CSE 167:
Introduction to Computer Graphics
Lecture #7: Textures

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Announcements

- Project 2 due this Friday at 2pm
  - Grading in CSE basement labs B260 and B270
  - This time using Autograder (no whiteboard)
  - Upload code to TritonEd by 2pm

Faculty Mentor Program

UC San Diego faculty members can support undergraduate research by participating in the 2017-18 Faculty Mentor Program (FMP) and providing an undergraduate an opportunity to serve as a research assistant. In addition to the research experience, **students in the program receive two quarters of 199 credit** (10h/week), attend training sessions and workshops conducted by Academic Enrichment Programs (AEP), and present their findings at the annual Spring FMP Symposium.

Students participating in FMP must have junior or senior standing, and must meet GPA and other requirements.

Those faculty members who have a student in mind can refer the student to AEP for formal placement. Faculty members working with more than one student can work with AEP to create a cohort experience for them.

Early application is encouraged (students have an **application deadline of November 1st**). More information is available at fmp.ucsd.edu.

Texture Mapping

Lecture Overview

- Texture Mapping
  - Overview
  - Wrapping
  - Texture coordinates
  - Anti-aliasing

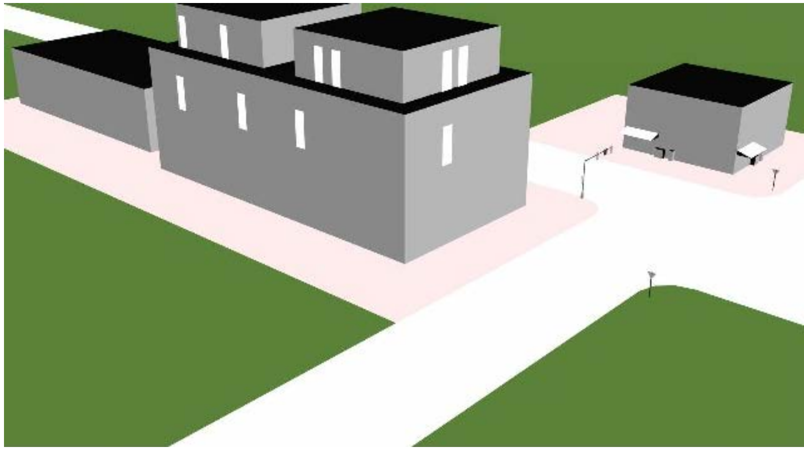
Large Triangles

Pros:

- Often sufficient for simple geometry
- Fast to render

Cons:

- Per vertex colors look boring and computer-generated

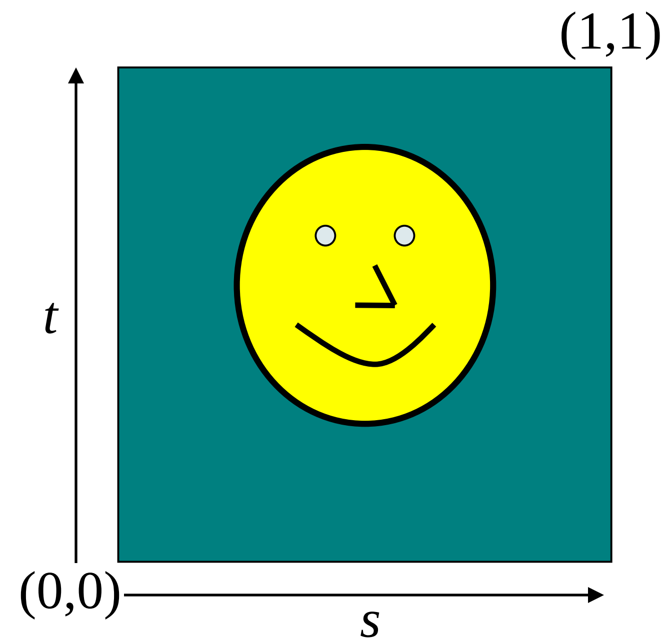


Texture Mapping

- Map textures (images) onto surface polygons
- Same triangle count, much more realistic appearance

Texture Mapping

- Goal: map locations in texture to locations on 3D geometry
- Texture coordinate space
  - Texture pixels (texels) have texture coordinates (s,t)
- Convention
  - Bottom left corner of texture is at $(s,t) = (0,0)$
  - Top right corner is at $(s,t) = (1,1)$



Texture coordinates

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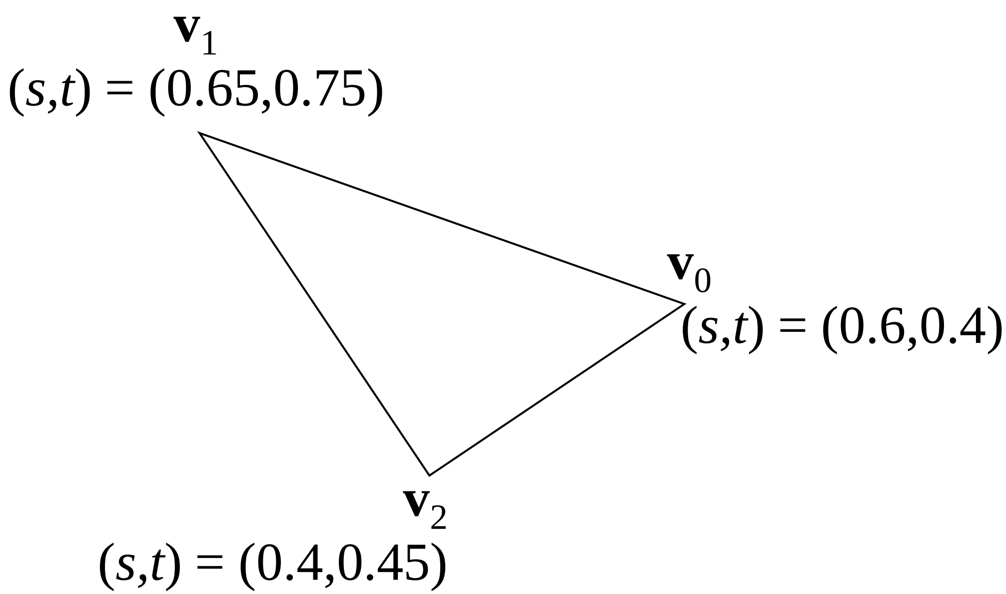
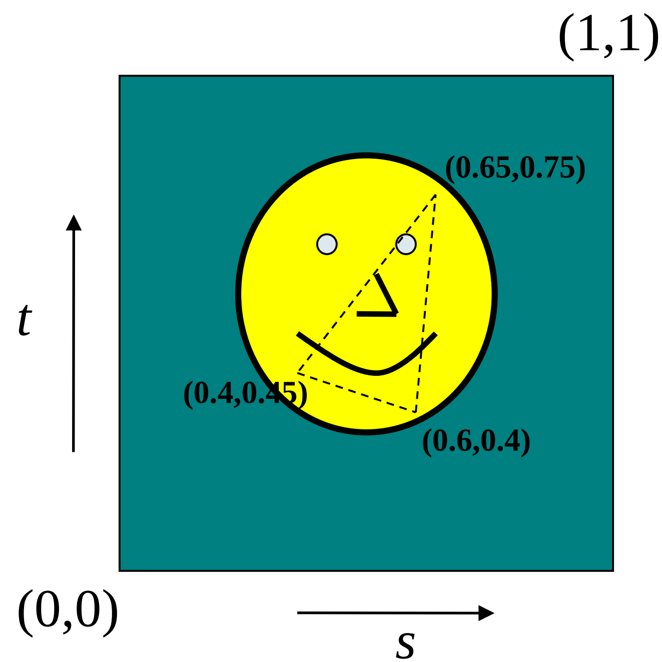
Texture Mapping

- Store 2D texture coordinates s,t with each triangle vertex



Triangle in any space before projection



Texture coordinates

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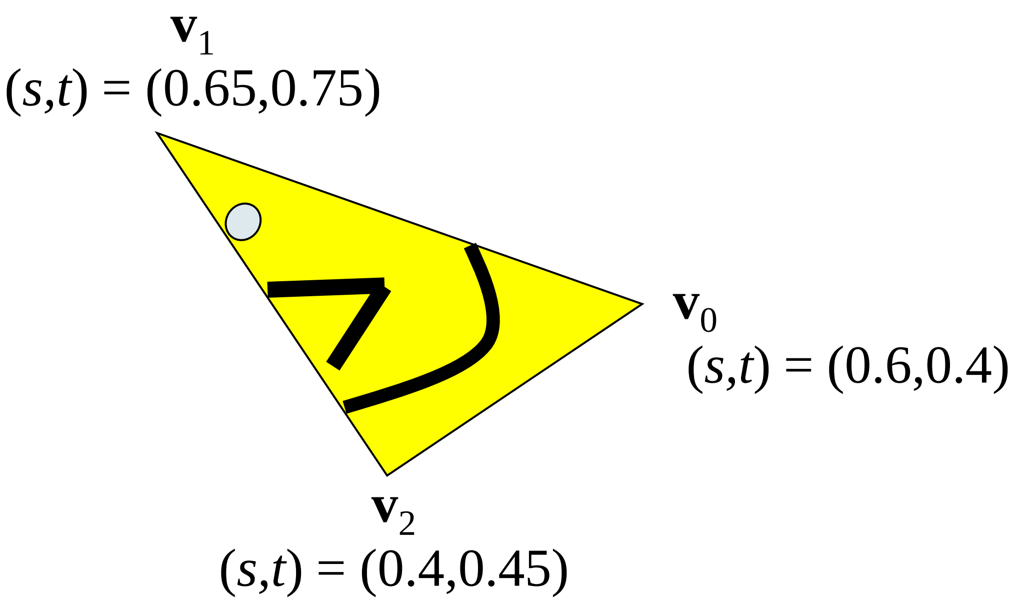
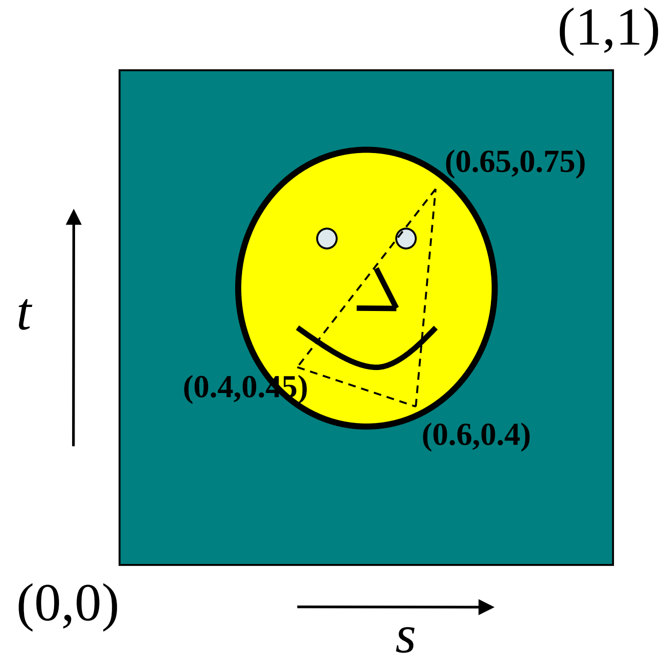
Texture Mapping

