Pipeline Operations

CS 465 Lecture 16

Pipeline overview

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

Operations in the pipeline

- Fundamental to (almost) all 3D applications:
  - vertex stage: coordinate transformation
  - fragment stage: hidden surface elimination
- Examples of additional operations:
  - Flat shading at the vertex stage
  - Gouraud shading at the vertex stage
  - Phong shading at the fragment stage
  - Texture mapping at the fragment stage

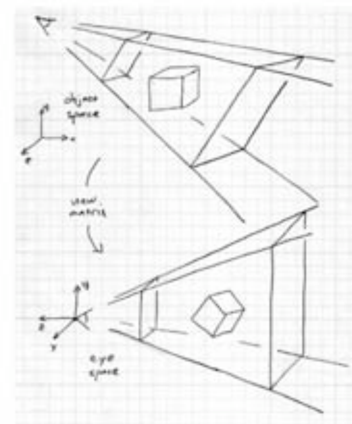
Modeling transformation

- Application specifies primitives in any convenient *object coordinates*
  - also specifies the transformation to world space (frame-to-canonical for object frame): the *modeling matrix*
  - e.g. car driving down street
    - car body specified in frame attached to car
    - tire specified in frame attached to wheel
  - often objects' coordinates can be constant over time

Viewing transformation

- The application also chooses a camera pose (position and orientation)
  - this defines a coordinate frame for the camera
  - transform geometry into that frame for rendering
  - *viewing matrix* is the c.-to-b. transform of the camera frame
  - the resulting coordinates are *eye coordinates*
  - we can now assume that the camera is in standard pose

Viewing transformation

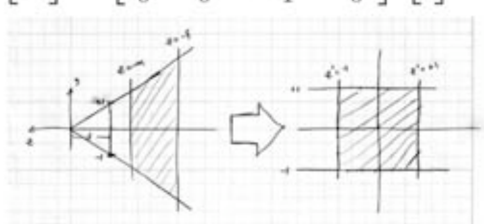


the view matrix rewrites all coordinates in eye space

Projection transformation

- Projection matrix maps from eye space to *clip space*
  - In this space, the two-unit cube $[-1, 1]^3$ contains exactly what needs to be drawn

$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} \sim \begin{bmatrix} \tilde{x} \\ \tilde{y} \\ \tilde{z} \\ -z \end{bmatrix} = \begin{bmatrix} \frac{2d}{r-l} & 0 & \frac{r+l}{r-l} & 0 \\ 0 & \frac{2d}{t-b} & \frac{t+b}{t-b} & 0 \\ 0 & 0 & -\frac{f+n}{f-n} & \frac{2fn}{f-n} \\ 0 & 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

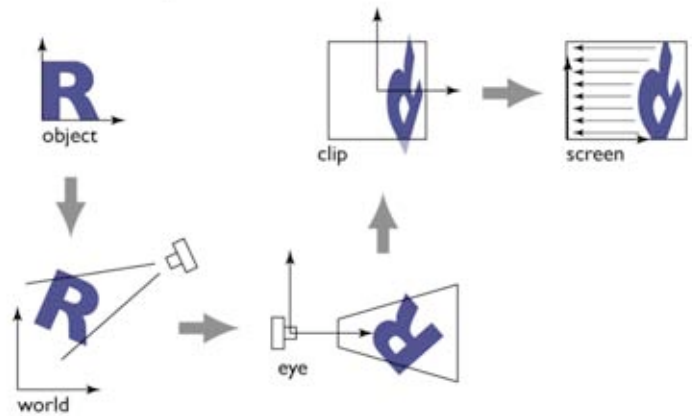


Viewport transformation

- A simple bookkeeping step to scale image
  - clip volume was a simple cube
  - rasterizer needs input in pixel coords
  - therefore scale and translate to map the [–1, 1] box to the desired rectangle in window coordinates, or *screen space*
- Also shift z' to the desired range
  - usually that range is [0, 1] so that it can be represented by a fixed-point fraction
- Homogeneous divide usually happens here

