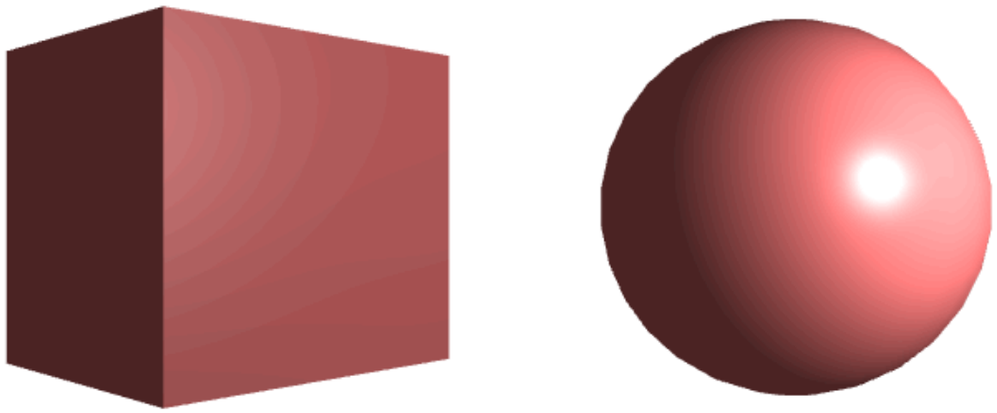


Computer Graphics

Lecture 19

The Graphics Pipeline

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.

~~Mid~~Lateterm 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!

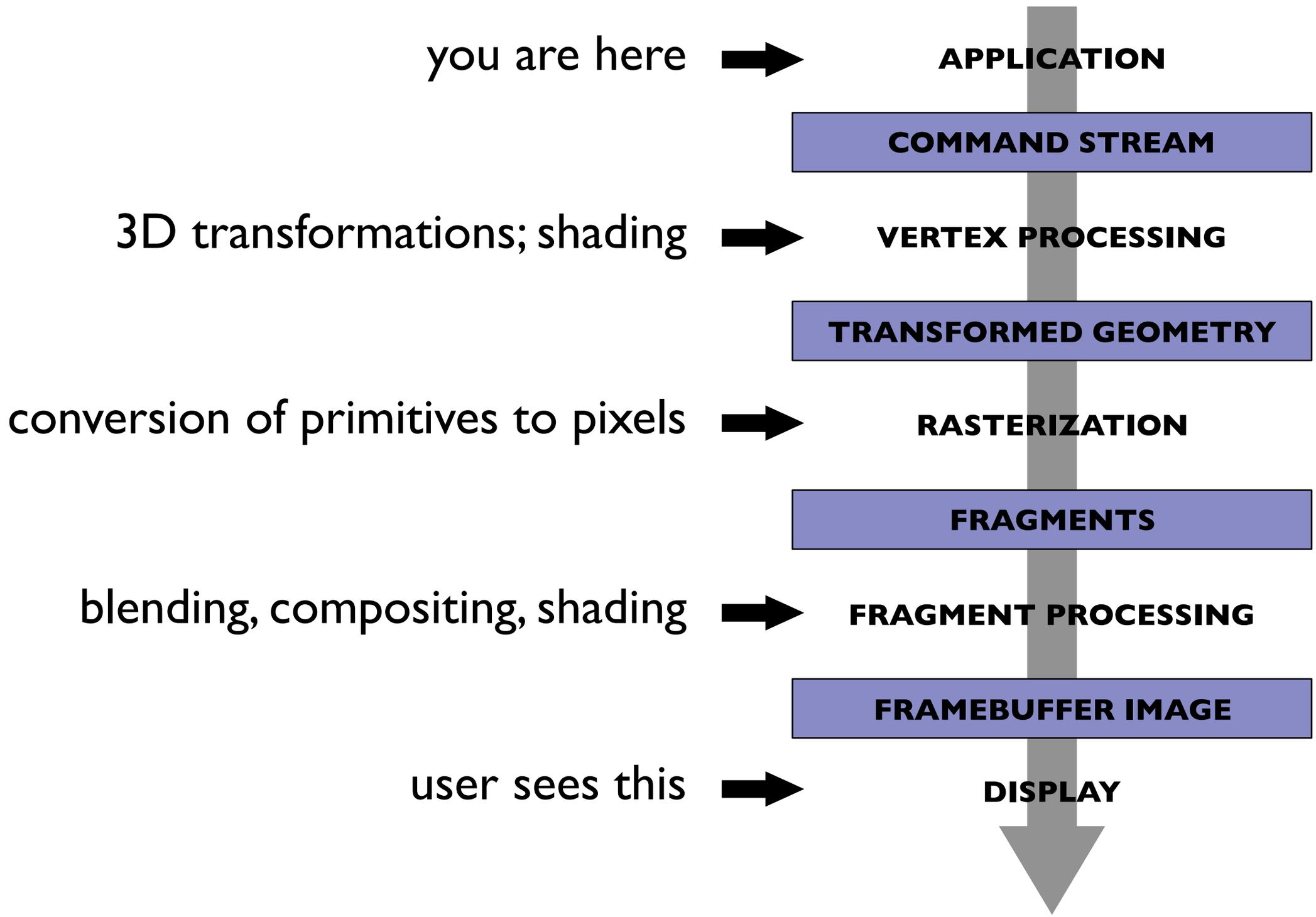
- Final Project proposal includes:
  - Group members; one assigned as project manager.
  - Milestone deliverable (progress made by Wed 3/4)
  - Final deliverable (finished product by 3/13)
  - Rough roadmap
- Due on paper(!) by 11am Friday 2/21.

What's a good final project?

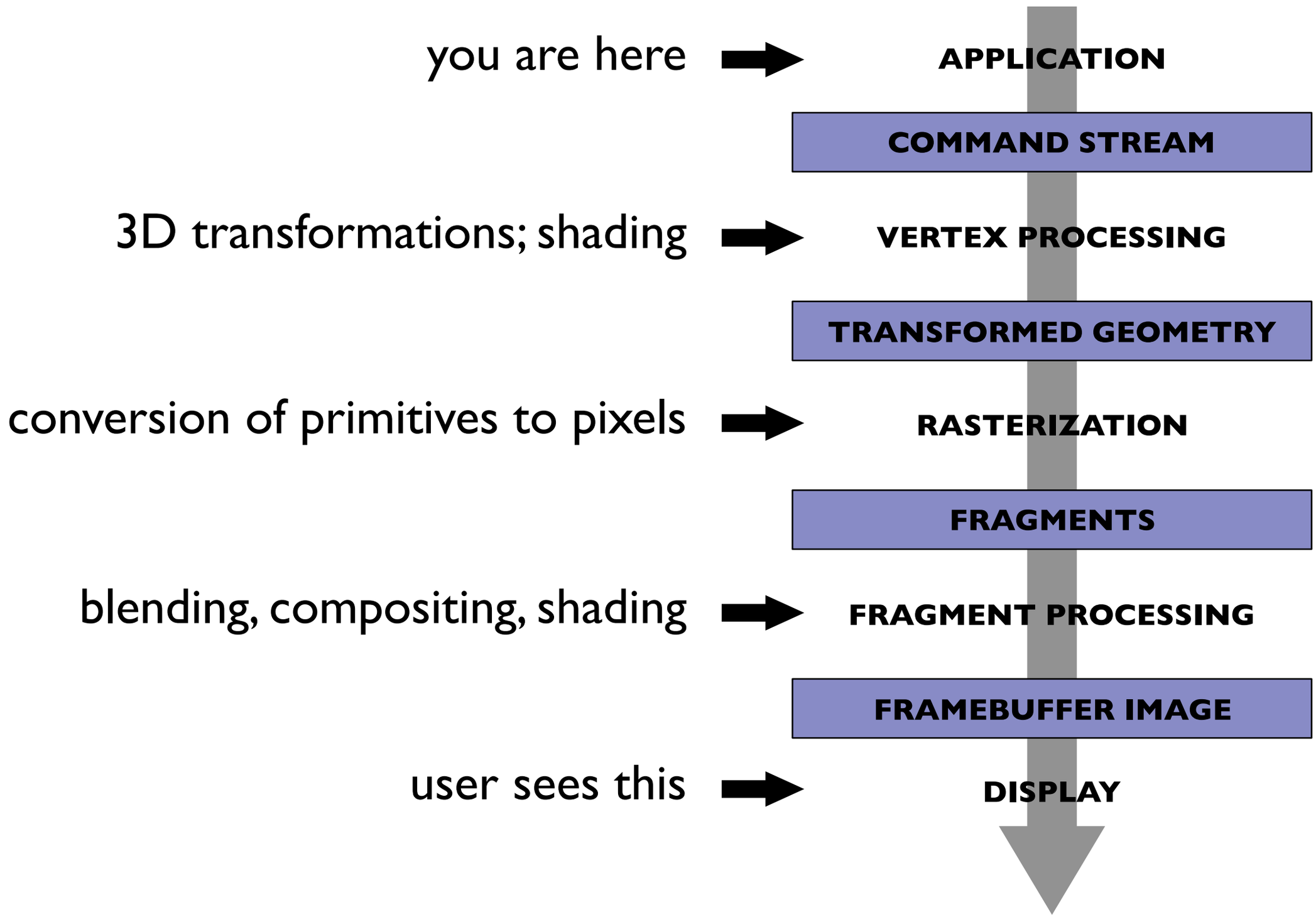
- Substantial extensions to A1, A2, or A3: (mesh processing tools; raytracing enhancements; advanced WebGL/shaders)
- Implementation of a topic we talked about but didn't appear in an assignment: (acceleration structures; scene graphs)
- Explore a topic we haven't touched on (yet): (animation; spline 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



Graphics Pipeline: Overview



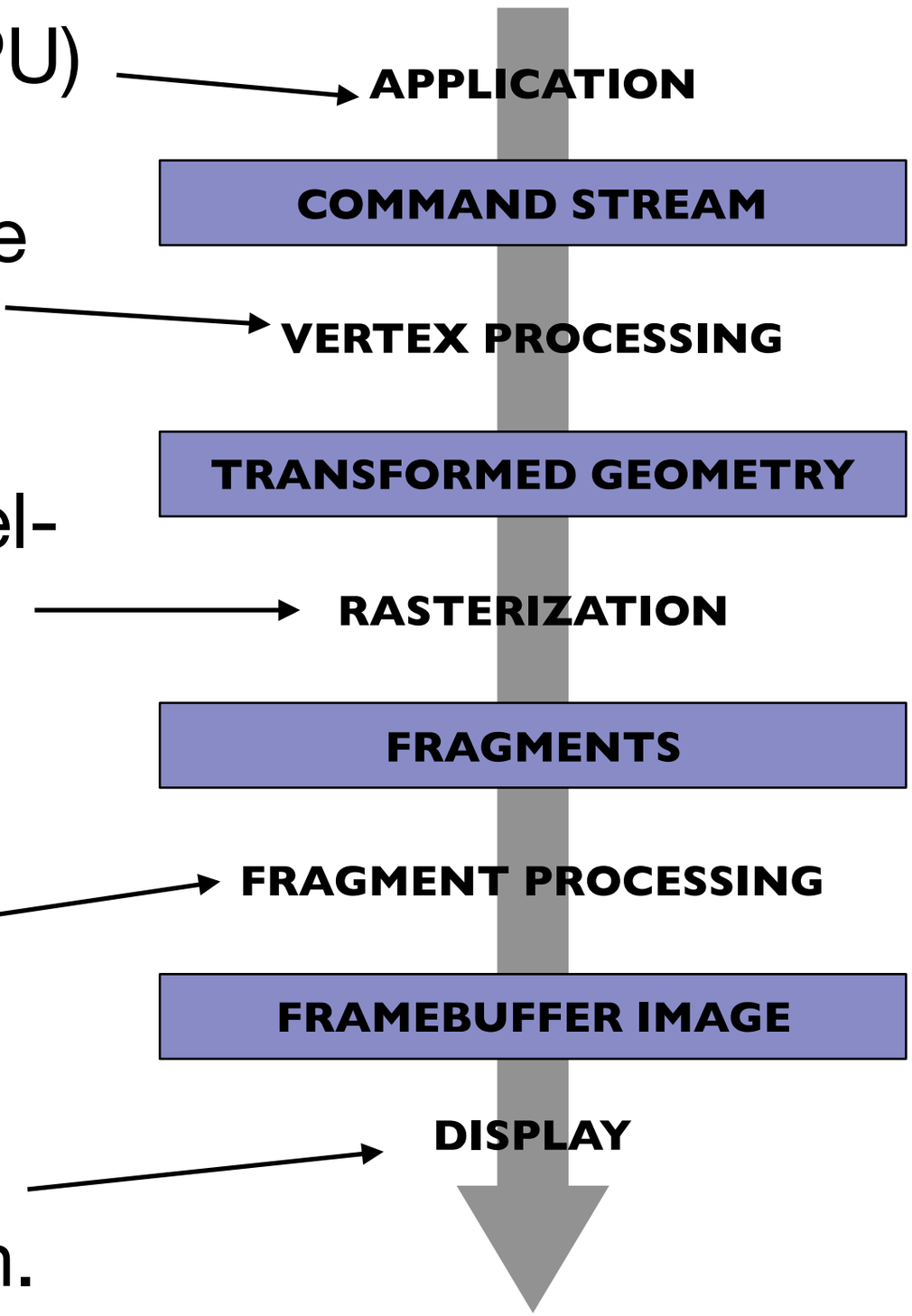
Application sends geometric primitives to renderer (e.g., to GPU)

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

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

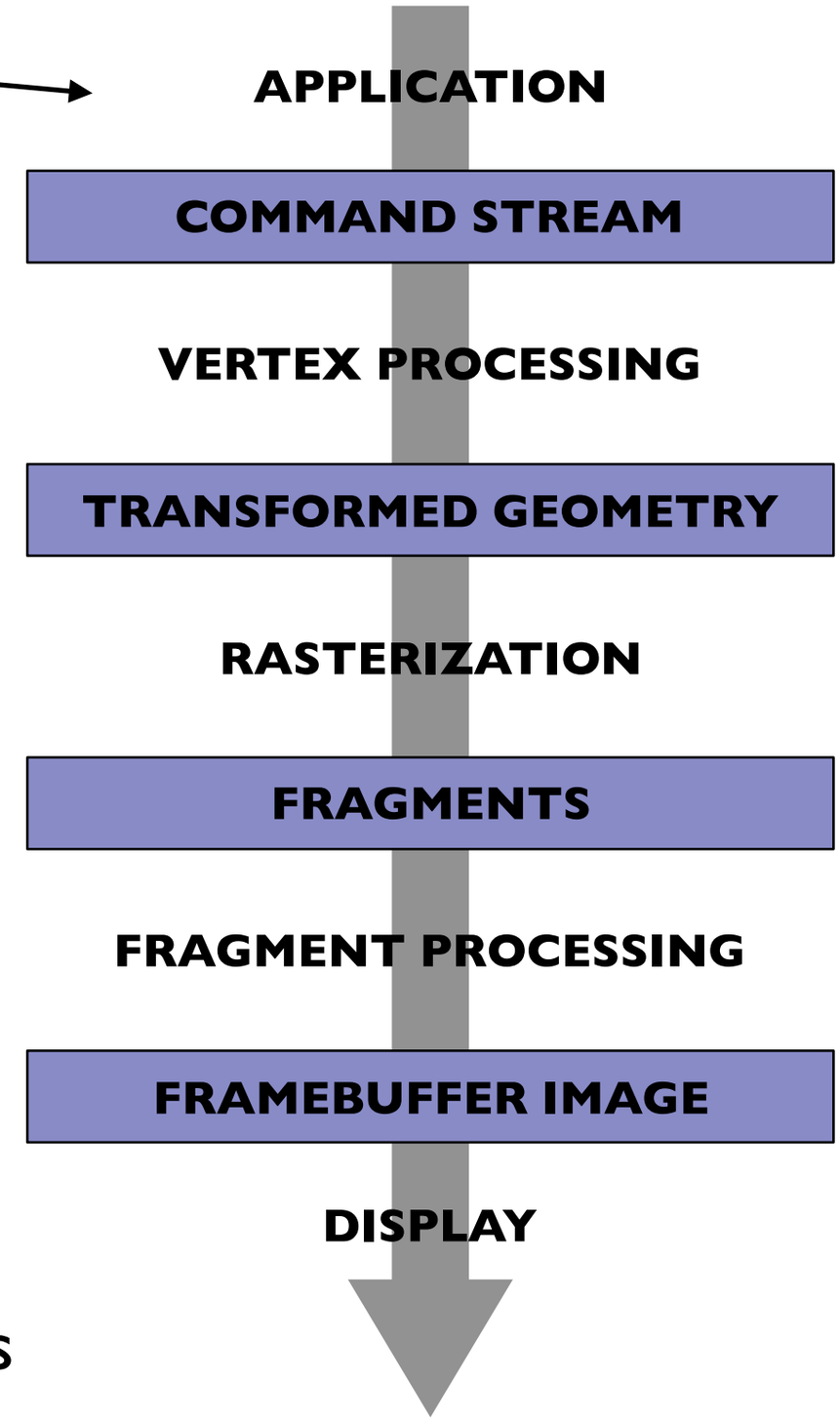
Fragments are shaded, blended, and composited to determine pixel colors.

Pixel colors written to the framebuffer appear on the screen.