- Each point on triangle gets color from its corresponding point in texture

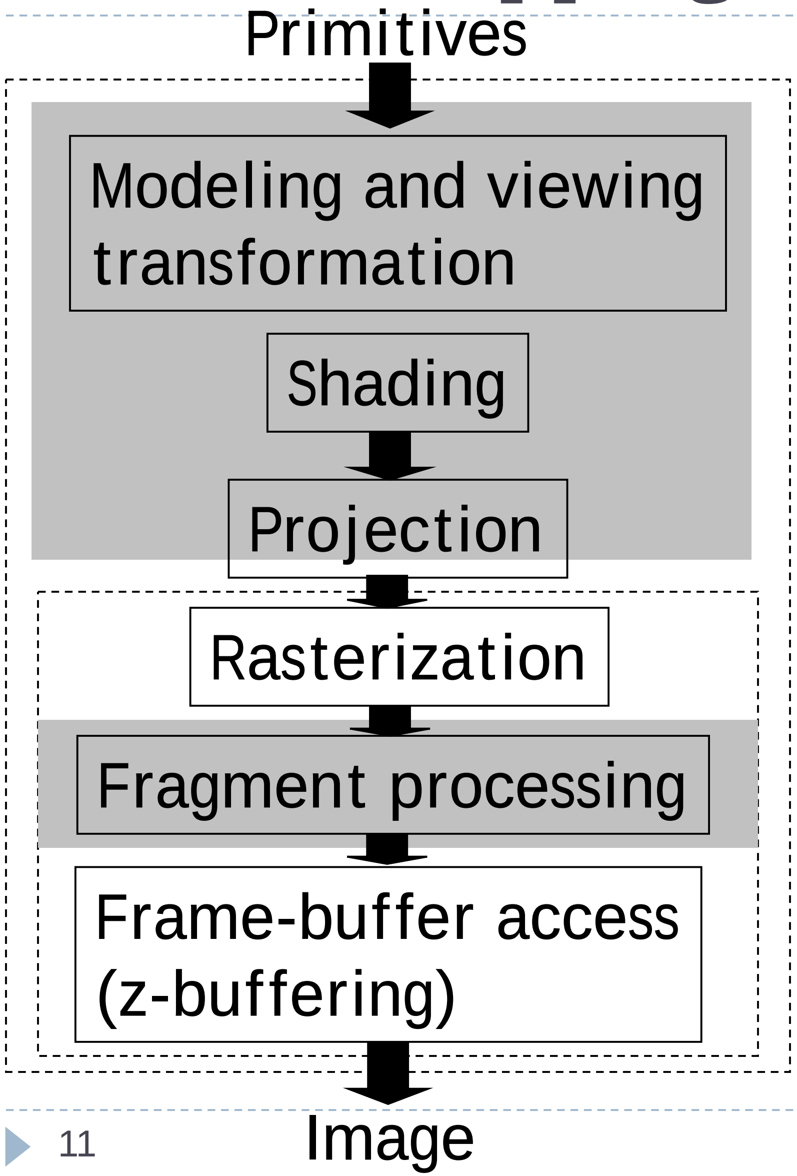


Triangle in any space before projection



Texture coordinates

Texture Mapping



Includes texture mapping

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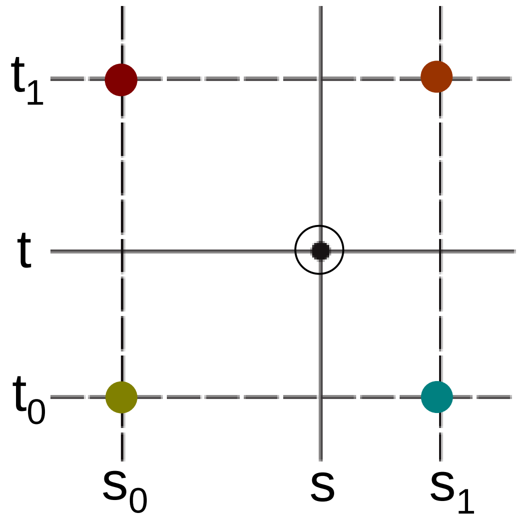
Texture Look-Up

- Given interpolated texture coordinates (s, t) at current pixel
- Closest four texels in texture space are at (s_0,t_0), (s_1,t_0), (s_0,t_1), (s_1,t_1)
- How to compute pixel color?



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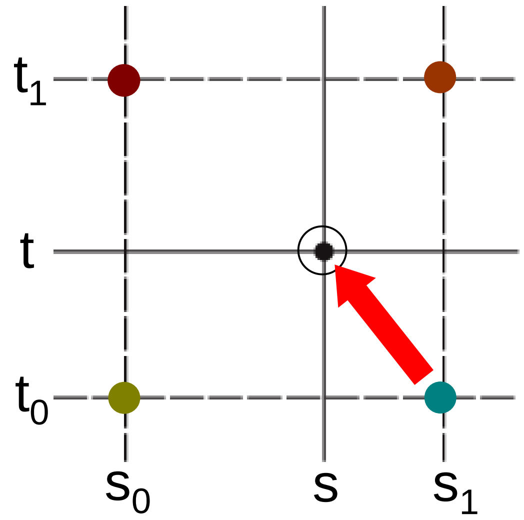
Nearest-Neighbor Interpolation

- Use color of closest texel



- Simple, but low quality and aliasing

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Bilinear Interpolation

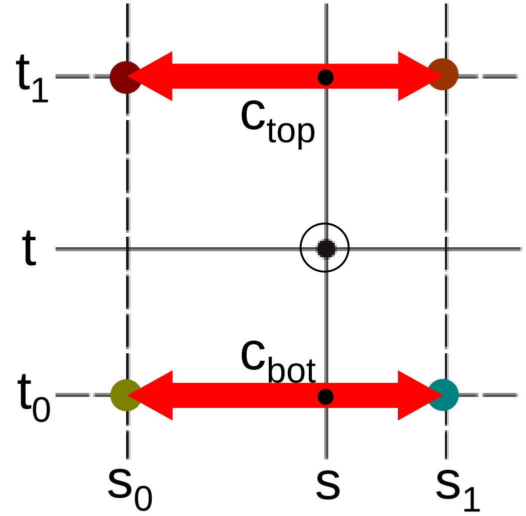
1. Linear interpolation horizontally:

   Ratio in s direction r_s:

$$r_s = \frac{s - s_0}{s_1 - s_0}$$

$c_{top} = tex(s_0, t_1)\,(1 - r_s) + tex(s_1, t_1)\, r_s$

$c_{bot} = tex(s_0, t_0)\,(1 - r_s) + tex(s_1, t_0)\, r_s$



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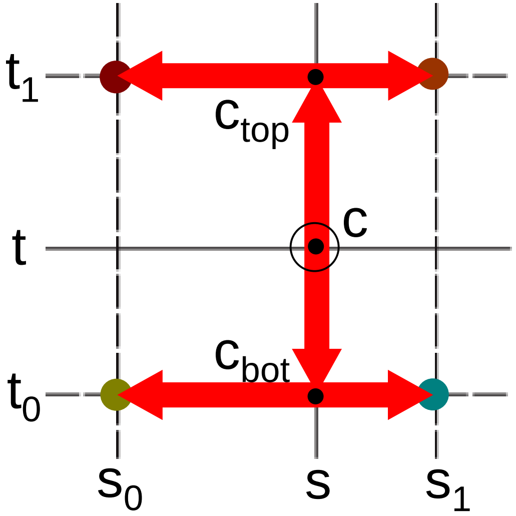
Bilinear Interpolation

2. Linear interpolation vertically

Ratio in t direction r_t:

$$r_t = \frac{t - t_0}{t_1 - t_0}$$

$$c = c_{bot}\,(1 - r_t) + c_{top}\, r_t$$



Texture Filtering in OpenGL

- GL_NEAREST: Nearest-Neighbor interpolation
- GL_LINEAR: Bilinear interpolation
- Example:
  - glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_LINEAR);
  - glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_LINEAR);

