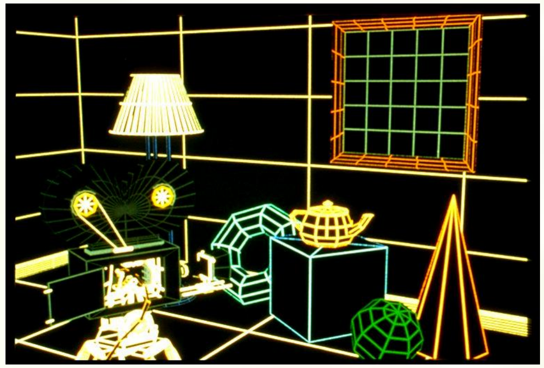
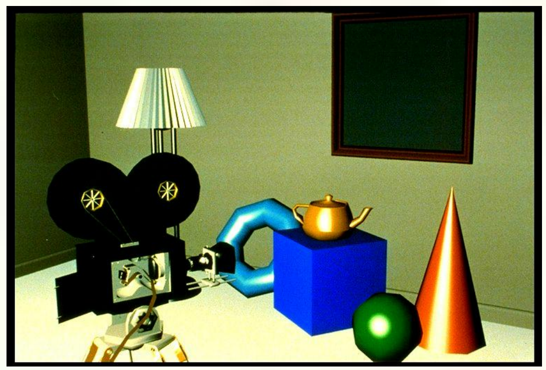
Texture Mapping

What adds visual realism?



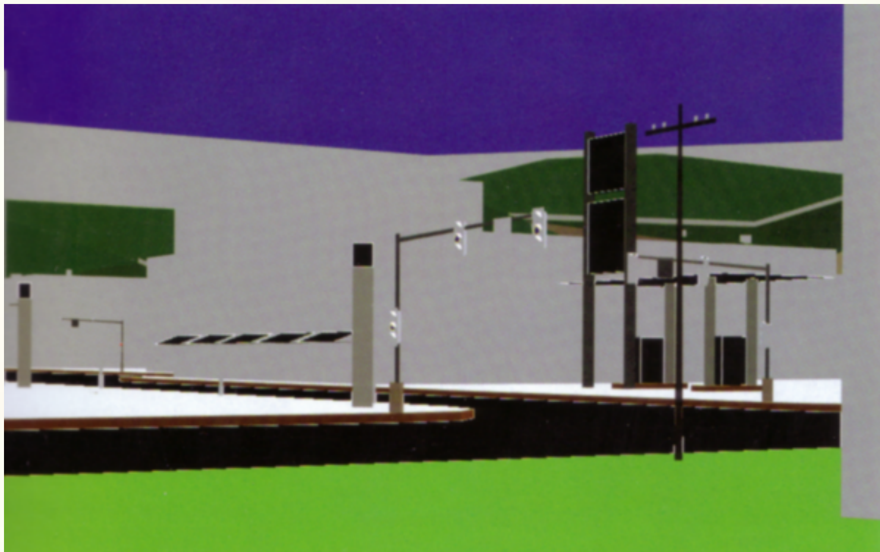
Geometry only



Phong shading

Phong shading +
Texture maps

Texture Supplies Detail to Rendered Scenes

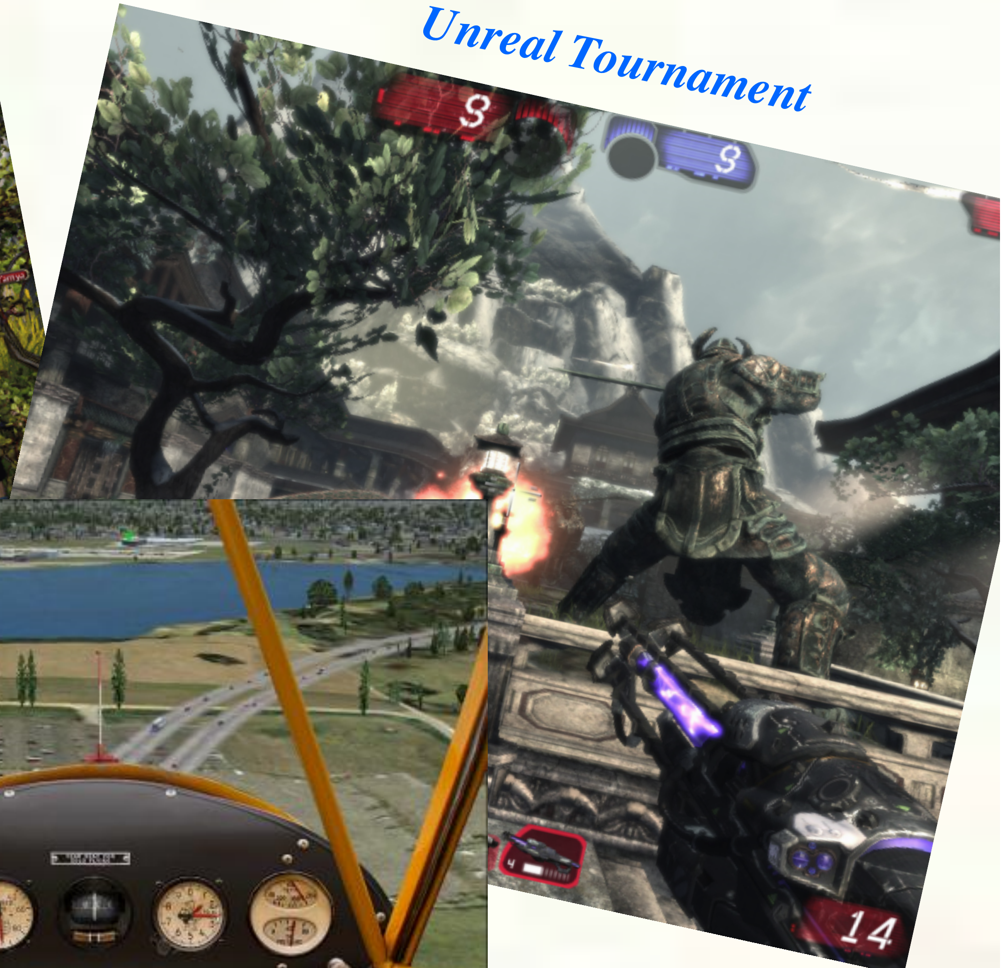


Without texture

With texture

Textures Make Graphics Pretty

Sacred 2



Unreal Tournament

Microsoft Flight Simulator X

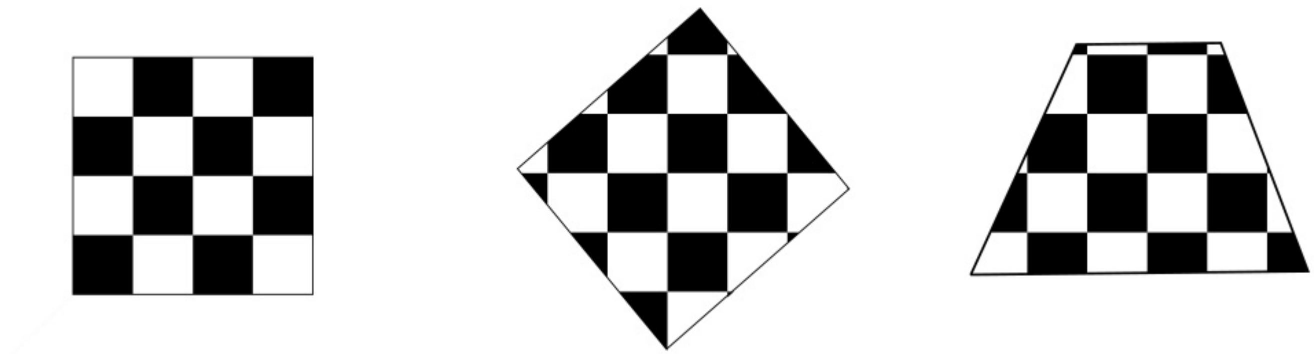
Texture → detail,
detail → immersion,
immersion → fun

Texture mapping

Texture mapping (Woo et al., fig. 9-1)

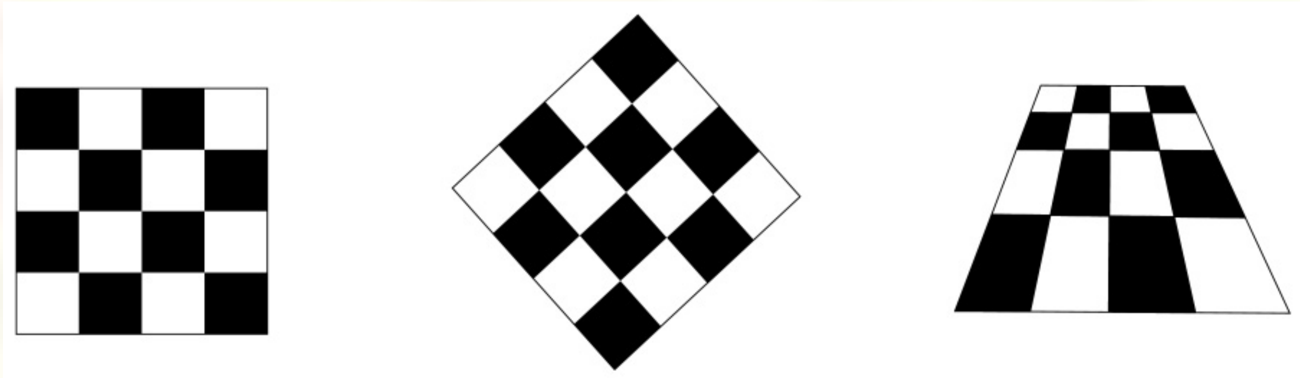
- Texture mapping allows you to take a simple polygon and give it the appearance of something much more complex.
  - Due to Ed Catmull, PhD thesis, 1974
  - Refined by Blinn & Newell, 1976
- Texture mapping ensures that “all the right things” happen as a textured polygon is transformed and rendered.

