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

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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

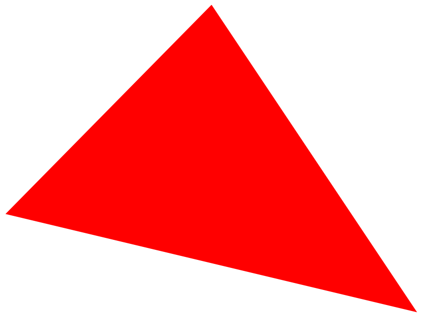
- Types of Geometry Shading
- Shading in OpenGL
    - Fixed-Function Shading
    - Programmable Shaders
        - Vertex Programs
        - Fragment Programs
        - GLSL

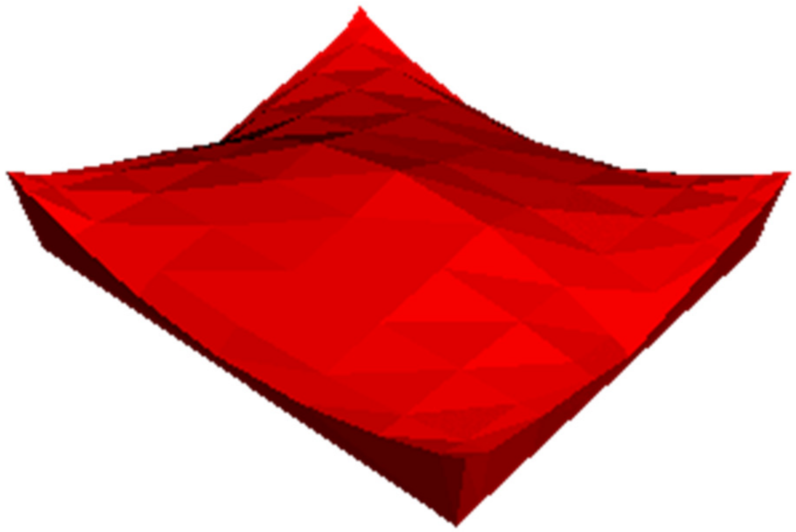
Types of Shading

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

Per-Triangle Shading

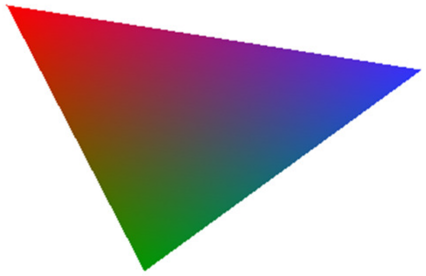
- A.k.a. *flat shading*
- Evaluate shading once per triangle
- Advantage
  - Fast
- Disadvantage
  - Faceted appearance

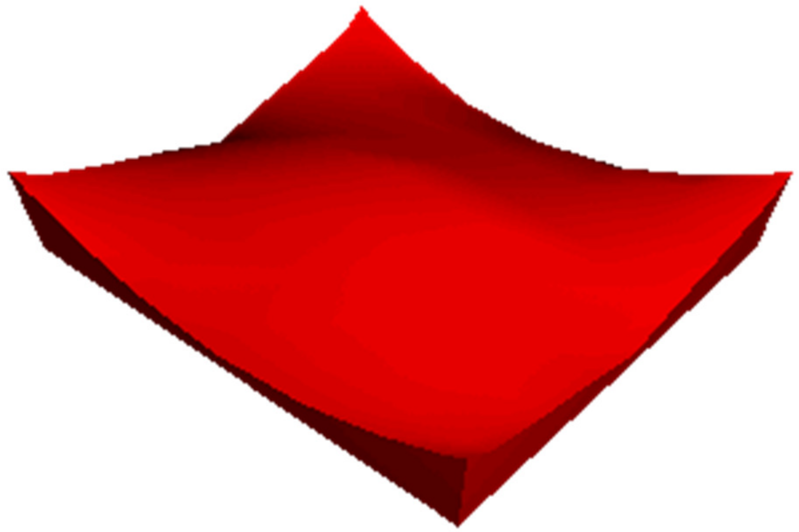




Per-Vertex Shading

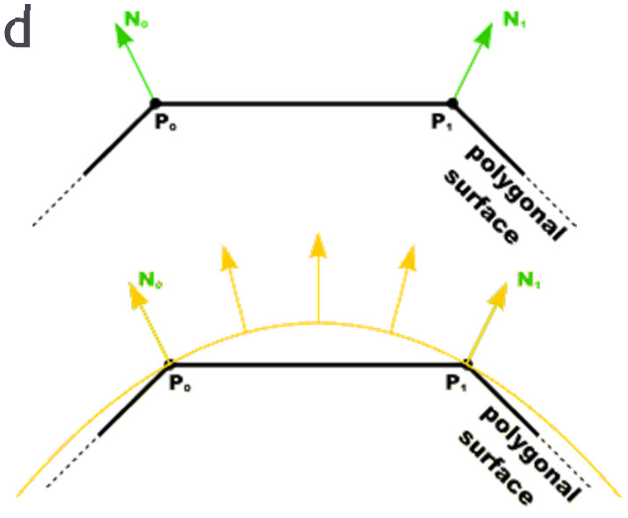
- Known as *Gouraud shading* (Henri Gouraud, 1971)
- Interpolates vertex colors across triangles
- Advantages
  - Fast
  - Smoother surface appearance than with flat shading
- Disadvantage
  - Problems with small highlights





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

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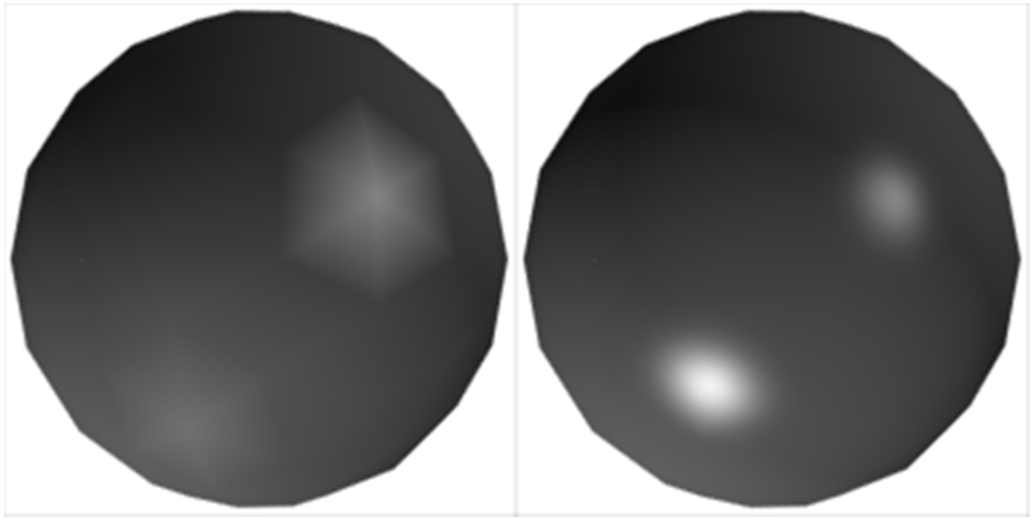
Gouraud vs. Per-Pixel Shading

- 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

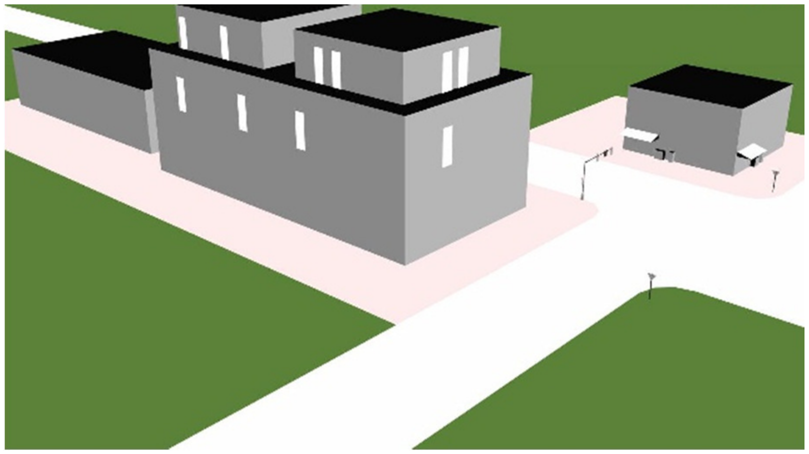
Large Triangles

Pros:

- Often sufficient for simple geometry
- Fast to render

Cons:

