University of British Columbia
CPSC 314 Computer Graphics
May-June 2005

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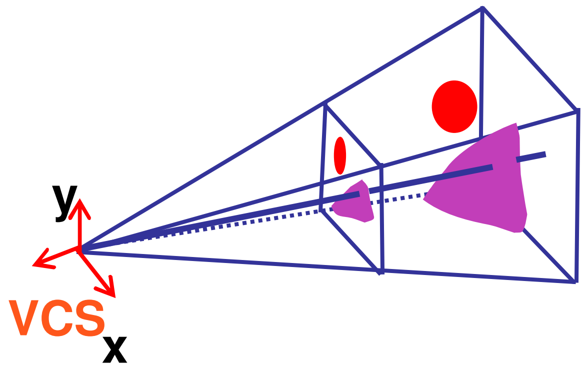
Textures, Procedural Approaches, Sampling

Week 4, Thu Jun 2

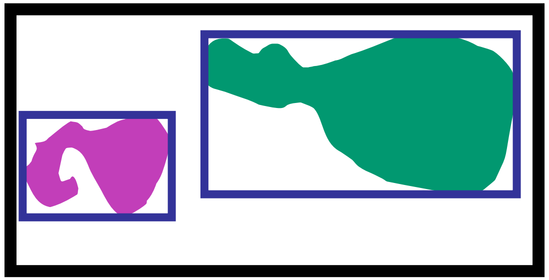
http://www.ugrad.cs.ubc.ca/~cs314/Vmay2005

Review: Picking Methods

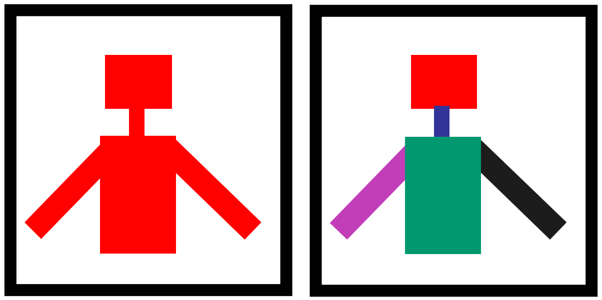
- manual ray intersection

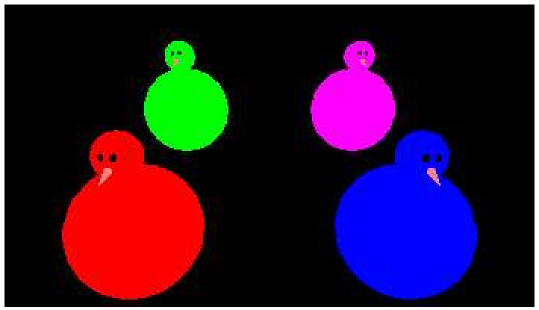


- bounding extents



- backbuffer coding





Review: Select/Hit Picking

- assign (hierarchical) integer key/name(s)
- small region around cursor as new viewport

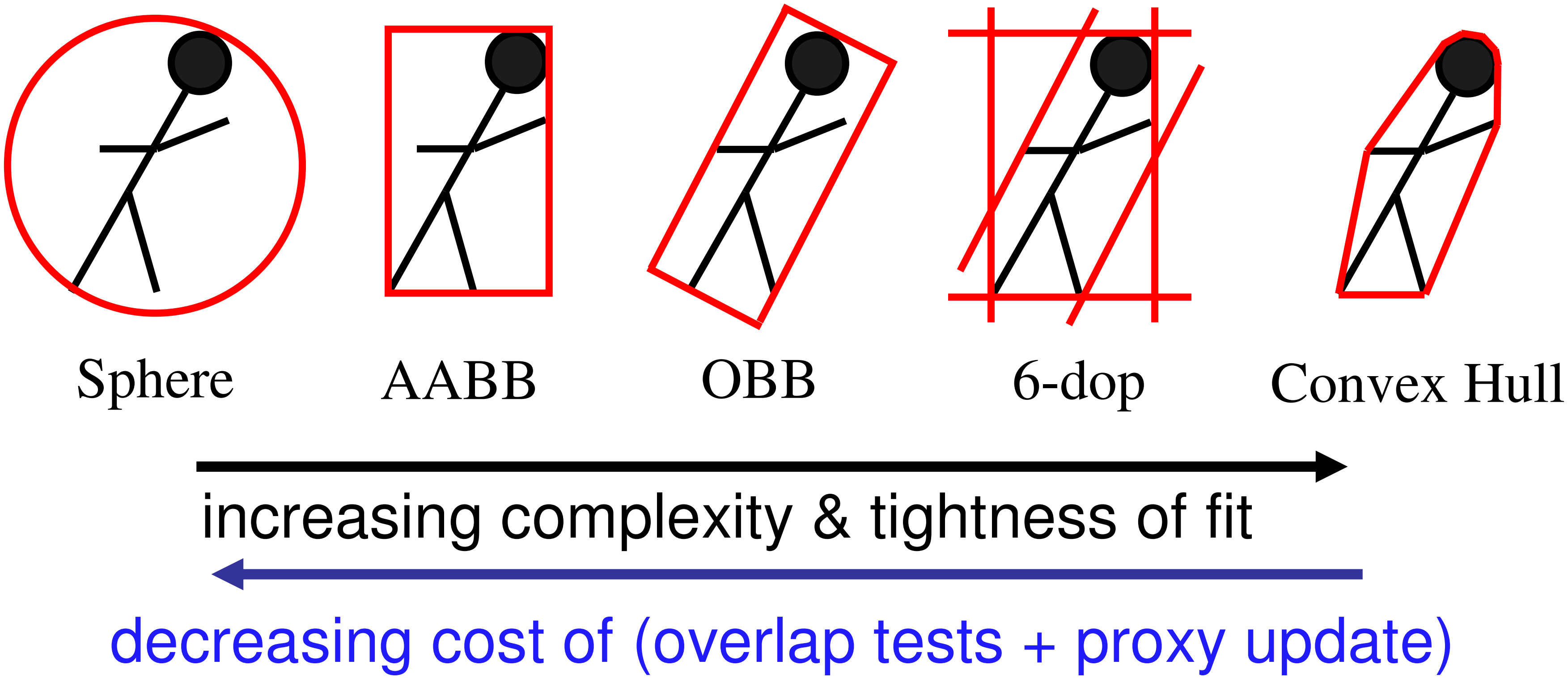
- redraw in selection mode
  - equivalent to casting pick “tube”
  - store keys, depth for drawn objects in hit list
- examine hit list
  - usually use frontmost, but up to application

Review: Collision Detection

- boundary check
  - perimeter of world vs. viewpoint or objects
    - 2D/3D absolute coordinates for bounds
    - simple point in space for viewpoint/objects
- set of fixed barriers
  - walls in maze game
    - 2D/3D absolute coordinate system
- set of moveable objects
  - one object against set of items
    - missile vs. several tanks
  - multiple objects against each other
    - punching game: arms and legs of players
    - room of bouncing balls

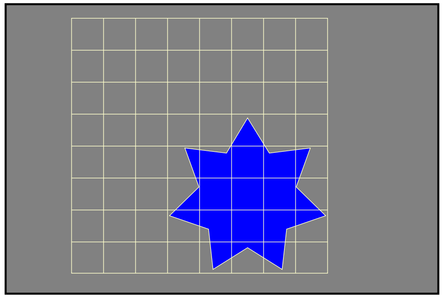
Review: Collision Proxy Tradeoffs

- collision proxy (bounding volume) is piece of geometry used to represent complex object for purposes of finding collision
- proxies exploit facts about human perception
  - we are bad at determining collision correctness
  - especially many things happening quickly

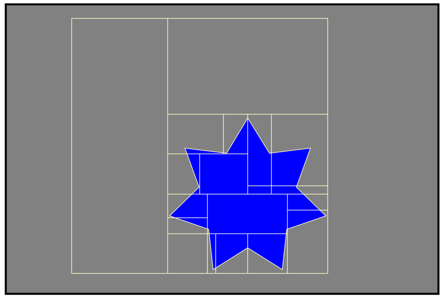


Review: Spatial Data Structures

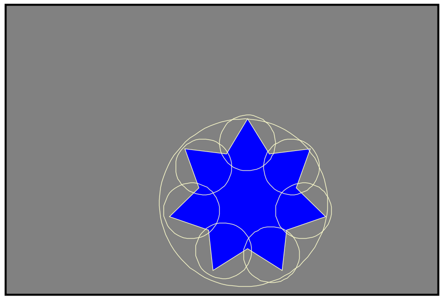
uniform grids



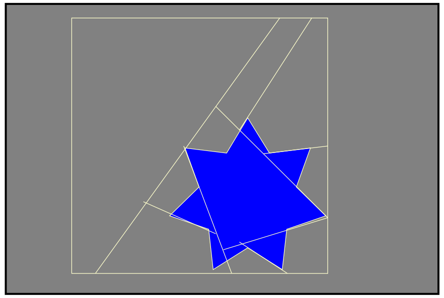
BSP trees



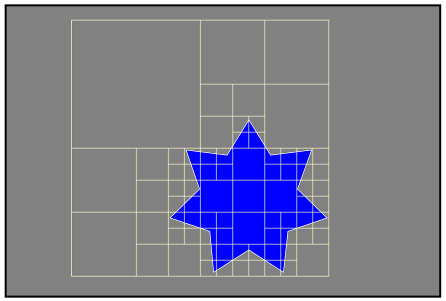
bounding volume hierarchies



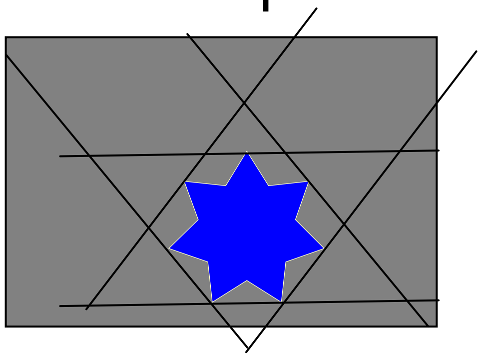
kd-trees



octrees



k-dops

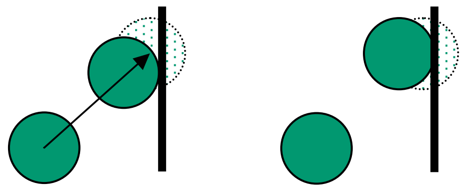


Review: Exploiting Coherence

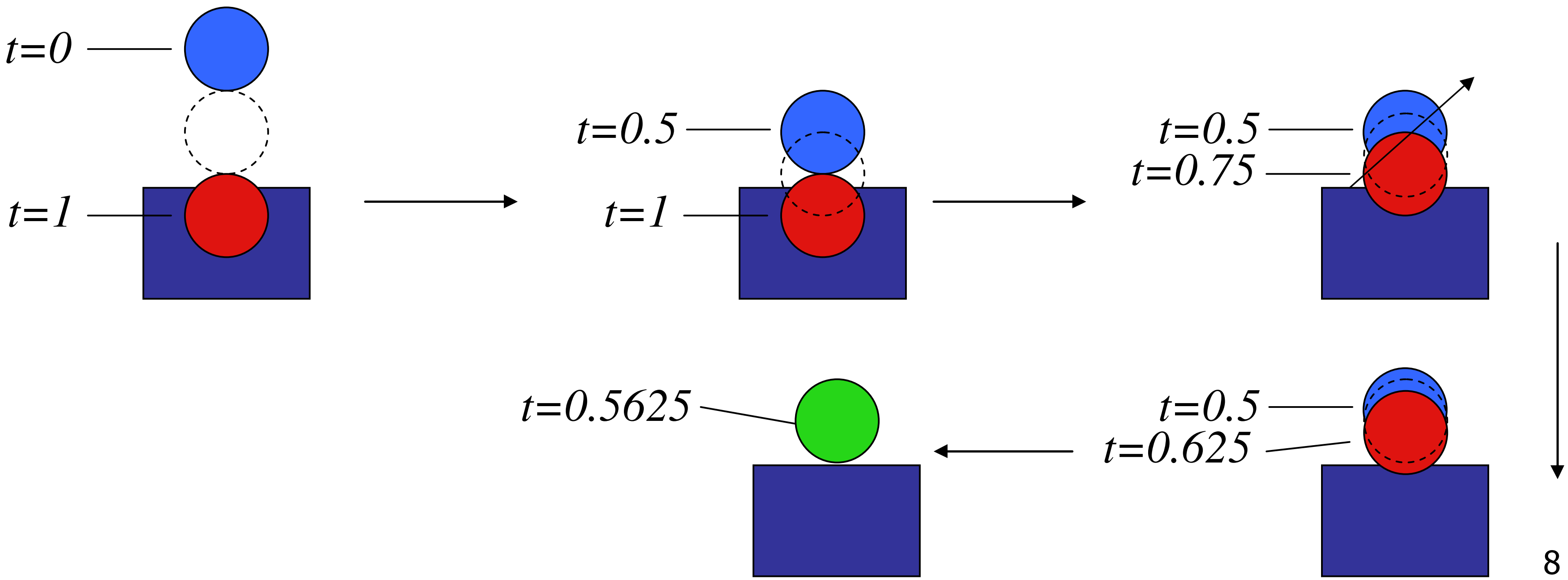
- player normally doesn't move far between frames
- track incremental changes, using previous results instead of doing full search each time
- keep track of entry and exit into cells through portals
  - probably the same cells they intersect now
  - or moved to neighbor

Review: Precise Collisions

- hacked clean up
  - simply move position so that objects just touch, leave time the same

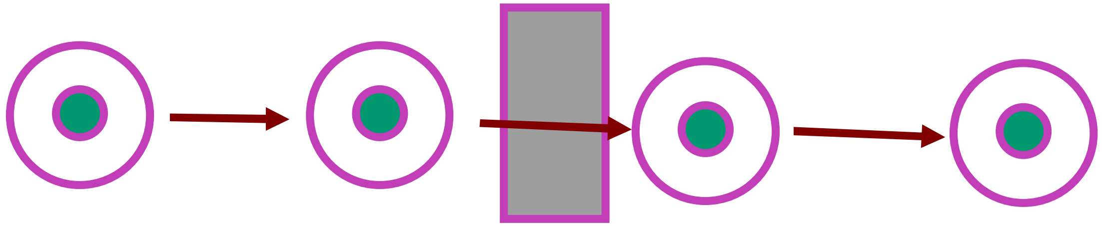


- interval halving
  - binary search through time to find exact collision point and time

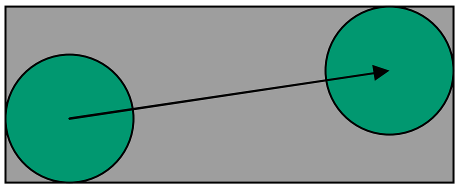


Review: Fast-Moving Objects

- temporal sampling
  - aliasing: can miss collision completely!



- movement line



- conservative prediction
  - assume maximum velocity, smallest feature size
  - increase temporal and spatial sampling rate
- simple alternative: just miss the hard cases
  - player may not notice!

Review: Collision Response

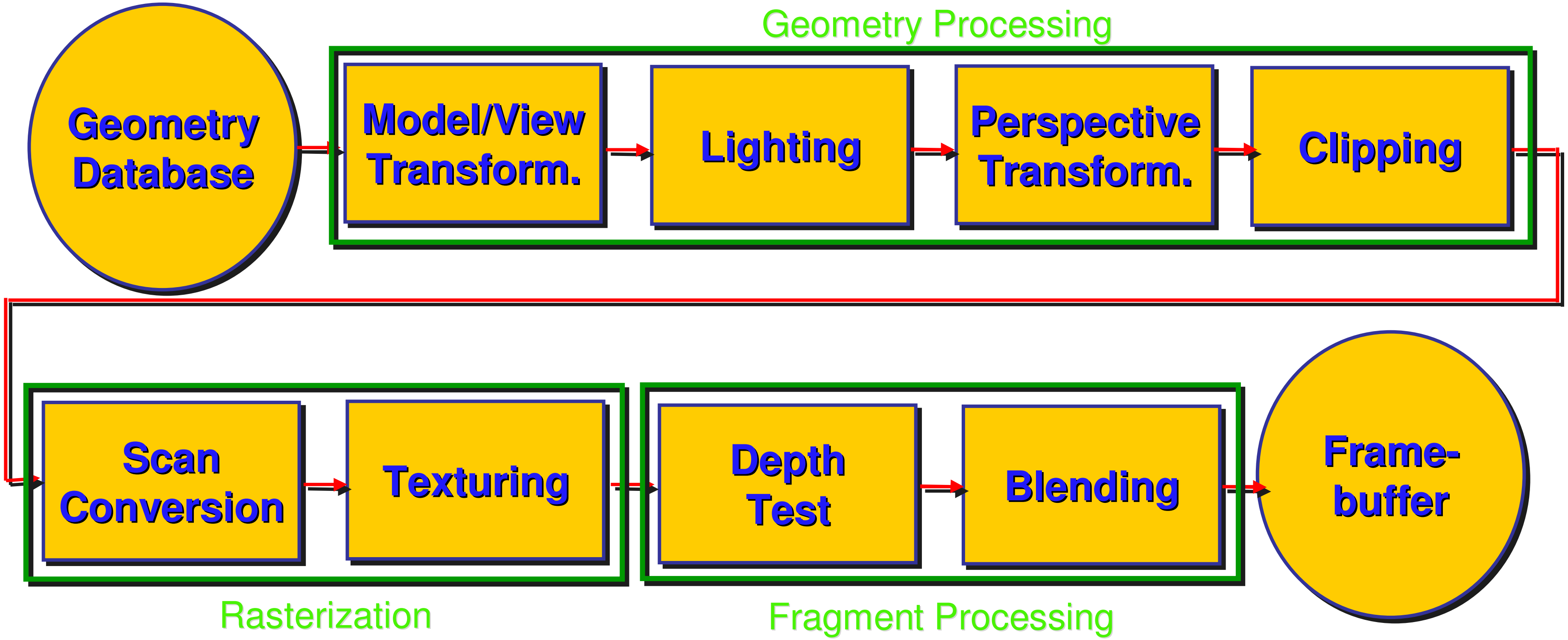
- frustrating to just stop player
  - often move tangentially to obstacle
- recursively to catch all collisions
- handling multiple simultaneous contacts

Texturing

Reading

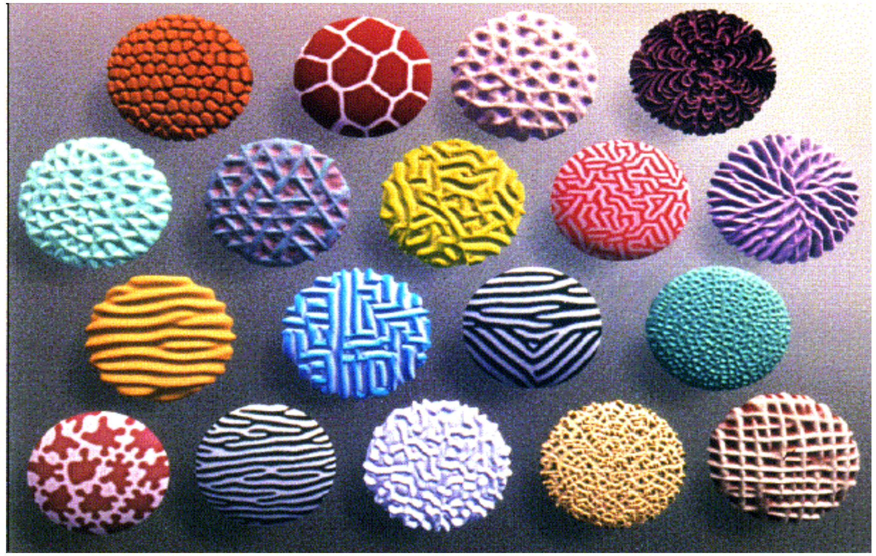
- FCG Chapter 10
- Red Book Chapter Texture Mapping

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

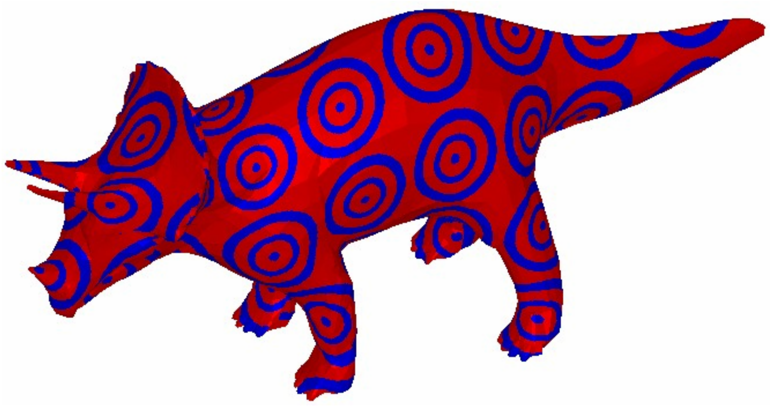


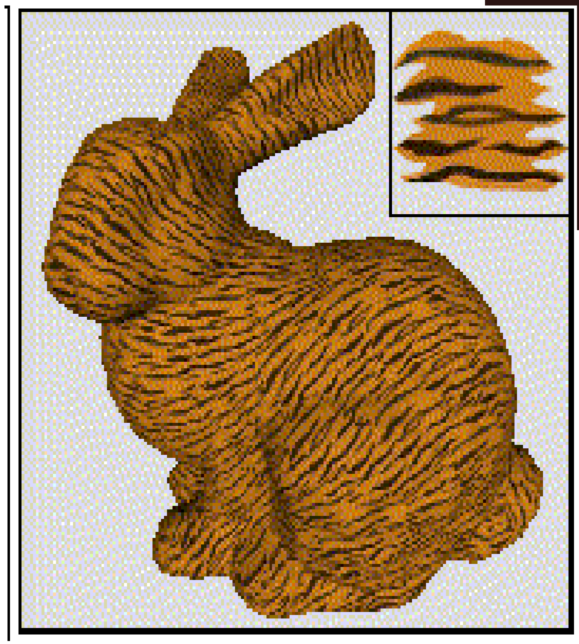
Texture Mapping

- 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 point on object surface
- two approaches
  - surface texture map
  - volumetric texture

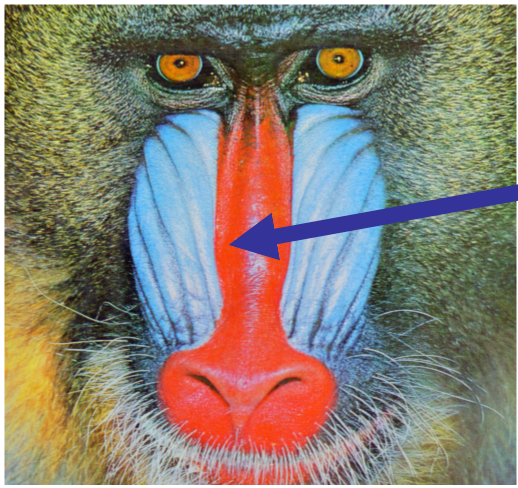


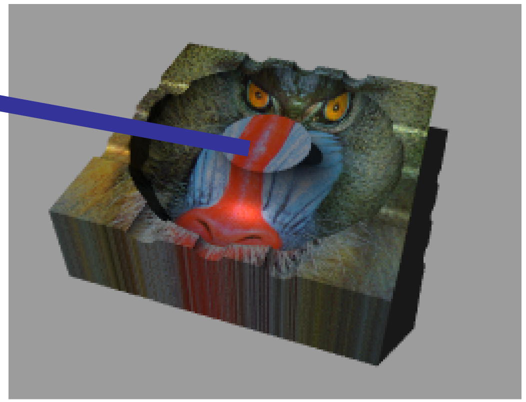


Texture Coordinates

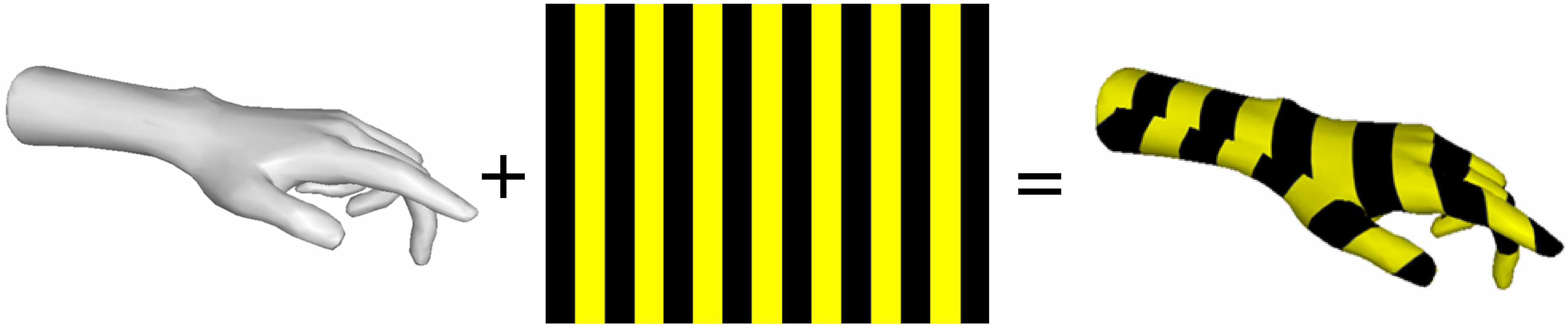
- texture image: 2D array of color values (texels)
- assigning texture coordinates (s,t) at vertex with object coordinates (x,y,z,w)
  - use interpolated (s,t) for texel lookup at each pixel
  - use value to modify a polygon's color
    - or other surface property
  - specified by programmer or artist

