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

Jürgen P. Schulze, Ph.D.
University of California, San Diego
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Announcements

- Project 3 due tomorrow at 2pm
  - Code submission on Ted
  - Also try submitting to Classroom Github; we'll use it for projects 4-7 (instructions on Piazza)
- Midterm
  - Monday: discussion
  - Thursday: in class written exam, closed book
  - Planning to have grades on Ted by Friday afternoon
  - May cover all material through Tuesday's lecture

Lecture Overview

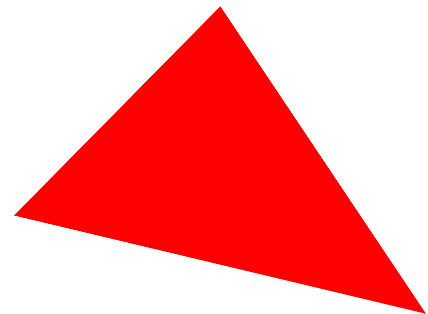
- Types of Geometry Shading
- Texture Mapping

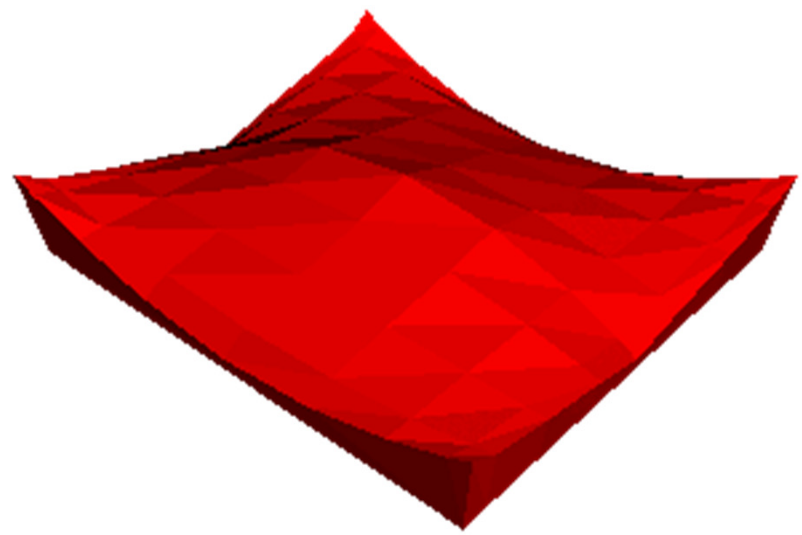
Types of Shading

- Per-triangle
- Per-vertex
- Per-pixel

Per-Triangle Shading

- A.k.a. *flat shading*
- Evaluate shading once per triangle
- Advantage
  - Fast
- Disadvantage
  - Faceted appearance





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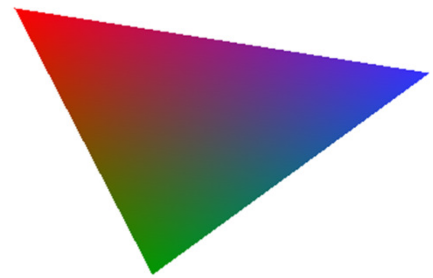
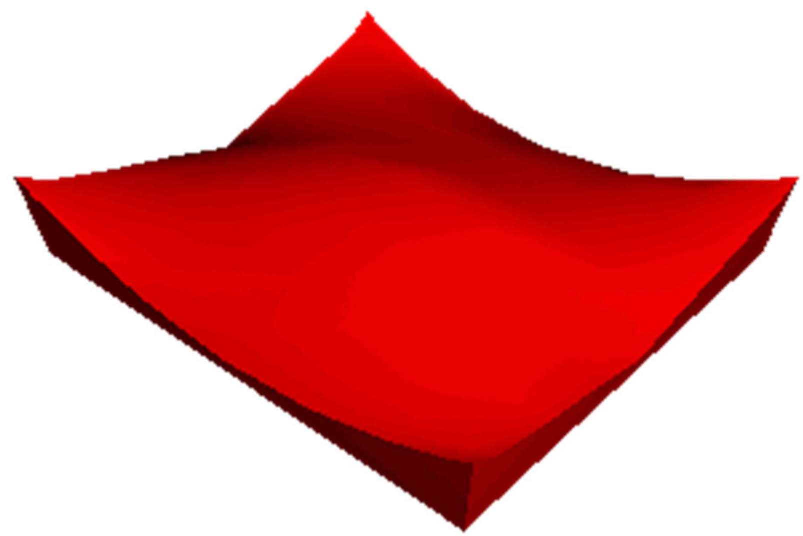
Per-Vertex Shading

- Known as *Gouraud shading* (Henri Gouraud, 1971)
- Interpolates vertex colors across triangles
- Advantages
  - Fast
  - Smoother surface appearance than with flat shading
- Disadvantage
  - Problems with small highlights





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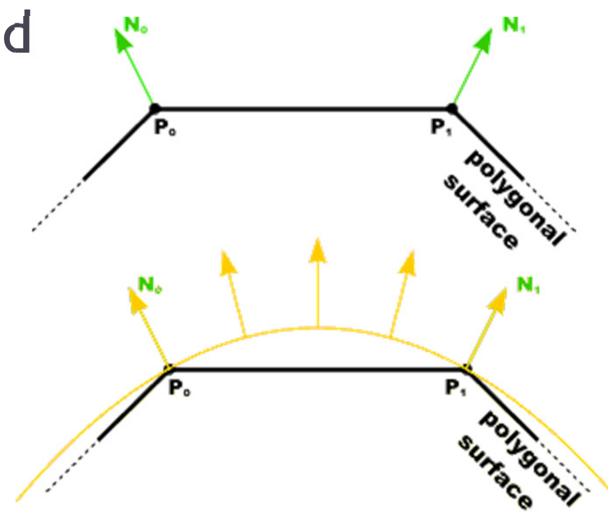
Per-Pixel Shading

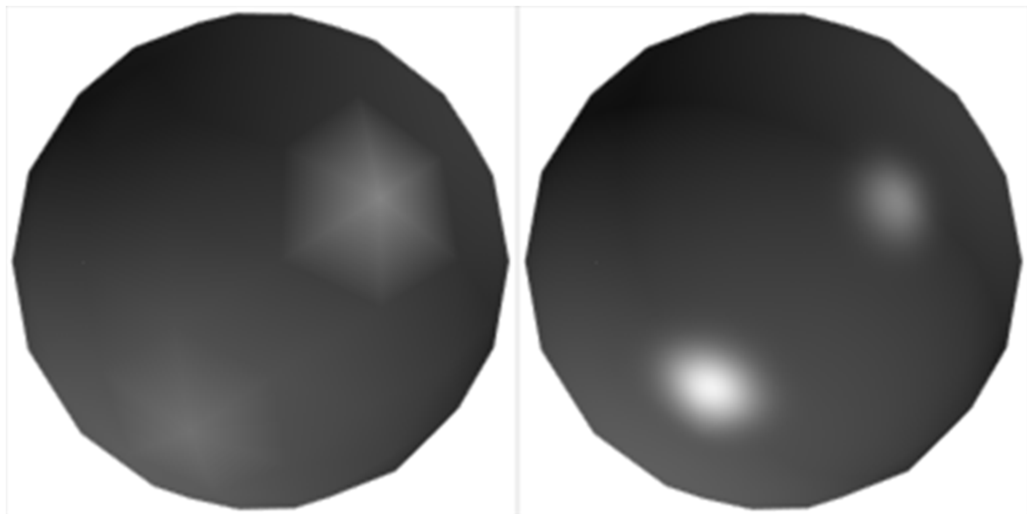
- A.k.a. *Phong Interpolation* (not to be confused with *Phong Illumination Model*)
  - Rasterizer interpolates normals (instead of colors) across triangles
  - Illumination model is evaluated at each pixel
  - Simulates shading with normals of a curved surface
- Advantage
  - Higher quality than Gouraud shading
- Disadvantage
  - Slow



Source: Penny Rheingans, UMBC

Gouraud vs. Per-Pixel Shading

- Gouraud shading has problems with highlights when polygons are large
- More triangles improve the result, but reduce frame rate



Gouraud　　　Per-Pixel

Lecture Overview

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

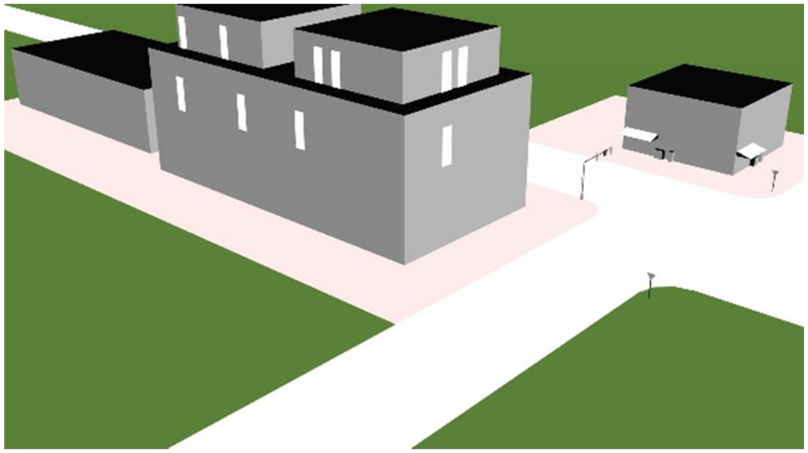
Large Triangles

Pros:

