CMSC427 fall 2017
Texture Mapping

Majority of slides credit to
Dr. Zwicker

Today

- Basic shader for texture mapping
- Texture coordinate assignment
- Antialiasing
- Fancy textures

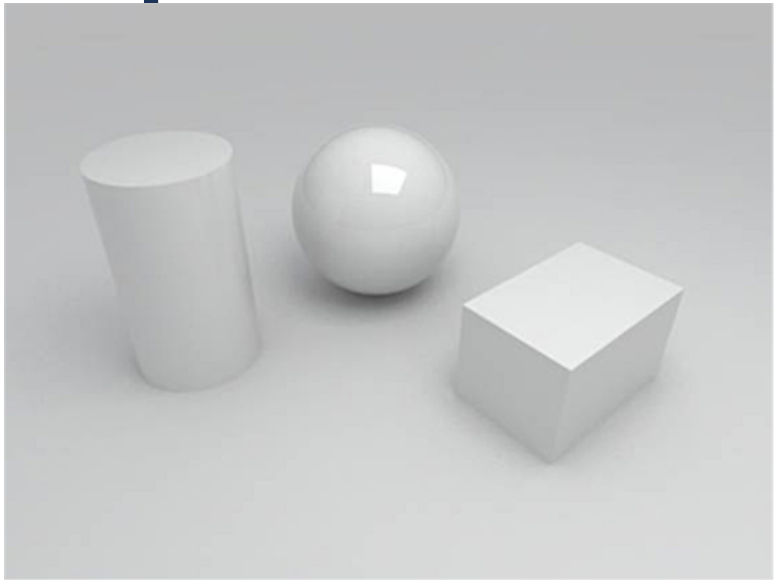
- Warning: side notes will include history of pyramids with Dr. Rosenfeld, revisiting bilinear interpolation,

Texture mapping

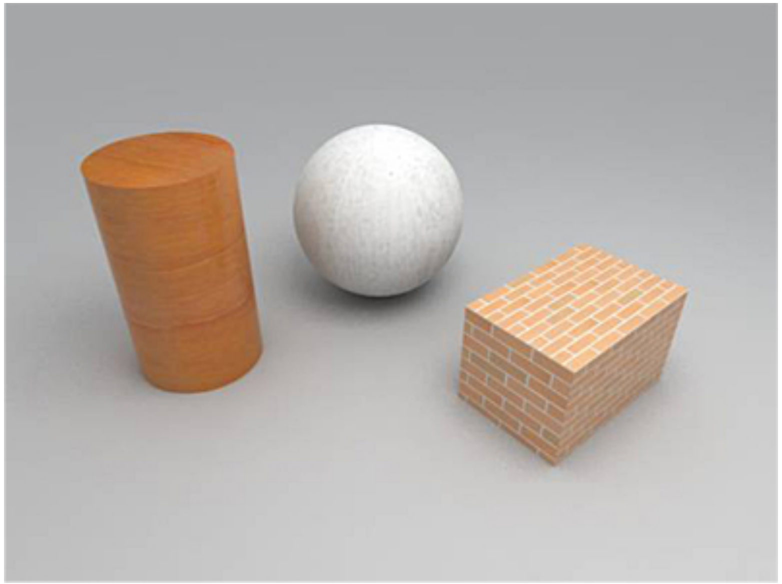
- Glue textures (images) onto surfaces
- Same triangles, much more interesting and detailed appearance
- Think of colors as reflectance coefficients

Texture mapping - quick

- Basic shading – material constant over objects



- Basic shading *plus* texture mapping – color varies over object



- How do?

Texture mapping in OpenGL

- Initializing and loading texture requires series of OpenGL API calls
  glPixelStorei
  glGenTextures
  glBindTexture
  glTexImage2D

  etc…

http://www.glprogramming.com/red/

- Look up details when you need them
- Learn from example code, GLTexture.java
- Documentation http://www.opengl.org/documentation/

Basic shaders for texturing

```
// Need to initialize texture using OpenGL API call

// Vertex shader
uniform mat4 modelview;
uniform mat4 projection;
in vec2 texcoords;
in vec4 position;
out frag_texcoords;

void main()
  gl_Position = projection * modelview * position; // predefined output
  frag_texcoords = texcoords; // pass texture coords. to fragment shader
}

// Fragment shader
uniform sampler2D tex;  // "tex" is reference to texture, set by host
in frag_texcoords;
out frag_color;
void main()
{
  frag_color = texture(tex, frag_texcoords); // "texture" is a GLSL fnct.
}
```

Getting a texture sampler

```
import com.jogamp.opengl.util.texture.*;

// Declare texture objects at class level
private int earthTexture; // Index to OpenGL texture unit
private Texture joglEarthTexture; // Actual texture data

// Read texture – as part of initialization
joglEarthTexture = loadTexture("earth.jpg");
earthTexture = joglEarthTexture.getTextureObject();

// Bind texture to GPU – as part of display
gl.glActiveTexture(GL_TEXTURE0);
gl.glUniform1i(gl.glGetUniformLocation(rendering_program, ”tex"), 0);
gl.glBindTexture(GL_TEXTURE_2D, earthTexture);

// Utility function
public Texture loadTexture (String textureFileName) {
   Texture tex = null;
   try { tex = TextureIO.newTexture(new File(textureFileName), false);
   catch (Exception e) { e.printStackTrace(); }
   return tex;
   }
```

Adding texture coordinates

```
// From Gordon program 5.1 Texture mapping on a pyramid
// From setVertices, one time initialization operation
float[] pyramid_positions = {   // Vertices
   -1.0f, -1.0f, 1.0f, 1.0f, -1.0f, 1.0f, 0.0f, 1.0f, 0.0f,    //front
    1.0f, -1.0f, 1.0f, 1.0f, -1.0f, -1.0f, 0.0f, 1.0f, 0.0f,    //right
    1.0f, -1.0f, -1.0f, -1.0f, -1.0f, -1.0f, 0.0f, 1.0f, 0.0f, //back
   -1.0f, -1.0f, -1.0f, -1.0f, -1.0f, 1.0f, 0.0f, 1.0f, 0.0f, //left
   -1.0f, -1.0f, -1.0f, 1.0f, -1.0f, 1.0f, -1.0f, -1.0f, 1.0f, //LF
    1.0f, -1.0f, 1.0f, -1.0f, -1.0f, -1.0f, 1.0f, -1.0f, -1.0f  //RR };
float[] texture_coordinates =    {
   0.0f, 0.0f, 1.0f, 0.0f, 0.5f, 1.0f,  // Range 0-1
   0.0f, 0.0f, 1.0f, 0.0f, 0.5f, 1.0f,
   0.0f, 0.0f, 1.0f, 0.0f, 0.5f, 1.0f,
   0.0f, 0.0f, 1.0f, 0.0f, 0.5f, 1.0f,
   0.0f, 0.0f, 1.0f, 1.0f, 0.0f, 1.0f,
   1.0f, 1.0f, 0.0f, 0.0f, 1.0f, 0.0f             };
// Create vertex Vertex Buffer Object
gl.glBindBuffer(GL_ARRAY_BUFFER, vbo[0]);
FloatBuffer pyrBuf = Buffers.newDirectFloatBuffer(pyramid_positions);
gl.glBufferData(GL_ARRAY_BUFFER, pyrBuf.limit()*4, pyrBuf, GL_STATIC_DRAW);

// Create texture coordinate Vertex Buffer Object
gl.glBindBuffer(GL_ARRAY_BUFFER, vbo[1]);
FloatBuffer texBuf = Buffers.newDirectFloatBuffer(texture_coordinates);
gl.glBufferData(GL_ARRAY_BUFFER, texBuf.limit()*4, texBuf, GL_STATIC_DRAW);
```

Using texture coordinates

```
// From Gordon program 5.1 Texture mapping on a pyramid
// From display, repeated for each frame

// Bind vertices
gl.glBindBuffer(GL_ARRAY_BUFFER, vbo[0]);
gl.glVertexAttribPointer(0, 3, GL_FLOAT, false, 0, 0);
gl.glEnableVertexAttribArray(0);

// Bind texture coordinates
gl.glBindBuffer(GL_ARRAY_BUFFER, vbo[1]);
gl.glVertexAttribPointer(1, 2, GL_FLOAT, false, 0, 0);
gl.glEnableVertexAttribArray(1);

// Activate texture 0
gl.glActiveTexture(GL_TEXTURE0);
gl.glBindTexture(GL_TEXTURE_2D, earthTexture);

// Active z-buffer
gl.glEnable(GL_DEPTH_TEST);
gl.glDepthFunc(GL_LEQUAL);

// Draw
gl.glDrawArrays(GL_TRIANGLES, 0, 18);
```

Side note: Java-Shader binding

// Option 1: using preset location index

```
//Option 1 in Java program
gl.glBindBuffer(GL_ARRAY_BUFFER, vbo[0]);
gl.glVertexAttribPointer(0, 3, GL_FLOAT, false, 0, 0);
gl.glEnableVertexAttribArray(0);  // We're connecting to location 0
```

// Option 2: query shader program

```
//Option 2 in Java program
gl.glActiveTexture(GL_TEXTURE0);
gl.glUniform1i( gl.glGetUniformLocation(rendering_program, "tex"), 0); // Query!
```

```
#version 430
layout (location=0) in vec3 pos;          // Option 1 in shader
layout (location=1) in vec2 texCoord;

out vec2 tc;

uniform mat4 mv_matrix;
uniform mat4 proj_matrix;

uniform sampler2D tex;

void main(void){
   gl_Position = proj_matrix * mv_matrix * vec4(pos,1.0);
   tc = texCoord;
}

// NOTE: MACS DON'T ALLOW OPTION 1 FOR TEXTURES, MUST QUERY
```

Today

- Basic shader for texture mapping
- Texture coordinate assignment
- Texture filtering
- Fancy textures

Texture coordinate assignment

- Surface parameterization
  - Mapping between 3D positions on surface and 2D texture coordinates
  - In practice, defined by texture coordinates of triangle vertices
- Various options to establish a parameterization

- Note: texture coordinates are often called (s,t) or equivalently (u,v)
- Can be in range [0,1] or [0,width], [0,height] of image

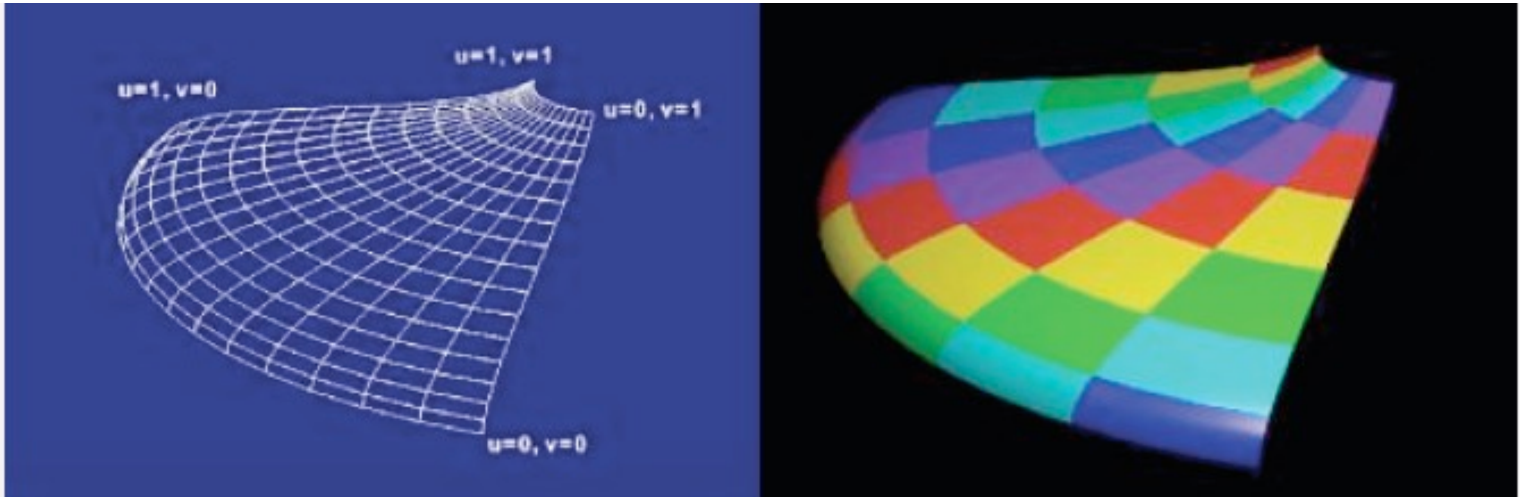
Parametric surfaces

http://en.wikipedia.org/wiki/Parametric_surface

- Surface position *x,y,z* given by three functions

$$x = f_x(u,v) \quad y = f_y(u,v) \quad z = f_z(u,v)$$

  of parameters *u, v*
- Very common in computer aided design (CAD)
- Use (*u,v*) parameters as texture coordinates
- Later in class: Bézier surfaces