GL_NEAREST

GL_LINEAR

Source: https://open.gl/textures

Lecture Overview

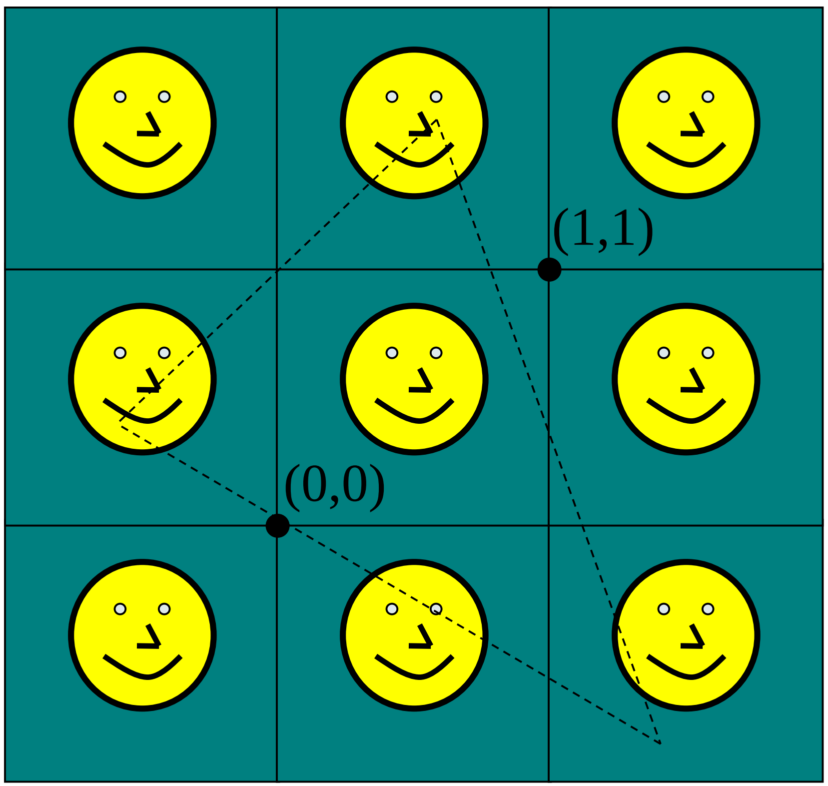
- Texture Mapping
  - Wrapping
  - Texture coordinates
  - Anti-aliasing

Wrap Modes

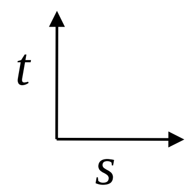
- Texture image extends from [0,0] to [1,1] in texture space
  - What if (s,t) texture coordinates are beyond that range?
- → Texture wrap modes

Repeat

- Repeat the texture
  - Creates discontinuities at edges
    - unless texture is designed to line up



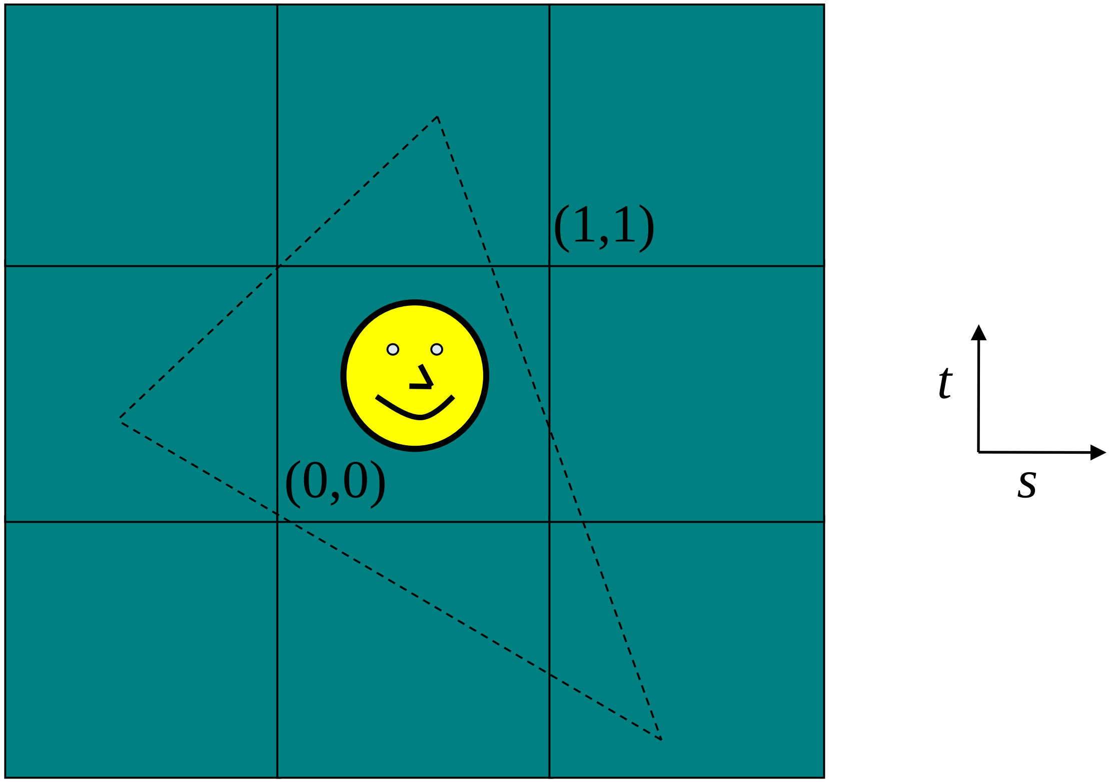
Texture Space



Seamless brick wall texture
(by Christopher Revoir)

Clamp

- Use edge value everywhere outside data range [0..1]
- Or use specified border color outside of range [0..1]



Texture Space

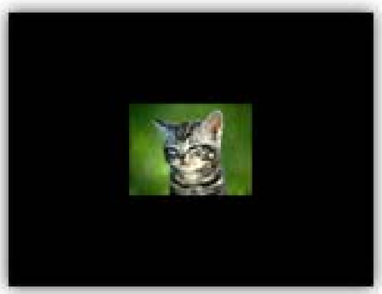
Wrap Modes in OpenGL

- Default:
  - glTexParameterf(GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_REPEAT);
  - glTexParameterf(GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_REPEAT);
- Options for wrap mode:
  - GL_REPEAT
  - GL_MIRRORED_REPEAT
  - GL_CLAMP_TO_EDGE: repeats last pixel in the texture
  - GL_CLAMP_TO_BORDER: requires border color to be set

GL_REPEAT

GL_MIRRORED_REPEAT

GL_CLAMP_TO_EDGE



GL_CLAMP_TO_BORDER

Source: https://open.gl/textures

Lecture Overview

- Texture Mapping
  - Wrapping
  - Texture coordinates
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Texture Coordinates

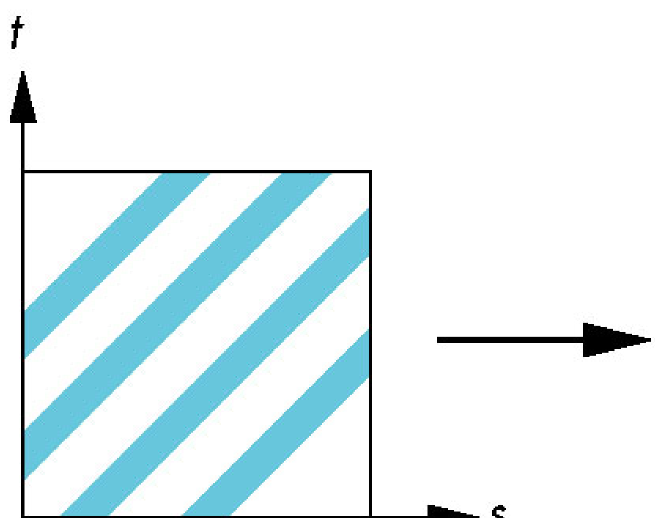
What if texture extends across multiple polygons?

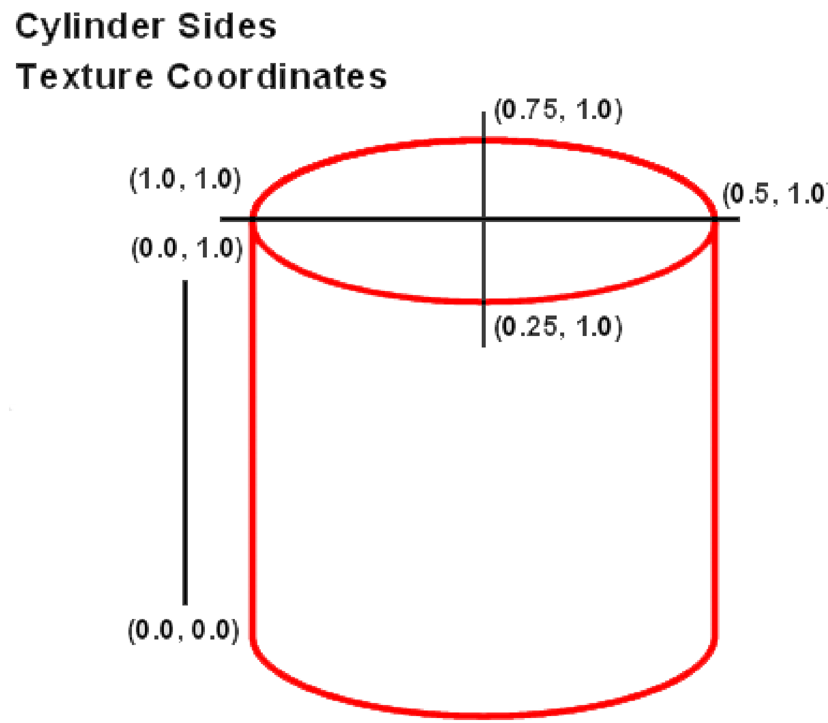
→ Surface parameterization

- Mapping between 3D positions on surface and 2D texture coordinates
  - Defined by texture coordinates of triangle vertices
- Options for mapping:
  - Cylindrical
  - Spherical
  - Orthographic
  - Parametric
  - Skin