- Often sufficient for simple geometry
- Fast to render

Cons:

- Per vertex colors look boring and computer-generated



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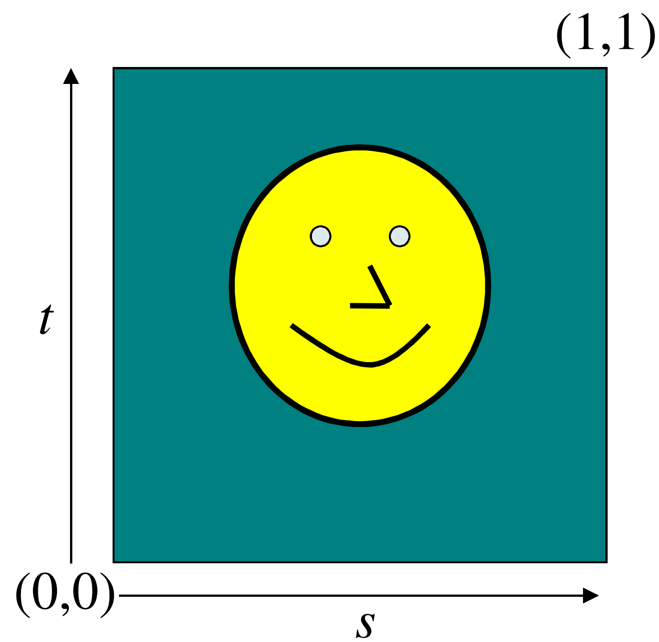
Texture Mapping

- 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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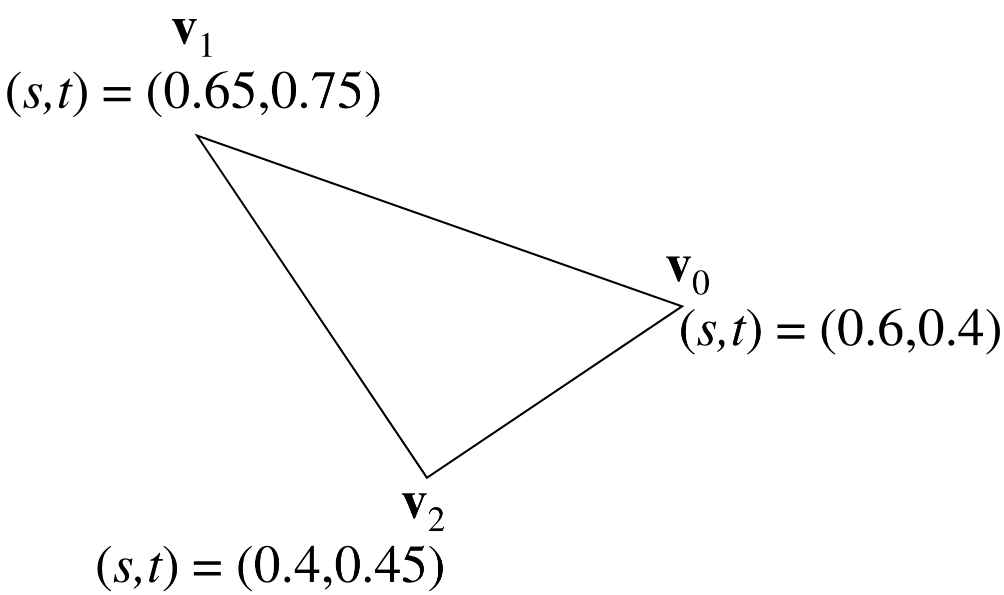
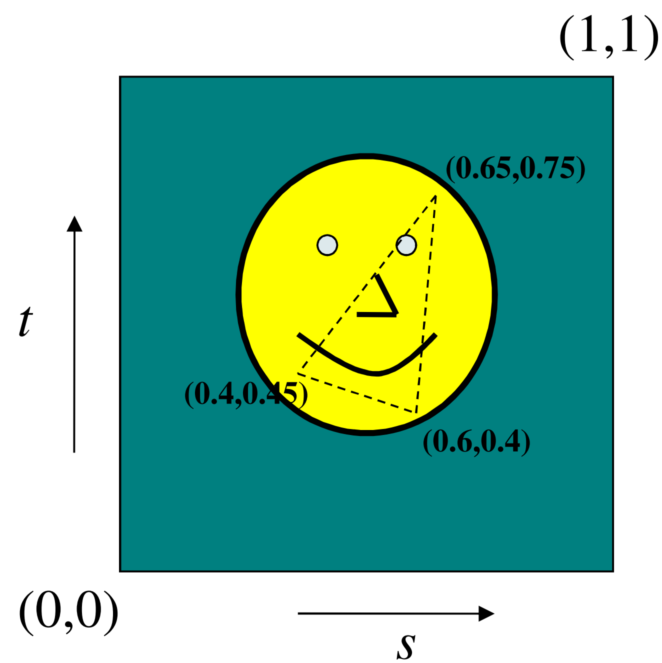
Texture Mapping