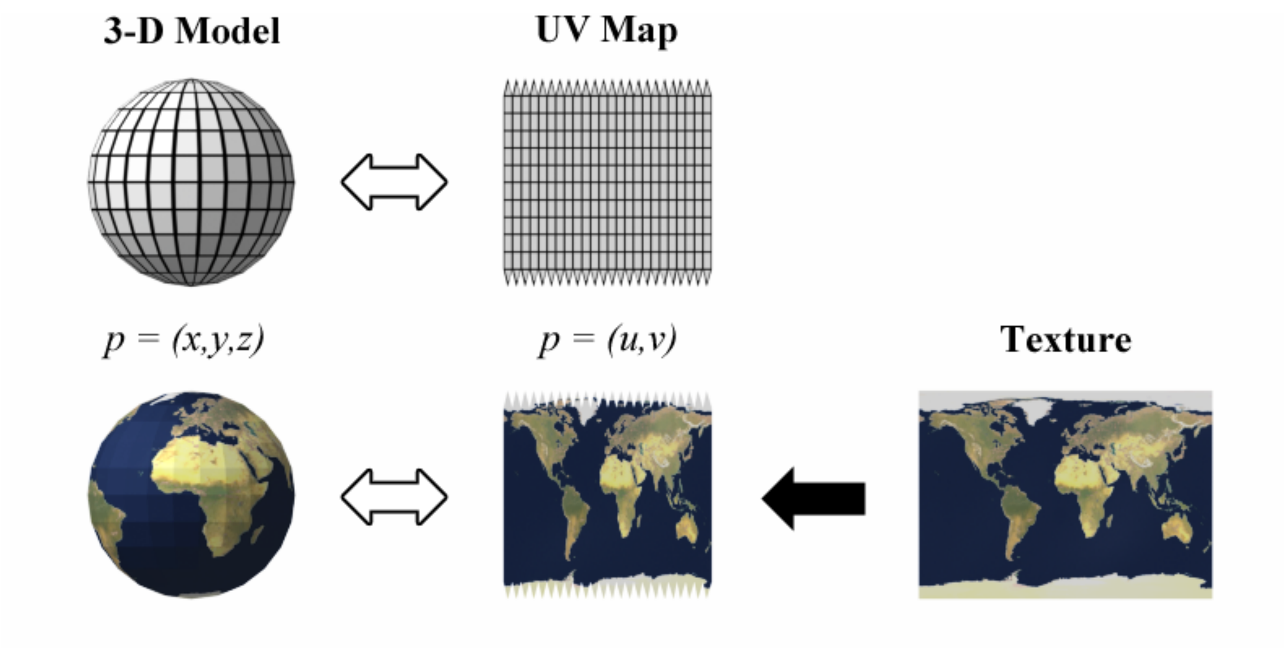
Cylinder

http://en.wikipedia.org/wiki/Parametric_surface

- Vertices (x,y,z) given by three functions

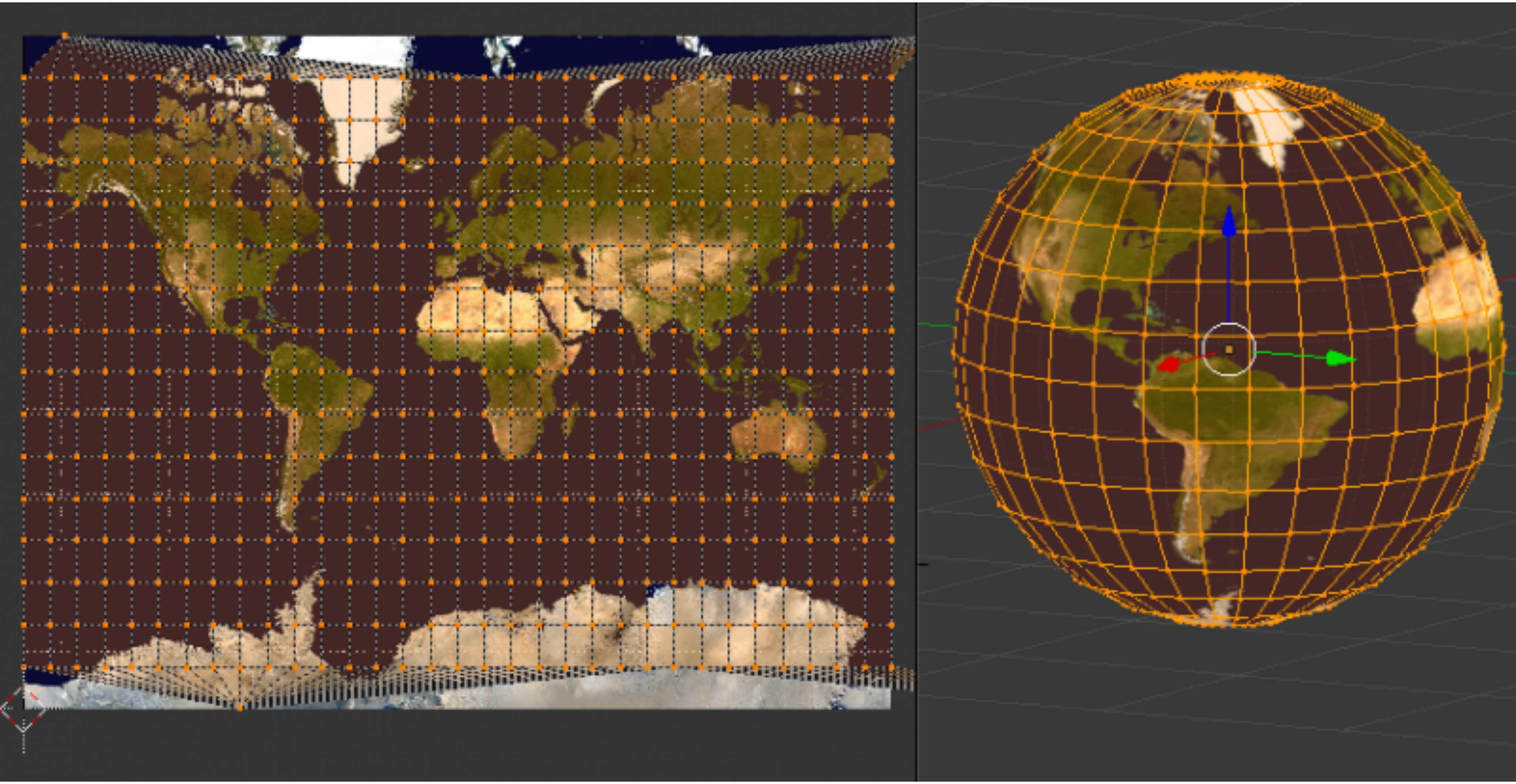
$$x = r\cos(2\pi u)$$
$$y = hv$$
$$z = r\sin(2\pi u)$$

- Texture coordinates given by $u, v \in [0,1]$



Sphere

- Mercator projection



As a function of vertex positions

- In general, may compute u and v using two functions of vertex positions x, y, z

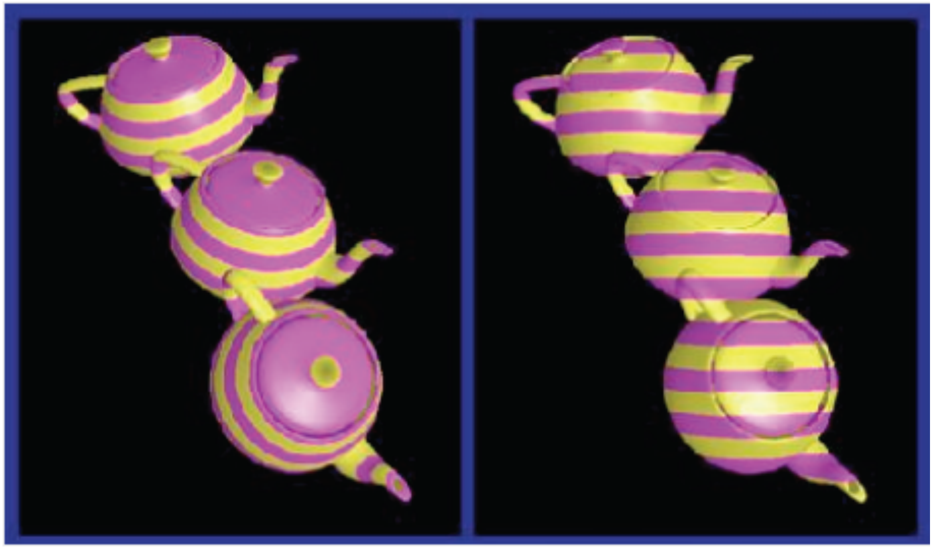
$$u = f_u(x,y,z), \ v = f_v(x,y,z)$$

- How to define f_u, f_v?

Linear functions

- Simplest form: linear function (transformation) of vertex x, y, z coordinates
- For example, orthographic transformation

$$\begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$



Projective transformation

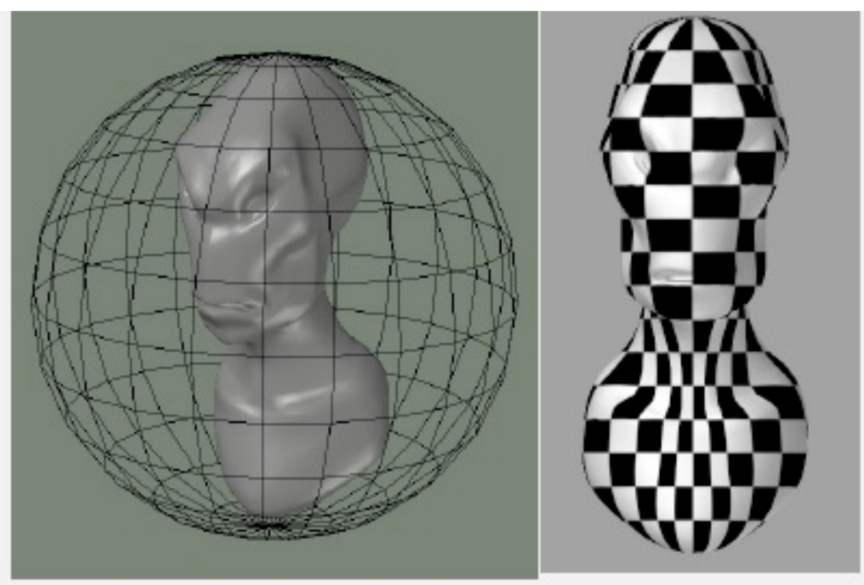
- Use perspective projection of x, y, z coordinates

$$\begin{bmatrix} u' \\ v' \\ w \end{bmatrix} = \mathbf{M} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}, \quad u = u'/w, v = v'/w$$