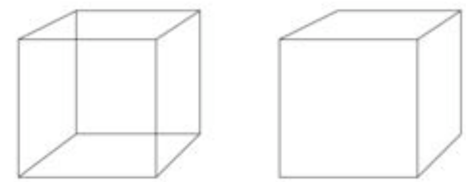
Vertex processing: spaces summary

- Standard sequence of transforms



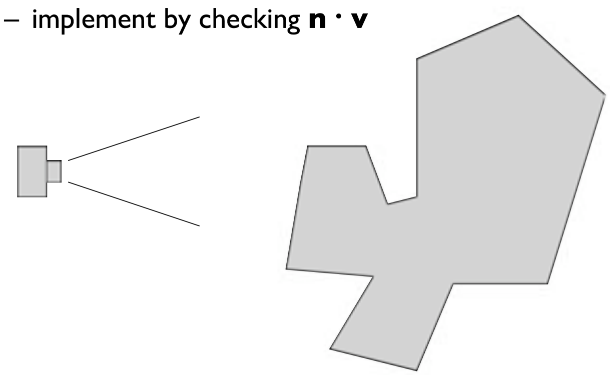
Hidden surface elimination

- 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 **n** · **v**



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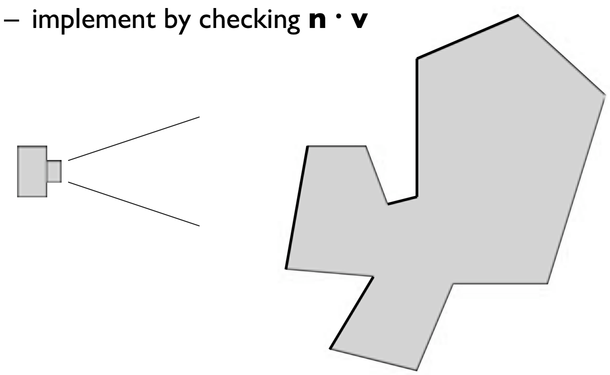

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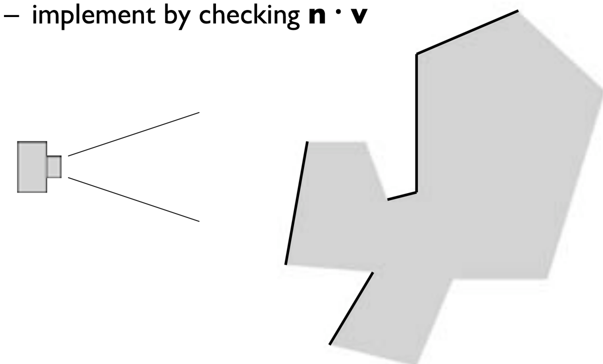

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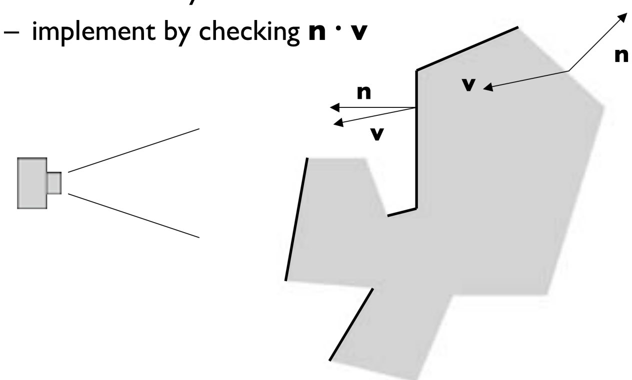

Painter's algorithm

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

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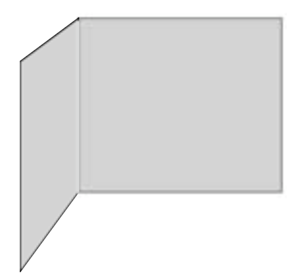