Non-parametric texture mapping



- With "non-parametric texture mapping":
  - Texture size and orientation are fixed
  - They are unrelated to size and orientation of polygon
  - Gives cookie-cutter effect

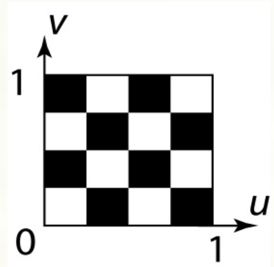
Parametric texture mapping



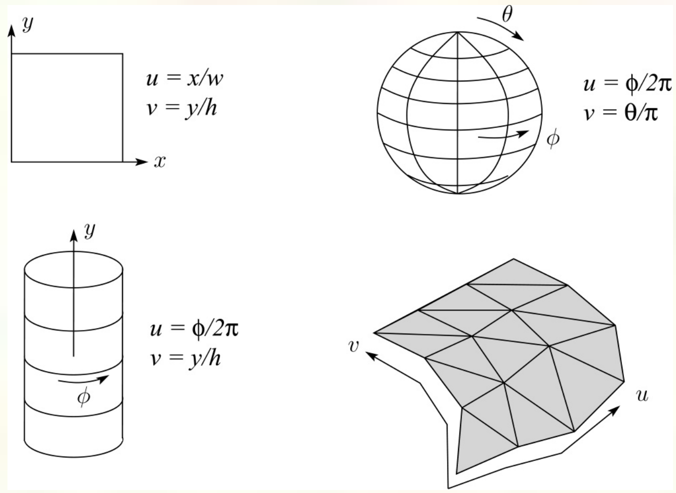
- With "parametric texture mapping," texture size and orientation are tied to the polygon.
- Idea:
  - Separate "texture space" and "screen space"
  - Texture the polygon as before, but in texture space
  - Deform (render) the textured polygon into screen space
- A texture can modulate just about any parameter – diffuse color, specular color, specular exponent, …

Implementing texture mapping

- A texture lives in it own abstract image coordinates parameterized by (*u,v*) in the range ([0..1], [0..1]):



- It can be wrapped around many different surfaces:



- Computing (*u,v*) texture coordinates in a ray tracer is fairly straightforward.
- Note: if the surface moves/deforms, the texture goes with it.

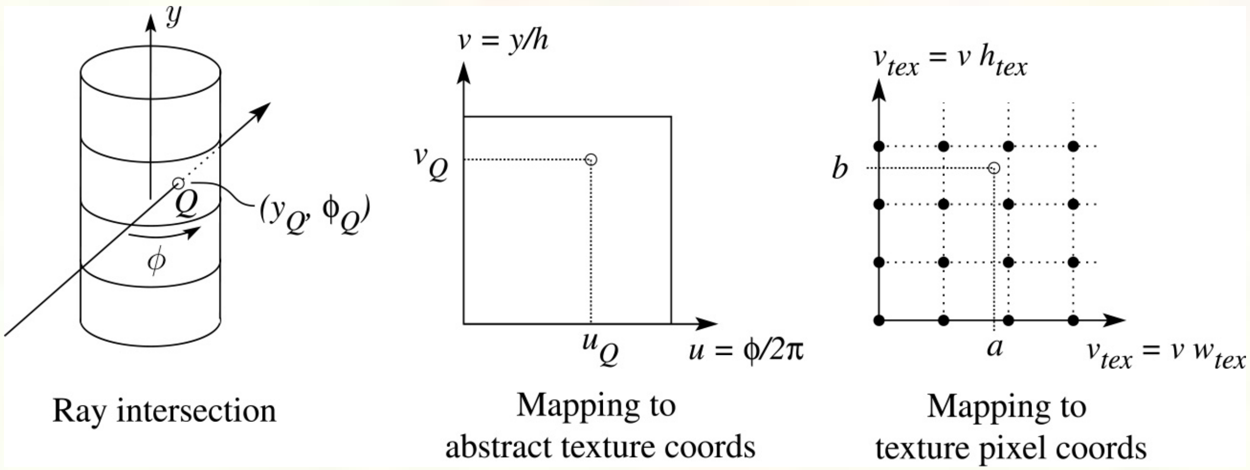
Mapping to texture image coords

- The texture is usually stored as an image. Thus, we need to convert from abstract texture coordinate:

  (u,v) in the range ([0..1], [0..1])

  to texture image coordinates:

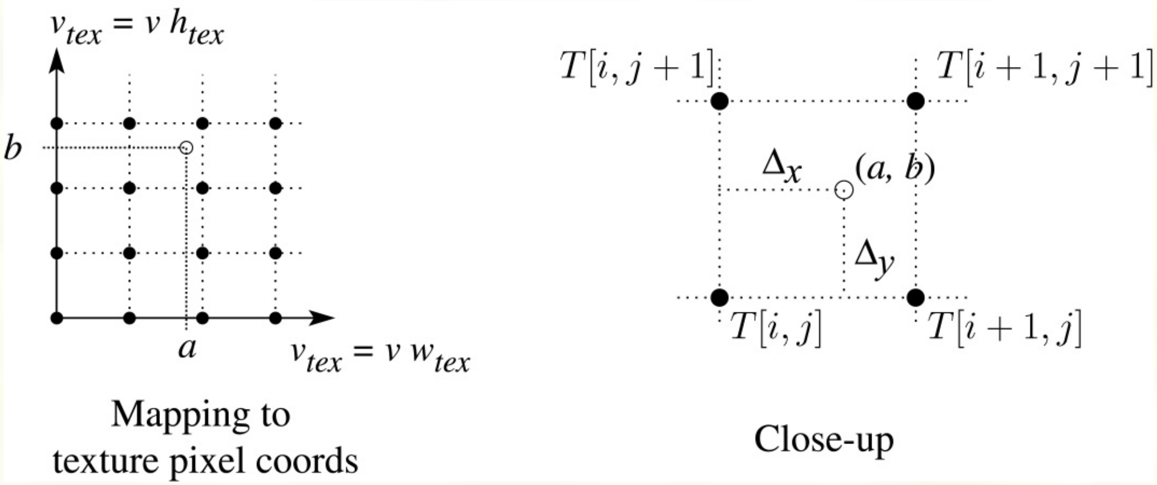
  (u_{tex}, v_{tex}) in the range ([0.. w_{tex}], [0.. h_{tex}])



- **Q**: What do you do when the texture sample you need lands between texture pixels?

Texture resampling

- We need to resample the texture:



- A common choice is **bilinear interpolation**:

$$
\begin{aligned}
T(a,b) &= T[i+\Delta_x, j+\Delta_y] \\
&= (1-\Delta_x)(1-\Delta_y)T[i,j] + \Delta_x(1-\Delta_y)T[i+1,j] \\
&\quad + (1-\Delta_x)\Delta_y T[i,j+1] + \Delta_x\Delta_y T[i+1,j+1]
\end{aligned}
$$

Interpolation

- First we need to interpolate (s,t,r,q)
- This is the `f[TEX3]` part of the TXP instruction
- Projective texturing means we want (s/q, t/q)
  - And possible r/q if shadow mapping
- In order to correct for perspective, hardware actually interpolates
  - (s/w, t/w, r/w, q/w)
- If not projective texturing, could linearly interpolate inverse w (or 1/w)
  - Then compute its reciprocal to get w
    - Since 1/(1/w) equals w
  - Then multiply (s/w,t/w,r/w,q/w) times w
    - To get (s,t,r,q)
- If projective texturing, we can instead
  - Compute reciprocal of q/w to get w/q
  - Then multiple (s/w,t/w,r/w) by w/q to get (s/q, t/q, r/q)

Observe projective texturing is same cost as perspective correction

Interpolation Operations

- Ax + By + C per scalar linear interpolation
  - 2 MADs
- One reciprocal to invert q/w for projective texturing
  - Or one reciprocal to invert 1/w for perspective texturing
- Then 1 MUL per component for s/w * w/q
  - Or s/w * w
- For (s,t) means
  - 4 MADs, 2 MULs, & 1 RCP
  - (s,t,r) requires 6 MADs, 3 MULs, & 1 RCP
- All floating-point operations

Interpolation Operations

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- All floating-point operations

