University of British Columbia
CPSC 314 Computer Graphics
Jan-Apr 2010

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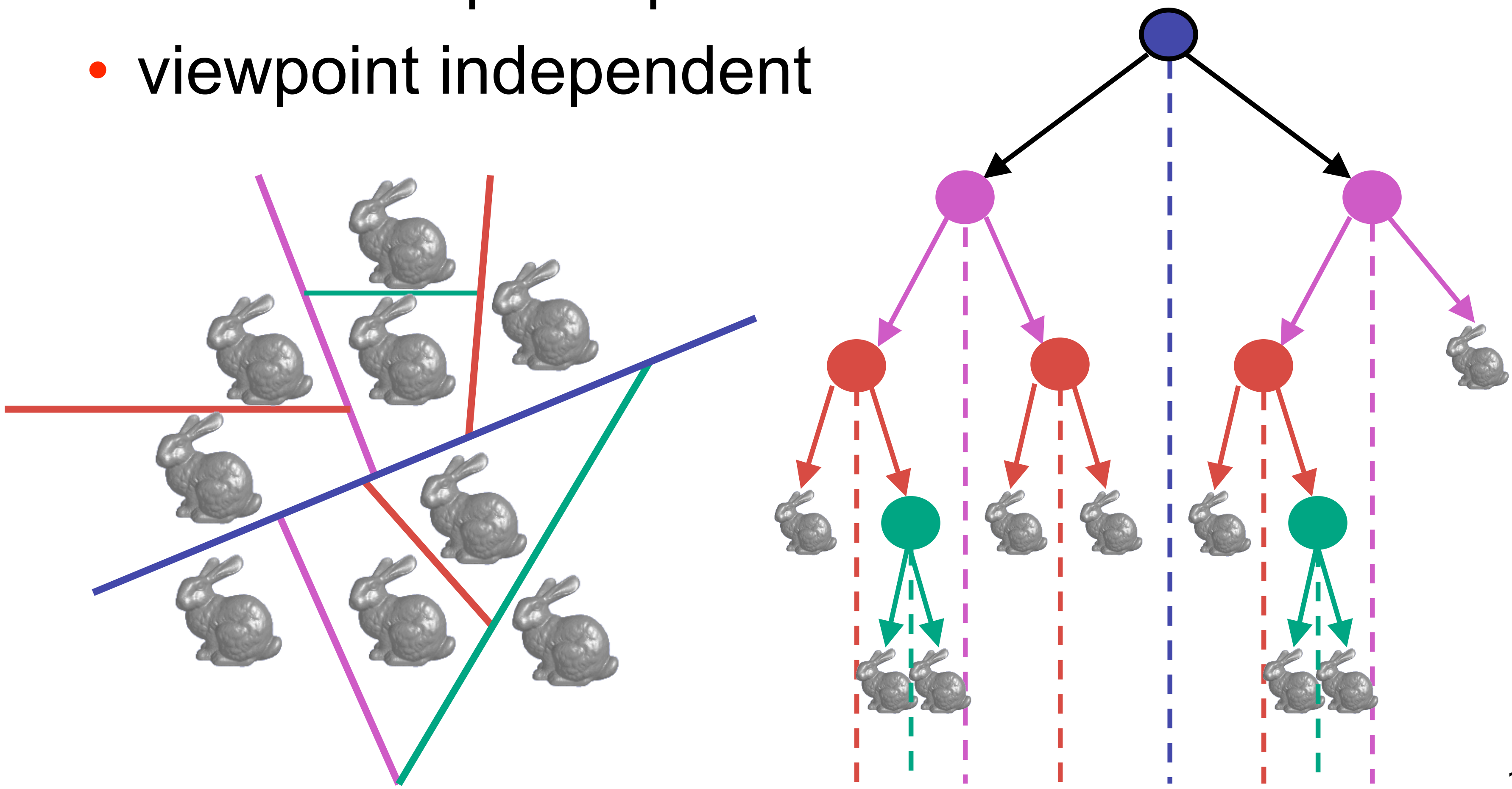
Hidden Surfaces III

Week 9, Wed Mar 17

http://www.ugrad.cs.ubc.ca/~cs314/Vjan2010

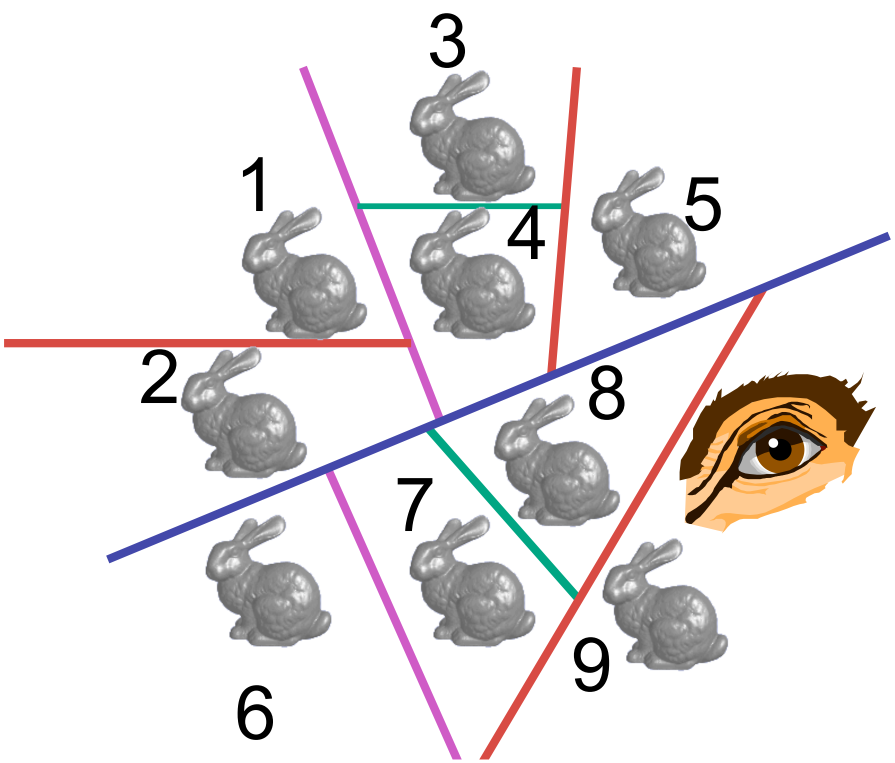
Review: BSP Trees

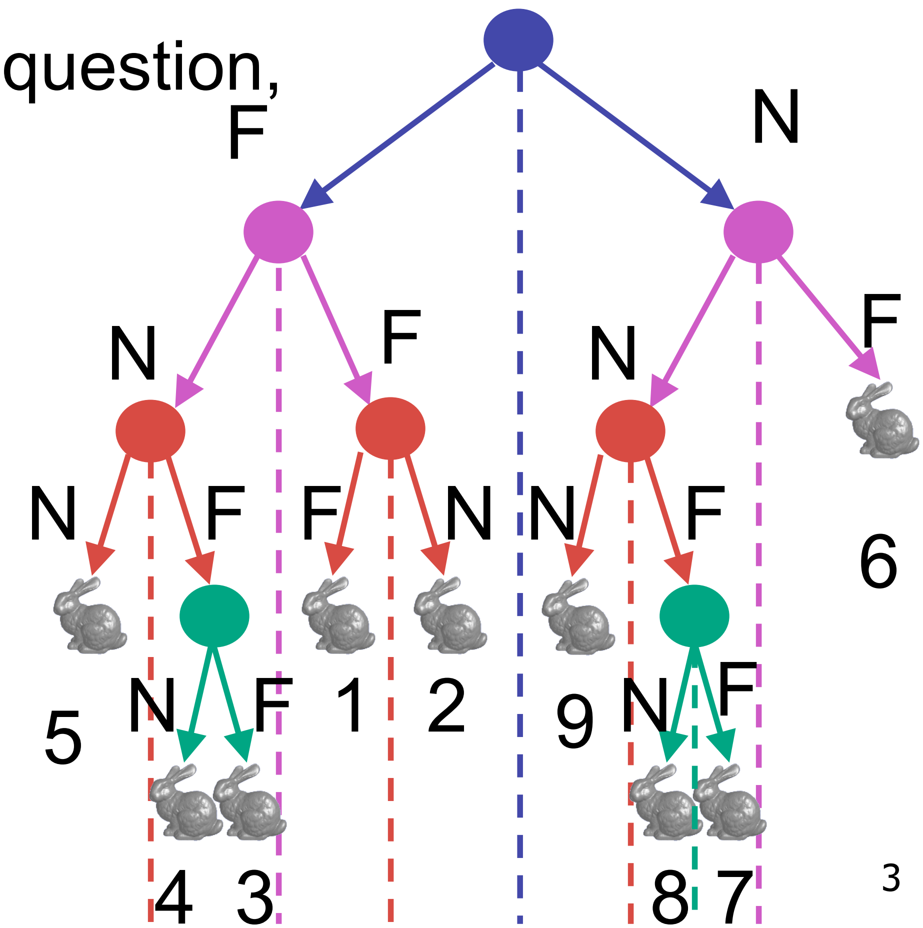
- preprocess: create binary tree
  - recursive spatial partition
  - viewpoint independent



Review: BSP Trees

- runtime: correctly traversing this tree enumerates objects from back to front
  - viewpoint dependent: check which side of plane viewpoint is on **at each node**
  - draw far, draw object in question, draw near





Review: The Z-Buffer Algorithm

- augment color framebuffer with Z-buffer or depth buffer which stores Z value at each pixel
  - at frame beginning, initialize all pixel depths to ∞
  - when rasterizing, interpolate depth (Z) across polygon
  - check Z-buffer before storing pixel color in framebuffer and storing depth in Z-buffer
  - don't write pixel if its Z value is more distant than the Z value already stored there

More: Integer Depth Buffer

- reminder from picking discussion
  - depth lies in the NDC z range [0,1]
  - format: multiply by 2^n -1 then round to nearest int
    - where n = number of bits in depth buffer
- 24 bit depth buffer = 2^24 = 16,777,216 possible values
  - small numbers near, large numbers far
- consider depth from VCS: (1<<N) * (a + b / z)
  - N = number of bits of Z precision
  - a = zFar / (zFar - zNear)
  - b = zFar * zNear / (zNear - zFar)
  - z = distance from the eye to the object

Review: Depth Test Precision

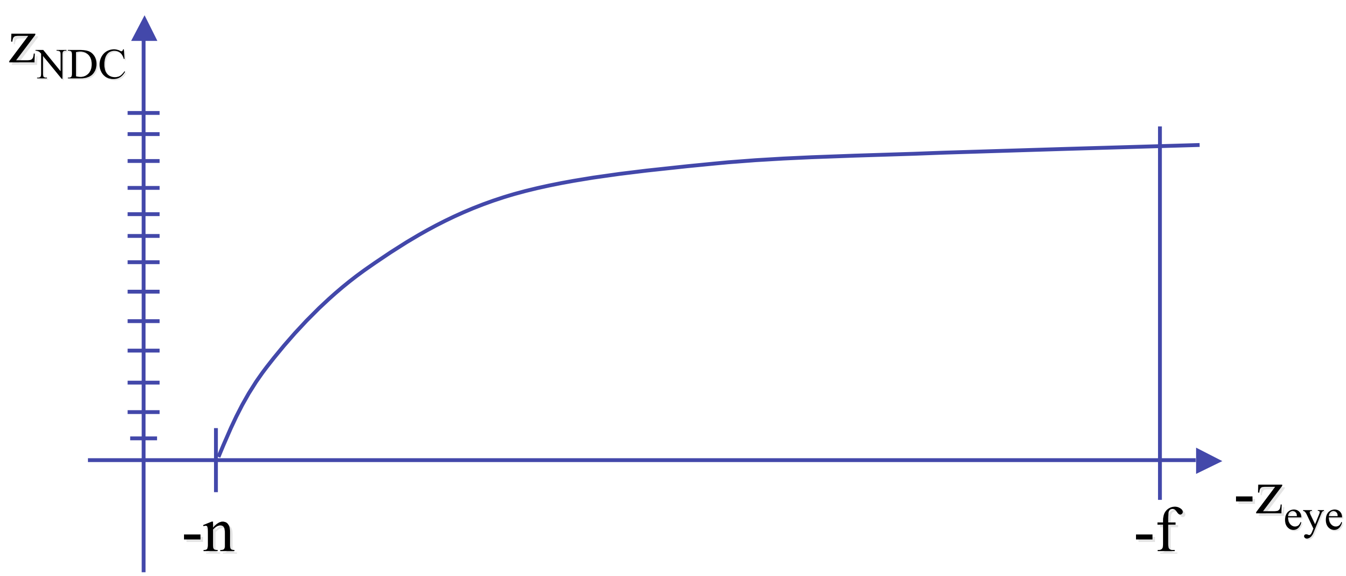
- reminder: perspective transformation maps eye-space (view) *z* to NDC *z*

$$\begin{bmatrix} E & 0 & A & 0 \\ 0 & F & B & 0 \\ 0 & 0 & C & D \\ 0 & 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} Ex + Az \\ Fy + Bz \\ Cz + D \\ -z \end{bmatrix} = \begin{bmatrix} -\left(\frac{Ex}{z} + Az\right) \\ -\left(\frac{Fy}{z} + Bz\right) \\ -\left(C + \frac{D}{z}\right) \\ 1 \end{bmatrix}$$

- thus: $z_{NDC} = -\left(C + \frac{D}{z_{eye}}\right)$

Review: Depth Test Precision

- therefore, depth-buffer essentially stores 1/z, rather than z!
- issue with integer depth buffers
  - high precision for near objects
  - low precision for far objects