Cylindrical Mapping

- Similar to spherical mapping, but with cylindrical coordinates





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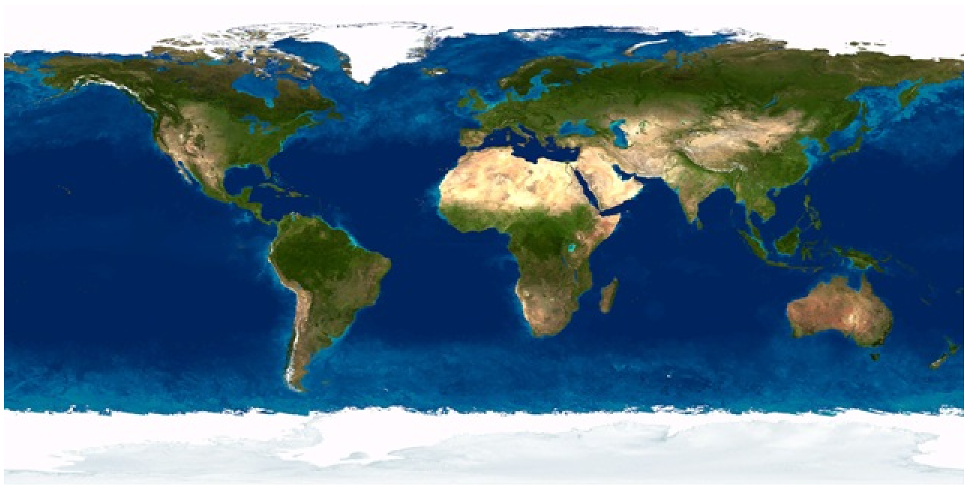
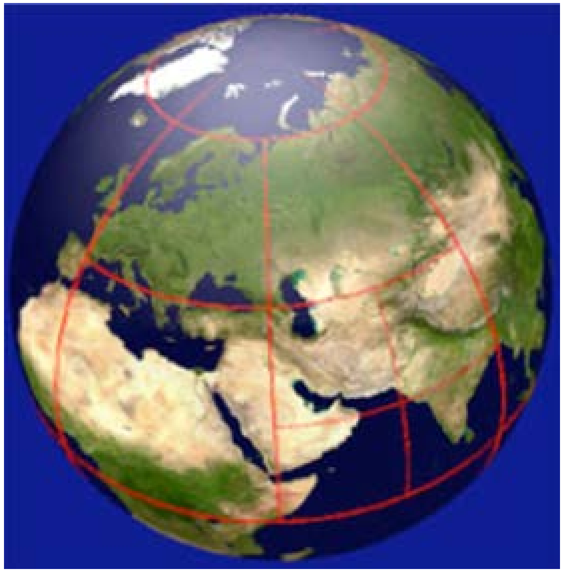
Spherical Mapping

- Use spherical coordinates
- "Shrink-wrap" sphere to object



Texture map

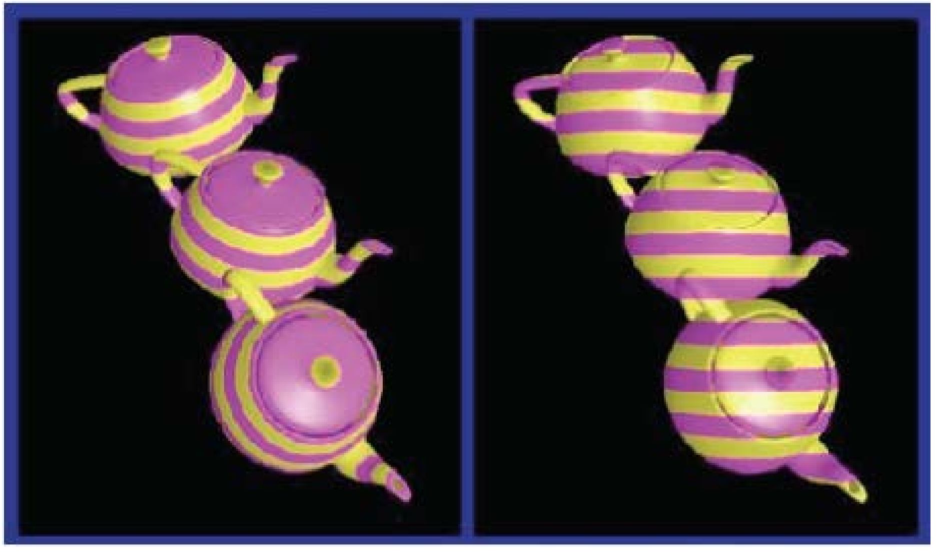


Mapping result

Orthographic Mapping

- Use linear transformation of object's xyz coordinates
- Example:

$$\begin{bmatrix} s \\ t \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ w \end{bmatrix}$$



xyz in object space — *xyz in camera space*

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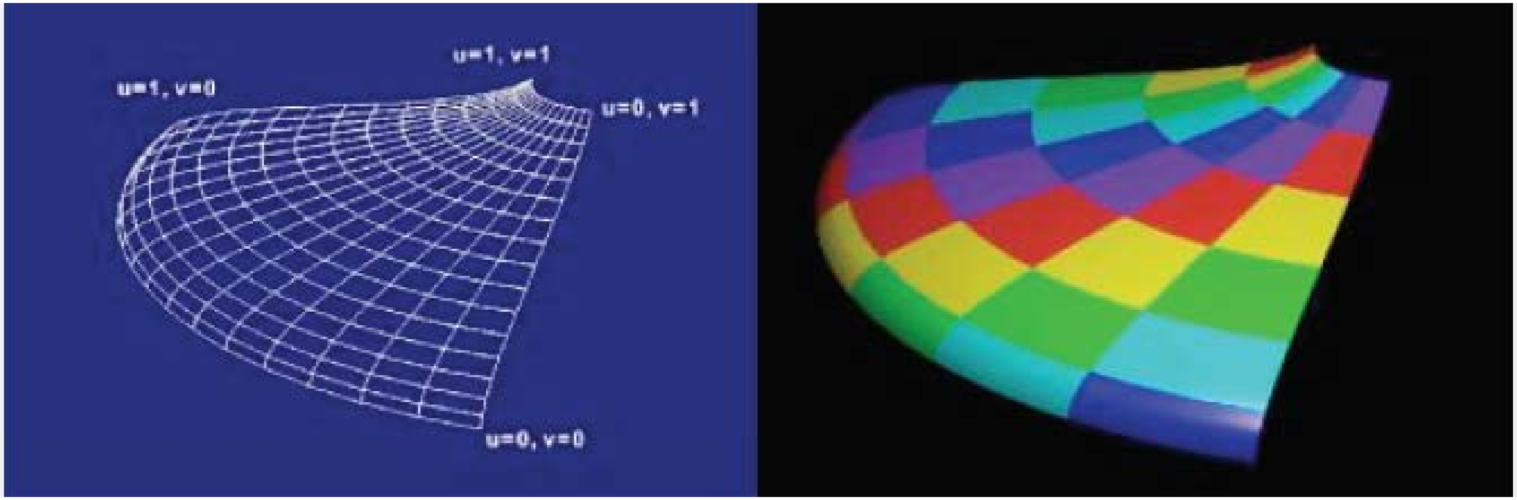
Parametric Mapping

- Surface given by parametric functions

$$x = f(u, v) \quad y = f(u, v) \quad z = f(u, v)$$

- Very common in CAD
- Clamp (u,v) parameters to [0..1] and use as texture coordinates (s,t)