- Per vertex colors look boring and computer-generated

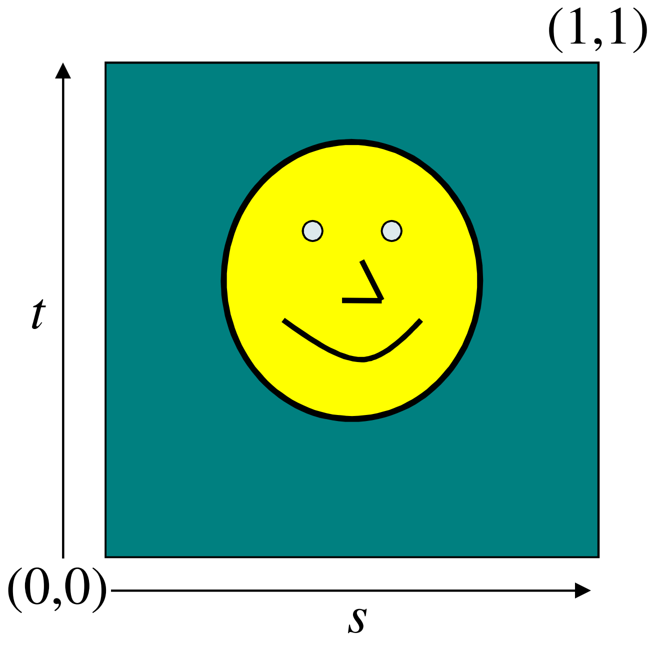


Texture Mapping

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

Texture Mapping

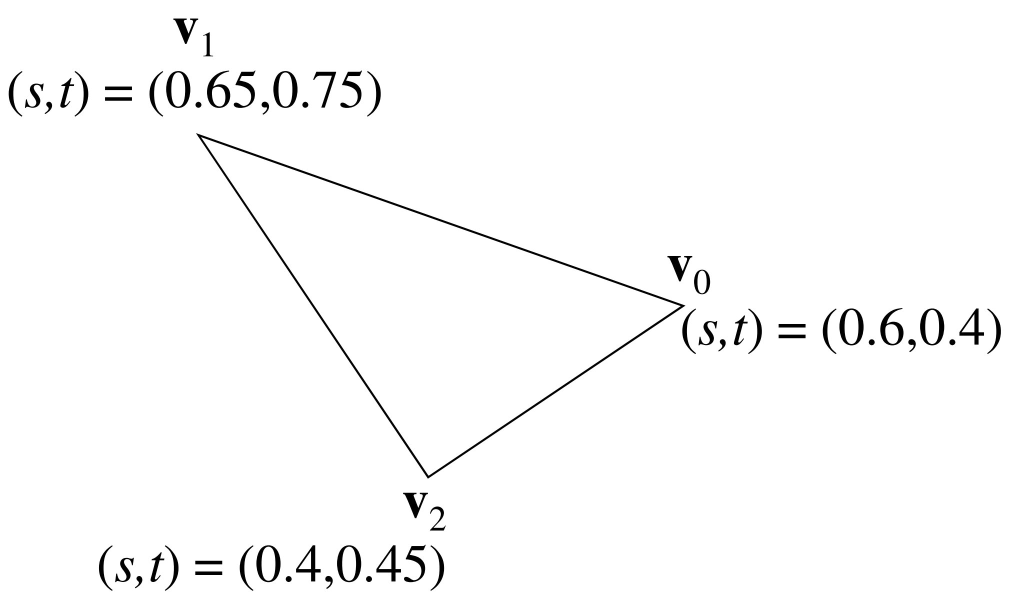
- Goal: map locations in texture to locations on 3D geometry
- Texture coordinate space
  - Texture pixels (texels) have texture coordinates (s,t)
- Convention
  - Bottom left corner of texture is at $(s,t) = (0,0)$
  - Top right corner is at $(s,t) = (1,1)$