Review: Depth Test Precision

- low precision can lead to depth fighting for far objects
  - two different depths in eye space get mapped to same depth in framebuffer
  - which object "wins" depends on drawing order and scan-conversion
- gets worse for larger ratios $f:n$
  - *rule of thumb:* $\mathrm{f{:}n} < 1000$ *for 24 bit depth buffer*
- with 16 bits cannot discern millimeter differences in objects at 1 km distance
- demo: sjbaker.org/steve/omniv/love_your_z_buffer.html

Correction: Ortho Camera Projection

week4.day2, slide 18

- camera's back plane parallel to lens
- infinite focal length
- no perspective convergence
- ~~just throw away z values~~
- x and y coordinates do not change with respect to z in this projection

$$\begin{bmatrix} x_p \\ y_p \\ z_p \end{bmatrix} = \begin{bmatrix} x \\ y \\ 0 \end{bmatrix} \qquad \begin{bmatrix} x_p \\ y_p \\ z_p \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

$$P' = \begin{bmatrix} \frac{2}{right-left} & 0 & 0 & -\frac{right+left}{right-left} \\ 0 & \frac{2}{top-bot} & 0 & -\frac{top+bot}{top-bot} \\ 0 & 0 & \frac{-2}{far-near} & -\frac{far+near}{far-near} \\ 0 & 0 & 0 & 1 \end{bmatrix} P$$

$$\begin{bmatrix} D & 0 & 0 & A \\ 0 & E & 0 & B \\ 0 & 0 & F & C \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} Dx + A \\ Ey + B \\ Fz + C \\ 1 \end{bmatrix}$$

Z-Buffer Algorithm Questions

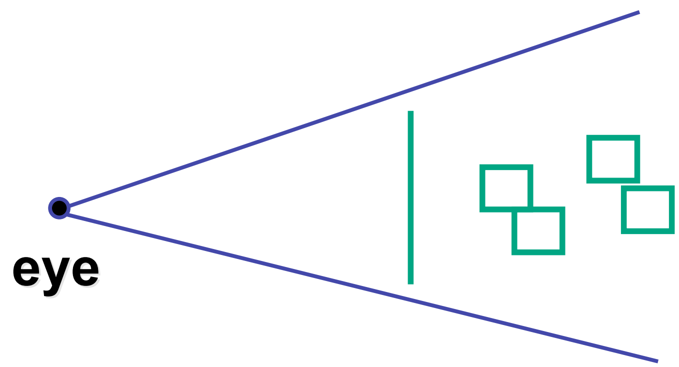
- how much memory does the Z-buffer use?
- does the image rendered depend on the drawing order?
- does the time to render the image depend on the drawing order?
- how does Z-buffer load scale with visible polygons? with framebuffer resolution?

Z-Buffer Pros

- simple!!!
- easy to implement in hardware
  - hardware support in all graphics cards today
- polygons can be processed in arbitrary order
- easily handles polygon interpenetration
- enables deferred shading
  - rasterize shading parameters (e.g., surface normal) and only shade final visible fragments

Z-Buffer Cons

- poor for scenes with high depth complexity
  - need to render all polygons, even if most are invisible



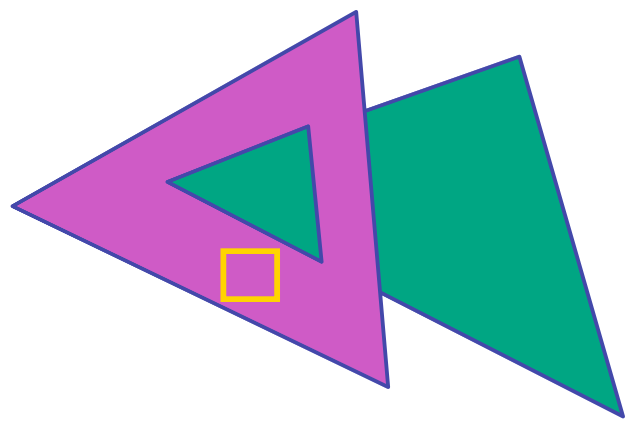
- shared edges are handled inconsistently
  - *ordering dependent*

Z-Buffer Cons

- requires lots of memory
  - (e.g. 1280x1024x32 bits)
- requires fast memory
  - Read-Modify-Write in inner loop
- hard to simulate translucent polygons
  - we throw away color of polygons behind closest one
  - works if polygons ordered back-to-front
    - extra work throws away much of the speed advantage

Hidden Surface Removal

- two kinds of visibility algorithms
  - object space methods
  - image space methods



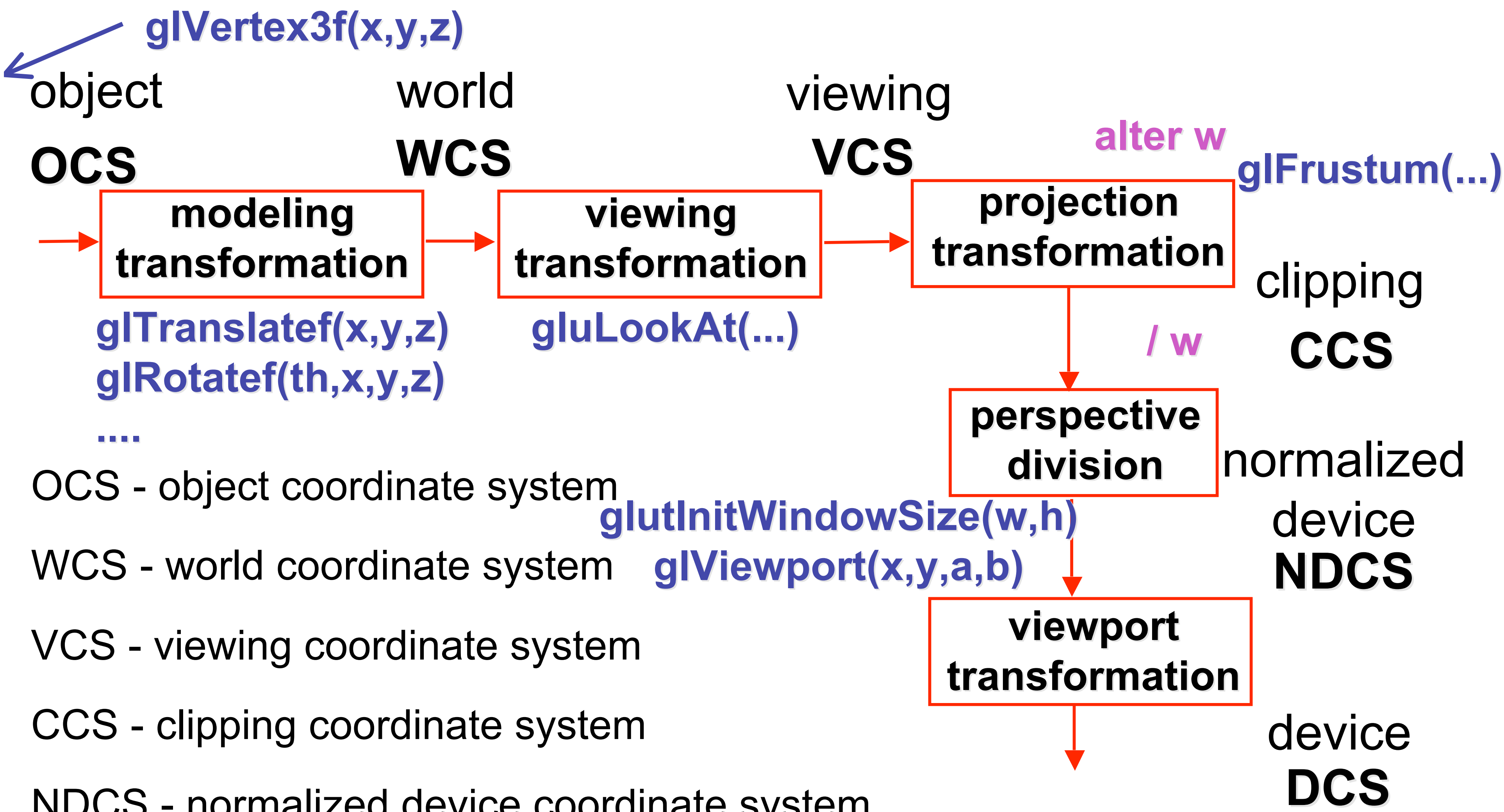
Object Space Algorithms

- determine visibility on object or polygon level
  - using camera coordinates
- resolution independent
  - explicitly compute visible portions of polygons
- early in pipeline
  - after clipping
- requires depth-sorting
  - painter's algorithm
  - BSP trees

Image Space Algorithms

- perform visibility test for in screen coordinates
  - limited to resolution of display
  - Z-buffer: check every pixel independently
- performed late in rendering pipeline

