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

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Sampling, Virtual Trackball, Hidden Surfaces

Week 5, Tue Jun 7

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

News

- Midterm handed back
  - solutions posted
  - distribution posted
  - all grades so far posted
- P1 Hall of Fame posted
- P3 grading
  - after 3:20
- P4 proposals
  - email or conversation to all

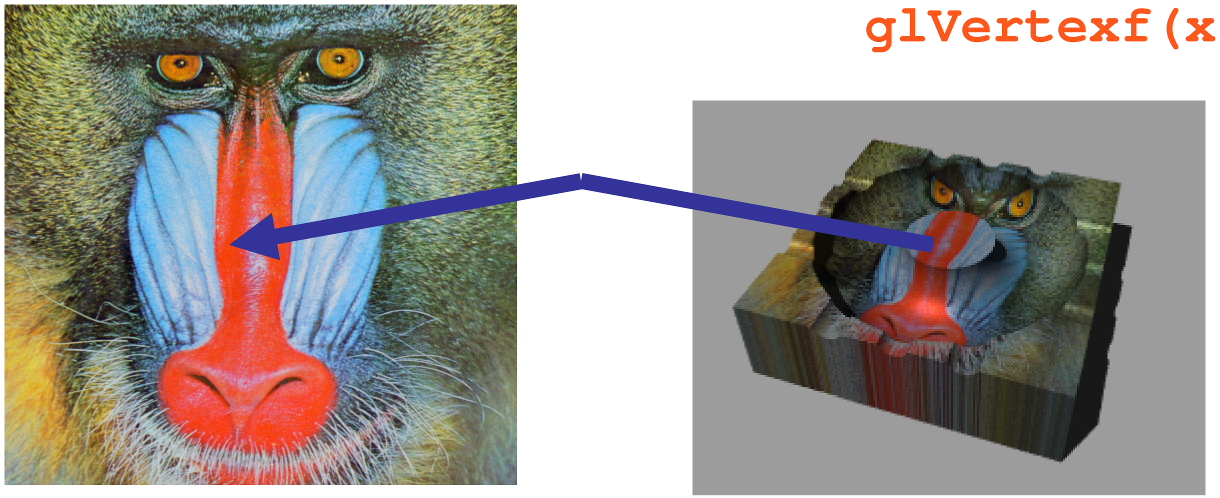
H3 Corrections/Clarifications

- Q1 should be from +infinity, not -infinity
- Q 2-4 correction for point B
- Q7 clarified: only x and y coordinates are given for P
- Q8 is deleted

Review: Texture Coordinates

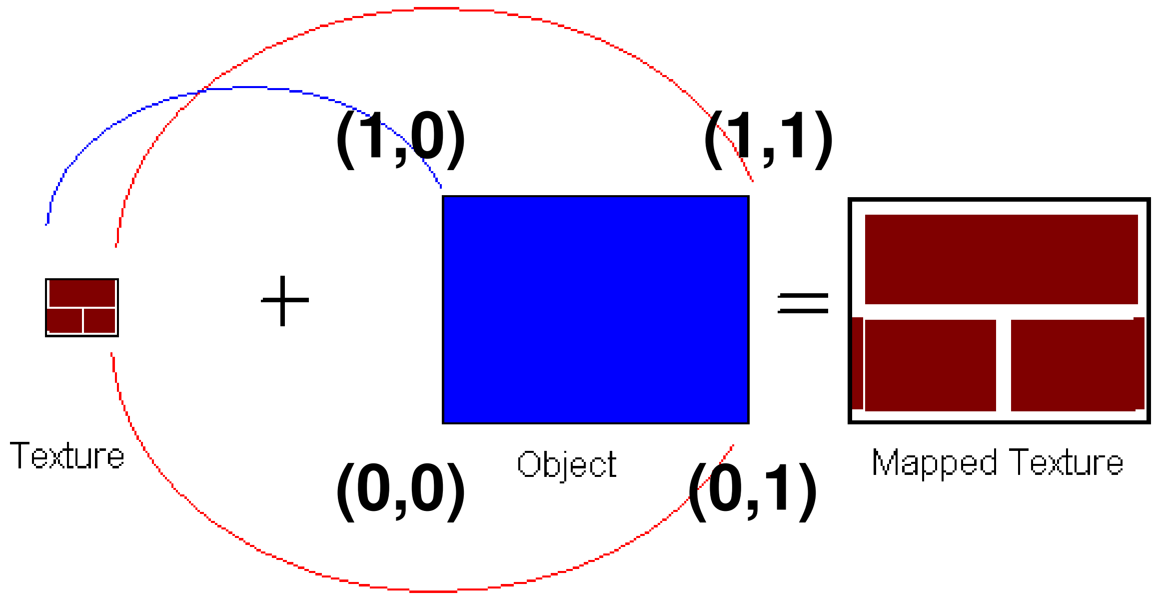
- texture image: 2D array of color values (texels)
- assigning texture coordinates (s,t) at vertex with object coordinates (x,y,z,w)
  - use interpolated (s,t) for texel lookup at each pixel
  - use value to modify a polygon's color
    - or other surface property
  - specified by programmer or artist

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

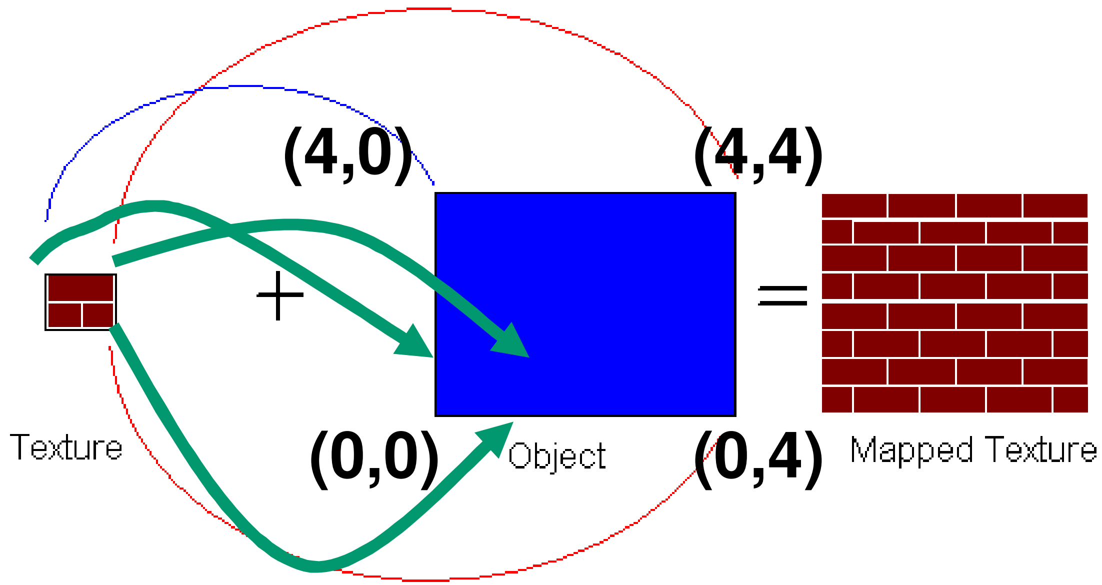


Review: Tiled Texture Map

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

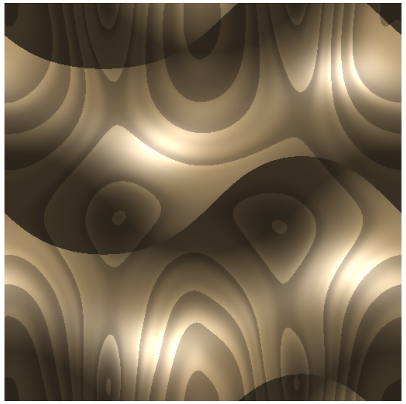


glTexCoord2d(4, 4);
glVertex3d (x, y, z);

