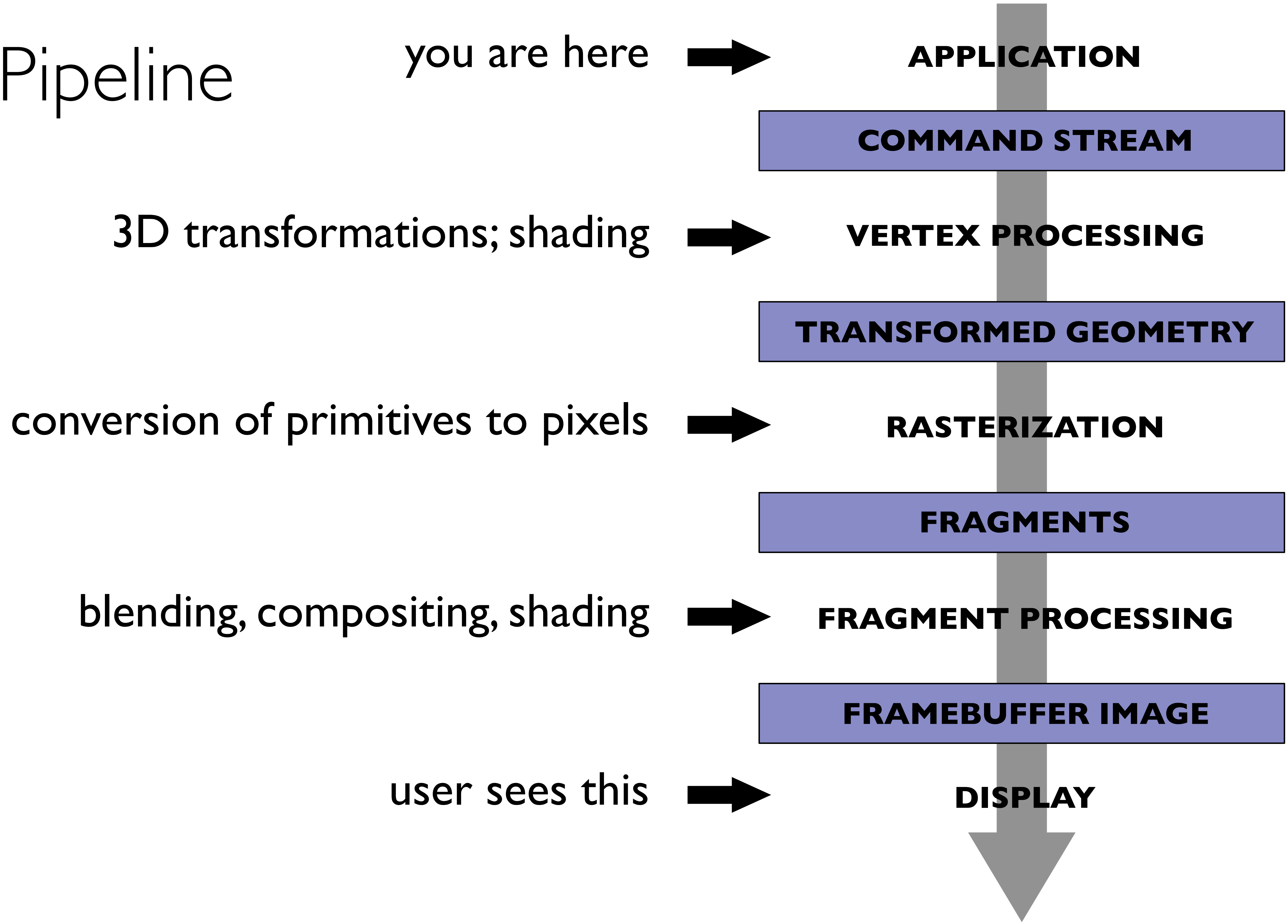
Pipeline Operations

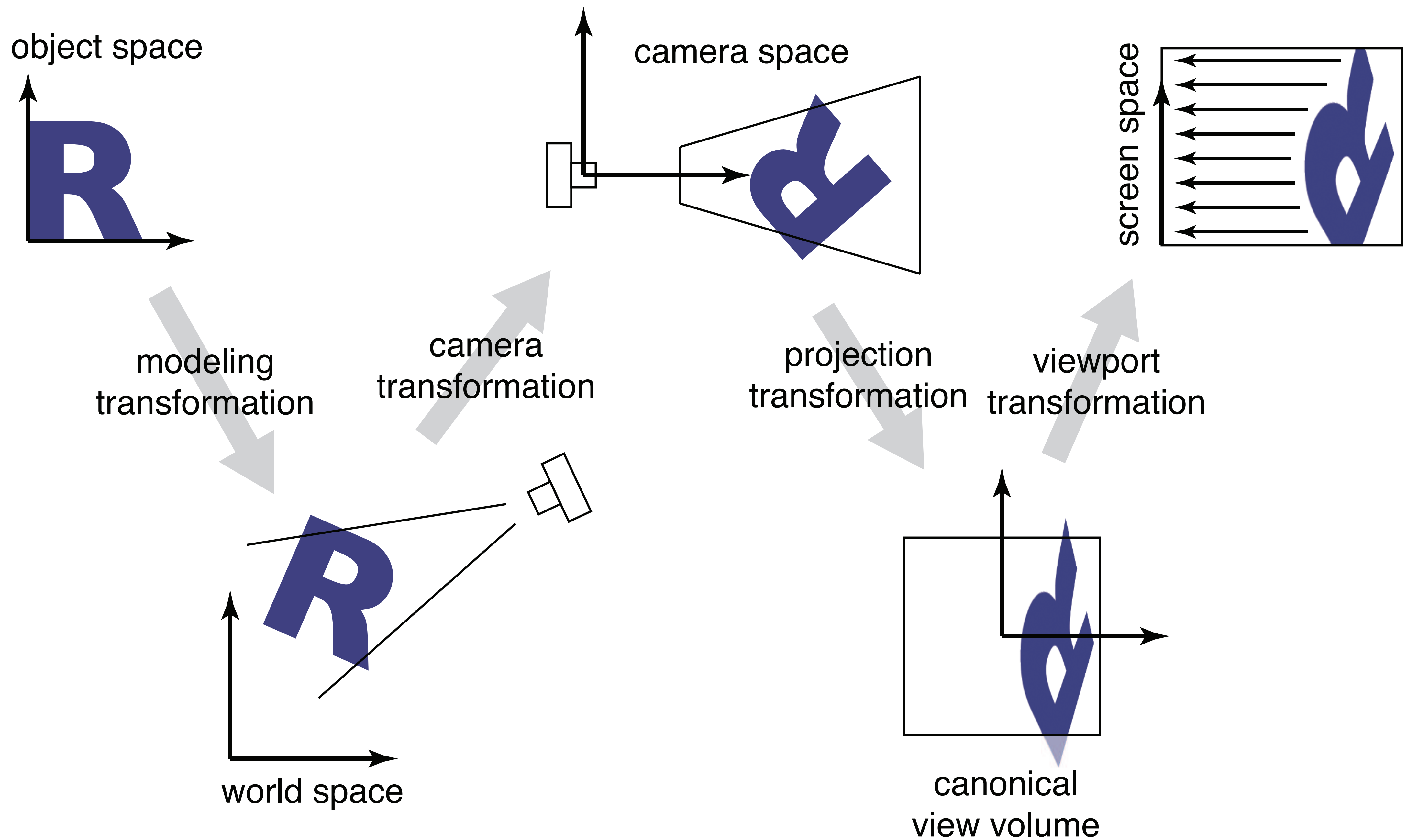
CS 4620 Lecture 11

Pipeline


you are here
APPLICATION
COMMAND STREAM
3D transformations; shading
VERTEX PROCESSING
TRANSFORMED GEOMETRY
conversion of primitives to pixels
RASTERIZATION
FRAGMENTS
blending, compositing, shading
FRAGMENT PROCESSING
FRAMEBUFFER IMAGE
user sees this
DISPLAY

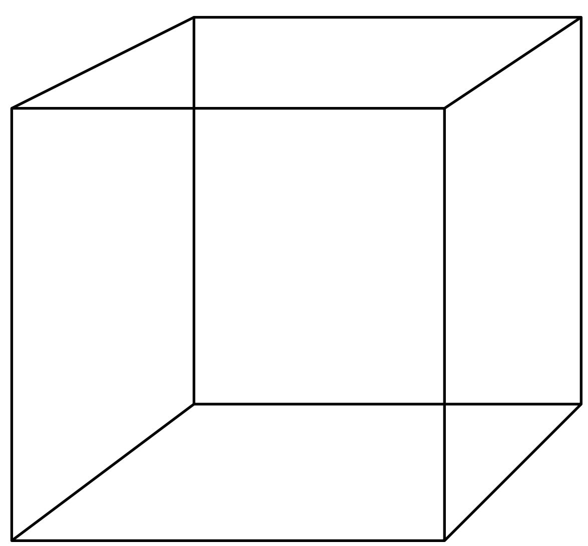
Pipeline of transformations

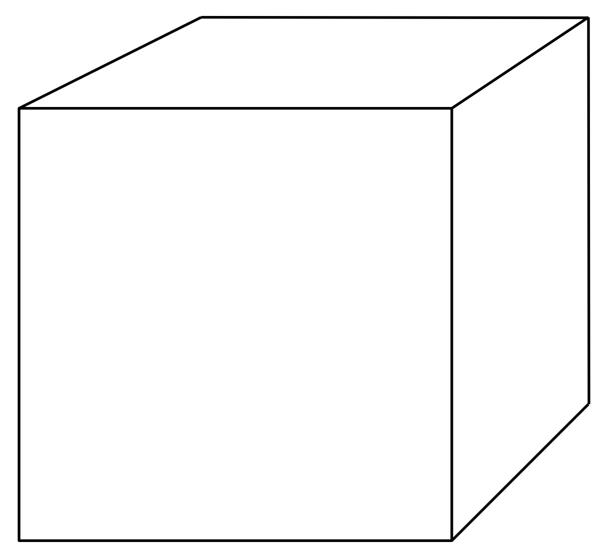
- **Standard sequence of transforms**



Hidden surface elimination

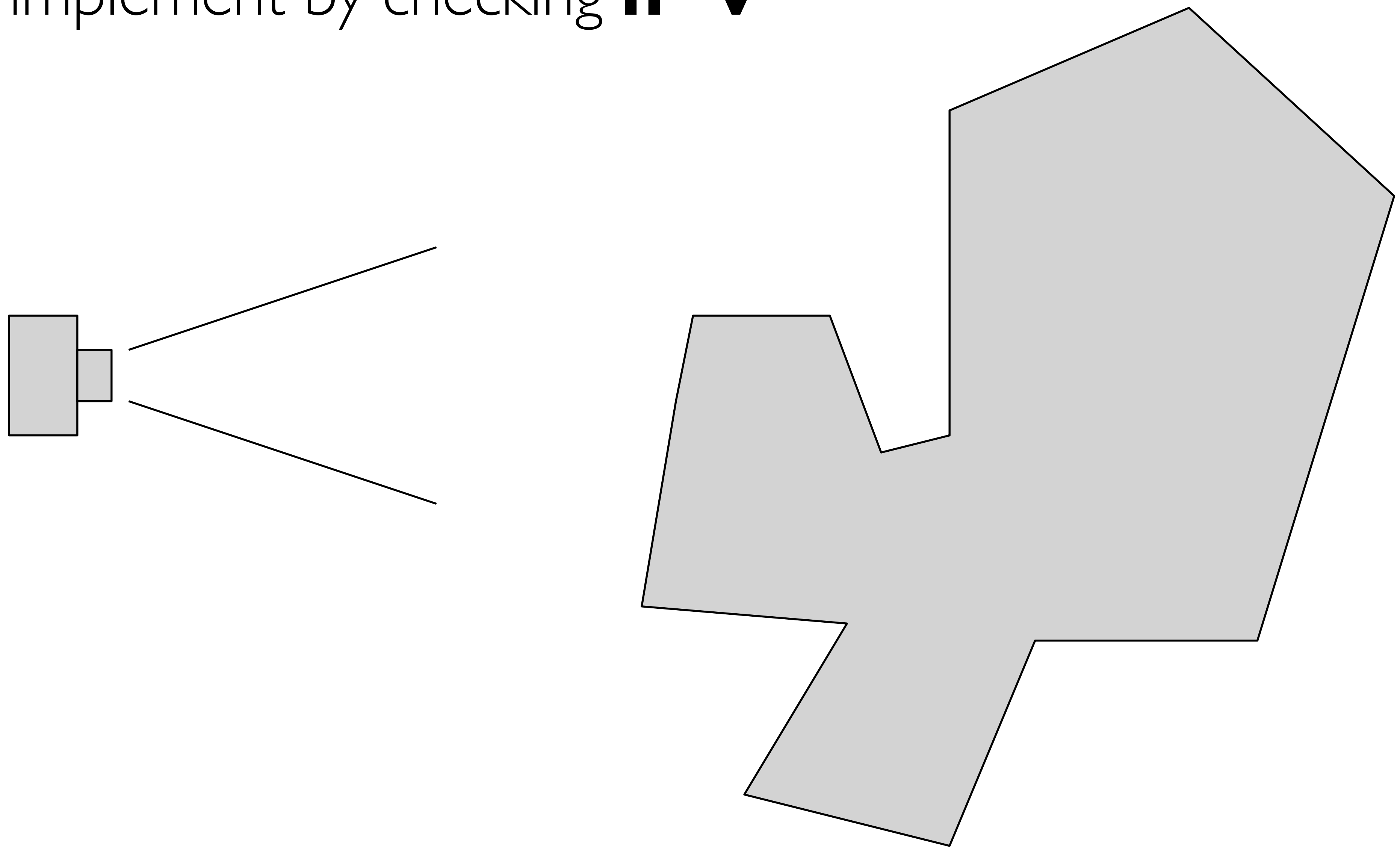
- **We have discussed how to map primitives to image space**
  - projection and perspective are depth cues
  - occlusion is another very important cue





Back face culling

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



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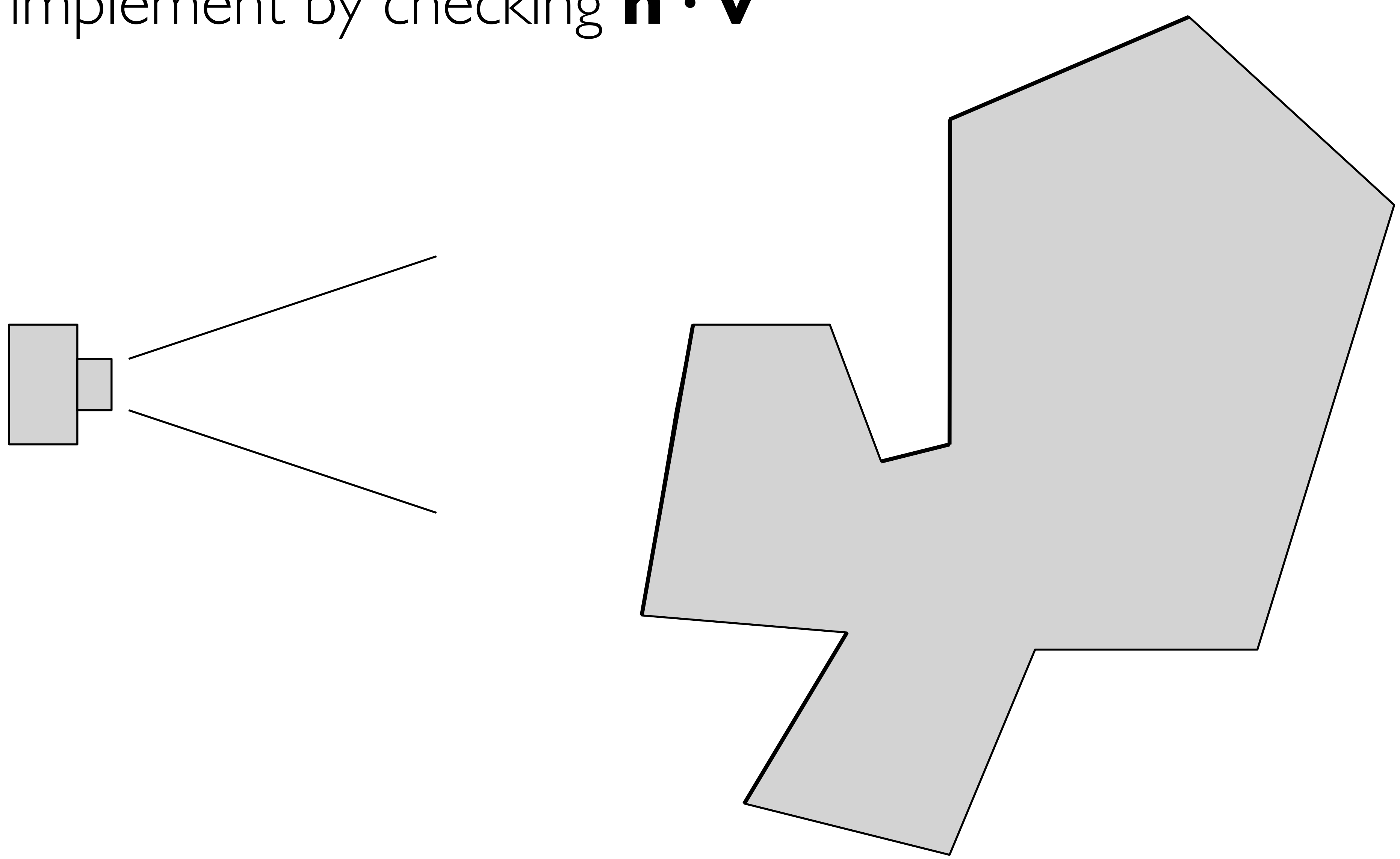