Projective Rendering Pipeline



OCS - object coordinate system

WCS - world coordinate system

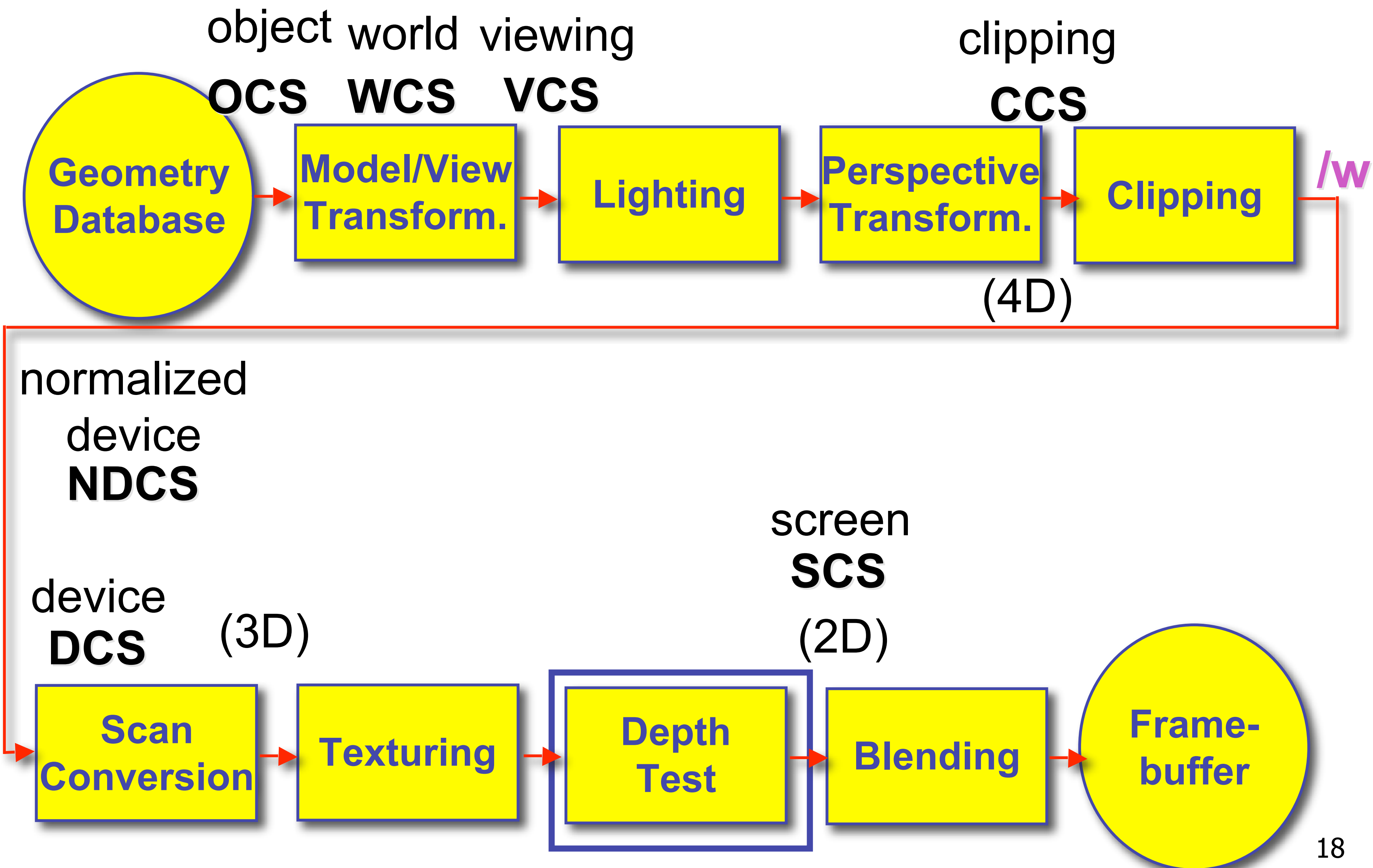
VCS - viewing coordinate system

CCS - clipping coordinate system

NDCS - normalized device coordinate system

DCS - device coordinate system

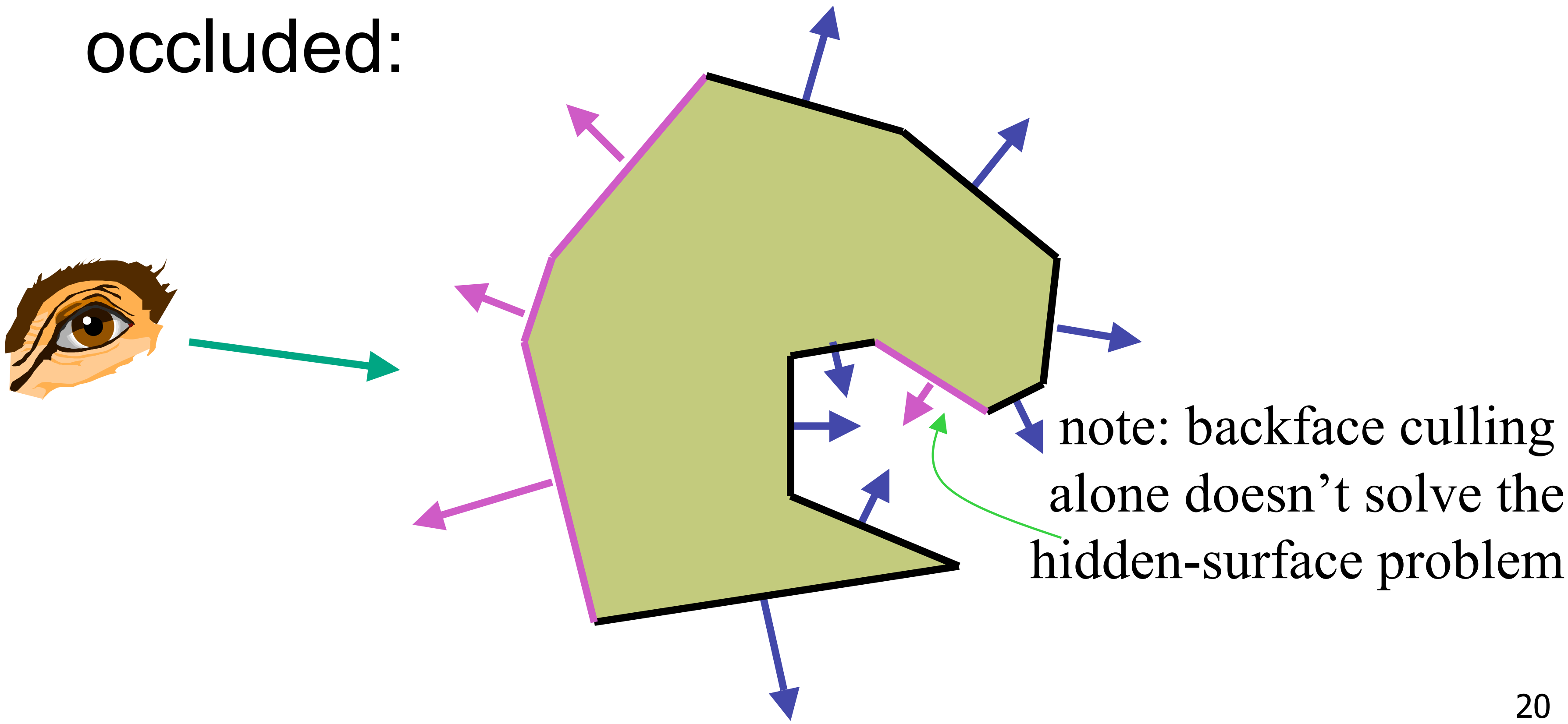
Rendering Pipeline



Backface Culling

Back-Face Culling

- on the surface of a closed orientable manifold, polygons whose normals point away from the camera are always occluded:



Back-Face Culling

- not rendering backfacing polygons improves performance
  - by how much?
    - reduces by about half the number of polygons to be considered for each pixel
  - optimization when appropriate

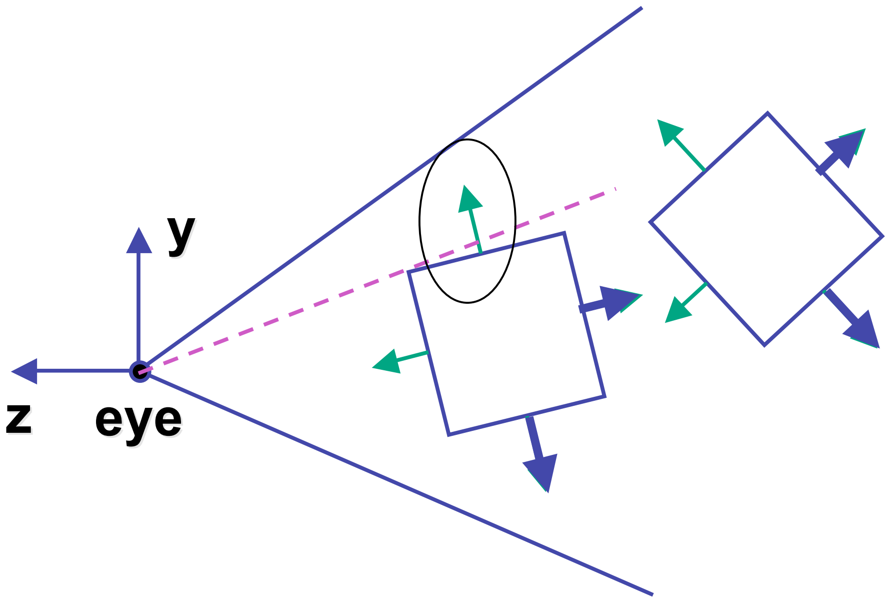
Back-Face Culling

- most objects in scene are typically “solid”
- rigorously: orientable closed manifolds
  - orientable: must have two distinct sides
    - cannot self-intersect
    - a sphere is orientable since has two sides, 'inside' and 'outside'.
    - a Mobius strip or a Klein bottle is not orientable
  - closed: cannot “walk” from one side to the other
    - sphere is closed manifold
    - plane is not

Back-Face Culling

- examples of non-manifold objects:
  - a single polygon
  - a terrain or height field
  - polyhedron w/ missing face
  - anything with cracks or holes in boundary
  - one-polygon thick lampshade

Back-face Culling: VCS

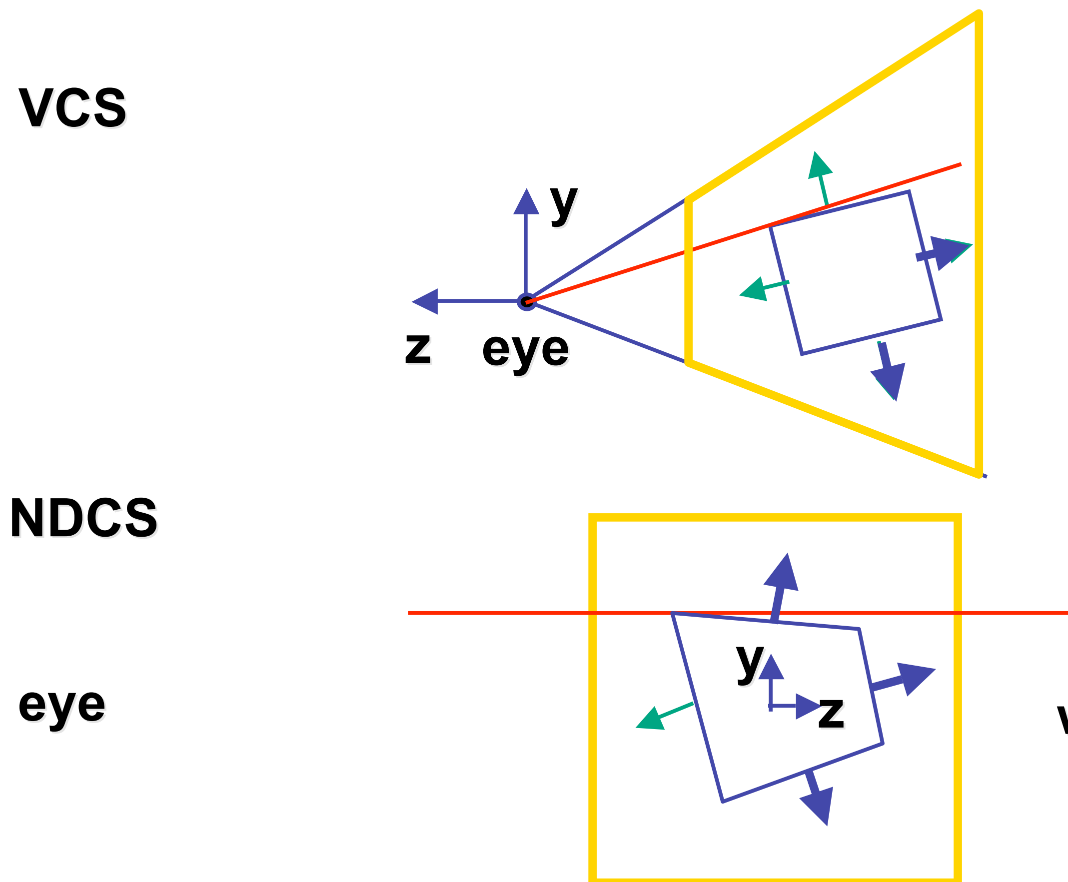


first idea:

cull if $N_Z < 0$

sometimes misses polygons that should be culled

Back-face Culling: NDCS



works to cull if $N_Z > 0$

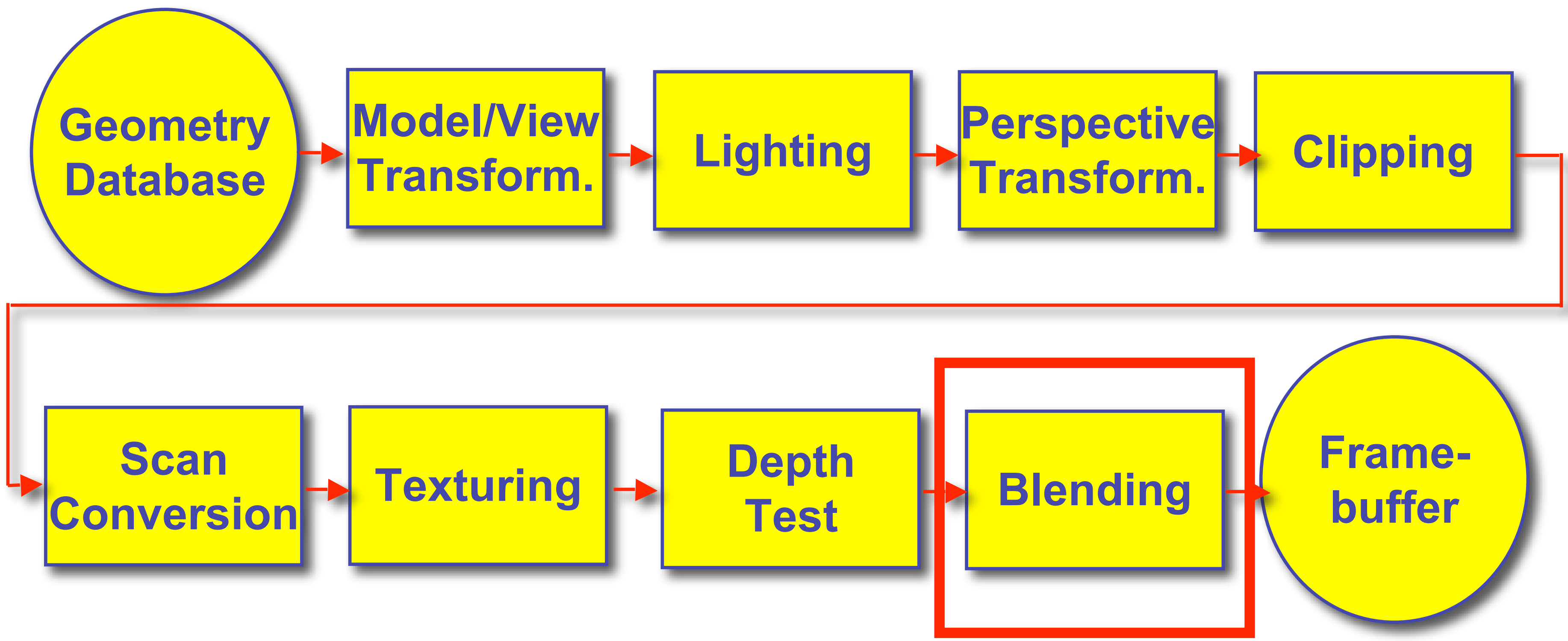
Invisible Primitives

- *why might a polygon be invisible?*
  - polygon outside the *field of view / frustum*
    - solved by clipping
  - polygon is *backfacing*
    - solved by backface culling
  - polygon is *occluded* by object(s) nearer the viewpoint
    - solved by hidden surface removal