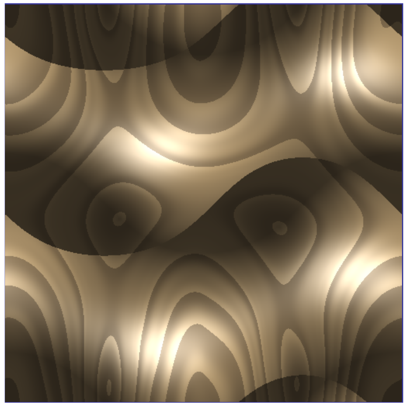


Review: Fractional Texture Coordinates

texture image

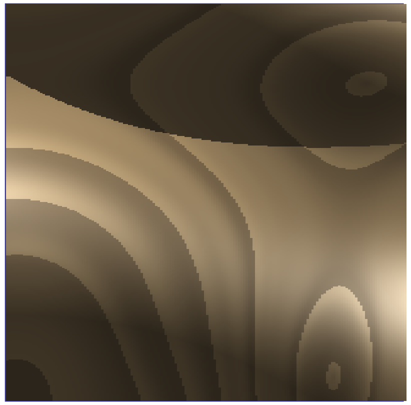


(0,1) (1,1)



(0,0) (1,0)

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



(0,0) (.25,0)

Review: Texture

- action when s or t is outside [0…1] interval
  - tiling
  - clamping
- functions
  - replace/decal
  - modulate
  - blend
- texture matrix stack

```
glMatrixMode( GL_TEXTURE );
```

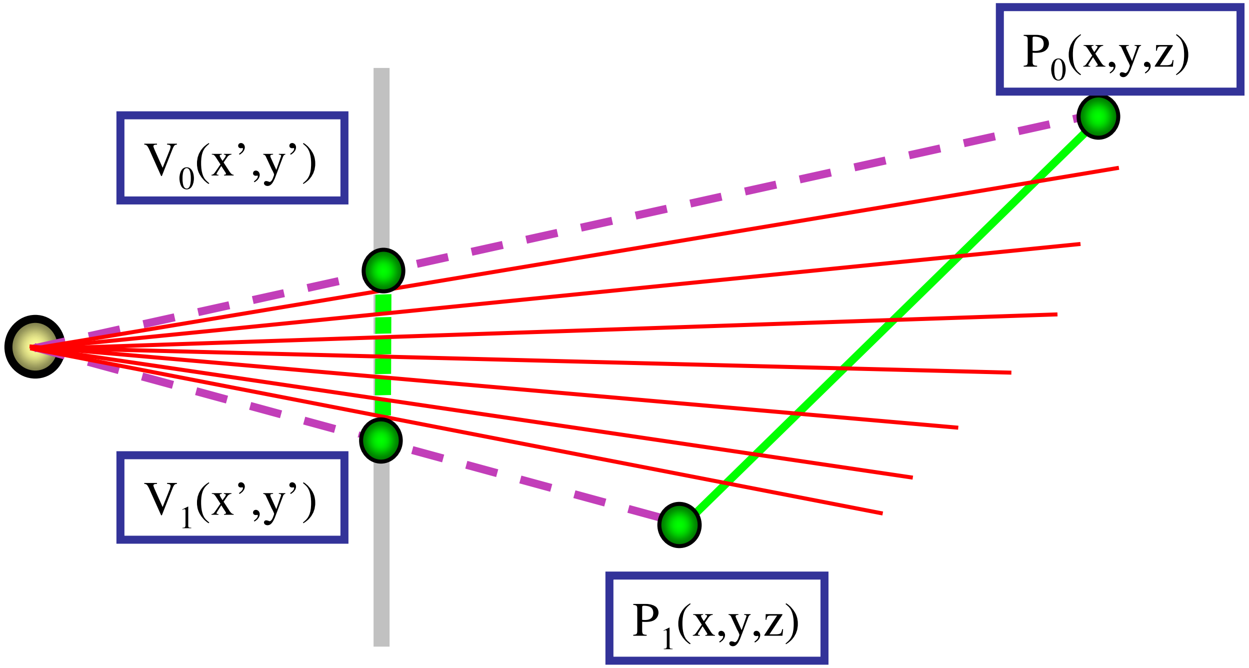
Review: Basic OpenGL Texturing

- setup
  - generate identifier: `glGenTextures`
  - load image data: `glTexImage2D`
  - set texture parameters (tile/clamp/...): `glTexParameteri`
  - set texture drawing mode (modulate/replace/...): `glTexEnvf`
- drawing
  - enable: `glEnable`
  - bind specific texture: `glBindTexture`
  - specify texture coordinates before each vertex: `glTexCoord2f`

