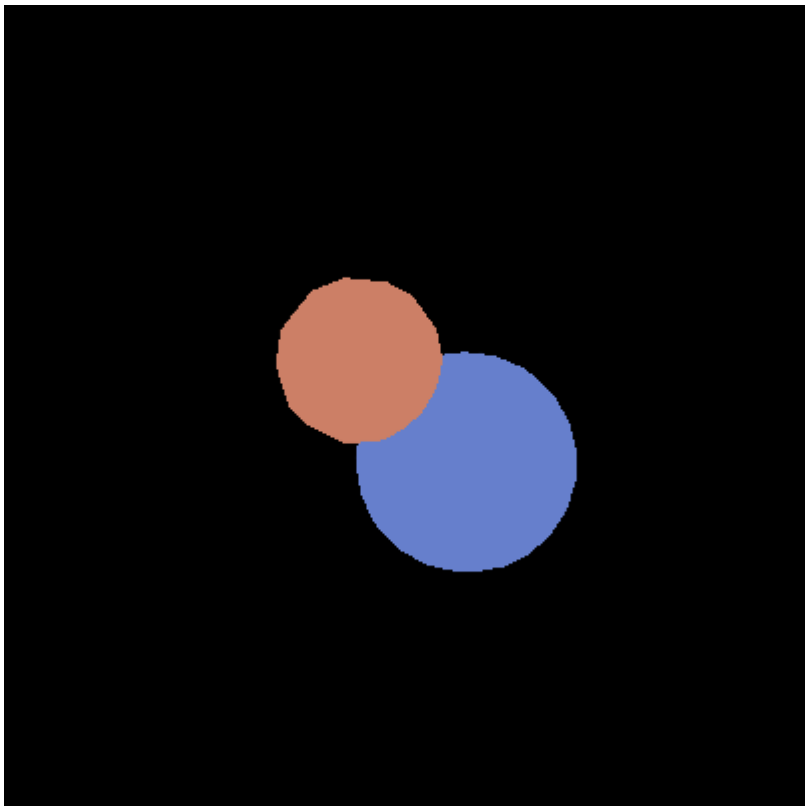
Pipeline for minimal operation

- 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_21w/pipeline_demo/

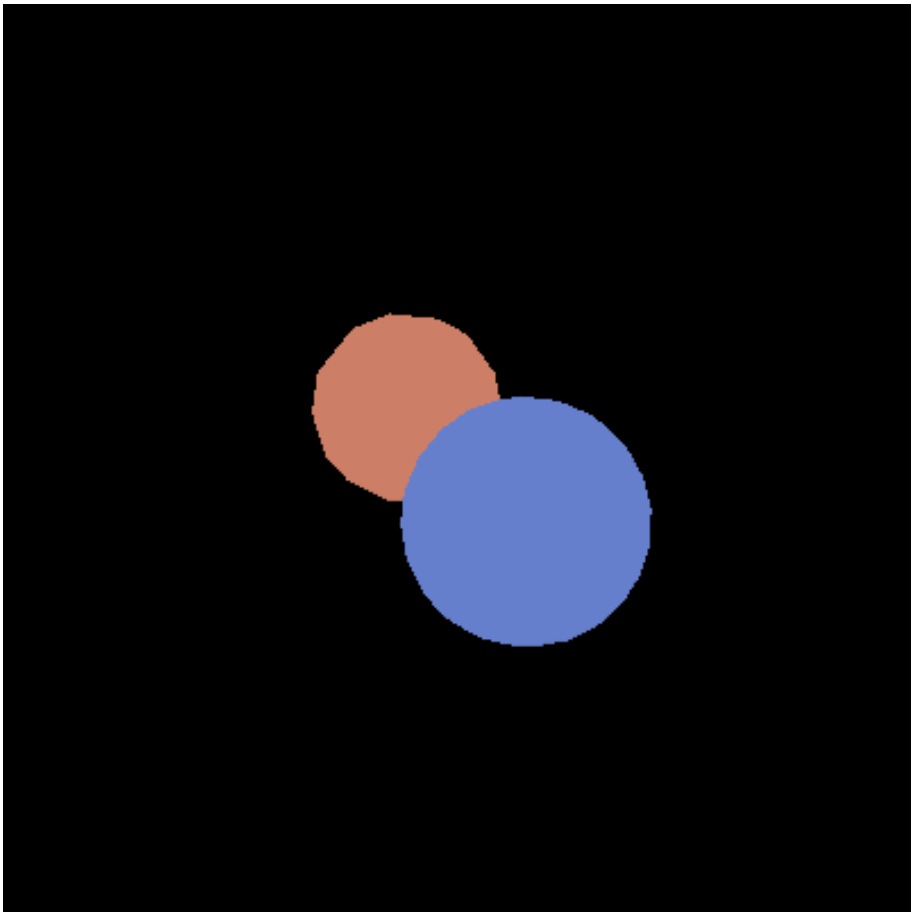


From drop-down select "constant color without depth".