INVISIBLE EVERYTHING
ICANHASCHEEZBURGER.COM

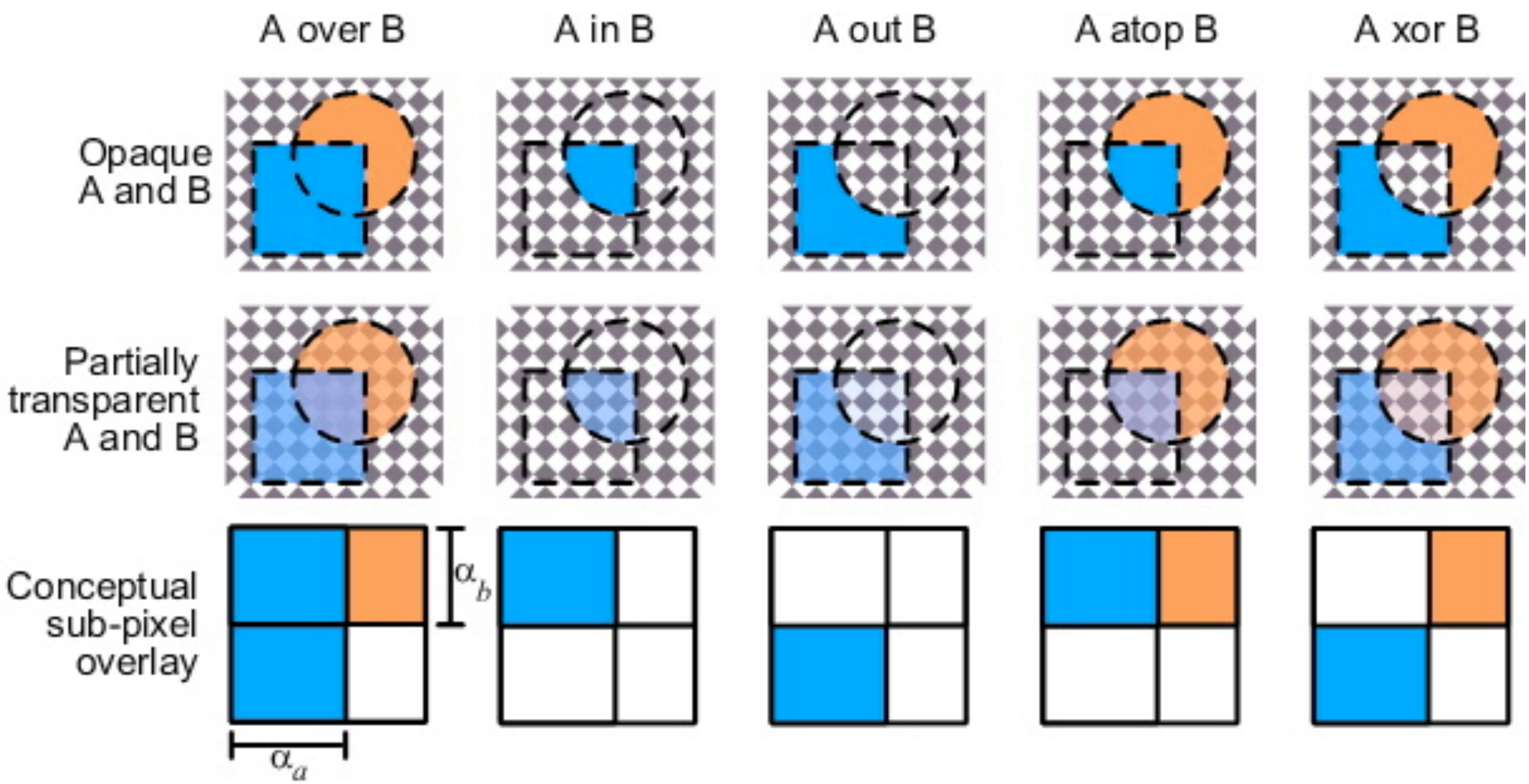
Blending

Rendering Pipeline



Blending/Compositing

- how might you combine multiple elements?
- foreground color **A**, background color **B**

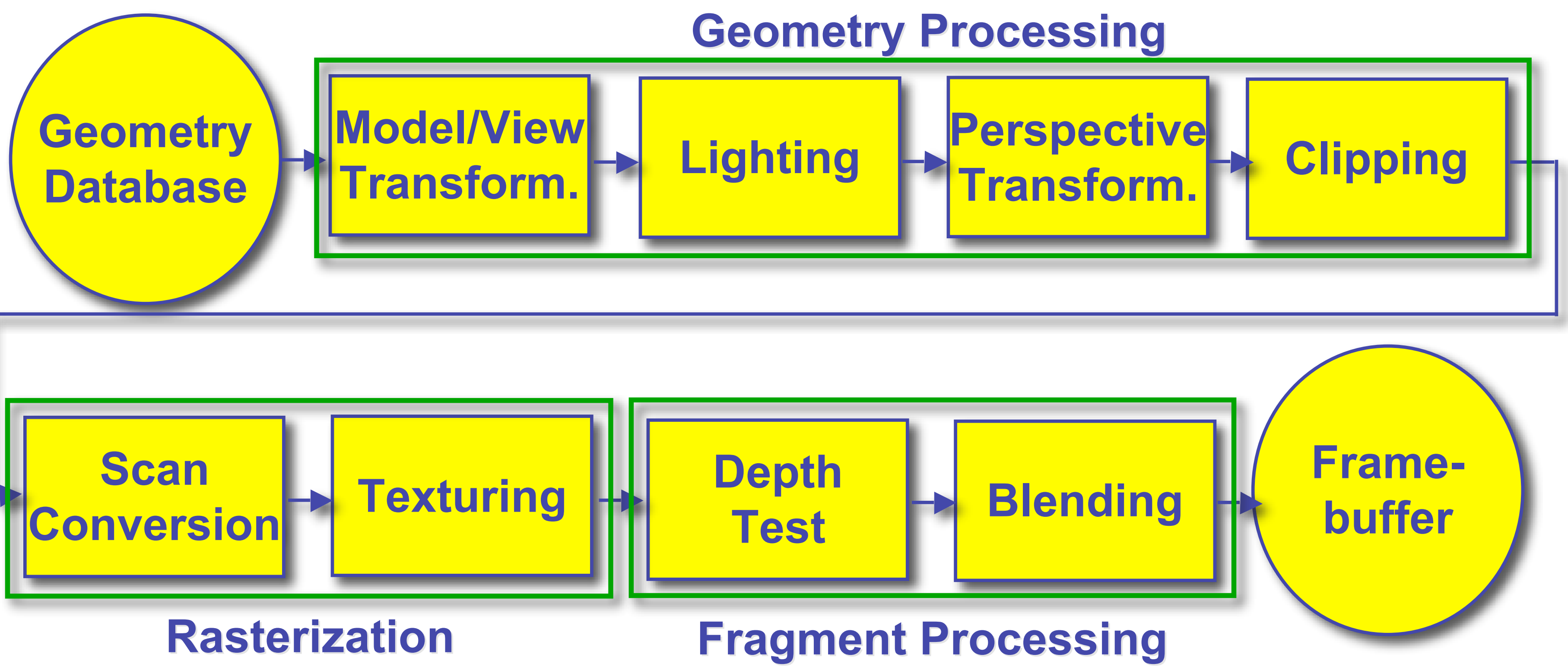


Premultiplying Colors

- specify opacity with alpha channel: (r,g,b,α)
  - α=1: opaque, α=.5: translucent, α=0: transparent
- **A** *over* **B**
  - $\mathbf{C} = \alpha\mathbf{A} + (1-\alpha)\mathbf{B}$
- but what if **B** is also partially transparent**?**
  - $\mathbf{C} = \alpha\mathbf{A} + (1-\alpha)\,\beta\mathbf{B} = \beta\mathbf{B} + \alpha\mathbf{A} + \beta\mathbf{B} - \alpha\,\beta\mathbf{B}$
  - $\gamma = \beta + (1-\beta)\alpha = \beta + \alpha - \alpha\beta$
    - 3 multiplies, different equations for alpha vs. RGB
- premultiplying by alpha
  - $\mathbf{C'} = \gamma\,\mathbf{C},\ \mathbf{B'} = \beta\mathbf{B},\ \mathbf{A'} = \alpha\mathbf{A}$
  - $\mathbf{C'} = \mathbf{B'} + \mathbf{A'} - \alpha\mathbf{B'}$
  - $\gamma = \beta + \alpha - \alpha\beta$
    - 1 multiply to find C, same equations for alpha and RGB

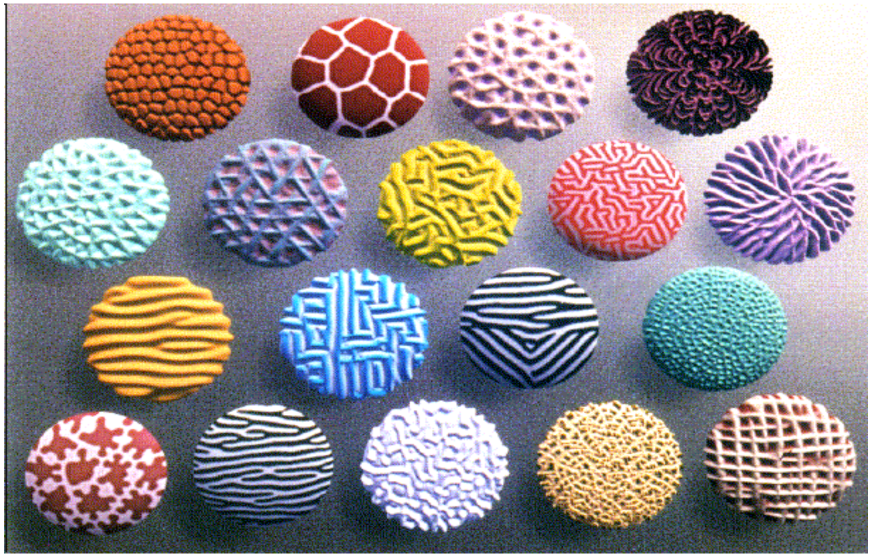
Texturing

Rendering Pipeline



Texture Mapping

- real life objects have nonuniform colors, normals
- to generate realistic objects, reproduce coloring & normal variations = **texture**
- can often replace complex geometric details

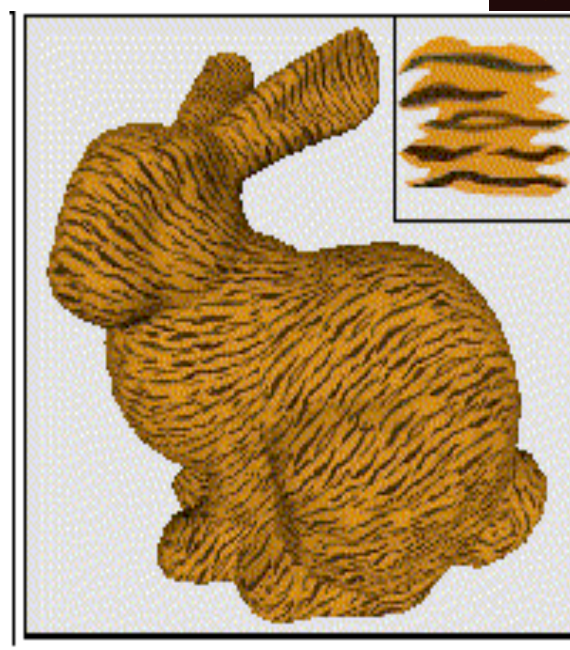


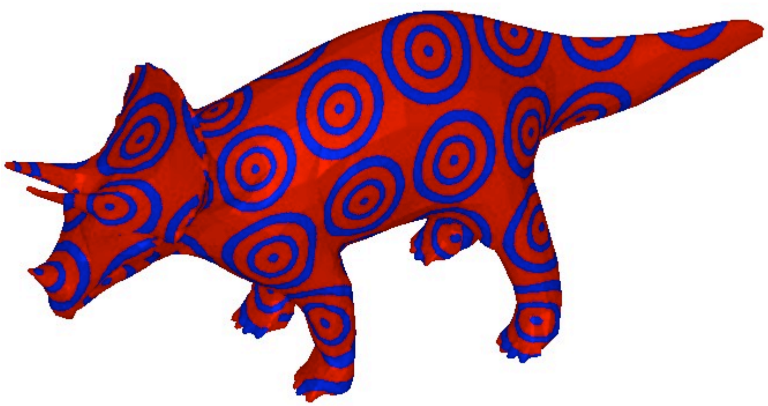
Texture Mapping

- introduced to increase realism
  - lighting/shading models not enough
- hide geometric simplicity
  - images convey illusion of geometry
  - map a brick wall texture on a flat polygon
  - create bumpy effect on surface
- associate 2D information with 3D surface
  - point on surface corresponds to a point in texture
  - “paint” image onto polygon

Color Texture Mapping

- define color (RGB) for each point on object surface
- two approaches
  - surface texture map
  - volumetric texture

