# Texture Mapping for Visualization

# The Problem with Geometric Models

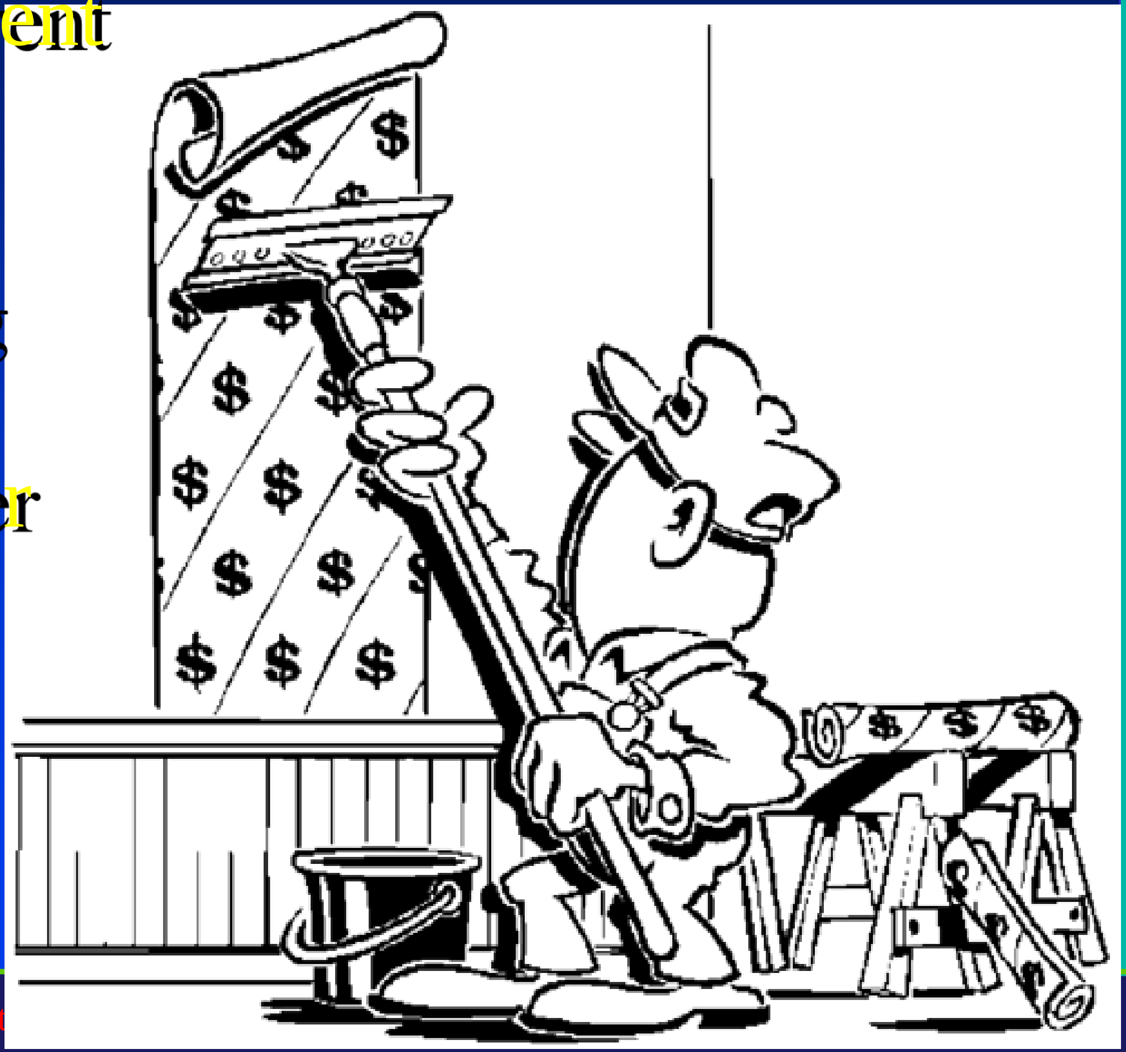
- We do not want to represent all of these details with geometry ONLY!!!

# The Limitations of Geometric Modeling

- Although graphics cards can render over 10 million polygons per second, that number is insufficient for many phenomena
  - Clouds
  - Grass
  - Terrain
  - Skin

# Texture Mapping: Basic Concept

- Increase the apparent complexity of simple geometry
- Like wallpapering or gift-wrapping with stretchy paper
- Curved surfaces require extra stretching or even cutting



# Objectives and Topics

- Introduction of mapping methods
  - Texture mapping
  - Environment mapping
  - Bump mapping
- Consider basic strategies
  - Forward vs. backward mapping
  - Point sampling vs. area averaging

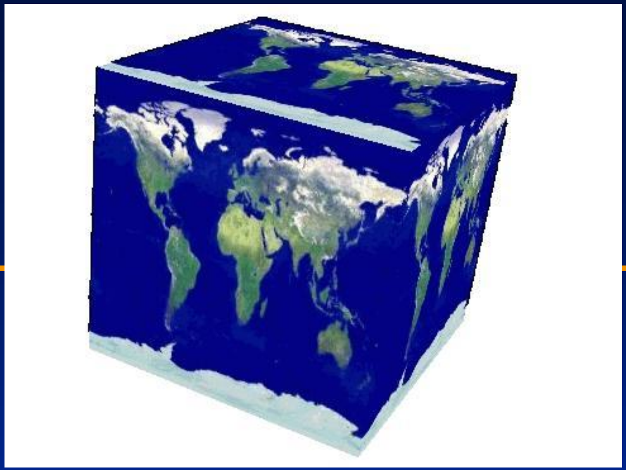
# Modeling an Orange (A Classical Example)

- Consider the problem of modeling an orange (the fruit)
- Start with an orange-colored sphere
  - Too simple
- Replace sphere with a more complex shape
  - Does not capture surface characteristics (small dimples)
  - Takes too many polygons to model all the dimples

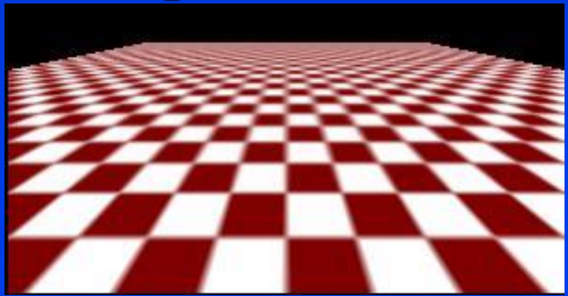
# Modeling an Orange

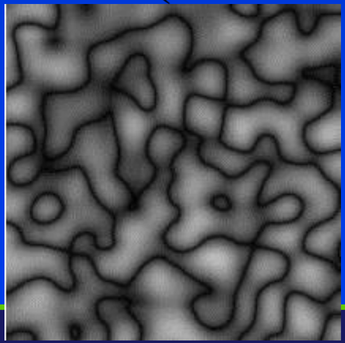
- Take a picture of a real orange, scan it, and "paste" onto simple geometric model
  - This process is known as texture mapping
- Still might not be sufficient because resulting surface will be smooth
  - Need to change local shape
  - Bump mapping

# Texture Mapping



- A clever way of adding surface details
- Two ways can achieve the goal:
  - ❖Surface detail polygons: create more and more polygons to model object details
    - ❖Add scene complexity and thus slow down the graphics rendering performance
    - ❖Some fine features are hard to model!
  - ✓Map a texture to the surface (a more popular approach)



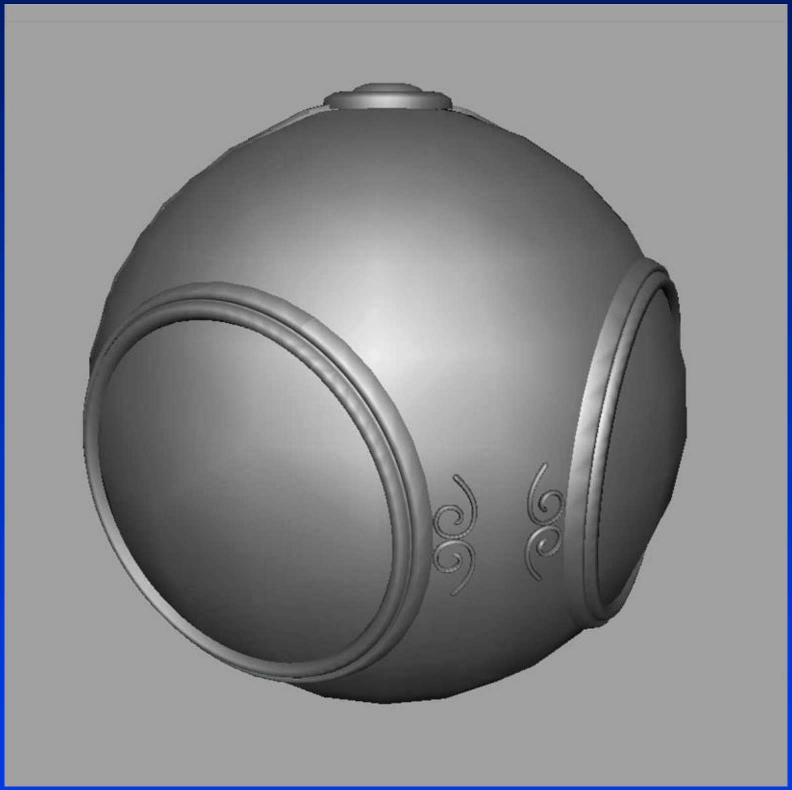


Complexity of images does not affect the complexity of geometry processing (transformation, clipping…)

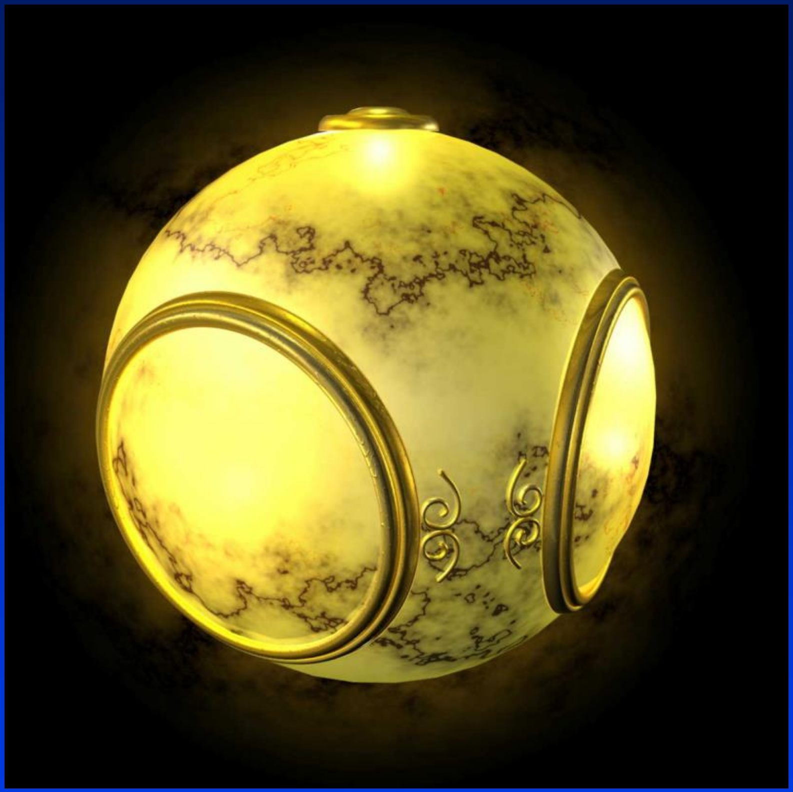
# Three Types of Mapping

- Texture mapping
  - Uses images to fill inside of polygons
- Environment (reflection mapping)
  - Uses a picture of the environment for texture maps
  - Allows simulation of highly specular surfaces
- Bump mapping
  - Emulates altering normal vectors during the rendering process

# Texture Mapping



geometric model

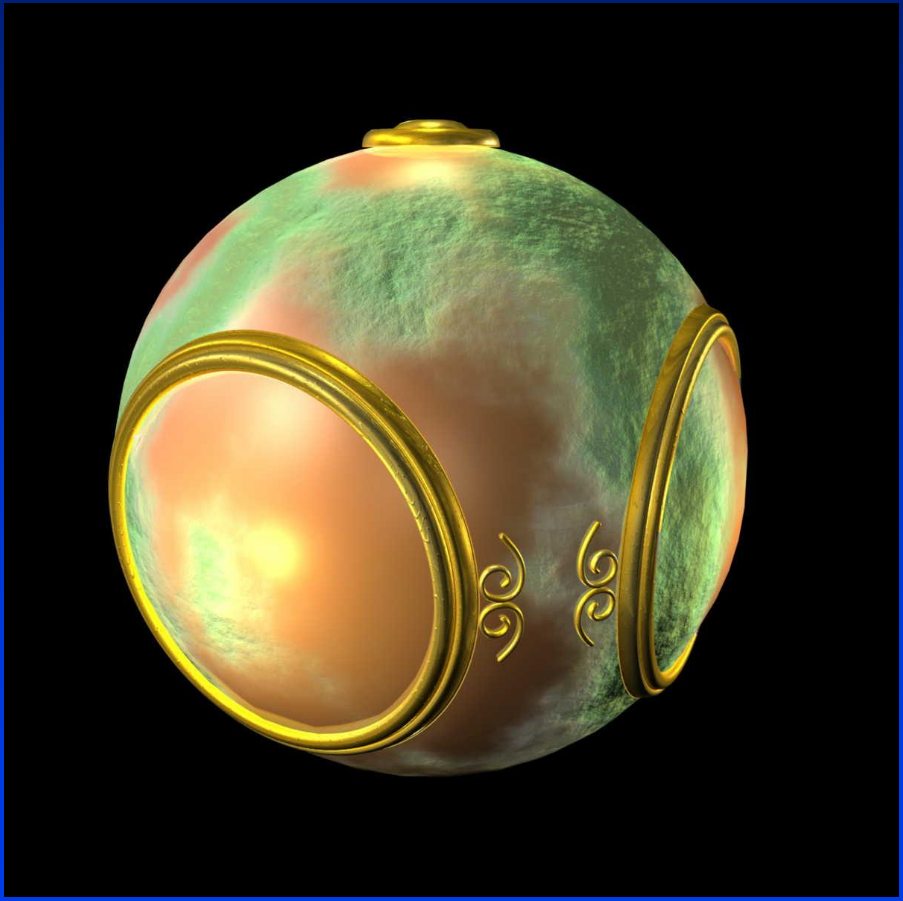


Texture-mapped model

# Environment Mapping

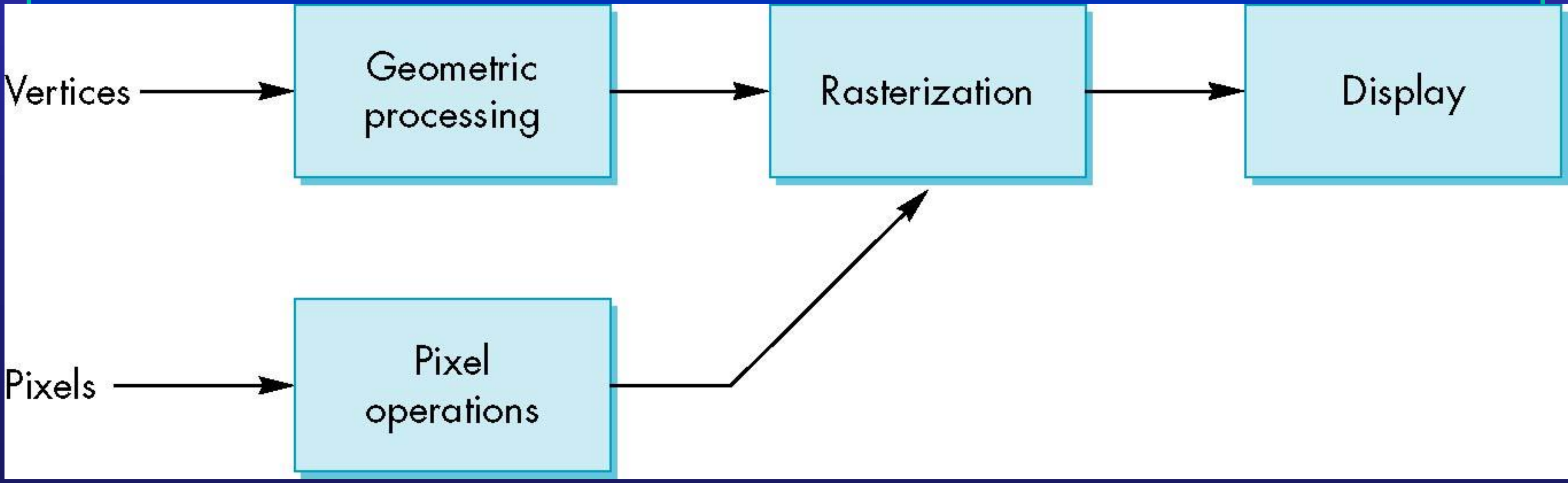
# Environment Mapping Example

# Bump Mapping



# Where Does Mapping Take Place?

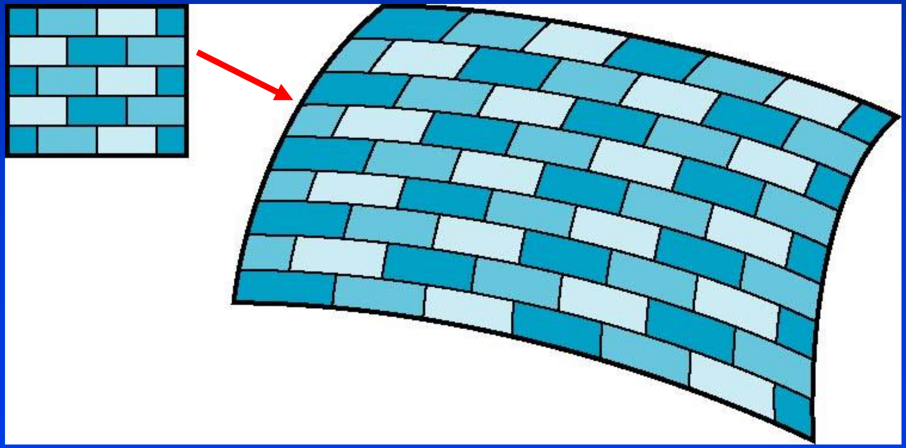
- Mapping techniques are implemented at the end of the rendering pipeline
  - Very efficient because few polygons make it past the clipper



# Is It Really Simple?

- Although the idea is simple - map an image to a surface - there are 3 or 4 coordinate systems involved