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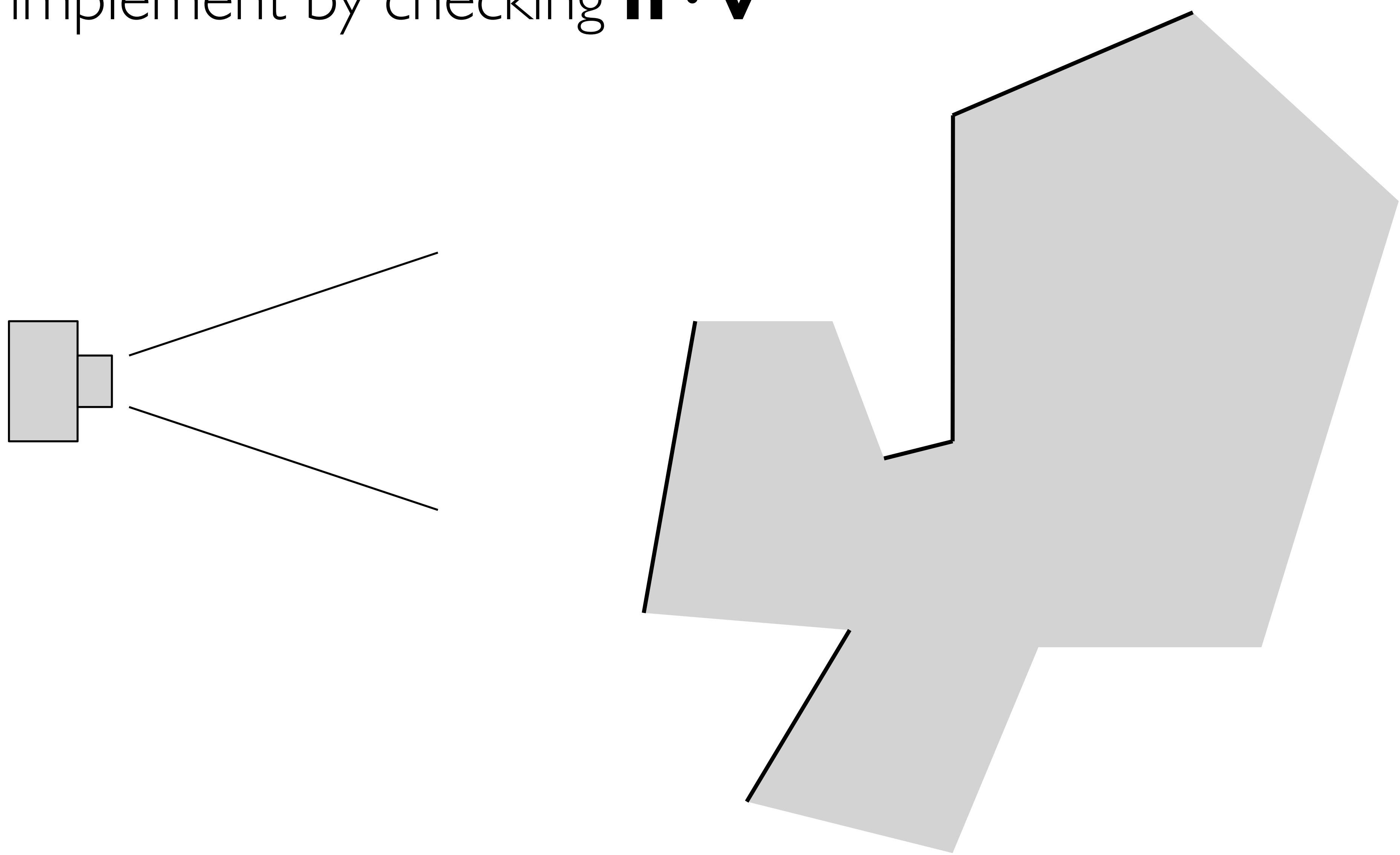

Back face culling

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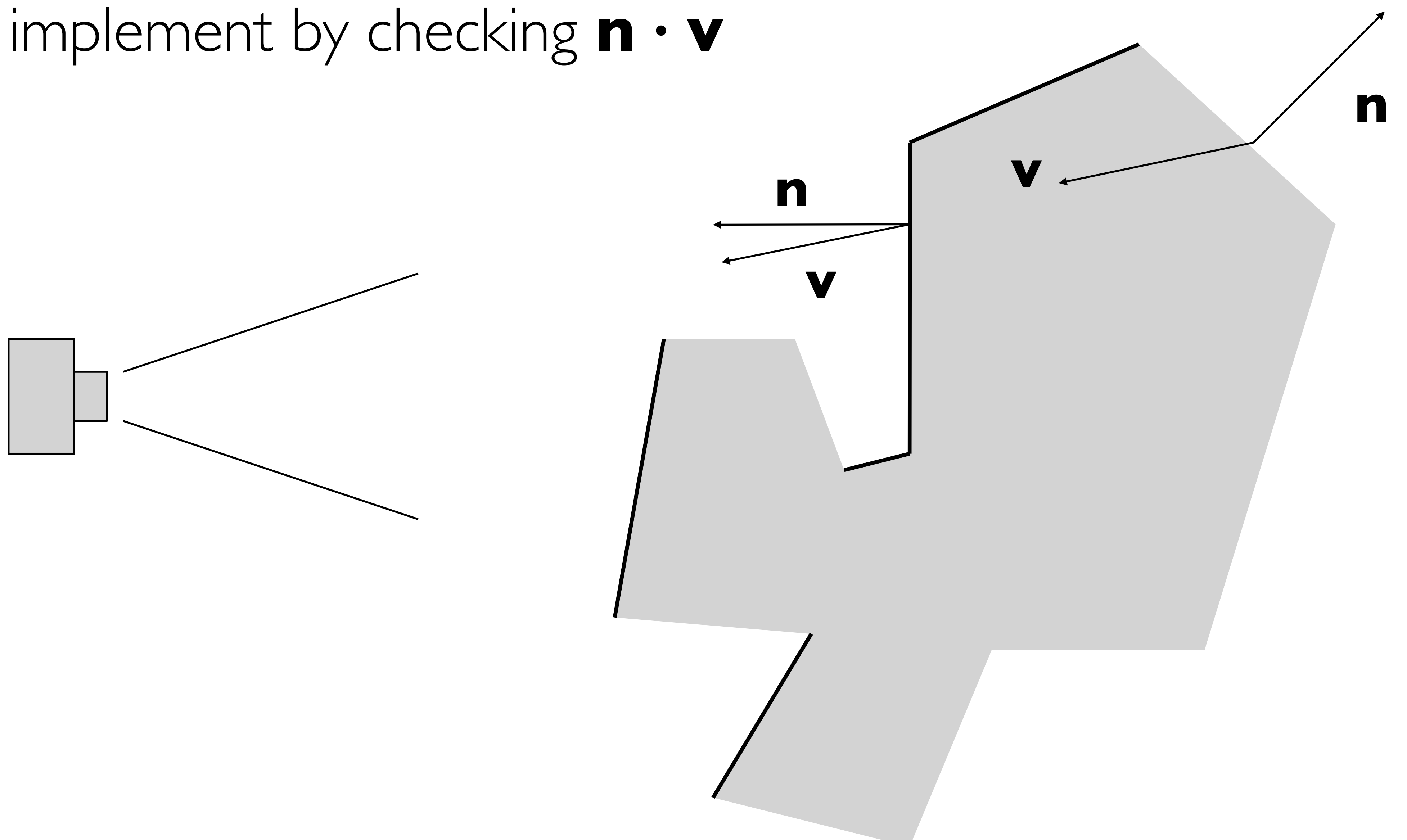
  - implement by checking **n · v**



Painter's algorithm

- **Simplest way to do hidden surfaces**
- **Draw from back to front, use overwriting in framebuffer**

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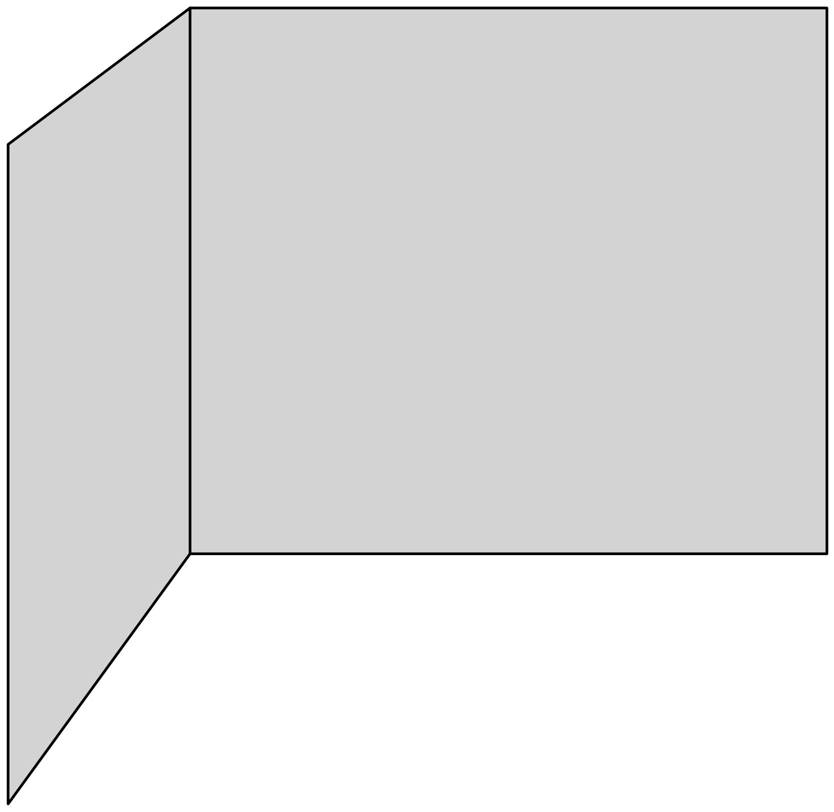

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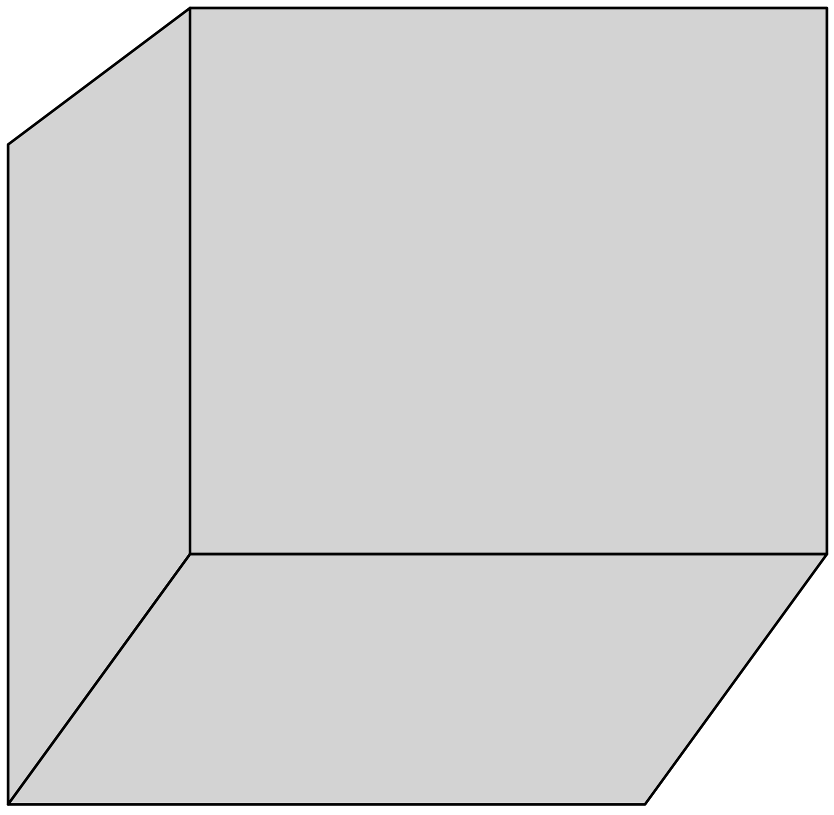

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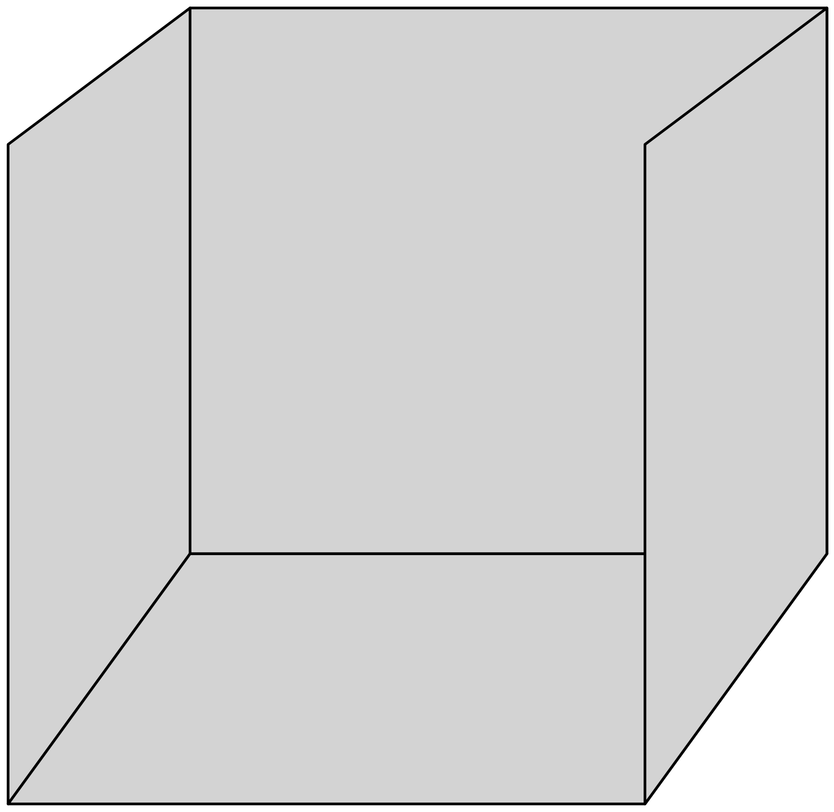

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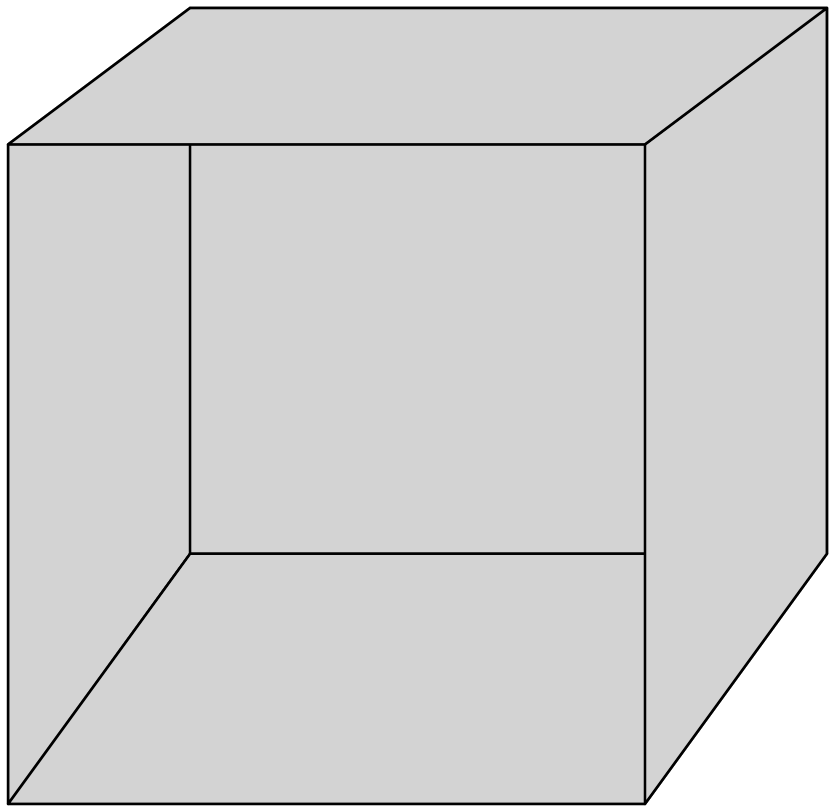

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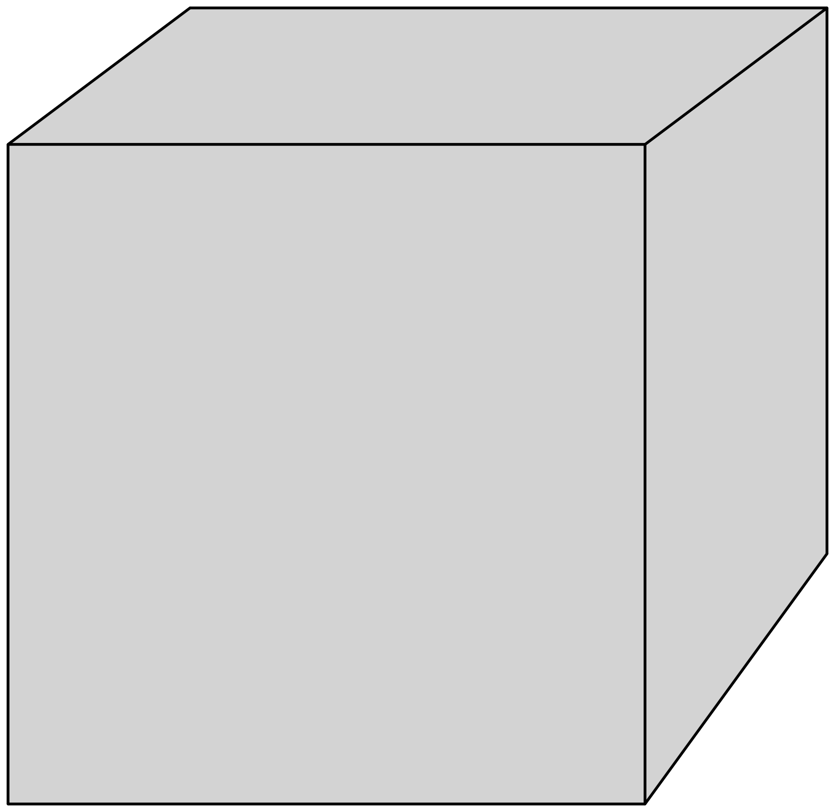
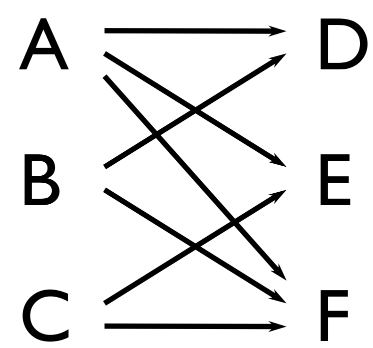
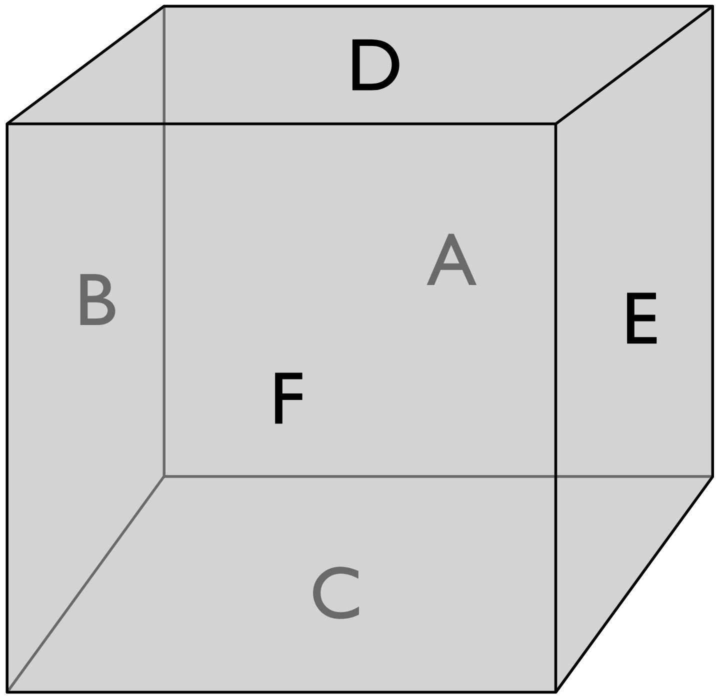