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



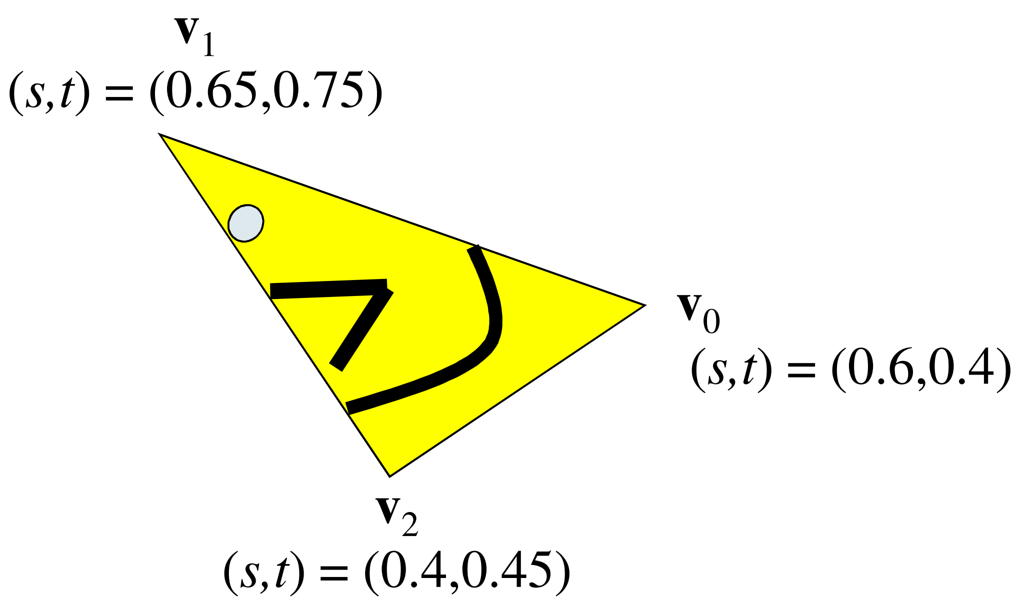
Triangle in any space before projection



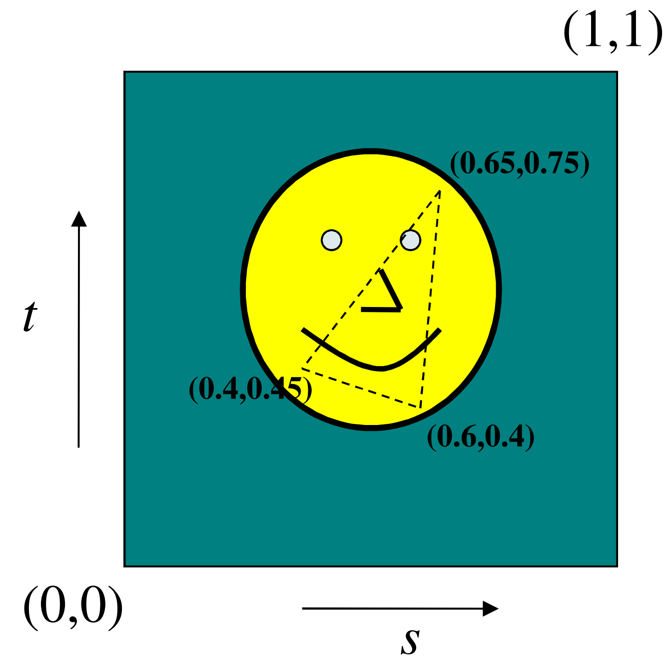
Texture coordinates

Texture Mapping

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

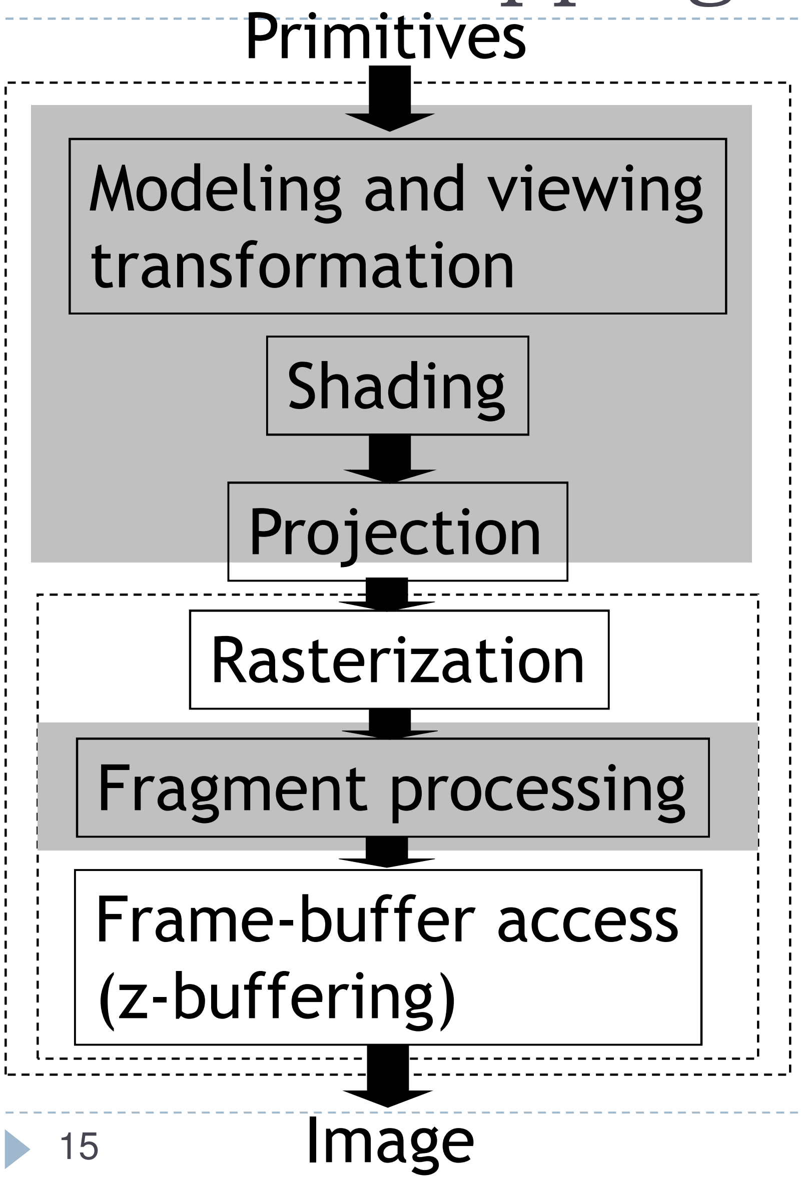


Triangle in any space before projection



Texture coordinates

Texture Mapping

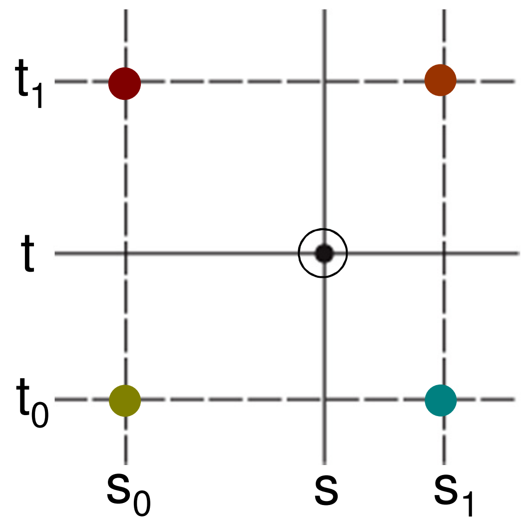


Includes texture mapping

Texture Look-Up

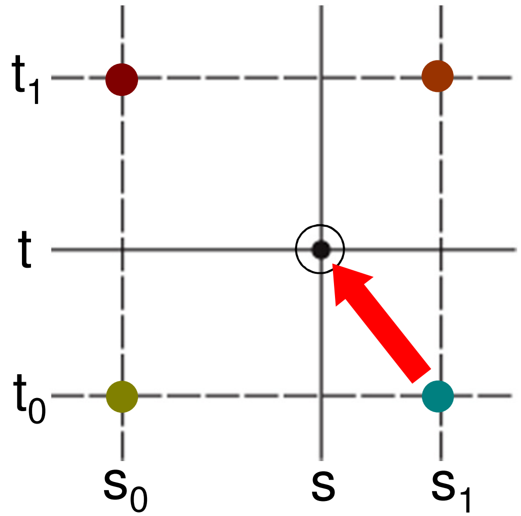
- Given interpolated texture coordinates (s, t) at current pixel
- Closest four texels in texture space are at

  (s_0,t_0), (s_1,t_0), (s_0,t_1), (s_1,t_1)
- How to compute pixel color?



Nearest-Neighbor Interpolation

- Use color of closest texel



- Simple, but low quality and aliasing

Bilinear Interpolation

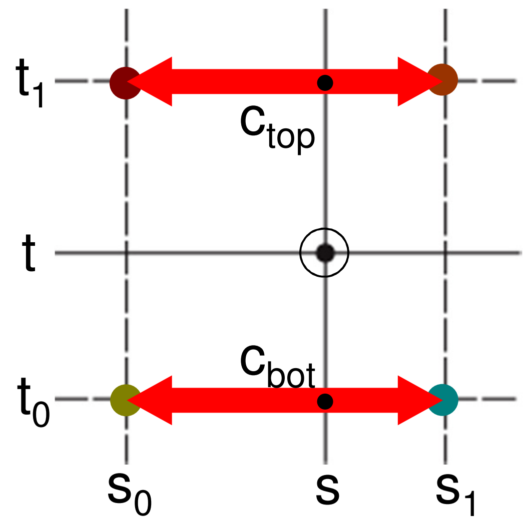
1. Linear interpolation horizontally:

   Ratio in s direction r_s:

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

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

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



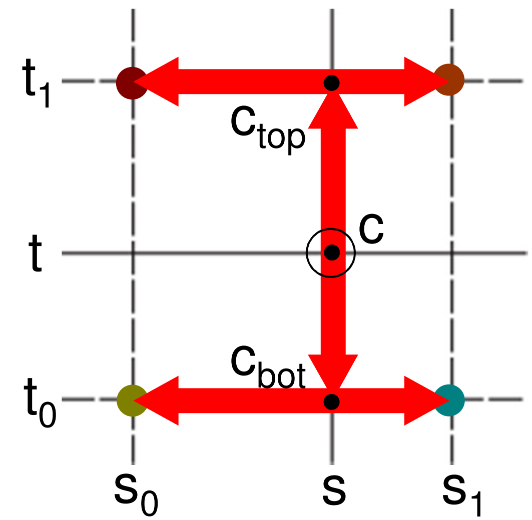
Bilinear Interpolation

2. Linear interpolation vertically

Ratio in t direction r_t:

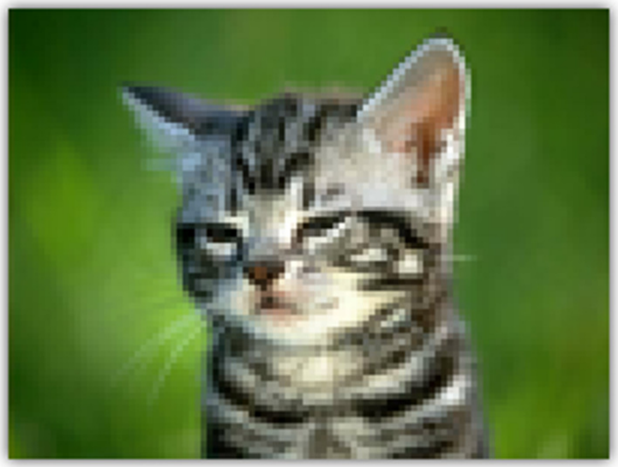
$$r_t = \frac{t - t_0}{t_1 - t_0}$$

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



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

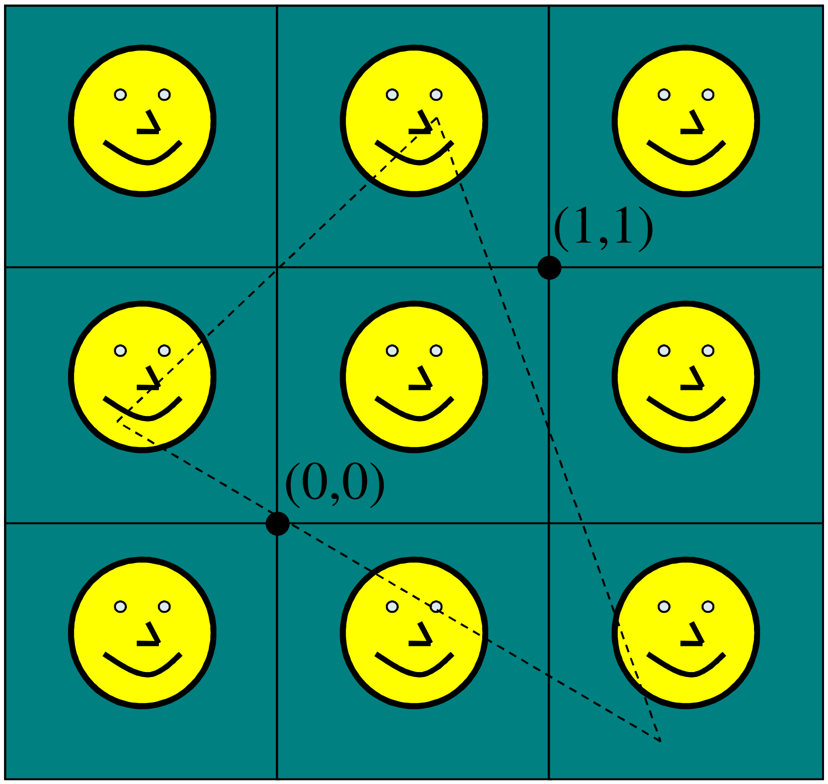
- Texture Mapping
  - Wrapping
  - Texture coordinates
  - Anti-aliasing