Command Stream

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

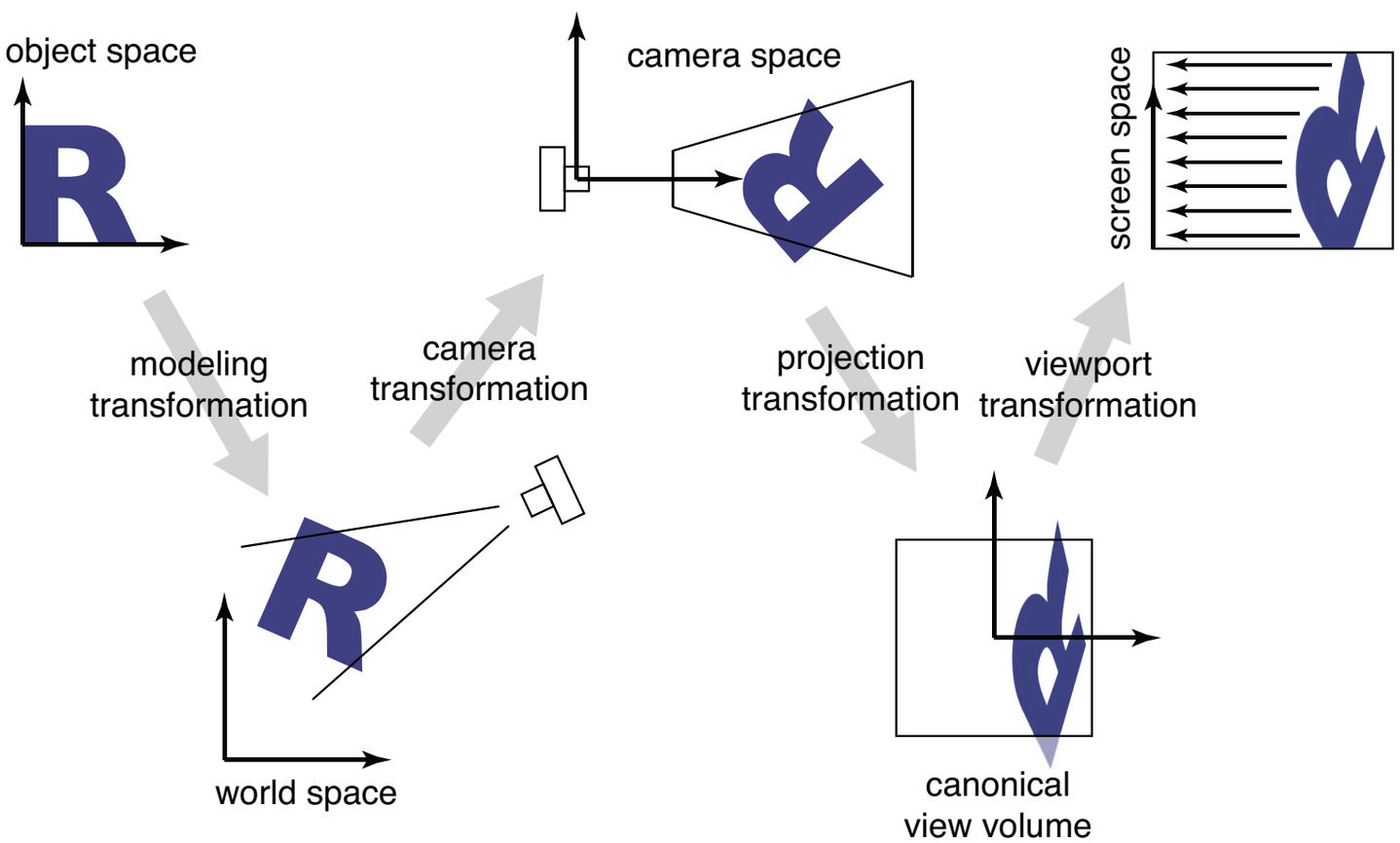


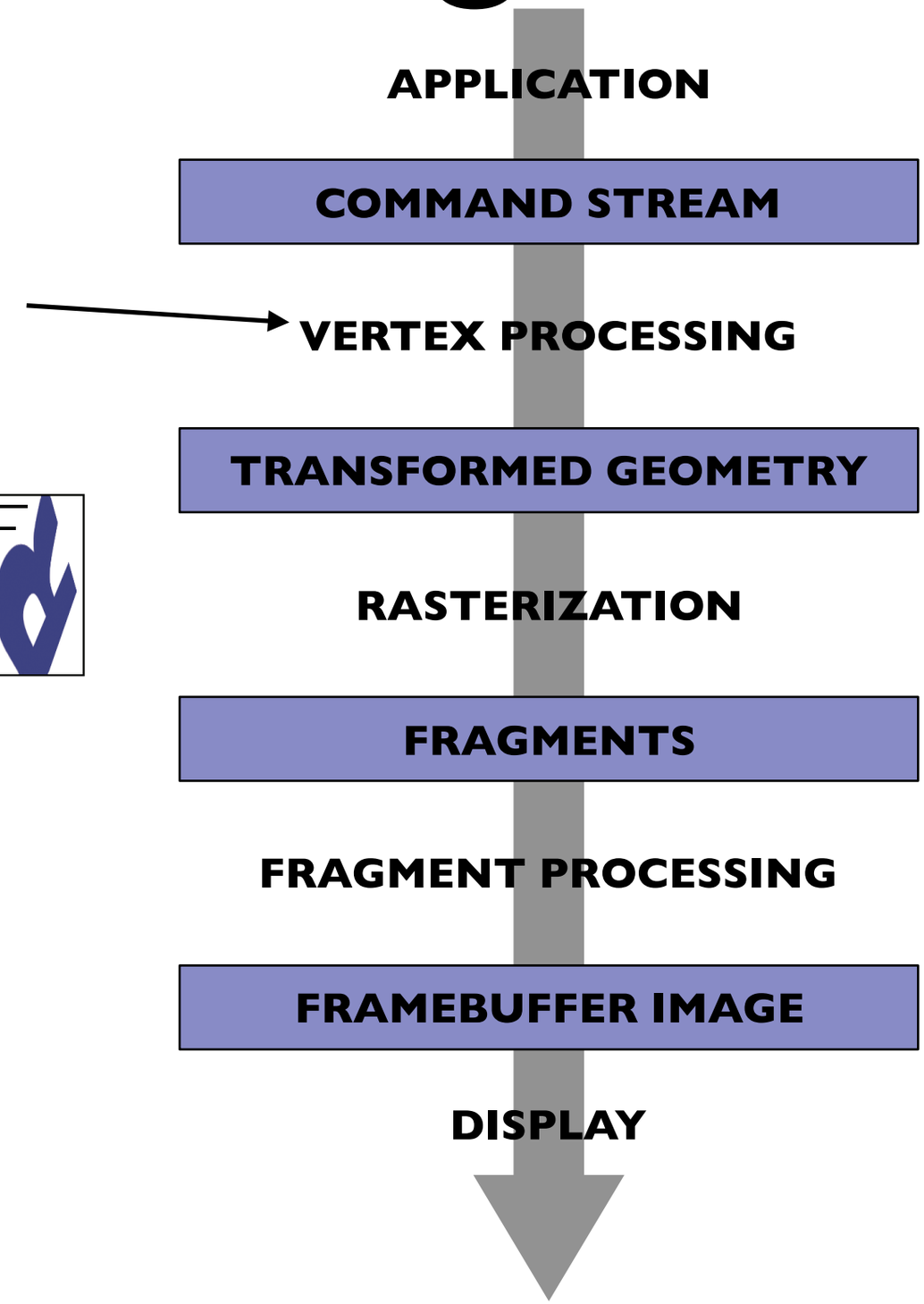
What primitives?

- 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

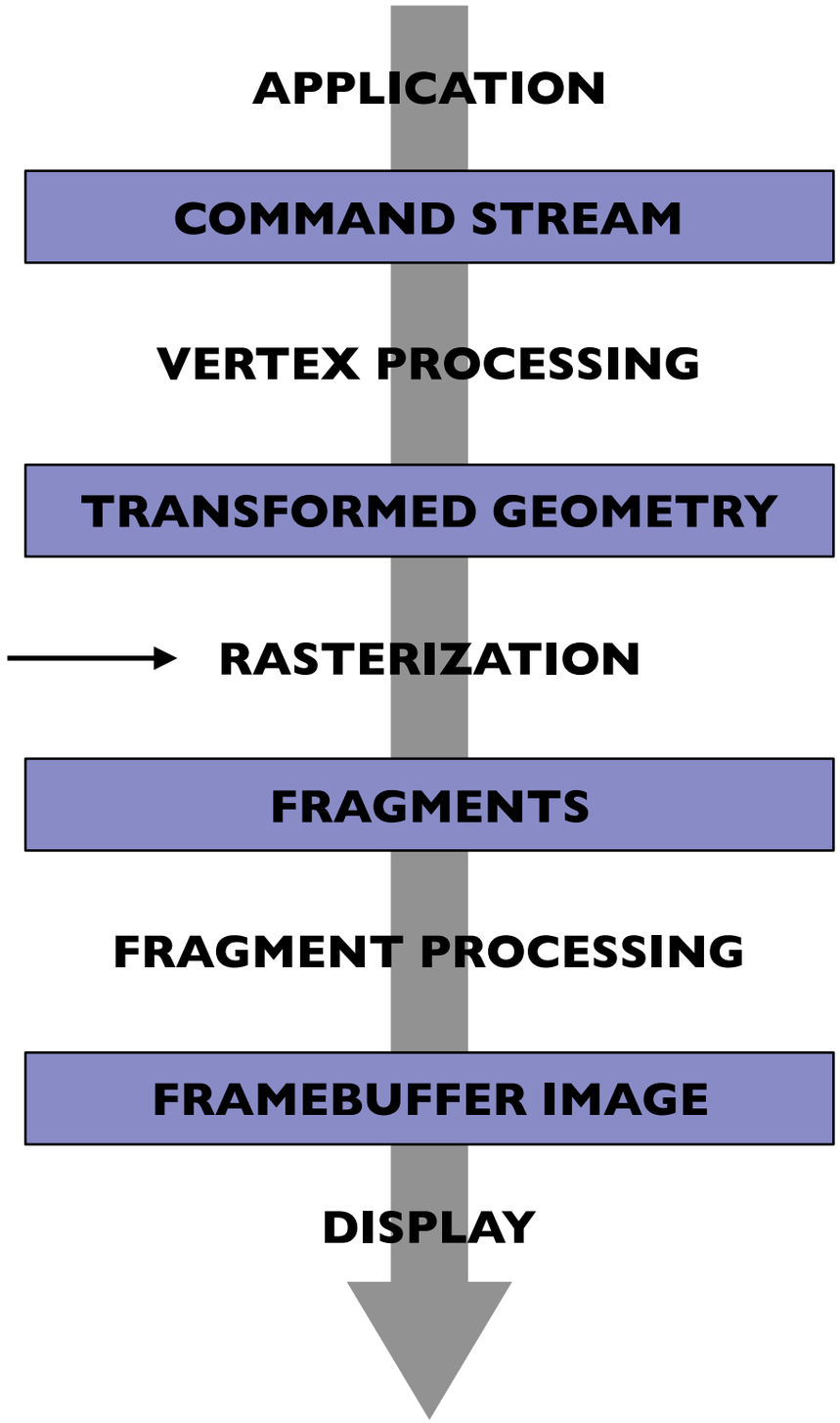
Vertices are transformed to clip space
Vertex values are computed
(we've done much of this part!)





Rasterization

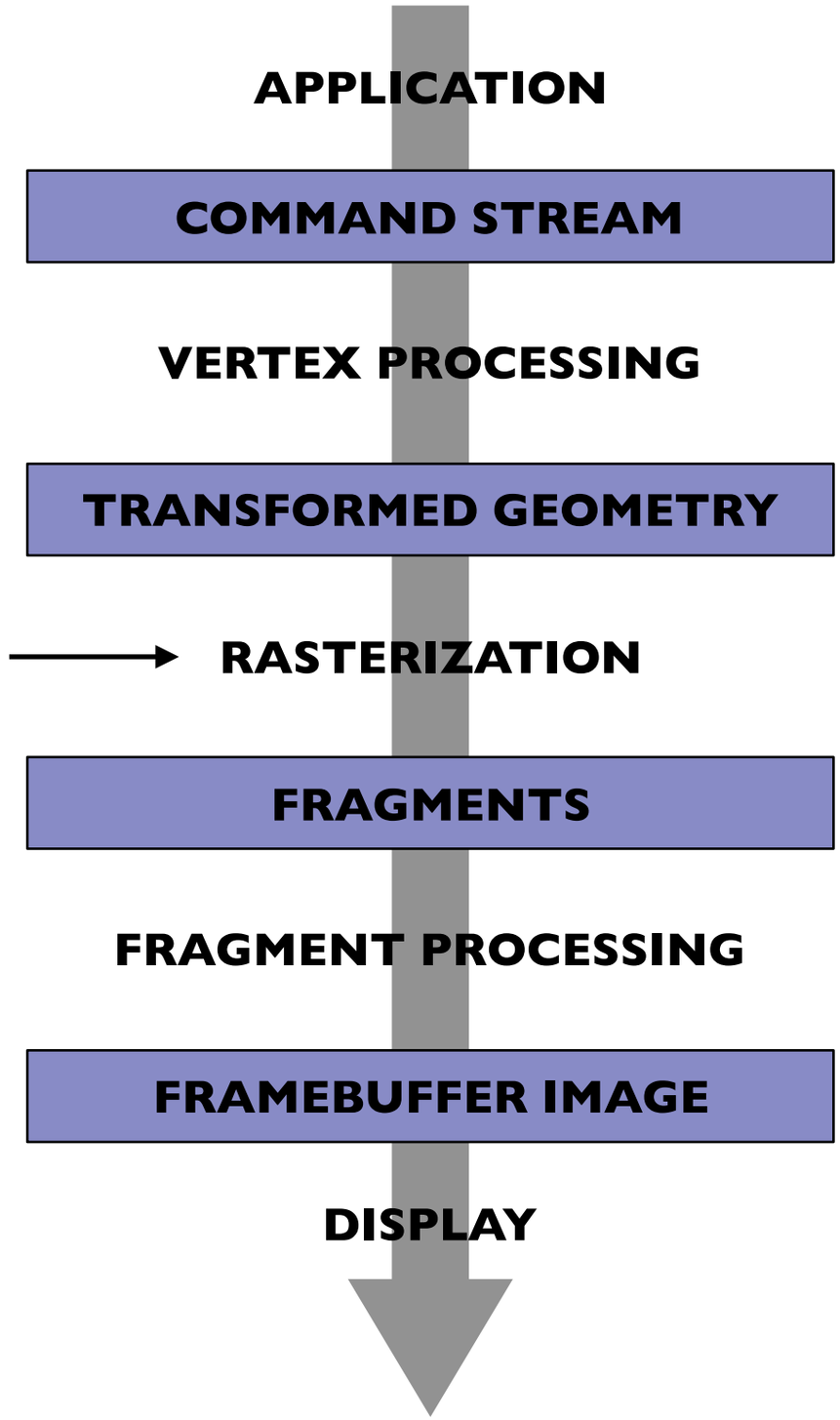
- First job: enumerate the pixels covered by a primitive
  - which pixels fall inside triangle?
  - includes "clipping" content outside view volume
- Second job: interpolate values across the primitive
  - e.g. colors computed at vertices
  - e.g. normals at vertices
  - e.g. texture coordinates