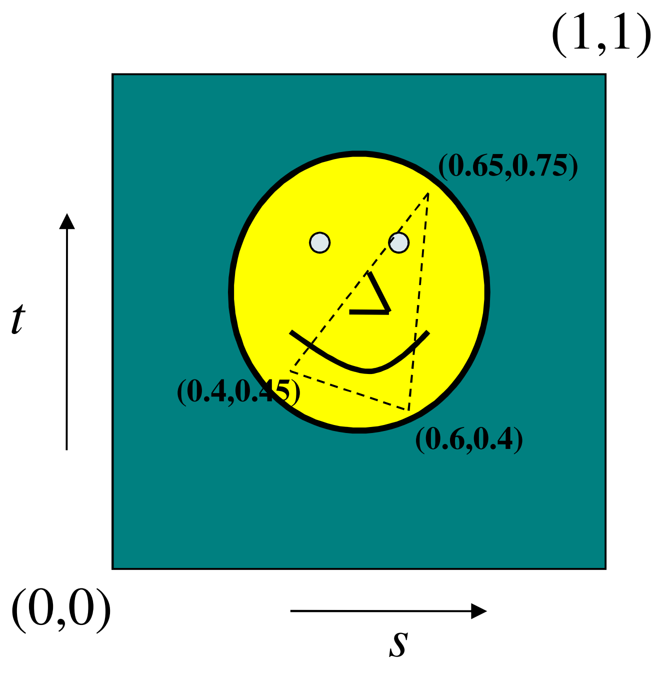
Texture coordinates

Texture Mapping

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



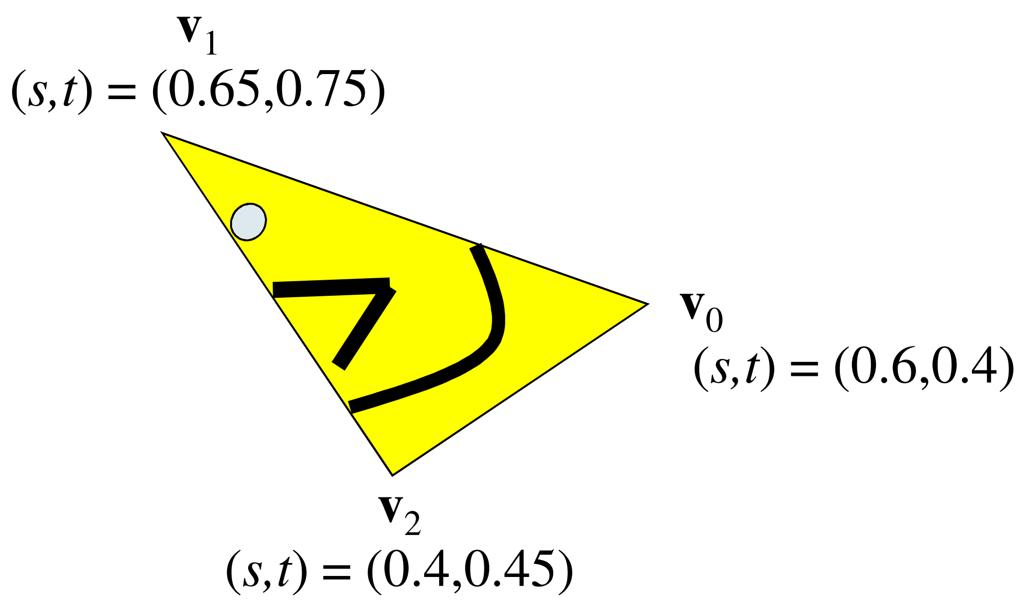
Triangle in any space before projection



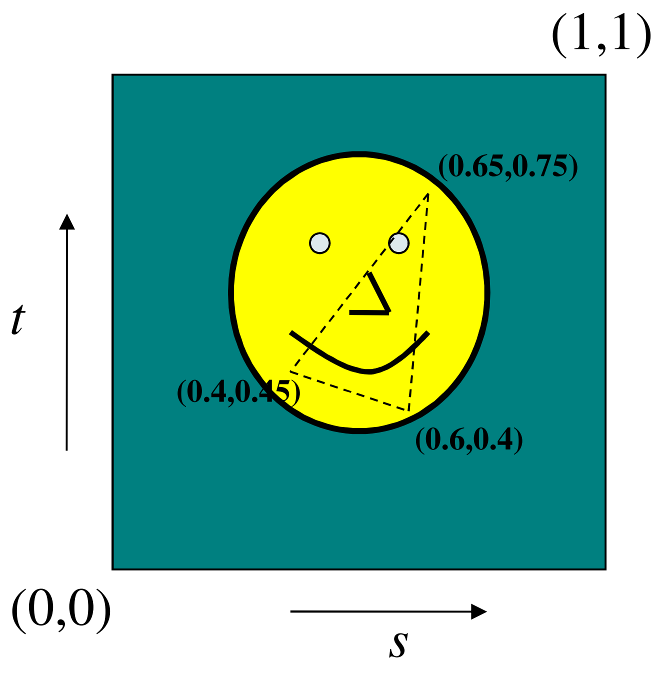
Texture coordinates

Texture Mapping

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

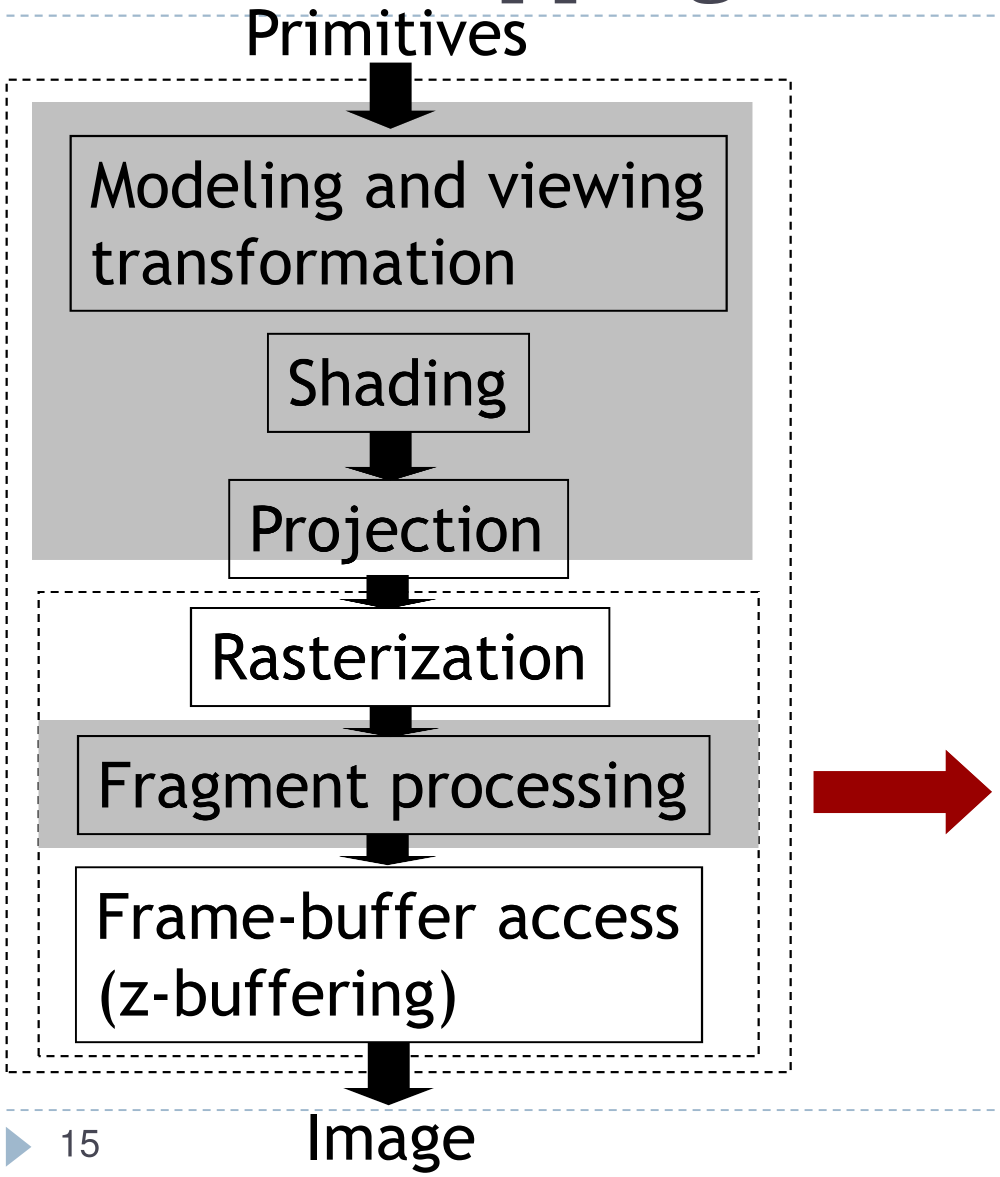


Triangle in any space before projection



Texture coordinates

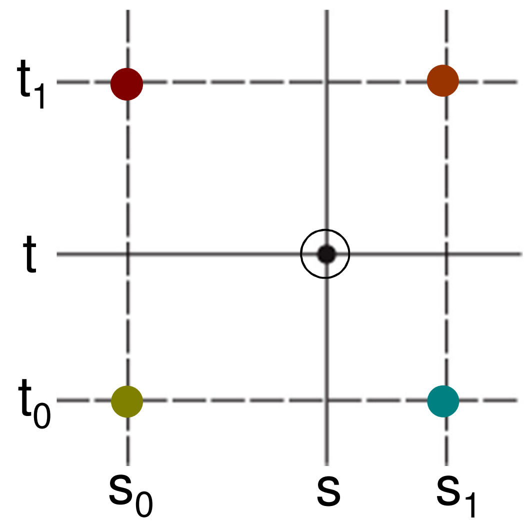
Texture Mapping


Primitives
Modeling and viewing transformation
Shading
Projection
Rasterization
Fragment processing
Frame-buffer access (z-buffering)
Image

Includes texture mapping

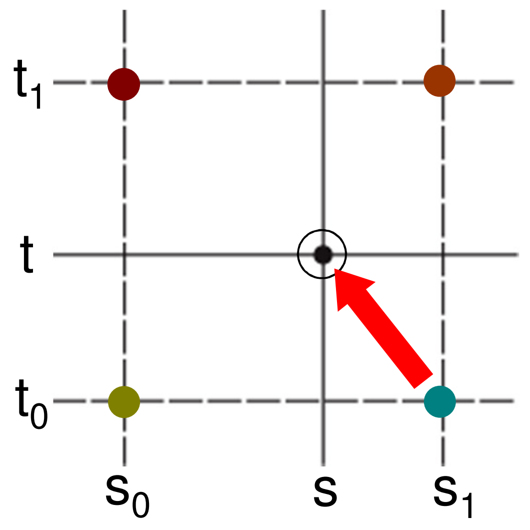
Texture Look-Up

- 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

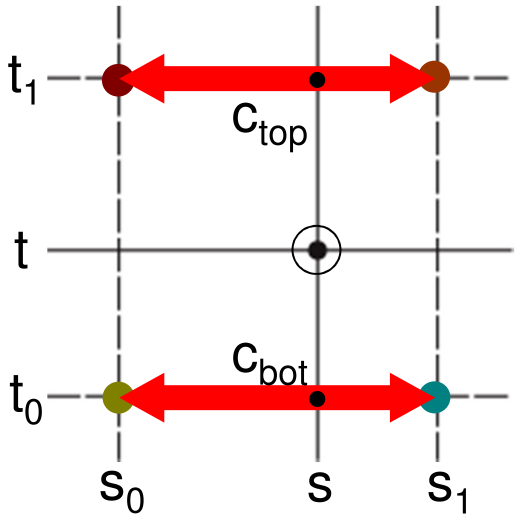
1. Linear interpolation horizontally:

   Ratio in s direction r_s:

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

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

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



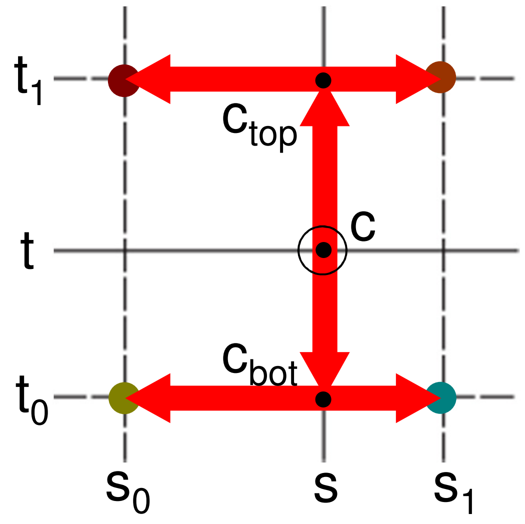
Bilinear Interpolation

2. Linear interpolation vertically

Ratio in t direction r_t:

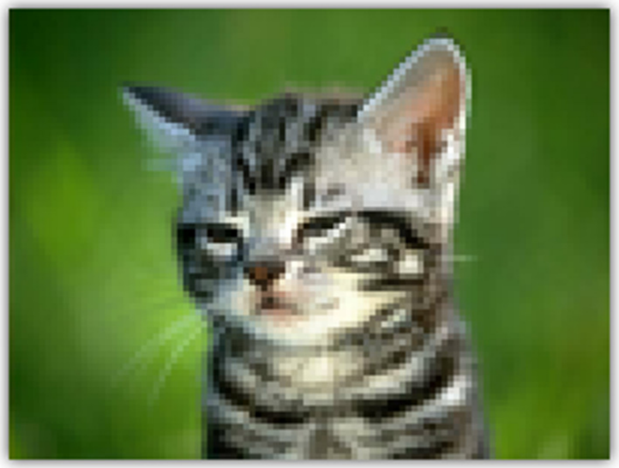
$$r_t = \frac{t - t_0}{t_1 - t_0}$$

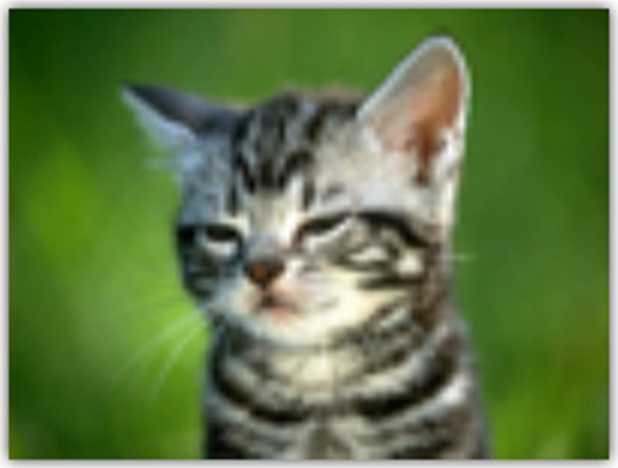
$c = c_{bot}\,(1 - r_t) + c_{top}\,r_t$



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

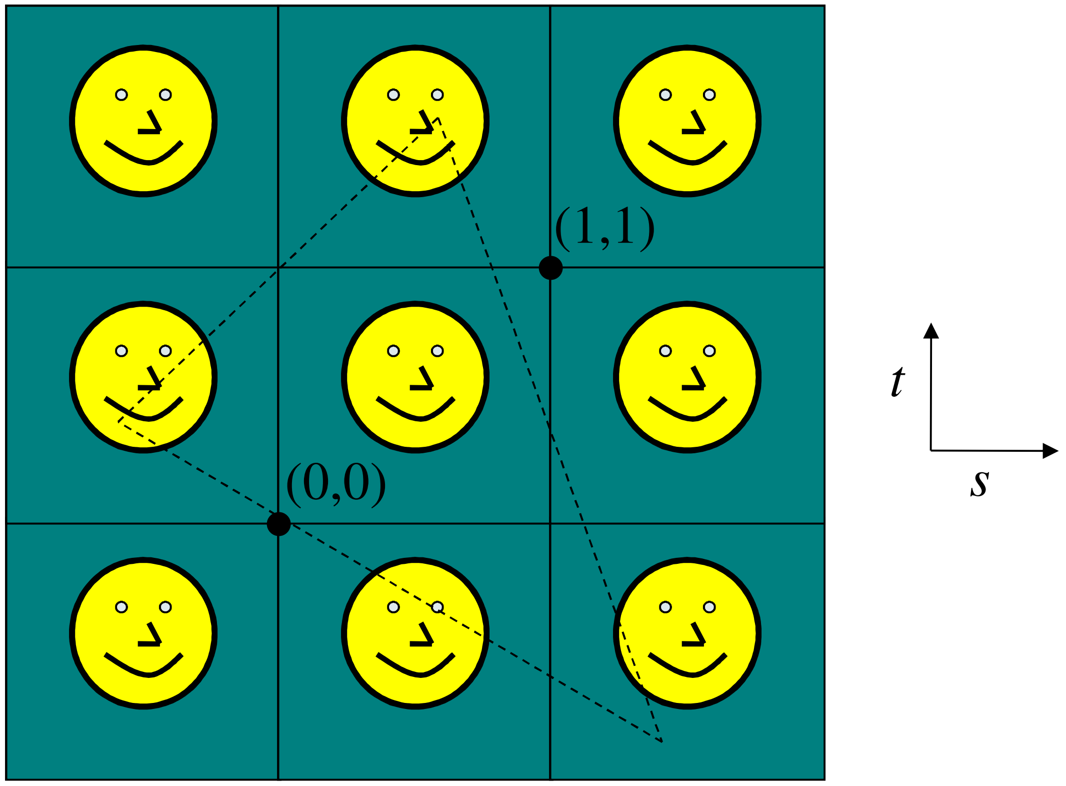
- Texture Mapping
  - Wrapping
  - Texture coordinates
  - Anti-aliasing

