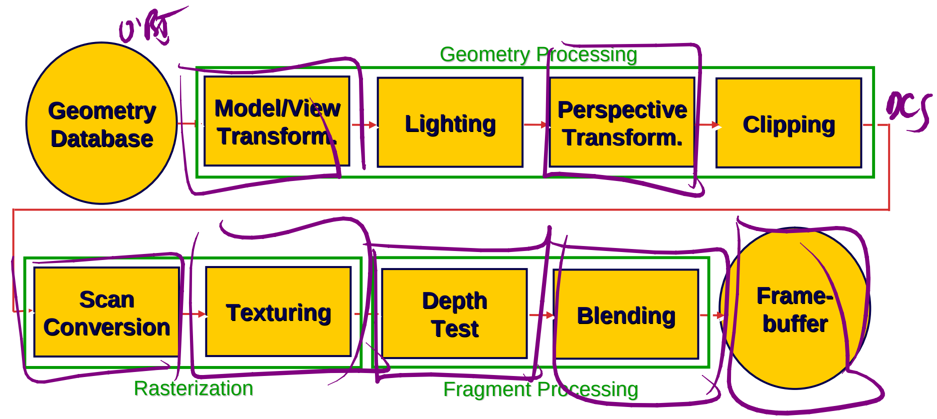
Texture Mapping and Sampling

CPSC 314

The Rendering Pipeline



Texture Mapping

- Real life objects have nonuniform colors, normals
- To generate realistic objects, reproduce coloring & normal variations = **texture**
- Can often replace complex geometric details

Texture Mapping

Introduced to increase realism

- Lighting/shading models not enough

Hide geometric simplicity

- Images convey illusion of geometry
- Map a brick wall texture on a flat polygon
- Create bumpy effect on surface

Associate 2D information with 3D surface

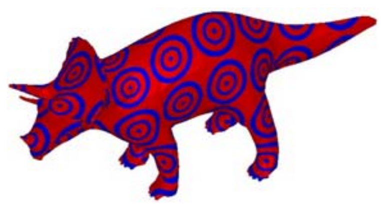
- Point on surface corresponds to a point in texture
- “Paint” image onto polygon

Color Texture Mapping

Define color (RGB) for each pt on surface

Two approaches

- Surface texture map
- Volumetric texture



Texture Coordinates

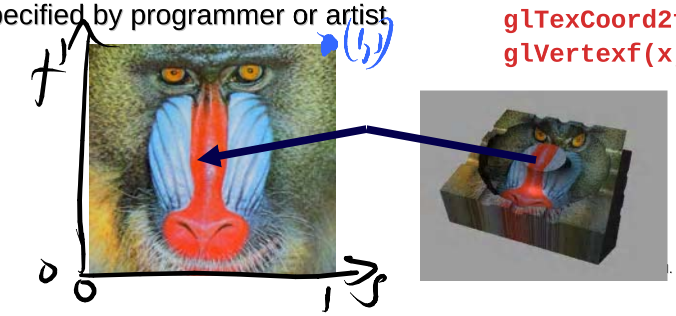
Texture image: 2D array of color values (texels)

Assigning texture coordinates (s,t) at vertex with object coordinates (x,y,z,w)

$s,t \in [0,1]$

- Use interpolated (s,t) for texel lookup at each pixel
- Use value to modify a polygon's color
  - *Or other surface property*
- Specified by programmer or artist

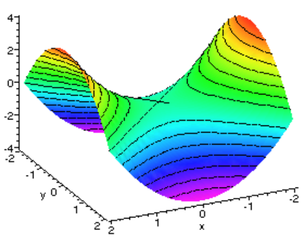
```
glTexCoord2f(s,t)
glVertexf(x,y,z,w)
```

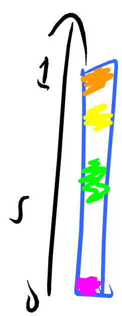


Texture Mapping

Textures of other dimensions

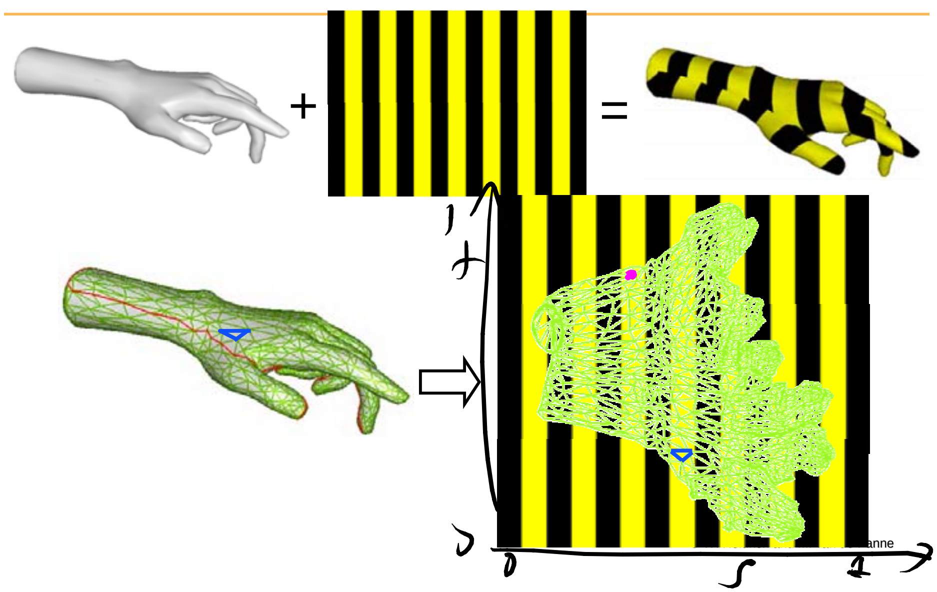
- 1D: represent isovalues
  - *e.g.: contour lines, temp, ...*
    `glTexCoord1f(s)`