Painter's algorithm

- **Amounts to a topological sort of the graph of occlusions**
  - that is, an edge from A to B means A sometimes occludes B
  - any sort is valid
    - ABCDEF
    - BADCFE
  - if there are cycles there is no sort





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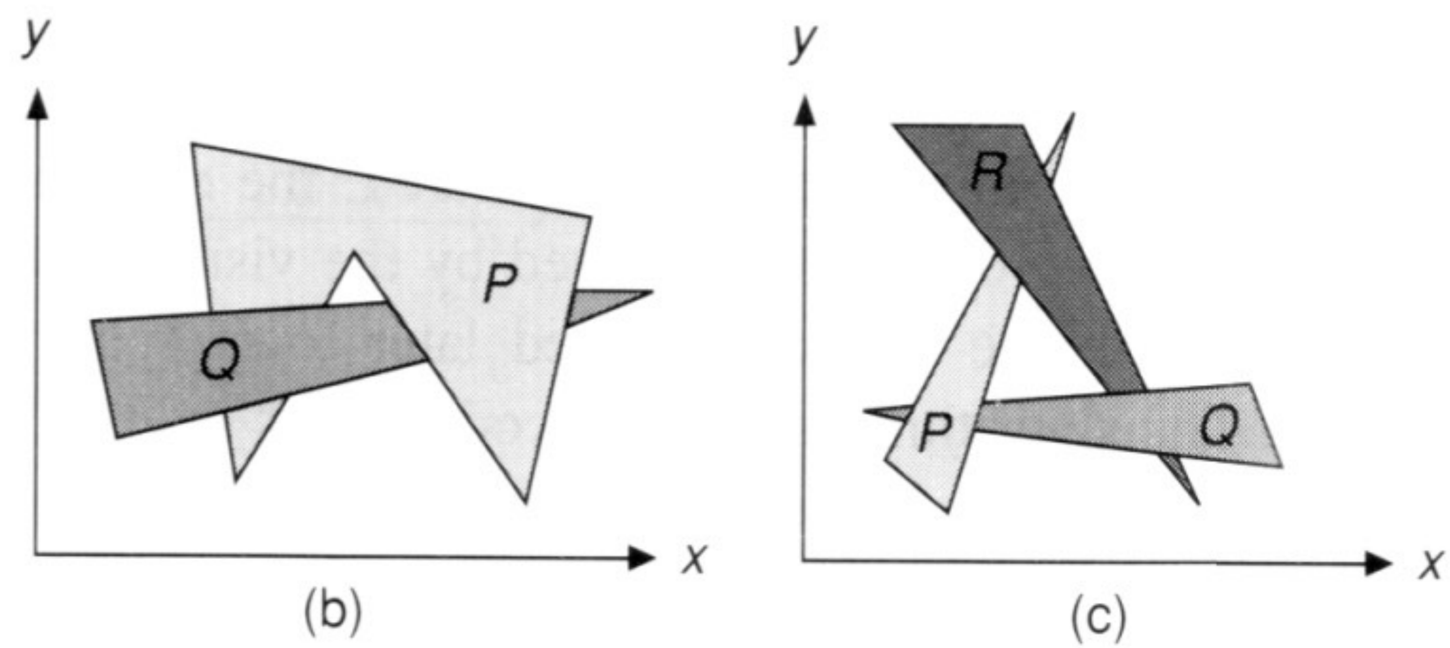
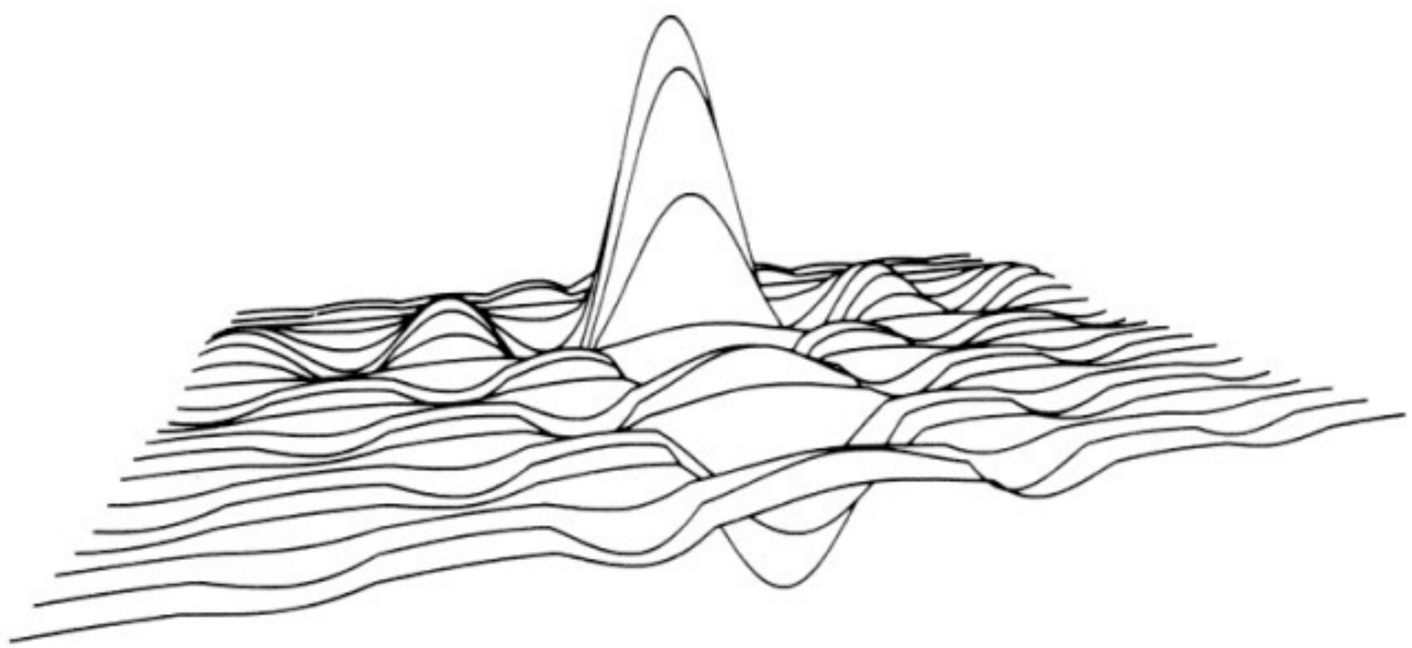


[Foley et al.]

Painter's algorithm

- **Useful when a valid order is easy to come by**
- **Compatible with alpha blending**

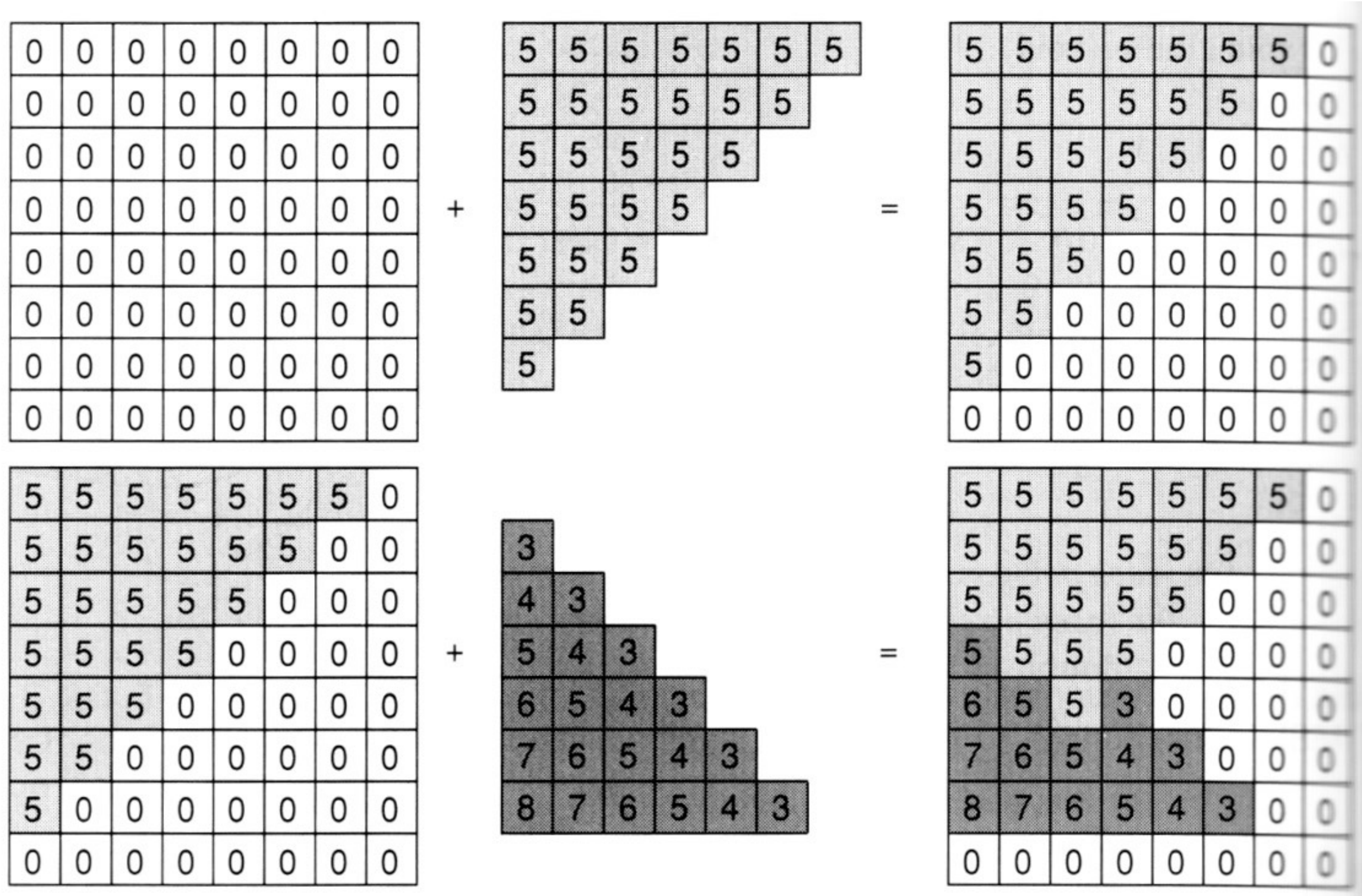


[Foley et al.]

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



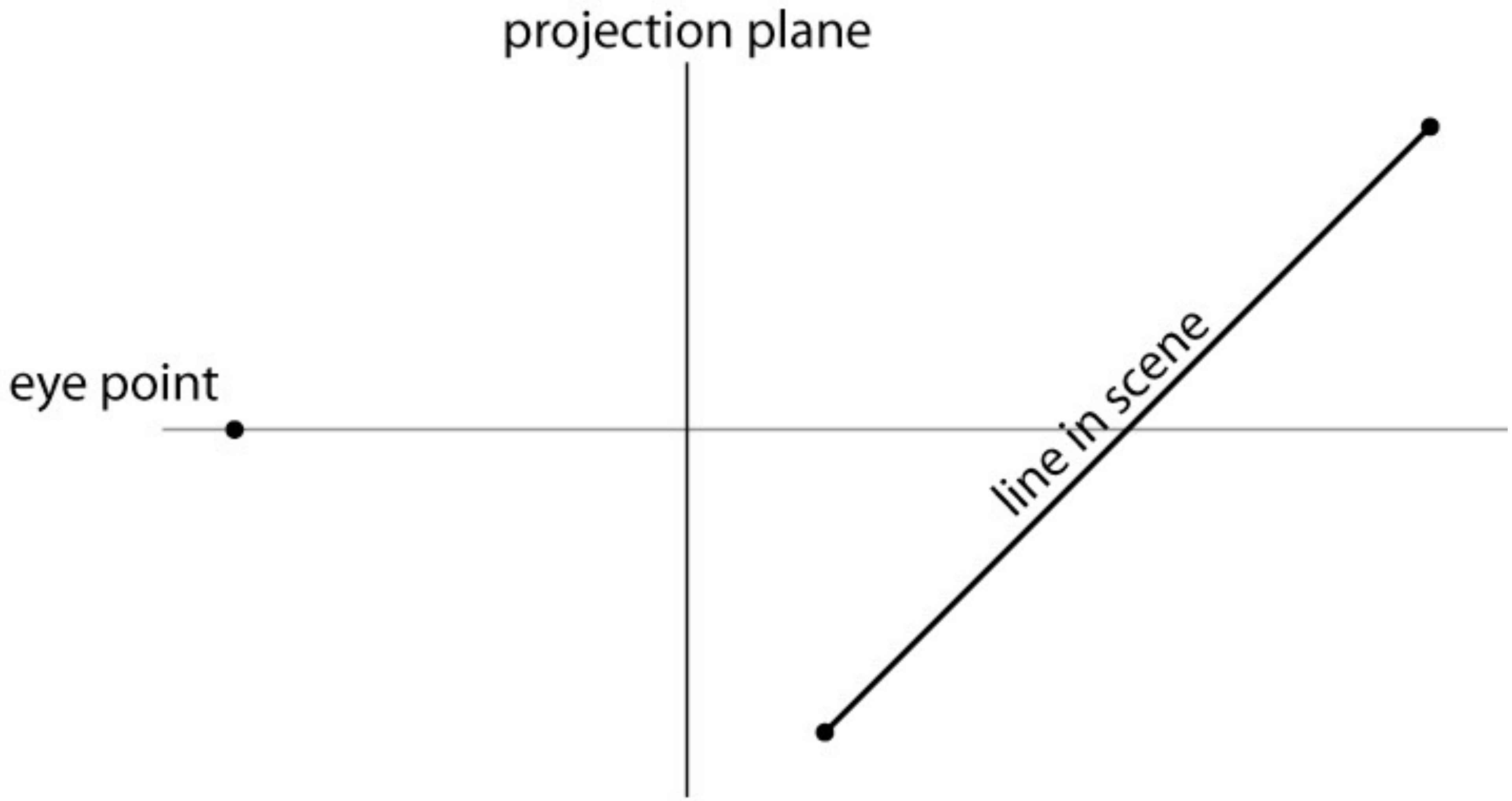
[Foley et al.]