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)

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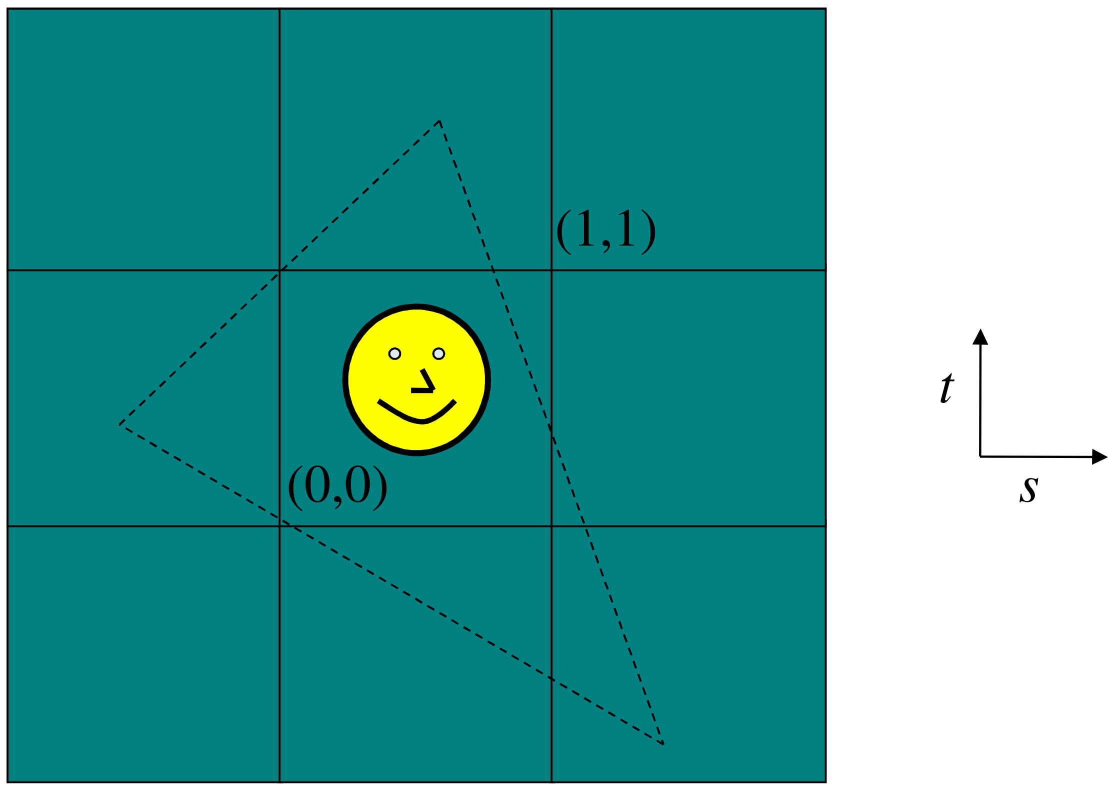
Clamp

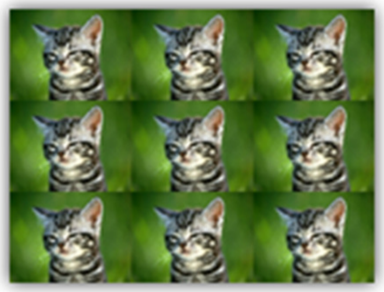
- Use edge value everywhere outside data range [0..1]
- Or use specified border color outside of range [0..1]

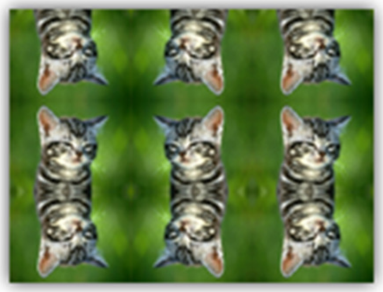


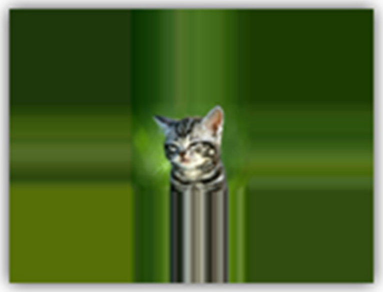
Texture Space

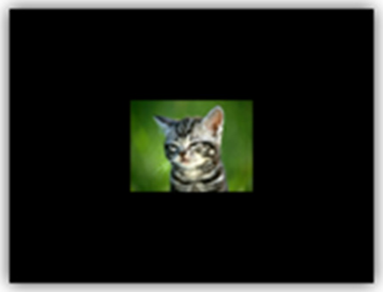
Wrap Modes in OpenGL

- 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

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Lecture Overview

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

Texture Coordinates

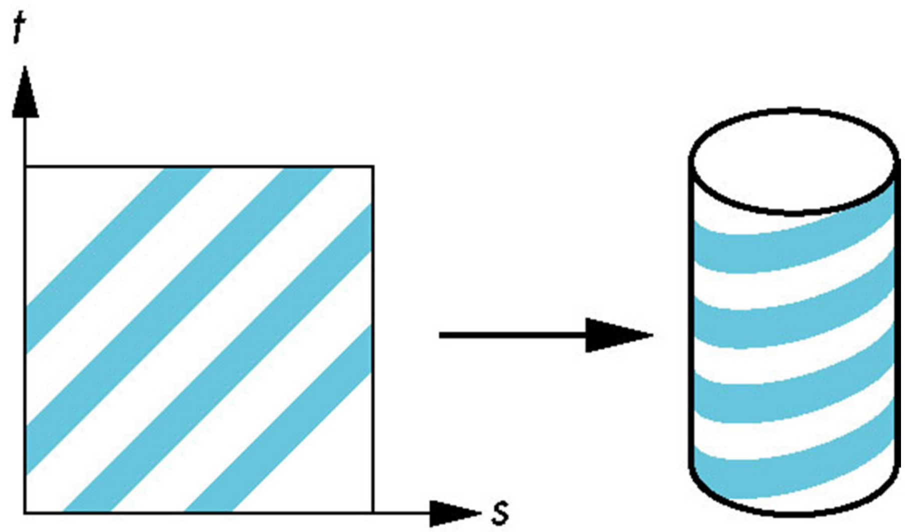
What if texture extends across multiple polygons?