- Useful to achieve “fake” lighting effects

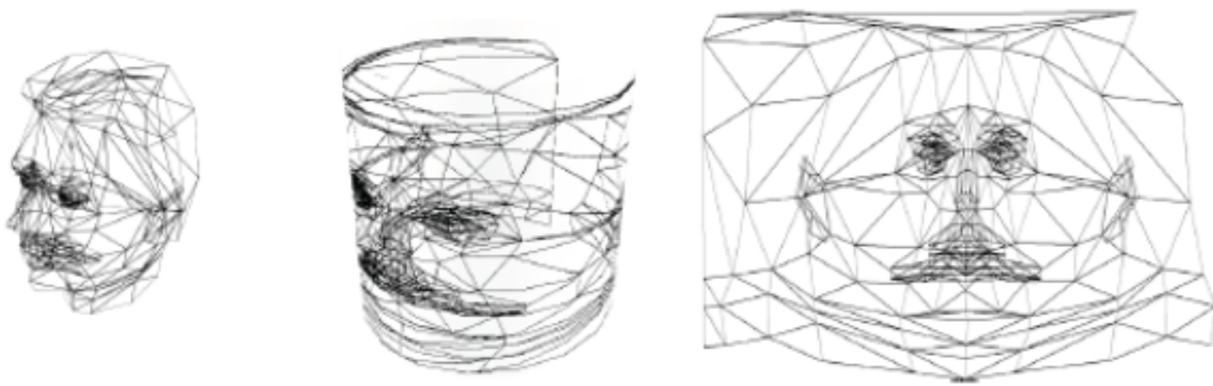
Spherical mapping

- Use, e.g., spherical coordinates for sphere
- Place object in sphere
- “shrink-wrap” sphere to object
  - Shoot ray from center of sphere through each vertex
  - Spherical coordinates of the ray are texture coordinates for vertex



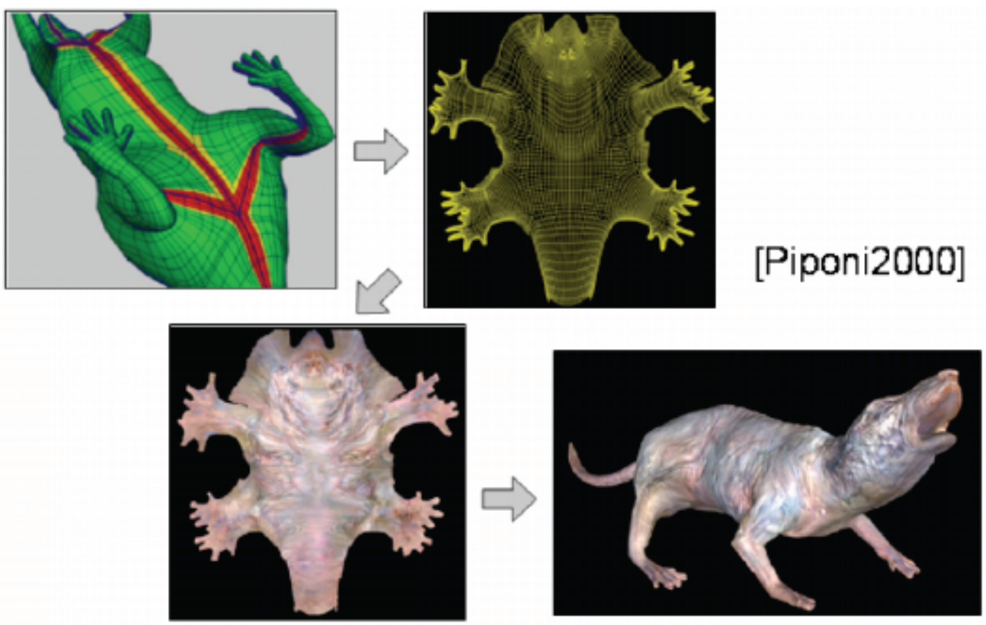
Cylindrical mapping

- Similar as spherical mapping, but with cylinder
- Useful for faces



Skin mapping

- Techniques to unfold surface onto plane
  - Minimize “distortions”
  - Preserve area, angle
- Sophisticated math
- Functionality usually provided by 3D modeling tools (Maya, Blender, etc.)

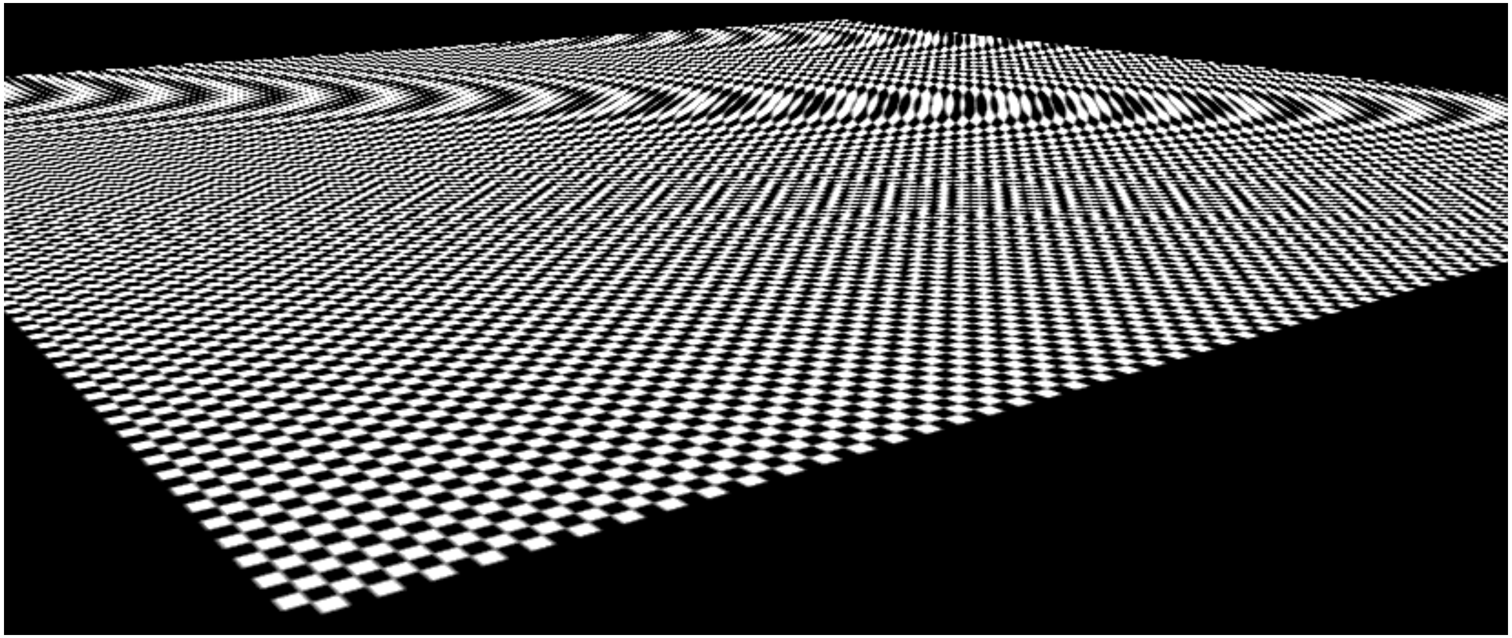


[Piponi2000]

Today

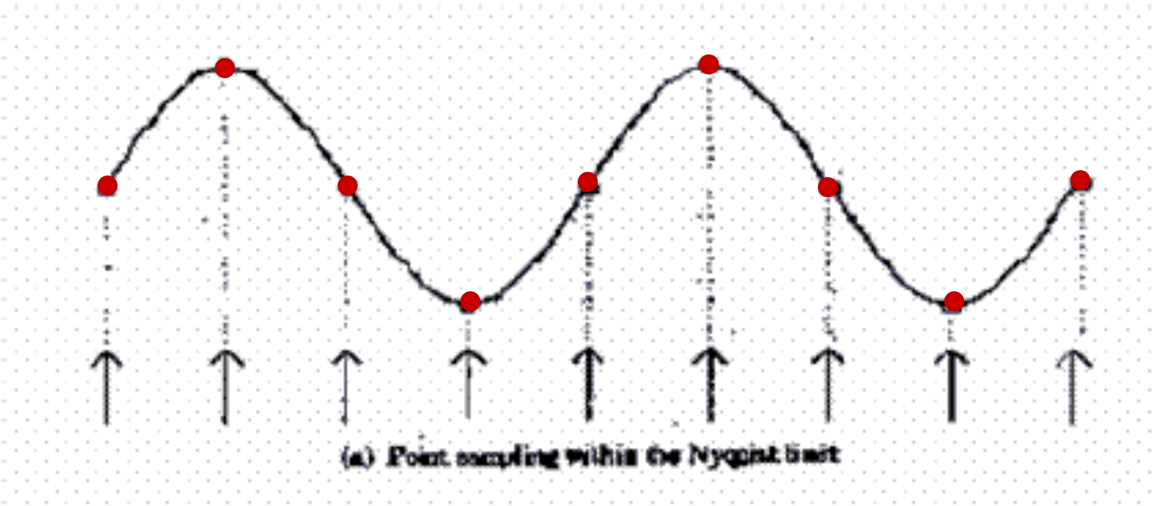
- Basic shader for texture mapping
- Texture coordinate assignment
- Antialiasing
- Fancy textures

What is going on here?