Review: Perspective Correct Interpolation

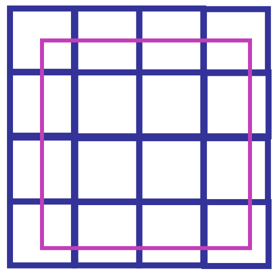
- screen space interpolation incorrect

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

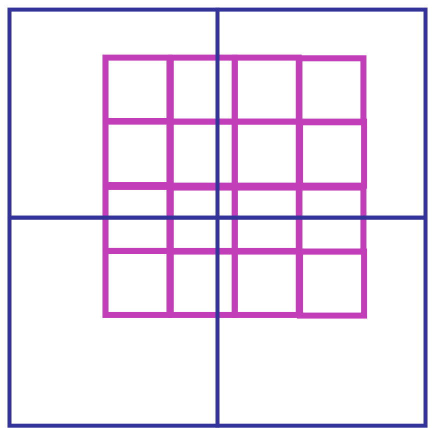


Review: Reconstruction

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

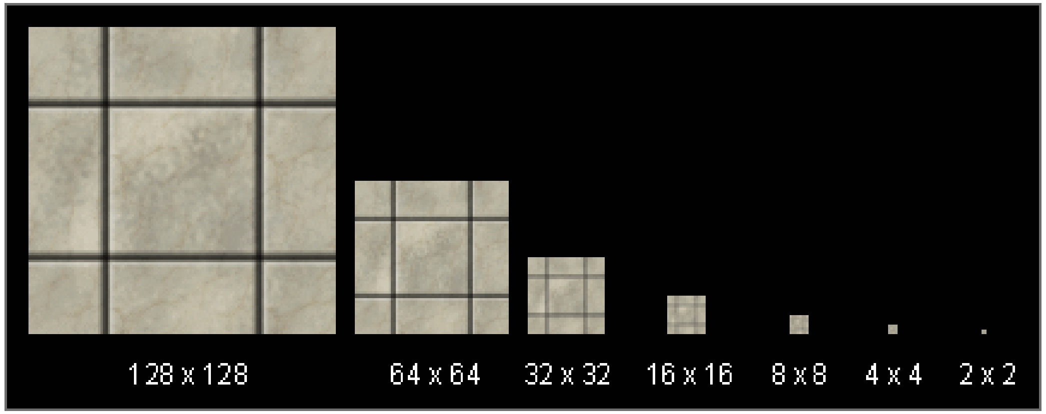


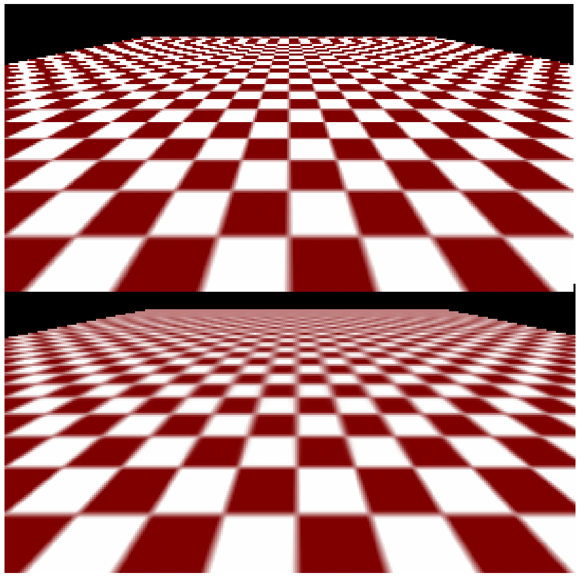
  - pixels that are much smaller than texels ?
    - interpolate

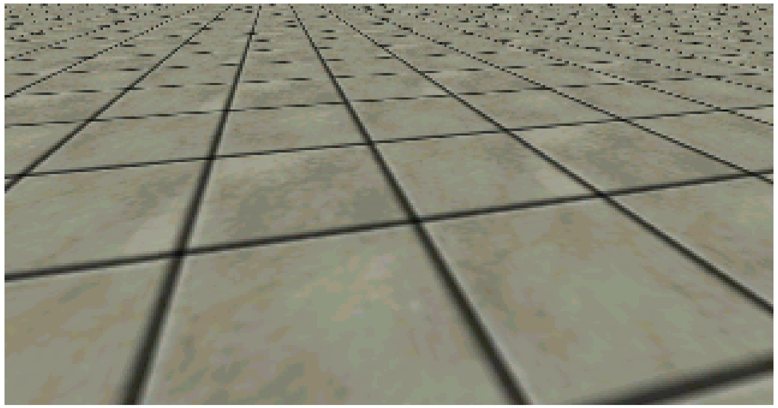


Review: MIPmapping

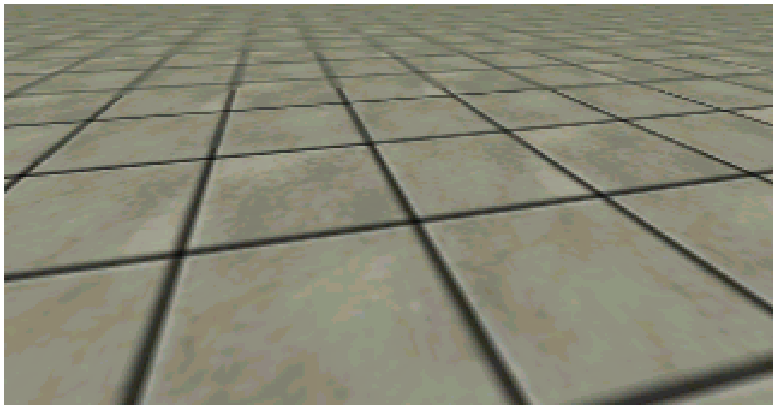
- image pyramid, precompute averaged versions







