

Dieter Schmalstieg

Texture Mapping

Based on material from Michael Wimmer, Eduard Gröller, Thomas Theussl, Michael Kenzel

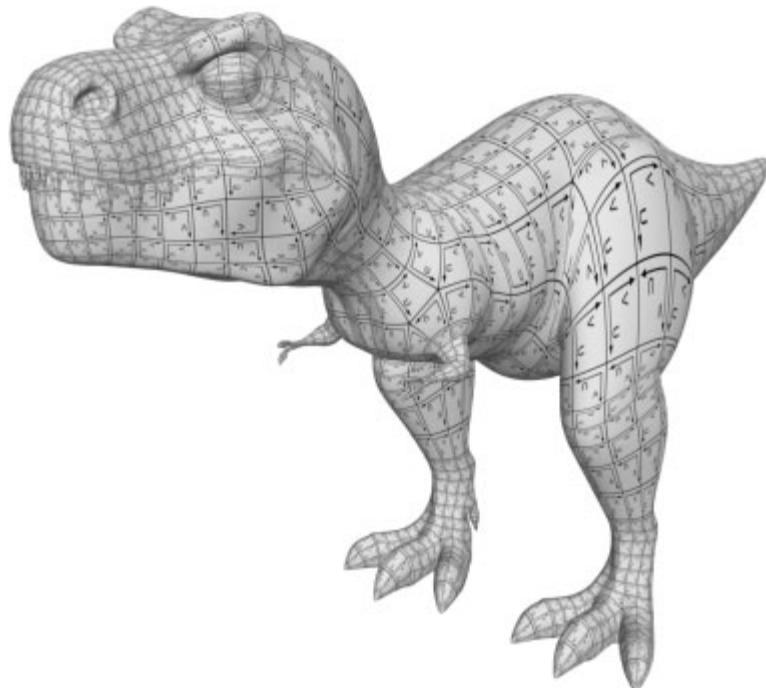


Overview

- Basic texture mapping
 - Texture coordinate generation
 - Filtering
- Advanced texture mapping
 - Multitexture/multipass
 - Projective texturing
 - Environment mapping
 - Bump mapping
 - Per-pixel lighting

Why Texturing?

- Enhance visual appearance of plain surfaces and objects by applying fine structured details



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Texture mapping

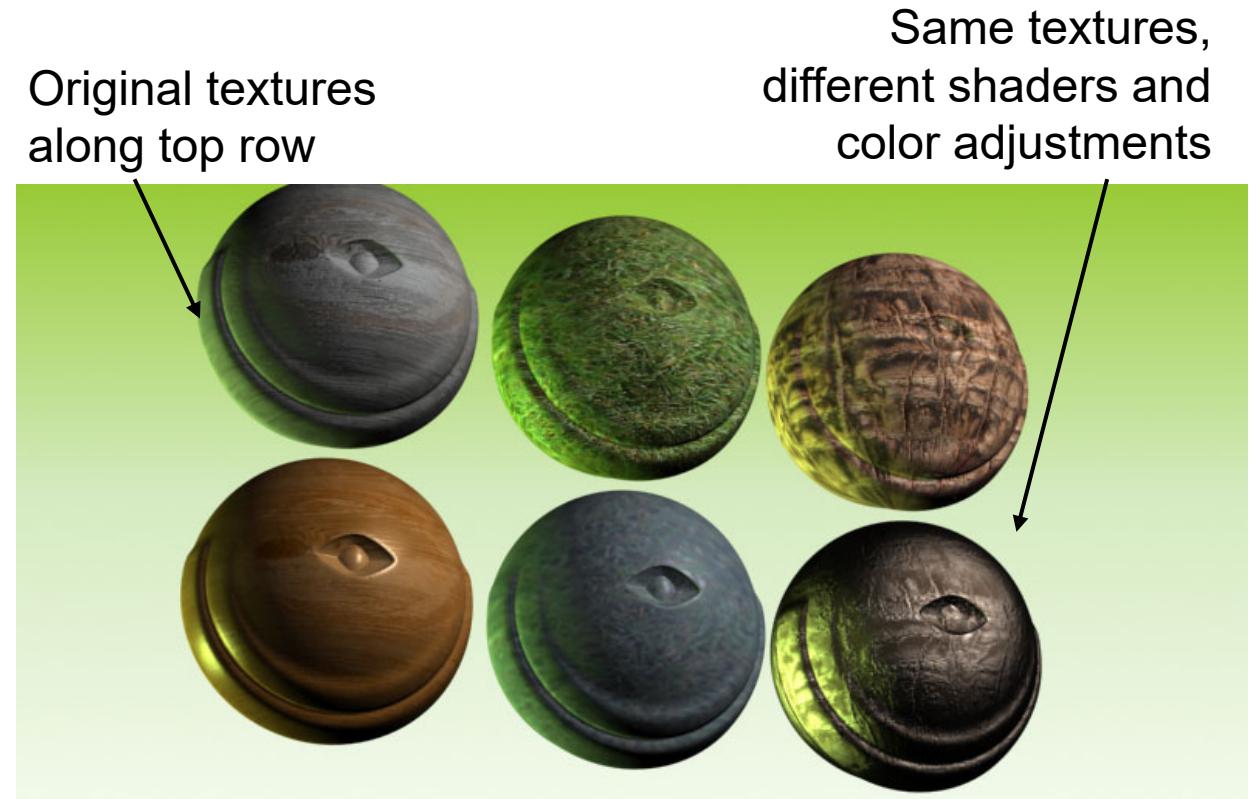
What is a Texture?

- Provides look and feel of a surface
- Definition
 - A *function* that is evaluated for every *fragment* of a surface
 - Usually given as a 2D image
- Can hold arbitrary information
 - Texture data interpreted in fragment shader
 - Basis for most advanced rendering effects

Textures as Patterns

Material properties simulation:

- Color
- Reflection
- Gloss
- Transparency
- Bumps

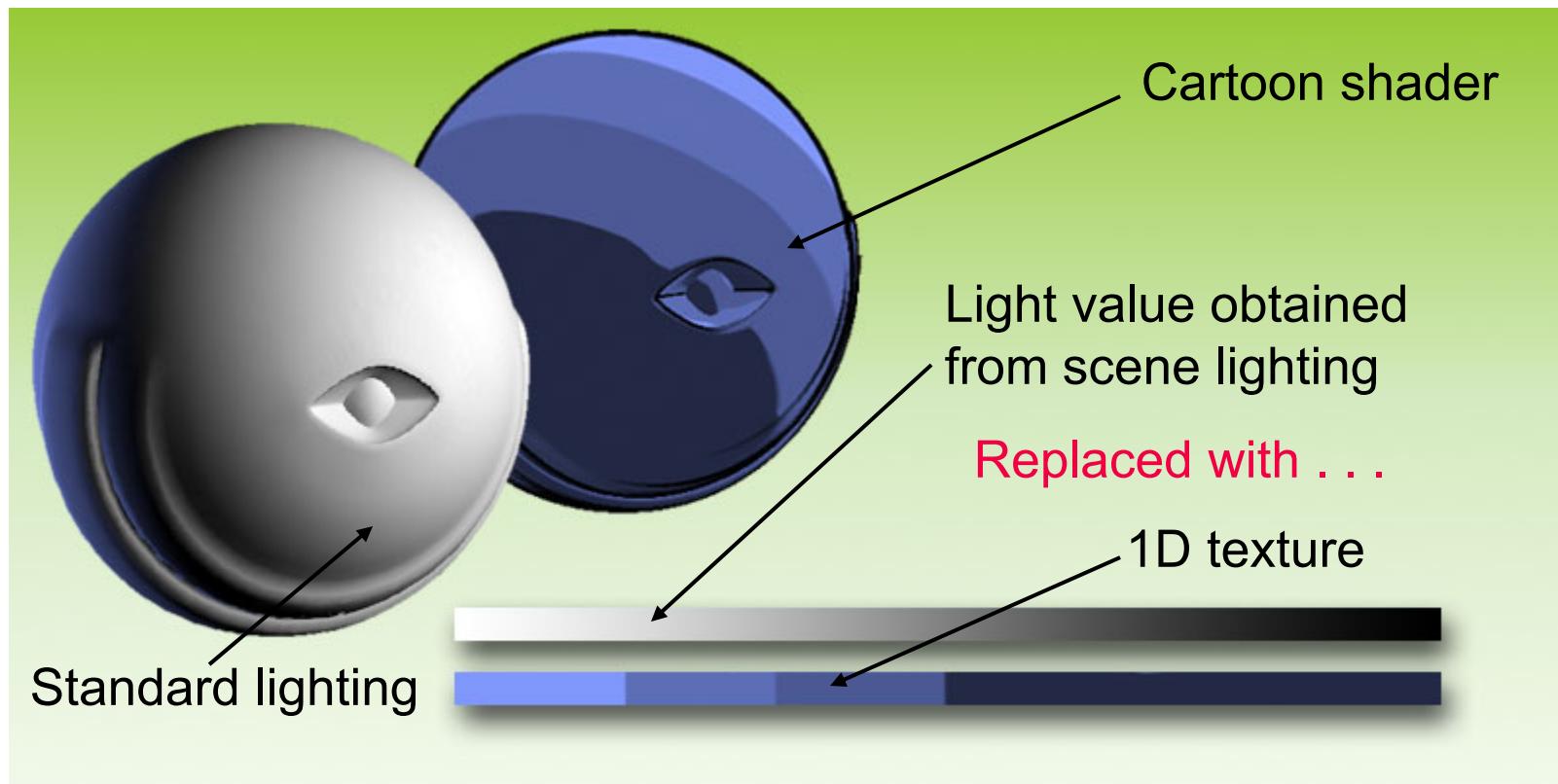


Textures are just color and value combinations, the same texture can be used in many different ways

Texture Types

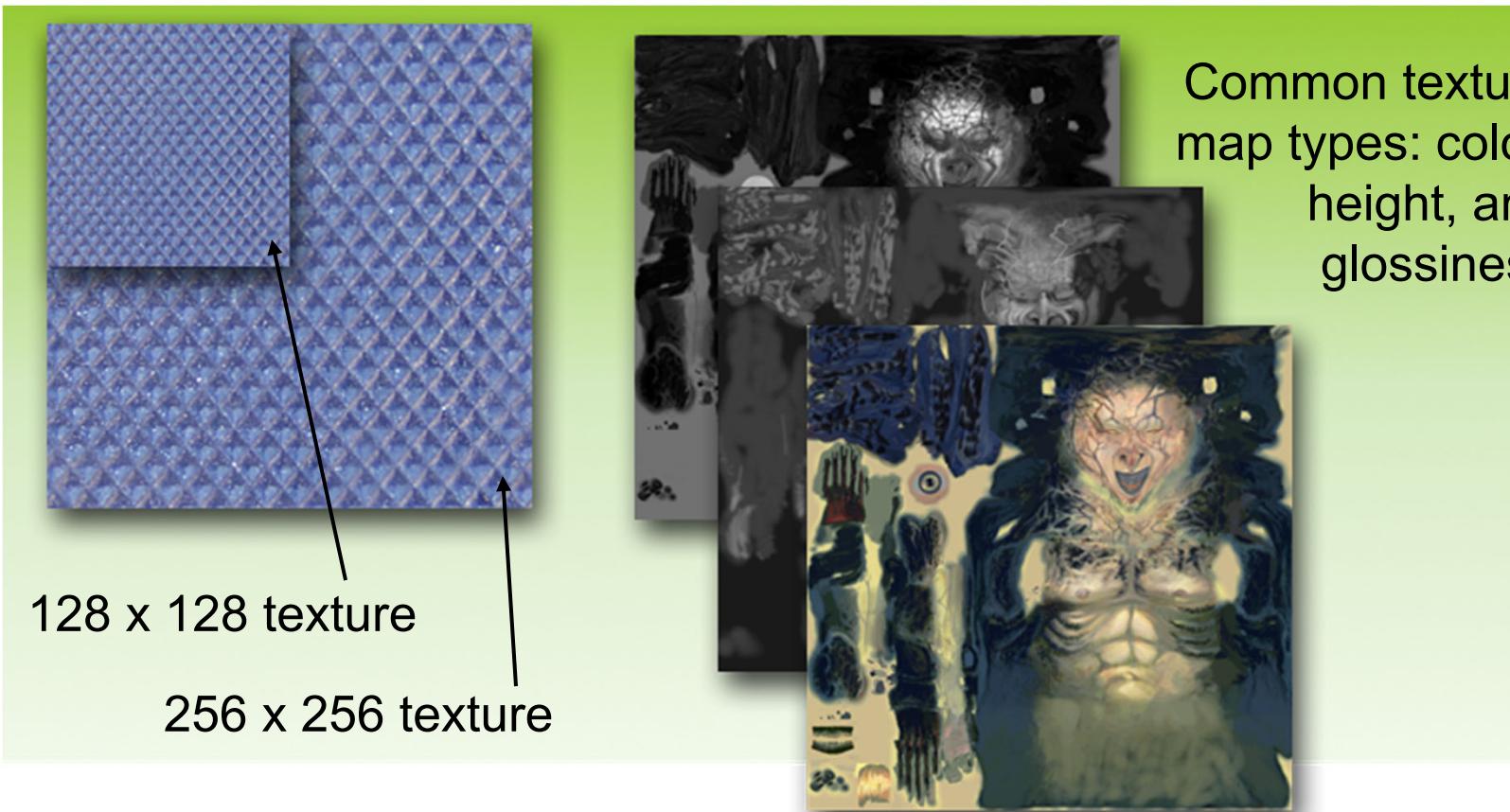
- One-dimensional functions
 - Parameter can have arbitrary domain
(e.g., incident angle)
- Two-dimensional functions
 - Information is calculated for every (u,v)
 - Many possibilities
- Raster images (“texels”)
 - Most often used method
 - Images from scanner or calculation
- Three-dimensional functions
 - Volume $T(u,v,w)$

1D Textures



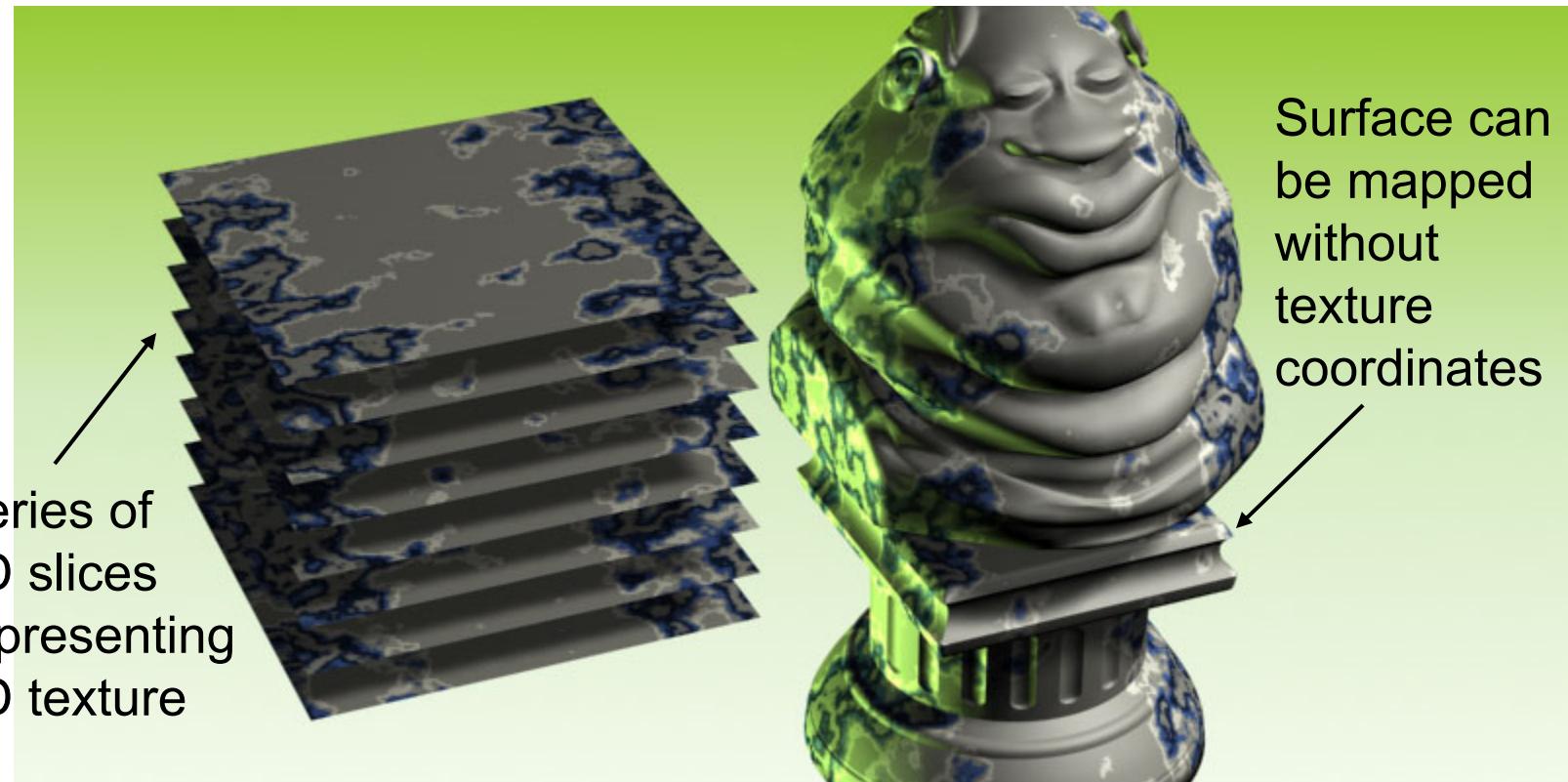
1D texture can be substituted for any linear value used in shader

2D Textures



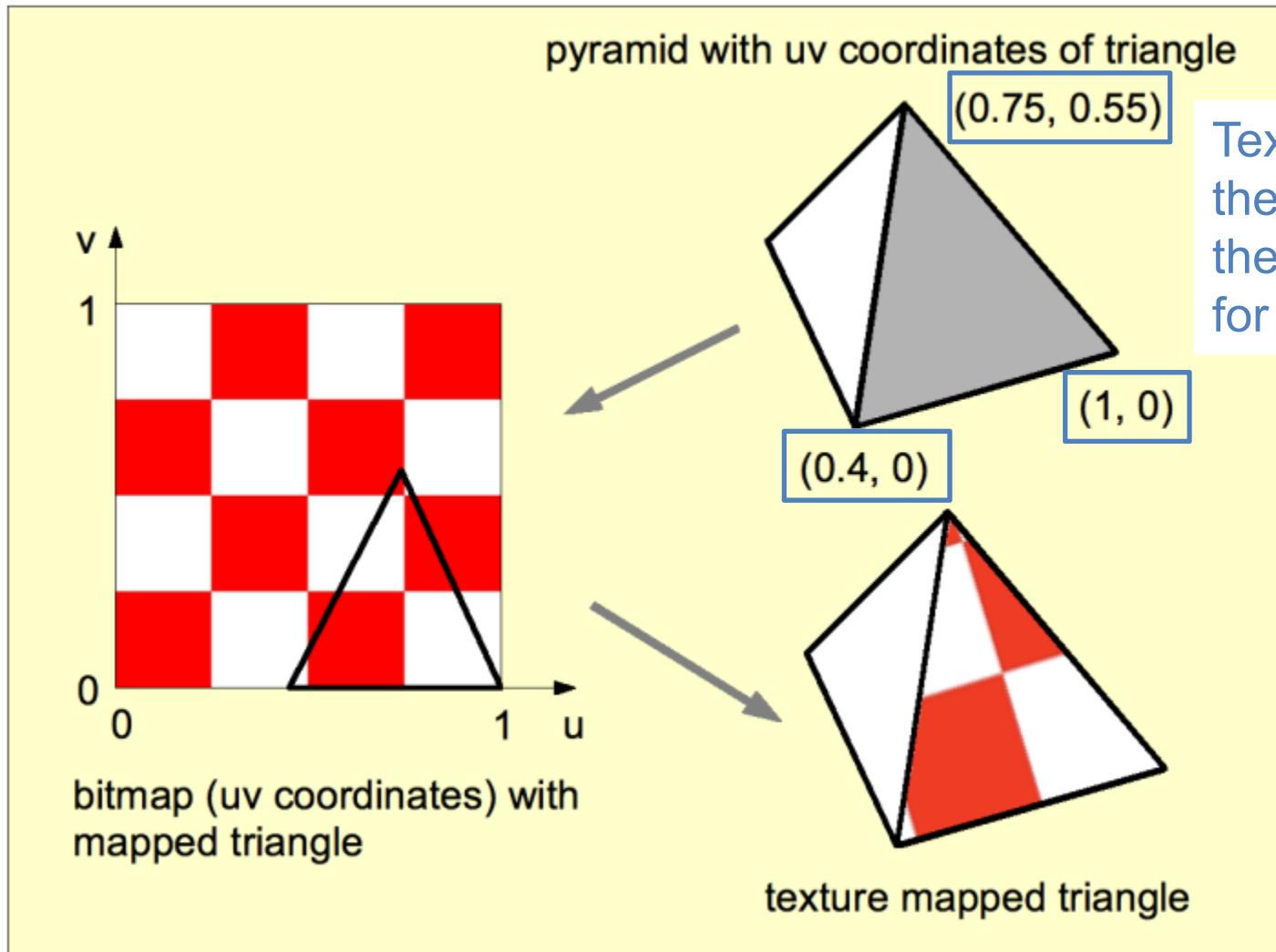
2D directly relate to surfaces

3D Textures



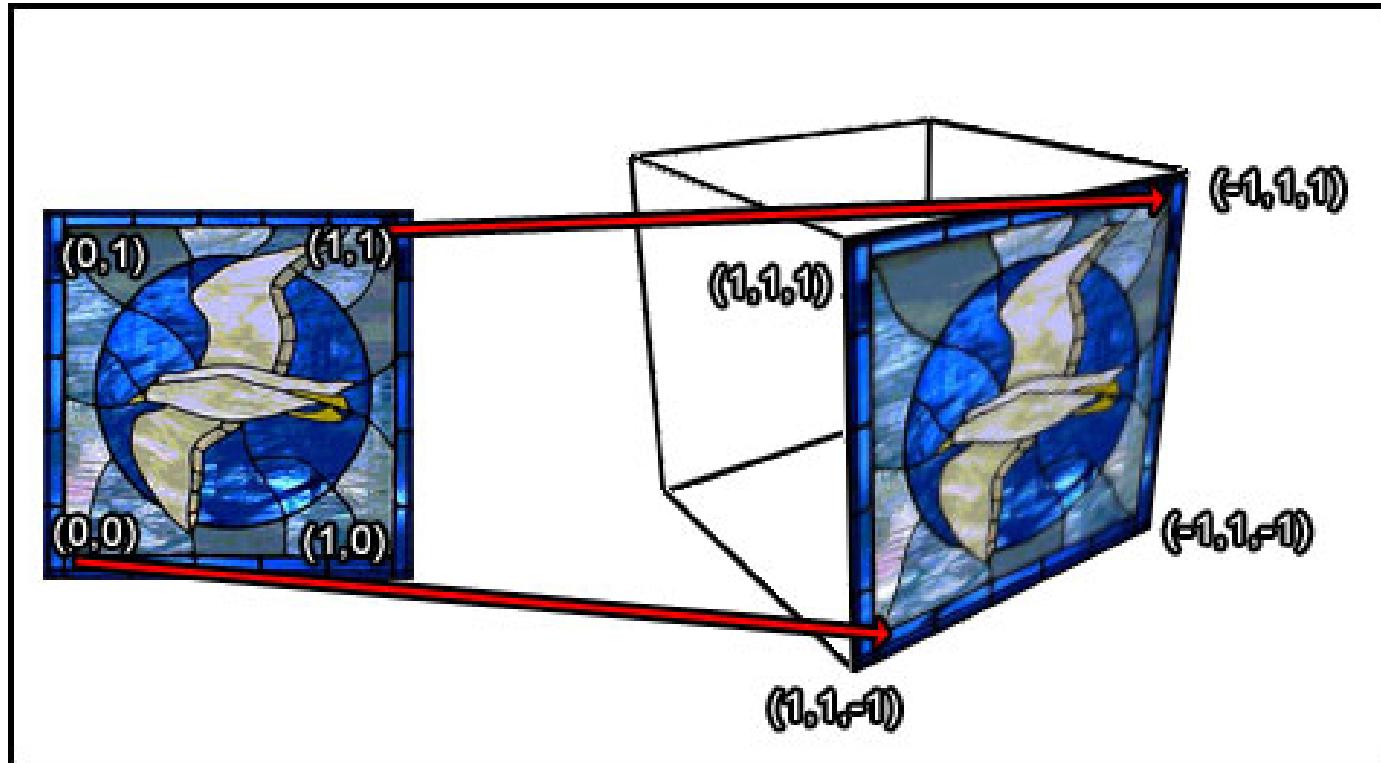
3D textures can represent procedural textures

Texture Coordinates



Parametrization

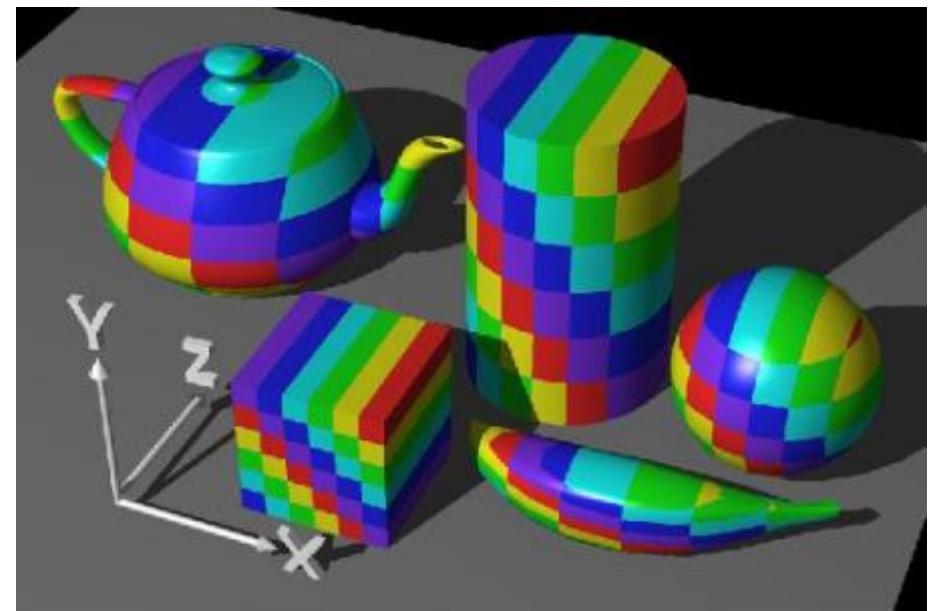
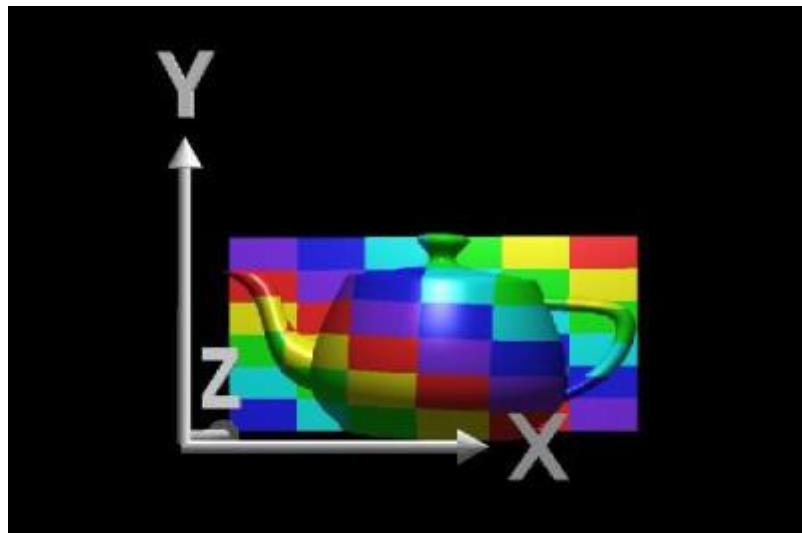
- How to do the mapping?