2D image

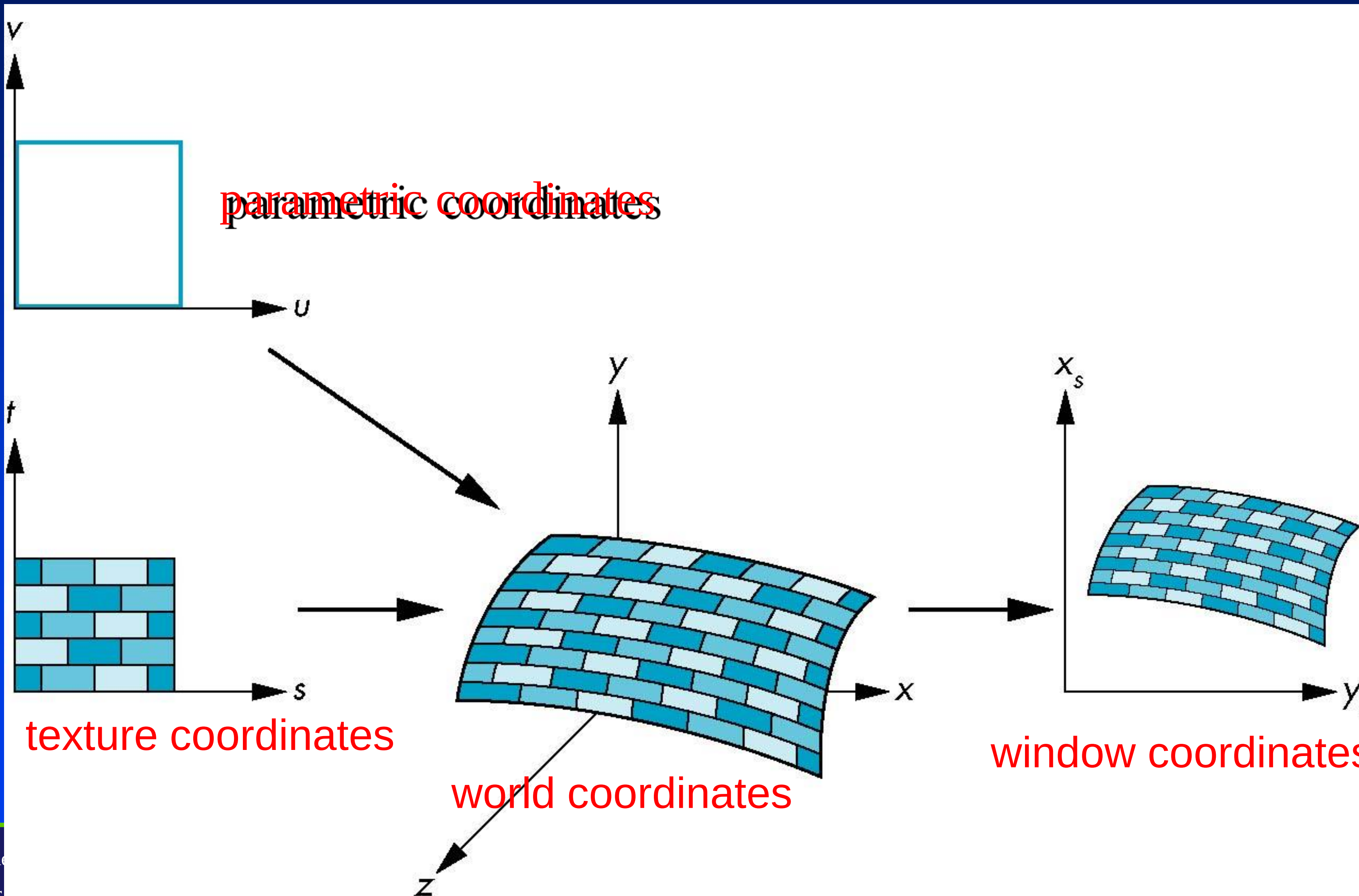


3D surface

# Coordinate Systems

- Parametric coordinates
  - May be used to model curves and surfaces
- Texture coordinates
  - Used to identify points in the image to be mapped
- Object or world coordinates
  - Conceptually, where the mapping takes place
- Window coordinates
  - Where the final image is really produced

# Texture Mapping

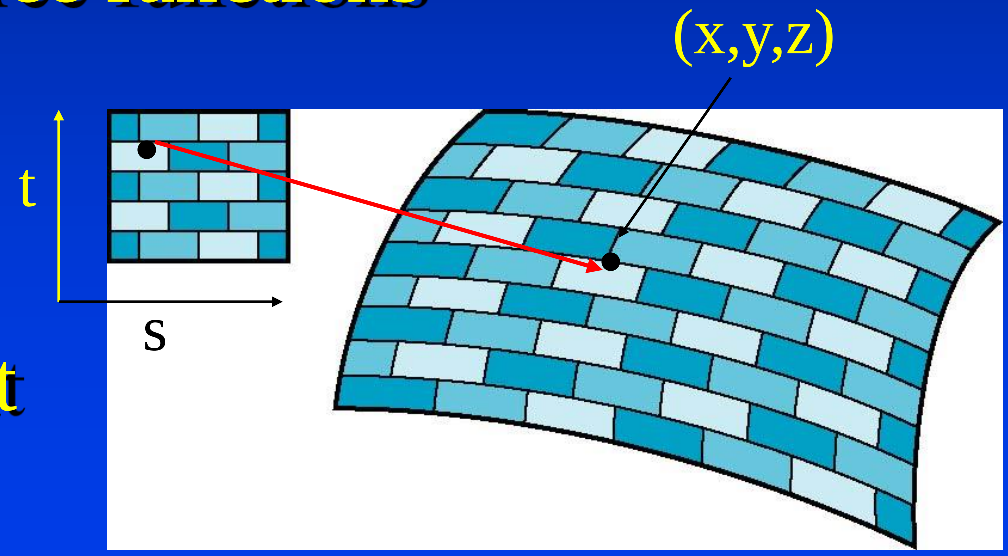


# Mapping Functions

- Basic problem is how to find the maps
- Consider mapping from texture coordinates to a point of a surface
- Appear to need three functions

$$x = x(s,t)$$
$$y = y(s,t)$$
$$z = z(s,t)$$

- But we really want to go the other way



# Backward Mapping

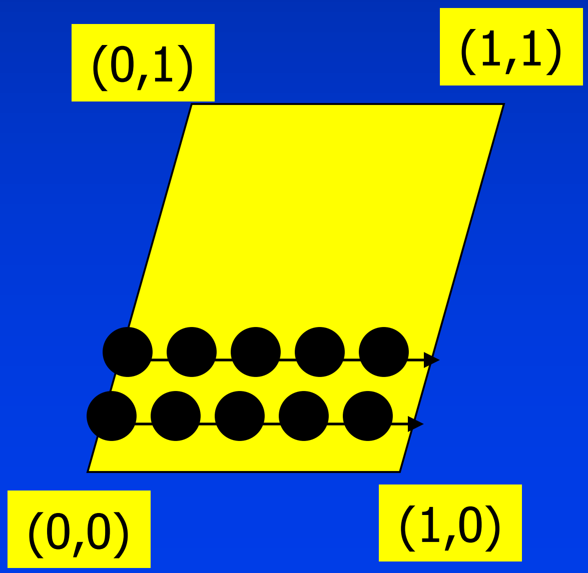
- We really want to go backwards
  - Given a pixel, we want to know to which point on an object it corresponds
  - Given a point on an object, we want to know to which point in the texture it corresponds
- Need a map of the form

  $s = s(x,y,z)$

  $t = t(x,y,z)$
- Such functions are difficult to find in general

# Map Textures to Surfaces

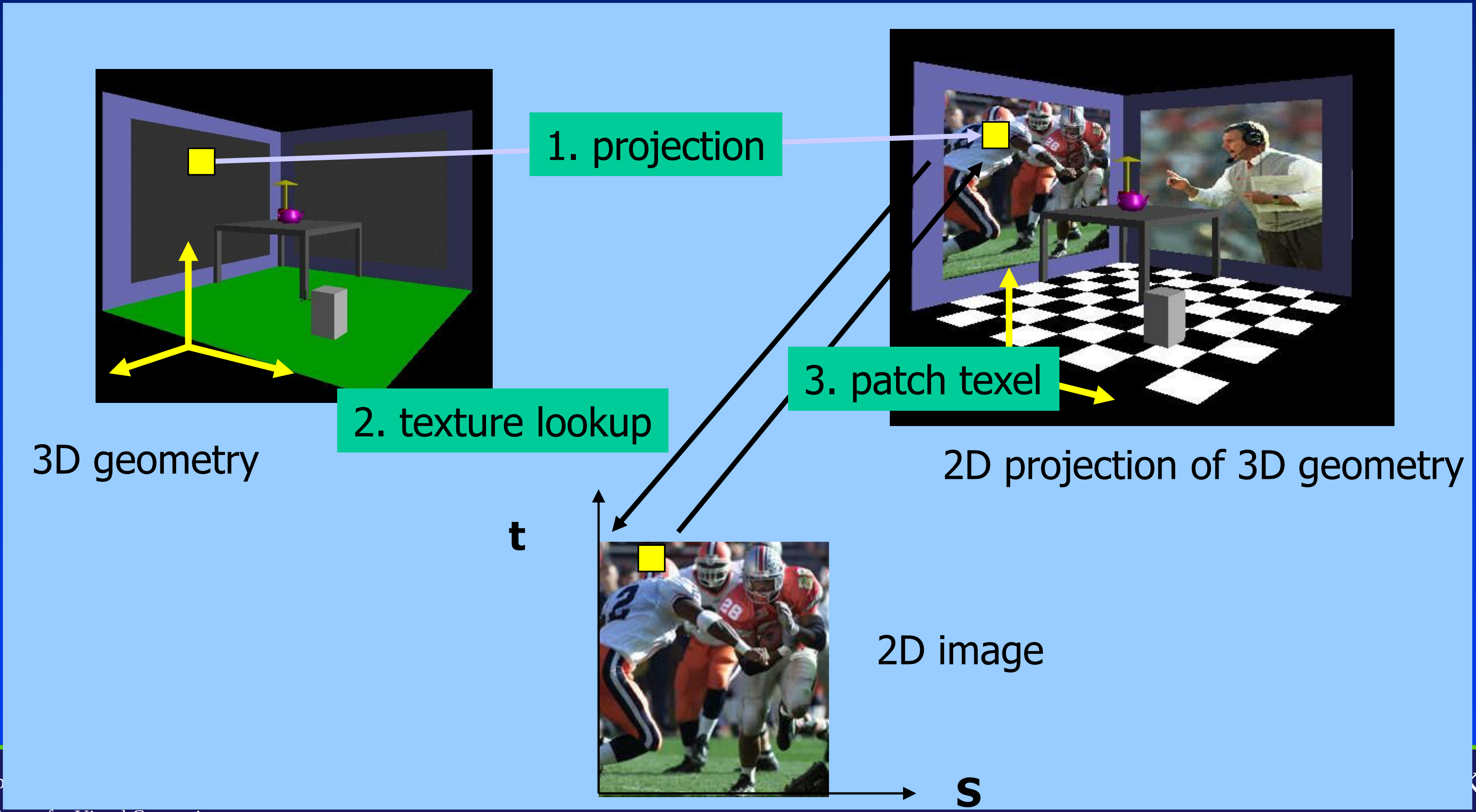
- Texture mapping is performed in rasterization (backward mapping)




For each pixel that is to be painted, its texture coordinates (s, t) are determined (interpolated) based on the corners' texture coordinates (why not just interpolate the color?)

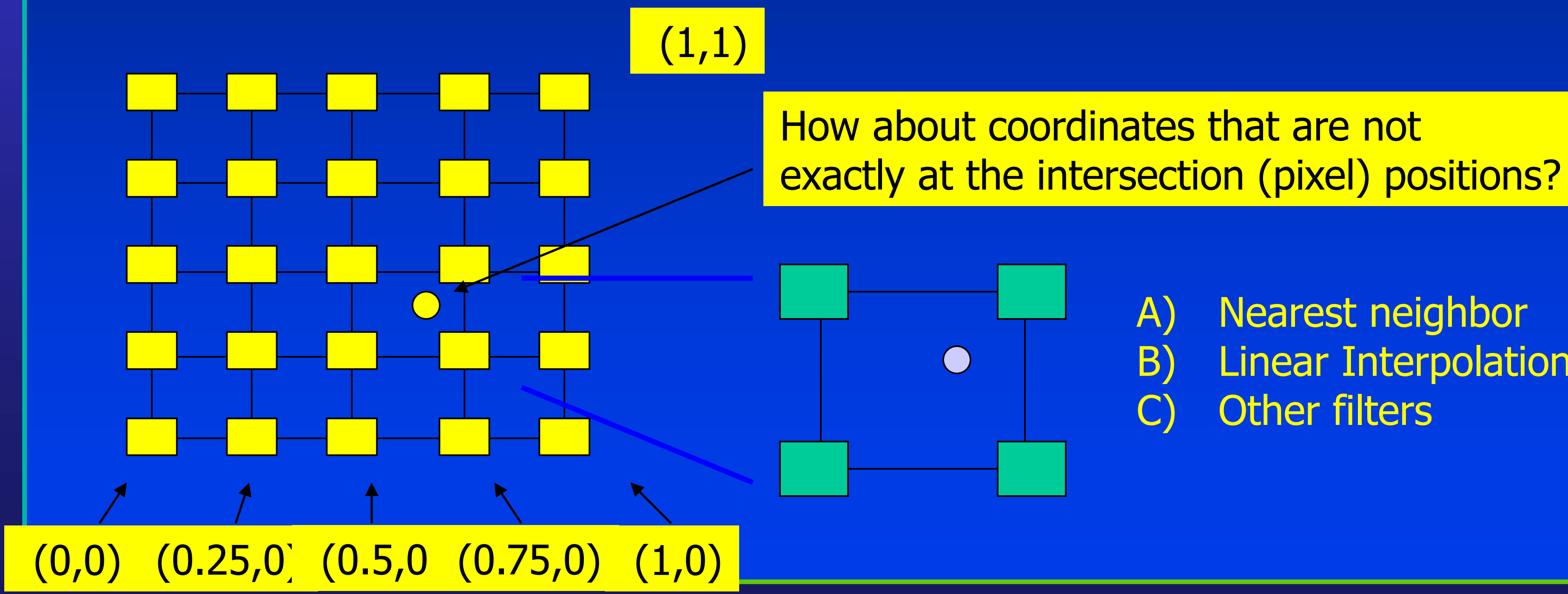
The interpolated texture coordinates are then used to perform texture lookup

# Texture Mapping Pipeline



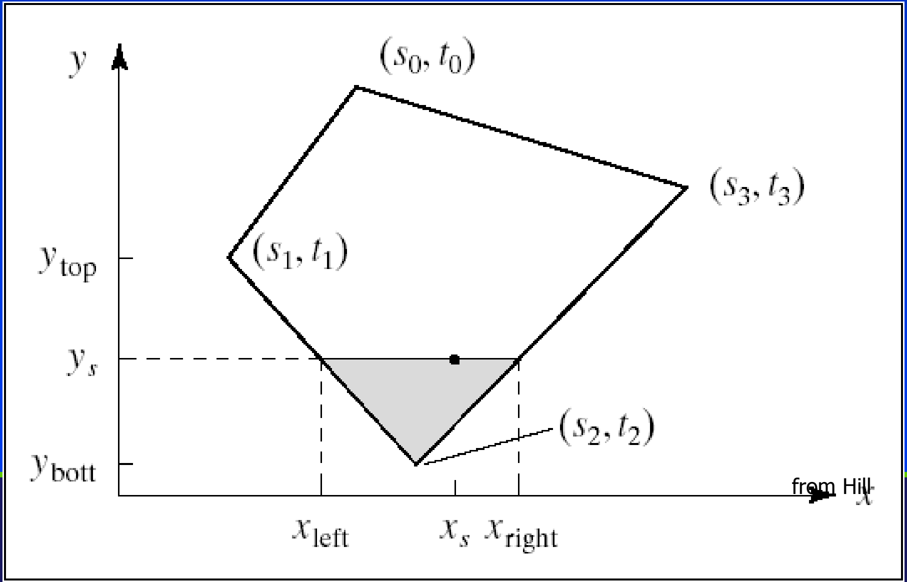
# Texture Value Lookup

- For the given texture coordinates (s,t), we can find a unique image value from the texture map



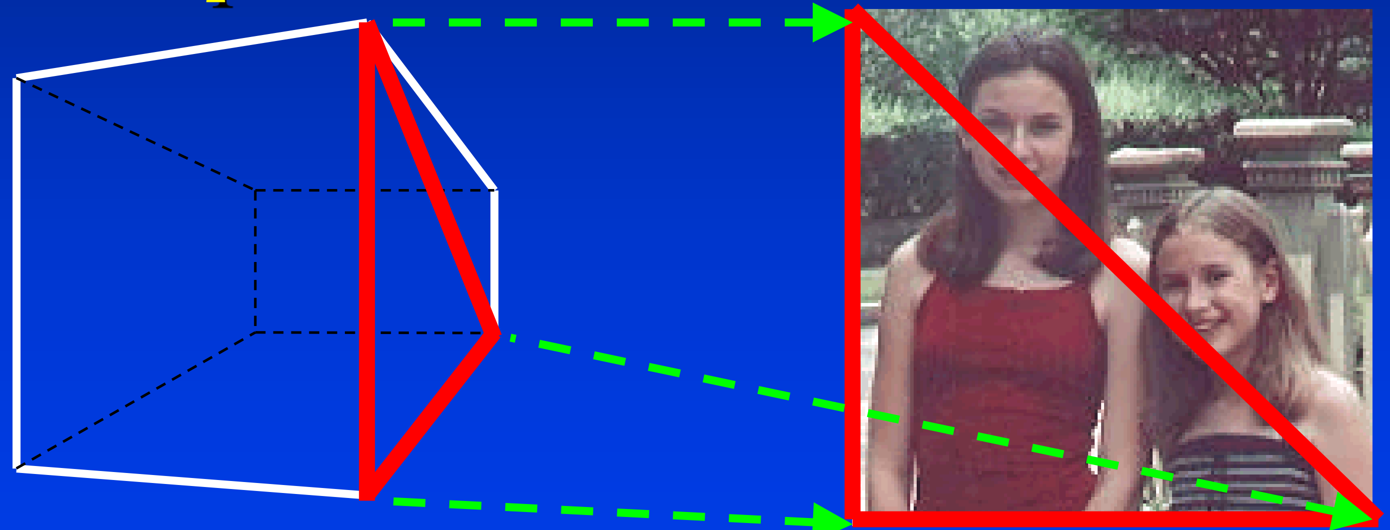
# Texture Rasterization

- Texture coordinates are interpolated from polygon vertices just like … remember line drawing …
  - ➢ Color : Gouraud shading
  - ➢ Depth: Z-buffer
  - – First along polygon edges between vertices
  - – Then along scanlines between left and right sides



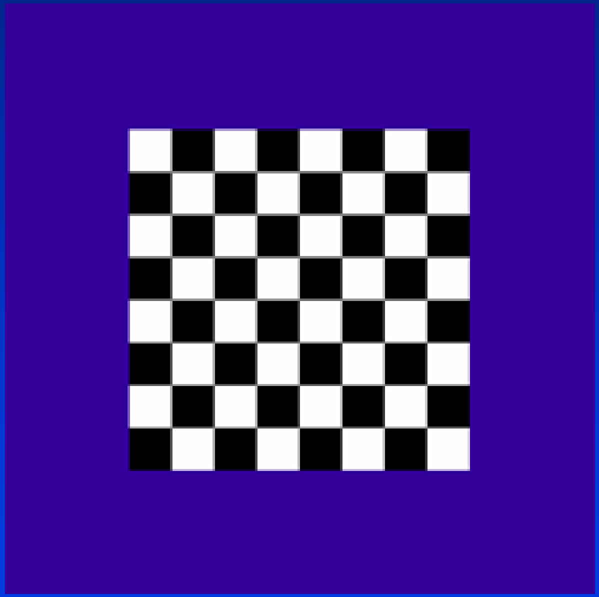
# Texture Interpolation

- Specify a texture coordinate (u,v) at each vertex
- Can we just linearly interpolate the values in screen space?