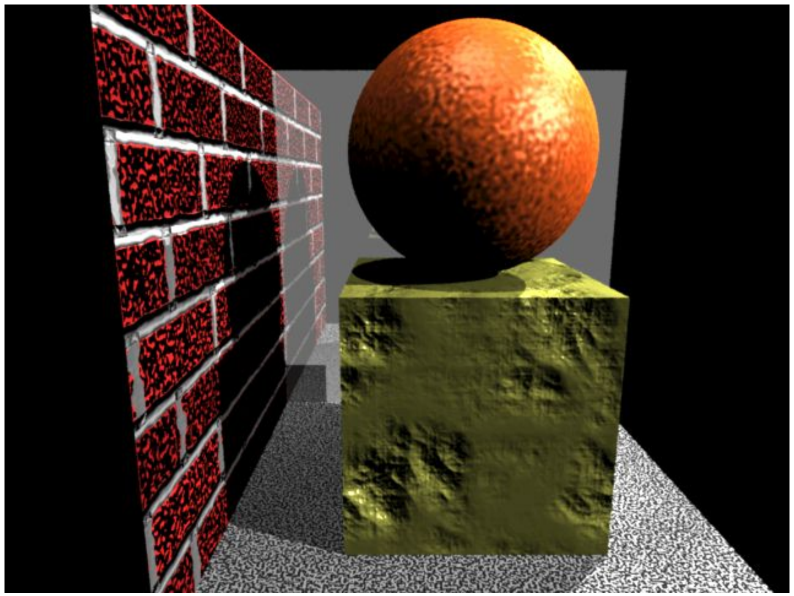
Without MIP-mapping

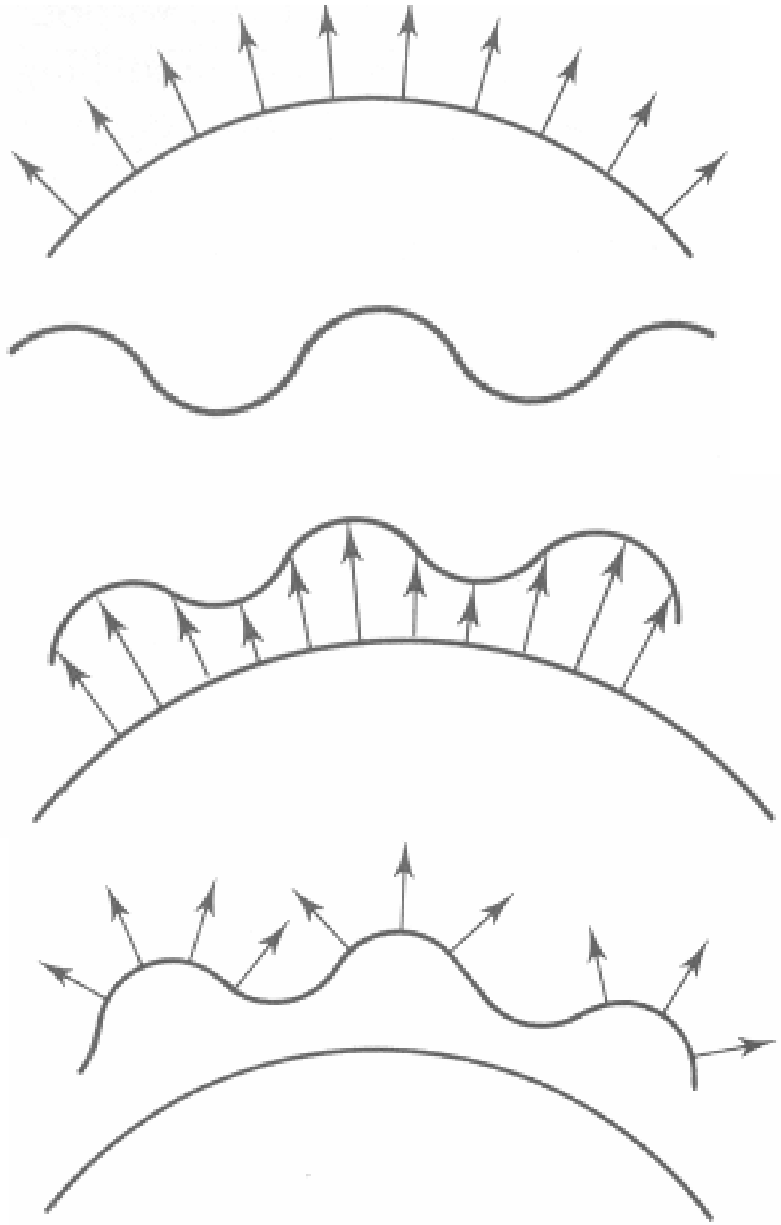


With MIP-mapping

Review: Bump Mapping: Normals As Texture

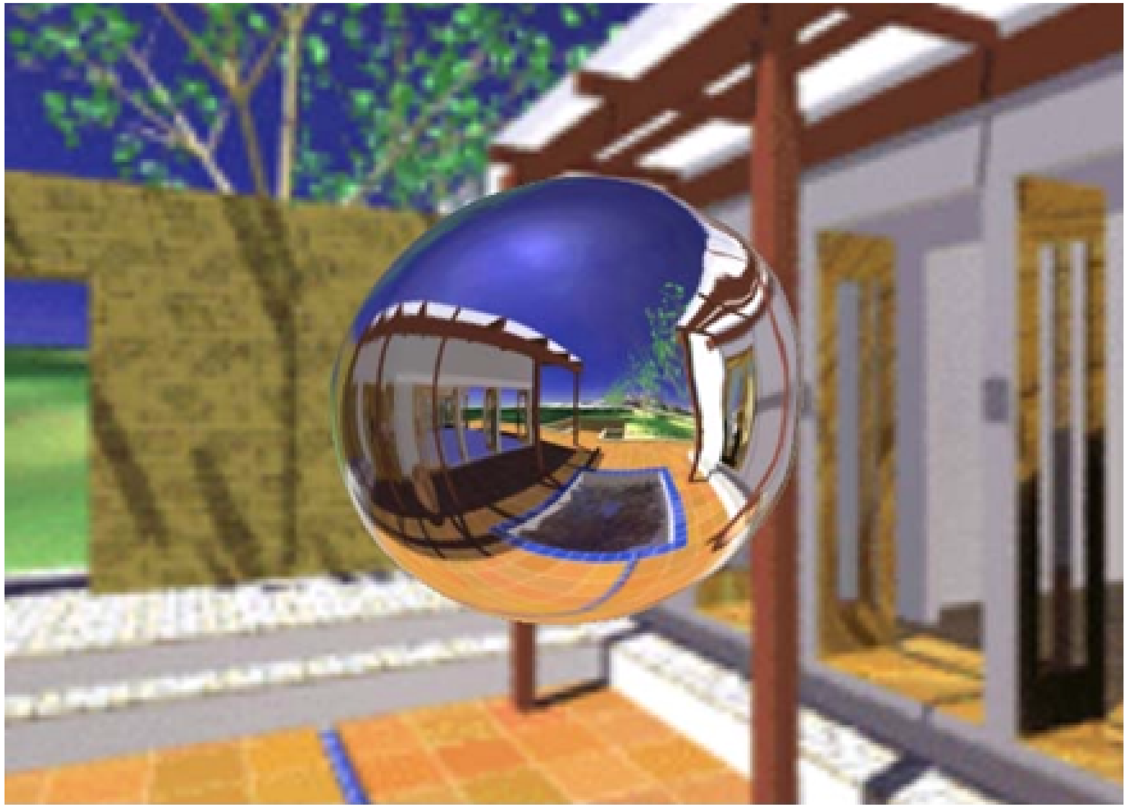
- create illusion of complex geometry model
- control shape effect by locally perturbing surface normal





Review: Environment Mapping

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

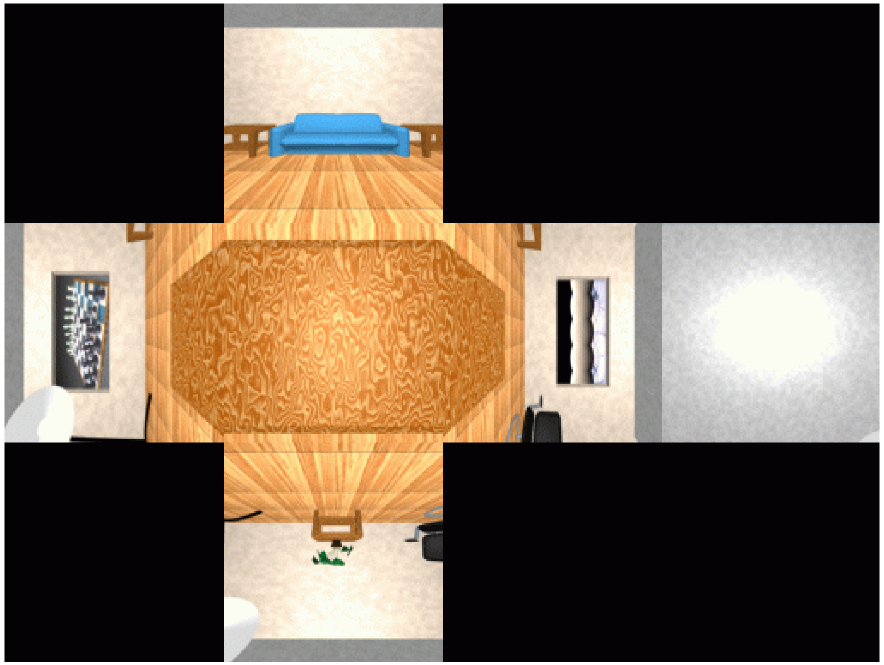


Review: Sphere Mapping

- texture is distorted fish-eye view
  - point camera at mirrored sphere
  - spherical texture coordinates