– another example of a memory-intensive brute force approach that works and has become the standard

Precision in **z** buffer

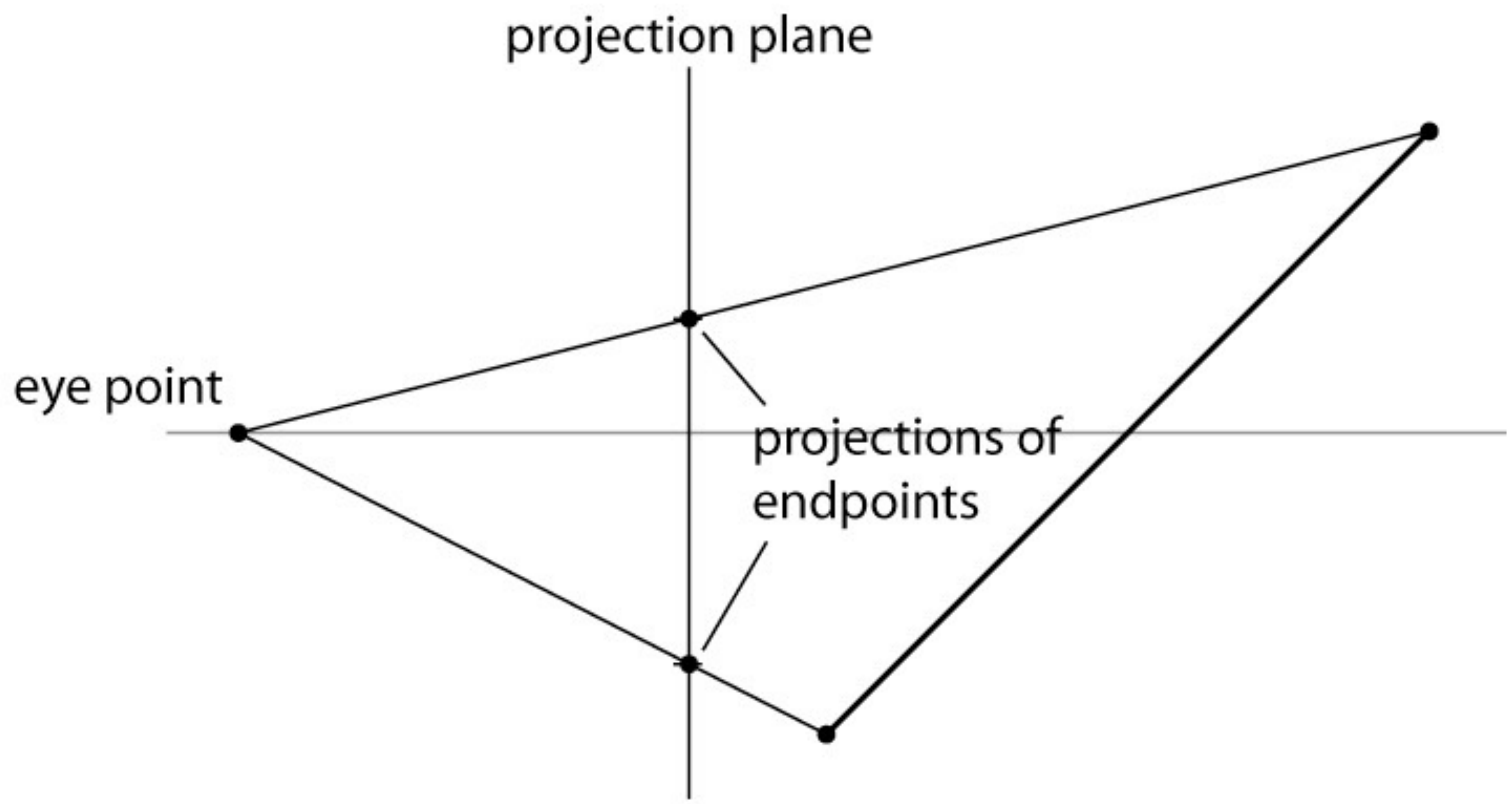
- **The precision is distributed between the near and far clipping planes**
  - this is why these planes have to exist
  - also why you can't always just set them to very small and very large distances
- **Generally use *z*' (not world *z*) in *z* buffer**

Interpolating in projection



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

Interpolating in projection



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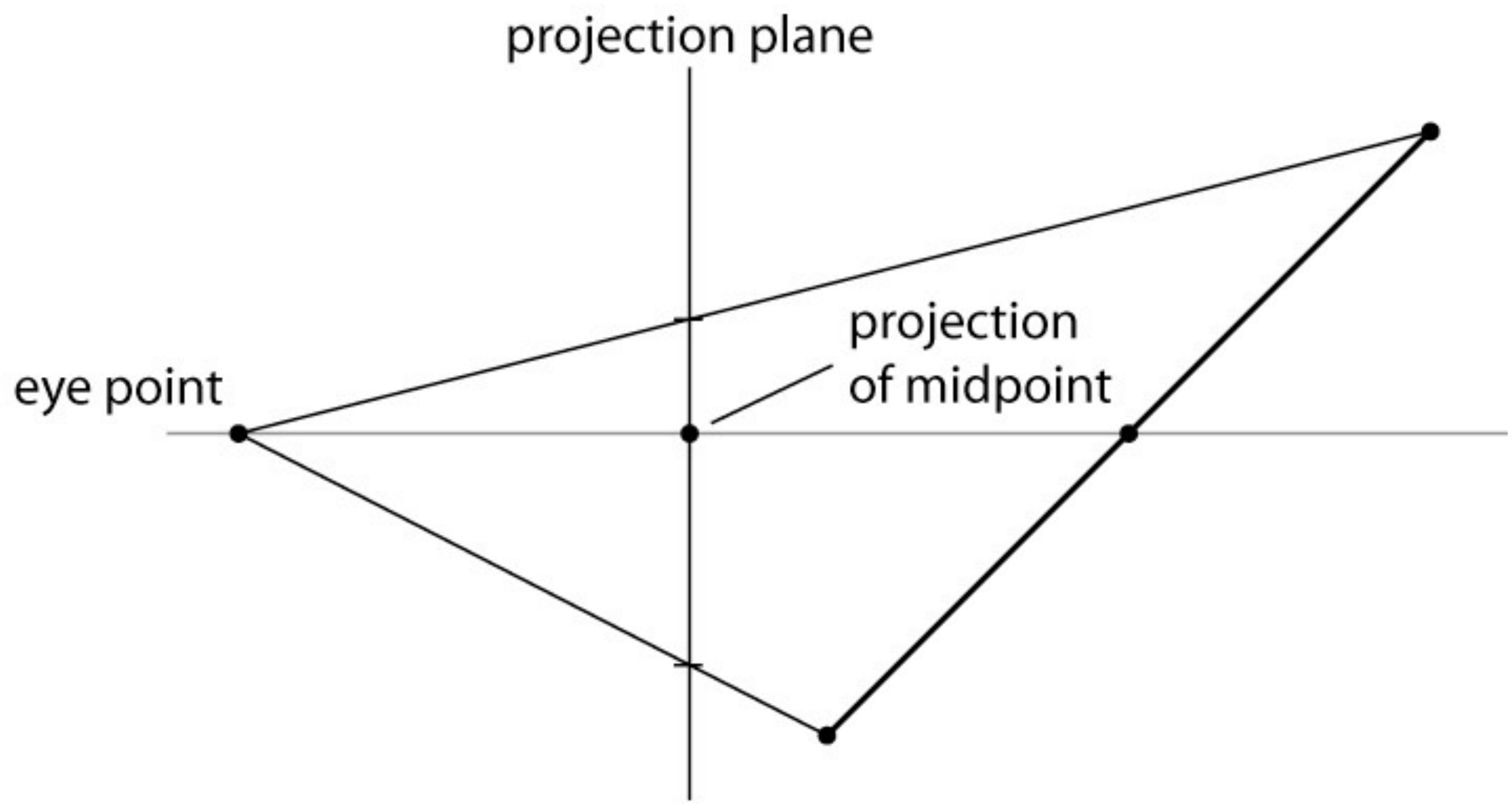

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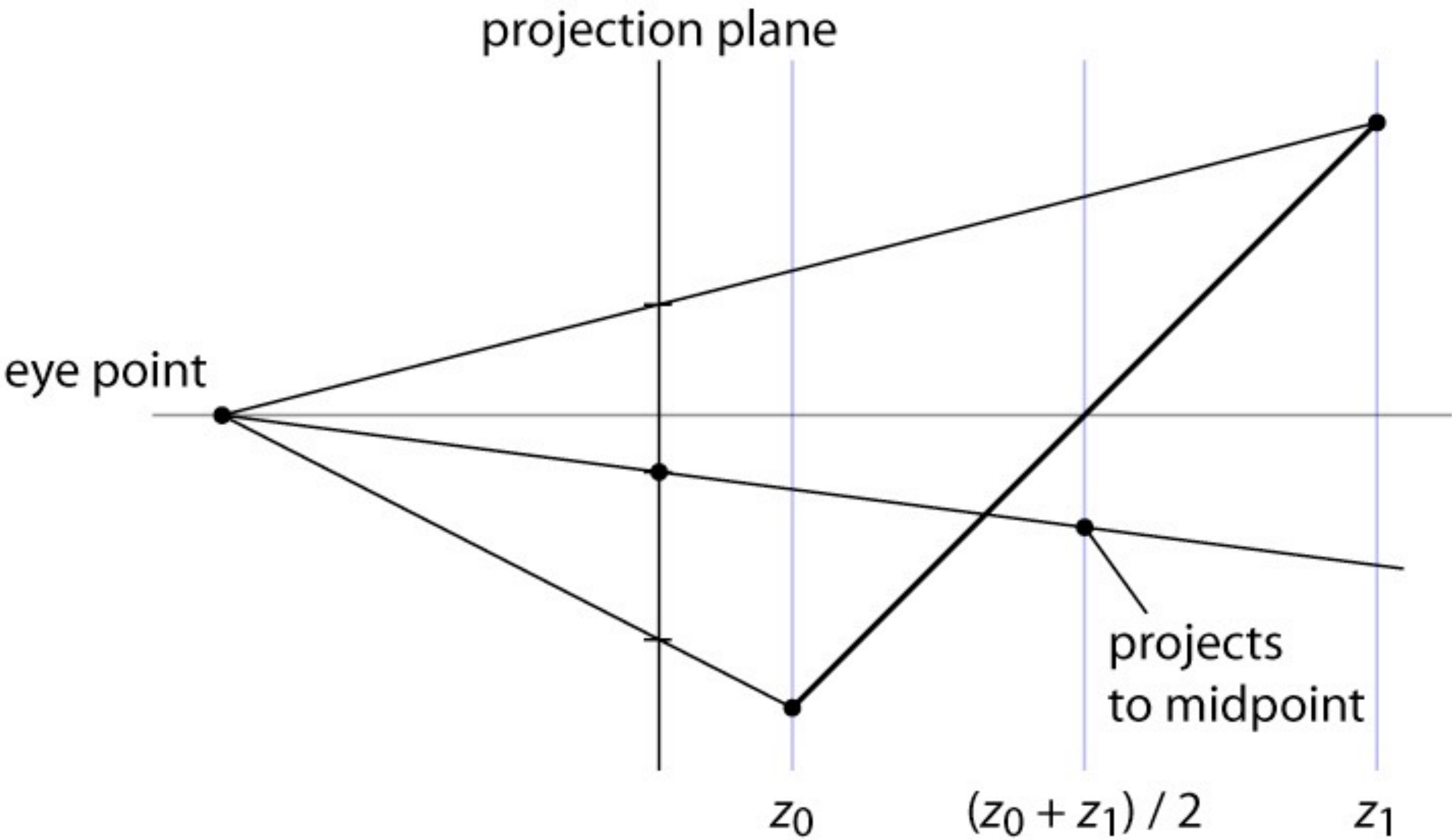

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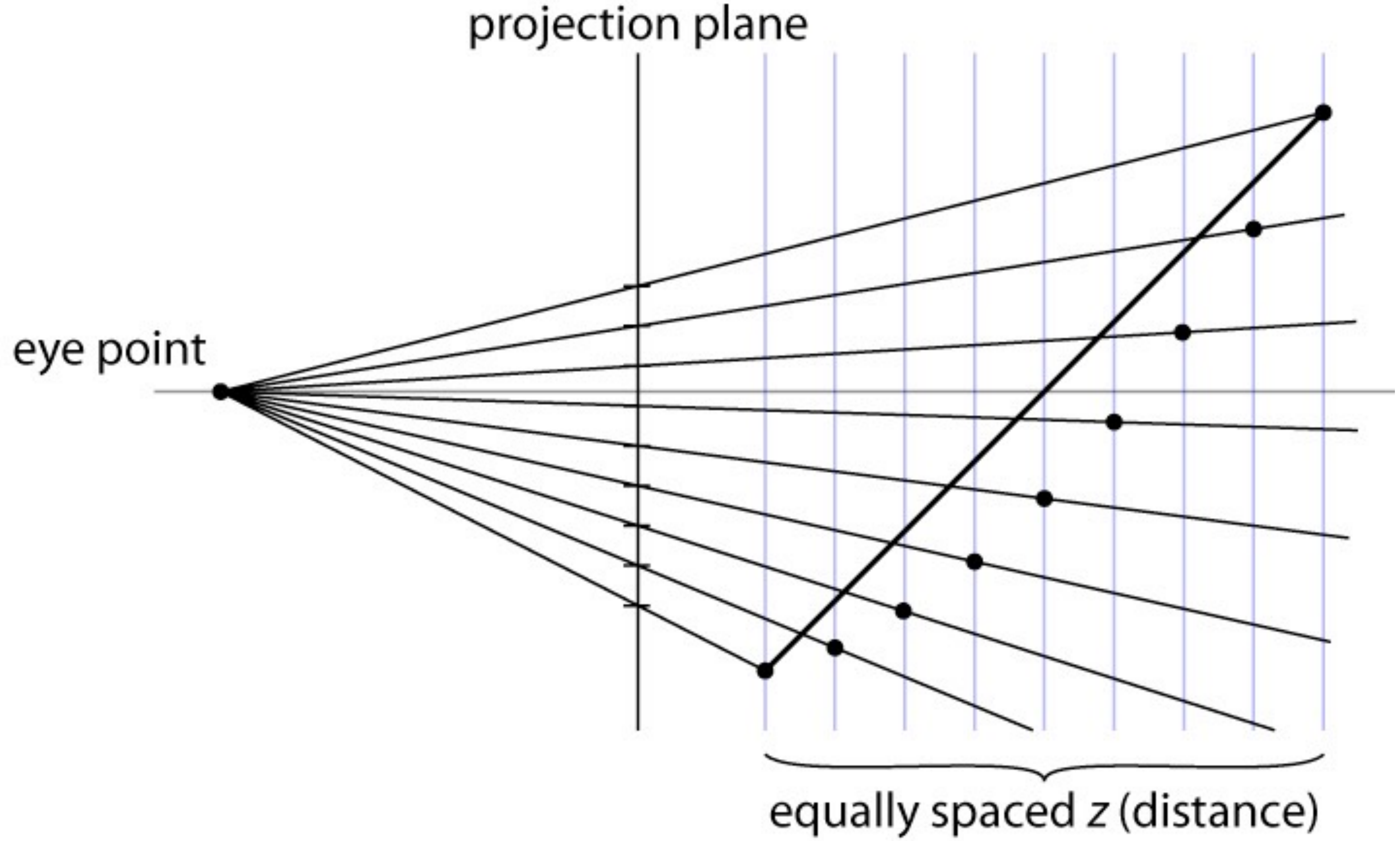

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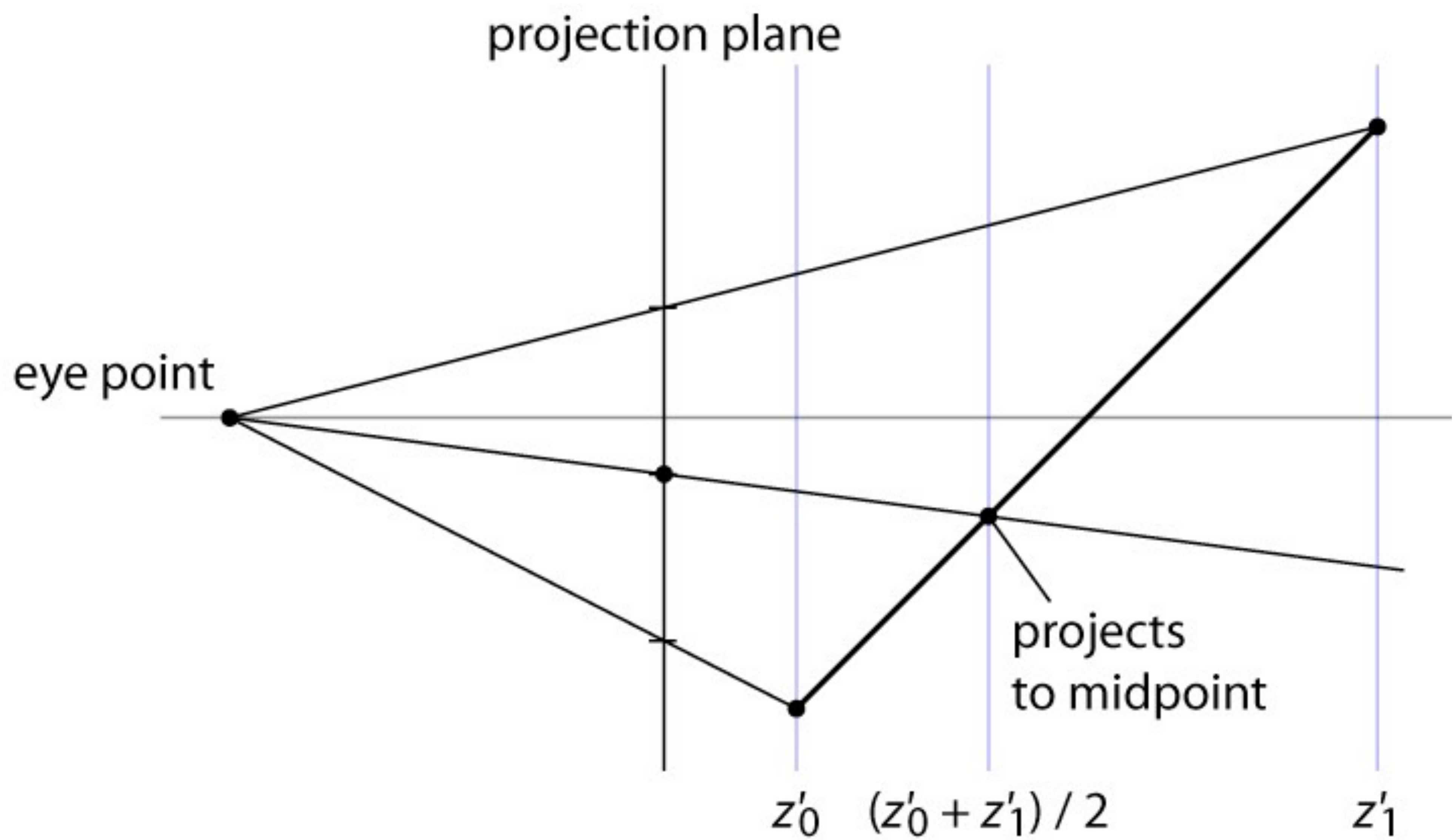