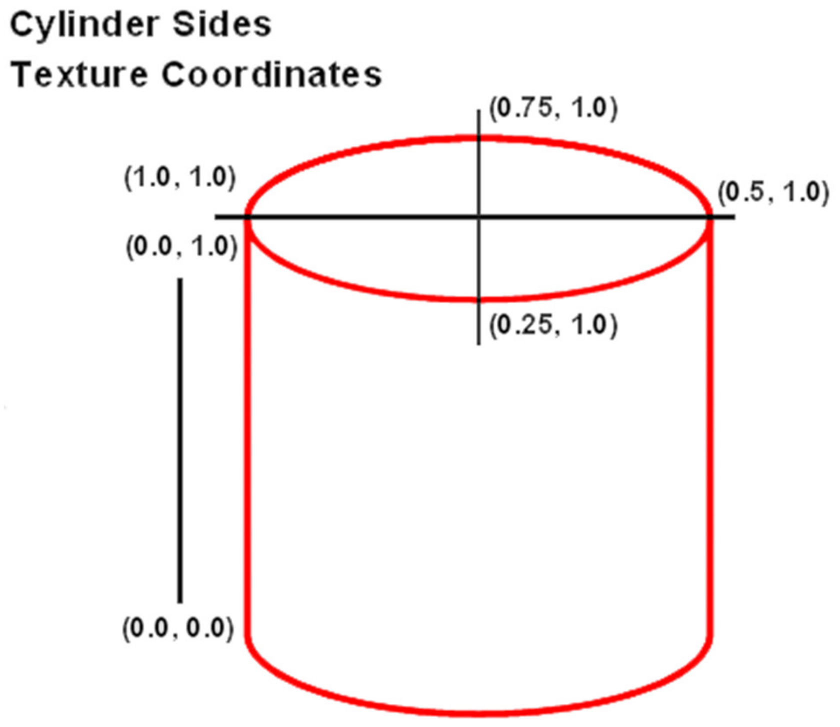
→ Surface parameterization

- 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

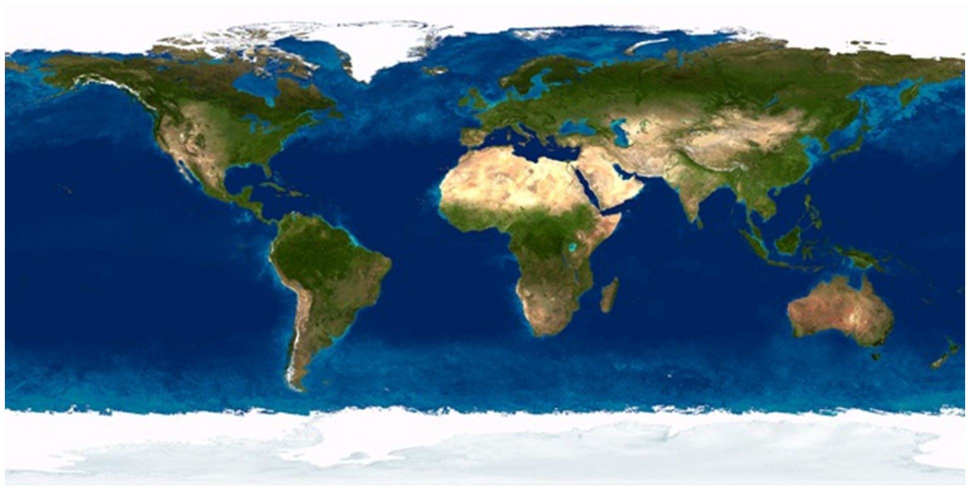
- Similar to spherical mapping, but with cylindrical coordinates



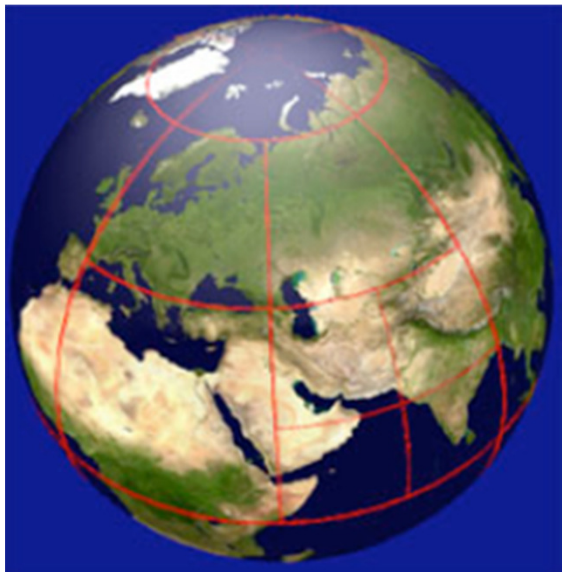


Spherical Mapping

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



Texture map

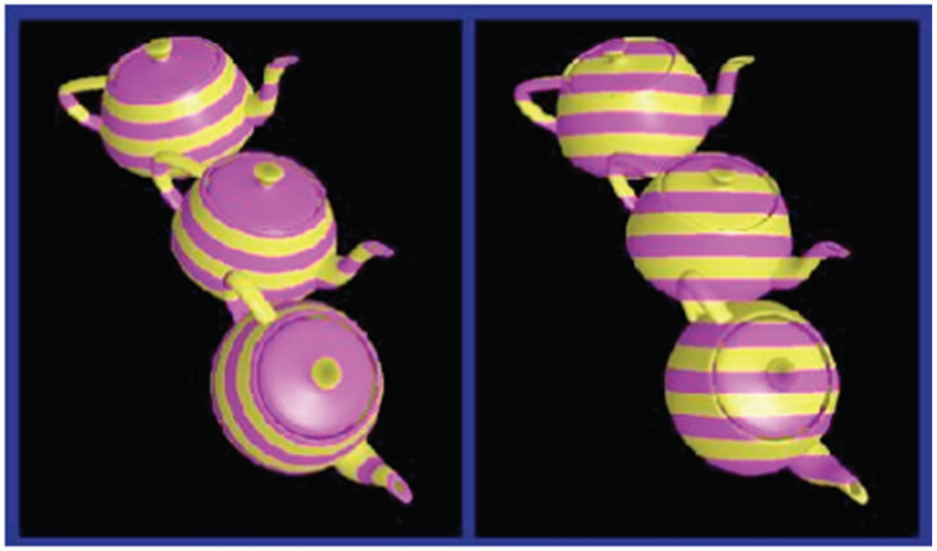


Mapping result

Orthographic Mapping

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

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



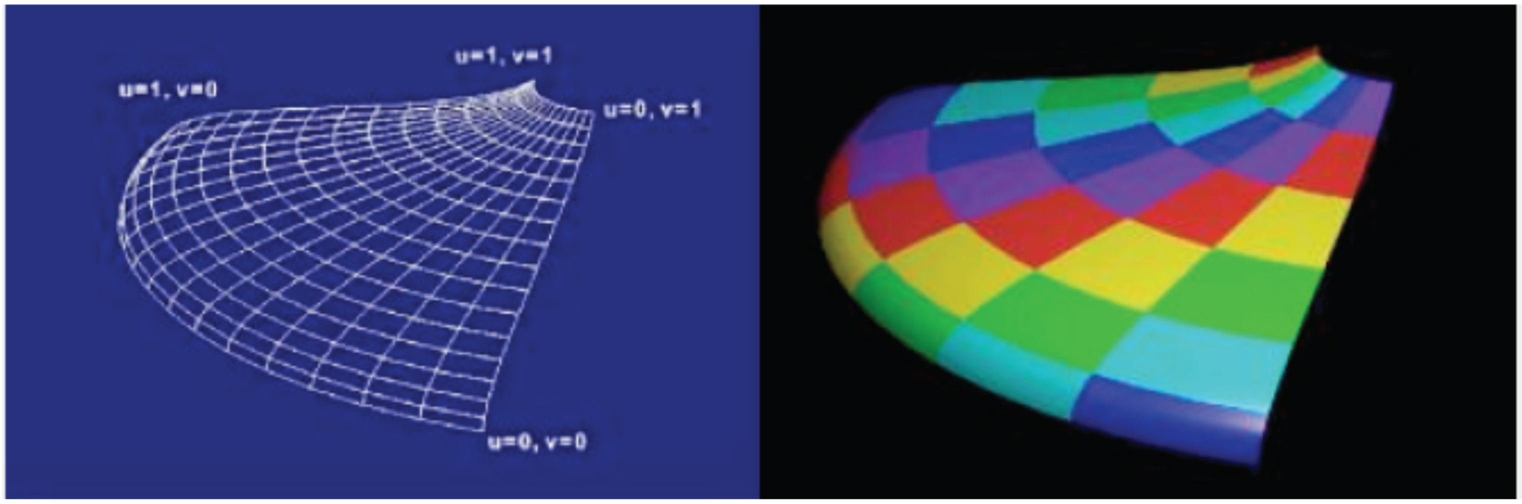
xyz in object space *xyz in camera space*

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)

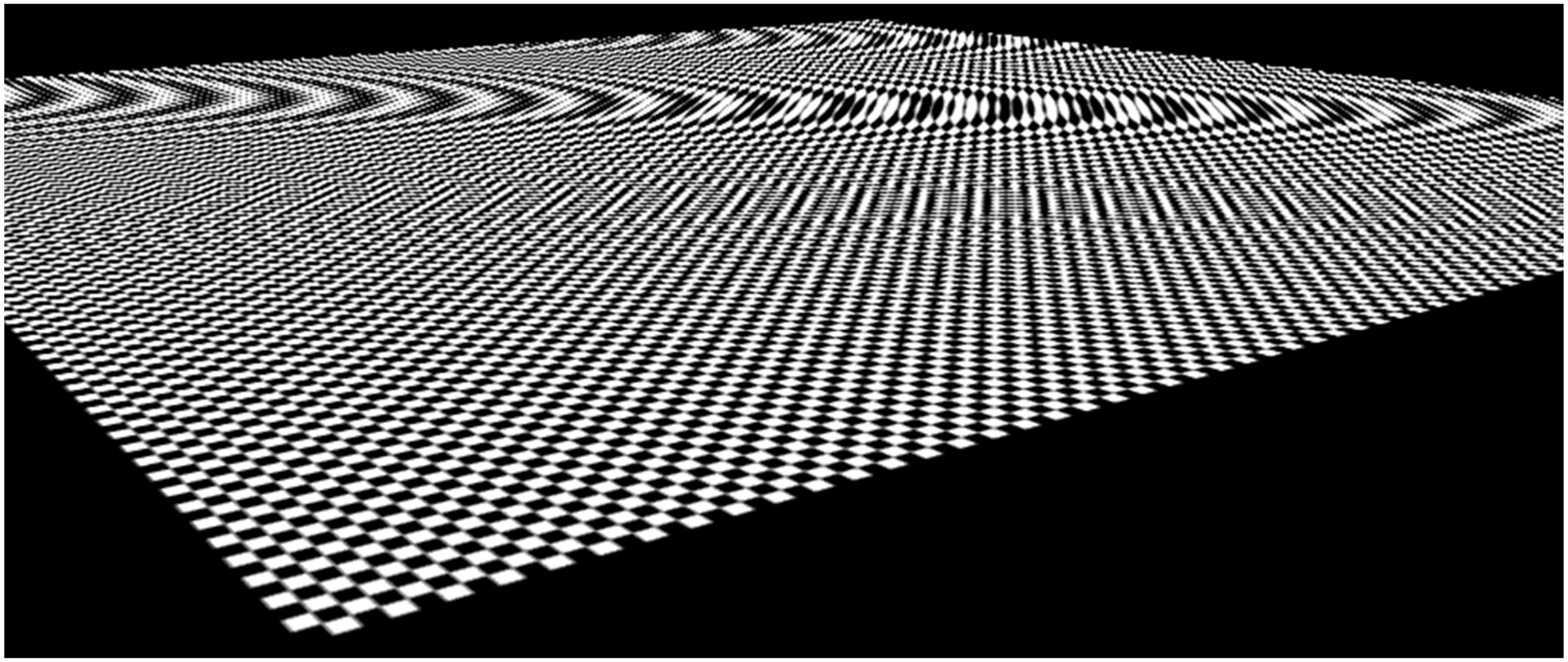


Lecture Overview

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

Aliasing

- What could cause this aliasing effect?