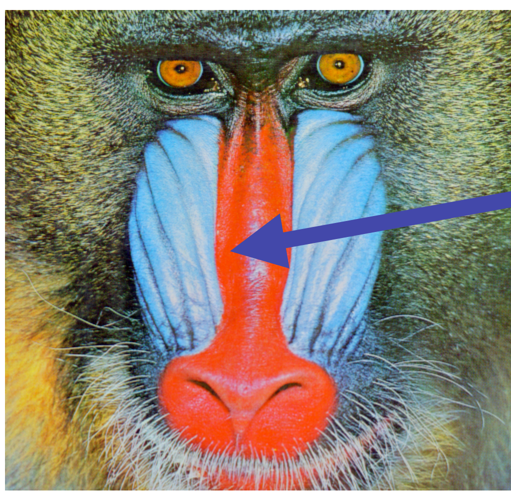


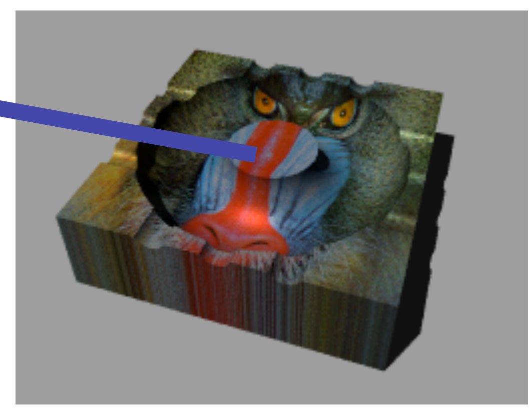


Texture Coordinates

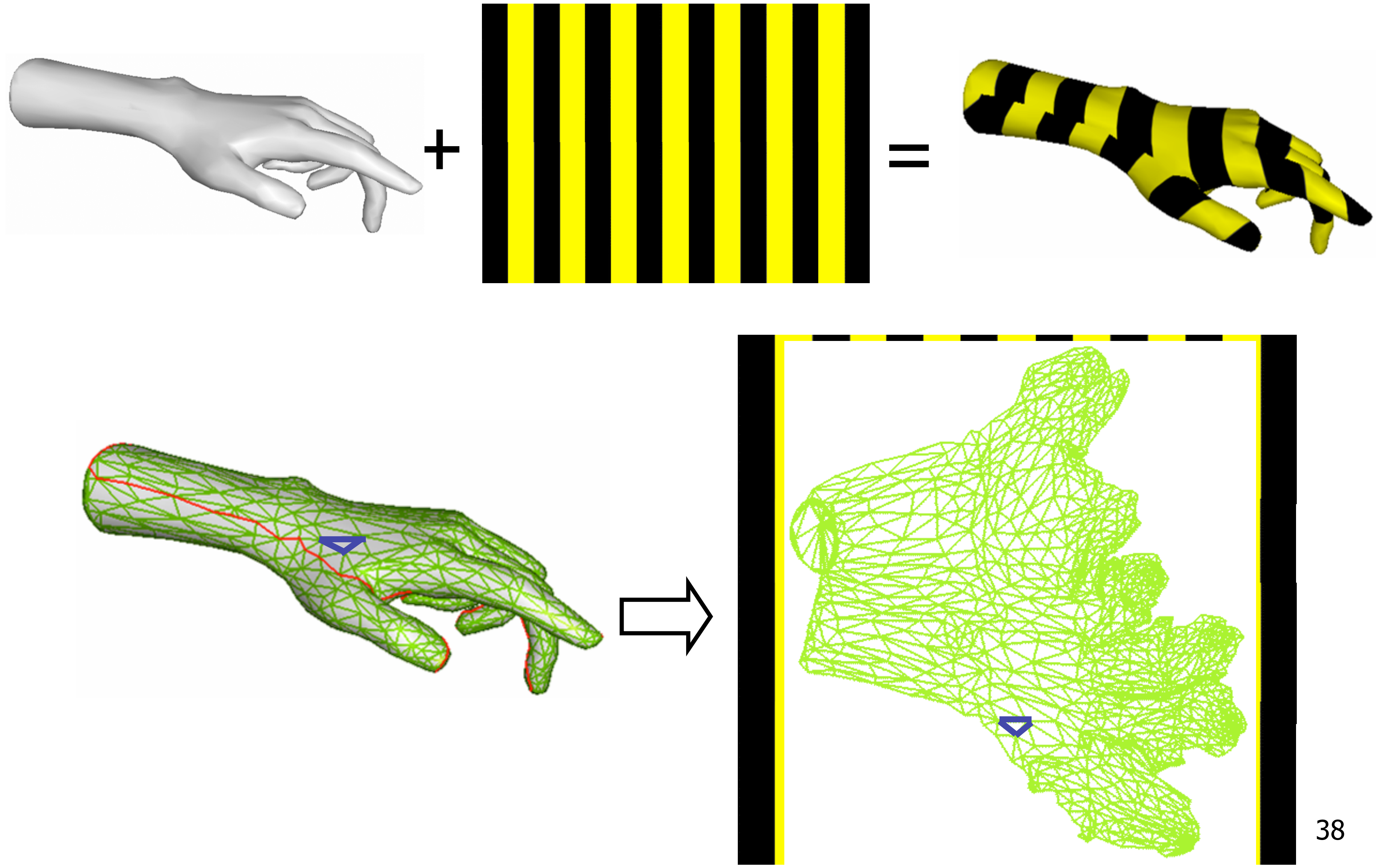
- texture image: 2D array of color values (texels)
- assigning texture coordinates (s,t) at vertex with object coordinates (x,y,z,w)
  - use interpolated (s,t) for texel lookup at each pixel
  - use value to modify a polygon's color
    - or other surface property
  - specified by programmer or artist

```
glTexCoord2f(s,t)
glVertexf(x,y,z,w)
```

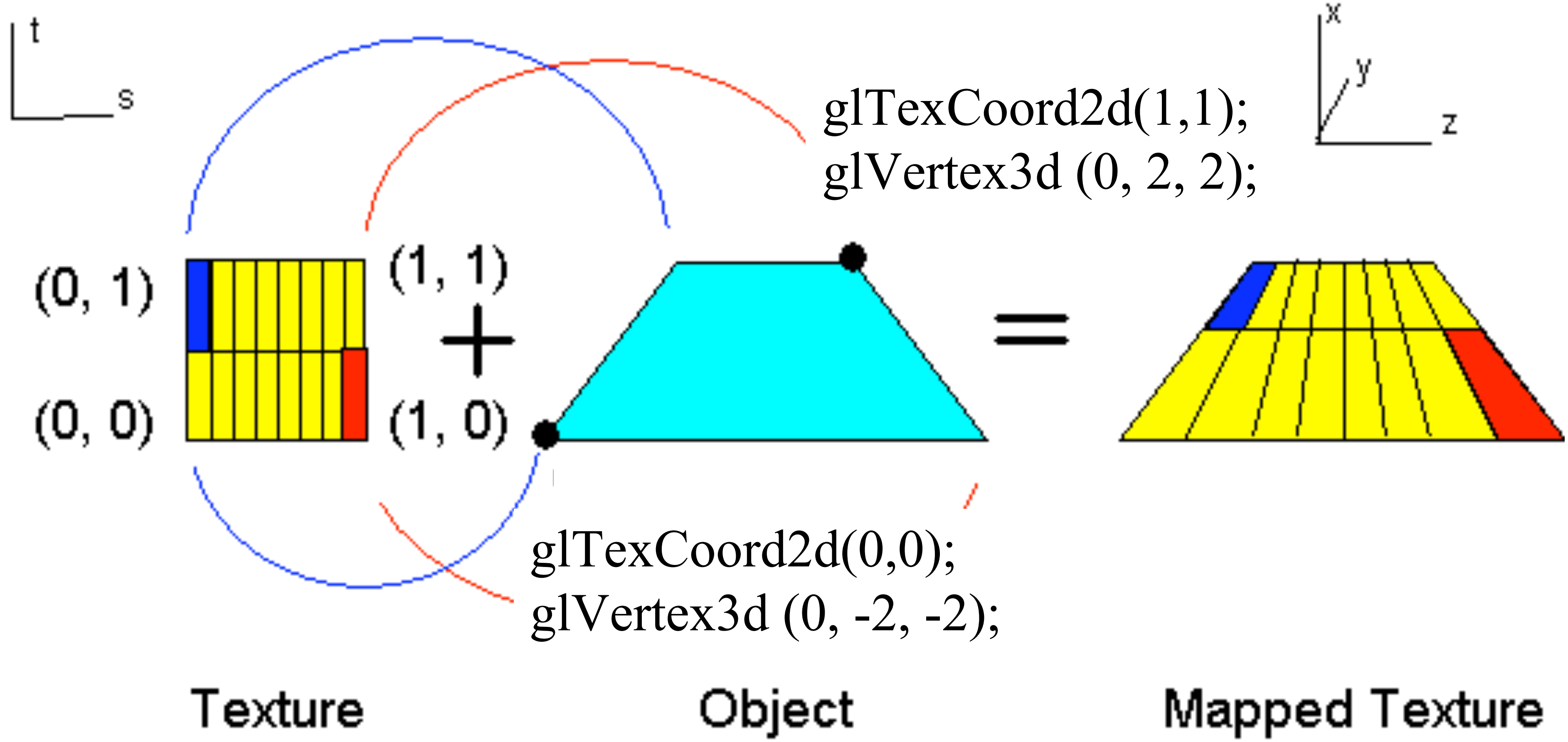




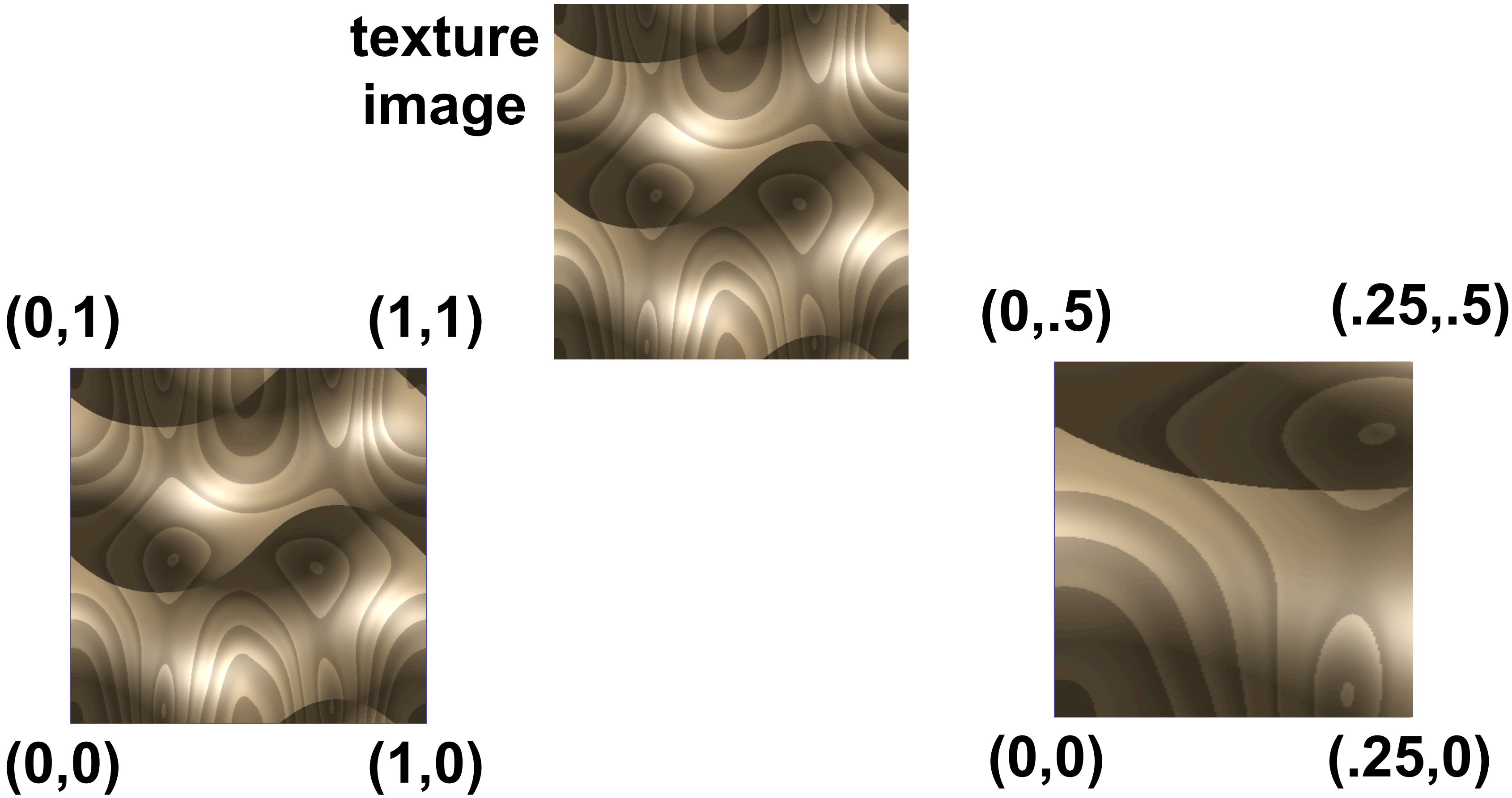
Texture Mapping Example



Example Texture Map



Fractional Texture Coordinates



Texture Lookup: Tiling and Clamping

- what if s or t is outside the interval [0…1]?
- multiple choices
  - use fractional part of texture coordinates
    - cyclic repetition of texture to tile whole surface

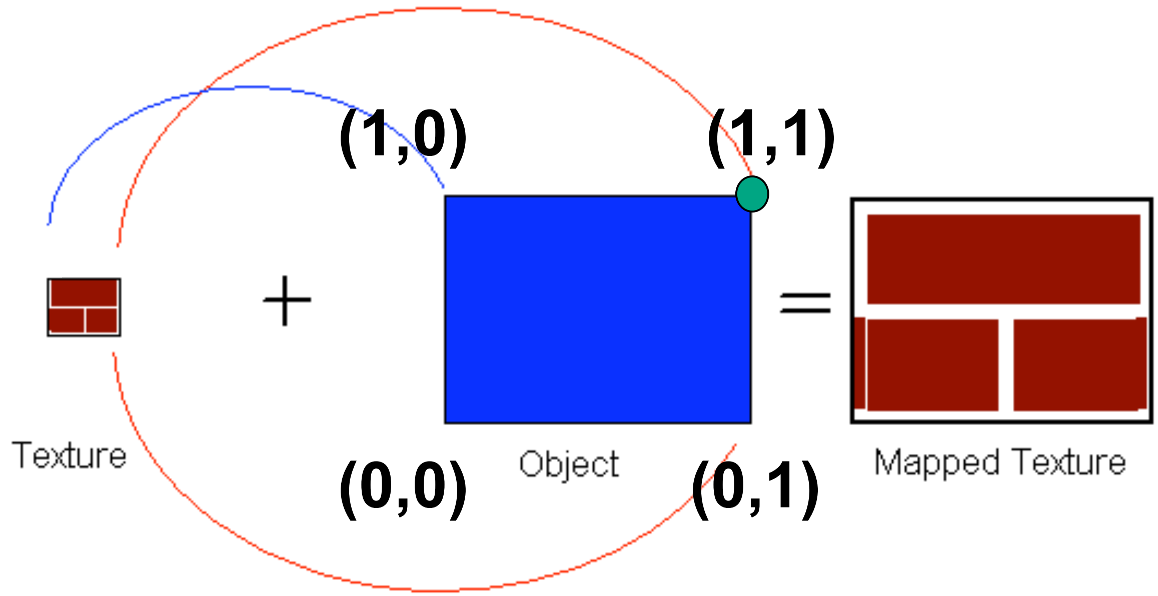
      glTexParameteri(…, GL_TEXTURE_WRAP_S, GL_REPEAT, GL_TEXTURE_WRAP_T, GL_REPEAT, ...)