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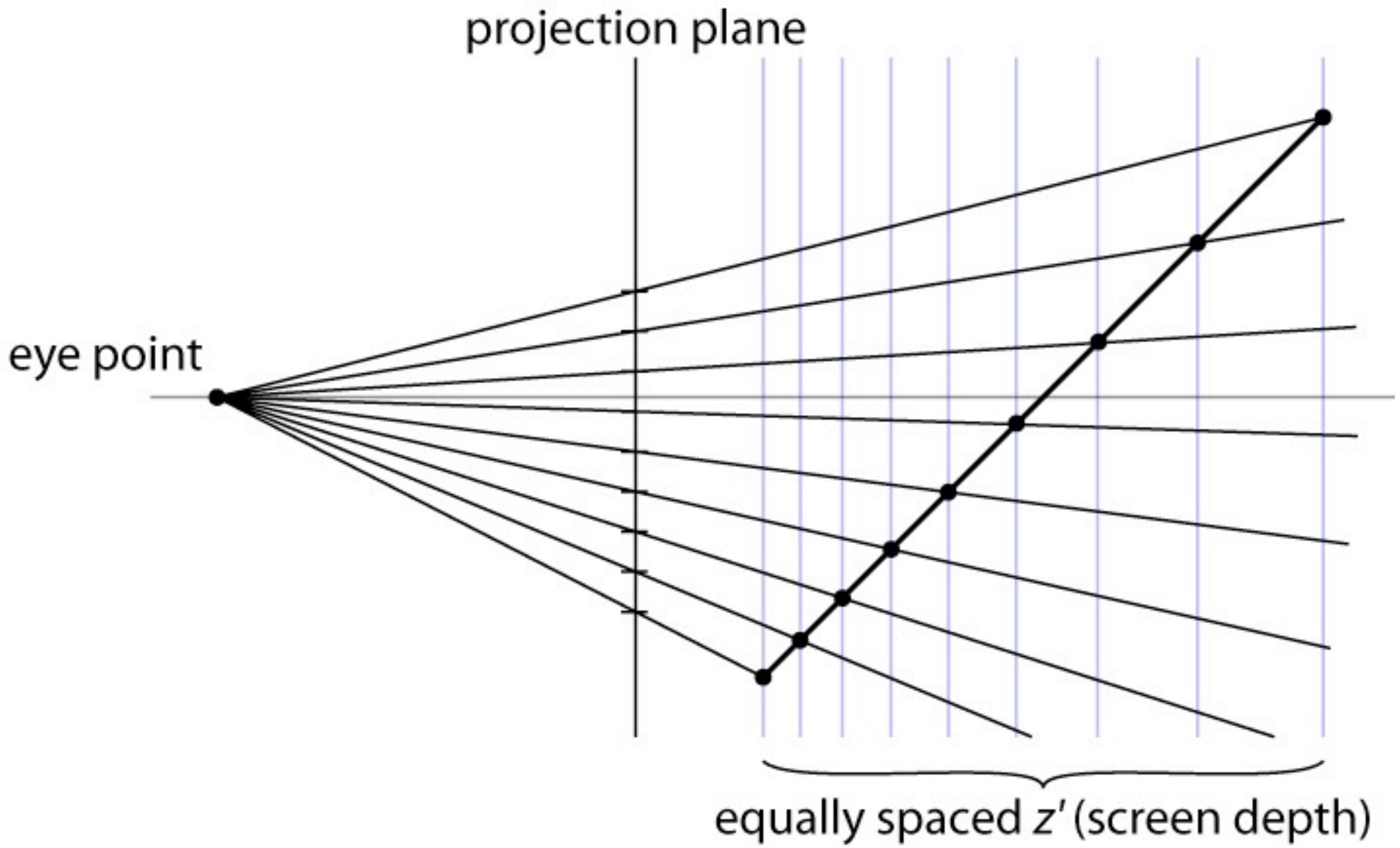
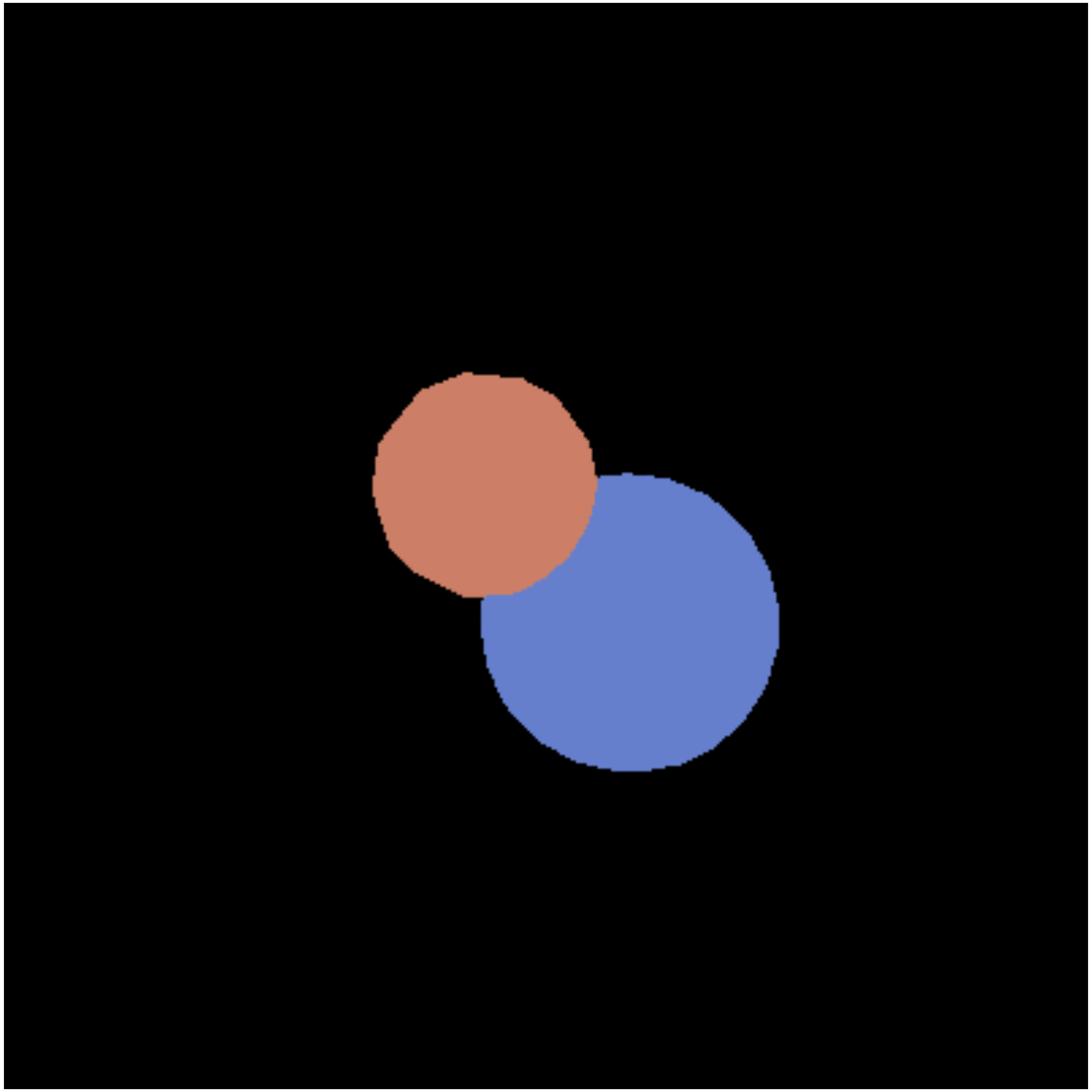


linear interp. in screen space ≠ linear interp. in world (eye) space

Pipeline for minimal operation

- **Vertex stage (input: position / vtx)**
  – transform position (object to screen space)
- **Rasterizer**
  – nothing (extra) to interpolate
- **Fragment stage (output: color)**
  – write a fixed color to color planes
  – (color is a "uniform" quantity that is infrequently updated)

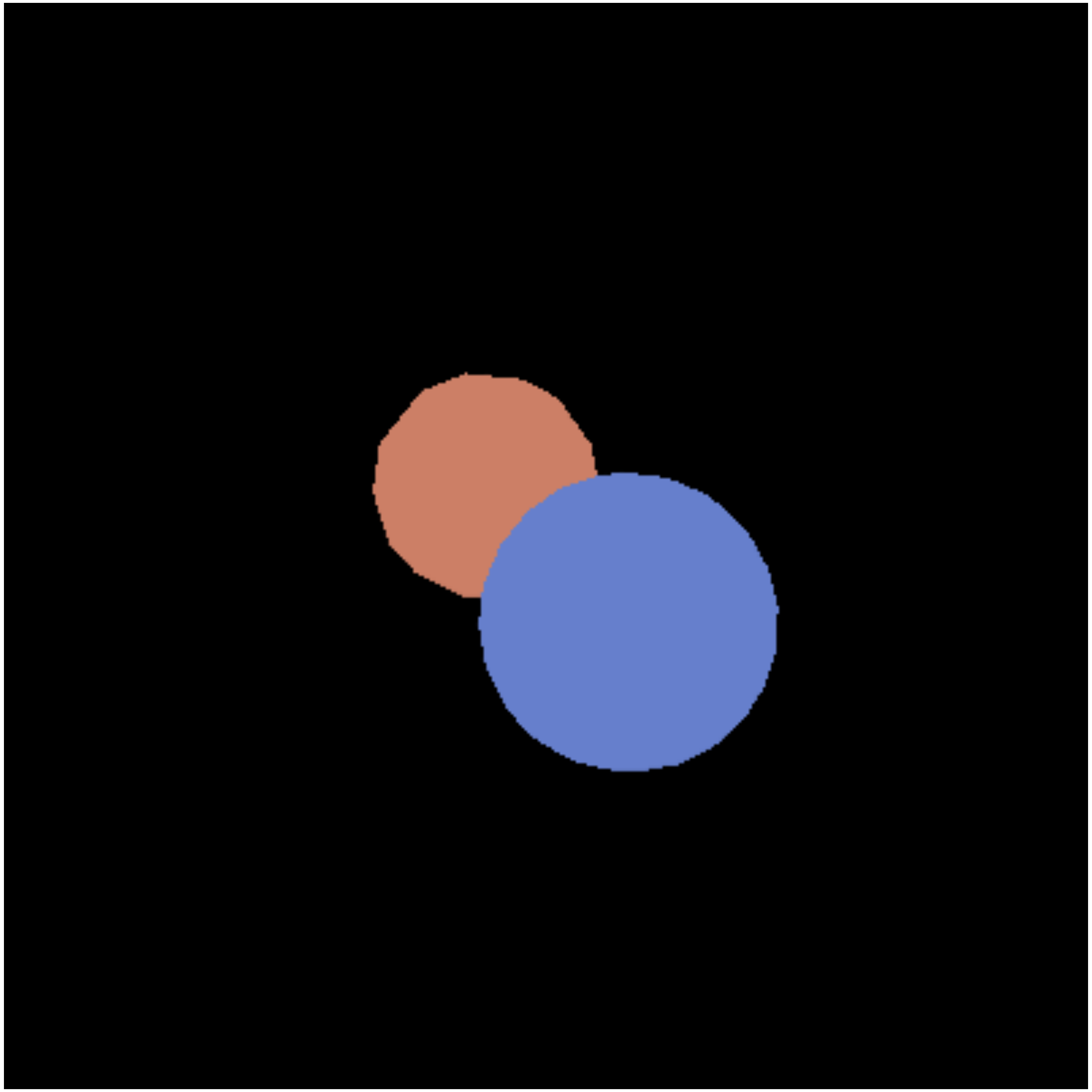
Result of minimal pipeline



Pipeline for basic *z* buffer

- **Vertex stage (input: position / vtx)**
  - transform position (object to screen space)
- **Rasterizer**
  - interpolated parameter: z' (screen z)
- **Fragment stage (output: color, z')**
  - write fixed color 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

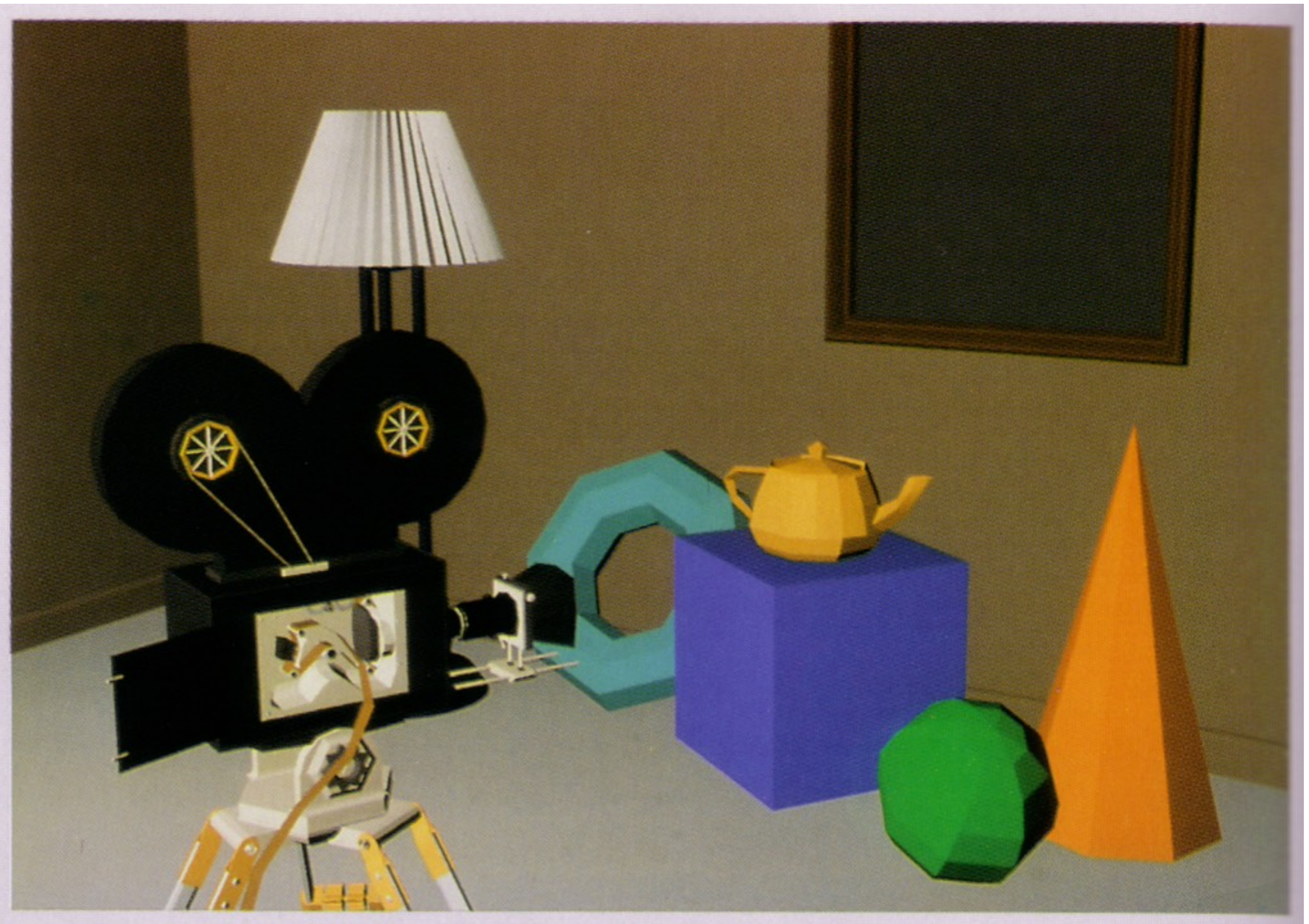


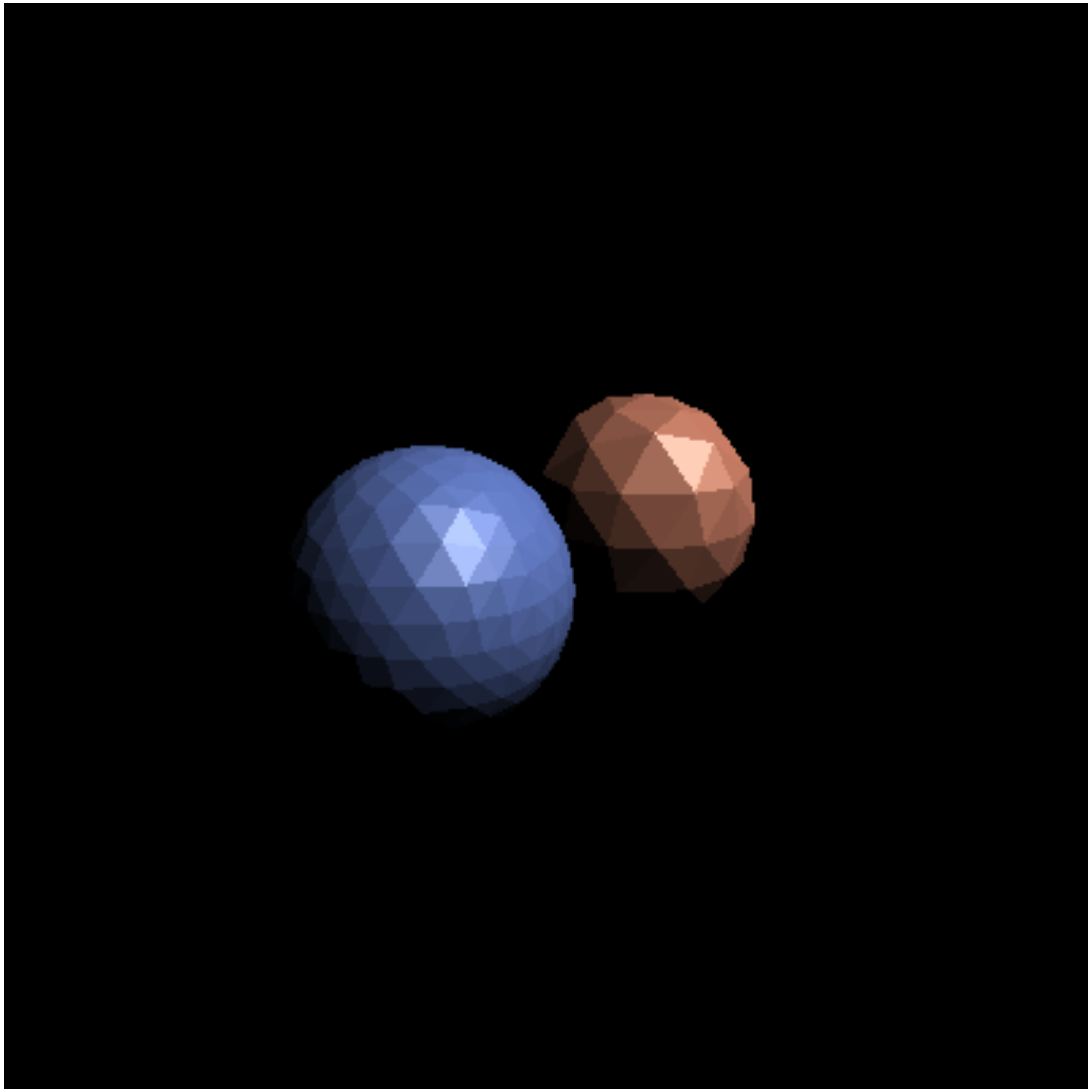
Plate II.29 *Shutterbug.* Individually shaded polygons with diffuse reflection (Sections 14.4.2 and 16.2.3). (Copyright © 1990, Pixar. Rendered by Thomas Williams and H.B. Siegel using Pixar's PhotoRealistic RenderMan™ software.)

[Foley et al.]