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



From drop-down select "constant color with depth".

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

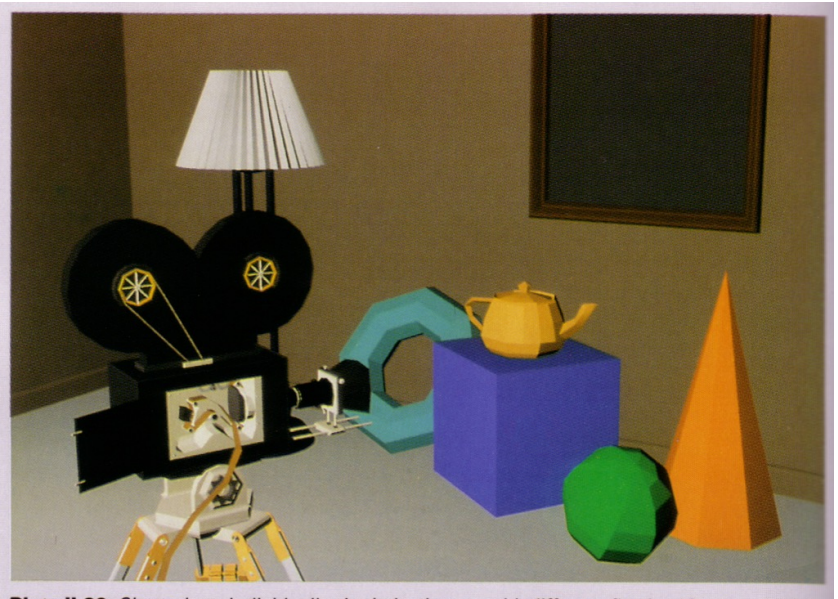


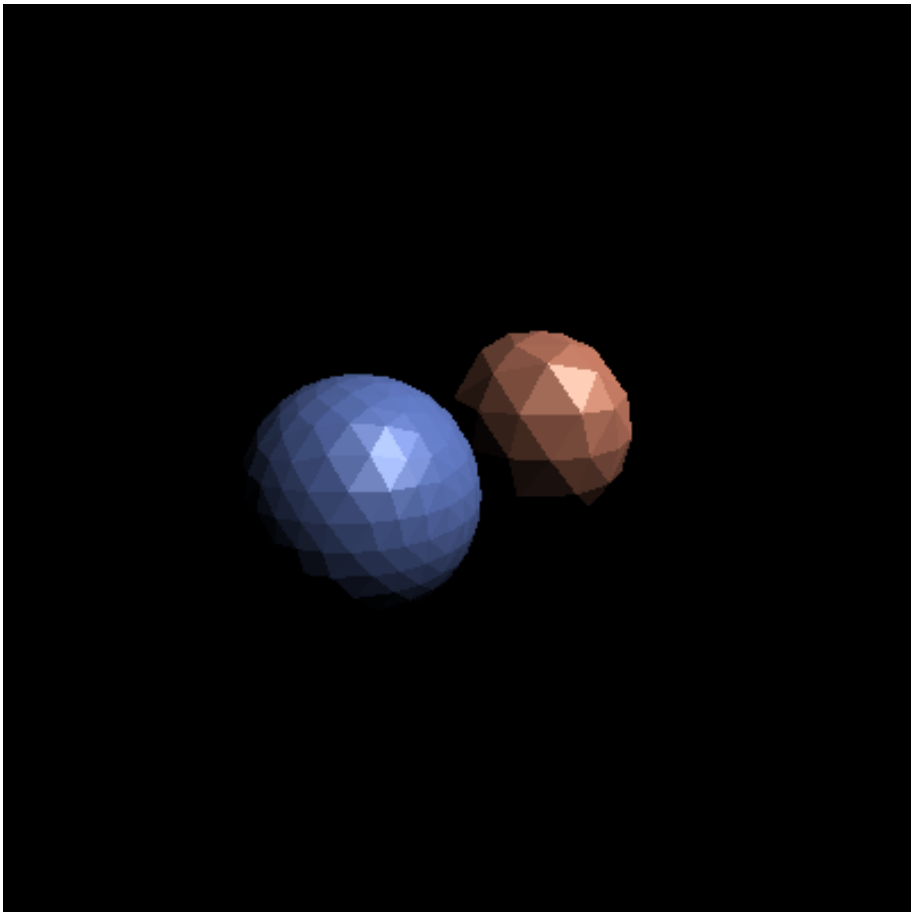
Plate II.29 *Shutterbug.* Individually shaded polygons with diffuse reflection (Sections 14.4.2 and 16.2.3). (Copyright © 1990, Pixar. Rendered by Thomas Williams and H.B. Siegel using Pixar's PhotoRealistic RenderMan™ software.)