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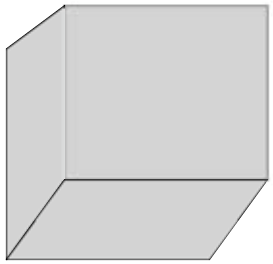

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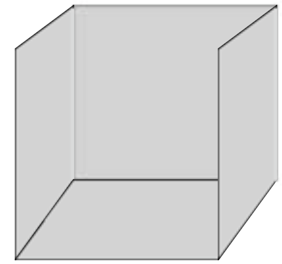

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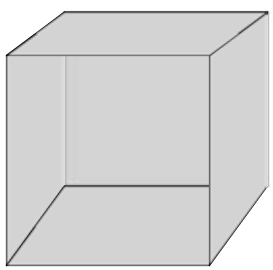

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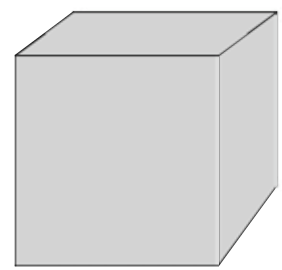

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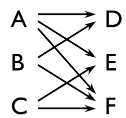
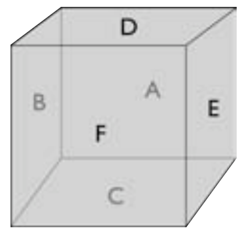
Painter's algorithm

- 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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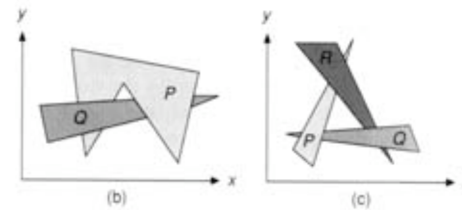
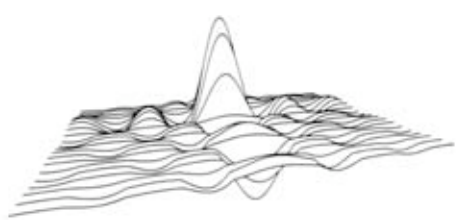


[Foley et al.]

Painter's algorithm

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

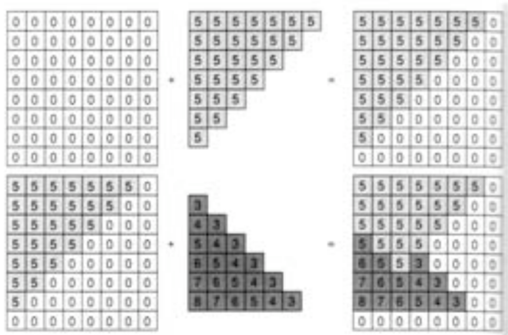


[Foley et al.]

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

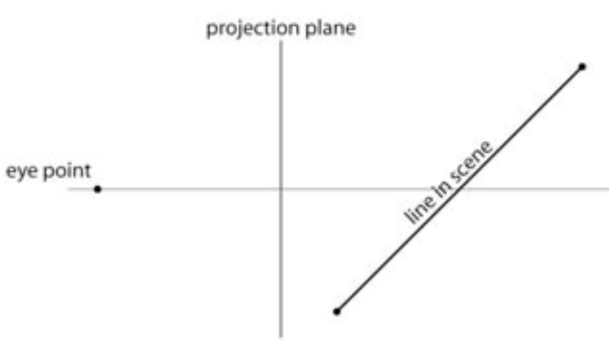


– another example of a memory-intensive brute force approach that works and has become the standard