  - clamp every component to range [0…1]
    - re-use color values from texture image border

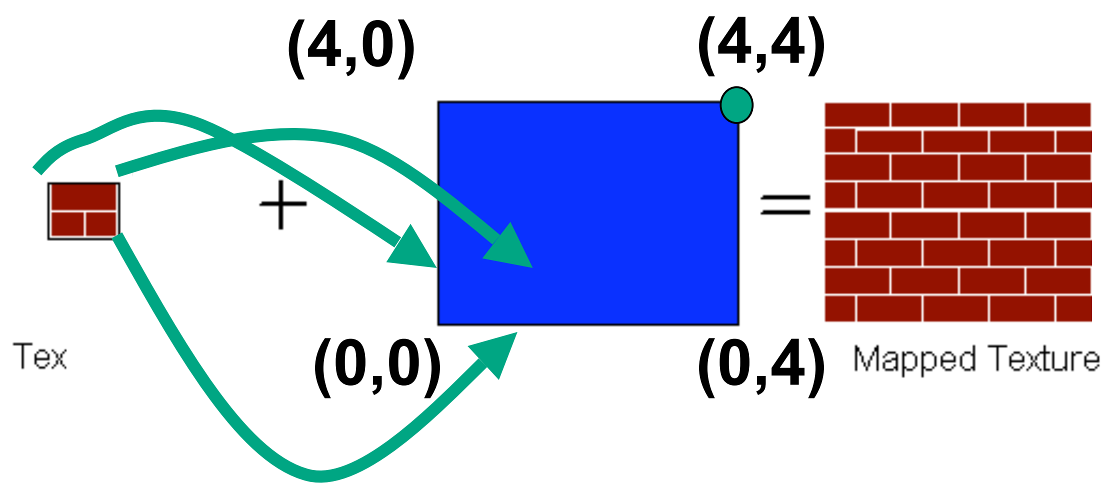
      glTexParameteri(…, GL_TEXTURE_WRAP_S, GL_CLAMP, GL_TEXTURE_WRAP_T, GL_CLAMP, ...)

Tiled Texture Map

glTexCoord2d(1, 1);
glVertex3d (x, y, z);



glTexCoord2d(4, 4);
glVertex3d (x, y, z);



Demo

- Nate Robbins tutors
  - texture

Texture Coordinate Transformation

- motivation
  - change scale, orientation of texture on an object
- approach
  - *texture matrix stack*
  - transforms specified (or generated) tex coords

```
glMatrixMode( GL_TEXTURE );
glLoadIdentity();
glRotate();
    ...
```

  - more flexible than changing (s,t) coordinates
- [demo]

Texture Functions

- once have value from the texture map, can:
  - directly use as surface color: `GL_REPLACE`
    - throw away old color, lose lighting effects
  - modulate surface color: `GL_MODULATE`
    - multiply old color by new value, keep lighting info
    - texturing happens **after** lighting, not relit
  - use as surface color, modulate alpha: `GL_DECAL`
    - like replace, but supports texture transparency
  - blend surface color with another: `GL_BLEND`
    - new value controls which of 2 colors to use
    - indirection, new value not used directly for coloring
- specify with `glTexEnvi(GL_TEXTURE_ENV, GL_TEXTURE_ENV_MODE, <mode>)`
- [demo]

Texture Pipeline

(x, y, z)

Object position

(-2.3, 7.1, 17.7)

(s, t)

Parameter space

(0.32, 0.29)

(s', t')

Transformed parameter space

(0.52, 0.49)

Texel space

(81, 74)

Texel color

(0.9,0.8,0.7)

Object color

(0.5,0.5,0.5)

Final color

(0.45,0.4,0.35)

Texture Objects and Binding

- texture object
  - an OpenGL data type that keeps textures resident in memory and provides identifiers to easily access them
  - provides efficiency gains over having to repeatedly load and reload a texture
  - you can prioritize textures to keep in memory
  - OpenGL uses least recently used (LRU) if no priority is assigned
- texture binding
  - which texture to use right now
  - switch between preloaded textures

Basic OpenGL Texturing

- create a texture object and fill it with texture data:
  - `glGenTextures(num, &indices)` to get identifiers for the objects
  - `glBindTexture(GL_TEXTURE_2D, identifier)` to bind
    - following texture commands refer to the bound texture
  - `glTexParameteri(GL_TEXTURE_2D, …, …)` to specify parameters for use when applying the texture
  - `glTexImage2D(GL_TEXTURE_2D, ….)` to specify the texture data (the image itself)
- enable texturing: `glEnable(GL_TEXTURE_2D)`
- state how the texture will be used:
  - `glTexEnvf(…)`
- specify texture coordinates for the polygon:
  - use `glTexCoord2f(s,t)` before each vertex:
    - `glTexCoord2f(0,0); glVertex3f(x,y,z);`

Low-Level Details

- large range of functions for controlling layout of texture data
  - state how the data in your image is arranged
  - e.g.: `glPixelStorei(GL_UNPACK_ALIGNMENT, 1)` tells OpenGL not to skip bytes at the end of a row
  - you must state how you want the texture to be put in memory: how many bits per “pixel”, which channels,…
- textures must be square and size a power of 2
  - common sizes are 32x32, 64x64, 256x256
  - smaller uses less memory, and there is a finite amount of texture memory on graphics cards
- ok to use texture template sample code for project 4
  - http://nehe.gamedev.net/data/lessons/lesson.asp?lesson=09

Texture Mapping

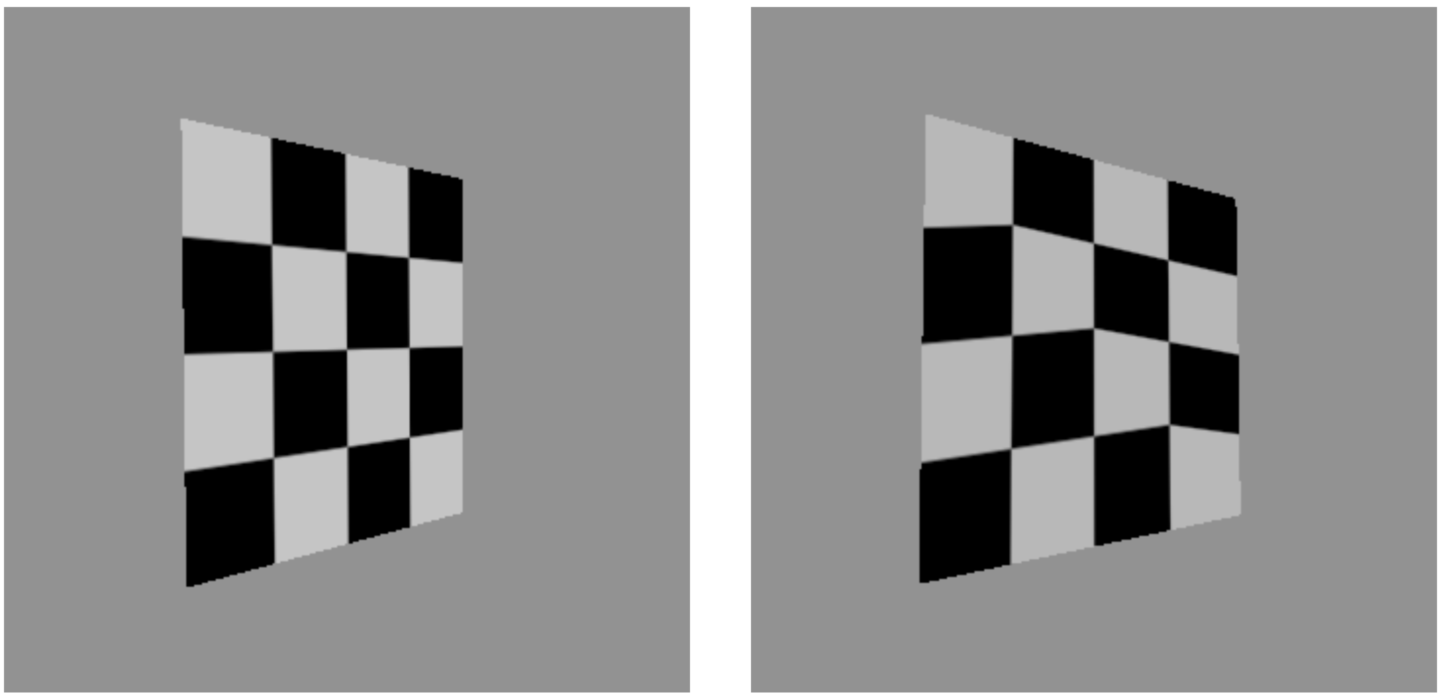
- texture coordinates
  - specified at vertices

```
glTexCoord2f(s,t);
glVertexf(x,y,z);
```

  - interpolated across triangle (like R,G,B,Z)
    - …well not quite!

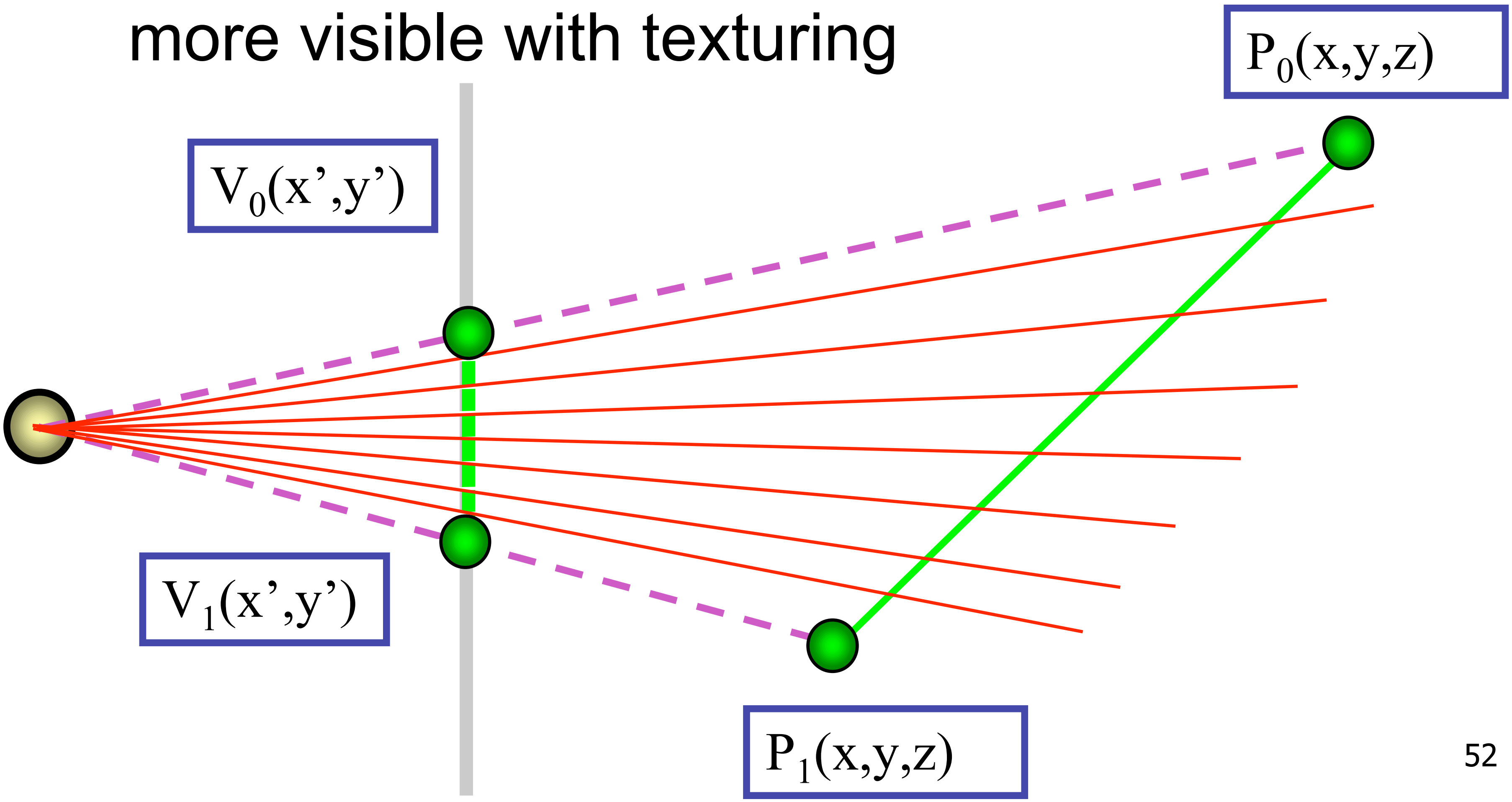
Texture Mapping

- texture coordinate interpolation
  - perspective foreshortening problem



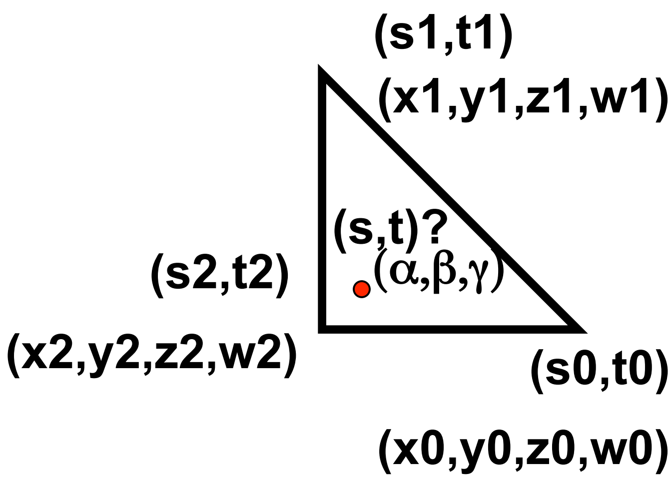
Interpolation: Screen vs. World Space

- screen space interpolation incorrect
  - problem ignored with shading, but artifacts more visible with texturing