Wrap Modes

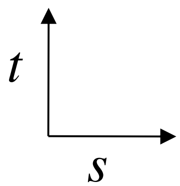
- Texture image extends from $[0,0]$ to $[1,1]$ in texture space
  - What if (s,t) texture coordinates are beyond that range?
- → Texture wrap modes

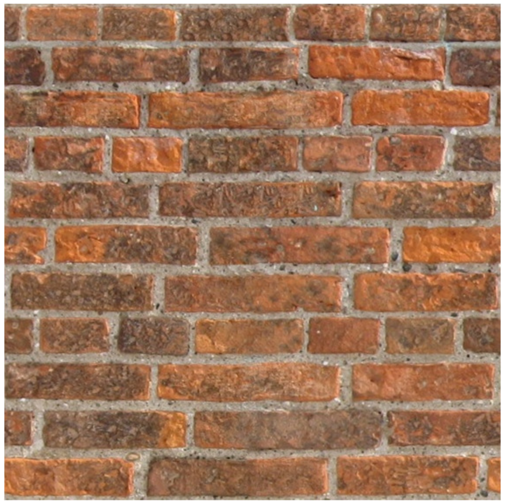
Repeat

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



Texture Space

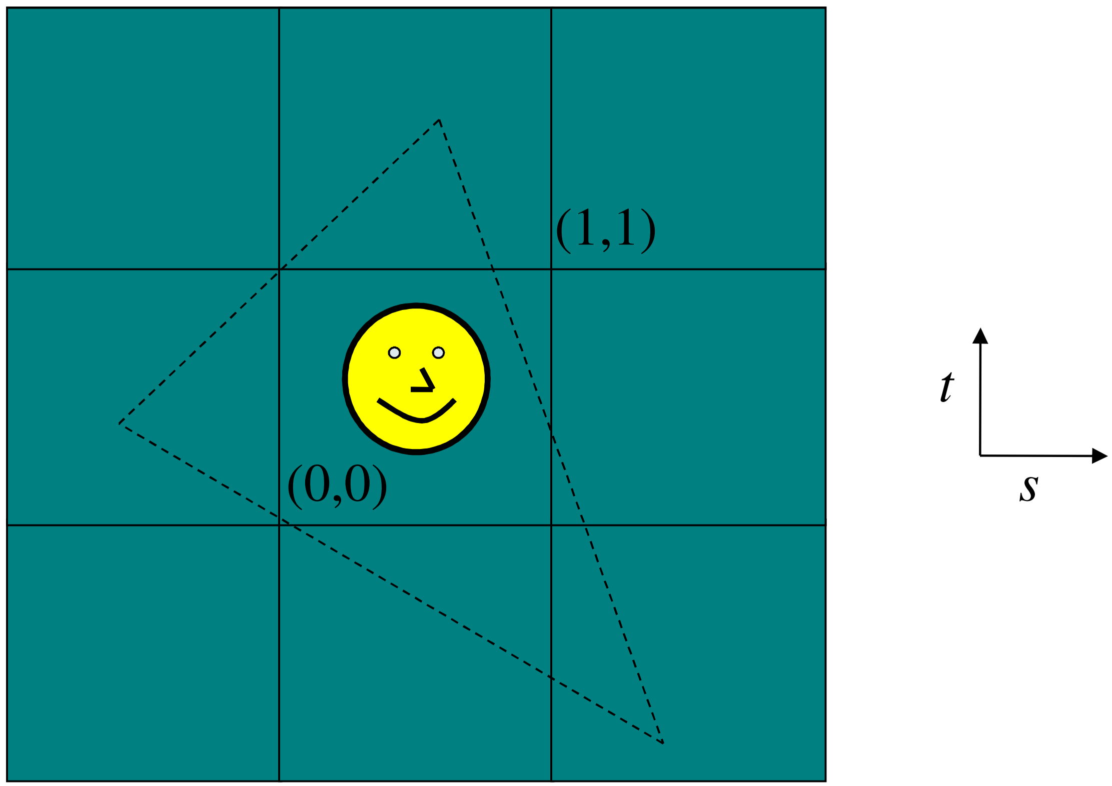




Seamless brick wall texture
(by Christopher Revoir)

Clamp

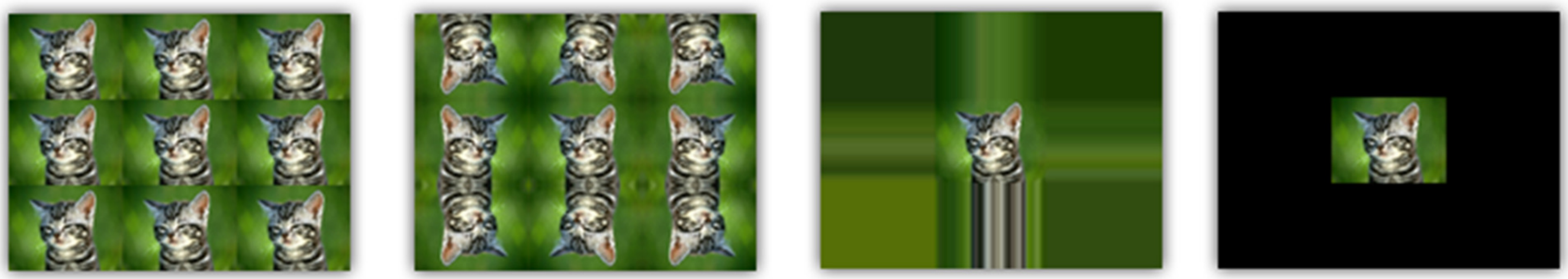
- Use edge value everywhere outside data range [0..1]
- Or use specified border color outside of range [0..1]



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
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  - Anti-aliasing

Texture Coordinates

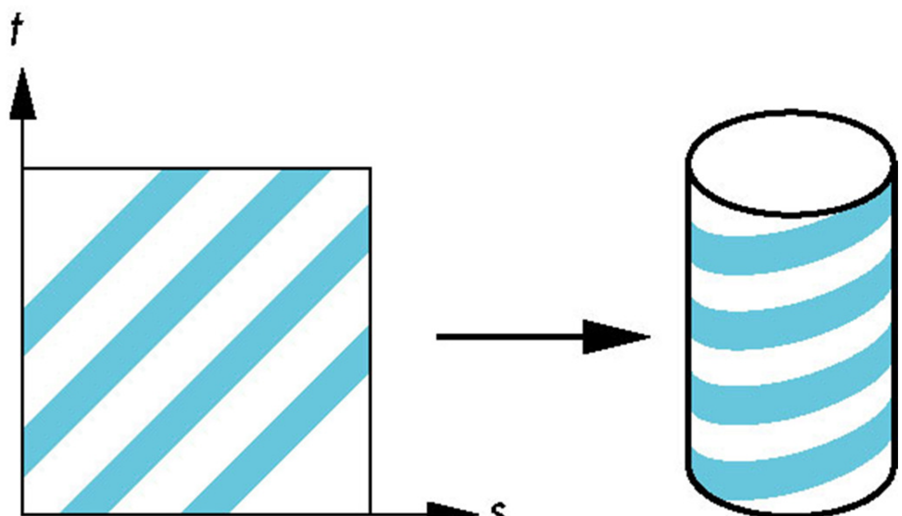
What if texture extends across multiple polygons?