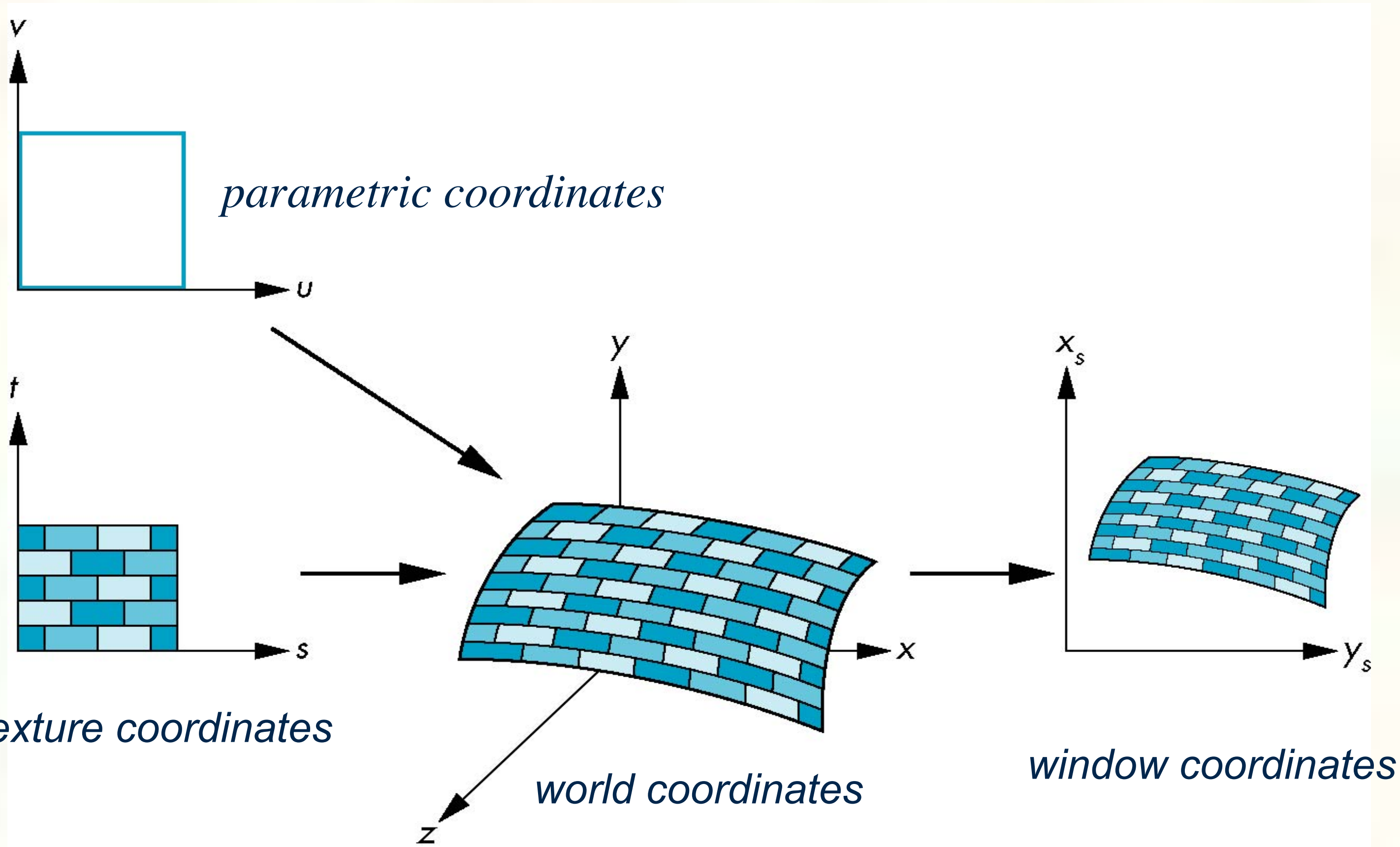
Texture Space Mapping

- Have interpolated & projected coordinates
- Now need to determine what texels to fetch

- Multiple (s,t) by (width,height) of texture base level
  - Could convert (s,t) to fixed-point first
    - Or do math in floating-point
  - Say based texture is 256x256 so
    - So compute (s*256, t*256)=(u,v)

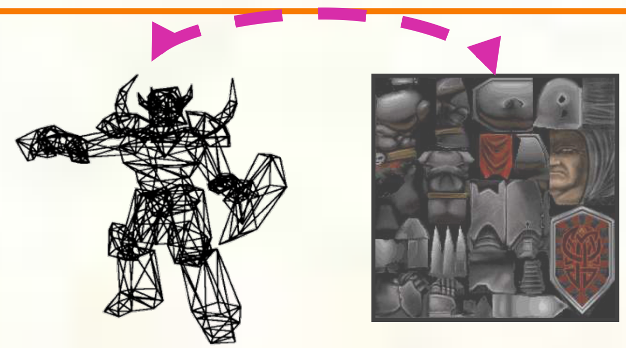
Texture Coordinates Associated with Transformed Vertices

- Interpolated over rasterized primitives



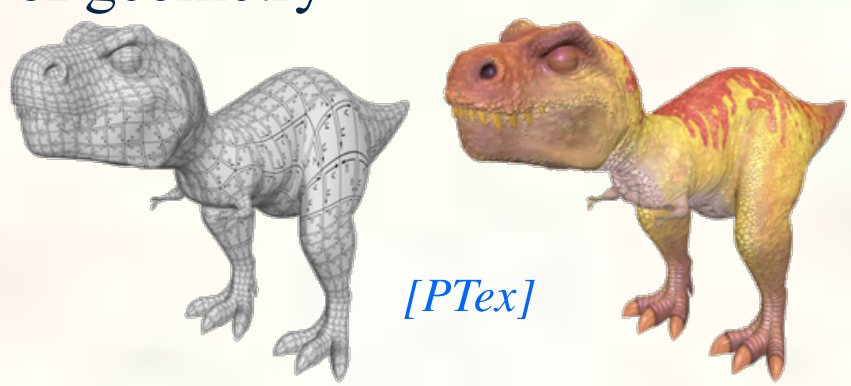
Source of texture coordinates?

- Assigned ad-hoc by artist
  - Tedious!
  - Has gift wrapping problem



- Computed based on XYZ position
  - Texture coordinate generation ("texgen")
  - Hard to map to "surface space"
  - Function maps (x,y,z) to (s,t,r,q)

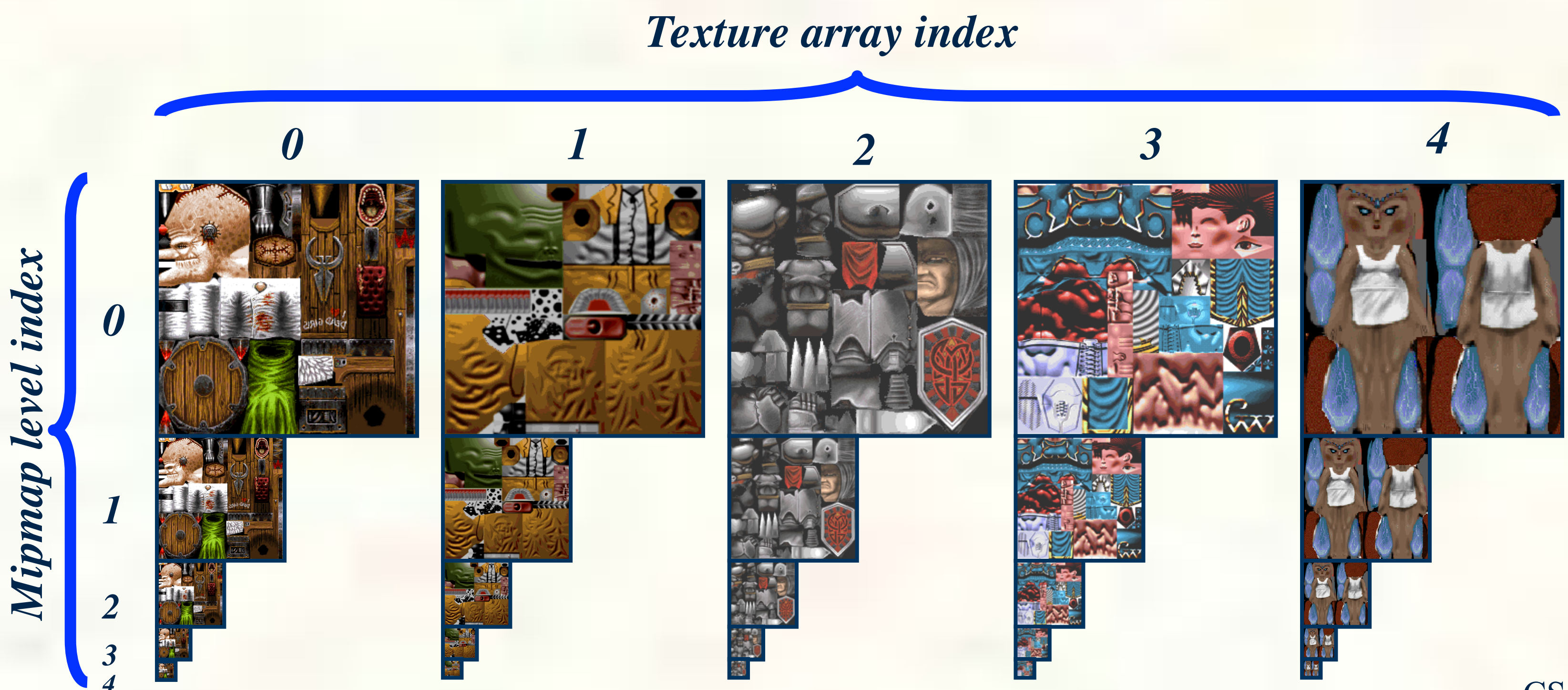
- From bi-variate parameterization of geometry
  - Good when geometry is generated from patches
  - So (u,v) of patch maps to (x,y,z) and (s,t)



