CSE160 – Oct 29 - Textures

- What are textures for?
- UV Coordinates
- Where do UV come from?
- Texture sampling NOT 1:1
- Magnification
- Minification
- Mipmapping
- Anisotropic Texturing
- OpenGL Texture
- Beyond 2D Colored Surfaces
- Administrative
- Q&A

Blocky Animal Contest

What are textures for?

Texture mapping

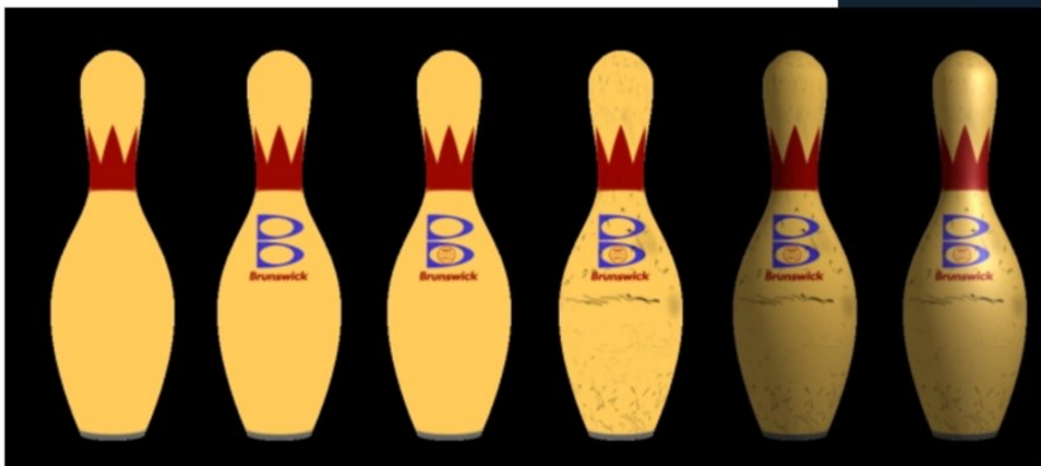
Many uses of texture mapping

Define variation in surface reflectance

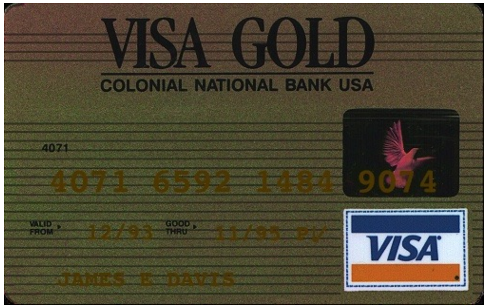
Pattern on ball

Wood grain on floor

Describe surface material properties



Multiple layers of texture maps for color, logos, scratches, etc.



4071 6592 1484 9074
12/93 11/95 P/
JAMES E DAVIS

4071 6592 1484 [redacted]
12/93 11/95 P/
JAMES E DAVIS

CS348B -1993
Student: James Davis

Represent precomputed lighting and shadows

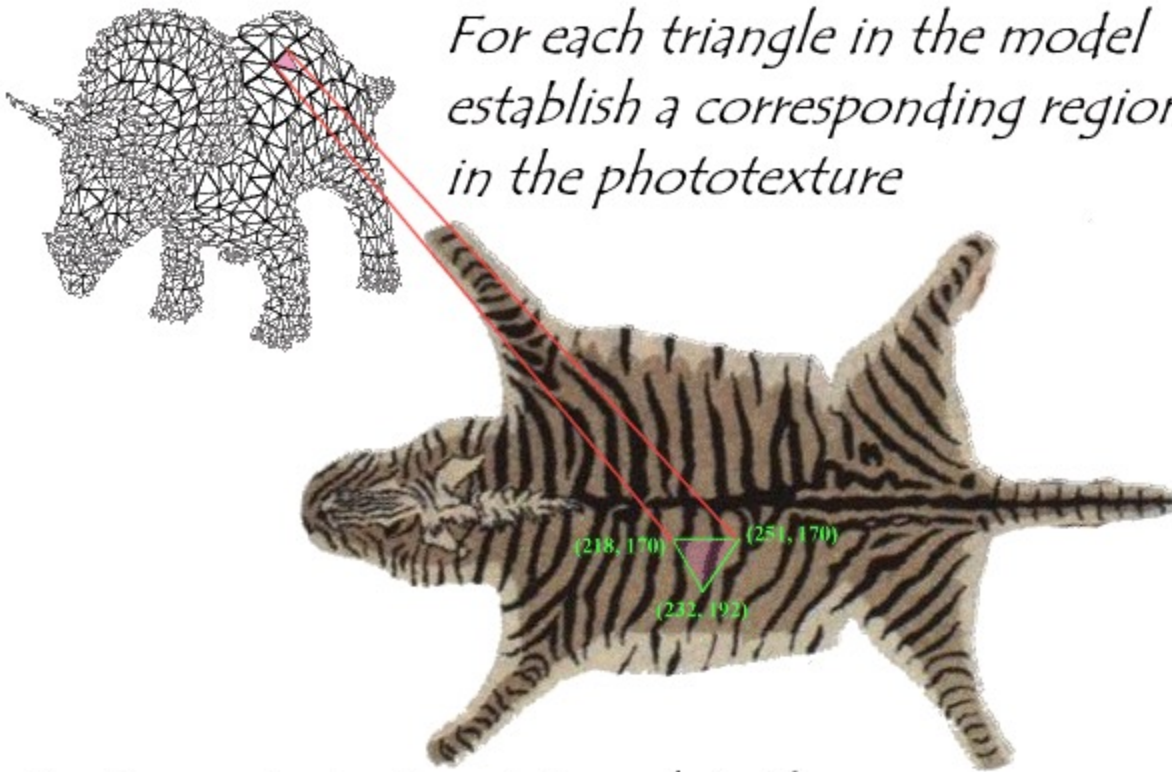
Original model   With ambient occlusion   Extracted ambient occlusion map

Grace Cathedral environment map

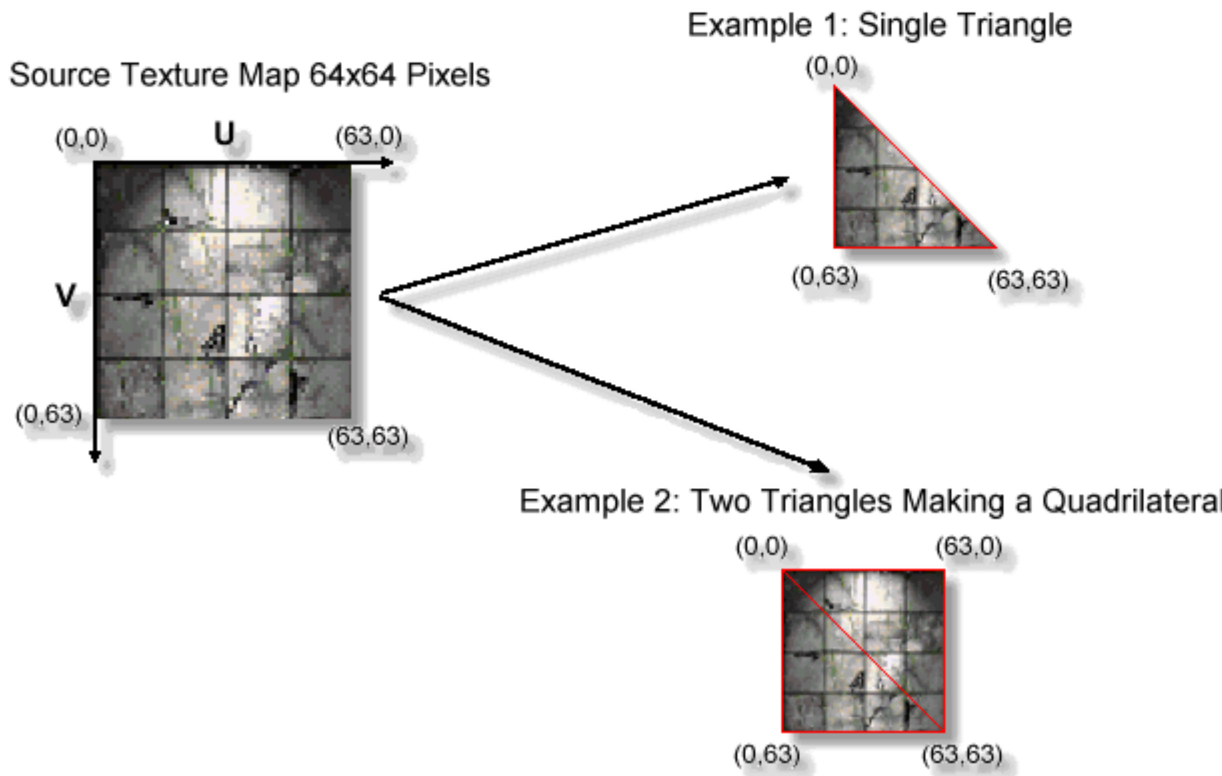
Environment map used in rendering

UV Coordinates

For each triangle in the model establish a corresponding region in the phototexture

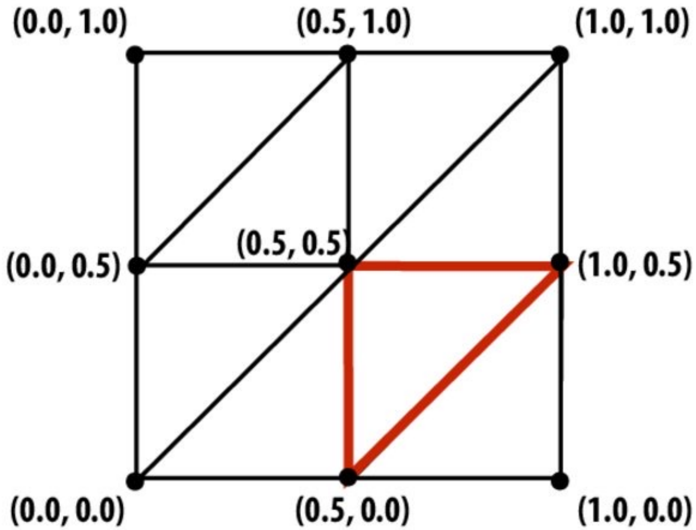


During rasterization interpolate the coordinate indices into the texture map

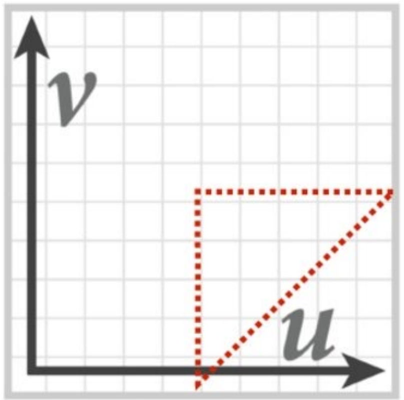

Source Texture Map 64x64 Pixels
(0,0)
U
(63,0)
V
(0,63)
(63,63)
Example 1: Single Triangle
(0,0)
(0,63)
(63,63)
Example 2: Two Triangles Making a Quadrilateral
(0,0)
(63,0)
(0,63)
(63,63)

Texture coordinates

"Texture coordinates" define a mapping from surface coordinates (points on triangle) to points in texture domain.

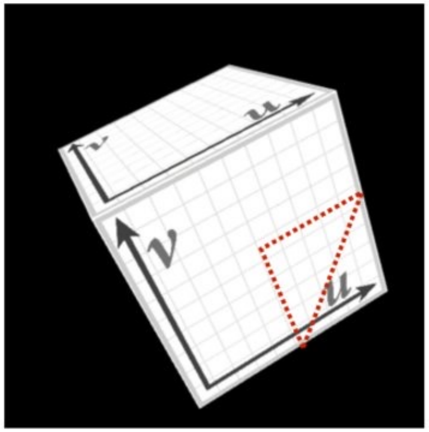


Eight triangles (one face of cube) with surface parameterization provided as per-vertex texture coordinates.



`myTex(u,v)` is a function defined on the $[0,1]^2$ domain (represented by 2048x2048 image)

Location of highlighted triangle in texture space shown in red.



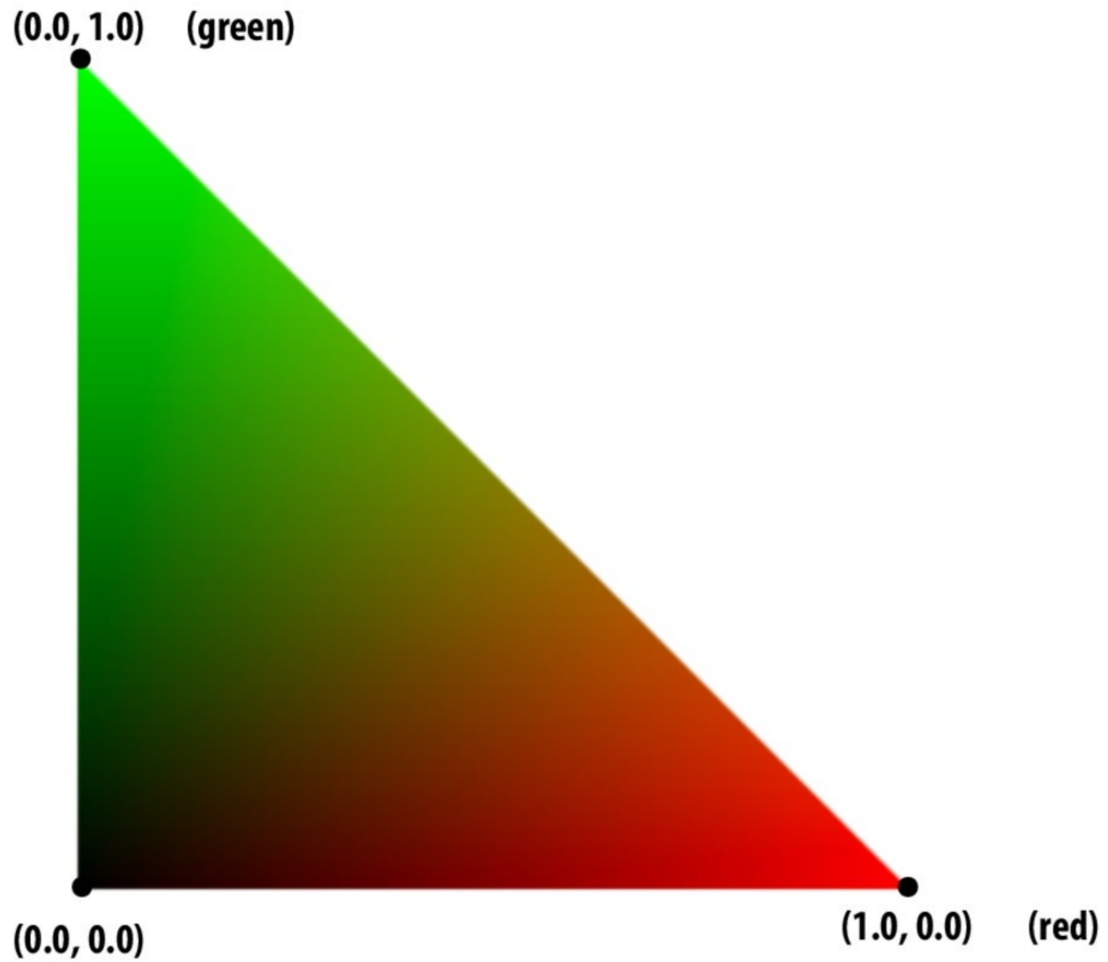
Final rendered result (entire cube shown).

Location of triangle after projection onto screen shown in red.

Today we'll assume surface-to-texture space mapping is provided as per vertex attribute
(Not discussing methods for generating surface texture parameterizations)

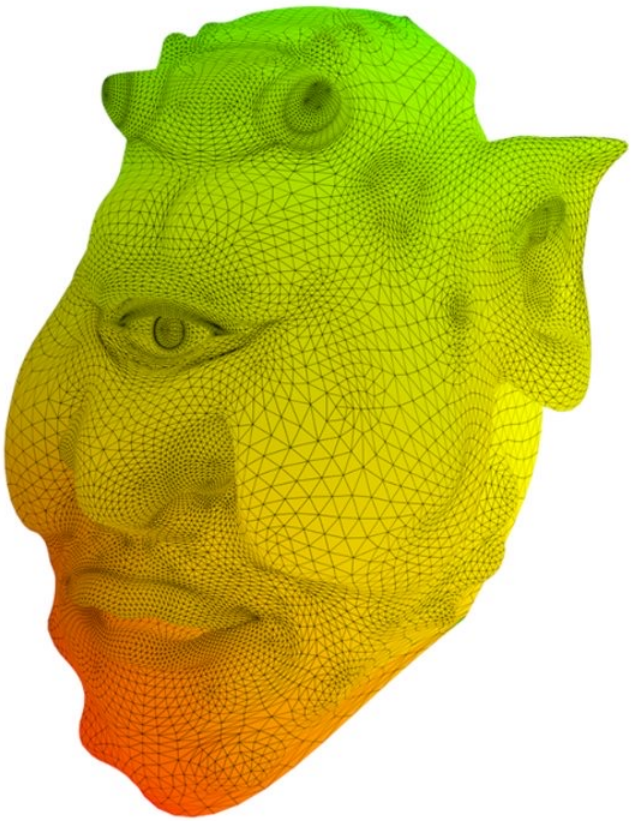
Visualization of texture coordinates

Texture coordinates linearly interpolated over triangle

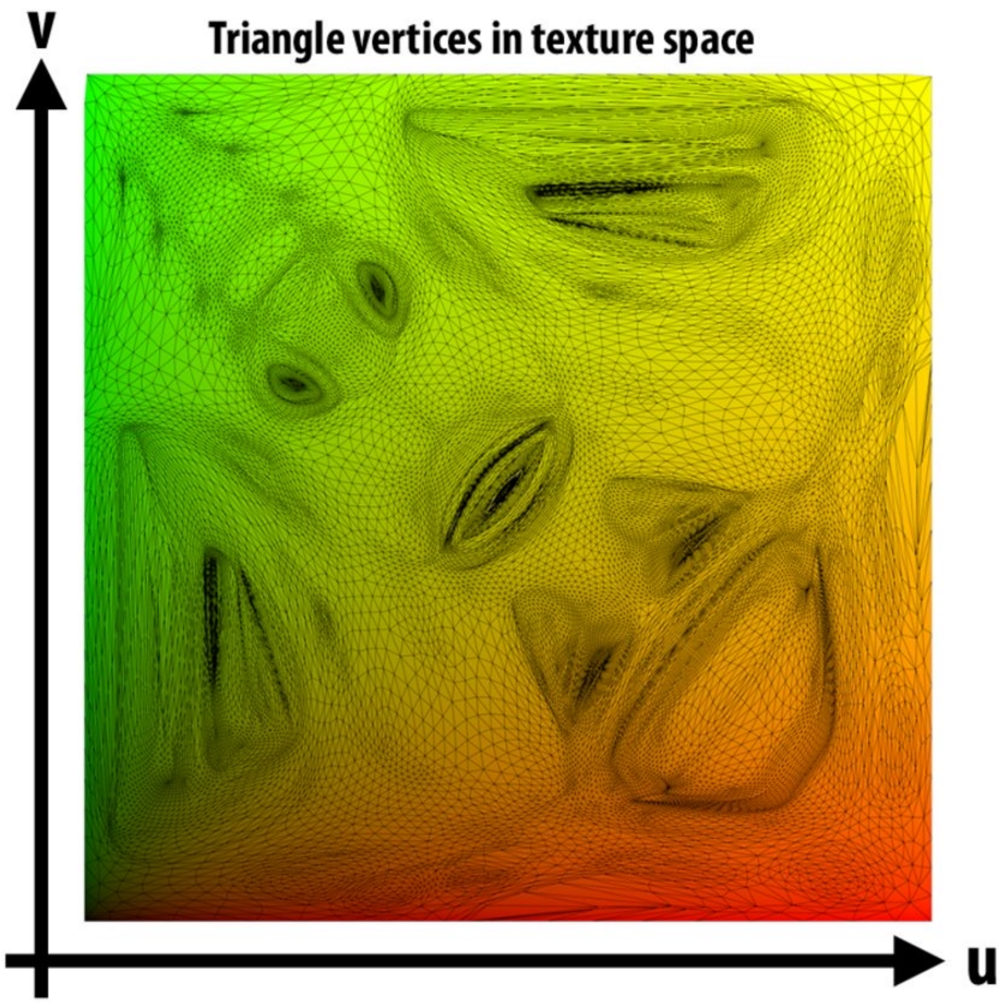


More complex mapping

Visualization of texture coordinates



Triangle vertices in texture space

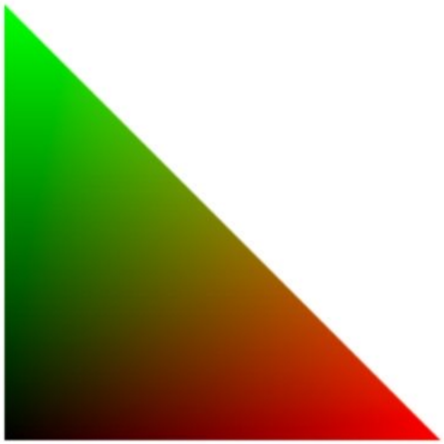


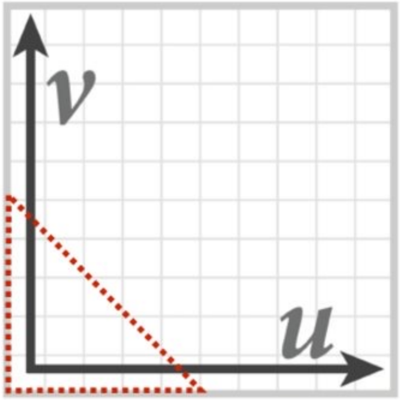
Each vertex has a coordinate (u,v) in texture space.

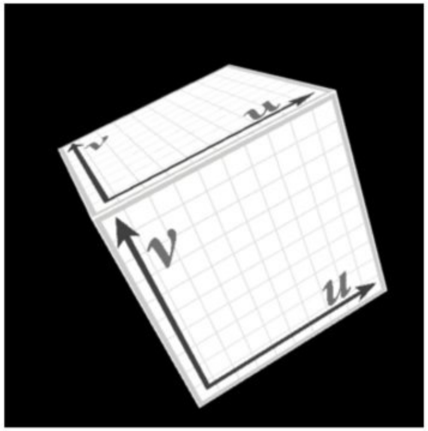
(Actually coming up with these coordinates is another story!)

Texture sampling 101

- Basic algorithm for mapping texture to surface:
  - For each color sample location (X,Y)
    - Interpolate U and V coordinates across triangle to get value at (X,Y)
    - Sample (evaluate) texture at (U,V)
    - Set color of fragment to sampled texture value

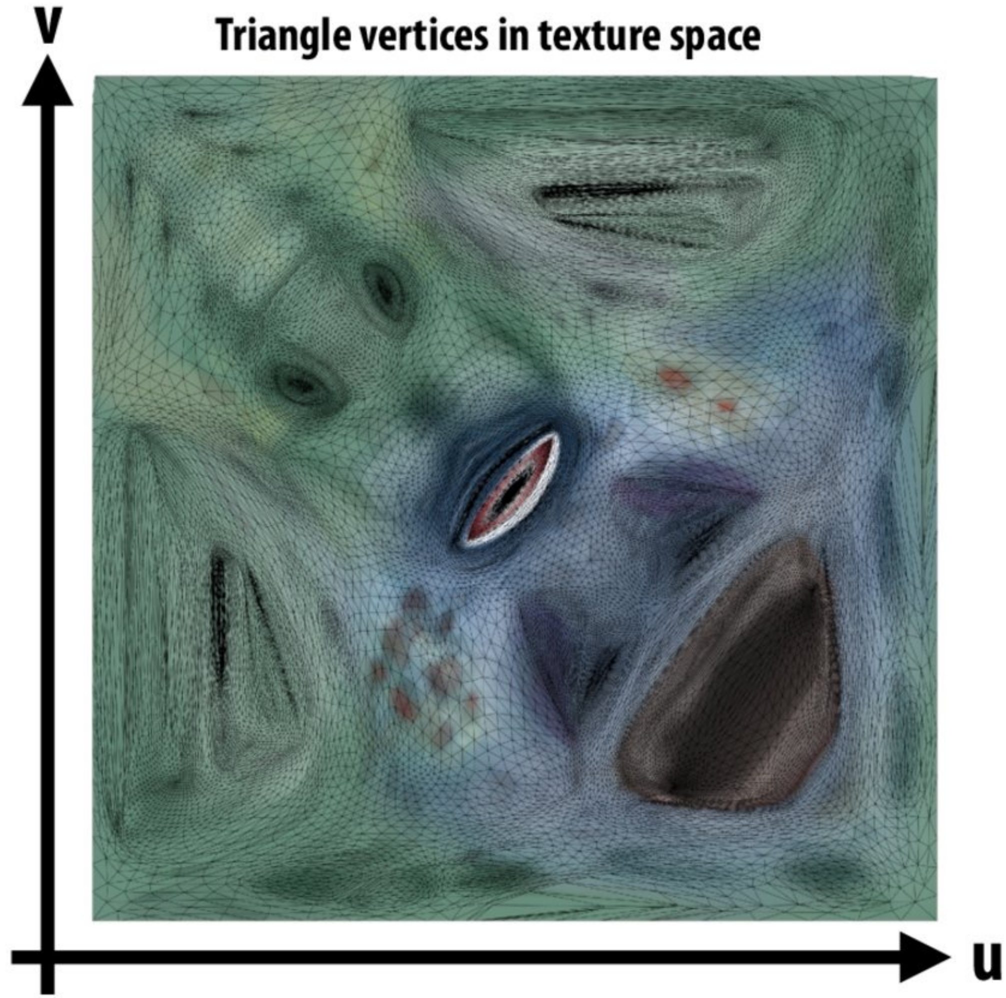






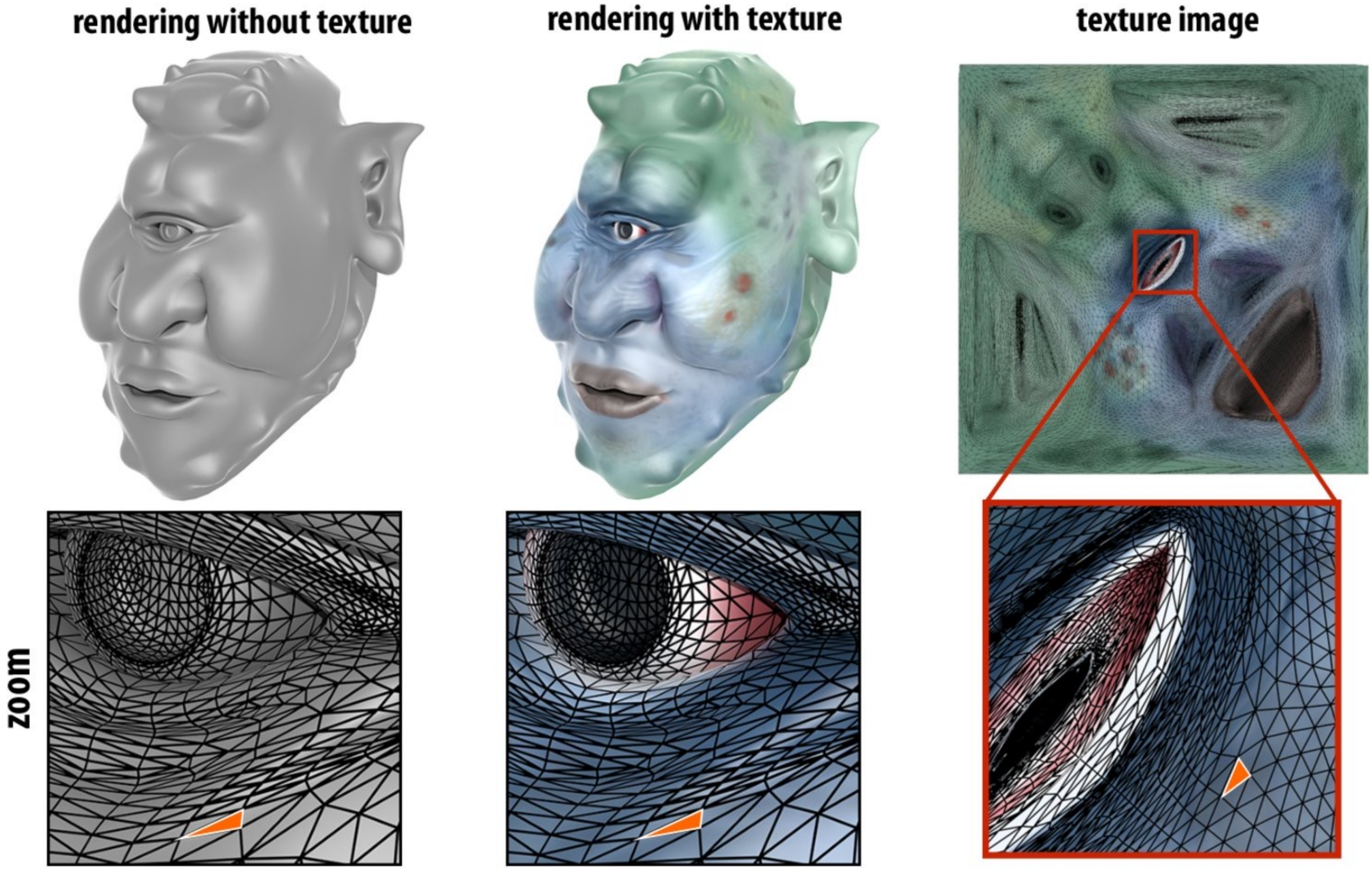
Texture mapping adds detail

Rendered result



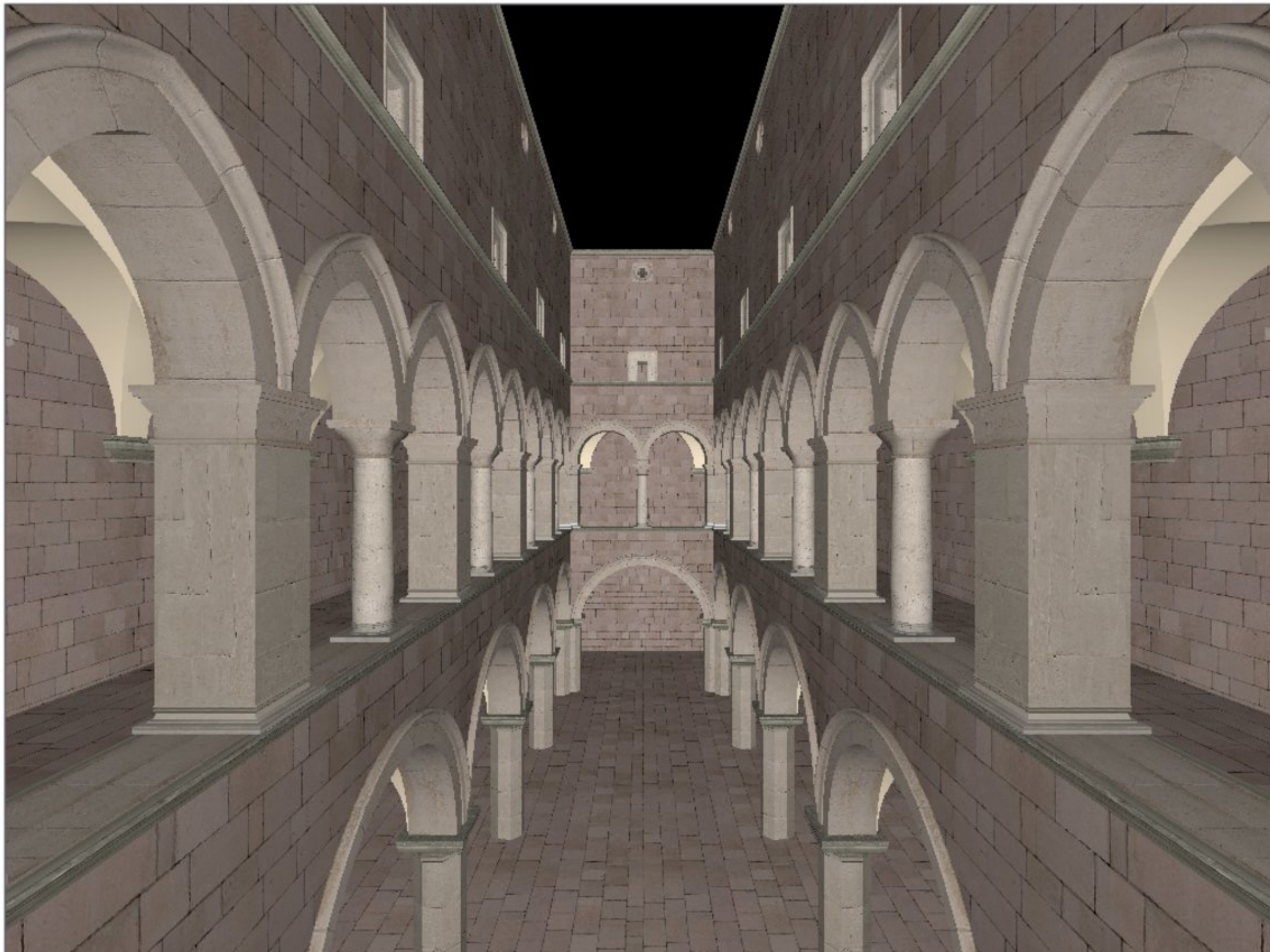
Triangle vertices in texture space

Texture mapping adds detail

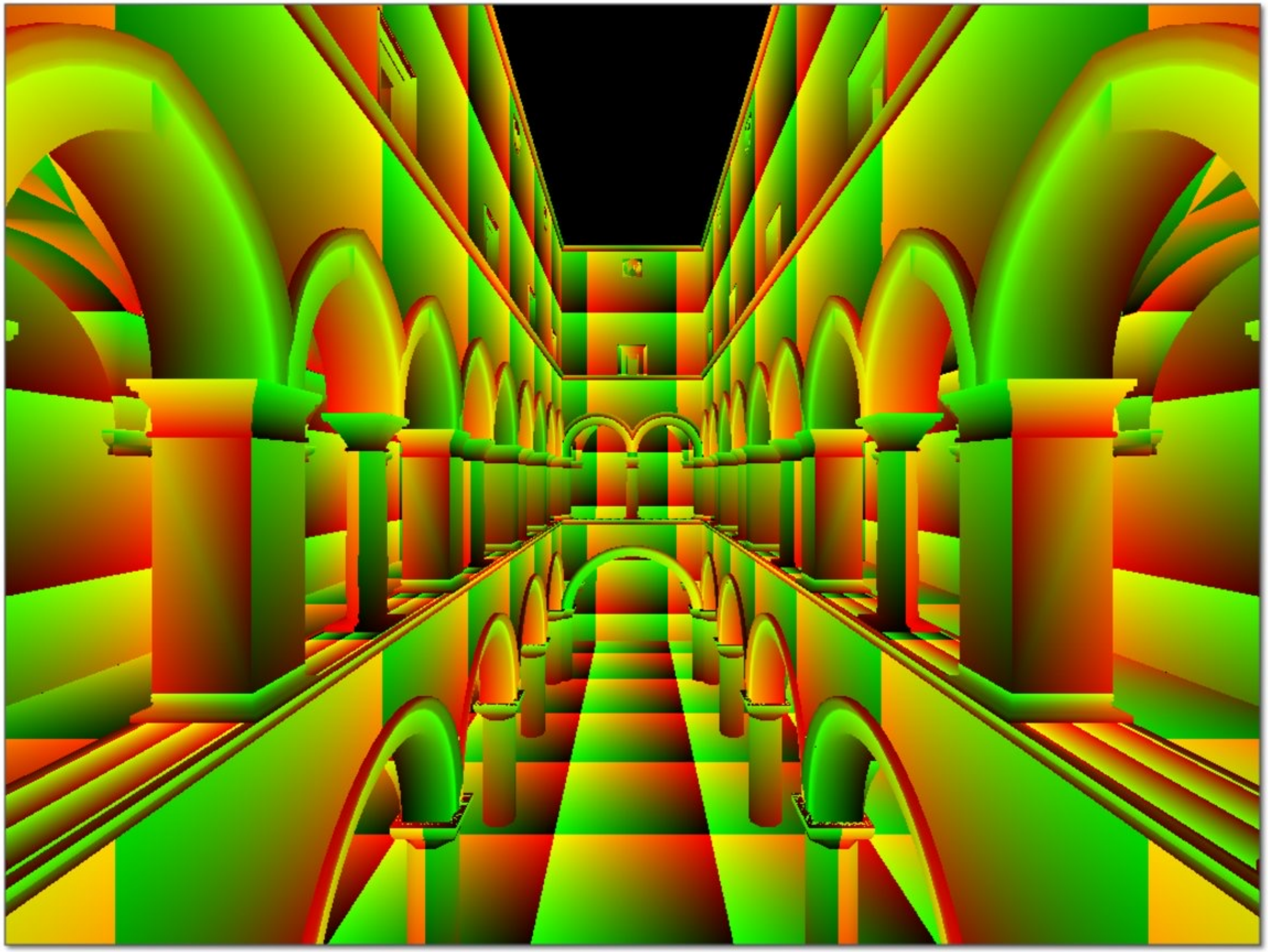


Each triangle “copies” a piece of the image back to the surface.

Textured Sponza

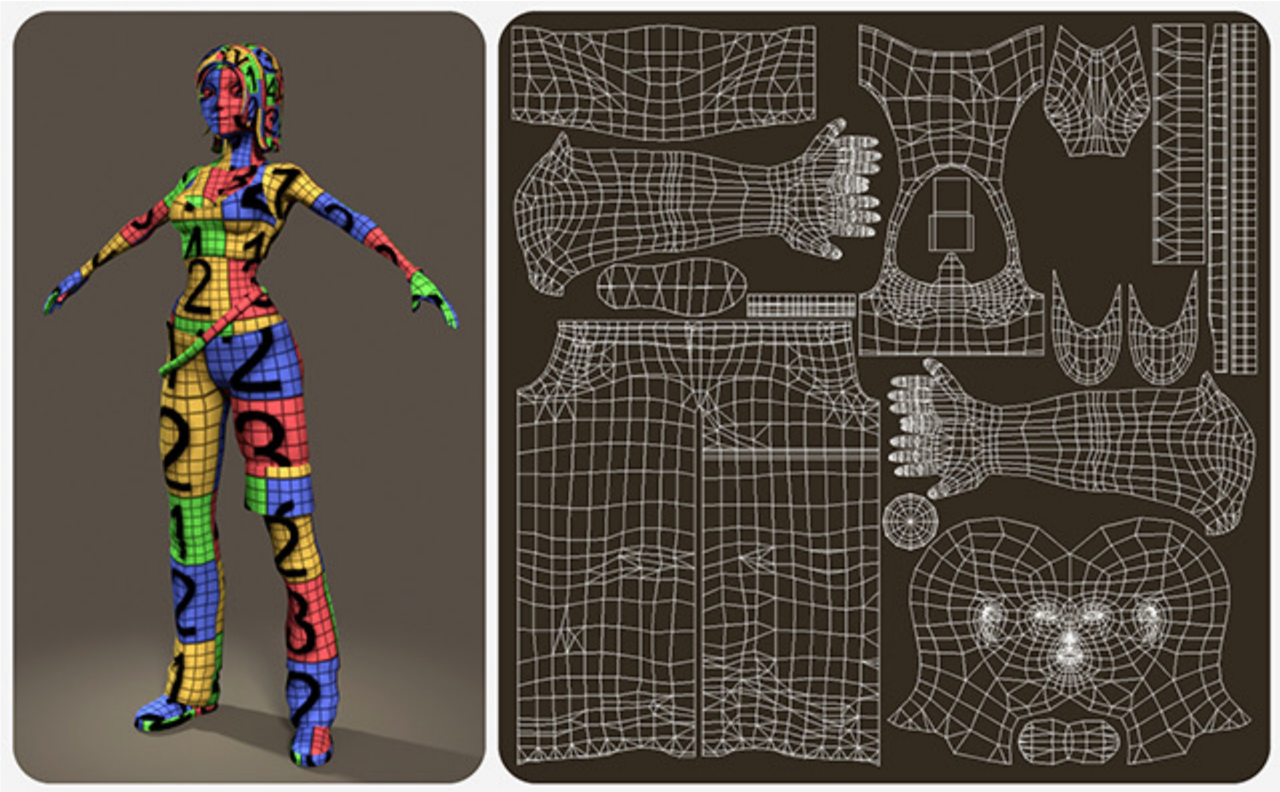


Another example: Sponza



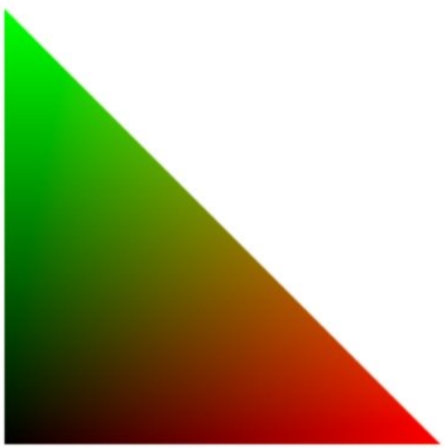
Notice texture coordinates repeat over surface.