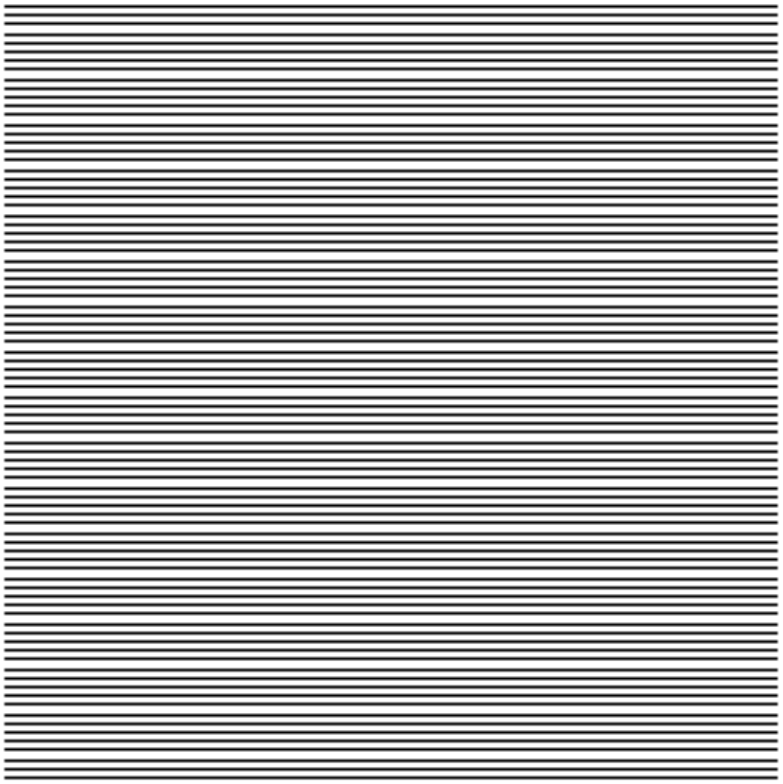
Texture Coordinate Interpolation

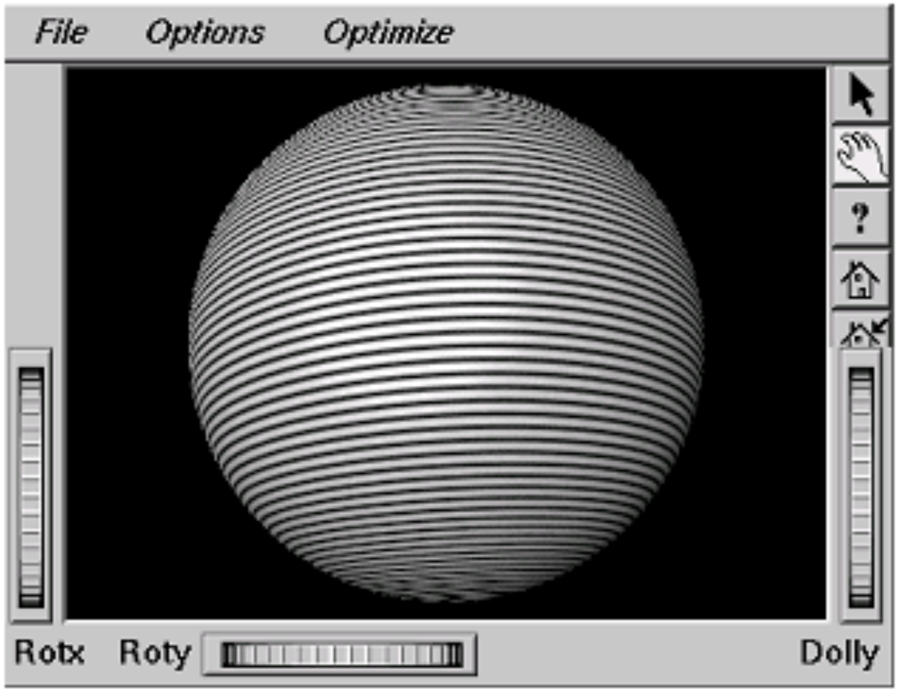
- perspective correct interpolation
  - α, β, γ :
    - barycentric coordinates of a point **P** in a triangle
  - *s0*, *s1*, *s2* :
    - texture coordinates of vertices
  - *w0*, *w1*,*w2* :
    - homogeneous coordinates of vertices



$$s = \frac{\alpha \cdot s_0 / w_0 + \beta \cdot s_1 / w_1 + \gamma \cdot s_2 / w_2}{\alpha / w_0 + \beta / w_1 + \gamma / w_2}$$

Reconstruction

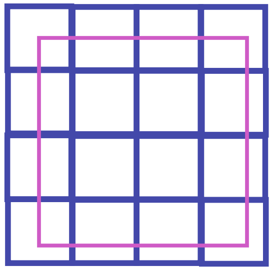




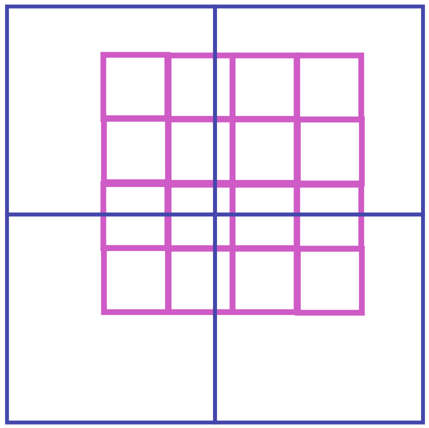
(image courtesy of Kiriakos Kutulakos, U Rochester)

Reconstruction

- how to deal with:
  - pixels that are much larger than texels?
    - apply filtering, “averaging”

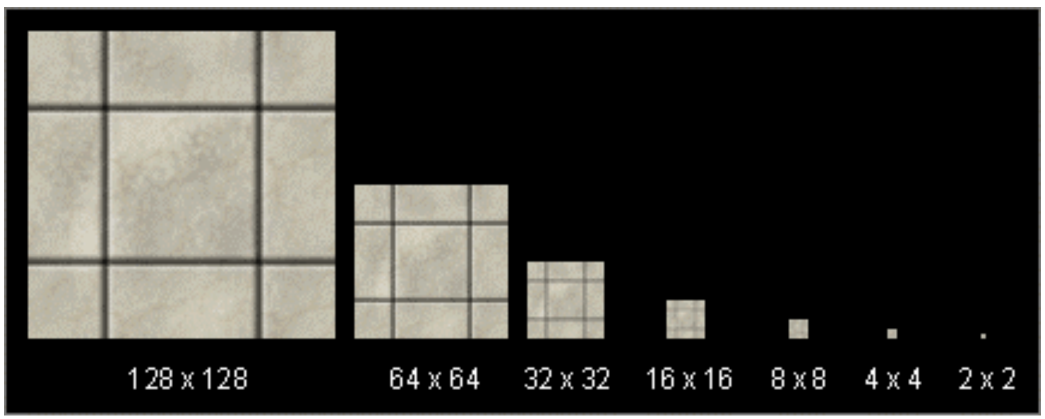


  - pixels that are much smaller than texels ?
    - interpolate

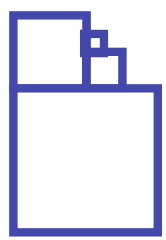


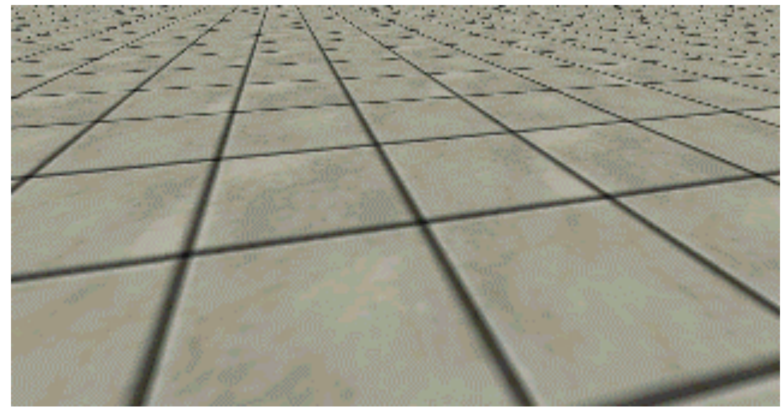
MIPmapping

use "image pyramid" to precompute averaged versions of the texture

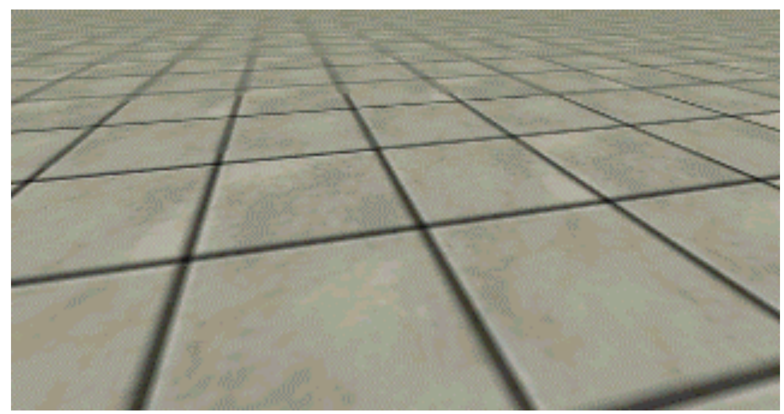


store whole pyramid in single block of memory





Without MIP-mapping

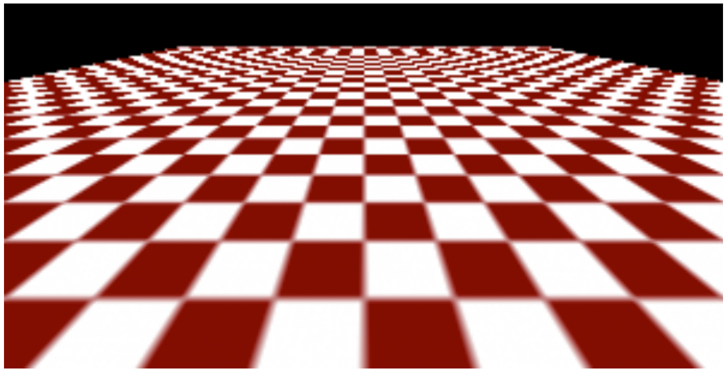


With MIP-mapping

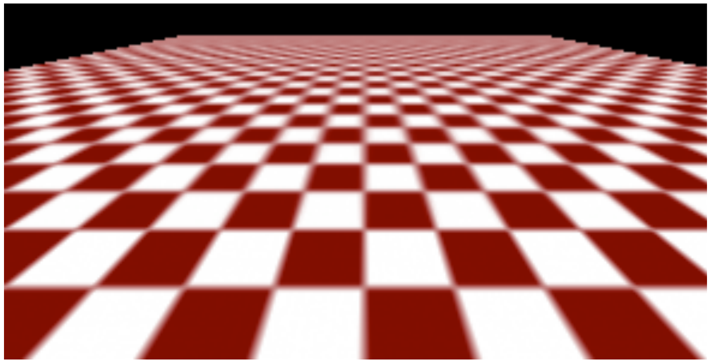
MIPmaps

- **multum in parvo** -- many things in a small place
  - prespecify a series of prefiltered texture maps of decreasing resolutions
  - requires more texture storage
  - avoid shimmering and flashing as objects move
- `gluBuild2DMipmaps`
  - automatically constructs a family of textures from original texture size down to 1x1