Aliasing

Sufficiently sampled, no aliasing

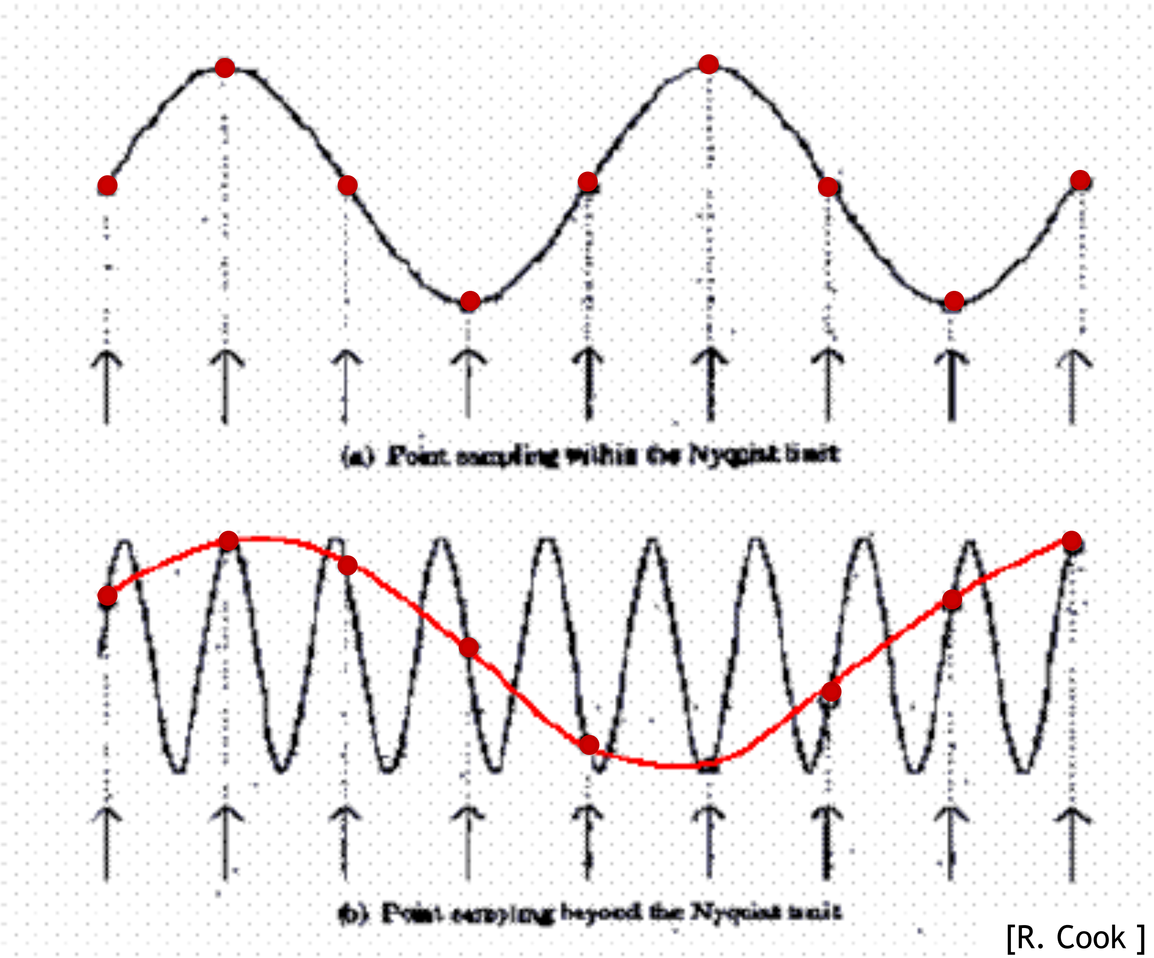


http://en.wikipedia.org/wiki/Aliasing

Aliasing

Sufficiently sampled, no aliasing

Insufficiently sampled, aliasing



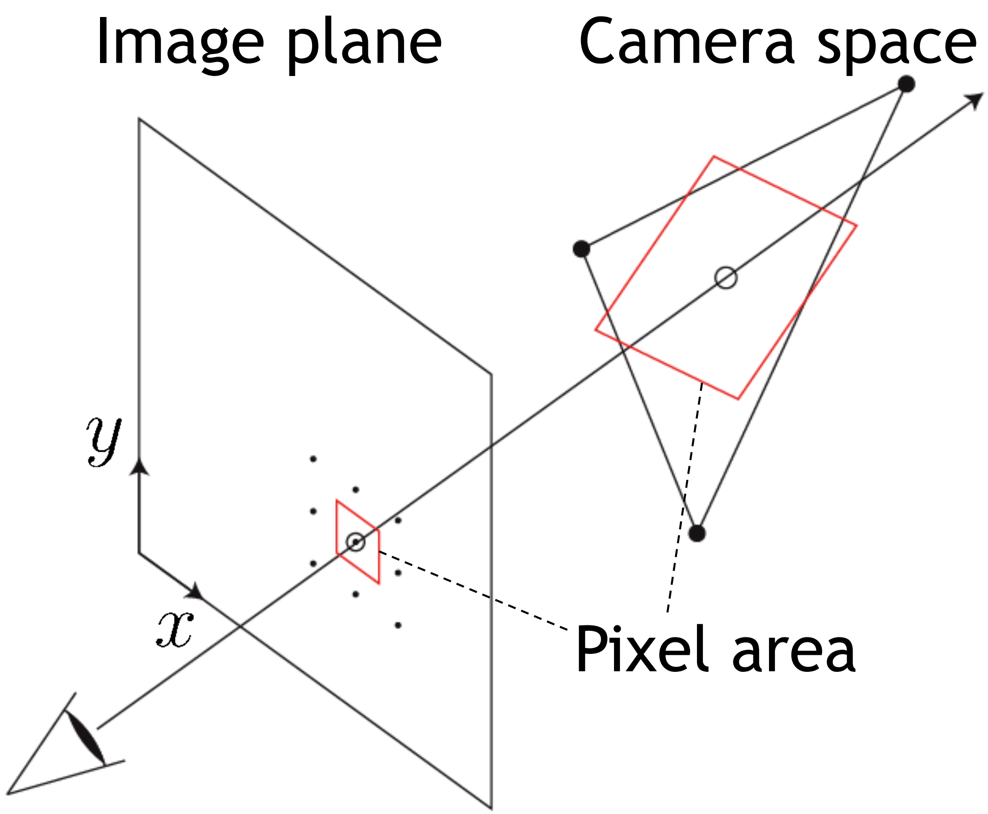
[R. Cook]

High frequencies in the input appear as low frequencies in the sampled signal

http://en.wikipedia.org/wiki/Aliasing

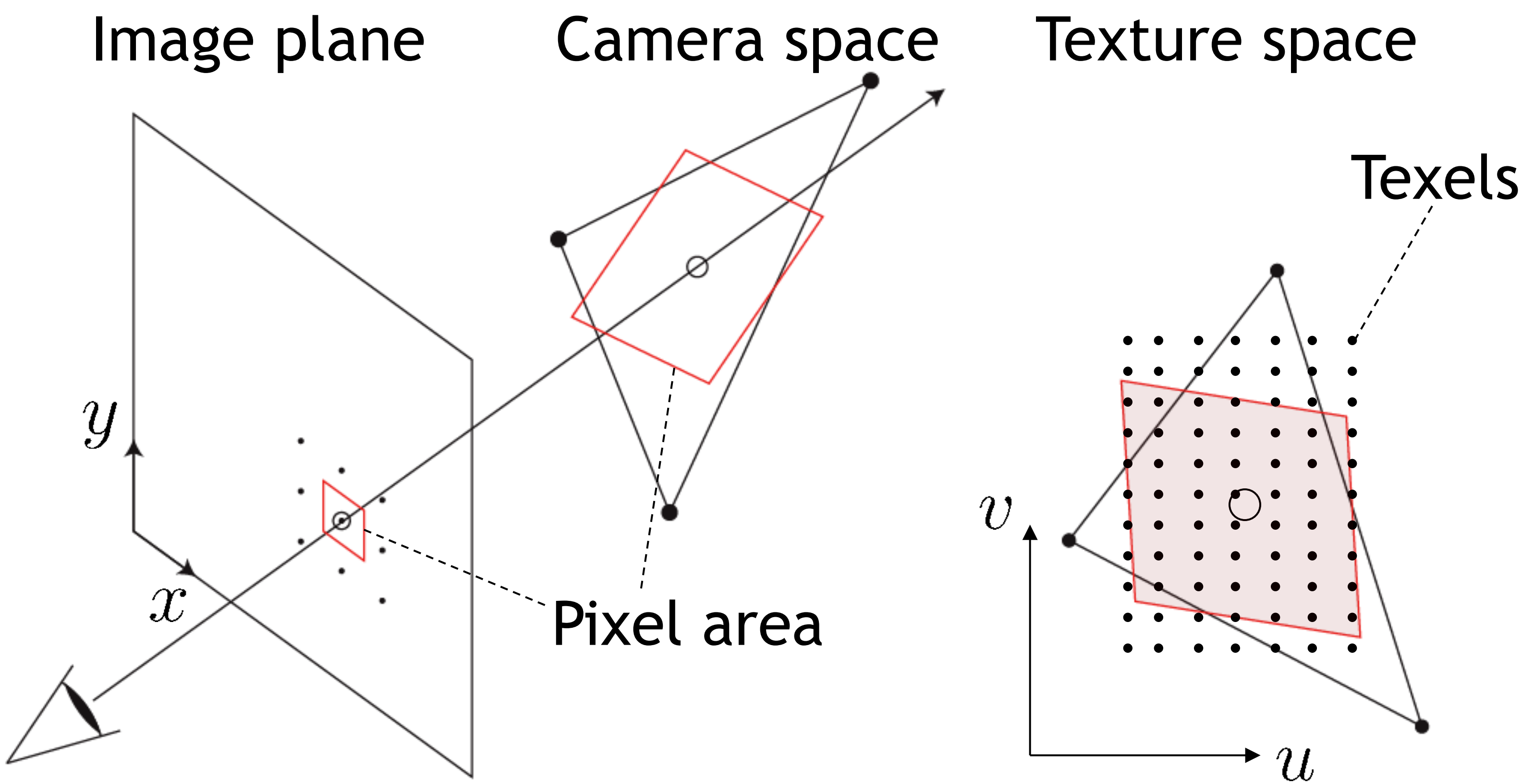
Antialiasing: intuition

- Pixel may cover large area on triangle in camera space



Antialiasing: intuition

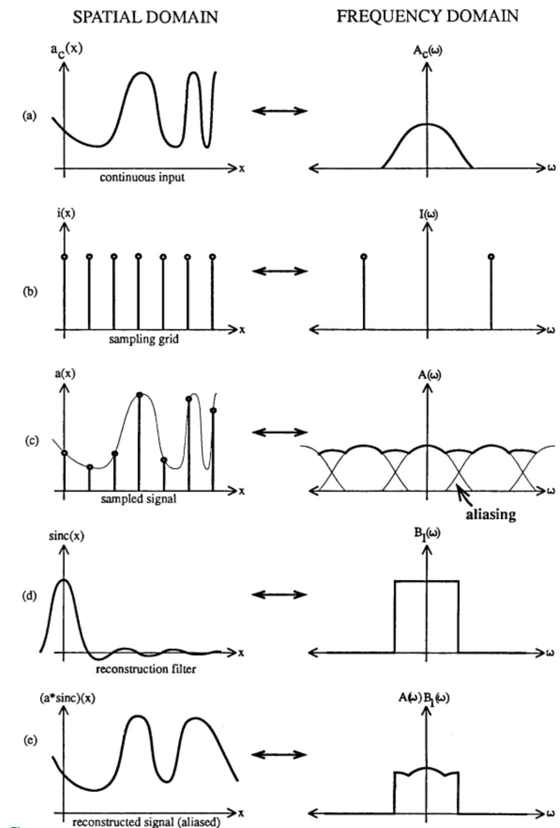
- Pixel may cover large area on triangle in camera space
- Corresponds to many texels in texture space
- Should compute "average" of texels over pixel area



Antialiasing: the math

- Pixels are samples, not little squares
  http://alvyray.com/Memos/CG/Microsoft/6_pixel.pdf
- Use frequency analysis to explain sampling artifacts
  - Fourier transforms
    http://en.wikipedia.org/wiki/Fourier_transform
- If you are interested
  - Heckbert, “Fundamentals of texture mapping”
    http://www.cs.cmu.edu/~ph/texfund/texfund.pdf
  - Glassner, “Principles of digital image synthesis”
    http://www.glassner.com/portfolio/principles-of-digital-image-synthesis/

Schematic explanation of aliasing

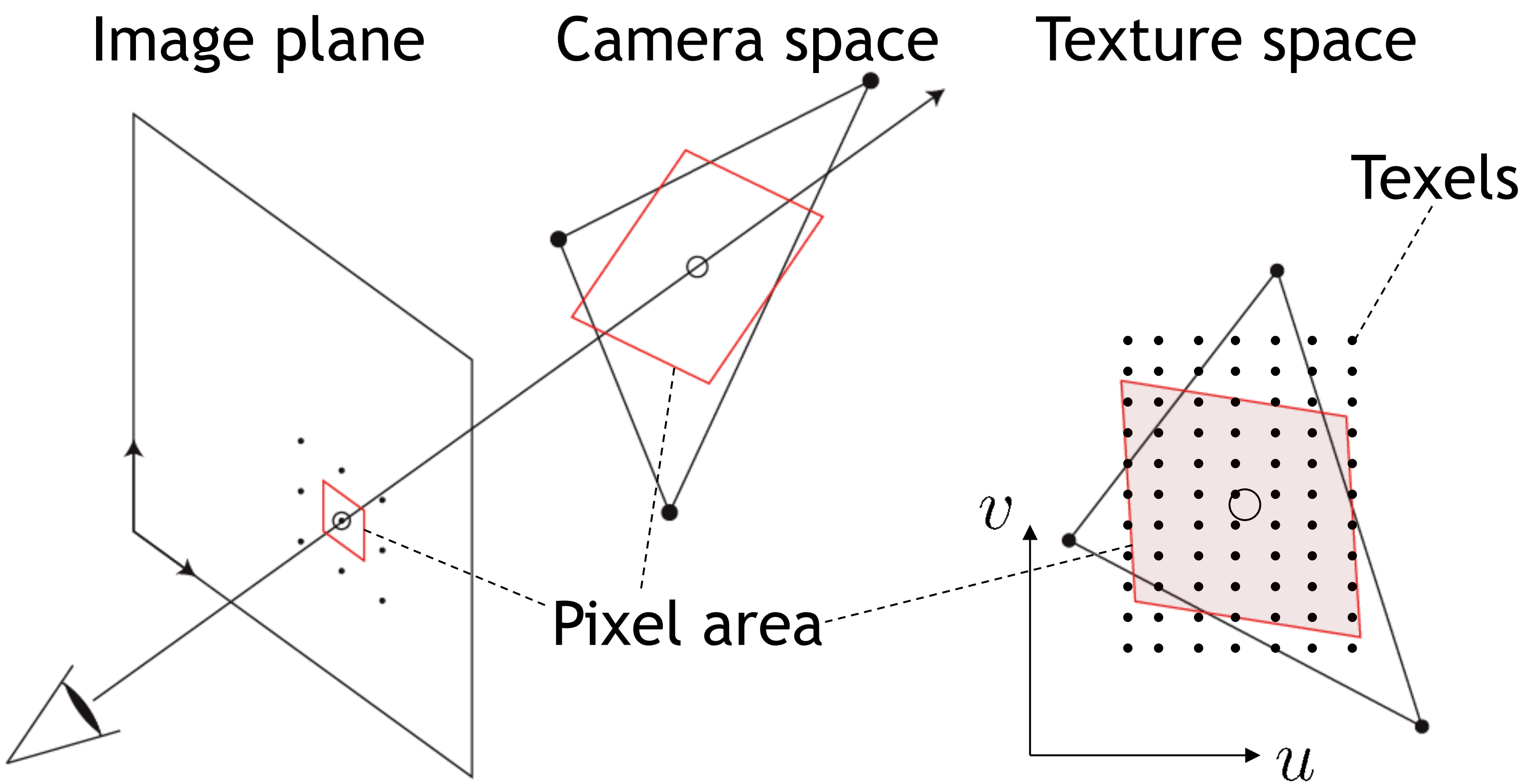


http://www.cs.cmu.edu/~ph/texfund/texfund.pdf

Antialiasing

- Can be achieved by „averaging“ texels over pixel area

- Problems, disadvantages?