Rasterization

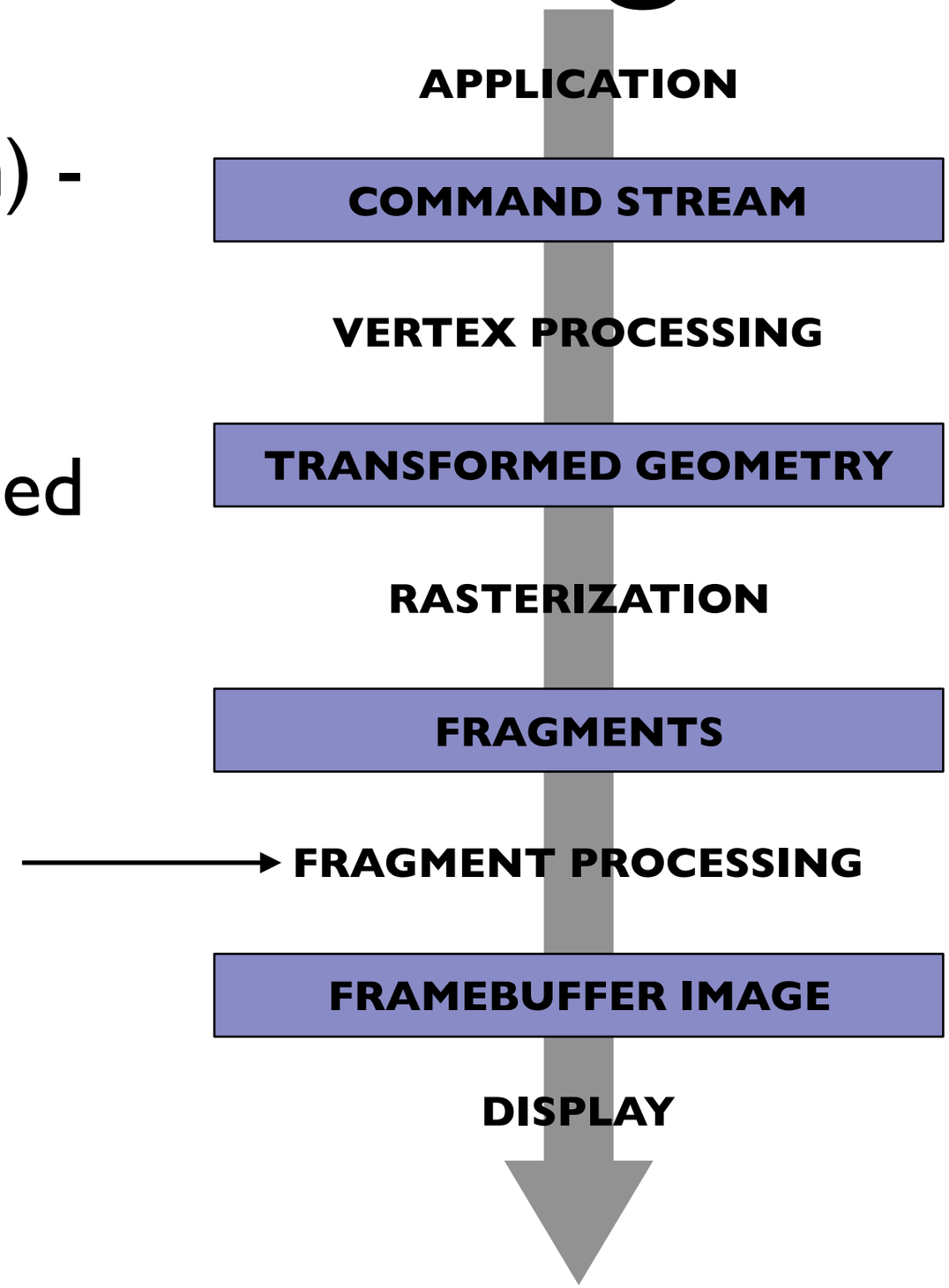
Rasterization algorithms: next week

- 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



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.:
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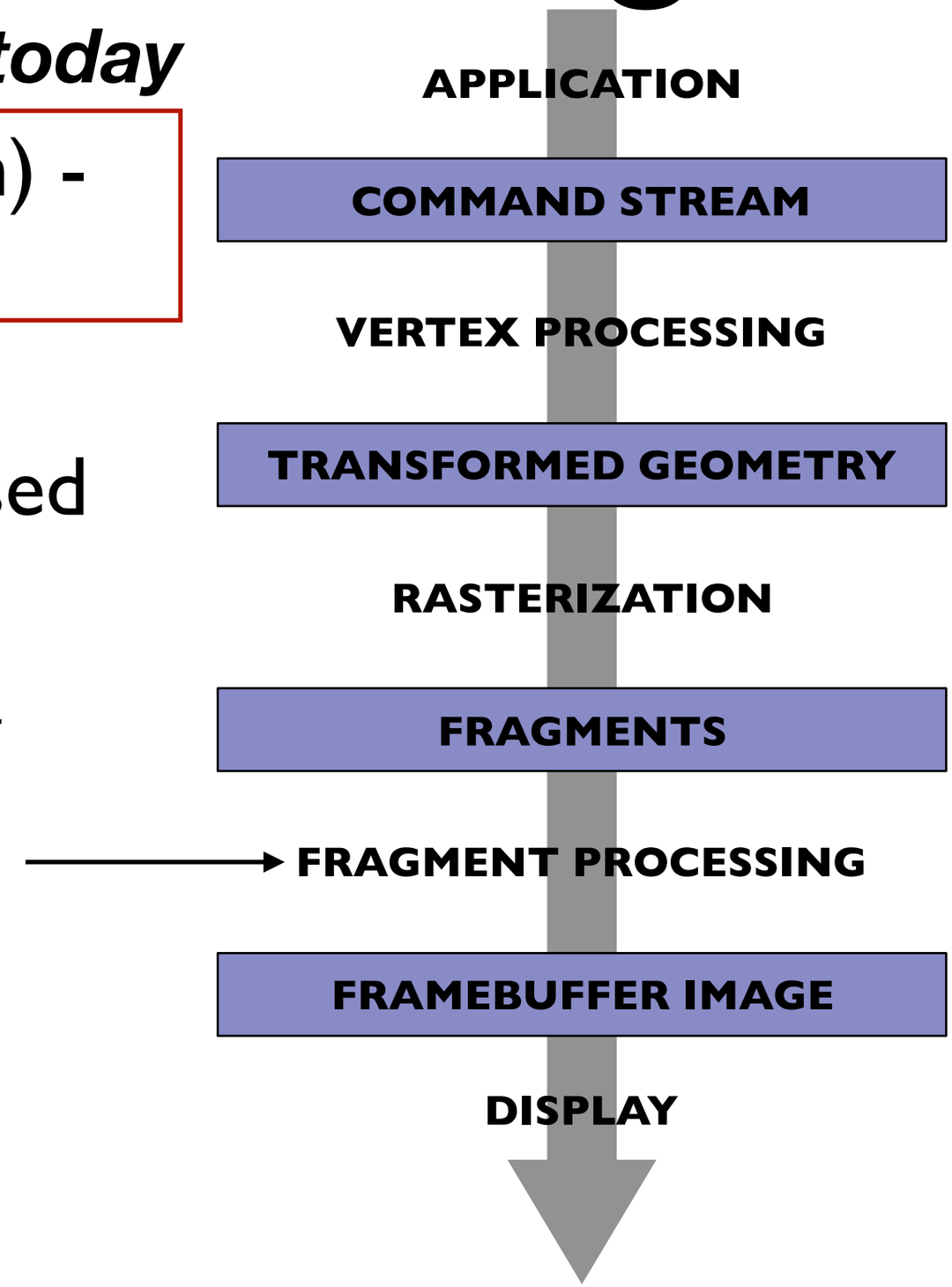
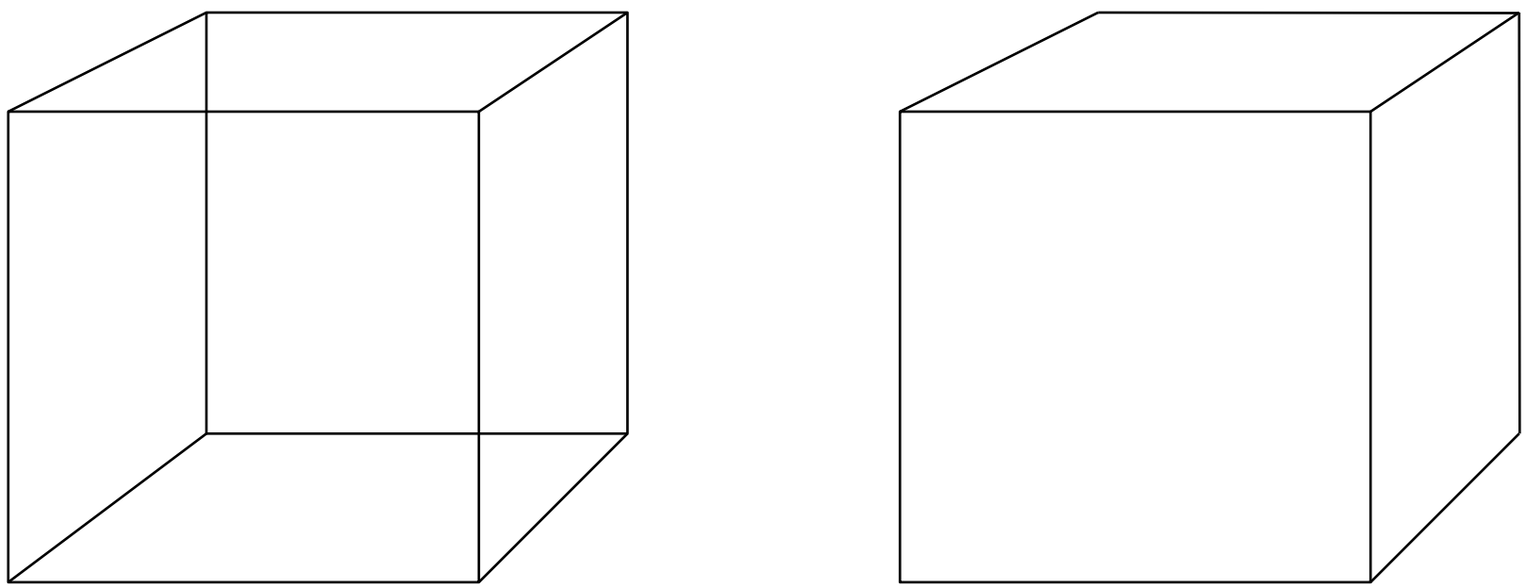


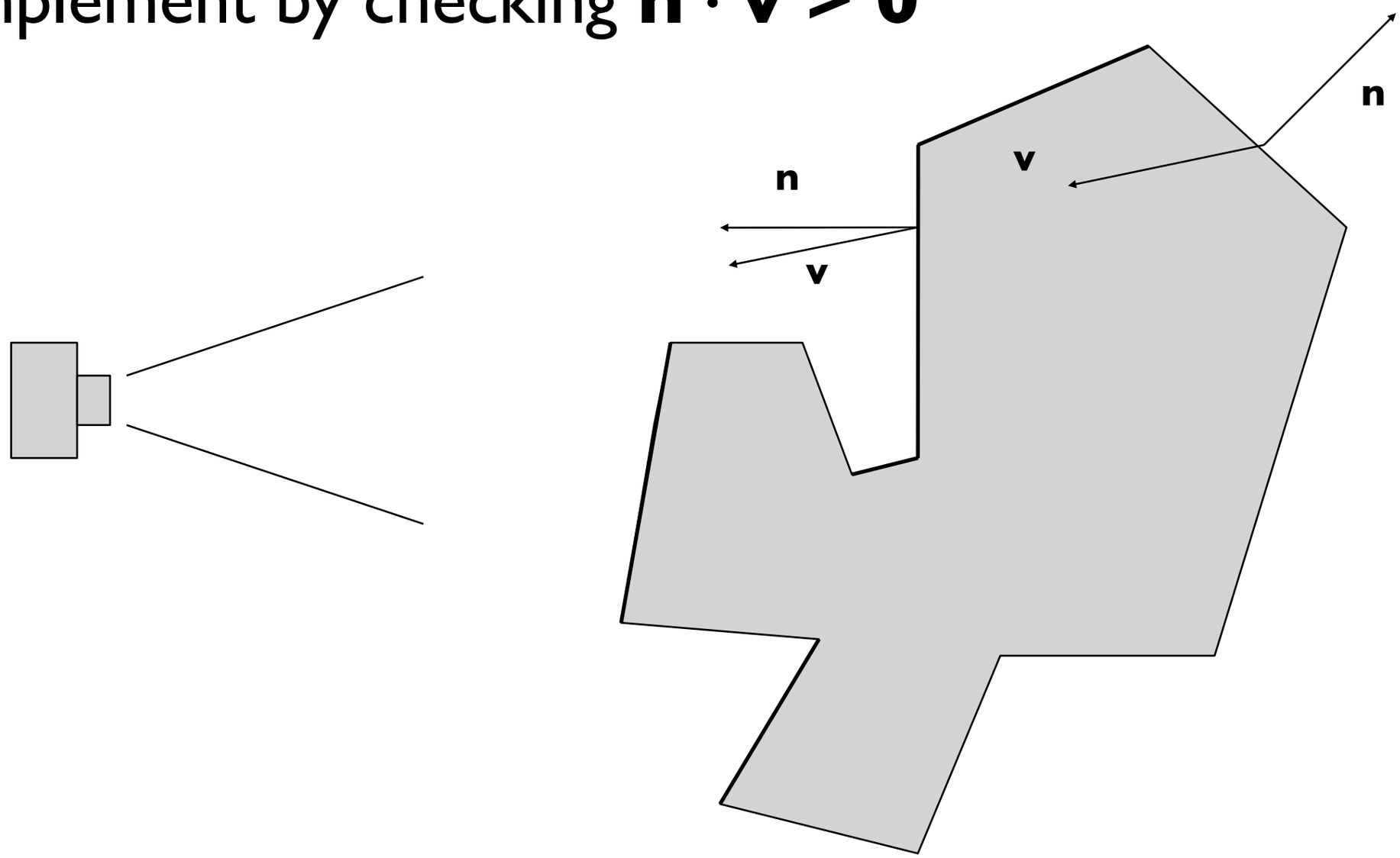
Hidden Surface Removal

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

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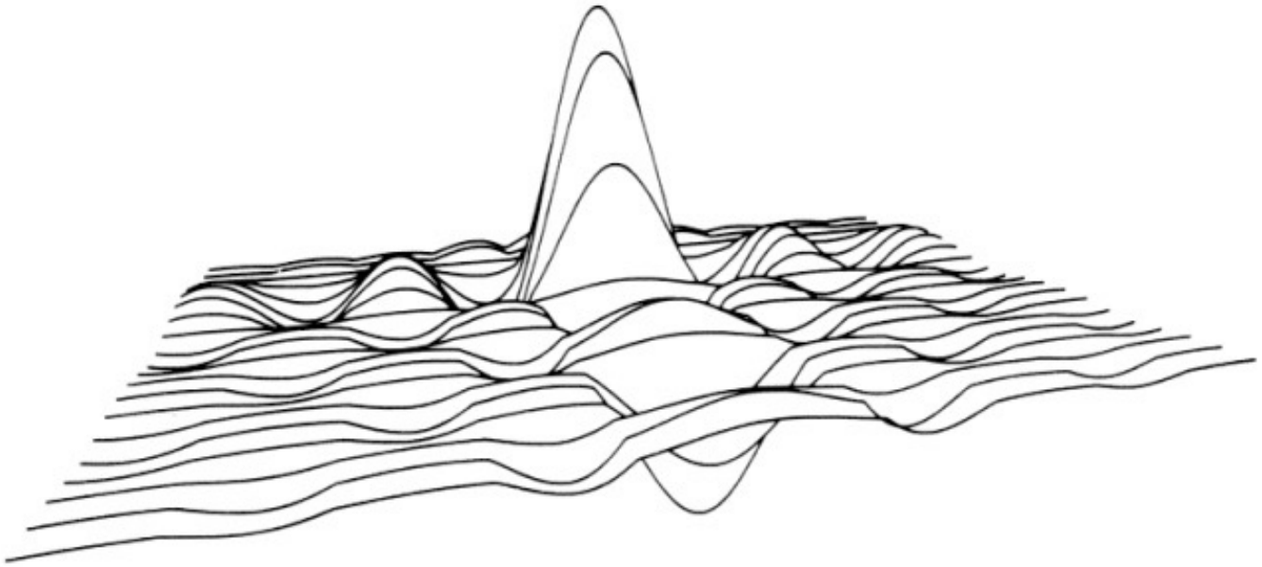

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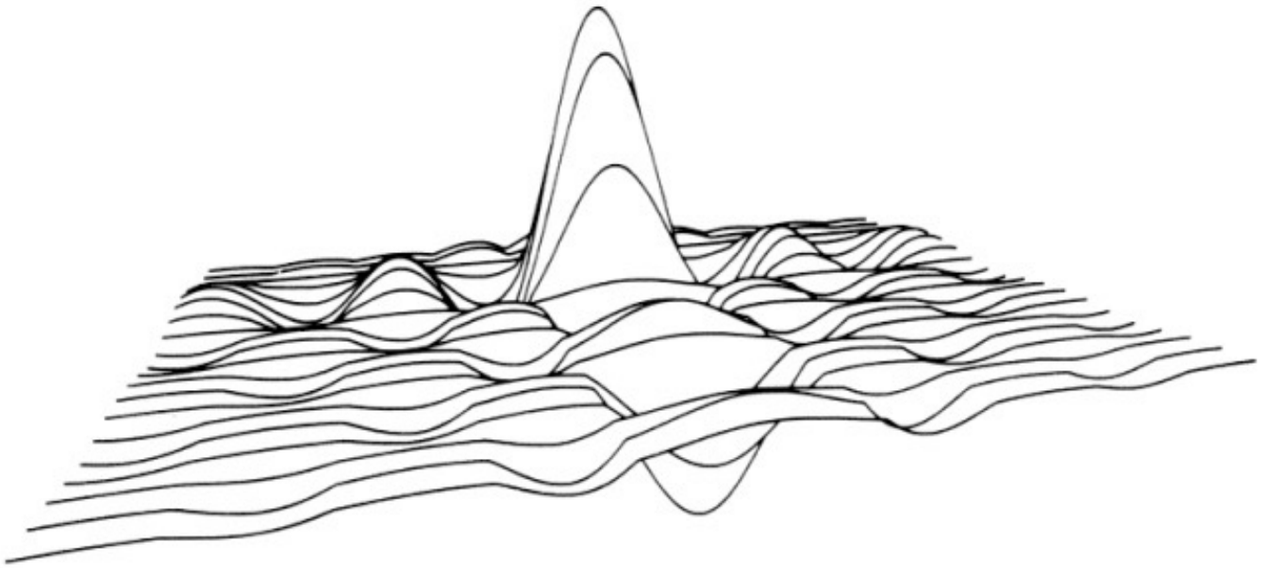
Works great if the ordering is easy to find...



Handling Occlusion

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- **Painter's algorithm:** draw them back-to-front
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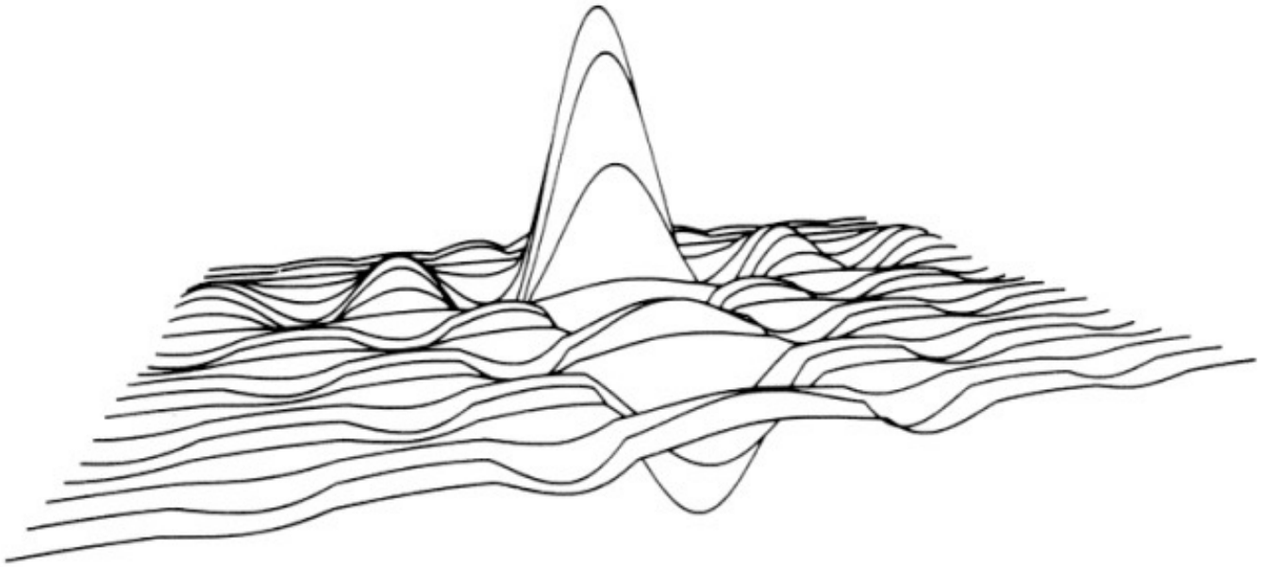
Works great if the ordering is easy to find...