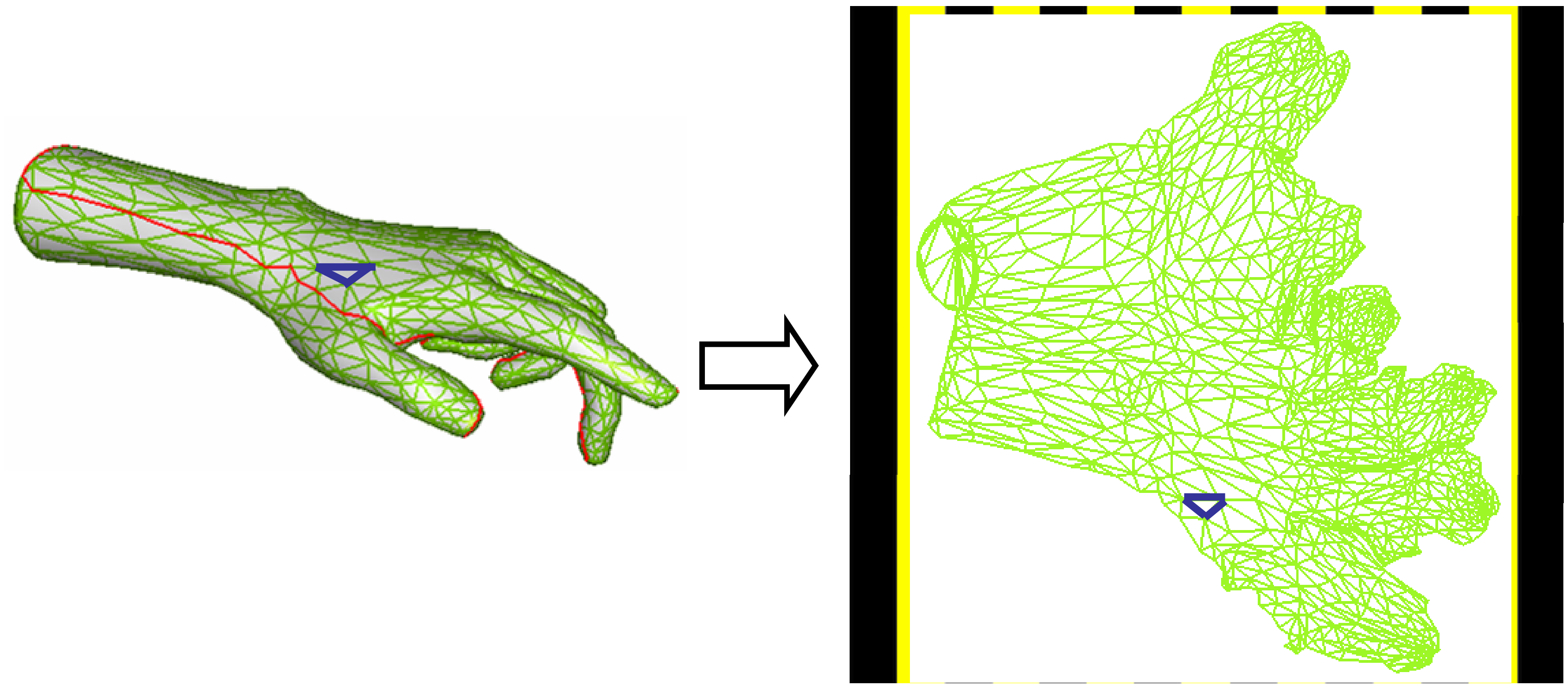
```
glTexCoord2f(s,t)
glVertexf(x,y,z,w)
```



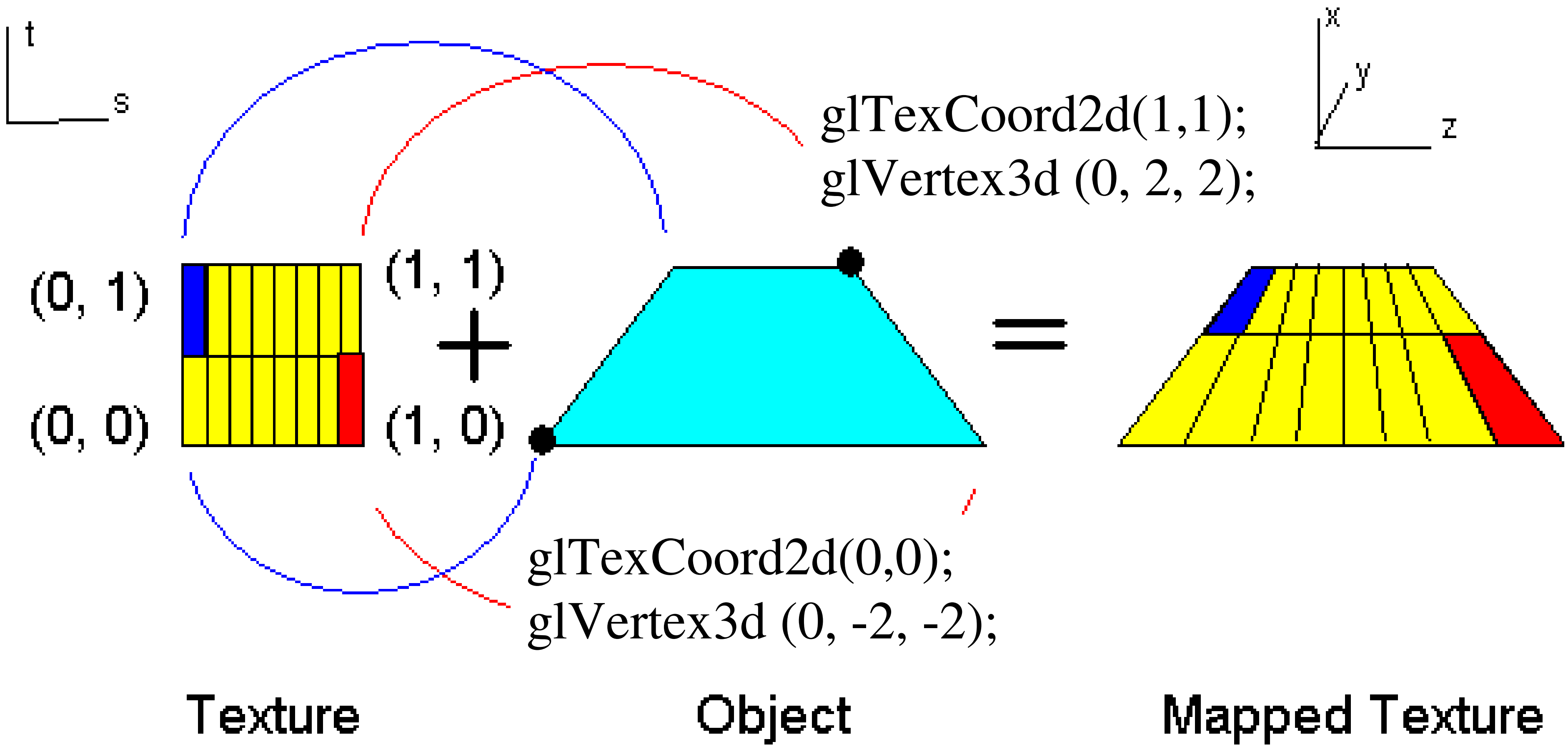


Texture Mapping Example



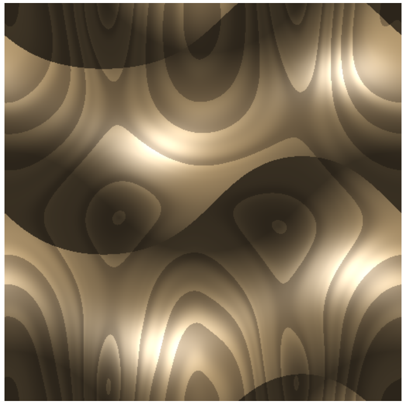


Example Texture Map

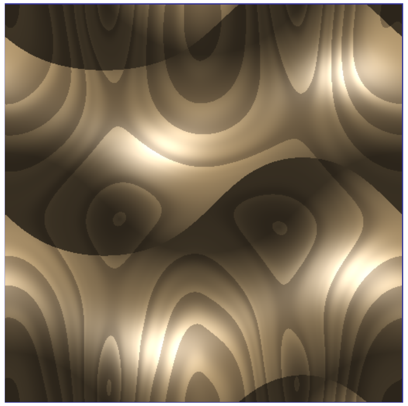


Fractional Texture Coordinates

texture image

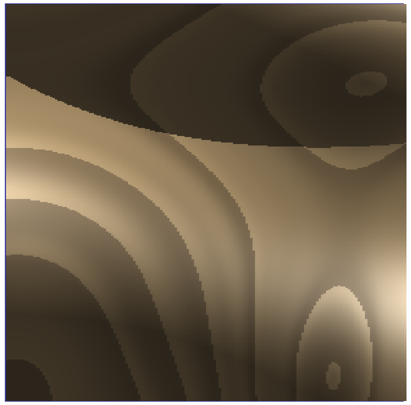


(0,1) (1,1)



(0,0) (1,0)

(0,.5) (.25,.5)



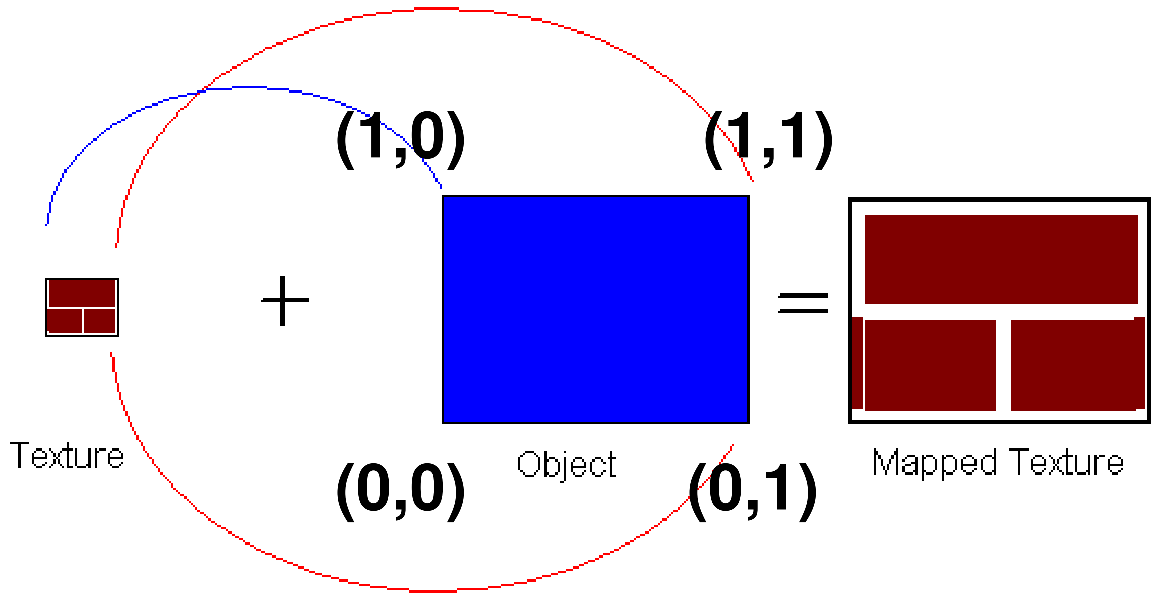
(0,0) (.25,0)

Texture Lookup: Tiling and Clamping

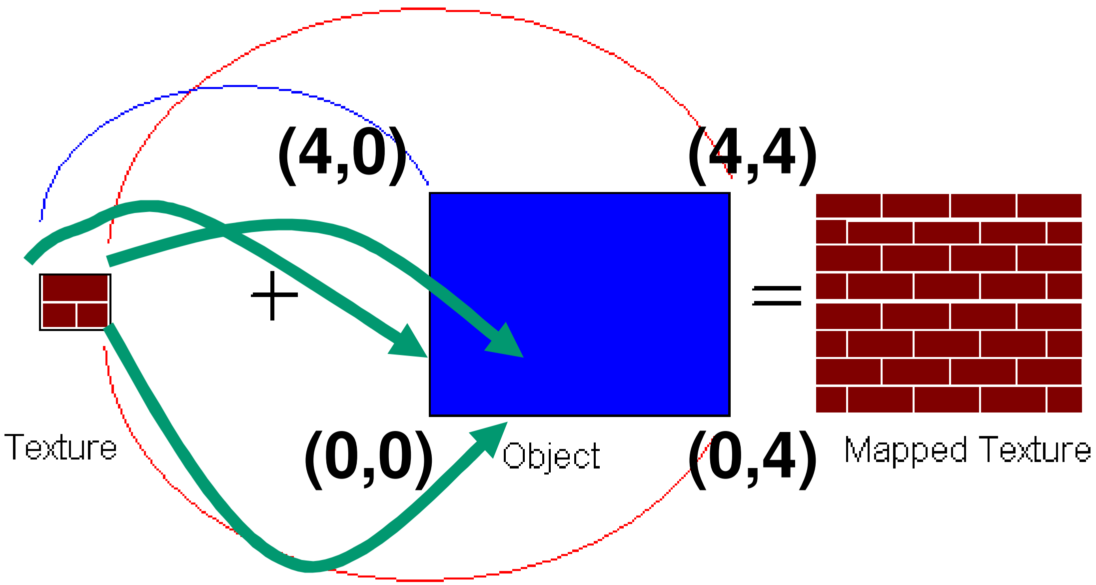
- what if s or t is outside the interval [0…1]?
- multiple choices
  - use fractional part of texture coordinates
    - cyclic repetition of texture to tile whole surface
      glTexParameteri(…, GL_TEXTURE_WRAP_S, GL_REPEAT, GL_TEXTURE_WRAP_T, GL_REPEAT, ...)
  - clamp every component to range [0…1]
    - 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);



Demo

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
- [demo]

Texture Functions

- once have value from the texture map, can:
  - directly use as surface color: `GL_REPLACE`
    - throw away old color, lose lighting effects
  - modulate surface color: `GL_MODULATE`
    - multiply old color by new value, keep lighting info
    - texturing happens **after** lighting, not relit
  - use as surface color, modulate alpha: `GL_DECAL`
    - like replace, but supports texture transparency
  - blend surface color with another: `GL_BLEND`
    - new value controls which of 2 colors to use
    - indirection, new value not used directly for coloring
- specify with `glTexEnvi(GL_TEXTURE_ENV, GL_TEXTURE_ENV_MODE, <mode>)`

Texture Pipeline

(x, y, z) | **(s, t)** | **(s', t')**

Object position → **Parameter space** → **Transformed parameter space** →

(-2.3, 7.1, 17.7) | **(0.32, 0.29)** | **(0.52, 0.49)**

Texel space → **Texel color** → **Final color**

(81, 74) | **(0.9,0.8,0.7)** | **(0.45,0.4,0.35)**

Object color → **Final color**

(0.5,0.5,0.5)

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)
- 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 be square and size a power of 2
  - common sizes are 32x32, 64x64, 256x256
  - smaller uses less memory, and there is a finite amount of texture memory on graphics cards
- ok to use texture template sample code for project 4
  - http://nehe.gamedev.net/data/lessons/lesson.asp?lesson=09

Texture Mapping

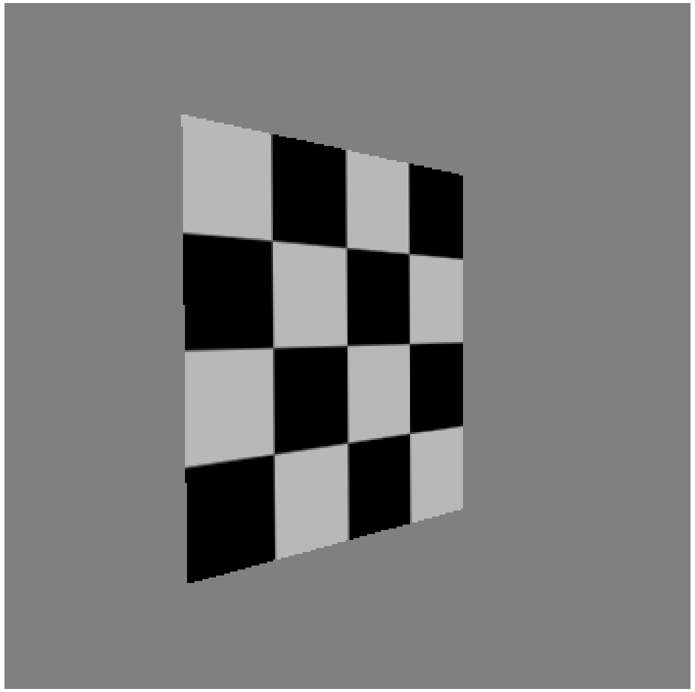
- texture coordinates
  - specified at vertices

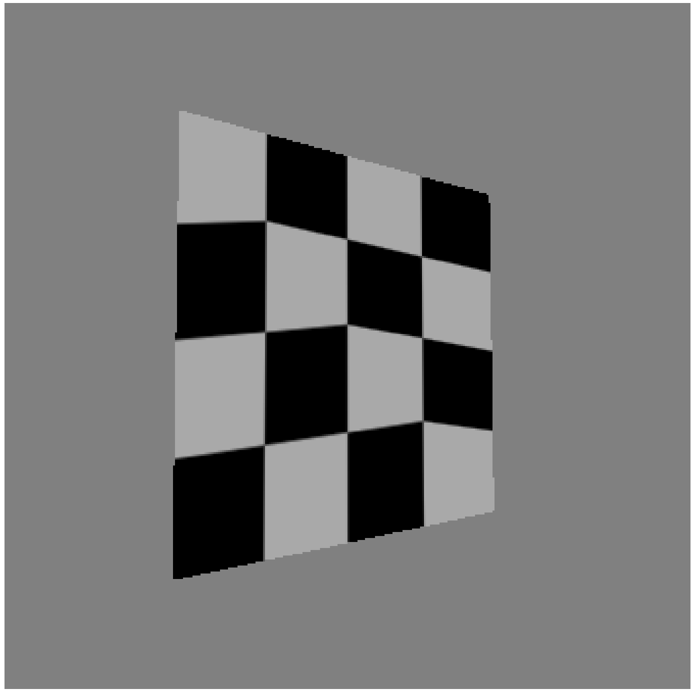
```
glTexCoord2f(s,t);
glVertexf(x,y,z);
```

  - interpolated across triangle (like R,G,B,Z)
    - …well not quite!

Texture Mapping

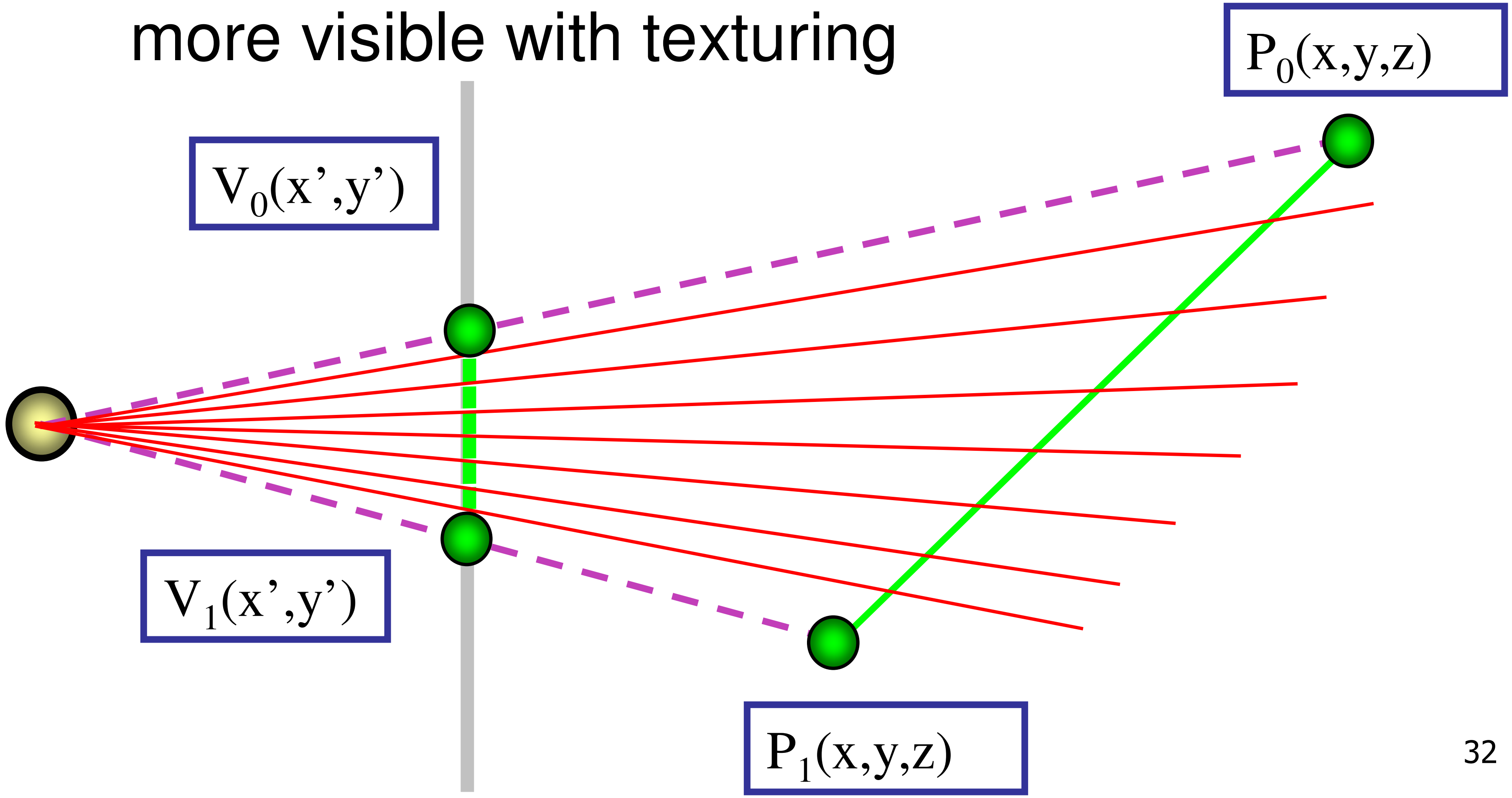
- texture coordinate interpolation
  - perspective foreshortening problem





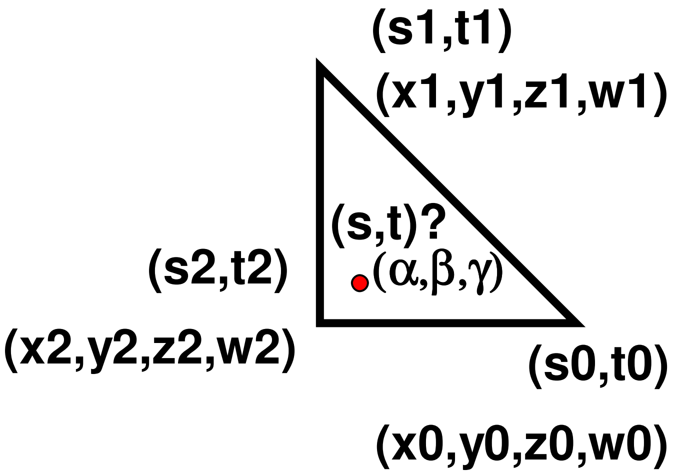
Interpolation: Screen vs. World Space

- screen space interpolation incorrect
  - problem ignored with shading, but artifacts more visible with texturing