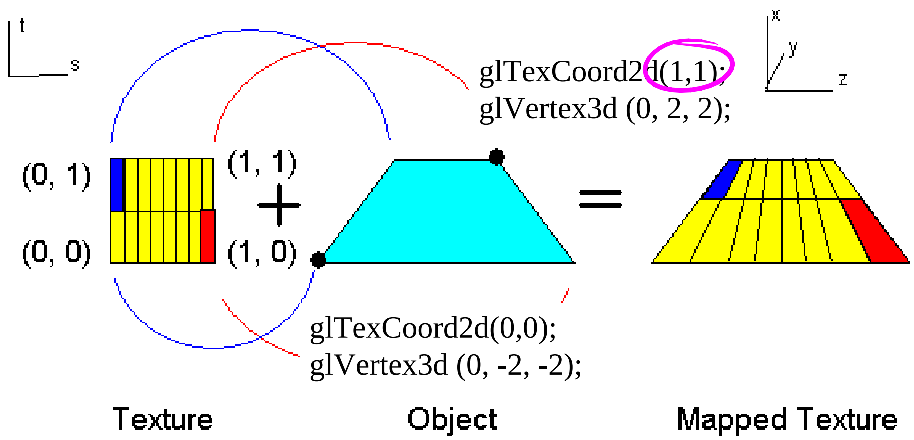


For color-coded height field, use $s = az+b$

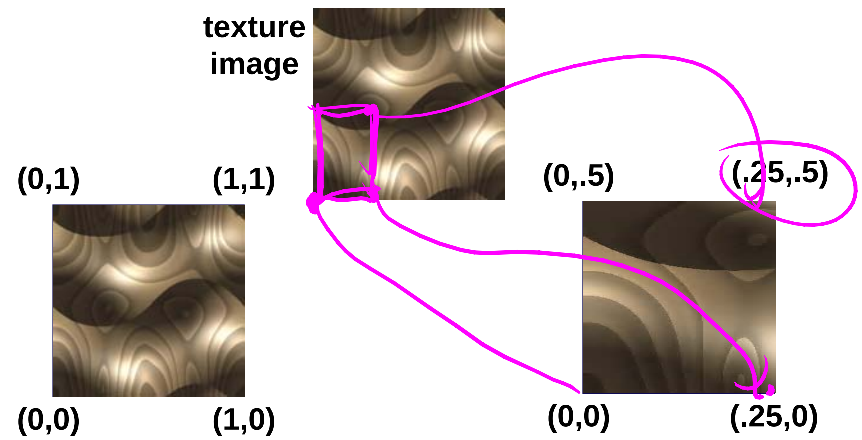
Texture Mapping Example



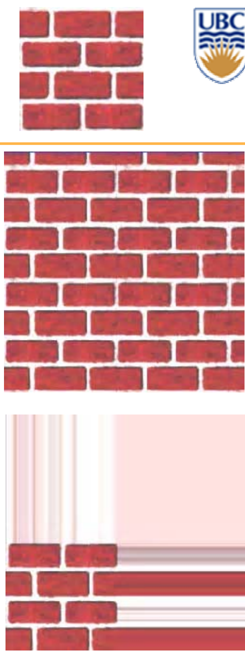
Example Texture Map



Fractional Texture Coordinates



Texture Lookup: Tiling and Clamping



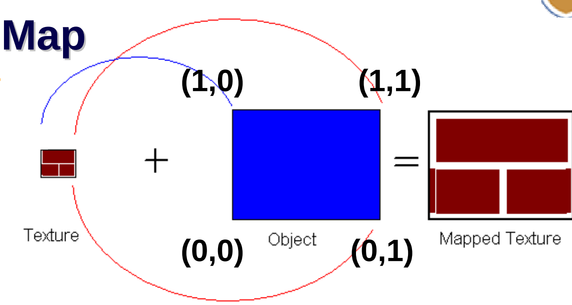
What if s or t is outside the interval [0…1]?

Multiple choices

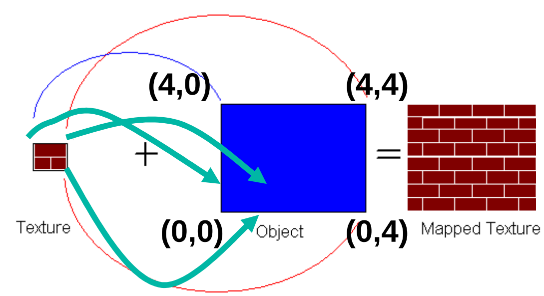
- Use fractional part of texture coordinates
  - *Cyclic repetition*
    glTexParameteri(…, GL_TEXTURE_WRAP_S, GL_REPEAT, GL_TEXTURE_WRAP_T, GL_REPEAT, ...)
- Clamp every component to range [0…1]
  - *Re-use color values from texture image border glTexParameteri(…, GL_TEXTURE_WRAP_S, GL_CLAMP, GL_TEXTURE_WRAP_T, GL_CLAMP, ...)*

Tiled Texture Map

glTexCoord2d(1, 1);
glVertex3d (x, y, z);



glTexCoord2d(4, 4);
glVertex3d (x, y, z);



Texture Coordinate Transformation

Motivation

- Change scale, orientation of texture on an object

Approach

- *Texture matrix stack*
- Transforms specified (or generated) tex coords

```
glMatrixMode( GL_TEXTURE );
glLoadIdentity();
glRotate();
  …
```

- More flexible than changing (s,t) coordinates

Texture Functions

Ways of applying texture colour:

- GL_REPLACE
  - *Directly use as surface color; no lighting effects*
- GL_MODULATE
  - *Modulate surface color: multiply old color by new value*
  - *Texturing happens after lighting, not relit*
- GL_DECAL
  - *Like replace, but modulate alpha to support transparency*
- GL_BLEND
  - *Blend surface color with existing on-screen colour*

glTexEnvi(GL_TEXTURE_ENV, GL_TEXTURE_ENV_MODE, <mode>)

Texture Pipeline

(s, t) → **(s', t')** → **Texel space** → **Texel color**

Parameter space → **Transformed parameter space** → **(81, 74)** → **(0.9,0.8,0.7)**

(0.32, 0.29) → **(0.52, 0.49)**

glColor3f(0.5,0.5,0.5)

Object color

(0.5,0.5,0.5)

GL_MODULATE

blending

Final color

(0.45,0.4,0.35)

Texture Objects and Binding

Texture object

- An OpenGL data type that keeps textures resident in memory and provides identifiers to easily access them
- Provides efficiency gains over having to repeatedly load and reload a texture
- You can prioritize textures to keep in memory
- OpenGL uses least recently used (LRU) if no priority is assigned

Texture binding

- Which texture to use right now
- Switch between preloaded textures

Basic OpenGL Texturing

Create a texture object and fill it with texture data:

- `glGenTextures(num, &indices)` to get identifiers for the objects
- `glBindTexture(GL_TEXTURE_2D, identifier)` to bind
  - *Following texture commands refer to the bound texture*
- `glTexParameteri(GL_TEXTURE_2D, …, …)` to specify parameters for use when applying the texture
- `glTexImage2D(GL_TEXTURE_2D, ….)` to specify the texture data (the image itself)

Basic OpenGLTexturing (cont.)