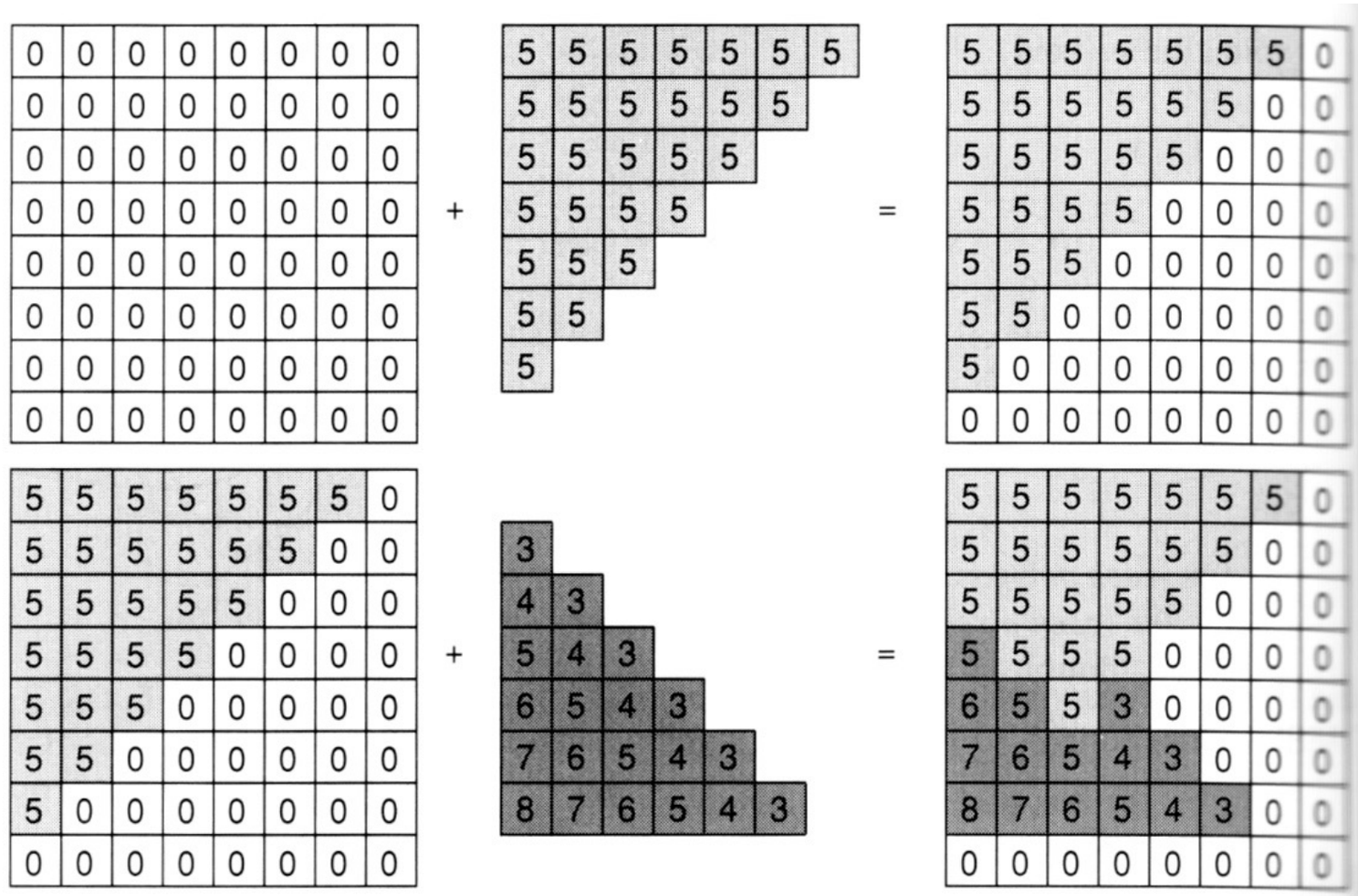
... but often it isn't.



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

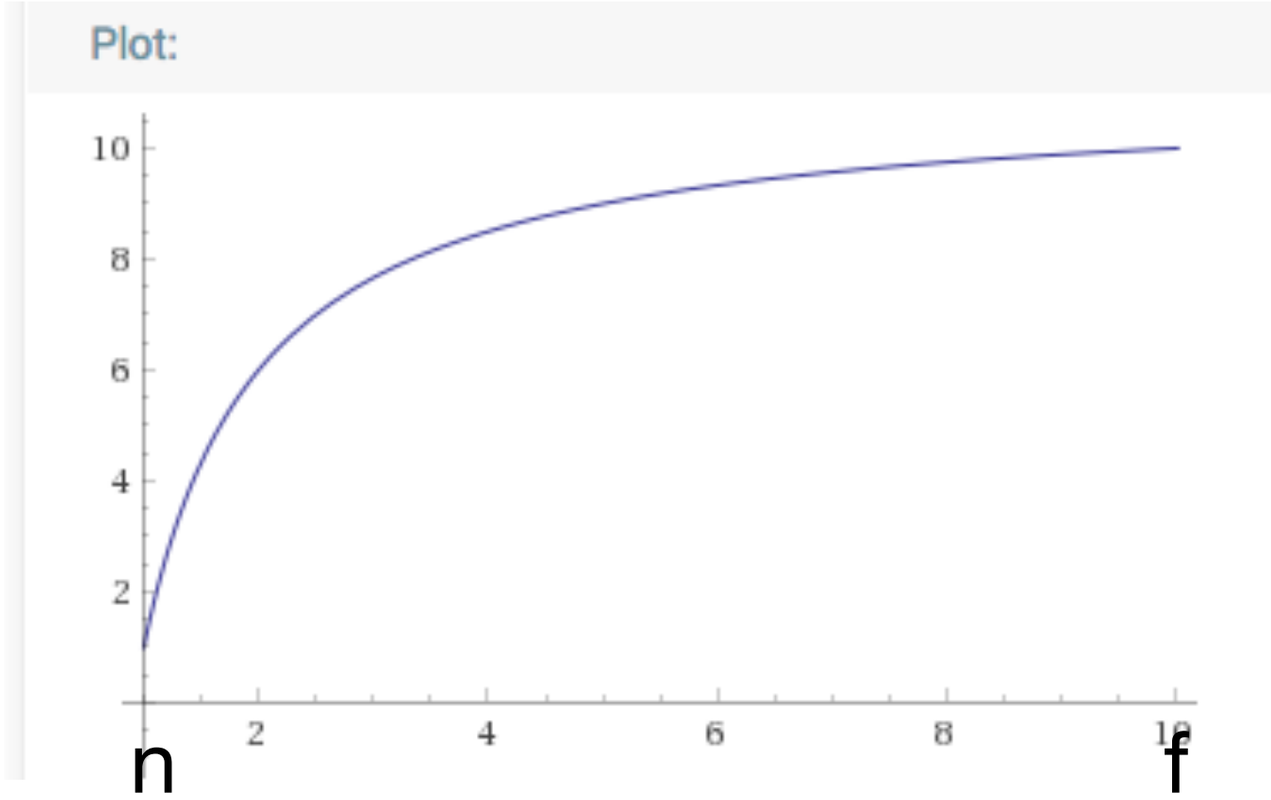


[Foley et al.]

- 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!)

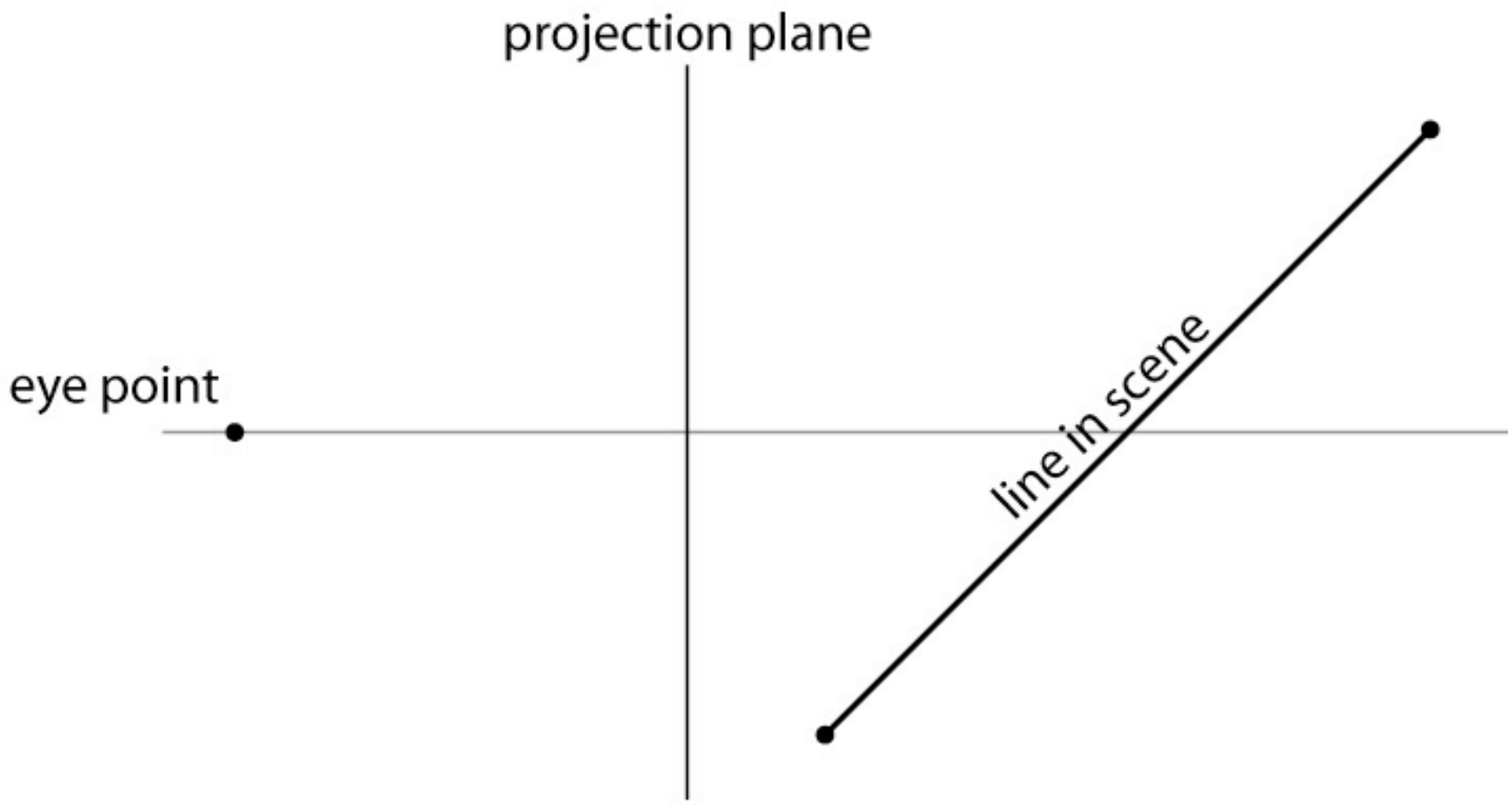
Precision in z buffer: Throwback

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



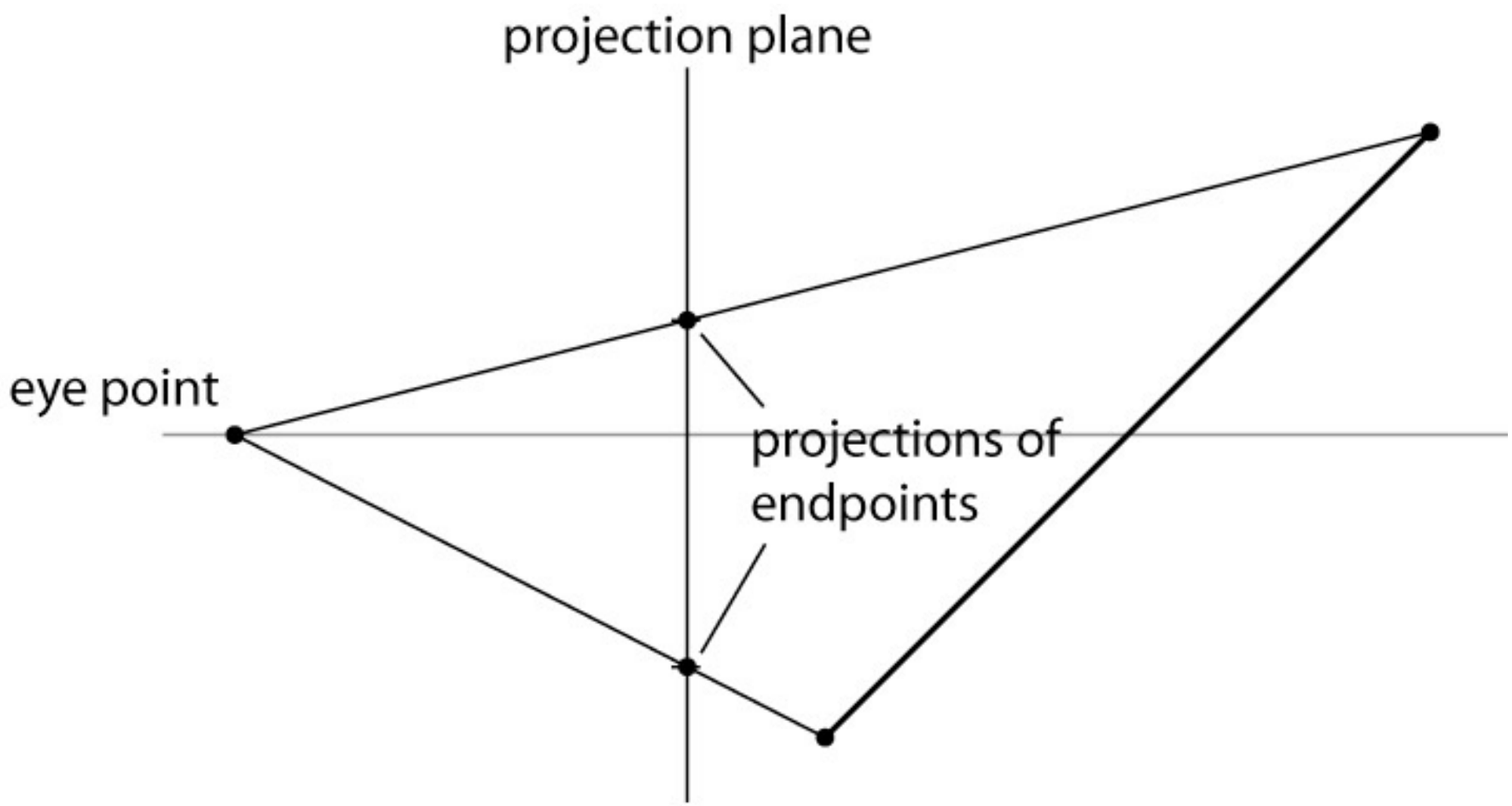
- The precision is distributed between the near and far clipping planes
  - this is why these planes have to exist
  - also why you can't always just set them to very small and very large distances
- Generally use z' (not world z) in z buffer

Interpolating in projection



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

Interpolating in projection



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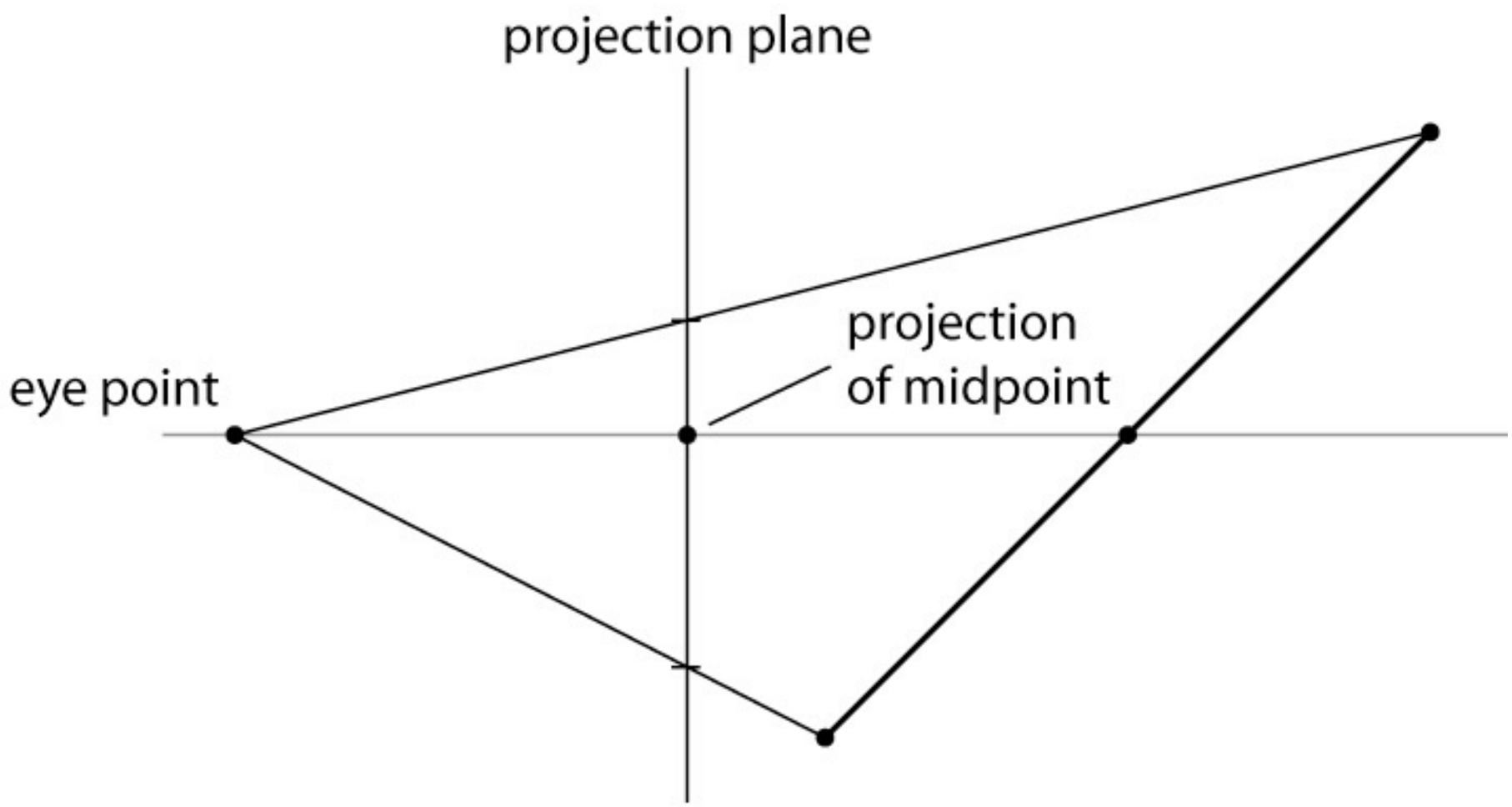