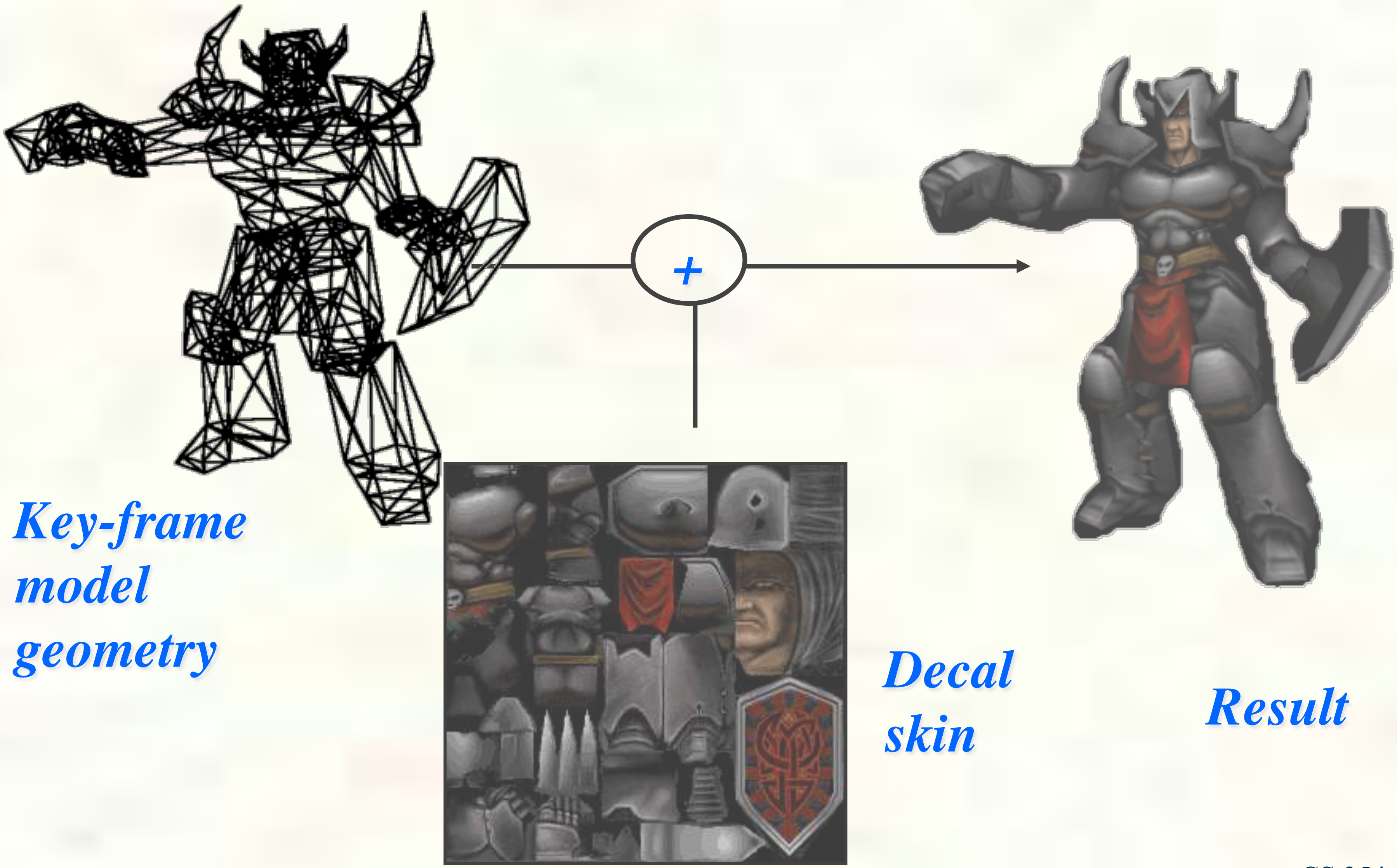
[PTex]

Texture Arrays

- **Multiple skins packed in texture array**
  - Motivation: binding to one multi-skin texture array avoids texture bind per object



Textured Polygonal Models



Multiple Textures

lightmaps only

×

(modulate)

decal only

=

combined scene

** Id Software's Quake 2*
circa 1997

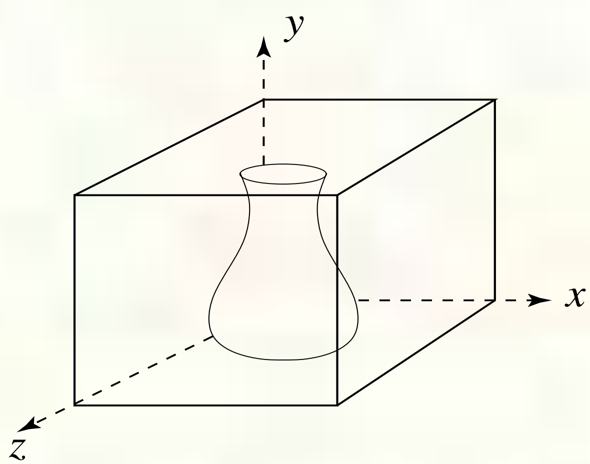
Can define material by program

- A 'surface shader' computes the color of each ray that hits the surface.
- Example: Renderman surface shader

```
/*
 * Checkerboard
 */
surface checker(float Kd=.5, Ka=.1) {
  float smod = mod(10*s, 1);
  float tmod = mod(10*t, 1);
  if (smod < 0.5) {
    if (tmod < 0.5) Ci=Cs; else Ci=color(0,0,0);
  } else {
    if (tmod < 0.5) Ci=color(0,0,0); else Ci=Cs;
  }
  Oi = Os;
  Ci = Oi*Ci*(
          Ka*ambient() +
          Kd*diffuse(faceforward(normalize(N),I)));
}
```

Solid textures

- **Q**: What kinds of artifacts might you see from using a marble veneer instead of real marble?



- One solution is to use **solid textures**:
  - Use model-space coordinates to index into a 3D texture
  - Like "carving" the object from the material

- One difficulty of solid texturing is coming up with the textures.

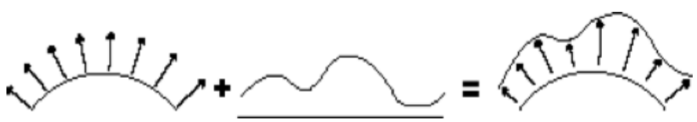
Solid textures (cont'd)

- Here's an example for a vase cut from a solid marble texture:

- *Solid marble texture by Ken Perlin, (Foley, IV-21)*

Displacement and Bump Mapping

- Use surface offsets stored in texture
  - Perturb or displace the surface
  - Shade on the resulting surface normals



$$\mathbf{P}(u,v)$$

$$\mathbf{S}(u,v) = \frac{\partial \mathbf{P}(u,v)}{\partial u} \qquad \mathbf{T}(u,v) = \frac{\partial \mathbf{P}(u,v)}{\partial v}$$

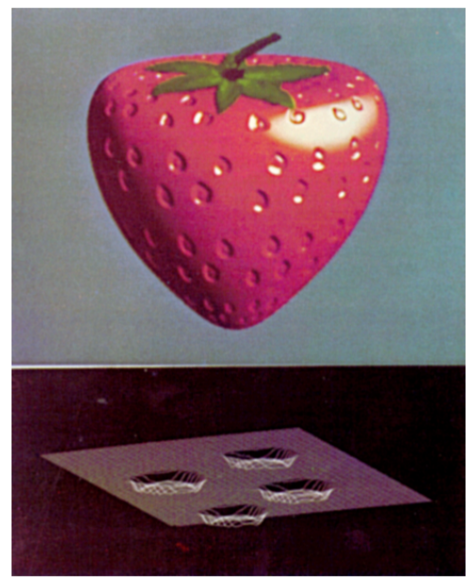
$$\mathbf{N}(u,v) = \mathbf{S} \times \mathbf{T}$$

- **Displacement**

$$\mathbf{P}'(u,v) = \mathbf{P}(u,v) + h(u,v)\mathbf{N}(u,v)$$

- **Perturbed normal**

$$\mathbf{N}'(u,v) = \mathbf{P}'_u \times \mathbf{P}'_v$$
$$= \mathbf{N} + h_u(\mathbf{T} \times \mathbf{N}) + h_v(\mathbf{S} \times \mathbf{N})$$



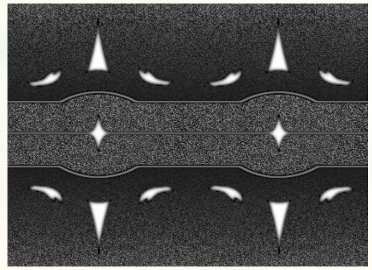
From Blinn 1976

Normal Mapping

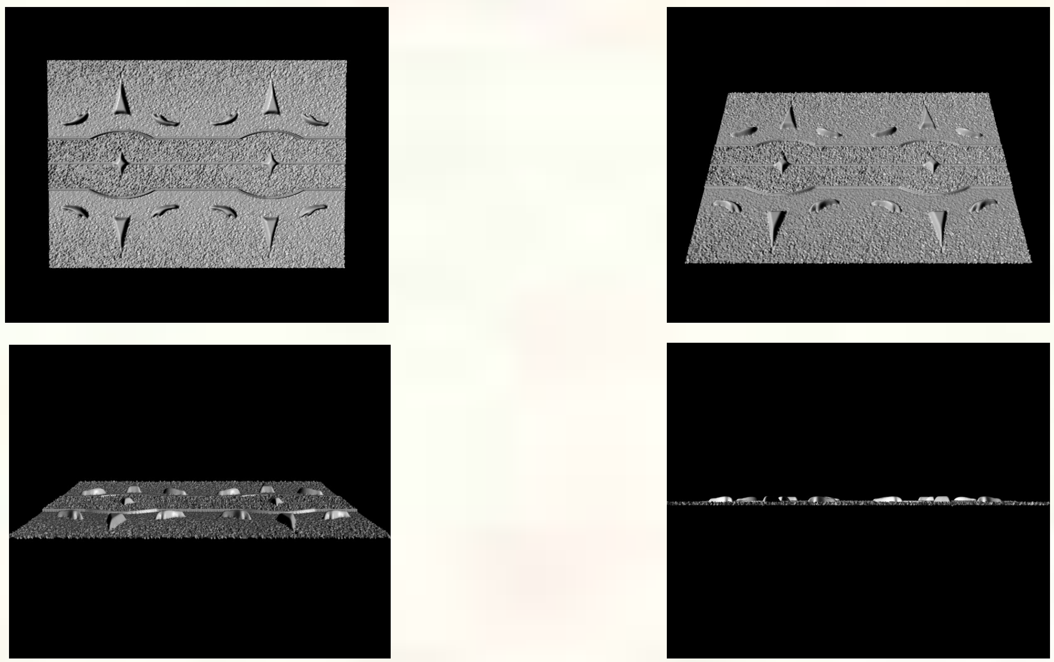
- Bump mapping via a normal map texture
  - Normal map – x,y,z components of actual normal
  - Instead of a height field 1 value per pixel
  - The normal map can be generated from the height field
  - Otherwise have to orient the normal coordinates to the surface

Displacement vs. bump mapping

- Input texture



- Rendered as displacement map over a rectangular surface



Displacement vs. bump mapping (cont'd)