- Usually objects are not that simple

Parametrization: Planar

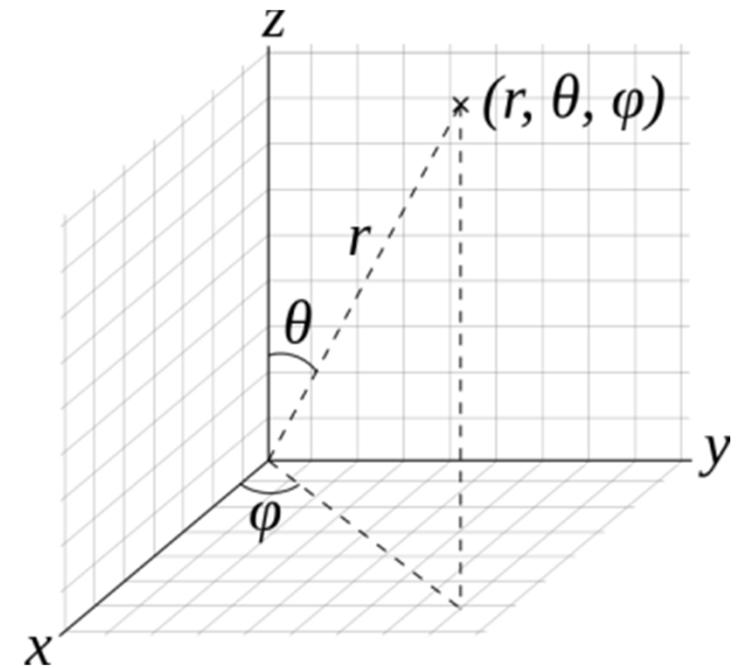
- Planar mapping: dump one of the coordinates



Only looks good from the front!

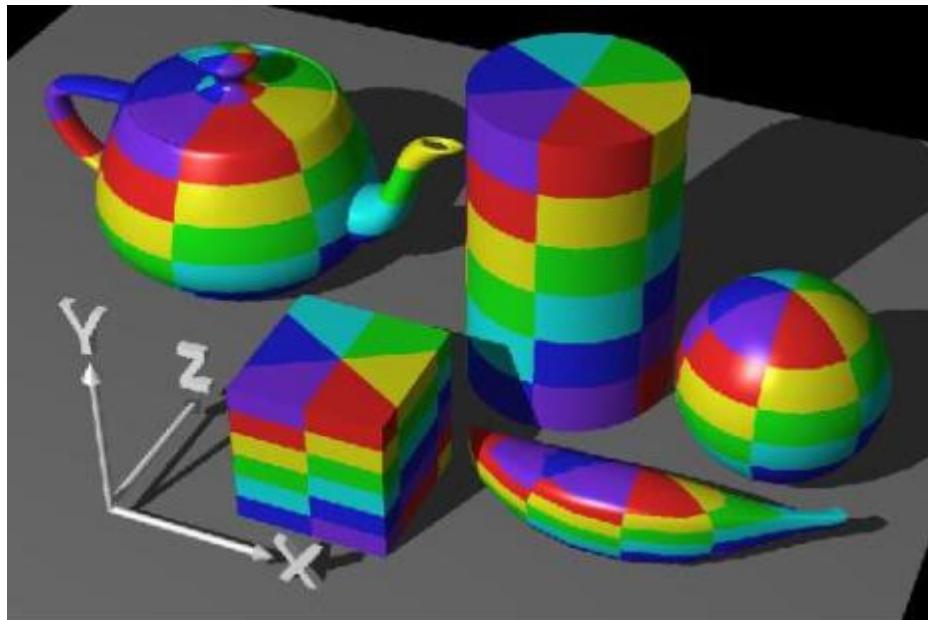
Parametrization: Cylindrical

- Cylindrical and spherical mapping: compute angles between vertex and object center
- Compare to polar/spherical coordinate systems

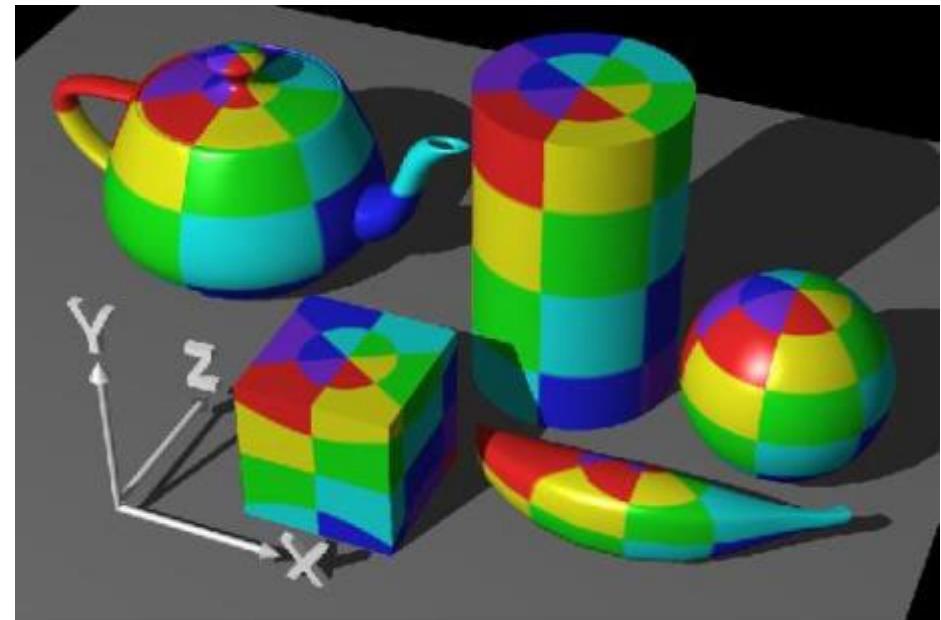


Parametrization: Polar

- Cylindrical and spherical mapping



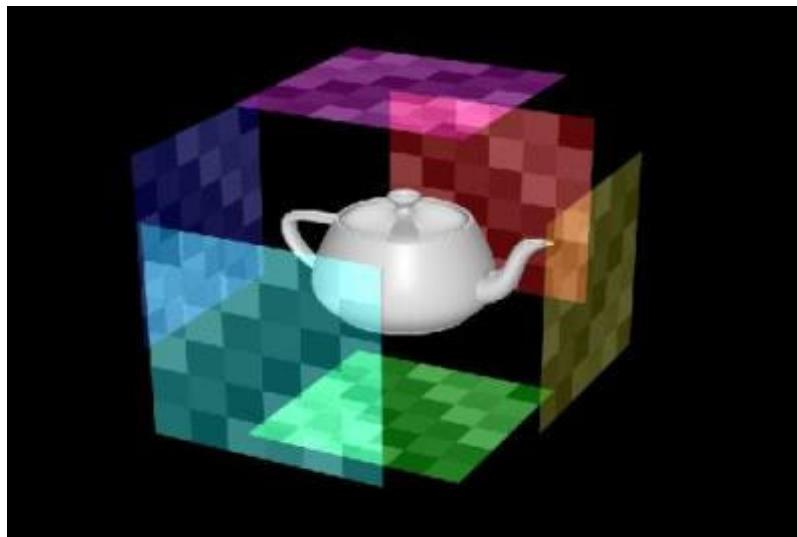
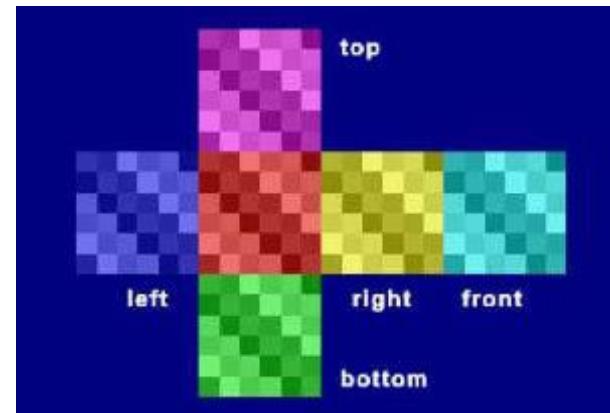
Cylindrical



Spherical

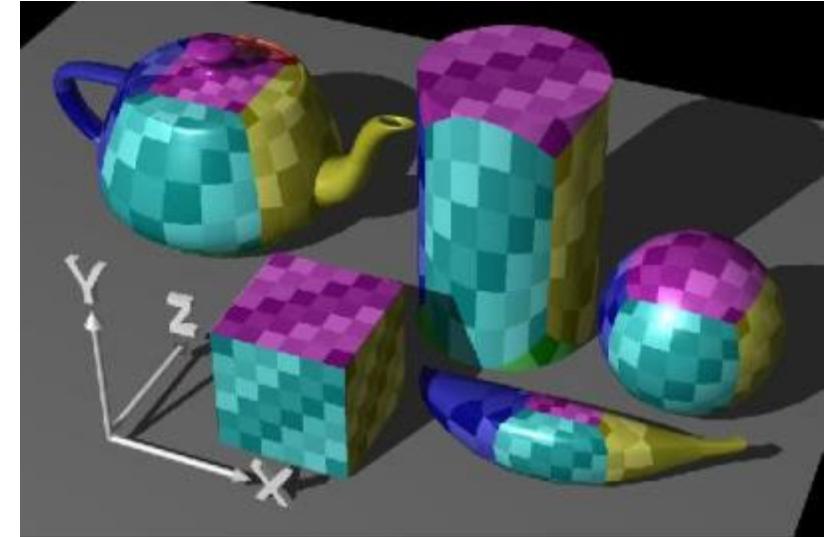
Parametrization: Box

- Box mapping: used mainly for environment mapping
(see later)



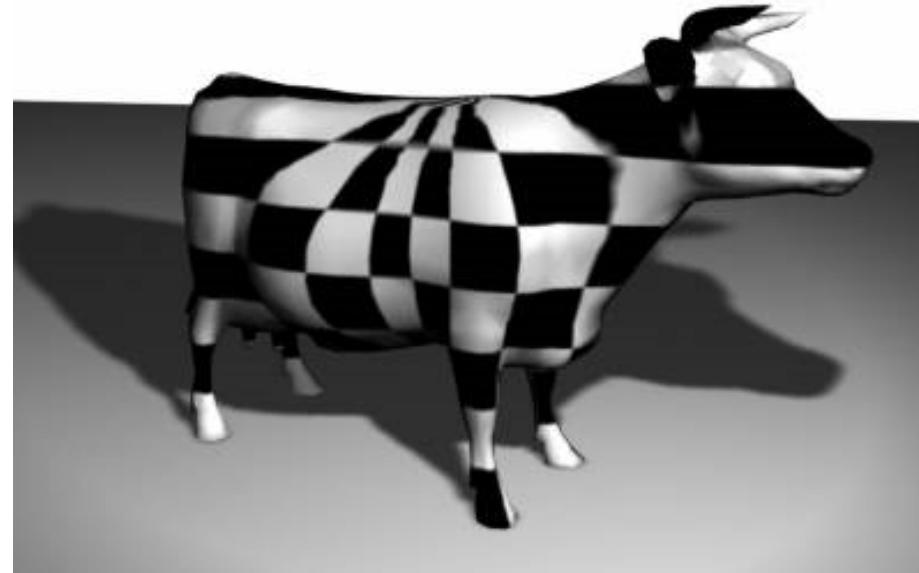
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Texture mapping



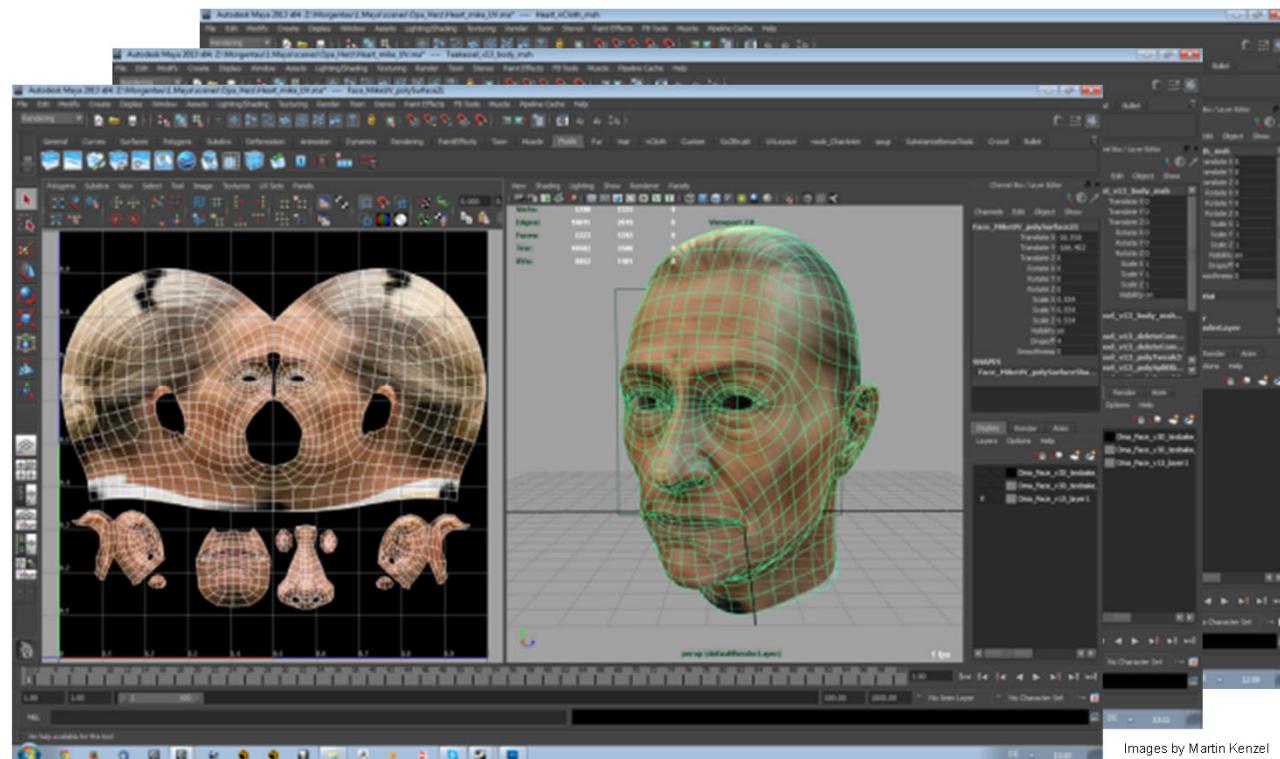
Parametrization Problems

- All mappings have distortions and singularities
- Often they need to be fixed manually (CAD software)



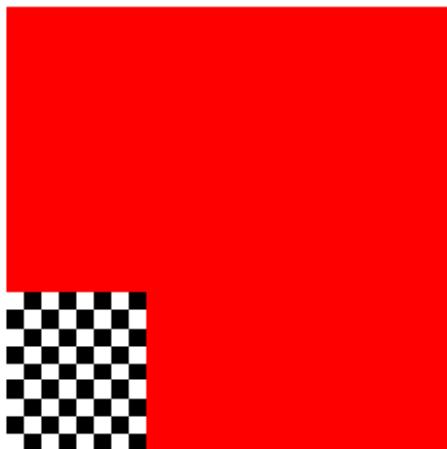
Manual Parametrization

- Manual mapping using CAD Software
 - “Unwrapping”



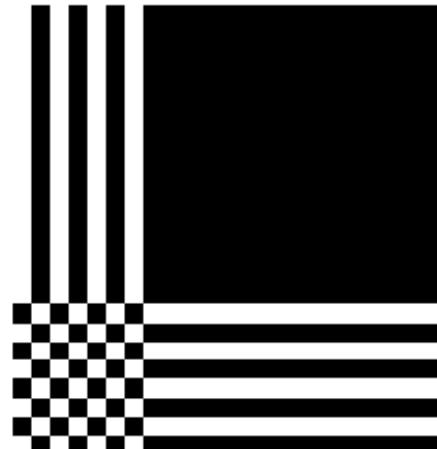
Texture Addressing

- What happens outside $[0,1]$?
- Border, repeat, clamp, mirror
- Also called texture addressing modes



Texture with red border applied to primitive

Static color

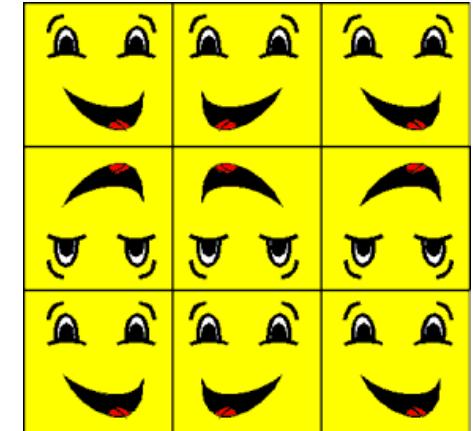


Clamped texture applied to primitive

Clamped



Repeated



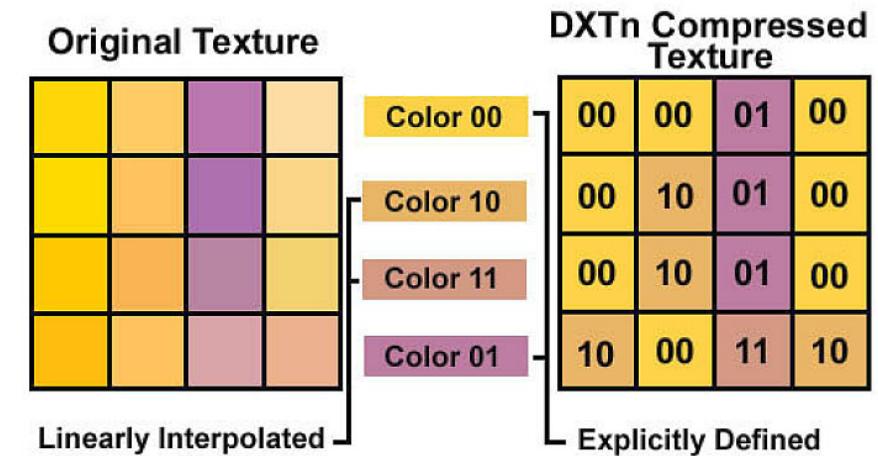
Mirrored

Texture Animation

- Texture Matrix
 - Can specify an arbitrary 4x4 Matrix, each frame!
 - `glMatrixMode(GL_TEXTURE);`
 - There is also a texture matrix stack!
 - Possibilities: moving water or sky
- Custom shader programs
 - Can use video as texture
 - Allows arbitrary texture animations

Texture Compression

- S3TC texture compression
 - Represent 4x4 texel block by two 16bit colors (RGB 5/6/5bit)
 - Store 2 bits per texel
- Uncompress
 - Create 2 additional colors between c_1 and c_2
 - Use 2 bits to index into color map
- Compression ratio 4:1 or 6:1

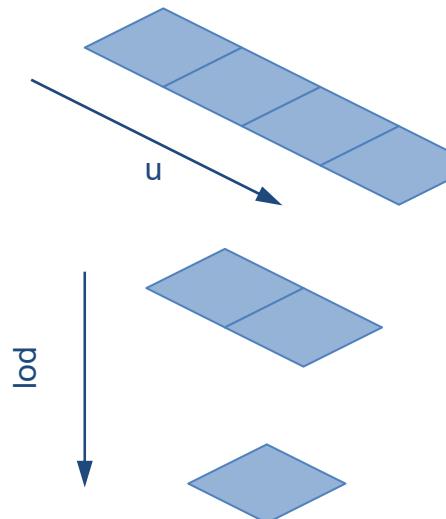


Texture Representation on GPU

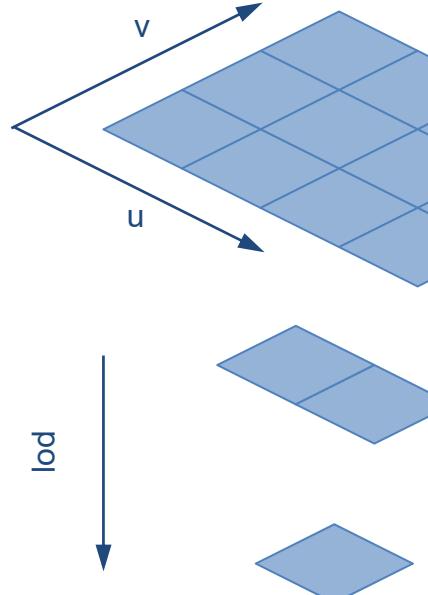
- Texture Image = array of *texels*
 - Certain dimensionality
 - Certain format (e. g., GL_RGBA8)
- Texture Objects
 - Group of one or more texture images
 - Images can represent mip levels, array slices...
- Sampler Objects
 - Configure texture sampling (interpolation mode...)