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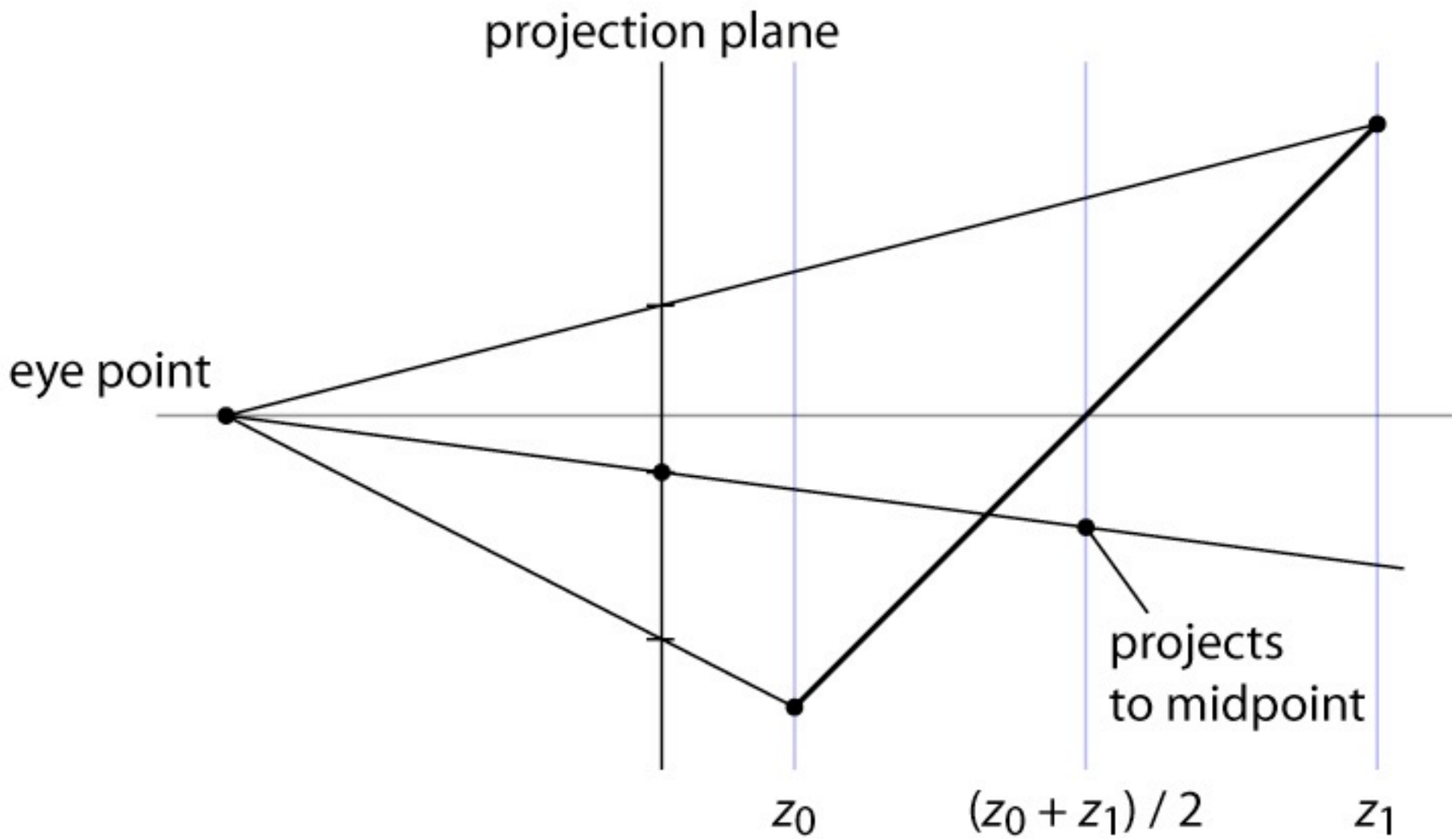

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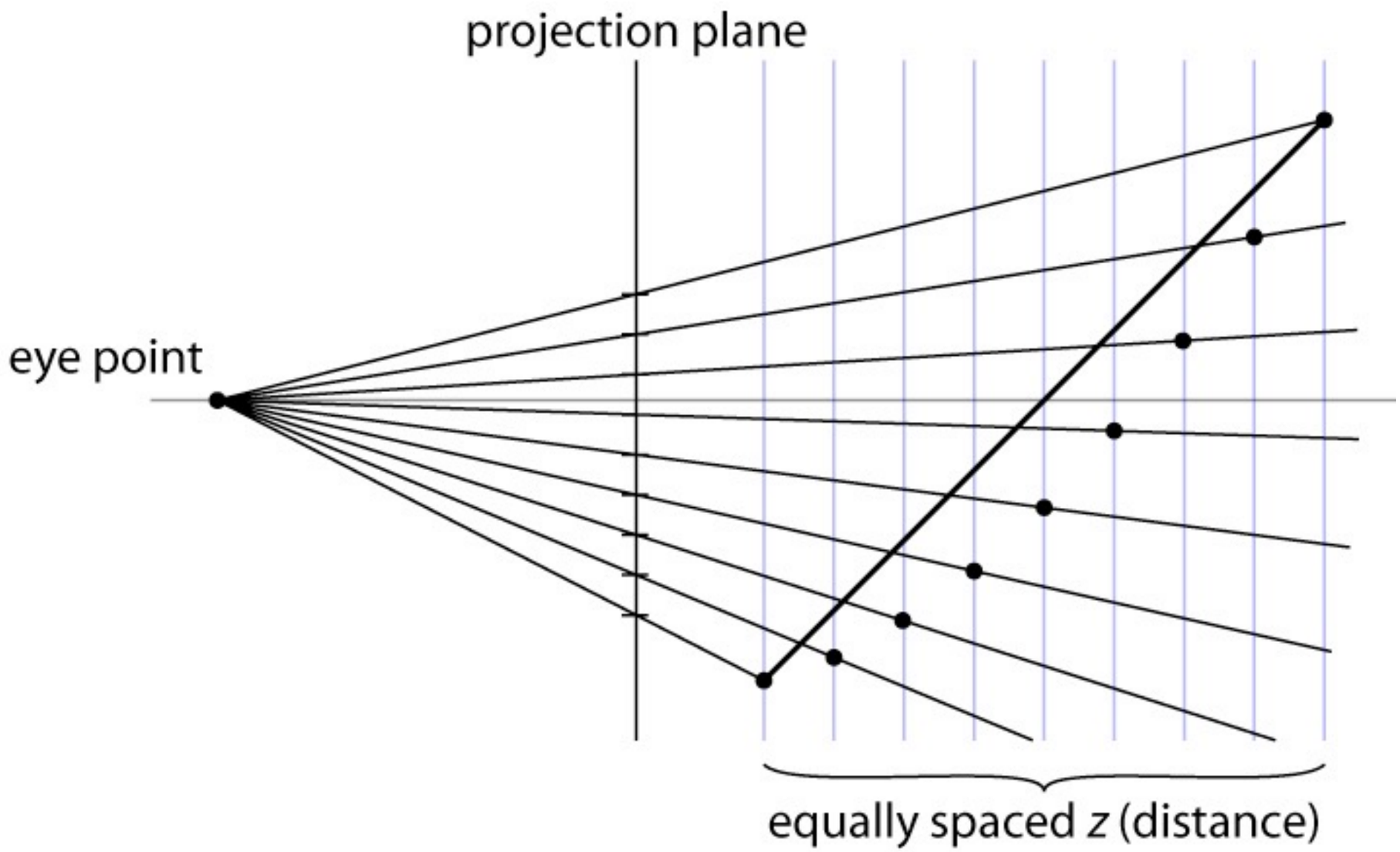

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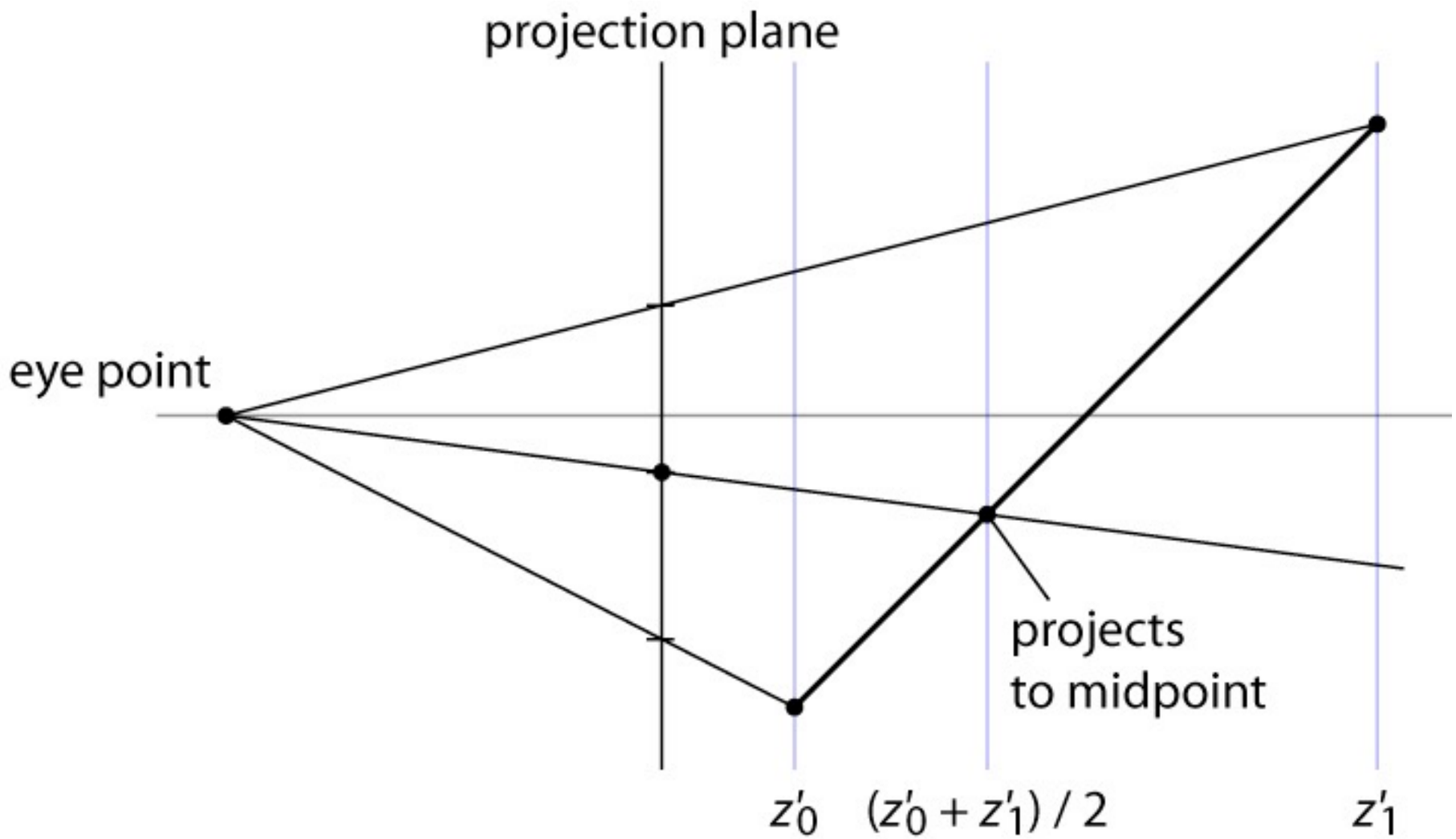

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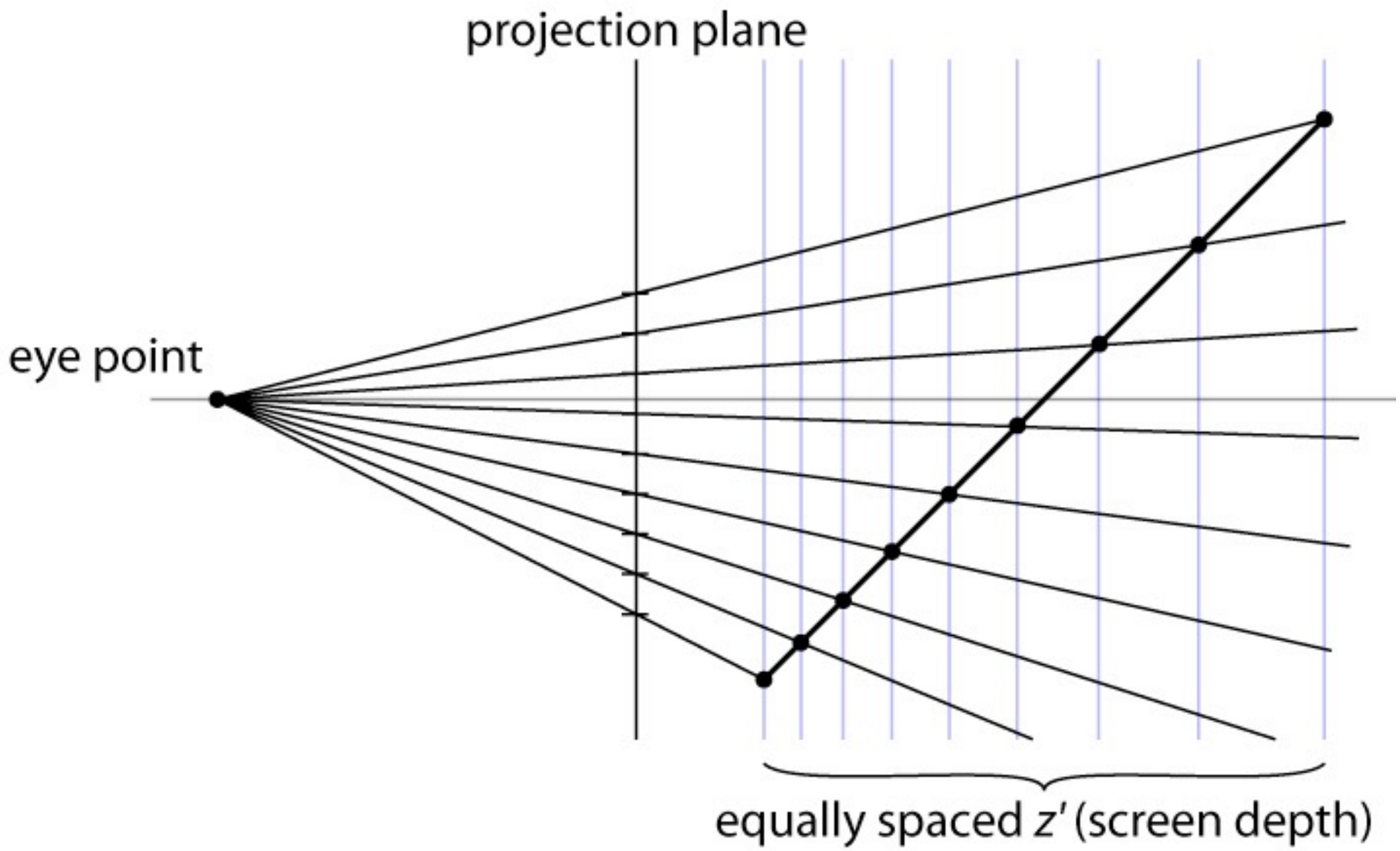

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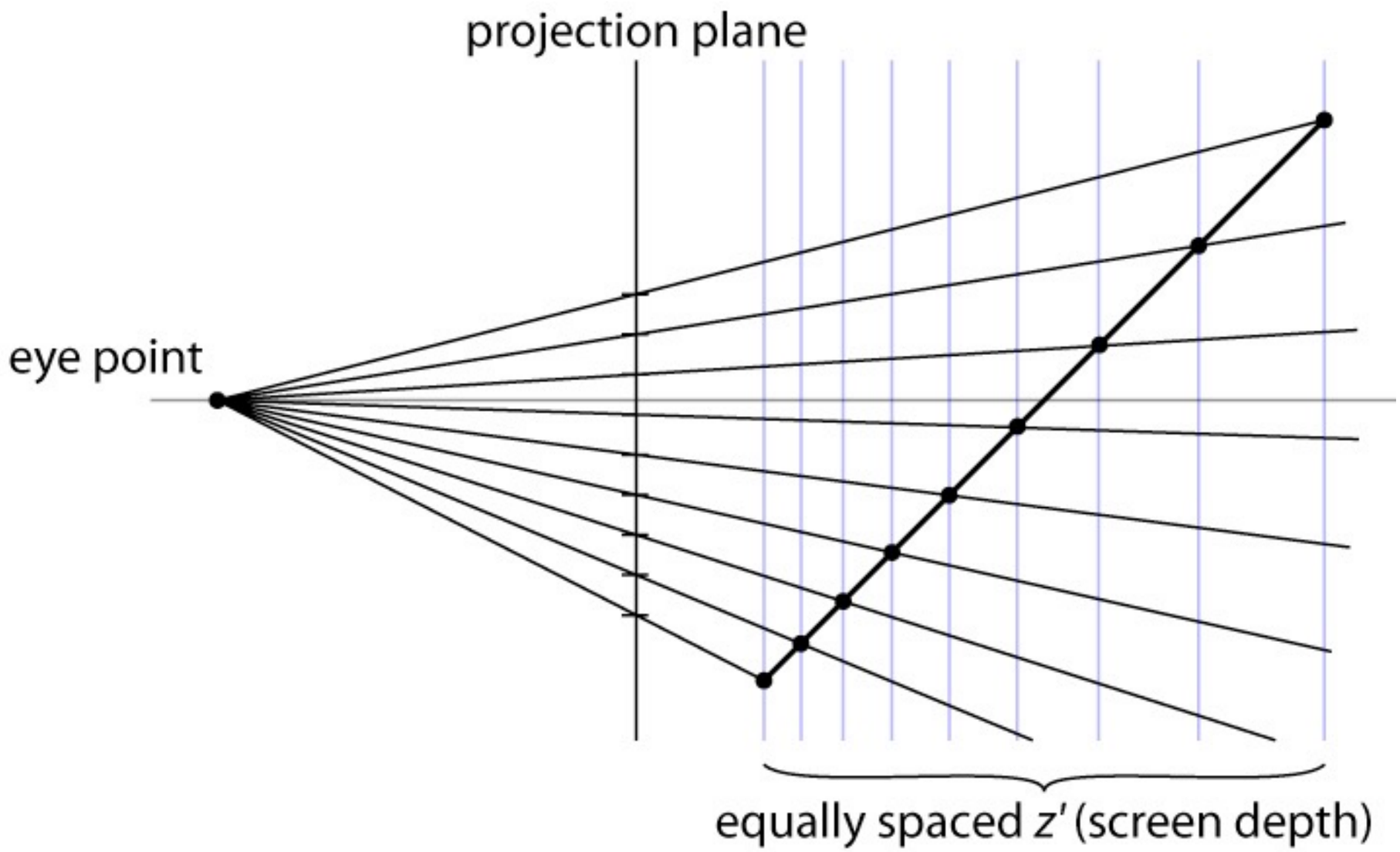

linear interp. in screen space ≠ linear interp. in world (eye) space

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.