Pipeline for flat shading

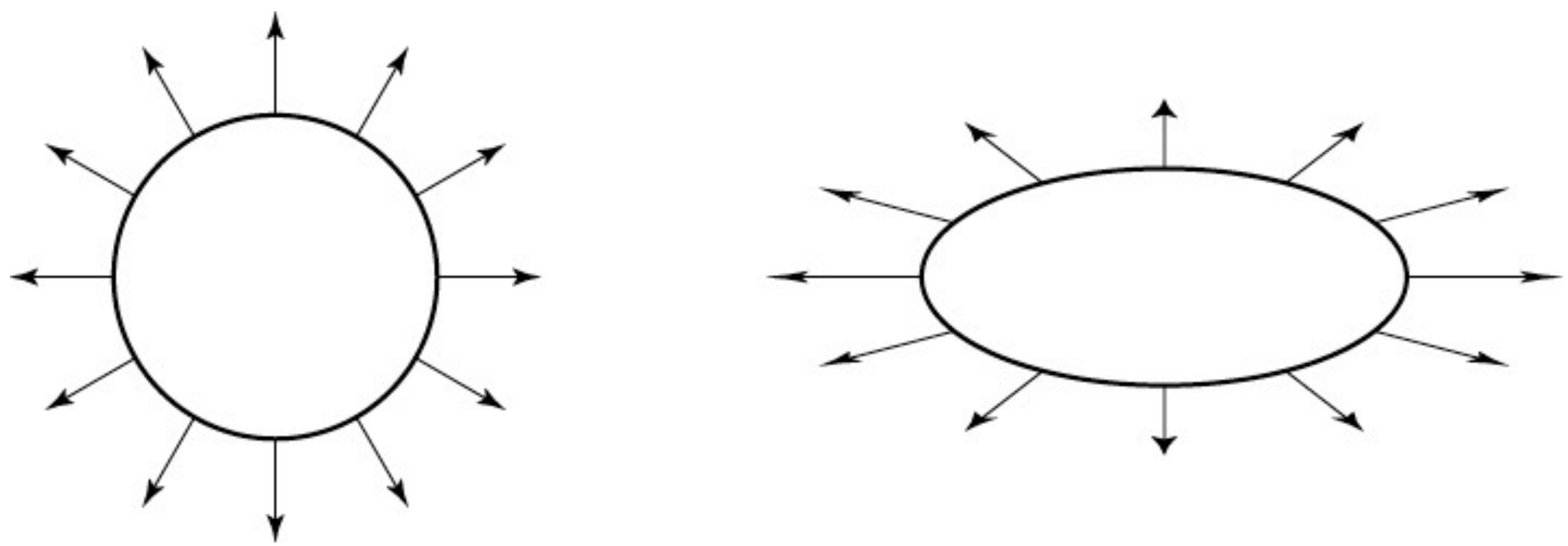
- **Vertex stage (input: position and normal / vtx)**
  - transform position and normal (object to eye space)
  - compute shaded color per triangle using normal
  - transform position (eye to screen space)
- **Rasterizer**
  - interpolated parameters: z' (screen z)
  - pass through color — non-default rasterization mode these days (rasterizer will use the color from the first vtx. for all fragments)
- **Fragment stage (output: color, z')**
  - write fixed color to color planes only if interpolated z' < current z'

Result of flat-shading pipeline



Transforming normal vectors

- **Transforming surface normals**
  - differences of points (and therefore tangents) transform OK
  - normals do not --> use inverse transpose matrix



have: $\mathbf{t} \cdot \mathbf{n} = \mathbf{t}^T \mathbf{n} = 0$
want: $M\mathbf{t} \cdot X\mathbf{n} = \mathbf{t}^T M^T X \mathbf{n} = 0$
so set $X = (M^T)^{-1}$
then: $M\mathbf{t} \cdot X\mathbf{n} = \mathbf{t}^T M^T (M^T)^{-1} \mathbf{n} = \mathbf{t}^T \mathbf{n} = 0$

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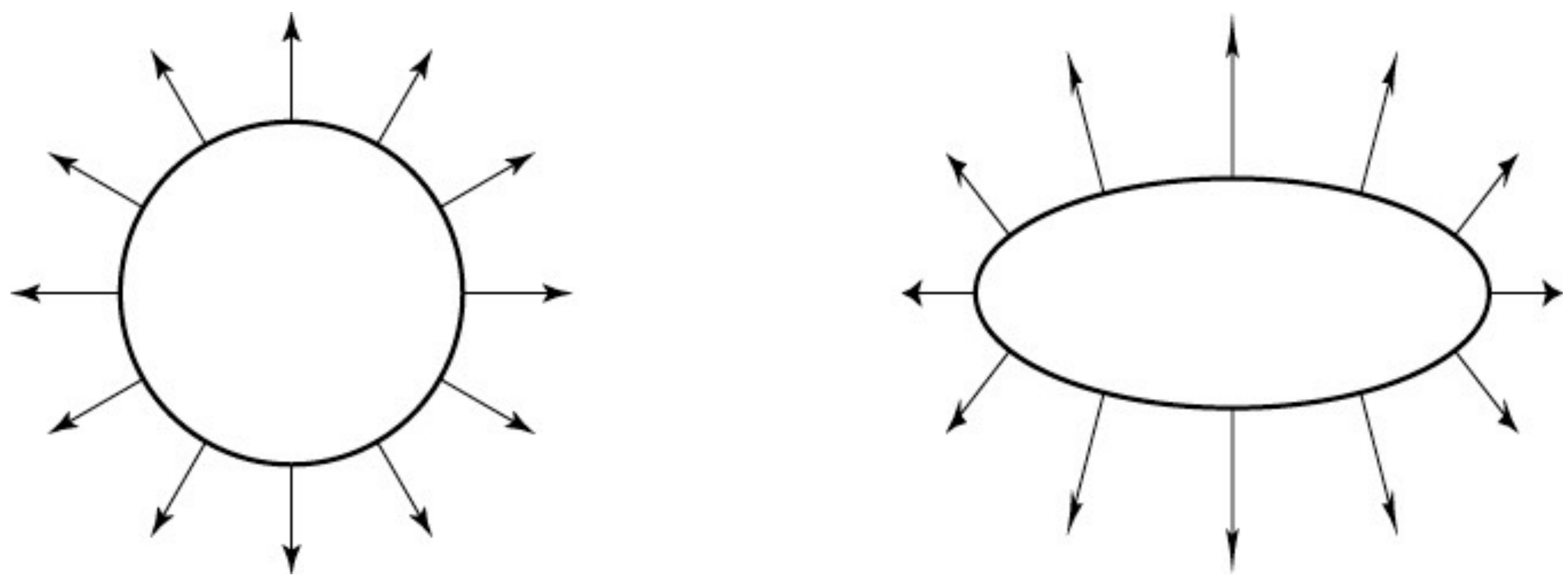

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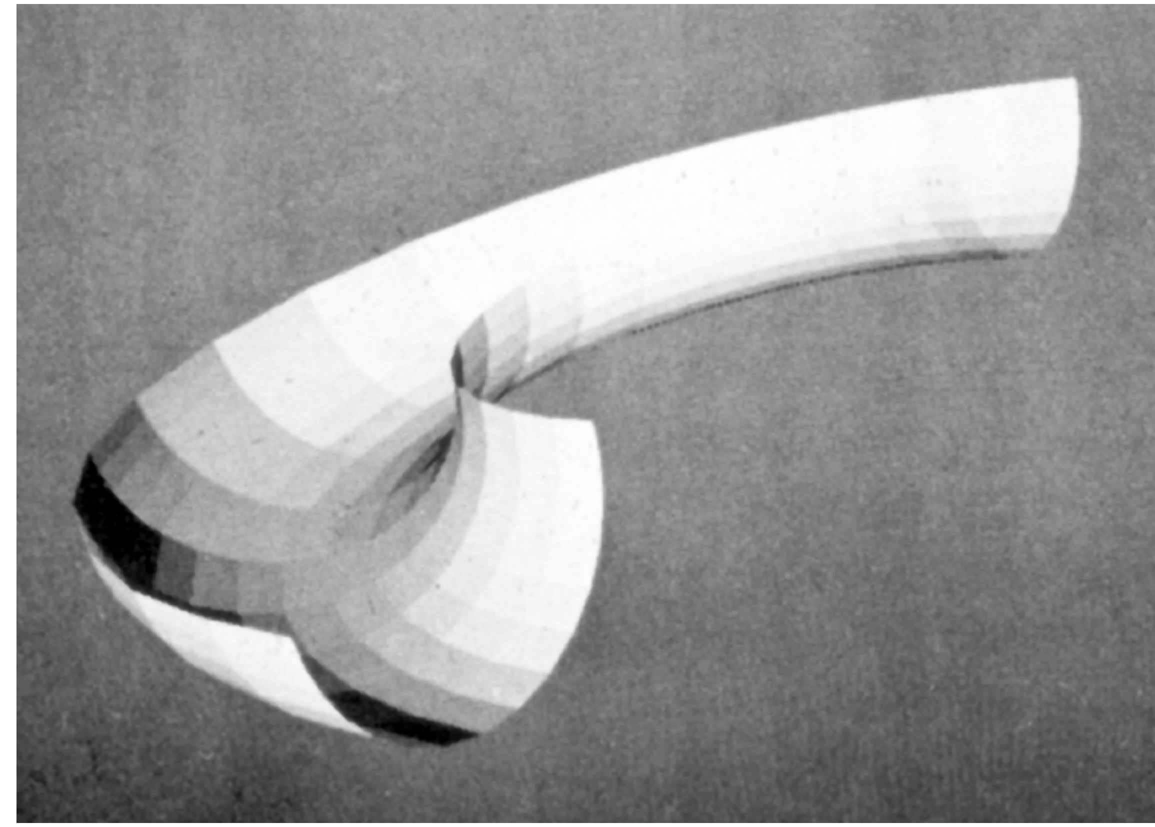
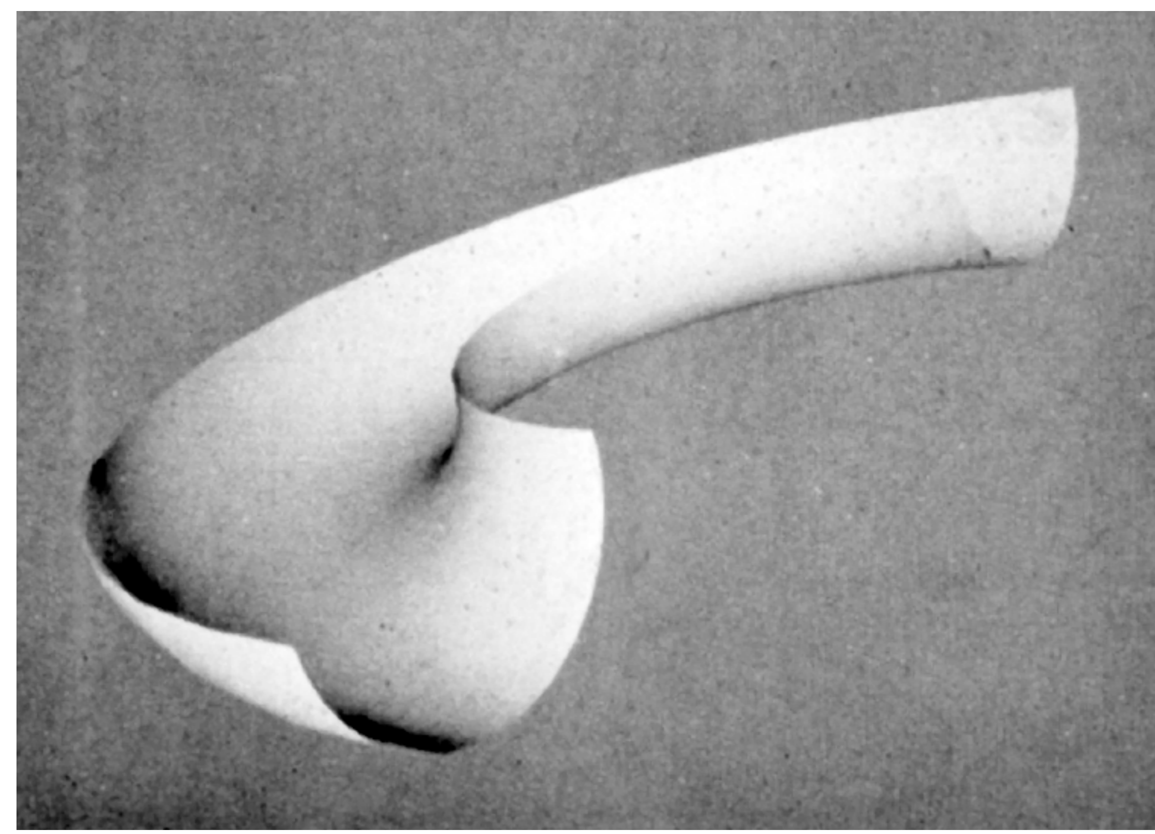
Gouraud shading

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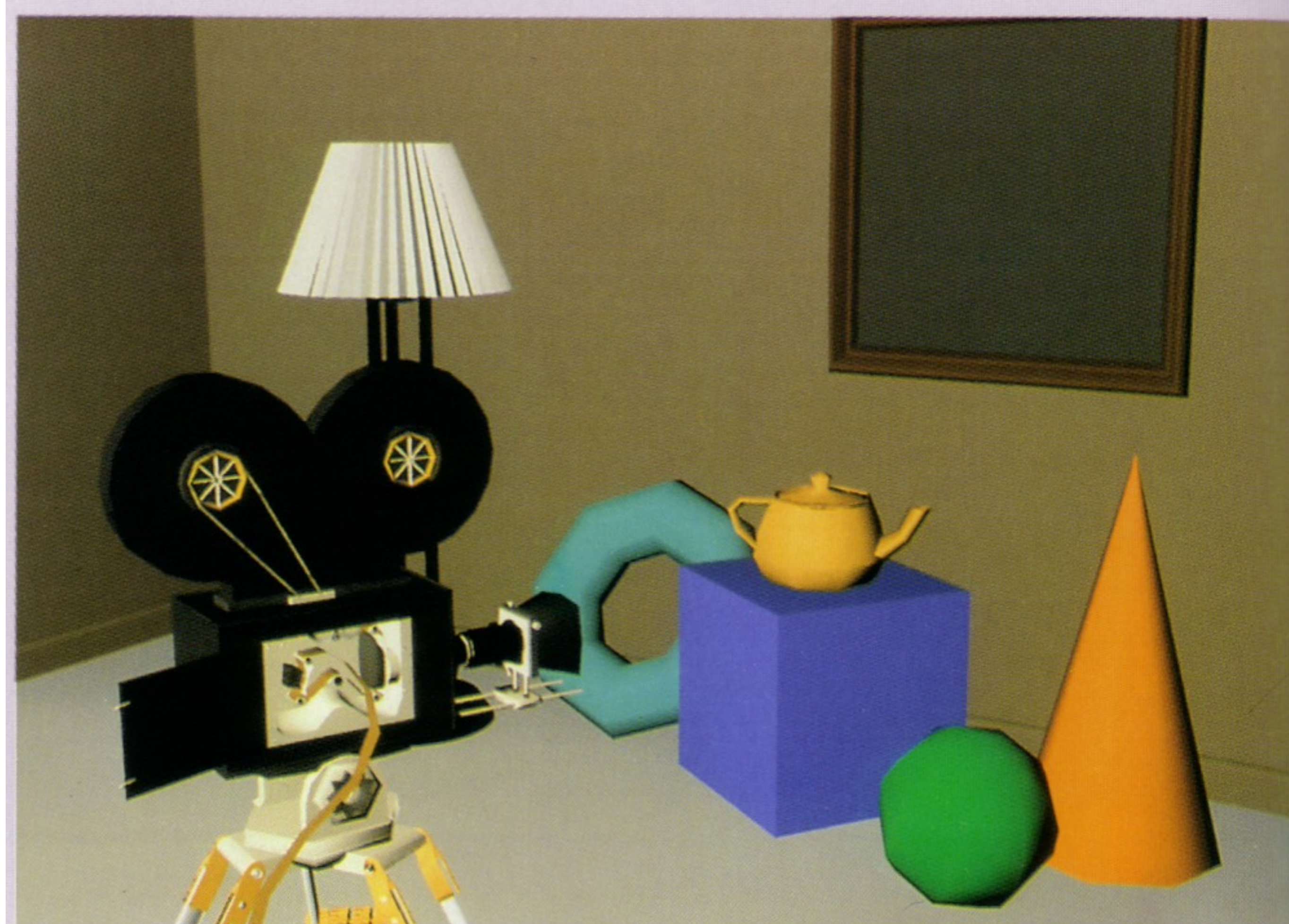
Plate II.30 *Shutterbug.* Gouraud shaded polygons with diffuse reflection (Sections 14.4.3 and 16.2.4). (Copyright © 1990, Pixar. Rendered by Thomas Williams and H.B. Siegel using Pixar's PhotoRealistic RenderMan™ software.)