Original rendering

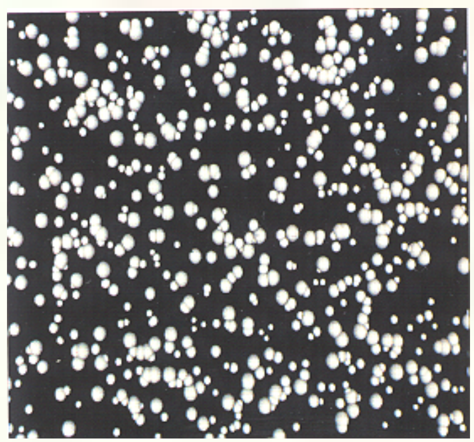
Rendering with bump map wrapped around a cylinder

Bump map and rendering by Wyvern Aldinger

Bump mapping example

Texture #1
(diffuse color)

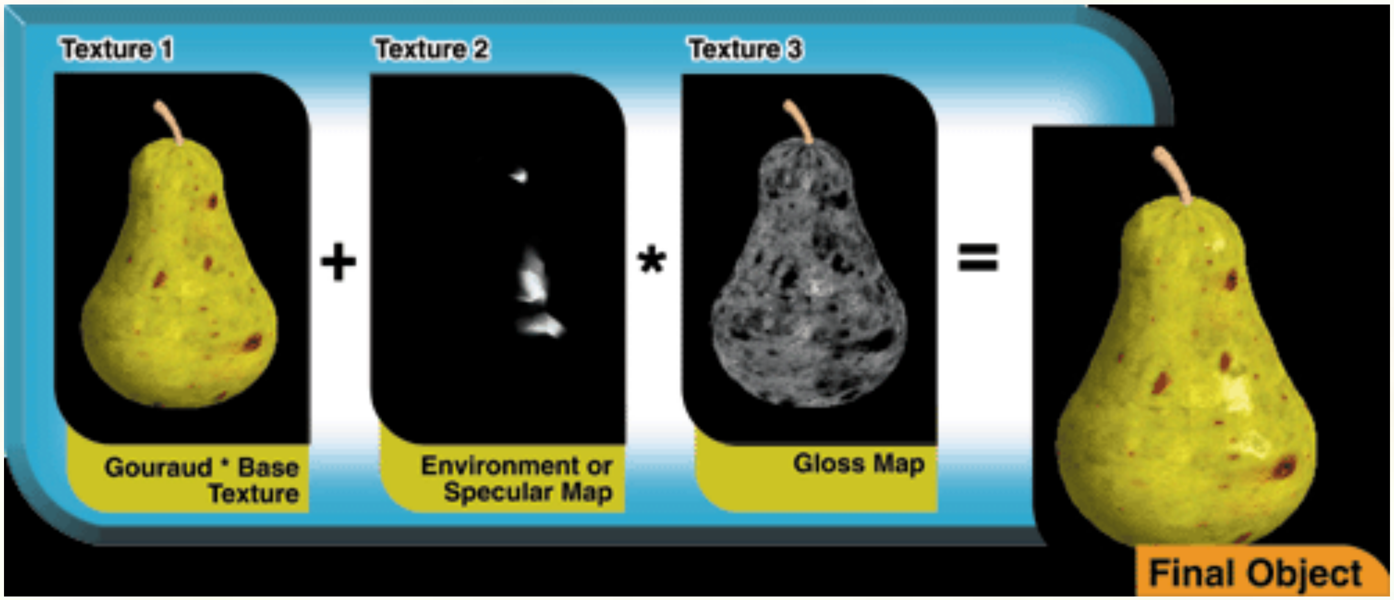
Texture #2
(bump map)



Rendered Image

Combining texture maps

- Using texture maps in combination gives even better effects.



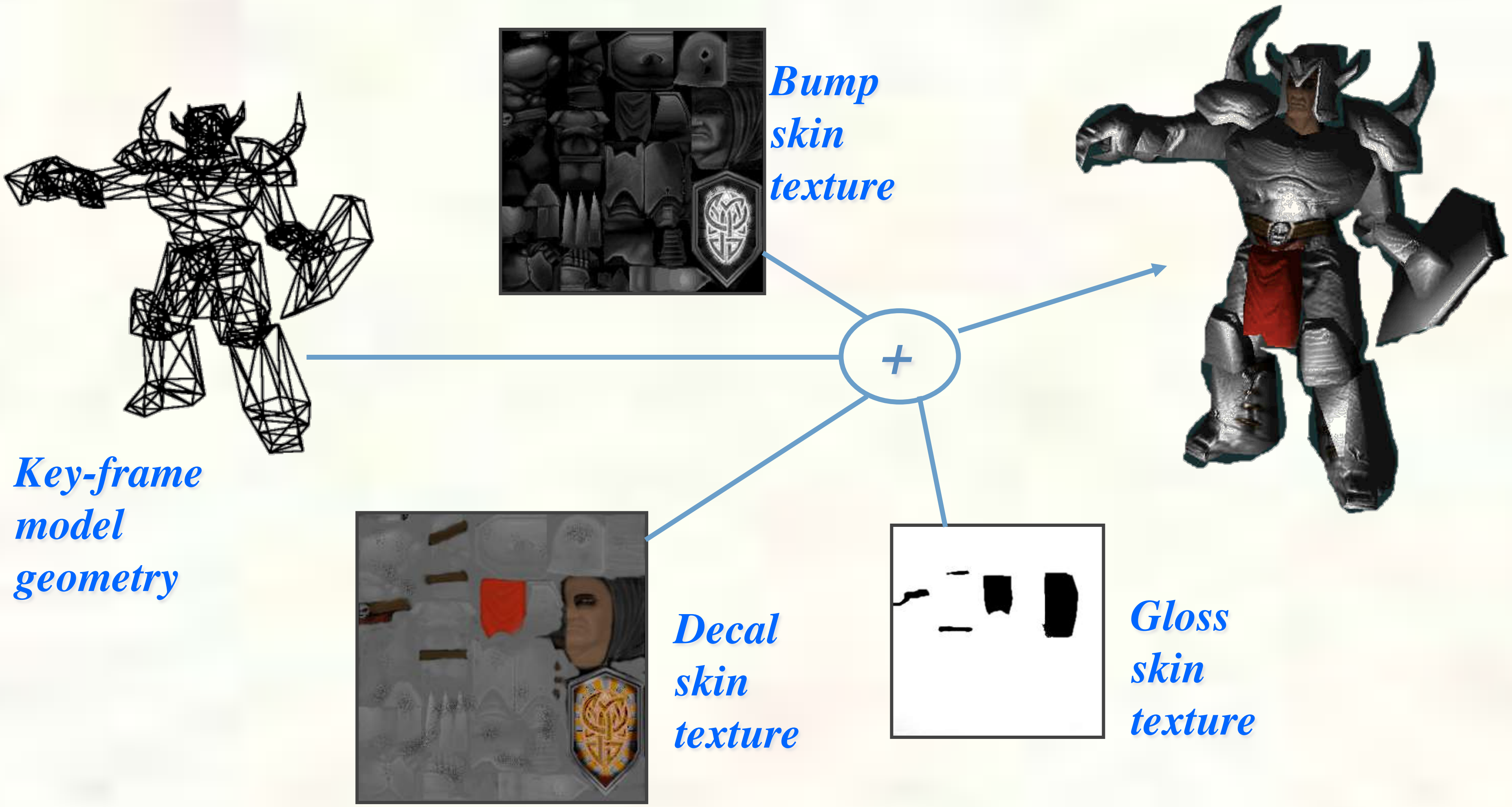
Diffuse color

Environment map (not necessary in ray tracer)

Specular coefficient

Material properties (coefficients in shading equation)

Multiple Textures



Multitexturing

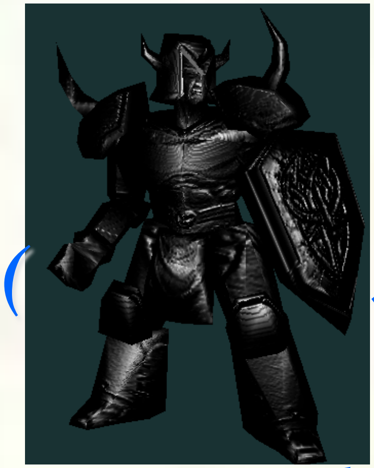
(

Diffuse

×


Decal

) + (


Specular

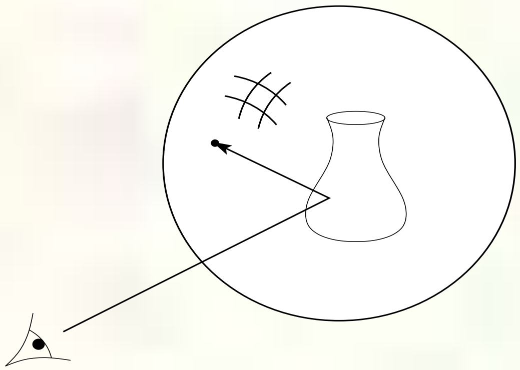
×


Gloss

) =

Final result!