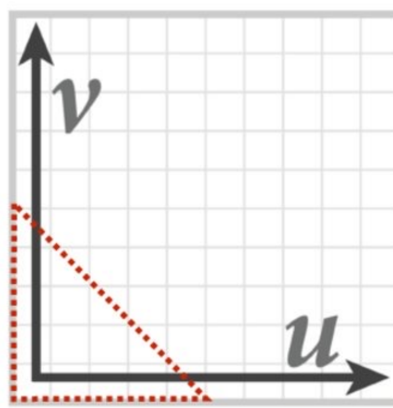
Debugging – Get an easy to understand texture

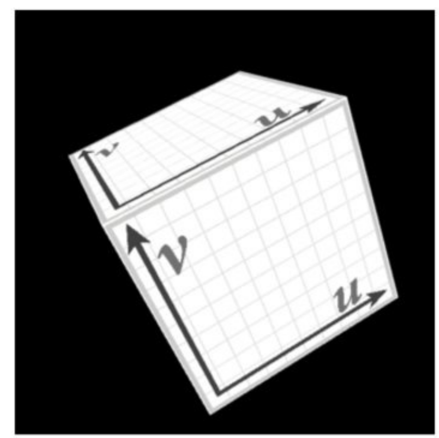


Summary

- Basic algorithm for mapping texture to surface:
  - For each color sample location (X,Y)
    - Interpolate U and V coordinates across triangle to get value at (X,Y)
    - Sample (evaluate) texture at (U,V)
    - Set color of fragment to sampled texture value







...sadly not this easy in general!

Texture

(0,1) (1,1)

(0,0) (1,0)

Which polygon below is textured correctly?

X,Y=(0,1) U,V=(0,0) X,Y=(1,1) U,V=(1,0)

X,Y=(0,0) U,V=(0,1) X,Y=(1,0) U,V=(1,1)

(A)

X,Y=(0,1) U,V=(0,0) X,Y=(1,1) U,V=(1,0)

X,Y=(0,0) U,V=(0,1) X,Y=(1,0) U,V=(1,1)

(B)

X,Y=(0,1) U,V=(0,0) X,Y=(1,1) U,V=(1,0)

X,Y=(0,0) U,V=(0,1) X,Y=(1,0) U,V=(1,1)

(C)

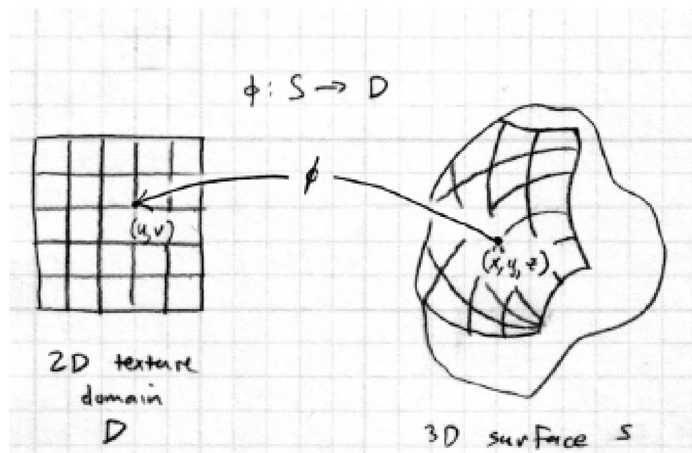
Where do UV come from?

Texture coordinate functions

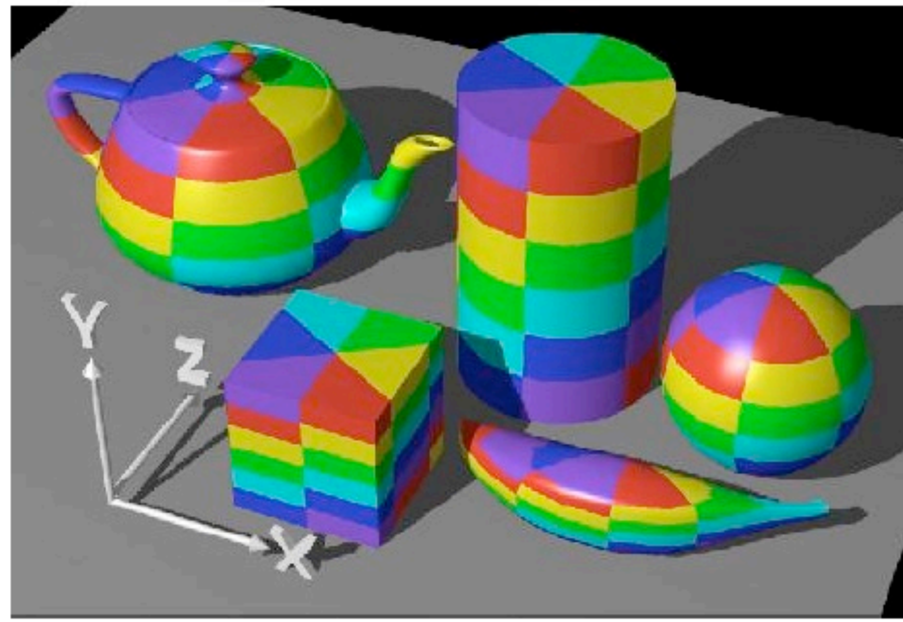
- Non-parametrically defined surfaces: more to do
  - can't assign texture coordinates as we generate the surface
  - need to have the *inverse* of the function *f*
- Texture coordinate fn.

  $\phi : S \to \mathbb{R}^2$

  - for a vtx. at **p** get texture at f (**p**)



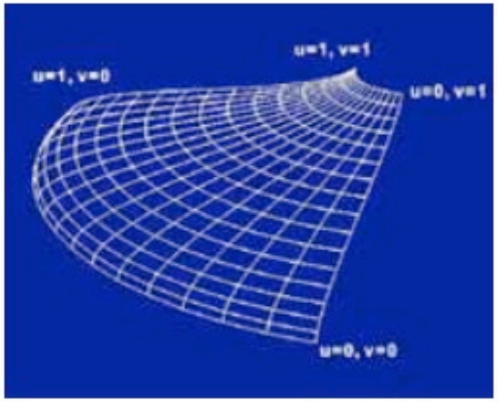
Cylindrical Parameterization

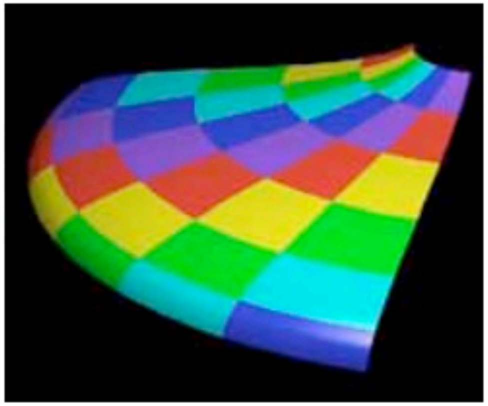


$$f : (x, y, z) \rightarrow (r, \theta, h) \rightarrow (u_\theta, v_h)$$

Examples of coordinate functions

- A parametric surface (e.g. spline patch)
  - surface parameterization gives mapping function directly (well, the inverse of the parameterization)



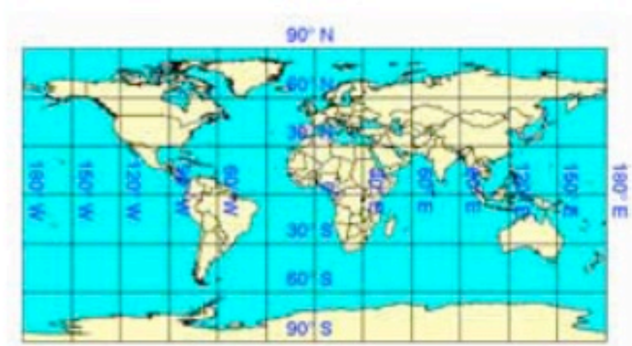


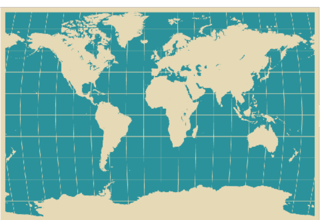
[Wolfe / SG97 Slide set]

Examples of coordinate functions

- For a sphere: latitude-longitude coordinates
  - f maps point to its latitude and longitude

[map: Peter H. Dana]






NORTH
NORTH-NORTHWEST
NORTH-NORTHEAST
NORTHWEST
NORTHEAST
WEST-NORTHWEST
EAST-NORTHEAST
WEST
EAST
WEST-SOUTHWEST
EAST-SOUTHEAST
SOUTHWEST
SOUTHEAST
SOUTH-SOUTHWEST
SOUTH-SOUTHEAST
SOUTH
Indian Ocean
Indian Ocean
EQUATOR
ASIA
MADAGASCAR
AFRICA
NORTH POLE
Arctic Ocean
North Atlantic Ocean
North Pacific Ocean
SAN FRANCISCO
NORTH AMERICA
South Atlantic Ocean
AUSTRALIA
SOUTH AMERICA
South Pacific Ocean
SOUTH POLE
ANTARCTICA
10,000 MILES
LEGEND
THE WORLD
Centered on the
SAN FRANCISCO

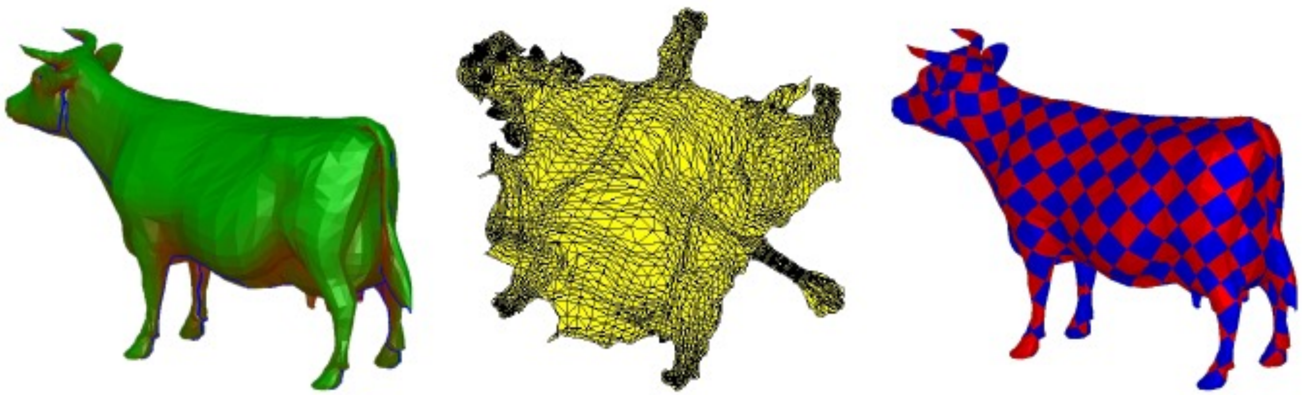
Parameterization

Parameterizing Polygonal Models

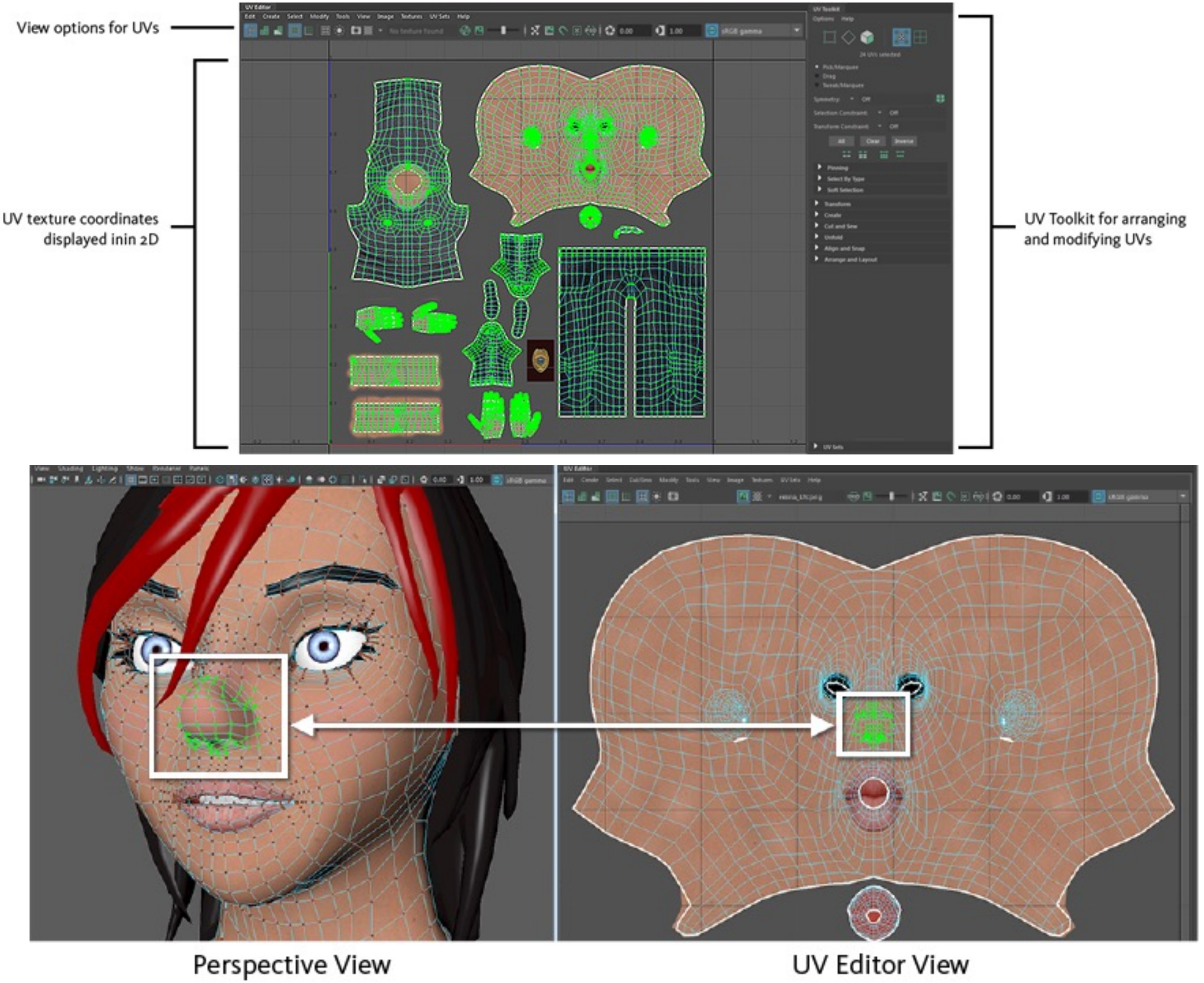
- Need mapping from vertices to **texels** (texture elements):

$$f : (x,y,z) \rightarrow (u,v)$$

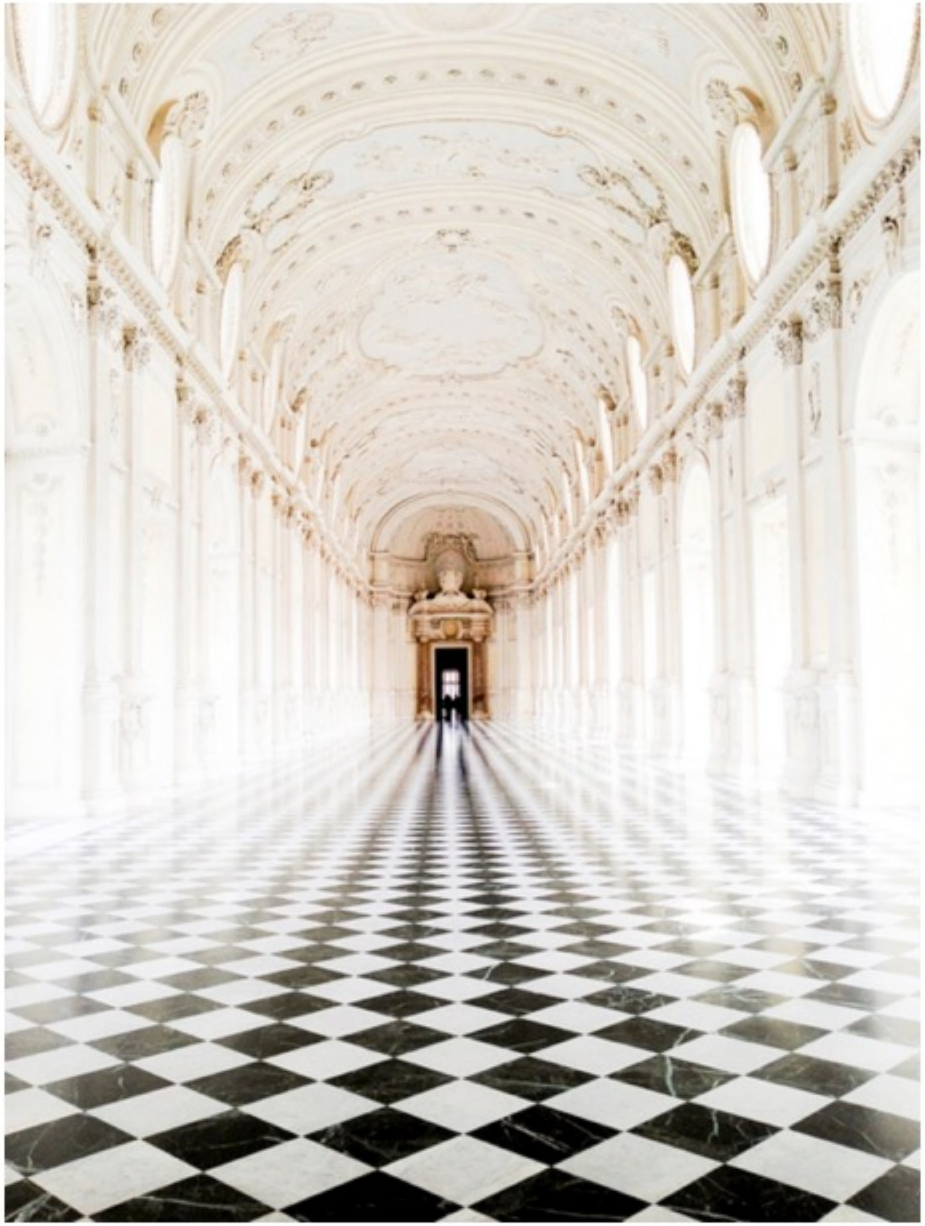
- Most 3D geometric models don't have natural 2D parameterizations
- Creating these parameterizations can be difficult:
  - Must avoid parameter-space distortion
  - Have to handle seams and cracks
  - Should minimize wasted texture memory
- Use natural projections (planar, spherical, cylindrical, etc.) when possible



UV Editor in artist tool (Maya)

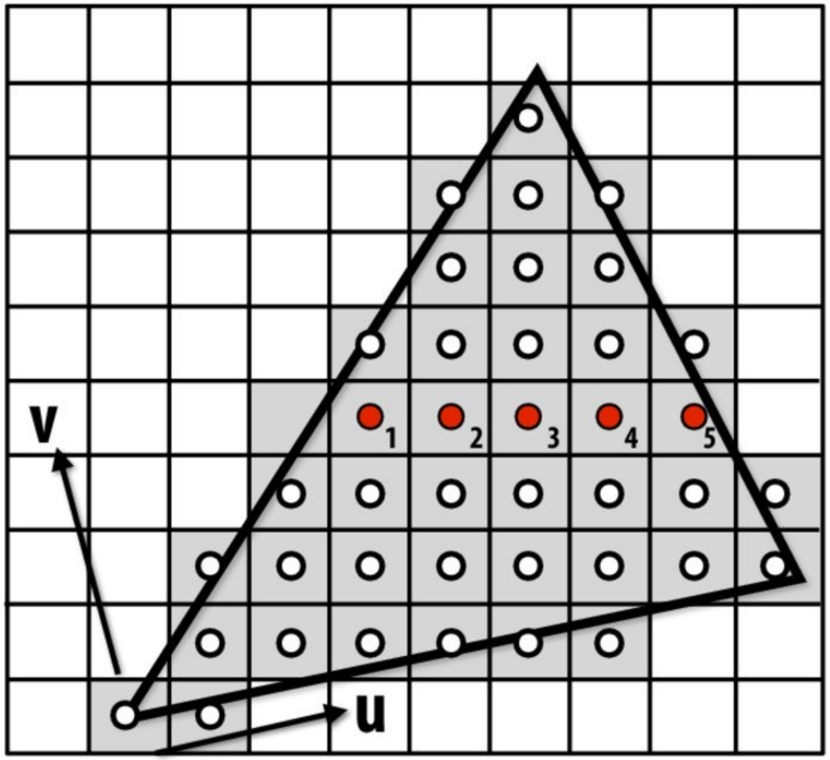


Texture sampling NOT 1:1



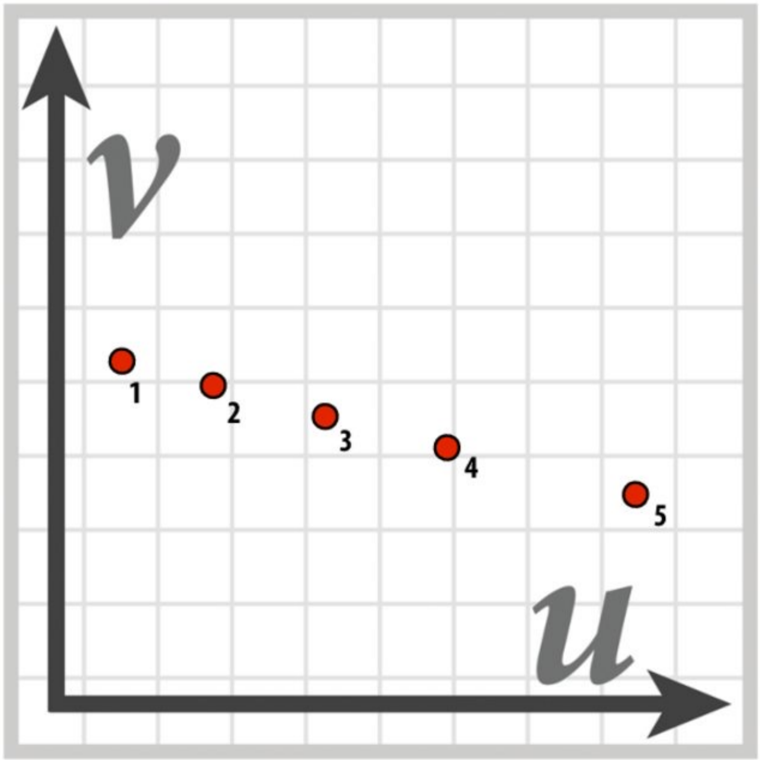
Texture space samples

Sample positions in XY screen space

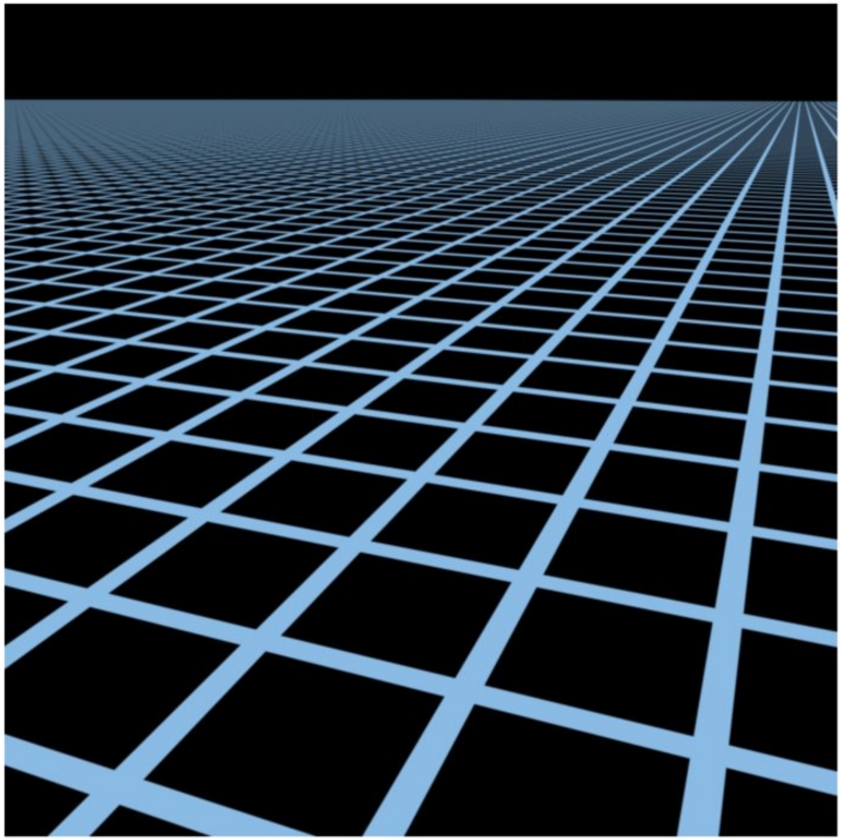


Sample positions are uniformly distributed in screen space (rasterizer samples triangle's appearance at these locations)

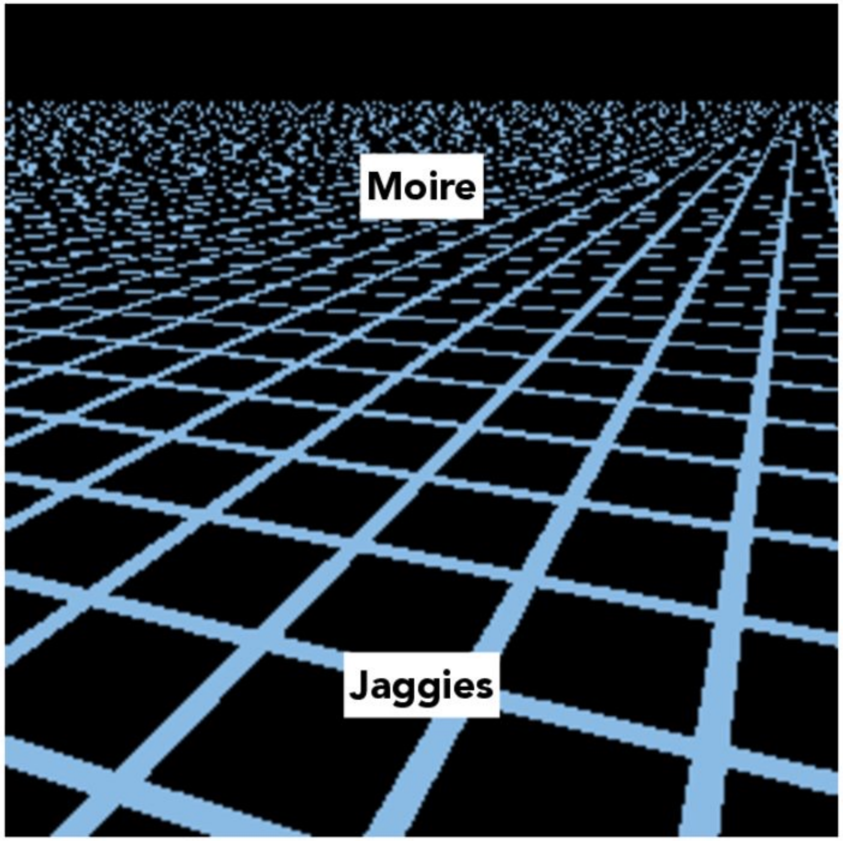
Sample positions in texture space



Texture sample positions in texture space (texture function is sampled at these locations)



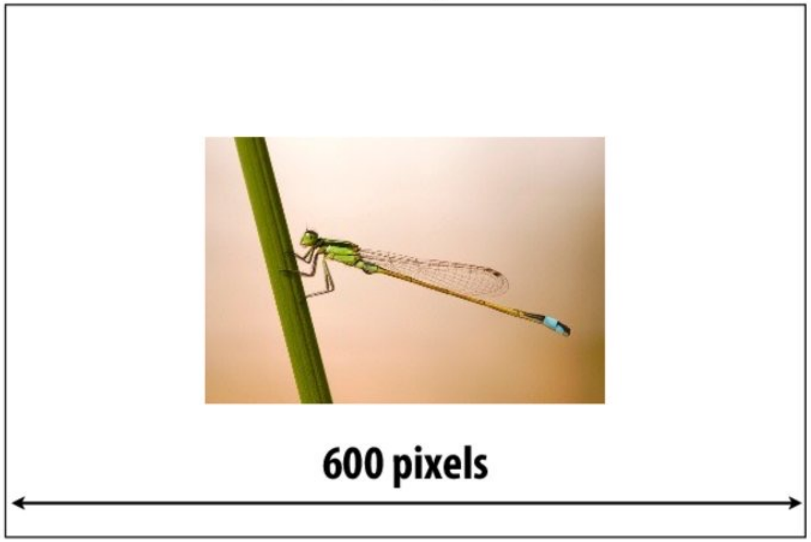
Source image: 1280x1280 pixels



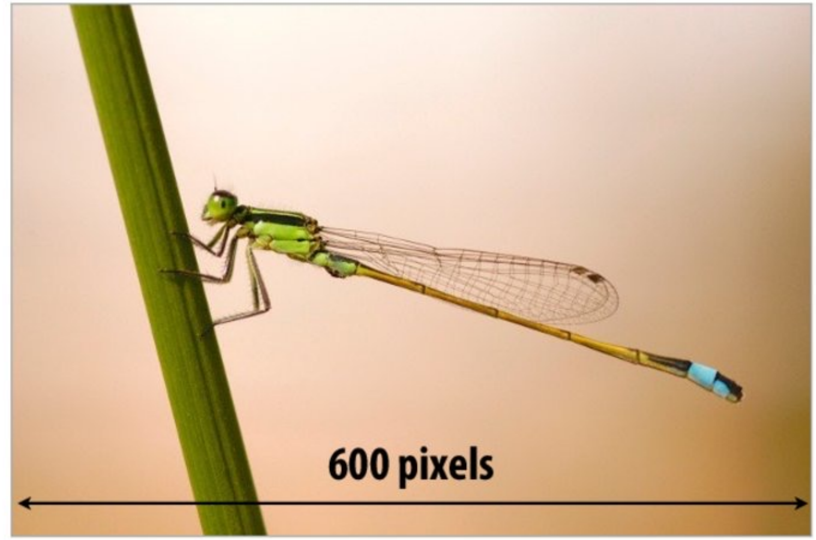
Rendered image: 256x256 pixels

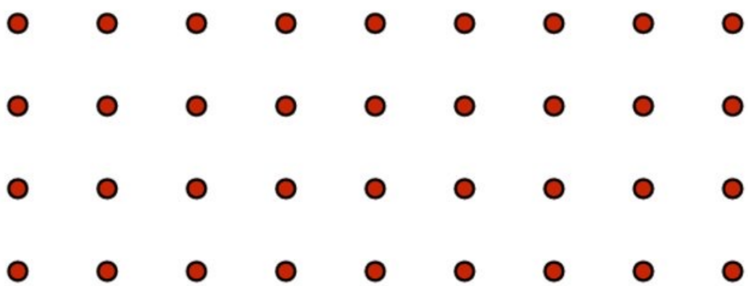
Sampling rate on screen vs texture

Rendered image (object zoomed out)

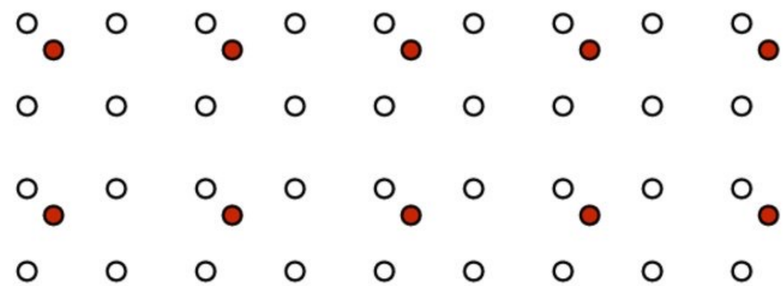


Texture Image





Screen space (x,y)



Texture space (u,v)

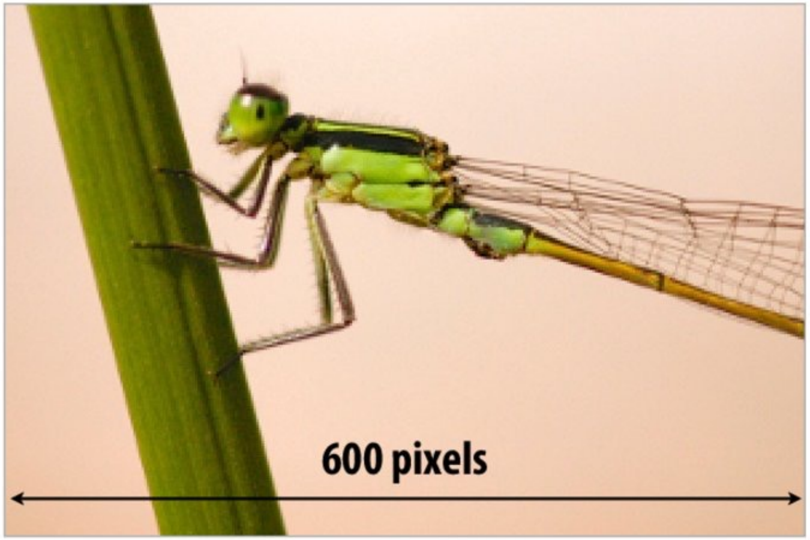
Texture is "minified"

Red dots = samples needed to render

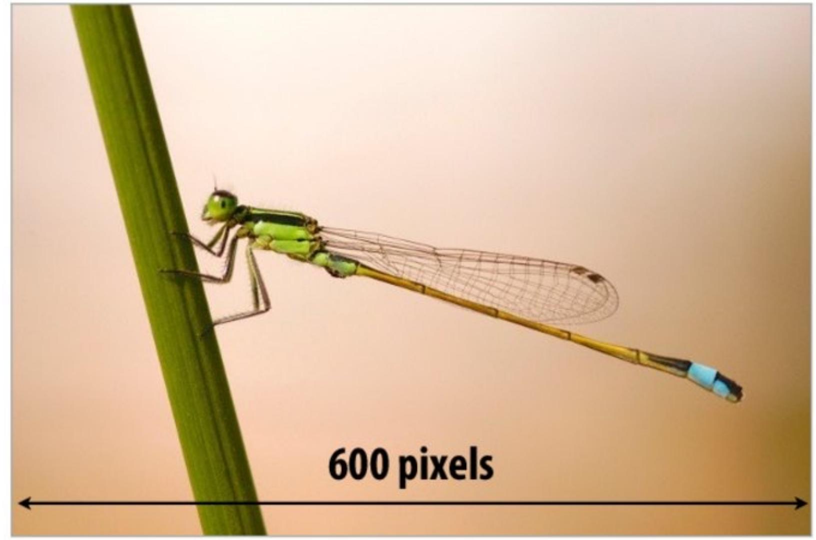
White dots = samples existing in texture map

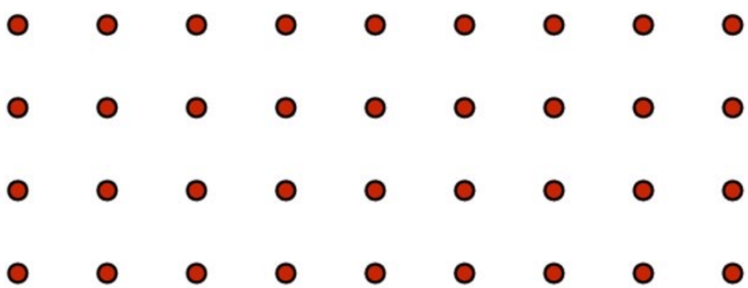
Sampling rate on screen vs texture

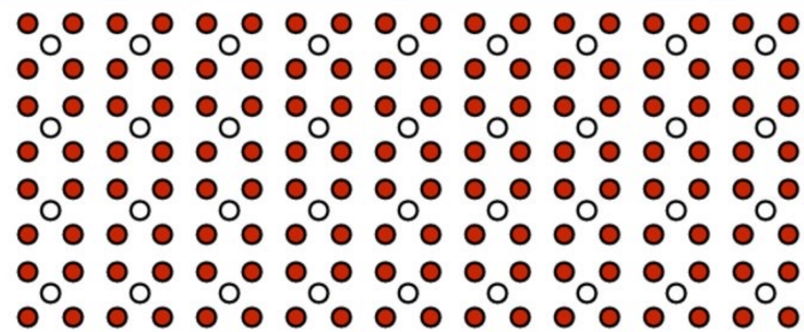
Rendered image (zoomed in)



Texture Image







Screen space (x,y)

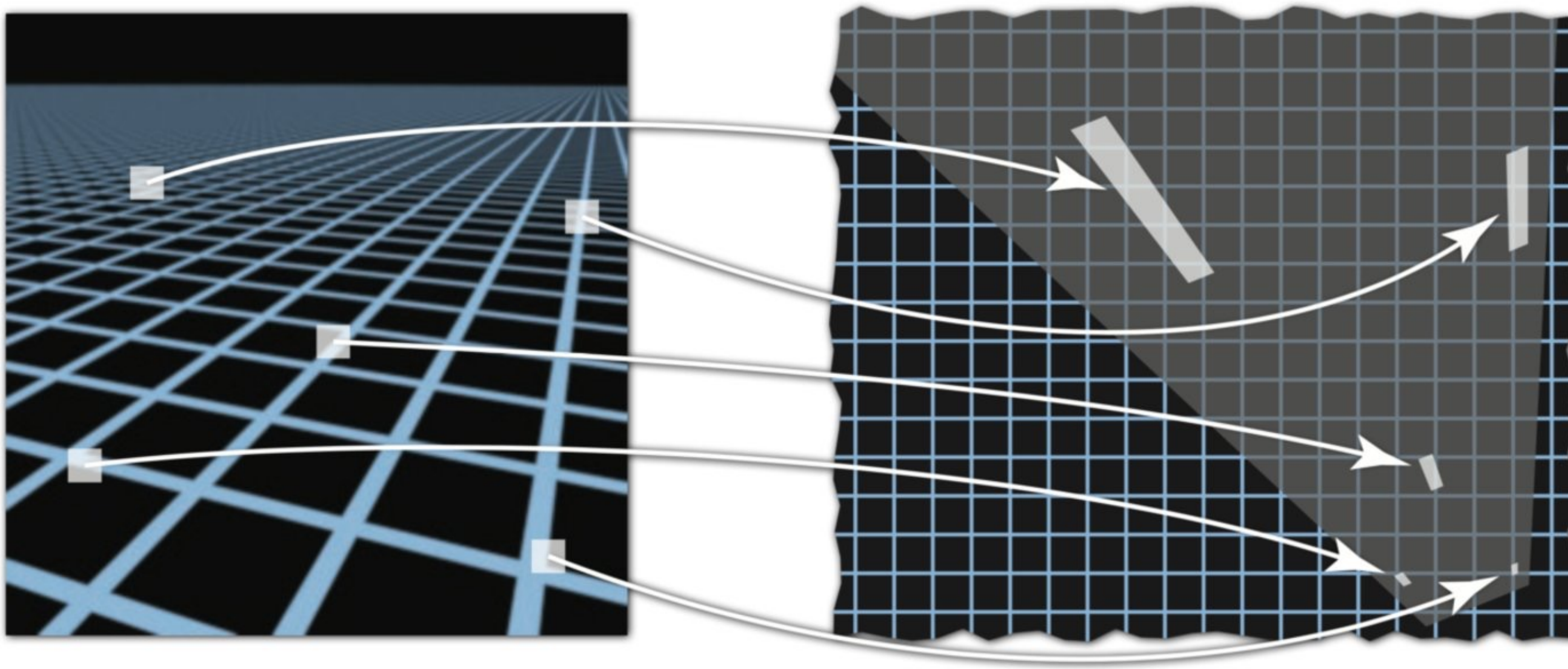
Texture space (u,v)