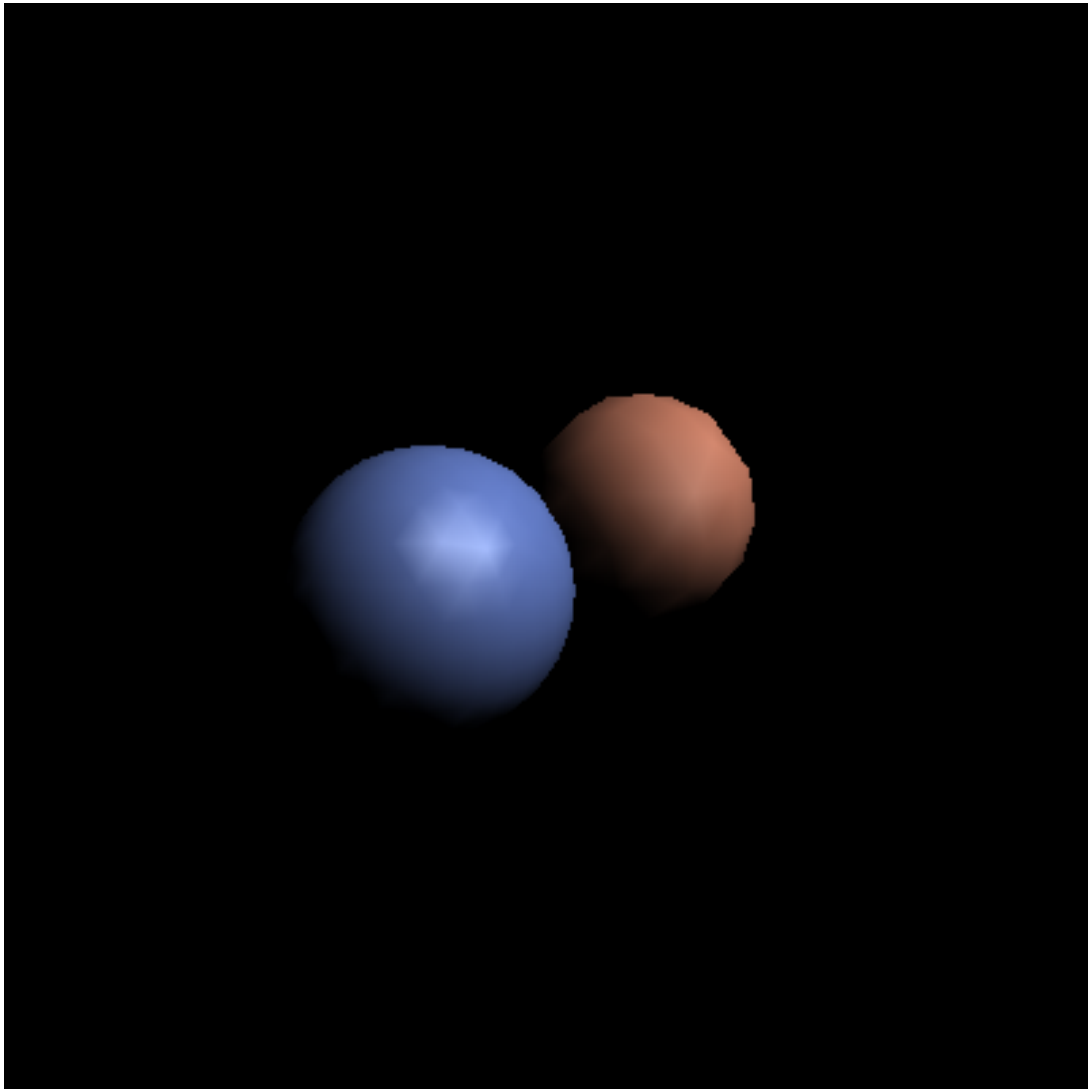


[Foley et al.]

Pipeline for Gouraud shading

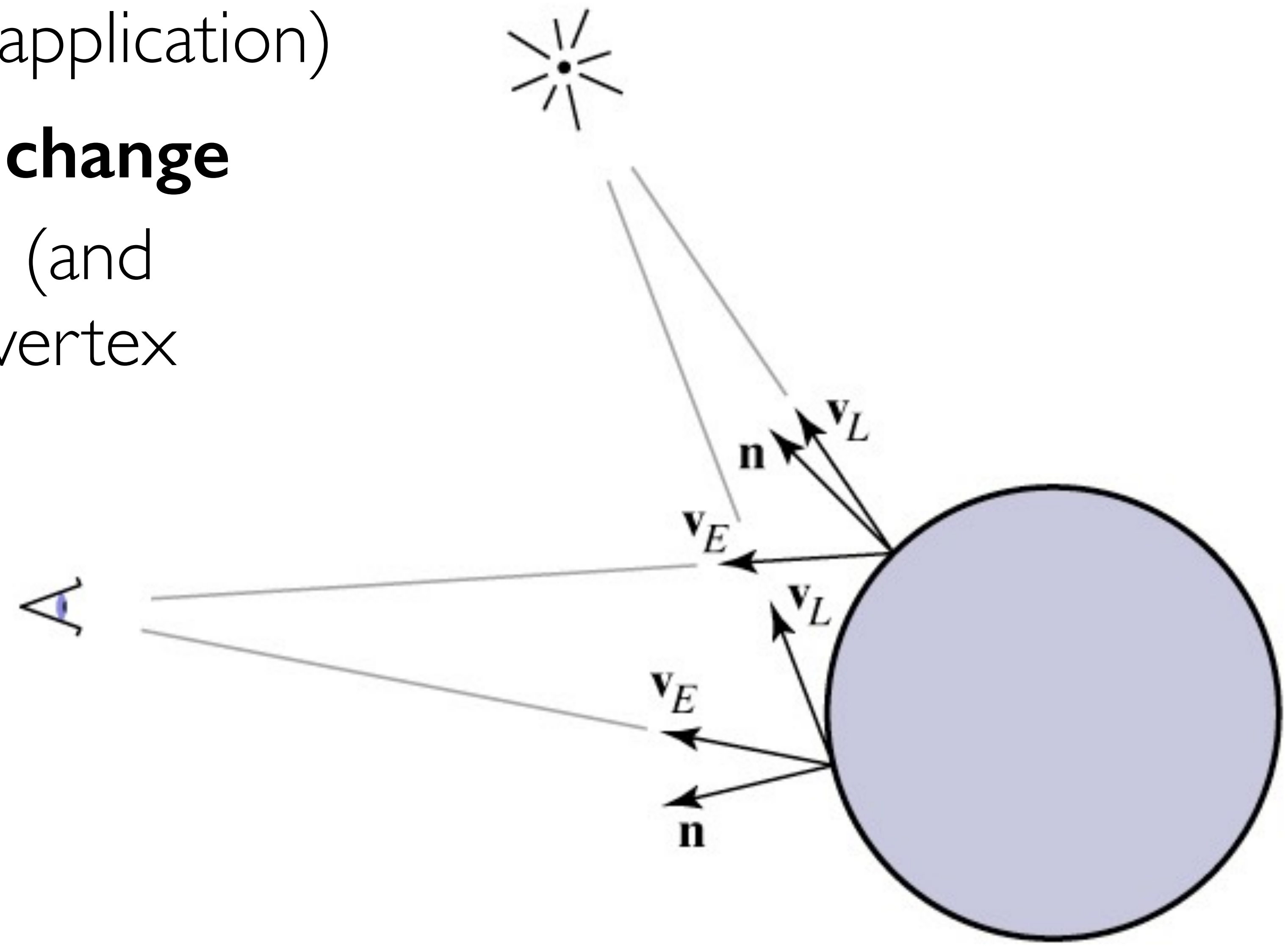
- **Vertex stage (input: position and normal / vtx)**
  - transform position and normal (object to eye space)
  - compute shaded color per vertex (using fixed diffuse color)
  - transform position (eye to screen space)
- **Rasterizer**
  - interpolated parameters: z' (screen z); r, g, b color
- **Fragment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

Result of Gouraud shading pipeline



Local vs. infinite viewer, light

- **Phong illumination requires geometric information:**
  - light vector (function of position)
  - eye vector (function of position)
  - surface normal (from application)
- **Light and eye vectors change**
  - need to be computed (and normalized) for each vertex

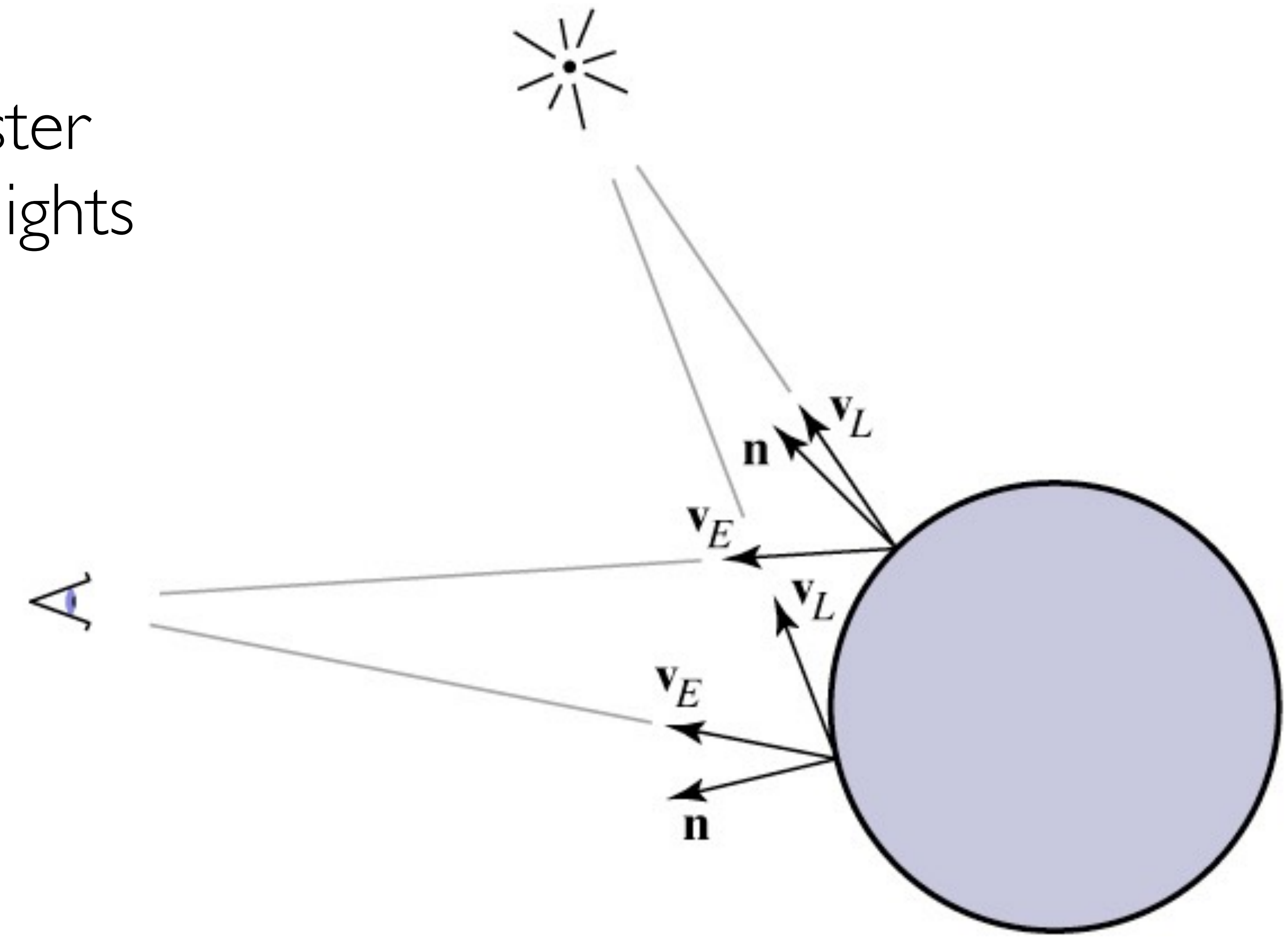


Local vs. infinite viewer, light

- **Look at case when eye or light is far away:**
  - distant light source: nearly parallel illumination
  - distant eye point: nearly orthographic projection
  - in both cases, eye or light vector changes very little
- **Optimization: approximate eye and/or light as infinitely far away**

Directional light

- **Directional (infinitely distant) light source**
  - light vector always points in the same direction
  - often specified by position [*x* *y* *z* 0]
  - many pipelines are faster if you use directional lights



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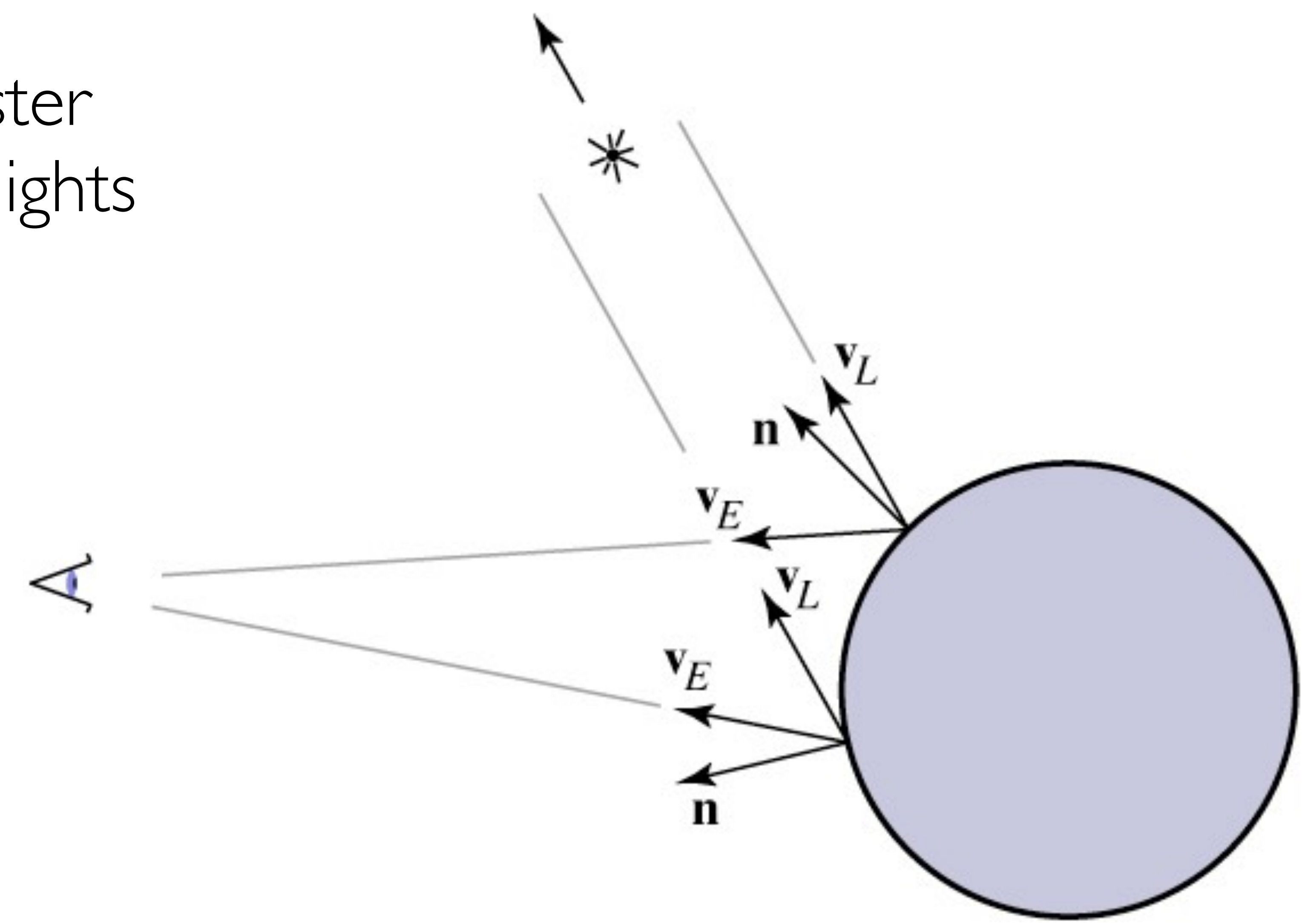
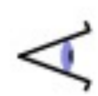
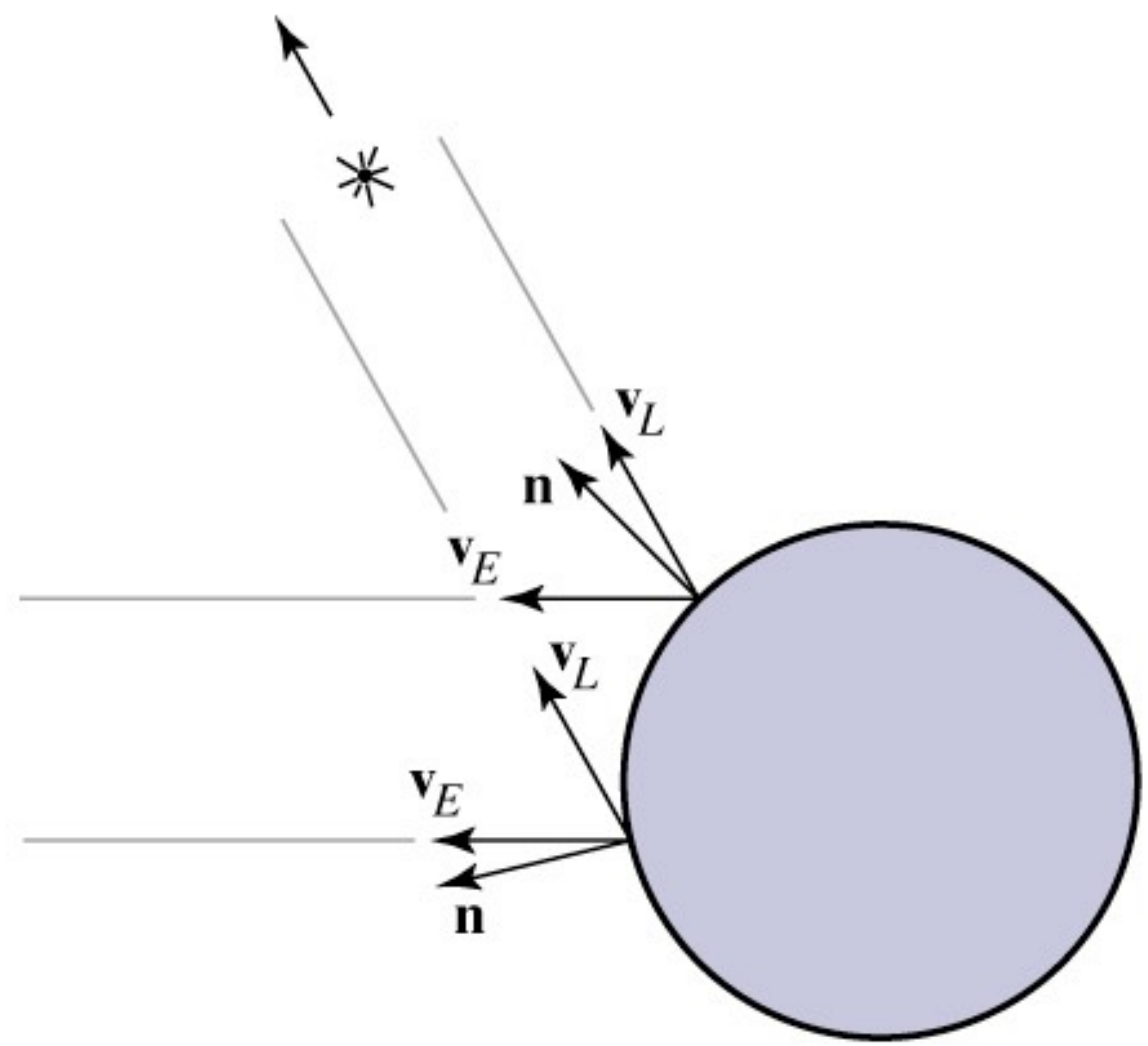