Enable texturing:

- `glEnable(GL_TEXTURE_2D)`

State how the texture will be used:

- `glTexEnvf(…)`

Specify texture coordinates for the polygon:

- Use `glTexCoord2f(s,t)` before each vertex:
  - *`glTexCoord2f(0,0);`*
    `glVertex3f(x,y,z);`

Low-Level Details

Large range of functions for controlling layout of texture data

- State how the data in your image is arranged
- e.g.: `glPixelStorei(GL_UNPACK_ALIGNMENT, 1)` tells OpenGL not to skip bytes at the end of a row
- You must state how you want the texture to be put in memory: how many bits per "pixel", which channels,…

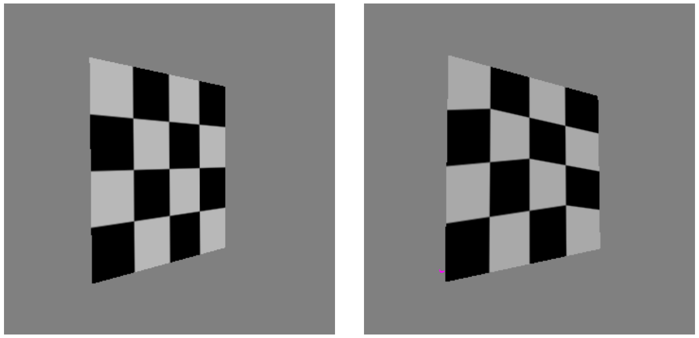
Textures must have a size of power of 2

- Common sizes are 32x32, 64x64, 256x256
- But don't need to be square, i.e. 32x64 is fine
- Smaller uses less memory, and there is a finite amount of texture memory on graphics cards

Texture Mapping

Texture coordinate interpolation

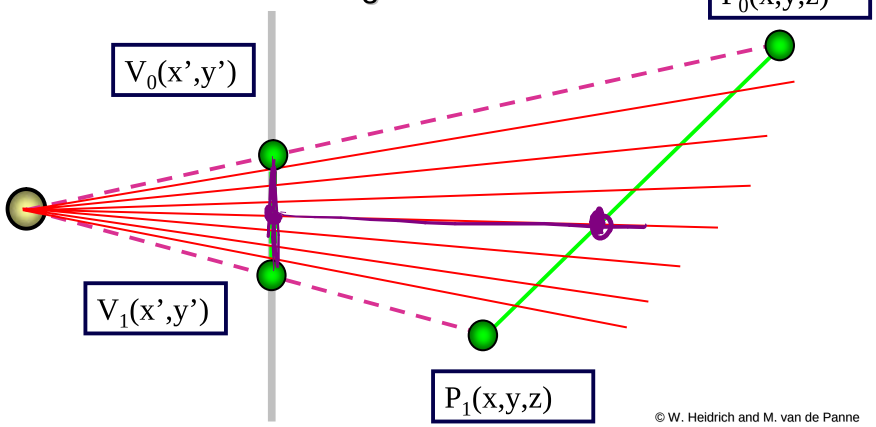
- Perspective foreshortening problem



Interpolation: Screen vs. World Space

Screen space interpolation incorrect

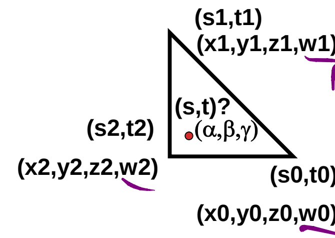
- Problem ignored with shading, but artifacts more visible with texturing



Texture Coordinate Interpolation

Perspective correct interpolation

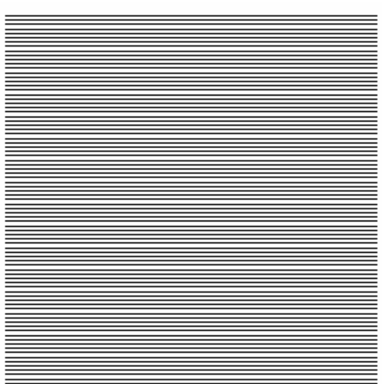
- α, β, γ :
  - *Barycentric coordinates of a point **P** in a triangle*
- *s0, s1, s2* :
  - *Texture coordinates of vertices*
- *w0, w1,w2* :
  - *Homogeneous coordinates of vertices*

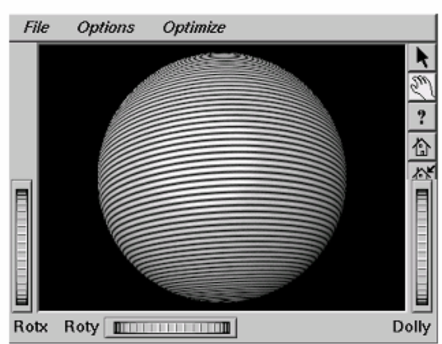


homog. coords.

$$s = \frac{\alpha \cdot s_0 / w_0 + \beta \cdot s_1 / w_1 + \gamma \cdot s_2 / w_2}{\alpha / w_0 + \beta / w_1 + \gamma / w_2}$$

Reconstruction

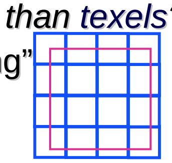




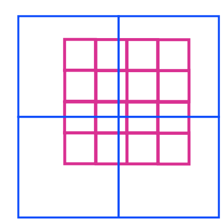
(image courtesy of Kiriakos Kutulakos, U Rochester)

Reconstruction

- How to deal with:
  - *Pixels that are much larger than texels?*
    - Apply filtering, "averaging"



  - *Pixels that are much smaller than texels ?*
    - Interpolate

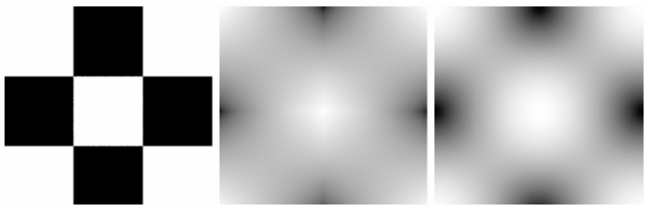


Interpolating Textures

- Nearest neighbor
- Bilinear
- Hermite

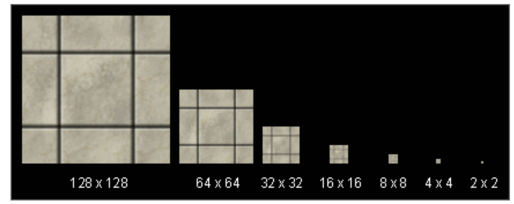
texels ≡ pixels of your texturemaps

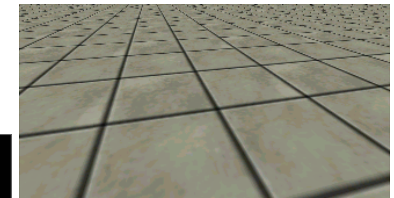
1	0	1
0	1	0
1	0	1



MIPmapping

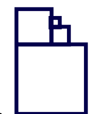
use "image pyramid" to precompute averaged versions of the texture



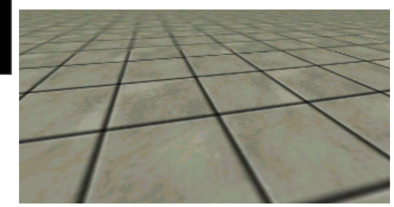


Without MIP-mapping

store whole pyramid in single block of memory



Mem usage = $\frac{4}{3}$ of original



With MIP-mapping

MIPmaps

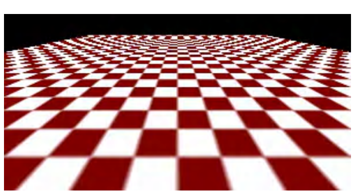
Multum in parvo ***-- many things in a small place***