# Interpolation - What Goes Wrong?

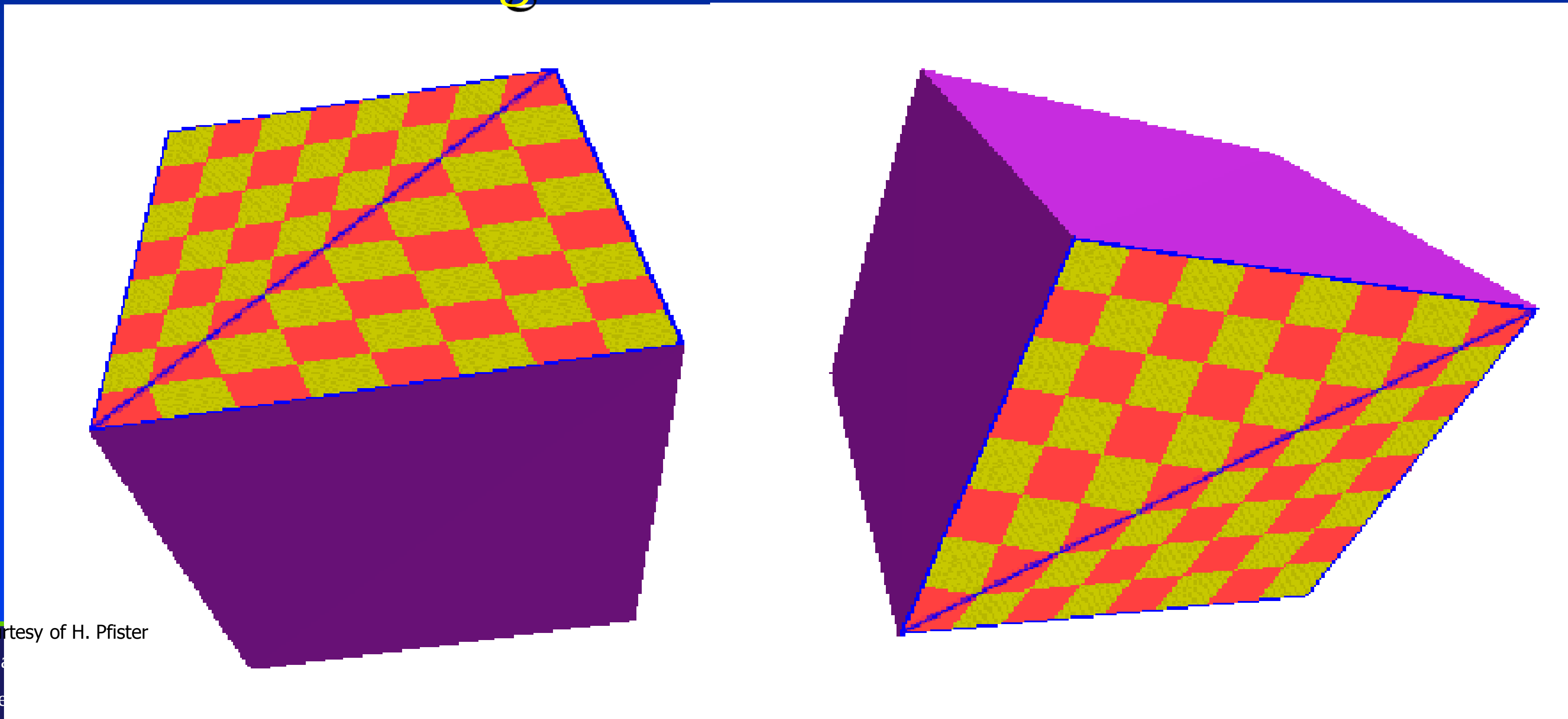
- **Linear interpolation in screen space:**



texture source image | what we get | what we want

# Linear Texture Coordinate Interpolation

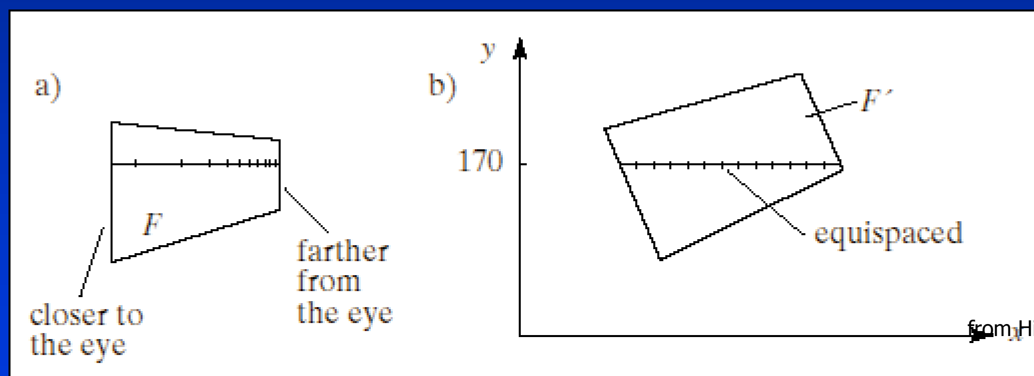
- This doesn't work in perspective projection!
- The textures look warped along the diagonal
- Noticeable during an animation

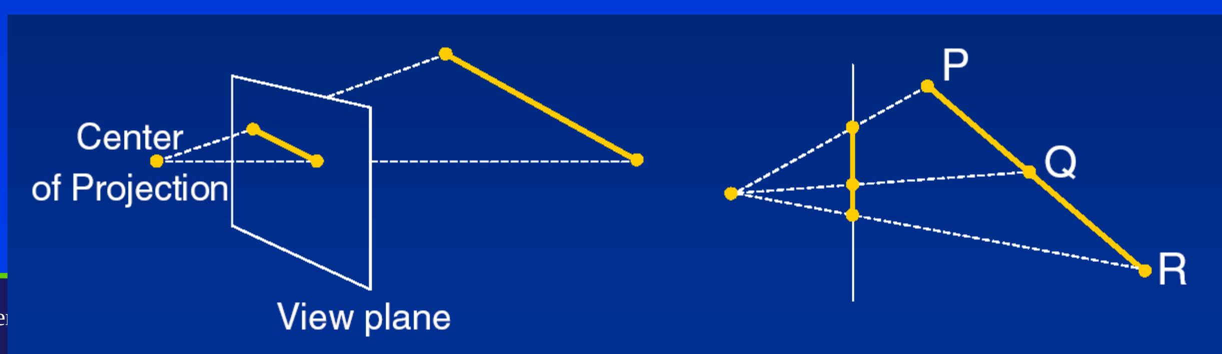


courtesy of H. Pfister

# Why?

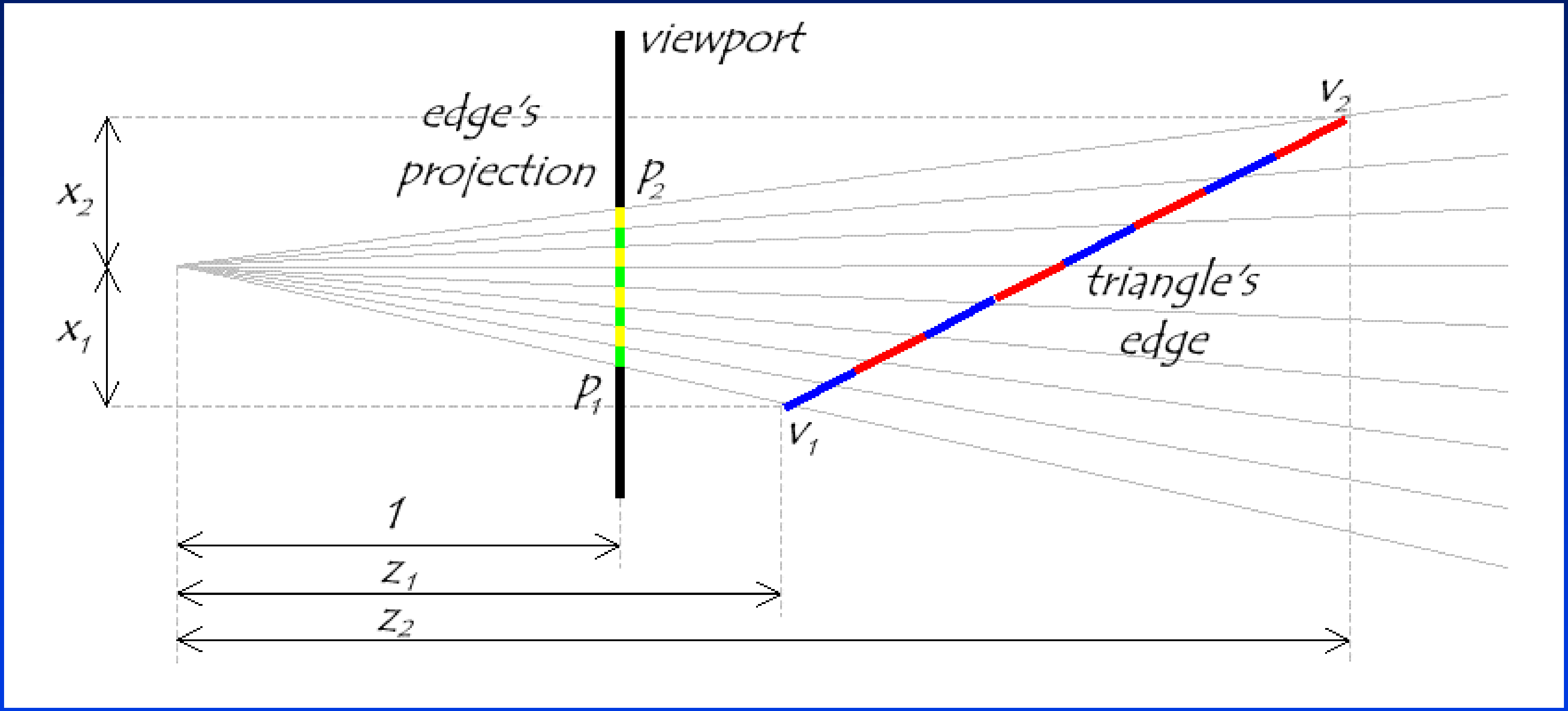
- Equal spacing in screen (pixel) space is **<u>not</u>** the same as in texture space in perspective projection
  - **Perspective foreshortening**




courtesy of H. Pfister

# Visualizing the Problem



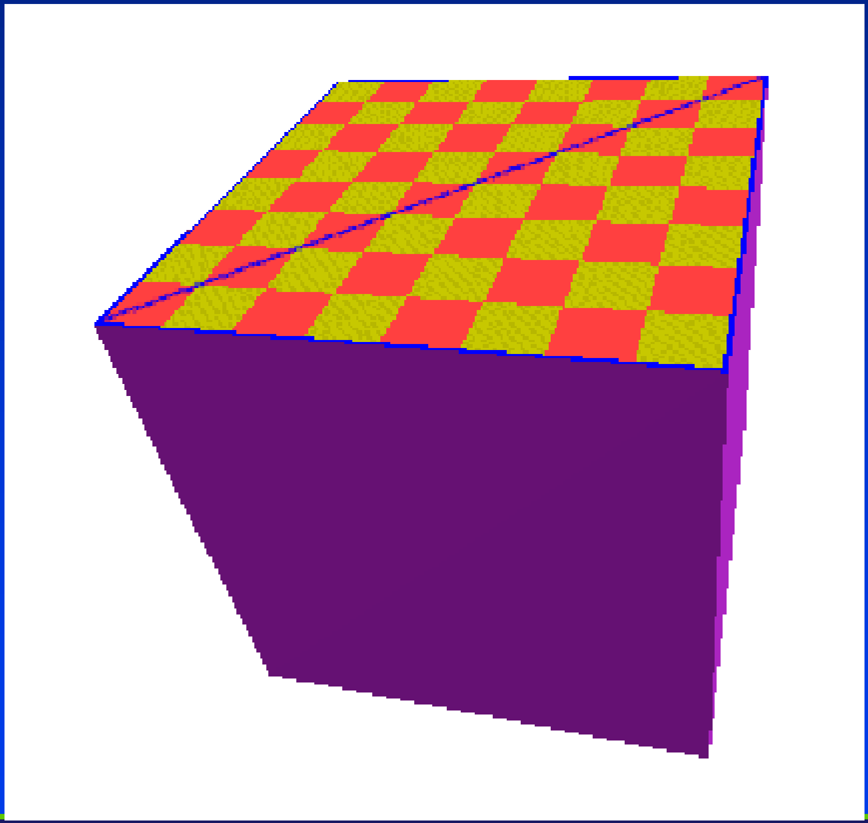

- Notice that uniform steps on the image plane do not correspond to uniform steps along the edge.

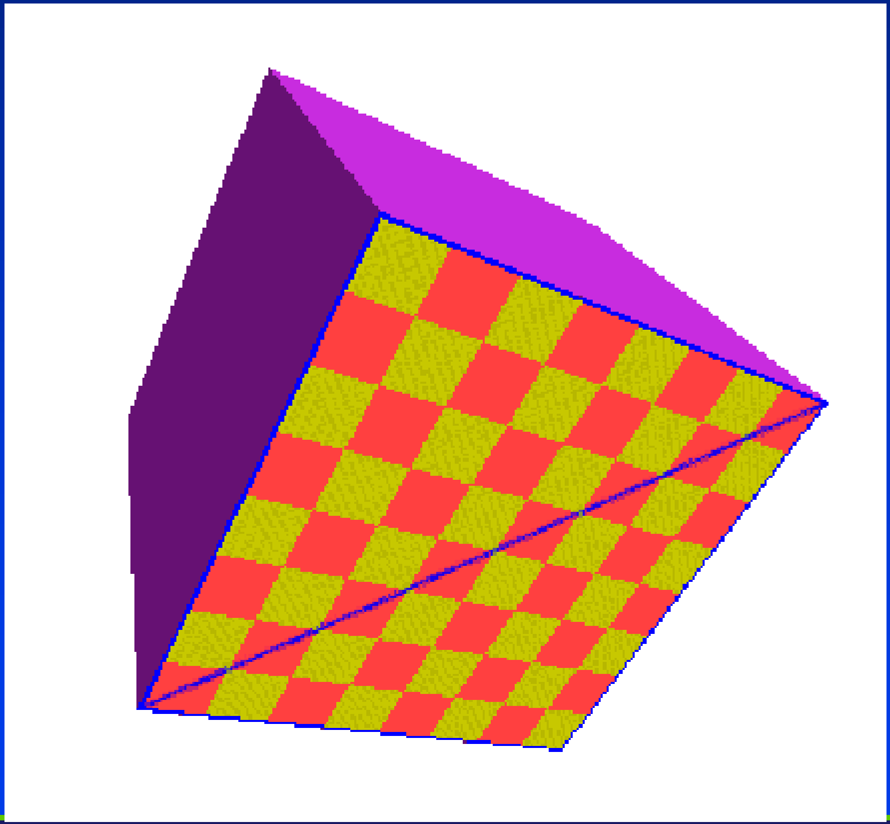
# Perspective-Aware Texture Coordinate Interpolation

- Interpolate (tex_coord/*w*) over the polygon, then do perspective division after interpolation
- Compute at each vertex after perspective transformation
  - "Numerators" $s/w$, $t/w$
  - "Denominator" $1/w$
- Linearly interpolate $1/w$, $s/w$, and $t/w$ across the polygon
- At each pixel
  - Perform perspective division of interpolated texture coordinates ($s/w$, $t/w$) by interpolated $1/w$ (i.e., numerator over denominator) to get ($s$, $t$)

# Perspective-Correct Interpolation

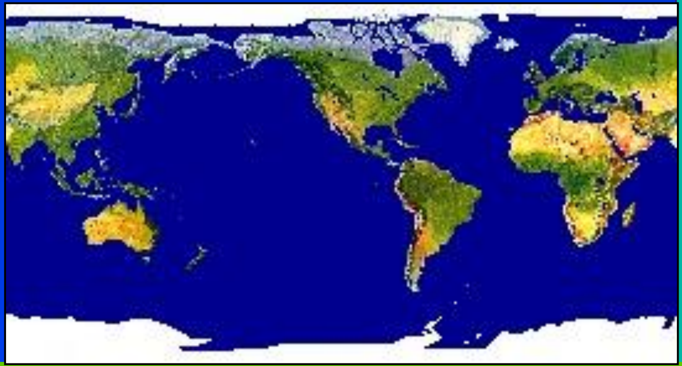
- That fixed it!





# Common Texture Coordinate Mappings

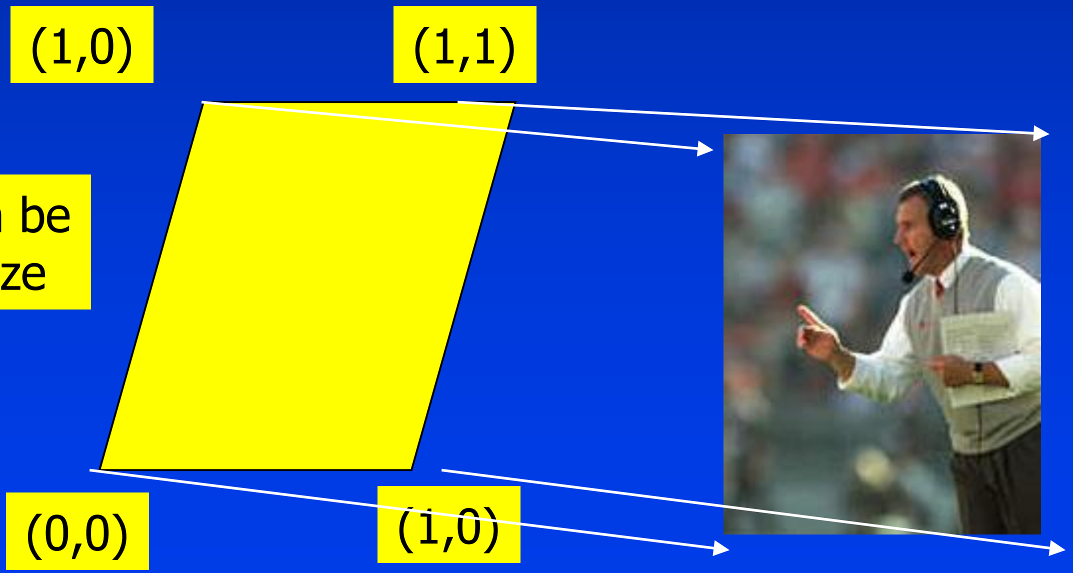
- Orthogonal
- Cylindrical
- Spherical
- Perspective Projection
- Texture Chart

# Map Textures to Surfaces

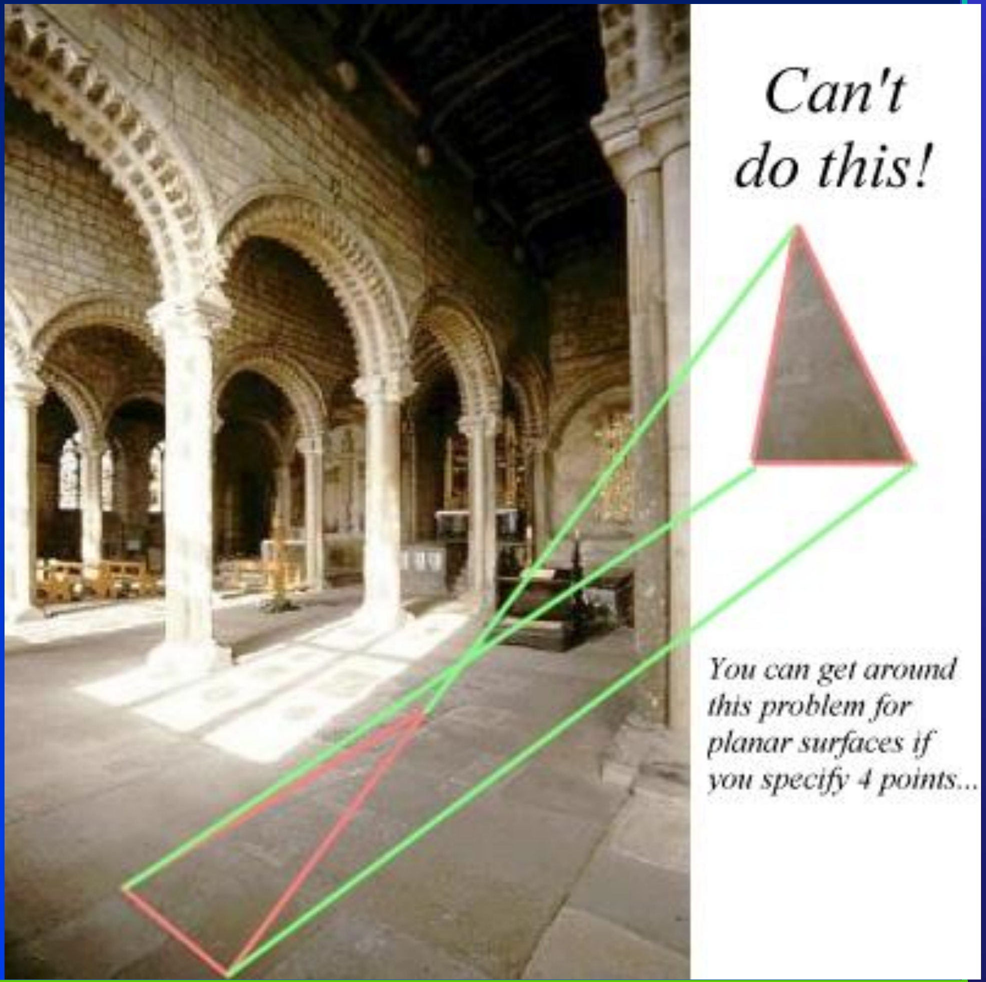
- The key question: Establish mapping from texture to surfaces (polygons):
  - Application program needs to specify texture coordinates for each corner of the polygon