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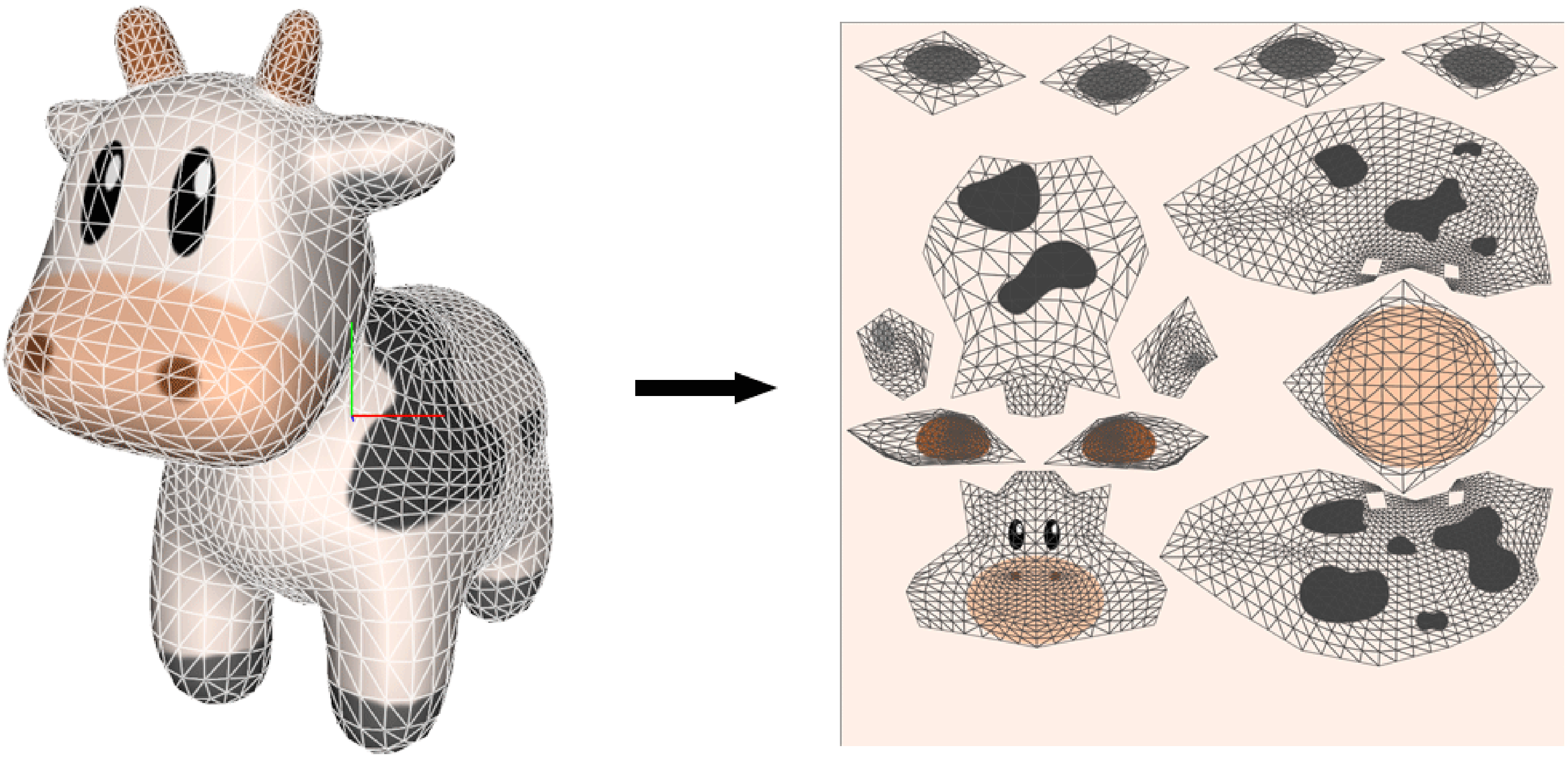
Skin Mapping

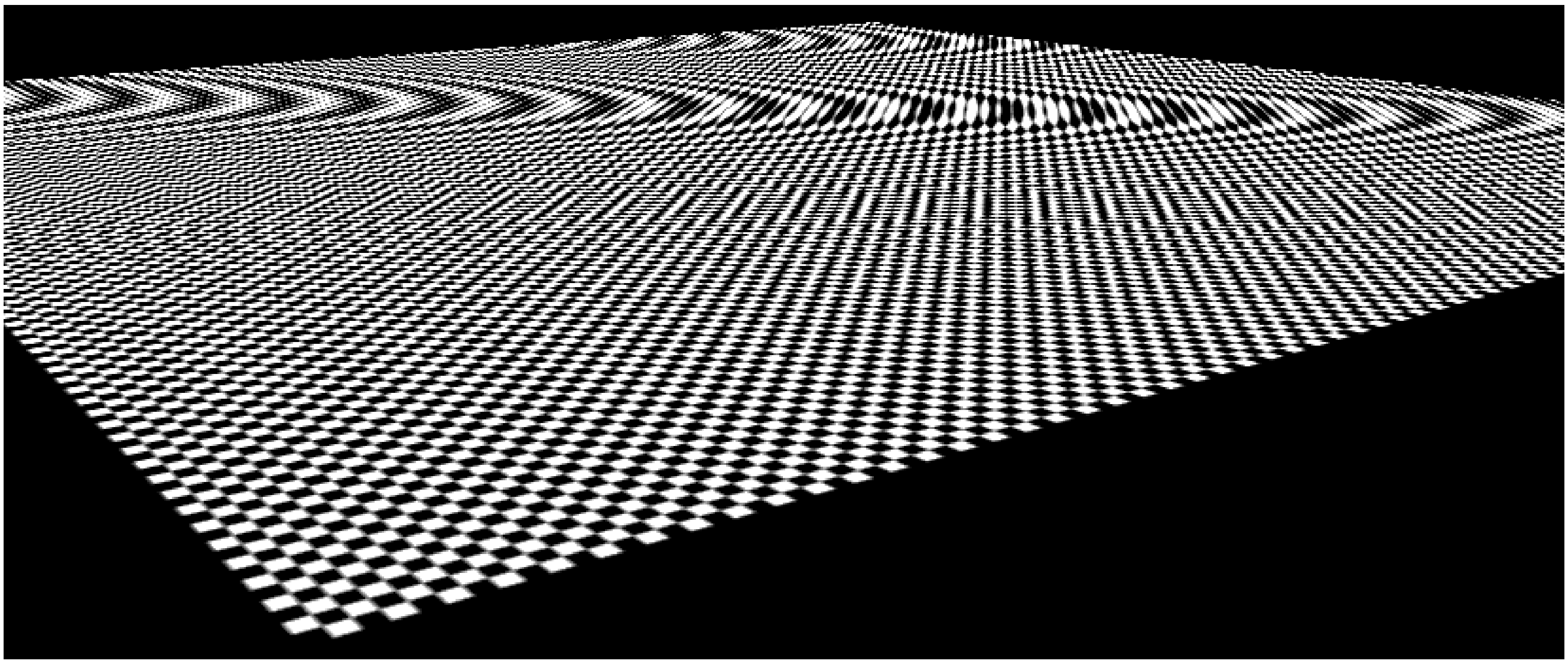


Lecture Overview

- Texture Mapping
  - Wrapping
  - Texture coordinates
  - Anti-aliasing

Aliasing

- What could cause this aliasing effect?



Aliasing

Sufficiently sampled, no aliasing

Insufficiently sampled, aliasing

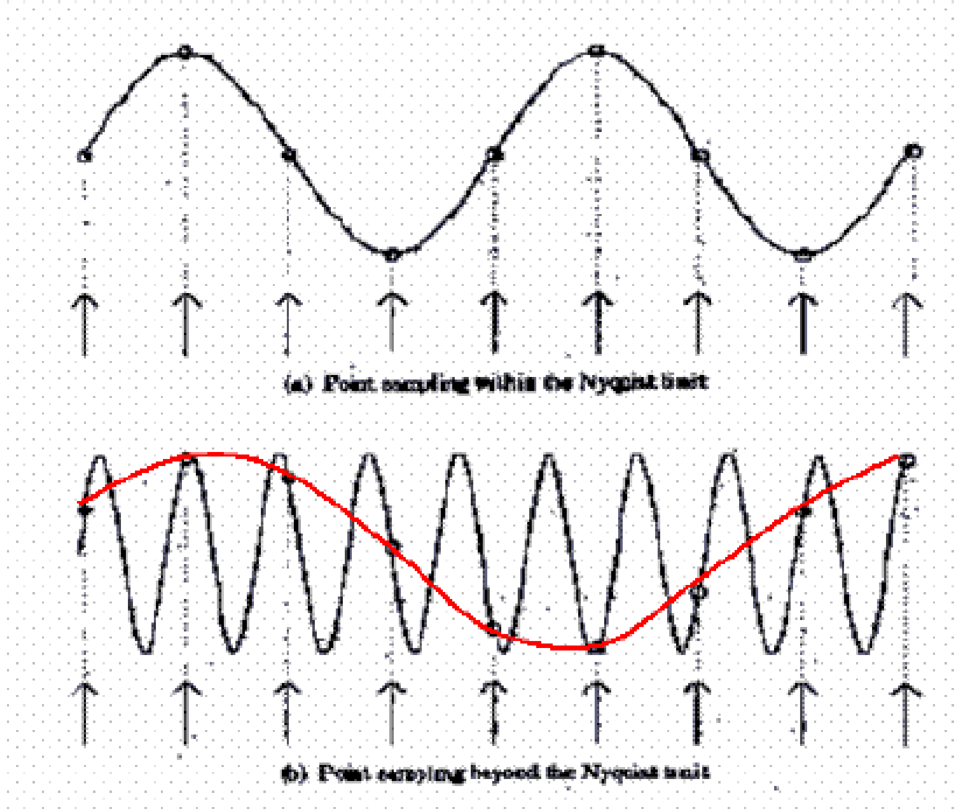
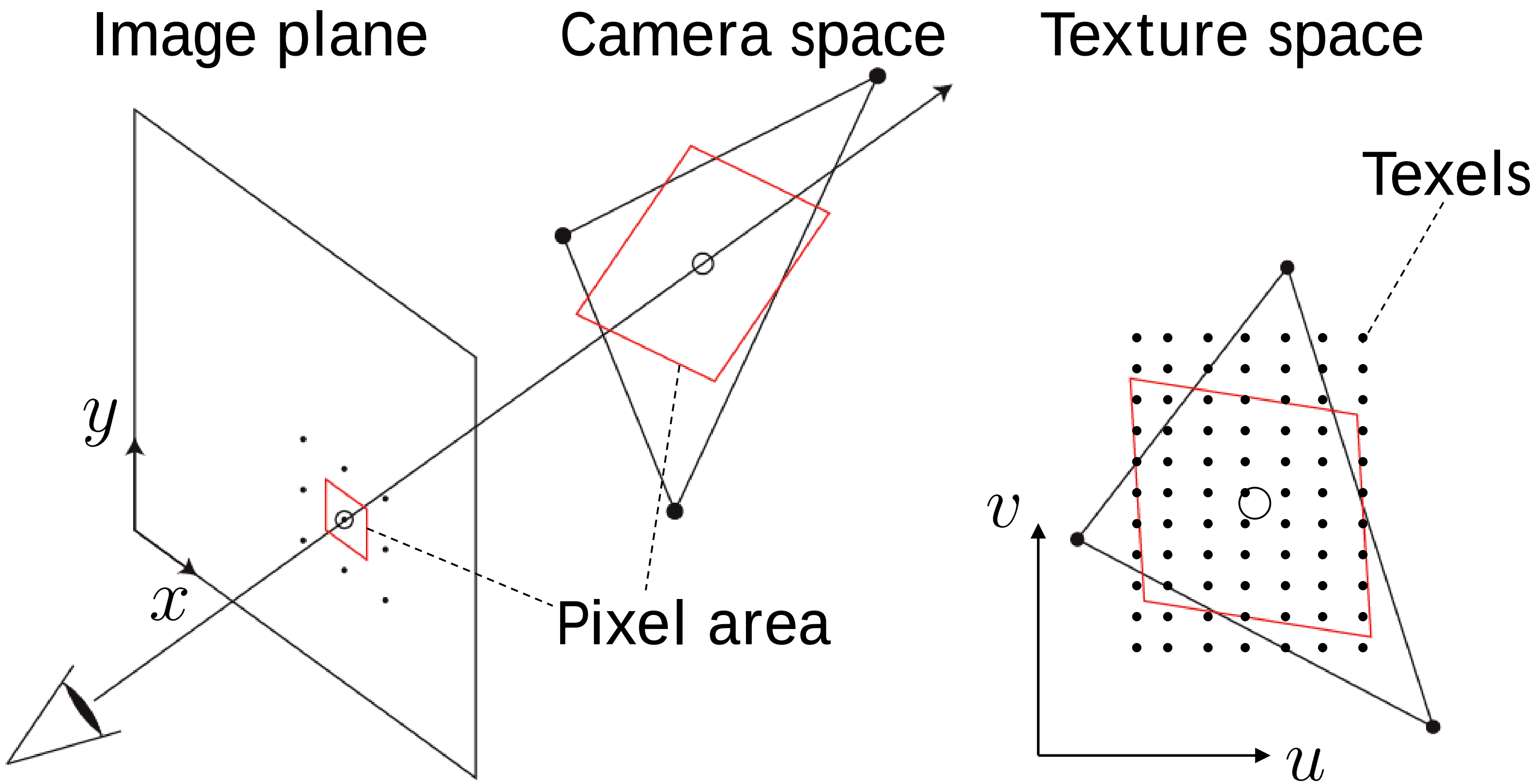