Texture Dimensions

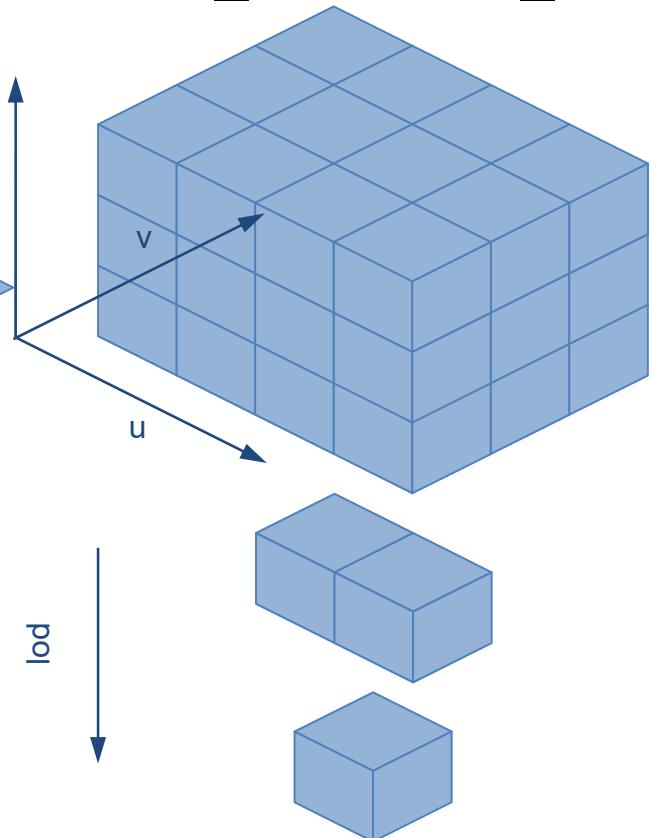
GL_TEXTURE_1D



GL_TEXTURE_2D



GL_TEXTURE_3D



Texture Format and Specification

Format

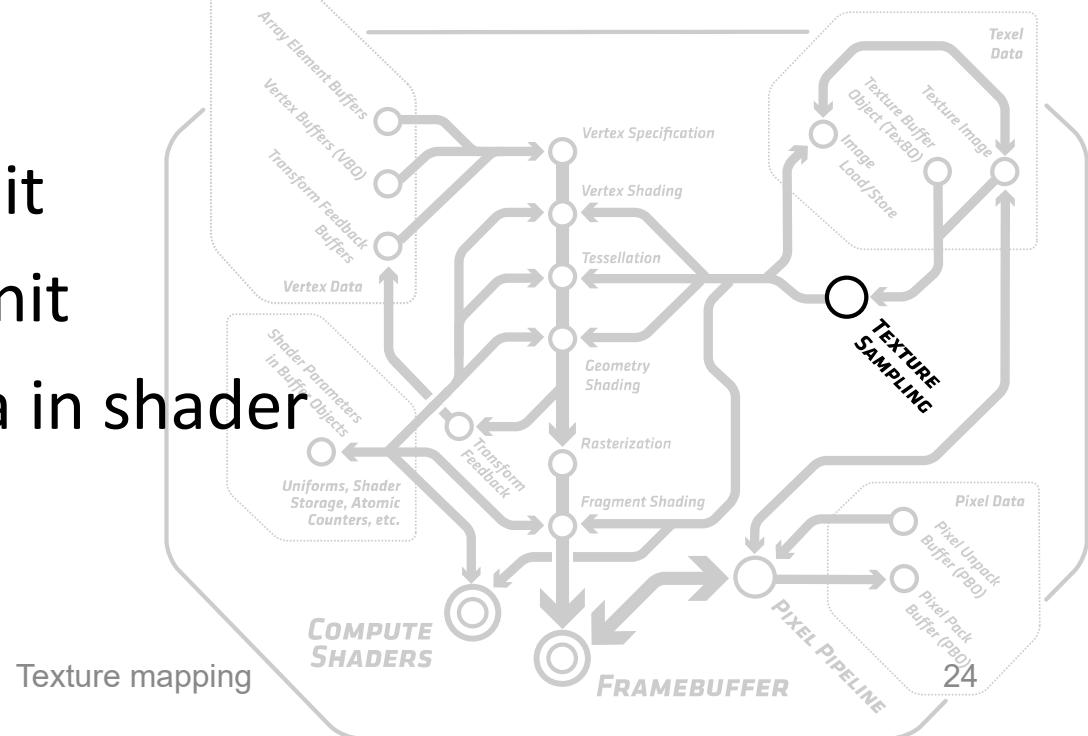
- Numerical format
 - Integer, float, double
- Bits per number
 - 8, 16, 32, 64
- Channels
 - Red, green, blue, alpha, depth, stencil

Specification

- Texture id
- Dimension
- External format
- Internal format
- Width, height
- Pointer to raw data

Sampler Objects

- Samplers configure texture units
 - Filtering, address mode, ...
- How texture units work
 - There is a limited number of units
 - Activate the unit
 - Bind texture to a unit
 - Bind sampler to a unit
 - Sample texture data in shader

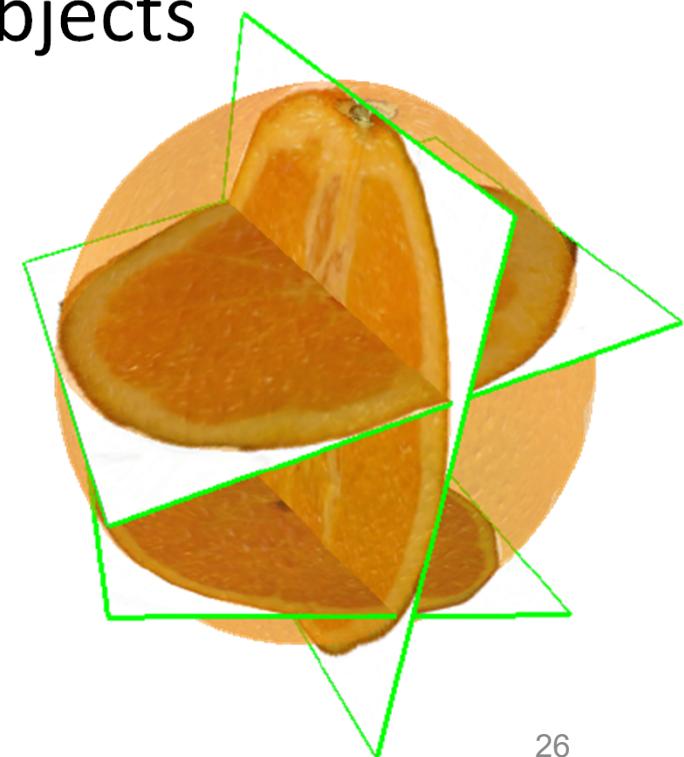


2D Texture Example: Fragment Shader

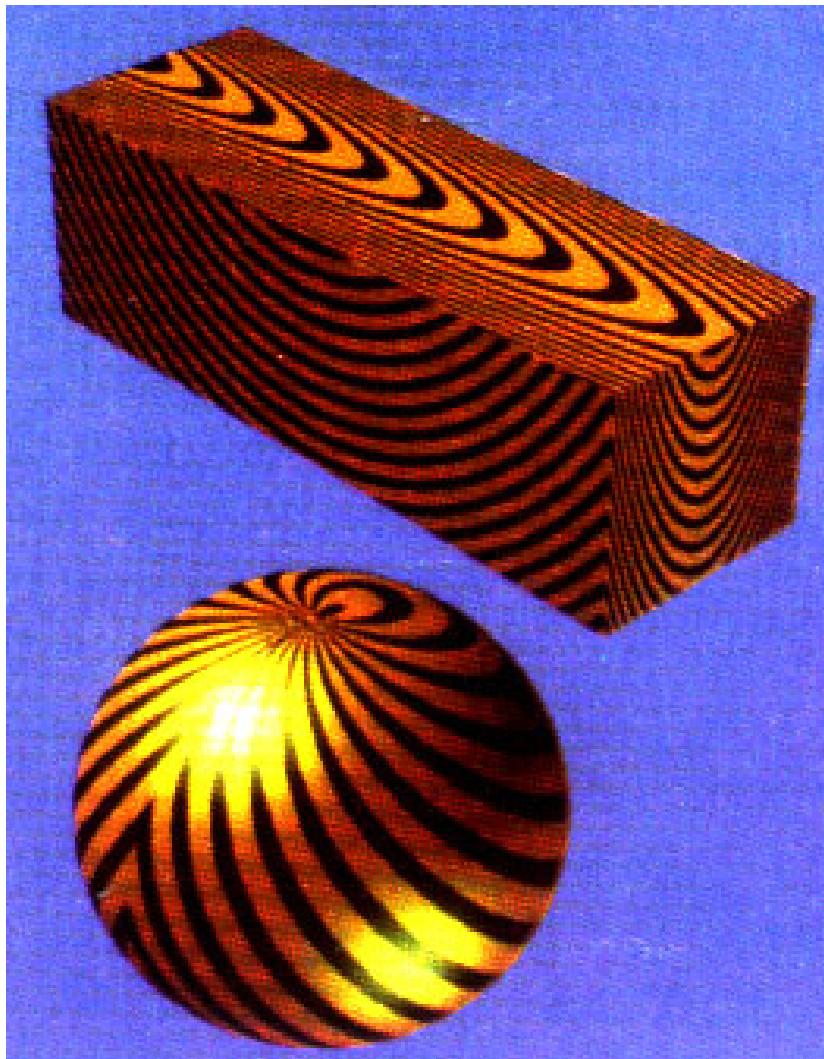
```
1 #version 330
2
3 uniform sampler2D my_texture;
4
5 in vec2 tex_coords;
6
7 layout(location = 0) out vec4 fragment_color;
8
9 void main()
10 {
11     fragment_color = texture(my_texture, tex_coords);
12 }
```

3D Texture Mapping

- Often referred to as *solid texturing*
- Directly map object space $T(x,y,z)$ to (u,v,w)
- Possible to slice/carve/open objects

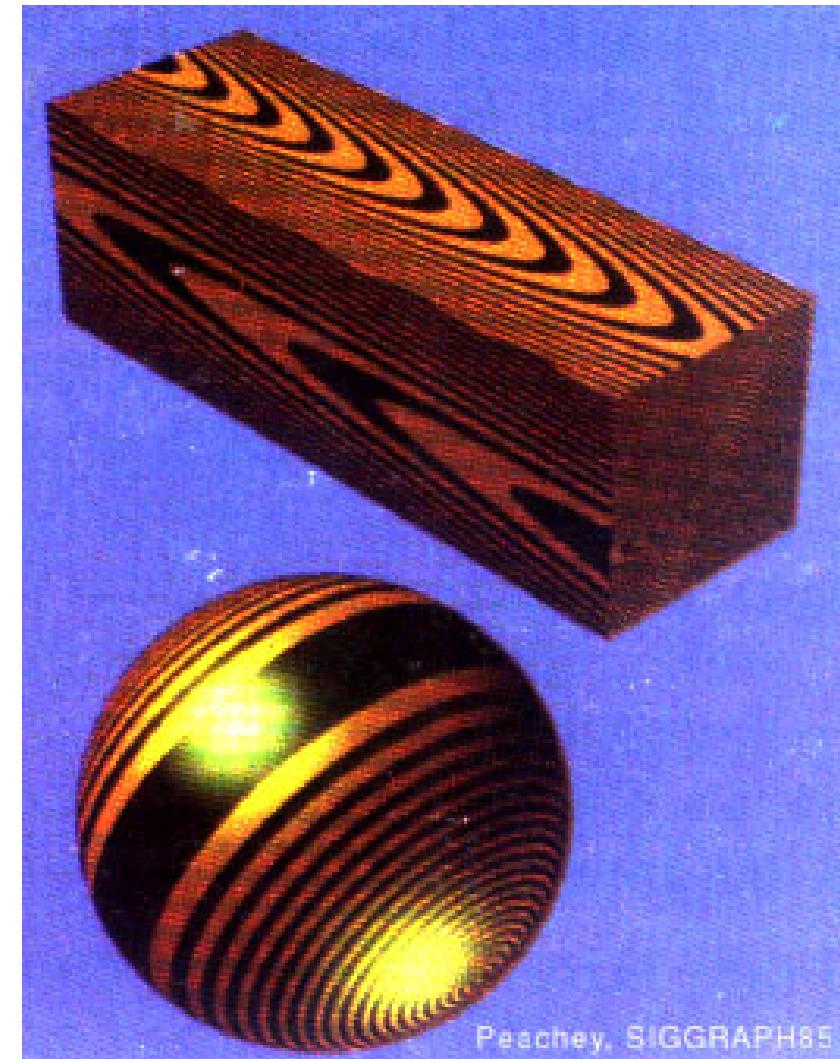


Mapping vs Solid Texturing



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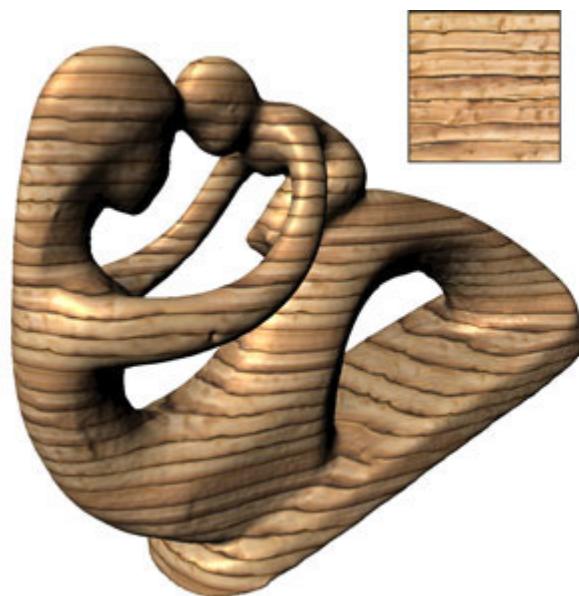
Texture mapping



Peachey, SIGGRAPH85

Solid Texturing Examples

- Carved objects: wood, marble, stone...



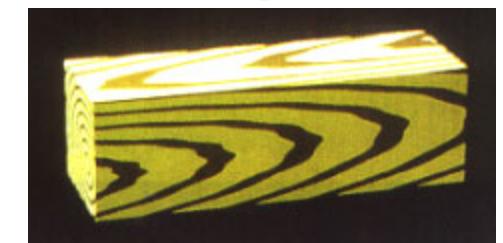
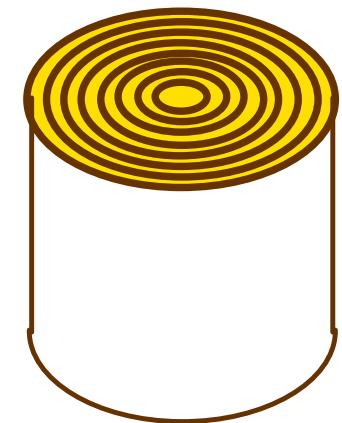
Procedural Solid Textures

- **3D functions**

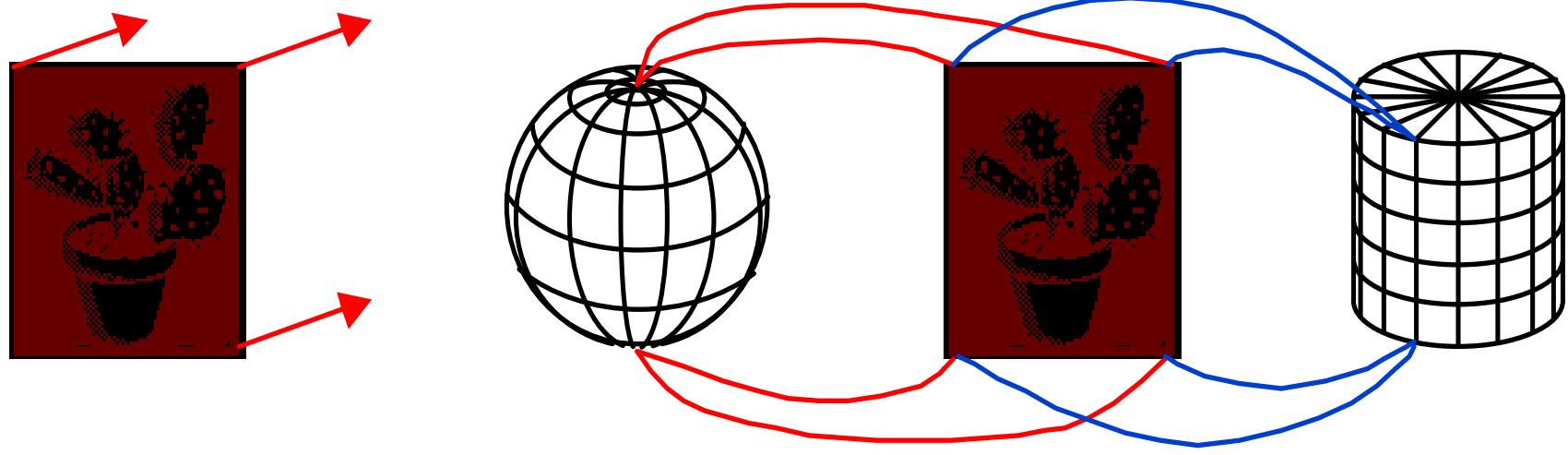
e.g., $0 \leq x^2+y^2 < 1 \Rightarrow$ light brown

$1 \leq x^2+y^2 < 2 \Rightarrow$ dark brown

$2 \leq x^2+y^2 < 3 \Rightarrow$ yellow etc.



- **Projections of 2D data**



Volumetric Textures

- 3D „voxel“ array of texture values
- Explicit, sampled function
- E.g., from medical scanners (CT, MRT, ...)
 - + Works in real time
 - Lots of memory needed...

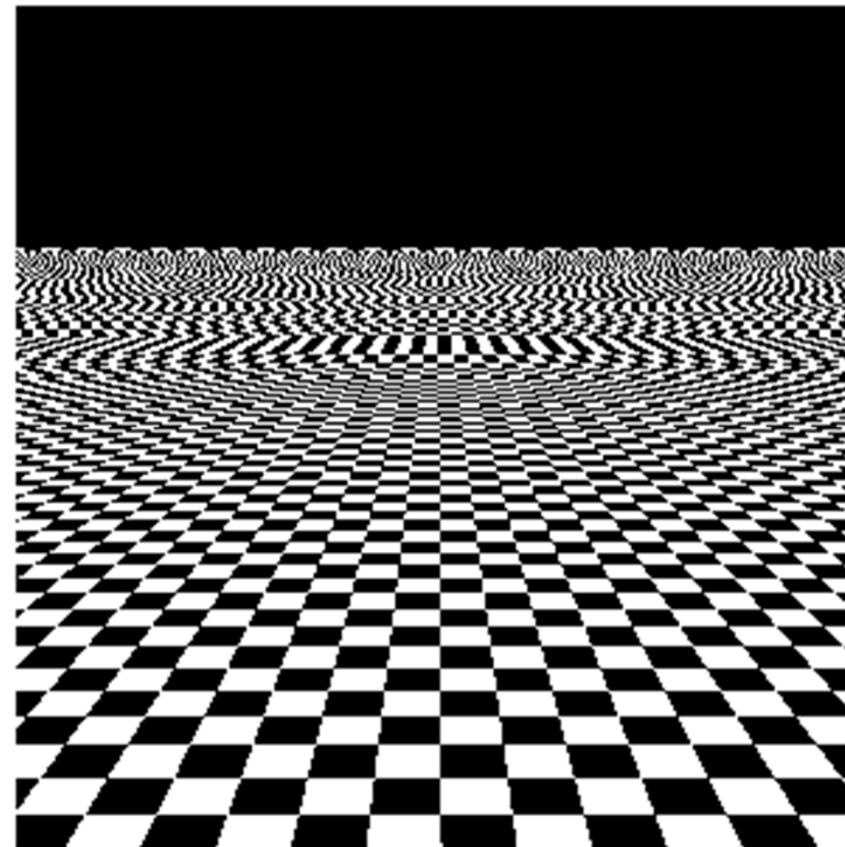


Volumetric Fog



Aliasing

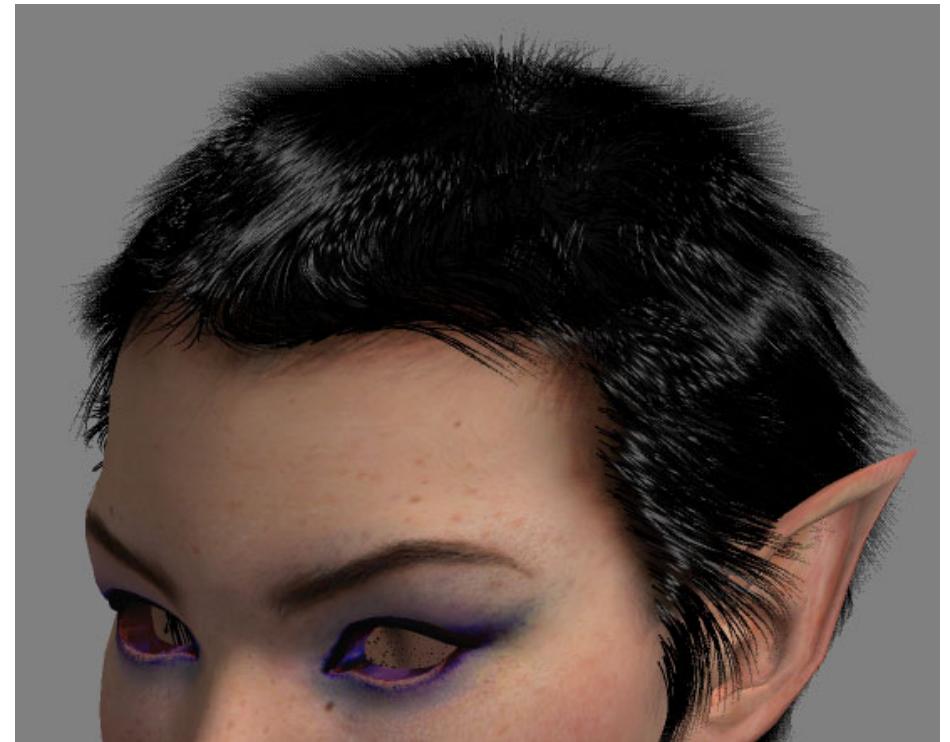
One screen pixel maps to many texels → Aliasing!