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

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- 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

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OpenGL: Nowadays

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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

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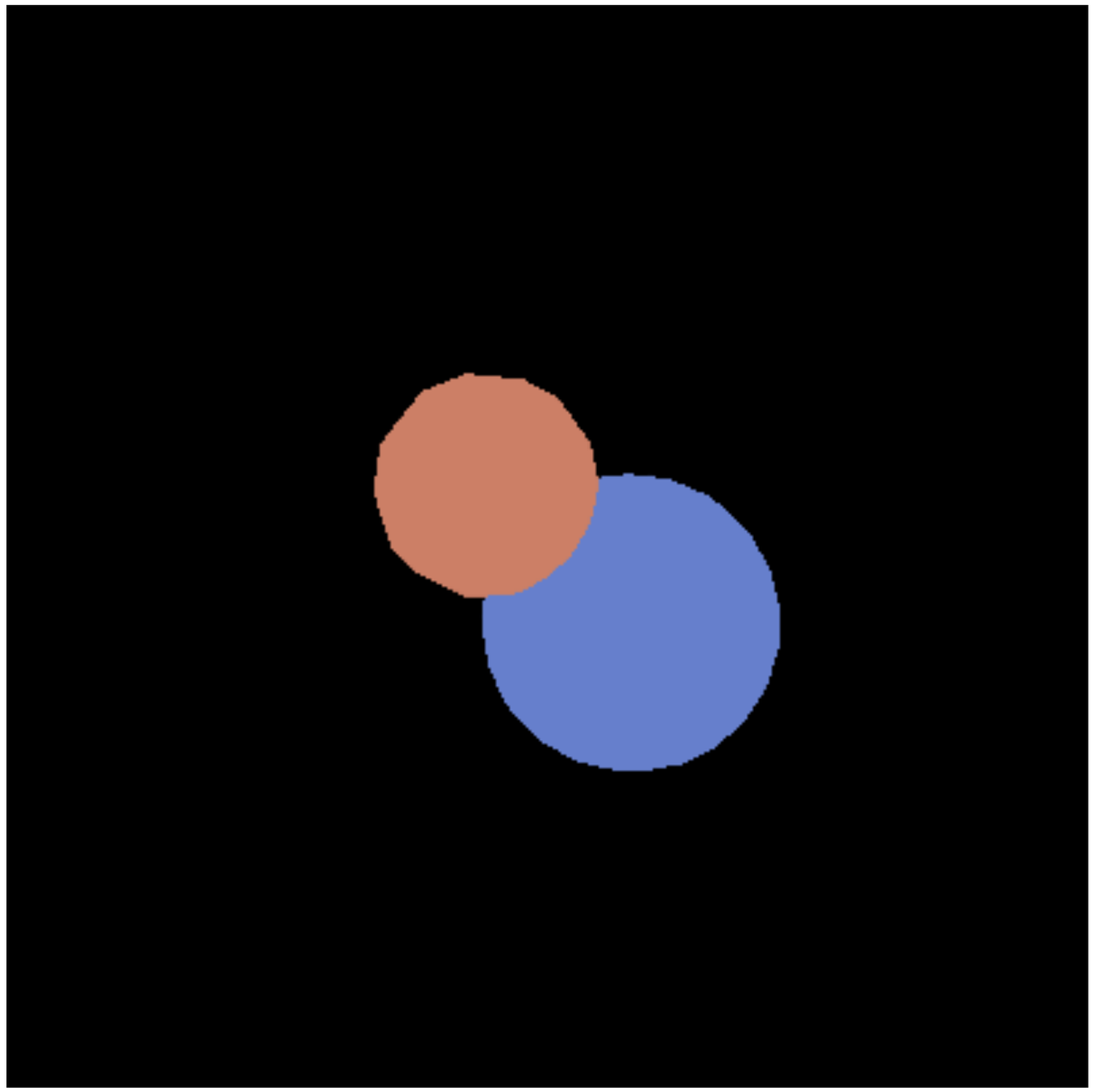
Result of minimal pipeline

https://facultyweb.cs.wwu.edu/~wehrwes/courses/csci480_20w/pipeline_demo/



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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'

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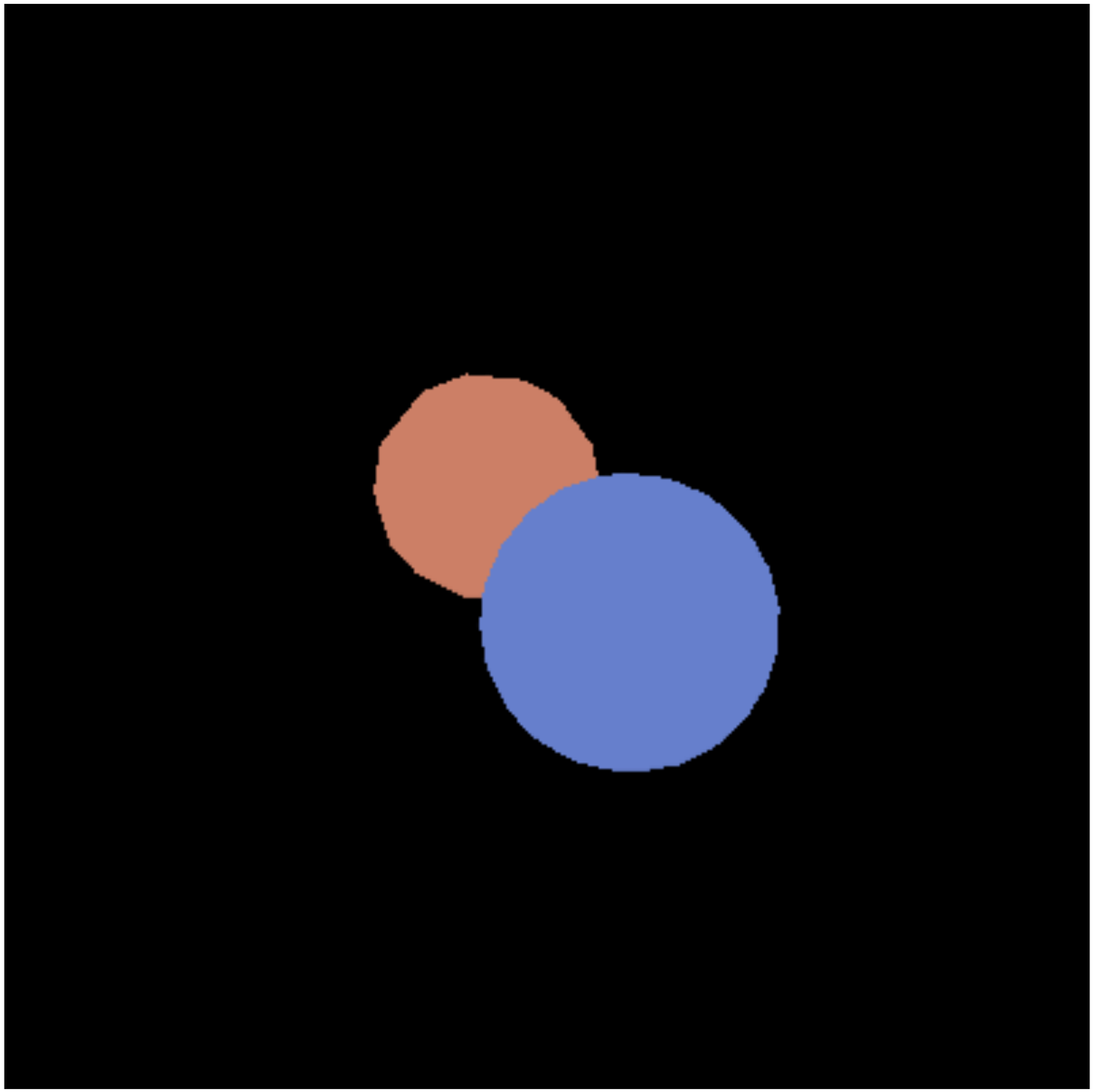
Result of z-buffer pipeline



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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

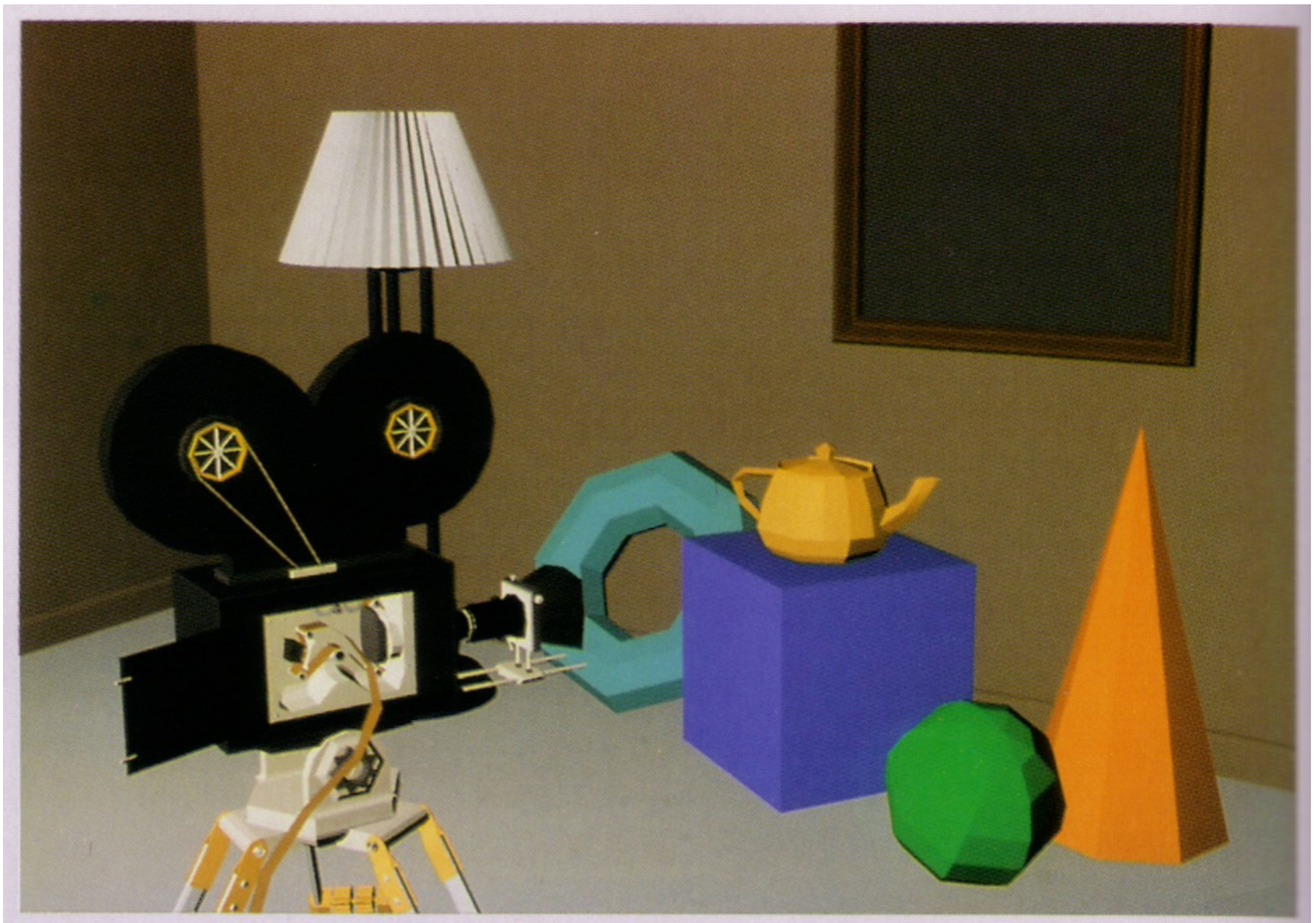

Plate II.29 *Shutterbug.* Individually shaded polygons with diffuse reflection (Sections 14.4.2 and 16.2.3). (Copyright © 1990, Pixar. Rendered by Thomas Williams and H.B. Siegel using Pixar's PhotoRealistic RenderMan™ software.)

[Foley et al.]

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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'

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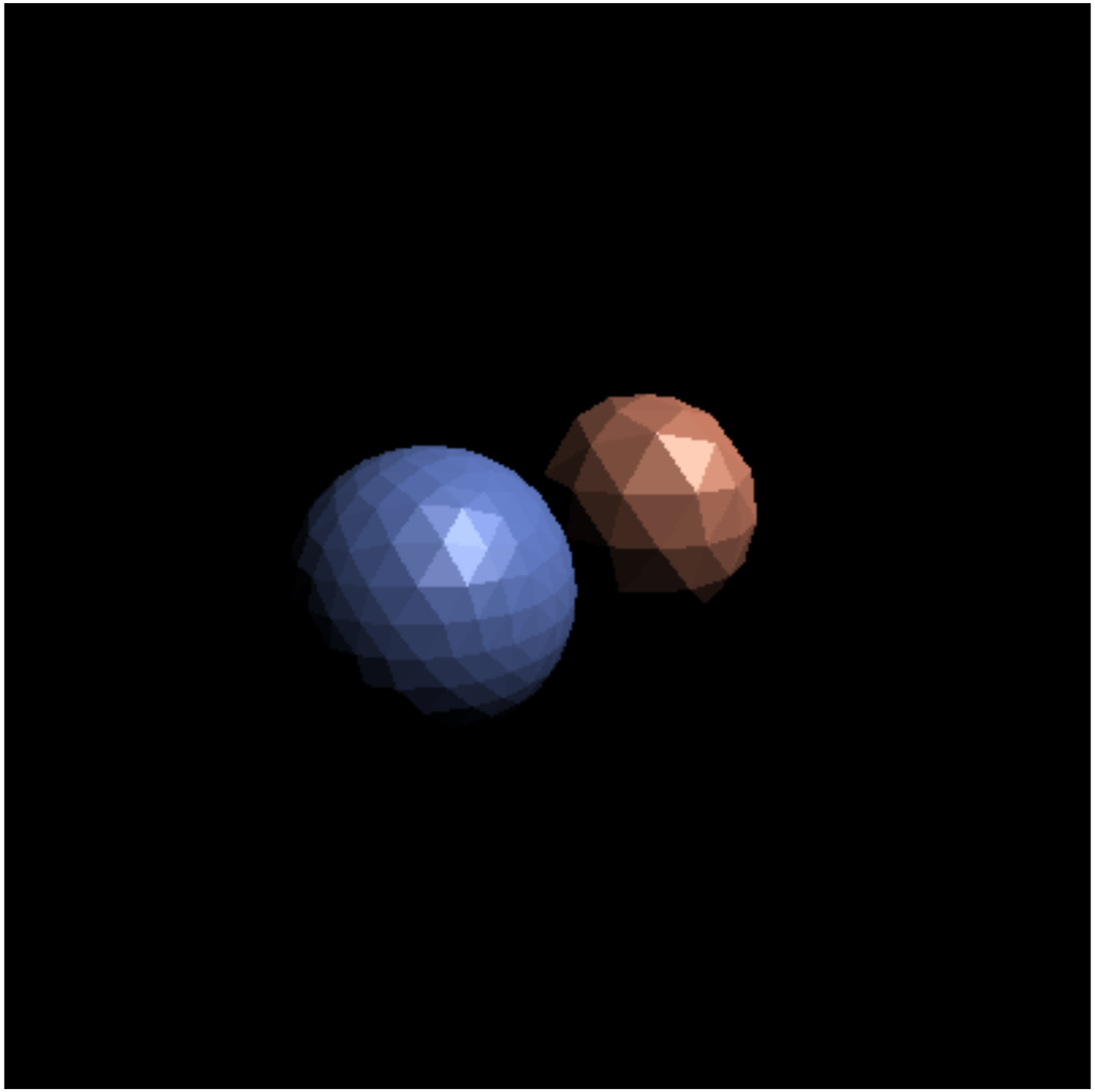
Result of flat-shading pipeline