Antialiasing using mipmaps

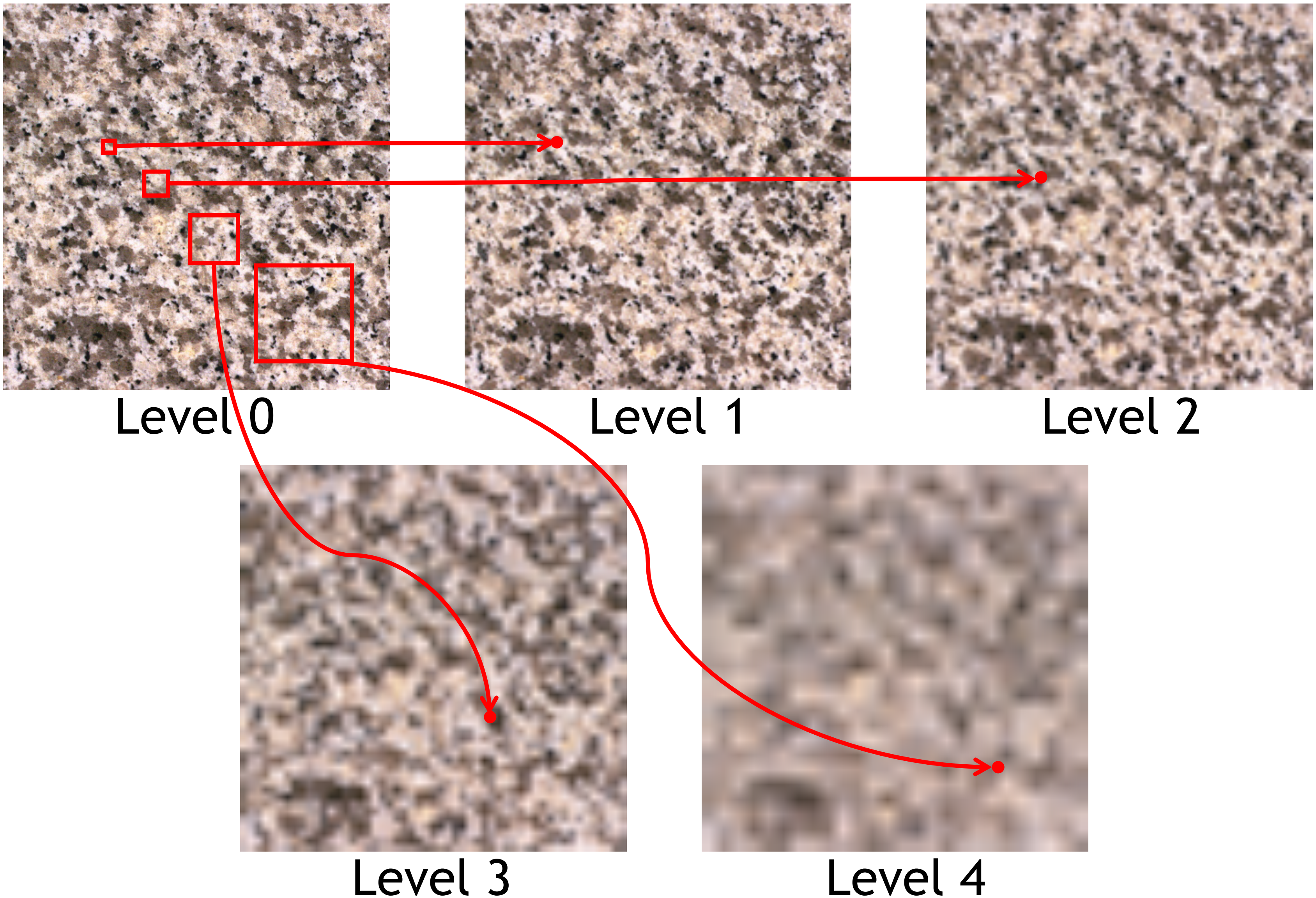
- Averaging over texels during rendering is expensive
  - Many texels as objects get smaller
  - Large memory access and computation cost
- Precompute and store "averaged" (filtered) textures
  - Mipmaps, http://en.wikipedia.org/wiki/Mipmap
  - MIP stands for "multum in parvo" (Williams 1983)
- Practical solution to aliasing problem
  - Fast and simple
  - Available in OpenGL, implemented in GPUs
  - Reasonable quality

Mipmaps

Before rendering

- Precompute and store several filtered versions of textures (mipmaps)
- Filtering performs “local averaging”
  - Simplest: box filter, uniform weighting in a square window; replace each pixel by average of pixels in its neighborhood
- Use higher quality filter to avoid aliasing
- Precompute several filtered textures with different sizes of filtering window

Mipmaps



Double the size of the filtering window from level to level!

Computing mipmaps

- Filtering implemented using convolution
  http://en.wikipedia.org/wiki/Convolution
  - Input function f, convolution kernel (filter) g
  - Continuous formulation

$$(f * g)(t) \stackrel{\text{def}}{=} \int_{-\infty}^{\infty} f(\tau) \cdot g(t-\tau)\, d\tau$$

  - Discrete formulation

$$(f * g)[n] \stackrel{\text{def}}{=} \sum_{m=-\infty}^{\infty} f[m] \cdot g[n-m]$$

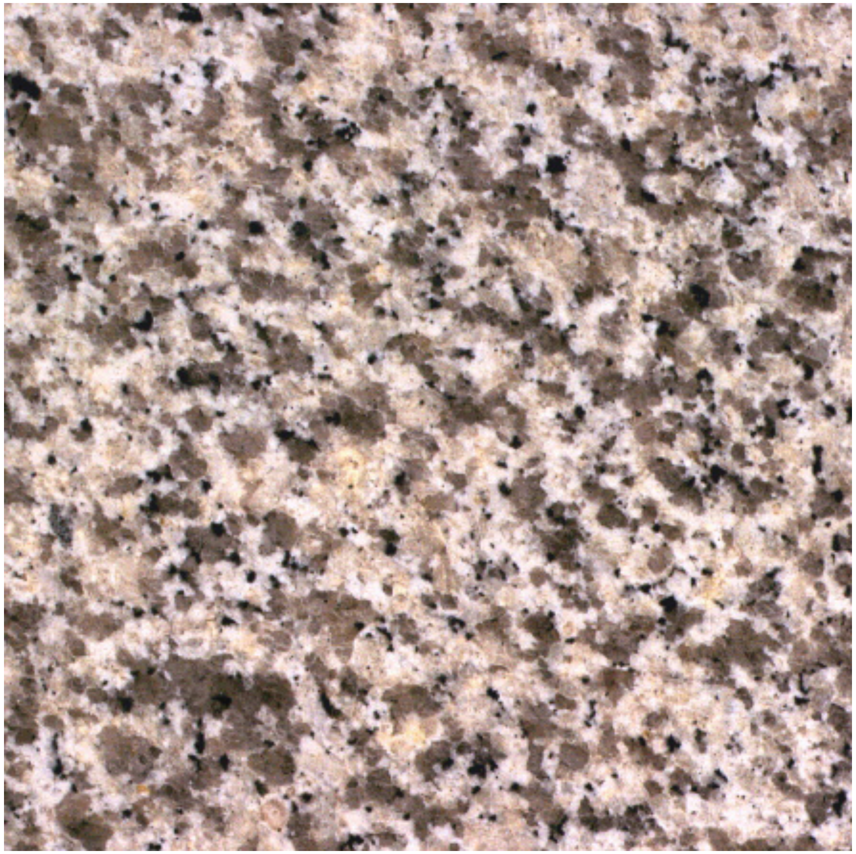
- Two-dimensional convolution is a straightforward extension

Computing mipmaps

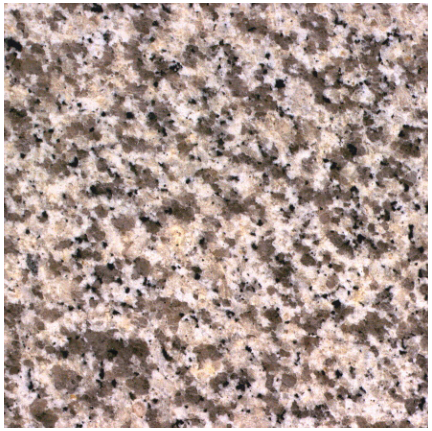
- Filtered textures are blurry
  - Reduce resolution by factor 2 successively without losing information
- Increases memory cost only by 1/3
  - $1/3 = ¼+1/16+1/64+…$
- Width, height of texture needs to be power of two

Example

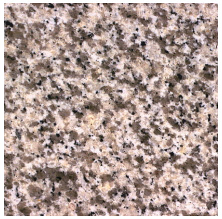
- Resolutions 512x512, 256x256, 128x128, 64x64, 32x32



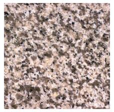
Level 0



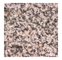
Level 1



2



3



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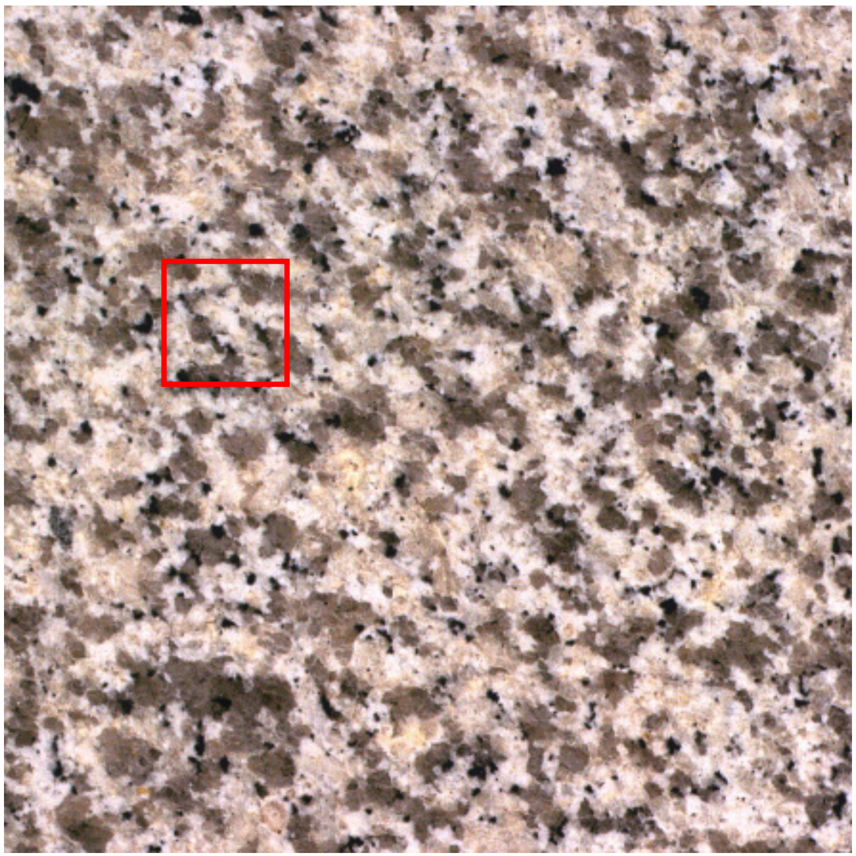
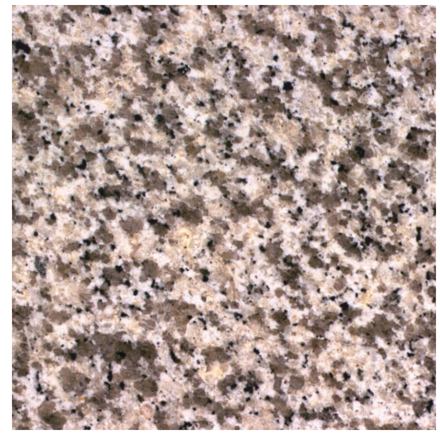
“multum in parvo”