Texture is "magnified" on screen

Red dots = samples needed to render

White dots = samples existing in texture map

Screen pixel footprint in texture space

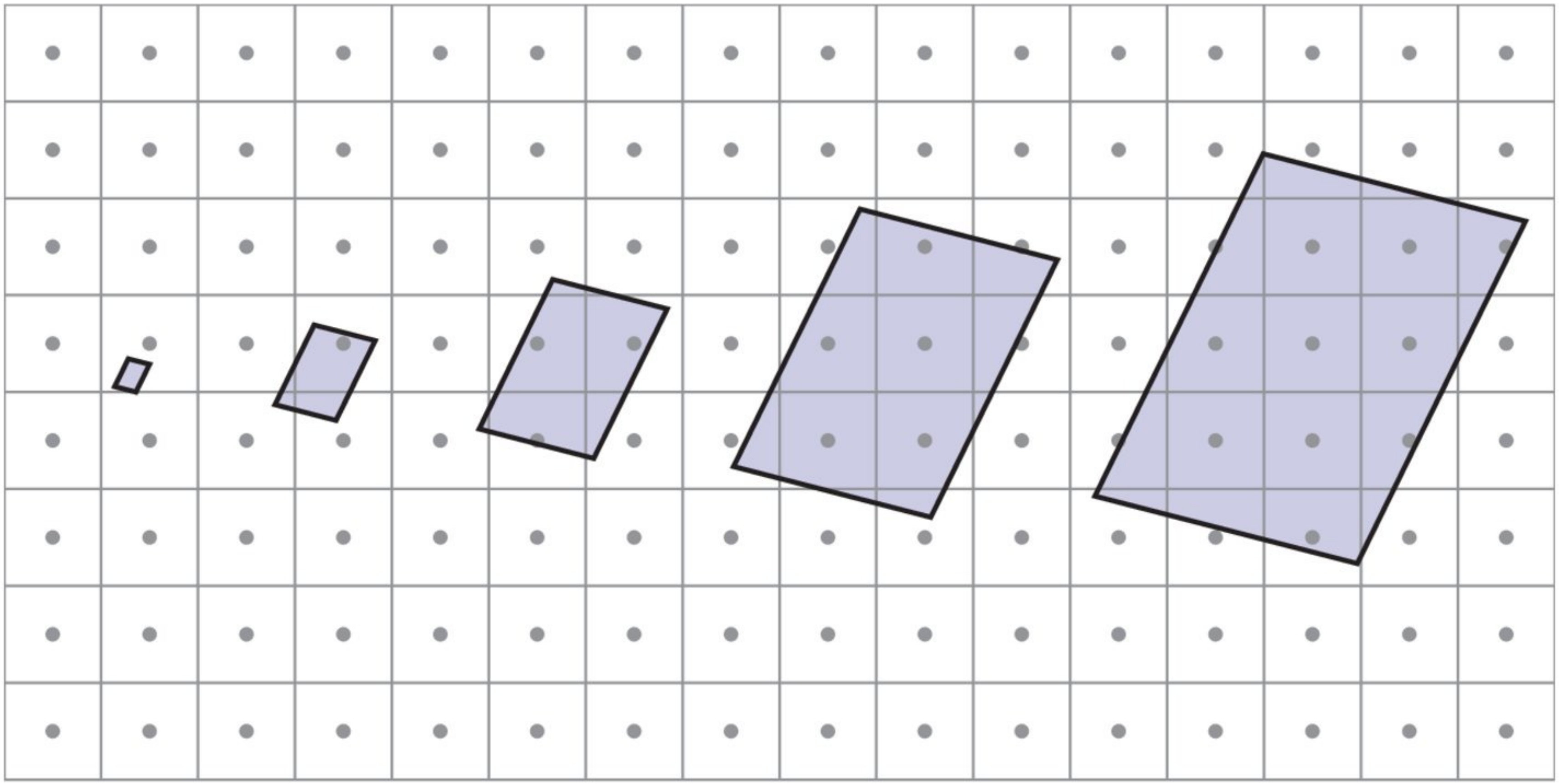


Screen space

Texture space

Texture sampling pattern not rectilinear or isotropic

Screen pixel footprint in texture space



Upsampling (Magnification) ⟷ **Downsampling (Minification)**

Camera zoomed in close to object

Camera far away from object

Participation Apr 28

Form description

This form is automatically collecting email addresses for UC Santa Cruz users. Change settings

I was in class Apr 28

- ◯ Yes
- ◯ No

Roughly how long did you spend on A2 (Blocky Animal)

- ◯ 0-5 hours
- ◯ 5-10 hours
- ◯ 10-15 hours
- ◯ 15+ hours

There were YouTube videos to help with coding for A2:

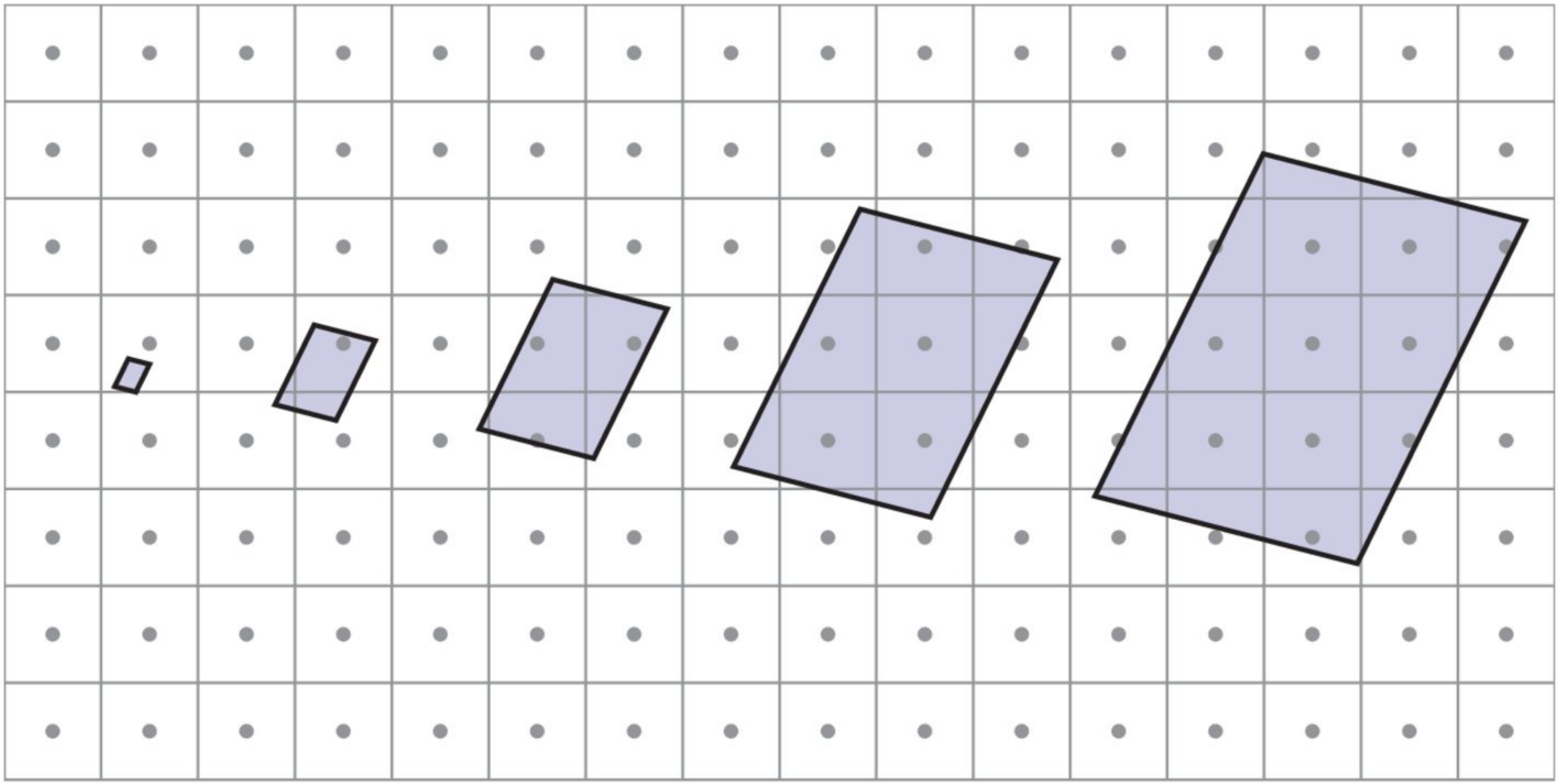
Suggestions: Add all | Yes No Maybe

- ◯ I didn't watch them, I just did the assignment
- ◯ I watched them, they were NOT helpful
- ◯ I watched them, they WERE helpful
- ◯ Other...

The textbook introduces the concepts needed for Asg2. (Matsuda WebGL) Is this book good, or it should be replaced?

Magnification

Screen pixel footprint in texture space



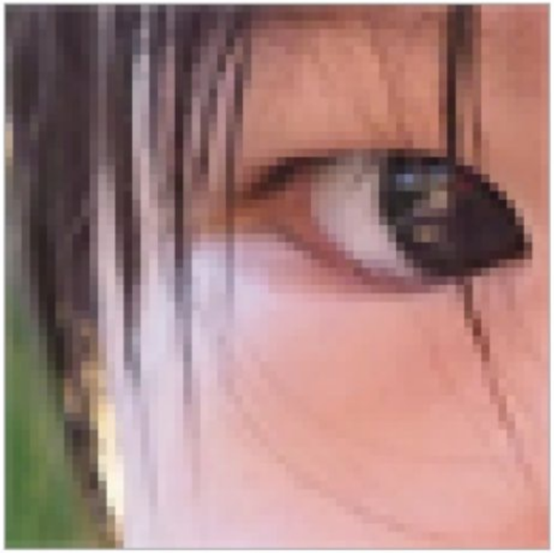
Upsampling (Magnification) ⟷ **Downsampling (Minification)**

Camera zoomed in close to object

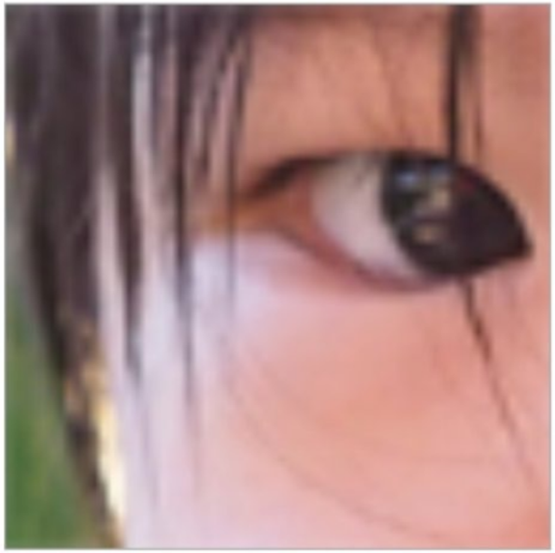
Camera far away from object

Texture magnification - easy case

- Generally don't want this situation — it means we have insufficient texture resolution)
- This is image interpolation (below: three different kernel functions)



Nearest

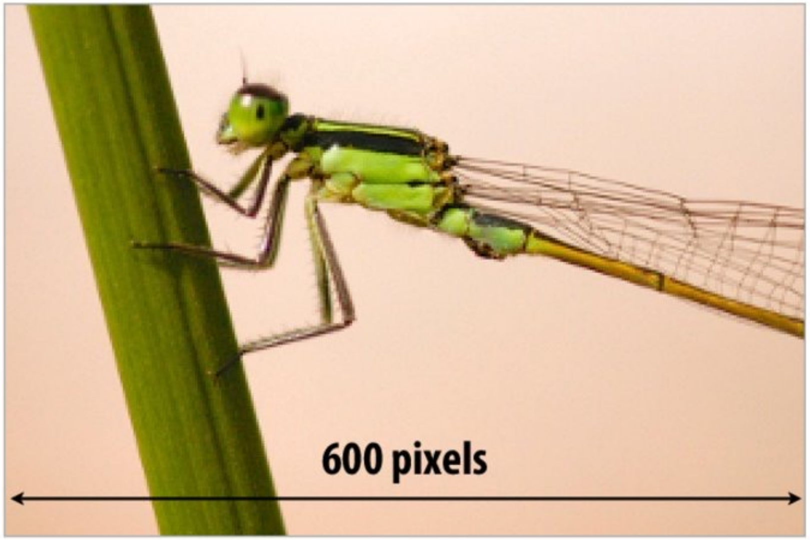


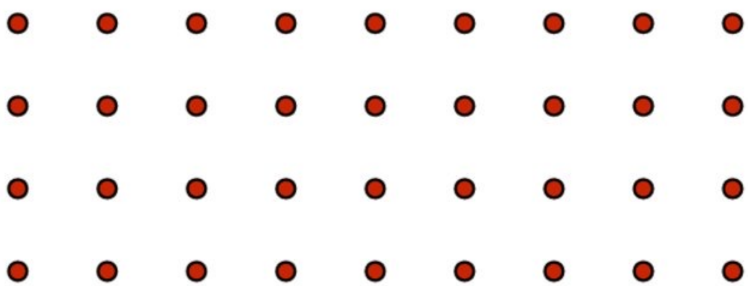
Bilinear

Bicubic

Sampling rate on screen vs texture

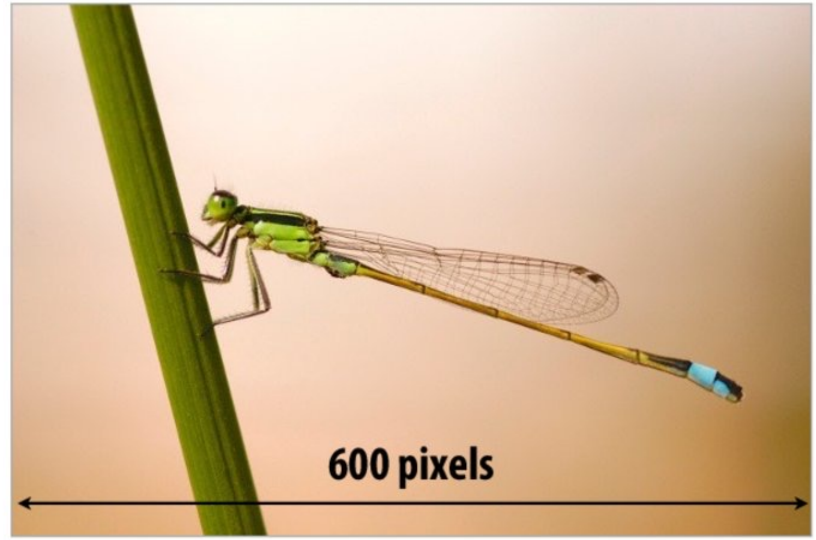
Rendered image (zoomed in)

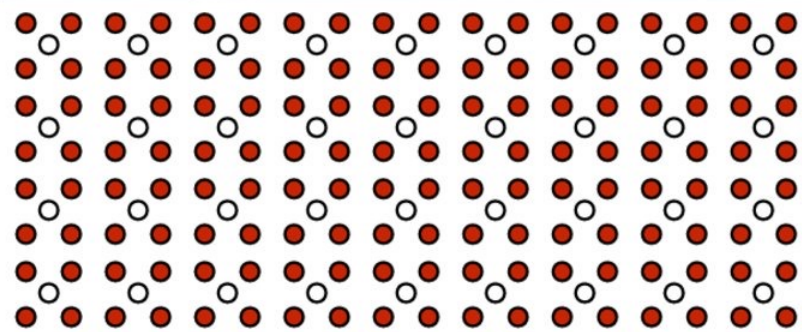




Screen space (x,y)

Texture Image





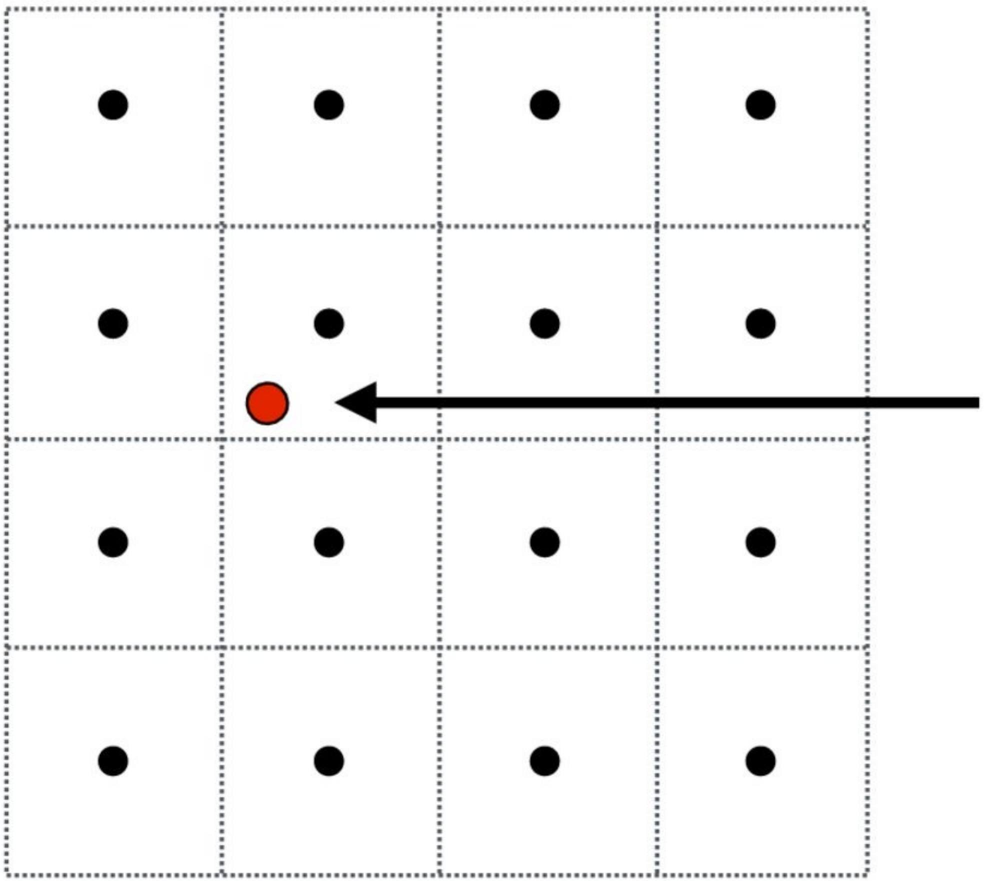
Texture space (u,v)

Texture is "magnified" on screen

Red dots = samples needed to render

White dots = samples existing in texture map

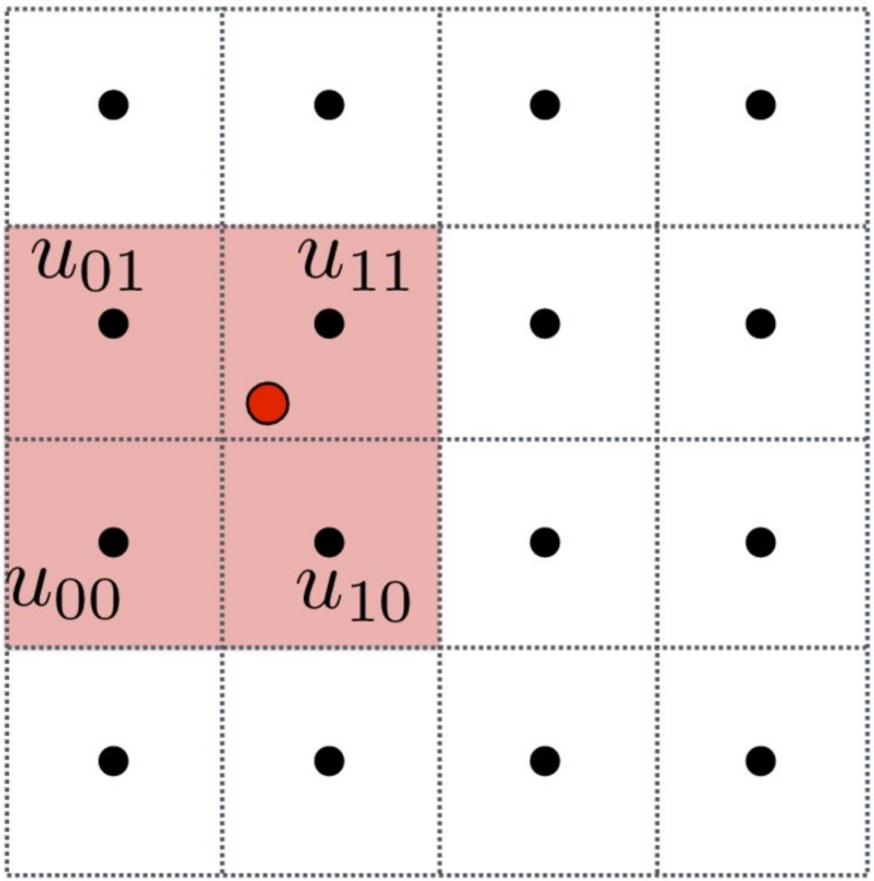
Bilinear filtering



Want to sample texture value f(x,y) at red point

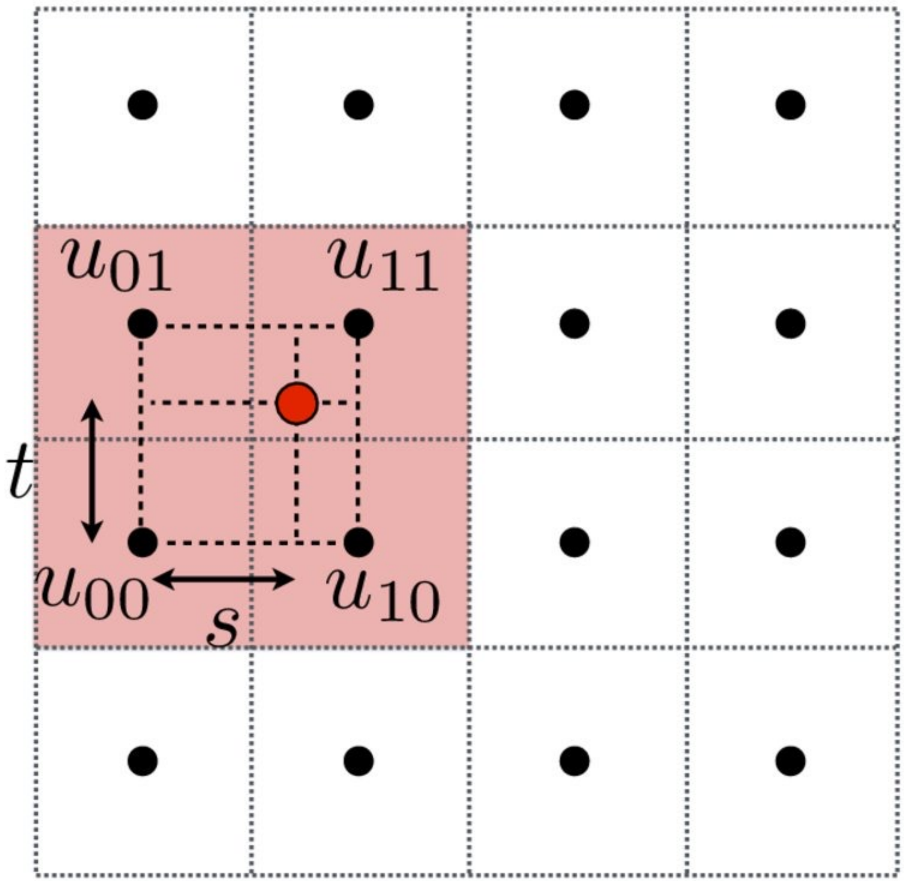
Black points indicate texture sample locations

Bilinear filtering



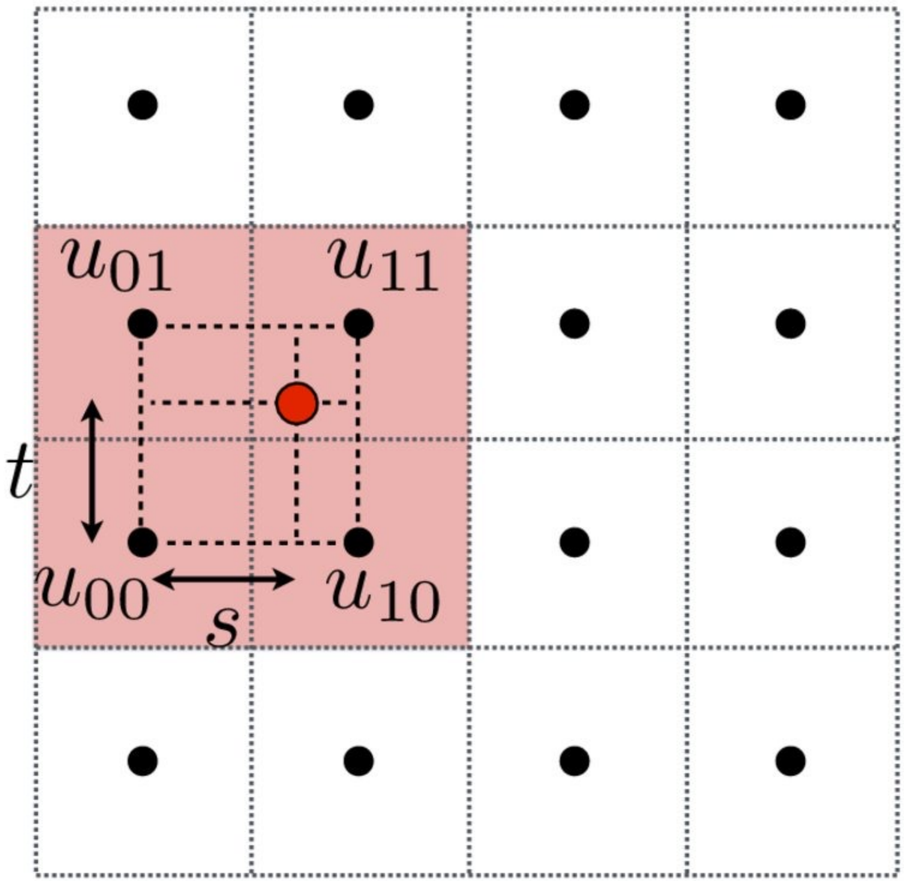
Take 4 nearest sample locations, with texture values as labeled.

Bilinear filtering



And fractional offsets, (s,t) as shown

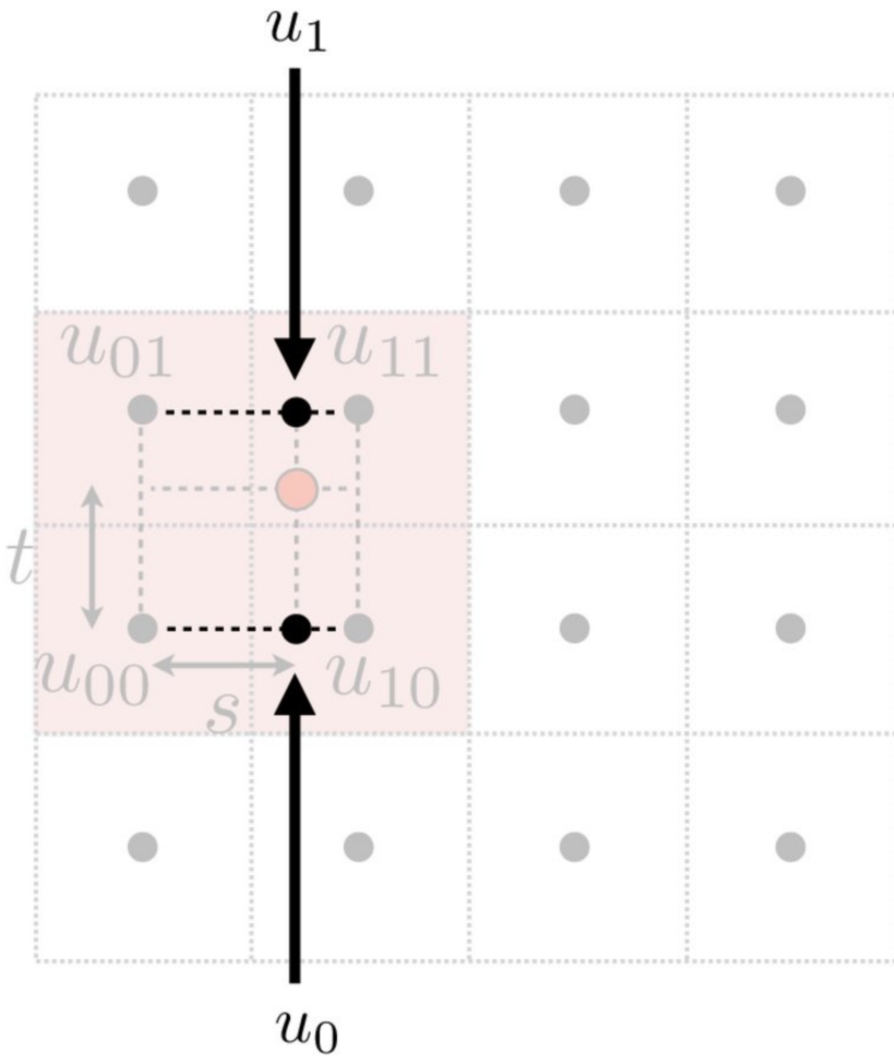
Bilinear filtering



Linear interpolation (1D)

$$\text{lerp}(x, v_0, v_1) = v_0 + x(v_1 - v_0)$$

Bilinear filtering



Linear interpolation (1D)

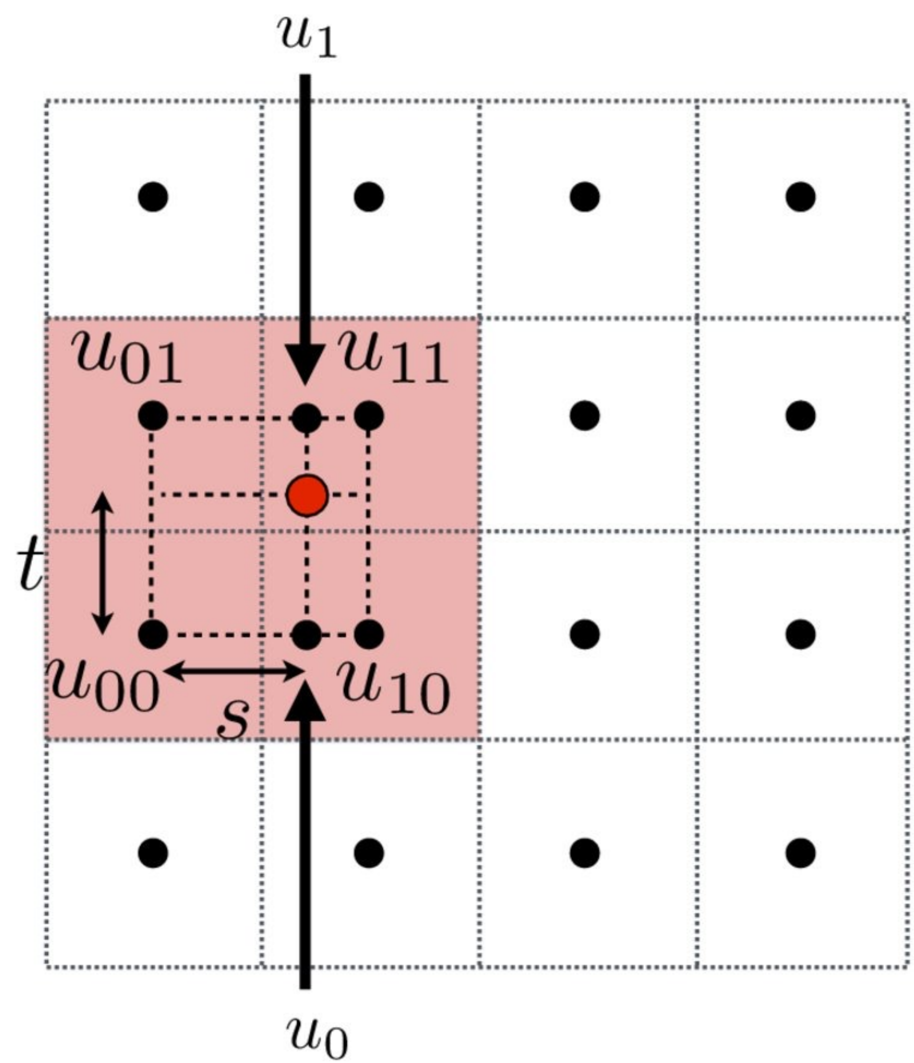
$$\text{lerp}(x, v_0, v_1) = v_0 + x(v_1 - v_0)$$

Two helper lerps (horizontal)

$$u_0 = \text{lerp}(s, u_{00}, u_{10})$$

$$u_1 = \text{lerp}(s, u_{01}, u_{11})$$

Bilinear filtering



Linear interpolation (1D)

$$\text{lerp}(x, v_0, v_1) = v_0 + x(v_1 - v_0)$$

Two helper lerps

$$u_0 = \text{lerp}(s, u_{00}, u_{10})$$

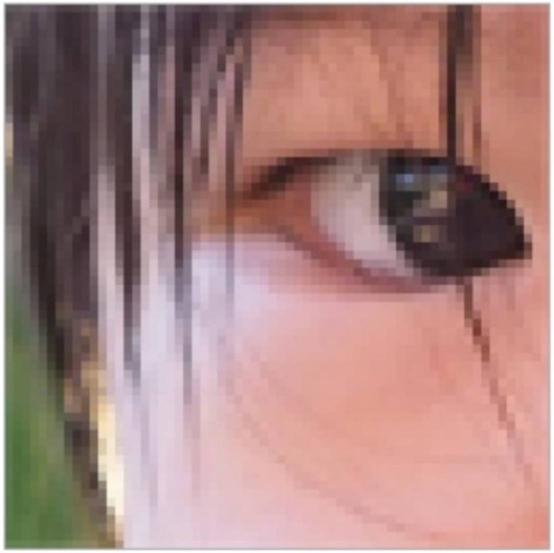
$$u_1 = \text{lerp}(s, u_{01}, u_{11})$$

Final vertical lerp, to get result:

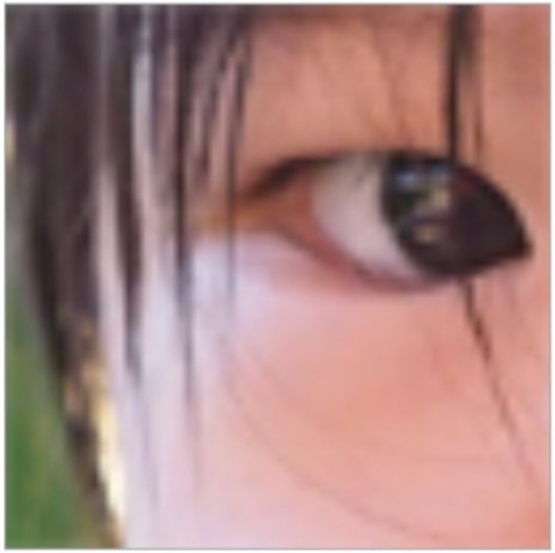
$$f(x, y) = \text{lerp}(t, u_0, u_1)$$

Texture magnification - easy case

- Generally don't want this situation — it means we have insufficient texture resolution)
- This is image interpolation (below: three different kernel functions)



Nearest

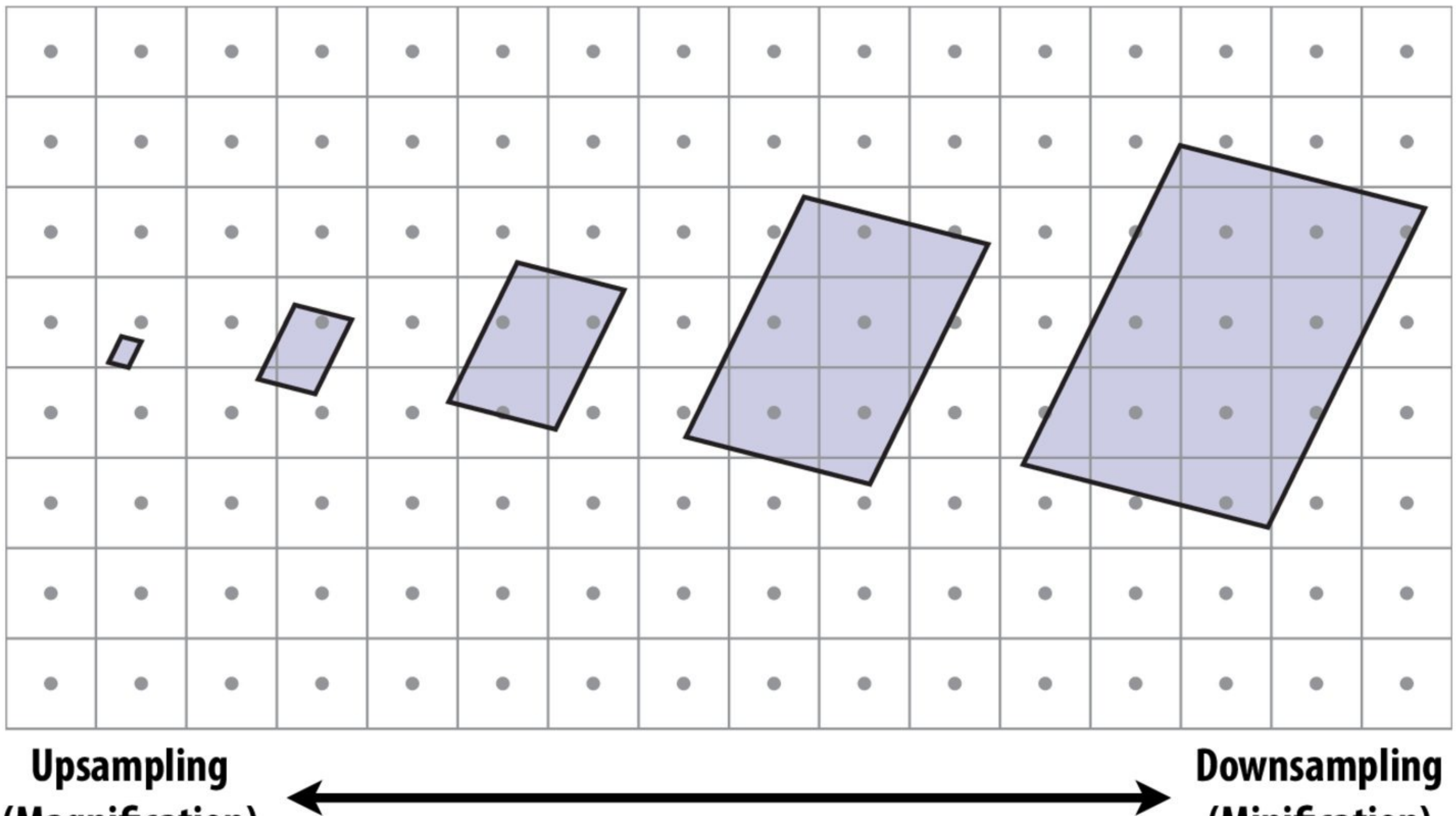


Bilinear

Bicubic

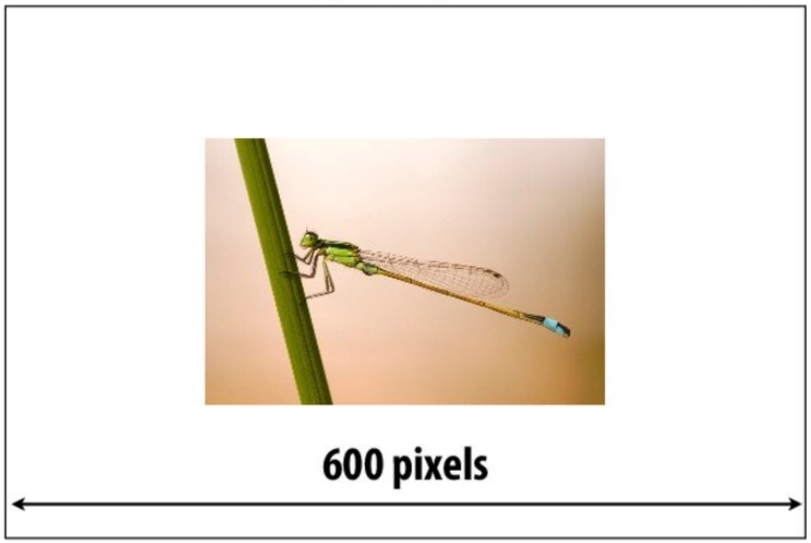
Minification

Screen pixel footprint in texture space

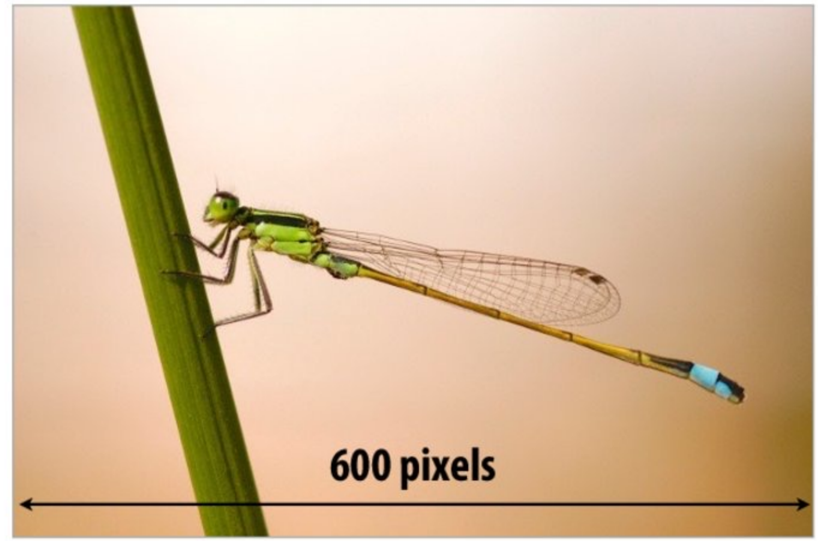


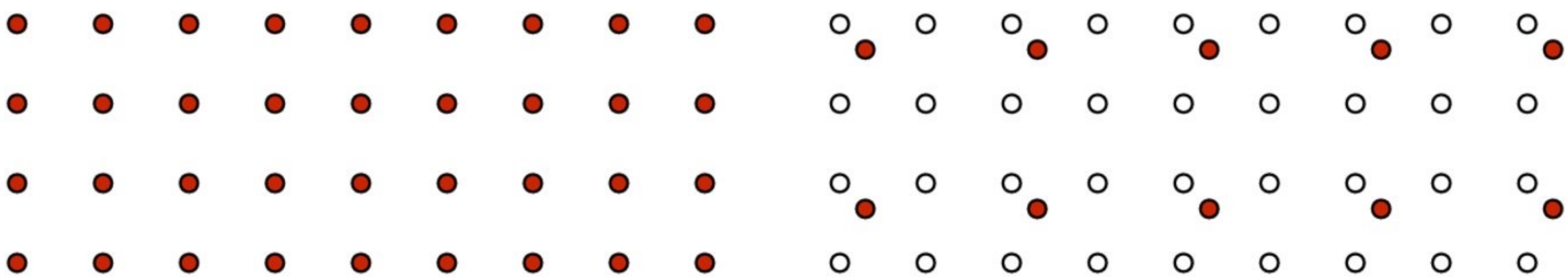
Sampling rate on screen vs texture

Rendered image (object zoomed out)