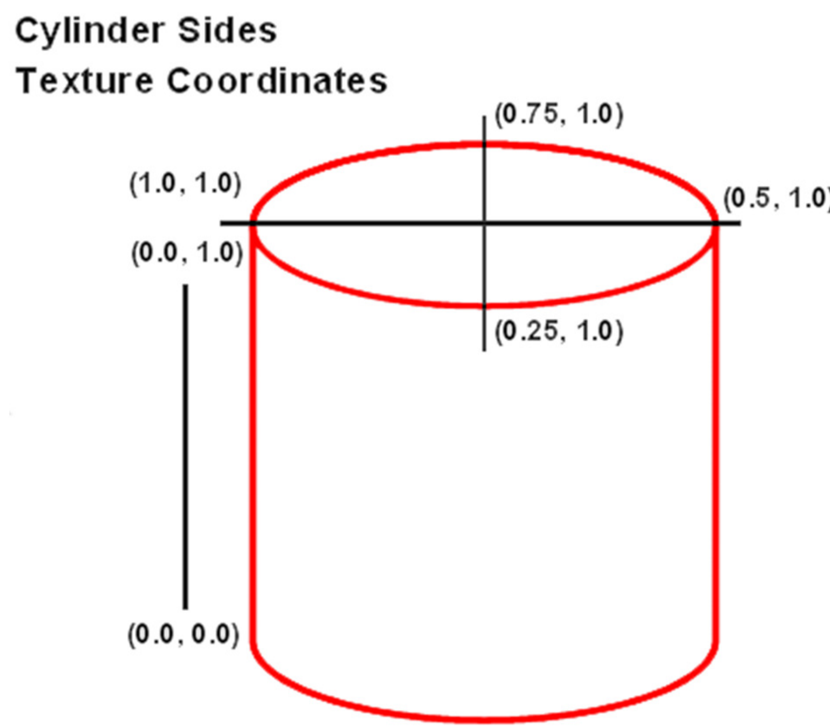
→ Surface parameterization

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

Cylindrical Mapping

- Similar to spherical mapping, but with cylindrical coordinates





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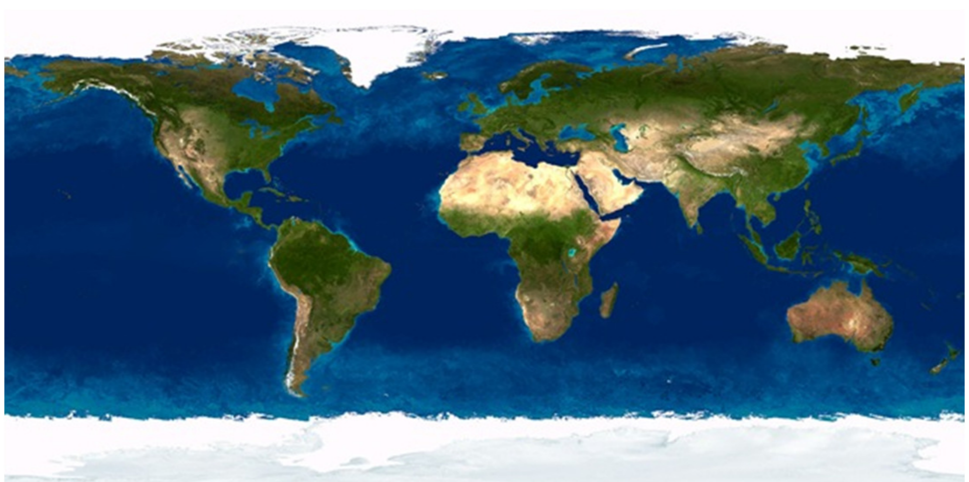
Spherical Mapping

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



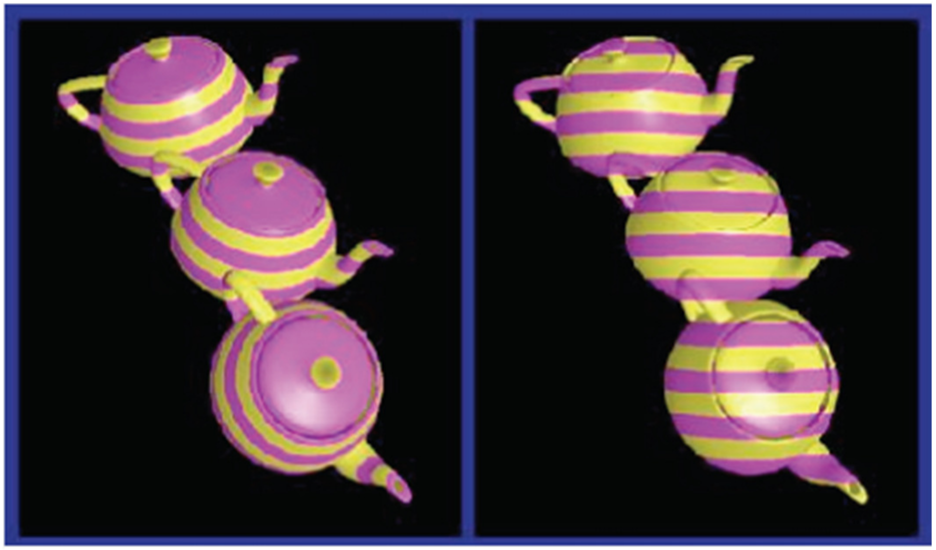
Texture map

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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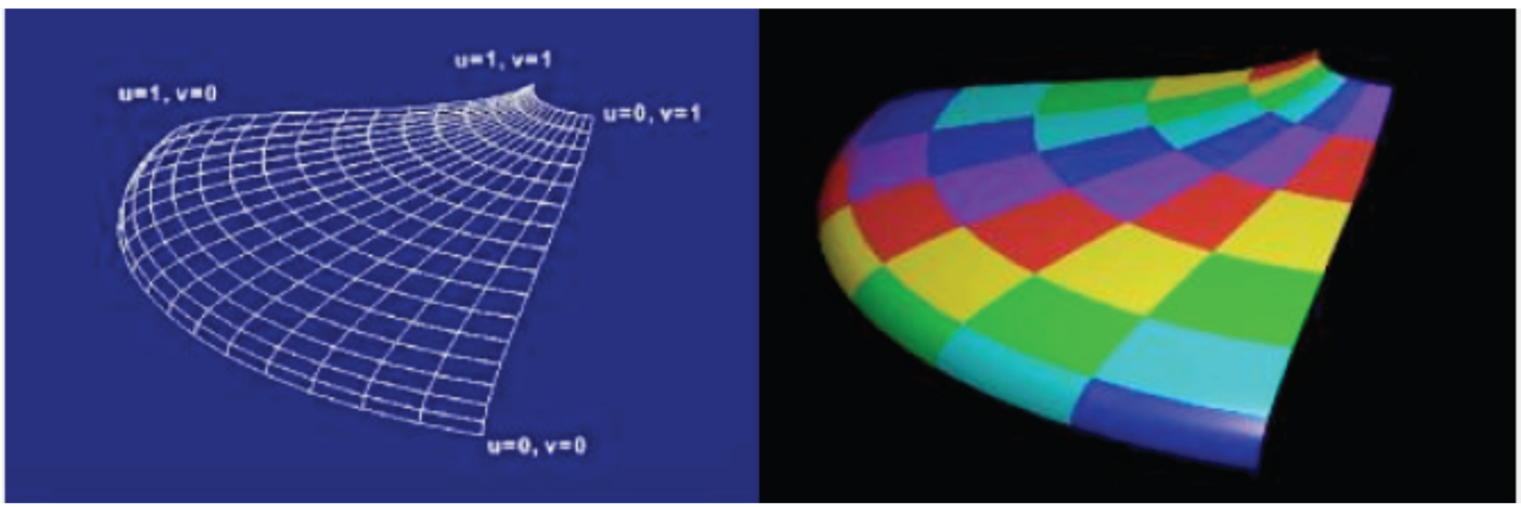
Parametric Mapping

- 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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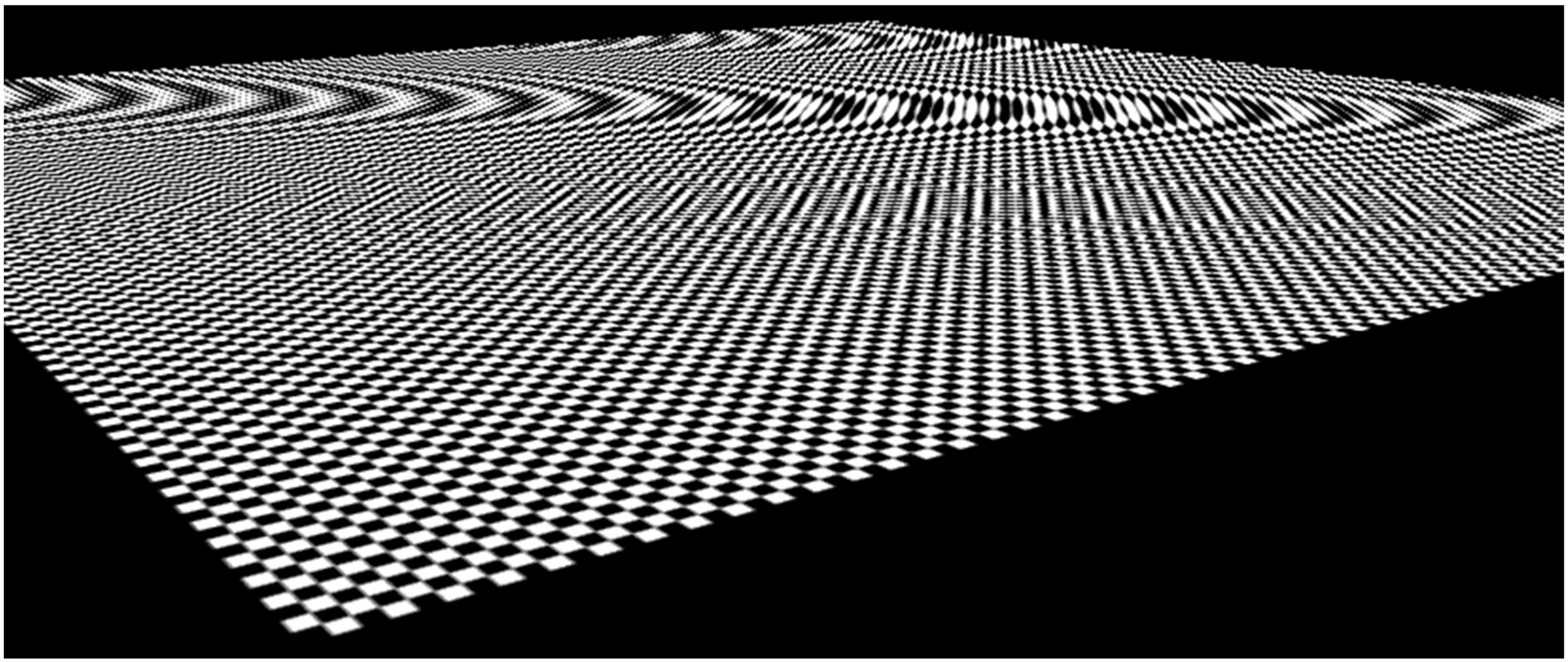
Lecture Overview

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

Aliasing

- What could cause this aliasing effect?