The polygon can be in an arbitrary size



# Texture Mapping Difficulties

- Tedious to specify texture coordinates
- Acquiring textures is surprisingly difficult
  - Photographs have projective distortions
  - Variations in reflectance and illumination
  - Tiling problems

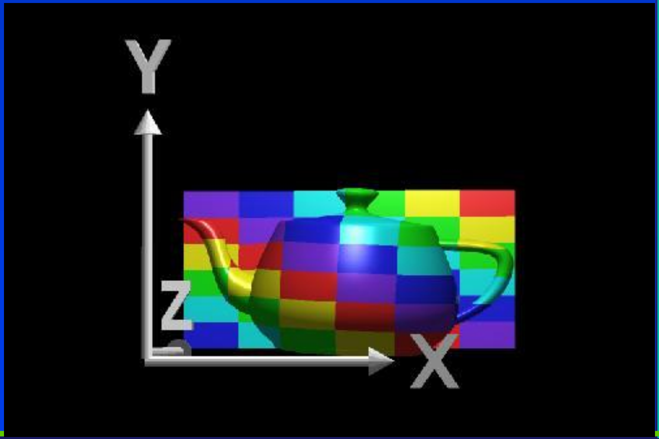


# Projector Functions

- How do we map the texture onto a arbitrary (complex) object?
  - ➢ Construct a mapping between the 3-D point to an intermediate surface
- ➢ Idea: Project each object point to the intermediate surface with a parallel or perspective projection
  - ➢ The focal point is usually placed inside the object

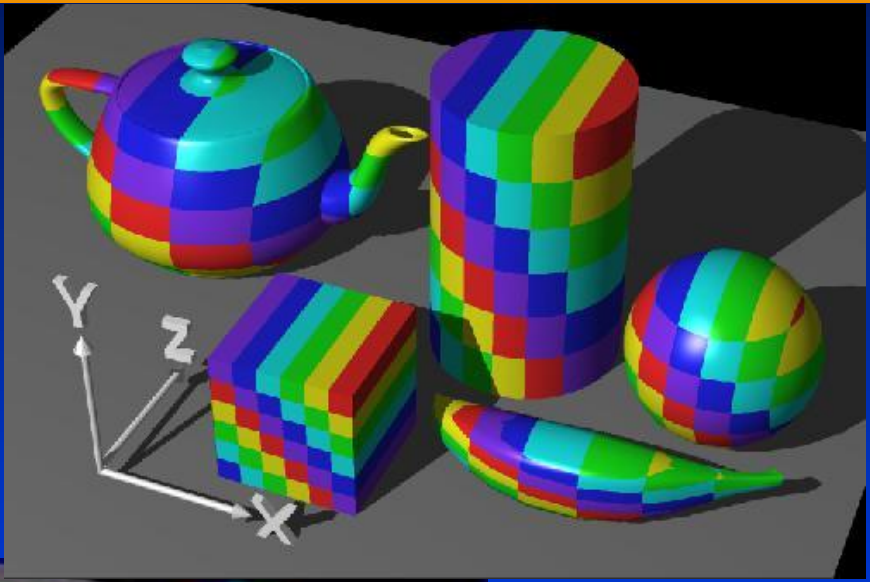
– Plane
– Cylinder
– Sphere
– Cube

Planar projector

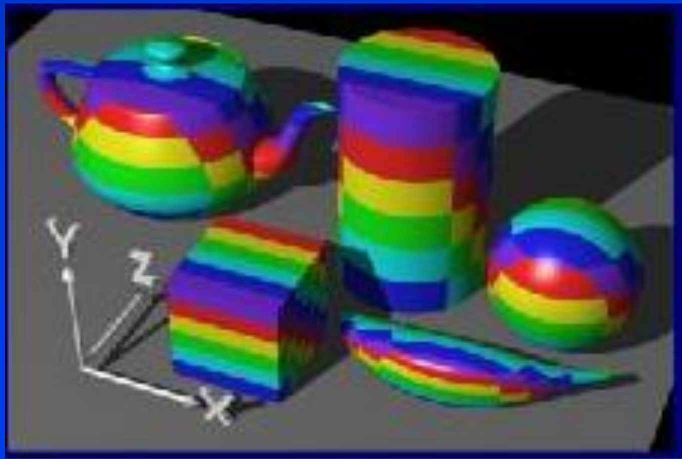


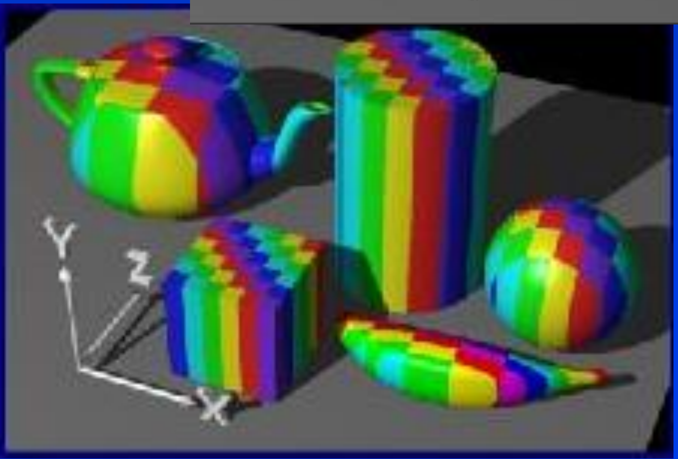
# Planar Projector

Orthographic projection onto XY plane:
$u = x, \; v = y$




...onto YZ plane

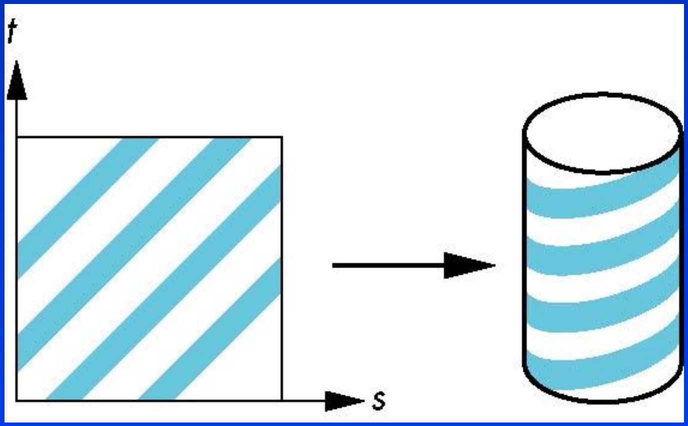



...onto XZ plane

# Two-part Mapping

- One solution to the mapping problem is to first map the texture to a simple intermediate surface
- Example: map to cylinder



# Cylindrical Projector

- Convert rectangular coordinates ($x$, $y$, $z$) to cylindrical ($r$, $\mu$, $h$), use only ($h$, $\mu$) to index texture image

# Cylindrical Mapping

Parametric cylinder

$$x = r \cos 2\pi\, u$$

$$y = r \sin 2\pi u$$

$$z = v/h$$

maps rectangle in u,v space to cylinder
of radius r and height h in world coordinates

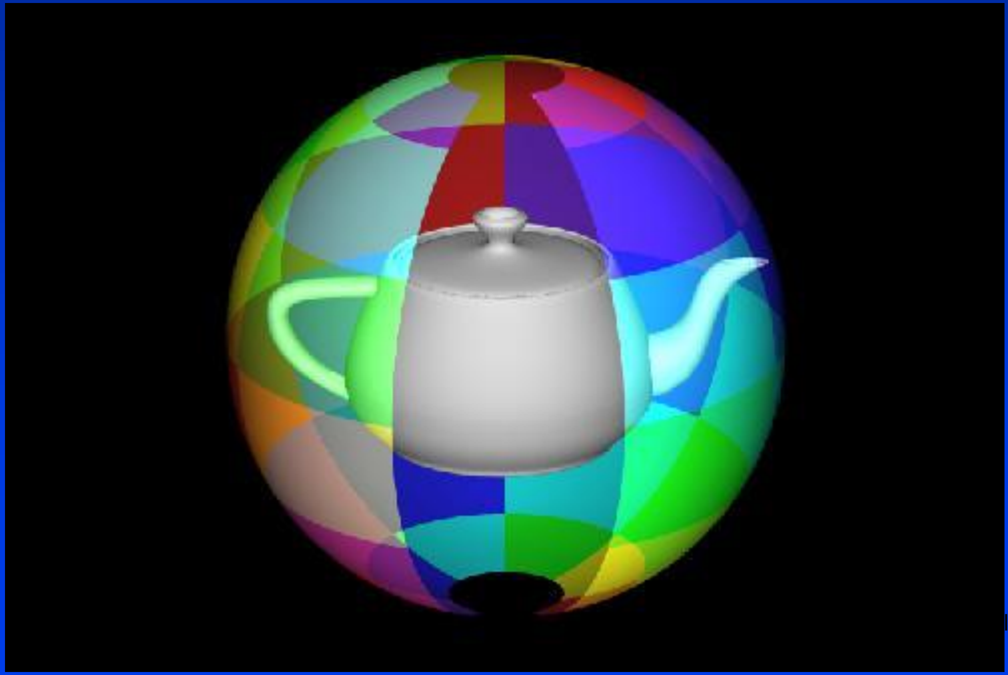
$$s = u$$

$$t = v$$

maps from texture space

# Spherical Projector

- Convert rectangular coordinates ($x$, $y$, $z$) to spherical ($\theta$, $\phi$)



# Spherical Map

We can use a parametric sphere

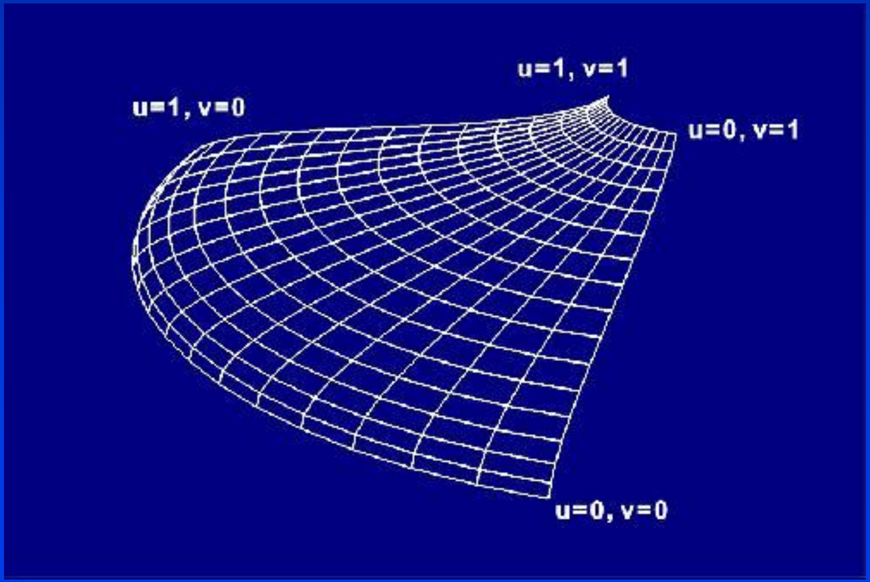
$$x = r \cos 2\pi u$$
$$y = r \sin 2\pi u \cos 2\pi v$$
$$z = r \sin 2\pi u \sin 2\pi v$$

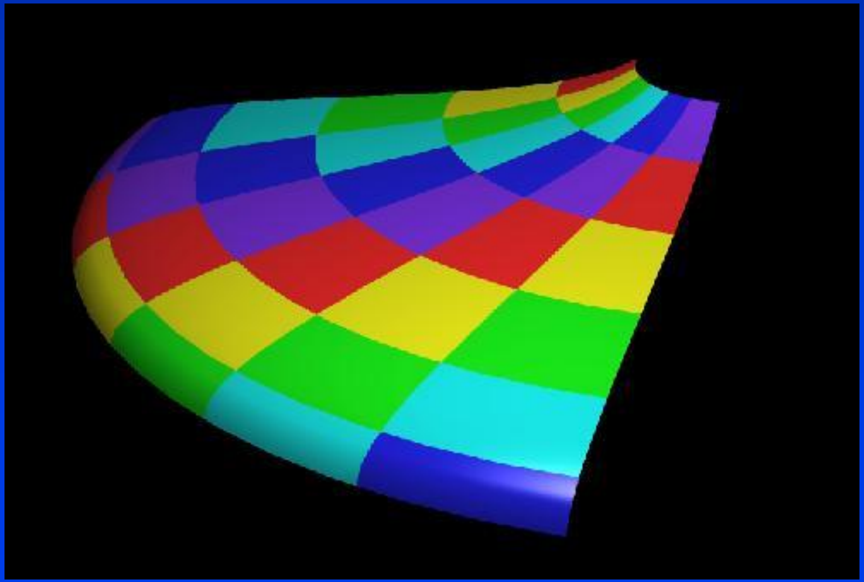
in a similar manner to the cylinder
but have to decide where to put
the distortion

Spheres are used in environmental maps

# Parametric Surfaces

- A parameterized surface patch
  - $x = f(u, v)$, $y = g(u, v)$, $z = h(u, v)$
  - You will get the mapping via parameterization

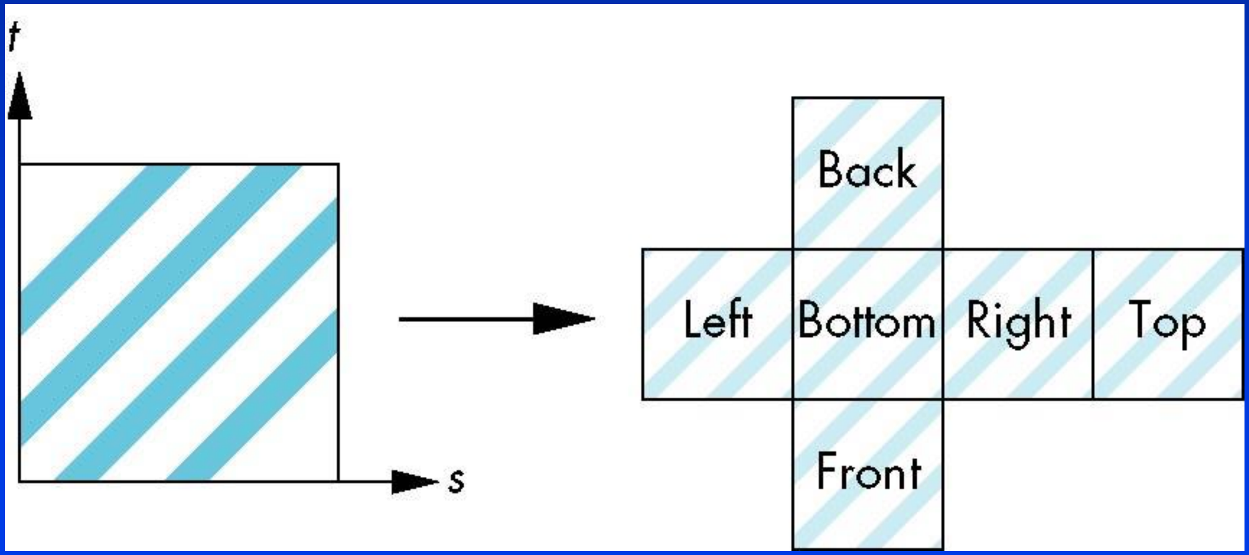


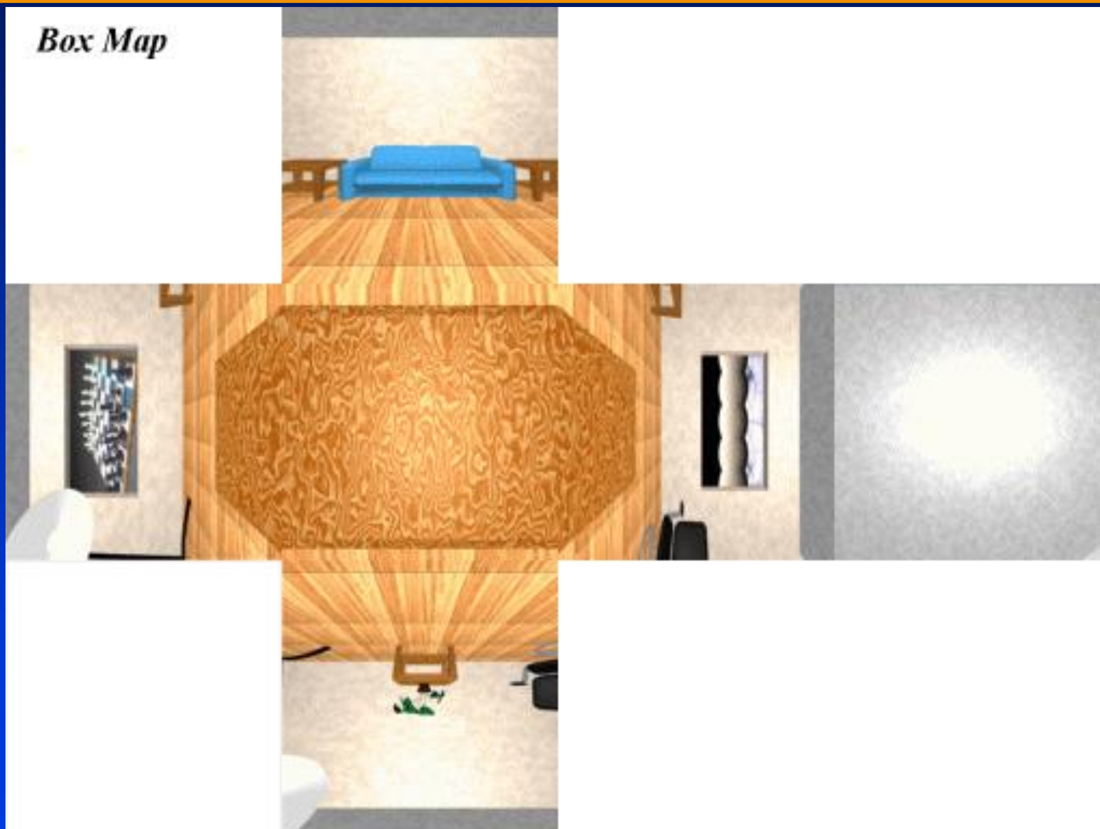
courtesy of R. Wolfe

# Box Mapping

- Easy to use with simple orthographic projection
- Also used in environment maps



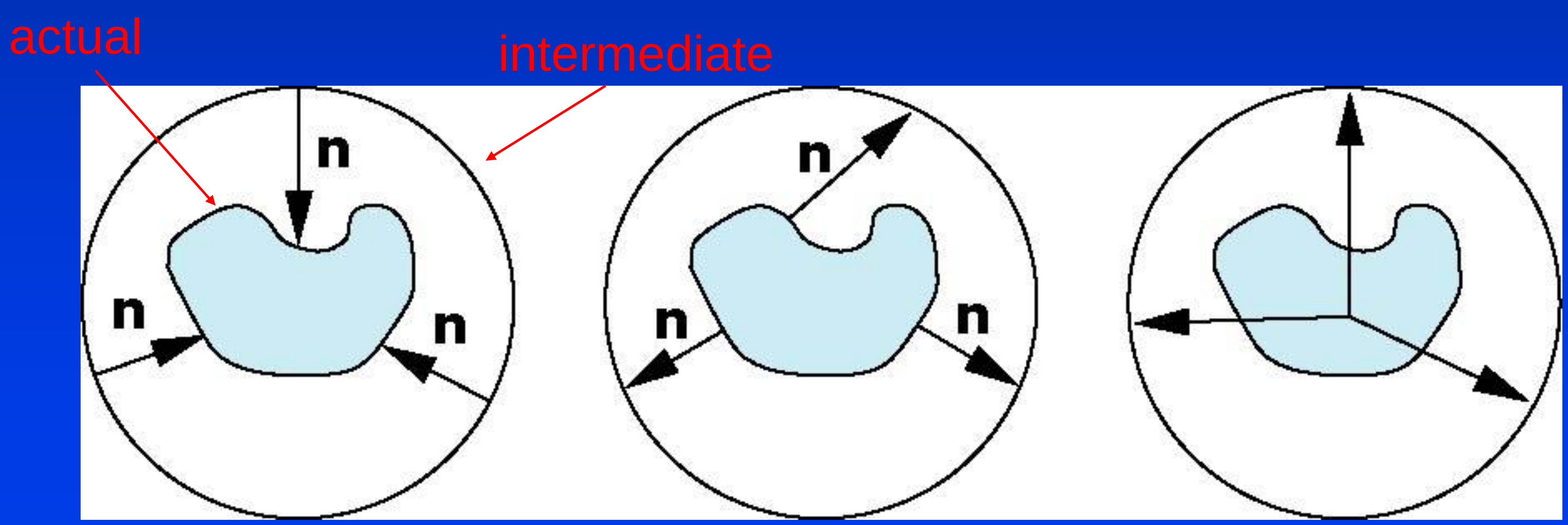
# What's the Best Chart?