[Foley et al.]

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'

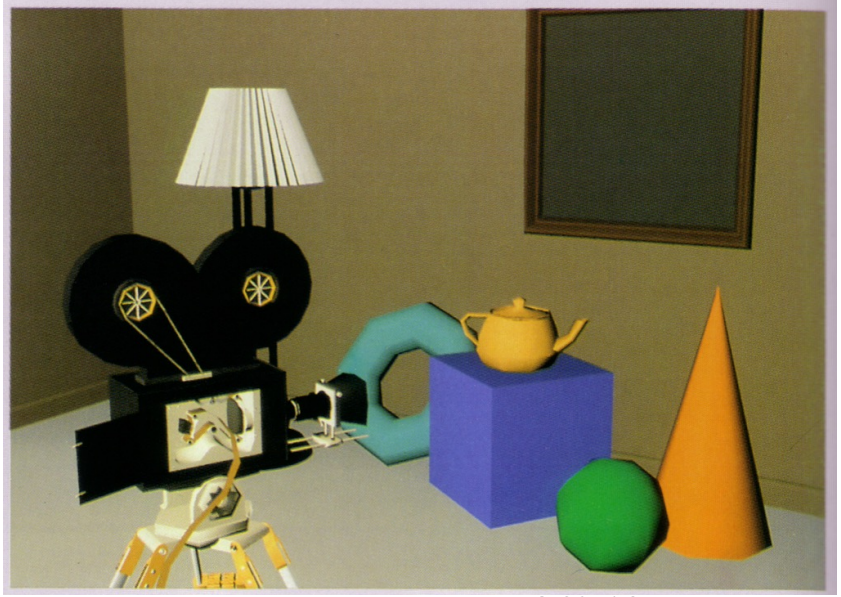
Result of flat-shading pipeline



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"

Plate II.30 *Shutterbug.* Gouraud shaded polygons with diffuse reflection (Sections 14.4.3 and 16.2.4). (Copyright © 1990, Pixar. Rendered by Thomas Williams and H.B. Siegel using Pixar's PhotoRealistic RenderMan™ software.)