Aliasing

Sufficiently sampled, no aliasing

Insufficiently sampled, aliasing

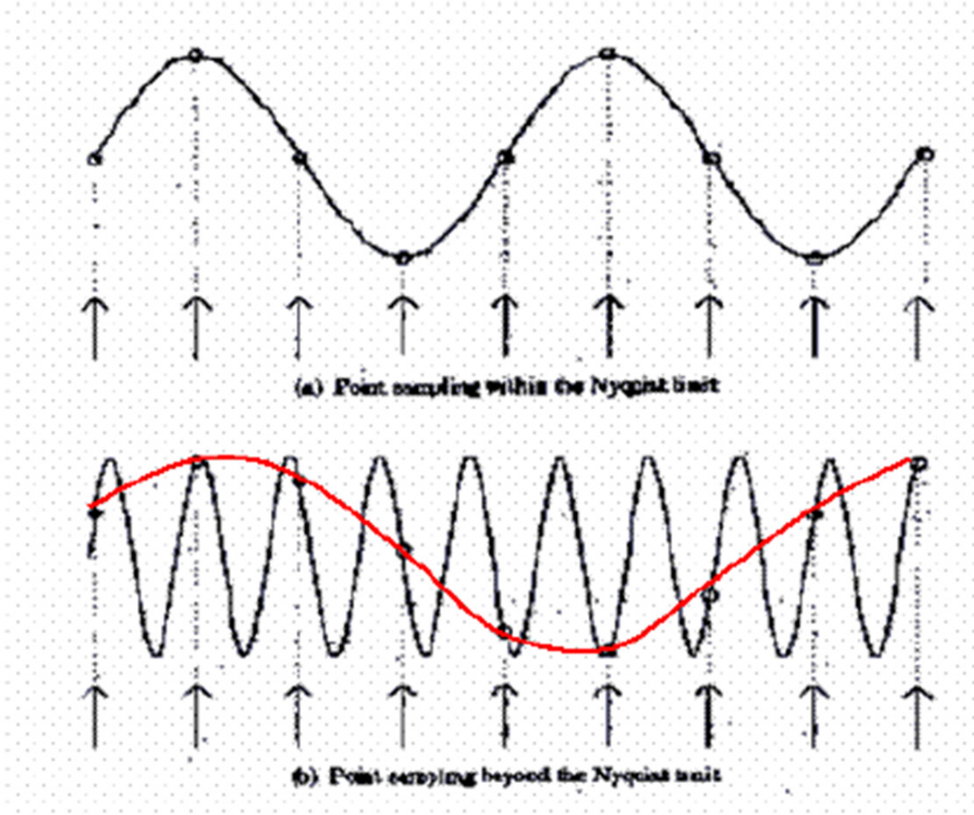
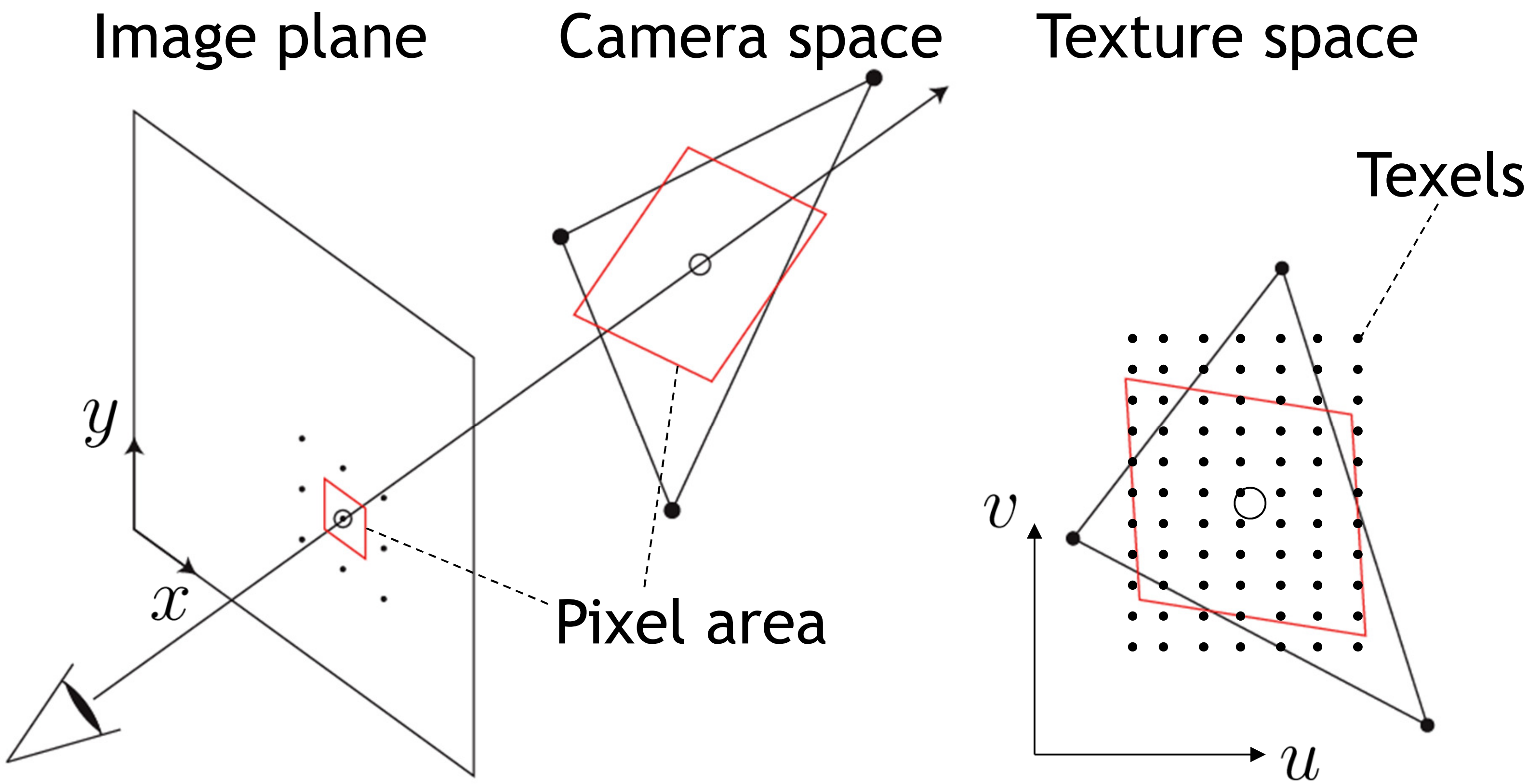


Image: Robert L. Cook

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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Lecture Overview

- Texture Mapping
  - Mip Mapping

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

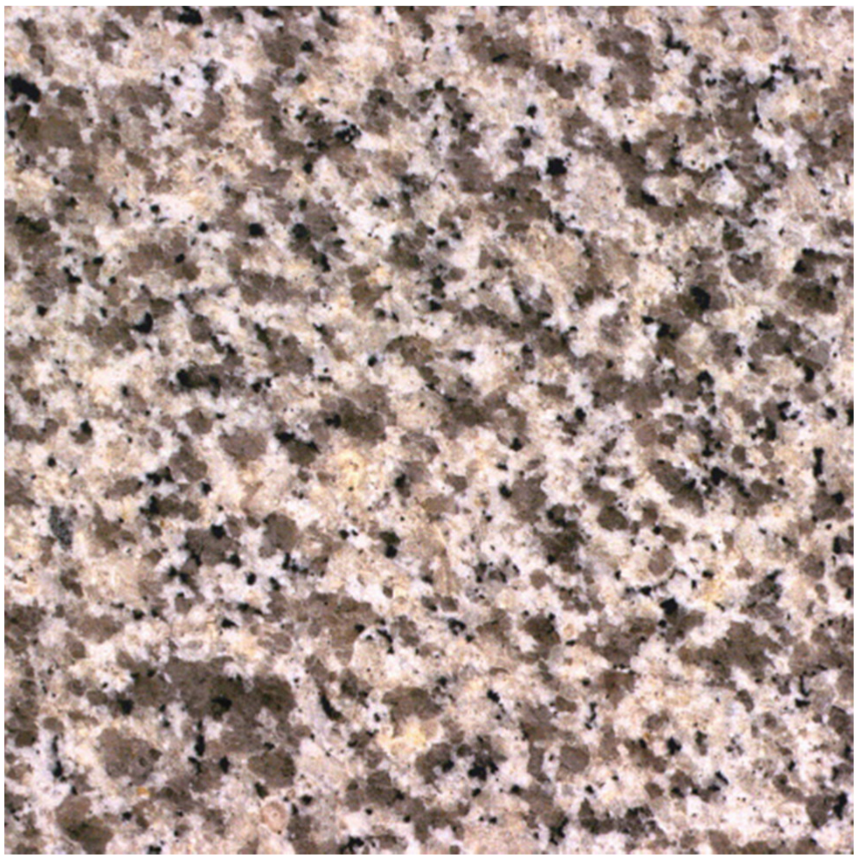
- MIP stands for *multum in parvo* = "*much in little*" (Williams 1983)

Before rendering

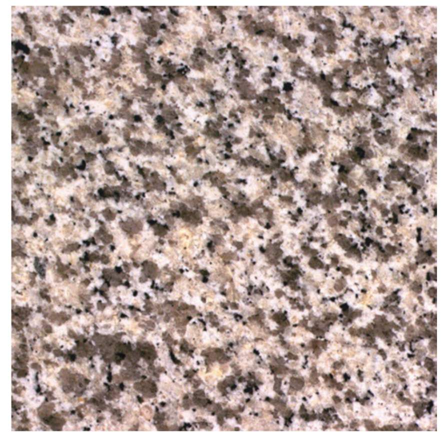
- Pre-compute and store down scaled versions of textures
  - Reduce resolution by factors of two successively
  - Use high quality filtering (averaging) scheme
- Increases memory cost by 1/3
  - $1/3 = 1/4 + 1/16 + 1/64 + \ldots$
- Width and height of texture should be powers of two (non-power of two supported since OpenGL 2.0)