Texture Image





Screen space (x,y)

Texture space (u,v)

Texture is "minified"

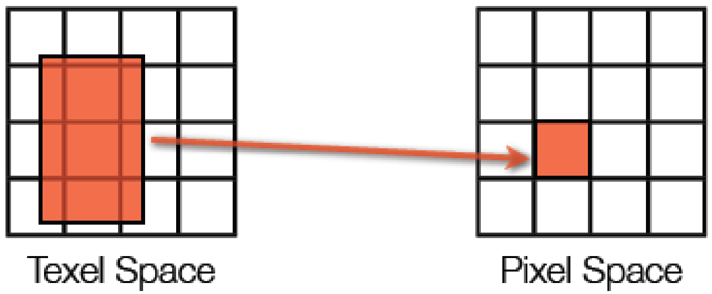
Red dots = samples needed to render

White dots = samples existing in texture map

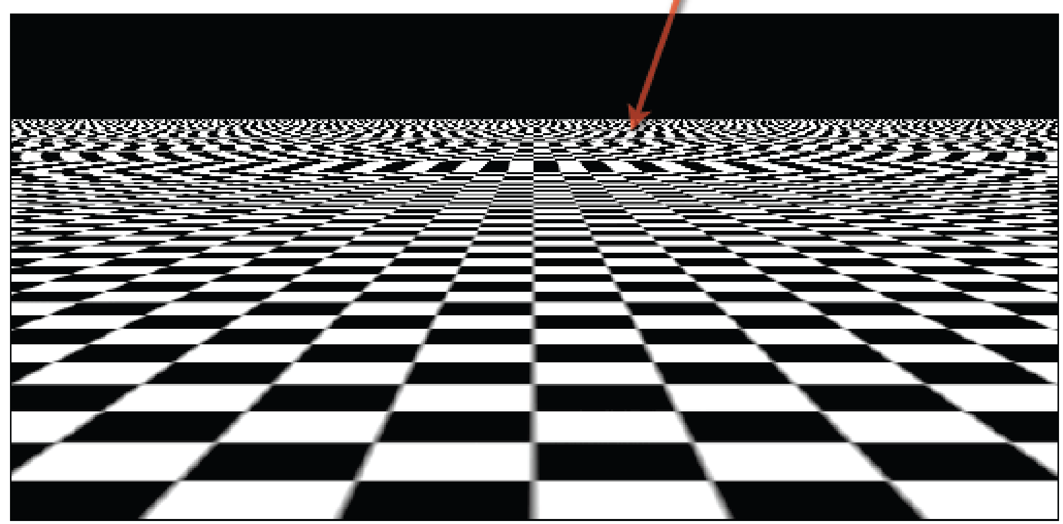
Minification

Texel Shrinking

- One pixel is covered by multiple texels:

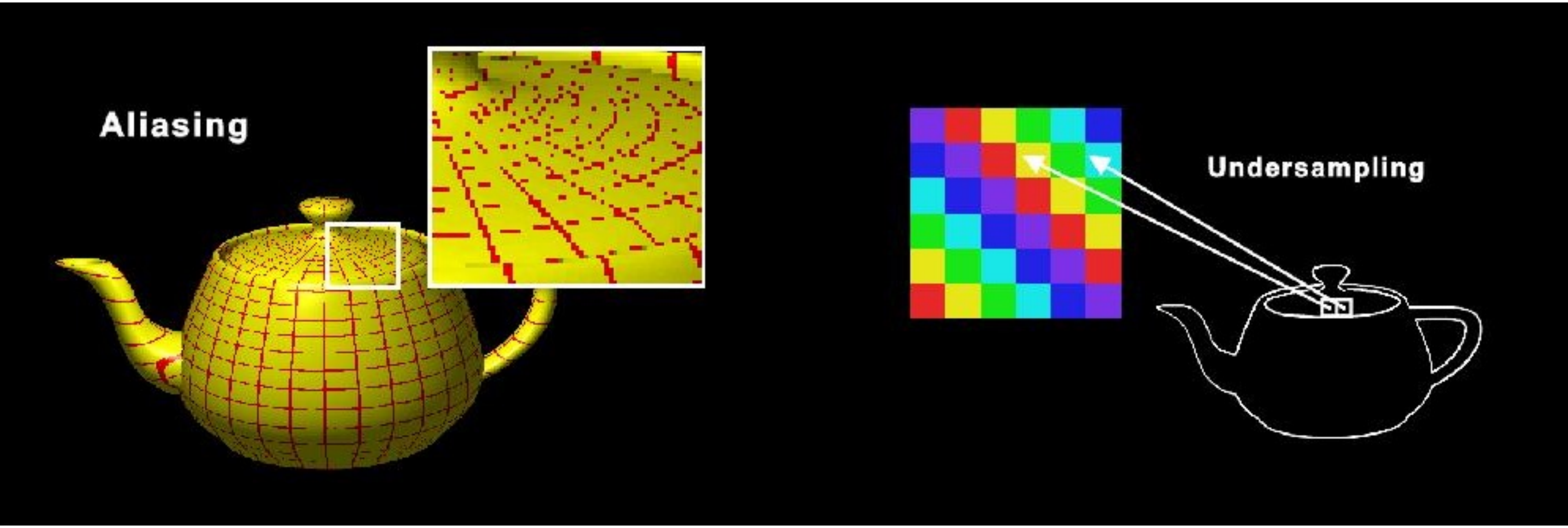


Can cause severe **aliasing**

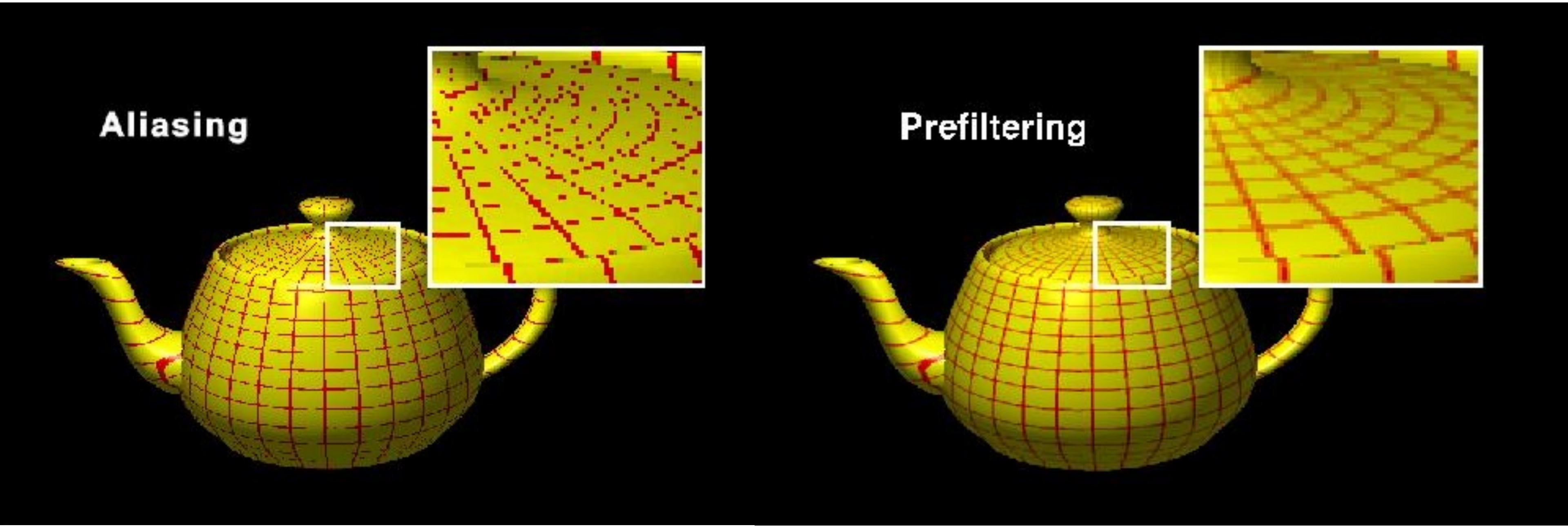


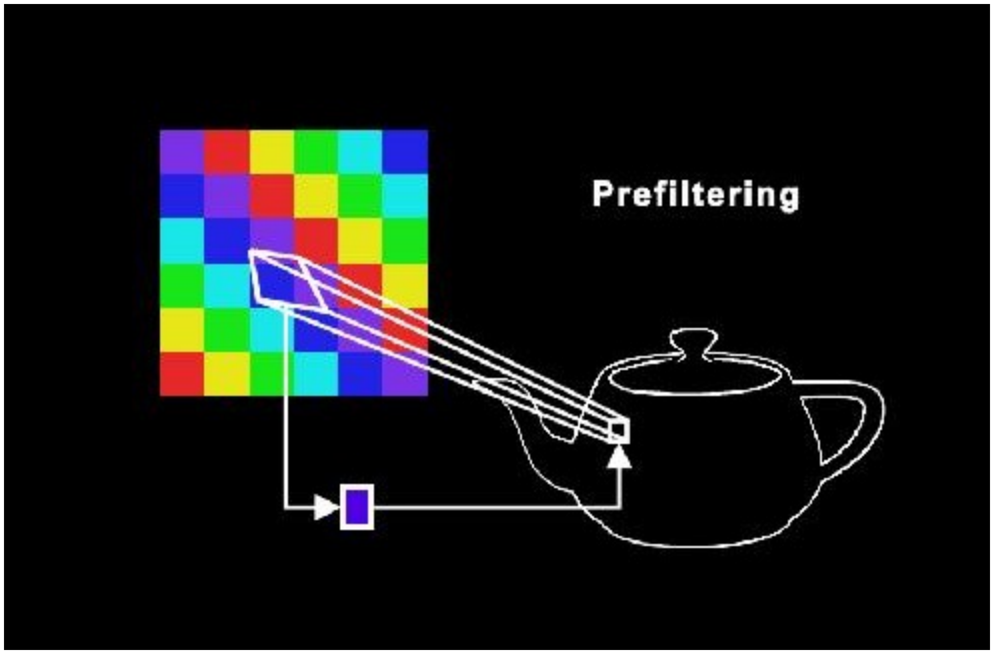
Filtering Techniques

- Nearest neighbor
- Bilinear interpolation
- Mipmapping



[http://escience.anu.edu.au/lecture/cg/Texture/printNotes.en.html]

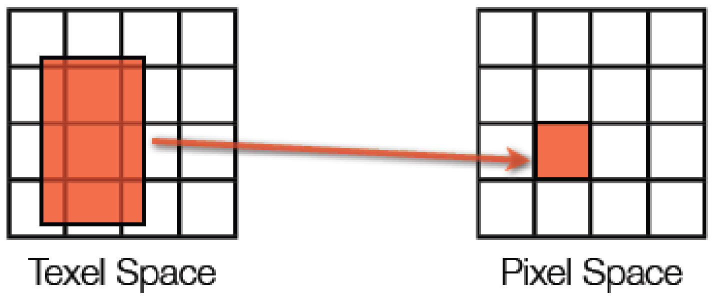

Aliasing
Prefiltering


Prefiltering

Minification

Texel Shrinking

- One pixel is covered by multiple texels:



Its slow to add up all those values!
How do we make it faster?

Mipmapping

Computer Graphics Volume 17, Number 3 July 1983

Pyramidal Parametrics

Lance Williams

Computer Graphics Laboratory
New York Institute of Technology
Old Westbury, New York

Abstract

The mapping of images onto surfaces may substantially increase the realism and information content of computer-generated

1. Pyramidal Data Structures

Pyramidal data structures may be based on various subdivisions: binary

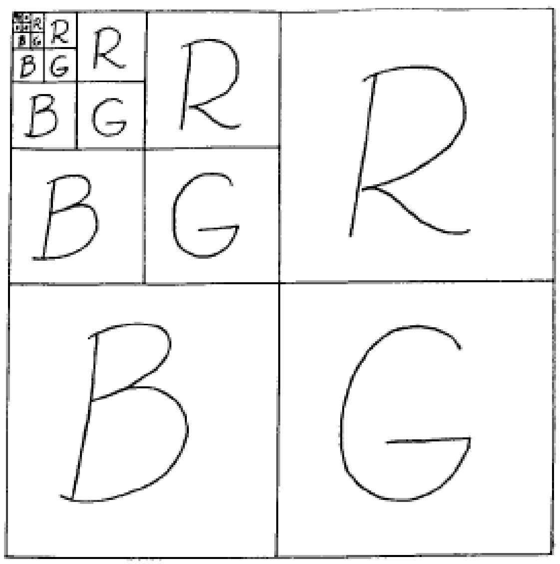
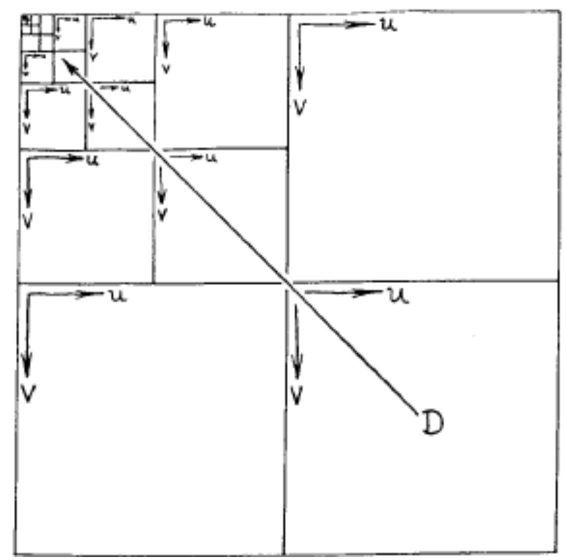


Figure (1)
Structure of a Color Mip Map
Smaller and smaller images diminish into the upper left corner of the map. Each of the images is averaged down from its larger predecessor.

Mip maps are indexed by three coordinates: U, V, and D. U and V are spatial coordinates of the map; D is the variable used to index, and interpolate between, the different levels of the pyramid.



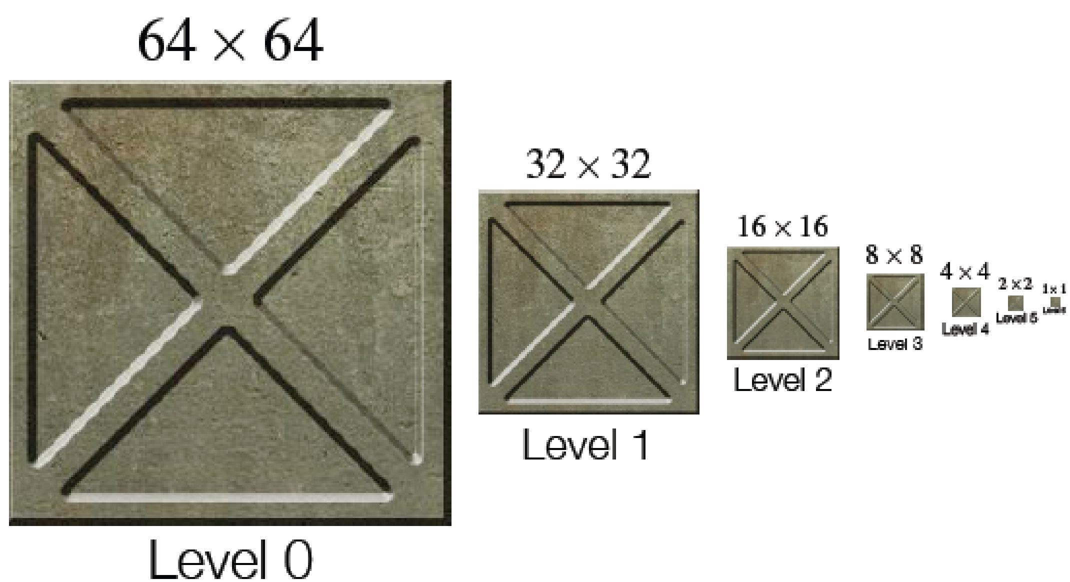
Mipmapping

Mipmaps

- From the Latin *multum in parvo*, many things in a small place
- Create pyramid of successively smaller versions of original texture:

$$Area(k+1) = \left(\frac{1}{4}\right) Area(k)$$

- Quality of pyramid heavily dependent on filter used in downsampling



Mipmap (L. Williams 83)

Each mipmap level is downsampled (low-pass filtered) version of the previous

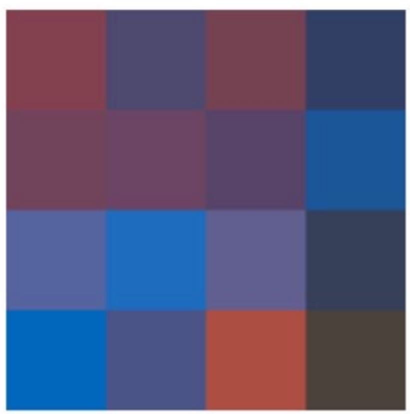

Level 0 = 128x128

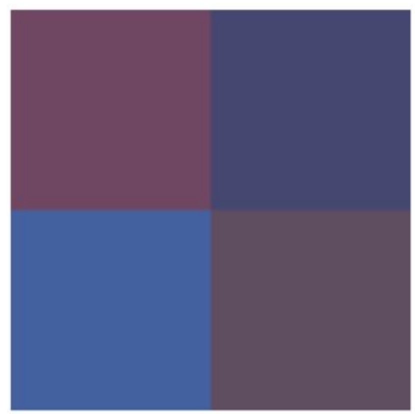

Level 1 = 64x64


Level 2 = 32x32


Level 3 = 16x16


Level 4 = 8x8


Level 5 = 4x4

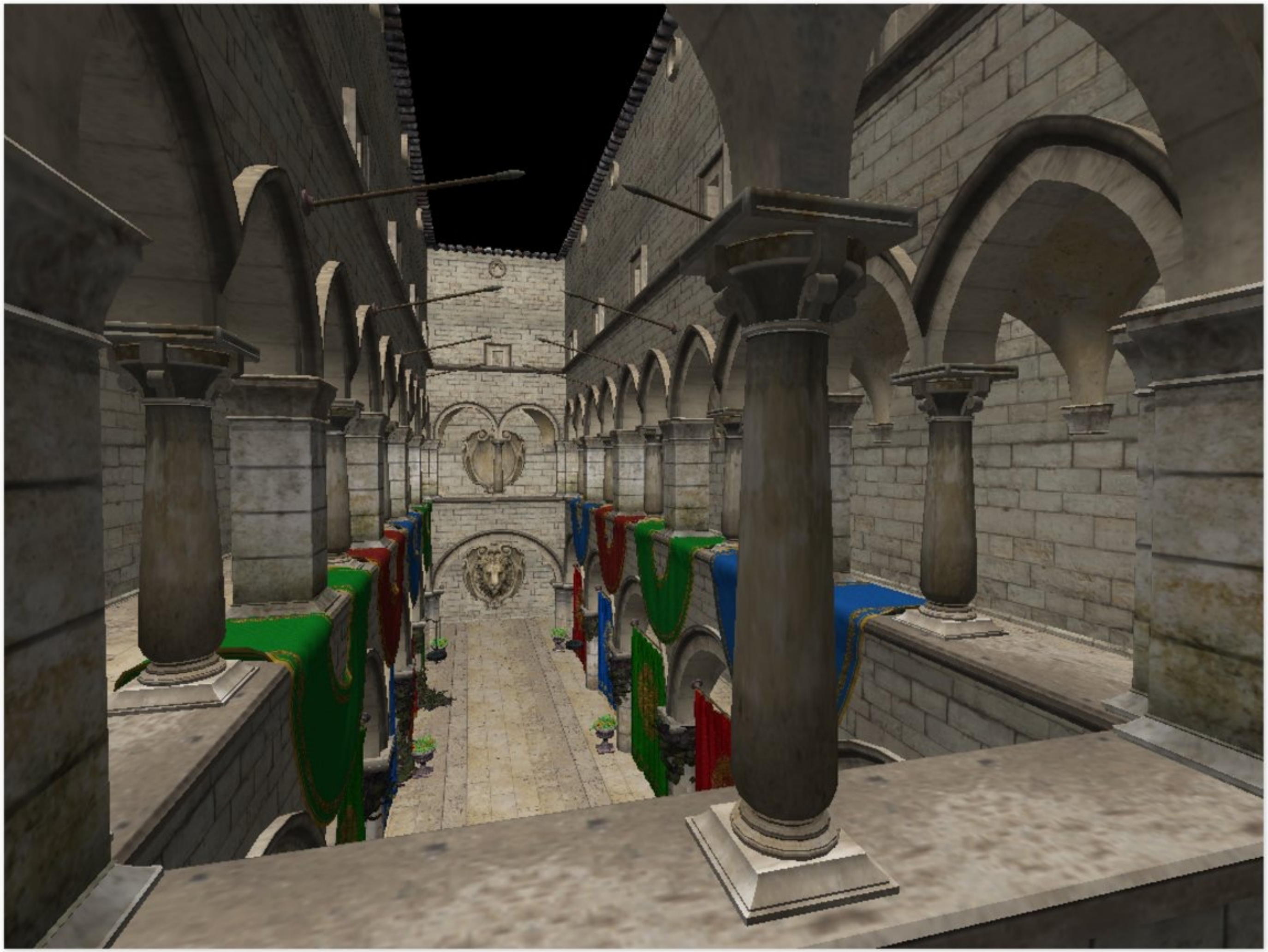

Level 6 = 2x2


Level 7 = 1x1

"Mip" comes from the Latin "multum in parvo", meaning a multitude in a small space

Bilinear resampling at level 0

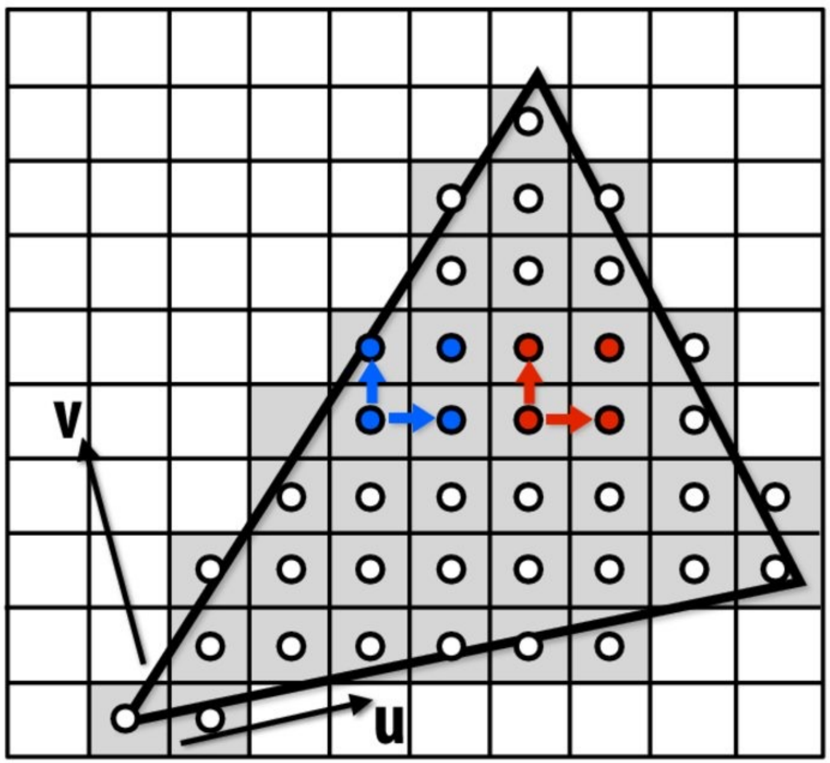
Bilinear resampling at level 2



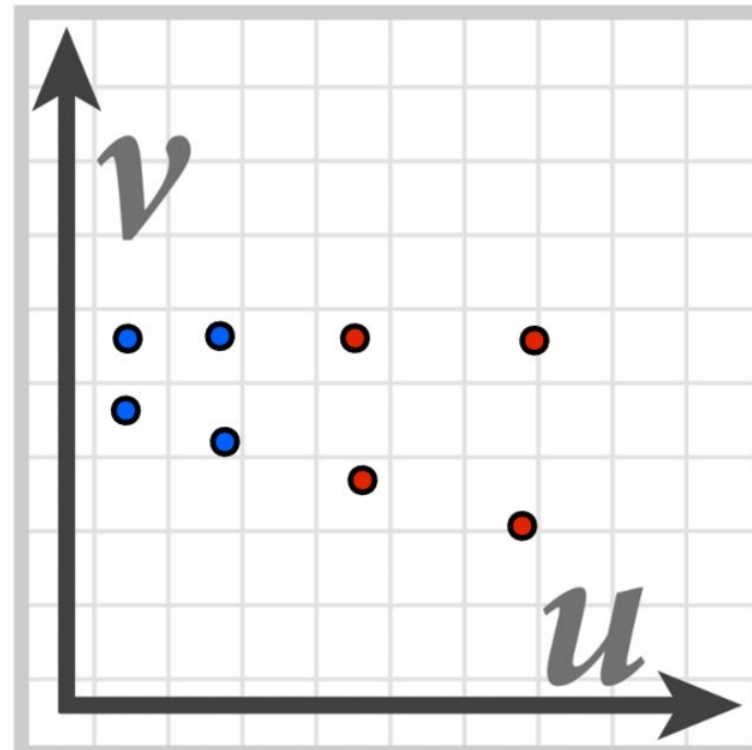
Bilinear resampling at level 4

Computing mipmap level

Compute differences between texture coordinate values of neighboring screen samples



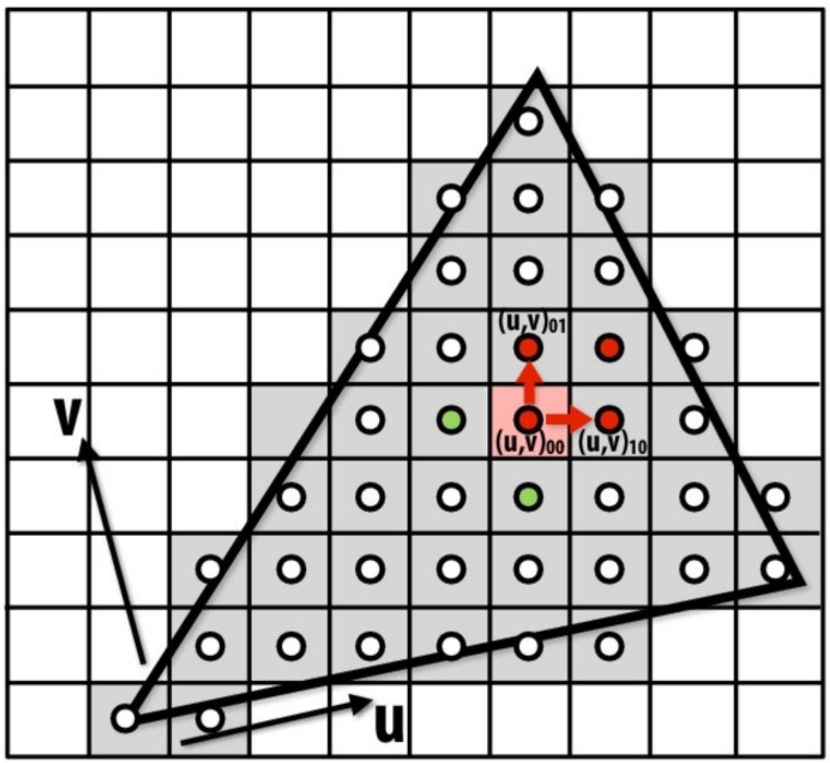
Screen space



Texture space

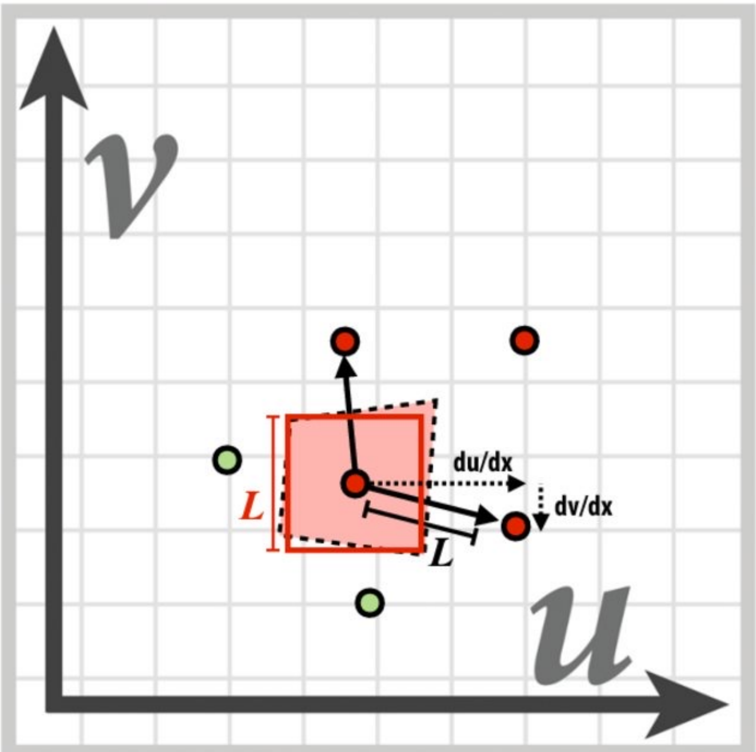
Computing mipmap level

Compute differences between texture coordinate values of neighboring screen samples



du/dx = u_{10}-u_{00} **dv/dx = v_{10}-v_{00}**

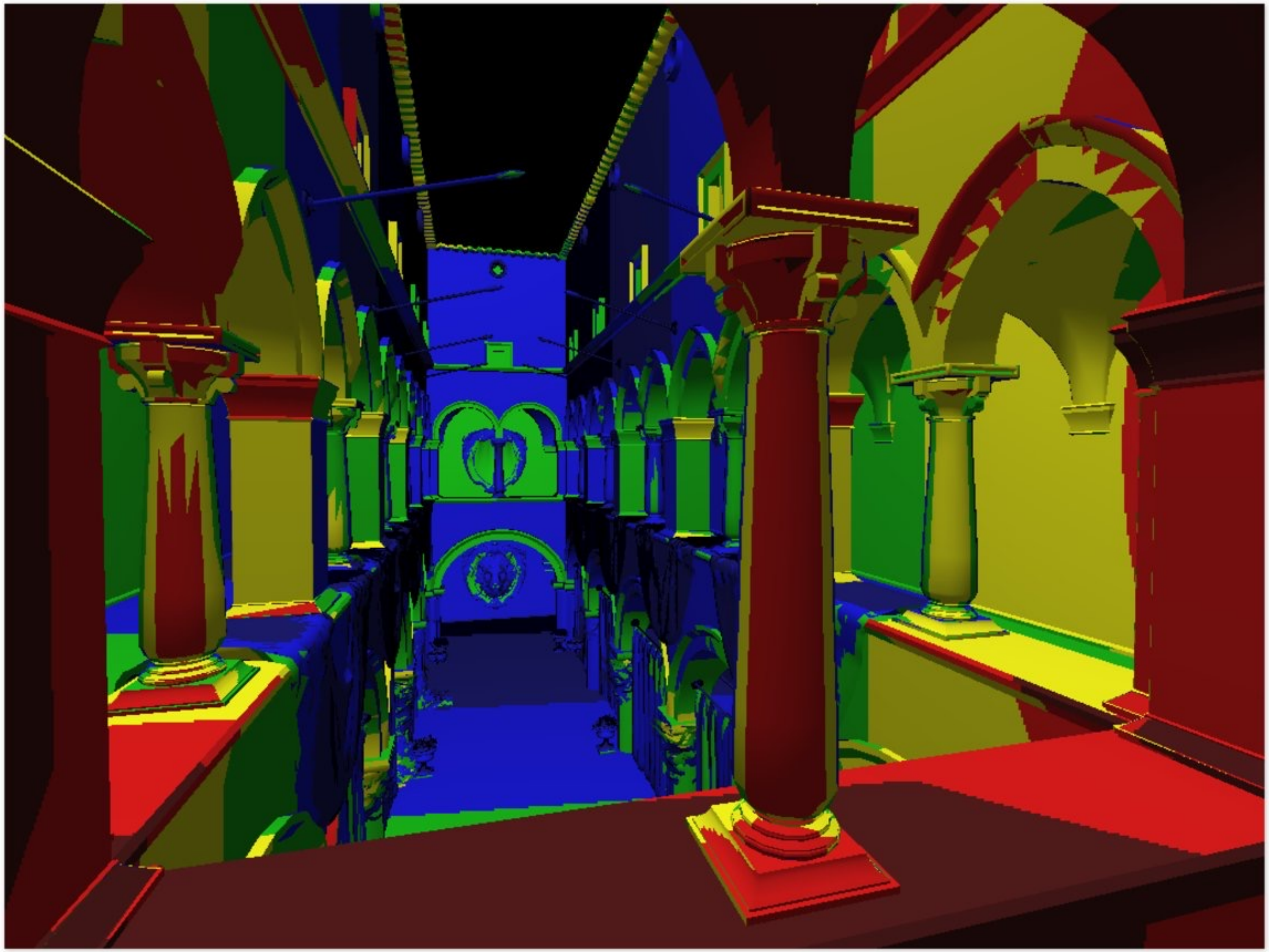
du/dy = u_{01}-u_{00} **dv/dy = v_{01}-v_{00}**



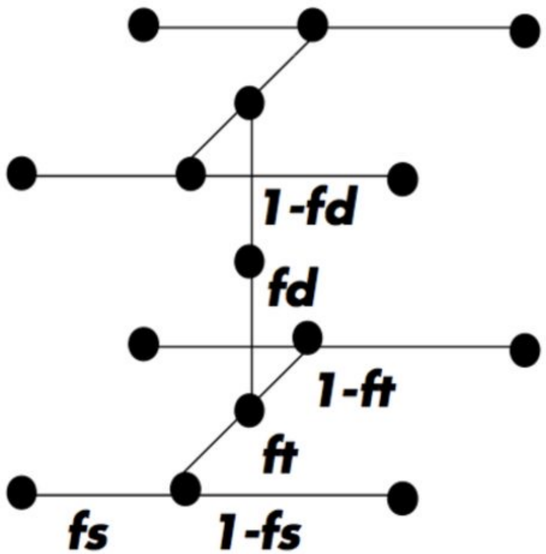
$$L = \max\left(\sqrt{\left(\frac{du}{dx}\right)^2 + \left(\frac{dv}{dx}\right)^2}, \sqrt{\left(\frac{du}{dy}\right)^2 + \left(\frac{dv}{dy}\right)^2}\right)$$

$$\textit{mip-map } d = \log_2 L$$

Visualization of mipmap level
(bilinear filtering only: *d* clamped to nearest level)



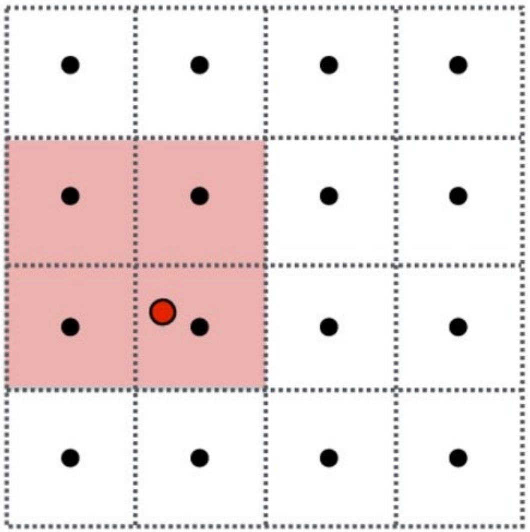
"Tri-linear" filtering



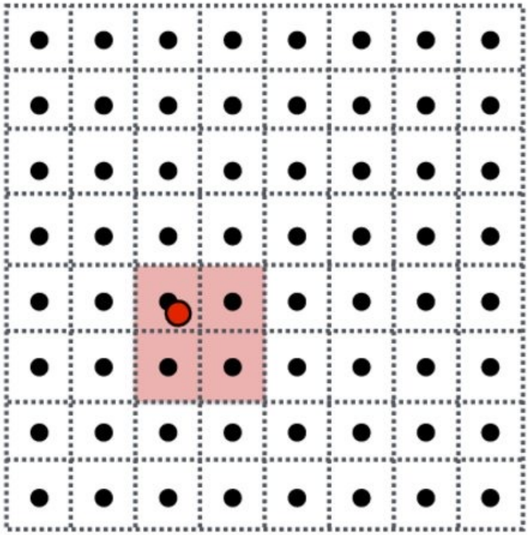
$$lerp(t, v_1, v_2) = v_1 + t(v_2 - v_1)$$

Bilinear resampling:
four texel reads
3 lerps (3 mul + 6 add)

Trilinear resampling:
eight texel reads
7 lerps (7 mul + 14 add)



mip-map texels: level d+1

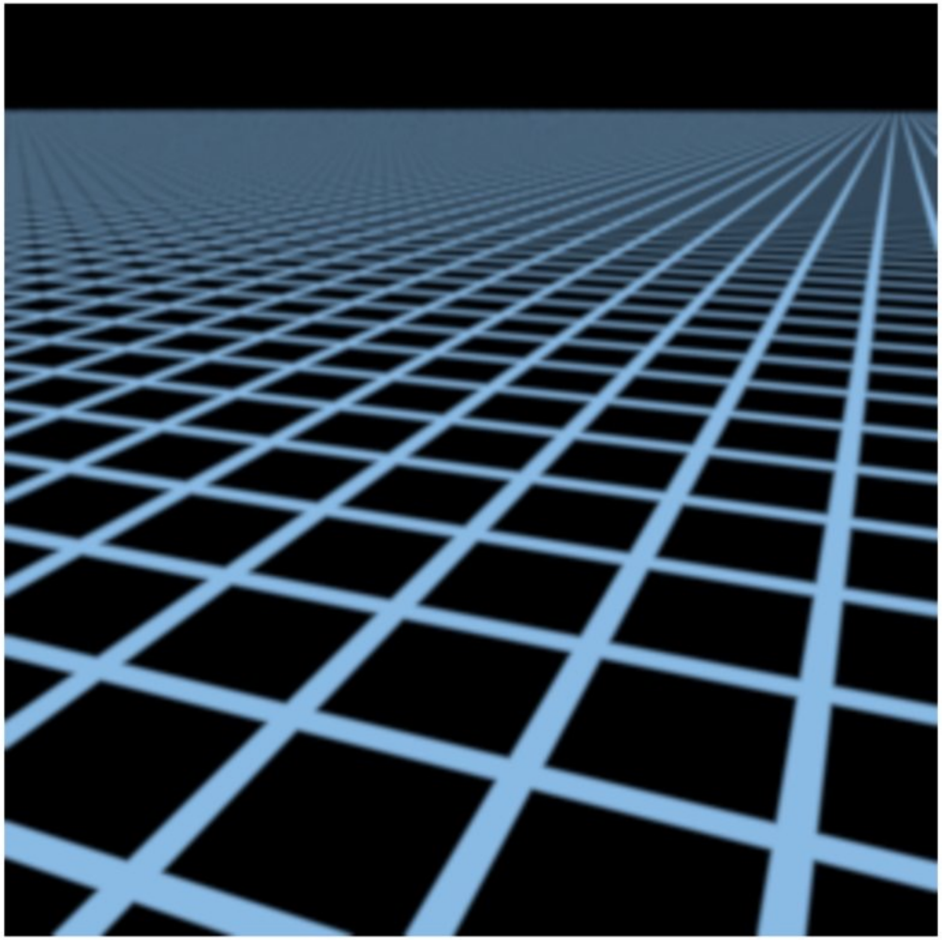


mip-map texels: level d

Figure credit: Akeley and Hanrahan

http://escience.anu.edu.au/lecture/cg/Texture/printNotes.en.html

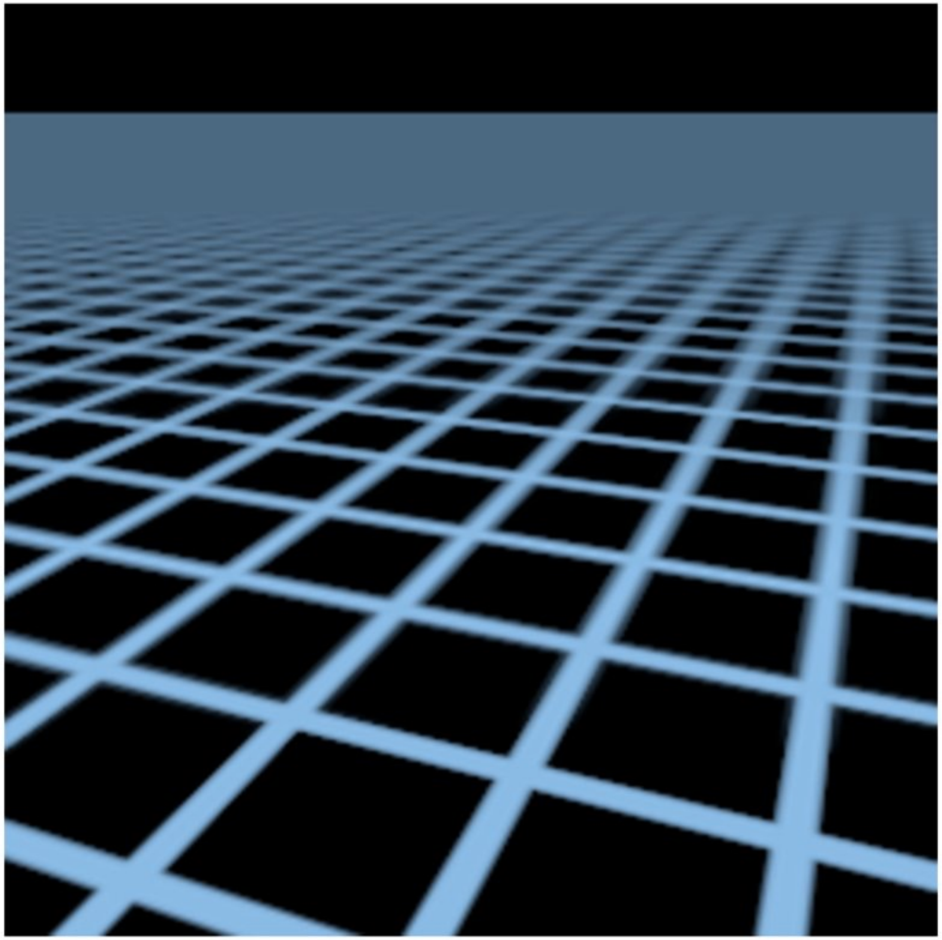
Example: mipmap limitations



Supersampling 512x
(desired answer)