Hair



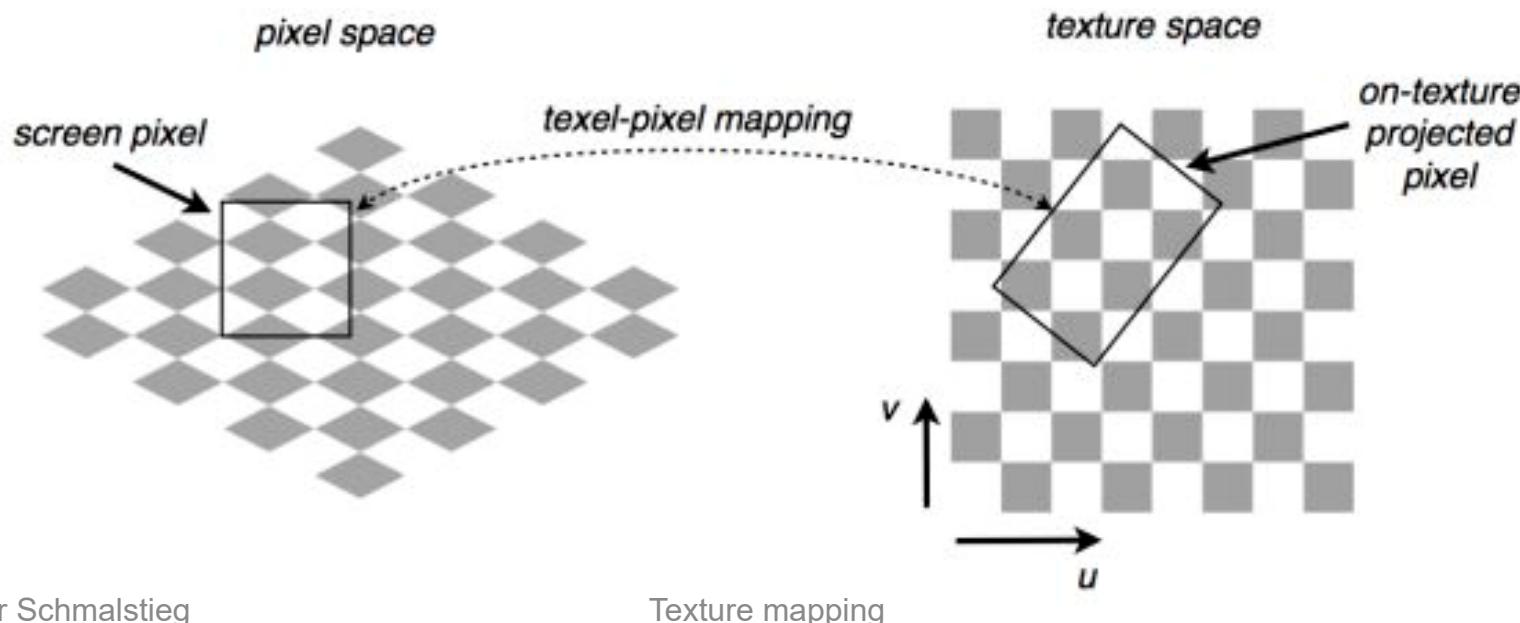
Without antialiasing



With antialiasing

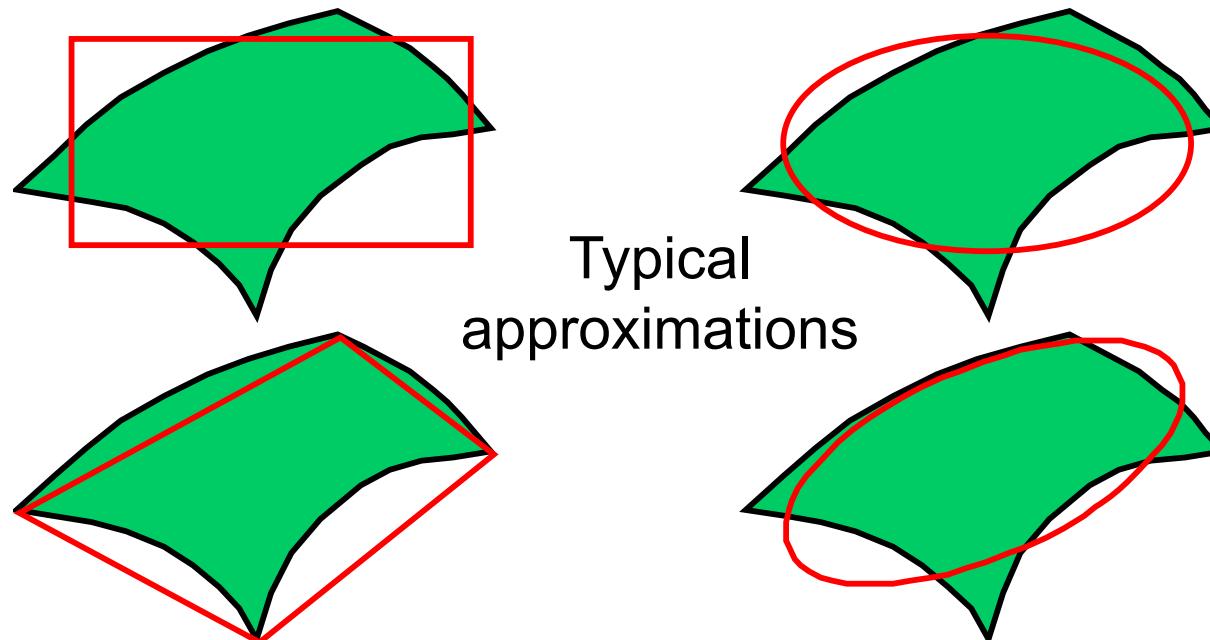
Antialiasing of Textures

- Correct pixel value is (weighted) mean of pixel area projected (back) into texture space
- Two approaches:
 - Direct convolution
 - Prefiltering



Direct Convolution

Calculate weighted mean of relevant texels



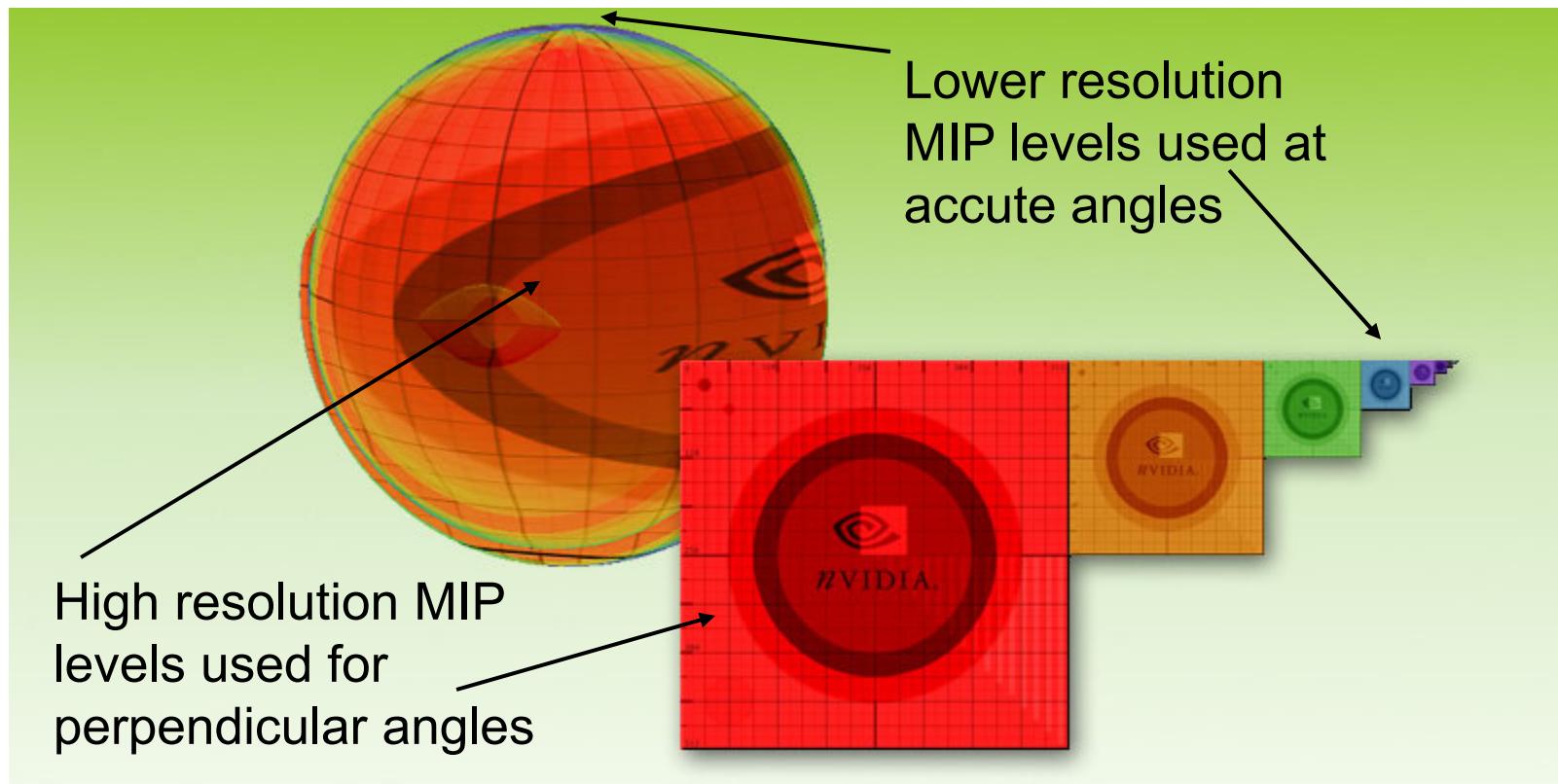
Real-time: approximate with fixed sample num.

Mip Mapping

downsampling \Rightarrow much in a small area
= “multum in parvo” (mip)

- Texture is precalculated for different sizes
- Heavily used in real-time graphics
- Texture is reduced by factors of two
 - Simple
 - Memory efficient
- The last image is only one texel

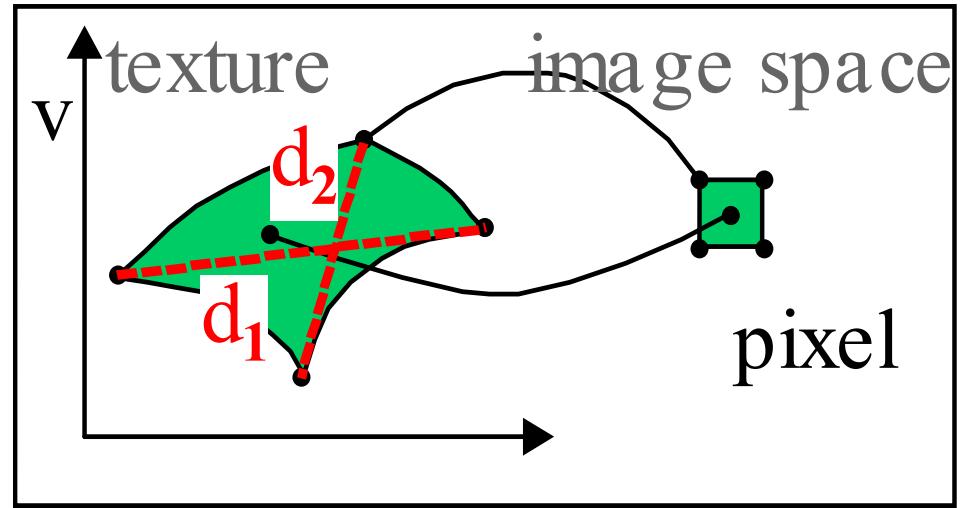
Mip Mapping Example



Mip Maps reduce bandwidth requirements of distant textures and minimize scintillating pixels

Mip Mapping Algorithm

$$D := \lfloor d(\max(|d_1|, |d_2|)) \rfloor$$



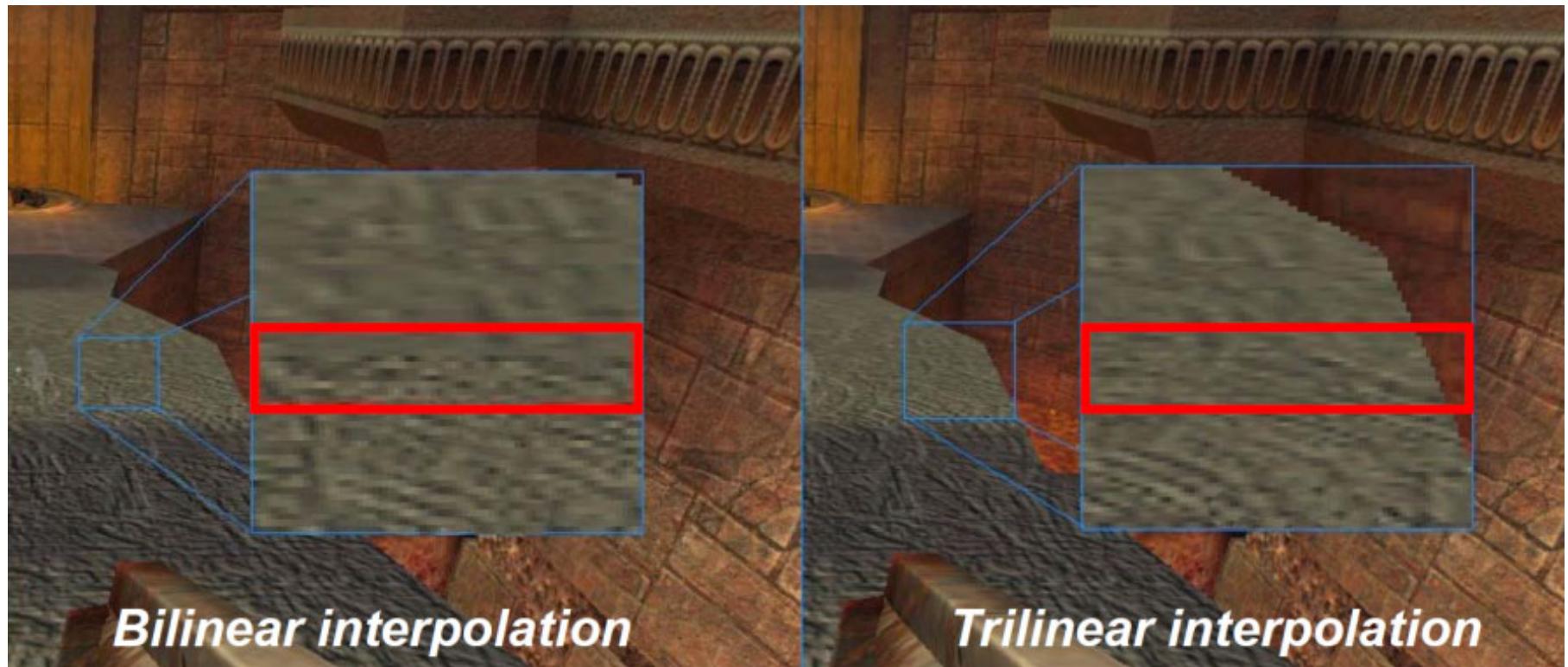
$T_0 :=$ value from table $D_0 = \text{trunc}(D)$

$T_1 :=$ value from table $D_1 = D_0 + 1$

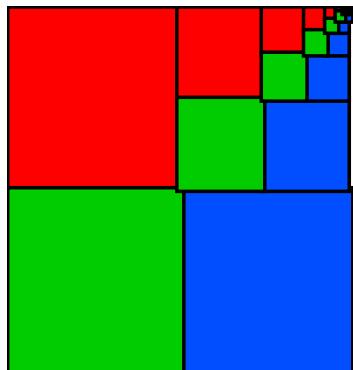
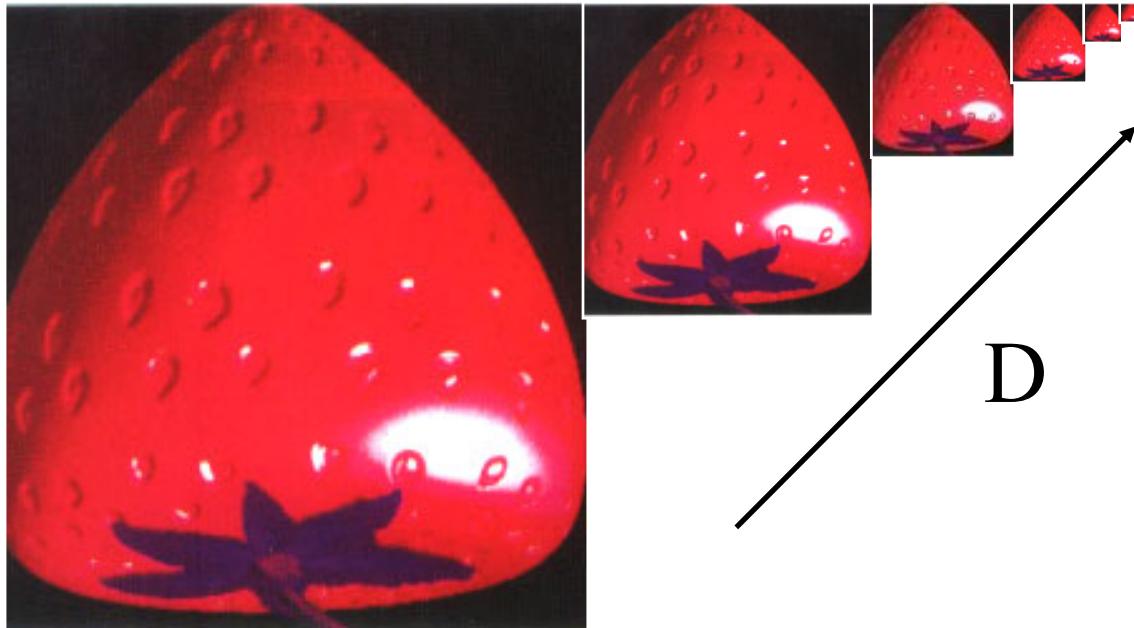
- T_0, T_1 obtained with bilinear interpolation
- How to combine T_0, T_1 ?

Bilinear vs Trilinear

- **Bilinear** := $(D_1 - D > 0.5) ? T_1 : T_0$
- **Trilinear** := $(D_1 - D) \cdot T_0 + (D - D_0) \cdot T_1 =$
 $= (D_1 - D) \cdot (T_0 - T_1) + T_1$

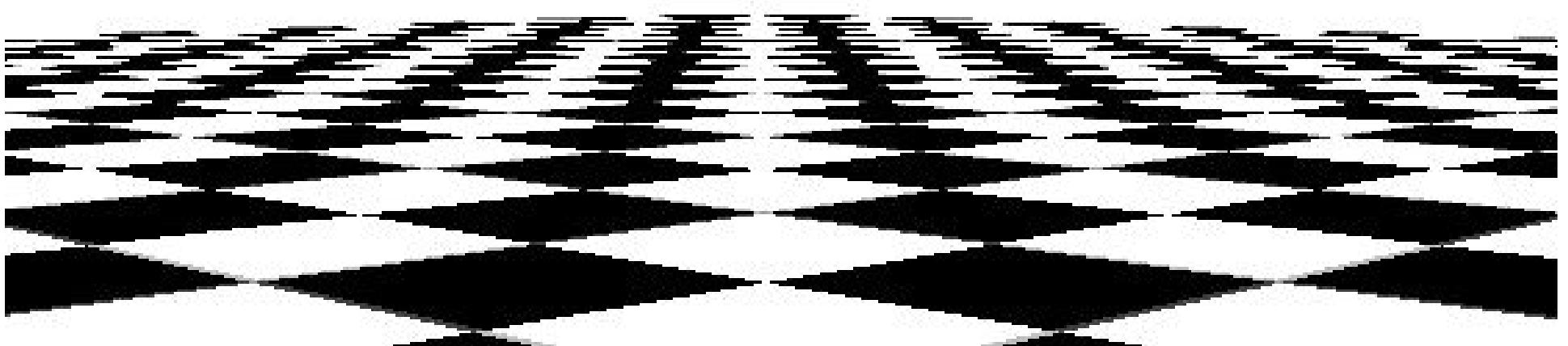


Mip Mapping Memory Layout



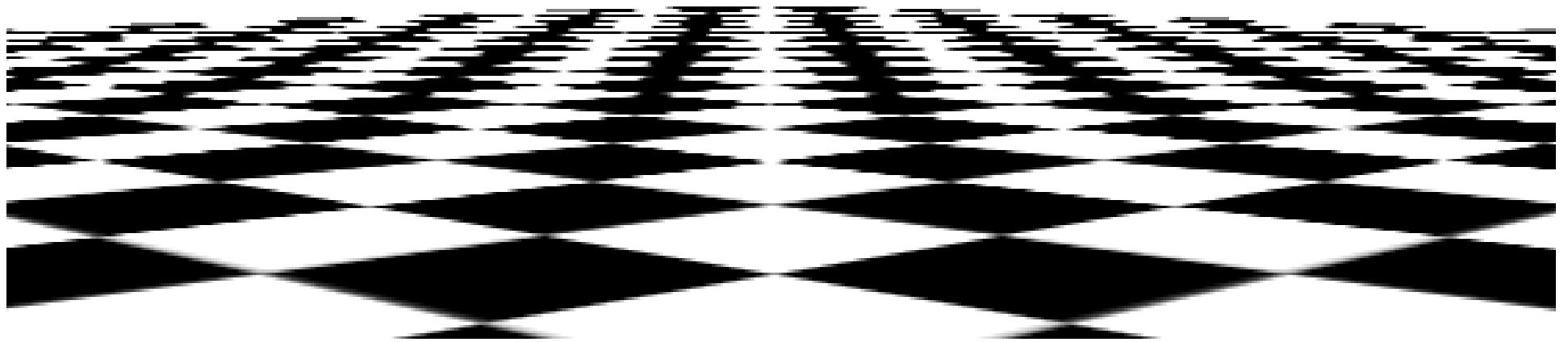
Memory overhead is just 33%
when channels are packed this way

Comparison: Nearest Neighbor



Simple, but bad quality

Comparison: Linear Interpolation



Fixes some aliasing in the front,
but in the back it's still not good

Comparison: Mip Mapping



Replaces objectionable artifacts with blur

What Causes this Problem?

- Problem with mip mapping
 - Blurs in every direction equally
- Not optimal if distortion due to projection is not uniform



ok →

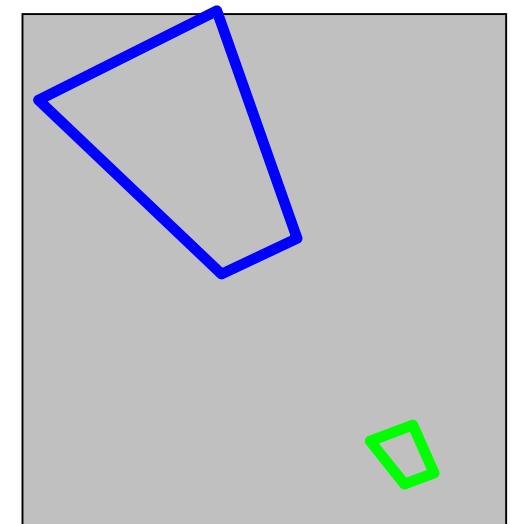
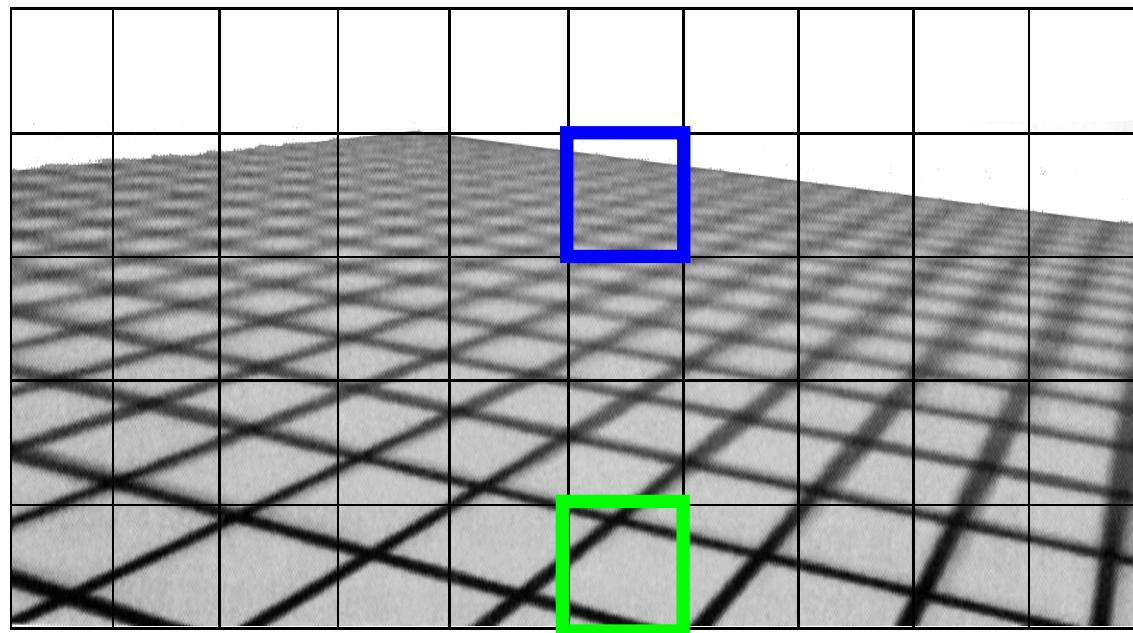