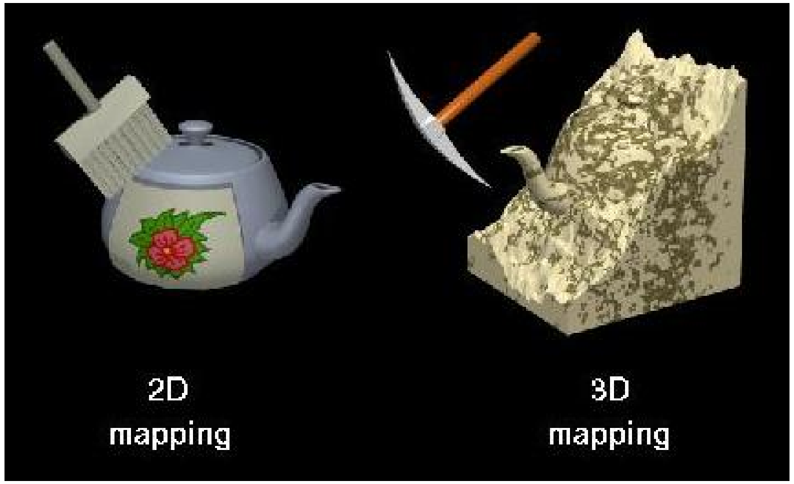
Review: Cube Mapping

- 6 planar textures, sides of cube
  - point camera outwards to 6 faces
    - use largest magnitude of vector to pick face
    - other two coordinates for (s,t) texel location



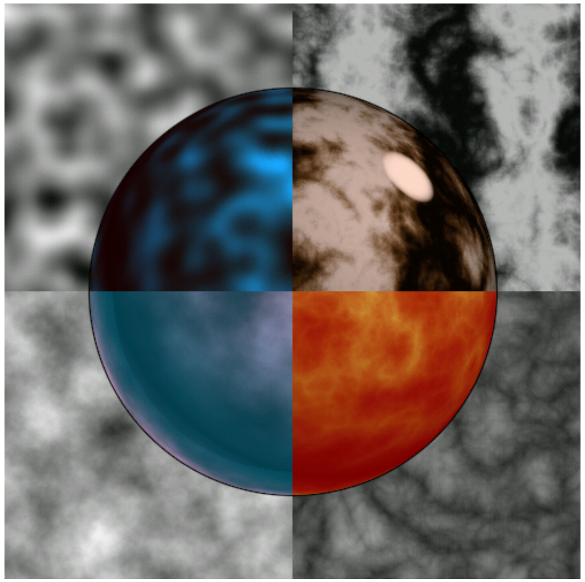
Review: Volumetric Texture

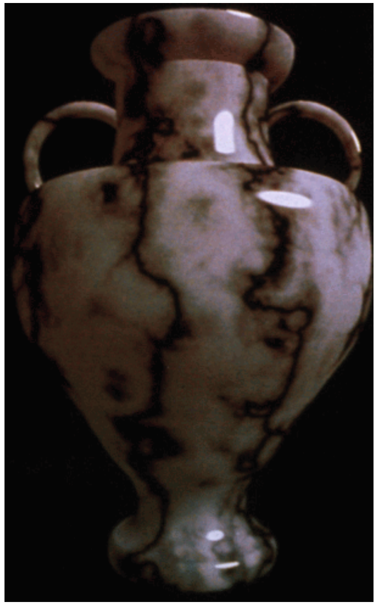
- define texture pattern over 3D domain - 3D space containing the object
  - texture function can be digitized or procedural
  - for each point on object compute texture from point location in space
- 3D function $\rho(x,y,z)$



Review: Perlin Noise: Procedural Textures

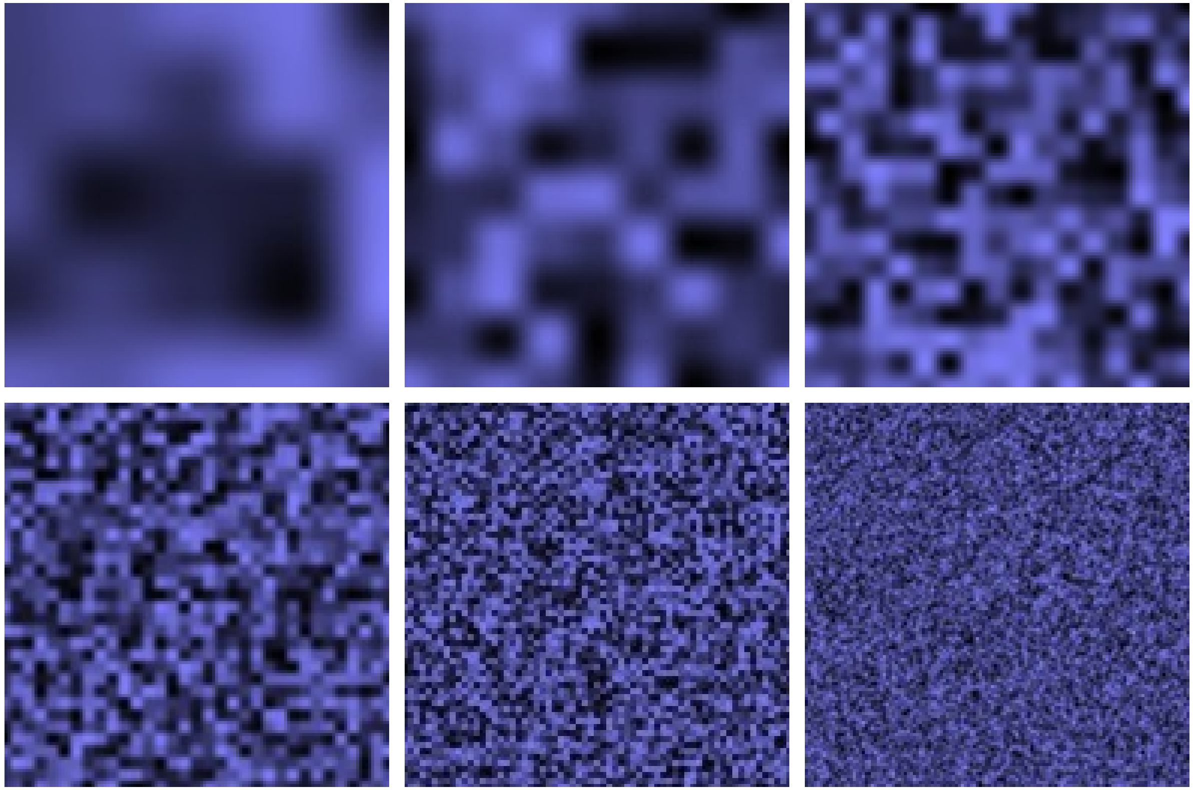
```
function marble(point)
  x = point.x + turbulence(point);
  return marble_color(sin(x))
```