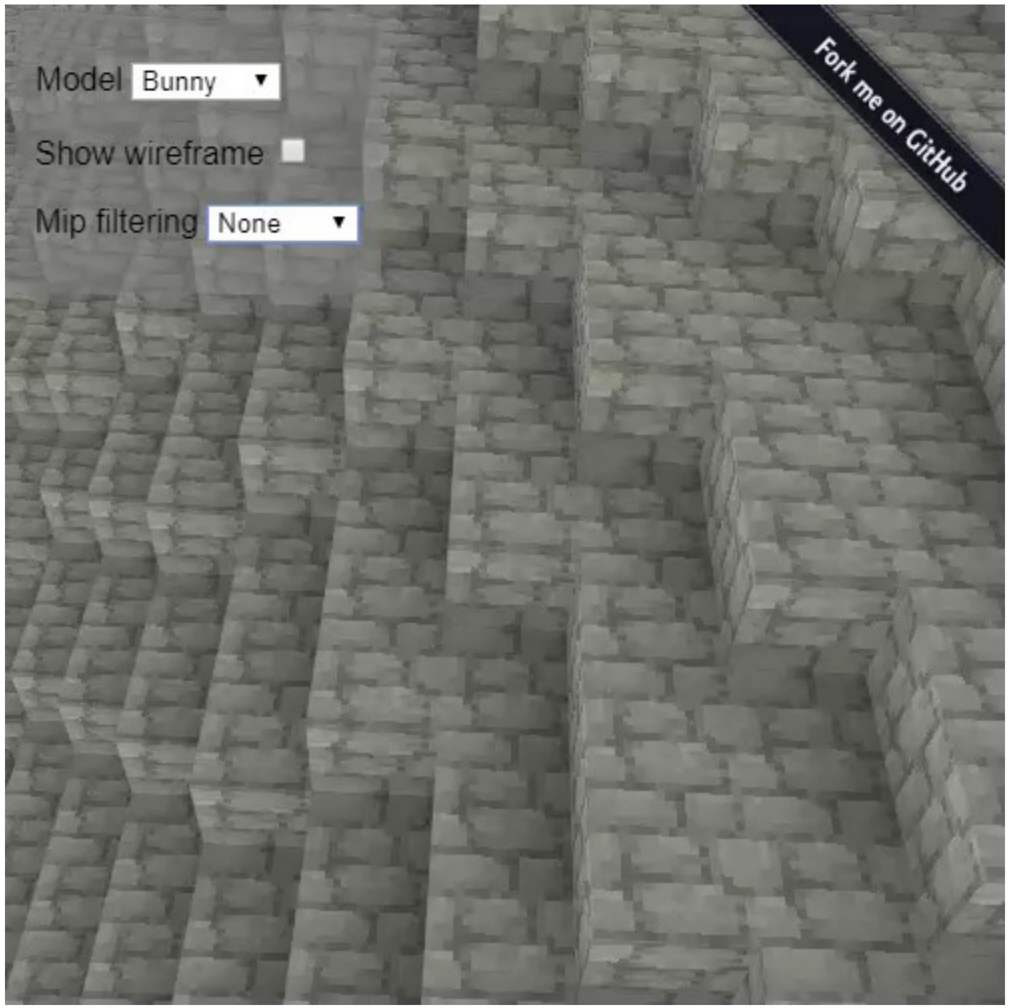
Example: mipmap limitations

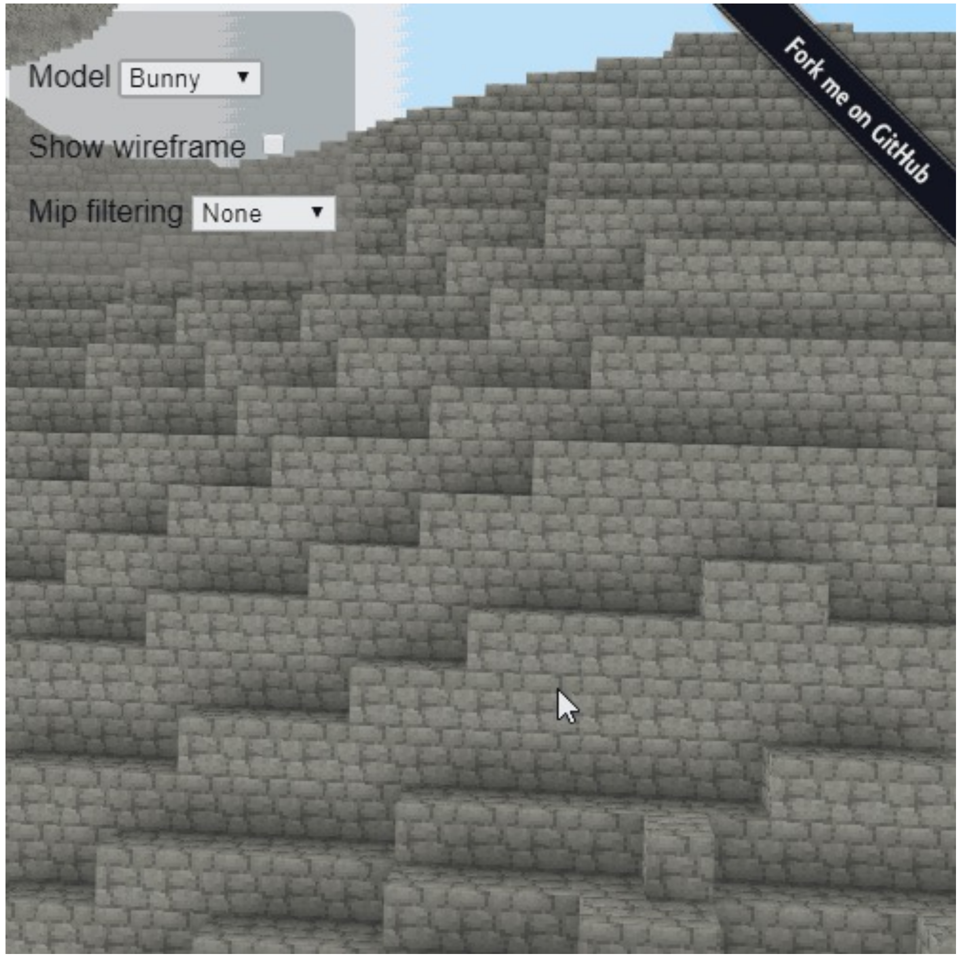
Overblur
Why?



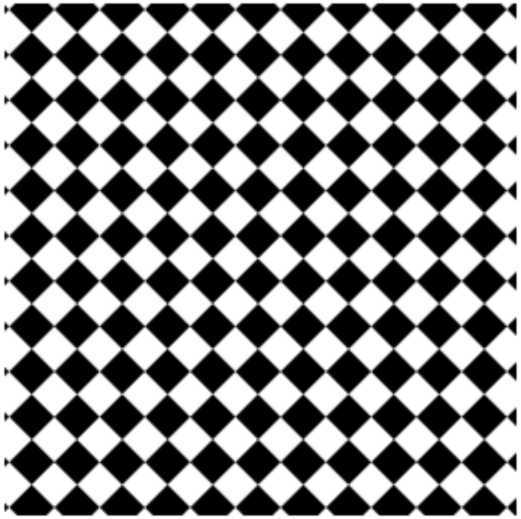
Mipmap trilinear sampling

Video example: mipmapping

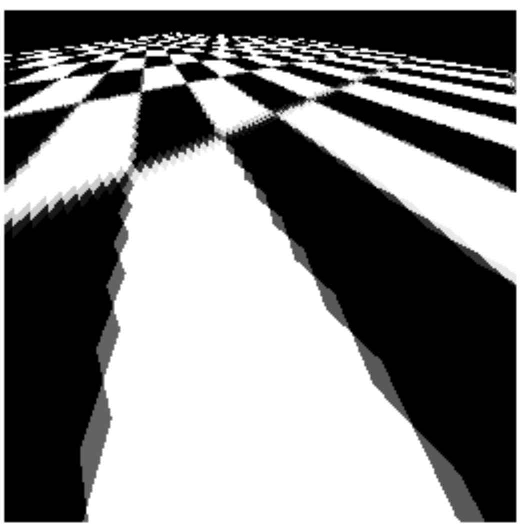



Model
Bunny
Show wireframe
Mip filtering
None
Fork me on GitHub

Initial Image



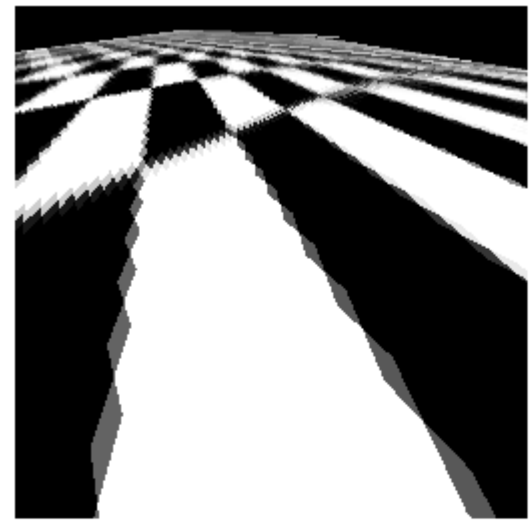
Point sampled

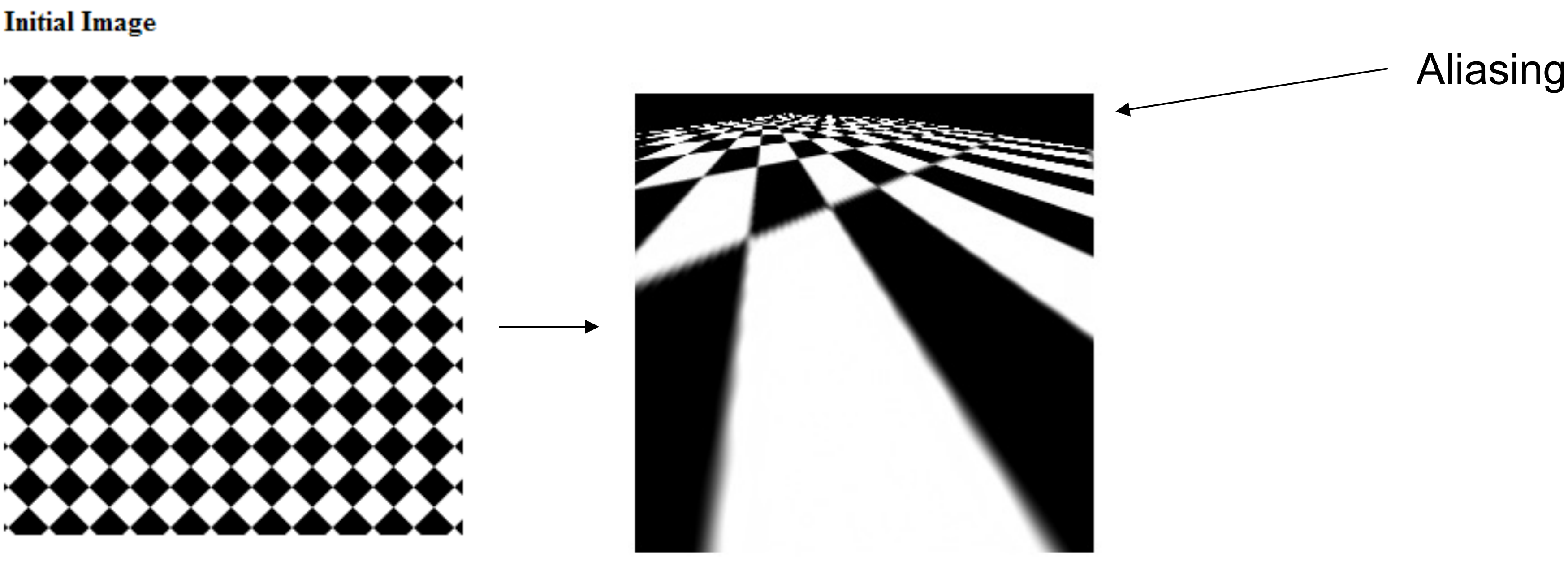


Bilinear interpolation AND mipmap filtering

Bilinear interpolation
but not mipmap filtering

NOT Bilinear interpolation
but yes mipmap filtering

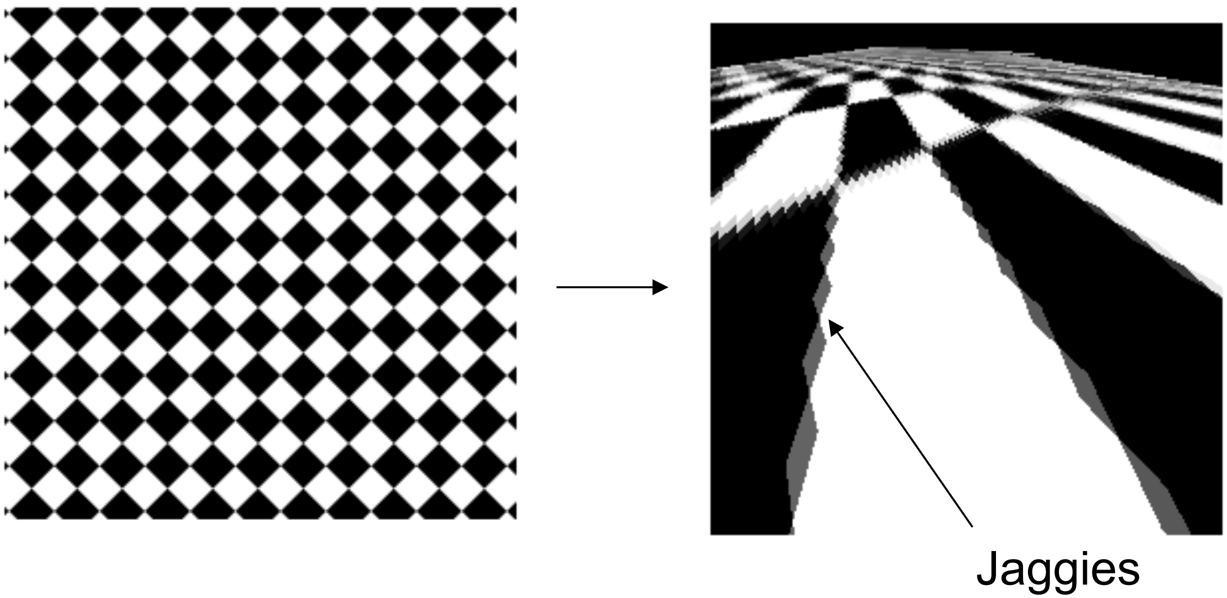




How do we fix the aliasing in the back of this rendered image?

- A - Need to turn on bi-linear interpolation
- B - Need to turn on mipmapping
- C - Need to turn on both to fix this
- D - This can’t be fixed, both are already on
- E - Don’t know

Initial Image



How do we fix the aliasing in the front of this rendered image?

- A - Need to turn on bi-linear interpolation
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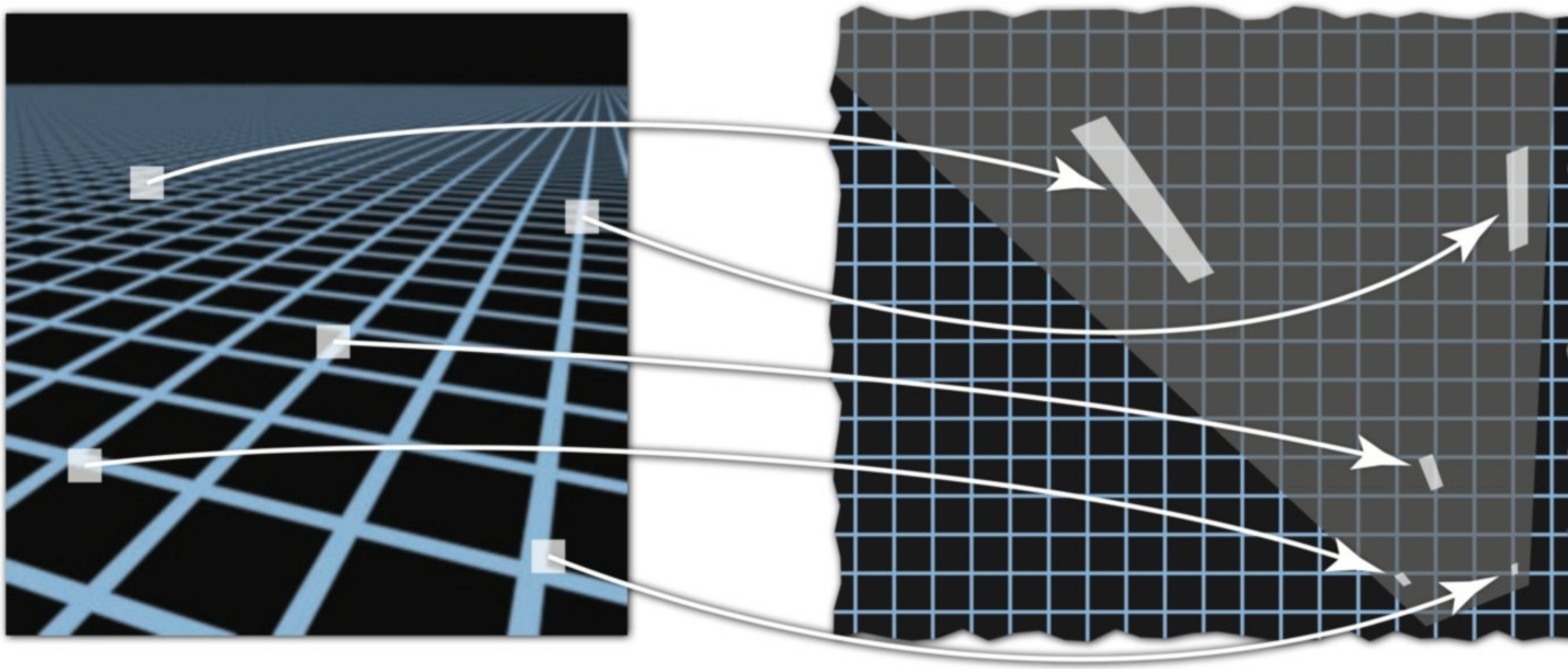
- C - Need to turn on both to fix this
- D - This can’t be fixed, both are already on
- E - Don’t know

Anisotropic texturing

Screen pixel footprint in texture space



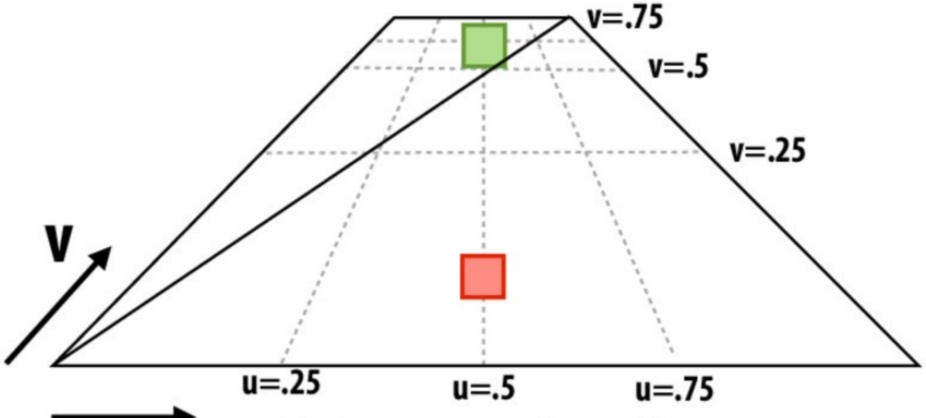
Screen space

Texture space

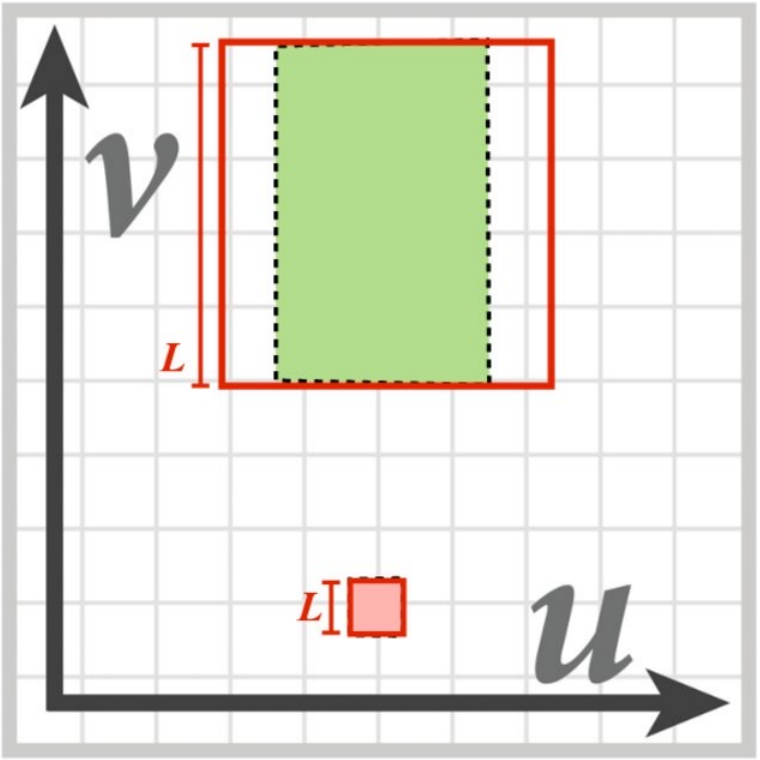
Texture sampling pattern not rectilinear or isotropic

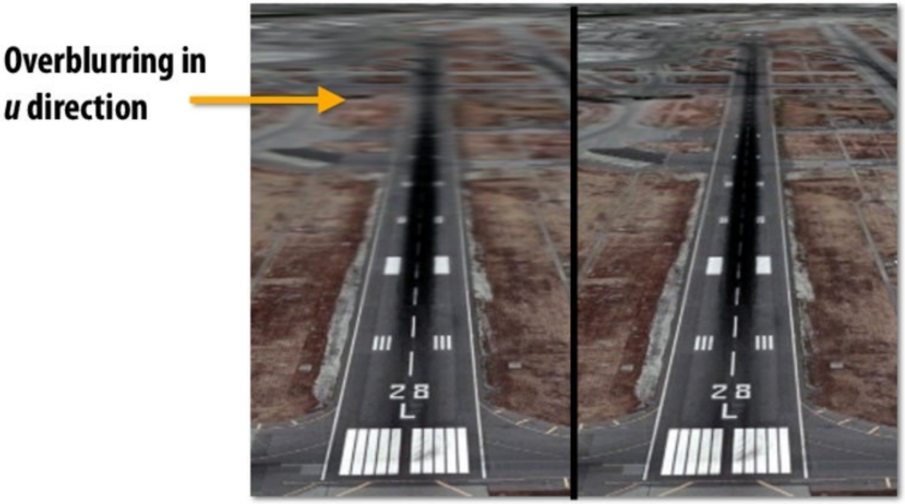
Pixel area may not map to isotropic region in texture space

Proper filtering requires anisotropic filter footprint



Texture space: viewed from camera with perspective





Trilinear (Isotropic) Filtering | Anisotropic Filtering

(Modern anisotropic texture filtering solutions combine multiple mip map samples)

Summed-Area Tables for Texture Mapping

Franklin C. Crow
Computer Sciences Laboratory
Xerox Palo Alto Research Center

Abstract

Texture-map computations can be made tractable through use of precalculated tables which allow computational costs independent of the texture density. The first example of this technique, the "mip" map, uses a set of tables containing successively lower-resolution representations filtered down from the discrete texture function. An alternative method using a single table of values representing the integral over the texture function rather than the function itself may yield superior results at similar cost. The necessary algorithms to support the new technique are explained. Finally, the cost and performance of the new technique is compared to previous techniques.

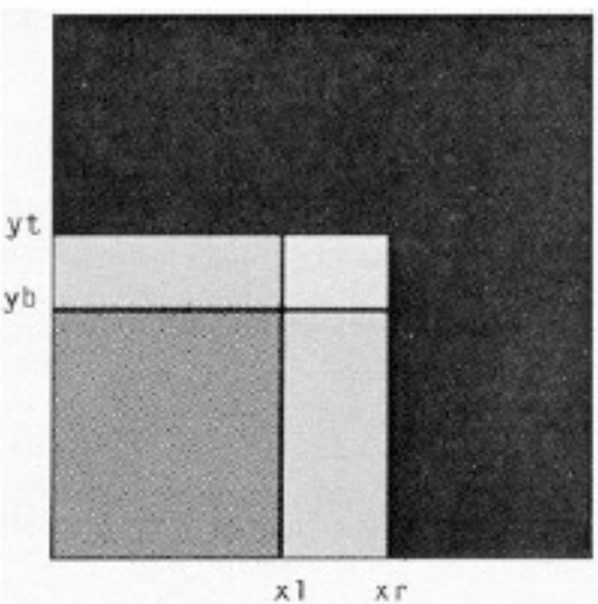


Figure 2: Calculation of summed area from table.

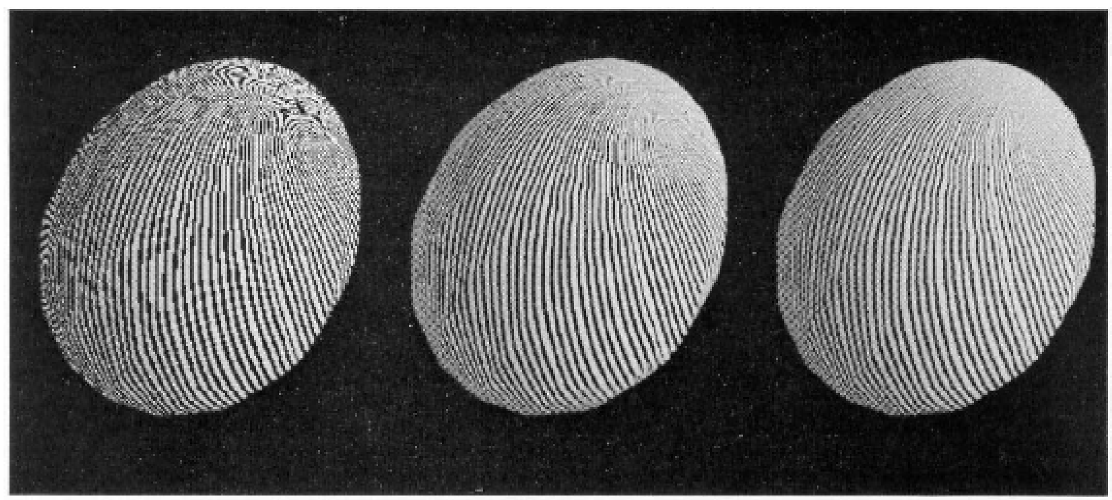
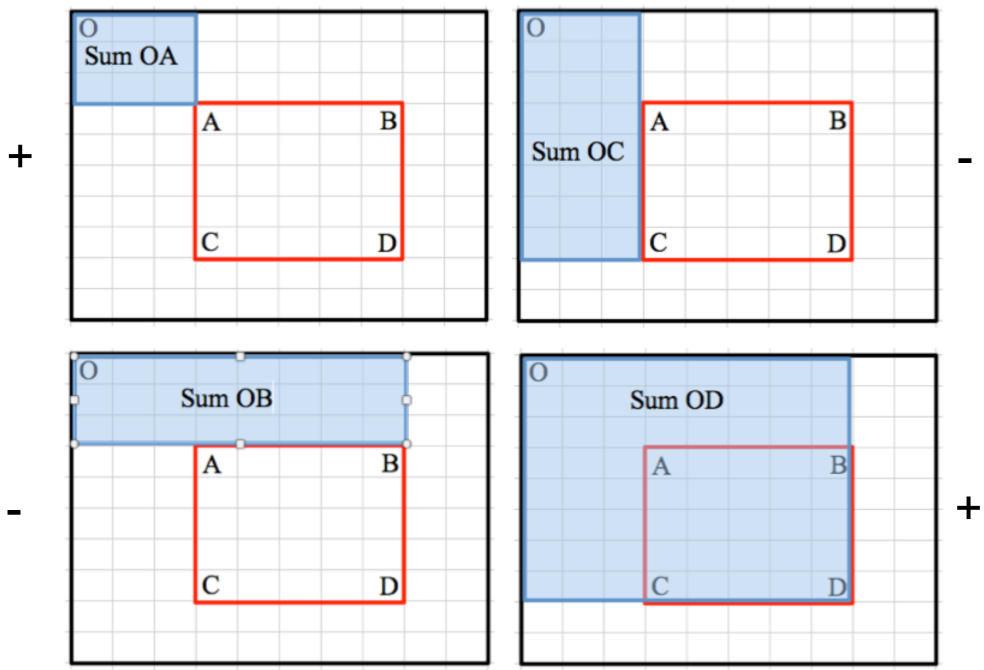


Figure 3: Left: nearest pixel (1 min. CPU time), middle: multiple table (2 1/4 min.), right: summed table (2 min.).

Summed Area Table

Stores the sum in each pixel



1.

31	2	4	33	5	36
12	26	9	10	29	25
13	17	21	22	20	18
24	23	15	16	14	19
30	8	28	27	11	7
1	35	34	3	32	6

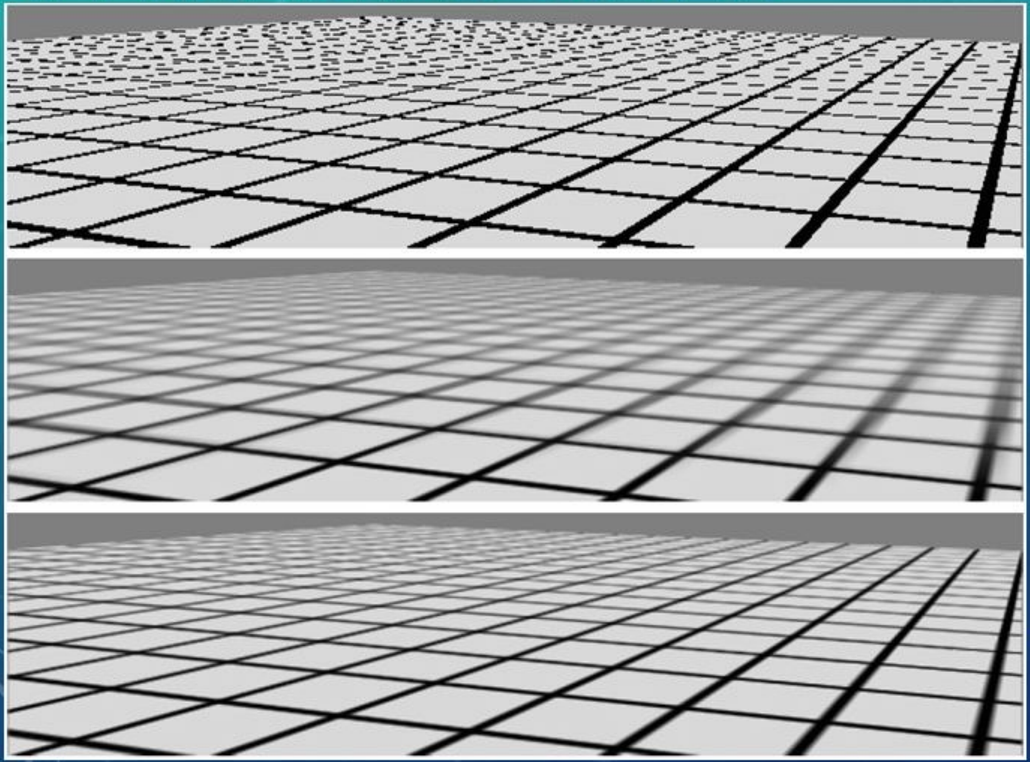
2.

31	33	37	70	75	111
43	71	84	127	161	222
56	101	135	200	254	333
80	148	197	278	346	444
110	186	263	371	450	555
111	222	333	444	555	666

$$15 + 16 + 14 + 28 + 27 + 11 =$$

$$101 + 450 - 254 - 186 = 111$$

MINIFICATION: COMPARISON OF APPROACHES SO FAR



Nearest neighbor

Mipmapping

Summed area tables

Shape of the region

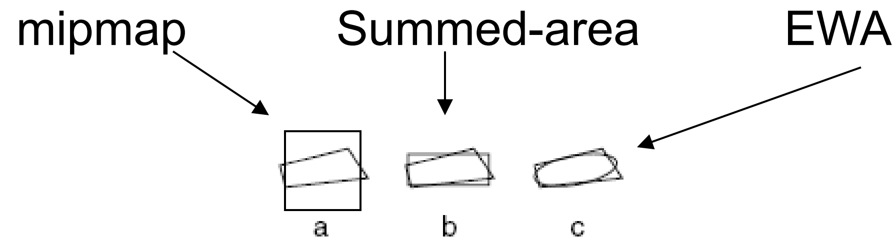
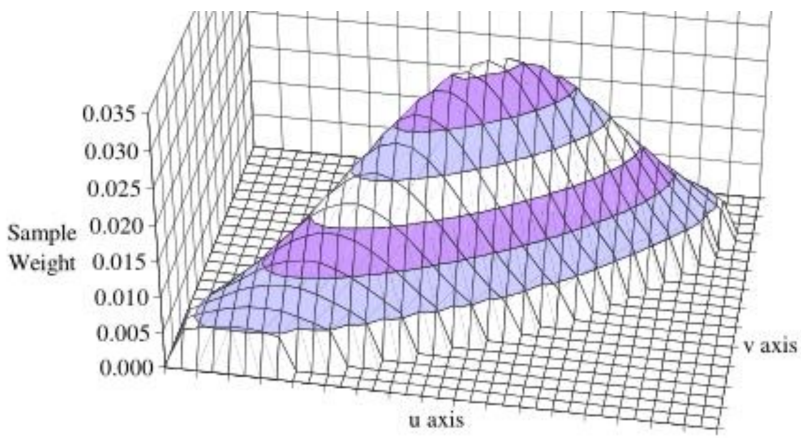


Figure 4: Approximating a quadrilateral texture area with (a) a square, (b) a rectangle, and (c) an ellipse. Too small an area causes aliasing; too large an area causes blurring.

The weighting when we average pixels together



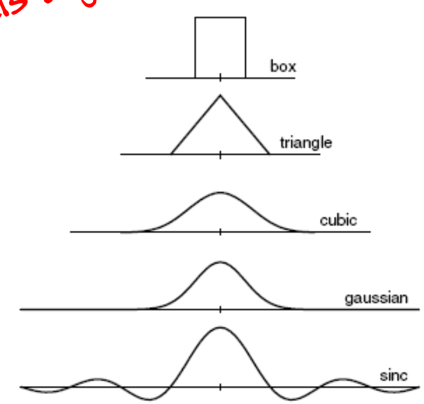
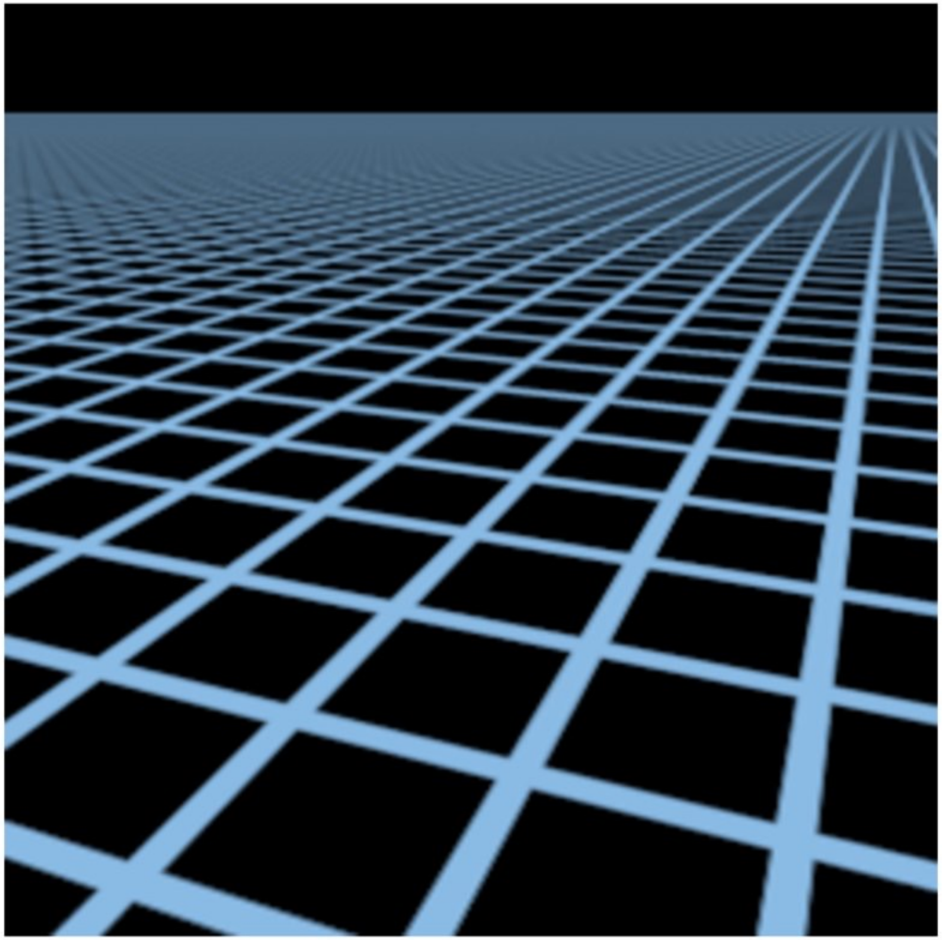
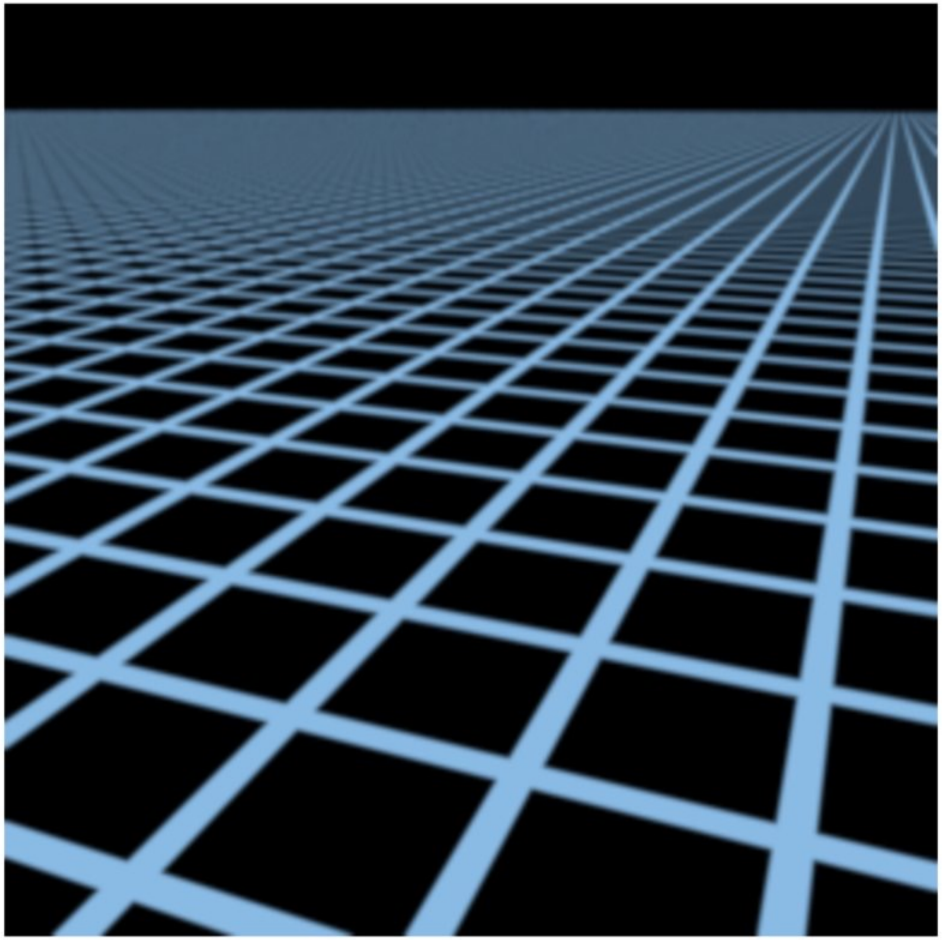


Figure 3: Cross sections of some common texture filters, ordered by quality. The top three are finite impulse response filters.