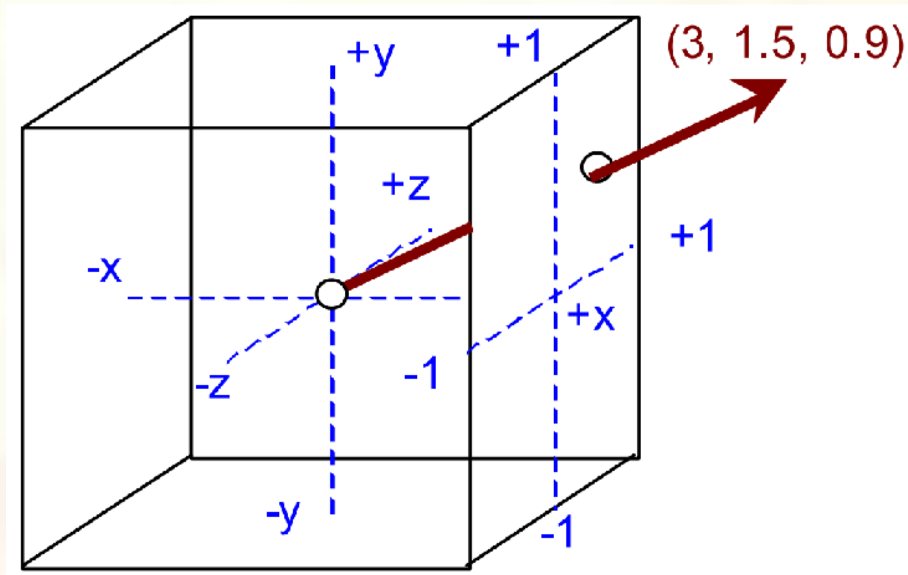
Environment mapping



- In **environment mapping** (also known as **reflection mapping**), a texture is used to model an object's environment:
  - Rays are bounced off objects into environment
  - Color of the environment used to determine color of the illumination
  - Really, a simplified form of ray tracing
  - Environment mapping works well when there is just a single object – or in conjunction with ray tracing
- Under simplifying assumptions, environment mapping can be implemented in hardware.
- With a ray tracer, the concept is easily extended to handle refraction as well as reflection.

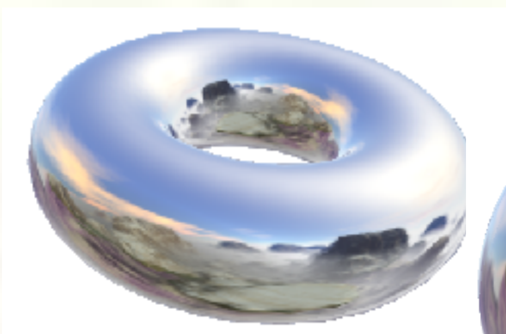
Cube Map Textures

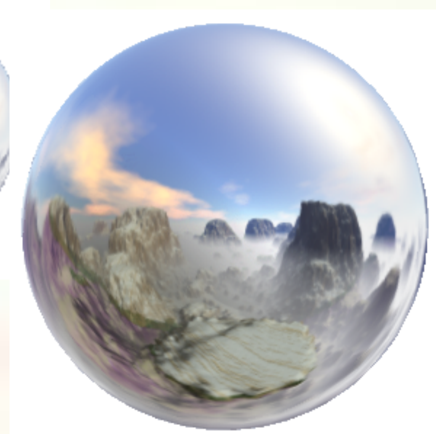
- Instead of one 2D images
  - Six 2D images arranged like the faces of a cube
    - +X, -X, +Y, -Y, +Z, -Z
- Indexed by 3D (*s*,*t*,*r*) un-normalized vector
  - Instead of 2D (*s*,*t*)
  - Where on the cube images does the vector "poke through"?
    - That's the texture result

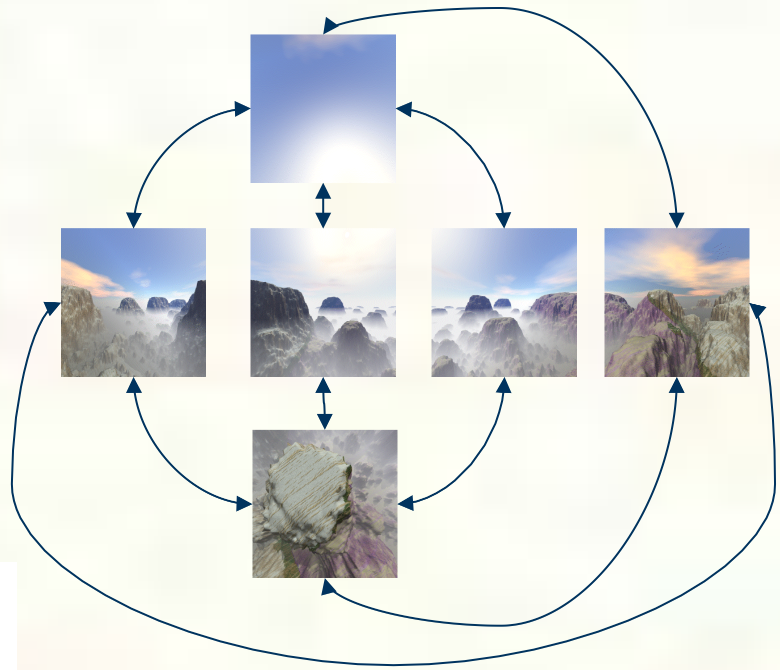


More Cube Mapping

Omni-directional Lighting

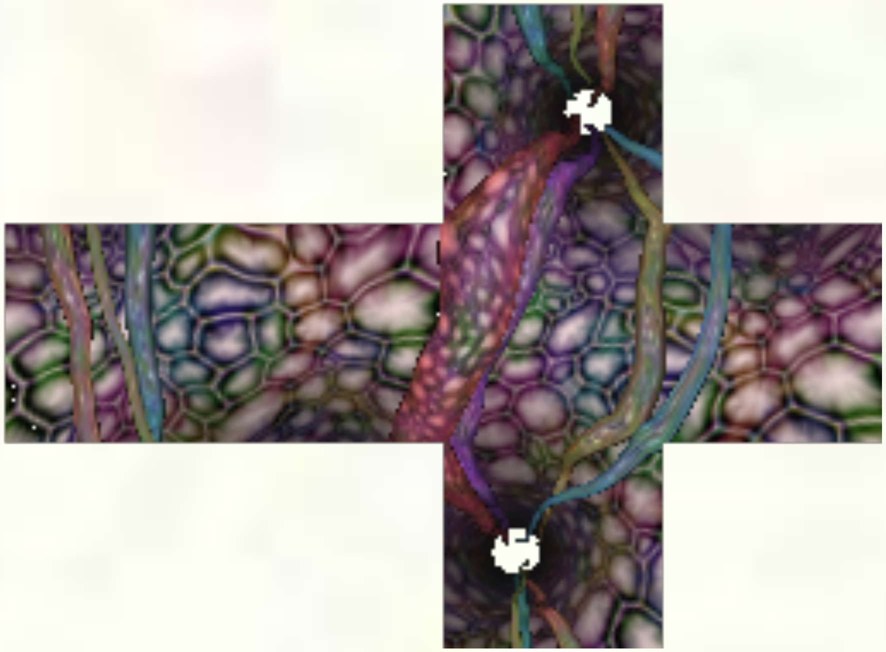






Access texture by surface reflection vector

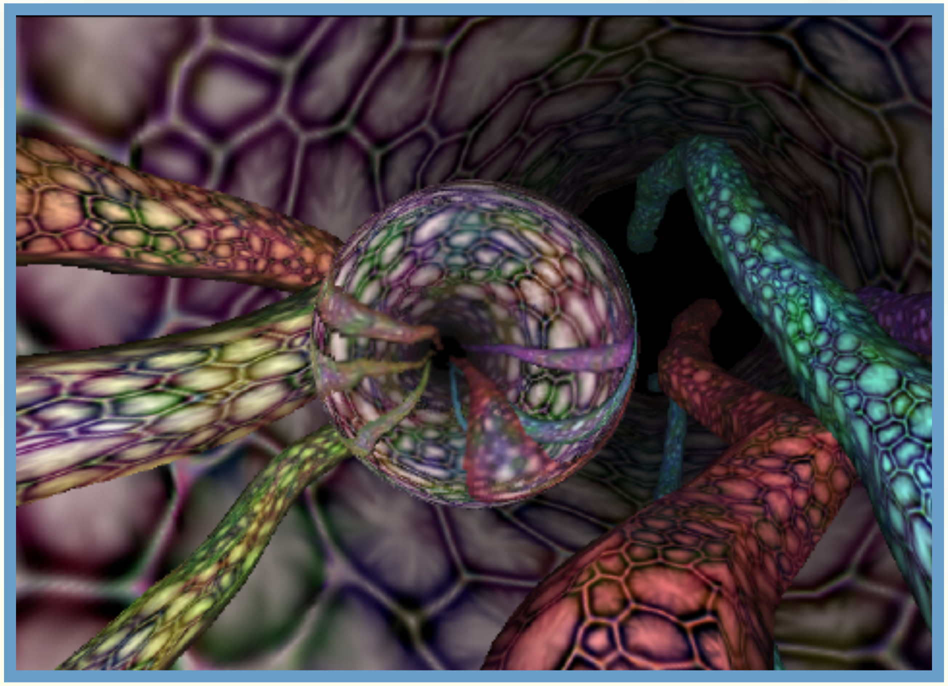
Dynamic Cube Map Textures



Dynamically created cube map image

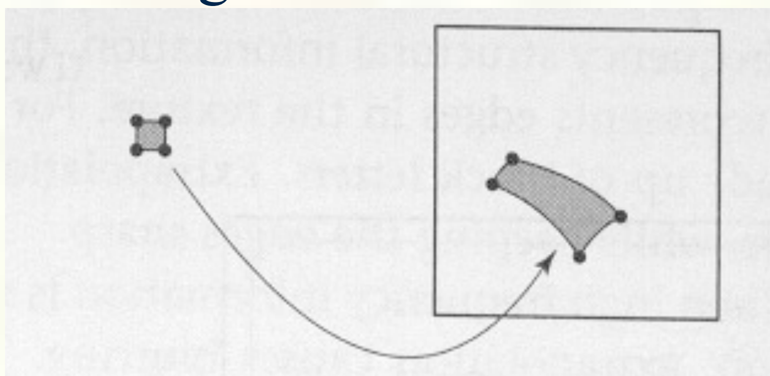
Image credit:
"Guts" GeForce 2 GTS demo, Thant Thessman

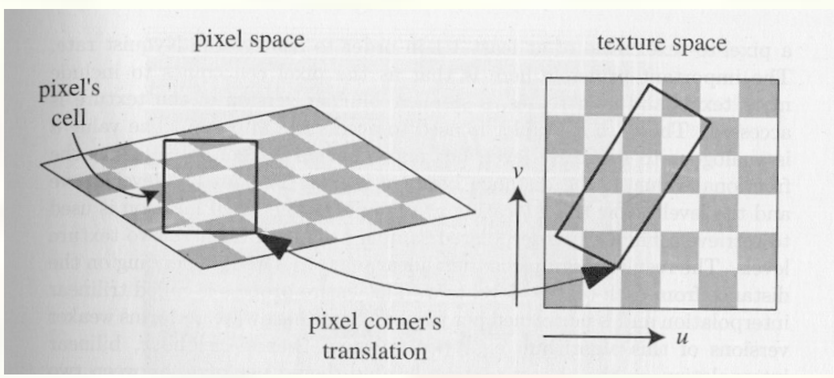
Rendered scene



How do we anti-alias textures?