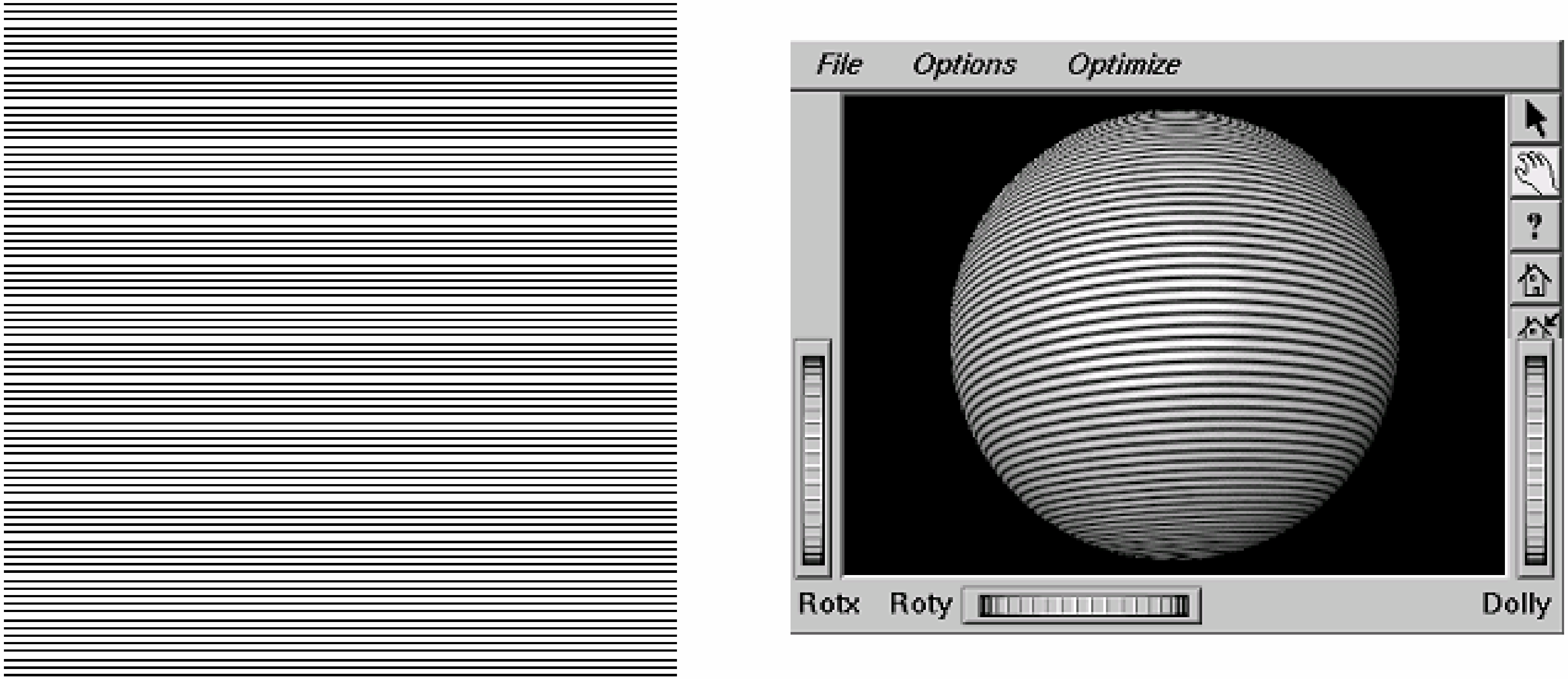
Texture Coordinate Interpolation

- 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



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

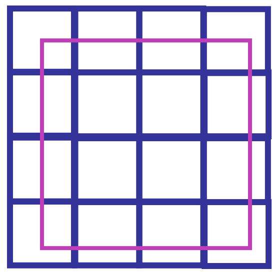
Reconstruction



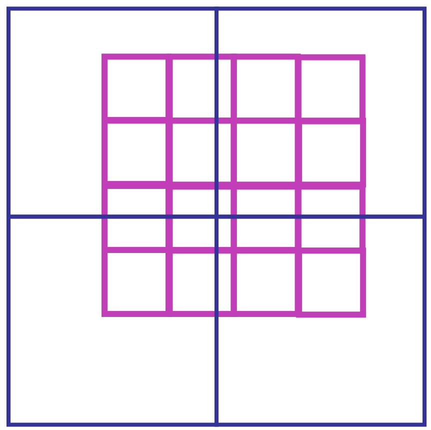
(image courtesy of Kiriakos Kutulakos, U Rochester)

Reconstruction

- how to deal with:
  - pixels that are much larger than texels?
    - apply filtering, "averaging"

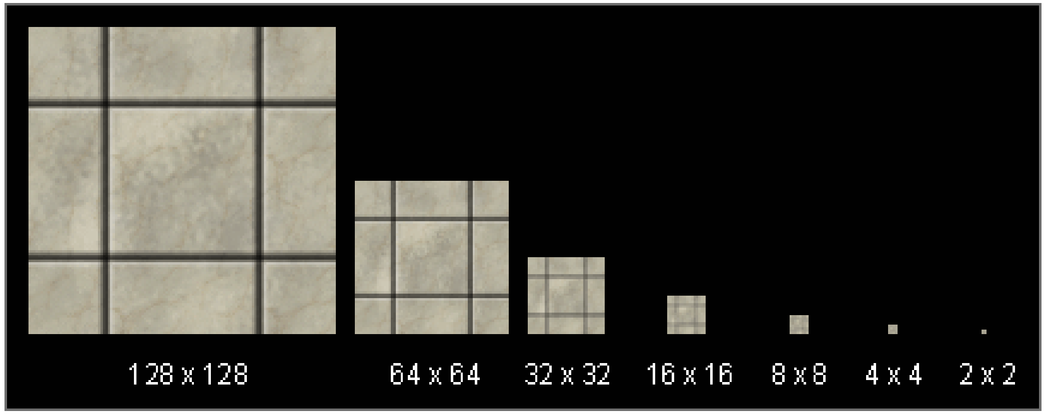


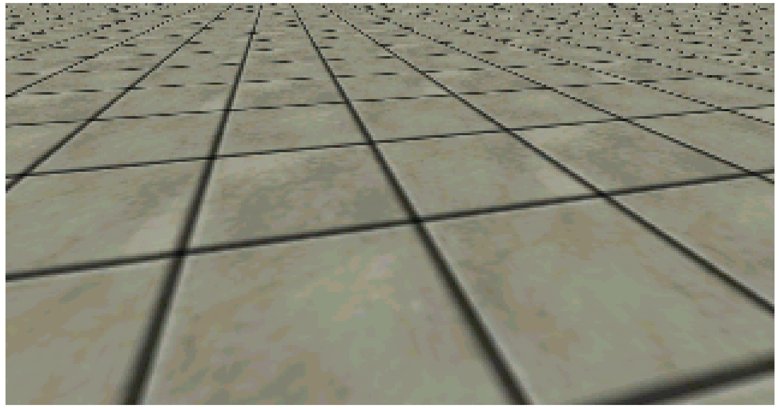
  - pixels that are much smaller than texels ?
    - interpolate



MIPmapping

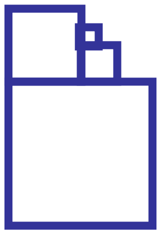
use "image pyramid" to precompute averaged versions of the texture

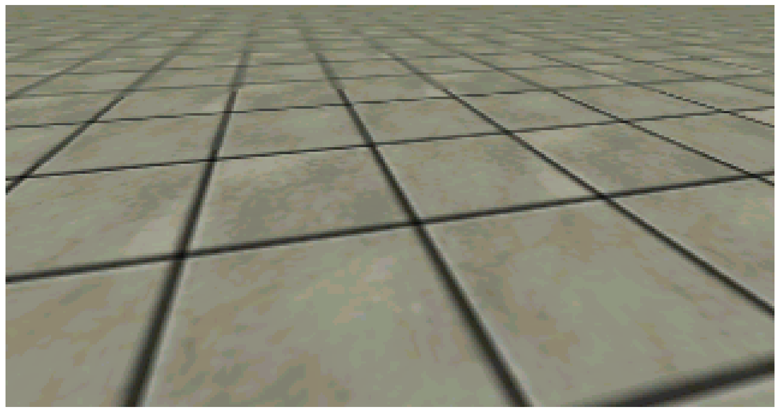




Without MIP-mapping

store whole pyramid in single block of memory



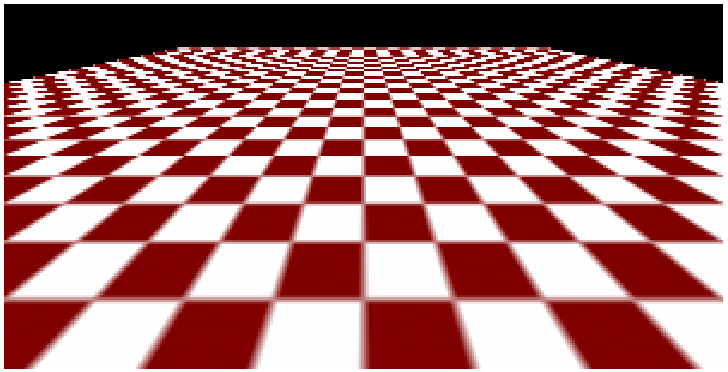


With MIP-mapping

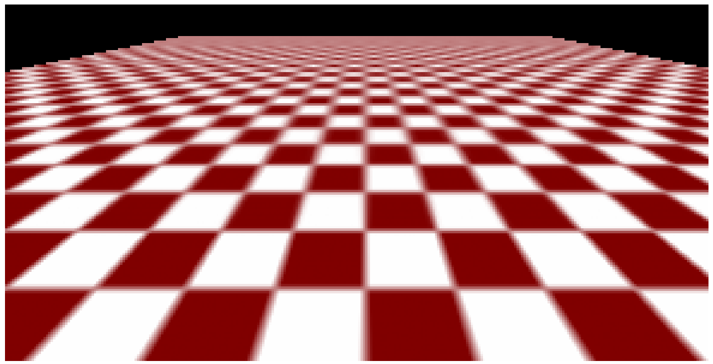
MIPmaps

- **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

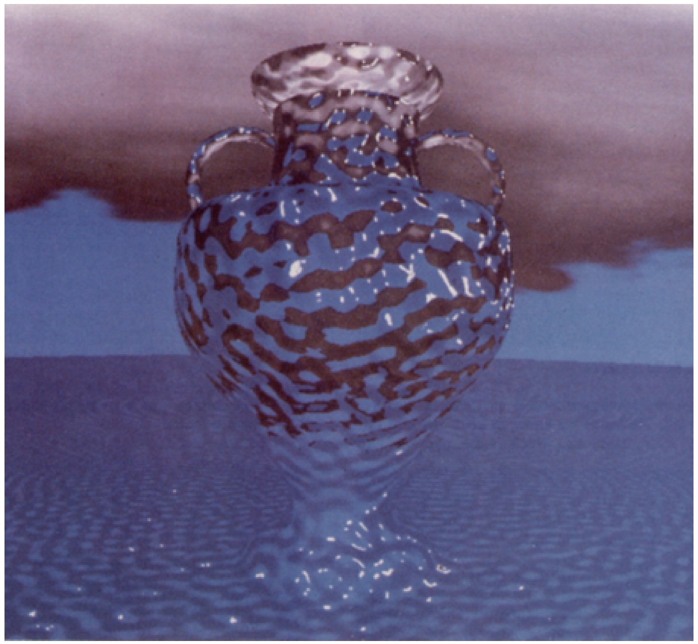


MIPmap storage

- only 1/3 more space required

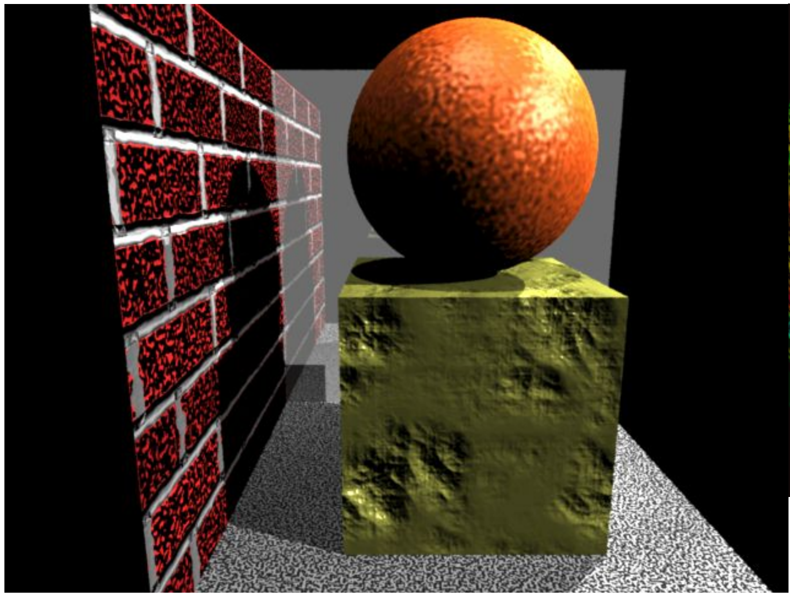
Texture Parameters

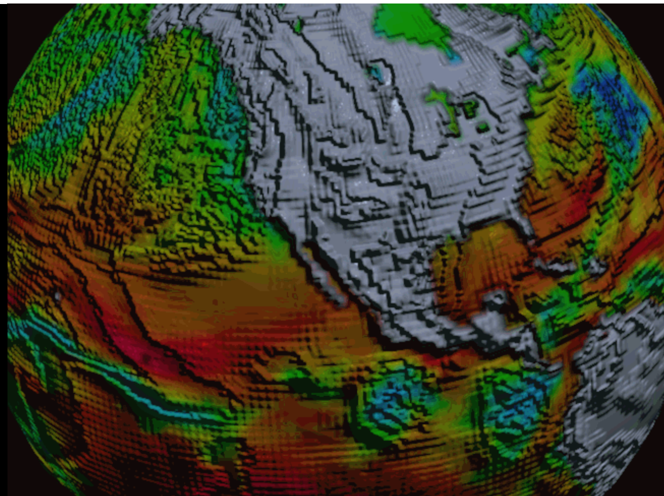
- in addition to color can control other material/object properties
  - surface normal (bump mapping)
  - reflected color (environment mapping)

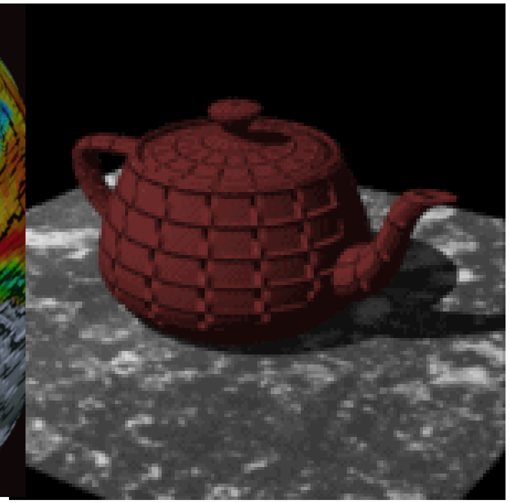


Bump Mapping: Normals As Texture

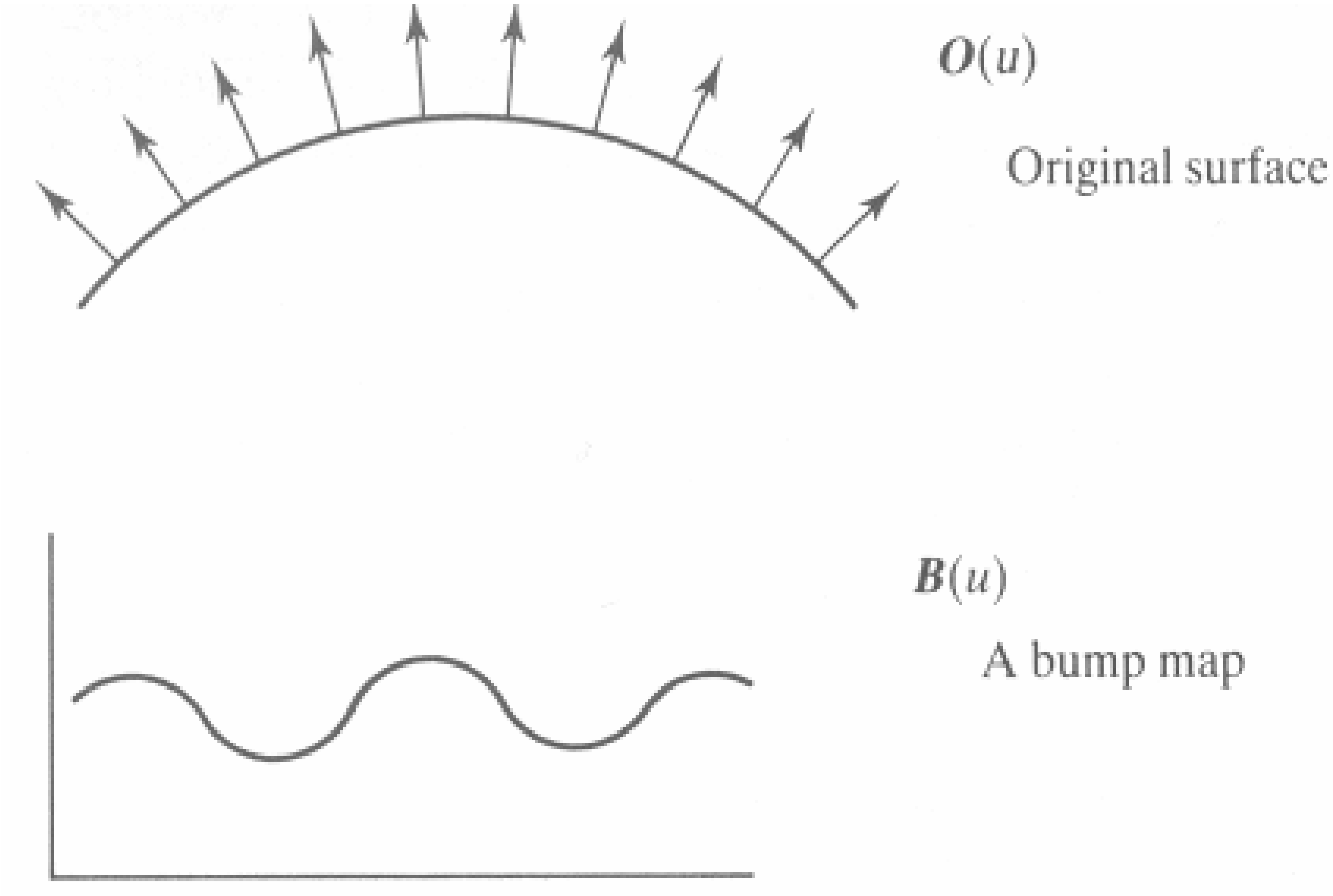
- object surface often not smooth – to recreate correctly need complex geometry model
- can control shape "effect" by locally perturbing surface normal
  - random perturbation
  - directional change over region



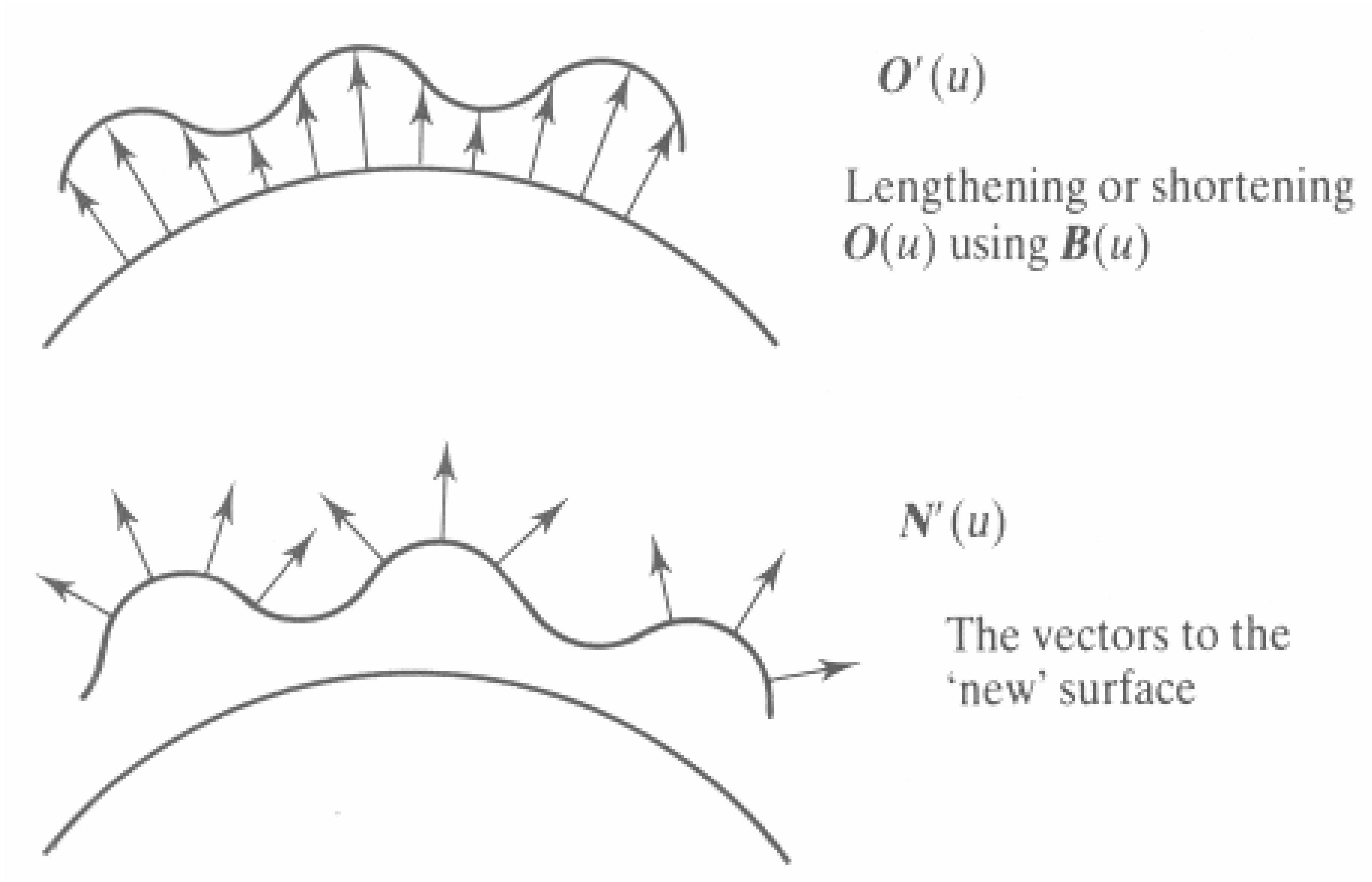




Bump Mapping

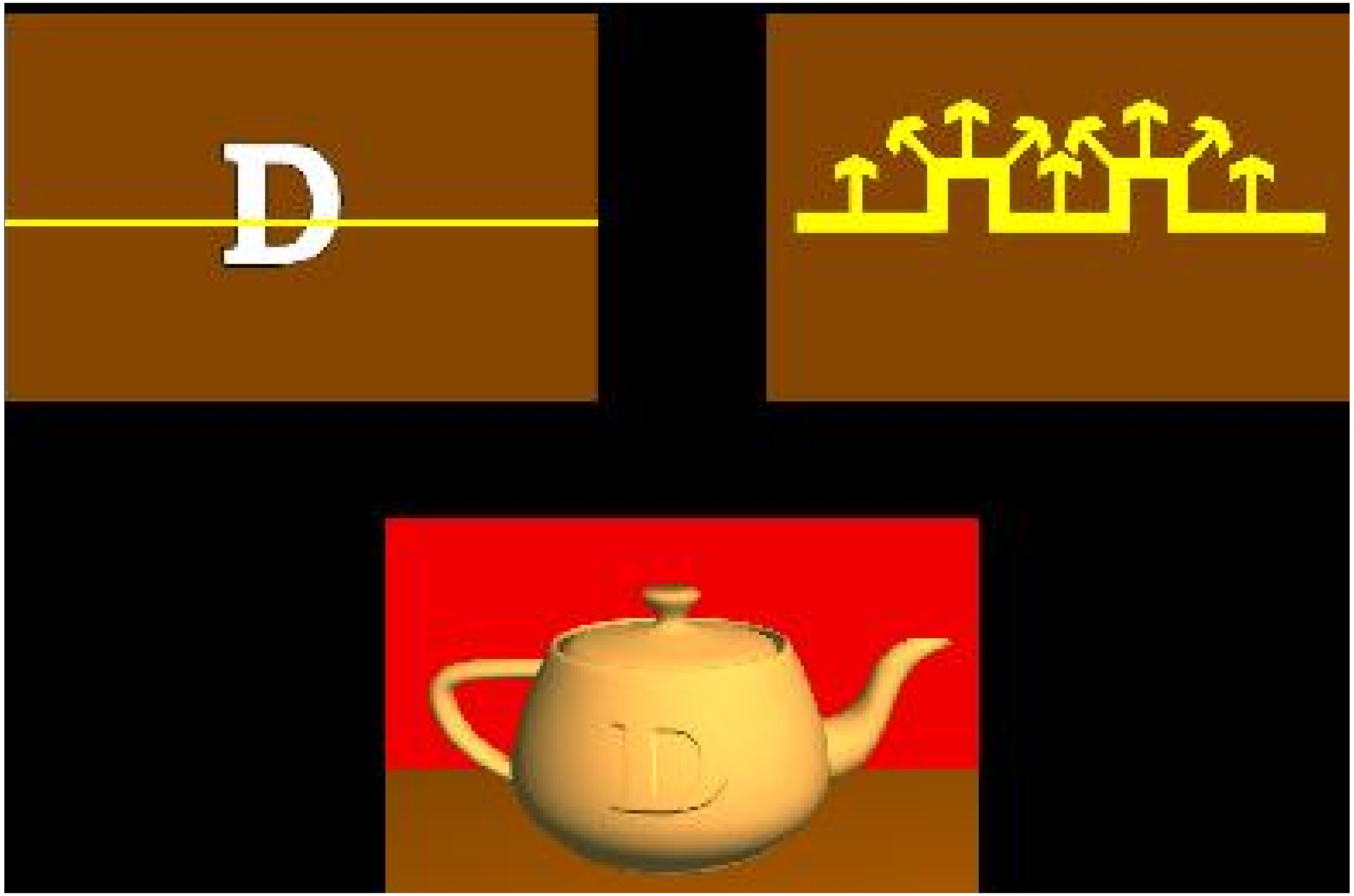


Bump Mapping



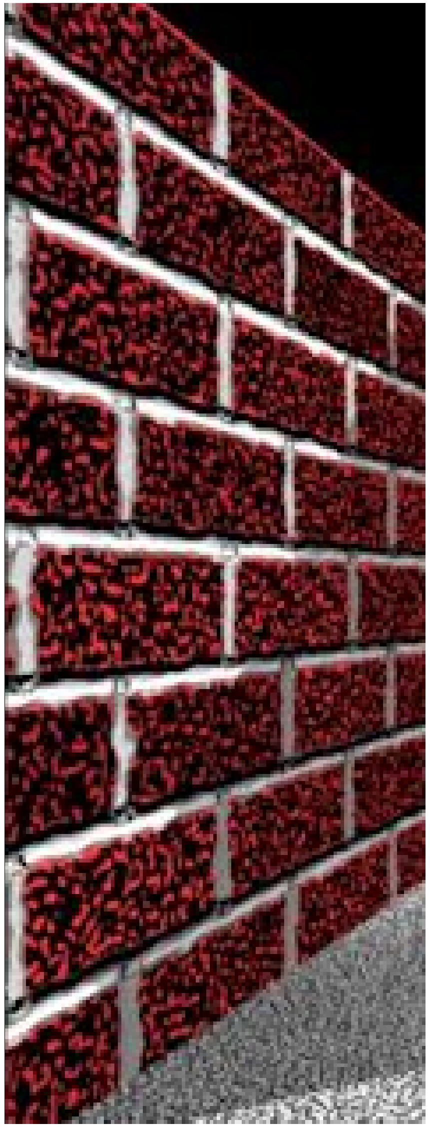
Embossing

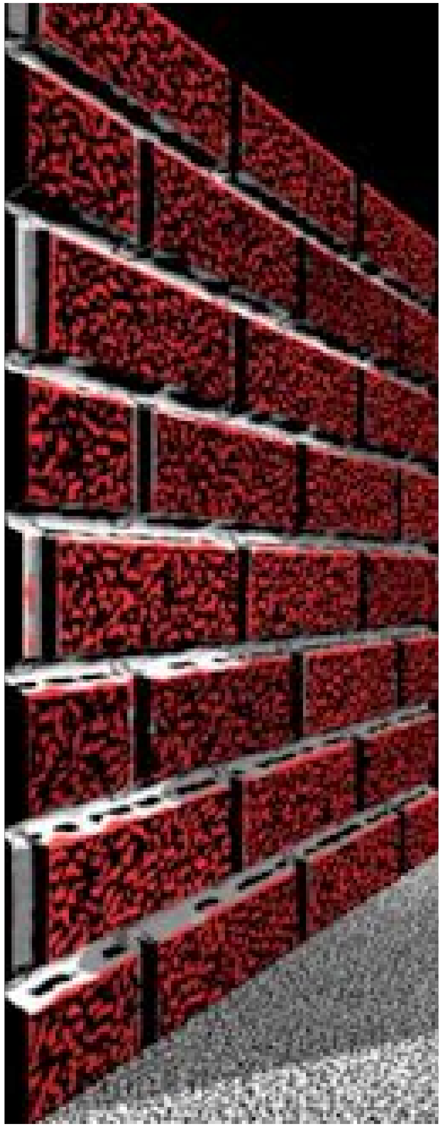
- at transitions
  - rotate point's surface normal by θ or - θ