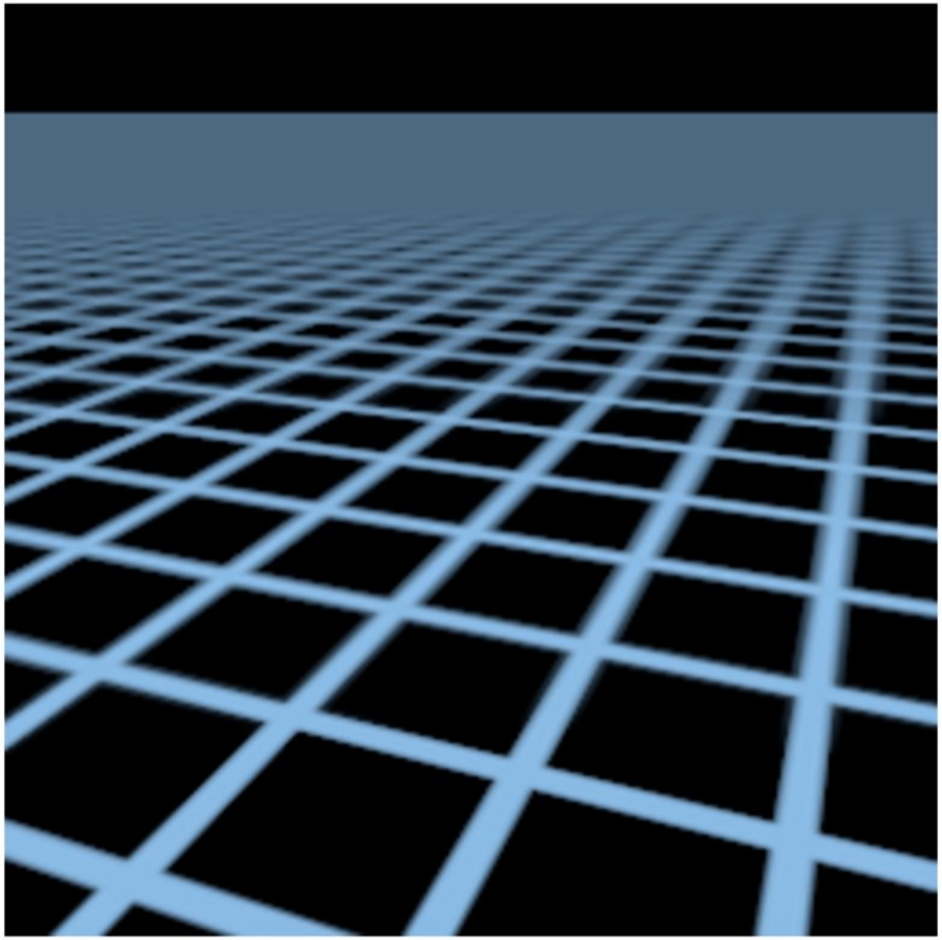
Anisotropic filtering



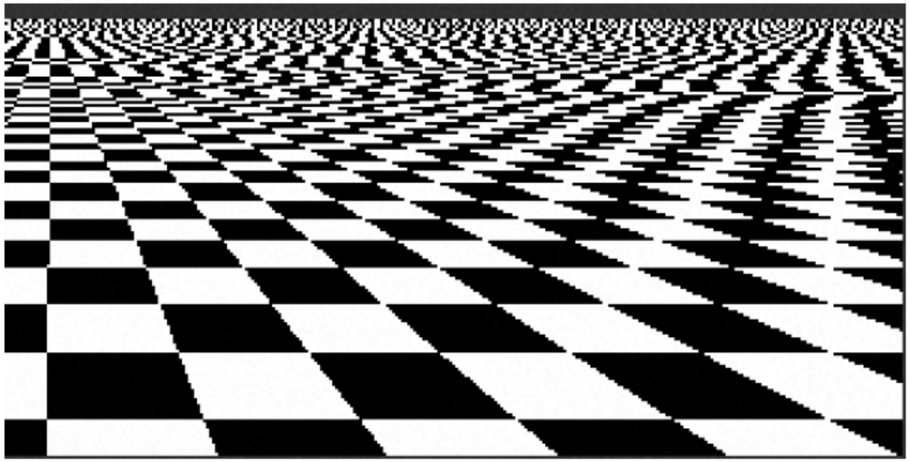
Elliptical weighted average (EWA) filtering
(uses multiple lookups into mip-map to approximate filter region)



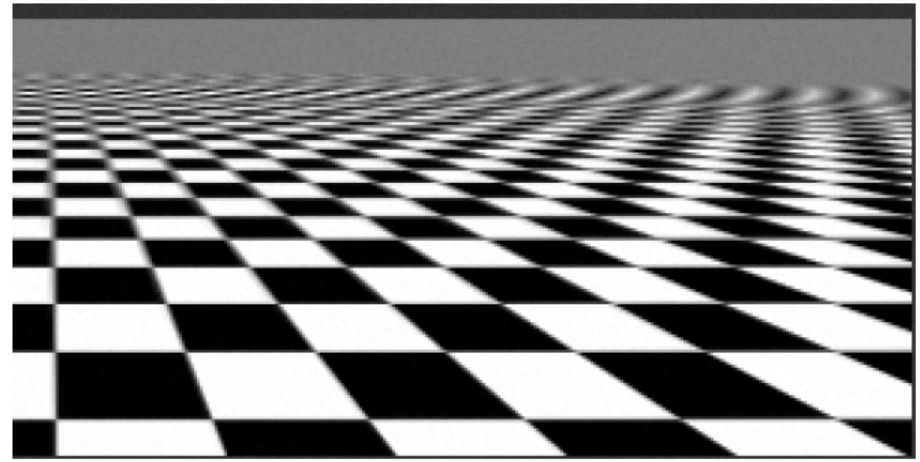
Supersampling 512x
(desired answer)



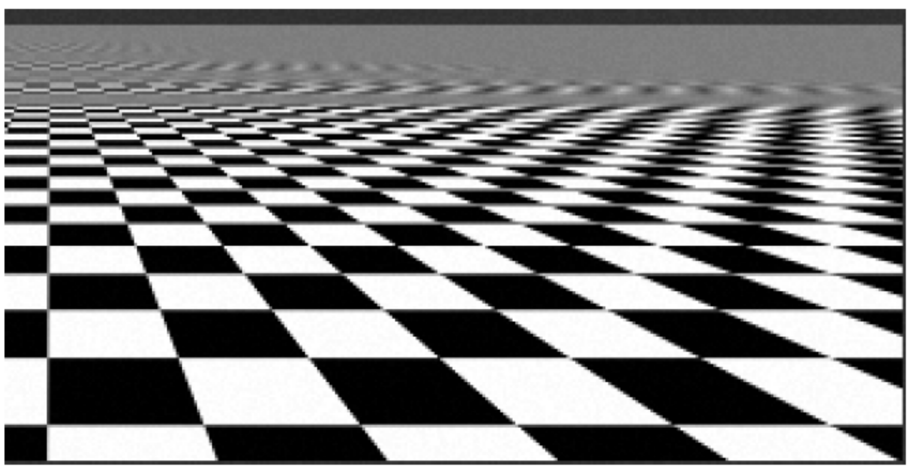
Mipmap trilinear sampling



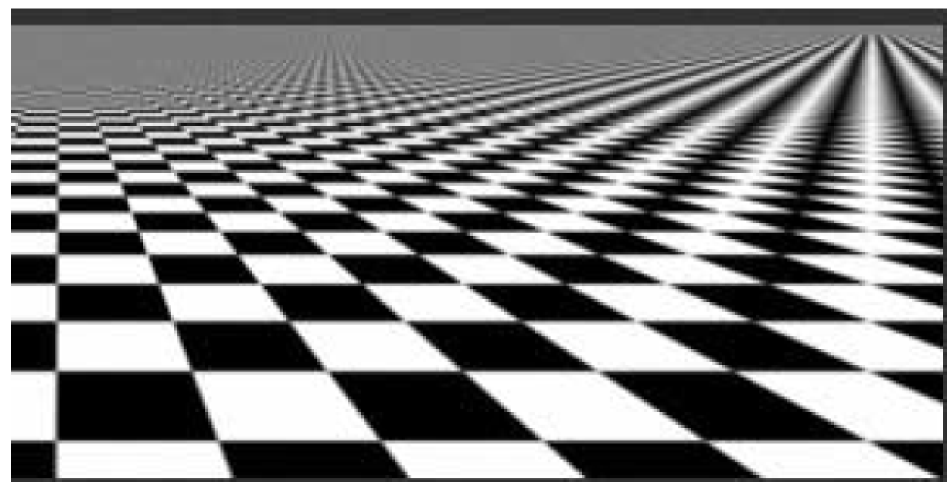
(a) Point sampling.



(b) Trilinear interpolation on a pyramid.

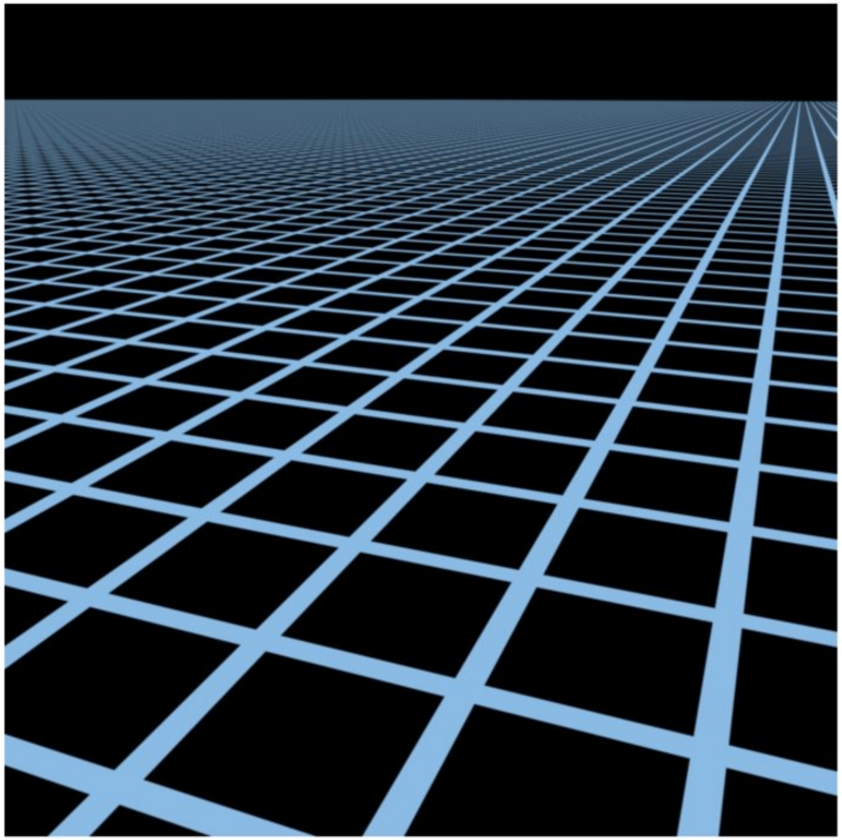


(c) First-order repeated integration (summed area table).

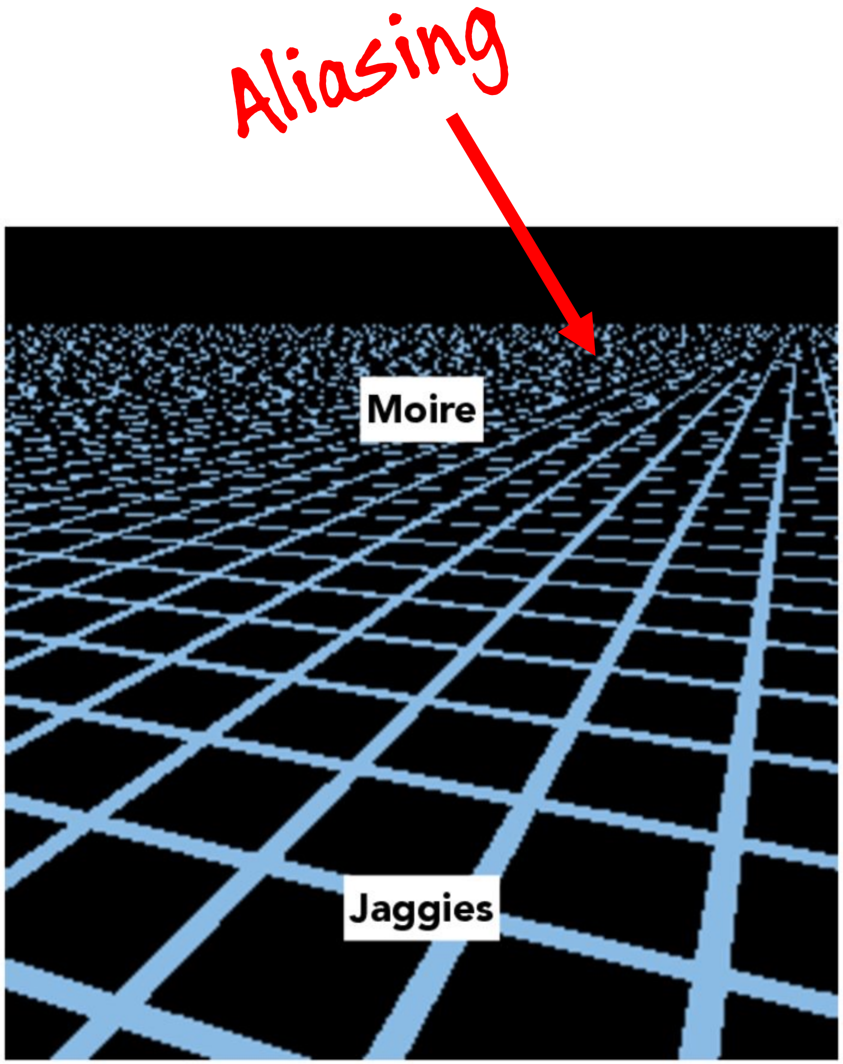


(e) EWA filter with Gaussian cross section on a pyramid.

Antialiasing

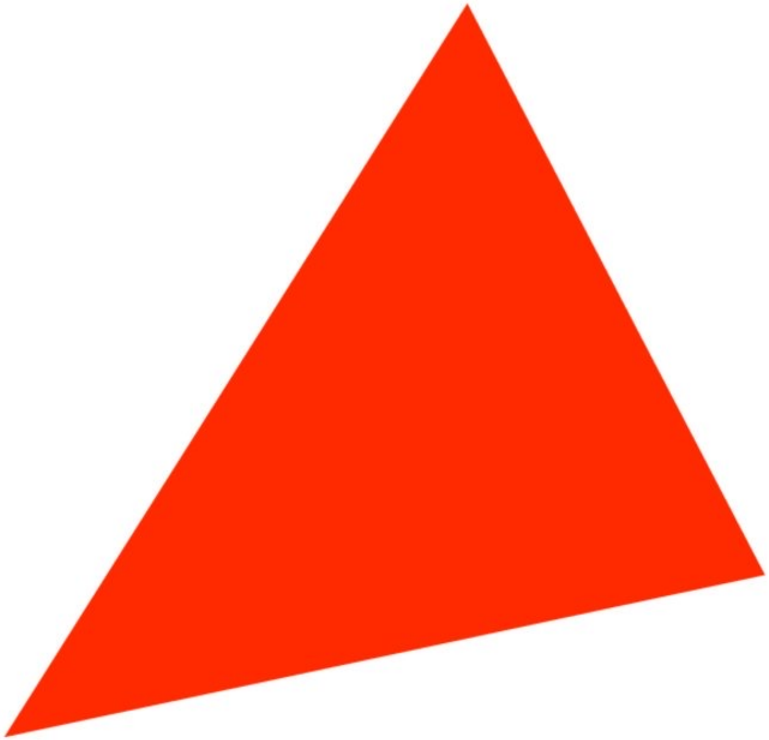


Source image: 1280x1280 pixels

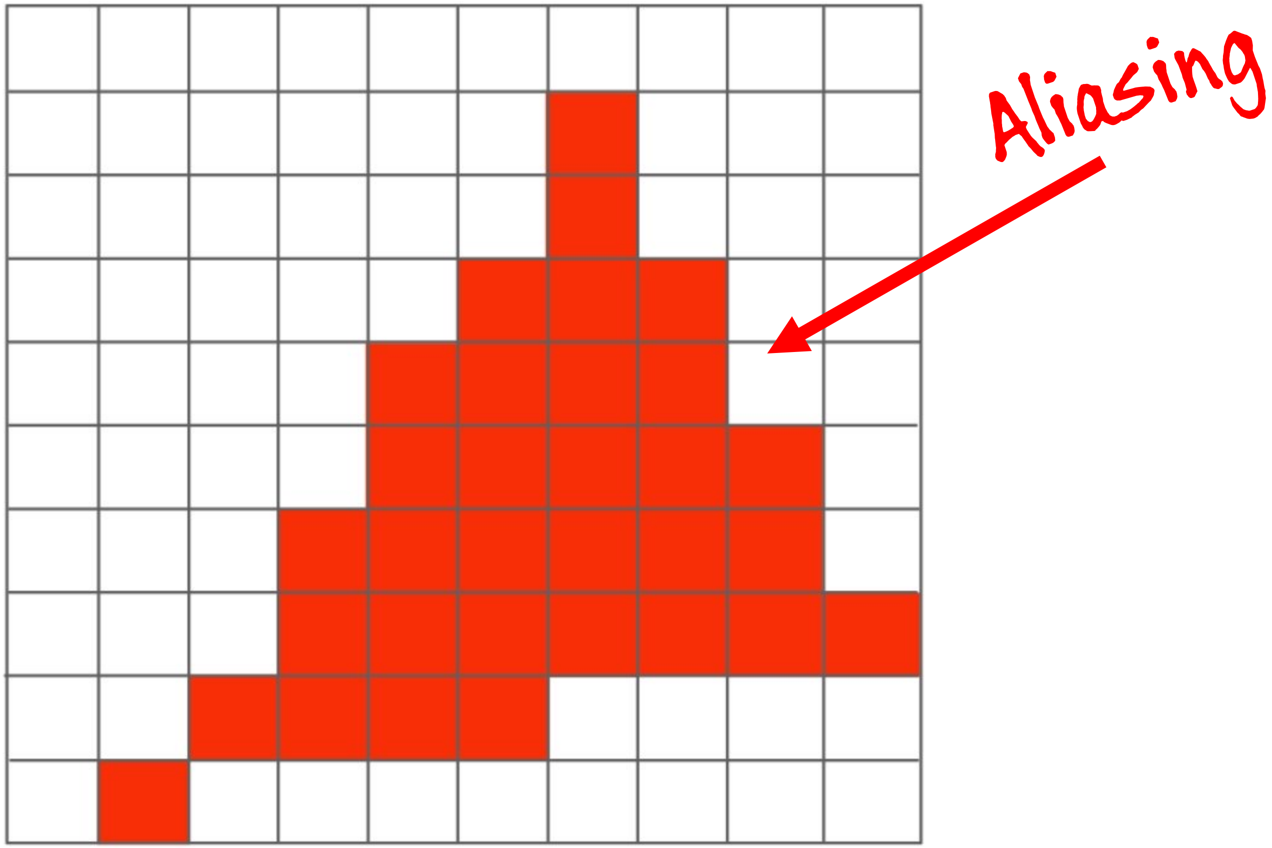


Rendered image: 256x256 pixels

Compare: the continuous triangle function

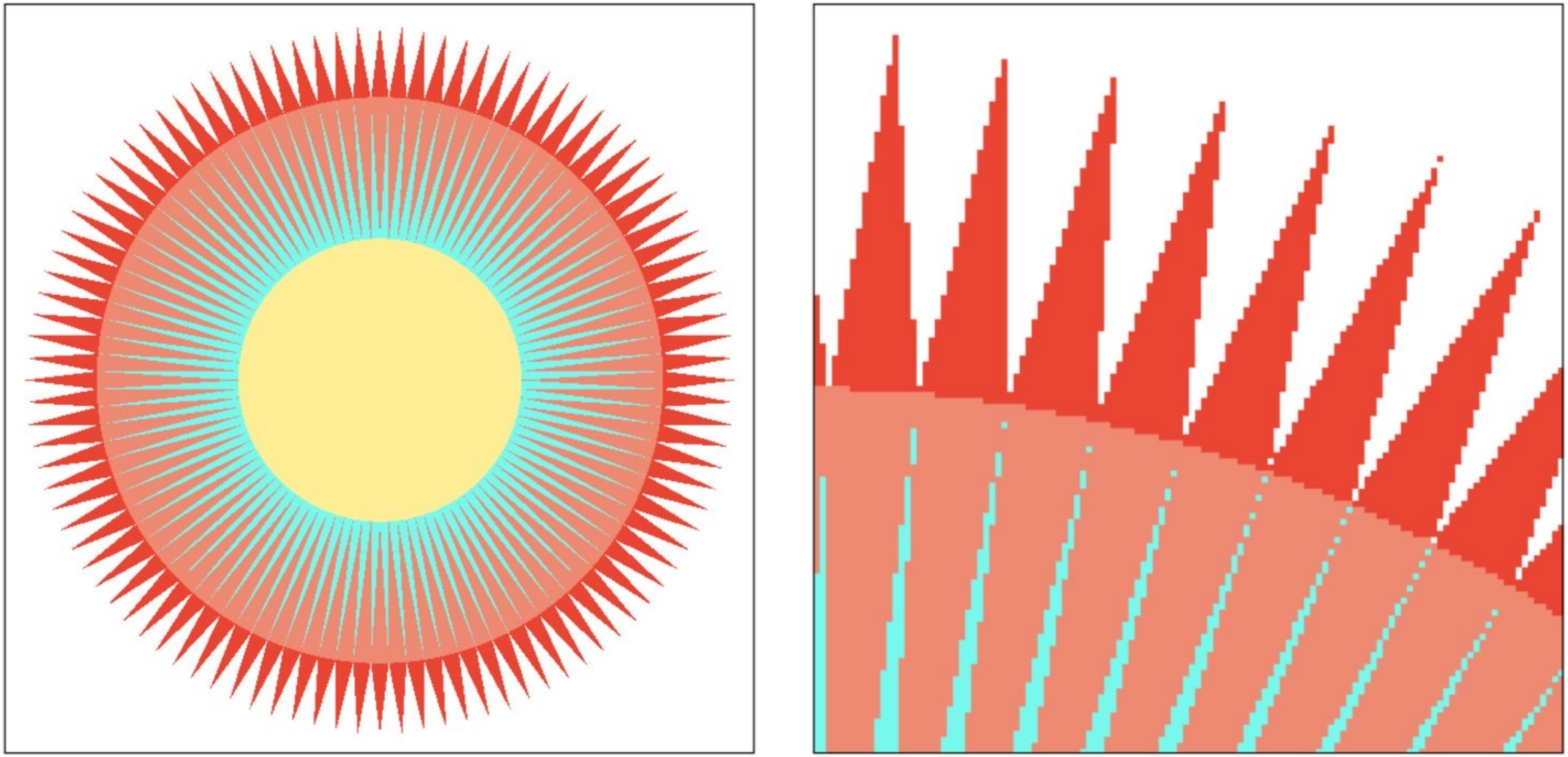


What's wrong with this picture?



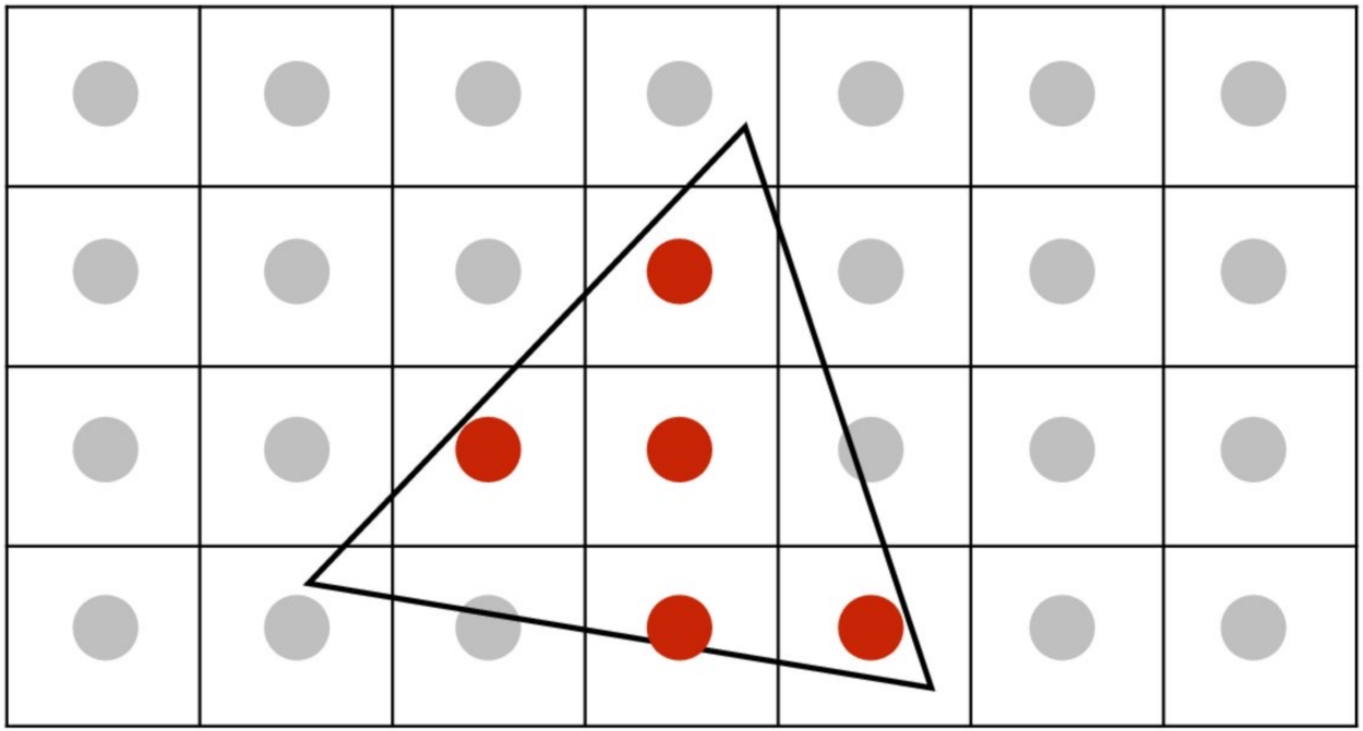
Jaggies!

Jaggies (staircase pattern)



Is this the best we can do?

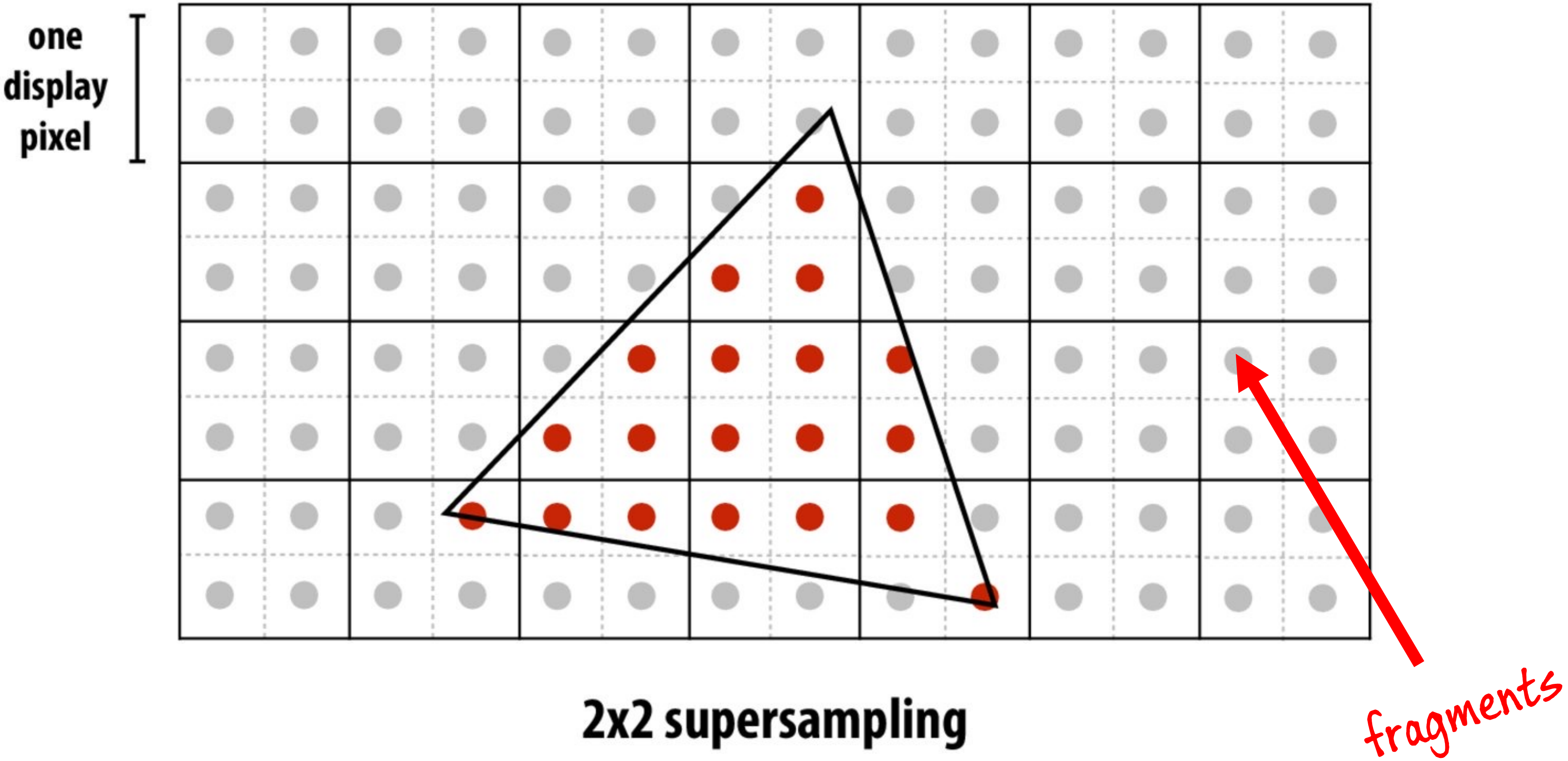
Point sampling: one sample per pixel



Supersampling: step 1

Take NxN samples in each pixel

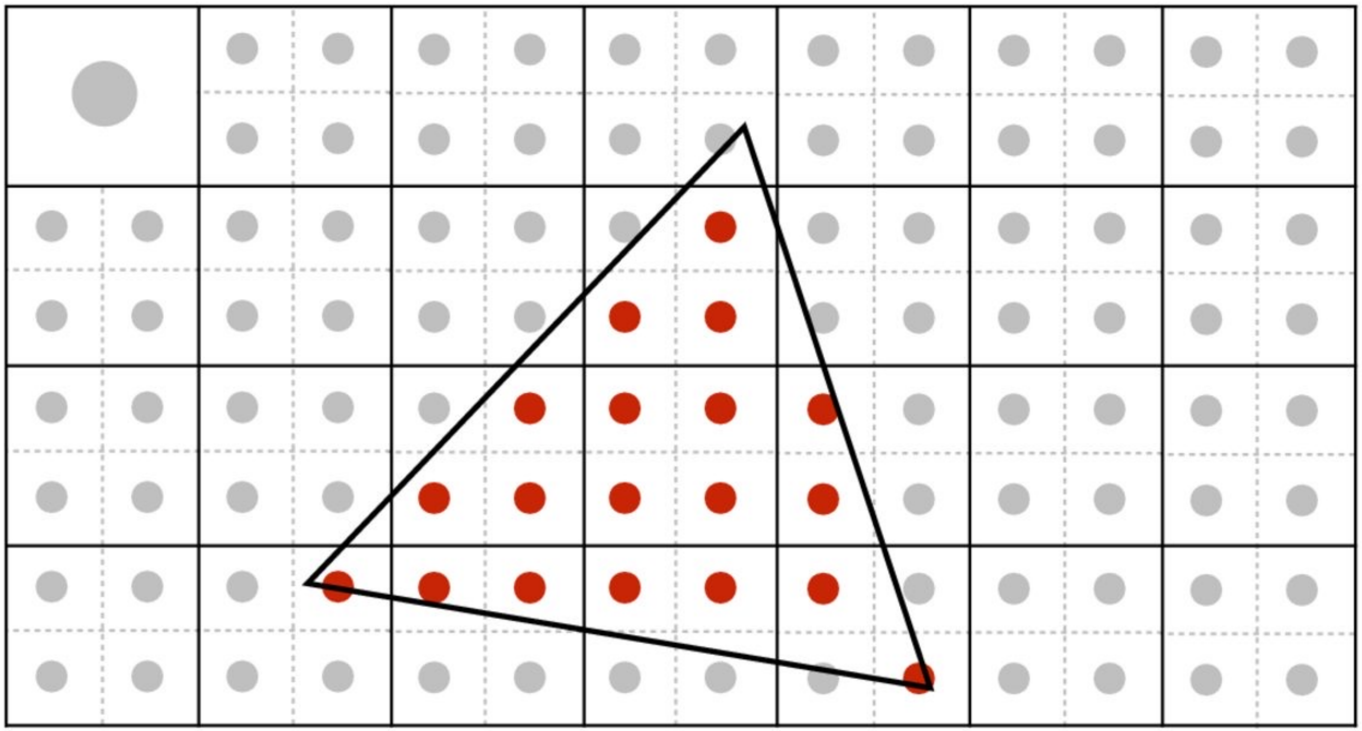
(but… how do we use these samples to drive a display, since there are four times more samples than display pixels!)



2x2 supersampling

Supersampling: step 2

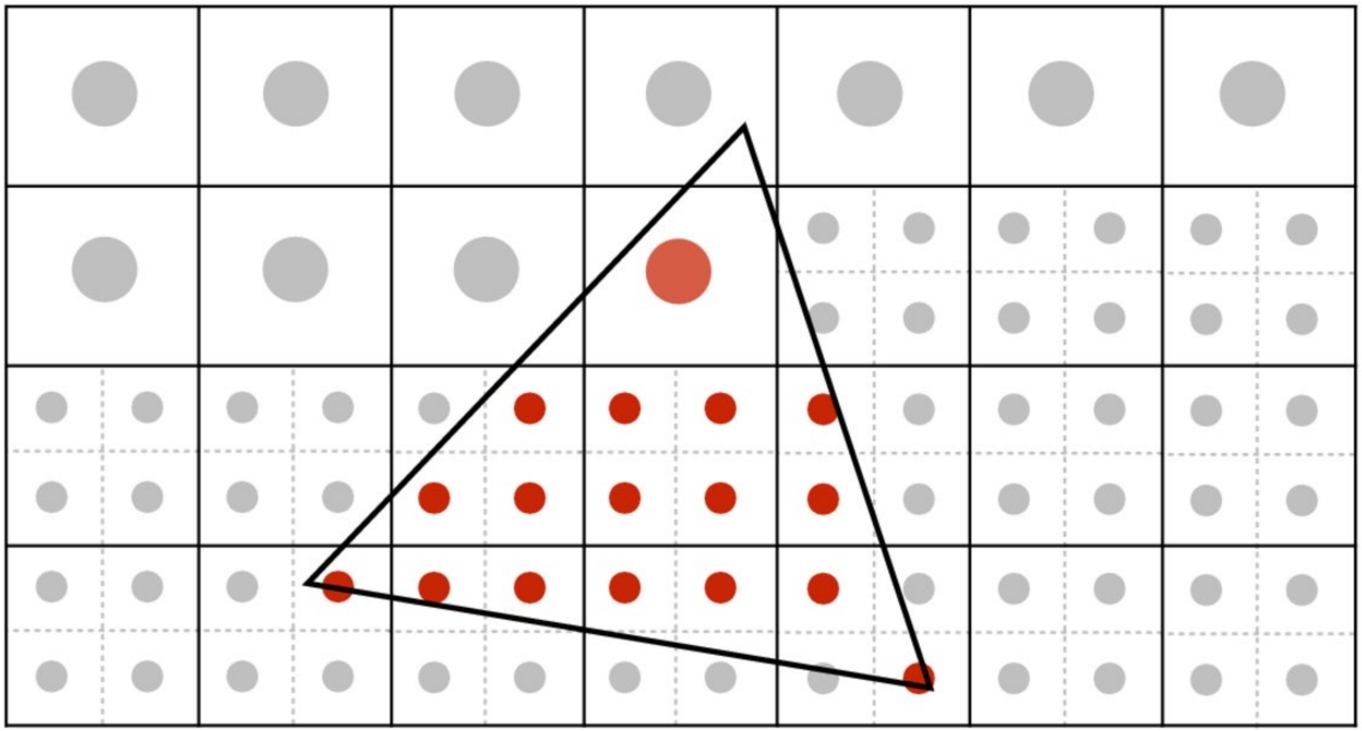
Average the NxN samples “inside” each pixel



Averaging down

Supersampling: step 2

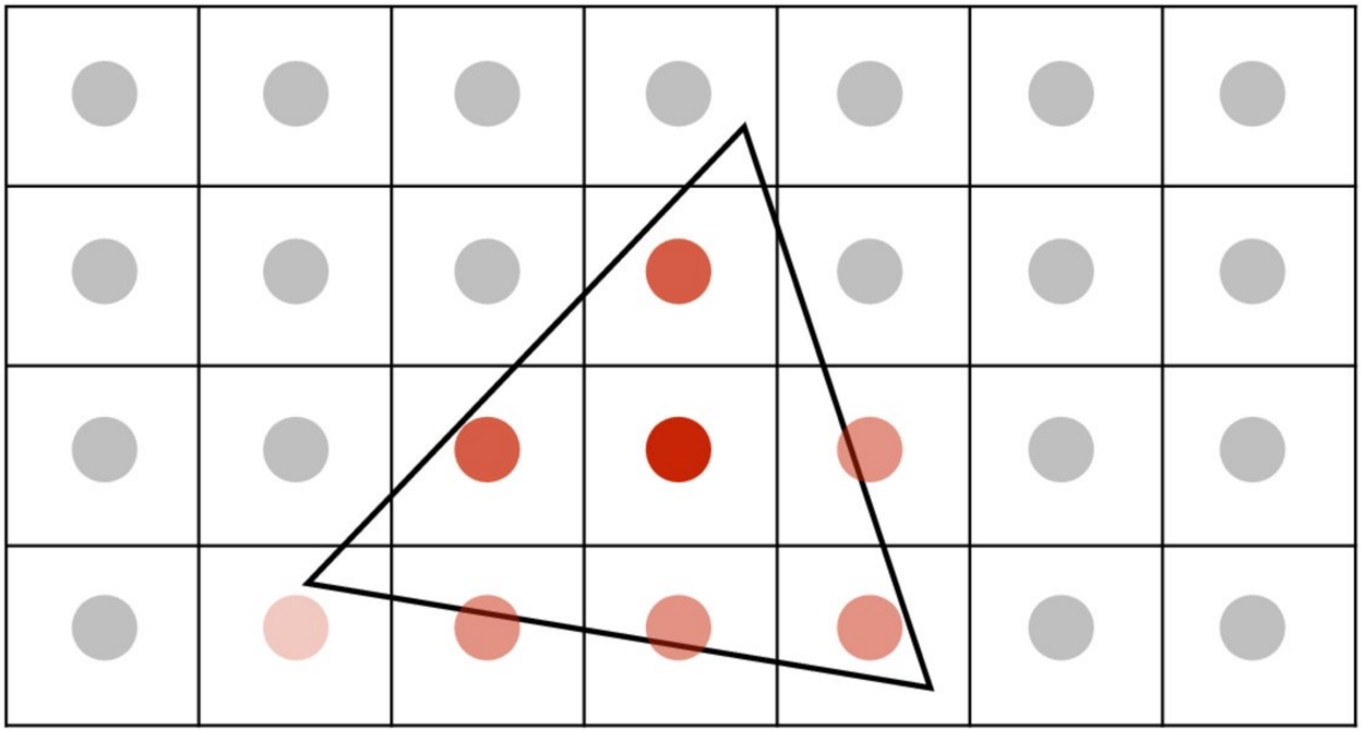
Average the NxN samples "inside" each pixel