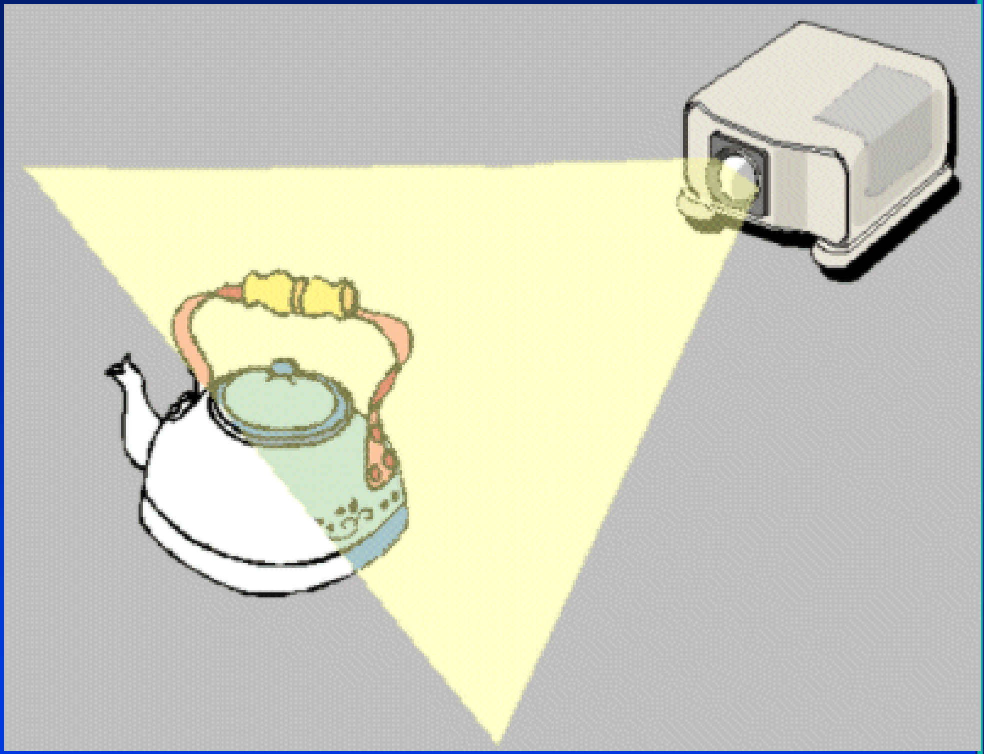
# Second Mapping

- Map from intermediate object to actual object
  - Normals from intermediate to actual
  - Normals from actual to intermediate
  - Vectors from center of intermediate



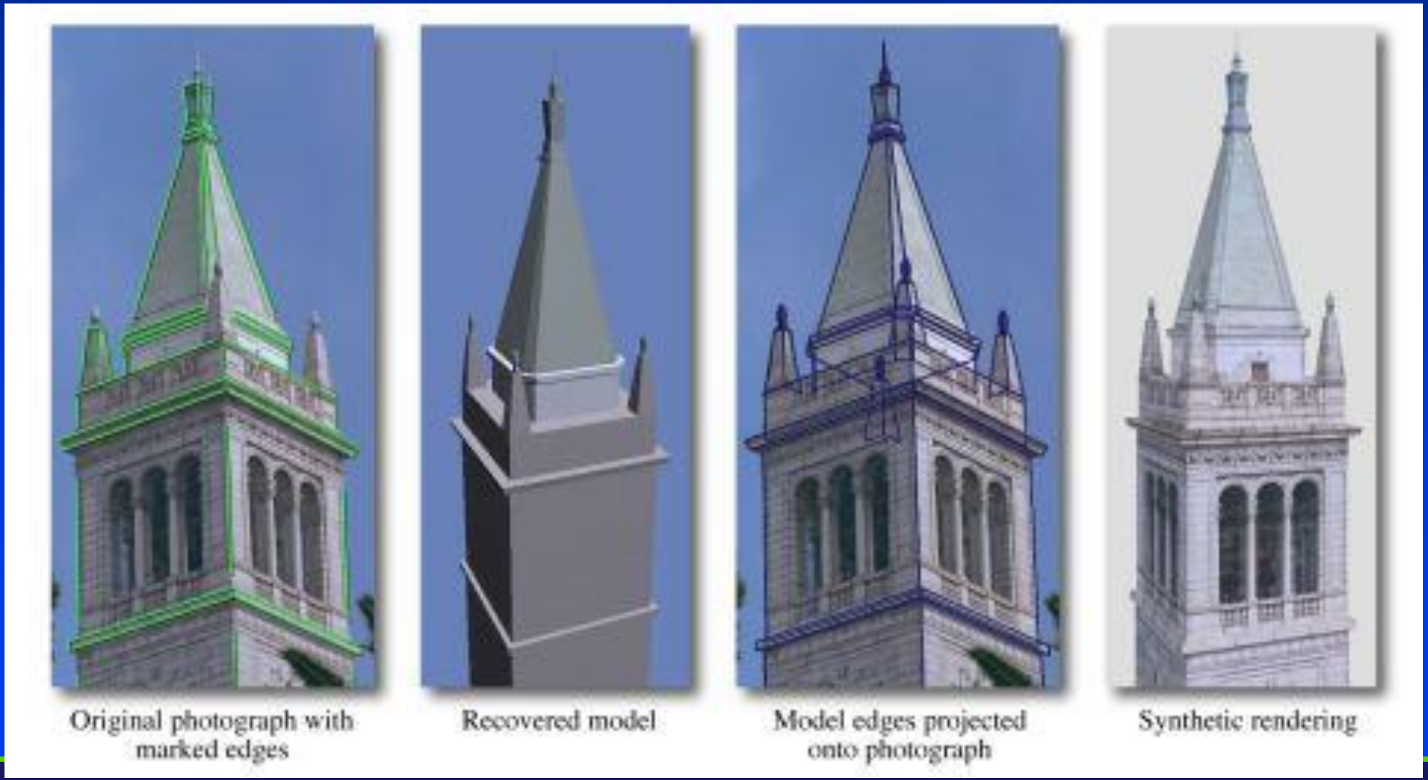
# Projective Textures

- Use the texture like a slide projector
- No need to specify texture coordinates explicitly
- A good model for shading variations due to illumination
- A fair model for reflectance (can use pictures)



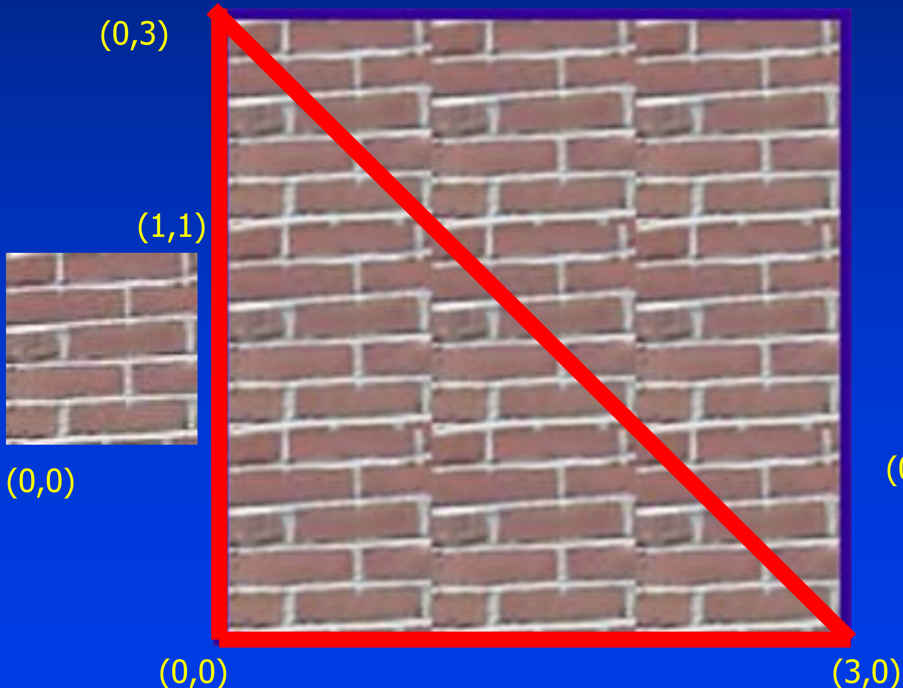
# Projective Texture Example

- Modeling from photographs
- Using input photos as textures

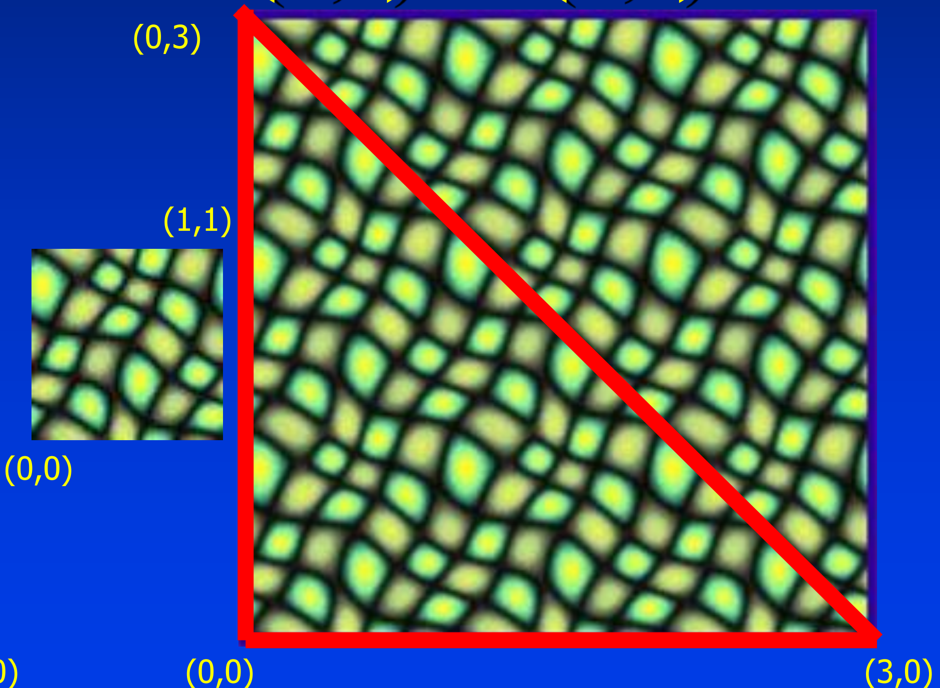


# Texture Tiling

- Specify a texture coordinate (u,v) at each vertex
- Canonical texture coordinates (0,0) → (1,1)



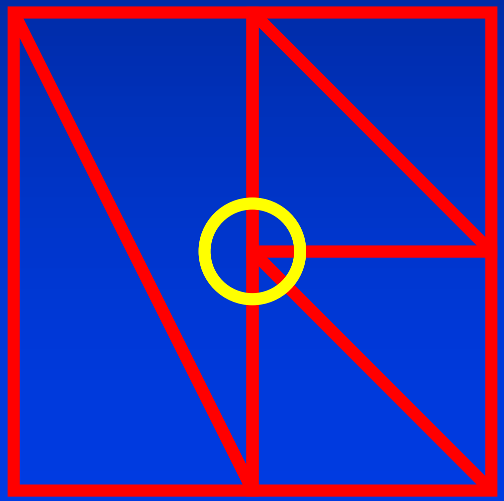
**tiles with visible seams**



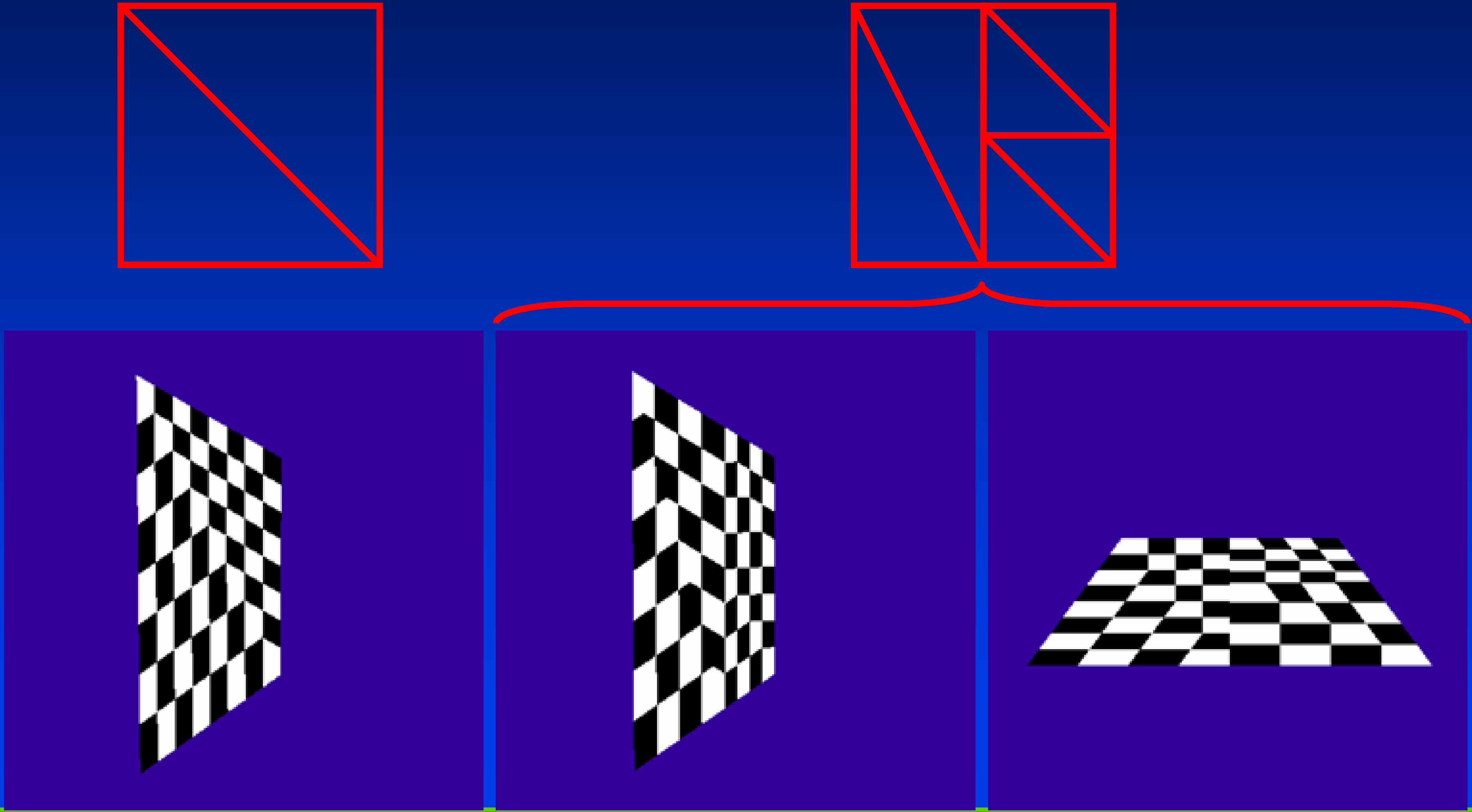
**seamless tiling (repeating)**

# Specify More Coordinates?

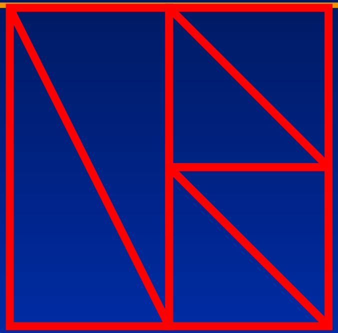
- We can reduce the perceived artifacts by subdividing the model into smaller triangles.
- However, sometimes the errors become obvious
  - At "T" joints
  - Between levels-of-details

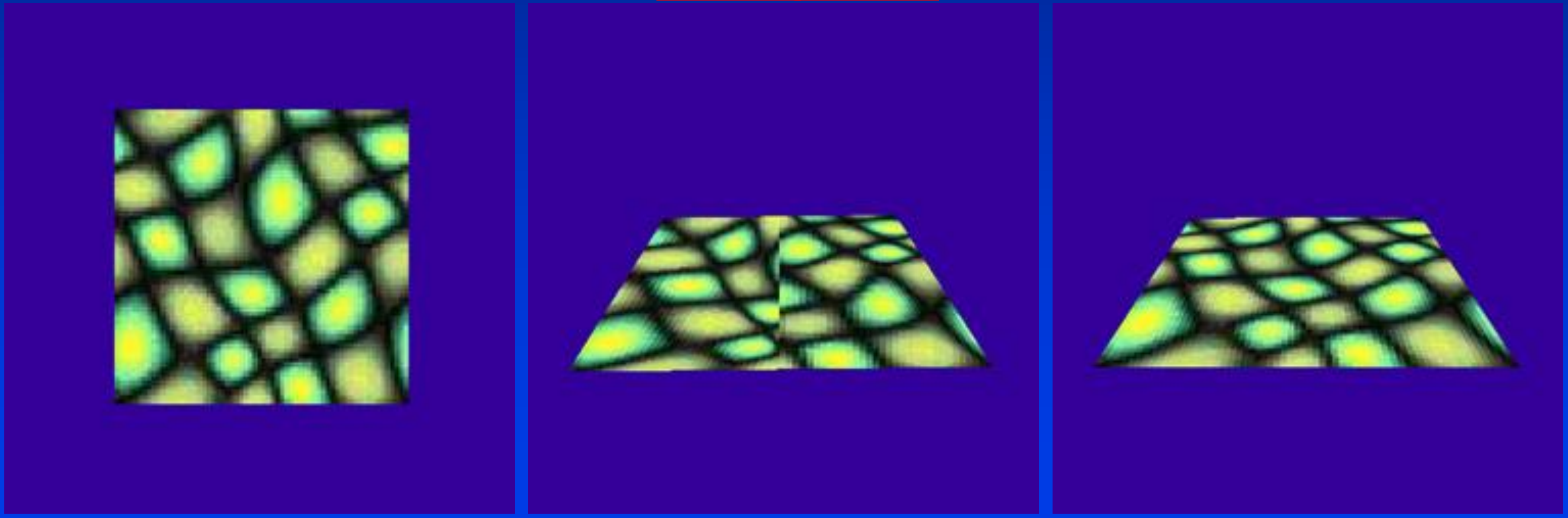


# Subdivision



# Subdivision





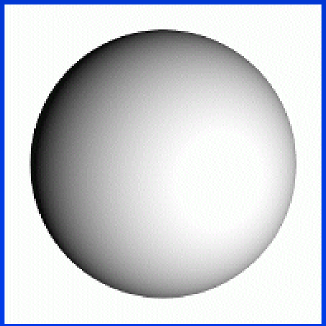
texture source what we get what we want

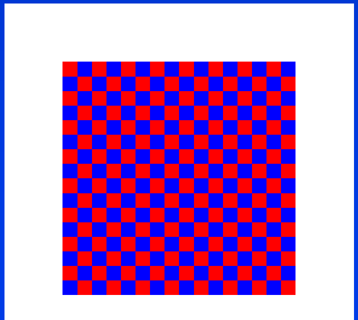
# Texture Mapping & Illumination

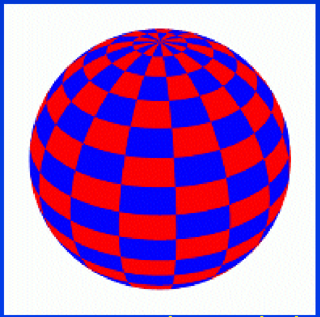
- Texture mapping can be used to alter some or all of the constants in the illumination equation:
  - pixel color, diffuse color, alter the normal, ….