not ok →



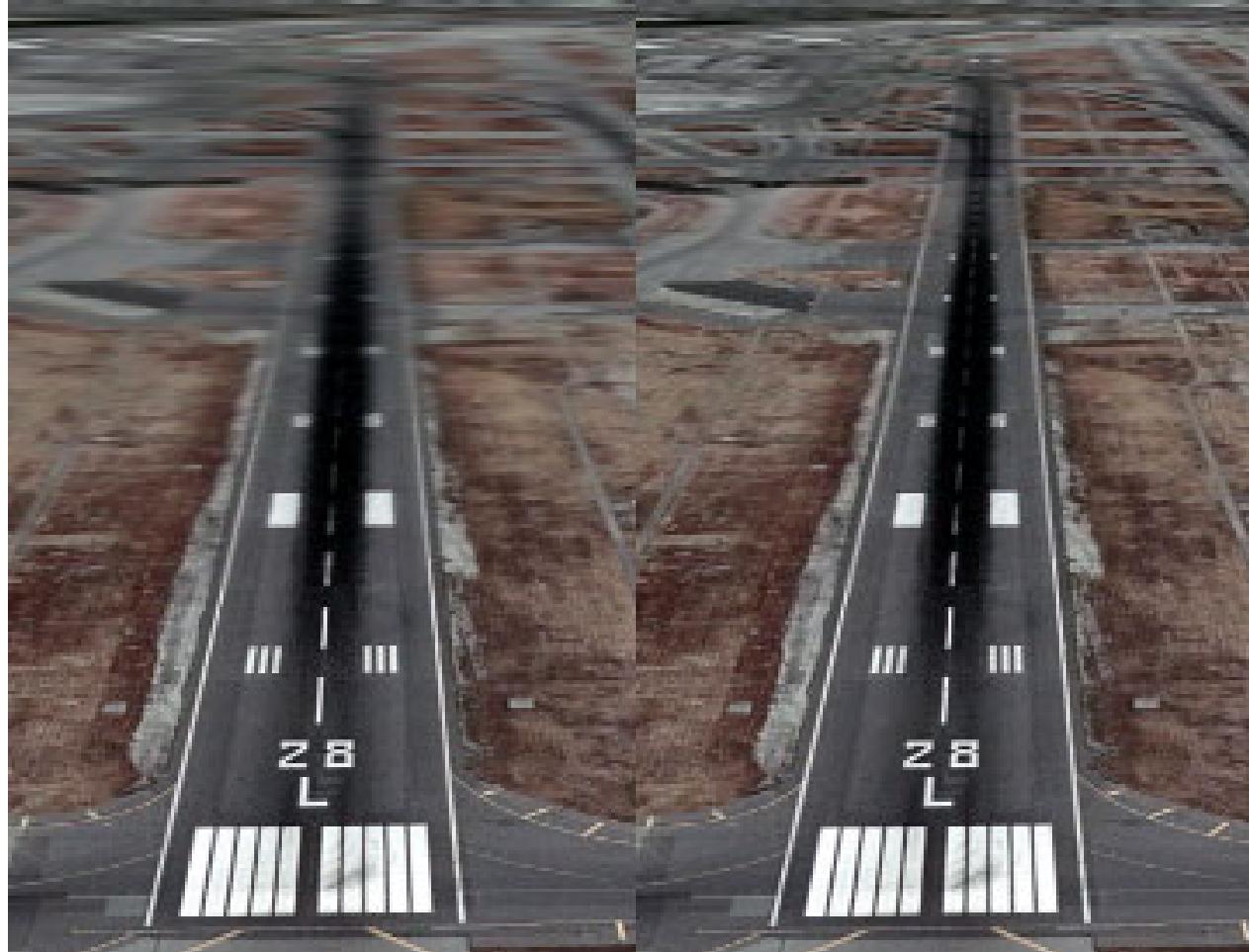
Anisotropic Filtering

Needs a view-dependent filter kernel



Texture space

Anisotropic Filtering Example

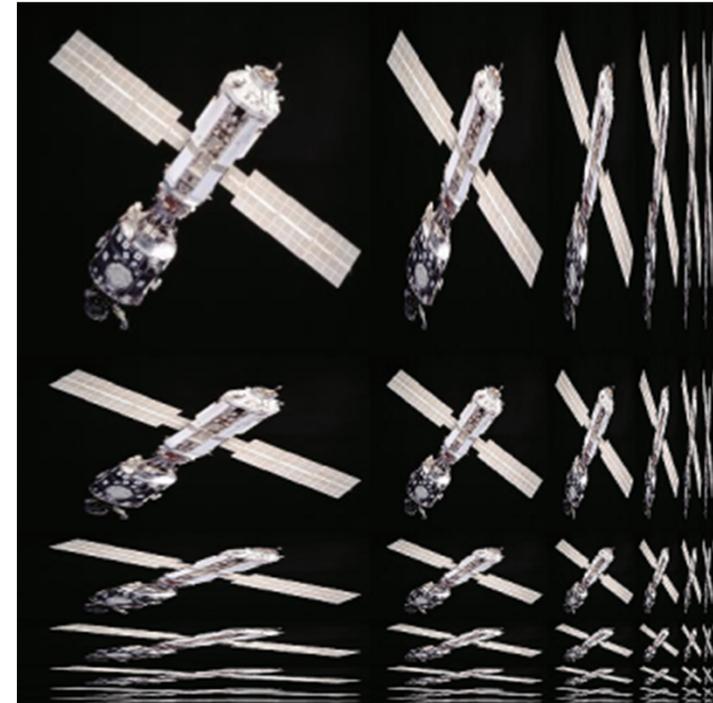


Mip mapped

With anisotropic filtering

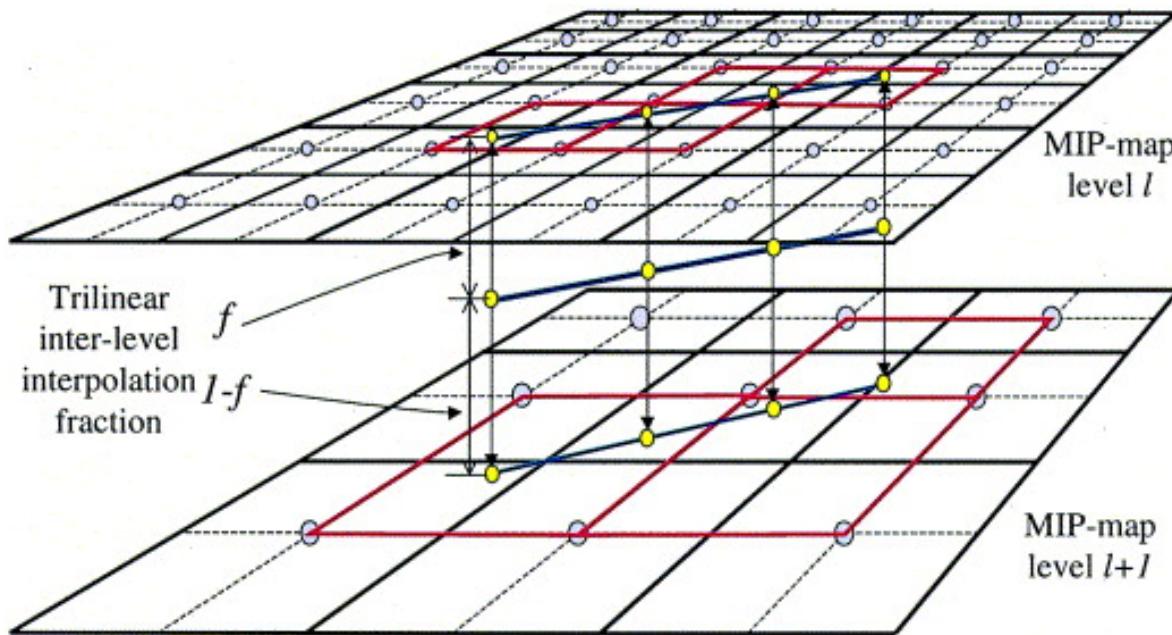
Rip Mapping

- Anisotropic filtering as extension to mip map
- Prefilter also anisotropic (non-uniform) scales
- Computed offline
- Needs 4x the memory



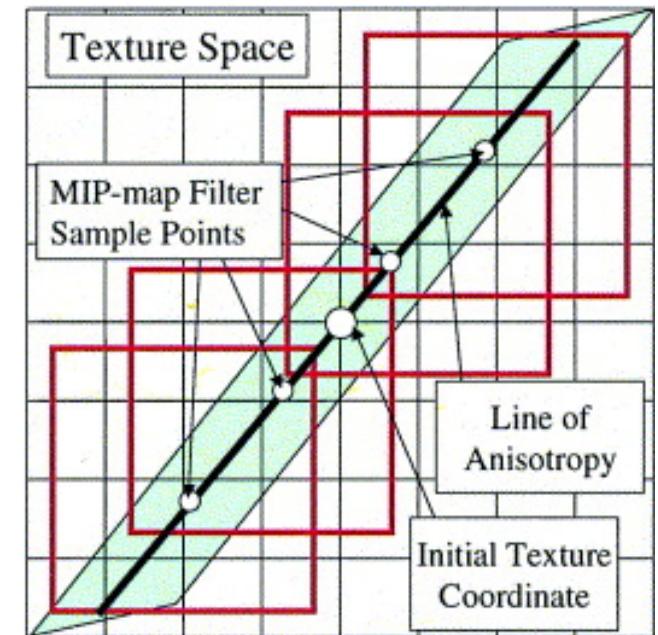
Anisotropic Real-Time Sampling

- Determine major line of anisotropy (=longer axis)
- Fixed number of sample along line of anisotropy
- Trilinear interpolation for each sample



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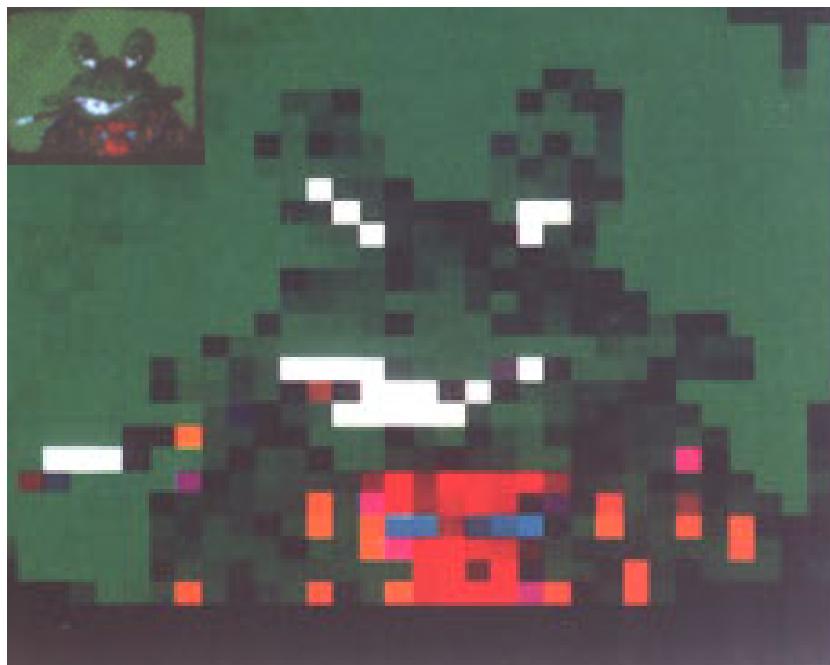
Texture mapping



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Mip Mapping Upsampling

- When the texture resolution is too small:
Upsampling of the mip level with highest res.
- „Magnification“



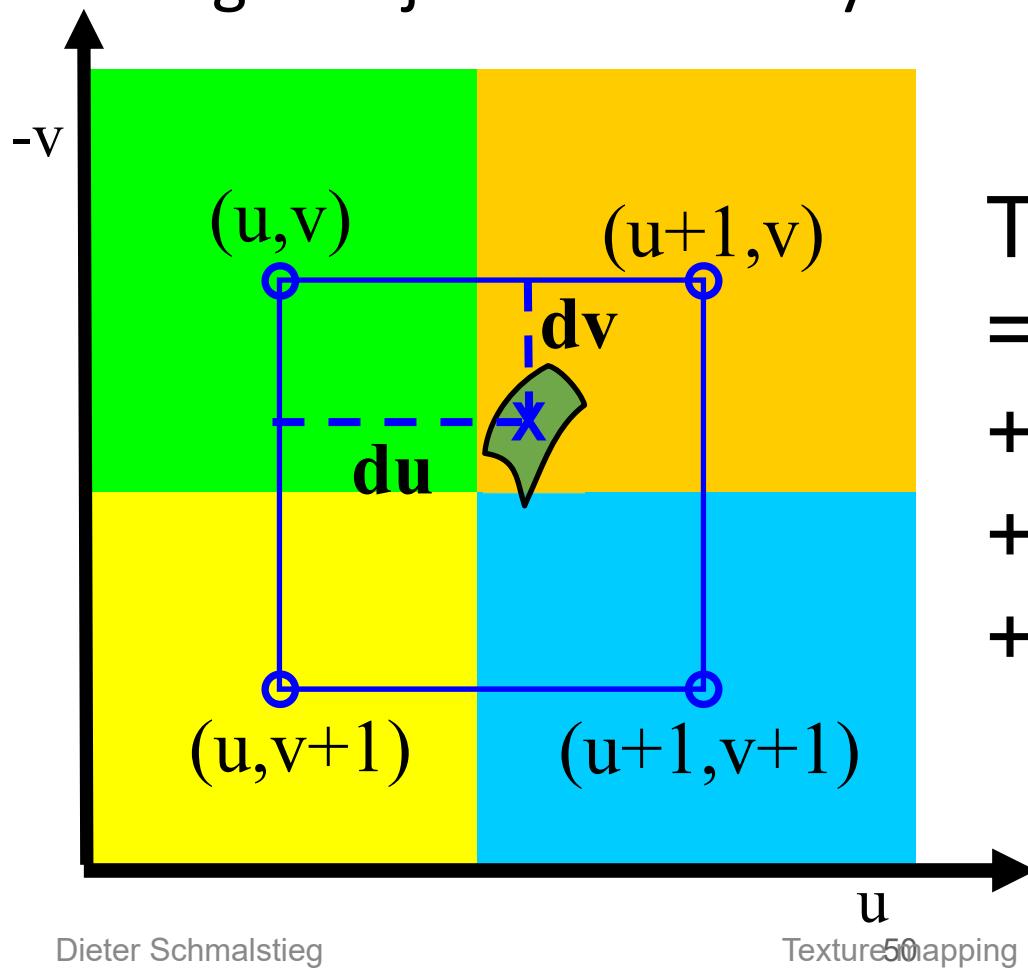
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Texture mapping

Bilinear Upsampling

- Bilinear reconstruction for texture magnification ($D < 0$)
- Weight adjacent texels by distance to pixel position



$$\begin{aligned}
 T(u+du, v+dv) \\
 = du \cdot dv \cdot T(u+1, v+1) \\
 + du \cdot (1-dv) \cdot T(u+1, v) \\
 + (1-du) \cdot dv \cdot T(u, v+1) \\
 + (1-du) \cdot (1-dv) \cdot T(u, v)
 \end{aligned}$$

Bilinear Upsampling Result



Original image



Nearest neighbor

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Bilinear filtering

Texture Sampling

Multipass Rendering

- Basic GPU lighting model is
 - Local
 - Limited in complexity
- Many effects possible with multiple passes
 - Environment maps
 - Shadow maps
 - Reflections, mirrors
 - Transparency

Multipass Rendering: How?

Two main methods

- Render to auxiliary buffers, use result as texture
 - E.g.: environment maps, shadow maps
 - Requires FBO support
- Redraw scene using fragment operations
 - E.g.: reflections, mirrors, light mapping
 - Uses framebuffer blending
 - Uses depth, stencil, alpha, ... tests
- Can mix both techniques

Multipass via Render to Texture

Auxiliary buffer method = *render to texture* (RTT)

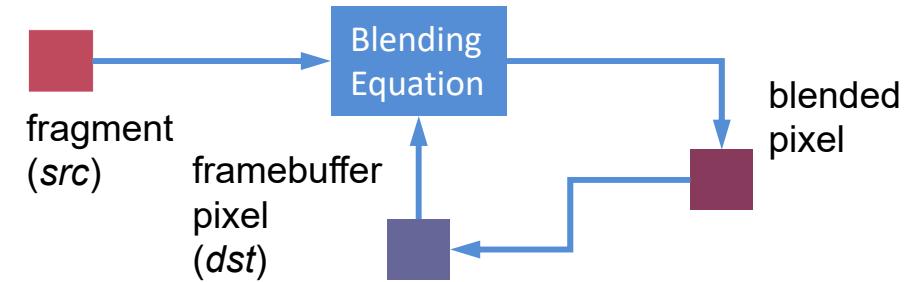
1. Frame buffer with color attachment is bound
2. Scene (or subset) is rendered,
possibly using a custom shader program
3. Frame buffer is unbound
Color attachment is bound as texture
4. Scene is rendered to the back buffer,
Rendered texture can be used either by
fixed function pipeline or a custom shader

Example: Fragment Shader Multiple Outputs

```
1 #version 330
2
3     layout(location = 0) out vec4 color0;
4     layout(location = 1) out vec4 color1;
5
6     void main()
7     {
8         color0 = ...
9         color1 = ...
10    }
```

Blending

- So far, every new pixel simply overwrote existing framebuffer
- Blending combines new pixels with what is already in the framebuffer
- Blending does not always require alpha buffer



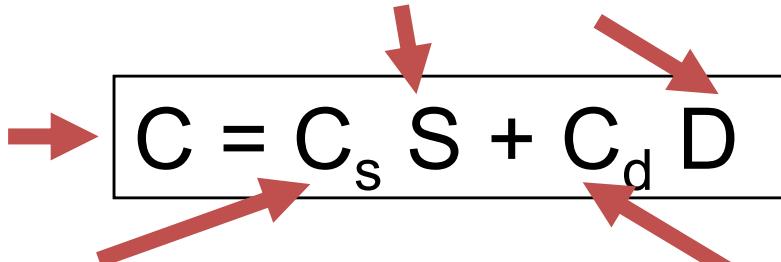
Multipass – Framebuffer Blending

- Select a blend equation
- Hardware supports a finite number of equations
- Most common is linear blending

weighting factors

$$\text{result color} \rightarrow C = C_s S + C_d D$$

incoming fragment color framebuffer color



Other Blend Equations

- **GL_FUNC_ADD**

$$\mathbf{c}_d \leftarrow \mathbf{c}_s \otimes \mathbf{w}_s + \mathbf{c}_d \otimes \mathbf{w}_d$$

- **GL_FUNC_SUBTRACT**

$$\mathbf{c}_d \leftarrow \mathbf{c}_s \otimes \mathbf{w}_s - \mathbf{c}_d \otimes \mathbf{w}_d$$

- **GL_FUNC_REVERSE_SUBTRACT**

$$\mathbf{c}_d \leftarrow \mathbf{c}_d \otimes \mathbf{w}_d - \mathbf{c}_s \otimes \mathbf{w}_s$$

- **GL_FUNC_MIN**

$$\mathbf{c}_d \leftarrow \min(\mathbf{c}_s, \mathbf{c}_d)$$

- **GL_FUNC_MAX**

$$\mathbf{c}_d \leftarrow \max(\mathbf{c}_s, \mathbf{c}_d)$$

Blending Source and Destination

- Weights can be defined arbitrarily
- Alpha/color weights can be defined separately
- Choices of weight
 - *One, zero, dst color, src color, alpha, 1 - src color...*
- Example: transparency blending (window)

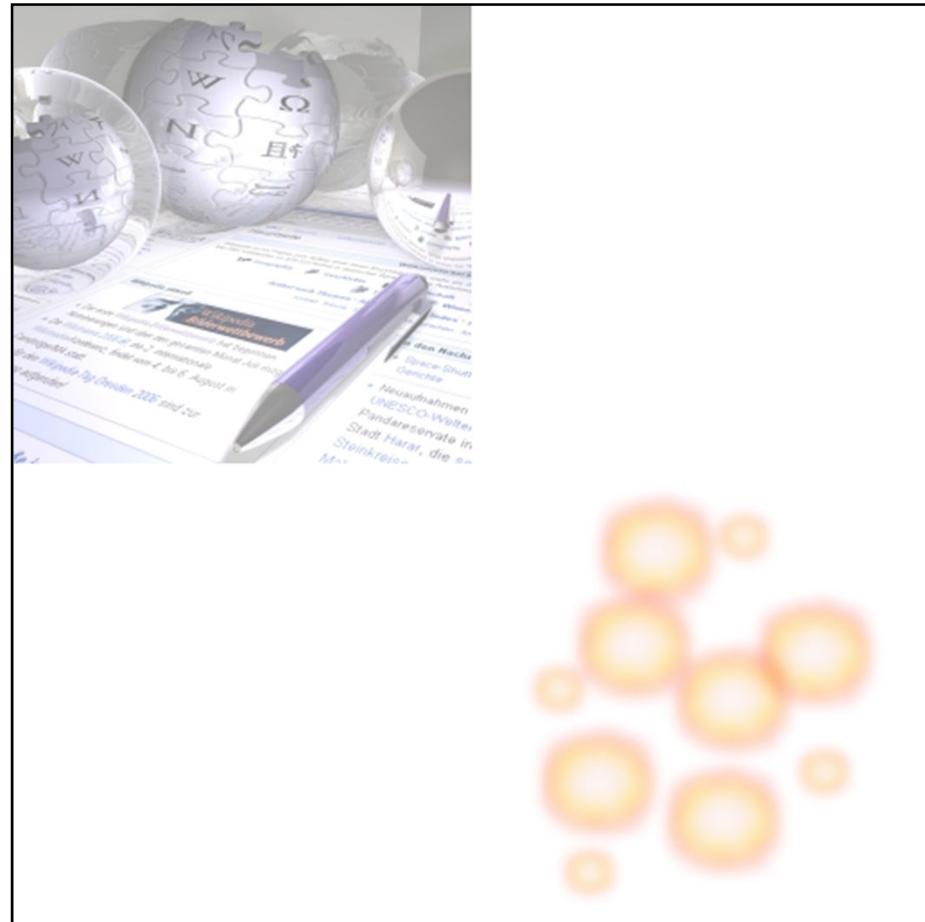
$$C = C_s \cdot \alpha + C_d \cdot (1 - \alpha)$$

Alpha Buffer

- Measure of opacity to
 - Simulate translucent objects (glass, water, etc.)
 - Composite images
 - Antialiasing
- Do not forget to enable blending first!
- Beware
 - Usage of alpha requires depth-sorting of objects
 - Z-Buffer not helpful for partially transparent pixels

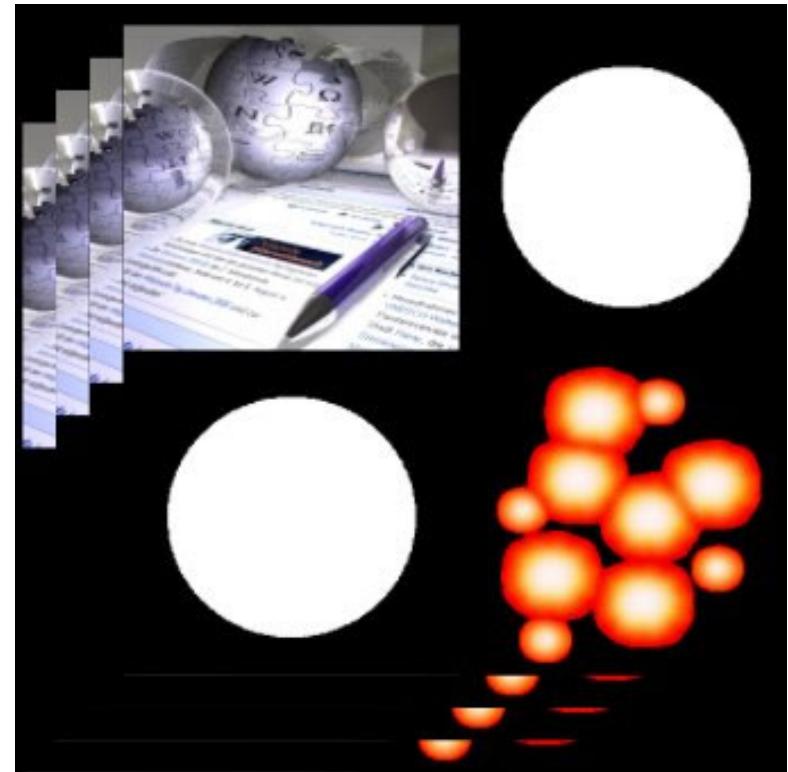
Blending Examples (1)

Texture with alpha
channel for the
following examples...



Blending Examples (2)

- `glBlendFunc(GL_ONE, GL_ZERO);`
 - Everything works as if blending was disabled
 - Alpha values also ignored

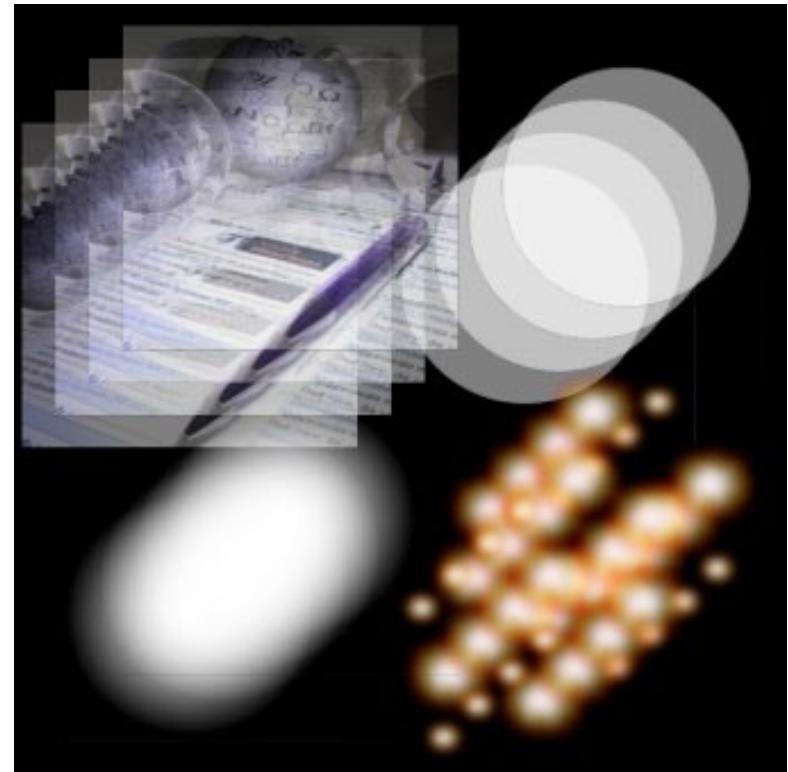


Blending Examples (3)

- `glBlendFunc(GL_ZERO, GL_ONE);`
 - Nothing is drawn
 - Not really useful...