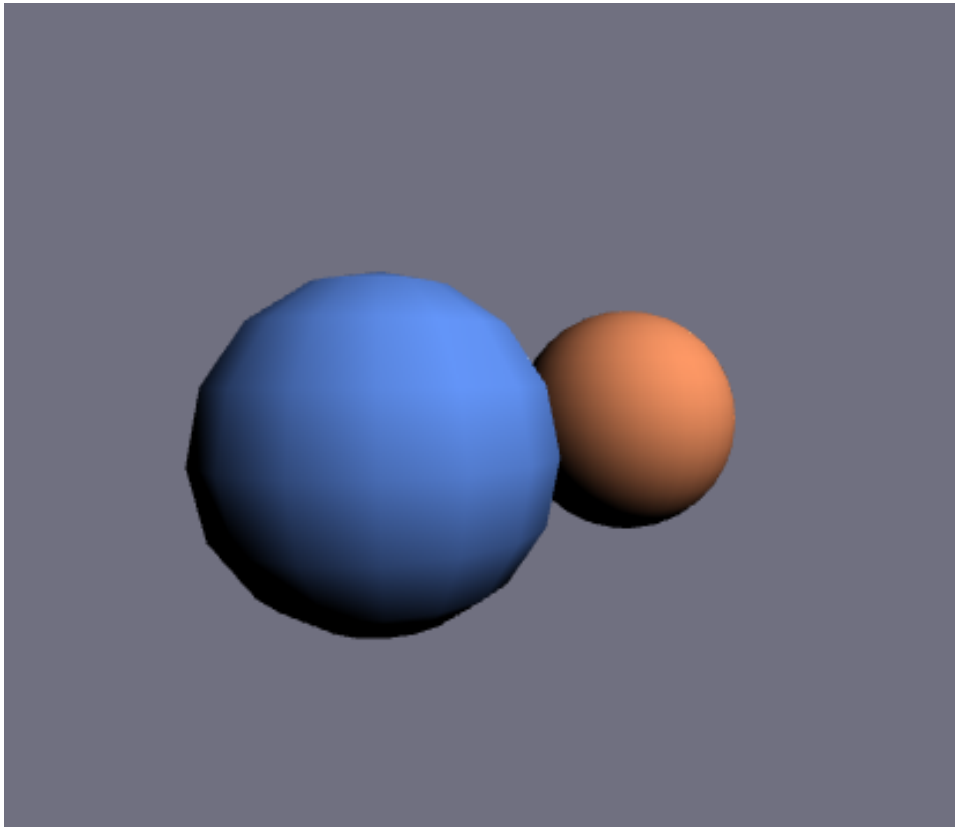


[Foley et al.]

Pipeline for Gouraud shading

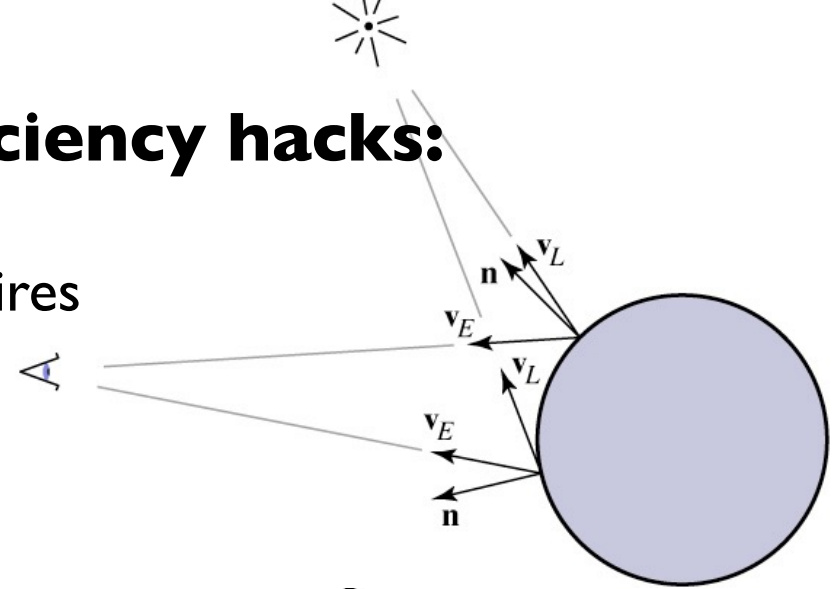
- Vertex stage (input: position, color, and normal / vtx)
  - transform position and normal (object to eye space)
  - compute shaded color per vertex
  - transform position (eye to screen space)
- Rasterizer
  - interpolated parameters: *z'* (screen *z*); *r, g, b* color
- Fragment stage (output: color, *z'*)
  - write to color planes only if interpolated *z'* < current *z'*

Result of Gouraud shading pipeline



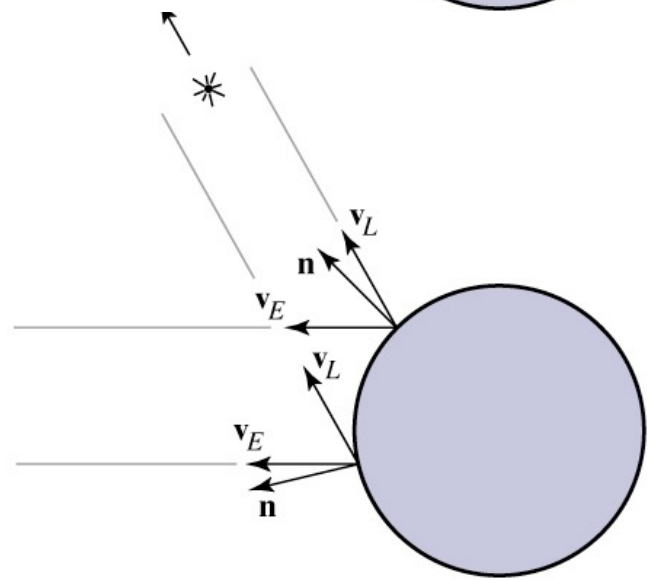
Some possible efficiency hacks:

- 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.