Aliasing

Sufficiently sampled, no aliasing

Insufficiently sampled, aliasing

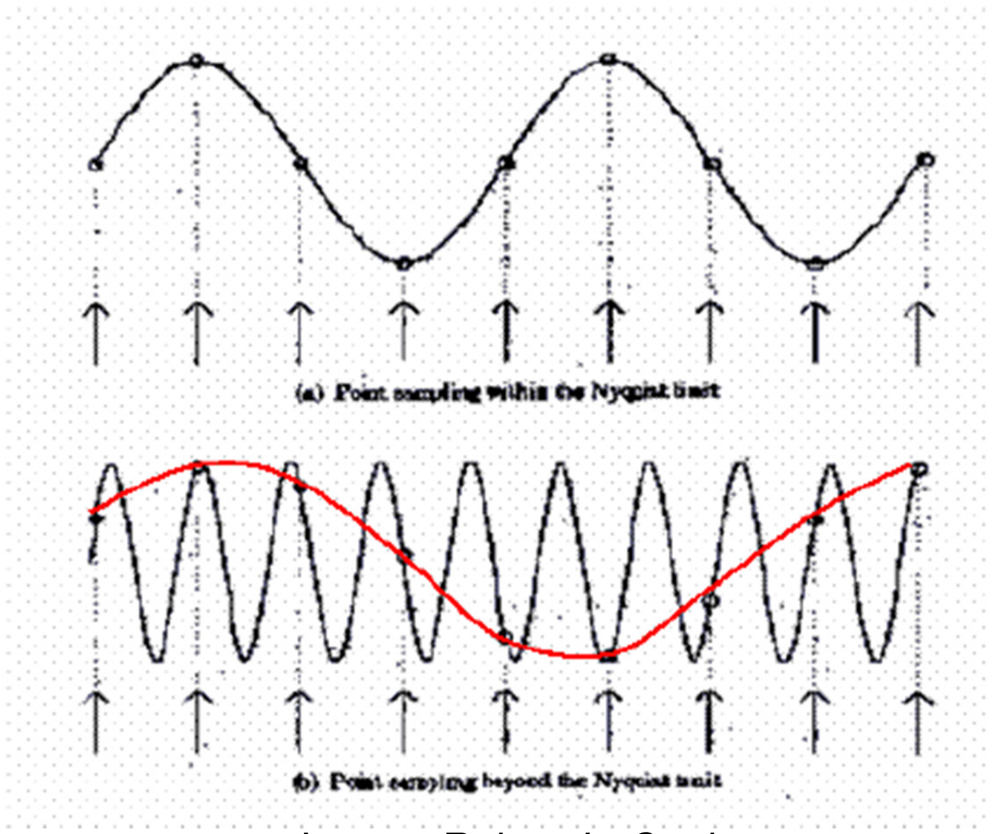
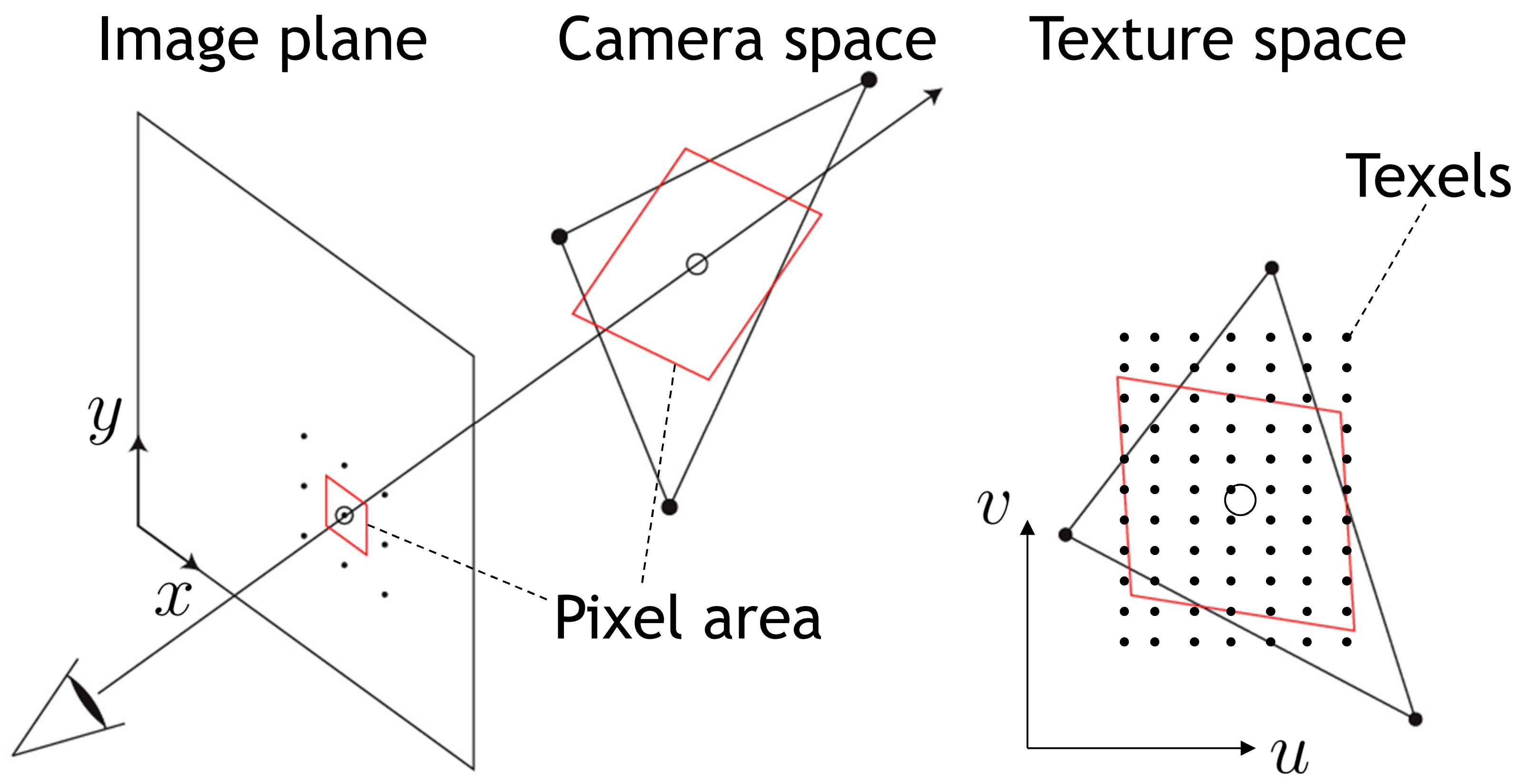

(a) Point sampling within the Nyquist limit
(b) Point sampling beyond the Nyquist limit

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



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

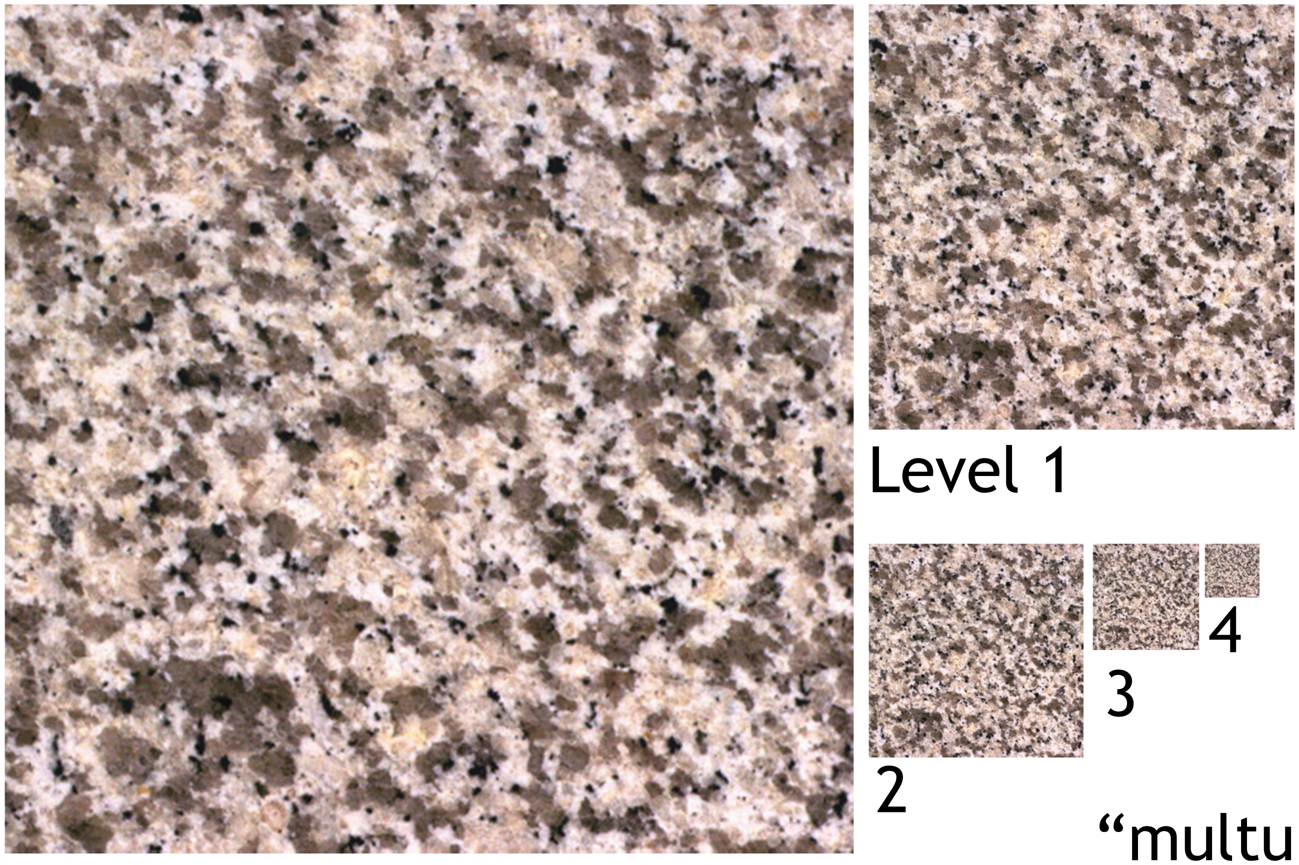
- MIP stands for *multum in parvo* = *"much in little"* (Williams 1983)