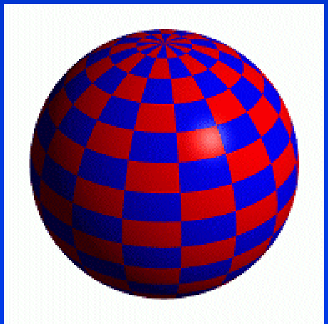
$$I_{total} = k_a I_{ambient} + \sum_{i=1}^{lights} I_i \left( k_d \left(\hat{N} \cdot \hat{L}\right) + k_s \left(\hat{V} \cdot \hat{R}\right)^{n_{shiney}} \right)$$

**Phong's Illumination Model**


Constant Diffuse Color

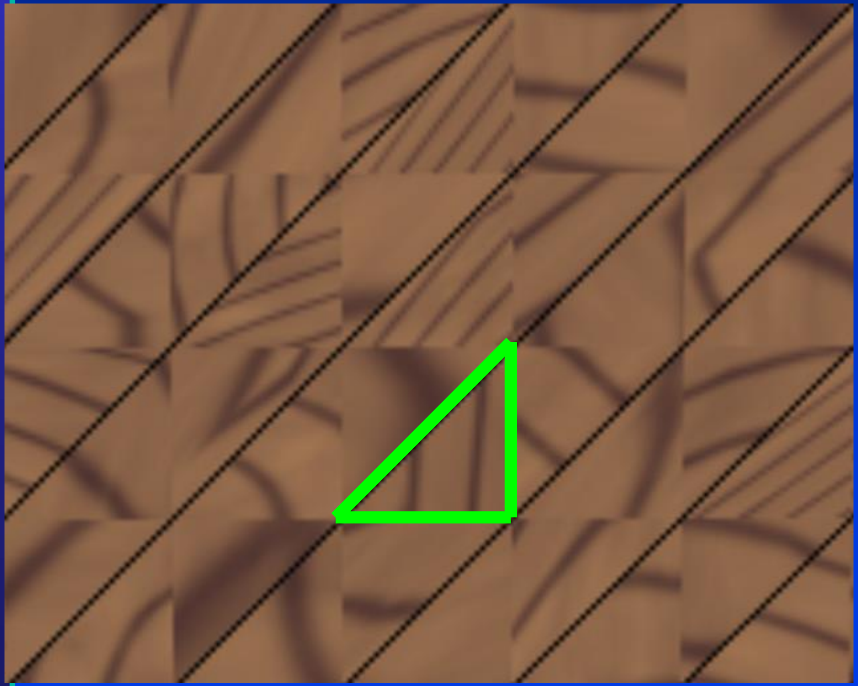

Diffuse Texture Color

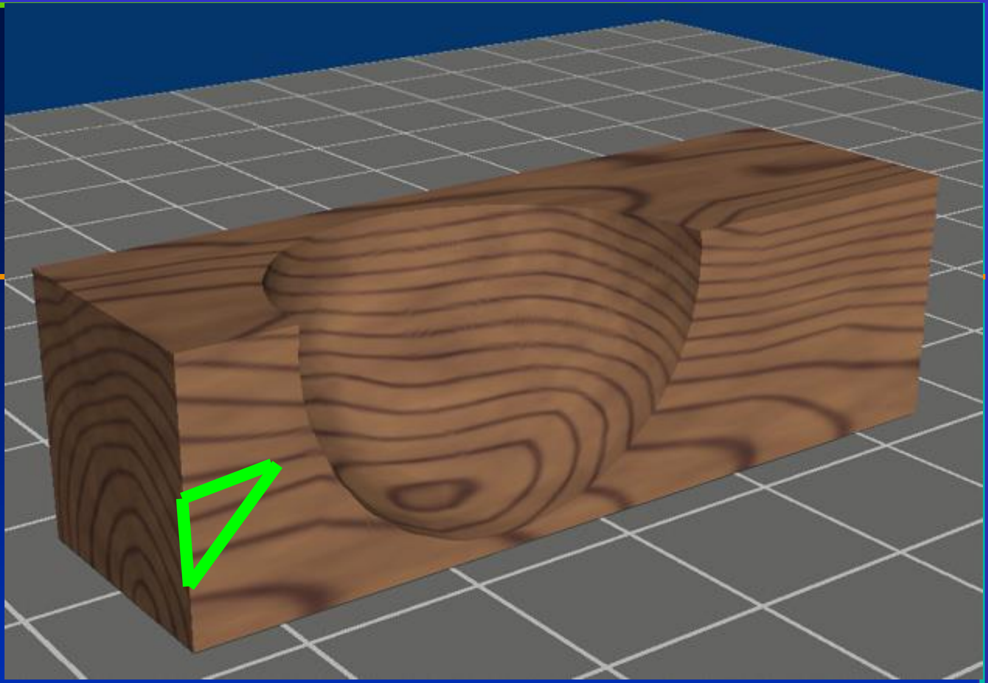

Texture used as Label

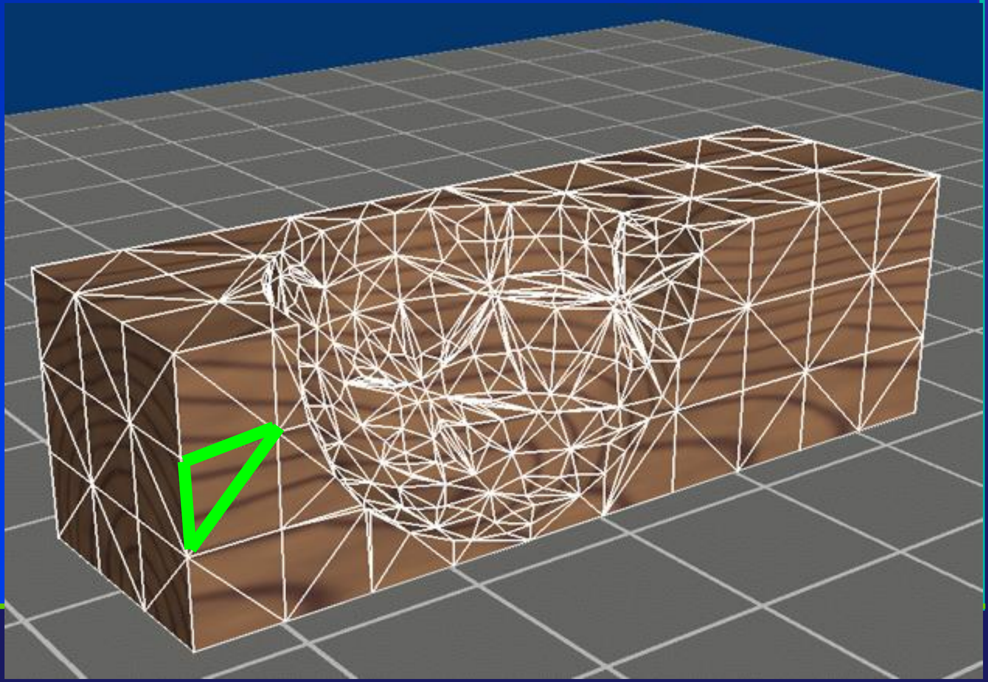

Texture used as Diffuse Color

# Texture Chart

- Pack triangles into a single image



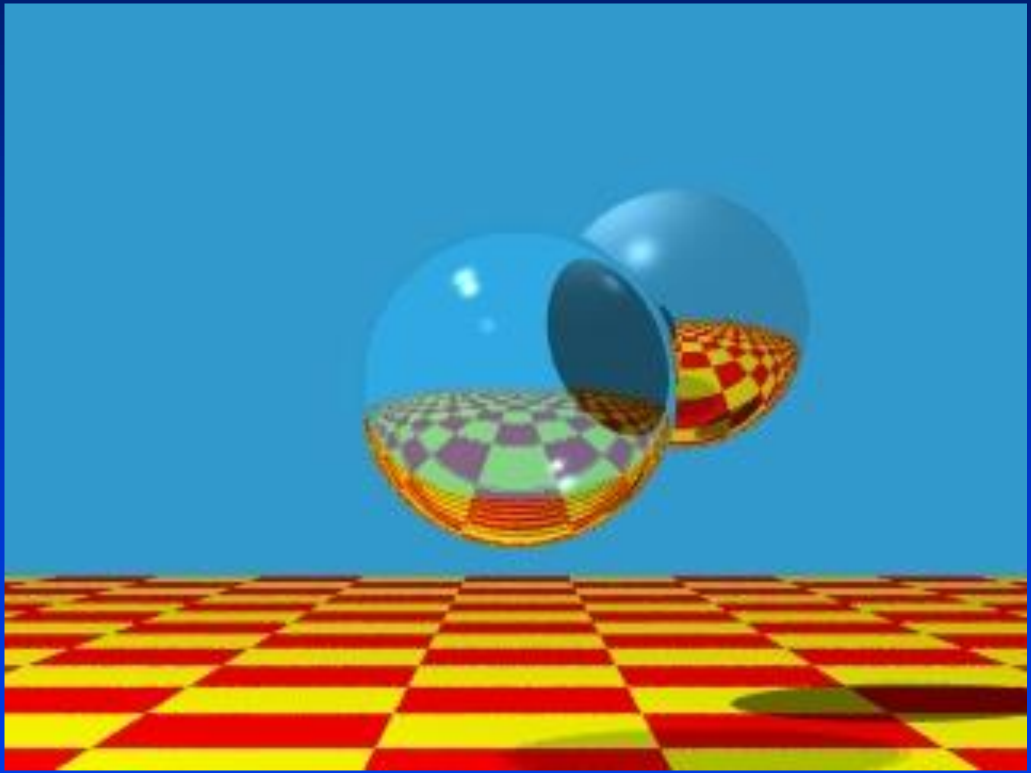




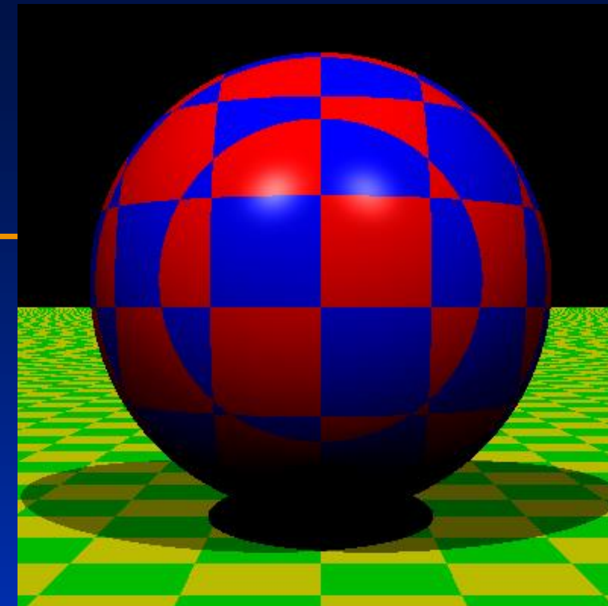
# Procedural and Solid Textures

# Procedural Textures

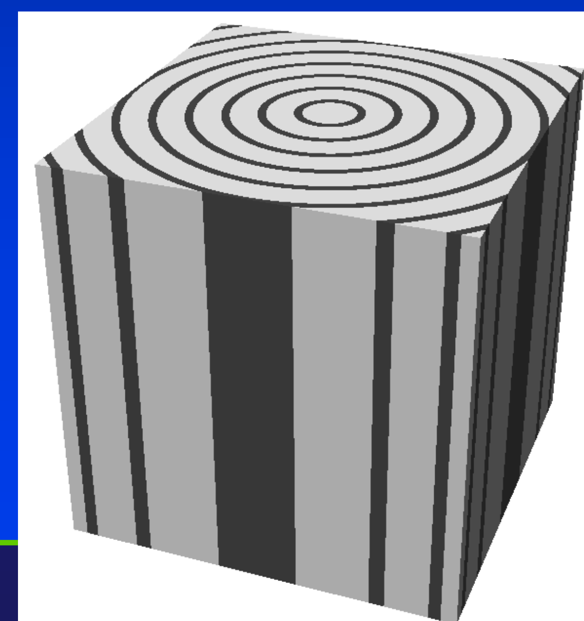
$f(x,y,z) \rightarrow \text{color}$



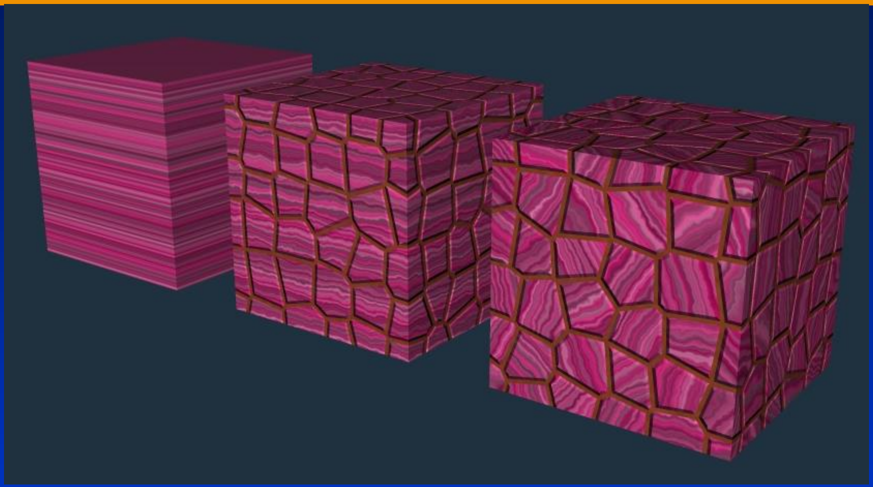
# Procedural Textures

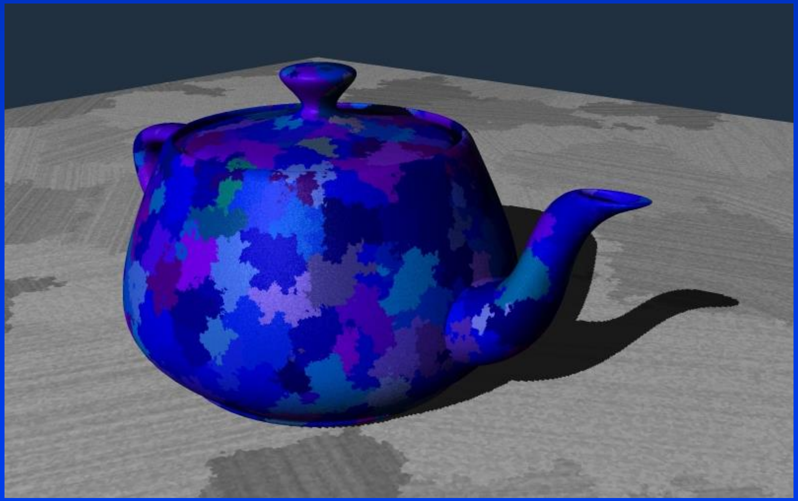


- Advantages:
  - easy to implement in ray tracer
  - more compact than texture maps
  - especially for solid textures
  - infinite resolution
- Disadvantages
  - non-intuitive
  - difficult to match existing texture



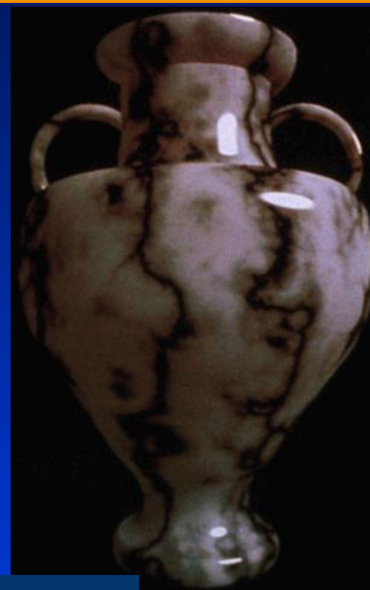
# Solid Texture Examples

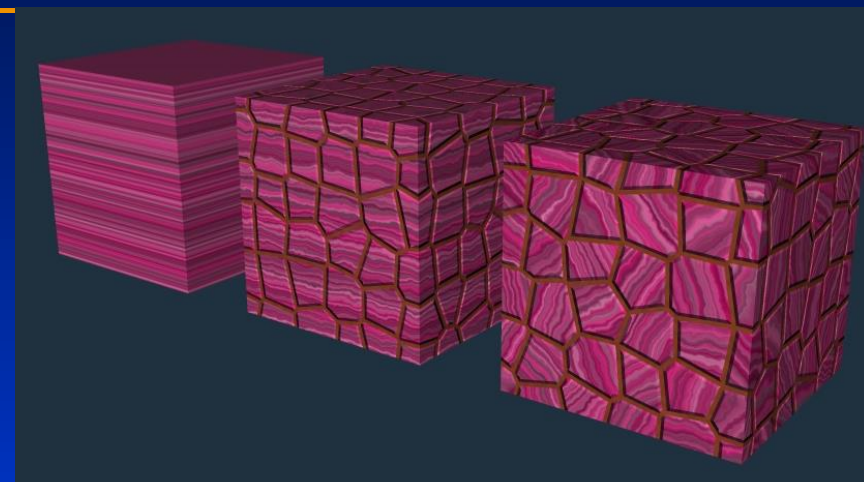


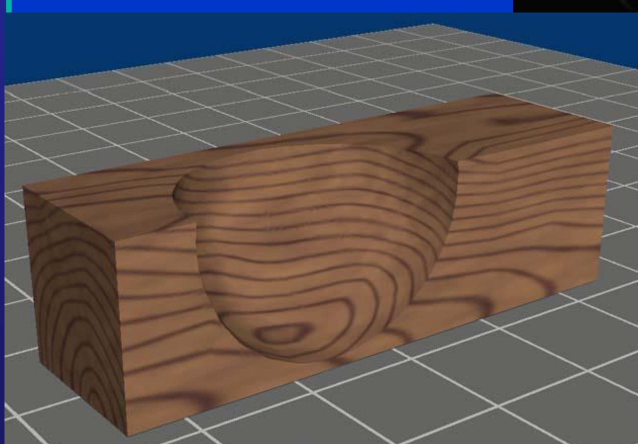


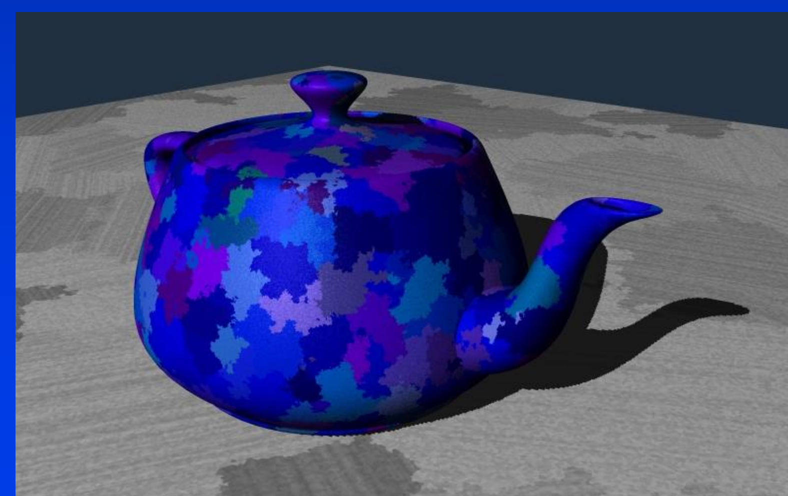
# Procedural Solid Textures

- Noise
- Turbulence



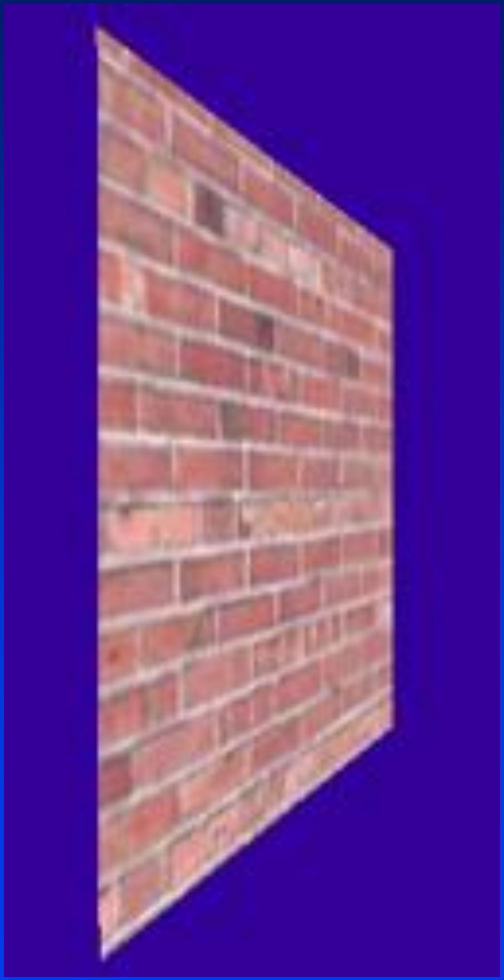






# What's Missing?

- What's the difference between a real brick wall and a photograph of the wall texture-mapped onto a plane?
- What happens if we change the lighting or the camera position?