- Prespecify a series of prefiltered texture maps of decreasing resolutions
- Requires more texture storage
- Avoid shimmering and flashing as objects move

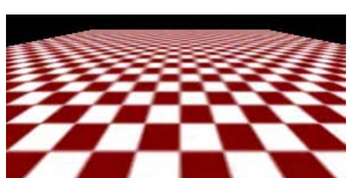
gluBuild2DMipmaps

- Automatically constructs a family of textures from original texture size down to 1x1

without

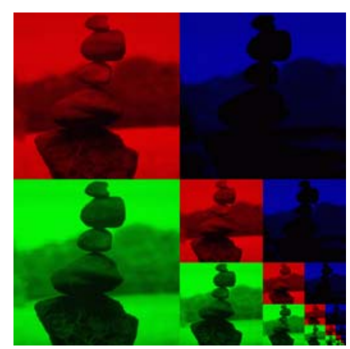


with



MIPmap storage

only 1/3 more space required



Texture Parameters

In addition to color can control other material/object properties

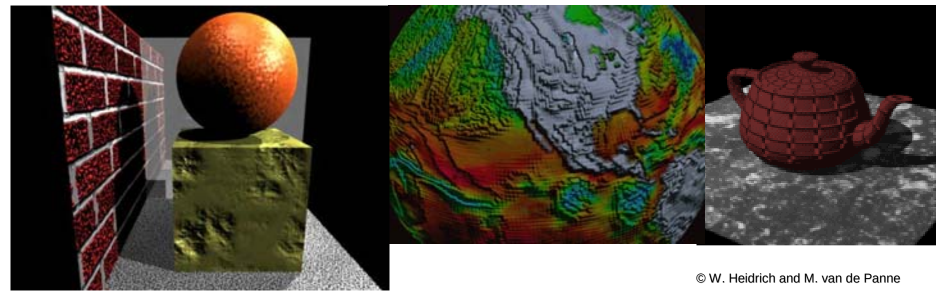
- Surface normal (bump mapping)
- Reflected color (environment mapping)

Bump Mapping: Normals As Texture

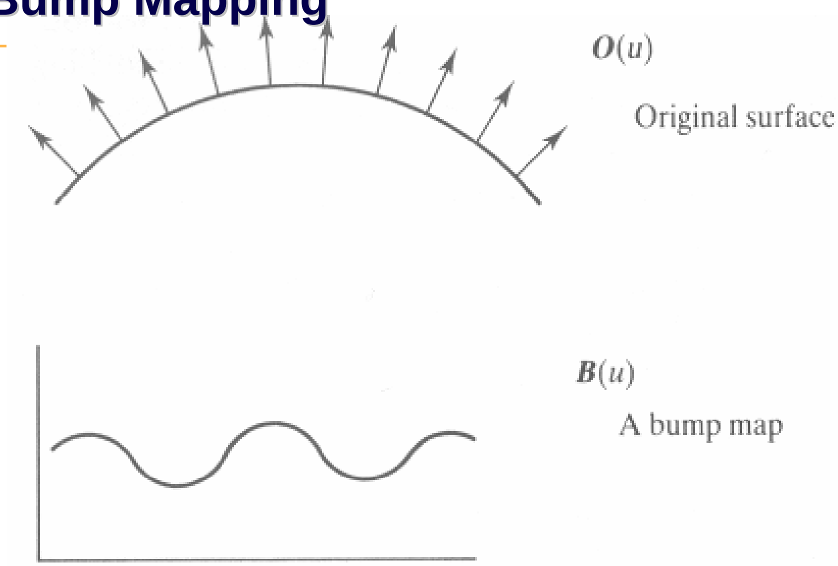
Object surface often not smooth – to recreate correctly need complex geometry model

Can control shape "effect" by locally perturbing surface normal

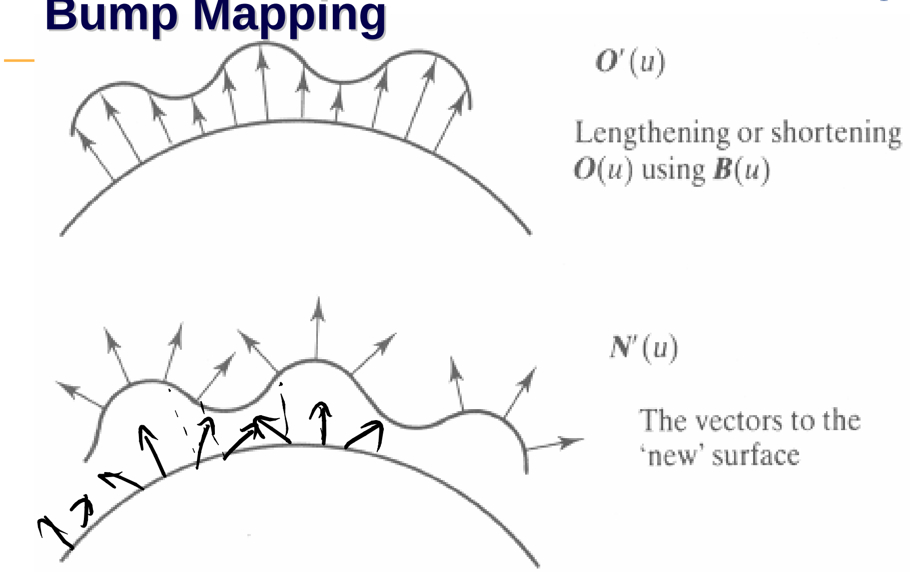
- Random perturbation
- Directional change over region



Bump Mapping



Bump Mapping



Displacement Mapping

Bump mapping gets silhouettes wrong

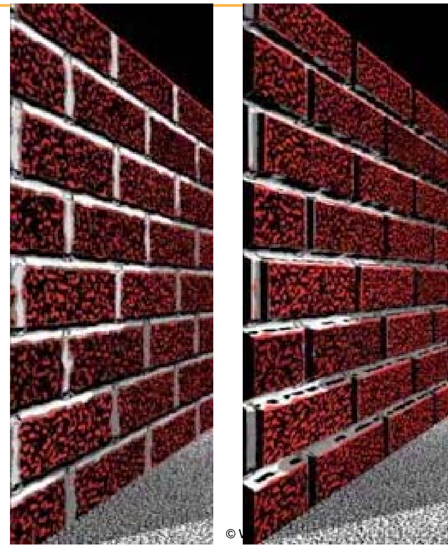
- Shadows wrong too

Change surface geometry instead

- Need to subdivide surface

GPU support

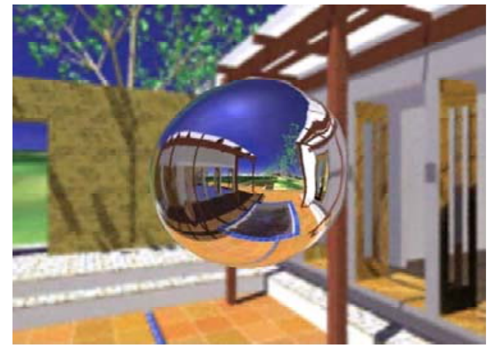
- Bump and displacement mapping not directly supported: require per-pixel lighting
- However: modern GPUs allow for programming both yourself