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 = 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

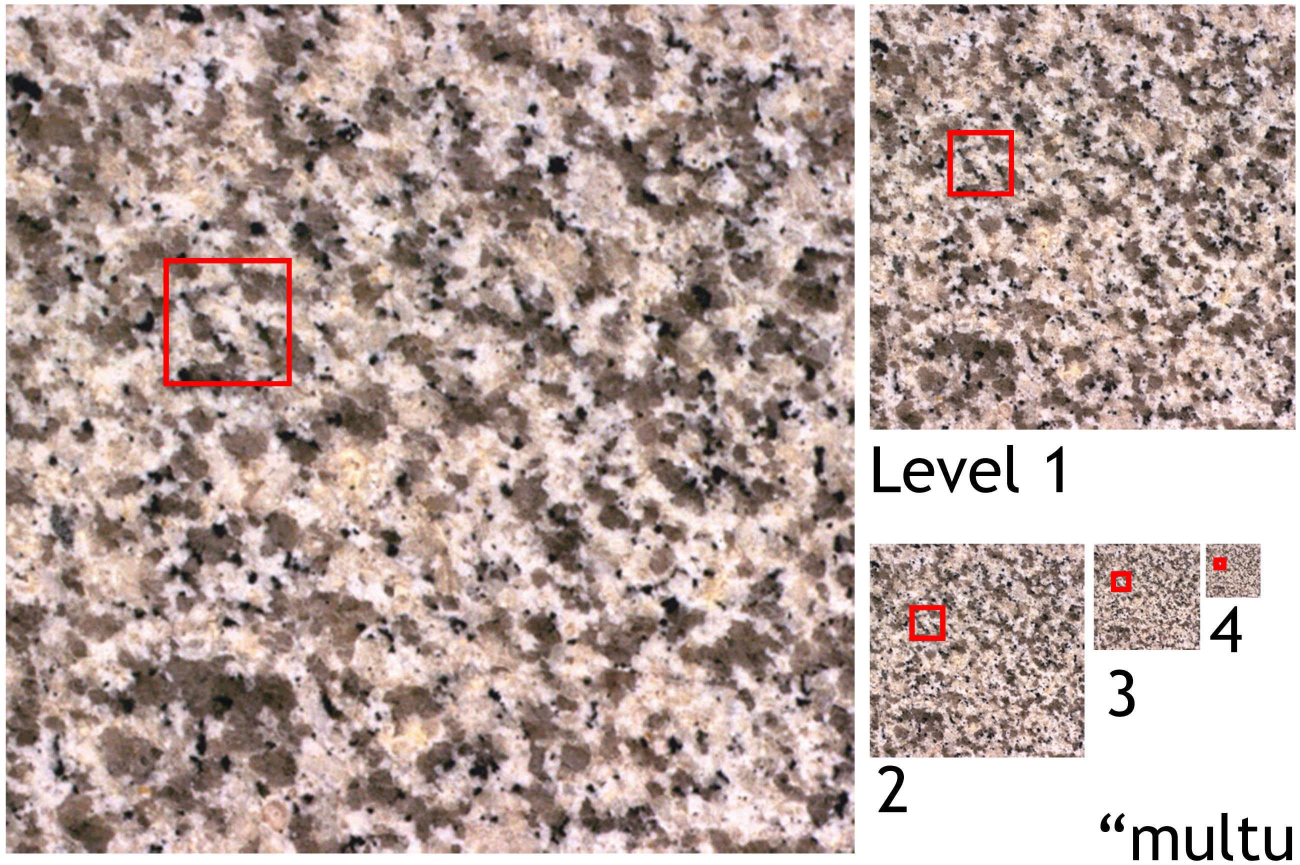
- Example: resolutions 512x512, 256x256, 128x128, 64x64, 32x32 pixels



“multum in parvo”

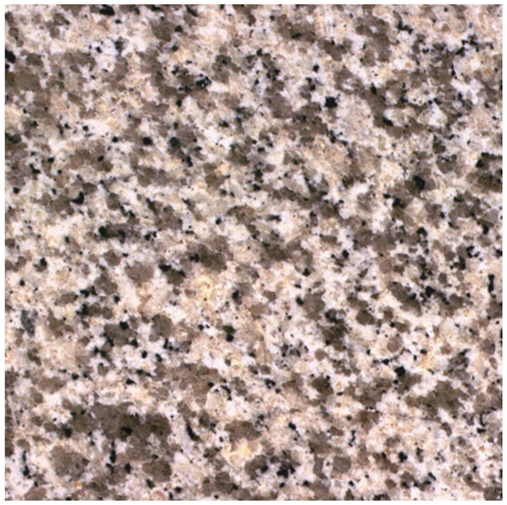
Mipmaps

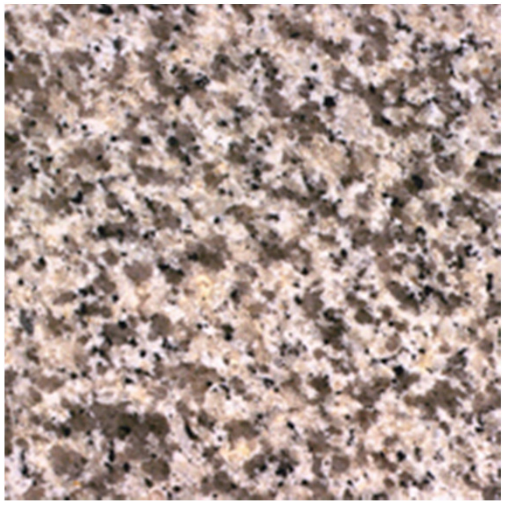
- One texel in level 4 is the average of $4^4=256$ texels in level 0

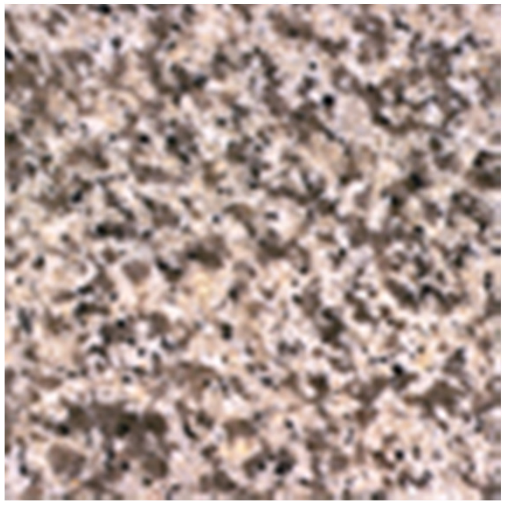


“multum in parvo”