Example

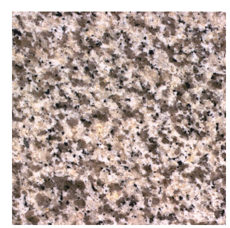
- 1 texel in level 4 is an average of $4^4=256$ texels in level 0



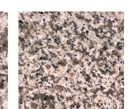
Level 0



Level 1



2



3

4

"multum in parvo"

Rendering with mipmaps

- Interpolate texture coordinate of each pixel as before
- Compute approximate size of pixel in texture space
- Look-up color in nearest mipmap
  - E.g., if pixel corresponds to 10x10 texels use mip-map level 3
  - Use nearest neighbor or bilinear interpolation as before

Mipmapping

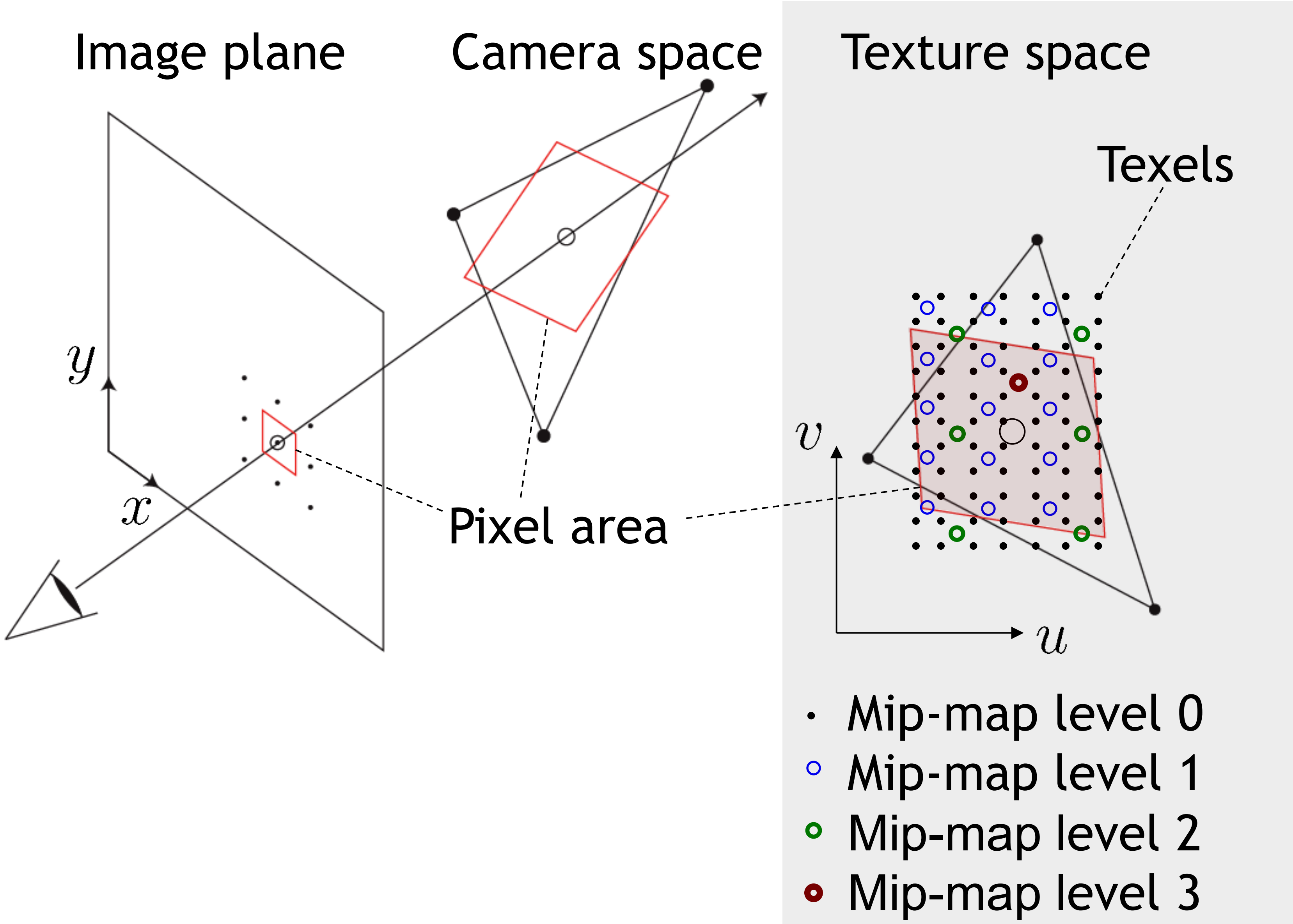
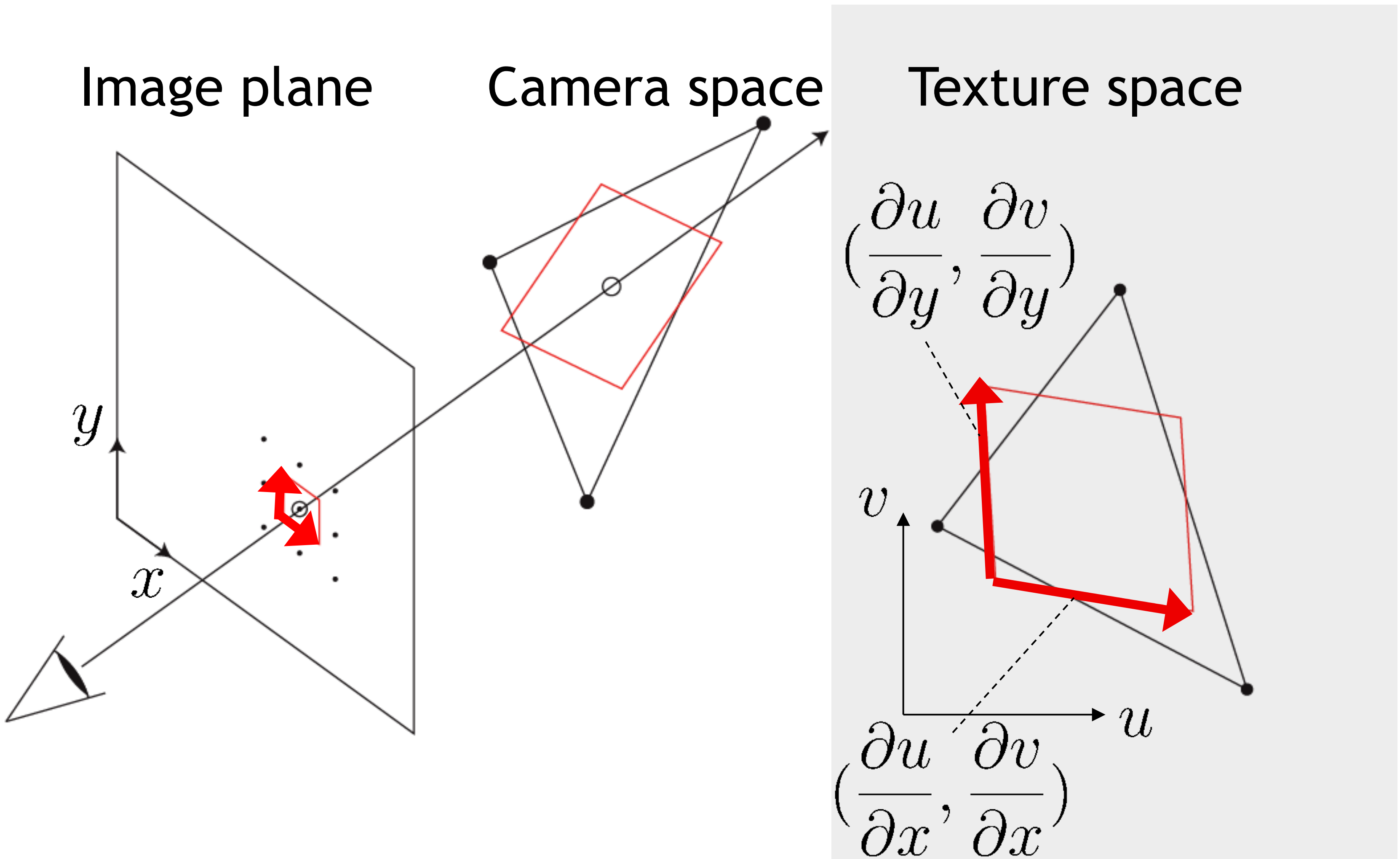


Image plane
Camera space
Texture space
Texels
y
x
v
u
Pixel area
Mip-map level 0
Mip-map level 1
Mip-map level 2
Mip-map level 3