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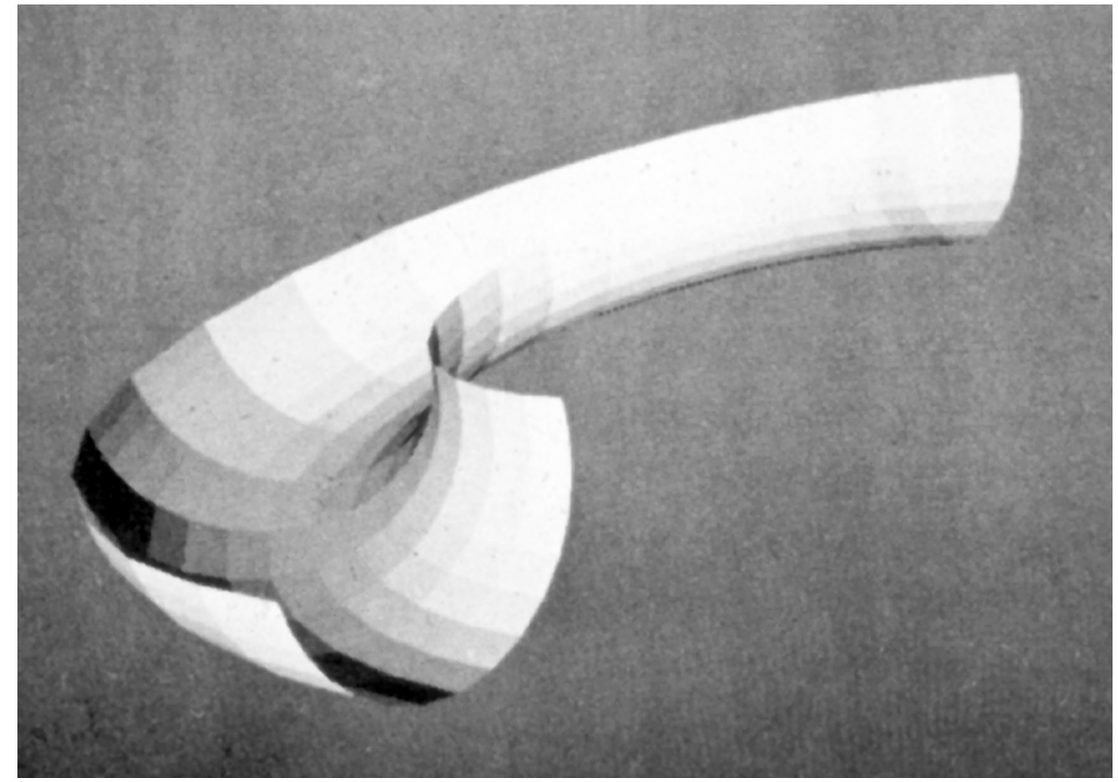
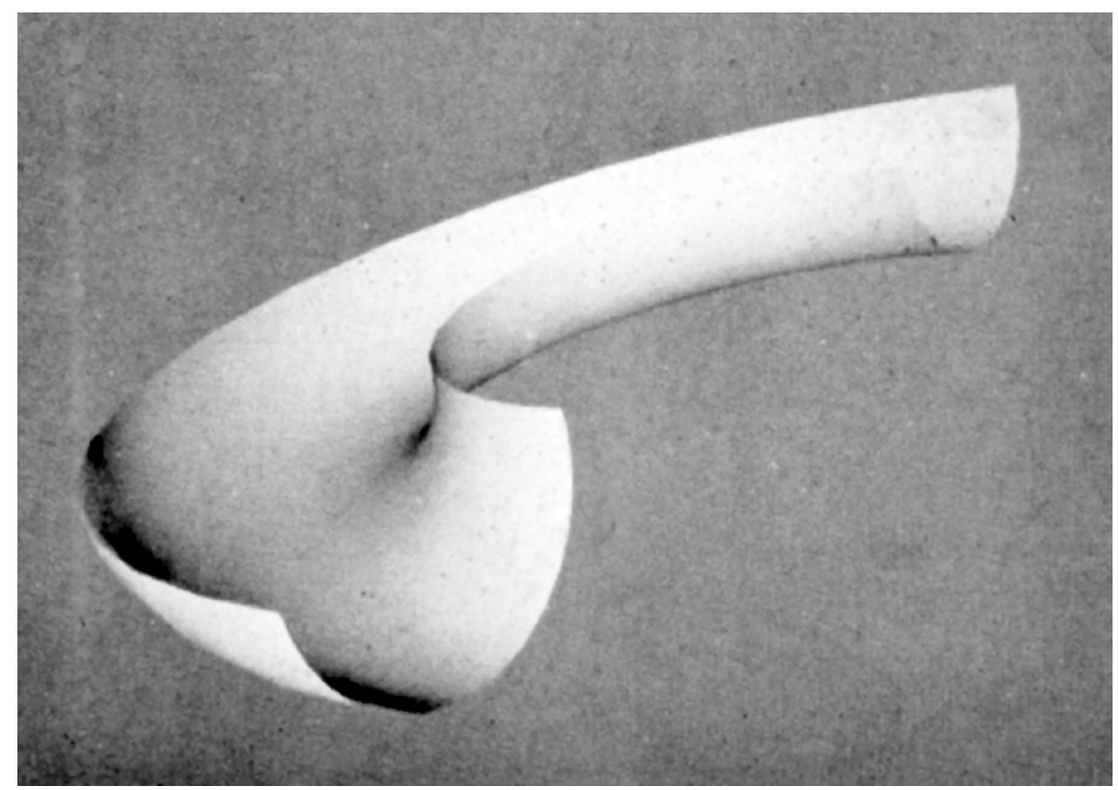
Gouraud shading

- 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 thesis]

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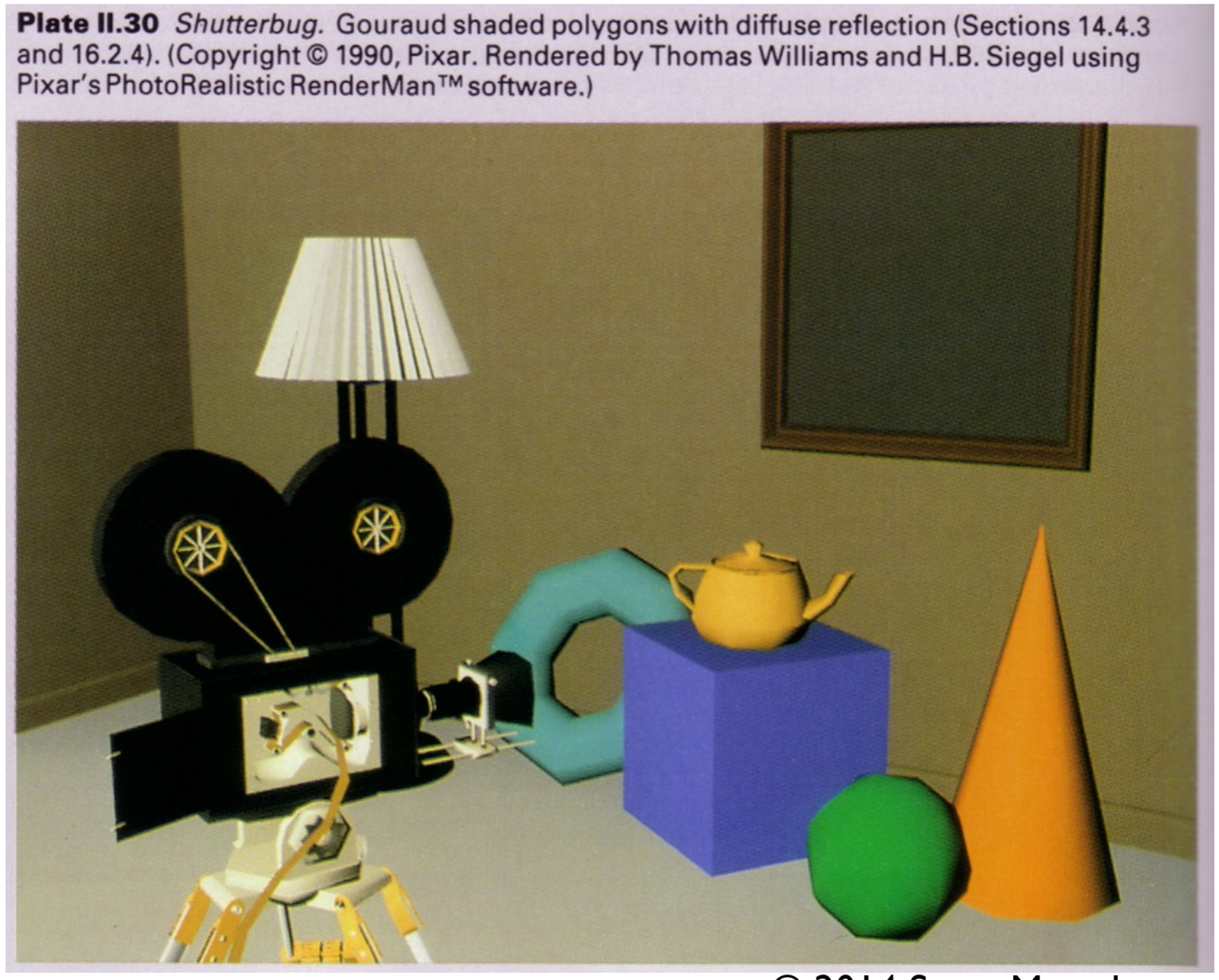

Plate II.30 *Shutterbug.* Gouraud shaded polygons with diffuse reflection (Sections 14.4.3 and 16.2.4). (Copyright © 1990, Pixar. Rendered by Thomas Williams and H.B. Siegel using Pixar's PhotoRealistic RenderMan™ software.)

[Foley et al.]

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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'

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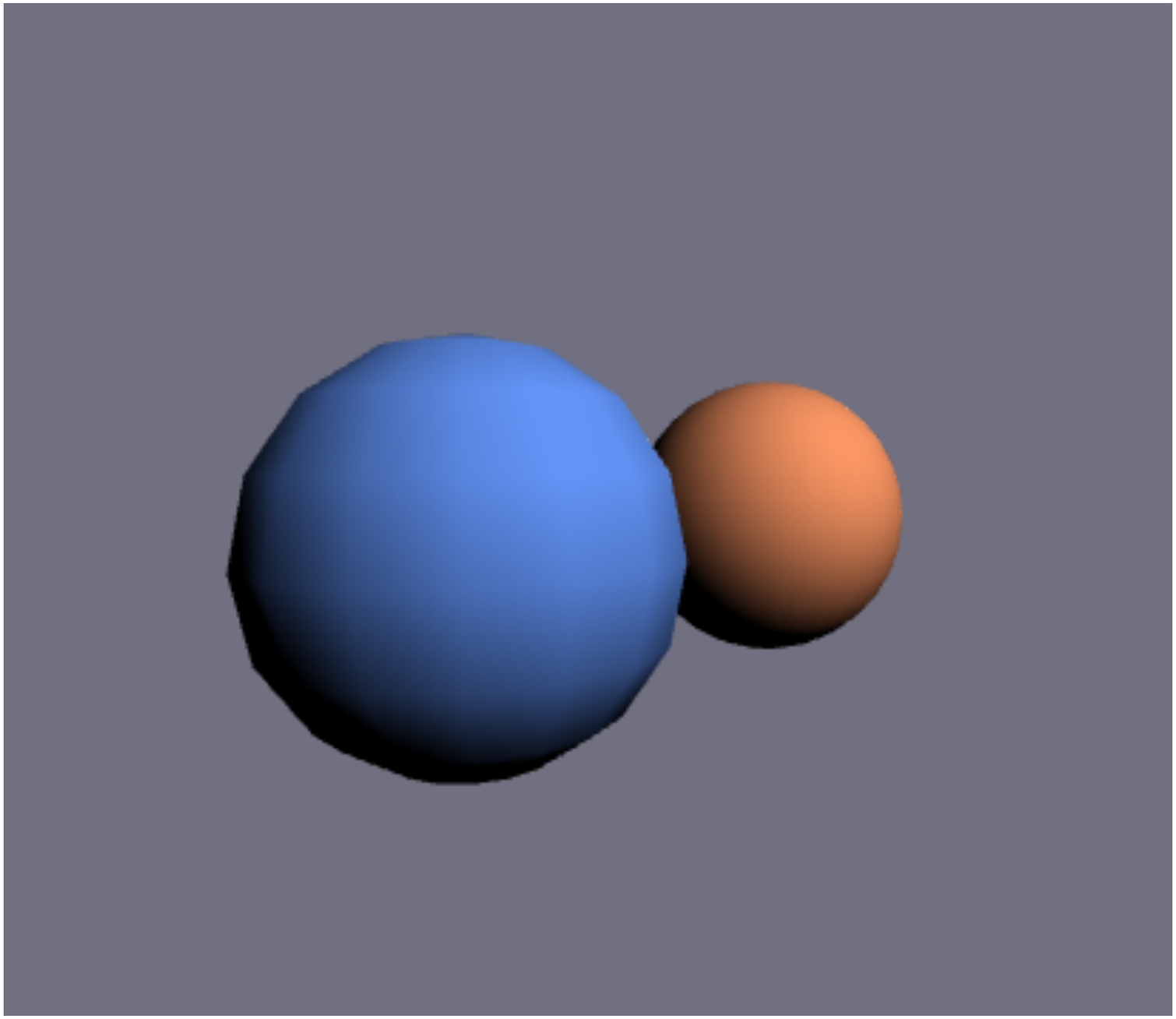
Result of Gouraud shading pipeline



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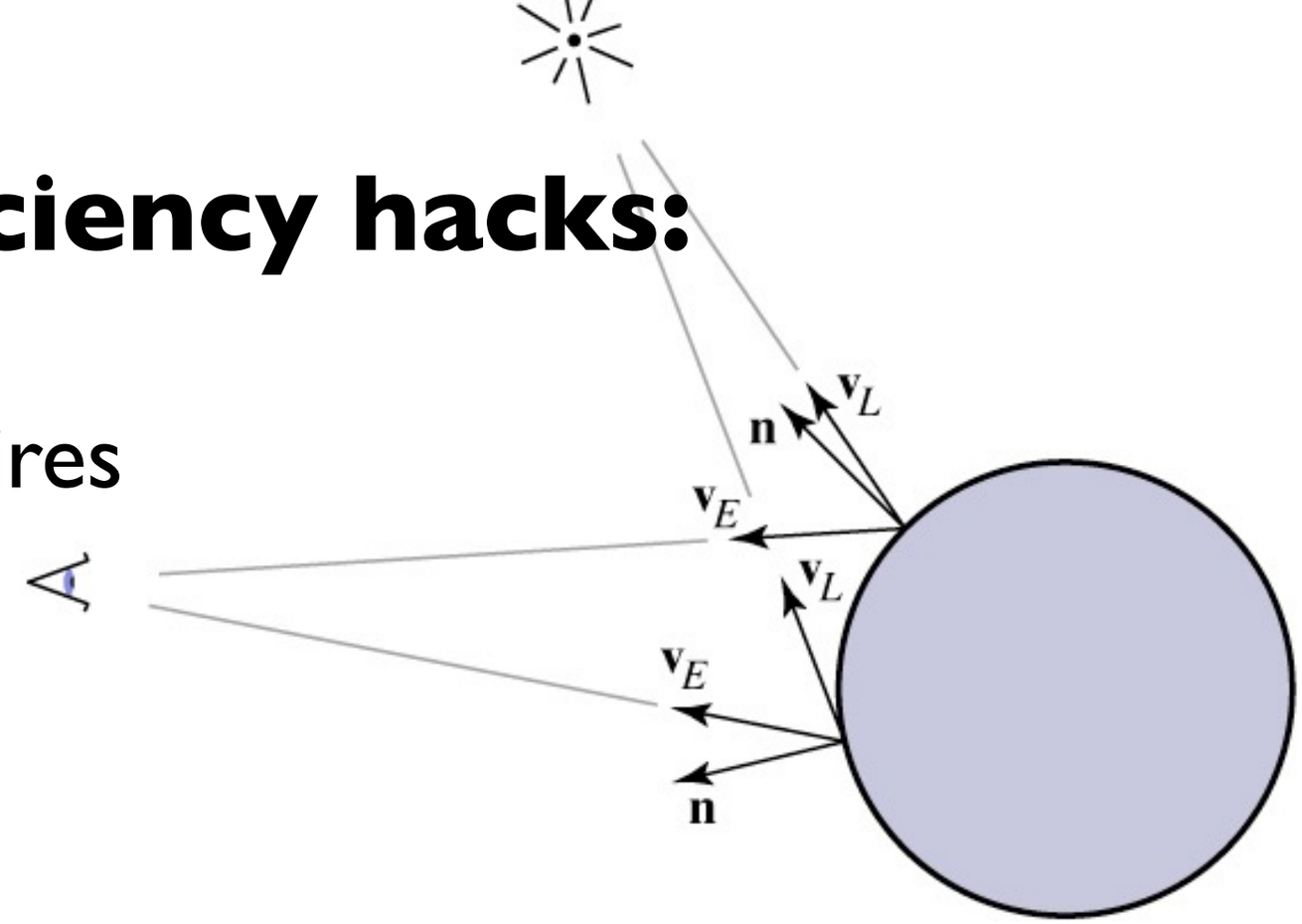
Some possible efficiency hacks:



- 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.

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Some possible efficiency hacks:

- Blinn-Phong model requires knowing
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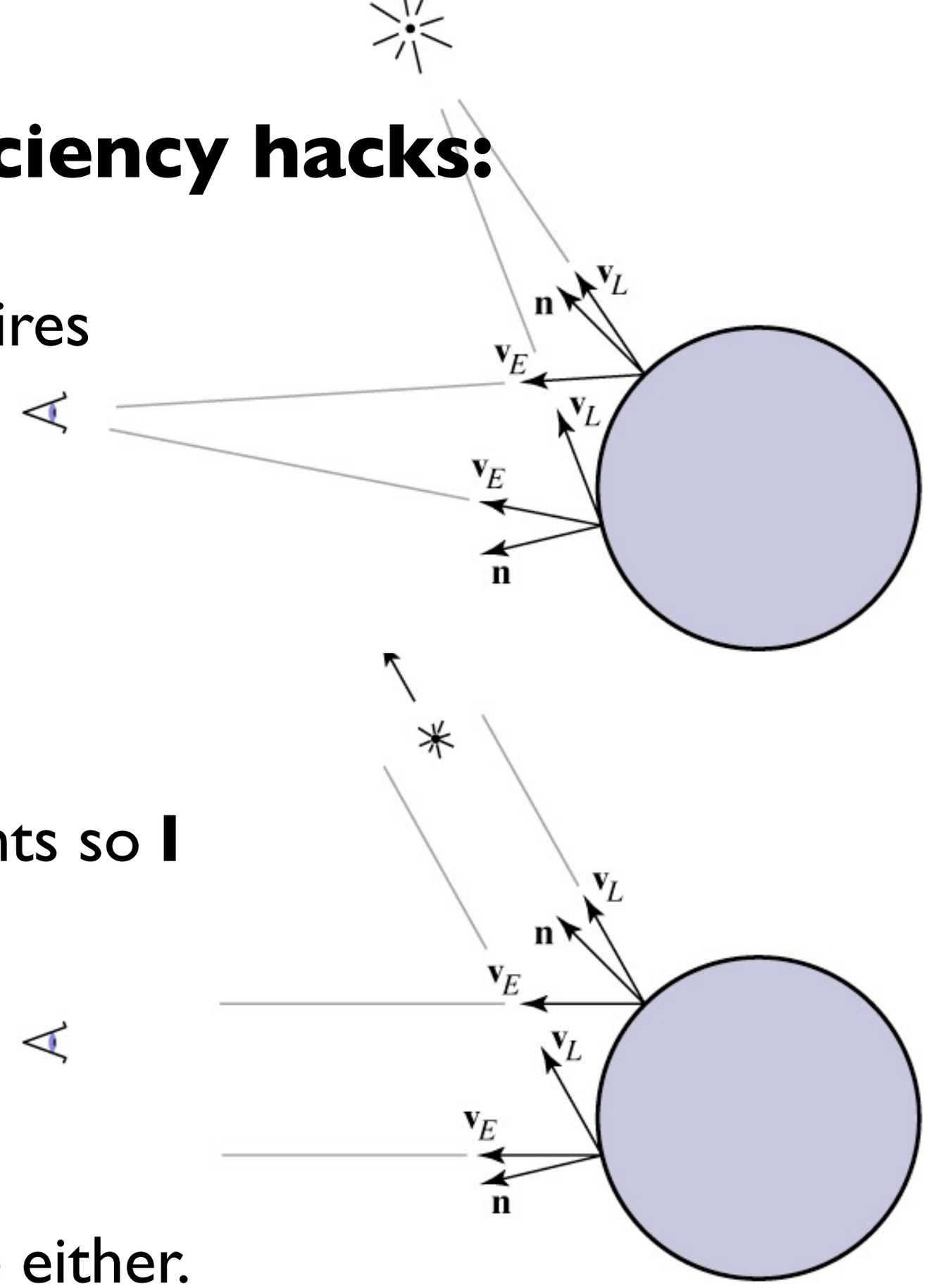