- We could just super-sample.
- But textures (and shader programs) are a special case; we can use true area integration!





- *Approximate footprint as parallelogram*
- *Determine this approximate footprint using discrete differences*

Pre-filtered Image Versions

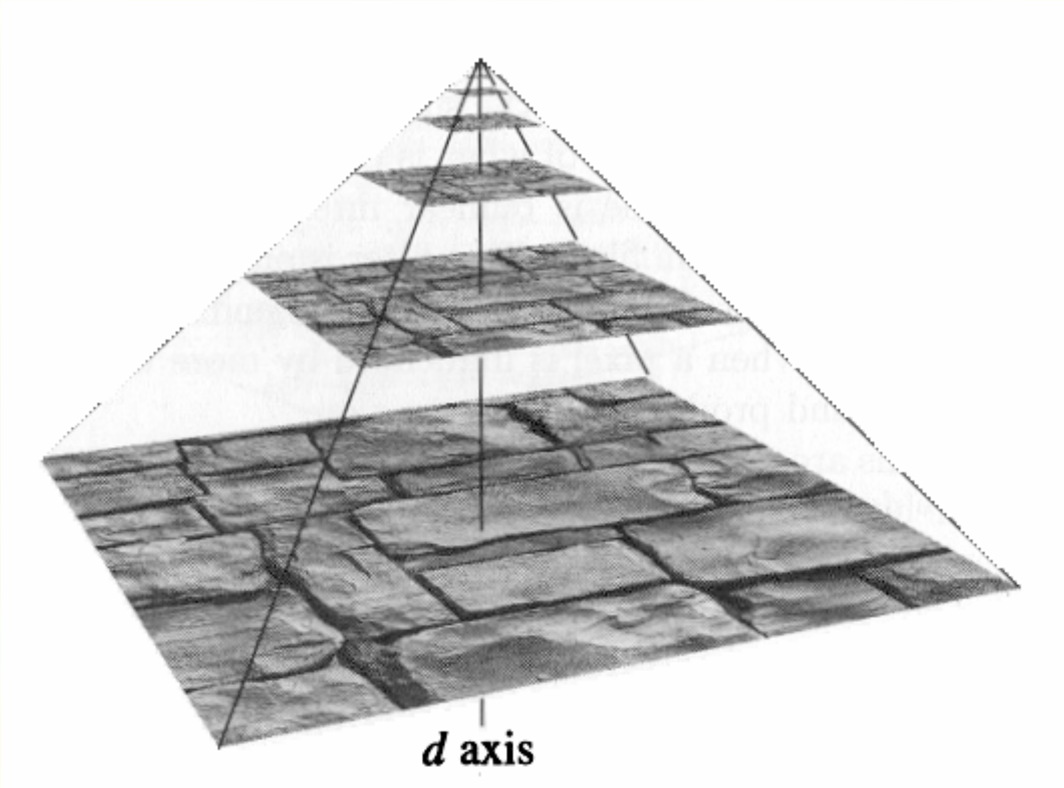
- Base texture image is say 256x256
  - Then down-sample 128x128, 64x64, 32x32, all the way down to 1x1

Trick: *When sampling the texture, pixel the mipmap level with the closest mapping of pixel to texel size*

Why? *Hardware wants to sample just a small (1 to 8) number of samples for every fetch—and want constant time access*

Cost of filtering can be reduced

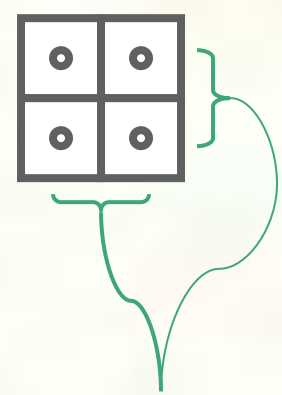
- Store a pyramid of pre-filtered images:



- During texture lookup, read from appropriate level of the pyramid.

Mipmap LOD Selection

- Tri-linear mip-mapping means compute appropriate mipmap level
- Hardware rasterizes in 2x2 pixel entities
  - Typically called quad-pixels or just *quad*
  - Finite difference with neighbors to get change in u and v with respect to window space
    - Approximation to $\partial u/\partial x$, $\partial u/\partial y$, $\partial v/\partial x$, $\partial v/\partial y$
    - Means 4 subtractions per quad (1 per pixel)
- Now compute approximation to gradient length
  - $p = \max(\mathrm{sqrt}((\partial u/\partial x)^2+(\partial u/\partial y)^2),$
    $\mathrm{sqrt}((\partial v/\partial x)^2+(\partial v/\partial y)^2))$



one-pixel separation

LOD Bias and Clamping

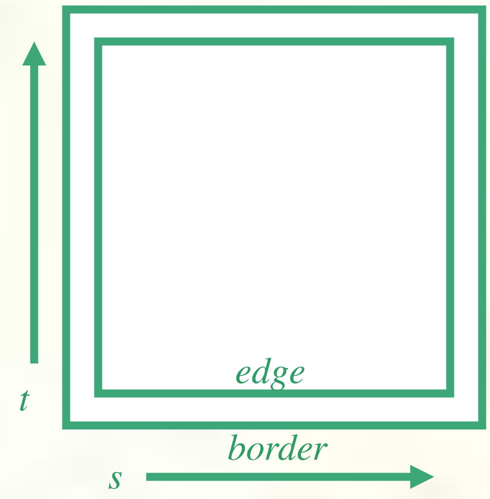
- Convert p length to power-of-two level-of-detail and apply LOD bias
  - $\lambda = \log2(p) + lodBias$
- Now clamp λ to valid LOD range
  - $\lambda' = \max(minLOD, \min(maxLOD, \lambda))$

Determine Levels and Interpolant

- Determine lower and upper mipmap levels
  - b = floor(λ’)) is bottom mipmap level
  - t = floor(λ’ +1) is top mipmap level
- Determine filter weight between levels
  - w = frac(λ’) is filter weight

Determine Texture Sample Point

- Get (u,v) for selected top and bottom mipmap levels
  - Consider a level l which could be either level t or b
    - With (u,v) locations (ul,vl)
- Perform GL_CLAMP_TO_EDGE wrap modes
  - u_w = max(1/2*widthOfLevel(l),
    min(1-1/2*widthOfLevel(l), u))
  - v_w = max(1/2*heightOfLevel(l),
    min(1-1/2*heightOfLevel(l), v))
- Get integer location (i,j) within each level
  - (i,j) = (floor(u_w* widthOfLevel(l)),
    floor(v_w*))



Determine Texel Locations

- Bilinear sample needs 4 texel locations
  - (i0,j0), (i0,j1), (i1,j0), (i1,j1)
- With integer texel coordinates
  - i0 = floor(i-1/2)
  - i1 = floor(i+1/2)
  - j0 = floor(j-1/2)
  - j1 = floor(j+1/2)
- Also compute fractional weights for bilinear filtering
  - a = frac(i-1/2)
  - b = frac(j-1/2)