Displacement Mapping

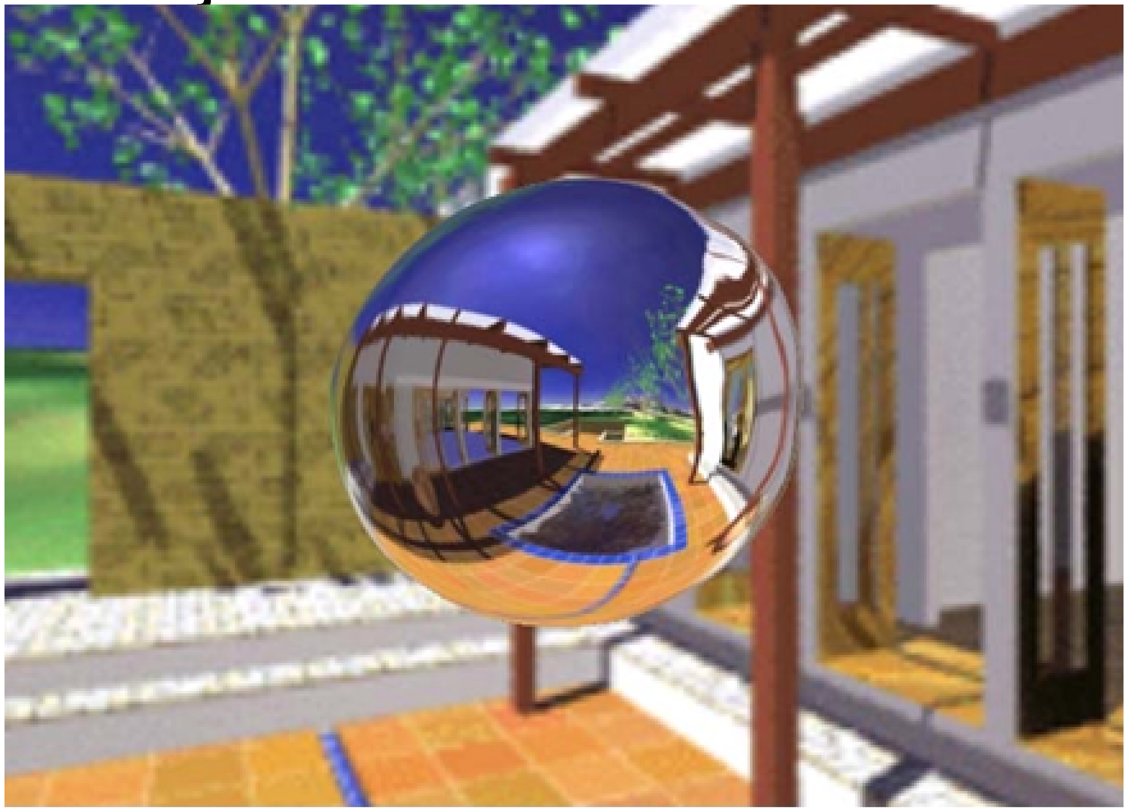
- bump mapping gets silhouettes wrong
  - shadows wrong too
- change surface geometry instead
  - only recently available with realtime graphics
  - need to subdivide surface





Environment Mapping

- cheap way to achieve reflective effect
  - generate image of surrounding
  - map to object as texture



Environment Mapping

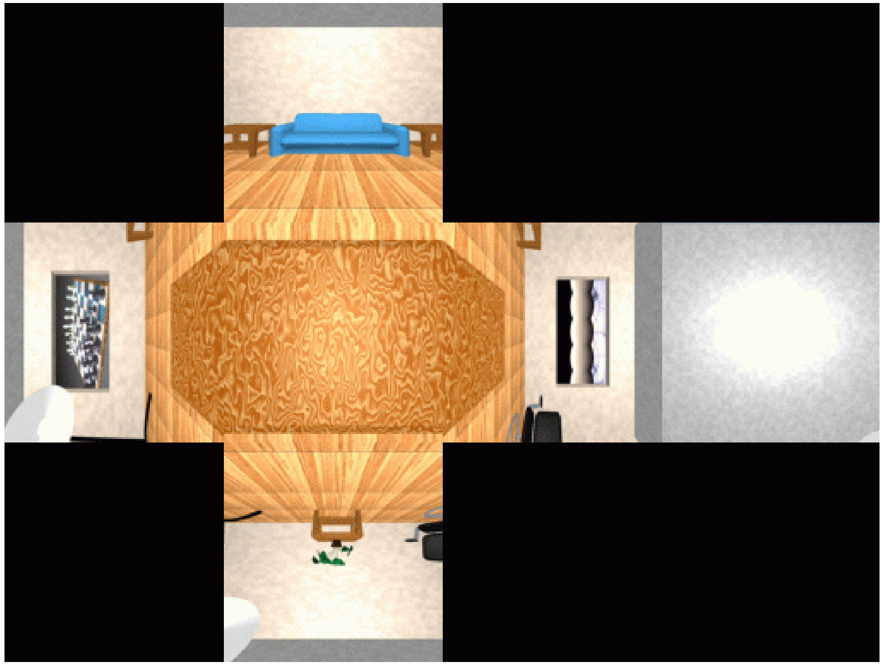
- used to model object that reflects surrounding textures to the eye
  - movie example: cyborg in Terminator 2
- different approaches
  - sphere, cube most popular
    - OpenGL support
      - `GL_SPHERE_MAP, GL_CUBE_MAP`
  - others possible too

Sphere Mapping

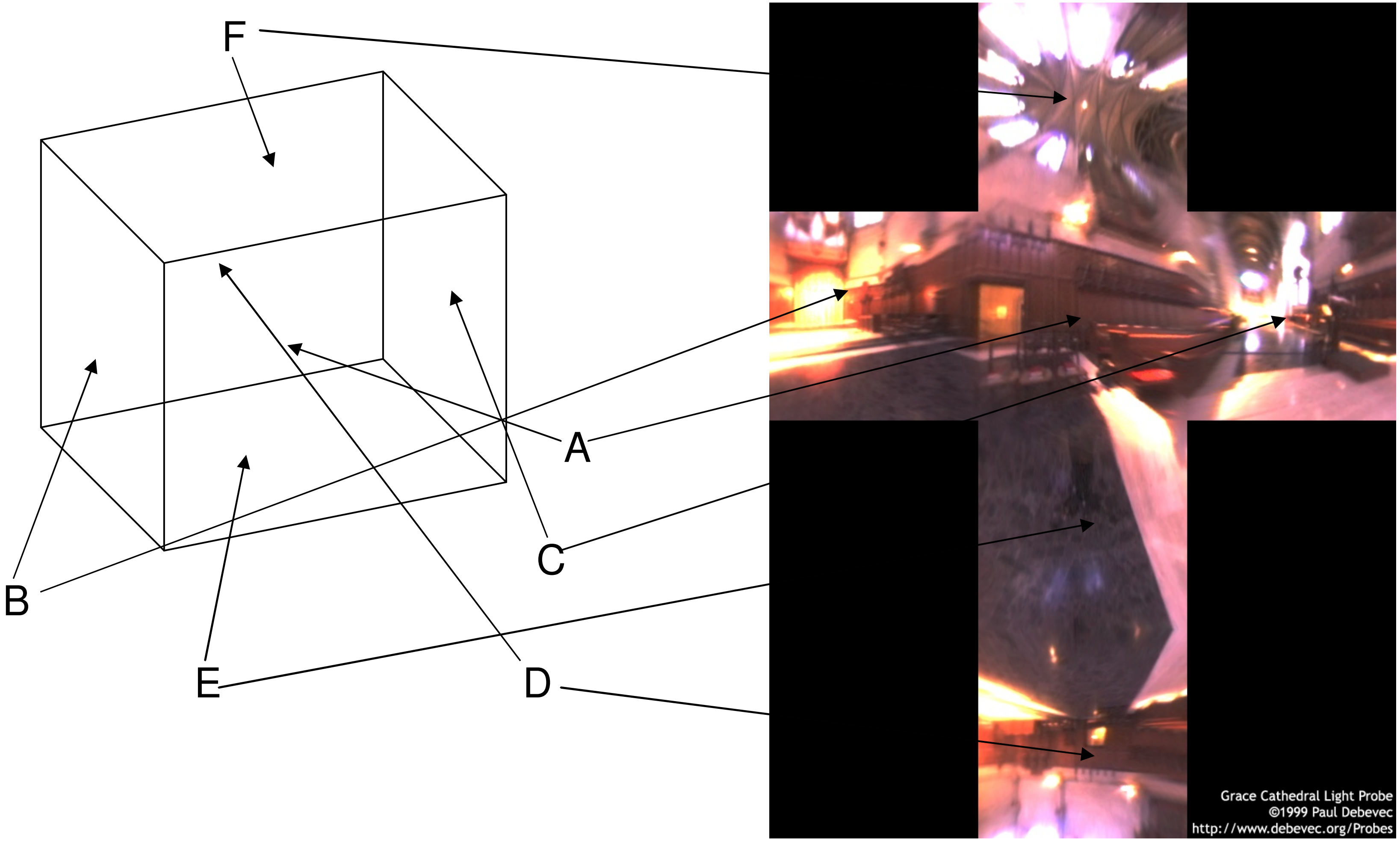
- texture is distorted fish-eye view
  - point camera at mirrored sphere
  - spherical texture mapping creates texture coordinates that correctly index into this texture map

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

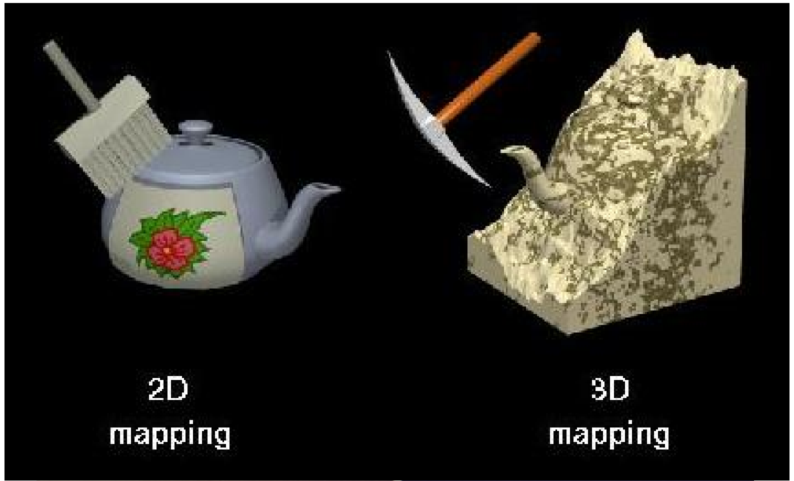
Blinn/Newell Latitude Mapping

Review: Texture Objects and Binding

- texture objects
  - texture management: switch with bind, not reloading
  - can prioritize textures to keep in memory
  - Q: what happens to textures kicked out of memory?
    - A: resident memory (on graphics card) vs. nonresident (on CPU)
    - details hidden from developers by OpenGL

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

Volumetric Texture Principles

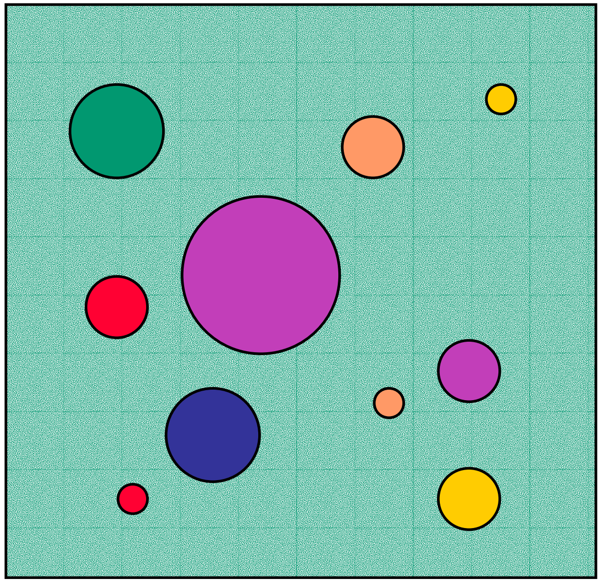
- 3D function ρ
  - $\rho = \rho(x,y,z)$
- texture space – 3D space that holds the texture (discrete or continuous)
- rendering: for each rendered point P(x,y,z) compute $\rho(x,y,z)$
- volumetric texture mapping function/space transformed with objects

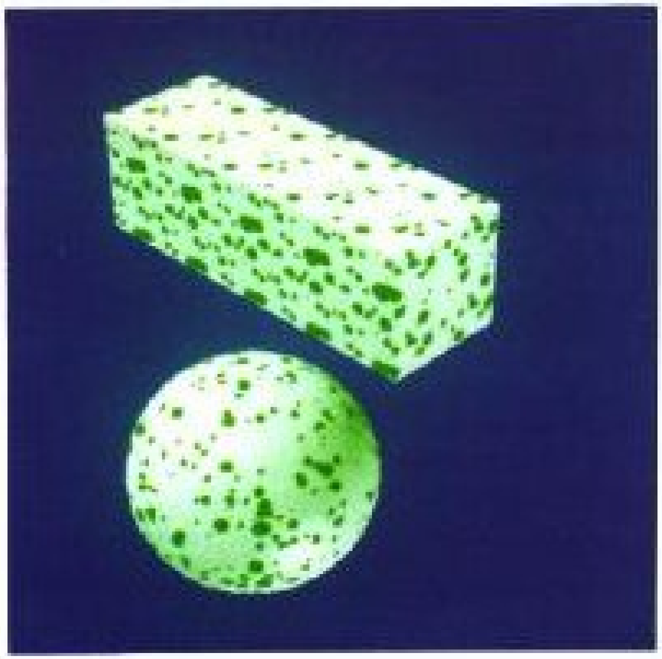
Procedural Textures

- generate “image” on the fly, instead of loading from disk
  - often saves space
  - allows arbitrary level of detail

Procedural Texture Effects: Bombing

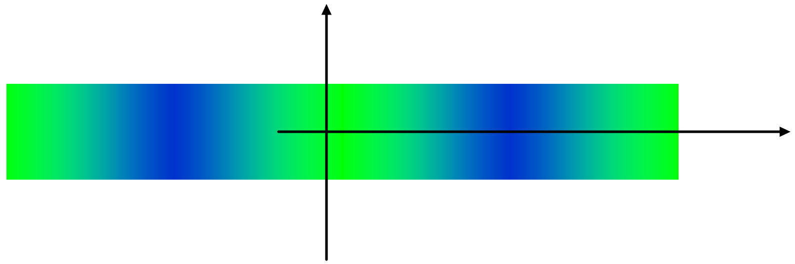
- randomly drop bombs of various shapes, sizes and orientation into texture space (store data in table)
  - for point P search table and determine if inside shape
    - if so, color by shape
    - otherwise, color by objects color





Procedural Texture Effects

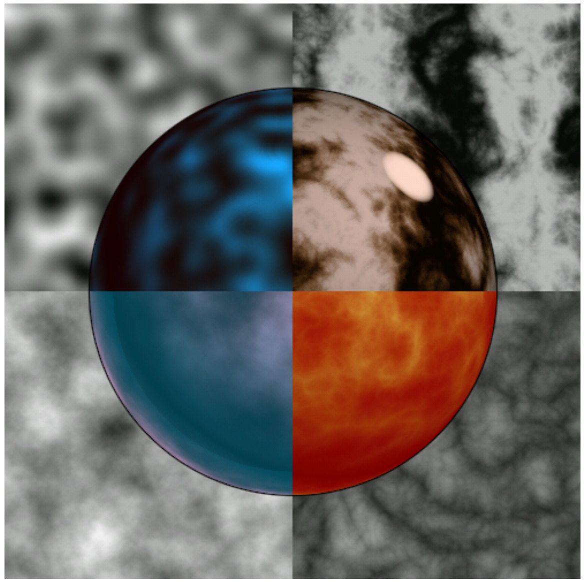
- simple marble

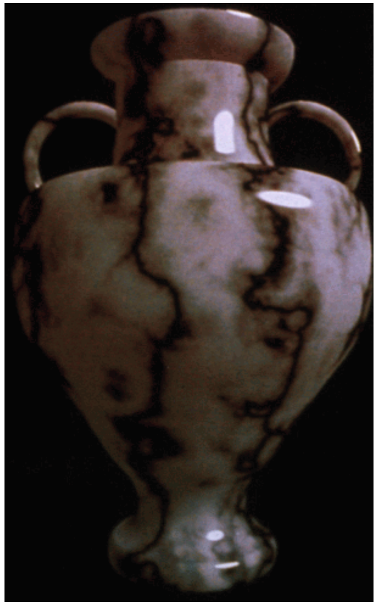


```
function boring_marble(point)
   x = point.x;
   return marble_color(sin(x));
   // marble_color maps scalars to colors
```

Perlin Noise: Procedural Textures

- several good explanations
  - FCG 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



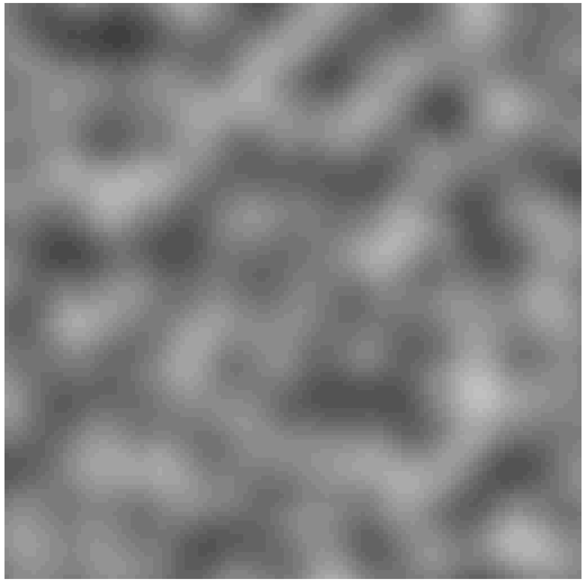


http://mrl.nyu.edu/~perlin/planet/

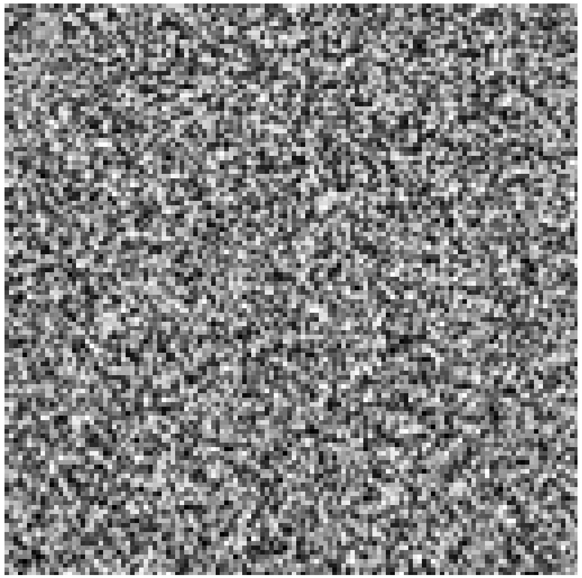
Perlin Noise: Coherency

- smooth not abrupt changes

coherent

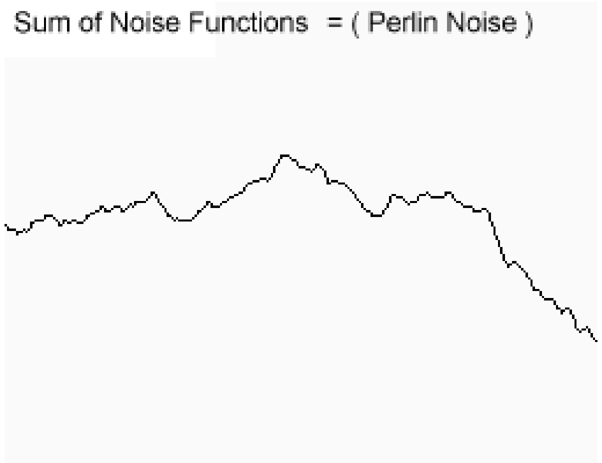


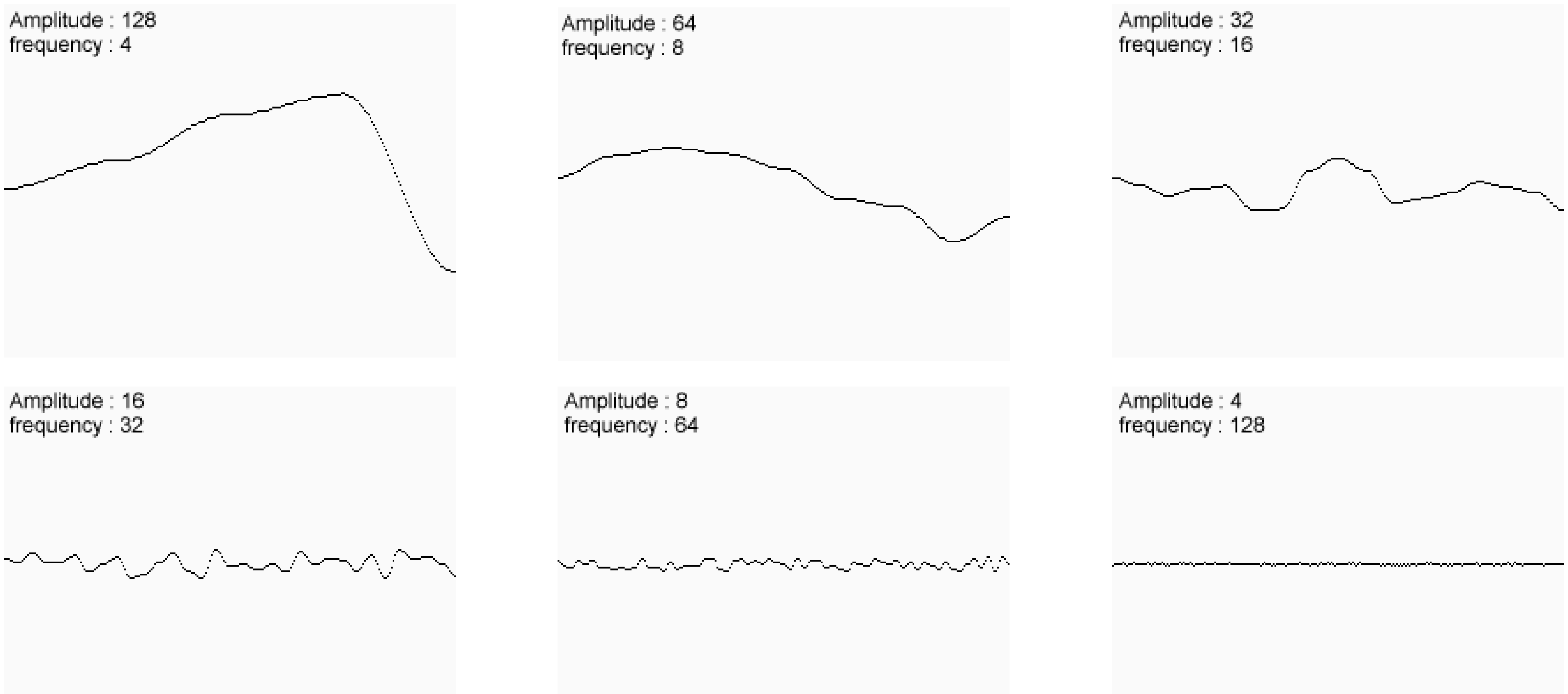
white noise



Perlin Noise: Turbulence

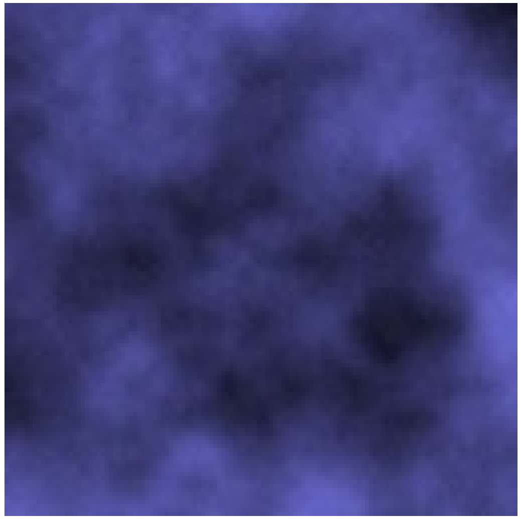
- multiple feature sizes
  - add scaled copies of noise