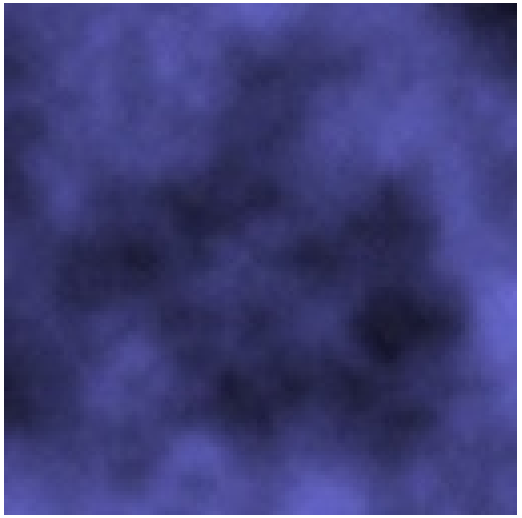




Review: Perlin Noise

- coherency: smooth not abrupt changes
- turbulence: multiple feature sizes





Review: Generating Coherent Noise

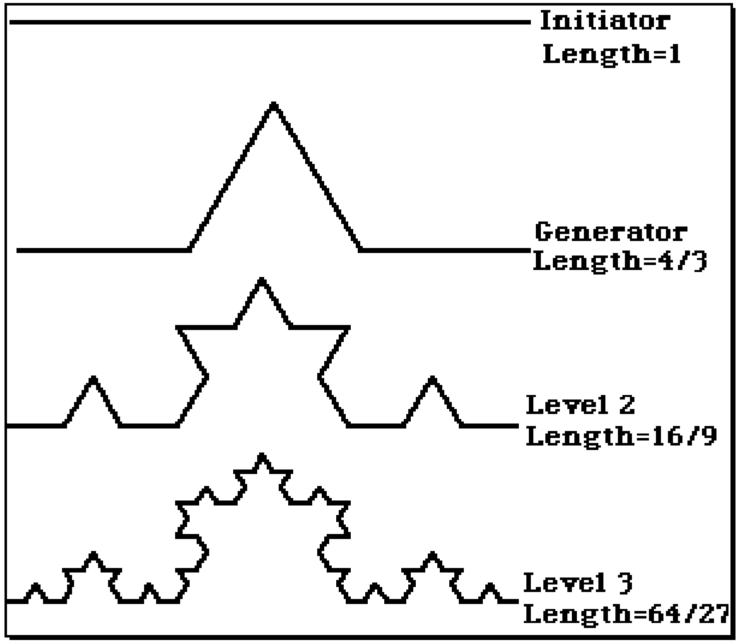
- just three main ideas
  - nice interpolation
  - use vector offsets to make grid irregular
  - optimization
    - sneaky use of 1D arrays instead of 2D/3D one

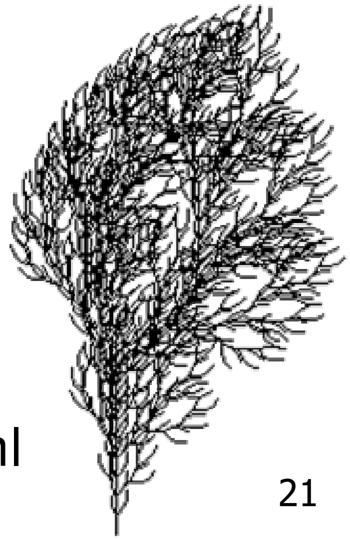
Review: Procedural Modeling

- textures, geometry
  - nonprocedural: explicitly stored in memory
- procedural approach
  - compute something on the fly
    - not load from disk
  - often less memory cost
  - visual richness
    - adaptable precision
- noise, fractals, particle systems

Review: Language-Based Generation

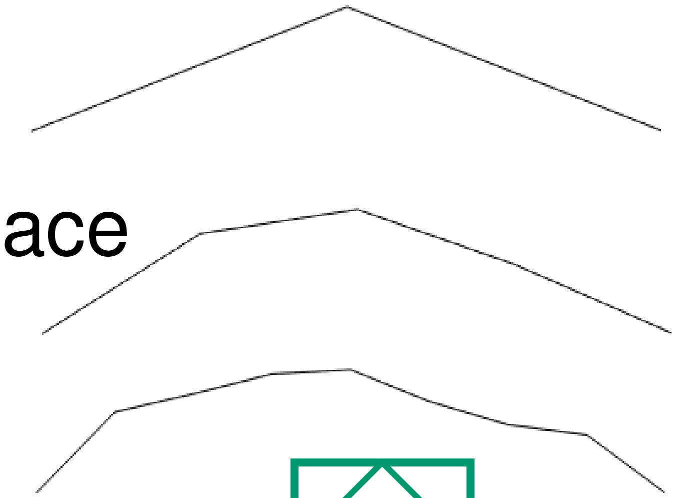
- L-Systems
  - F: forward, R: right, L: left
  - Koch snowflake:
    F = FLFRRFLF
  - Mariano's Bush:
    F=FF-[-F+F+F]+[+F-F-F]
    - angle 16



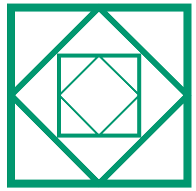


http://spanky.triumf.ca/www/fractint/lsys/plants.html

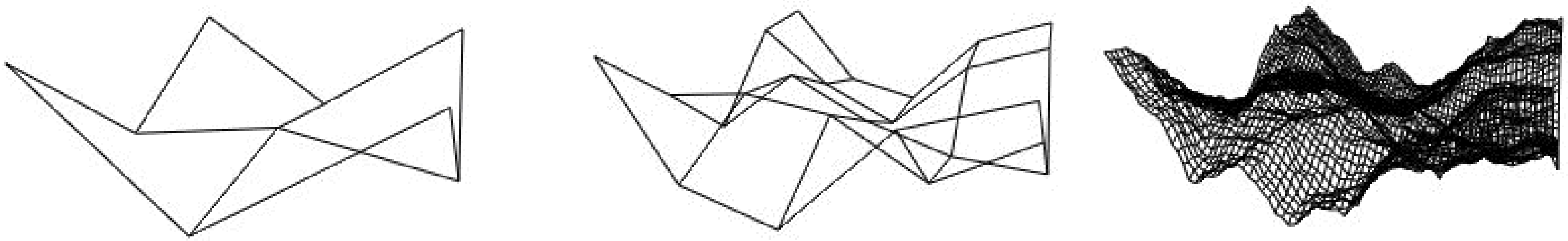
Correction/Review: Fractal Terrain



- 1D: midpoint displacement
  - divide in half, randomly displace
  - scale variance by half
- 2D: diamond-square



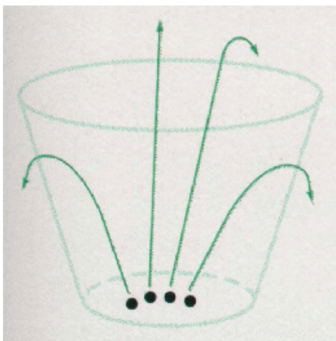
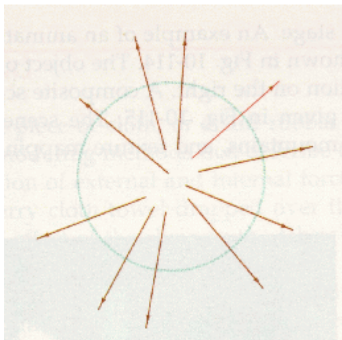
  - generate new value at midpoint
  - average corner values + random displacement
    - scale variance by half each time