Mipmaps

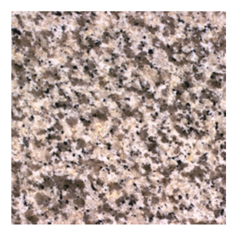
- Example: resolutions 512x512, 256x256, 128x128, 64x64, 32x32 pixels



Level 0



Level 1



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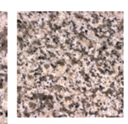

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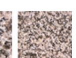
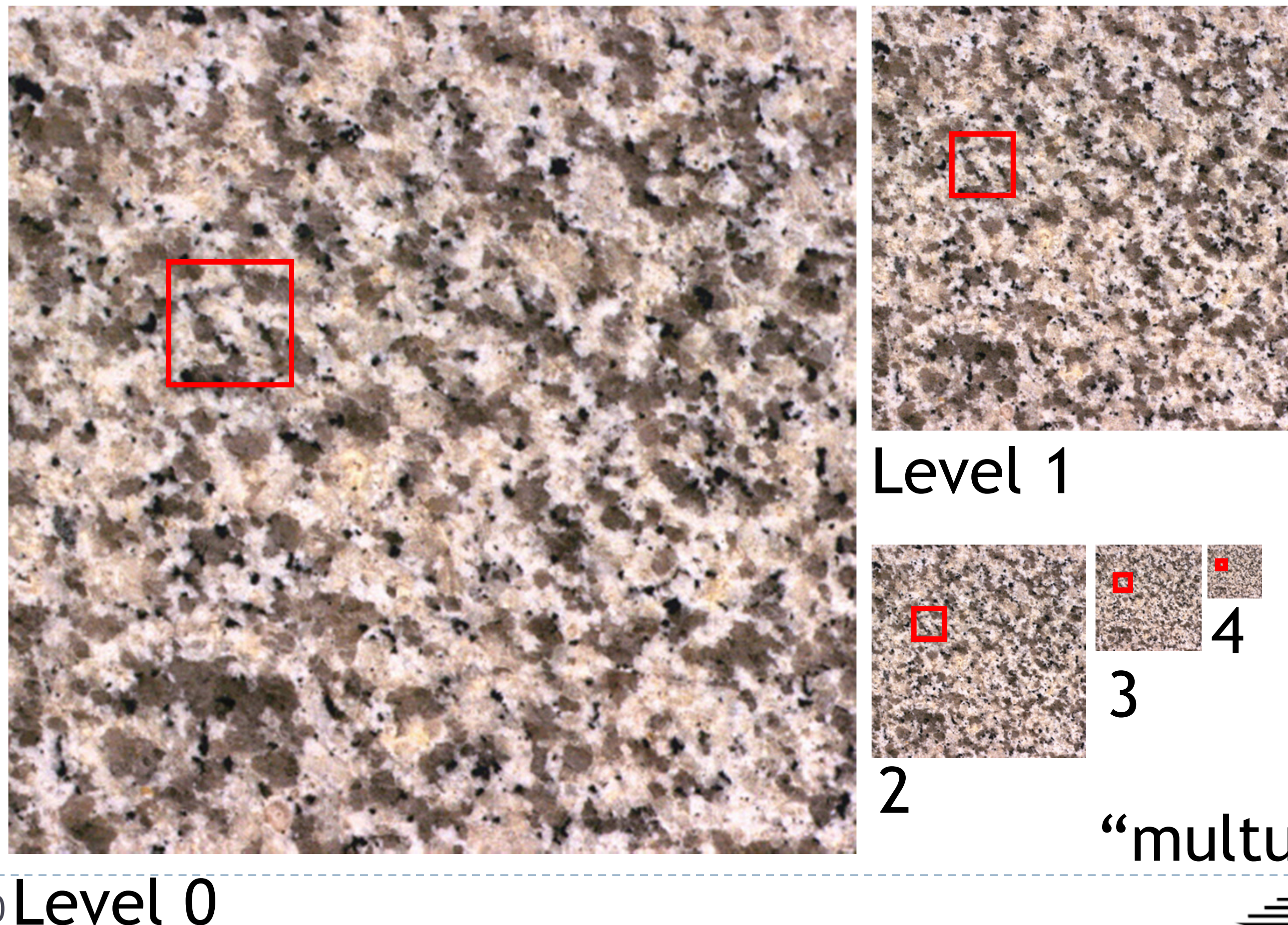


4

“multum in parvo”

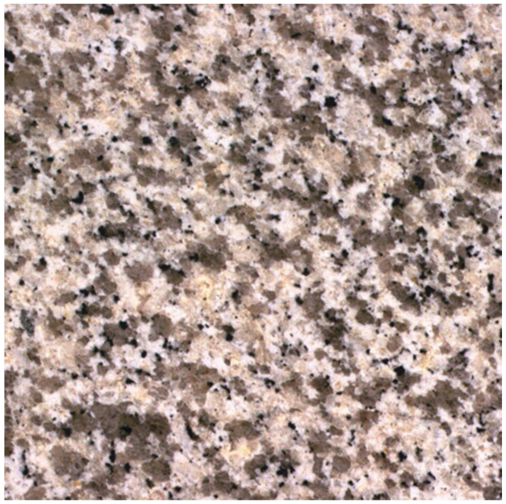
Mipmaps

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

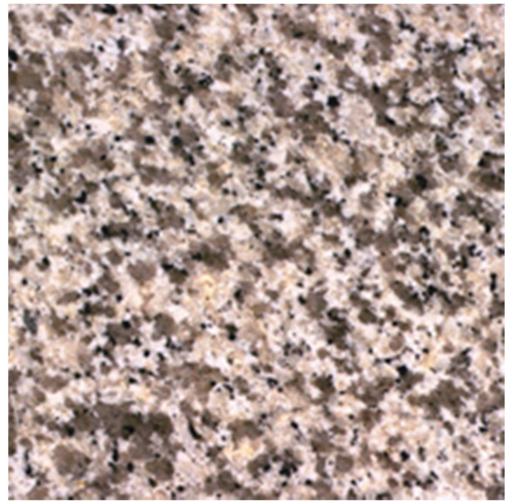


"multum in parvo"