Environment Mapping

Cheap way to achieve reflective effect

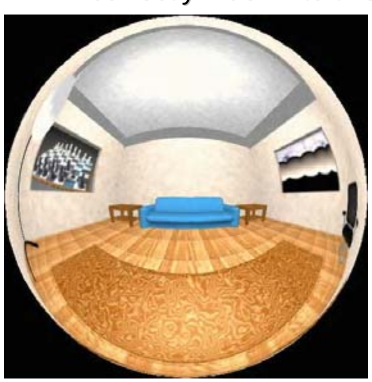
- Generate image of surrounding
- Map to object as texture



Sphere Mapping

Texture is distorted fish-eye view

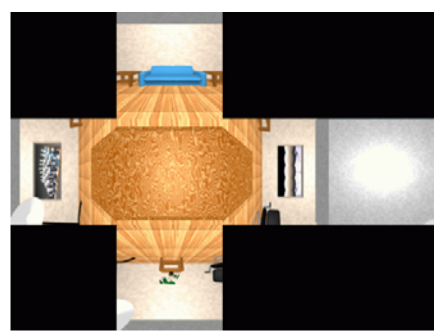
- Point camera at mirrored sphere
- Spherical texture mapping creates texture coordinates that correctly index into this texture map



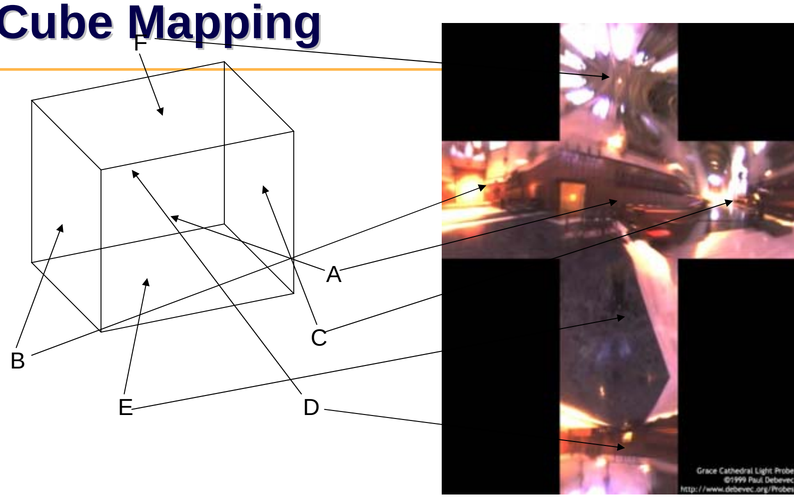
Cube Mapping

6 planar textures, sides of cube

- Point camera in 6 different directions, facing out from origin



Cube Mapping



Cube Mapping

Direction of reflection vector* r *selects the face of the cube to be indexed

- Co-ordinate with largest magnitude
  - *e.g., the vector (-0.2, 0.5, -0.84) selects the –Z face*
- Remaining two coordinates (normalized by the 3rd coordinate) selects the pixel from the face.
  - *E.g., (-0.2, 0.5) gets mapped to (0.38, 0.80).*

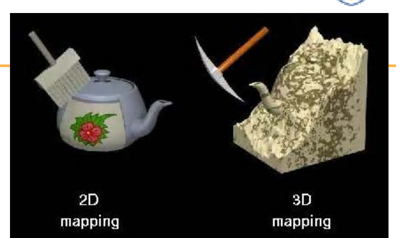
Difficulty in interpolating across faces

Volumetric Texture

Define texture pattern over 3D domain - 3D space containing the object

- Texture function can be digitized or procedural
- For each point on object compute texture from point location in space

Common for natural material/irregular textures (stone, wood,etc…)



Volumetric Bump Mapping

Marble

Bump

Procedural Textures

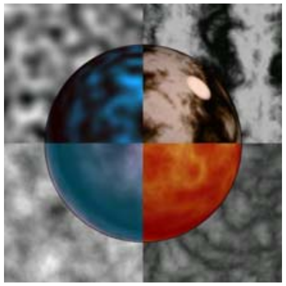
Generate "image" on the fly, instead of loading from disk

- Often saves space
- Allows arbitrary level of detail

Procedural Textures

Several good explanations

- Text book Section 10.1
- http://www.noisemachine.com/talk1
- http://freespace.virgin.net/hugo.elias/models/m_perlin.htm
- http://www.robo-murito.net/code/perlin-noise-math-faq.html



http://mrl.nyu.edu/~perlin/planet/

Sampling

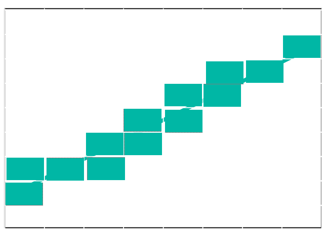
CPSC 314

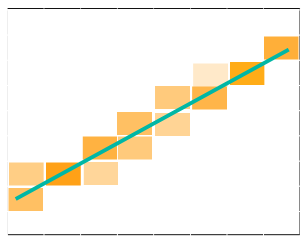
Samples

- Most things in the real world are continuous
- Everything in a computer is discrete
- The process of mapping a continuous function to a discrete one is called sampling
- The process of mapping a discrete function to a continuous one is called reconstruction
- The process of mapping a continuous variable to a discrete one is called quantization
- Rendering an image requires sampling and quantization
- Displaying an image involves reconstruction

Line Segments

- quantized pixel values to 0 or 1
- or, quantize to many shades





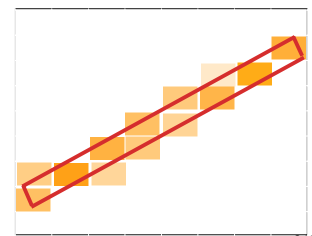
Unweighted Area Sampling

Shade pixels wrt area covered by thickened line

Equal areas cause equal intensity, regardless of distance from pixel center to area

- Rough approximation formulated by dividing each pixel into a finer grid of pixels

Primitive cannot affect intensity of pixel if it does not intersect the pixel

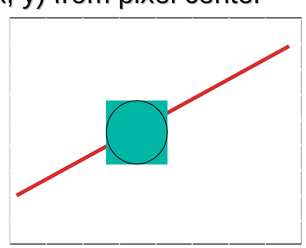


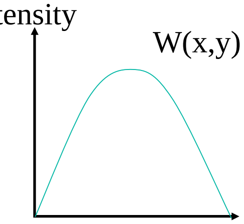
Weighted Area Sampling

Intuitively, pixel cut through the center should be more heavily weighted than one cut along corner