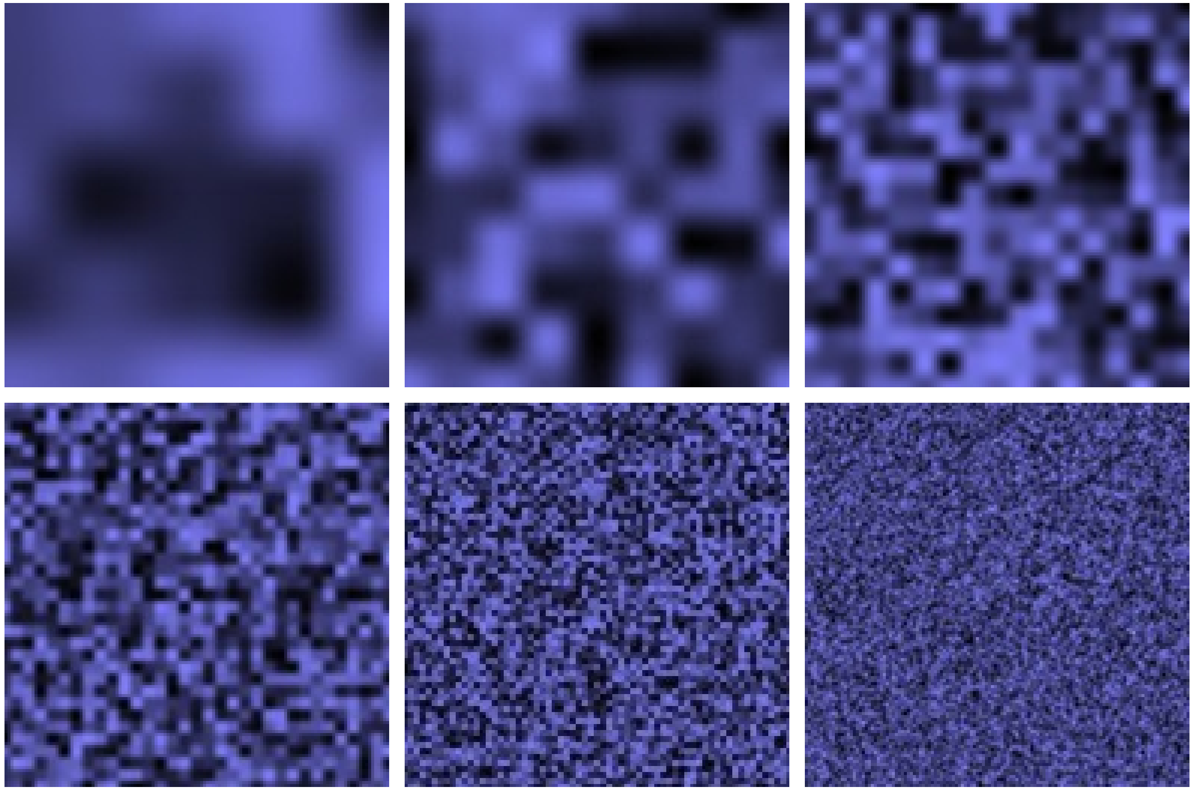




Perlin Noise: Turbulence

- multiple feature sizes
  - add scaled copies of noise





Perlin Noise: Turbulence

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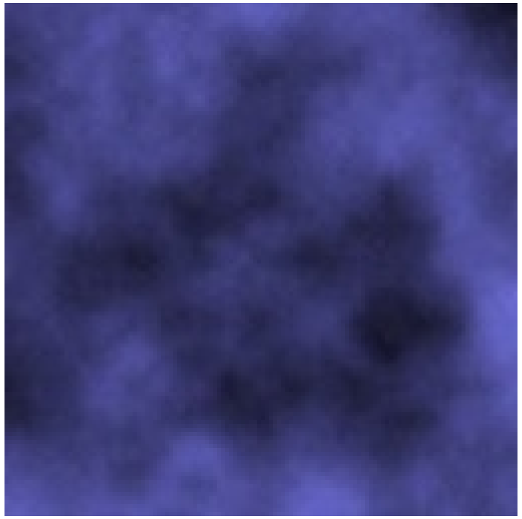


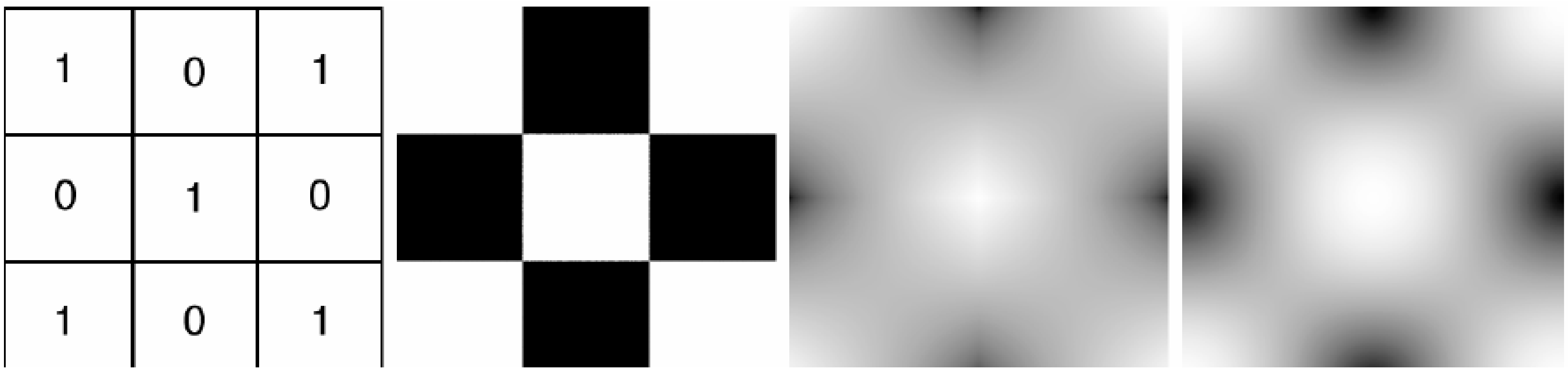
```
function turbulence(p)
      t = 0; scale = 1;
      while (scale > pixelsize) {
            t +=
abs(Noise(p/scale)*scale);
            scale/=2;
      } return t;
```

Generating Coherent Noise

- just three main ideas
  - nice interpolation
  - use vector offsets to make grid irregular
  - optmization
    - sneaky use of 1D arrays instead of 2D/3D one

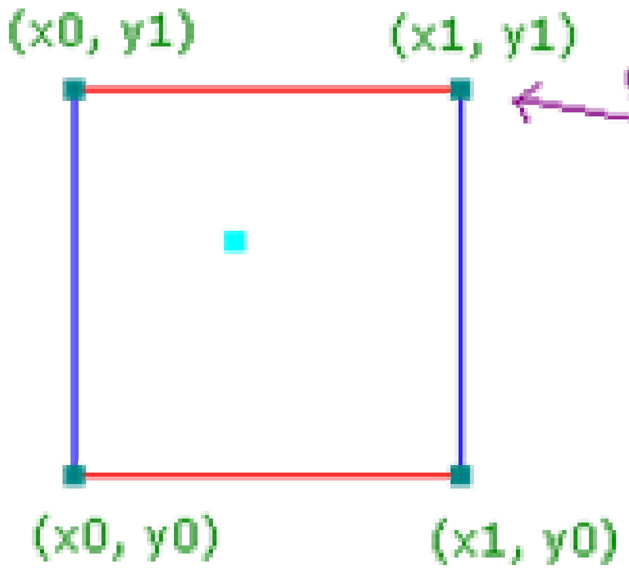
Interpolating Textures

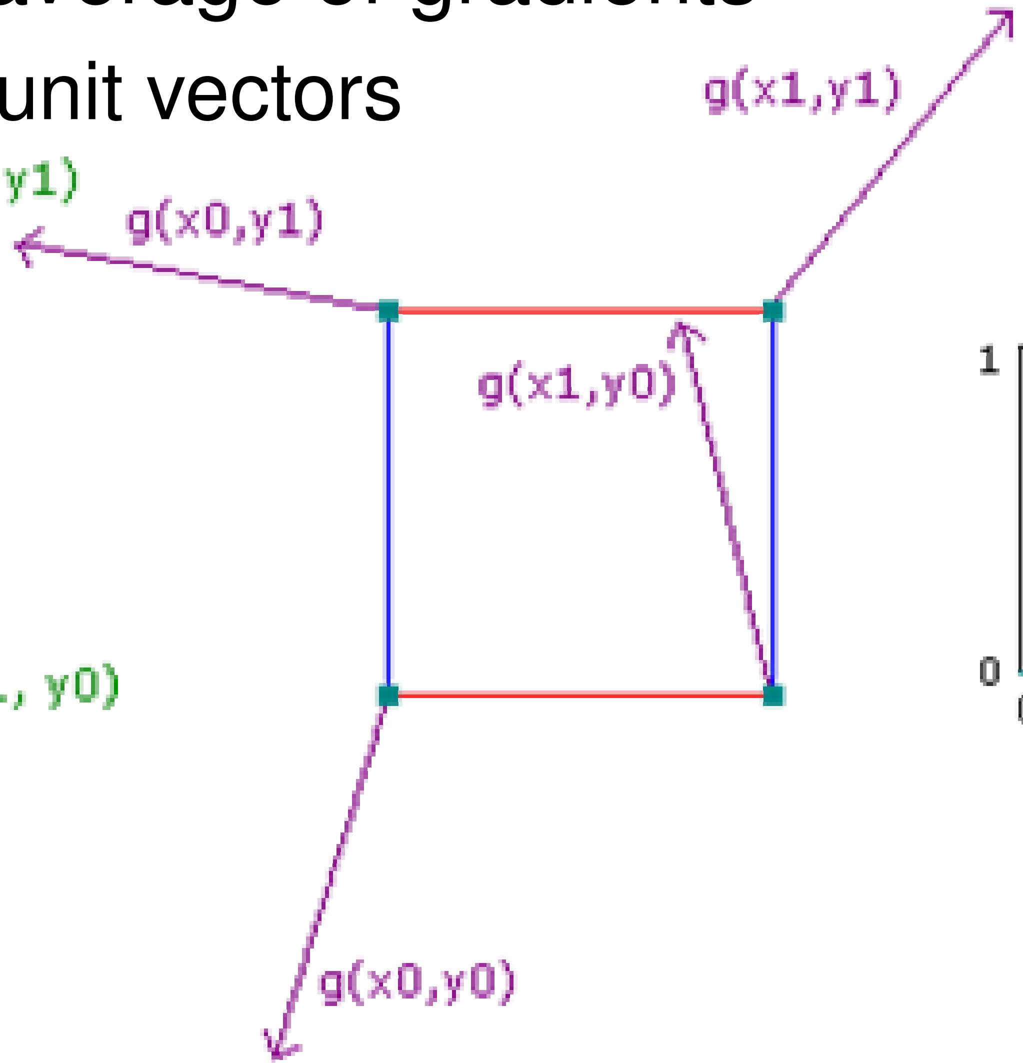
- nearest neighbor
- bilinear
- hermite

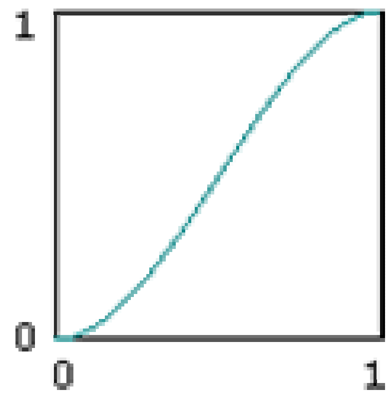


Vector Offsets From Grid

- weighted average of gradients
  - random unit vectors







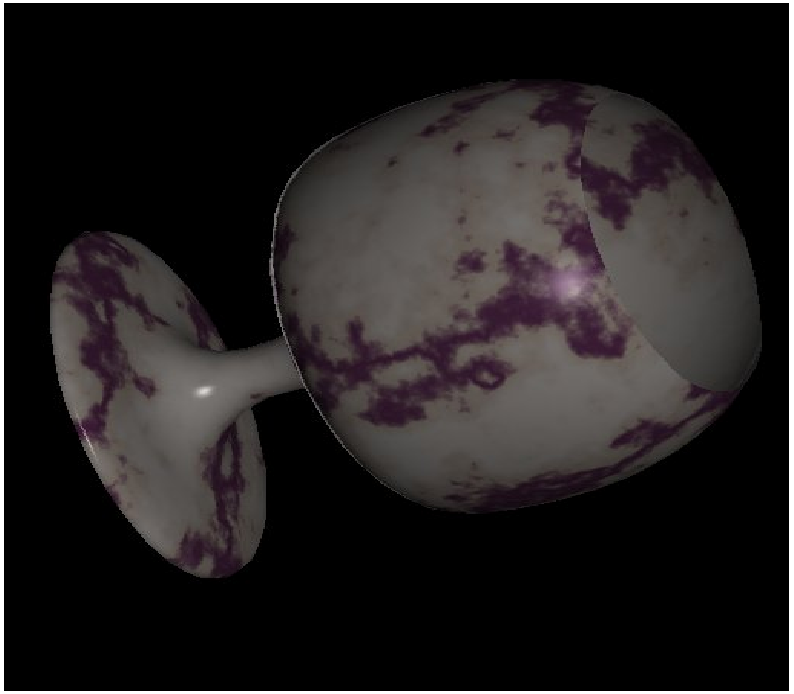
Optimization

- save memory and time
- conceptually:
  - 2D or 3D grid
  - populate with random number generator
- actually:
  - precompute two 1D arrays of size n (typical size 256)
    - random unit vectors
    - permutation of integers 0 to n-1
  - lookup
    - $g(i, j, k) = G[\ (\ i + P[\ (j + P[k]) \bmod n\ ]\ ) \bmod n\ ]$

Perlin Marble

- use turbulence, which in turn uses noise:

```
function marble(point)
  x = point.x + turbulence(point);
  return marble_color(sin(x))
```



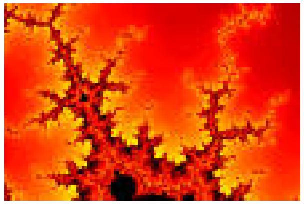
Procedural Approaches

Procedural Modeling

- textures, geometry
  - nonprocedural: explicitly stored in memory
- procedural approach
  - compute something on the fly
  - often less memory cost
  - visual richness
- fractals, particle systems, noise

Fractal Landscapes

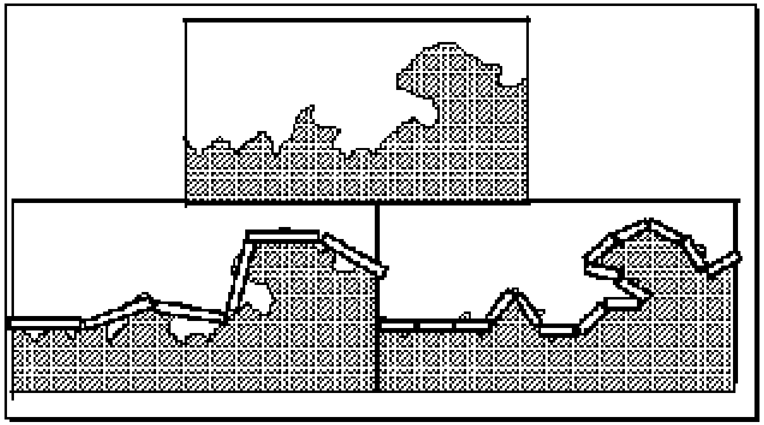
- fractals: not just for "showing math"
  - triangle subdivision
  - vertex displacement
  - recursive until termination condition



http://www.fractal-landscapes.co.uk/images.html

Self-Similarity

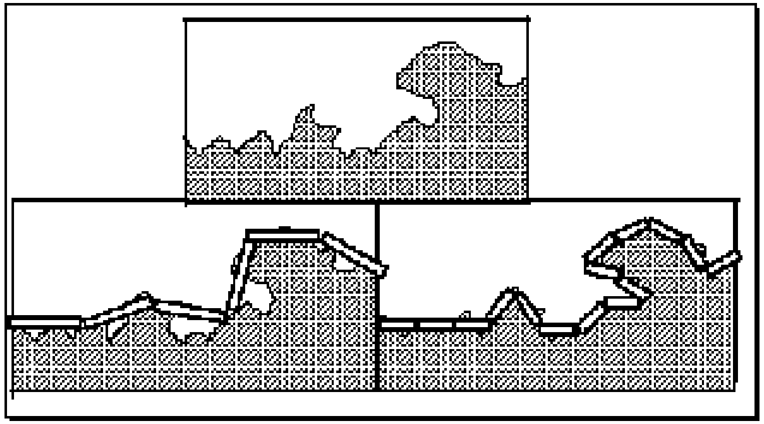
- infinite nesting of structure on all scales



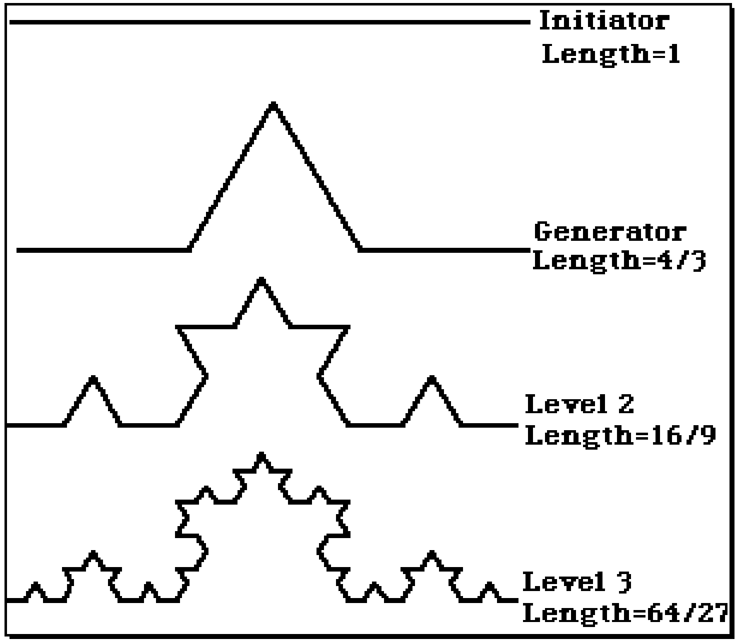
Fractal Dimension

- D = log(N)/log(r)
  N = measure, r = subdivision scale
  - Hausdorff dimension: noninteger

coastline of Britain



Koch snowflake

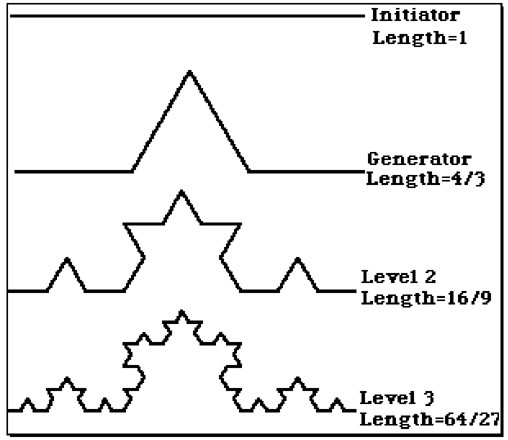


D = log(N)/log(r) D = log(4)/log(3) = 1.26

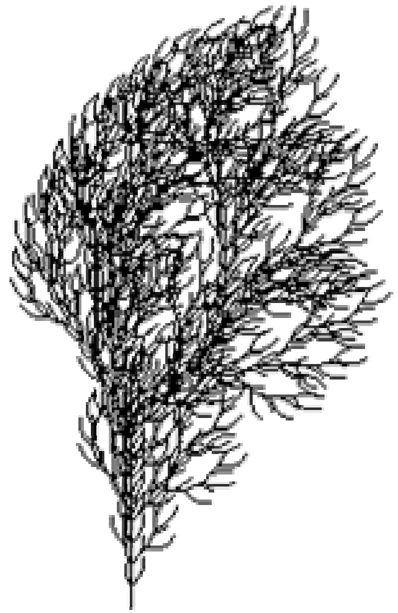
http://www.vanderbilt.edu/AnS/psychology/cogsci/chaos/workshop/Fractals.html

Language-Based Generation

- L-Systems: after Lindenmayer
  - Koch snowflake: F :- FLFRRFLF
    - F: forward, R: right, L: left



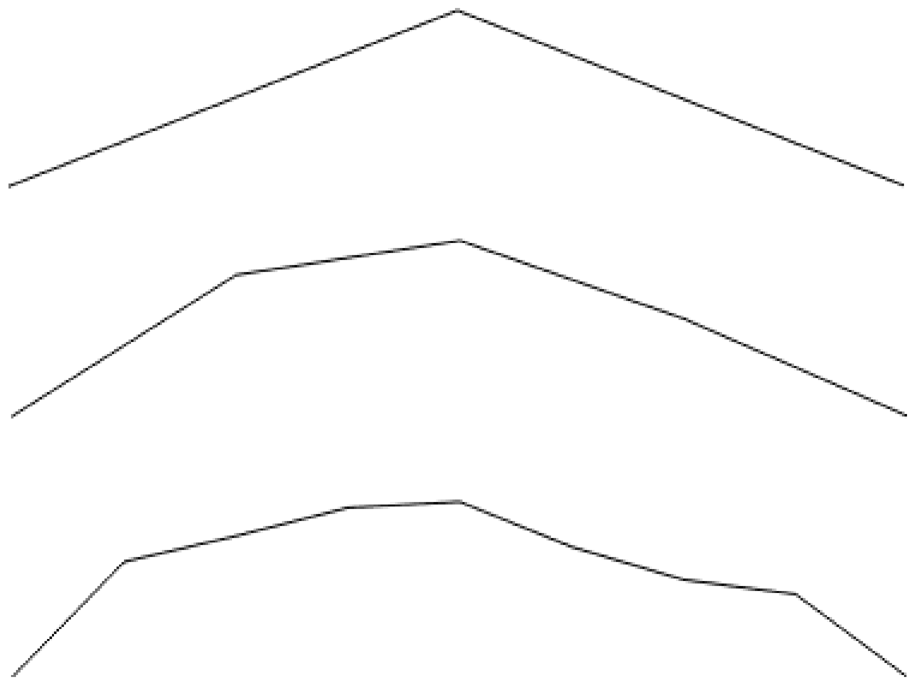
  - Mariano's Bush:
    F=FF-[-F+F+F]+[+F-F-F] }
    - angle 16



http://spanky.triumf.ca/www/fractint/lsys/plants.html

1D: Midpoint Displacement

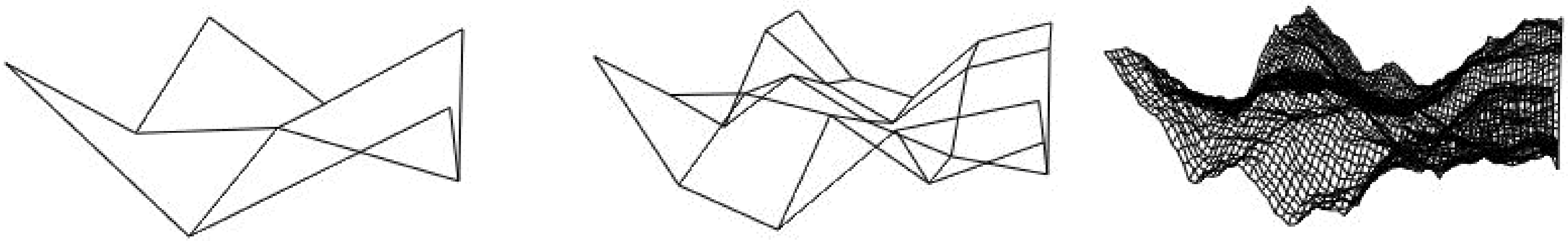
- divide in half
- randomly displace
- scale variance by half



http://www.gameprogrammer.com/fractal.html

2D: Diamond-Square

- diamond step
  - generate a new value at square midpoint
    - average corner values + random amount
    - gives diamonds when have multiple squares in grid
- square step
  - generate new value at diamond midpoint
    - average corner values + random amount
    - gives squares again in grid