Non-diffuse Gouraud shading

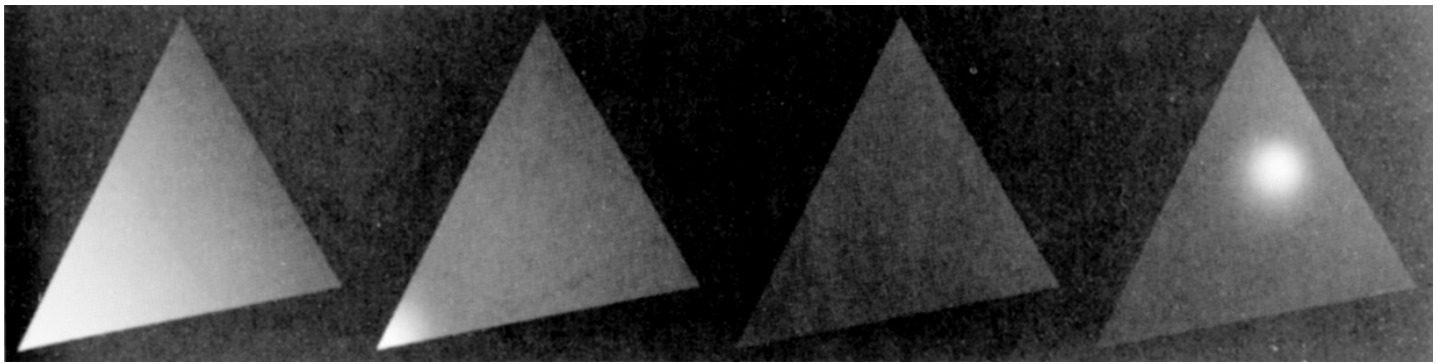
- Can apply Gouraud shading to any illumination model
  - it's just an interpolation method
- Results are not so good with fast-varying models like specular ones
  - problems with any highlights smaller than a triangle
  - (demo)

Plate II.31 *Shutterbug.* Gouraud shaded polygons with specular reflection (Sections 14.4.4 and 16.2.5). (Copyright © 1990, Pixar. Rendered by Thomas Williams and H.B. Siegel using Pixar's PhotoRealistic RenderMan™ software.)

[Foley et al.]

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

tterbug. Gouraud shaded polygons with specular reflection (Sections 14.4.4
yright © 1990, Pixar. Rendered by Thomas Williams and H.B. Siegel using
listic RenderMan™ software.)

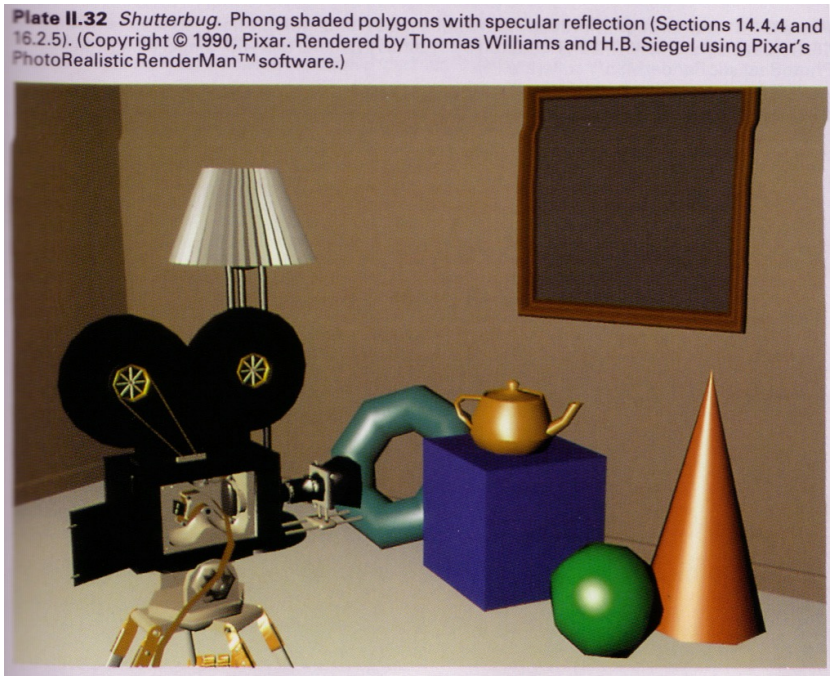


Plate II.32 *Shutterbug.* Phong shaded polygons with specular reflection (Sections 14.4.4 and 16.2.5). (Copyright © 1990, Pixar. Rendered by Thomas Williams and H.B. Siegel using Pixar's PhotoRealistic RenderMan™ software.)

[Foley et al.]

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