Mipmaps


Level 0


Level 1


Level 2

Level 3

Level 4

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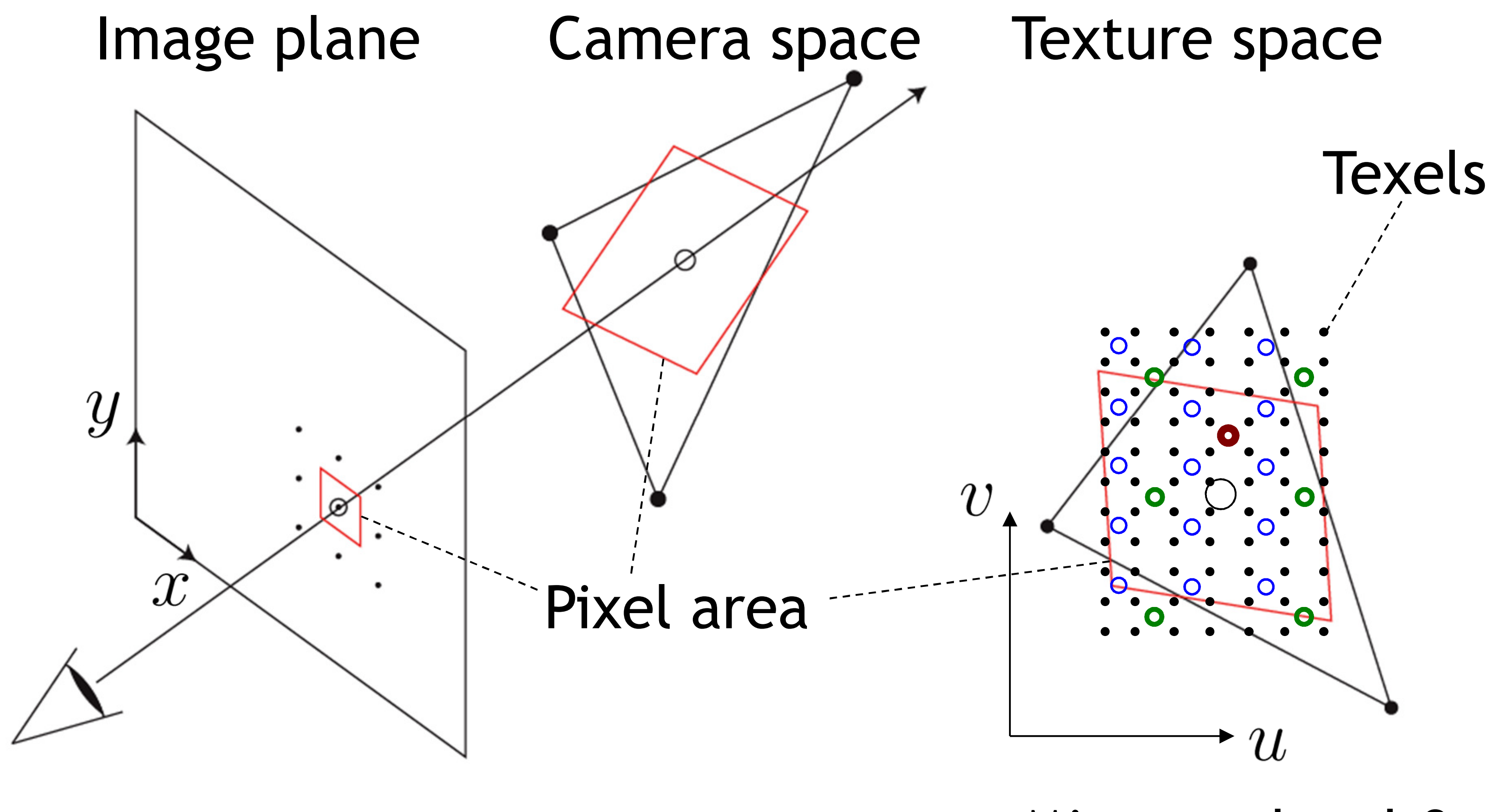
Rendering With Mipmaps

- "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

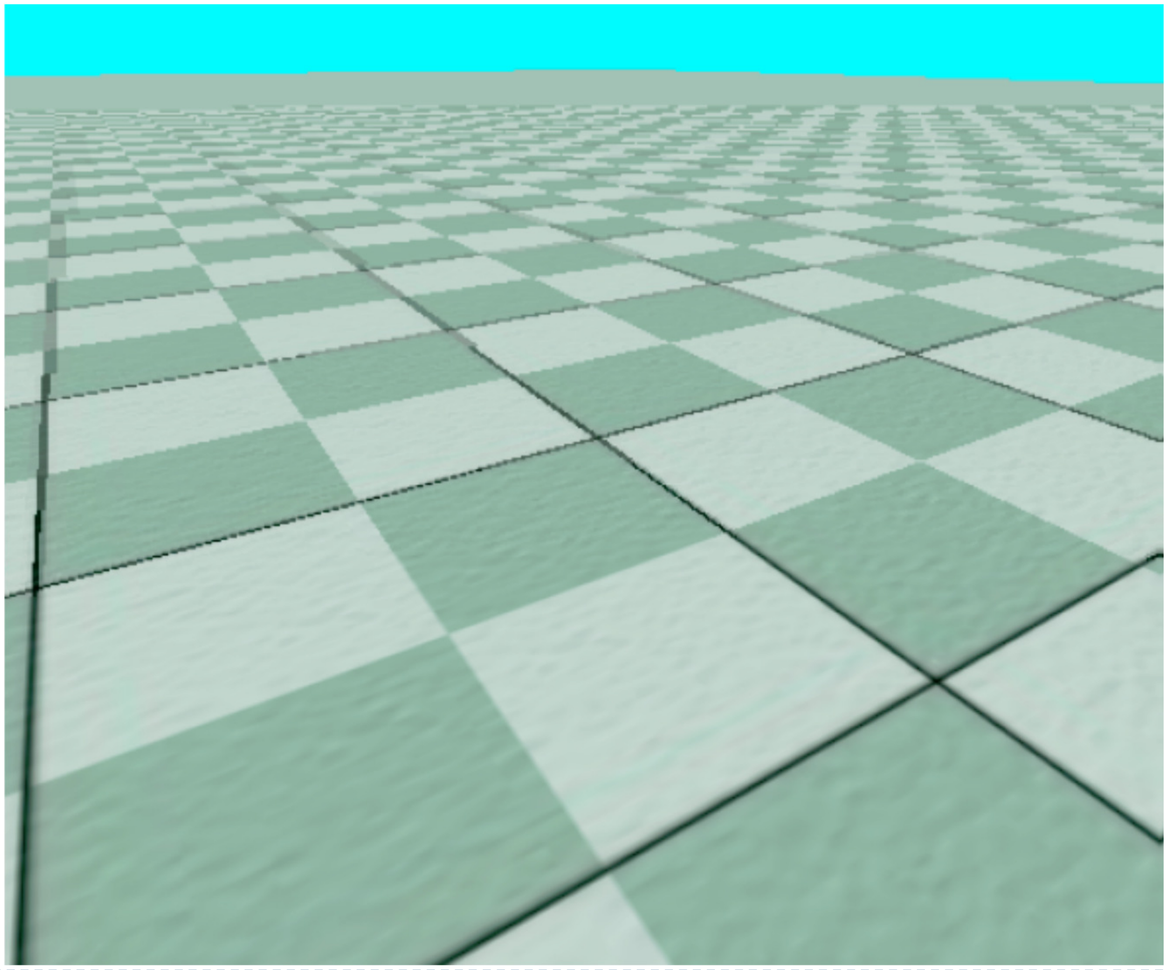
Mipmapping



- · Mip-map level 0
- ○ Mip-map level 1
- ○ Mip-map level 2
- ● Mip-map level 3

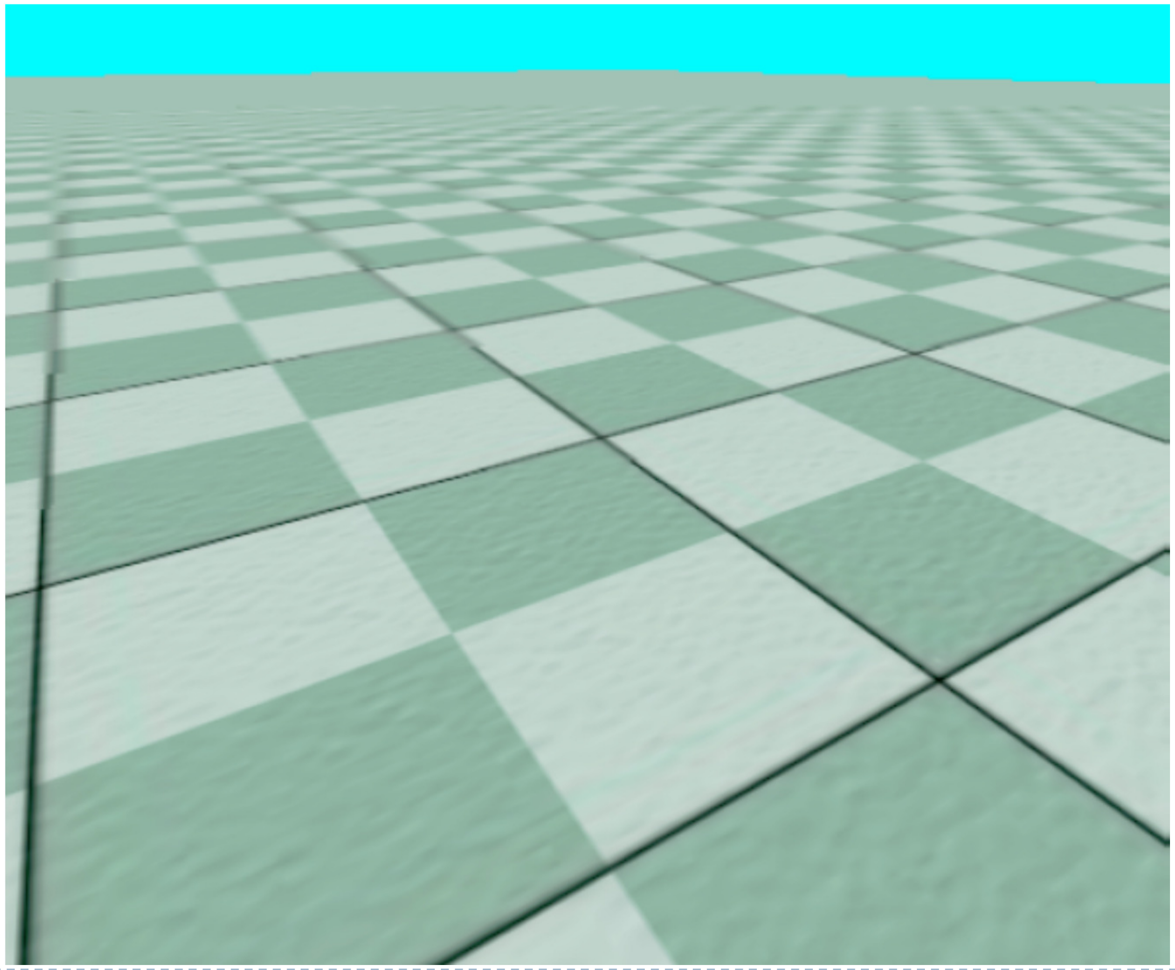
Nearest Mipmap, Nearest Neighbor

- 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

More Info

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