Precision in z buffer

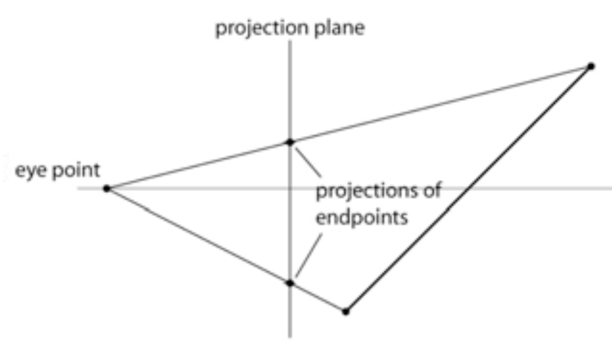
- The precision is distributed between the near and far clipping planes
  - this is why these planes have to exist
  - also why you can't always just set them to very small and very large distances
- Importance of using z' (not world z) in z buffer

Interpolating in projection



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

Interpolating in projection



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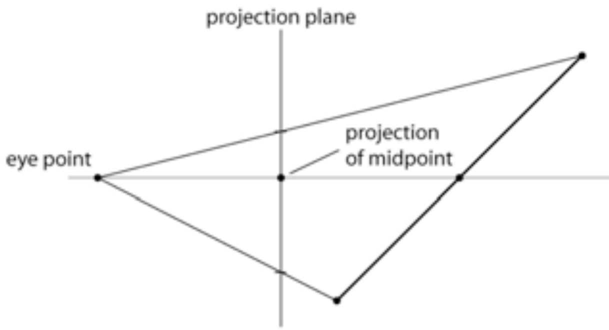

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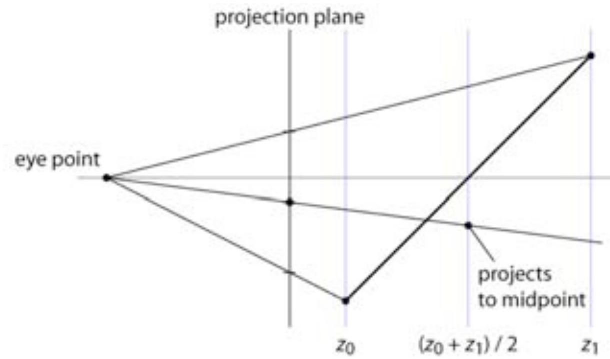

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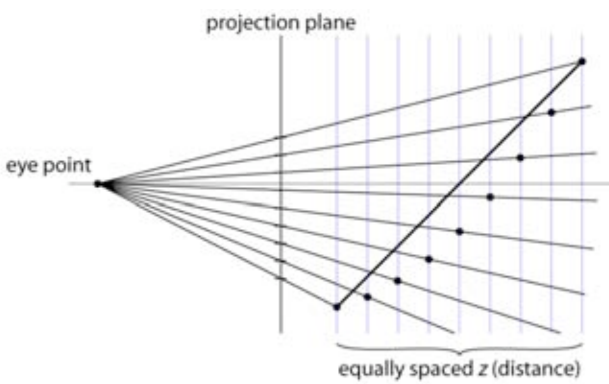

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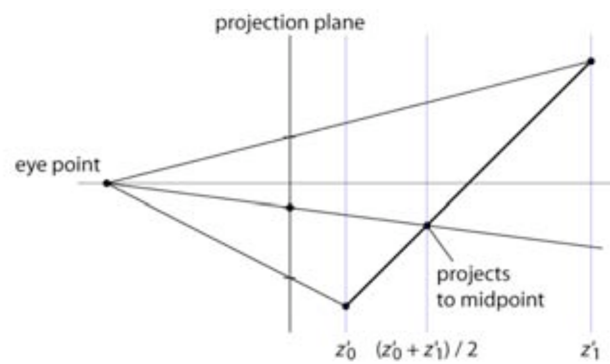