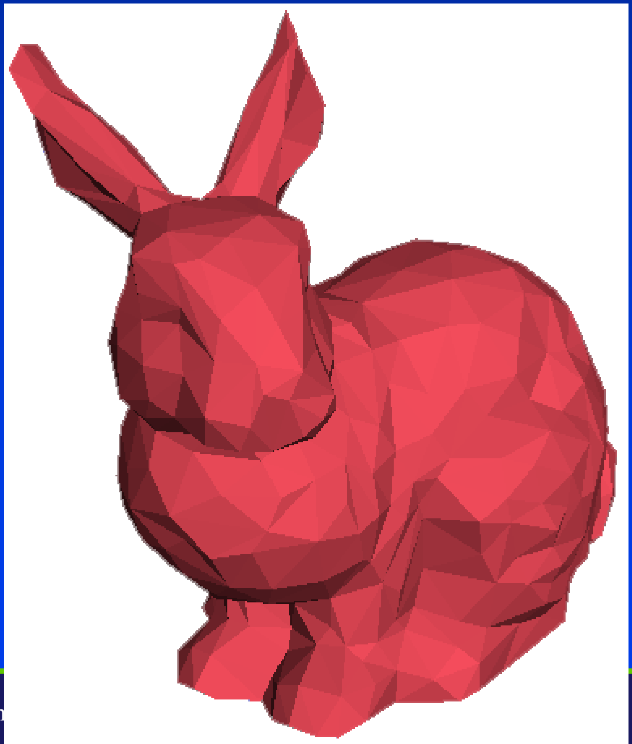


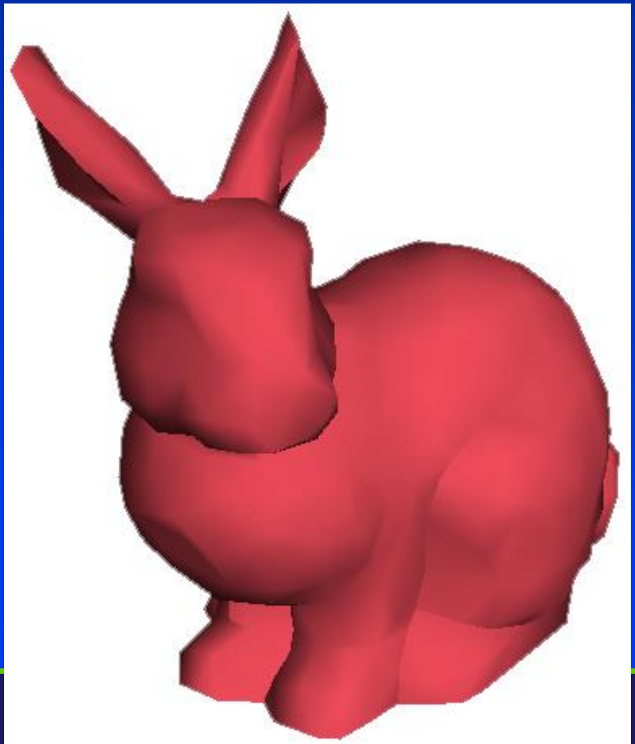
# Bump Mapping

- Other Mapping Techniques:
  - Bump Mapping
  - Displacement Mapping

# Remember Gouraud Shading?

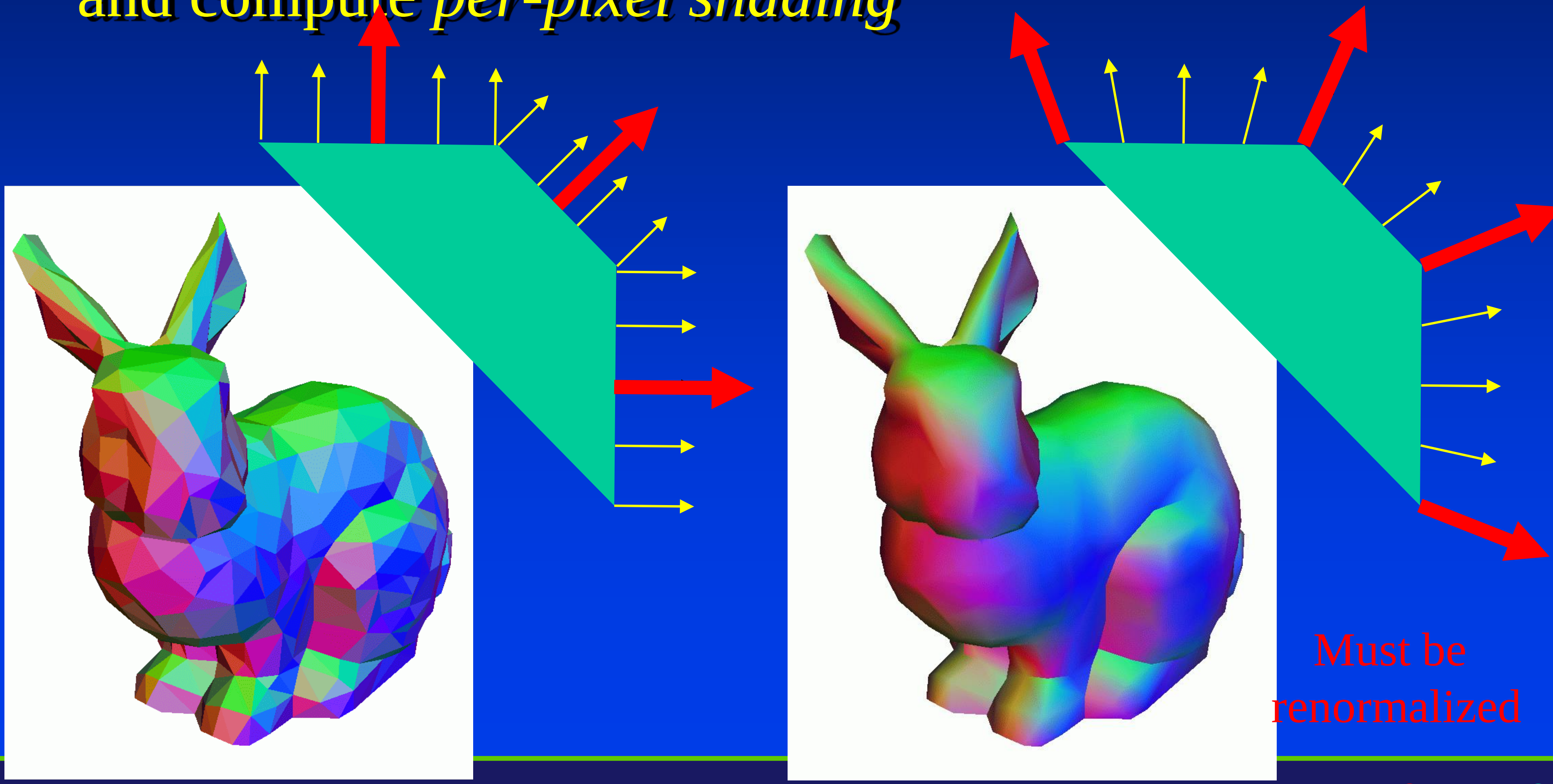
- Instead of shading with the normal of the triangle, shade the vertices with the *average normal* and interpolate the color across each face





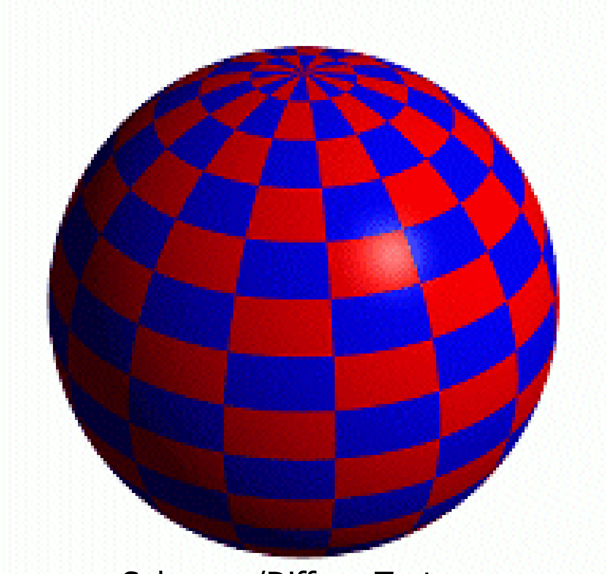
# Phong Normal Interpolation

- Interpolate the average vertex normals across the face and compute *per-pixel shading*

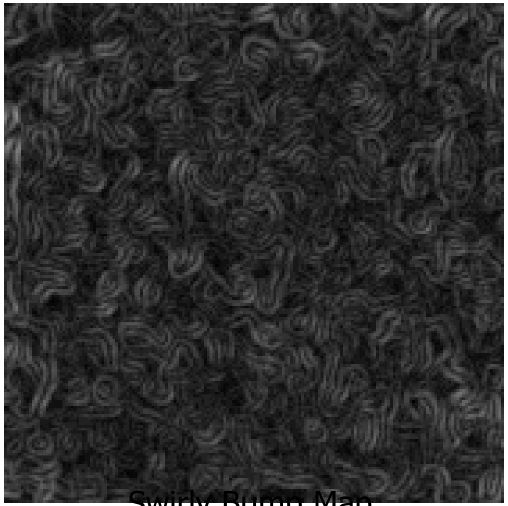


# Bump Mapping

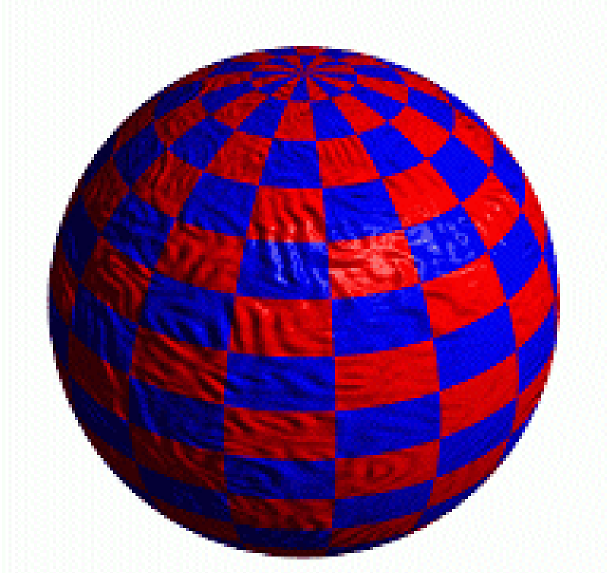
- Use textures to alter the surface normal
  - Does not change the actual shape of the surface
  - Just shade as if it were a different shape



Sphere w/Diffuse Texture



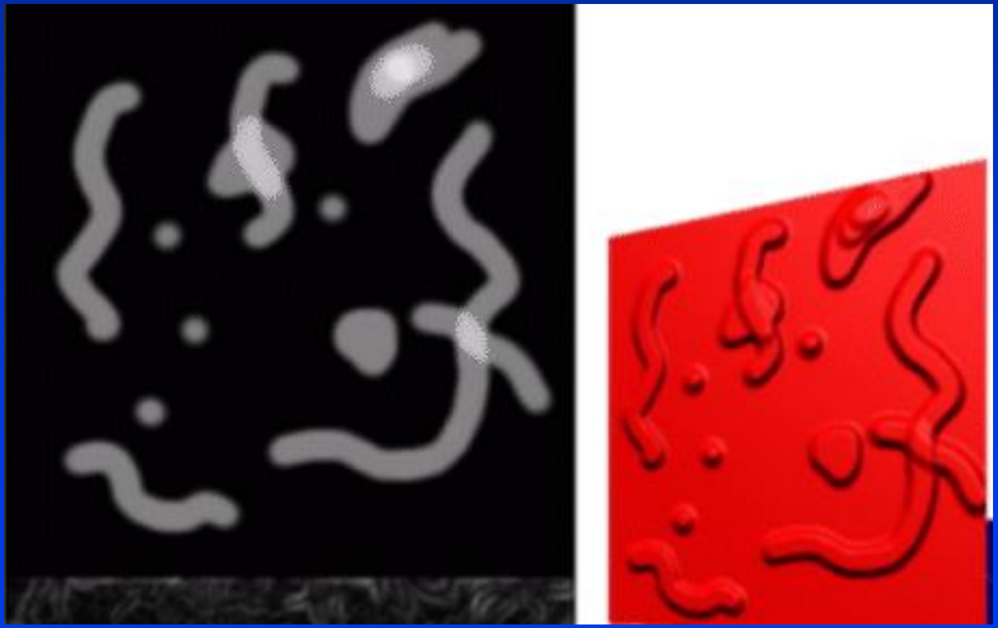
Swirly Bump Map

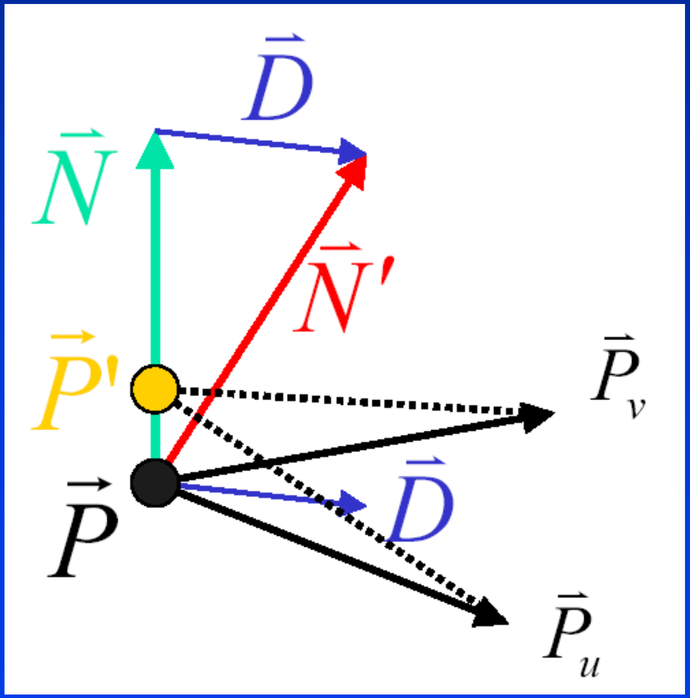


Sphere w/Diffuse Texture & Bump Map

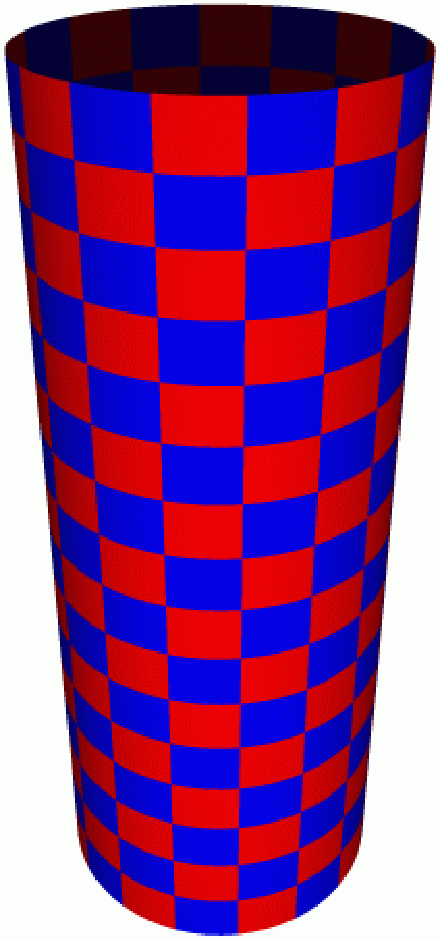
# Bump Mapping

- Treat the texture as a single-valued height function
- Compute the normal from the partial derivatives in the texture