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

Review: Particle Systems

- changeable/fluid stuff
  - fire, steam, smoke, water, grass, hair, dust, waterfalls, fireworks, explosions, flocks
- life cycle
  - generation, dynamics, death
- rendering tricks
  - avoid hidden surface computations

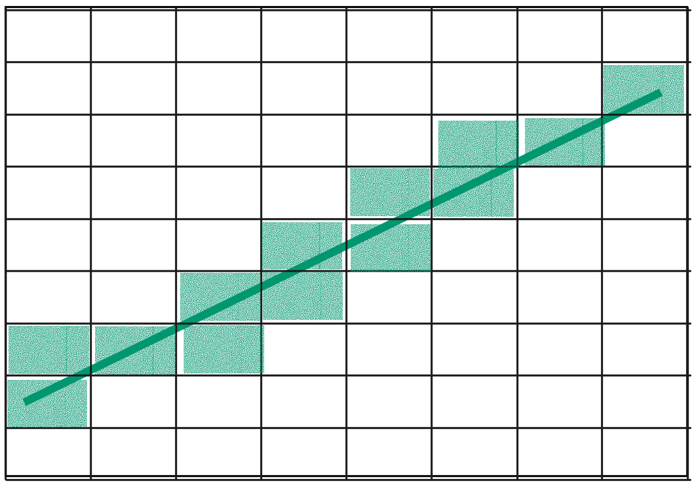
Sampling

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

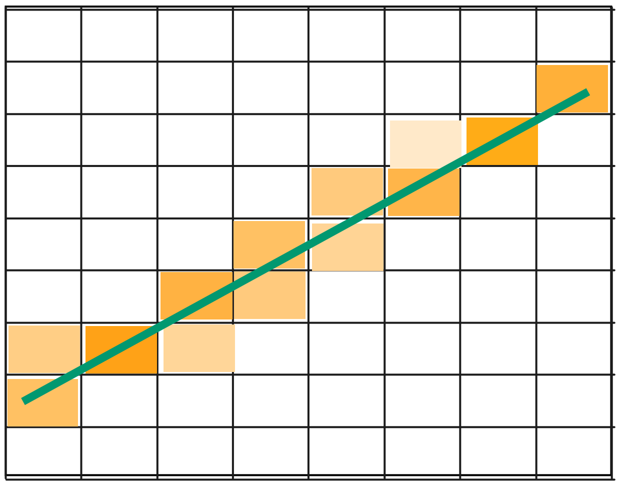
Line Segments

- 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



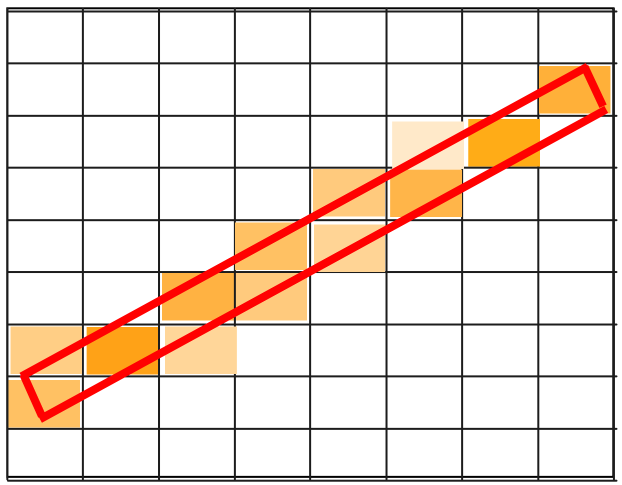
Line Segments

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



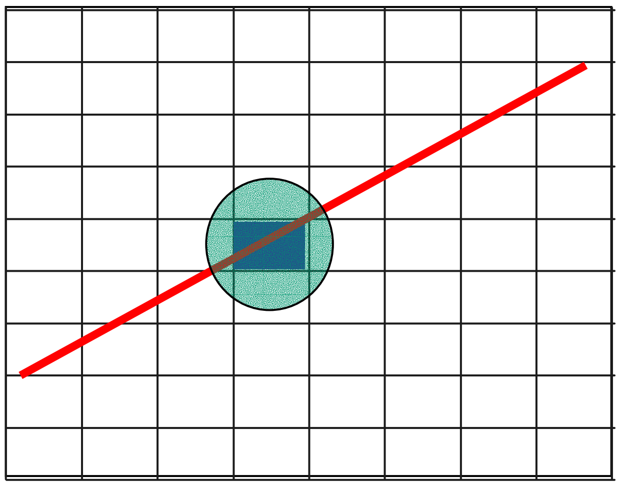
Unweighted Area Sampling

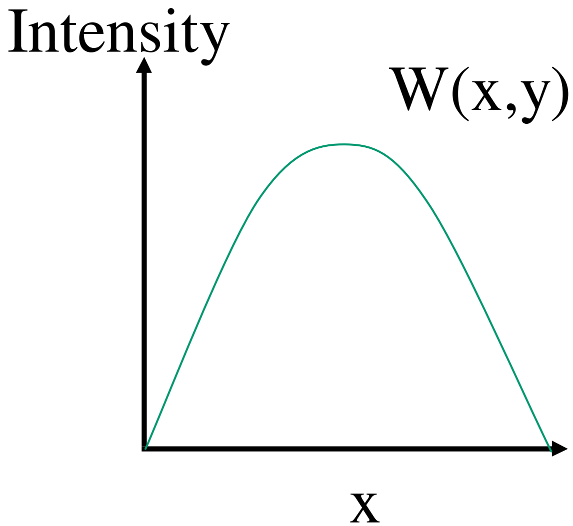
- shade pixels wrt area covered by thickened line
- equal areas cause equal intensity, regardless of distance from pixel center to area
  - rough approximation formulated by dividing each pixel into a finer grid of pixels
- primitive cannot affect intensity of pixel if it does not intersect the pixel



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)