Averaging down

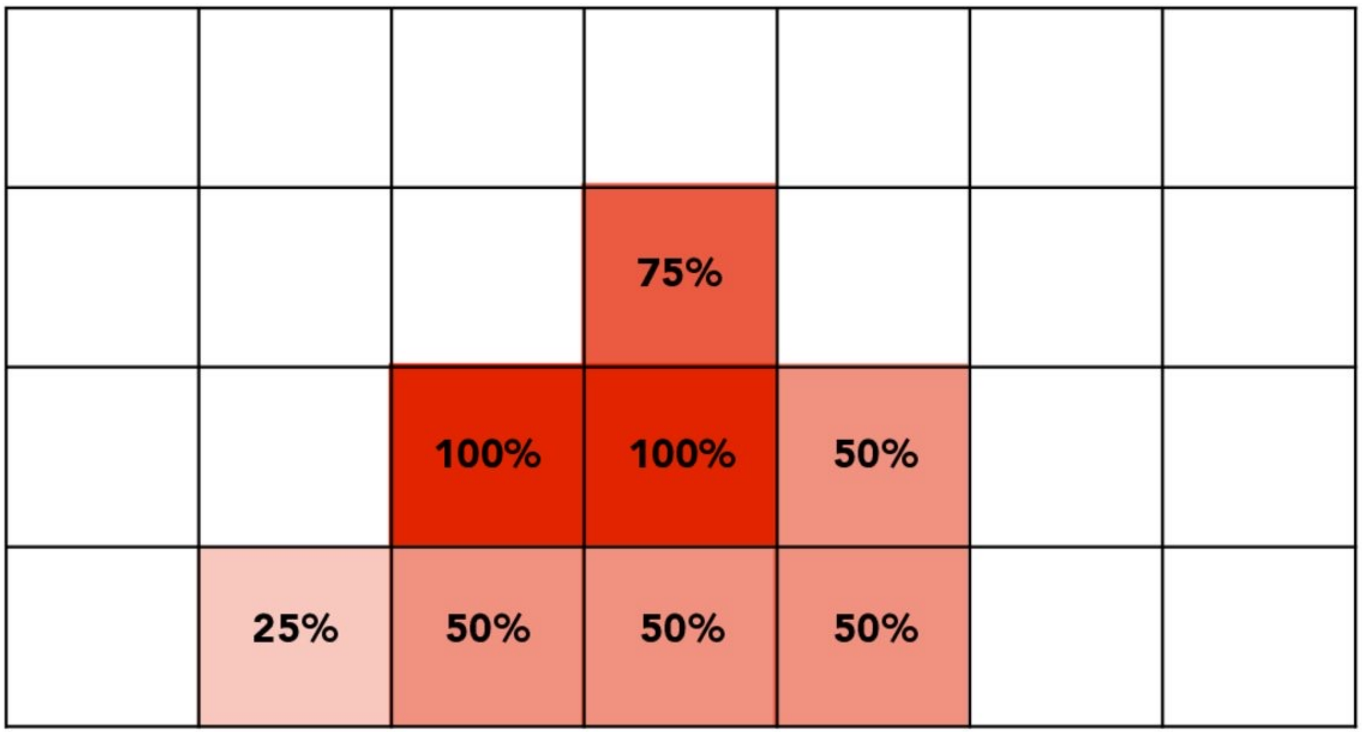
Supersampling: step 2

Average the NxN samples "inside" each pixel

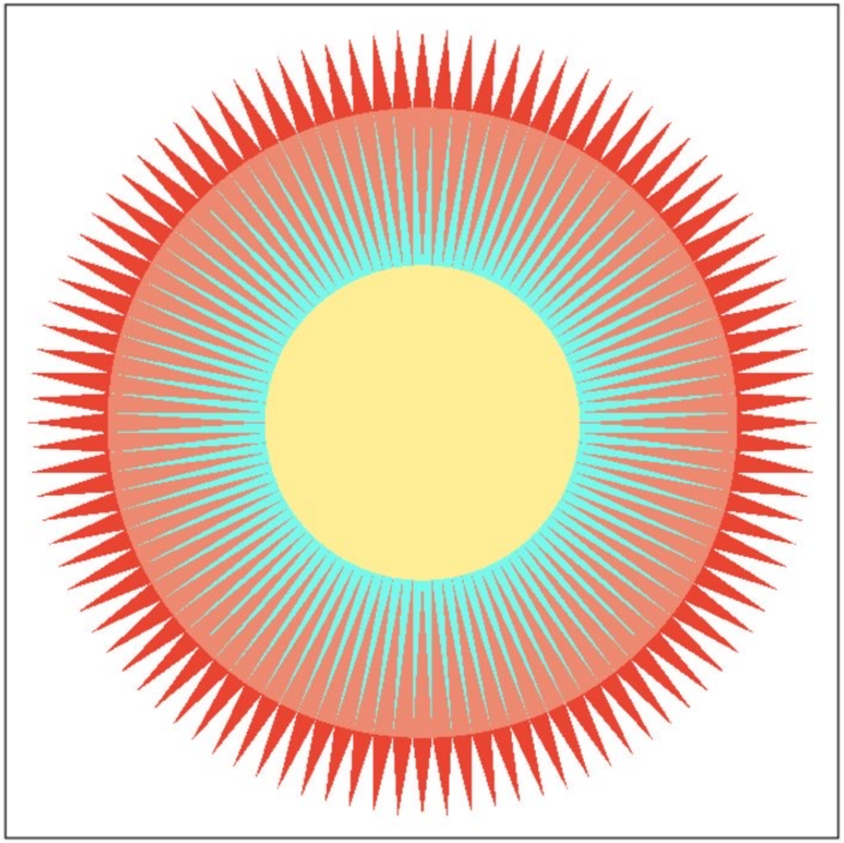


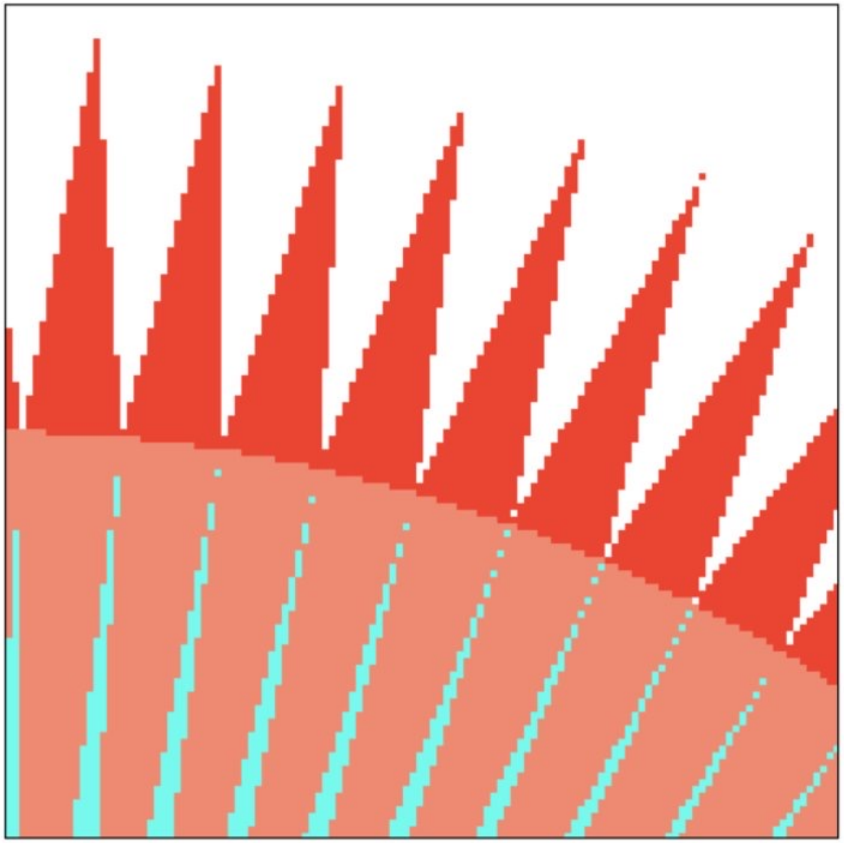
Supersampling: result

This is the corresponding signal emitted by the display



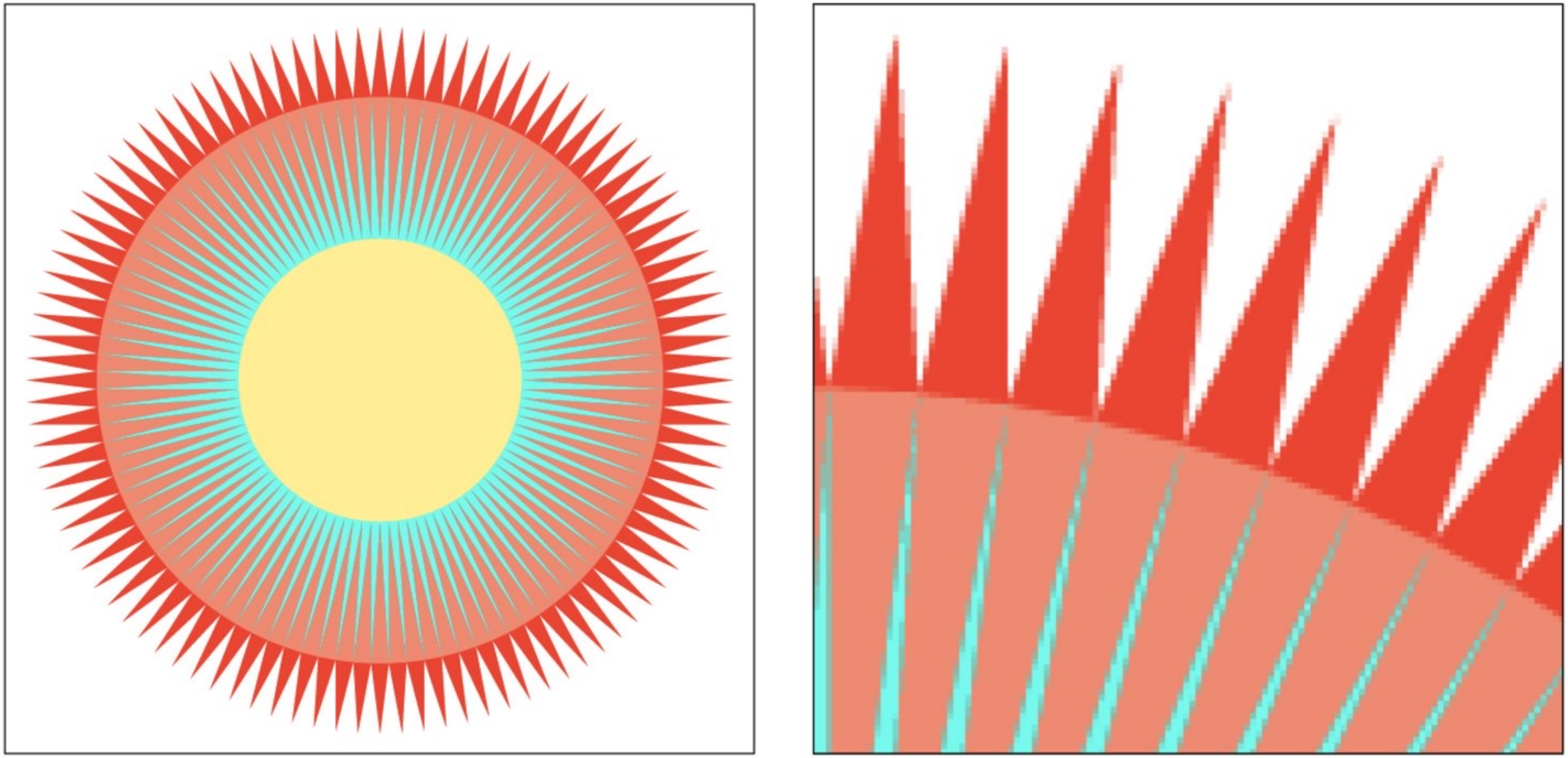
Point sampling





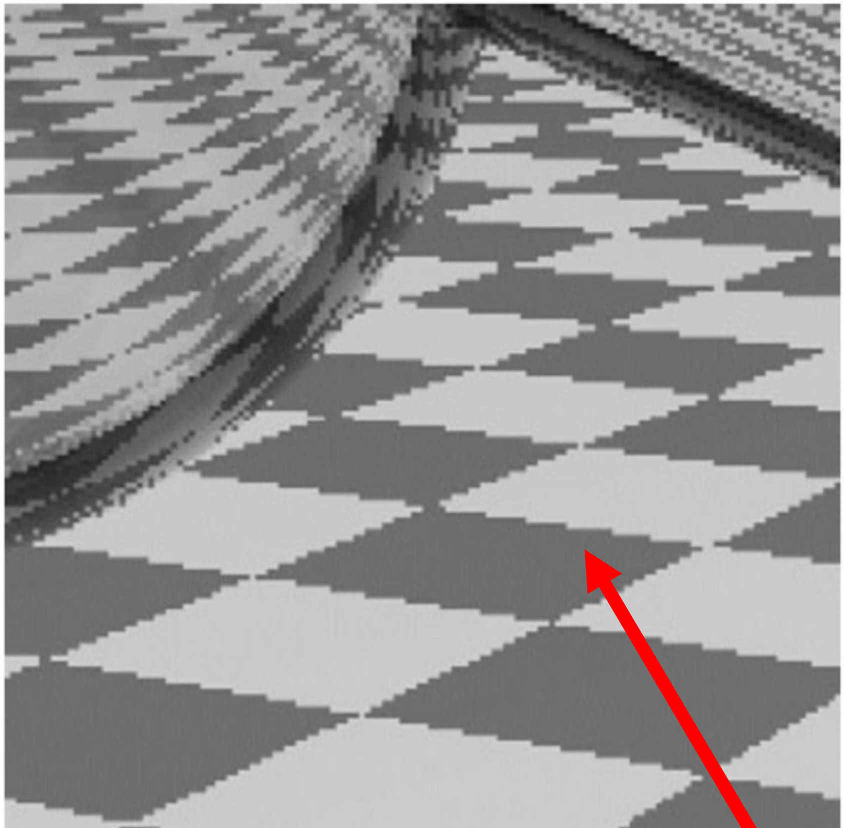
One sample per pixel

4x4 supersampling + downsampling

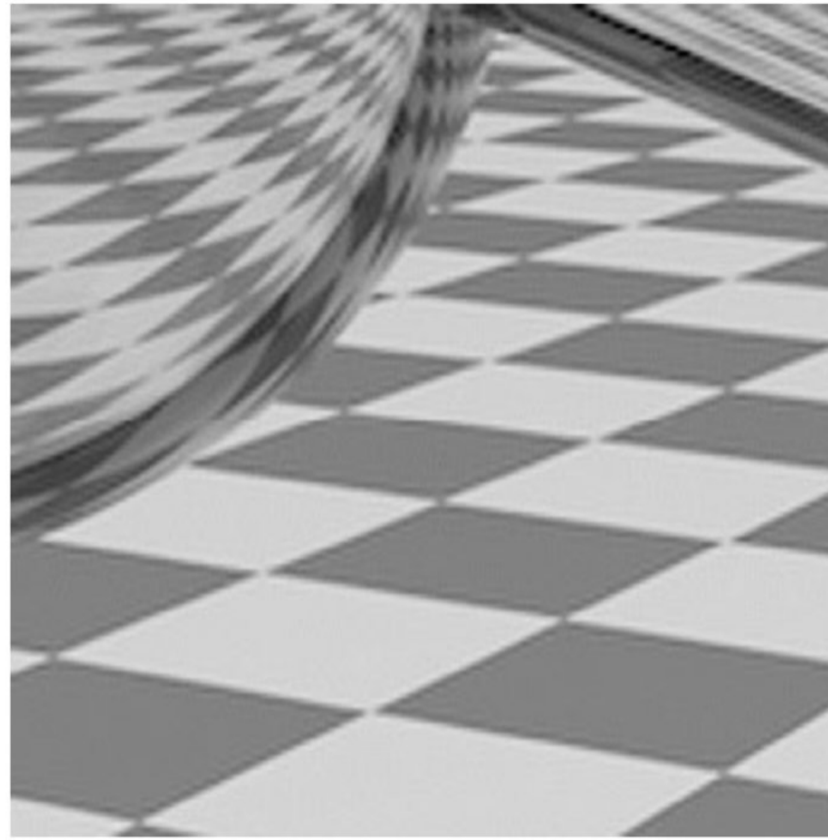


Pixel value is average of 4x4 samples per pixel

Point sampling vs anti-aliasing



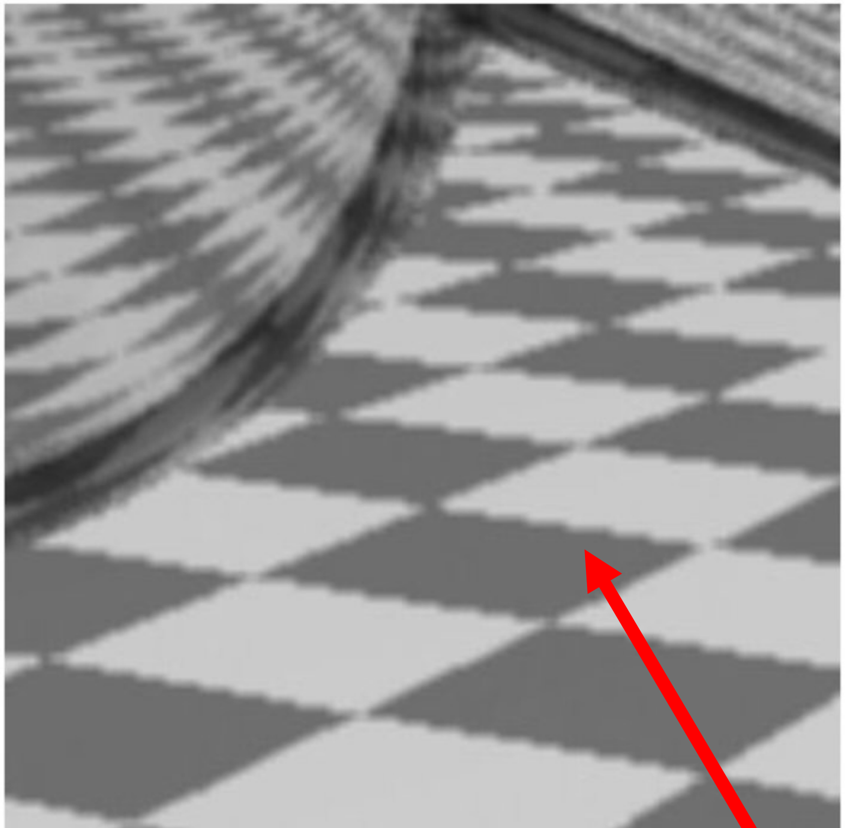
Jaggies



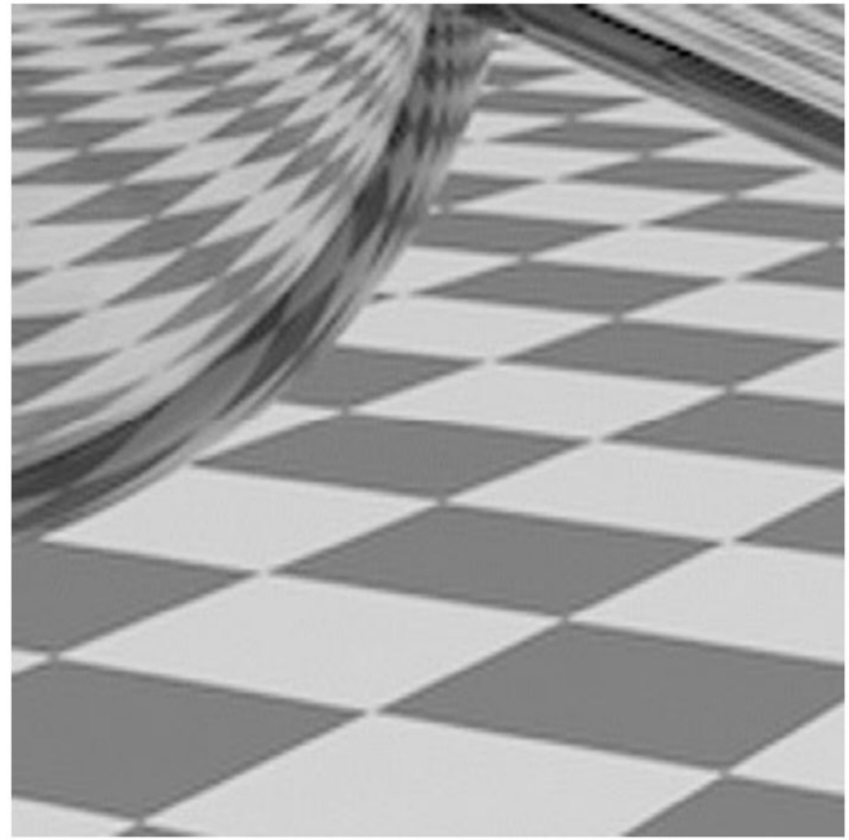
Pre-filtered

Could I just blur this and fix it?

Anti-aliasing vs blurring an aliased result



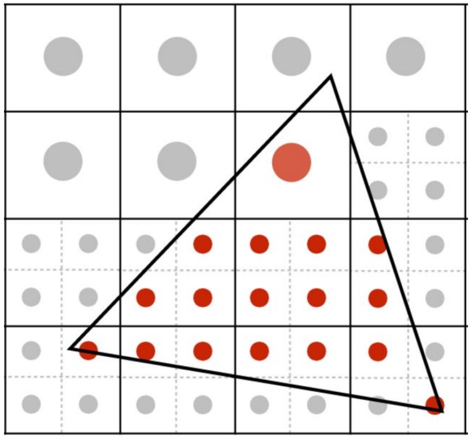
Blurred Jaggies
(Sample then filter)

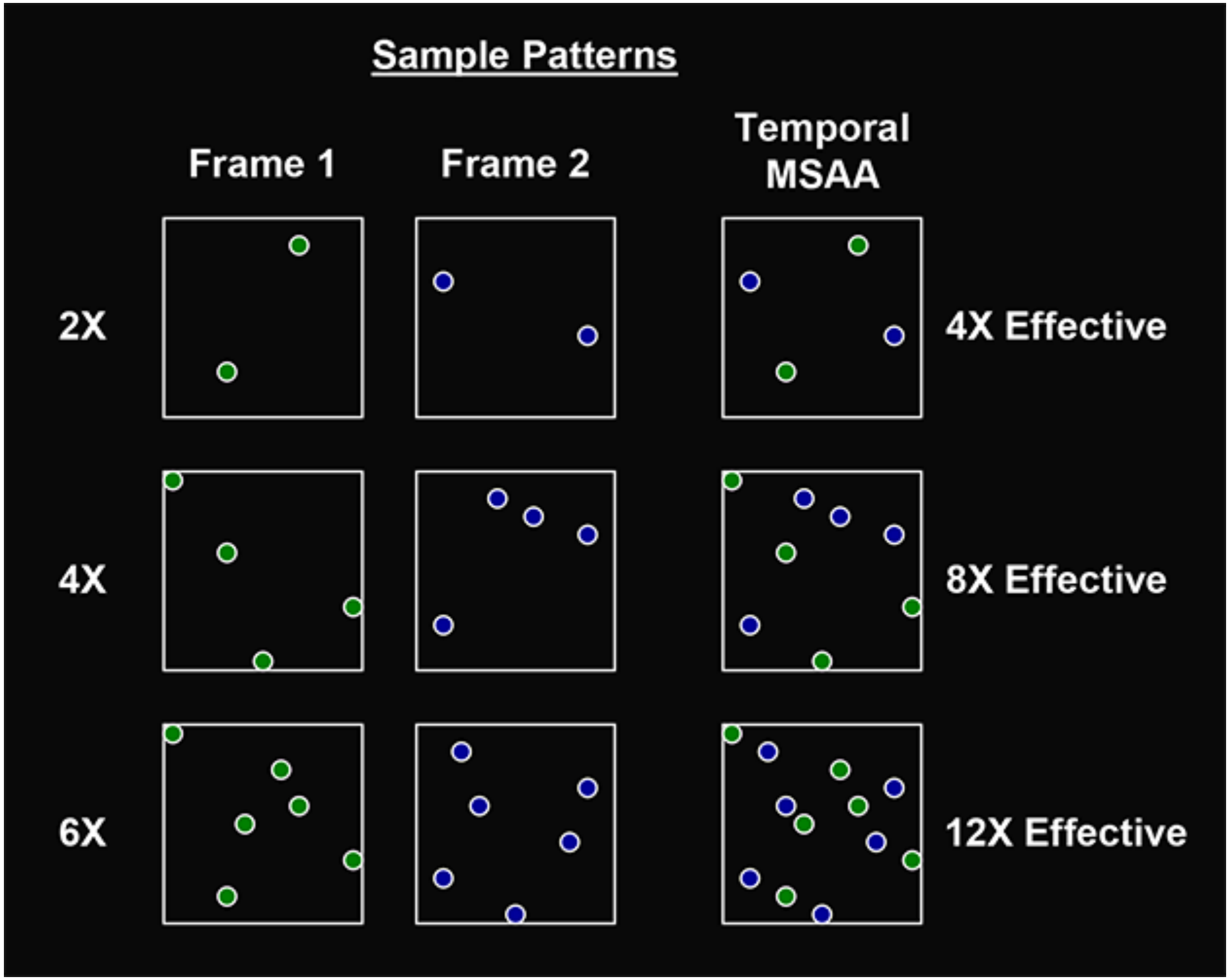


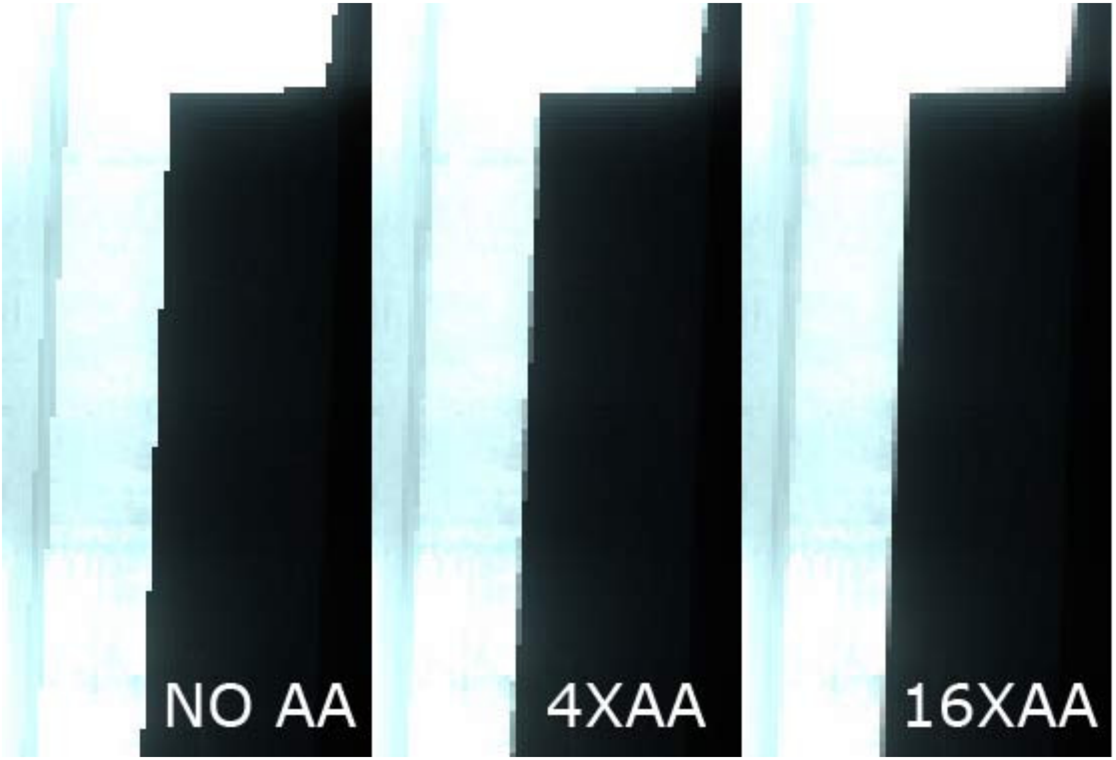
Pre-Filtered
(Filter then sample)

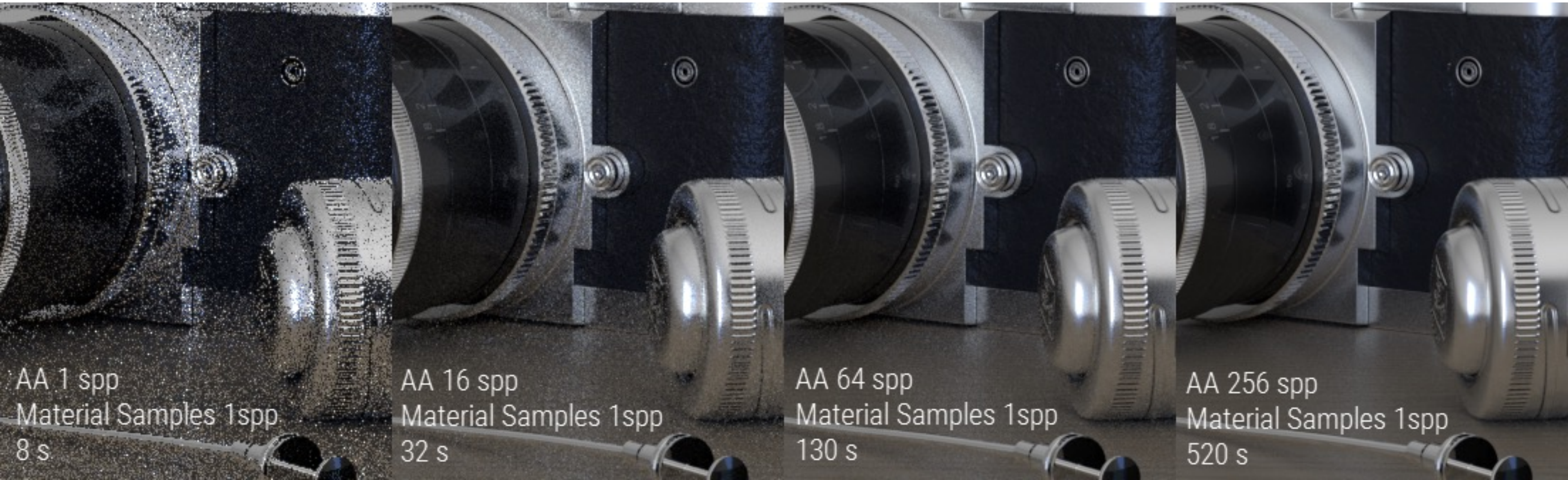
Once you have aliasing, its too late

How many samples per pixel and where?






NO AA
4XAA
16XAA


AA 1 spp
Material Samples 1spp
8 s
AA 16 spp
Material Samples 1spp
32 s
AA 64 spp
Material Samples 1spp
130 s
AA 256 spp
Material Samples 1spp
520 s


no aa
post aa
8x msaa

OpenGL

Specifying Texture Coordinates in OpenGL

```
glBegin(GL_TRIANGLES);
    glNormal3fv(n1);
    glTexCoord2f(s1,t1);
    glVertex3fv(v1);

    glNormal3fv(n2);
    glTexCoord2f(s2,t2);
    glVertex3fv(v2);

    glNormal3fv(n3);
    glTexCoord2f(s3,t3);
    glVertex3fv(v3);
glEnd();
```

Example Setup

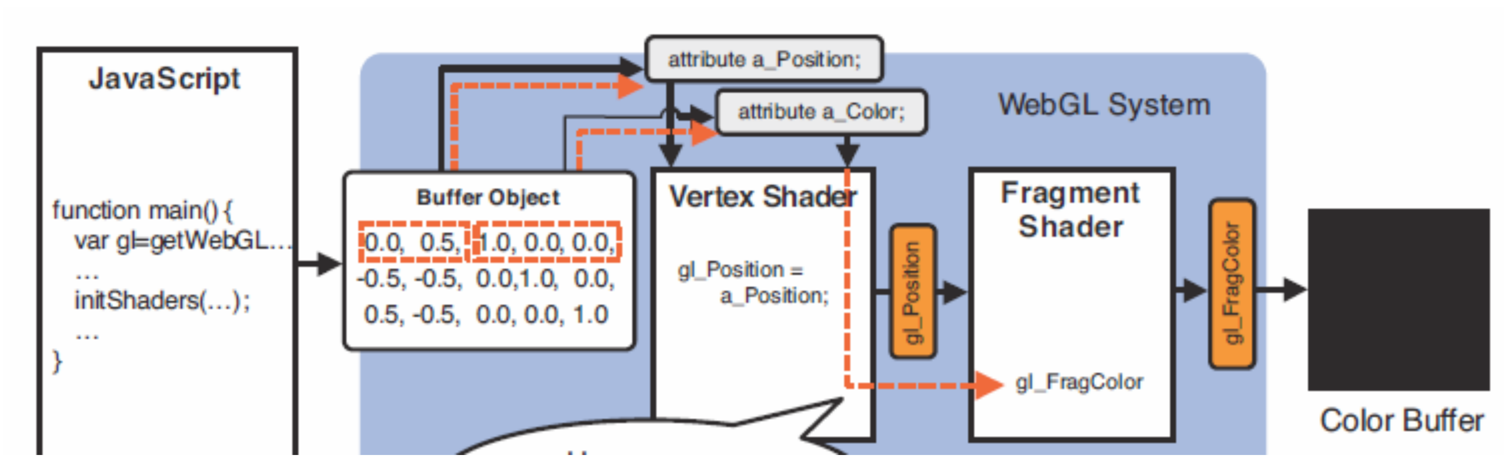
```
glEnable(GL_TEXTURE_2D);
glTexEnvf(GL_TEXTURE_ENV, GL_TEXTURE_ENV_MODE, GL_MODULATE);

glTexParameterf(GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_REPEAT);
glTexParameterf(GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_REPEAT);
glTexParameterf(GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER,
                GL_LINEAR);
glTexParameterf(GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER,
                GL_LINEAR_MIPMAP_LINEAR);

gluBuild2DMipmaps(GL_TEXTURE_2D, 3, width, height, GL_RGB,
                  GL_UNSIGNED_BYTE, image);

glTexImage2D(GL_TEXTURE_2D, 0, 3, width, height, 0, GL_RGB,
             GL_UNSIGNED_BYTE, image);
```

Multiple attributes



Passing data from vertex to fragment shader

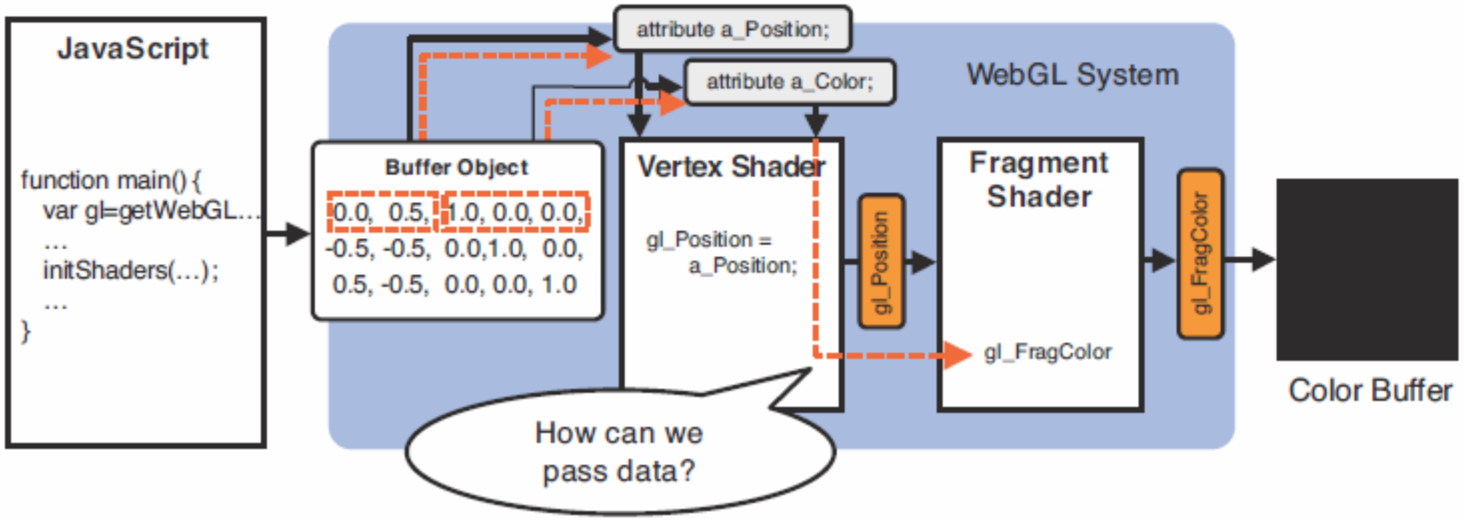


Figure 5.6 Passing data from a vertex shader to a fragment shader

Varying variable

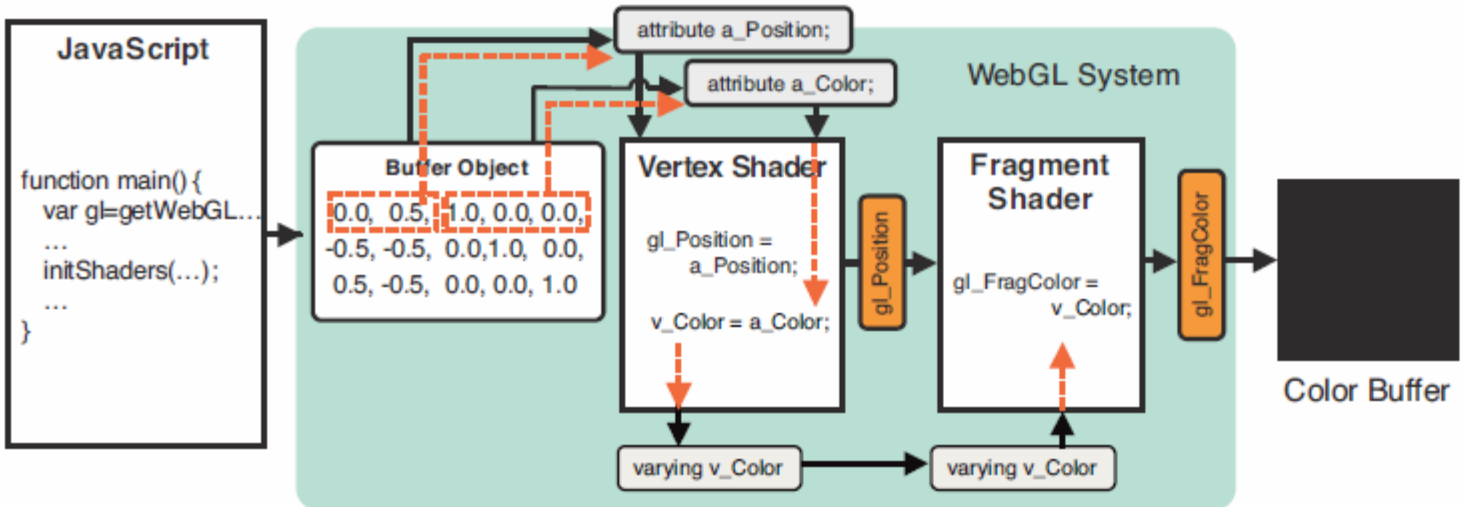


Figure 5.7 The behavior of a varying variable

```
var VSHADER_SOURCE =
  'attribute vec4 a_Position;\n' +
  'attribute vec2 a_TexCoord;\n' +
  'varying vec2 v_TexCoord;\n' +
  'void main() {\n' +
  '  gl_Position = a_Position;\n' +
  '  v_TexCoord = a_TexCoord;\n' +
  '}\n';
```

```
var FSHADER_SOURCE =
  ...
  'uniform sampler2D u_Sampler;\n' +
  'varying vec2 v_TexCoord;\n' +
  'void main() {\n' +
  '  gl_FragColor = texture2D(u_Sampler, v_TexCoord);\n' +
  '}\n';
```

```
function initTextures(gl, n)                              <- (Part4)
  var texture = gl.createTexture();   // Create a texture object
...
  // Get the storage location of the u_Sampler
  var u_Sampler = gl.getUniformLocation(gl.program, 'u_Sampler');
...
  var image = new Image();  // Create an image object
...
  // Register the event handler to be called on loading an image
  image.onload = function(){ loadTexture(gl, n, texture, u_Sampler, image); };
  // Tell the browser to load an image
  image.src = '../resources/sky.jpg';

  return true;
}

function loadTexture(gl, n, texture, u_Sampler, image){   <- (Part5)
   gl.pixelStorei(gl.UNPACK_FLIP_Y_WEBGL, 1); // Flip the image's y axis
  // Enable the texture unit 0
  gl.activeTexture(gl.TEXTURE0);
  // Bind the texture object to the target
  gl.bindTexture(gl.TEXTURE_2D, texture);

  // Set the texture parameters
  gl.texParameteri(gl.TEXTURE_2D, gl.TEXTURE_MIN_FILTER, gl.LINEAR);
  // Set the texture image
  gl.texImage2D(gl.TEXTURE_2D, 0, gl.RGB, gl.RGB, gl.UNSIGNED_BYTE, image);

  // Set the texture unit 0 to the sampler
  gl.uniform1i(u_Sampler, 0);
...
  gl.drawArrays(gl.TRIANGLE_STRIP, 0, n); // Draw a rectangle
}
```