- Hack: use directional lights so **l** doesn't change

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

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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)

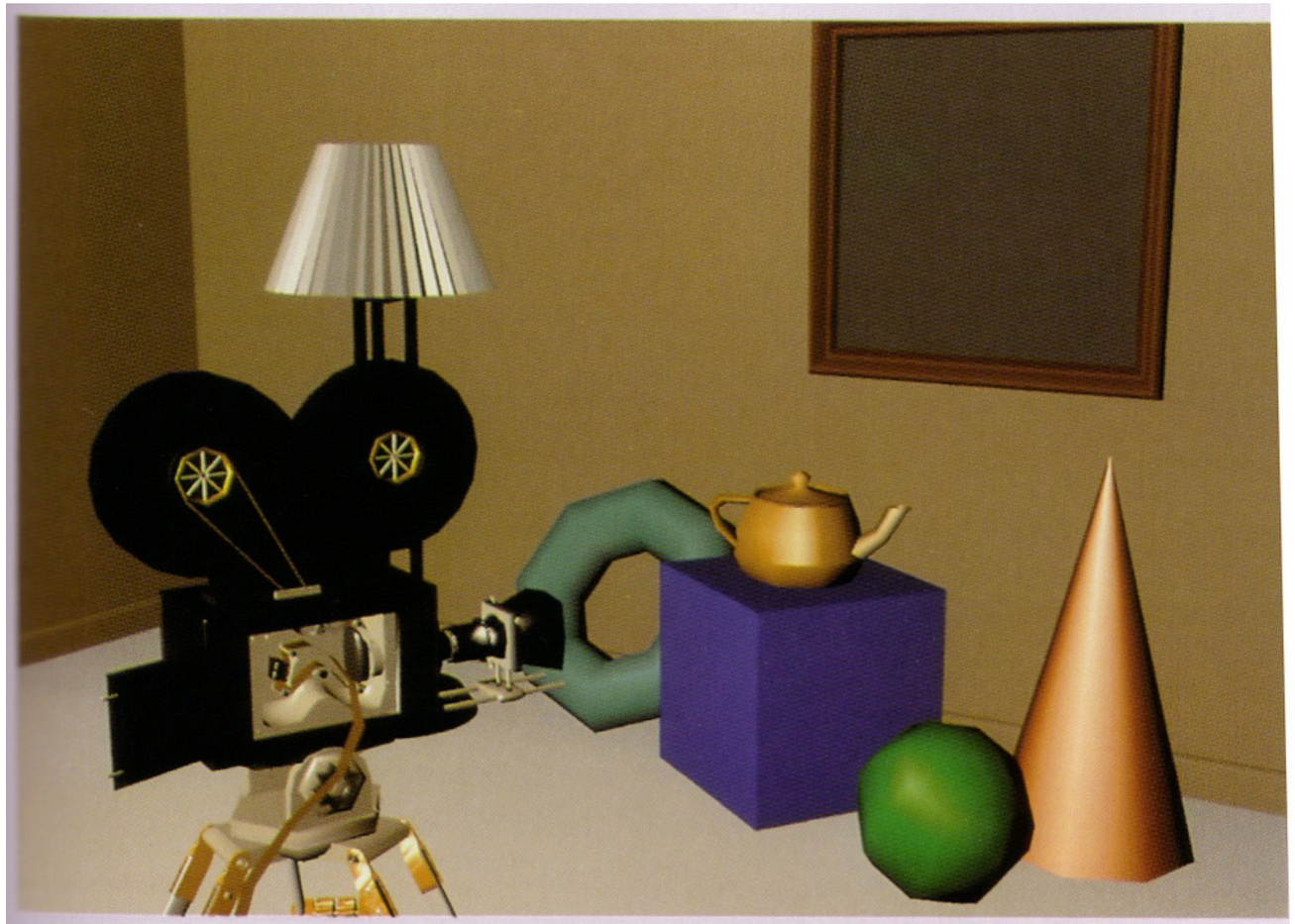

Plate II.31 *Shutterbug.* Gouraud shaded polygons with specular reflection (Sections 14.4.4 and 16.2.5). (Copyright © 1990, Pixar. Rendered by Thomas Williams and H.B. Siegel using Pixar's PhotoRealistic RenderMan™ software.)

[Foley et al.]

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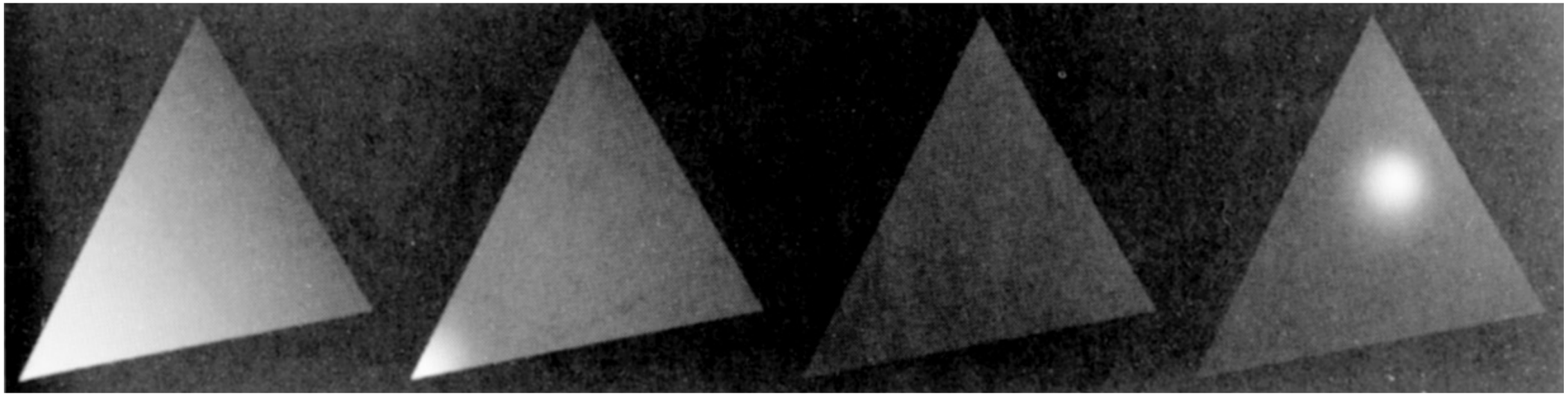
Per-pixel (Phong) shading

- 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



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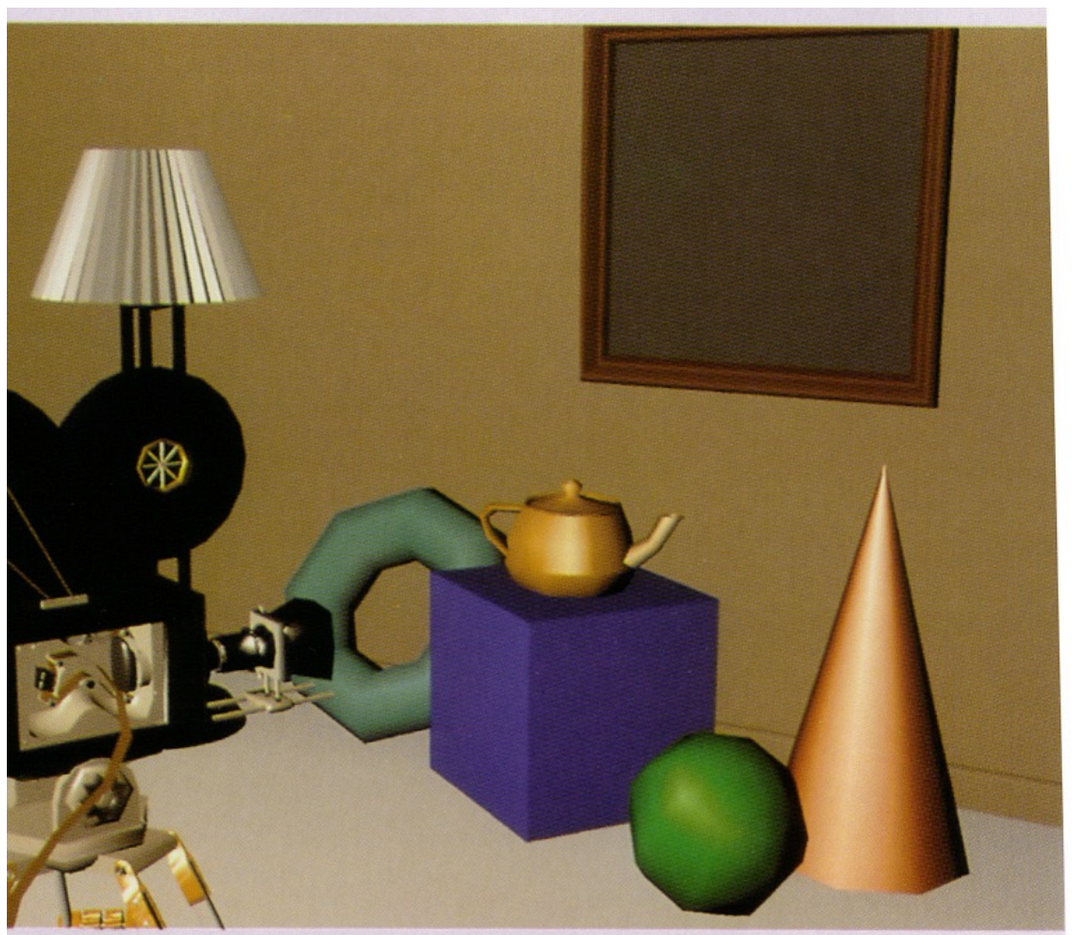
Per-pixel (Phong) shading

- 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
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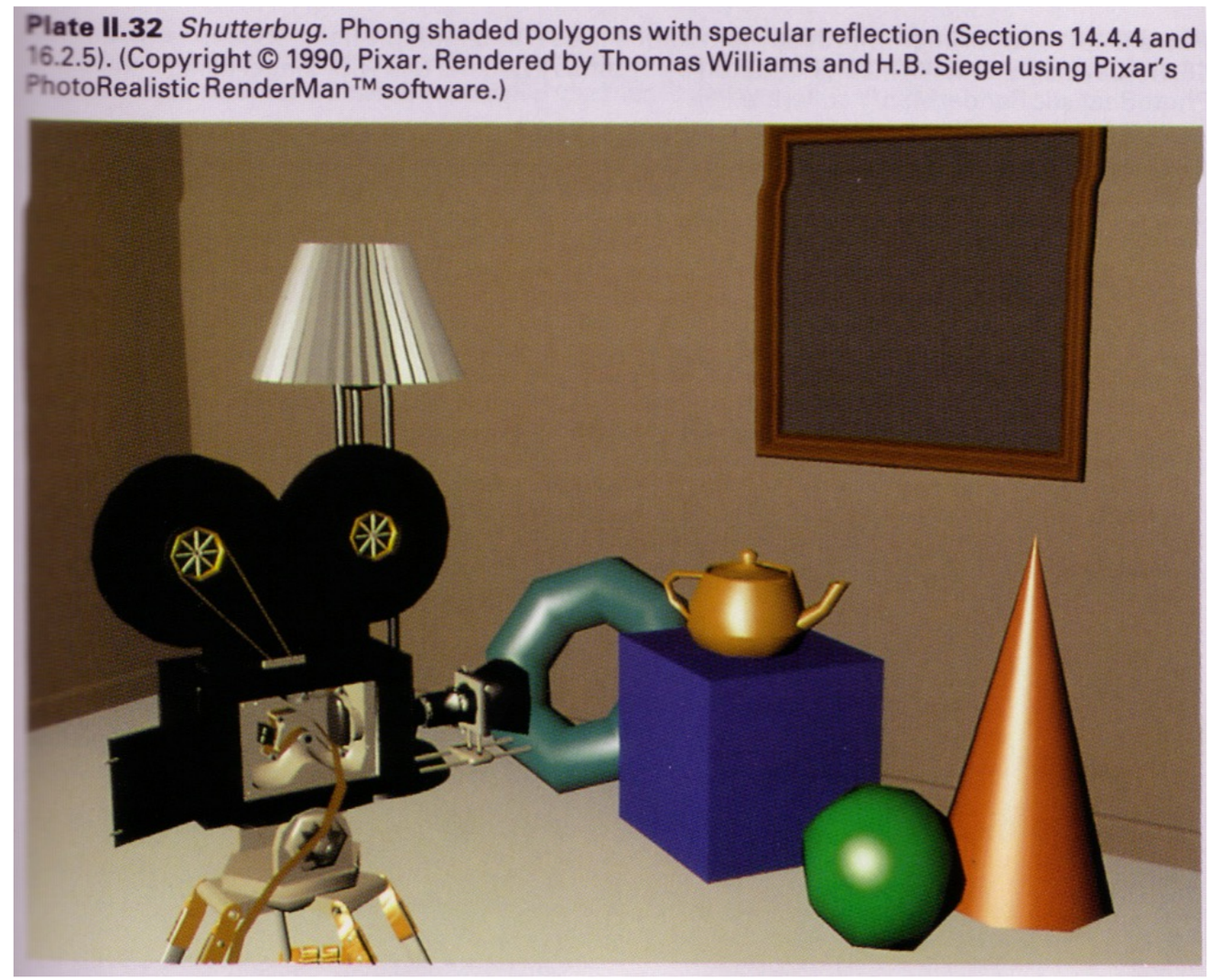

Plate II.32 *Shutterbug.* Phong shaded polygons with specular reflection (Sections 14.4.4 and 16.2.5). (Copyright © 1990, Pixar. Rendered by Thomas Williams and H.B. Siegel using Pixar's PhotoRealistic RenderMan™ software.)

[Foley et al.]

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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'*

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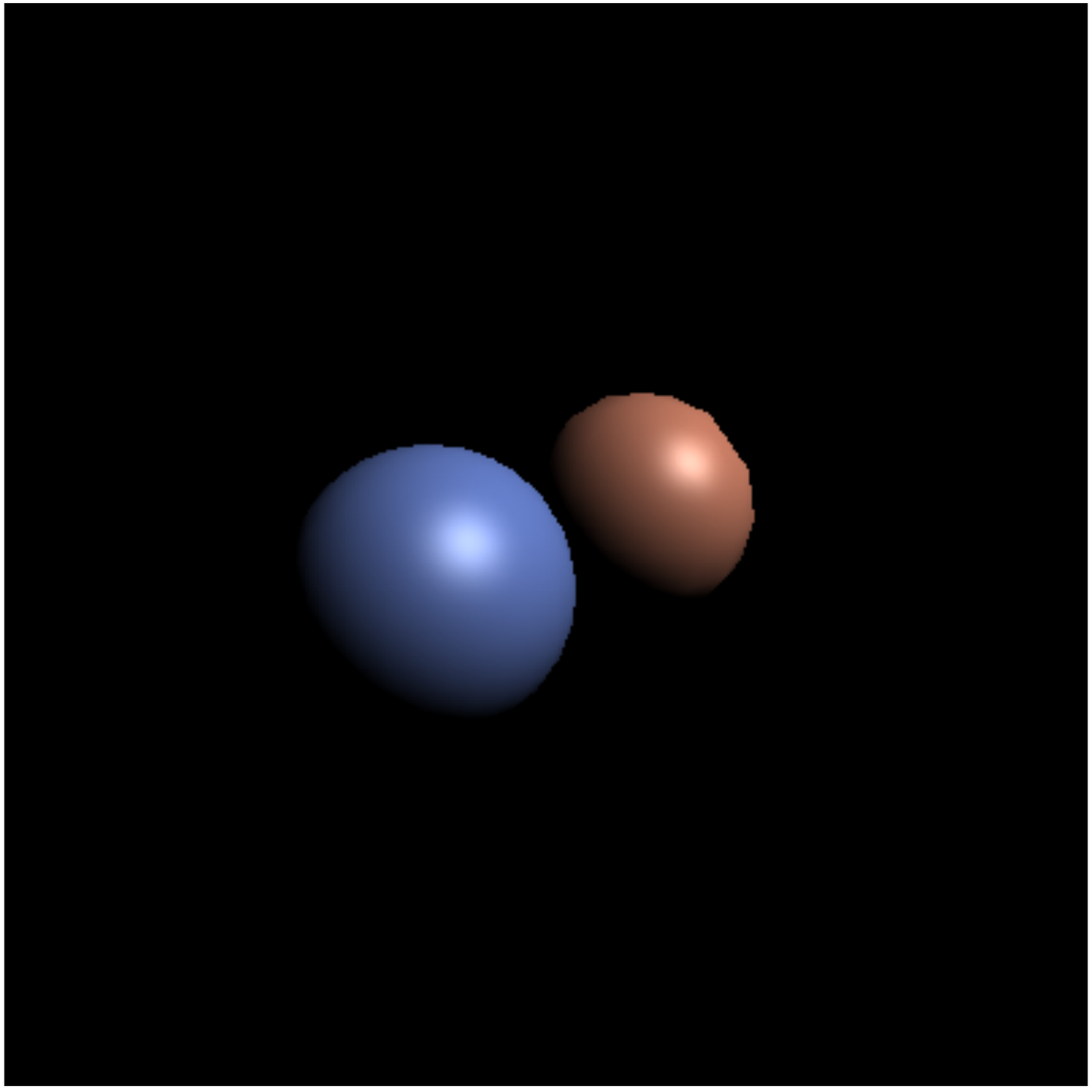
Result of per-pixel shading pipeline



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