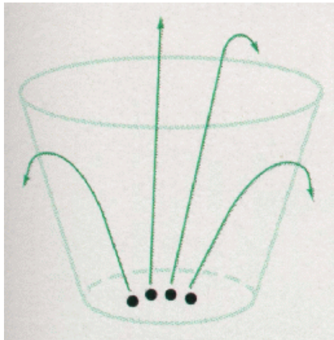


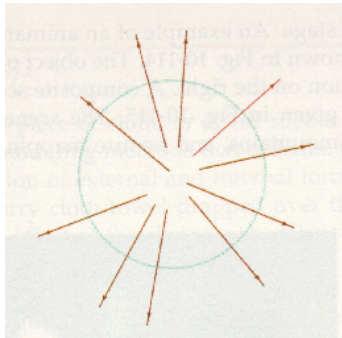
Particle Systems

- loosely defined
  - modeling, or rendering, or animation
- key criteria
  - collection of particles
  - random element controls attributes
    - position, velocity (speed and direction), color, lifetime, age, shape, size, transparency
    - predefined stochastic limits: bounds, variance, type of distribution

Particle System Examples

- objects changing fluidly over time
  - fire, steam, smoke, water
- objects fluid in form
  - grass, hair, dust
- physical processes
  - waterfalls, fireworks, explosions
- group dynamics: behavioral
  - birds/bats flock, fish school,
    human crowd, dinosaur/elephant stampede





Particle Systems Demos

- general particle systems
  - http://www.wondertouch.com
- boids: bird-like objects
  - http://www.red3d.com/cwr/boids/

Particle Life Cycle

- generation
  - randomly within “fuzzy” location
  - initial attribute values: random or fixed
- dynamics
  - attributes of each particle may vary over time
    - color darker as particle cools off after explosion
  - can also depend on other attributes
    - position: previous particle position + velocity + time
- death
  - age and lifetime for each particle (in frames)
  - or if out of bounds, too dark to see, etc

Particle System Rendering

- expensive to render thousands of particles
- simplify: avoid hidden surface calculations
  - each particle has small graphical primitive (blob)
  - pixel color: sum of all particles mapping to it
- some effects easy
  - temporal anti-aliasing (motion blur)
    - normally expensive: supersampling over time
    - position, velocity known for each particle
    - just render as streak

Procedural Approaches Summary

- Perlin noise
- fractals
- L-systems
- particle systems

- not at all a complete list!
  - big subject: entire classes on this alone

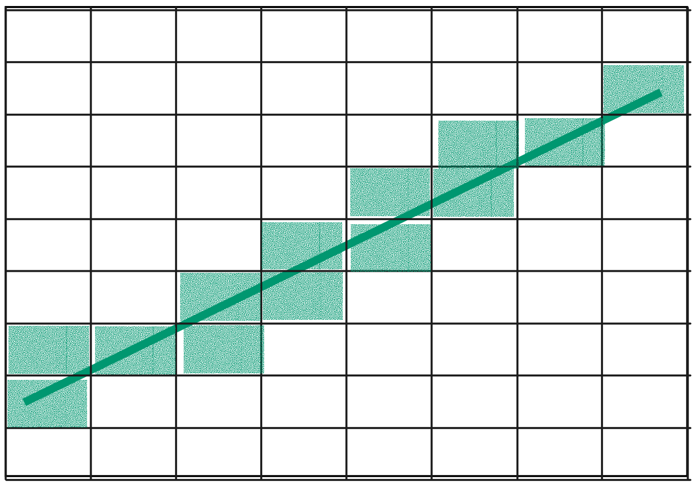
Sampling

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

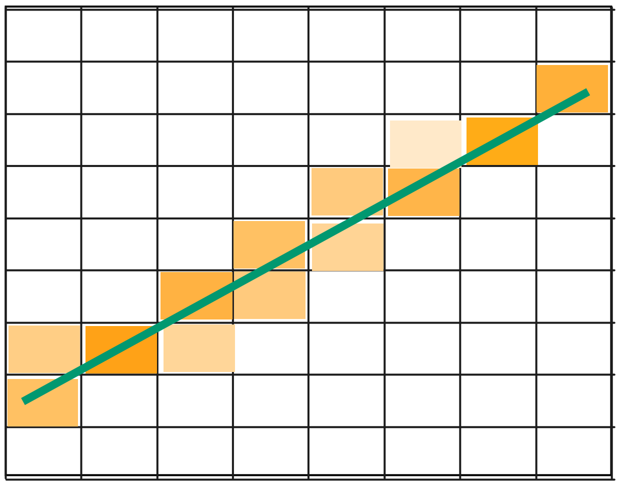
Line Segments

- we tried to sample a line segment so it would map to a 2D raster display
- we quantized the pixel values to 0 or 1
- we saw stair steps, or jaggies



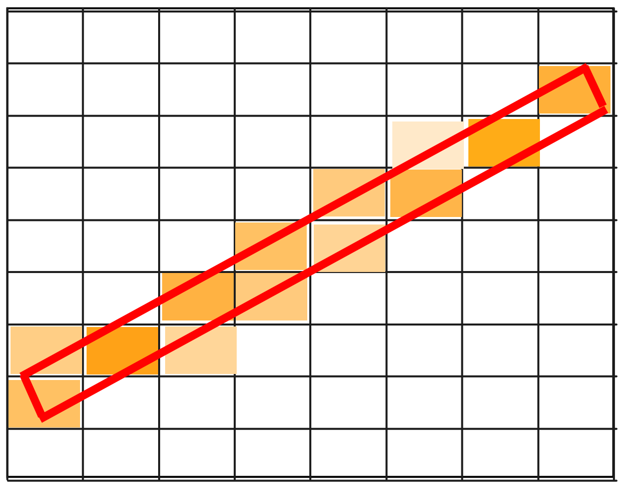
Line Segments

- instead, quantize to many shades
- but what sampling algorithm is used?



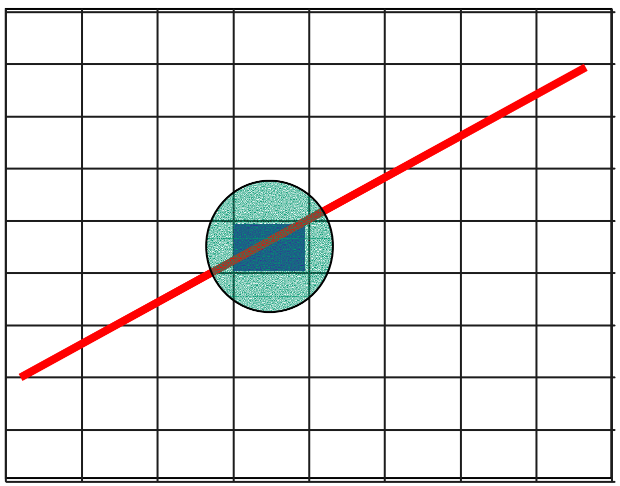
Unweighted Area Sampling

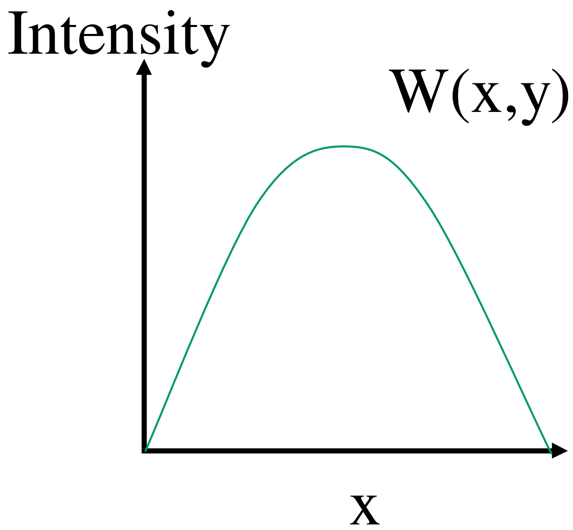
- shade pixels wrt area covered by thickened line
- equal areas cause equal intensity, regardless of distance from pixel center to area
  - rough approximation formulated by dividing each pixel into a finer grid of pixels
- primitive cannot affect intensity of pixel if it does not intersect the pixel



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) that specifies intensity for each point (x, y)

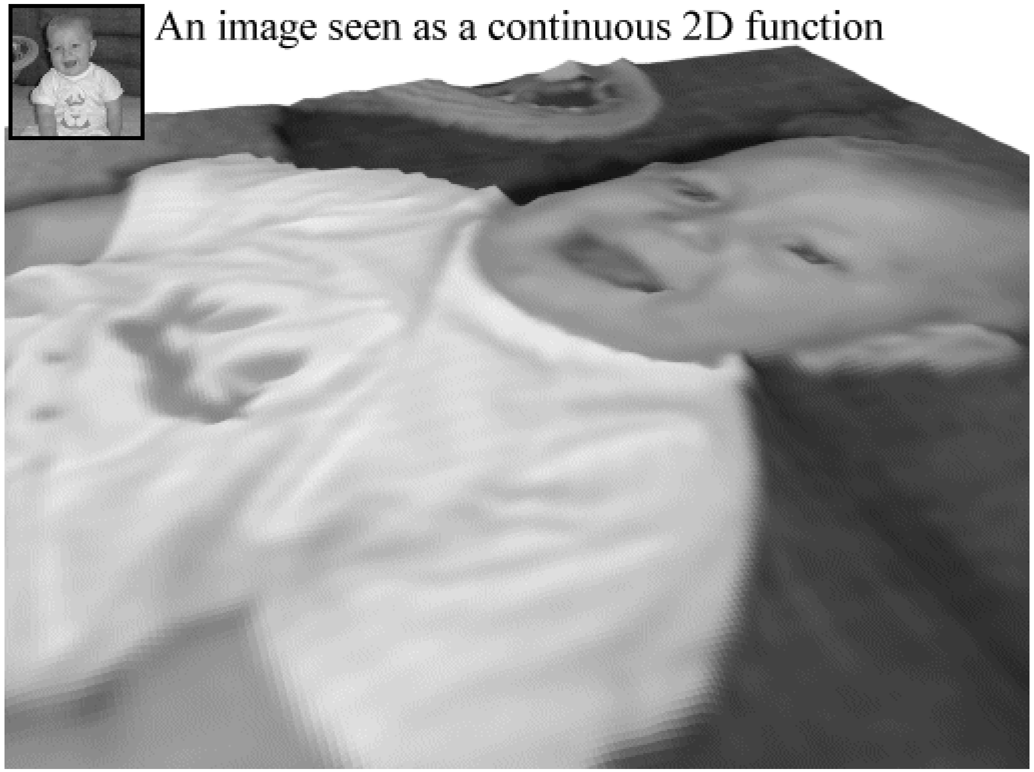
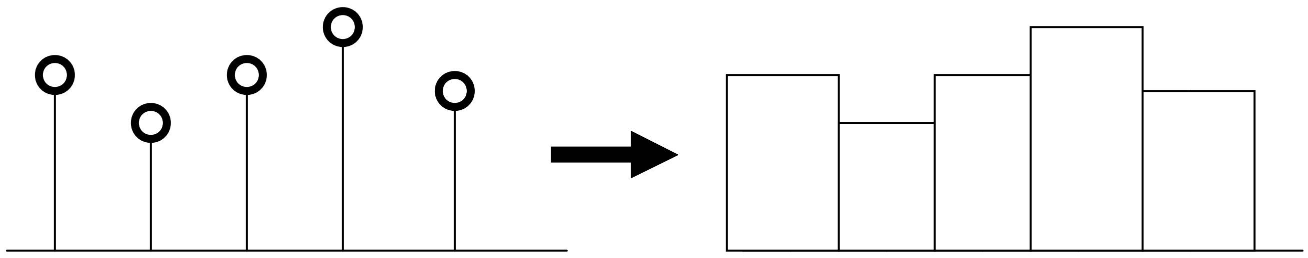


Image Sampling and Reconstruction

- convert continuous image to discrete set of samples
- display hardware reconstructs samples into continuous image
  - finite sized source of light for each pixel

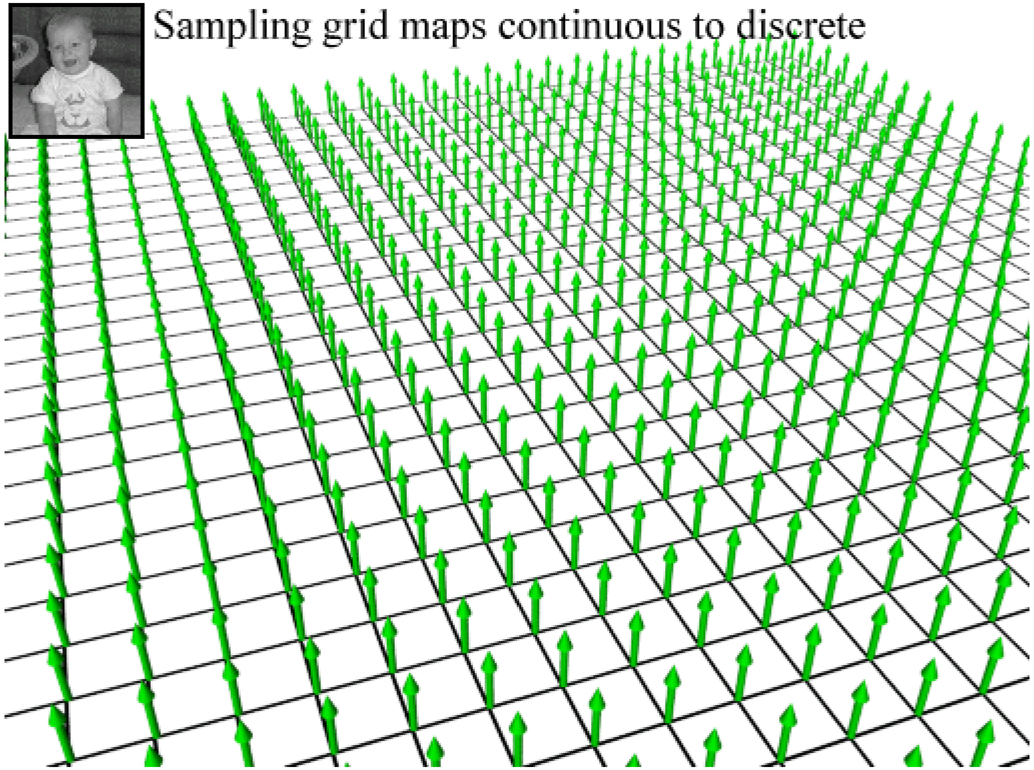


discrete input values

continuous light output

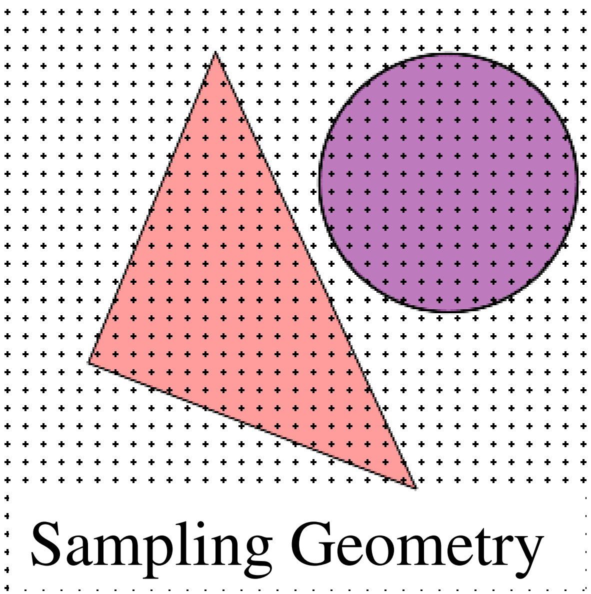
Point Sampling an Image

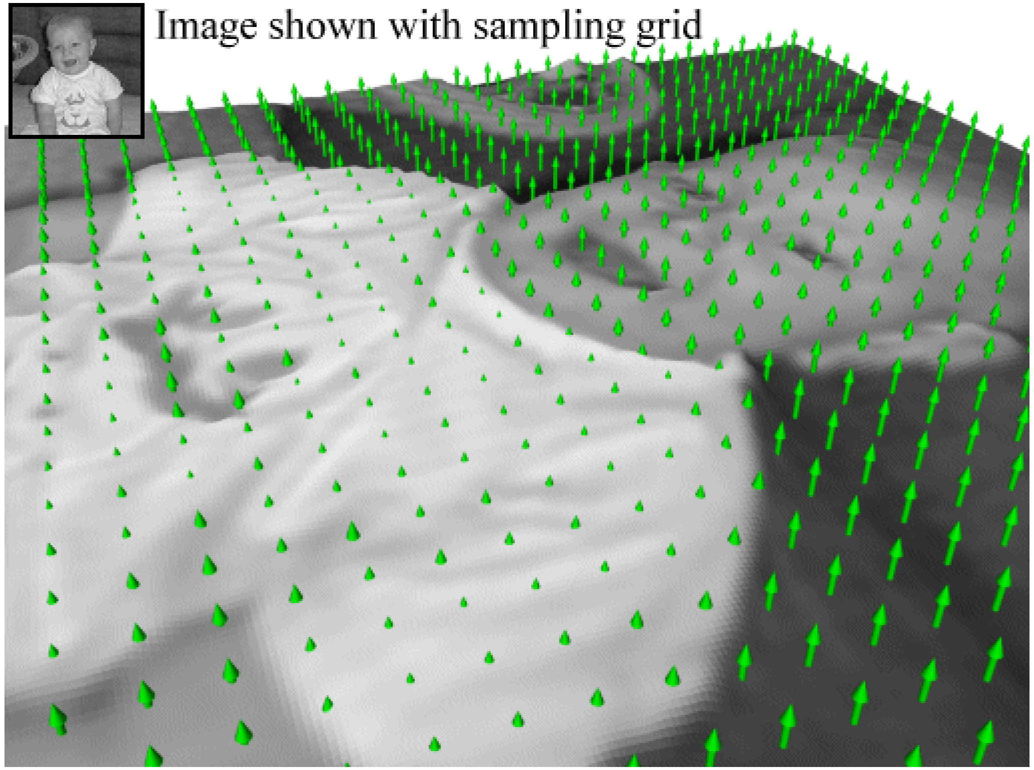
- simplest sampling is on a grid
- sample depends solely on value at grid points



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!

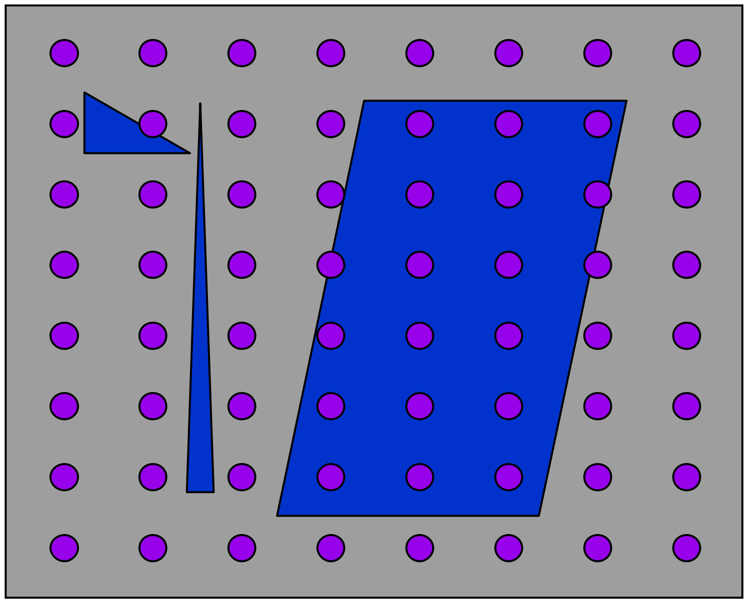
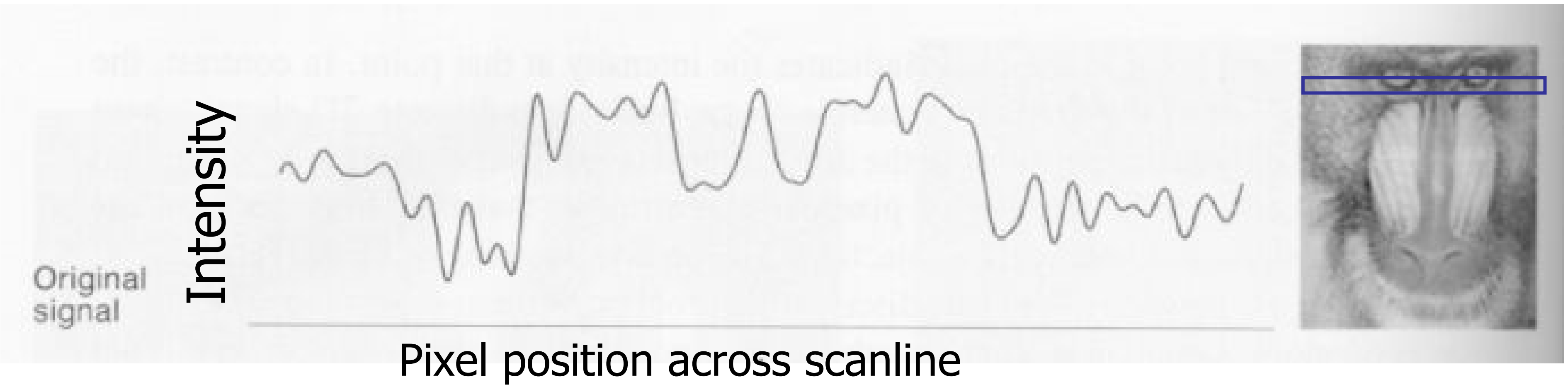


Image As Signal

- image as spatial signal
- 2D raster image
  - discrete sampling of 2D spatial signal
- 1D slice of raster image
  - discrete sampling of 1D spatial signal