Weighting function, W(x,y)

- Specifies the contribution of primitive passing through the point (x, y) from pixel center





Images

An image is a 2D function I(x, y)

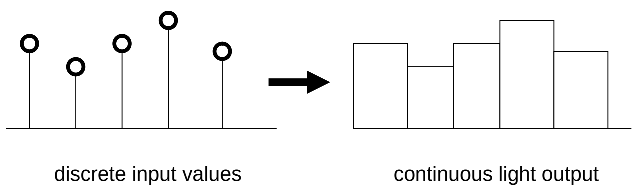
- Specifies intensity for each point (x, y)
- (we consider each color channel independently)

Image Sampling and Reconstruction

Convert continuous image to discrete set of samples

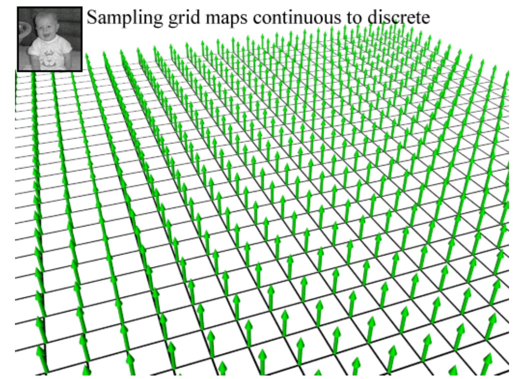
Display hardware reconstructs samples into continuous image

- Finite sized source of light for each pixel



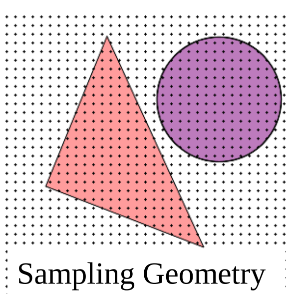
Point Sampling an Image

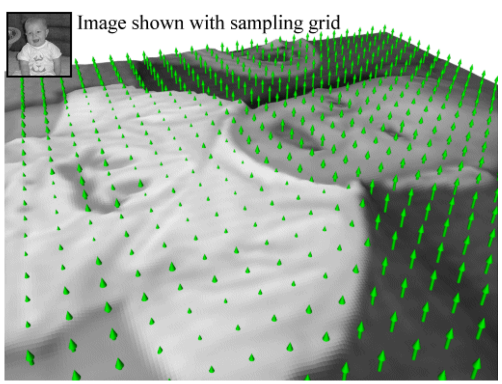
- Simplest sampling is on a grid
- Sample depends solely on value at grid points



Point Sampling

Multiply sample grid by image intensity to obtain a discrete set of points, or samples.





Sampling Errors

Some objects missed entirely, others poorly sampled

- Could try unweighted or weighted area sampling
- But how can we be sure we show everything?

Need to think about entire class of solutions!

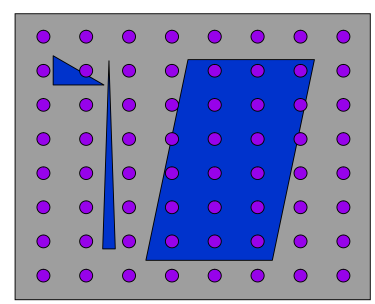


Image As Signal

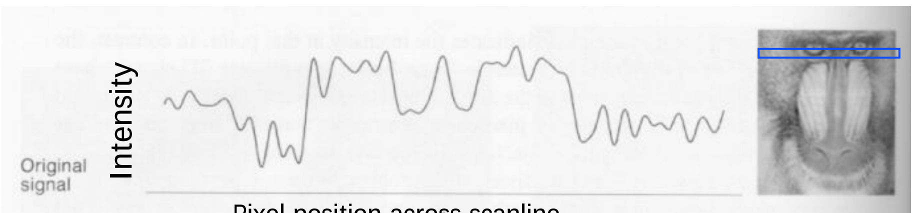
Image as spatial signal

2D raster image

- Discrete sampling of 2D spatial signal

1D slice of raster image

- Discrete sampling of 1D spatial signal



Pixel position across scanline

Examples from Foley, van Dam, Feiner, and Hughes

Sampling Theory

How would we generate a signal like this out of simple building blocks?

Theorem

- Any signal can be represented as an (infinite) sum of sine waves at different frequencies

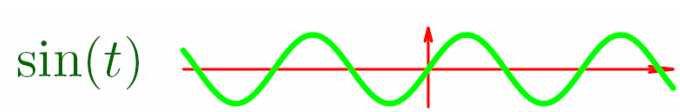
Sampling Theory in a Nutshell

Terminology

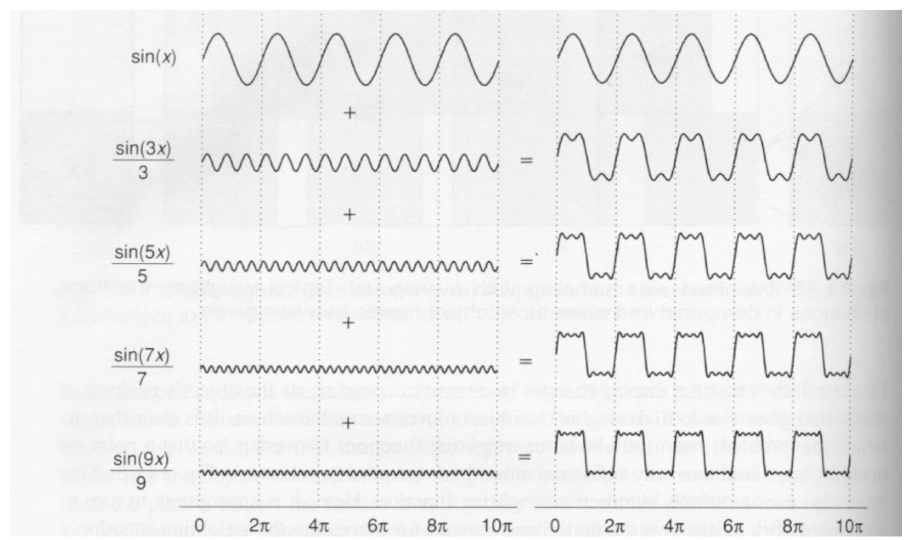
- Wavelength – length of repeated sequence on infinite signal
- Frequency – 1/wavelength (number of repeated sequences in unit length)