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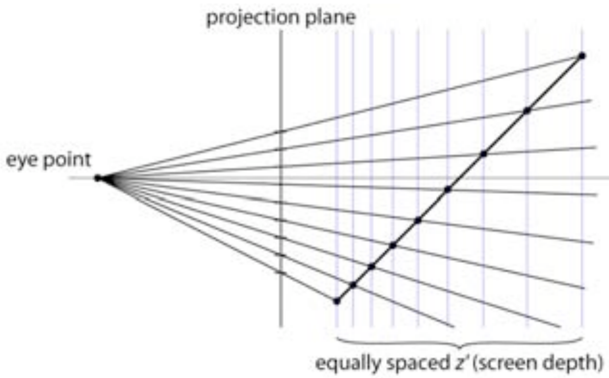

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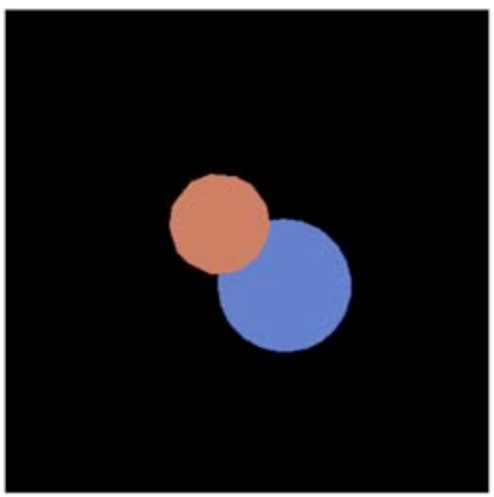
Pipeline for minimal operation

- 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

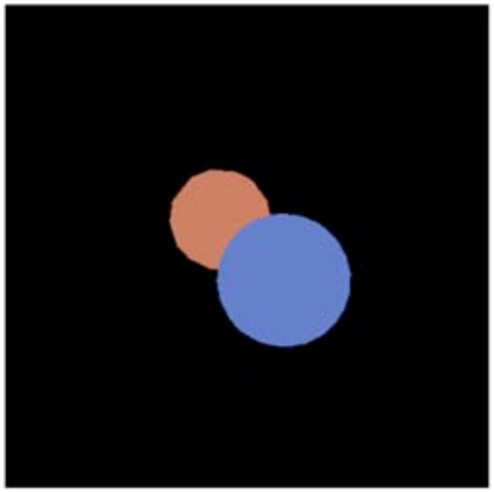
Result of minimal pipeline



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.)

[Foley et al.]