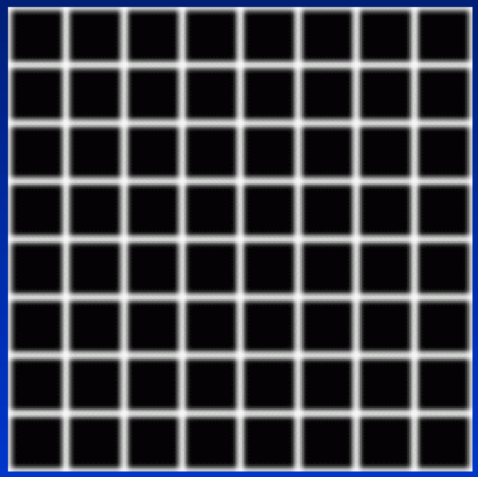




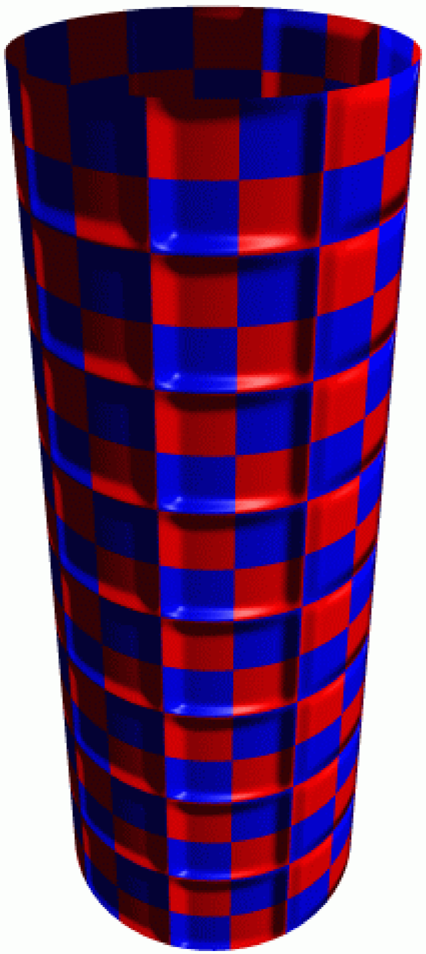
# Another Bump Map Example



Cylinder w/Diffuse Texture Map



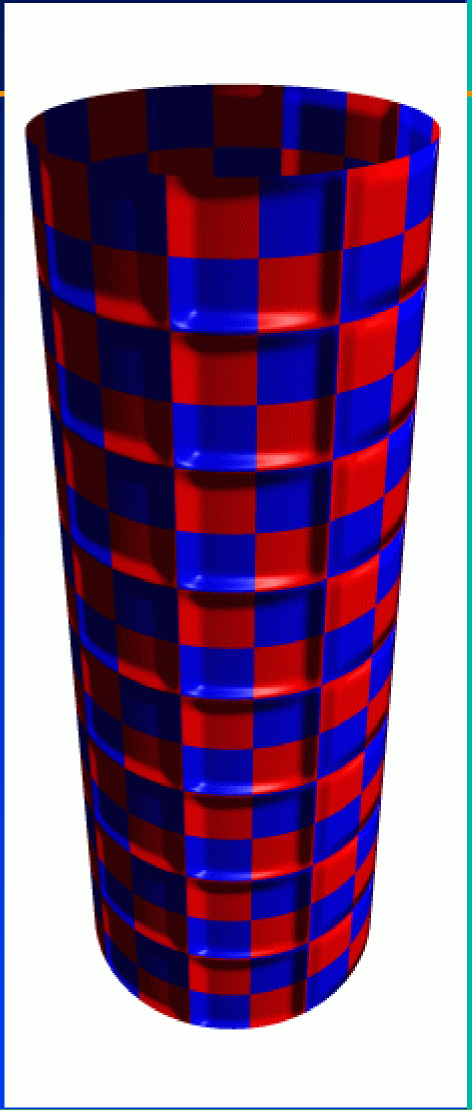
Bump Map



Cylinder w/Texture Map & Bump Map

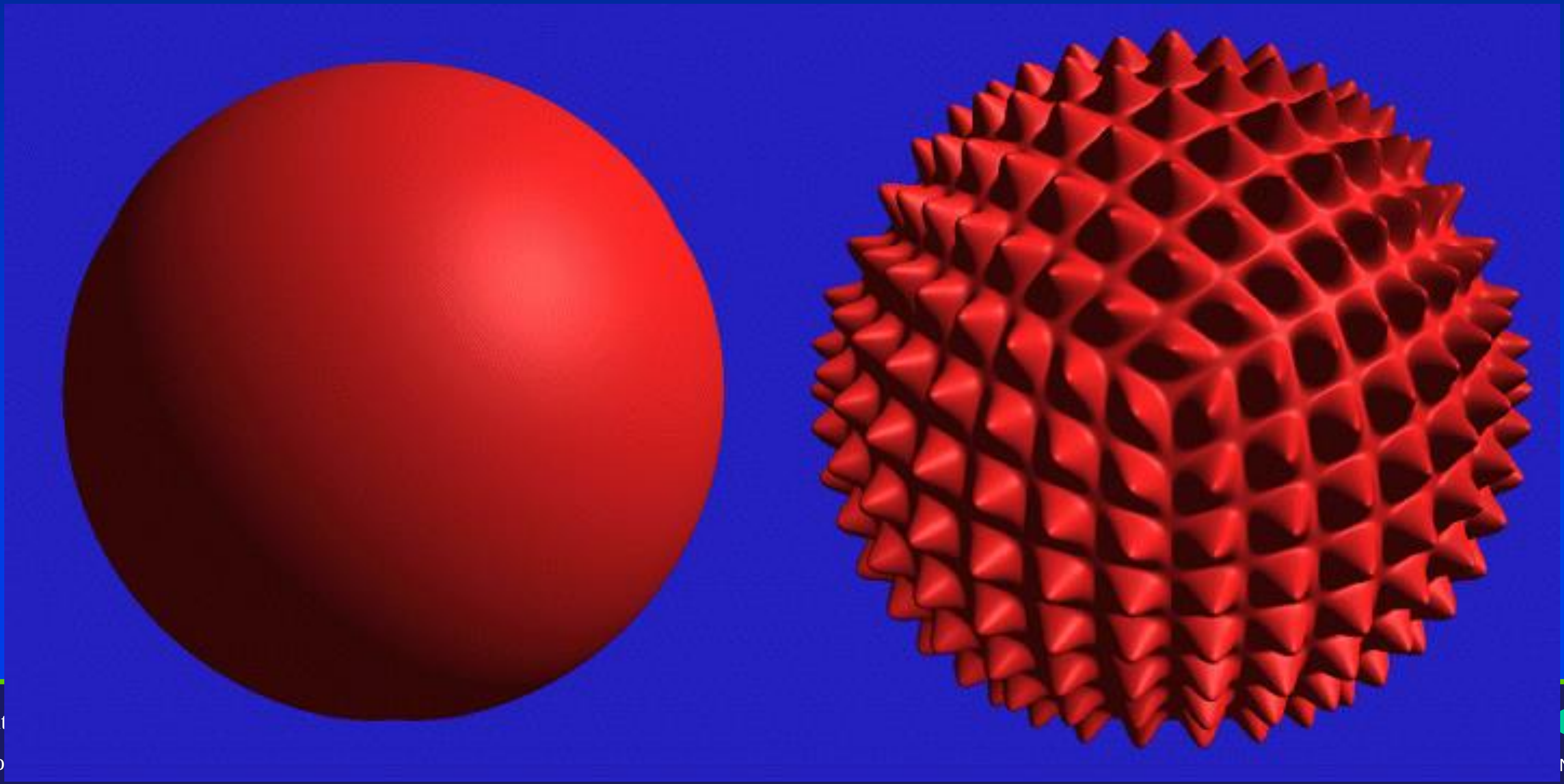
# What's Missing?

- There are no bumps on the silhouette of a bump-mapped object
- Bump maps don’t allow self-occlusion or self-shadowing



# Displacement Mapping

- Use the texture map to actually move the surface point
- The geometry must be displaced before visibility is determined



# Displacement Mapping

Image from:

*Geometry Caching for*
*Ray-Tracing Displacement Maps*

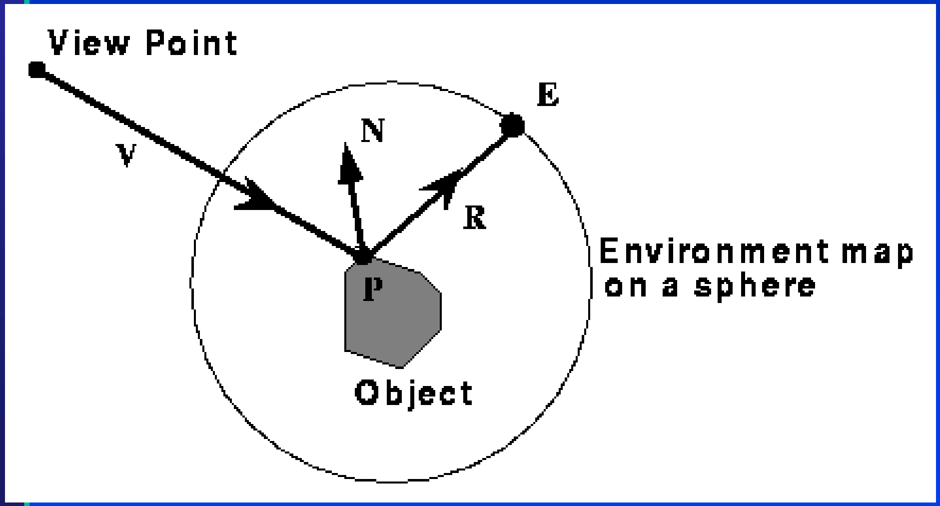
by Matt Pharr and Pat Hanrahan.

*note the detailed shadows*
*cast by the stones*

# Displacement Mapping

# Environment Maps

- We can simulate reflections by using the direction of the reflected ray to index a spherical texture map at "infinity".
- Assume that all reflected ra[ys] begin from the same point.




# Illumination + Texture Mapping

# Texture Maps for Illumination

- Also called "Light Maps"

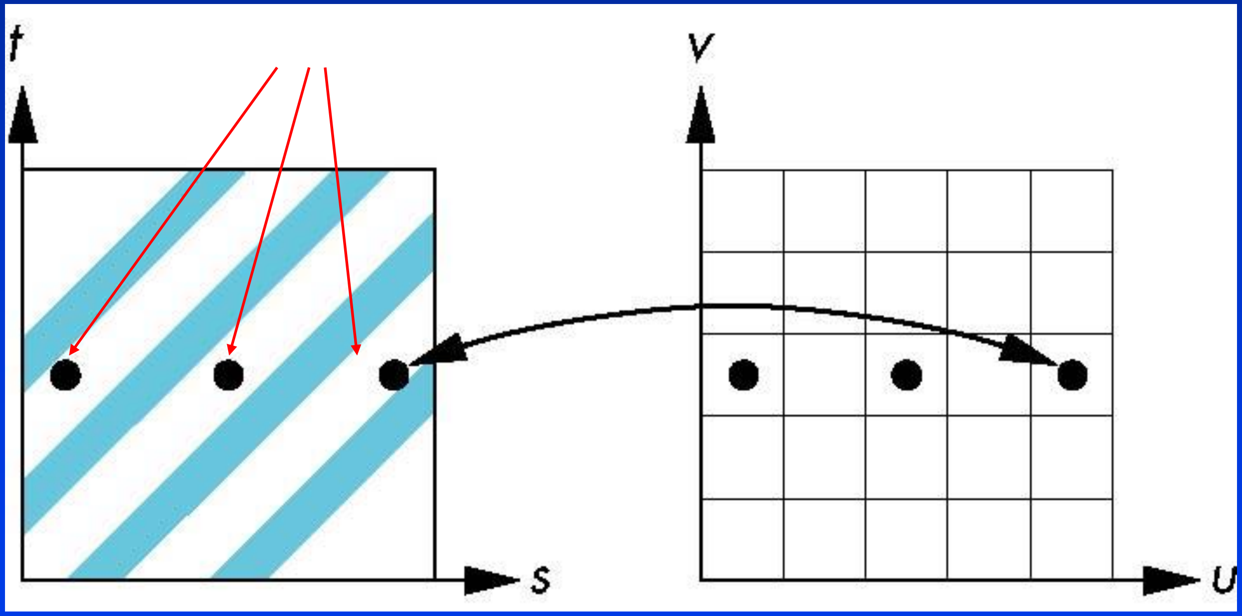
Quake

# Aliasing

- Point sampling of the texture can lead to aliasing errors

point samples in u,v (or x,y,z) space

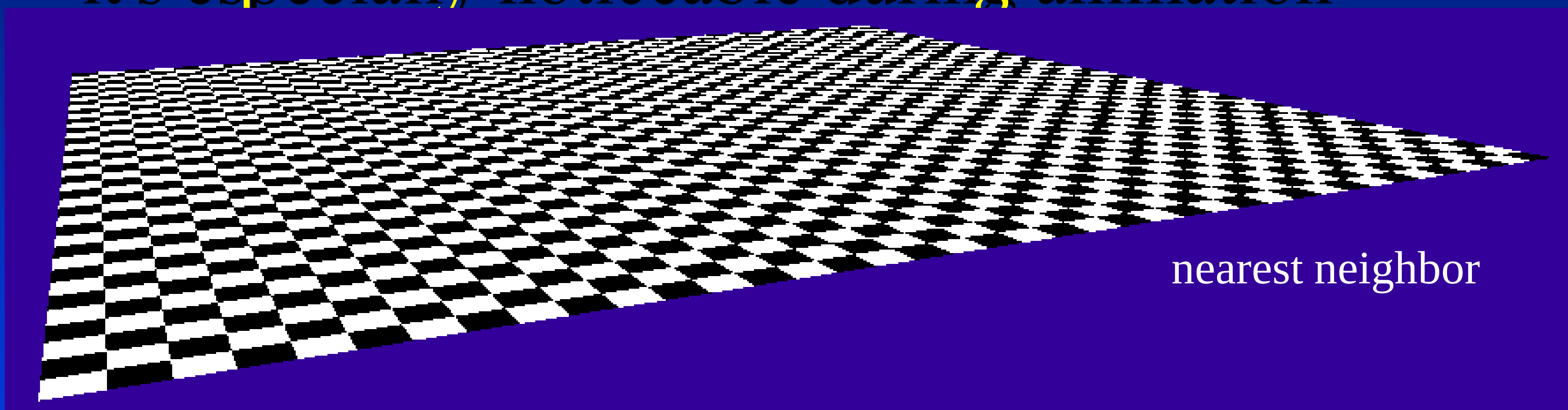
miss blue stripes

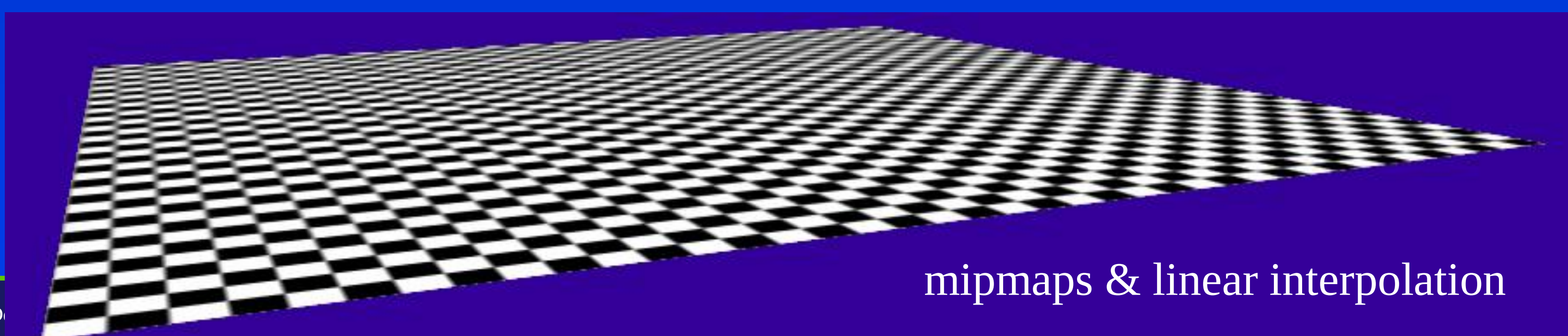



point samples in texture space

# Textures can Alias

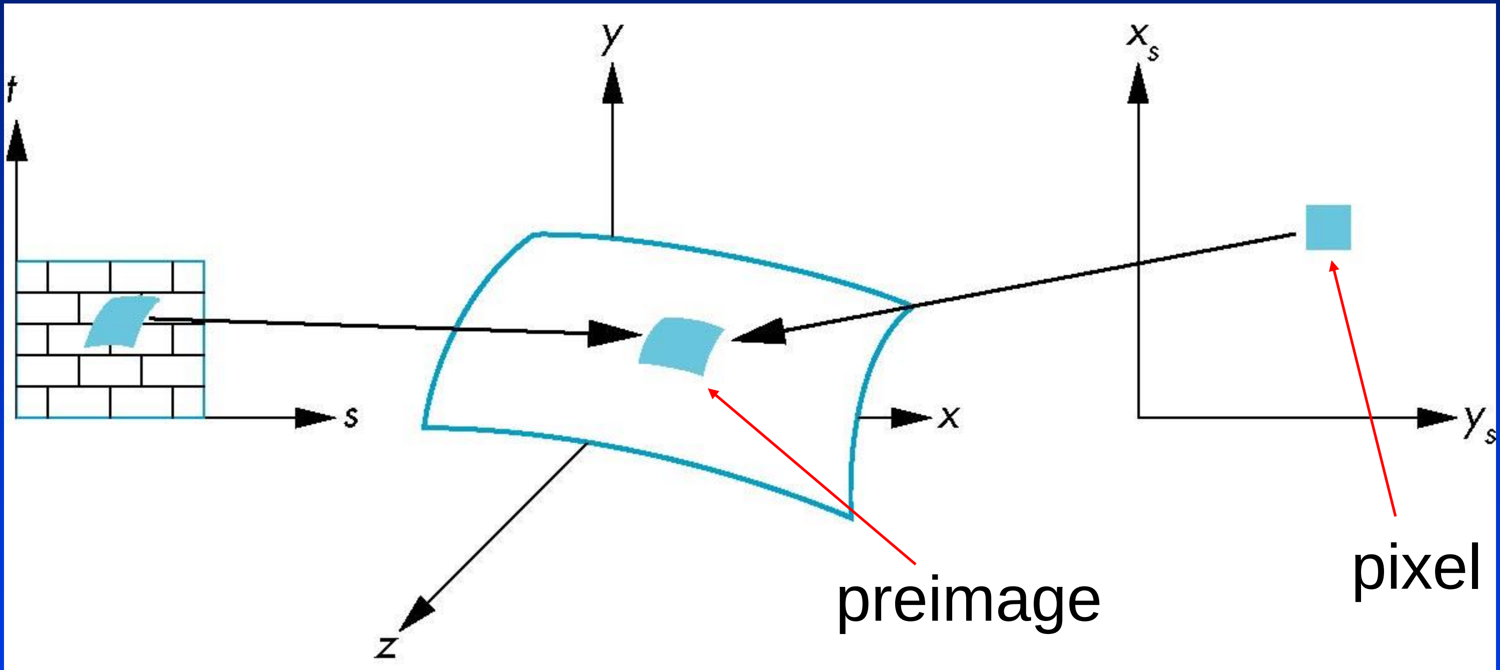
- *Aliasing* is the under-sampling of a signal, and it's especially noticeable during animation



# Area Averaging

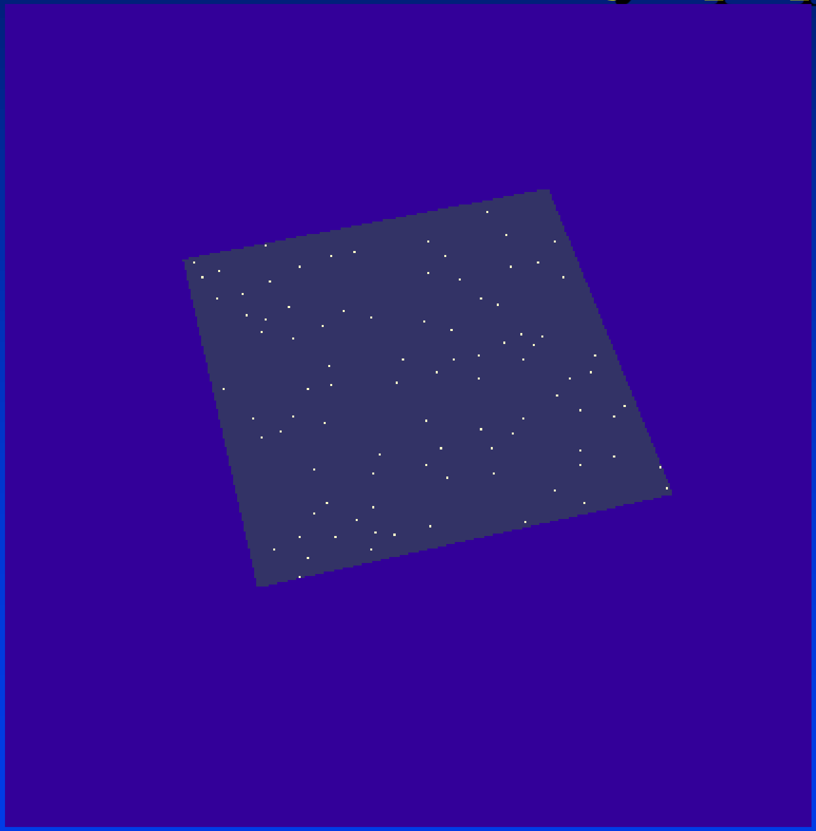
A better but slower option is to use *area averaging*



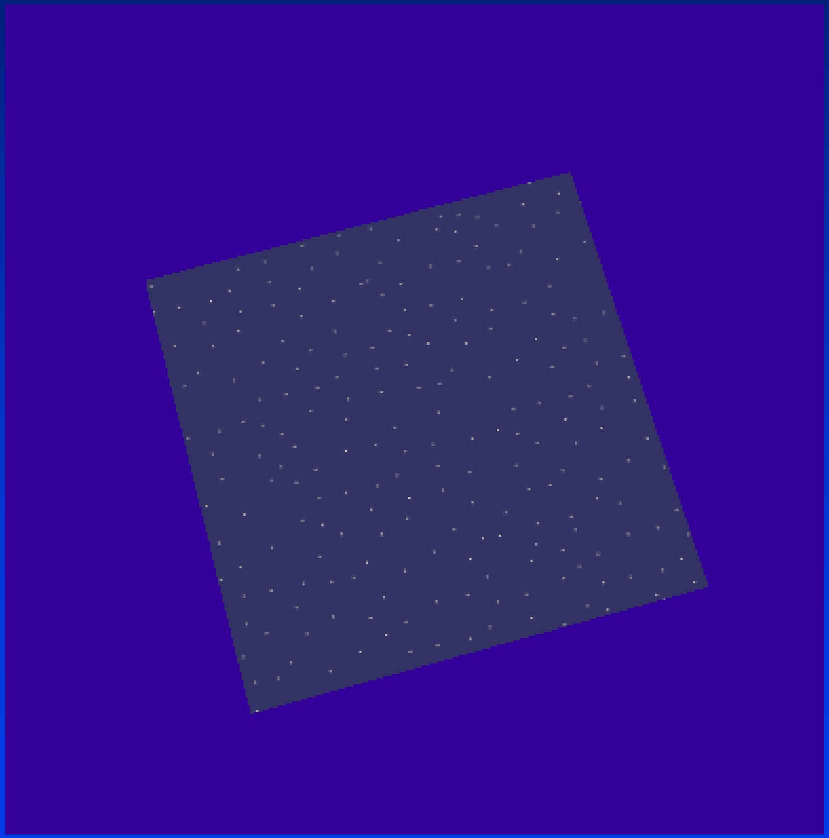

Note that *preimage* of pixel is curved

# Textures can Alias

- Small details may "pop" in and out of view



nearest neighbor



mipmaps & linear interpolation

# Questions?