without



with

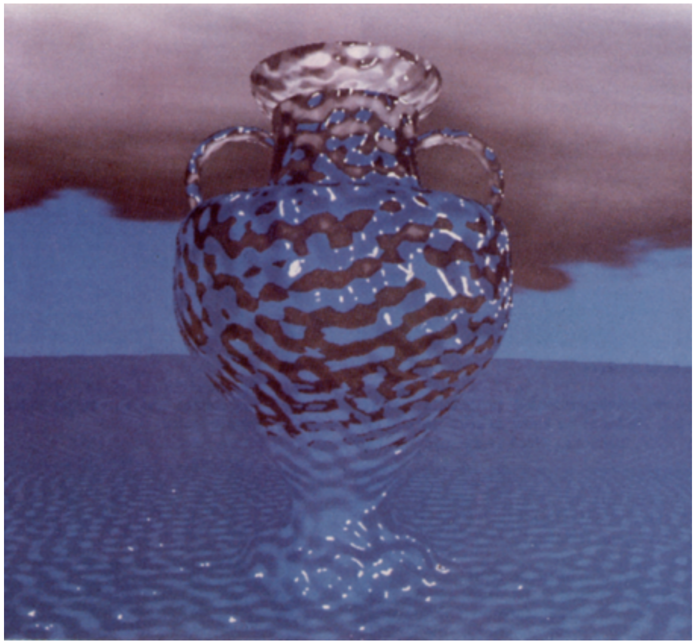


MIPmap storage

- only 1/3 more space required

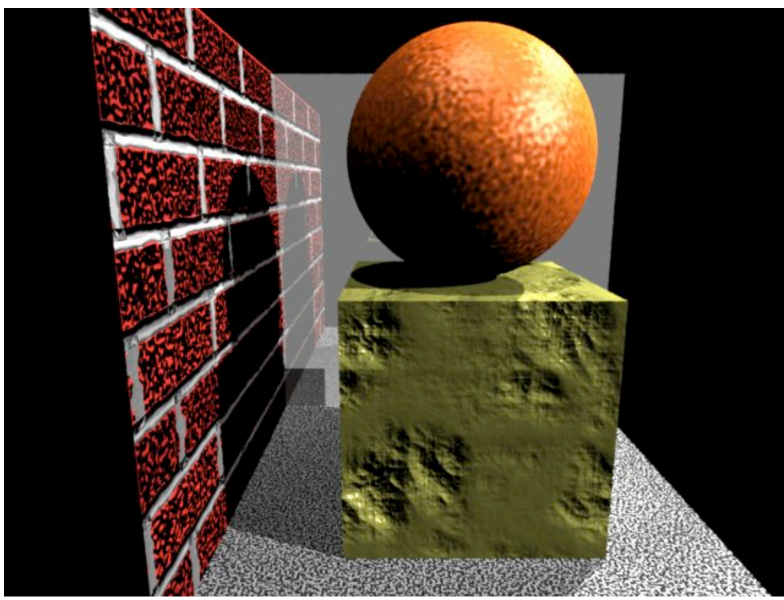
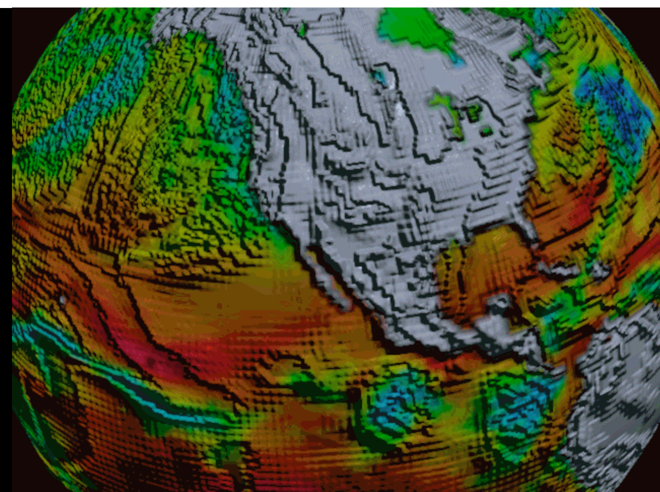
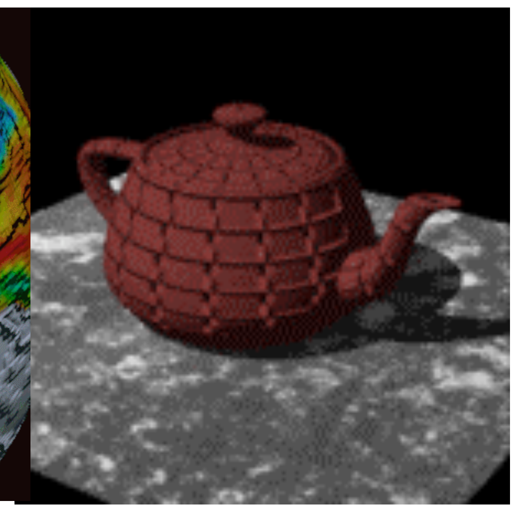
Texture Parameters

- in addition to color can control other material/object properties
  - surface normal (bump mapping)
  - reflected color (environment mapping)

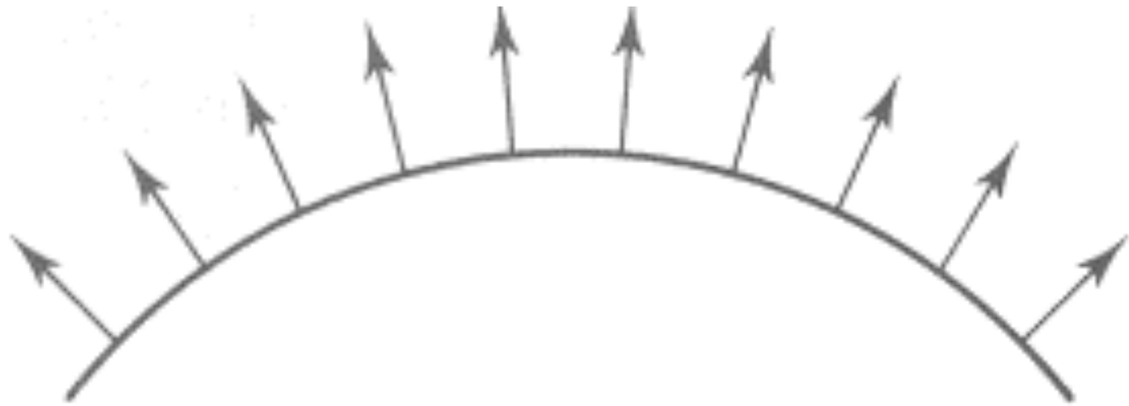


Bump Mapping: Normals As Texture

- object surface often not smooth – to recreate correctly need complex geometry model
- can control shape “effect” by locally perturbing surface normal
  - random perturbation
  - directional change over region

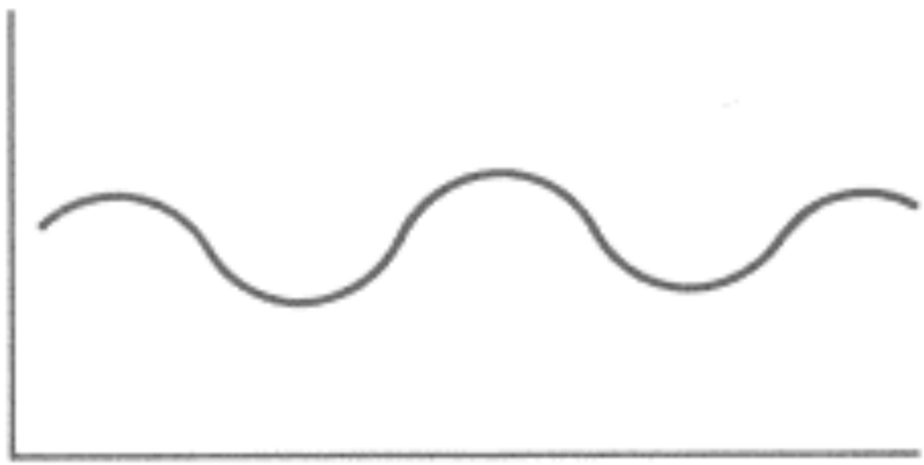




Bump Mapping



$O(u)$

Original surface



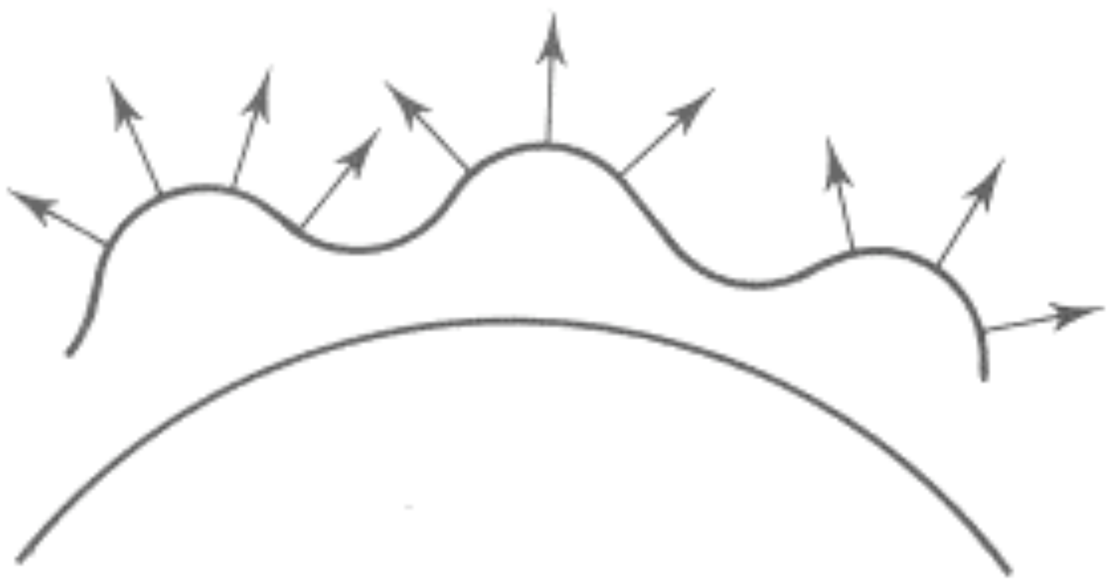
$B(u)$

A bump map

Bump Mapping

$O'(u)$

Lengthening or shortening $O(u)$ using $B(u)$

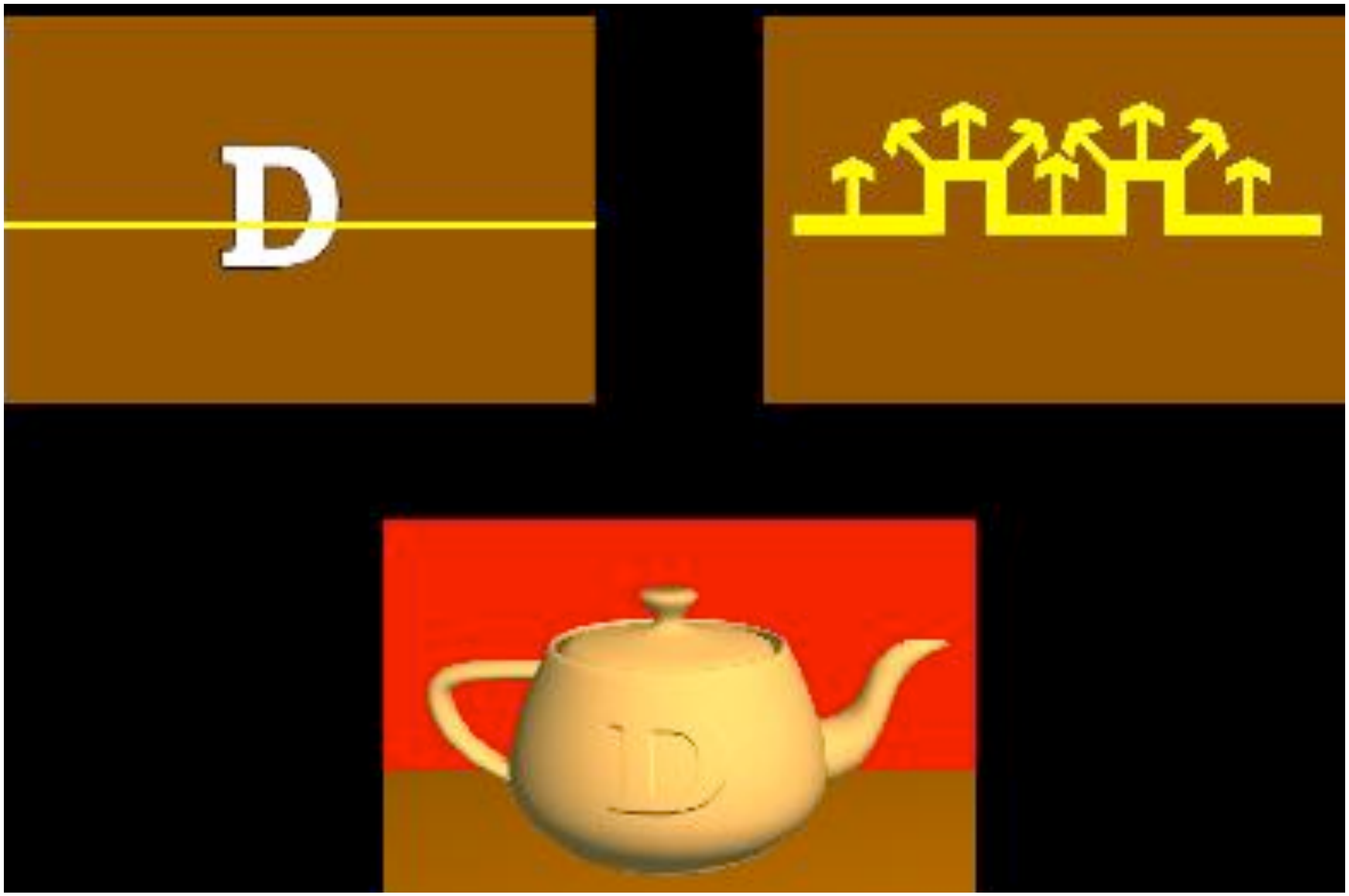


$N'(u)$

The vectors to the 'new' surface

Embossing

- at transitions
  - rotate point's surface normal by θ or - θ



Displacement Mapping

- bump mapping gets silhouettes wrong
  - shadows wrong too
- change surface geometry instead
  - only recently available with realtime graphics
  - need to subdivide surface