Blending Examples (4)

- `glBlendFunc(GL_SRC_ALPHA, GL_ONE_MINUS_SRC_ALPHA);`
 - Most common blending method
 - Simulates traditional transparency
 - Source color's alpha (usually from texture) defines opaqueness of object to render



Blending Examples (5)

- `glBlendFunc(GL_ONE, GL_ONE);`
 - Source and destination color are simply added
 - Values >1.0 are clamped to 1.0 (saturation)
 - Good for fire effects



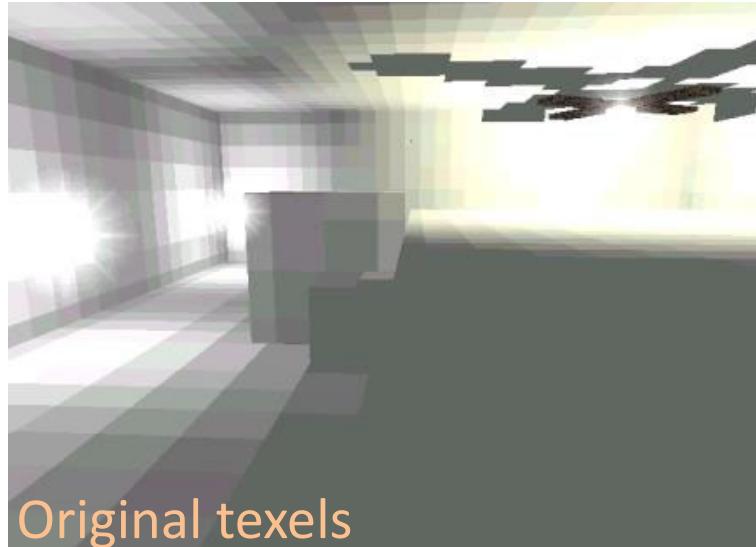
Multitexturing

- Idea: Apply multiple textures in one pass
- Textures can be combined arbitrarily (add, mul, ...)
- Indirect lookup
 - 1st texture lookup is used to index into 2nd texture
- Today, just use multiple *texture samplers* in a fragment shaders
- Texture samplers correspond to dedicated hardware units for accessing texture memory

Light Mapping

- Used in most first-person shooters
 - Precalculate (*bake*) diffuse lighting on static objects
 - Only low resolution necessary
 - Diffuse lighting is view independent!
 - Advantages
 - No runtime lighting necessary
(good for older cards)
 - More accurate than vertex lighting
(no need to tessellate for highlights)
 - Can take global effects (shadows, radiosity) into account
- 
- The diagram illustrates the light mapping process. It shows three images arranged horizontally: 1) A 4x4 grid of brownish-grey tiles representing a static object's surface. 2) A circular radial gradient from black to white, representing the pre-calculated diffuse lighting for that object. 3) The resulting image, which is a composite of the original tiles where their colors have been modified by the corresponding values in the light map, creating a more realistic illuminated appearance.

Light Mapping Example 1



Original texels



Gouraud shaded

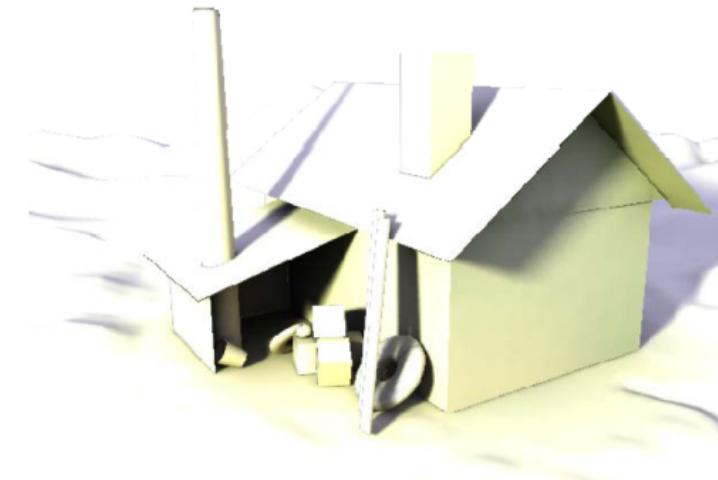
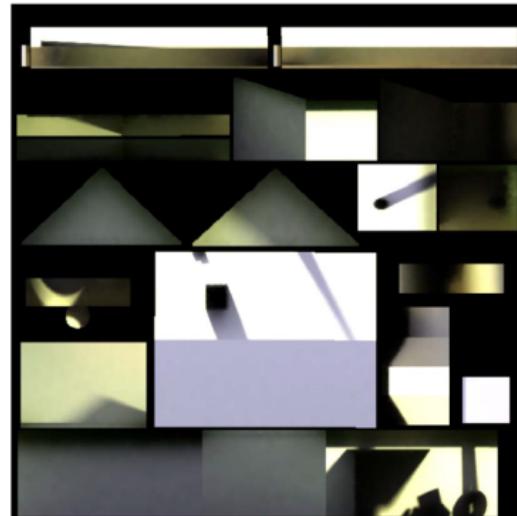


Original scene



Light-mapped

Light Mapping Example 2

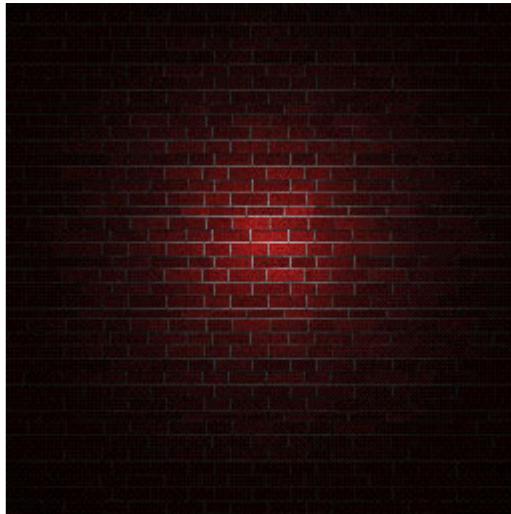


Light Mapping Procedure

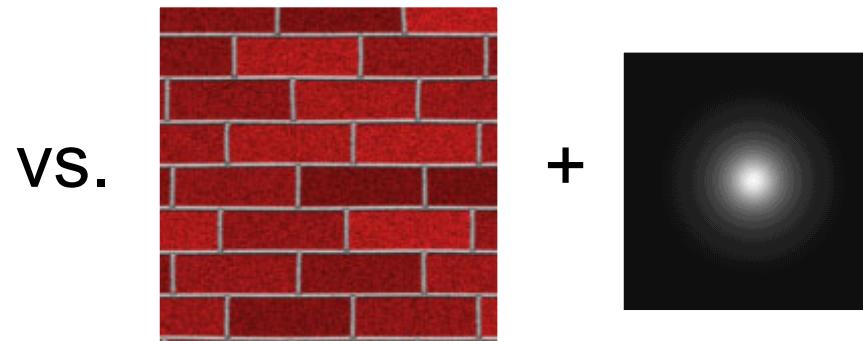
- Map generation
 - Use single map for group of coplanar polys
 - Map back to worldspace to calculate lighting
- Map application
 - Premultiply textures by light maps
 - Large textures, no dynamics
 - Multitexturing at runtime
 - Fast, flexible

Light Mapping Issues

- Why premultiplication is bad...



Full Size Texture
(with Lightmap)

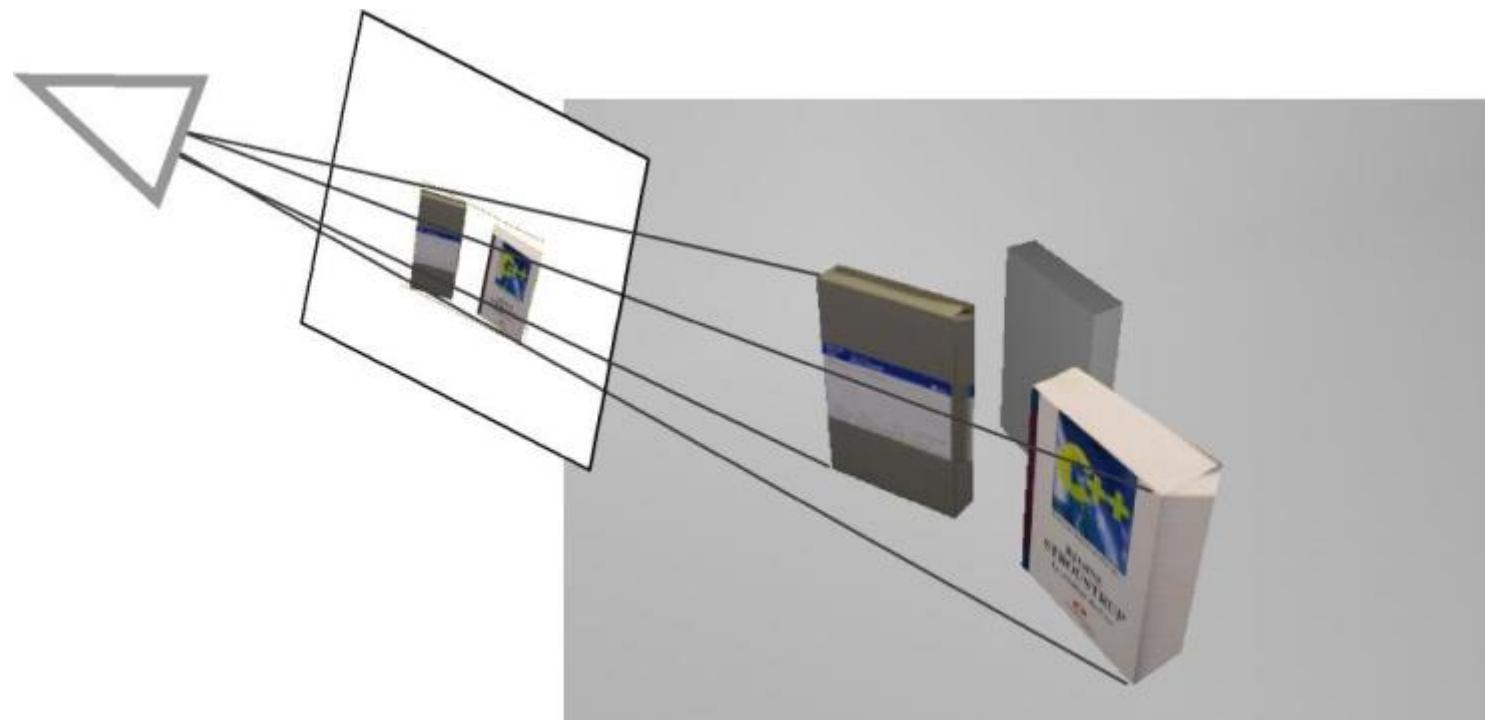


Tiled Surface Texture
plus Lightmap

- Use small surface textures and small maps
- Maybe calculate low-res light maps on the fly

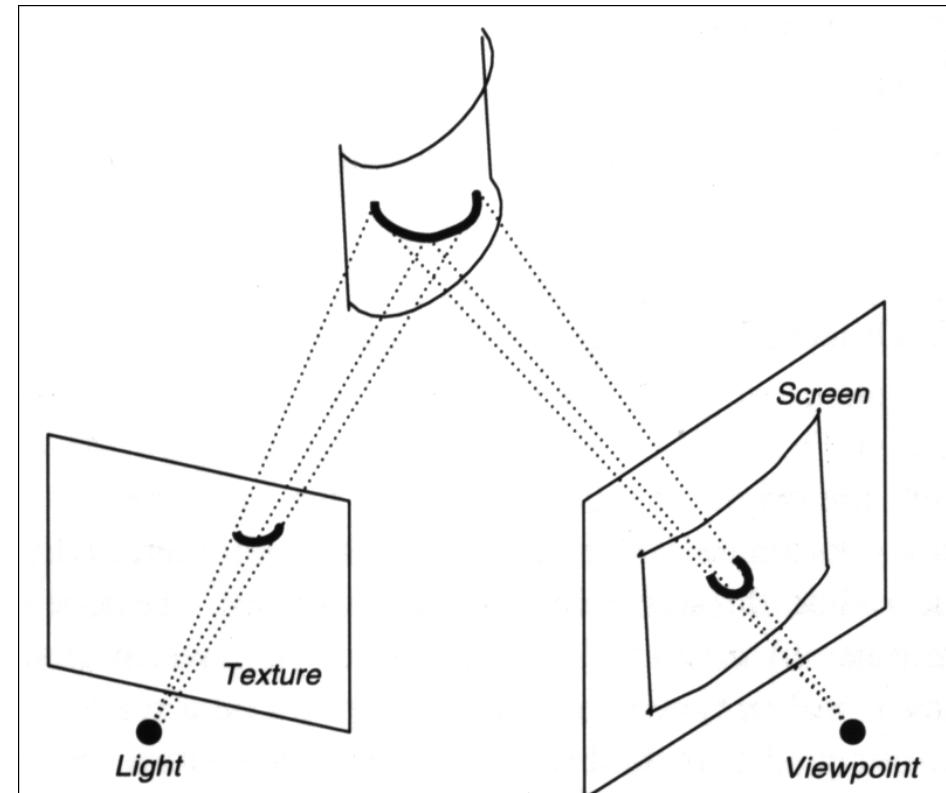
Projective Texture Mapping

- PTM simulates a video projector
 - Or a flashlight, slide projector, ...
- Using perspective projection



PTM: Geometry

- Map object coordinates to light frustum
- Express this as a projective transform
- Usually a 4x4 matrix
- Similarity to video projector observed by camera



PTM: Flashlights Examples



STALKER

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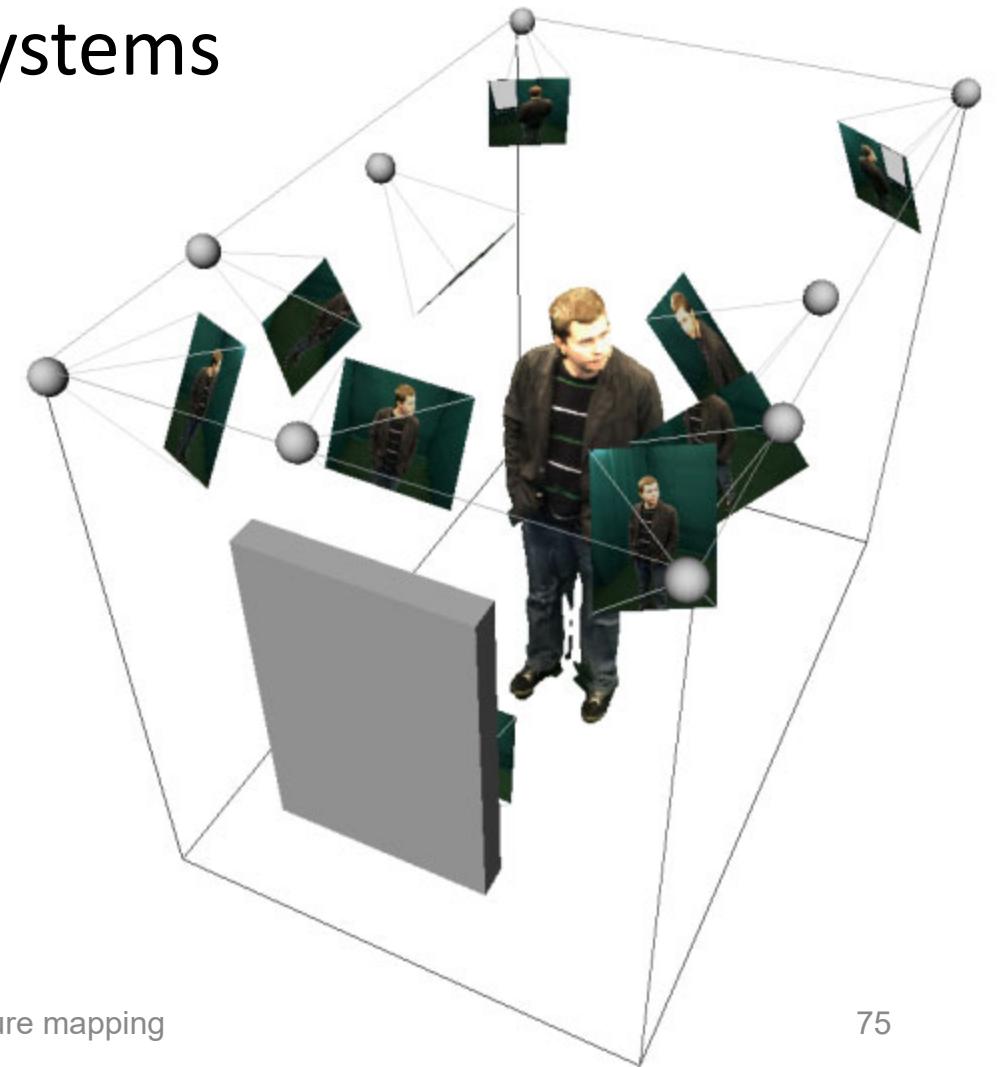


Doom 3

Texture mapping

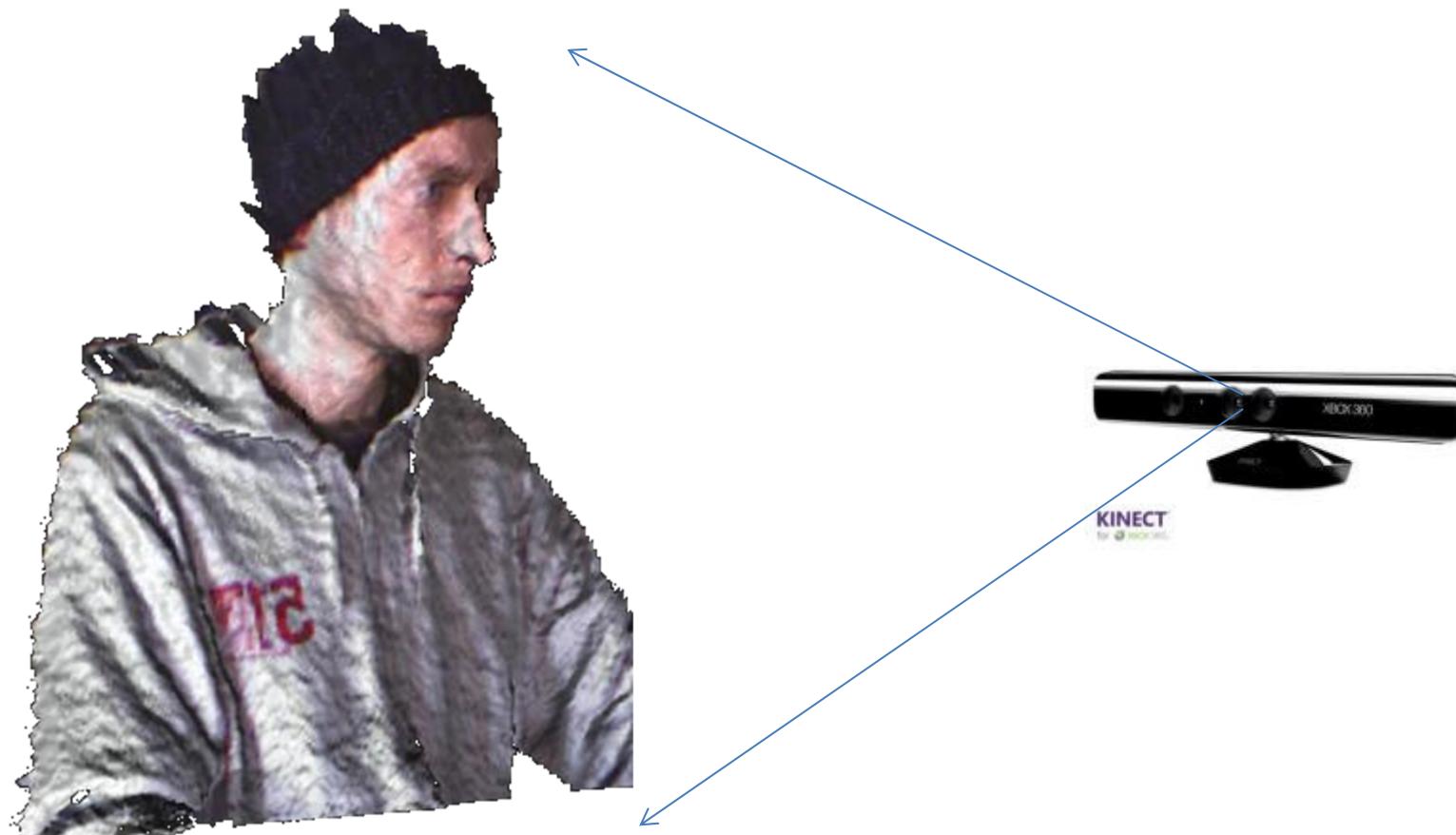
PTM from Multi-Camera

User in multi-camera systems



PTM from Depth Camera

Example: display a Microsoft Kinect point cloud

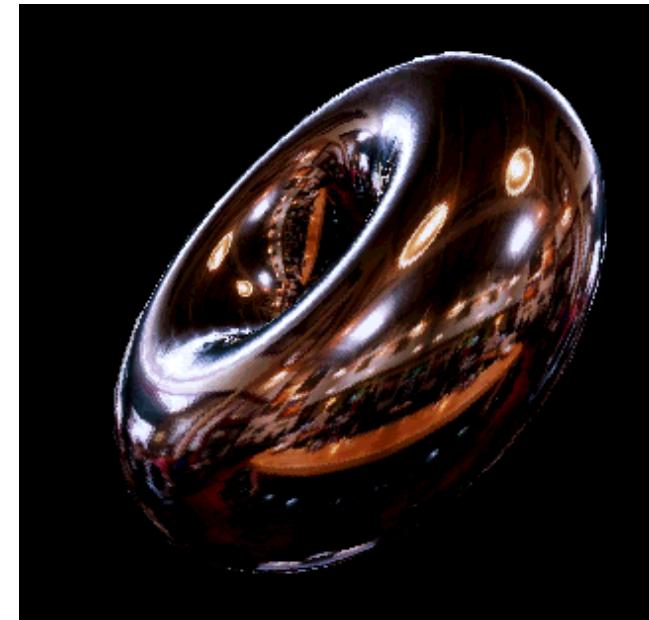


Environment Mapping

- Idea: use texture to create reflections
- Uses texture coordinate generation, multitexturing, RTT, ...