Examples from Foley, van Dam, Feiner, and Hughes

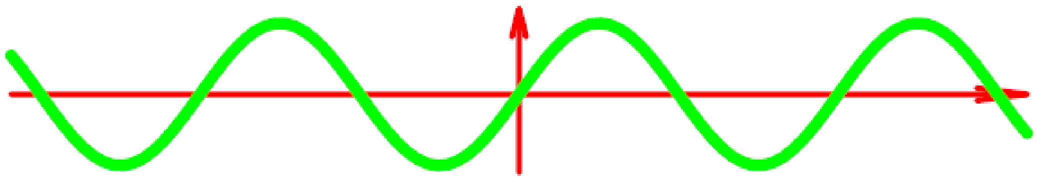
Sampling Theory

- 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

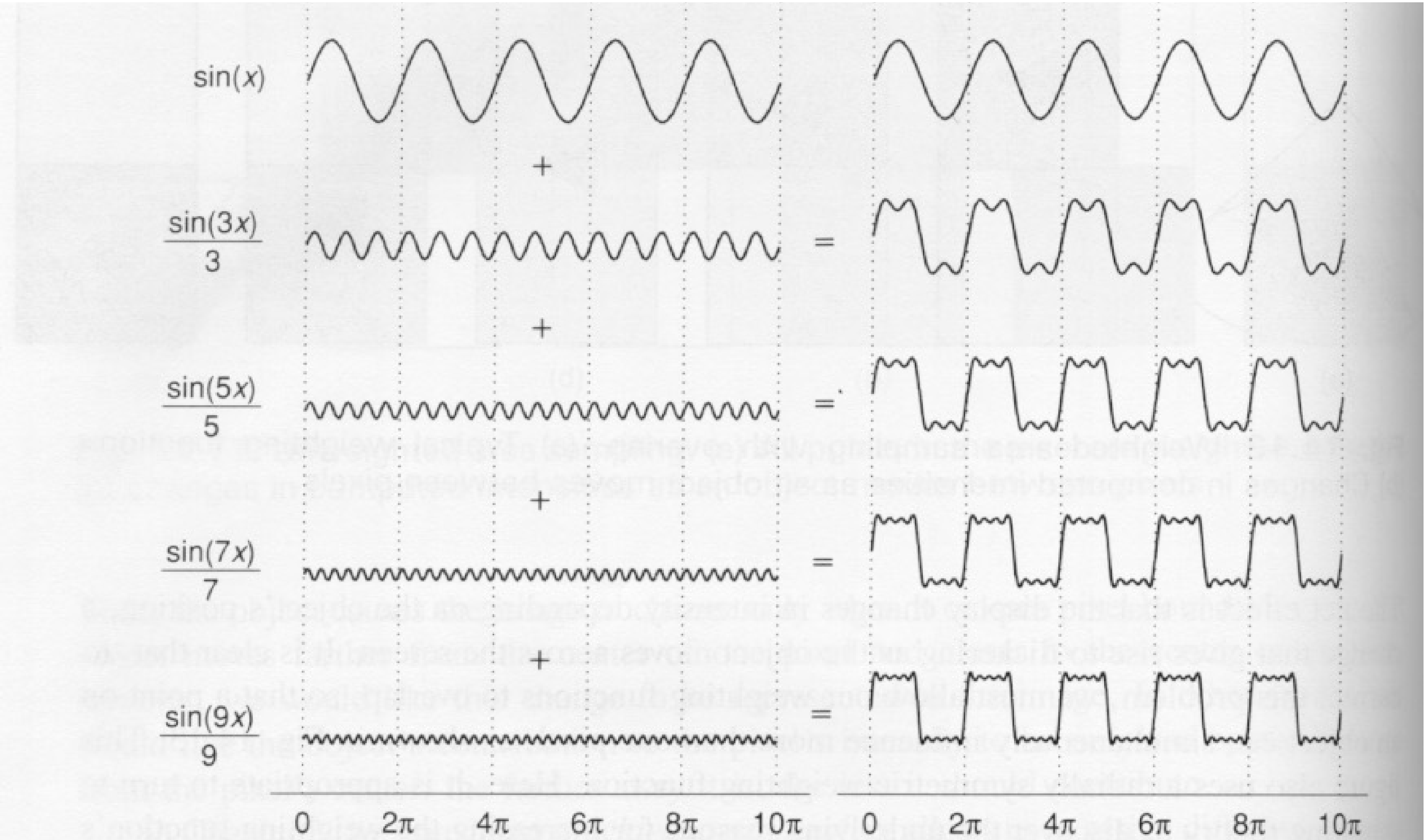
Sampling Theory in a Nutshell

- terminology
  - bandwidth – length of repeated sequence on infinite signal
  - frequency – 1/bandwidth (number of repeated sequences in unit length)
- example – sine wave
  - bandwidth = 2π
  - frequency = $1/ 2\pi$

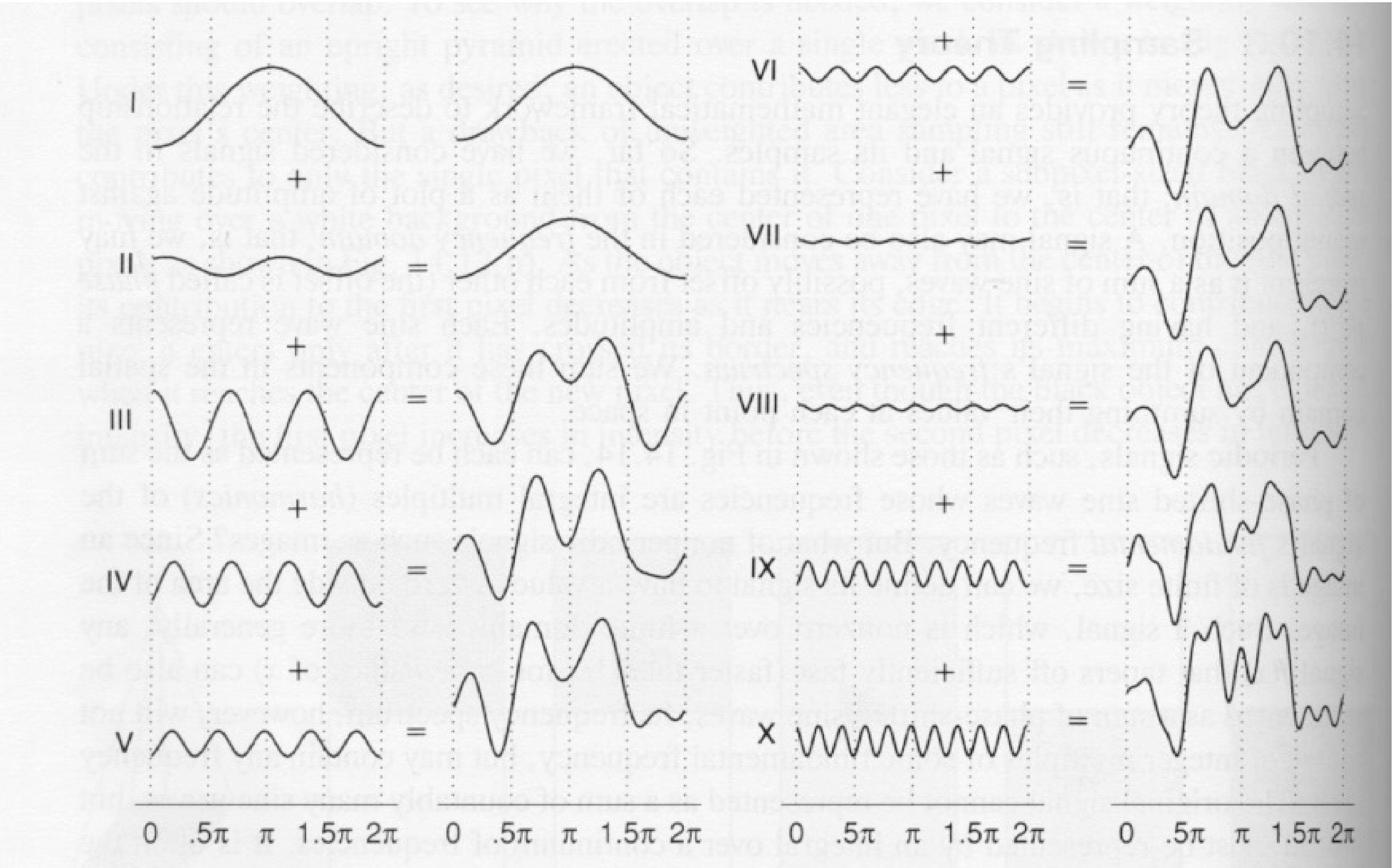
$\sin(t)$



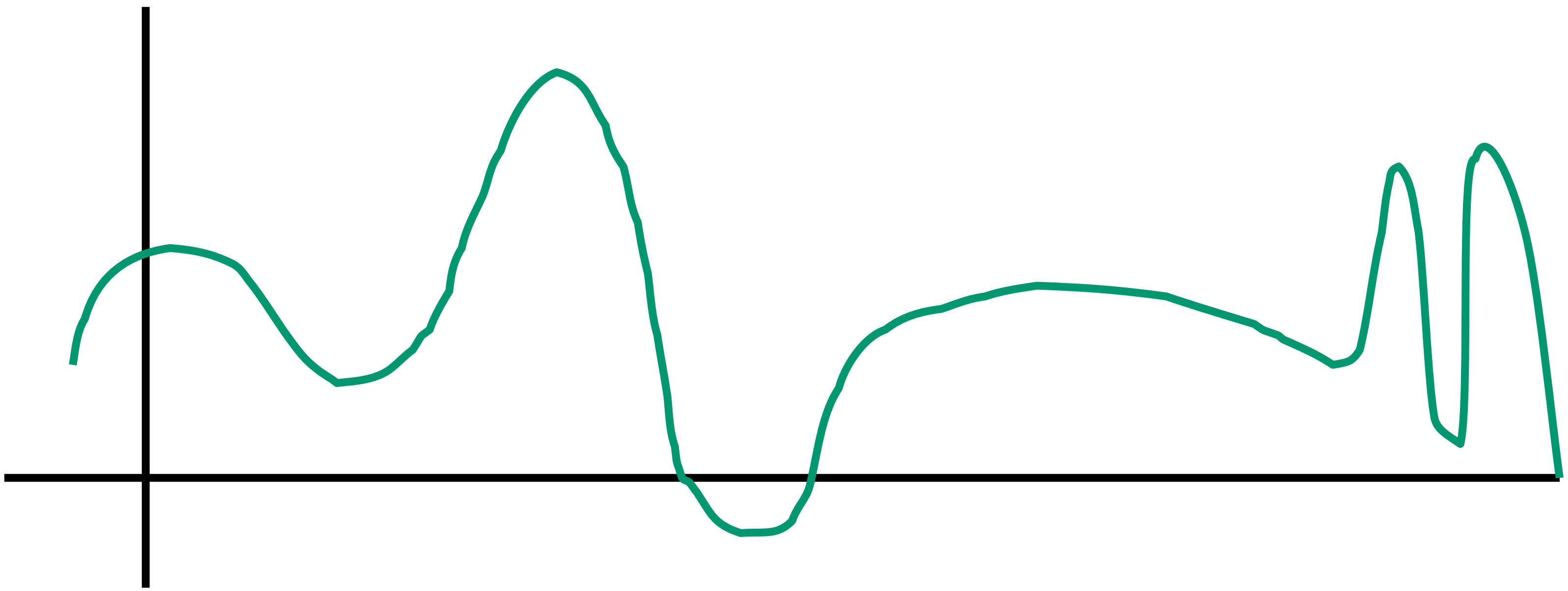
Summing Waves I



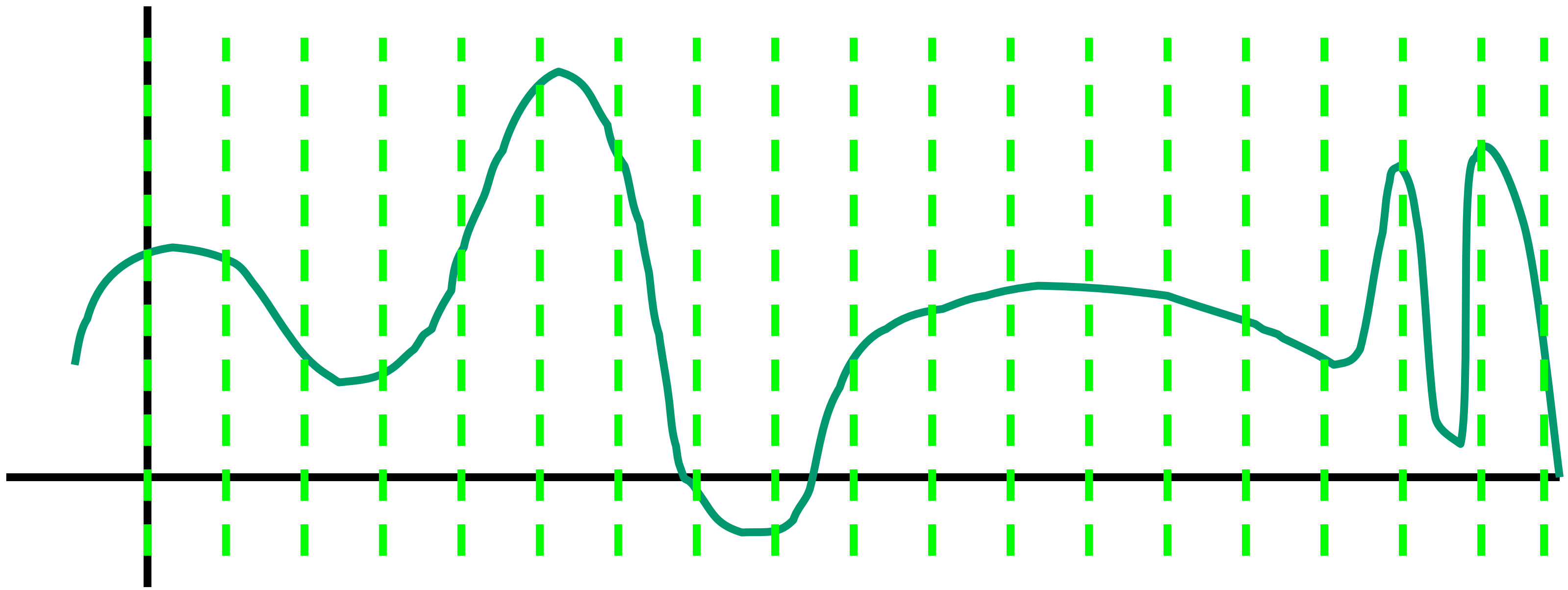
Summing Waves II



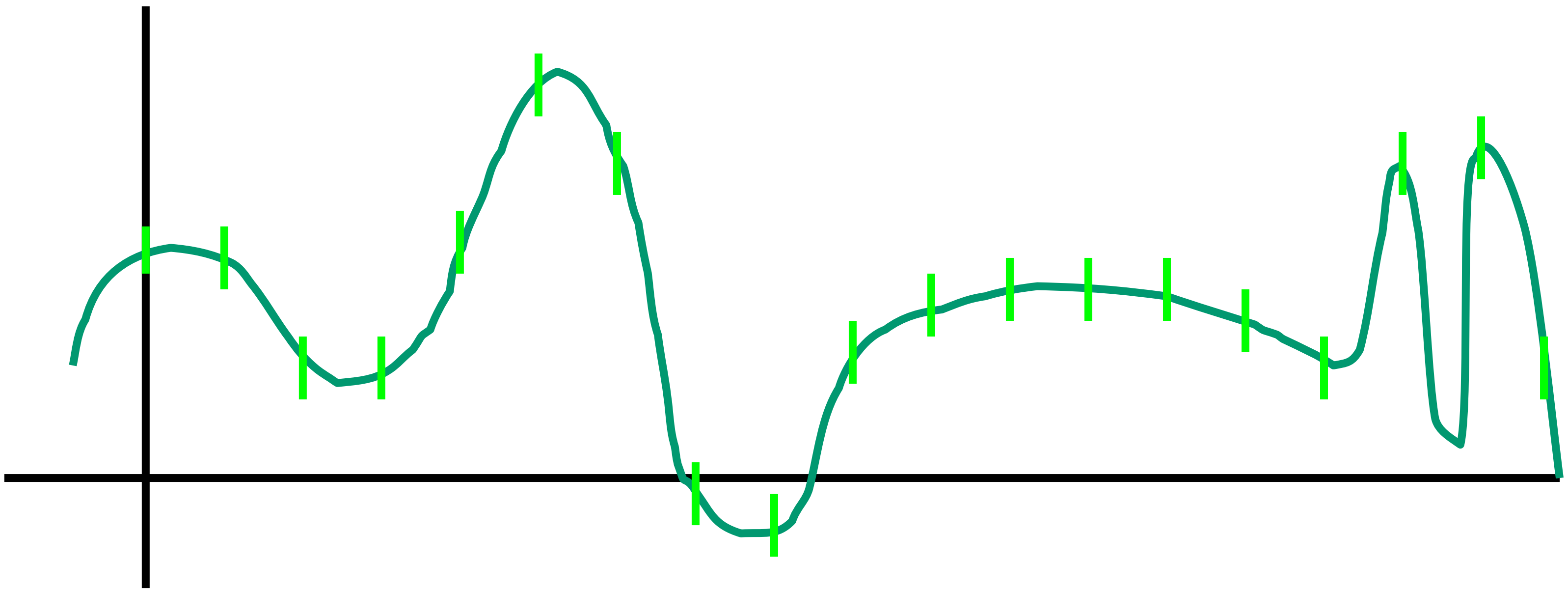
1D Sampling and Reconstruction



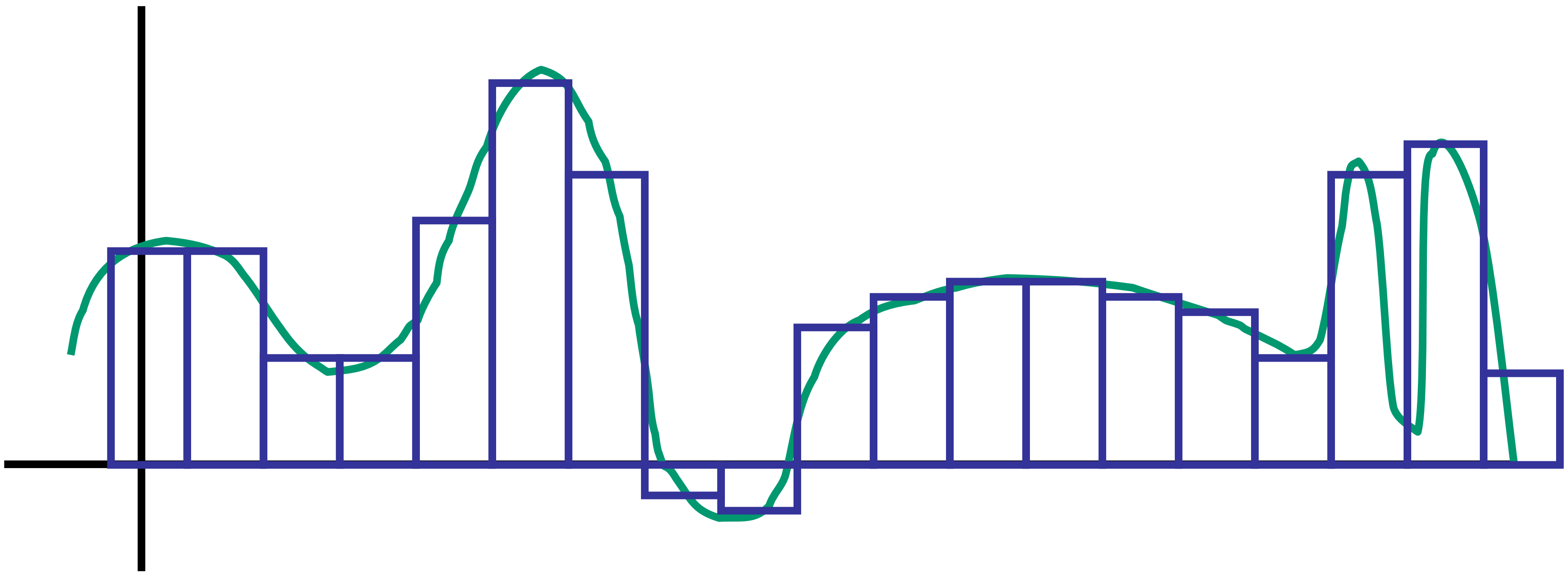
1D Sampling and Reconstruction



1D Sampling and Reconstruction

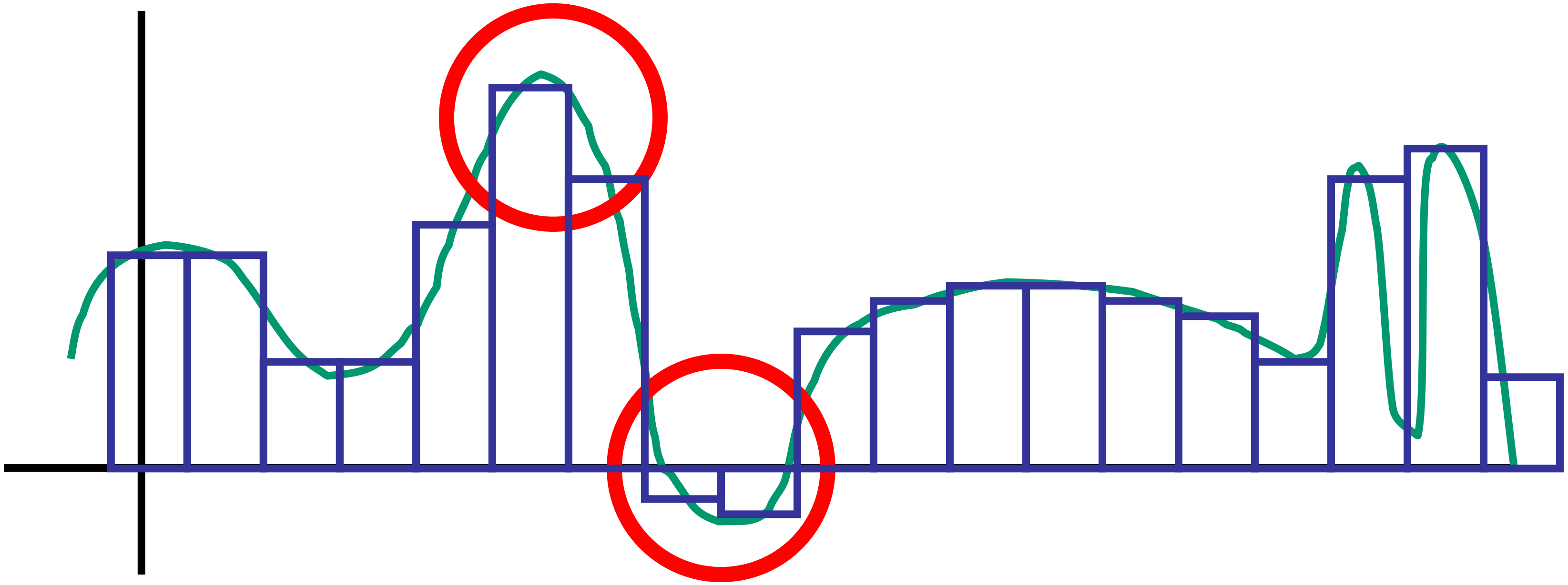


1D Sampling and Reconstruction



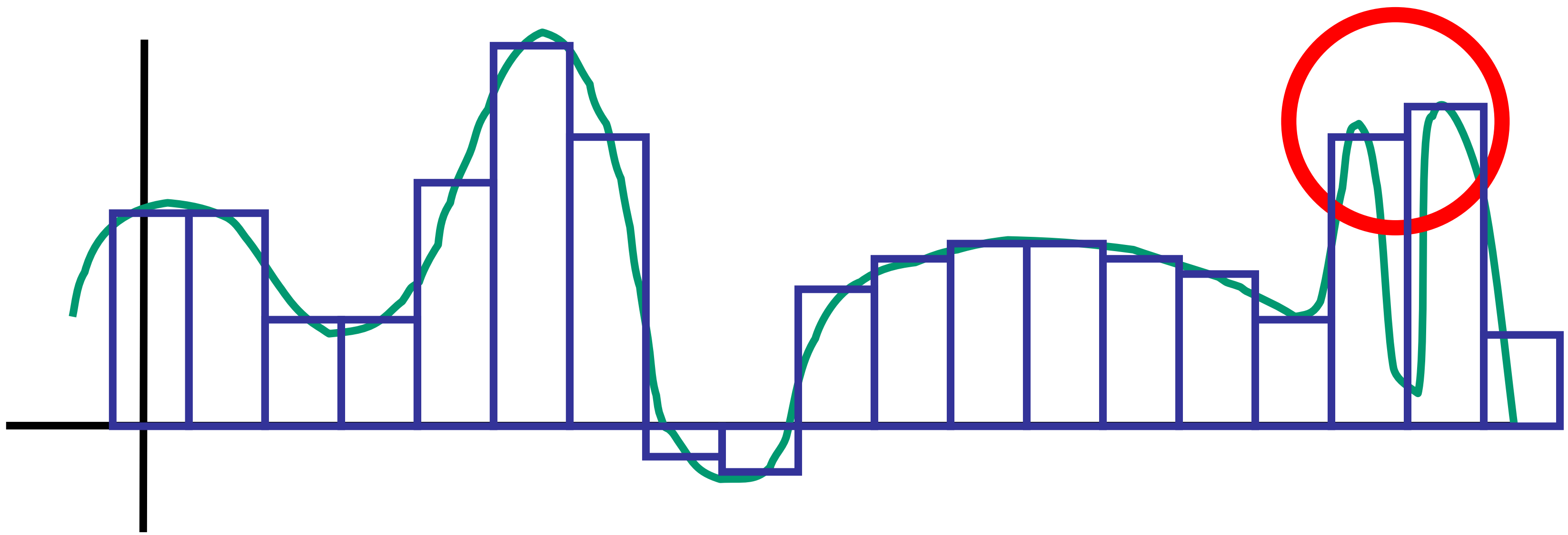
1D Sampling and Reconstruction

- 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

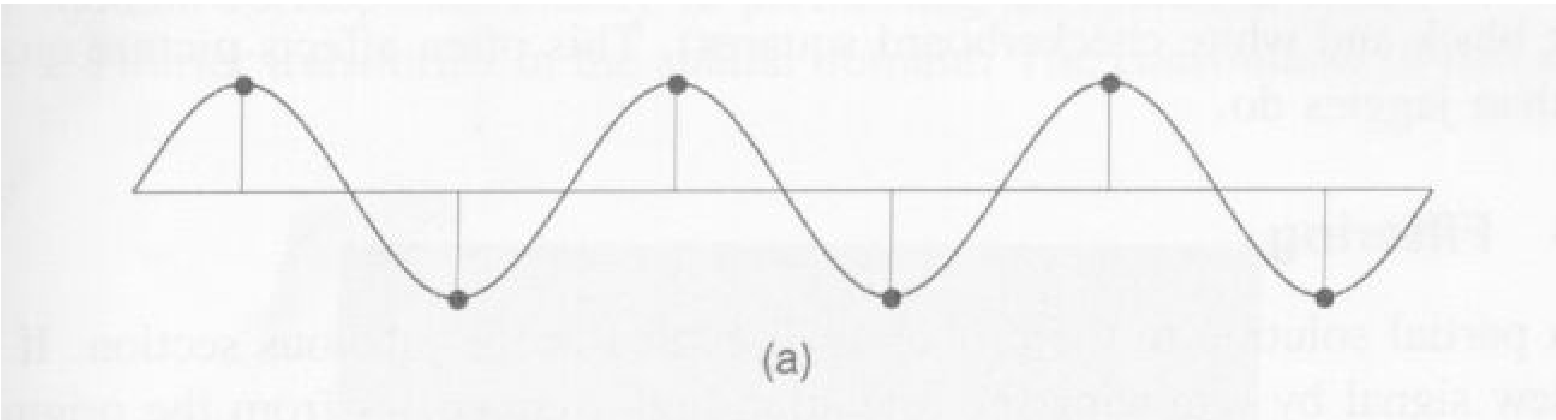
iff

sampling rate greater than twice maximum 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!