Image: Robert L. Cook

High frequencies in the input data can appear as lower frequencies in the sampled signal

Antialiasing: Intuition

- Pixel may cover large area on triangle in camera space
- Corresponds to many texels in texture space
- Need to compute average



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Antialiasing Using Mip-Maps

- Averaging over texels is expensive
  - Many texels as objects get smaller
  - Large memory access and compuation cost
- Precompute filtered (averaged) textures
  - Mip-maps
- Practical solution to aliasing problem
  - Fast and simple
  - Available in OpenGL, implemented in GPUs
  - Reasonable quality

Mipmaps

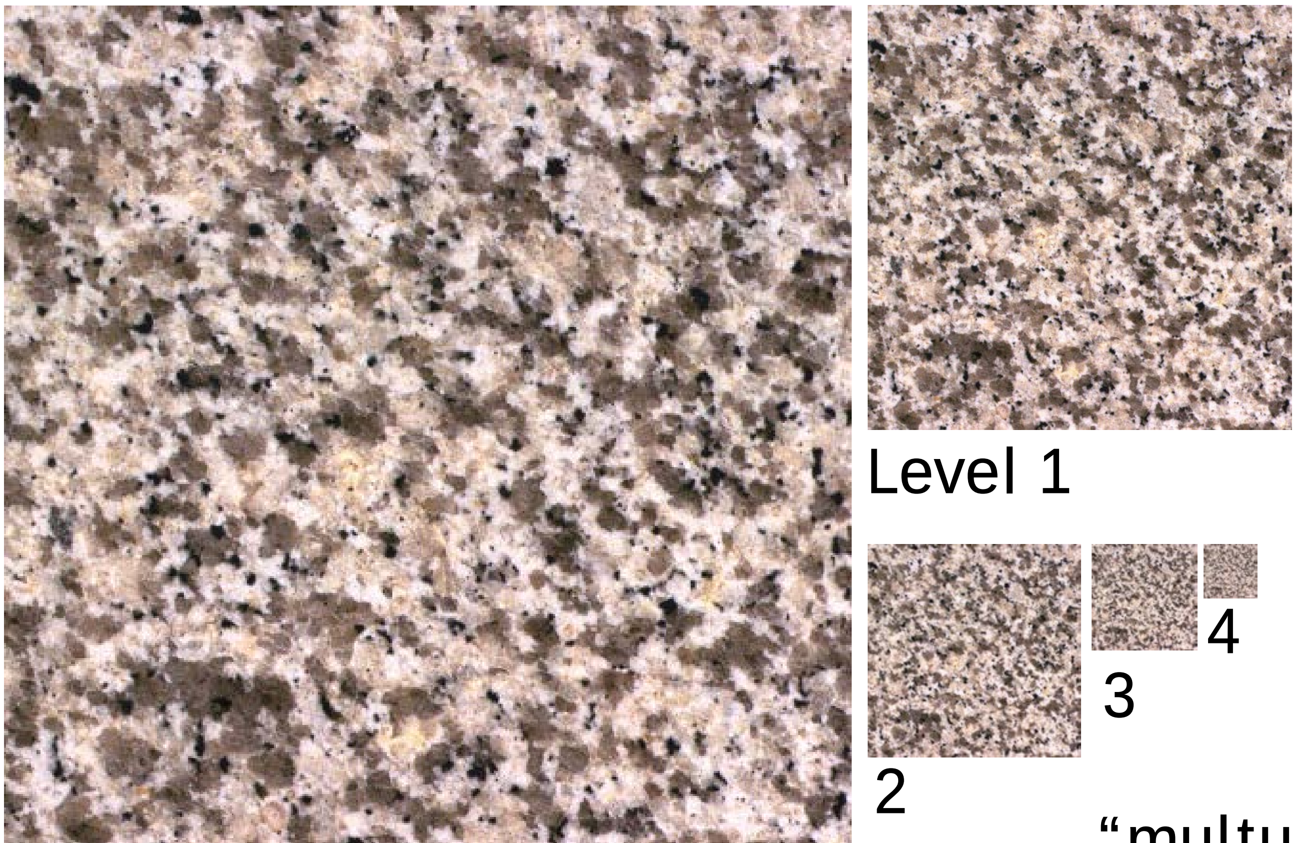
- MIP stands for *multum in parvo* = "*much in little*" (Williams 1983)

Before rendering

- Pre-compute and store down scaled versions of textures
  - Reduce resolution by factors of two successively
  - Use high quality filtering (averaging) scheme
- Increases memory cost by 1/3
  - 1/3 = ¼+1/16+1/64+…
- Width and height of texture should be powers of two (non-power of two supported since OpenGL 2.0)