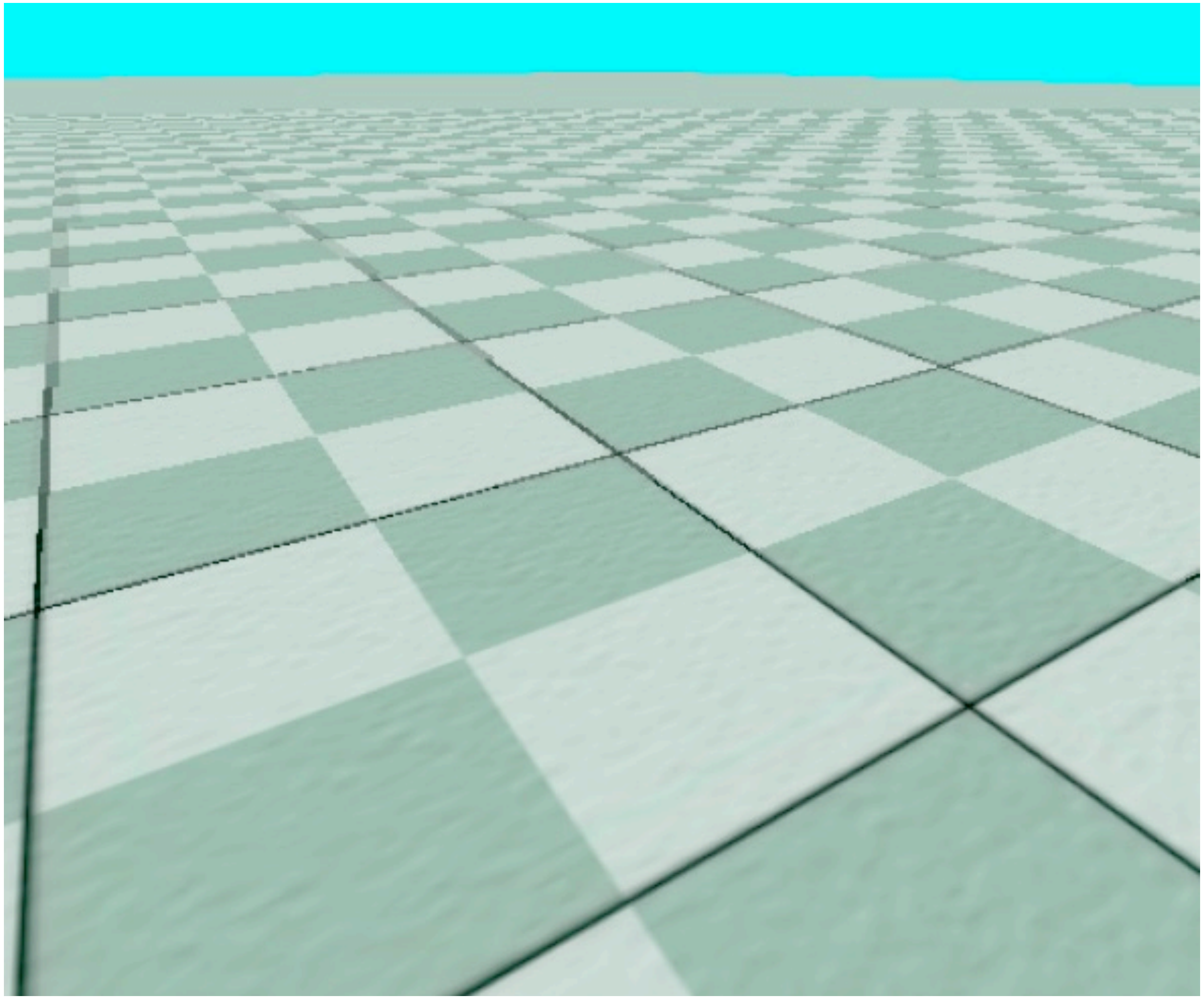
Size of a pixel in texture space

- Given by partial derivatives of mapping
  $u(x,y), v(x,y)$



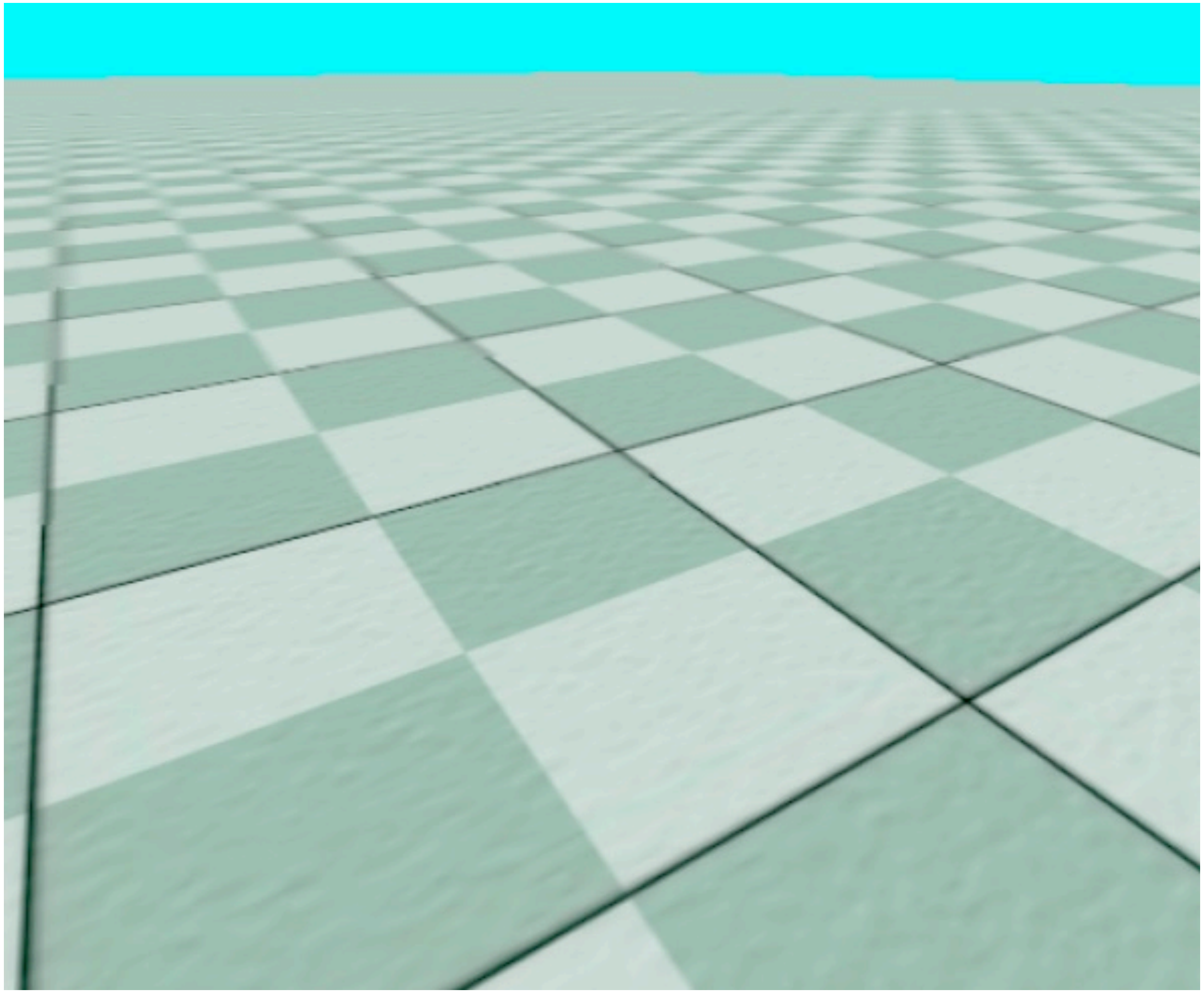
Nearest mipmap, nearest neighbor

- Visible transition between mipmap levels



Nearest mipmap, bilinear

- Visible transition between mipmap levels



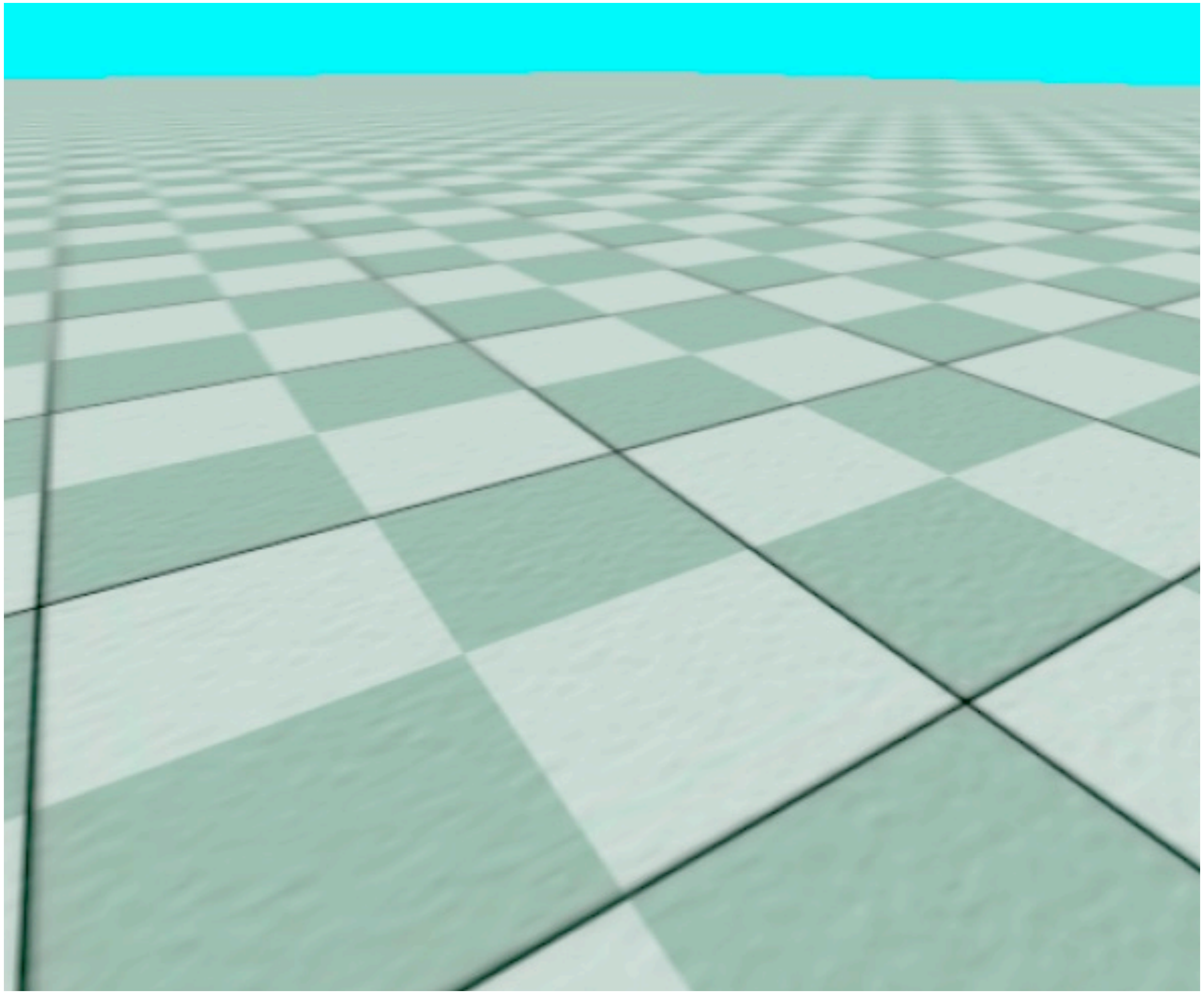
Trilinear mipmapping

http://en.wikipedia.org/wiki/Trilinear_filtering

- Use two nearest mipmap levels
  - E.g., if pixel corresponds to 10x10 texels, use mipmap level 3 and 4
- Perform bilinear interpolation in both mip-maps
- Linearly blend between the results
- Requires access to 8 texels for each pixel
- Standard method, supported by hardware with no performance penalty

Trilinear mipmapping

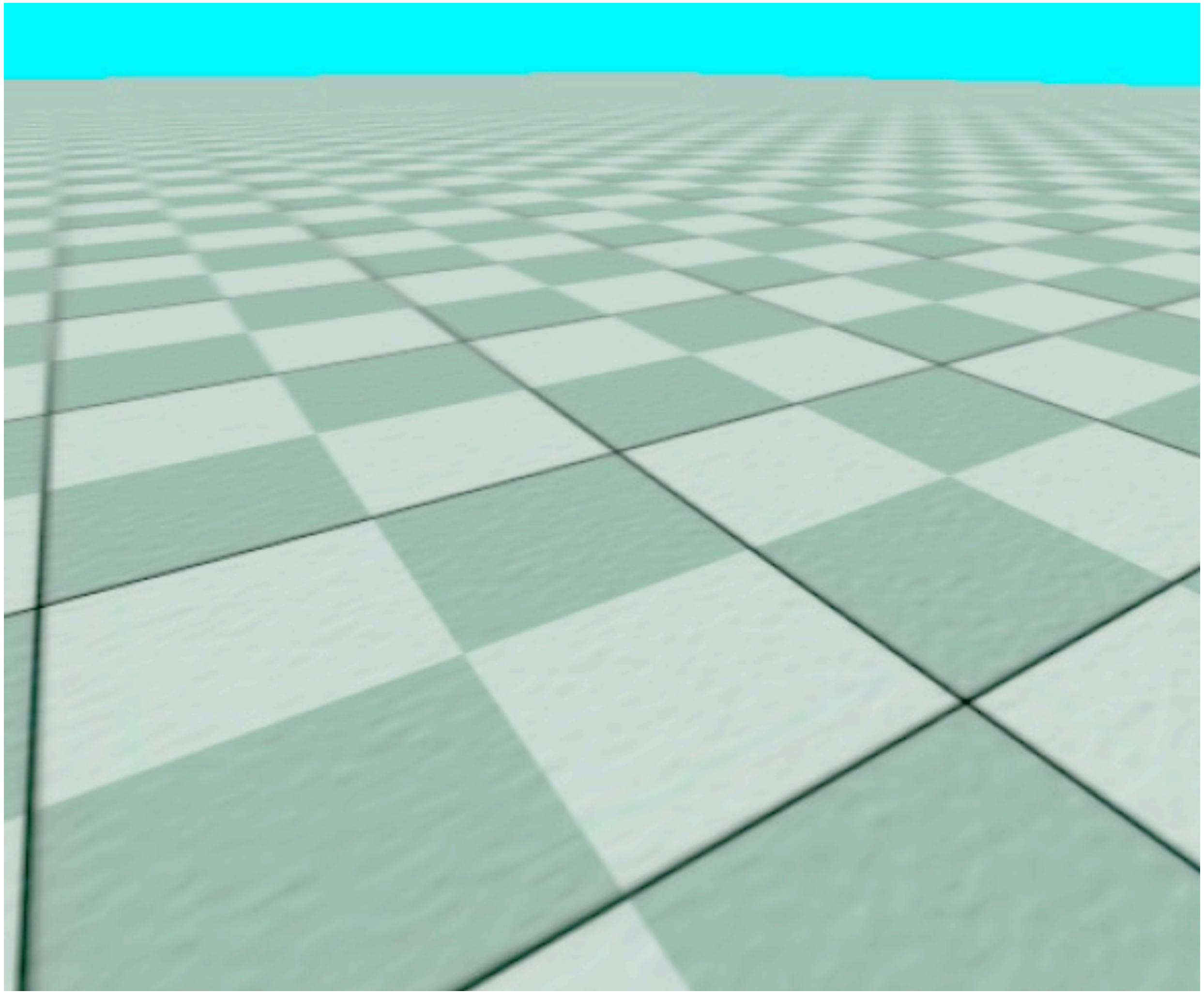
- Smooth transition between mipmap levels