Example – sine wave

- Wavelength = 2π
- Frequency = $1/ 2\pi$

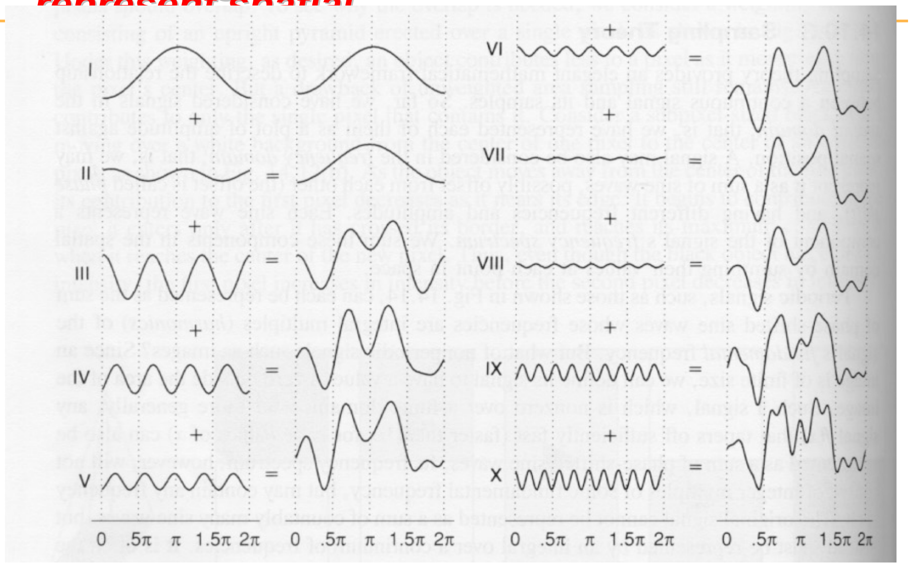


Summing Waves I

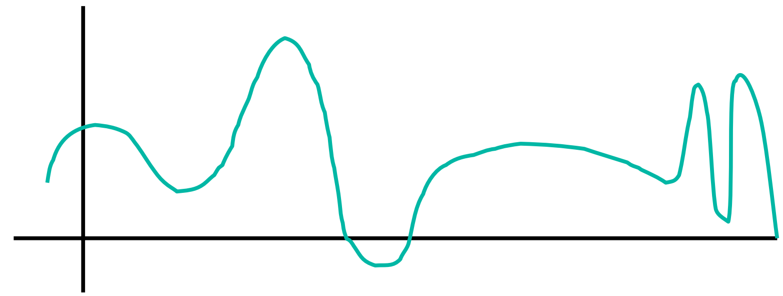


Summing Waves II

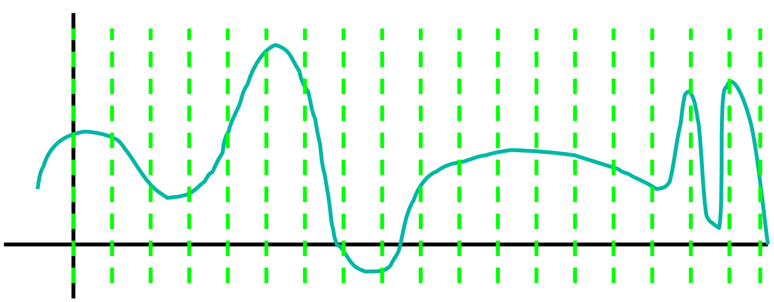
represent spatial



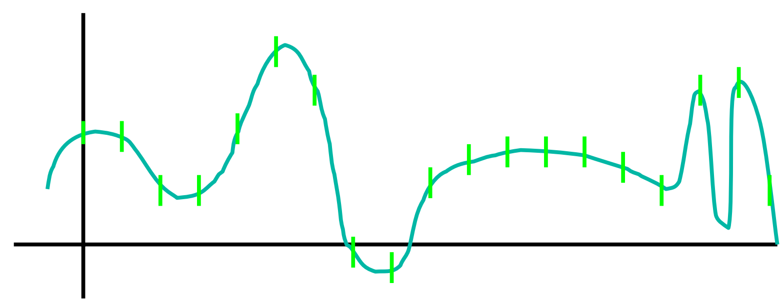
1D Sampling and Reconstruction



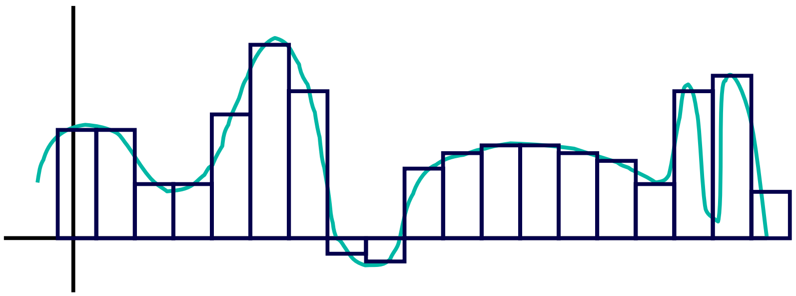
1D Sampling and Reconstruction



1D Sampling and Reconstruction



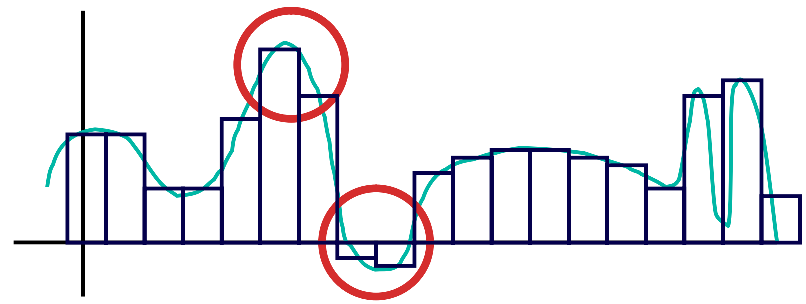
1D Sampling and Reconstruction



1D Sampling and Reconstruction

Problems

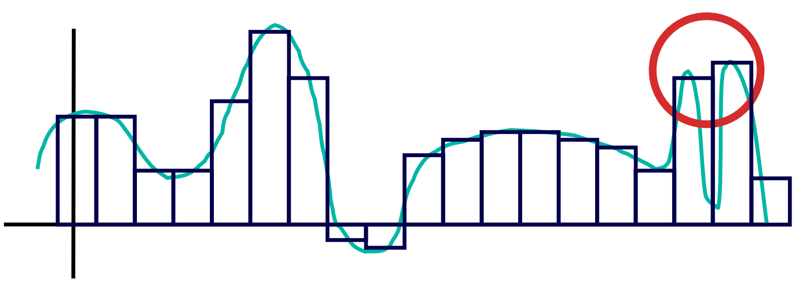
- Jaggies – abrupt changes



1D Sampling and Reconstruction

Problems

- Jaggies – abrupt changes
- Lose data



Sampling Theorem

- Continuous signal can be completely recovered from its samples

Iff

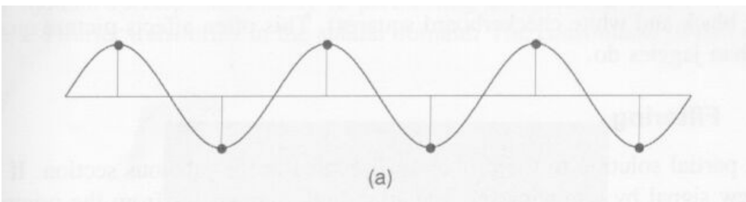
- Sampling rate greater than twice highest frequency present in signal

- Claude Shannon

Nyquist Rate

Lower bound on sampling rate

- Twice the highest frequency component in the image’s spectrum



Falling Below Nyquist Rate

When sampling below Nyquist Rate, resulting signal looks like a lower-frequency one

- This is aliasing!