Mipmaps

- Example: resolutions 512x512, 256x256, 128x128, 64x64, 32x32 pixels



Level 1

2

3

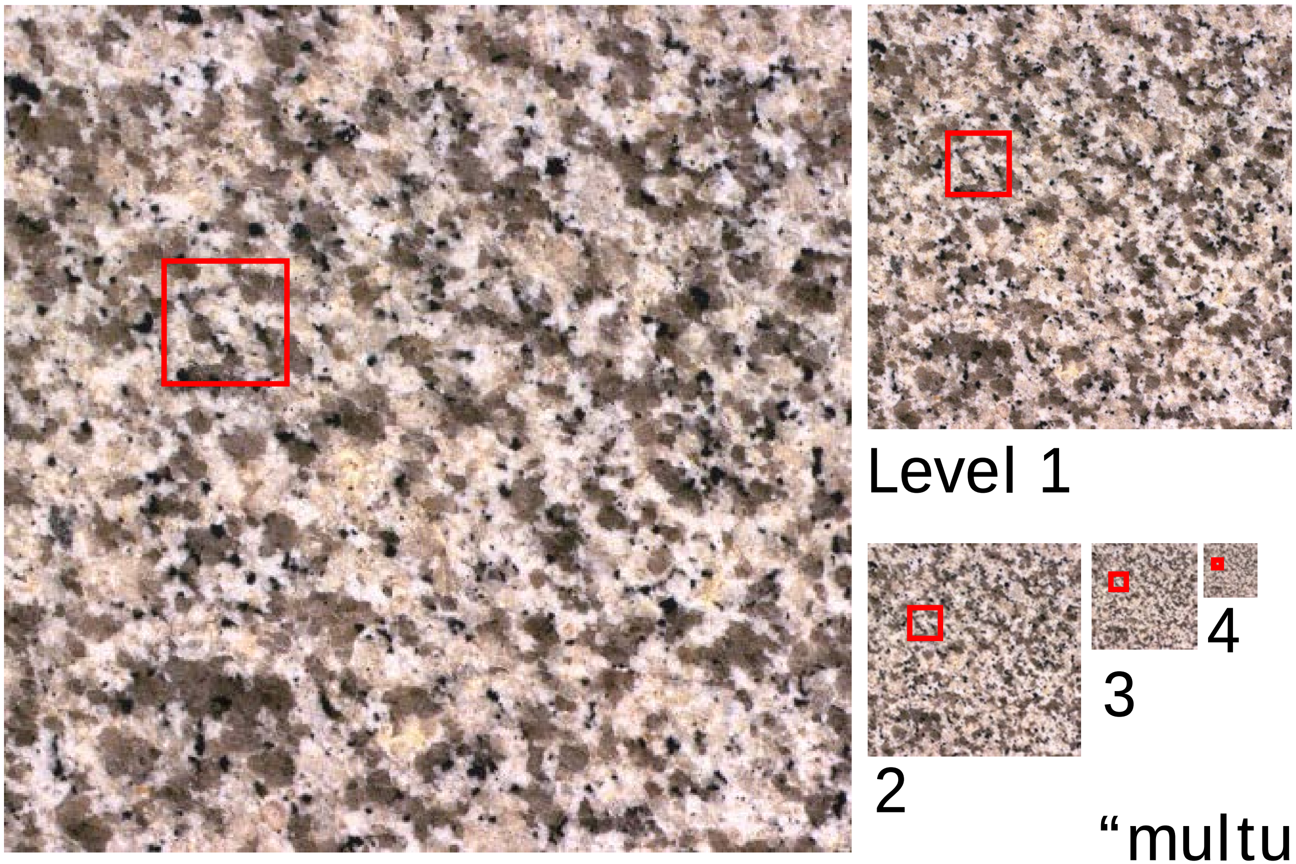
4

"multum in parvo"

Level 0

Mipmaps

- One texel in level 4 is the average of $4^4=256$ texels in level 0



“multum in parvo”

Level 0

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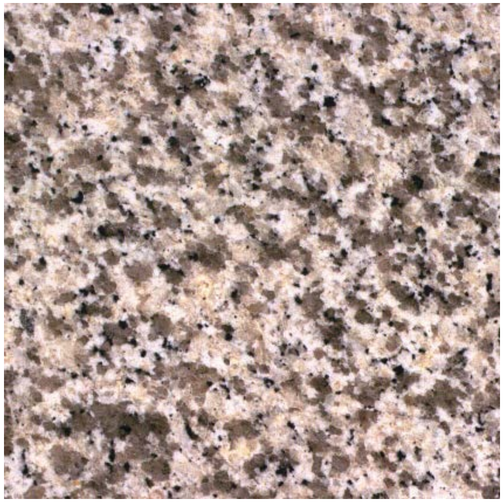
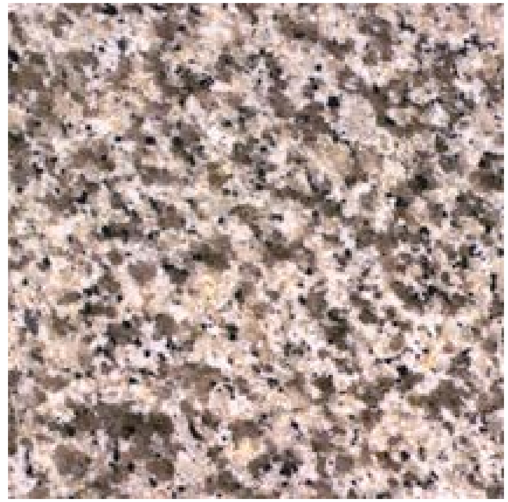
Mipmaps



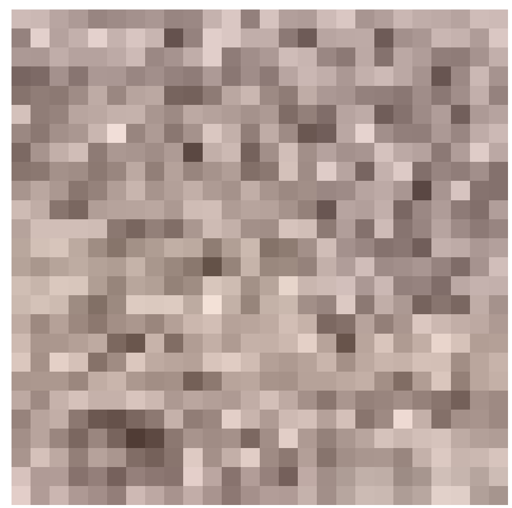
Level 0



Level 1

Level 2

Level 3



Level 4

Rendering With Mipmaps

- "Mipmapping"
- Interpolate texture coordinates of each pixel as without mipmapping
- Compute approximate size of pixel in texture space
- Look up color in nearest mipmap
  - E.g., if pixel corresponds to 10x10 texels use mipmap level 3
  - Use nearest neighbor or bilinear interpolation as before

Mipmapping

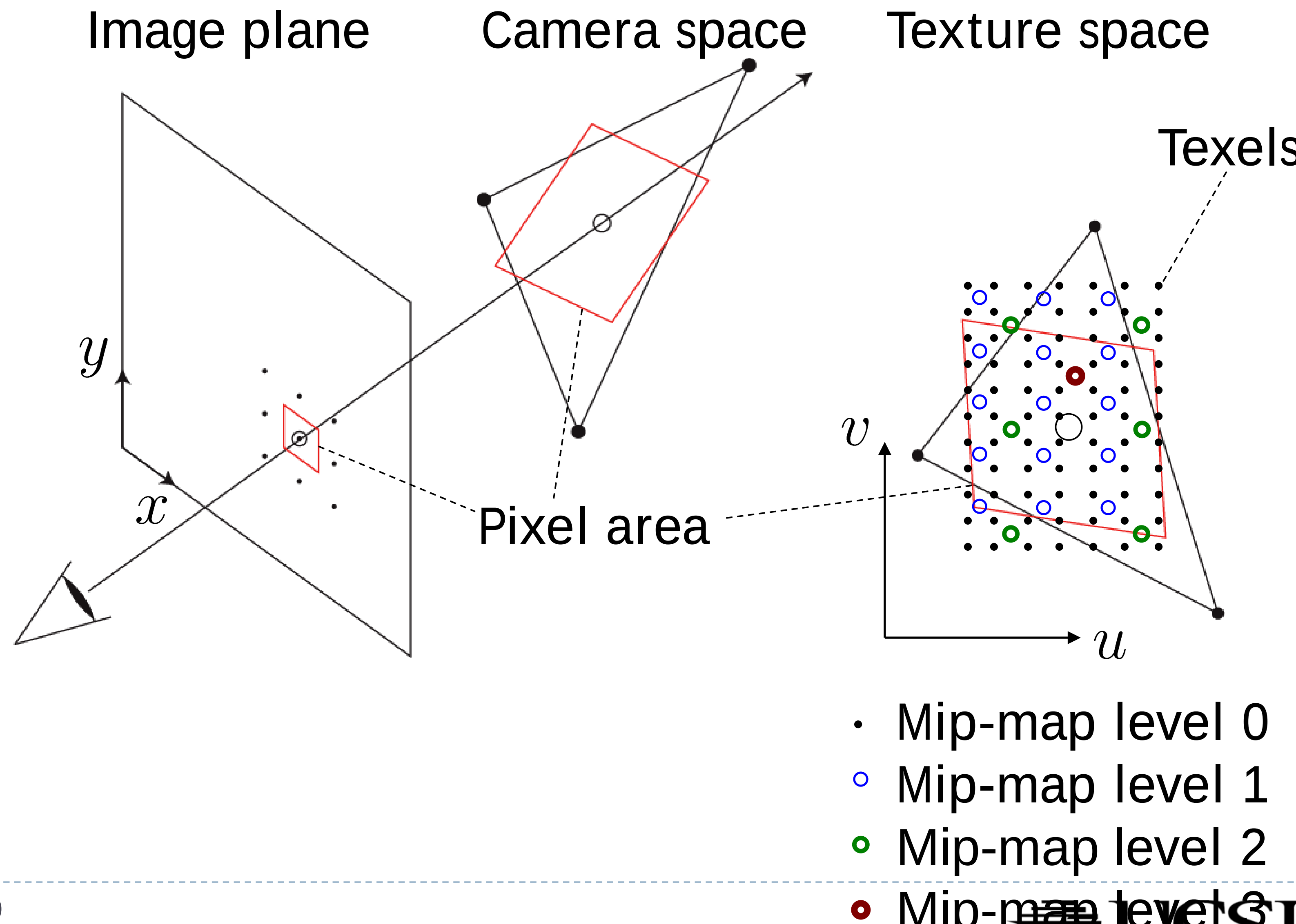
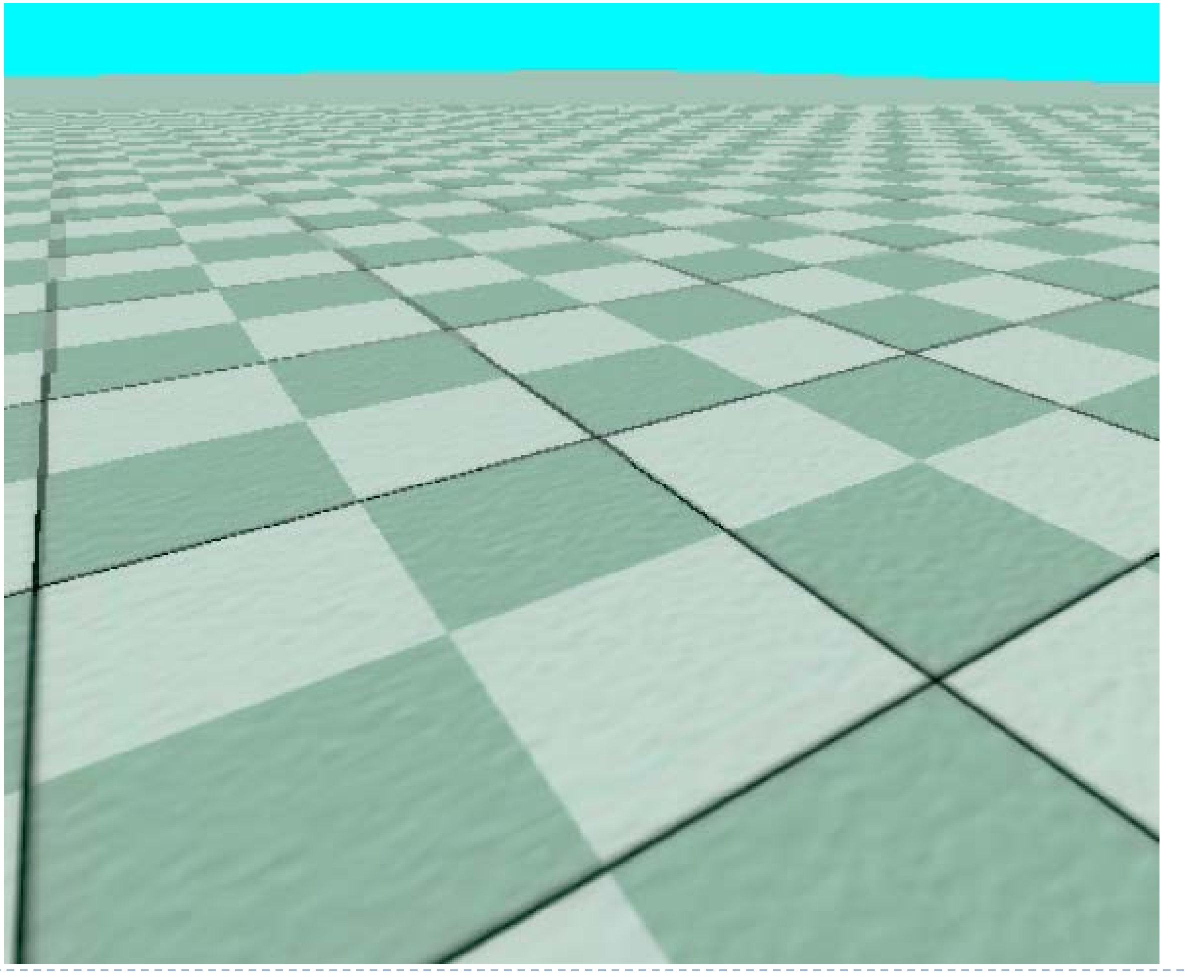