Note on OpenGL

- Distinguishes between minification and magnification
  - Minification: a texel is smaller than a pixel
  - Magnification: a texel is larger than a pixel
  - Minification, magnification may vary across pixels of individual triangles
- OpenGL allows you to specify different interpolation techniques separately
  - glTexParameteri

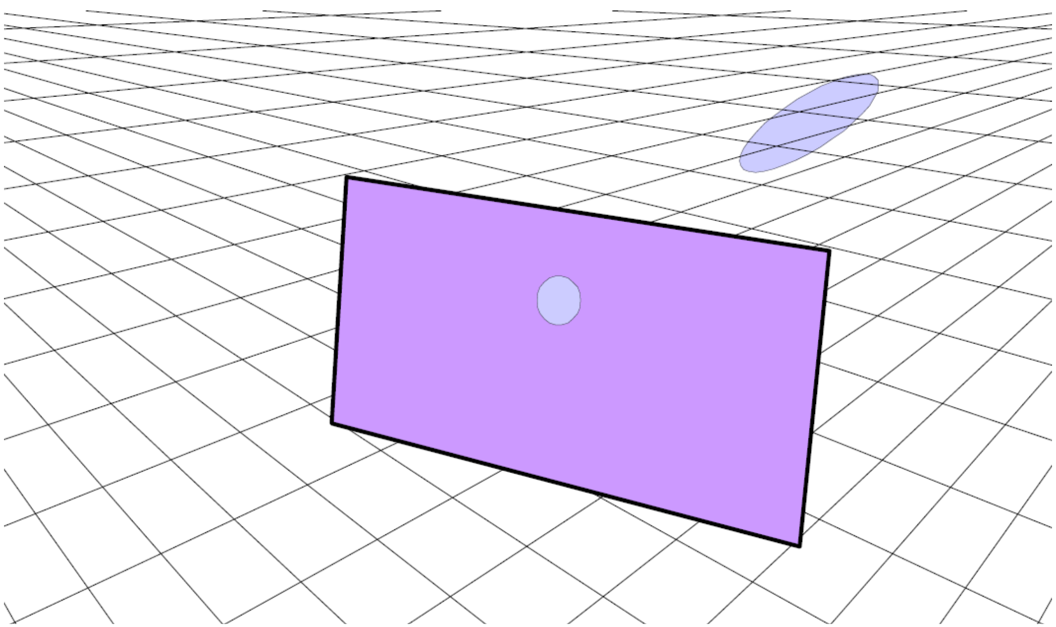
Are we satisfied?



Trilinear mipmapping

Mipmapping limitations

- Mipmap texels always represent square areas
- Pixel area is not always square in texture space
- Mipmapping makes trade-off between aliasing and blurriness



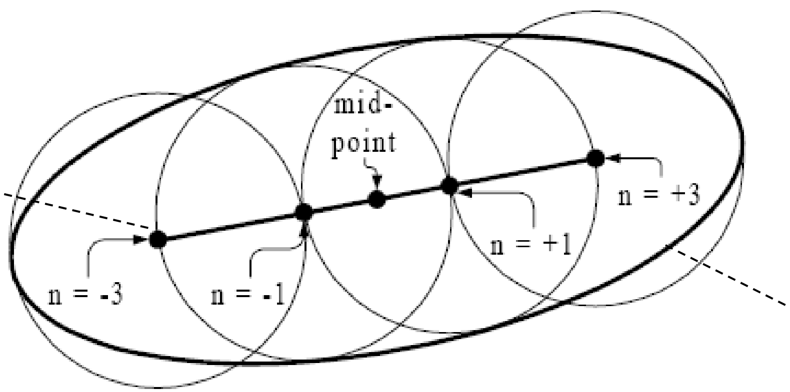
A circular pixel is back-projected to an ellipse

Anisotropic texture filtering

https://en.wikipedia.org/wiki/Anisotropic_filtering

- Average texture over elliptical area
  - Higher quality than trilinear mip-mapping
  - More expensive
- Anisotropic filtering in hardware
  - Take several bilinear probes approximating the ellipse
  - Reduces rendering performance on current GPUs

Bilinear probe



Ellipse of back-projected pixel

Texture space

Comparison

- Animation
- OpenGL 3D Game Tutorial 41: Antialiasing and Anisotropic Filtering
- First 3 minutes
- https://www.youtube.com/watch?v=Pdn13TRWEM0

Today

- Basic shader for texture mapping
- Texture coordinate assignment
- Antialiasing
- Fancy textures

Fancy textures

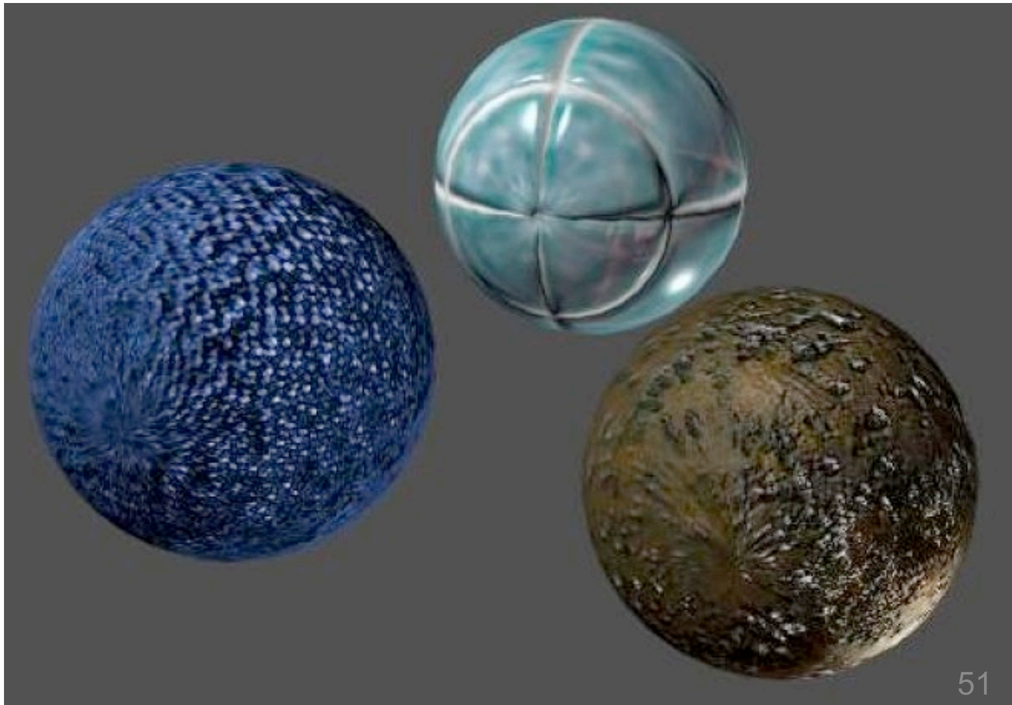
- Textures most commonly used to modulate ambient and diffuse reflection
- E.g., diffuse fragment shader with texture

```
in vec3 normal, lightstrength, lightDir;
uniform sampler2D tex;
out fragColor;

void main()

{

     fragColor = lightstrength *
    max(dot(normal, normalize(lightDir)),0.0) *
    texture(tex, texcoords);  // texture as diffuse coeff.

}
```

- Other applications?

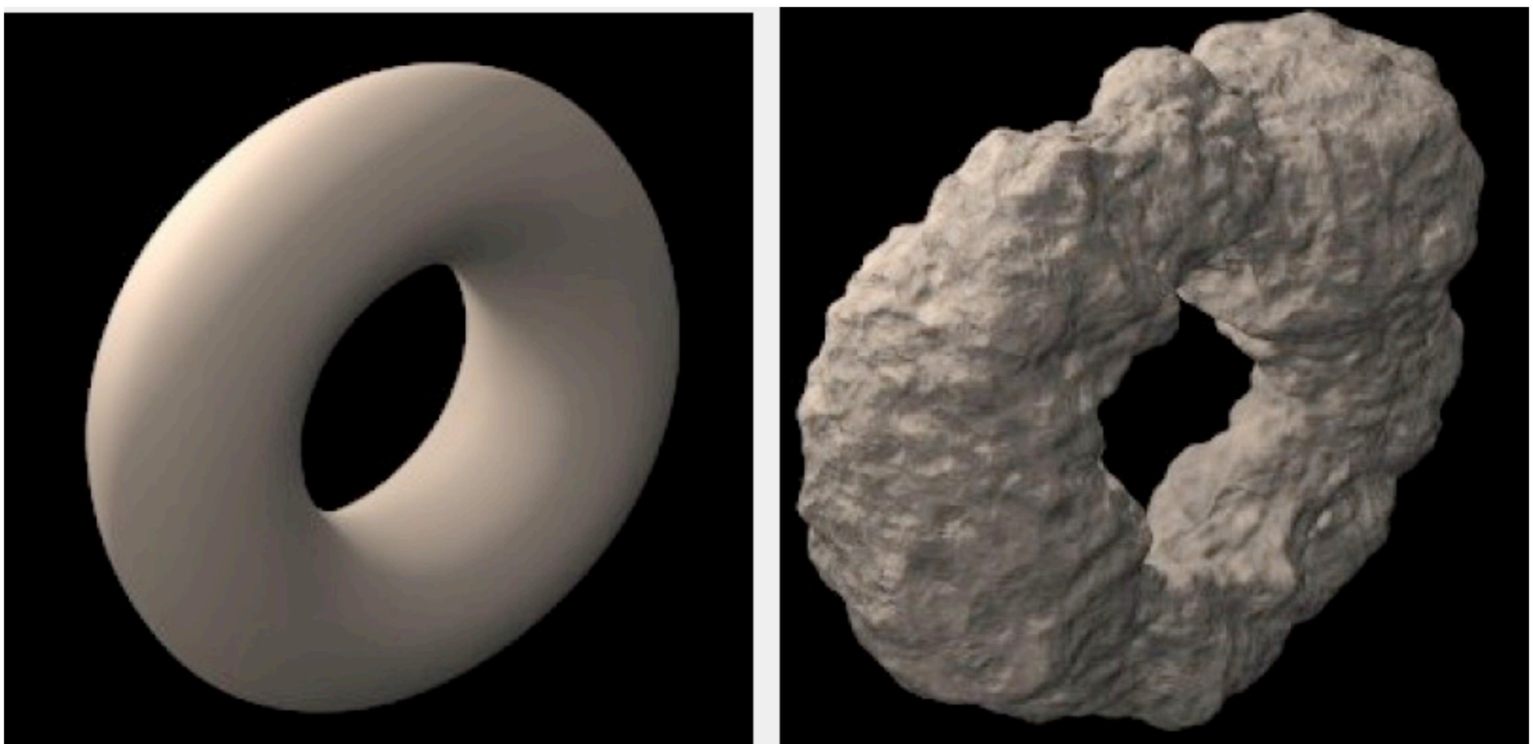
Bump mapping

- Texture map contains normal perturbations
- No modification of geometry
  - Visible mostly at silhouettes
- Render using per-pixel shading, fragment shader
  - Normal in each pixel is modified using texture map (later in course)



Displacement mapping

- Texture map contains local height field
- Modifies geometry
  - Correct silhouettes, shadows
- Requires complicated fragment shader



Other effects

Multi-texturing

- Several layers of textures for different effects
  - Scratches, dents, rust, …
  - Illumination textures

Multi-texturing

Animated textures

- Raindrops
- A TV screen, projector in a 3D scene