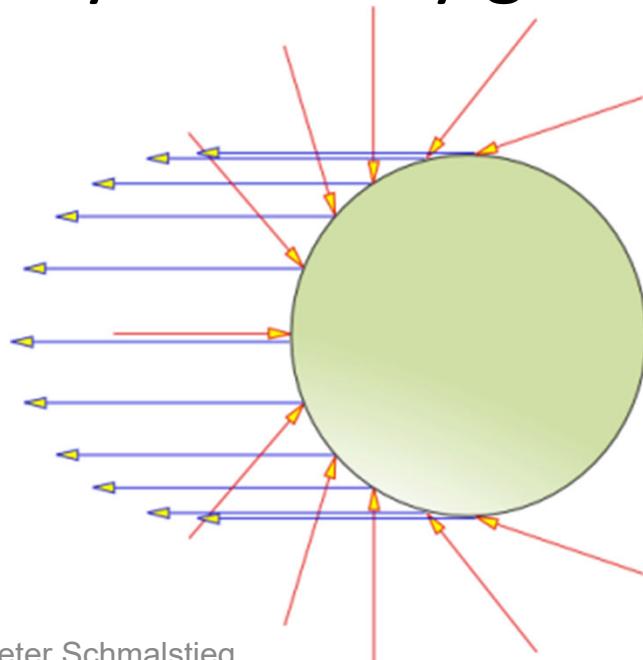
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Texture mapping

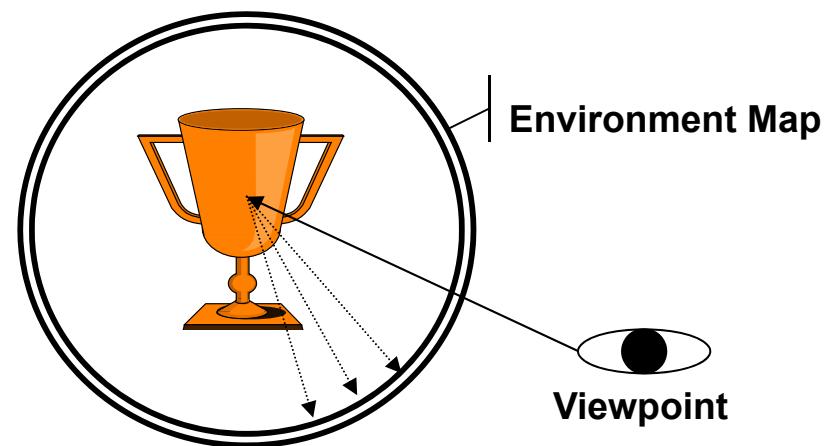
Environment Mapping Indexing

- Assumption: index envmap via orientation →
 - Reflecting object shrunk to a single point
 - Or: environment infinitely far away
- Eye not very good at discovering the fake



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Texture mapping

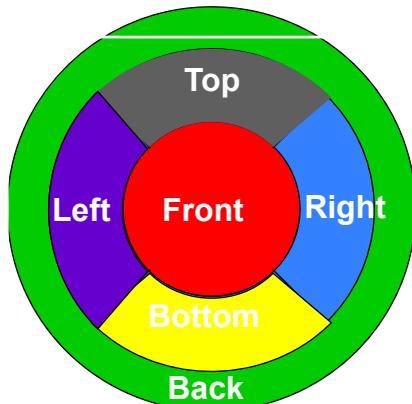


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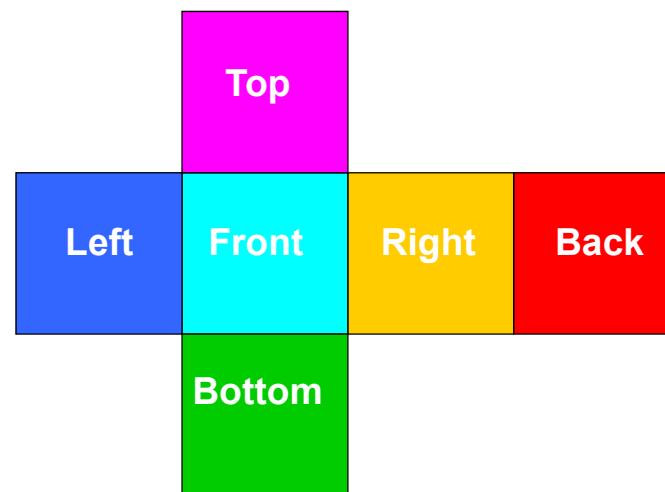
Environment Mapping Types

- Typical mappings:
Each maps all directions to a 2D texture

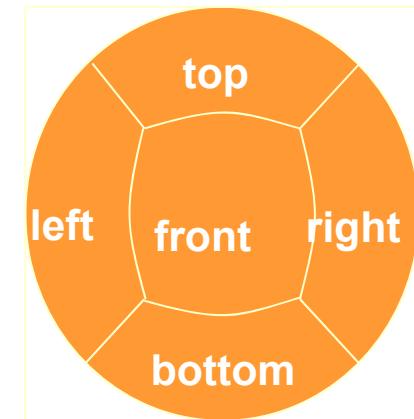
Sphere



Cube

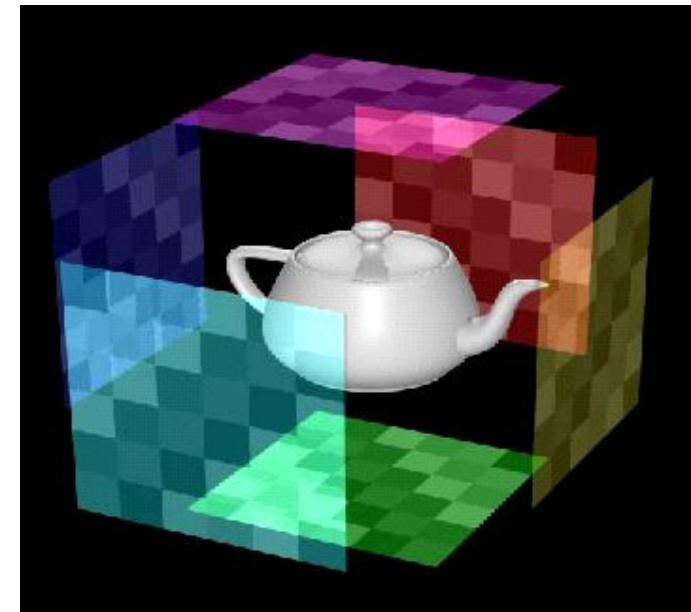
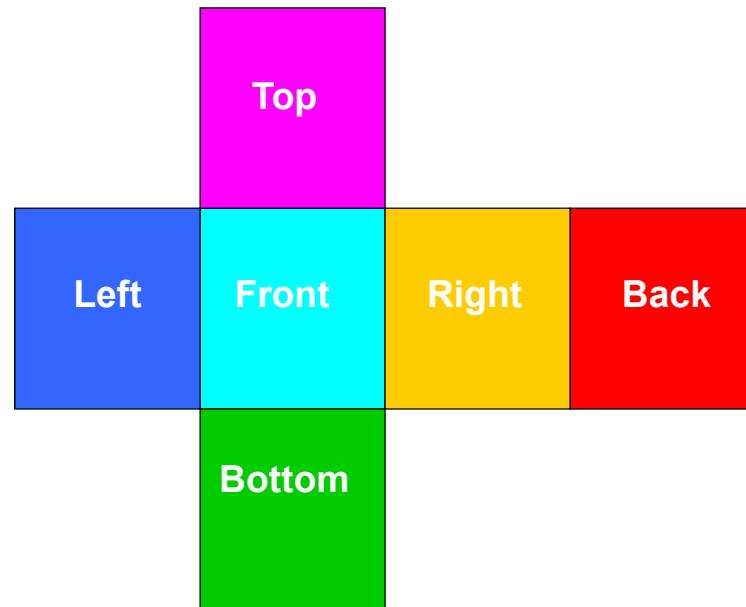


Dual paraboloid

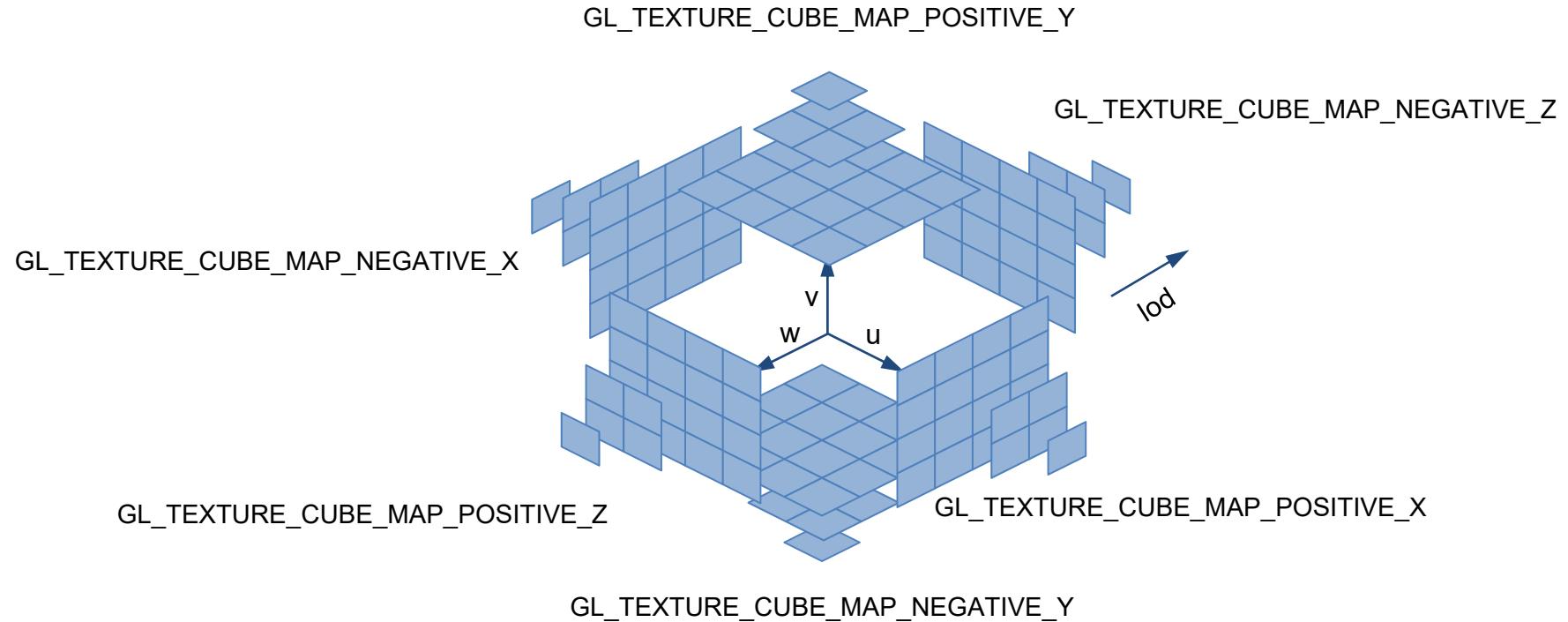


Cube Mapping

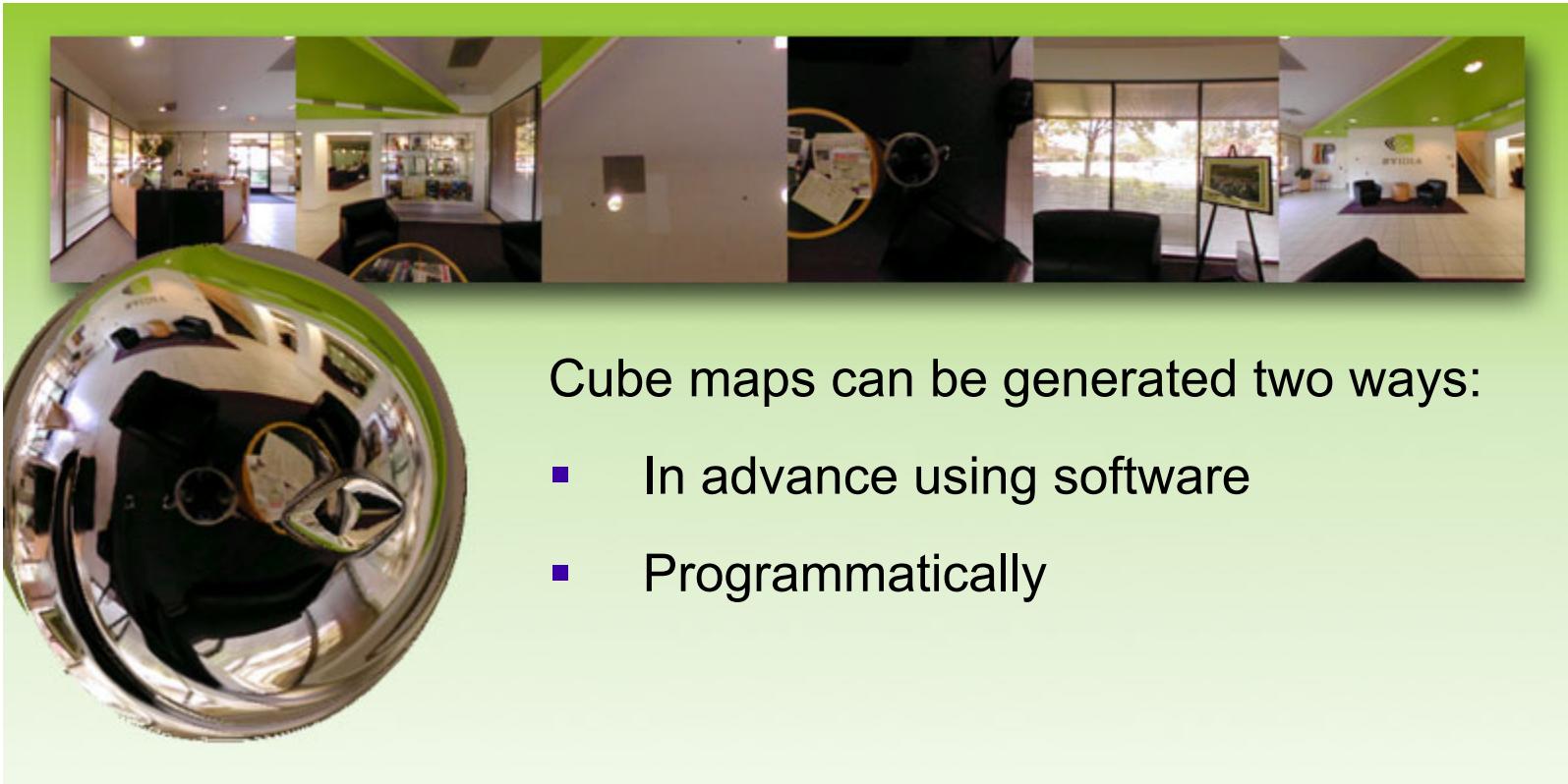
- Implemented in the OpenGL pipeline



OpenGL Cube Map Targets



Cube Map Generation



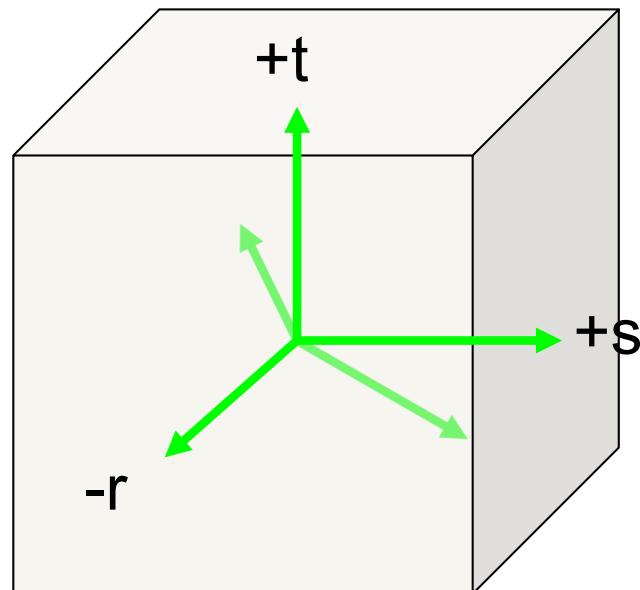
Cube maps can be generated two ways:

- In advance using software
- Programmatically

Cube maps are the primary method of generating reflections in real-time 3D

Cube Map Addressing

- Cube map accessed via **vectors** expressed as 3D texture coordinates (s, t, r)



Cube Map Address Calculation

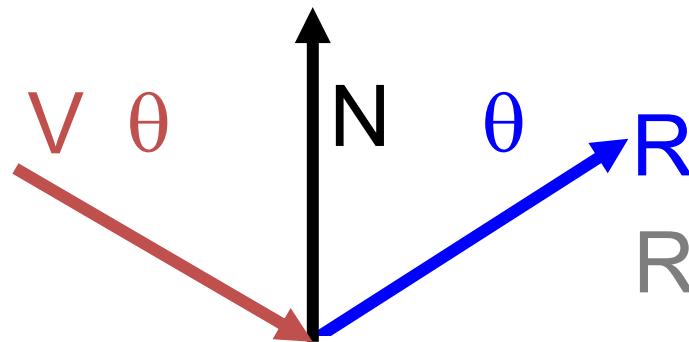
- 3D → 2D projection done by hardware
- Correct ray/quad intersection too slow, instead
 - Highest magnitude component selects which cube face to use (e.g., $-t$)
 - Divide other components by this, e.g.:
$$s' = s / -t$$
$$r' = r / -t$$
 - (s', r') select a texel from this face
- Does not define environment mapping itself
 - Need to generate useful texture coordinates

Cubic Environment Mapping

- Generate views of the environment
 - One for each cube face
 - 90° view frustum
 - Use hardware to render directly to a texture
- Use reflection vector to index cube map
 - Use hardware mode for sampling in cube map

Reflection Vector

- Angle of incidence = angle of reflection



$$R = V - 2 (N N^T) V$$

- OpenGL uses eye coordinates for R
 - Cube map needs reflection vector in world coordinates (where map was created)
- Load texture matrix with inverse 3x3 view matrix

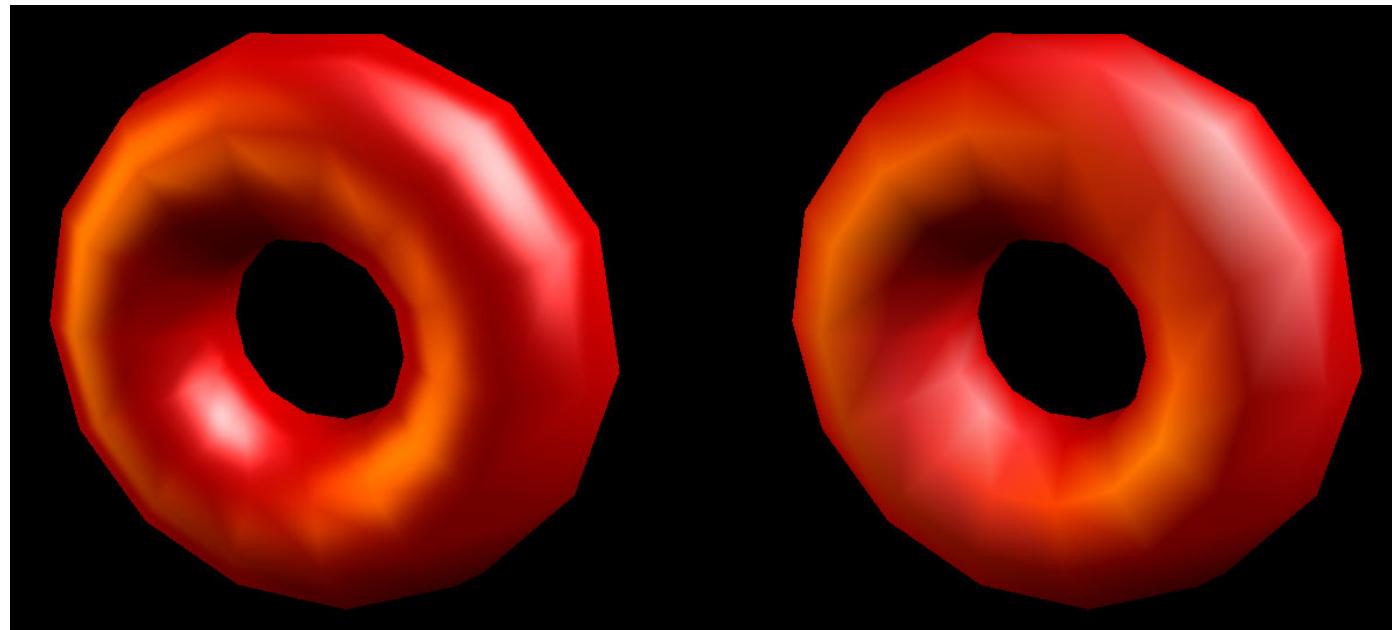
Cube Mapping Discussion

- Advantages
 - Minimal distortions
 - Creation and map entirely hardware accelerated
 - Can be generated dynamically
- Optimizations for dynamic scenes
 - Need not be updated every frame
 - Low resolution sufficient

Per-Pixel Lighting

- Simulating smooth surfaces by calculating illumination at each pixel (e.g., Phong shading)
- Advantage: better specular highlights

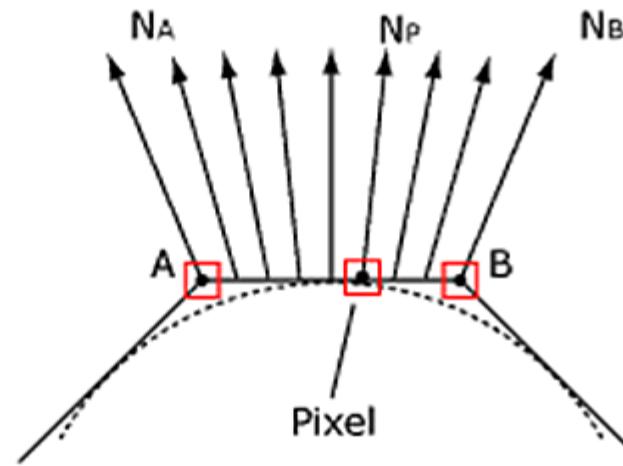
per-pixel evaluation linear intensity interpolation



Per-Pixel Lighting Algorithm

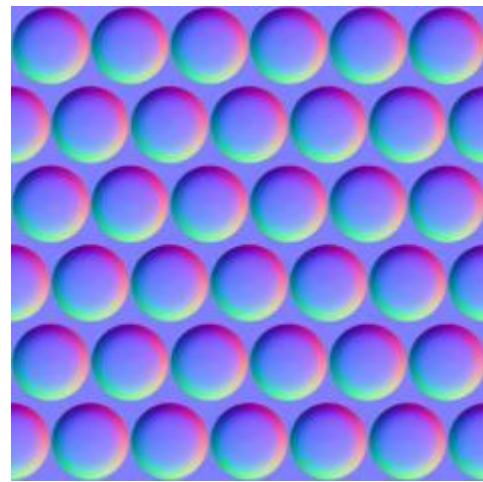
- Done in fragment shader programs
- Vertex normals are passed to fragment shader
- Rasterizer interpolates them

Phong-Shading

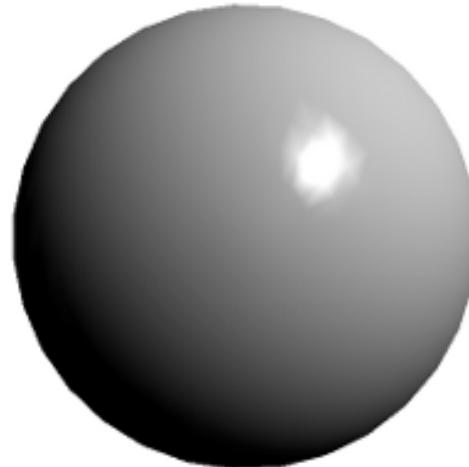


Bump Mapping

- Per-pixel normals are a prerequisite for BM
- Simulating rough surfaces by calculating per-pixel illumination
- Replace geometry with (faster) texture



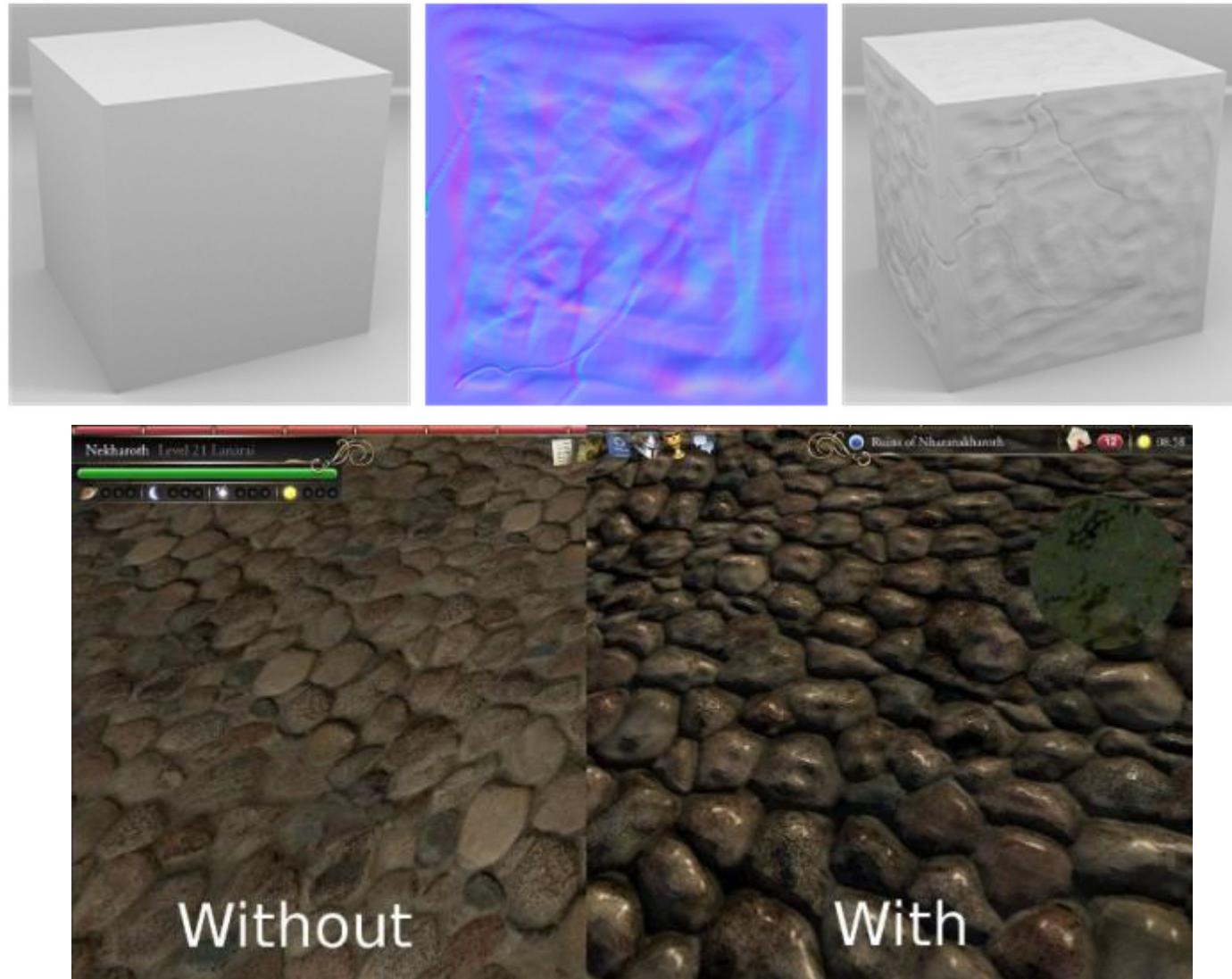
+



=

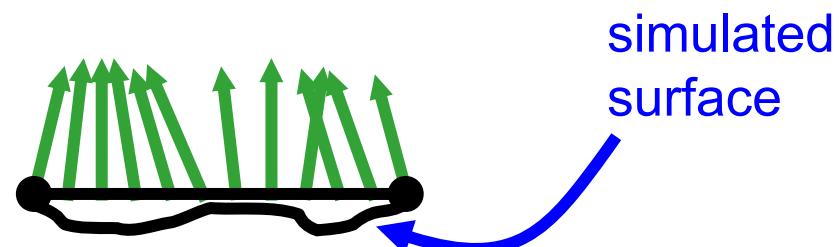


Bump Mapping Examples



Bump Mapping Basics

- Original idea from ray tracing [Blinn 1978]
- Simulate surface features with illumination only
- Instead of interpolating normals, take them from a map