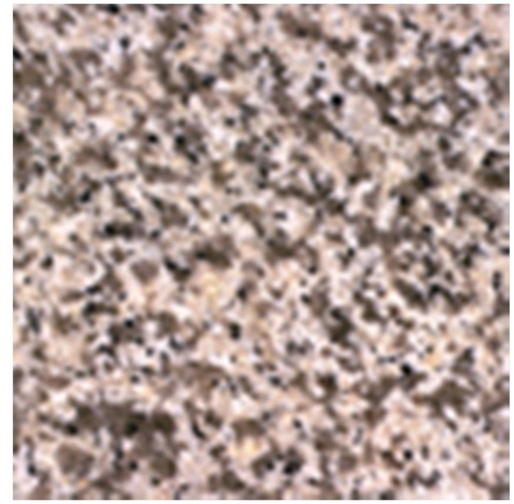
Mipmaps



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

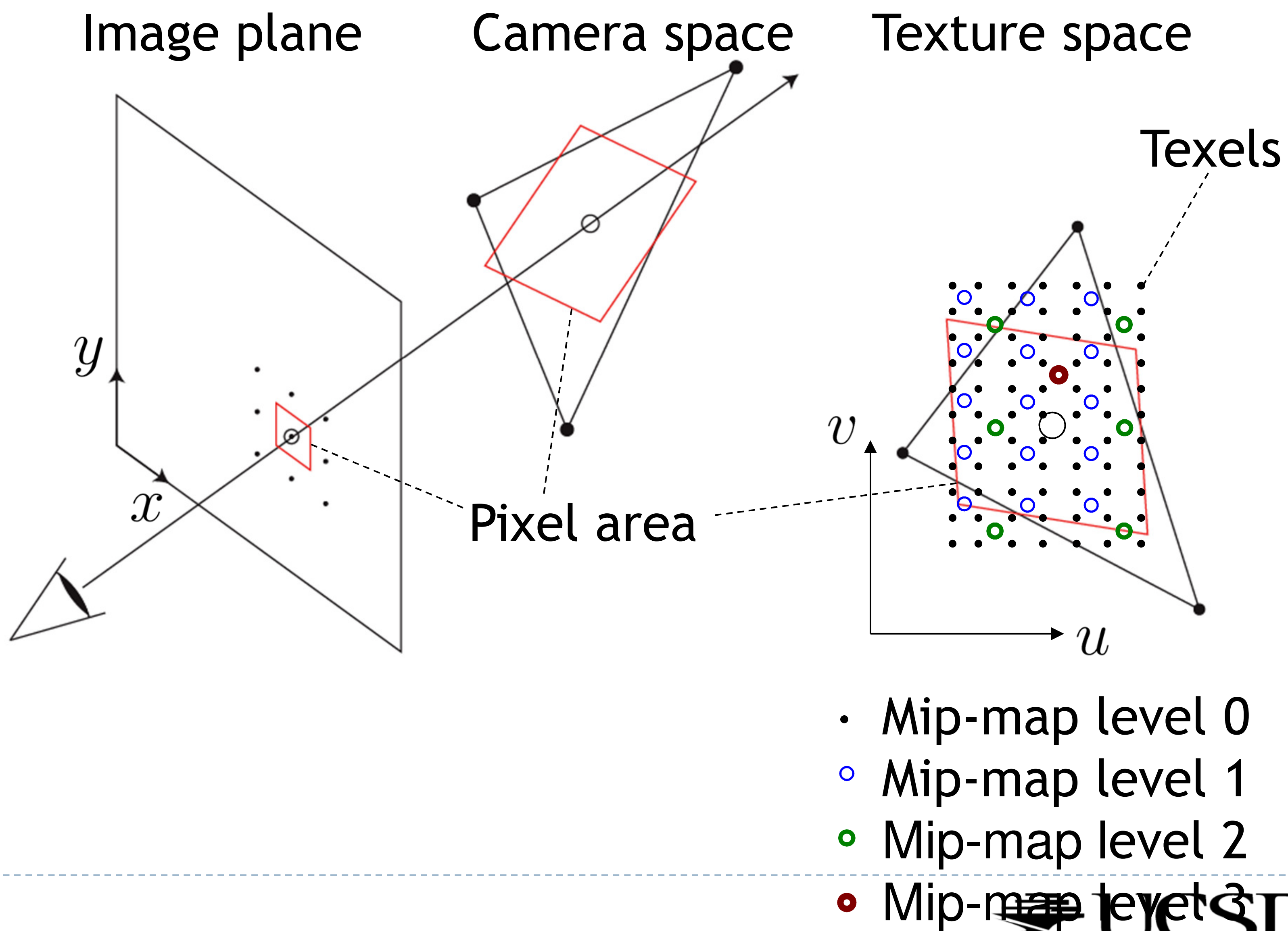
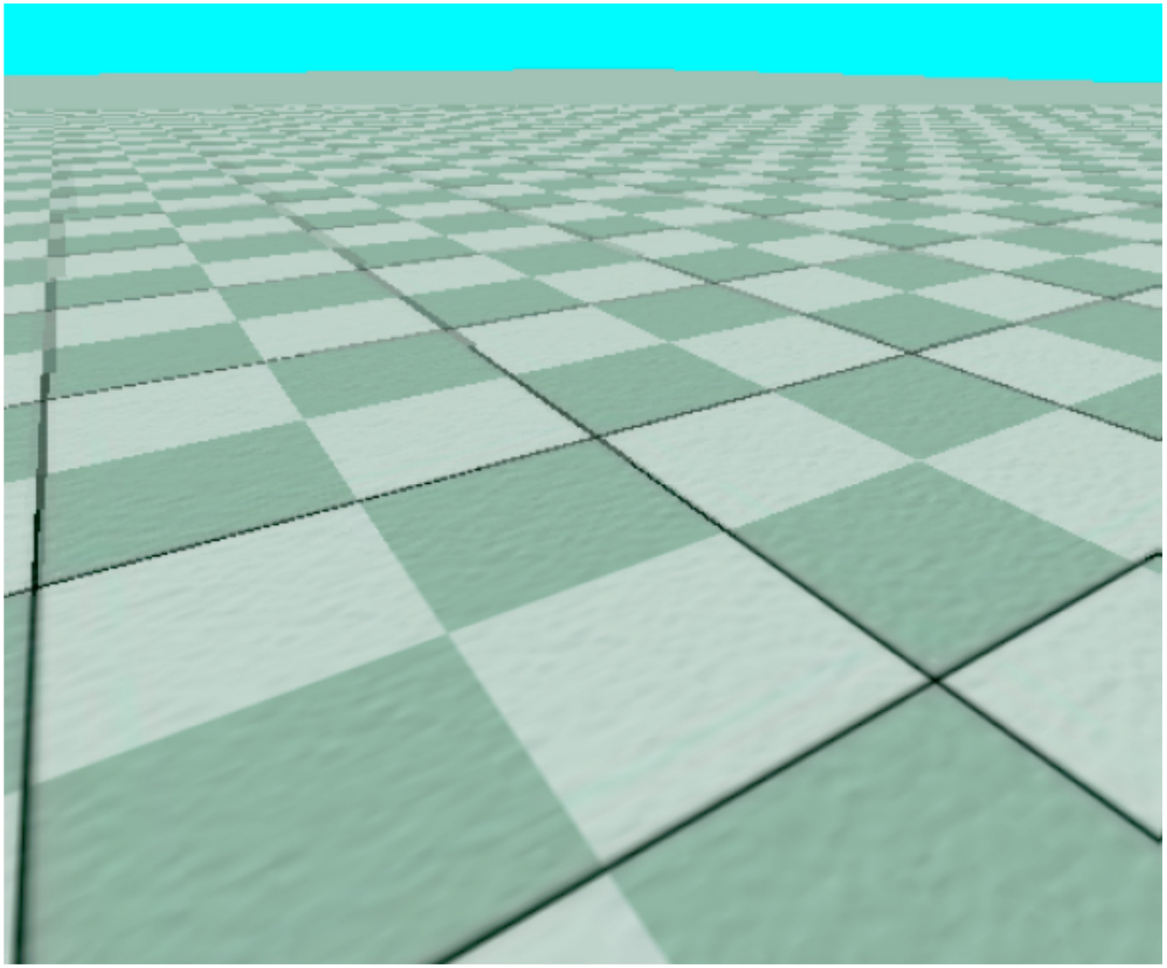


Image plane
Camera space
Texture space
Texels
y
x
Pixel area
v
u
Mip-map level 0
Mip-map level 1
Mip-map level 2
Mip-map level 3

Nearest Mipmap, Nearest Neighbor

- Visible transition between mipmap levels



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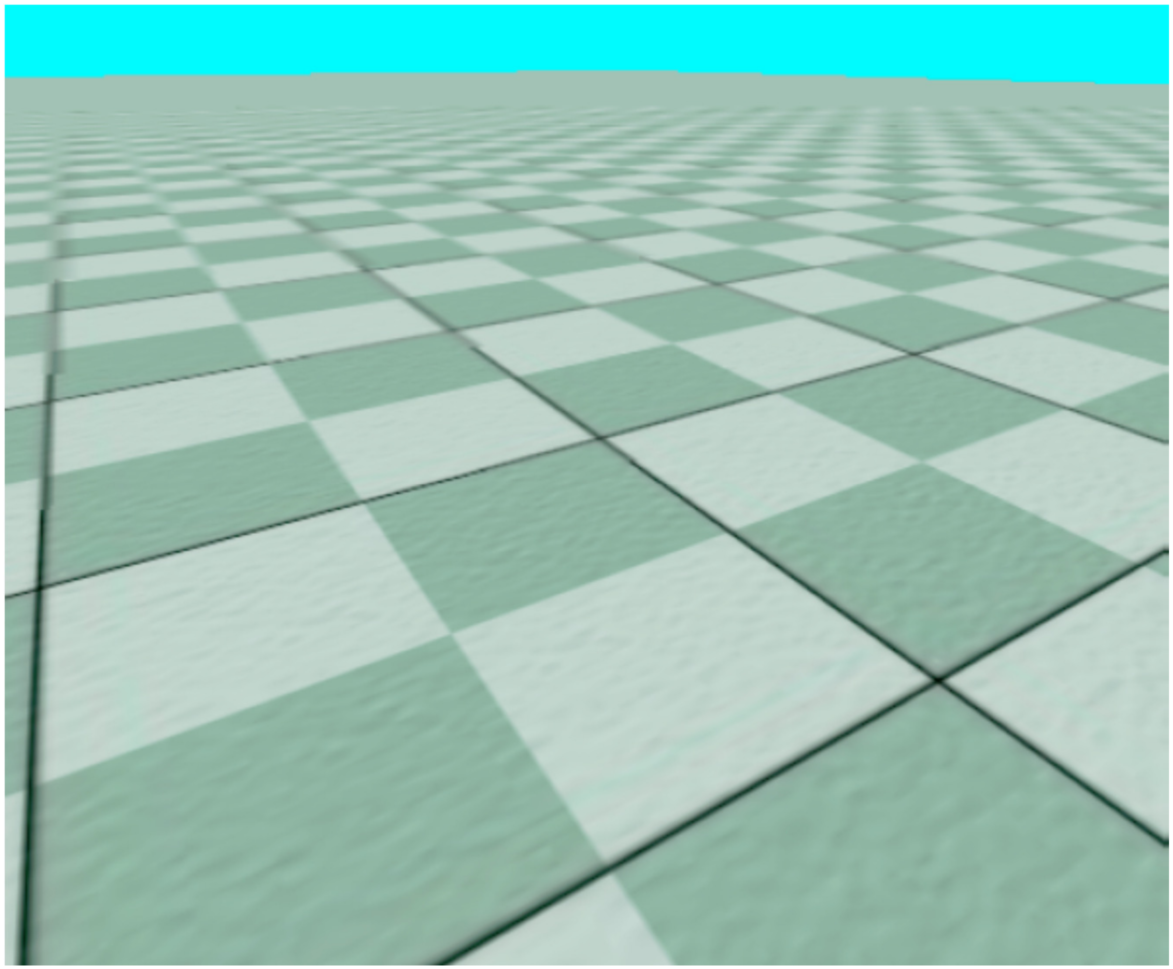
Nearest Mipmap, Bilinear

- Visible transition between mipmap levels



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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

More Info

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