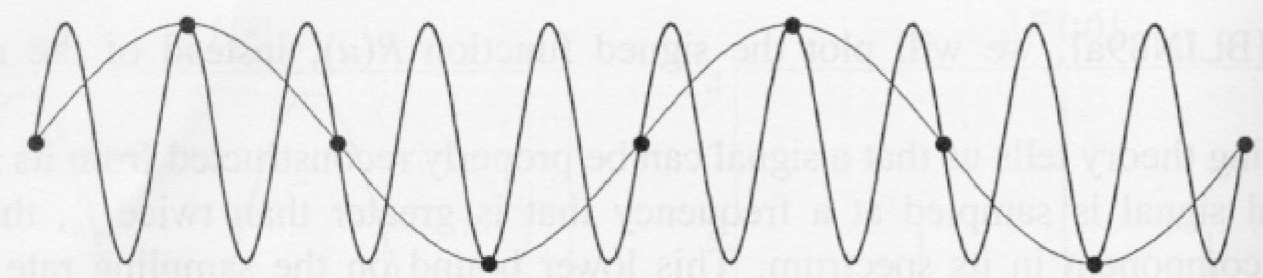
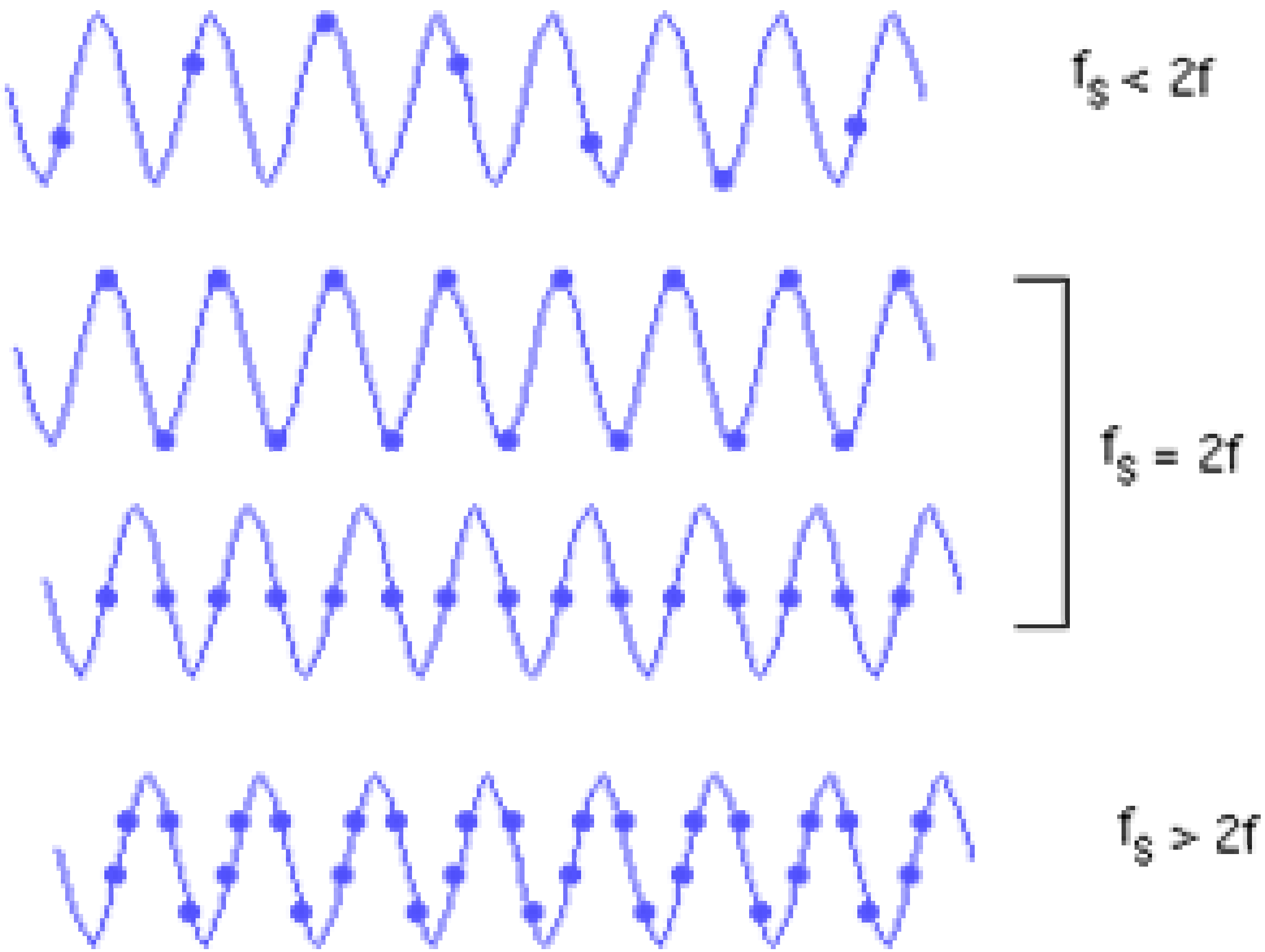


Fig. 14.17 Sampling below the Nyquist rate. (Courtesy of George Wolberg, Columbia University.)

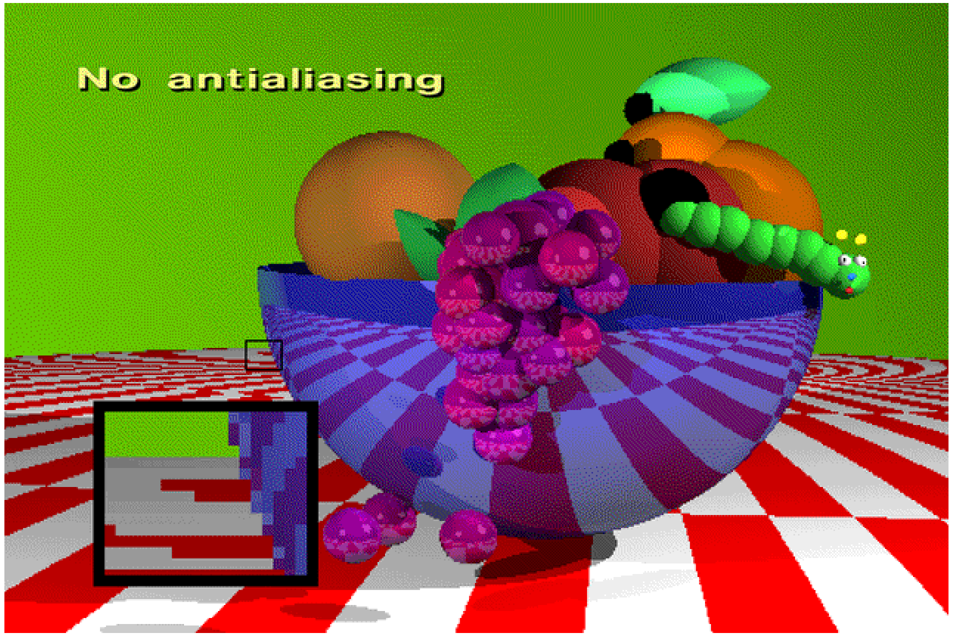
Nyquist Rate

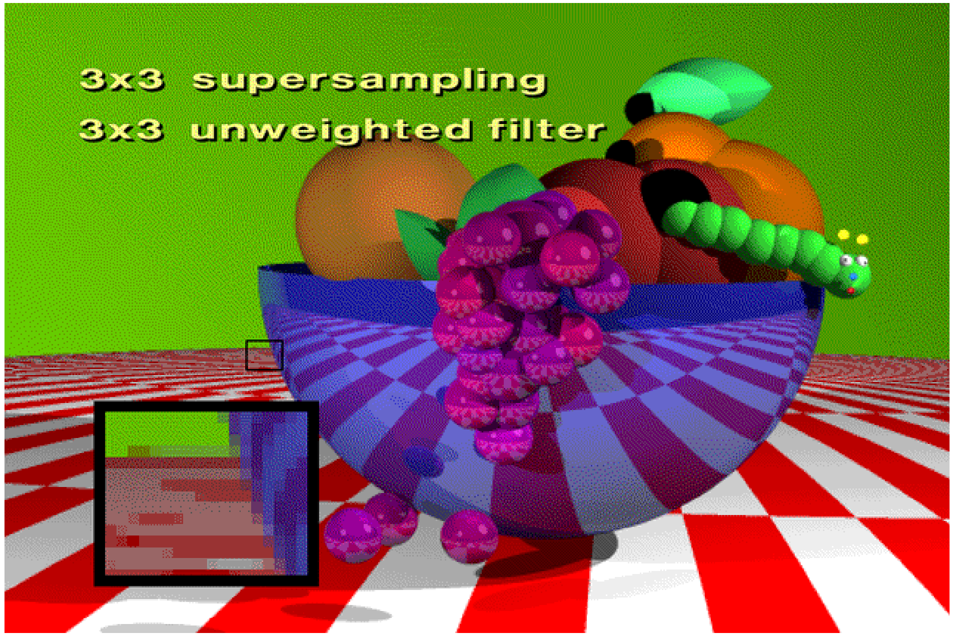


Aliasing

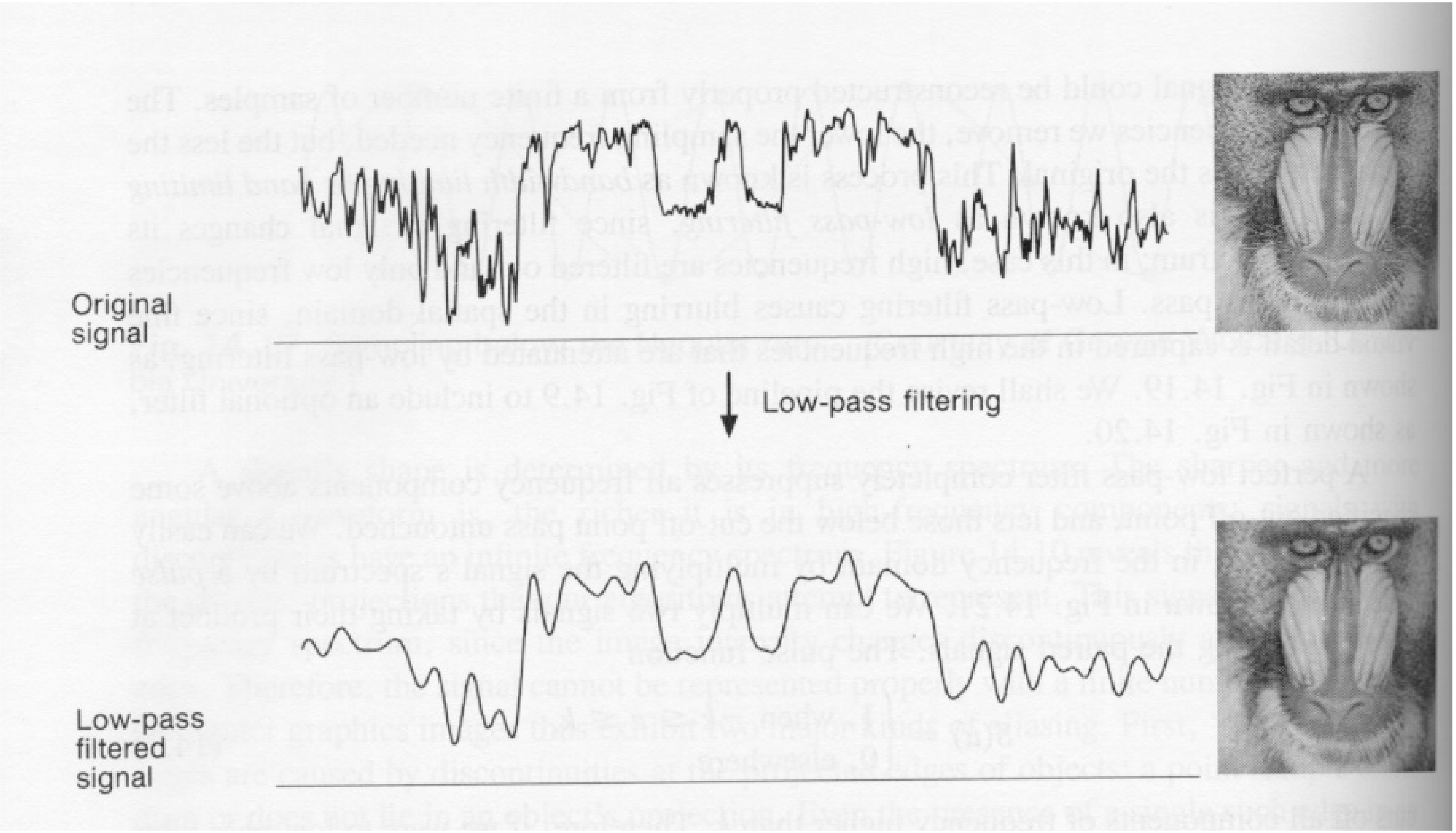
- incorrect appearance of high frequencies as low frequencies
- to avoid: antialiasing
  - supersample
    - sample at higher frequency
  - low pass filtering
    - remove high frequency function parts
    - aka prefiltering, band-limiting

Supersampling





Low-Pass Filtering



Low-Pass Filtering

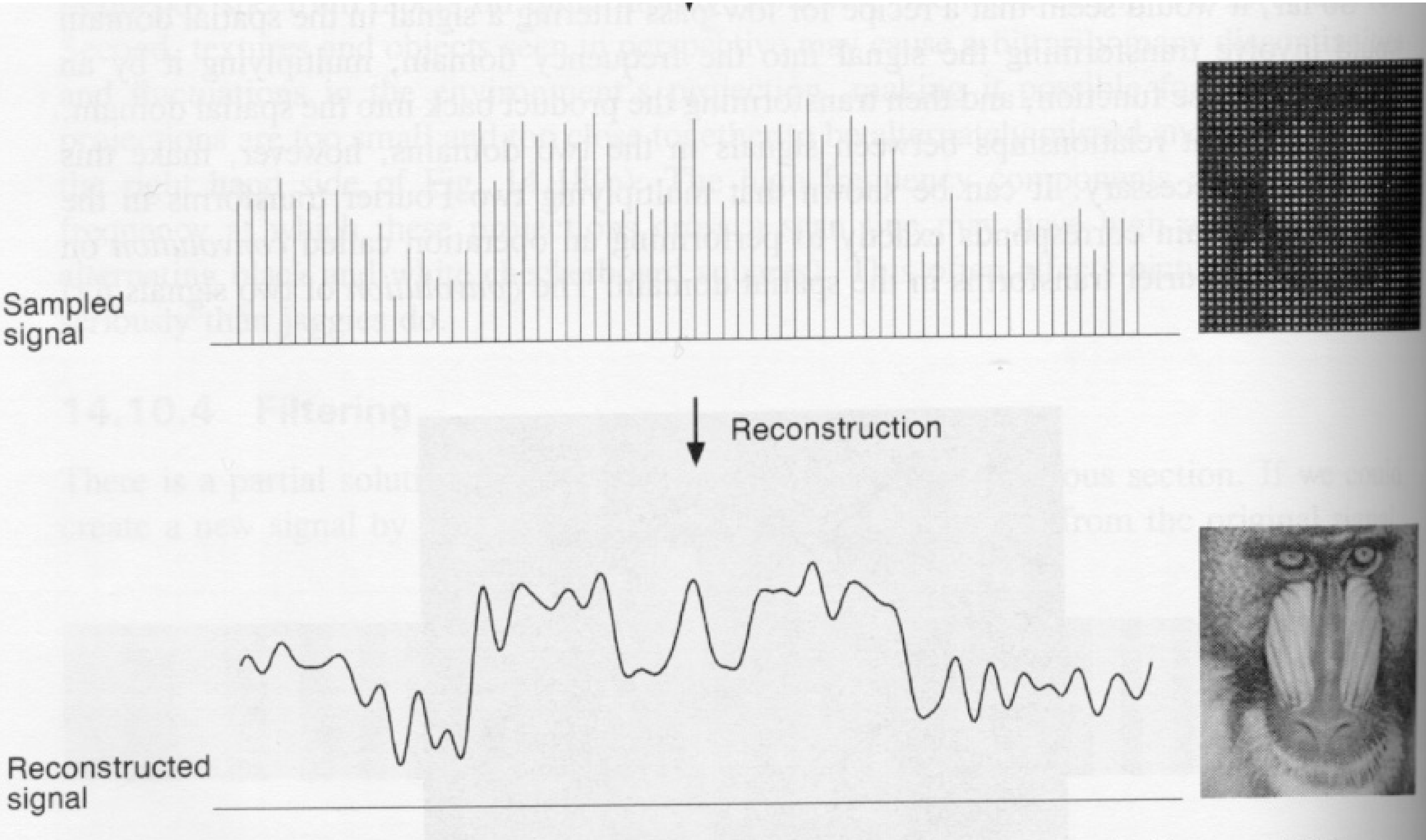
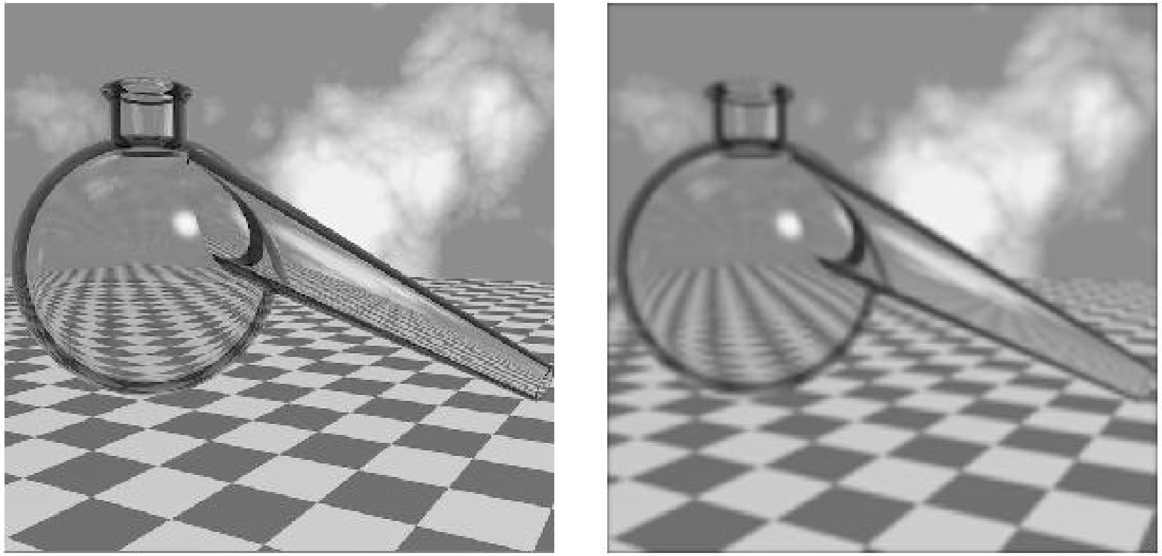


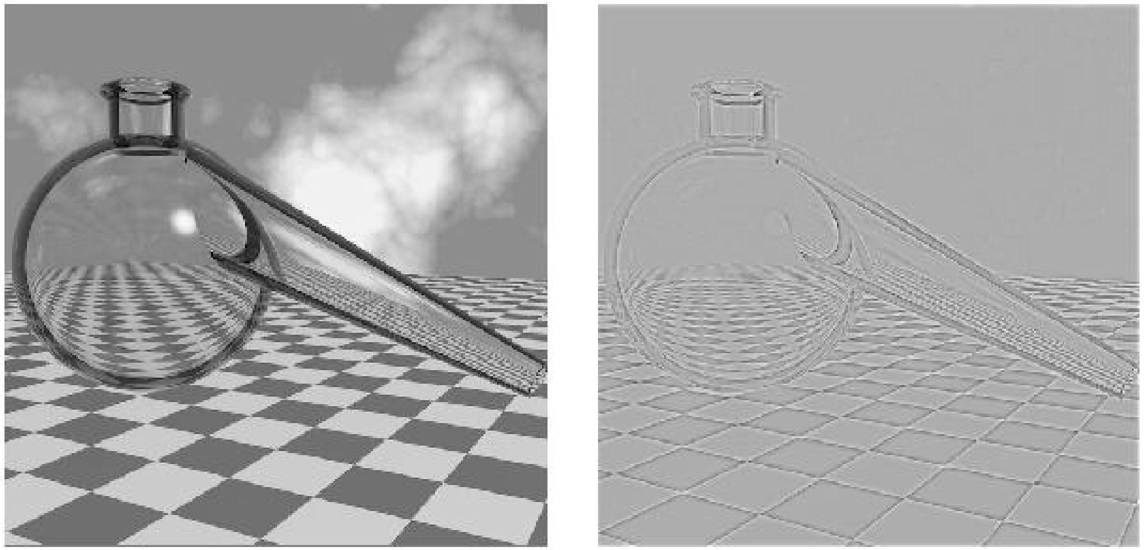
Fig. 14.20 The sampling pipeline with filtering. (Courtesy of George Wolberg, Columbia University.)

Filtering

- low pass
  - blur

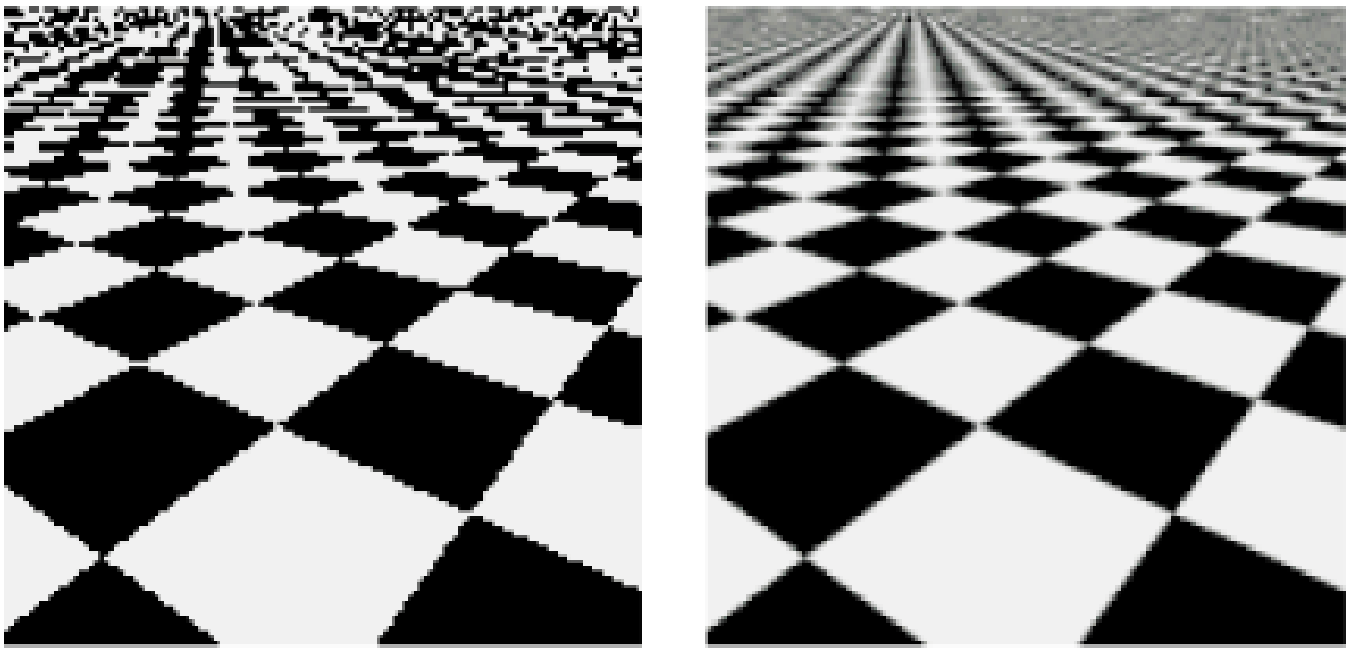


- high pass
  - edge finding



Previous Antialiasing Example

- texture mipmapping: low pass filter



(a) (b)