Takes a while to load, so set up a callback

```
function initTextures(gl, n)                              <- (Part4)
  var texture = gl.createTexture();   // Create a texture object
  ...
  // Get the storage location of the u_Sampler
  var u_Sampler = gl.getUniformLocation(gl.program, 'u_Sampler');
  ...
  var image = new Image();  // Create an image object
  ...
  // Register the event handler to be called on loading an image
  image.onload = function(){ loadTexture(gl, n, texture, u_Sampler, image); };
  // Tell the browser to load an image
  image.src = '../resources/sky.jpg';

  return true;
}

function loadTexture(gl, n, texture, u_Sampler, image){   <- (Part5)
   gl.pixelStorei(gl.UNPACK_FLIP_Y_WEBGL, 1); // Flip the image's y axis
  // Enable the texture unit 0
  gl.activeTexture(gl.TEXTURE0);
  // Bind the texture object to the target
  gl.bindTexture(gl.TEXTURE_2D, texture);

  // Set the texture parameters
  gl.texParameteri(gl.TEXTURE_2D, gl.TEXTURE_MIN_FILTER, gl.LINEAR);
  // Set the texture image
  gl.texImage2D(gl.TEXTURE_2D, 0, gl.RGB, gl.RGB, gl.UNSIGNED_BYTE, image);

  // Set the texture unit 0 to the sampler
  gl.uniform1i(u_Sampler, 0);
  ...
  gl.drawArrays(gl.TRIANGLE_STRIP, 0, n); // Draw a rectangle
}
```

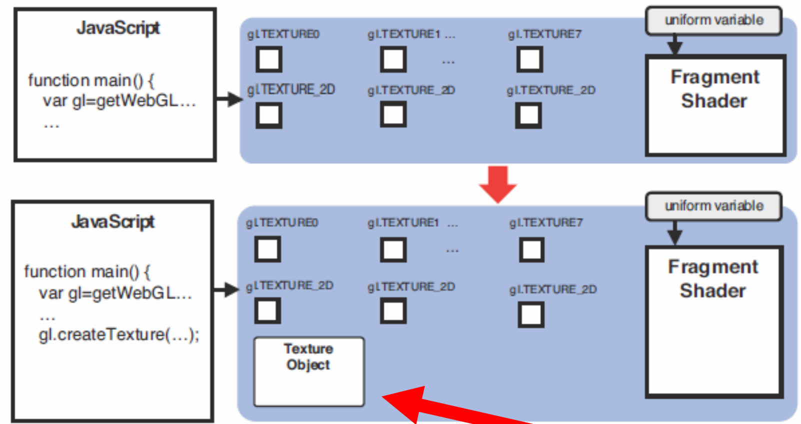


Figure 5.22 Create a texture object

```
function initTextures(gl, n)                              <- (Part4)
  var texture = gl.createTexture();   // Create a texture object
...
  // Get the storage location of the u_Sampler
  var u_Sampler = gl.getUniformLocation(gl.program, 'u_Sampler');
...
  var image = new Image();  // Create an image object
...
  // Register the event handler to be called on loading an image
  image.onload = function(){ loadTexture(gl, n, texture, u_Sampler, image); };
  // Tell the browser to load an image
  image.src = '../resources/sky.jpg';

  return true;
}

function loadTexture(gl, n, texture, u_Sampler, image){   <- (Part5)
   gl.pixelStorei(gl.UNPACK_FLIP_Y_WEBGL, 1); // Flip the image's y axis
  // Enable the texture unit 0
  gl.activeTexture(gl.TEXTURE0);
  // Bind the texture object to the target
  gl.bindTexture(gl.TEXTURE_2D, texture);

  // Set the texture parameters
  gl.texParameteri(gl.TEXTURE_2D, gl.TEXTURE_MIN_FILTER, gl.LINEAR);
  // Set the texture image
  gl.texImage2D(gl.TEXTURE_2D, 0, gl.RGB, gl.RGB, gl.UNSIGNED_BYTE, image);

  // Set the texture unit 0 to the sampler
  gl.uniform1i(u_Sampler, 0);
...
  gl.drawArrays(gl.TRIANGLE_STRIP, 0, n); // Draw a rectangle
}
```

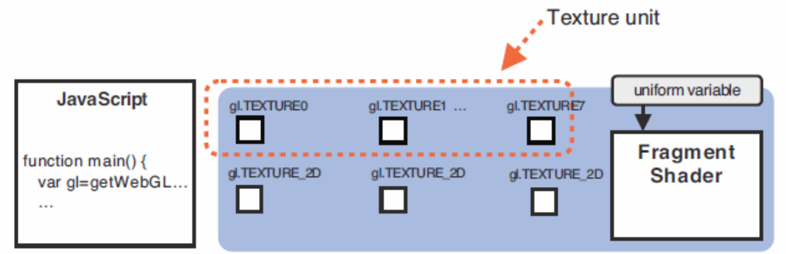


Figure 5.25 Multiple texture units managed by WebGL

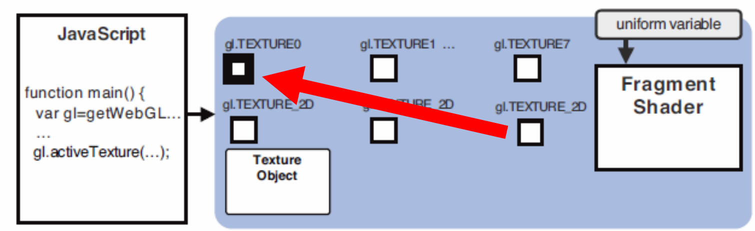


Figure 5.26 Activate texture unit (gl.TEXTURE0)

```
function initTextures(gl, n)                          <- (Part4)
  var texture = gl.createTexture();   // Create a texture object
...
  // Get the storage location of the u_Sampler
  var u_Sampler = gl.getUniformLocation(gl.program, 'u_Sampler');
...
  var image = new Image();  // Create an image object
...
  // Register the event handler to be called on loading an image
  image.onload = function(){ loadTexture(gl, n, texture, u_Sampler, image); };
  // Tell the browser to load an image
  image.src = '../resources/sky.jpg';

  return true;
}

function loadTexture(gl, n, texture, u_Sampler, image){   <- (Part5)
   gl.pixelStorei(gl.UNPACK_FLIP_Y_WEBGL, 1); // Flip the image's y axis
  // Enable the texture unit 0
  gl.activeTexture(gl.TEXTURE0);
  // Bind the texture object to the target
  gl.bindTexture(gl.TEXTURE_2D, texture);

  // Set the texture parameters
  gl.texParameteri(gl.TEXTURE_2D, gl.TEXTURE_MIN_FILTER, gl.LINEAR);
  // Set the texture image
  gl.texImage2D(gl.TEXTURE_2D, 0, gl.RGB, gl.RGB, gl.UNSIGNED_BYTE, image);

  // Set the texture unit 0 to the sampler
  gl.uniform1i(u_Sampler, 0);
...
  gl.drawArrays(gl.TRIANGLE_STRIP, 0, n); // Draw a rectangle
}
```

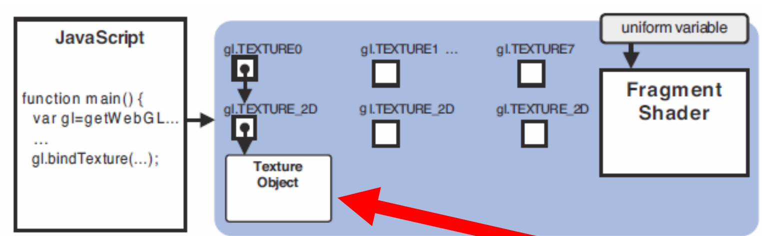


Figure 5.27 Bind a texture object to the target

```
function initTextures(gl, n)                              <- (Part4)
  var texture = gl.createTexture();   // Create a texture object
 ...
  // Get the storage location of the u_Sampler
  var u_Sampler = gl.getUniformLocation(gl.program, 'u_Sampler');
 ...
  var image = new Image();  // Create an image object
 ...
  // Register the event handler to be called on loading an image
  image.onload = function(){ loadTexture(gl, n, texture, u_Sampler, image); };
  // Tell the browser to load an image
  image.src = '../resources/sky.jpg';

  return true;
}

function loadTexture(gl, n, texture, u_Sampler, image){   <- (Part5)
   gl.pixelStorei(gl.UNPACK_FLIP_Y_WEBGL, 1); // Flip the image's y axis
  // Enable the texture unit 0
  gl.activeTexture(gl.TEXTURE0);
  // Bind the texture object to the target
  gl.bindTexture(gl.TEXTURE_2D, texture);

  // Set the texture parameters
  gl.texParameteri(gl.TEXTURE_2D, gl.TEXTURE_MIN_FILTER, gl.LINEAR);
  // Set the texture image
  gl.texImage2D(gl.TEXTURE_2D, 0, gl.RGB, gl.RGB, gl.UNSIGNED_BYTE, image);

  // Set the texture unit 0 to the sampler
  gl.uniform1i(u_Sampler, 0);
 ...
  gl.drawArrays(gl.TRIANGLE_STRIP, 0, n); // Draw a rectangle
}
```

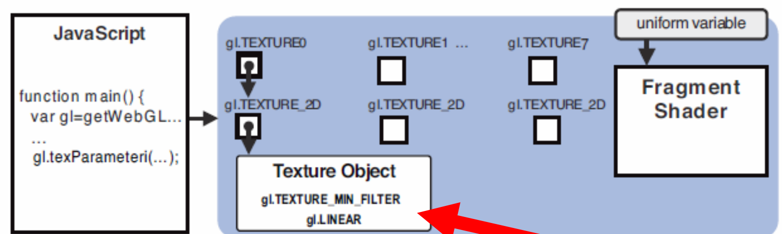


Figure 5.29 Set texture parameter

`gl.LINEAR`, `gl.NEAREST`, `gl.NEAREST_MIPMAP_NEAREST`, `gl.LINEAR_MIPMAP_NEAREST`, `gl.NEAREST_MIPMAP_LINEAR` (default value), `gl.LINEAR_MIPMAP_LINEAR`.

```
function initTextures(gl, n)                           <- (Part4)
  var texture = gl.createTexture();   // Create a texture object
 ...
  // Get the storage location of the u_Sampler
  var u_Sampler = gl.getUniformLocation(gl.program, 'u_Sampler');
 ...
  var image = new Image();  // Create an image object
 ...
  // Register the event handler to be called on loading an image
  image.onload = function(){ loadTexture(gl, n, texture, u_Sampler, image); };
  // Tell the browser to load an image
  image.src = '../resources/sky.jpg';

  return true;
}

function loadTexture(gl, n, texture, u_Sampler, image){   <- (Part5)
   gl.pixelStorei(gl.UNPACK_FLIP_Y_WEBGL, 1); // Flip the image's y axis
  // Enable the texture unit 0
  gl.activeTexture(gl.TEXTURE0);
  // Bind the texture object to the target
  gl.bindTexture(gl.TEXTURE_2D, texture);

  // Set the texture parameters
  gl.texParameteri(gl.TEXTURE_2D, gl.TEXTURE_MIN_FILTER, gl.LINEAR);
  // Set the texture image
  gl.texImage2D(gl.TEXTURE_2D, 0, gl.RGB, gl.RGB, gl.UNSIGNED_BYTE, image);

  // Set the texture unit 0 to the sampler
  gl.uniform1i(u_Sampler, 0);
 ...
  gl.drawArrays(gl.TRIANGLE_STRIP, 0, n); // Draw a rectangle
}
```

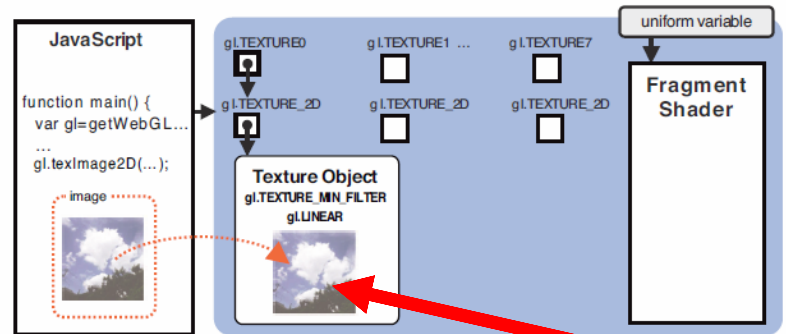


Figure 5.30 Assign an image to the texture object

```
function initTextures(gl, n)                              <- (Part4)
  var texture = gl.createTexture();   // Create a texture object
...
  // Get the storage location of the u_Sampler
  var u_Sampler = gl.getUniformLocation(gl.program, 'u_Sampler');
...
  var image = new Image();  // Create an image object
...
  // Register the event handler to be called on loading an image
  image.onload = function(){ loadTexture(gl, n, texture, u_Sampler, image); };
  // Tell the browser to load an image
  image.src = '../resources/sky.jpg';

  return true;
}

function loadTexture(gl, n, texture, u_Sampler, image){   <- (Part5)
   gl.pixelStorei(gl.UNPACK_FLIP_Y_WEBGL, 1); // Flip the image's y axis
  // Enable the texture unit 0
  gl.activeTexture(gl.TEXTURE0);
  // Bind the texture object to the target
  gl.bindTexture(gl.TEXTURE_2D, texture);

  // Set the texture parameters
  gl.texParameteri(gl.TEXTURE_2D, gl.TEXTURE_MIN_FILTER, gl.LINEAR);
  // Set the texture image
  gl.texImage2D(gl.TEXTURE_2D, 0, gl.RGB, gl.RGB, gl.UNSIGNED_BYTE, image);

  // Set the texture unit 0 to the sampler
  gl.uniform1i(u_Sampler, 0);
...
  gl.drawArrays(gl.TRIANGLE_STRIP, 0, n); // Draw a rectangle
}
```

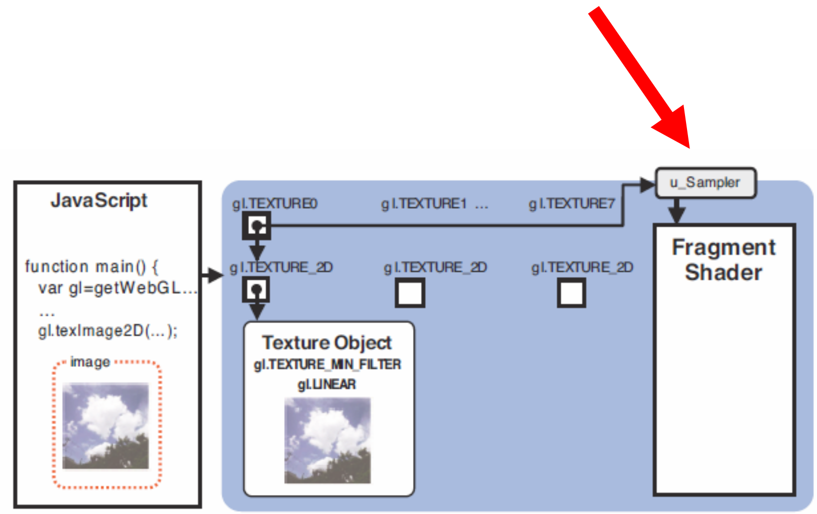


Figure 5.31 Set texture unit to uniform variable

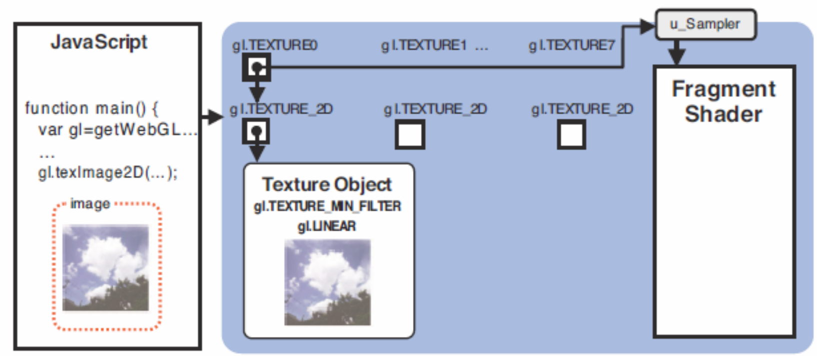


Figure 5.31 Set texture unit to uniform variable

```
var FSHADER_SOURCE =
  ...
  'uniform sampler2D u_Sampler;\n' +
  'varying vec2 v_TexCoord;\n' +
  'void main() {\n' +
  '  gl_FragColor = texture2D(u_Sampler, v_TexCoord);\n' +
  '}\n';
```

Beyond 2D Colored Surfaces

Solid Texturing

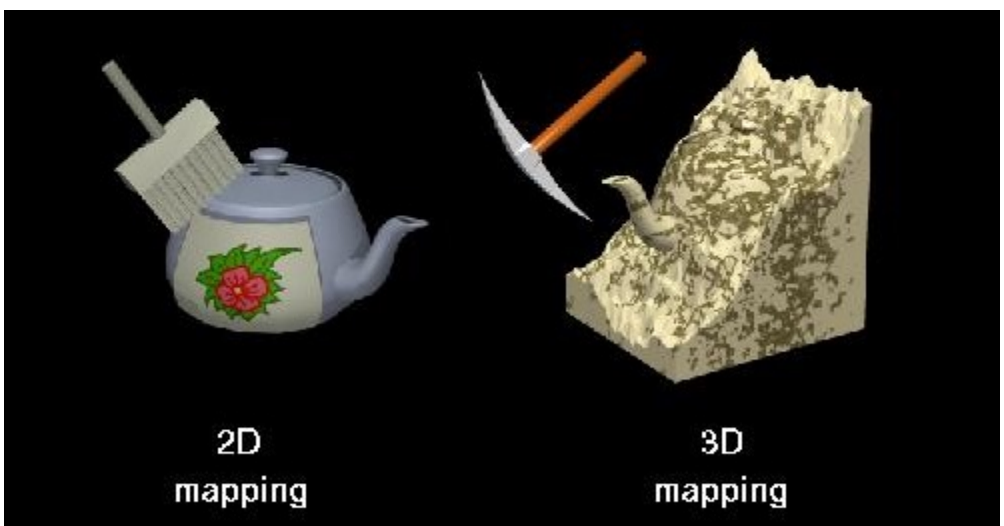
3D Texture Maps

- Instead of a texture image, define a texture volume
- Next, define a 3D parameterization:

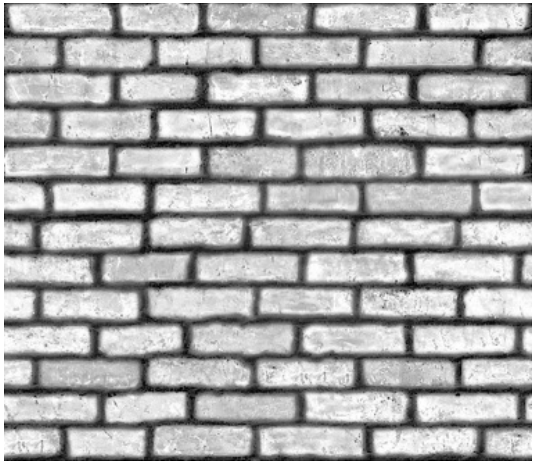
$$f : (x, y, z) \rightarrow (u, v, w)$$

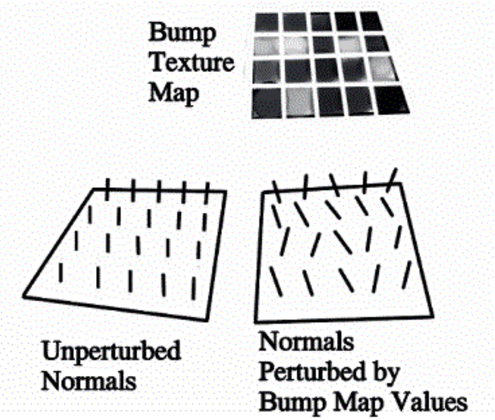
- Useful for procedurally generated textures from noise functions
- Works well for surfaces without natural 2D parameterizations
- But typically results in tremendous amounts of wasted memory

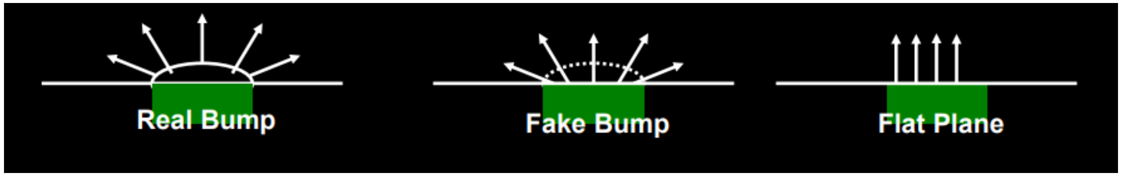
Example of using Perlin Noise

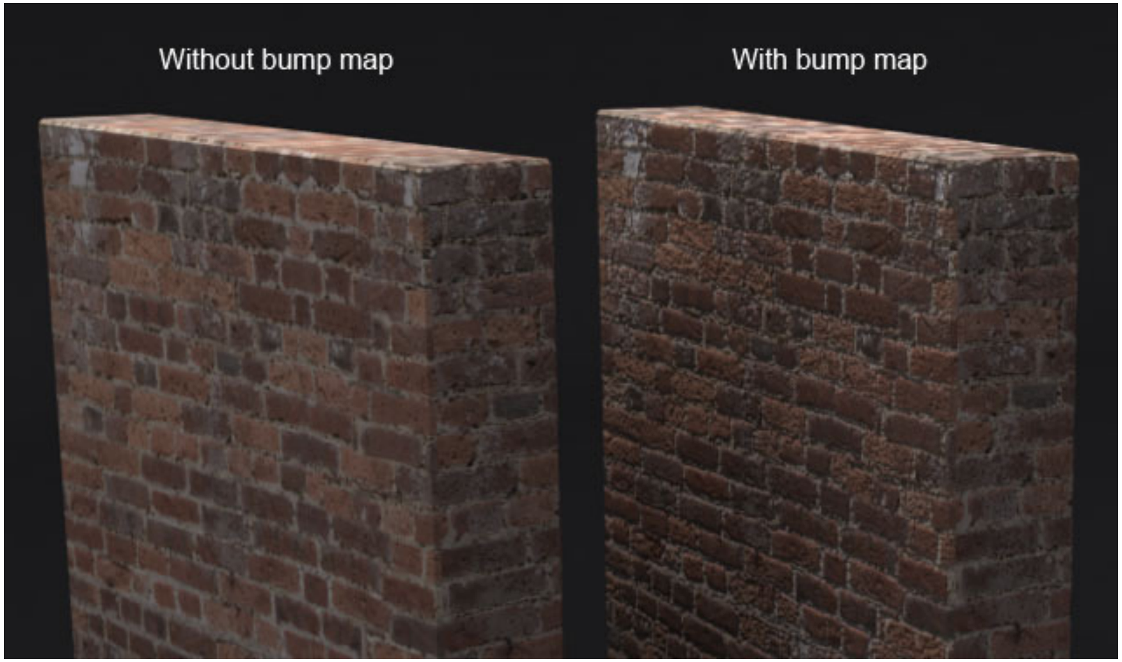


Bump mapping

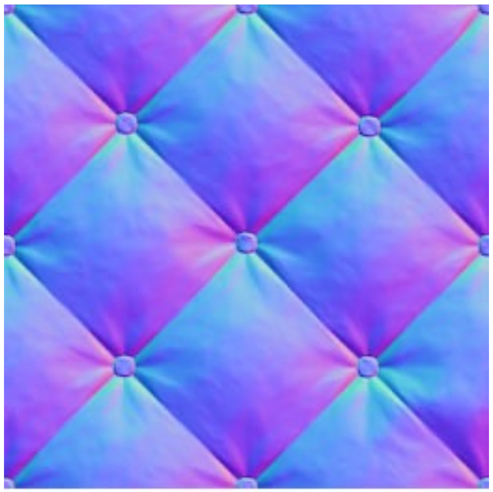


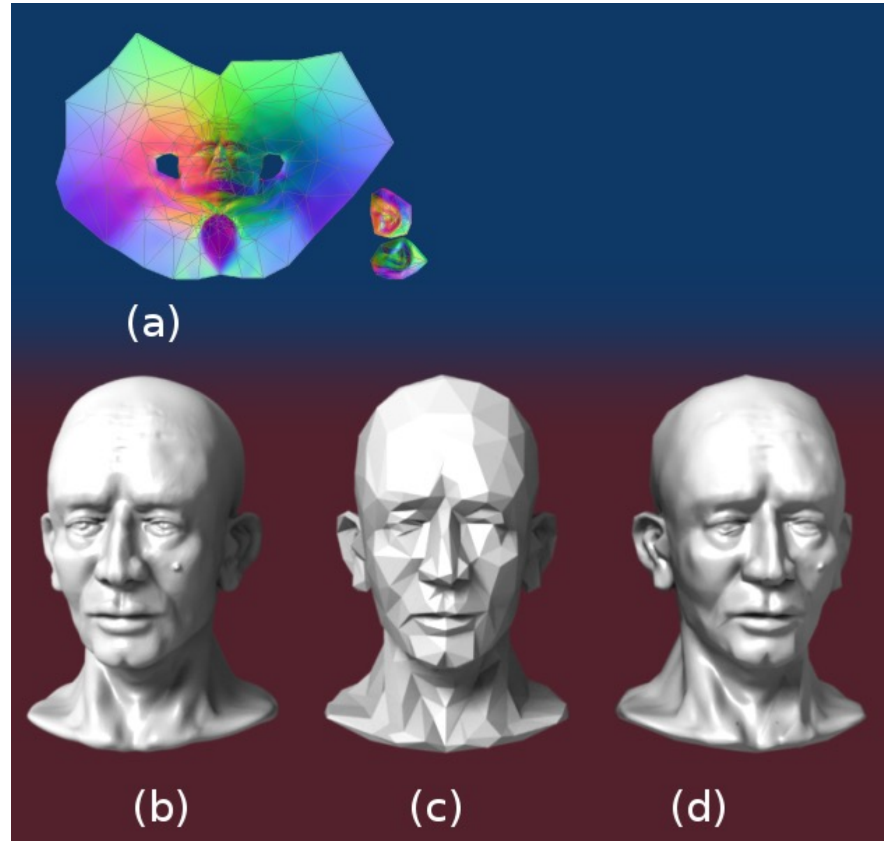


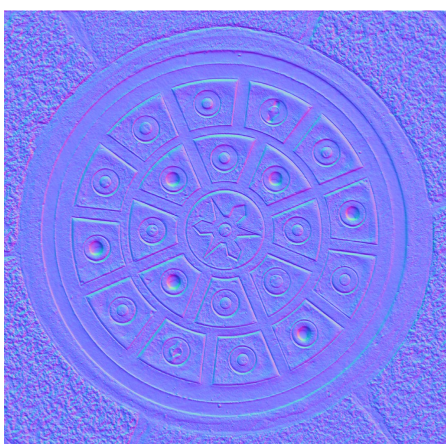


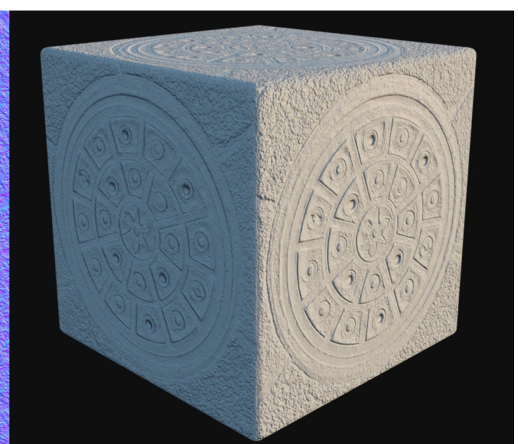


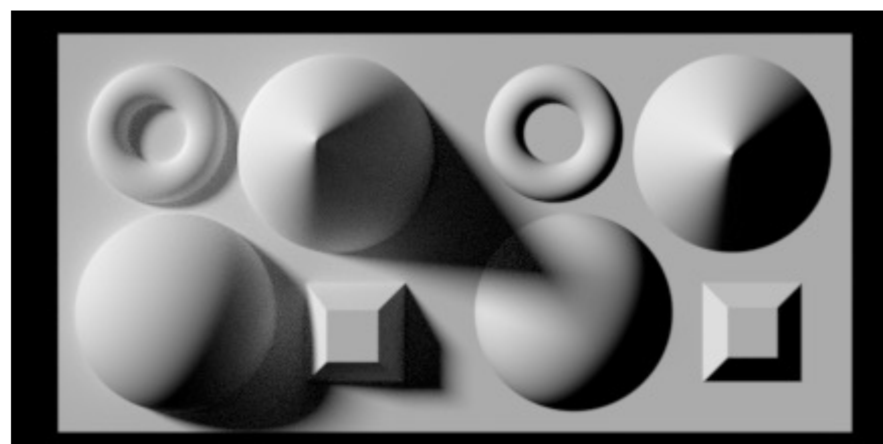
Normal Maps



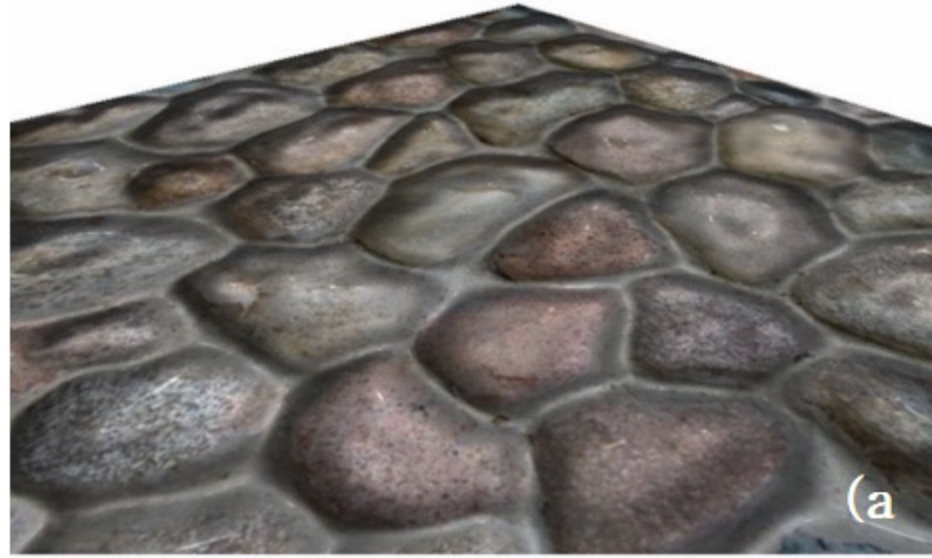




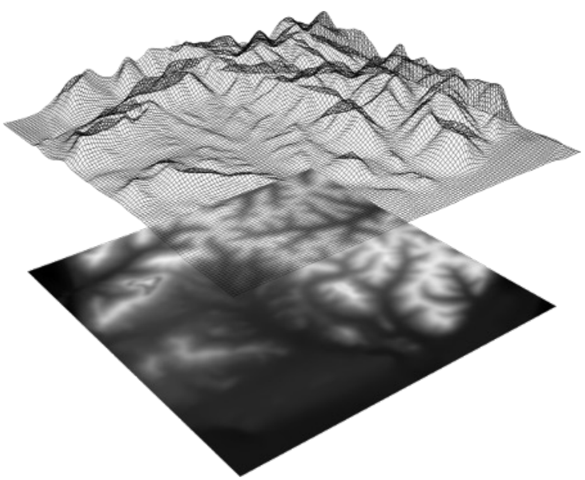


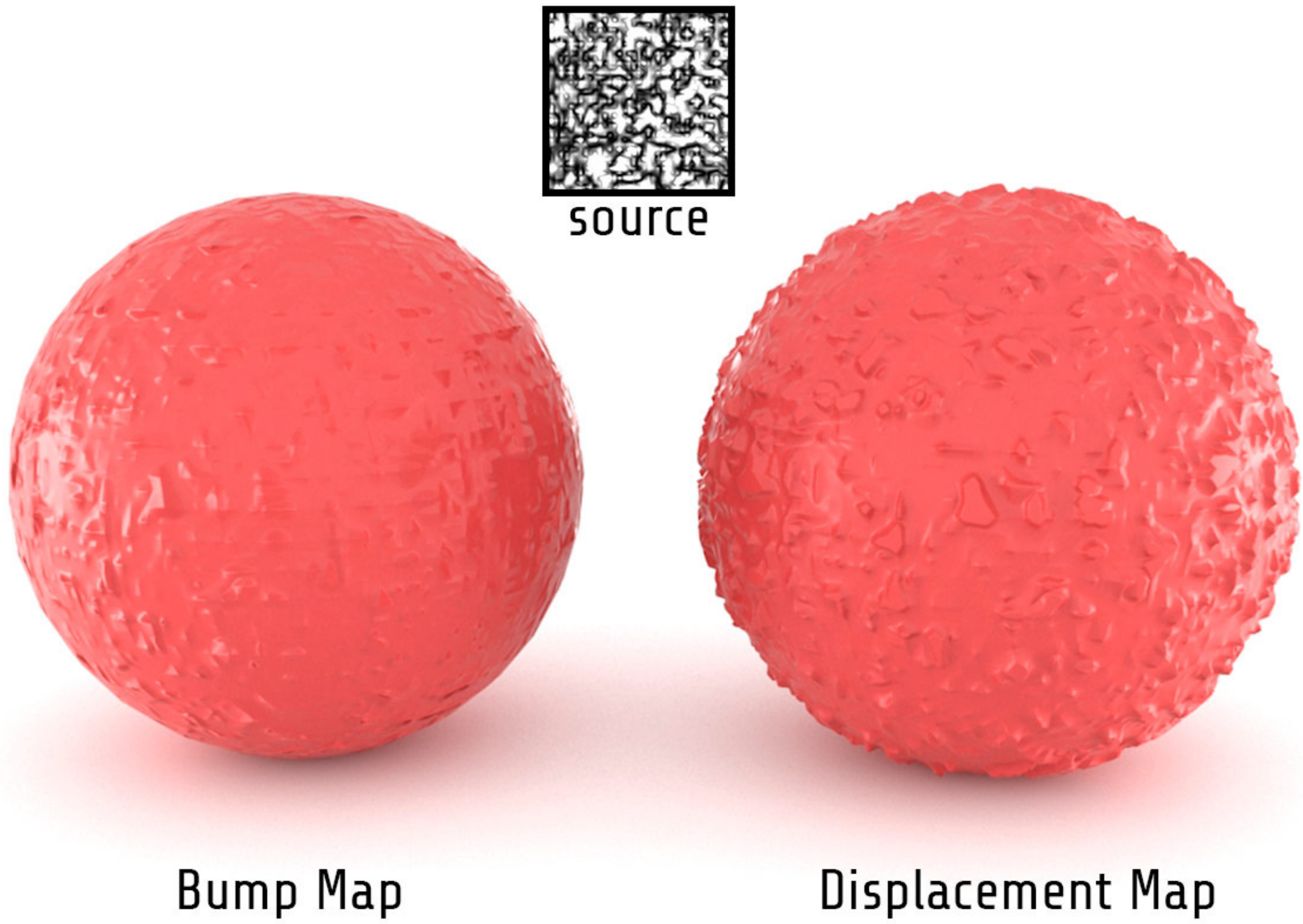


Color Map

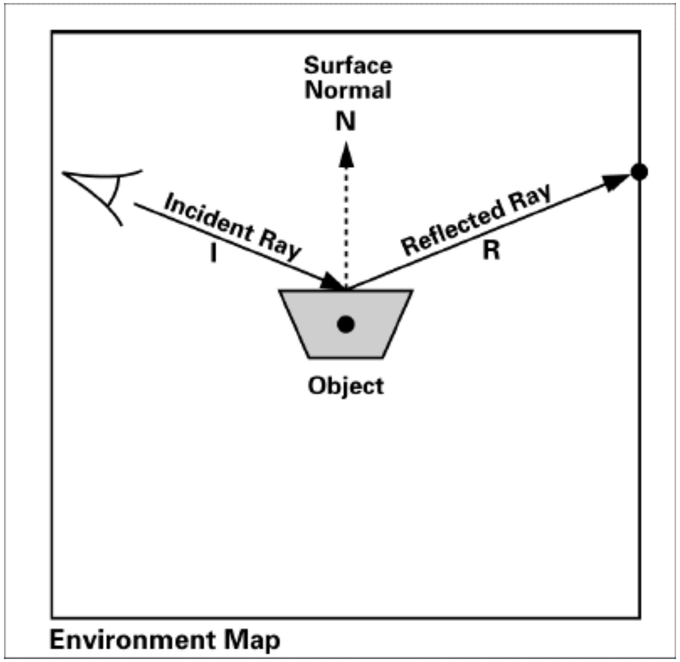


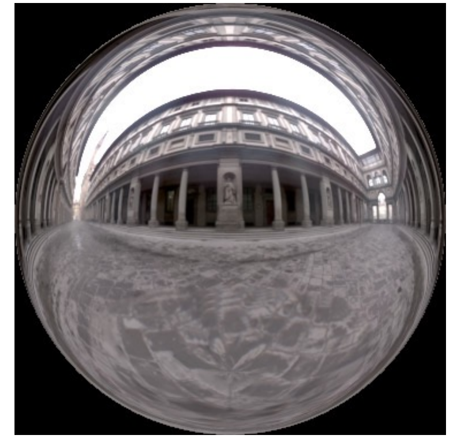
Displacement Map

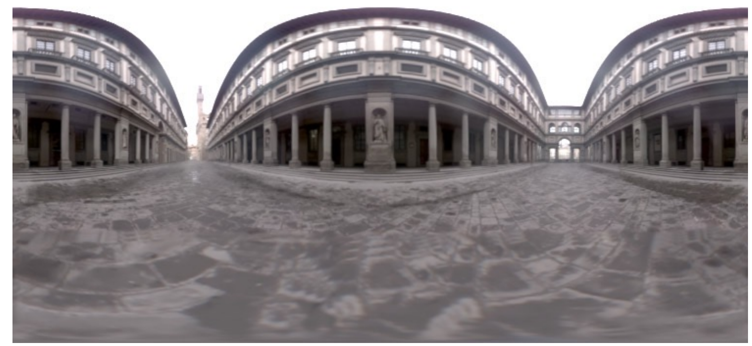



source
Bump Map
Displacement Map

Environment mapping





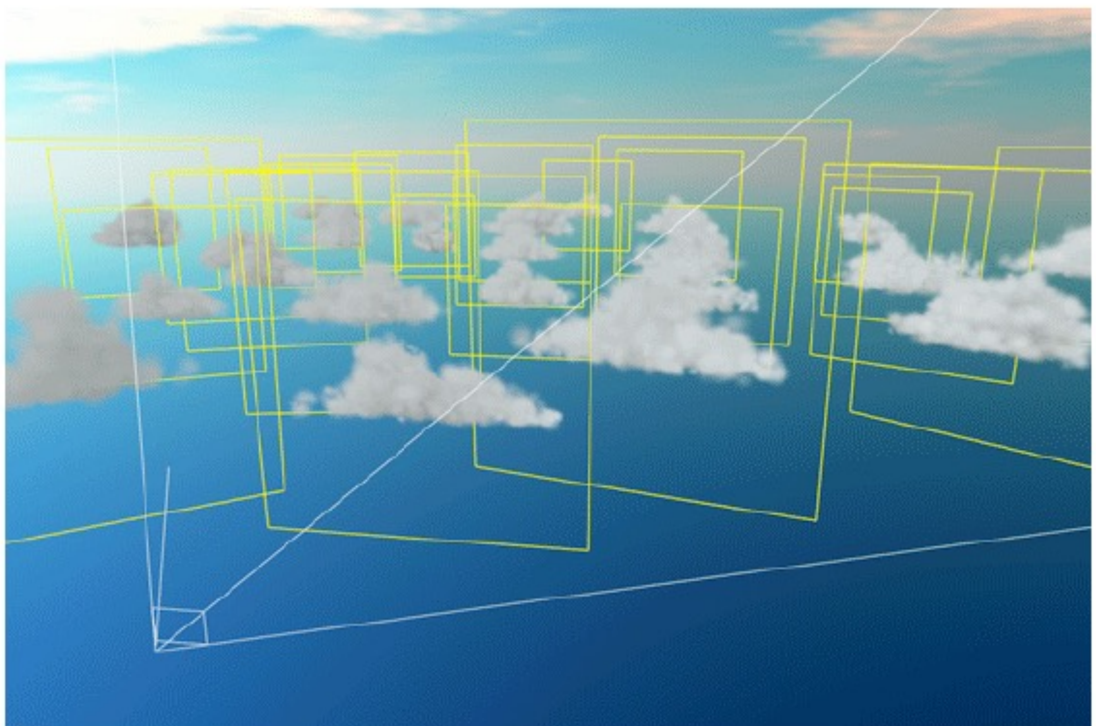



35.49

Billboarding

Texture Sprites

- Place image on a polygon that always rotates to face the viewer
- Use transparency to mask away unwanted geometry
- Useful for small or far-away effects (like clouds and trees)



Administrative

Due Dates

- Due Yesterday
  - Quiz 2
- Due next Monday
  - Lab 2 (Blocky Animal)

Q&A

End