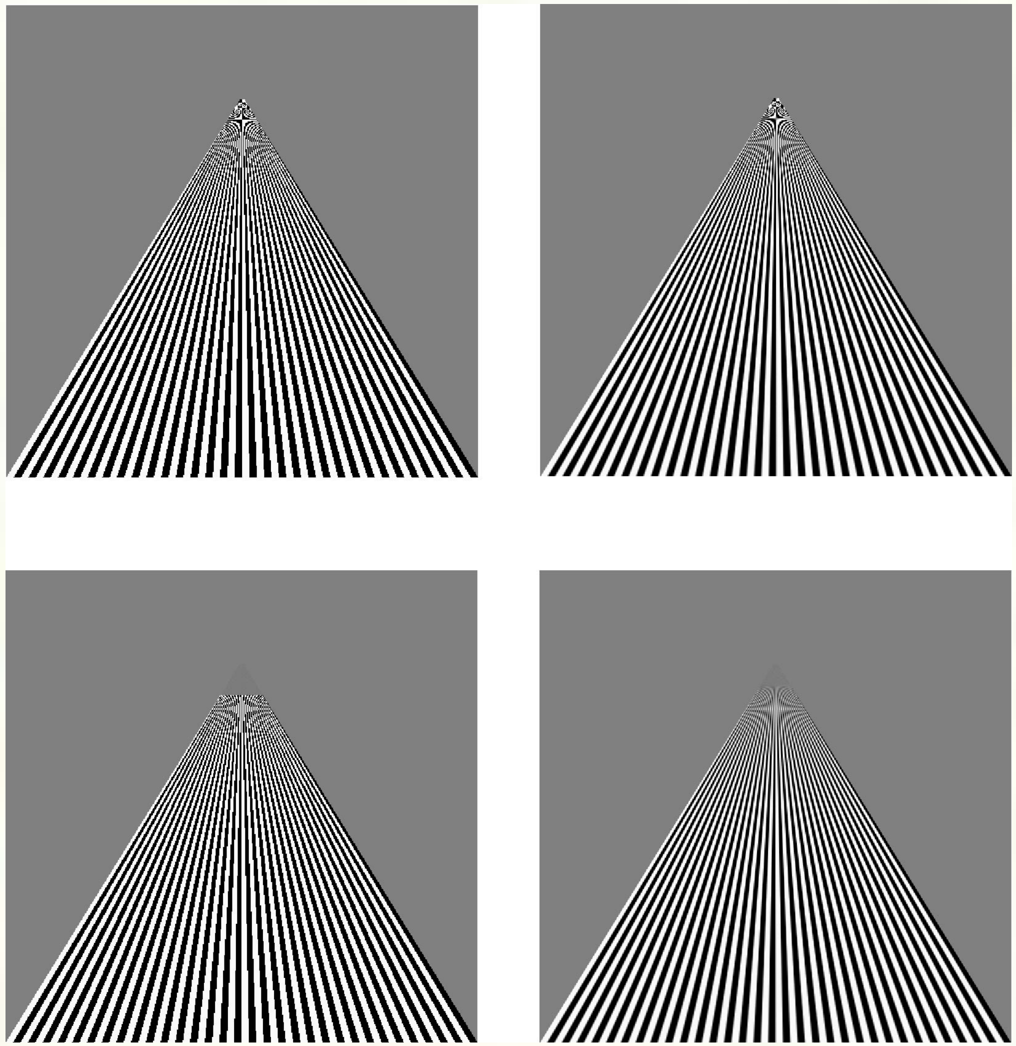
Determine Texel Addresses

- Assuming a texture level image's base pointer, compute a texel address of each texel to fetch
  - Assume bytesPerTexel = 4 bytes for RGBA8 texture
- Example
  - addr00 = baseOfLevel(l) + bytesPerTexel*(i0+j0*widthOfLevel(l))
  - addr01 = baseOfLevel(l) + bytesPerTexel*(i0+j1*widthOfLevel(l))
  - addr10 = baseOfLevel(l) + bytesPerTexel*(i1+j0*widthOfLevel(l))
  - addr11 = baseOfLevel(l) + bytesPerTexel*(i1+j1*widthOfLevel(l))
- More complicated address schemes are needed for good texture locality!

Mipmap Texture Filtering

point sampling

linear filtering



mipmapped point sampling

mipmapped linear filtering

Anisotropic Texture Filtering

- Standard (isotropic) mipmap LOD selection
  - Uses magnitude of texture coordinate gradient (not direction)
  - Tends to spread blurring at shallow viewing angles
- Anisotropic texture filtering considers gradients direction
  - Minimizes blurring

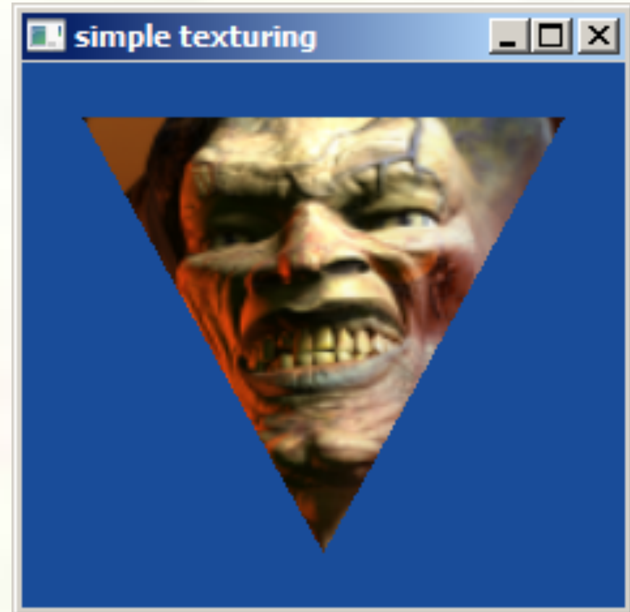
Isotropic

Anisotropic

Texture Mapping in OpenGL

ST = (0,0)

ST = (1,1)



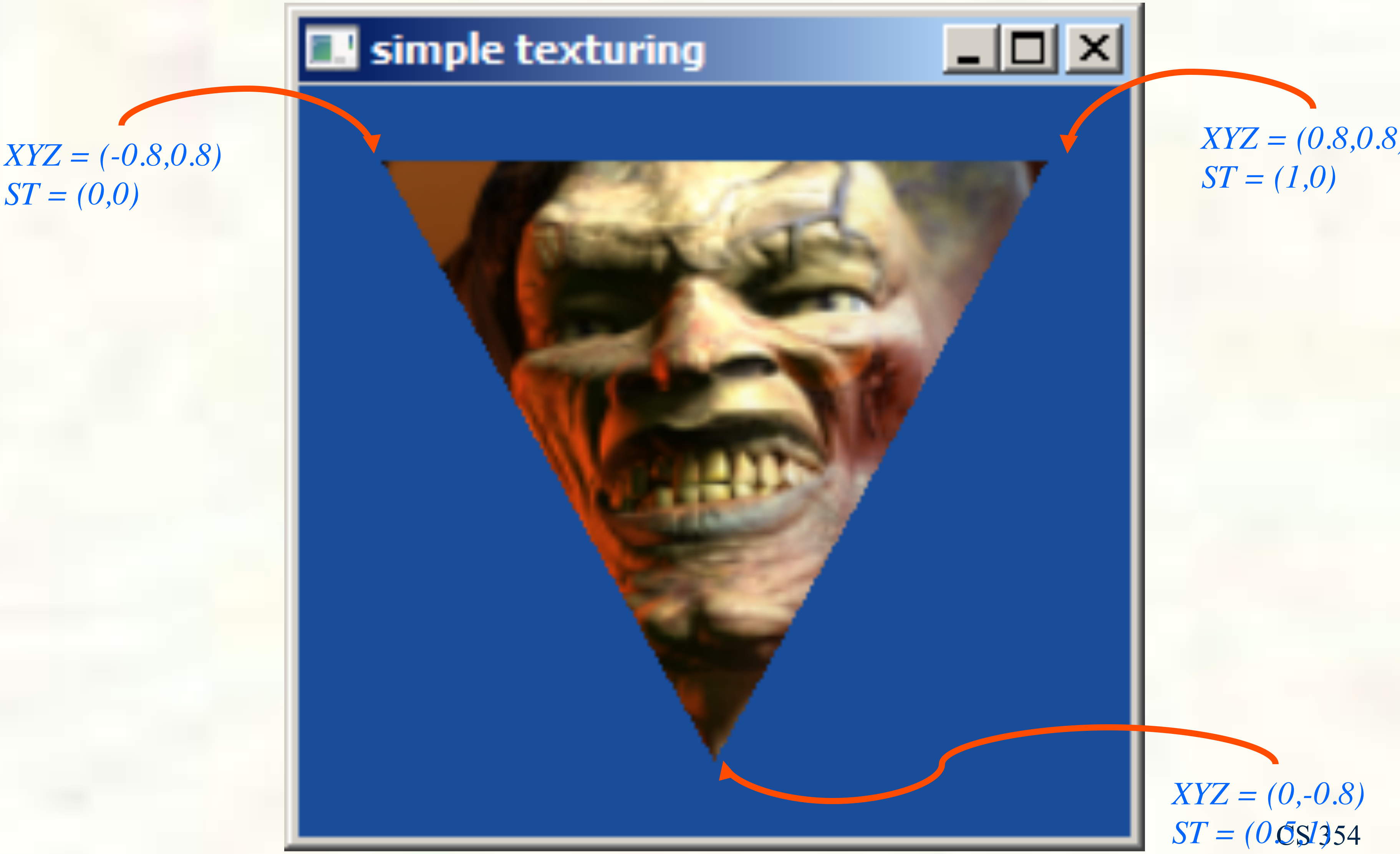

```
glBegin(GL_TRIANGLES);
  glTexCoord2f(0, 0);
  glVertex2f(-0.8, 0.8);

  glTexCoord2f(1, 0);
  glVertex2f(0.8, 0.8);

  glTexCoord2f(0.5, 1);
  glVertex2f(0.0, -0.8);
glEnd();
```

glTexCoord2f like glColor4f but sets "current" texture coordinate instead of color

glMultiTexCoord2f takes texture unit parameter so

glMultiTexCoord2f(GL_TEXTURE0, s,t) same as glTexCoord2f(s,t)

Vertex Texture Coordinates



Loose Ends of Texture Setup

- Texture object specification

```
static const GLubyte
myDemonTextureImage[3*(128*128)] = {
/* RGB8 image data for a mipmapped 128x128
    demon texture */
#include "demon_image.h"
};

/* Tightly packed texture data. */
glPixelStorei(GL_UNPACK_ALIGNMENT, 1);

glBindTexture(GL_TEXTURE_2D, 666);
/* Load demon decal texture with mipmaps. */
gluBuild2DMipmaps(GL_TEXTURE_2D, GL_RGB8,
  128, 128, GL_RGB, GL_UNSIGNED_BYTE,
    myDemonTextureImage);
glTexParameteri(GL_TEXTURE_2D,
  GL_TEXTURE_MIN_FILTER,
  GL_LINEAR_MIPMAP_LINEAR);
```

- Fixed-function texture binding and enabling

```
glActiveTexture(GL_TEXTURE0);
glTexEnvi(GL_TEXTURE_ENV,
  GL_TEXTURE_ENV_MODE, GL_REPLACE);
glEnable(GL_TEXTURE_2D);
glBindTexture(GL_TEXTURE_2D, 666);
```

gluBuild2DMipmaps calls glTexImage2D on image, then down-samples iteratively 64x64, 32x32, 16x16, 8x8, 4x4, 2x1, and 1x1 images (called mipmap chain)