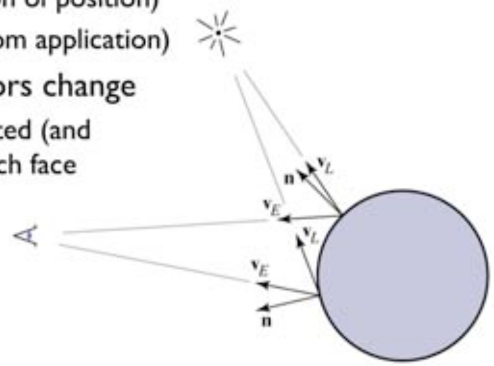
Pipeline for flat shading

- 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

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 face

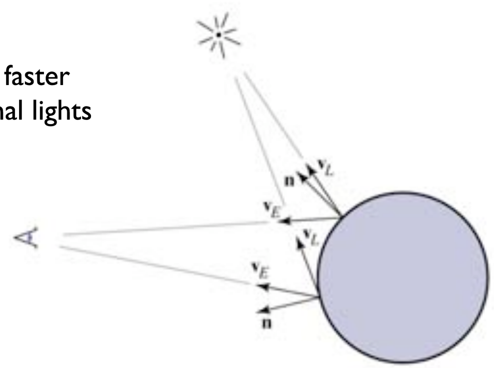


Local vs. infinite viewer, light

- 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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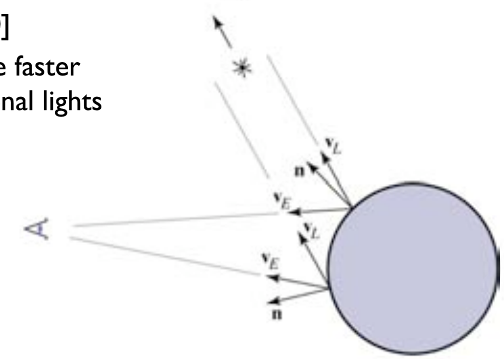
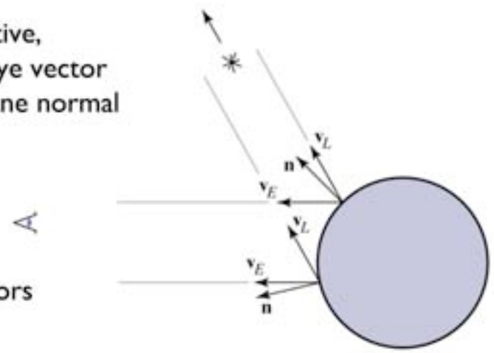


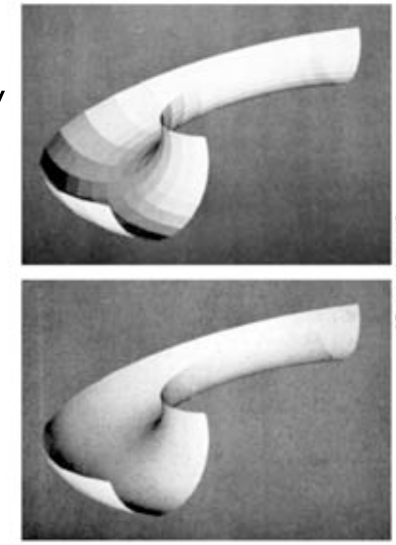
Infinite viewer

- 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
  - Blinn-Phong: light, eye, half vectors all constant!



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"



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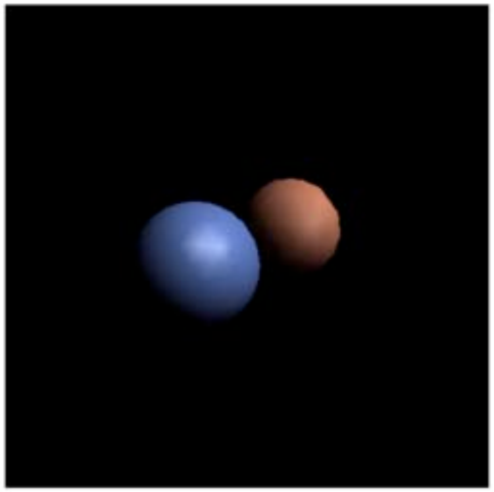
Pipeline for Gouraud shading

- 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'

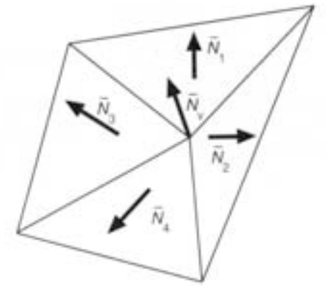
Result of Gouraud shading pipeline



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

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



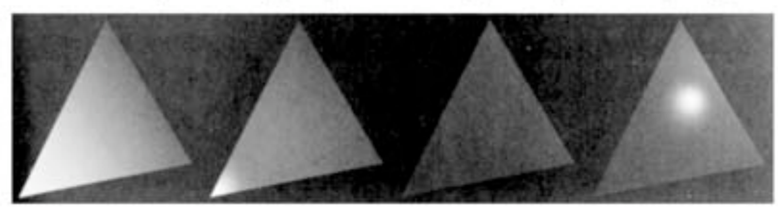
Non-diffuse Gouraud shading

- 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.)