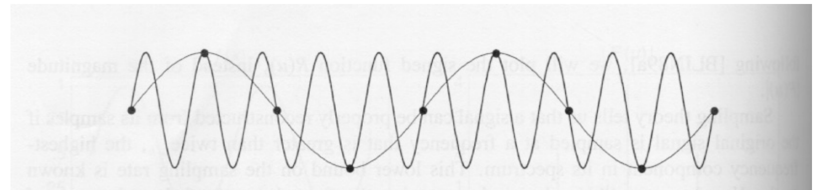
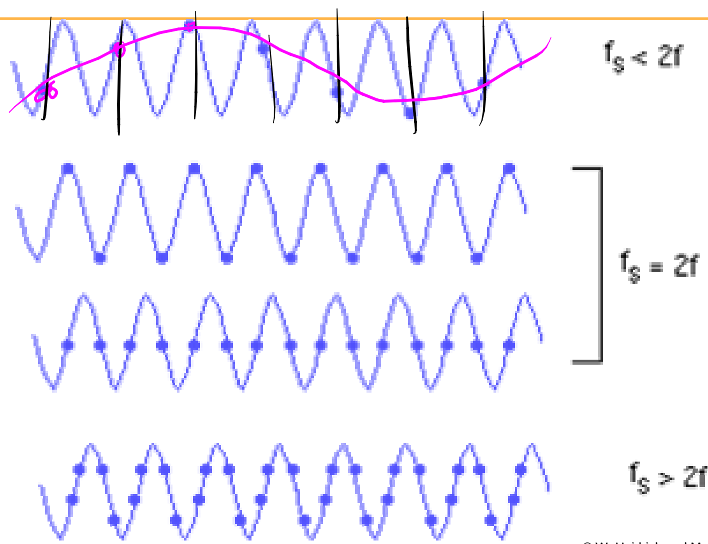


Fig. 14.17 Sampling below the Nyquist rate. (Courtesy of George Wolberg, Columbia University.)

Nyquist Rate



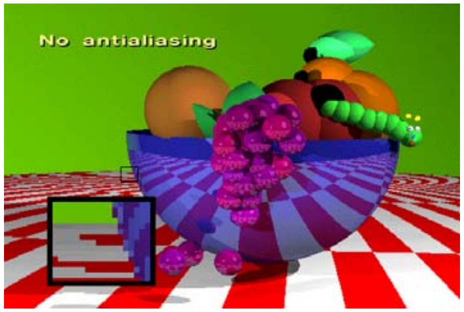
Aliasing

Incorrect appearance of high frequencies as low frequencies

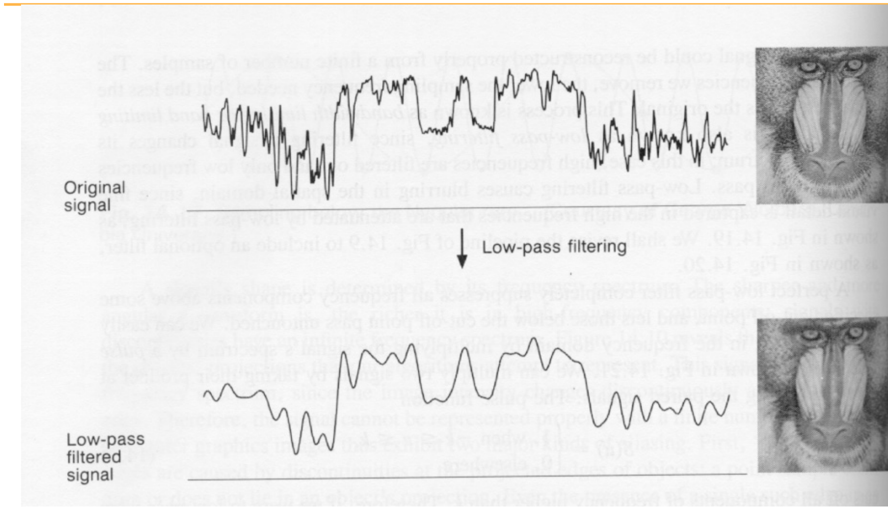
To avoid: anti-aliasing

- Supersample
  - *Sample at higher frequency*
- Low pass filtering
  - *Remove high frequency function parts*
  - *Aka prefiltering, band-limiting*

Supersampling



Low-Pass Filtering



Low-Pass Filtering

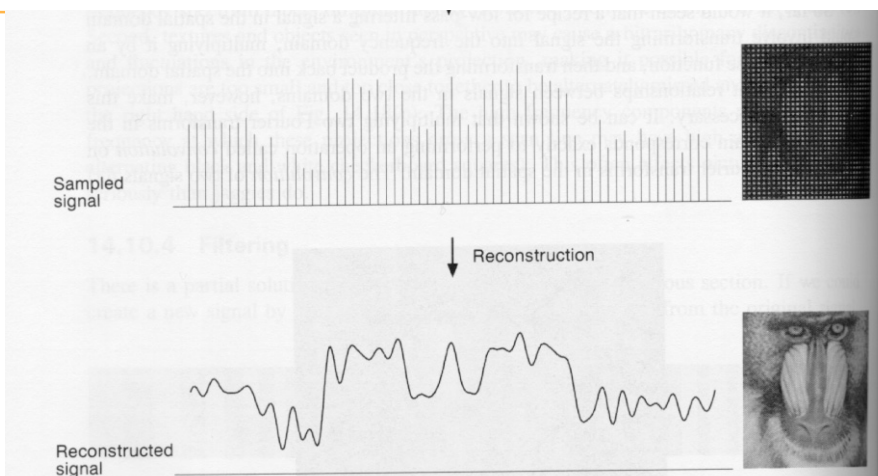
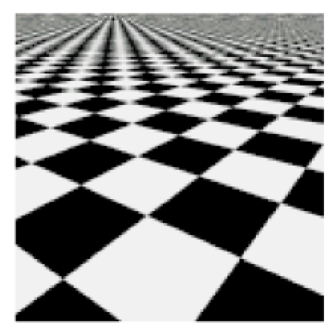


Fig. 14.20 The sampling pipeline with filtering. (Courtesy of George Wolberg, Columbia University.)

Previous Antialiasing Example

Texture mipmapping: low pass filter

(a)



(b)