Infinite viewer

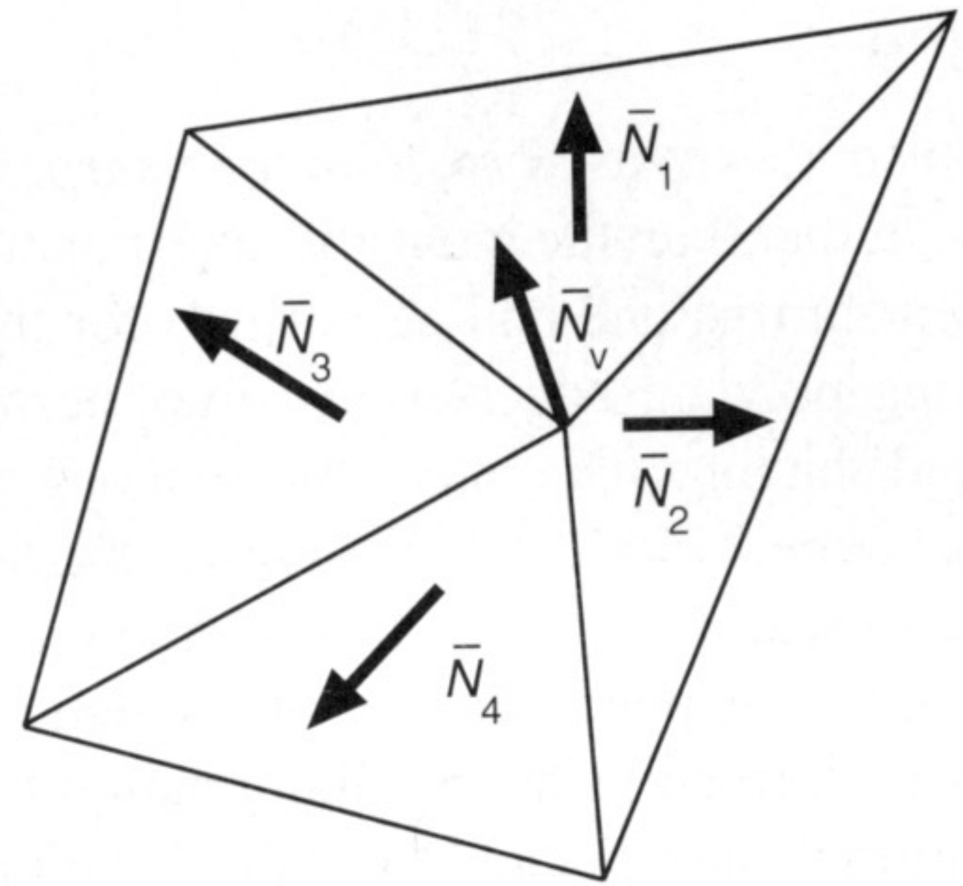
- **Orthographic camera**
  - projection direction is constant
- **“Infinite viewer”**
  - even with perspective, can approximate eye vector using the image plane normal
  - can produce weirdness for wide-angle views
  - light, eye, half vectors all constant! 



Vertex normals

- **Need normals at vertices to compute Gouraud shading**
- **Best to get vtx. normals from the underlying geometry**
  - e. g. spheres example
- **Otherwise have to infer vtx. normals from triangles**
  - simple scheme: average surrounding face normals

$$N_v = \frac{\sum_i N_i}{\|\sum_i N_i\|}$$



[Foley et al.]

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

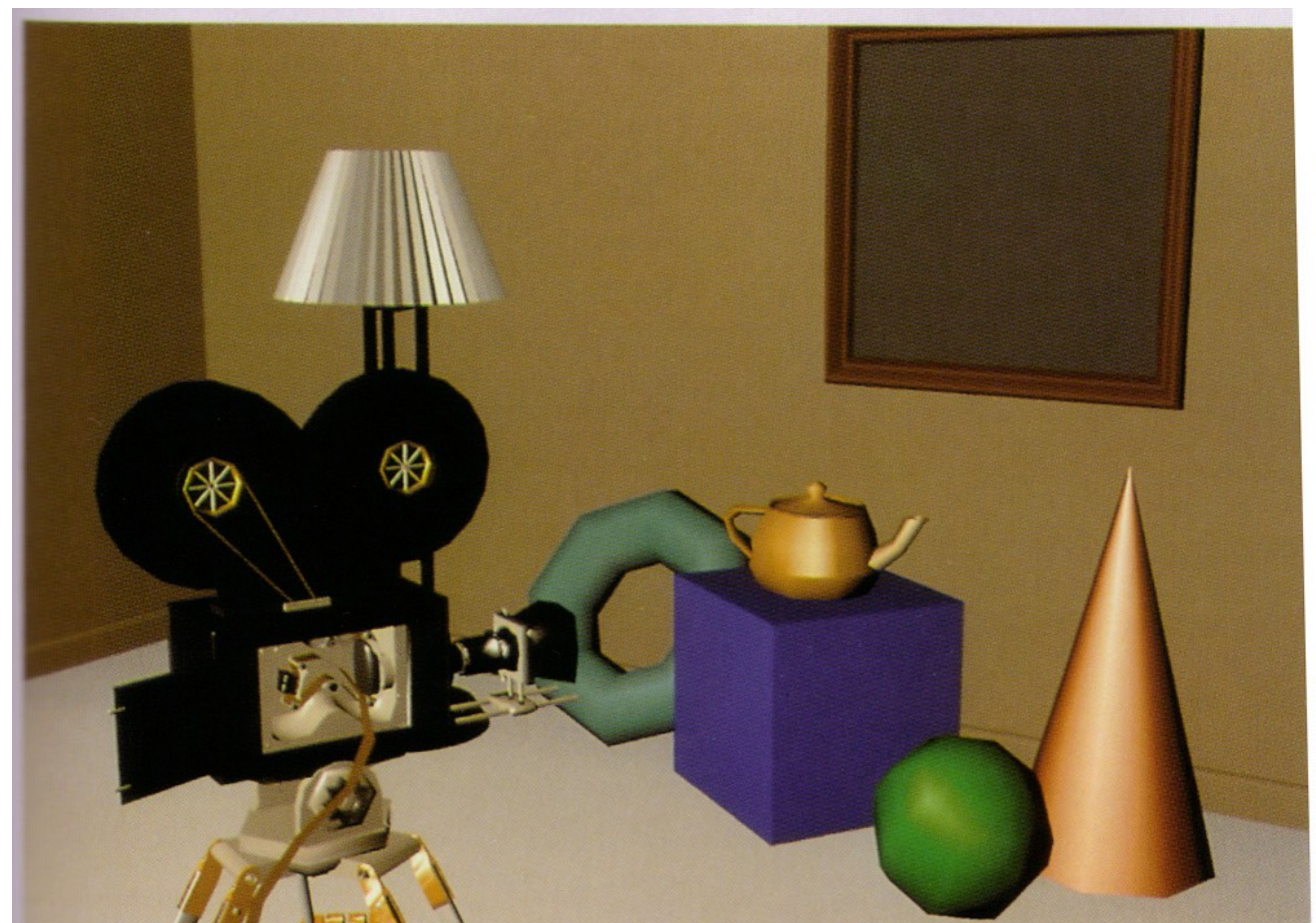
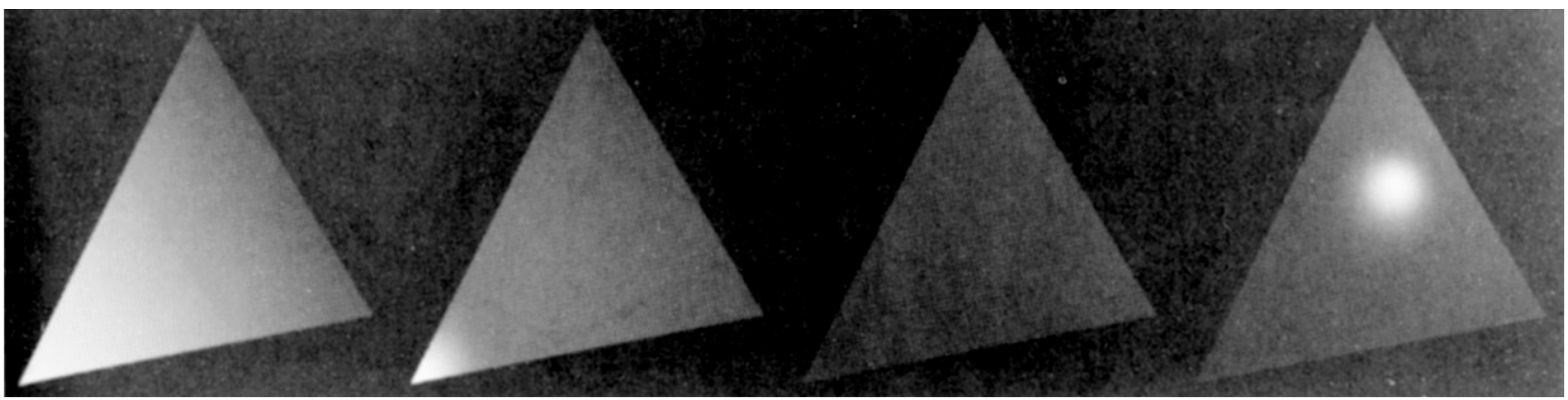


Plate II.31 *Shutterbug.* Gouraud shaded polygons with specular reflection (Sections 14.4.4 and 16.2.5). (Copyright © 1990, Pixar. Rendered by Thomas Williams and H.B. Siegel using Pixar's PhotoRealistic RenderMan™ software.)

[Foley et al.]

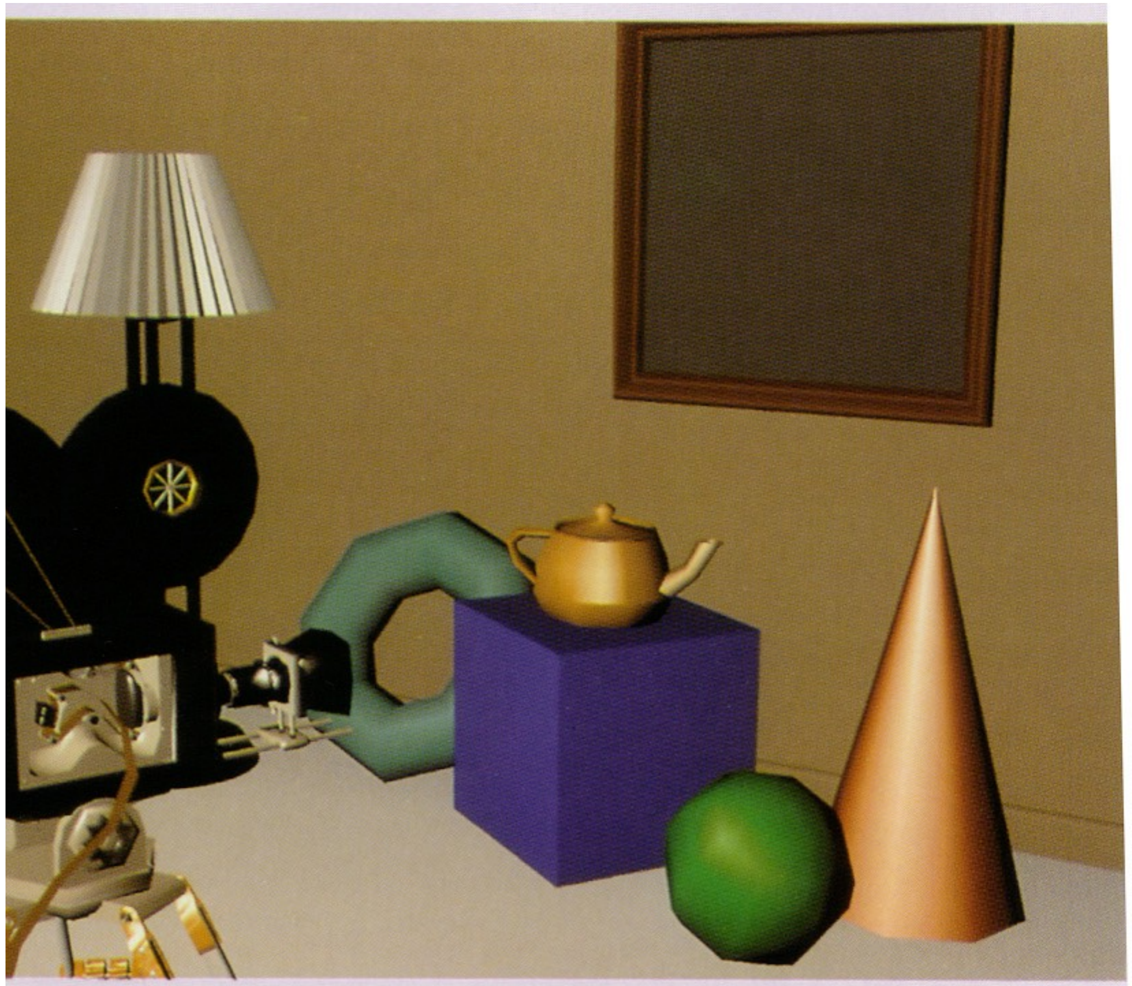
Per-pixel (Phong) shading

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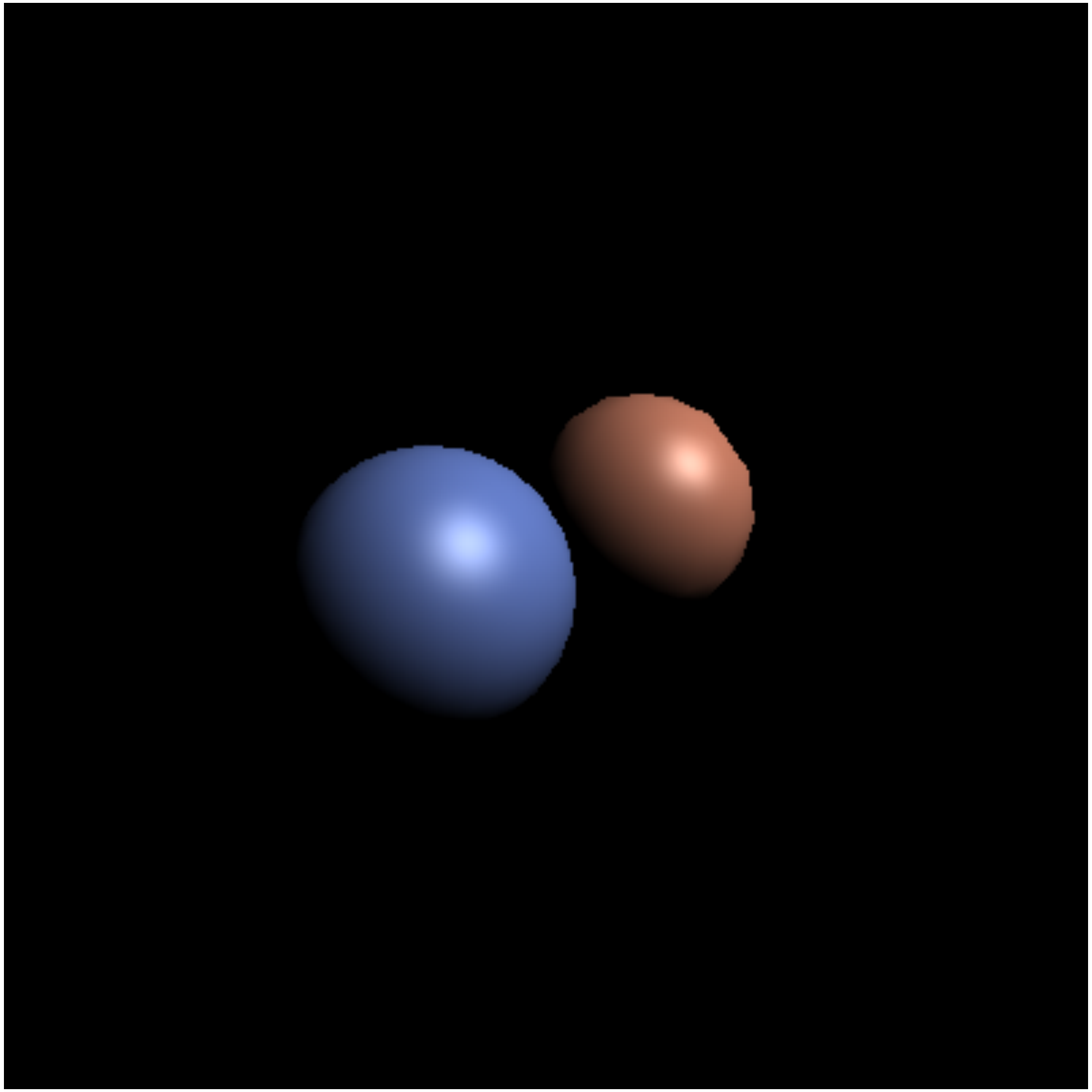
Plate II.32 *Shutterbug.* Phong shaded polygons with specular reflection (Sections 14.4.4 and 16.2.5). (Copyright © 1990, Pixar. Rendered by Thomas Williams and H.B. Siegel using Pixar's PhotoRealistic RenderMan™ software.)

[Foley et al.]

Pipeline for per-pixel shading

- **Vertex stage (input: position and normal / vtx)**
  – transform position and normal (object to eye space)
  – transform position (eye to screen space)
- **Rasterizer**
  – interpolated parameters: z' (screen z); x, y, z normal
- **Fragment stage (output: color, z')**
  – compute shading using fixed color and interpolated normal
  – write to color planes only if interpolated $z' <$ current z'

Result of per-pixel shading pipeline



Programming hardware pipelines

- **Modern hardware graphics pipelines are flexible**
  - programmer defines exactly what happens at each stage
  - do this by writing *shader programs* in domain-specific languages called *shading languages*
  - rasterization is fixed-function, as are some other operations (depth test, many data conversions, …)
- **One example: OpenGL and GLSL (GL Shading Language)**
  - several types of shaders process primitives and vertices; most basic is the *vertex program*
  - after rasterization, fragments are processed by a *fragment program*

GLSL Shaders