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



Phong shading

- Bottom line: produces much better highlights

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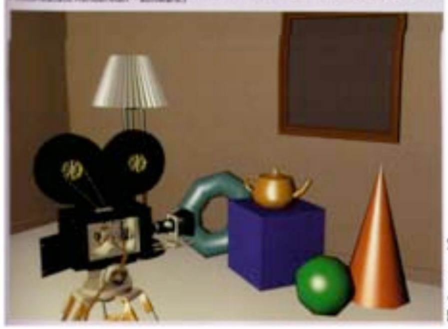
Plate II.32 *Shutterbug.* Phong shaded polygons with specular reflection (Sections 14.4.4 and 16.2.5). (Copyright © 1990, Pixar. Rendered by Thomas Williams and H.B. Siegel using Pixar's PhotoRealistic RenderMan™ software.)

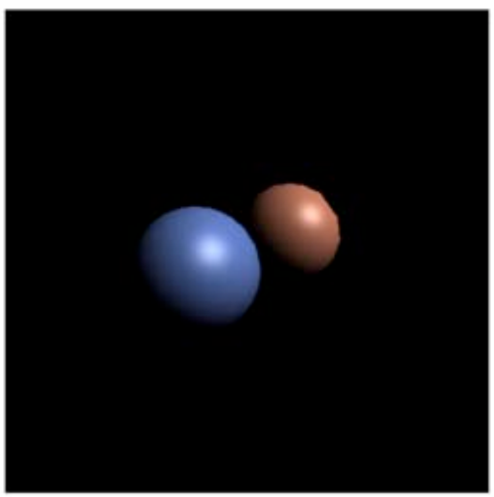


[Foley et al.]

Pipeline for Phong 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 Phong shading pipeline

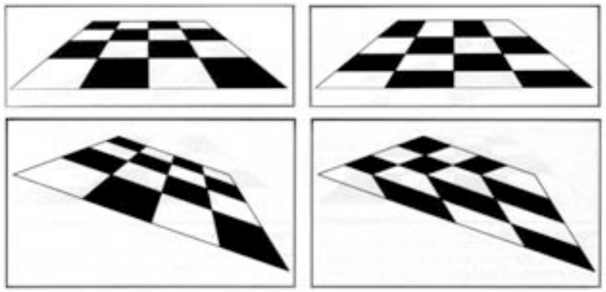


Texture in the graphics pipeline

- Texture coordinates are another attribute
  - the application sets them to control where the texture goes
- Texturing as a fragment operation
  - because the whole point is to vary quickly across the surface
- Interpolating coordinates across triangles
  - to do texturing at fragment stage, we need interpolated (*u*, *v*) coordinates at each fragment
  - but—sad to say—you can't interpolate *u* and *v* linearly in screen space
    - not only won't you get 0.5 at the midpoint, you'll get different answers depending on the view.

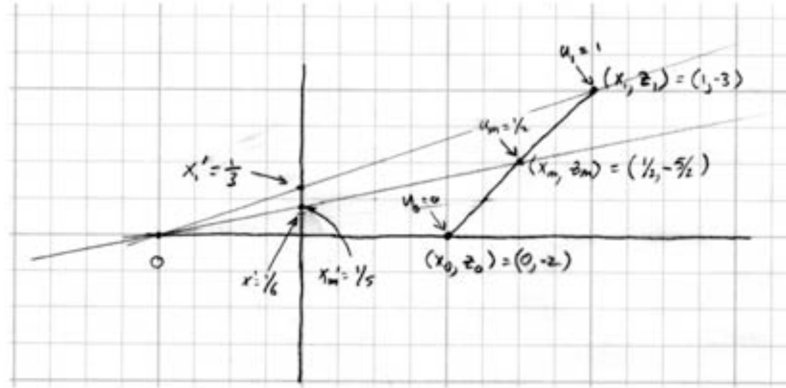
Rasterization: interpolation

- Interp. in screen space ≠ interp. in eye space
  - but perspective preserves lines & planes
  - safe to interpolate screen-z because it lives in screen space
  - not correct to interpolate world (x,y,z), texture (u,v), etc.



[Blinn 96]

Texture coordinate interp example



- Solution: interpolate u/w, 1/w and divide

Texture mapping demo