Image plane
Camera space
Texture space
Texels
y
x
v
u
Pixel area
Mip-map level 0
Mip-map level 1
Mip-map level 2
Mip-map level 3

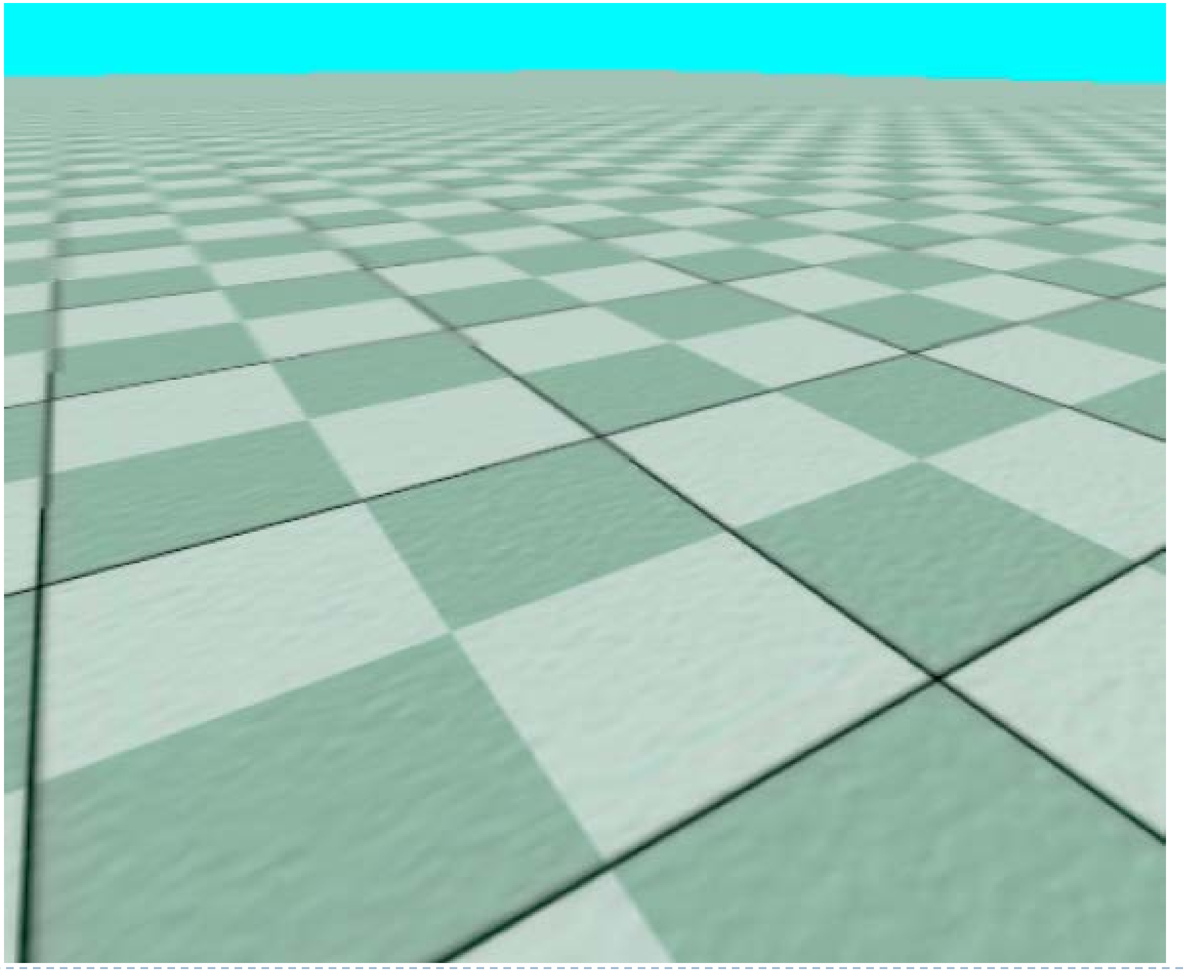
Nearest Mipmap, Nearest Neighbor

- Visible transition between mipmap levels



Nearest Mipmap, Bilinear

- Visible transition between mipmap levels



Trilinear Mipmapping

- Use two nearest mipmap levels
  - E.g., if pixel corresponds to 10x10 texels, use mipmap levels 3 (8x8) and 4 (16x16)
- 2-Step approach:
  - Step 1: perform bilinear interpolation in both mip-maps
  - Step 2: linearly interpolate between the results
- Requires access to 8 texels for each pixel
- Supported by hardware without performance penalty

Anisotropic Filtering

- Method of enhancing the image quality of textures on surfaces that are at oblique viewing angles
- Different degrees or ratios of anisotropic filtering can be applied
- The degree refers to the maximum ratio of anisotropy supported by the filtering process. For example, 4:1 anisotropic filtering supports pre-sampled textures up to four times wider than tall

More Info

- Mipmapping tutorial w/source code:
  - http://www.videotutorialsrock.com/opengl_tutorial/mipmapping/text.php

OpenGL Example: Loading a Texture

```
// Loads image as texture, returns ID of texture
GLuint loadTexture(Image* image)
{
  GLuint textureId;
  glGenTextures(1, &textureId); // Get unique ID for texture
  glBindTexture(GL_TEXTURE_2D, textureId); // Tell OpenGL which texture to edit
  glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_LINEAR); // set bi-linear interpolation
  glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_LINEAR); // for both filtering modes
  glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_CLAMP_TO_EDGE); // set texture edge mode
  glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_CLAMP_TO_EDGE);

  Image* image = loadJPG(“photo.jpg");  // load image from disk; uses third party Image library

  // Depending on the image library, the texture image may have to be flipped vertically

  // Load image into OpenGL texture in GPU memory:
  glTexImage2D(GL_TEXTURE_2D,      // Always GL_TEXTURE_2D for image textures
     0,                            // 0 for now
     GL_RGB,                       // Format OpenGL uses for image without alpha channel
     image->width, image->height,  // Width and height
     0,                            // The border of the image
     GL_RGB,           // GL_RGB, because pixels are stored in RGB format
     GL_UNSIGNED_BYTE, // GL_UNSIGNED_BYTE, because pixels are stored as unsigned numbers
     image->pixels);               // The actual RGB image data

  return textureId; // Return the ID of the texture
}
```

Vertex Shader

```
#version 150

in vec3 vert;
in vec2 vertTexCoord;
out vec2 fragTexCoord;

void main()
{
  // Pass the tex coord straight through to the fragment shader
  fragTexCoord = vertTexCoord;

  gl_Position = vec4(vert, 1);
}
```

Fragment Shader

```
#version 150

uniform sampler2D tex; // this is the texture
in vec2 fragTexCoord;  // these are the texture coordinates
out vec4 finalColor;   // this is the output color of the pixel

void main()
{
  finalColor = texture(tex, fragTexCoord);
}
```