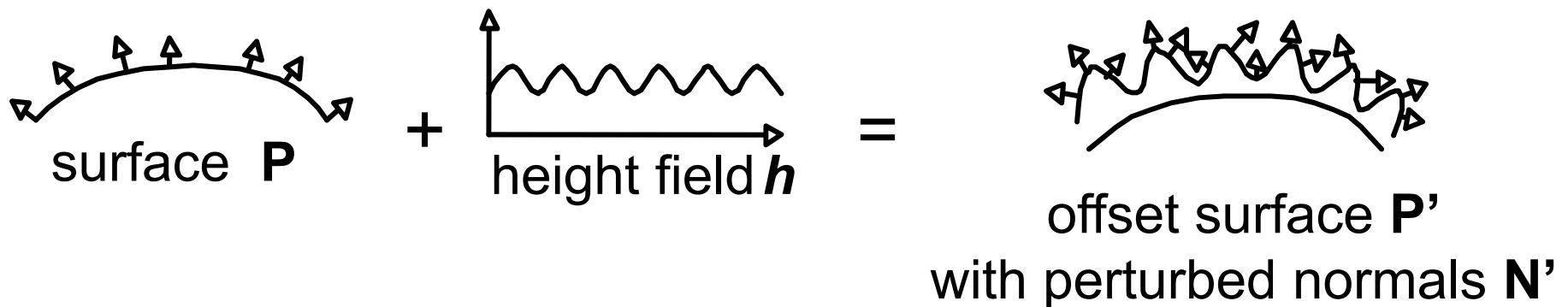


Per-Pixel vs. Bump Mapping

- Where is the difference?
- Per-pixel lighting = bump mapping *without the bump map!*
- Per-pixel lighting is a special case where normal vector is interpolated instead of looked up

Bump Mapping Basics

- Assume a (u,v) -parameterization
 - Points \mathbf{P} on the surface given as $\mathbf{P}(u,v)$
- Surface \mathbf{P} is modified by 2D height field h



Mathematics of Bump Mapping

- Displaced surface:

$$\mathbf{p}'(u, v) = \mathbf{p}(u, v) + h(u, v)\mathbf{n}(u, v)$$

- Partial derivatives:

$$\frac{\partial \mathbf{p}'}{\partial u} = \frac{\partial \mathbf{p}}{\partial u} + \frac{\partial h}{\partial u} \cdot \mathbf{n} + h \cdot \underbrace{\frac{\partial \mathbf{n}}{\partial u}}_{\text{blue bracket}}$$

$$\frac{\partial \mathbf{p}'}{\partial v} = \frac{\partial \mathbf{p}}{\partial v} + \frac{\partial h}{\partial v} \cdot \mathbf{n} + h \cdot \underbrace{\frac{\partial \mathbf{n}}{\partial v}}_{\text{blue bracket}}$$

- Perturbed normal:

$$\mathbf{n}'(u, v) = \frac{\partial \mathbf{p}'}{\partial u} \times \frac{\partial \mathbf{p}'}{\partial v}$$

= 0 for locally flat base surface

after some computation...

$$\Rightarrow \mathbf{n}' = \mathbf{n} + \frac{\partial h}{\partial u} \cdot \left(\mathbf{n} \times \frac{\partial \mathbf{p}}{\partial v} \right) - \frac{\partial h}{\partial v} \cdot \left(\mathbf{n} \times \frac{\partial \mathbf{p}}{\partial u} \right)$$

Multitexturing Example

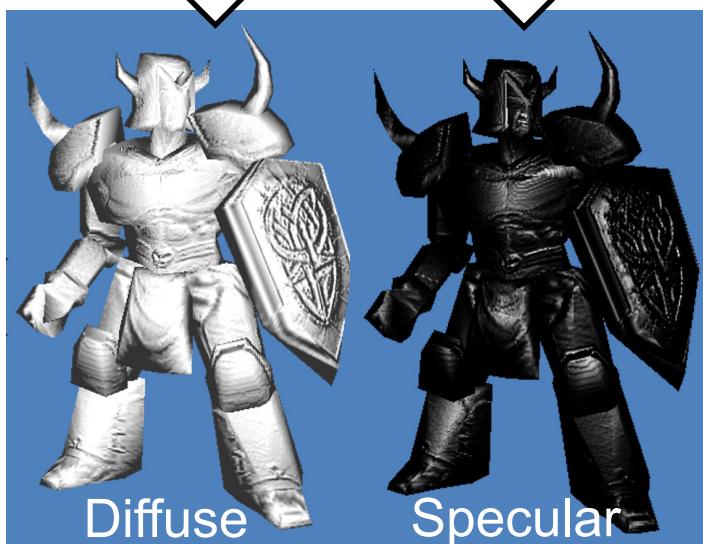
Bump Map



Diffuse Color



Per triangle
gloss value



Multitexturing Result



Note: Gloss map
defines where to
apply specular



**Final
result!**

Bump Mapping Representations

- Height fields
 - Must approximate derivatives during rendering
 - Simple case: emboss bump mapping
- Offset maps
 - Encode orthogonal offsets from unperturbed normal
 - e.g.: $\left(\frac{\partial h}{\partial u}, \frac{\partial h}{\partial v}\right)$, or whole vector, ...
 - Require renormalization
 - Enable bump environment mapping
 - Calculate using finite differencing on height field
- Normal (perturbation/rotation) maps
 - Encode direction vectors (in whatever space)
 - No normalization required
 - Standard method

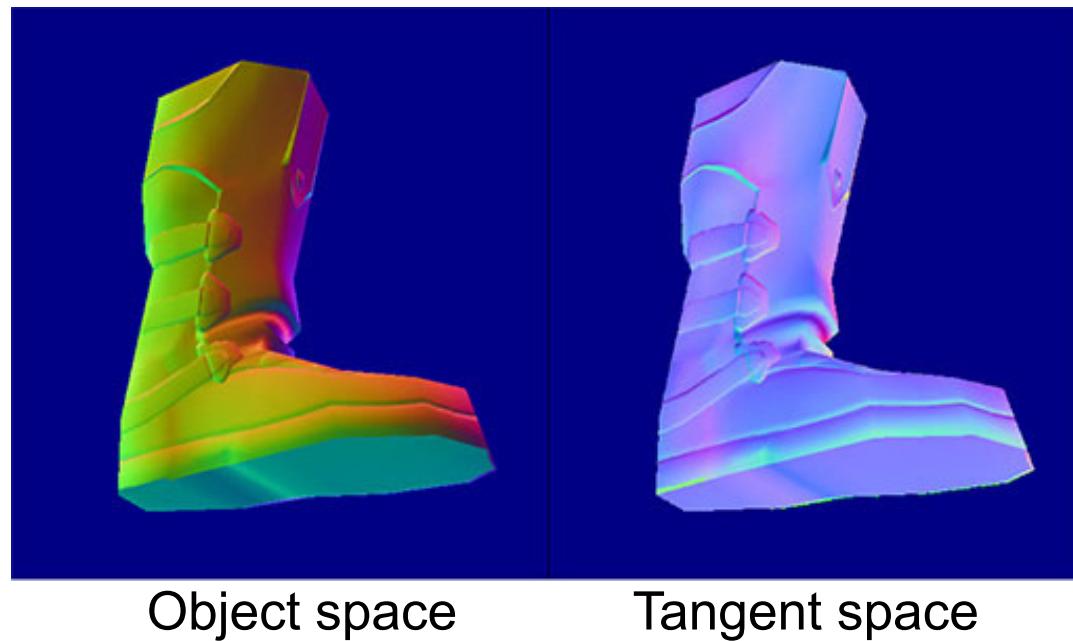
Coordinate Systems

Problem: where to calculate lighting?

- Object coordinates
 - Native space for object coordinates (P)
- World coordinates
 - Native space for light vector (\mathbf{l}), env-maps
 - Not explicit in OpenGL
- Eye Coordinates
 - Native space for view vector (\mathbf{v})
- Tangent Space
 - Native space for bump/normal maps (\mathbf{n})

Tangent Space

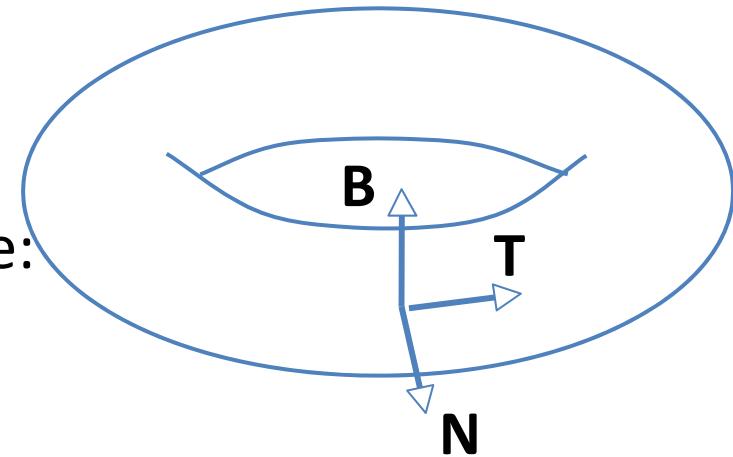
- Tangent space is most often used
- This variant is called normal mapping
- Normal maps usually blue-ish in RGB space, because perturbed normals are still mostly up-facing (0,0,1)



Tangent Space Basics

- Concept from differential geometry
- Set of all tangents on a surface
- Orthonormal coordinate system (frame) for each point on the surface:

$$\mathbf{n}(u, v) = \frac{\partial \mathbf{p}}{\partial u} \times \frac{\partial \mathbf{p}}{\partial v}$$



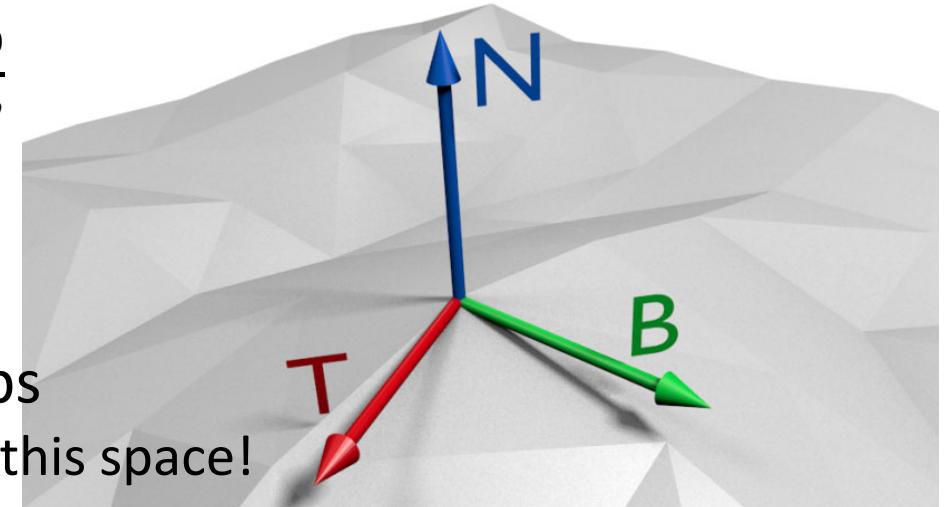
$$\mathbf{t} = \frac{\partial \mathbf{p}}{\partial u} \quad \mathbf{b} = \frac{\partial \mathbf{p}}{\partial v}$$

- Square patch assumption:

$$\mathbf{b} = \mathbf{n} \times \mathbf{t}$$

(watch out for handedness!)

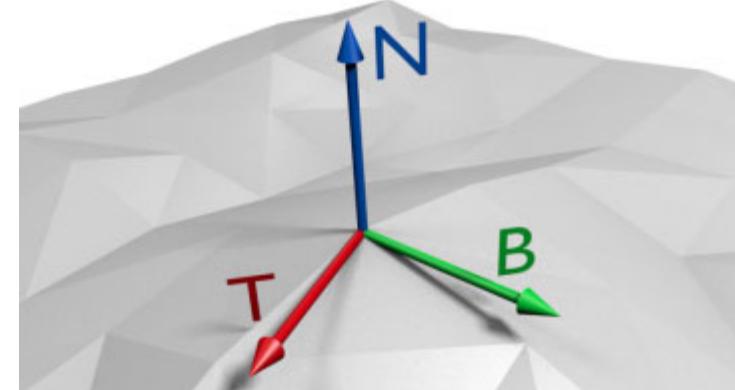
- A natural space for normal maps
 - Vertex normal $\mathbf{n} = (0, 0, 1)^T$ in this space!



Tangent Space Matrix

- Every vertex needs these three vectors
 - E.g., in attribute arrays
- They are interpolated for each fragment
- Fragment program can set up tangent space matrix **TSM**

$$\mathbf{TSM} = \begin{pmatrix} T_x & B_x & N_x & 0 \\ T_y & B_y & N_y & 0 \\ T_z & B_z & N_z & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$



Tangent Space Algorithm

- For each vertex
 - Transform \mathbf{I} and \mathbf{v} with **TSM** and normalize
 - Compute normalized \mathbf{h} from \mathbf{v} and \mathbf{I}
- For each fragment
 - Interpolate \mathbf{I} and \mathbf{h}
 - Renormalize \mathbf{I} and \mathbf{h}
 - Fetch $\mathbf{n}' = \text{texture}(u,v)$
 - Compute $\max(\mathbf{I} \cdot \mathbf{n}', 0)$ and $\max(\mathbf{h} \cdot \mathbf{n}', 0)^s$
 - Combine using standard Phong equation

Reflective Bump Mapping

- EMBM (Environment Map Bump Mapping)



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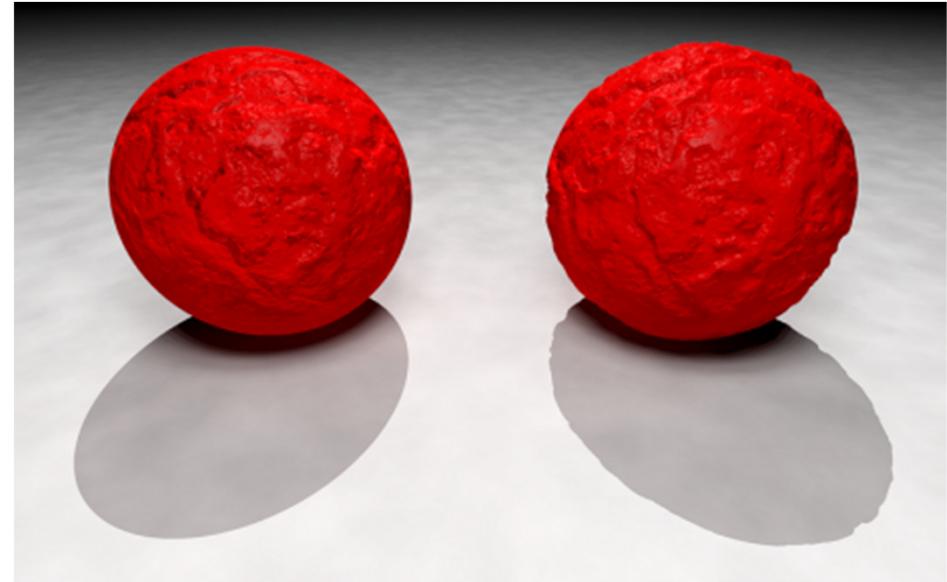
Texture mapping

EMBM in World Space

- For each vertex
 - Transform v to world space
 - Compute tangent space to world space transform (t, b, n)
- For each fragment
 - Interpolate and renormalize v
 - Interpolate frame (t, b, n)
 - Lookup $n' = \text{texture}(u, v)$
 - Transform n' from tangent space to world space
 - Compute reflection vector r (in world space) using n'
 - Lookup $c = \text{cubemap}(r)$
- Note: this is an example of dependent texturing

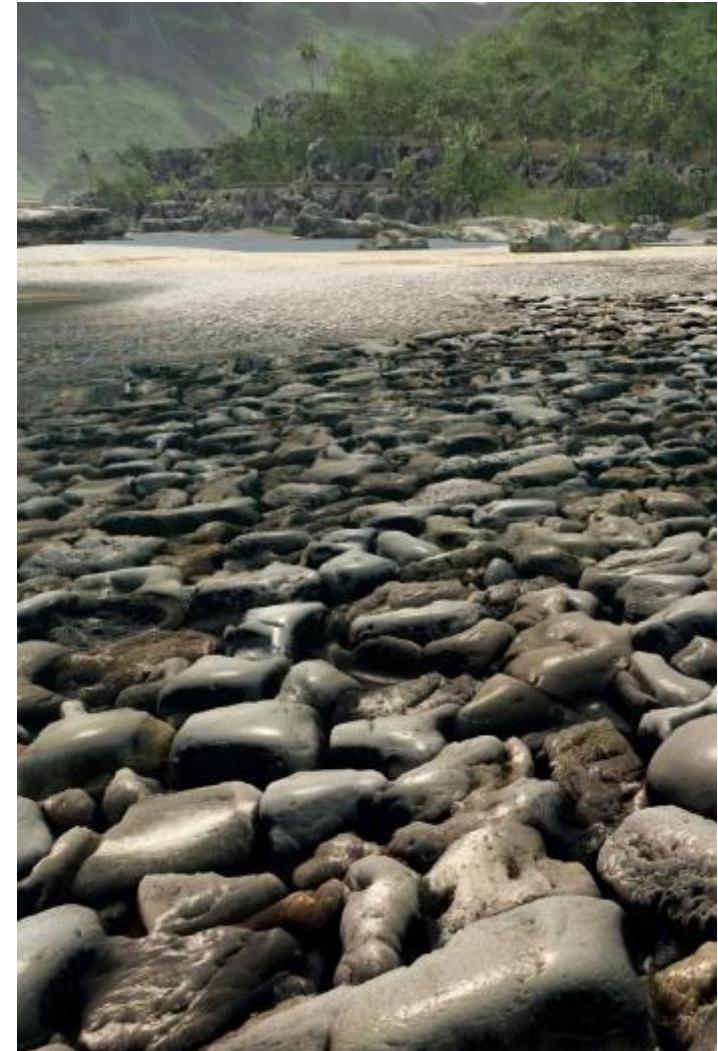
Bump Mapping Issues

- Artifacts
 - Shadows
 - Silhouettes edgy
 - No parallax
- Effectiveness
 - No effect if neither light nor object moves
 - In this case, use light maps
 - Exception: specular highlights



Parallax Mapping

- Also called *Relief Mapping*
- Enhanced bump mapping
 - Texture lookup is displaced according to viewing angle



Example: Crysis

Parallax Mapping Example

- Allows for more realism with motion parallax and steeper height maps with occlusions



https://commons.wikimedia.org/w/index.php?title=File%3AParallax_mapping.ogv

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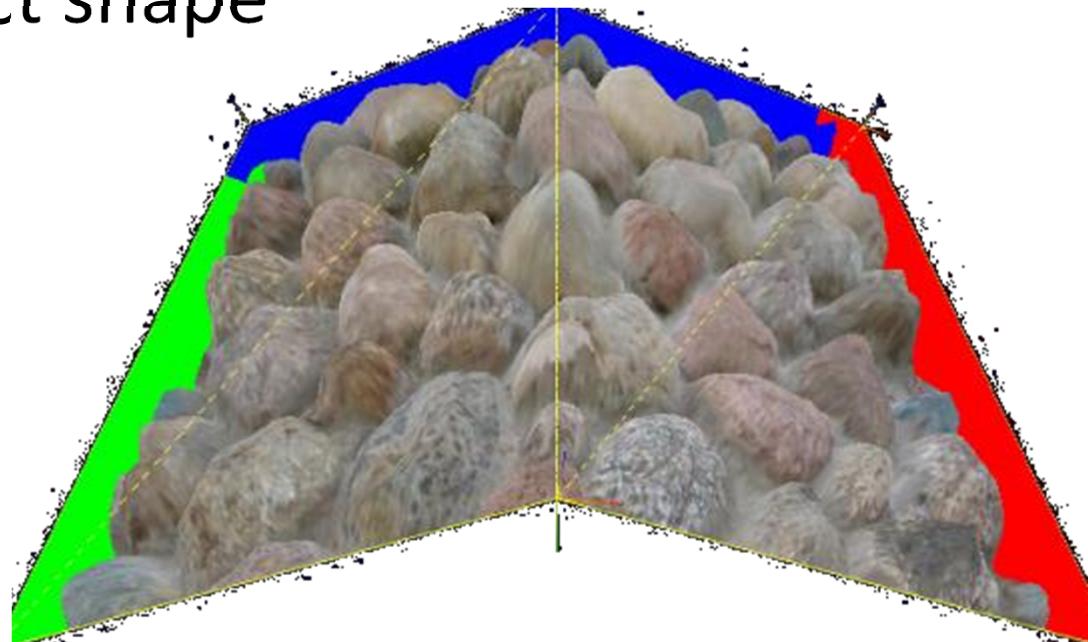
Texture mapping

<https://youtu.be/6PpWqUqeqeQ>

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Parallax Mapping Procedure

- Parallax occlusion mapping uses raycasting in the fragment shader
- Expensive, but silhouettes and shadows have correct shape



Parallax Mapping Discussion

- Can replace almost all geometry with good relief maps
- Result: a raycasting engine



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Texture mapping



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Thank You!

Questions?



Diligent Engine Texture Example

https://github.com/DiligentGraphics/DiligentSamples/tree/master/Tutorials/Tutorial03_Texturing



Vertex Shader

```
cbuffer Constants { float4x4 g_WorldViewProj;  
};  
struct VSInput { float3 Pos : ATTRIB0;  
                float2 UV : ATTRIB1; // texture coordinates in  
};  
struct PSInput { float4 Pos : SV_POSITION;  
                float2 UV : TEX_COORD; // texture coordinates out  
};  
void main(in VSInput VSIn, out PSInput PSIn) {  
    PSIn.Pos = mul(float4(VSIn.Pos,1.0), g_WorldViewProj);  
    PSIn.UV = VSIn.UV; // just copy the input  
}
```

Fragment Shader

```
Texture2D g_Tex; // texture object
SamplerState g_sampler; // sampler object
struct PSInput { float4 Pos : SV_POSITION;
                  float2 UV : TEX_COORD;
};
struct PSOutput { float4 Color : SV_TARGET; };
void main(in PSInput PSIn, out PSOutput PSOut) {
    PSOut.Color = g_Tex.Sample(g_sampler, PSIn.UV);
}
```

Initializing the Pipeline State

- We need to define mutable resource variable `g_texture`

```
ShaderResourceVariableDesc Vars[] = {
    { SHADER_TYPE_PIXEL, "g_Texture", SHADER_RESOURCE_VARIABLE_TYPE_MUTABLE }
};
```

- Pass it to pipeline state object

```
PSOCreateInfo.PSODesc.ResourceLayout.Variables      = Vars;
PSOCreateInfo.PSODesc.ResourceLayout.NumVariables = _countof(Vars);
```

- Define an immutable sampler (sampling does not change)

```
SamplerDesc SamLinearClampDesc {
    FILTER_TYPE_LINEAR, FILTER_TYPE_LINEAR, FILTER_TYPE_LINEAR,
    TEXTURE_ADDRESS_CLAMP, TEXTURE_ADDRESS_CLAMP, TEXTURE_ADDRESS_CLAMP
};
ImmutableSamplerDesc ImtblSamplers[] = {
    { SHADER_TYPE_PIXEL, "g_Texture", SamLinearClampDesc }
};
PSOCreateInfo.PSODesc.ResourceLayout.ImmutableSamplers = ImtblSamplers;
PSOCreateInfo.PSODesc.ResourceLayout.NumImmutableSamplers= _countof(ImtblSamplers);
```

Load Texture and Bind It

- Diligent loads jpg, png, tiff

```
TextureLoadInfo loadInfo;  
loadInfo.IsSRGB = true;  
RefCntAutoPtr<ITexture> Tex;  
CreateTextureFromFile("DGLogo.png", loadInfo, m_pDevice, &Tex)
```

- Get shader resource view from the texture

```
m_TextureSRV = Tex->GetDefaultView(TEXTURE_VIEW_SHADER_RESOURCE);
```

- Create shader resource binding object from PSO

```
m_pPSO->CreateShaderResourceBinding(&m_SRB, true);
```

- Set shader resource view

```
m_SRB->GetVariableByName(SHADER_TYPE_PIXEL, "g_Texture")->Set(m_TextureSRV);
```

Render Textured Object

- ... (set vertex buffer etc. omitted here)
- Select our prepared pipeline

```
m_pImmediateContext->SetPipelineState(m_pPSO);
```

- Commit the shader resources

```
m_pImmediateContext->CommitShaderResources(m_SRB, RESOURCE_STATE_TRANSITION_MODE_TRANSITION);
```

- Draw Call (here: indexed draw)

```
DrawIndexedAttribs DrawAttrs = {...}; // This is an indexed draw
m_pImmediateContext->DrawIndexed(DrawAttrs);
```