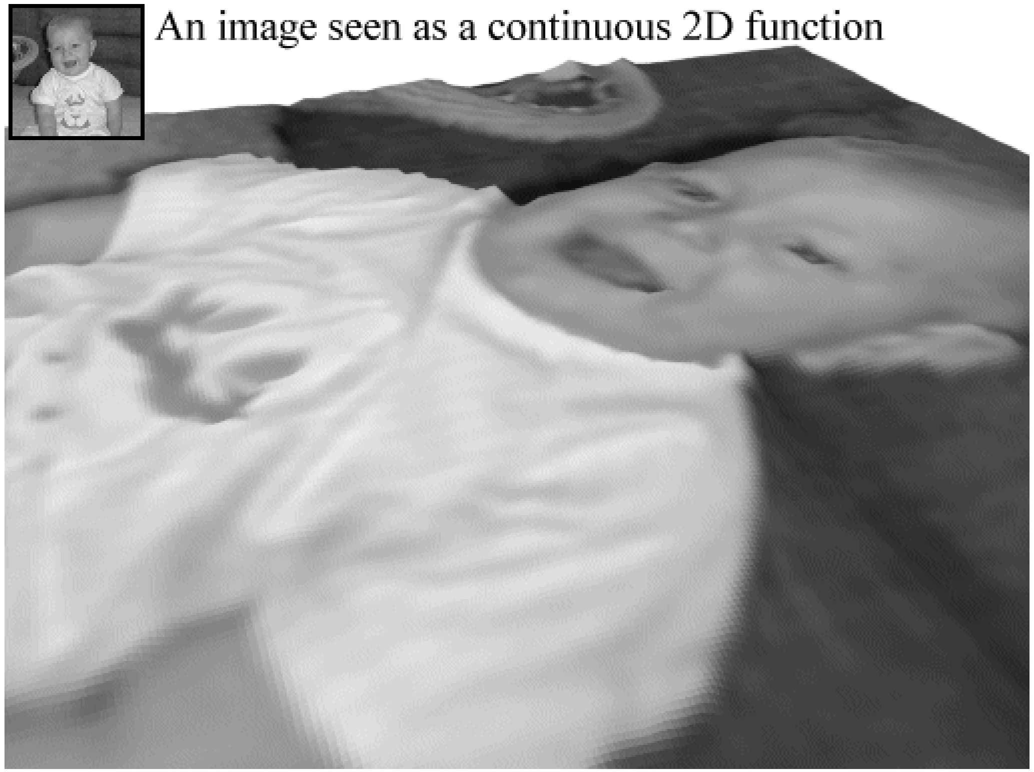
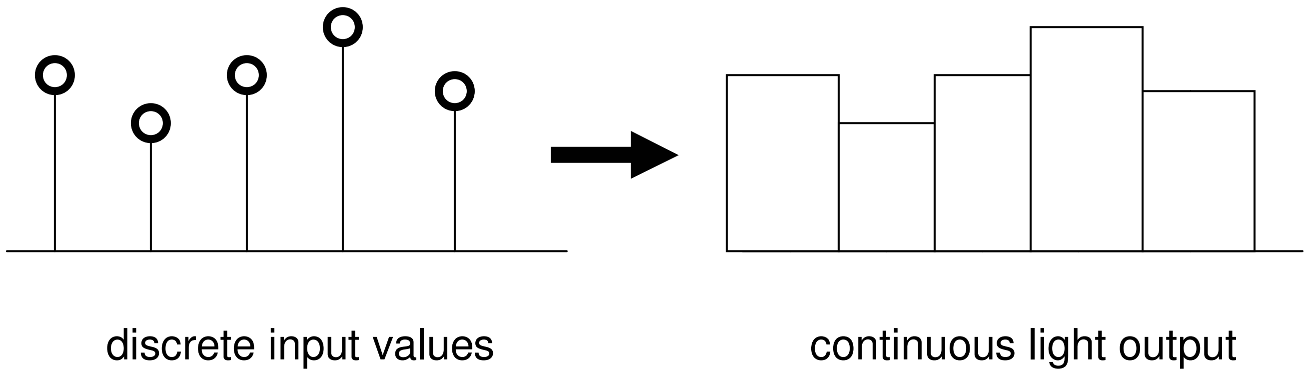


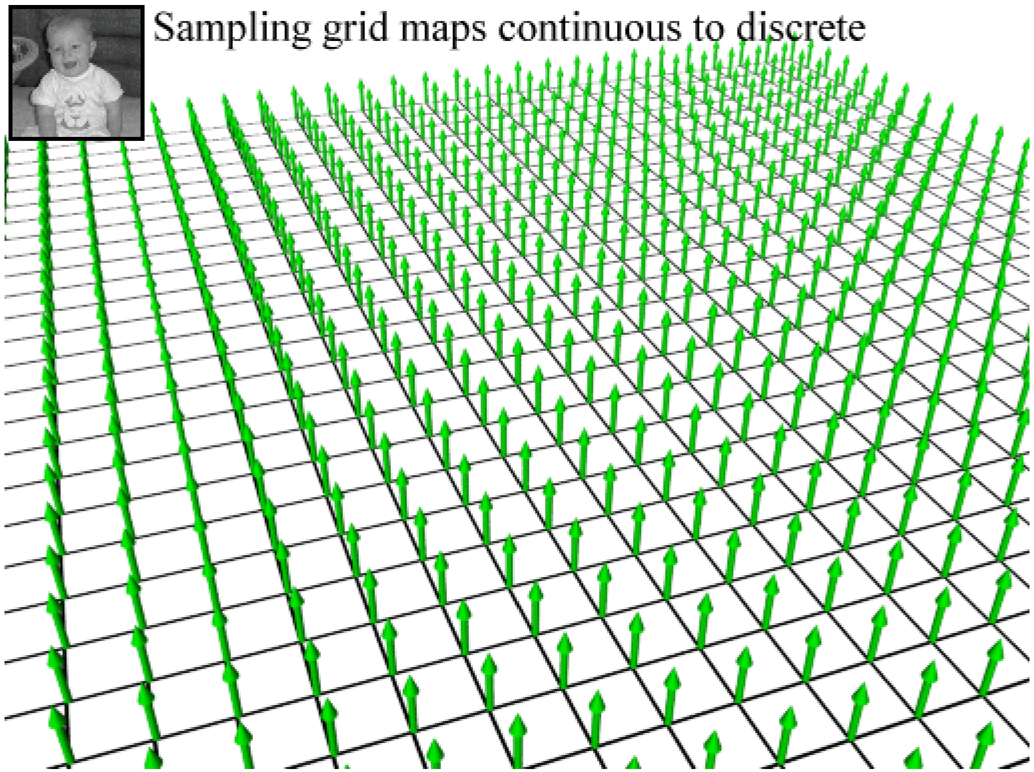
Image Sampling and Reconstruction

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



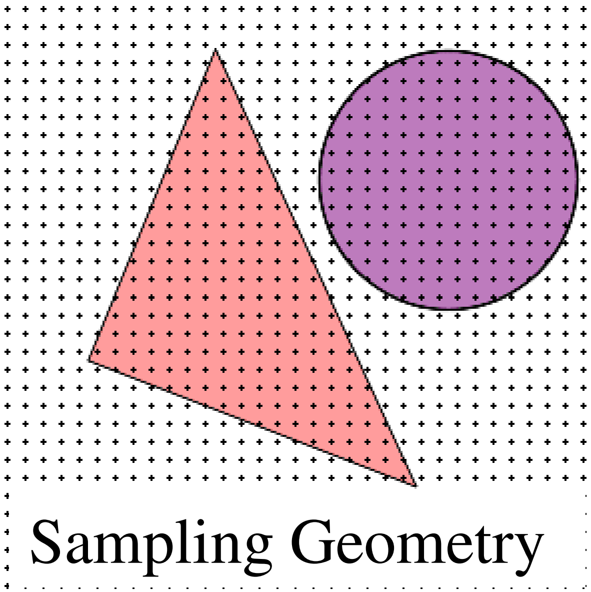
Point Sampling an Image

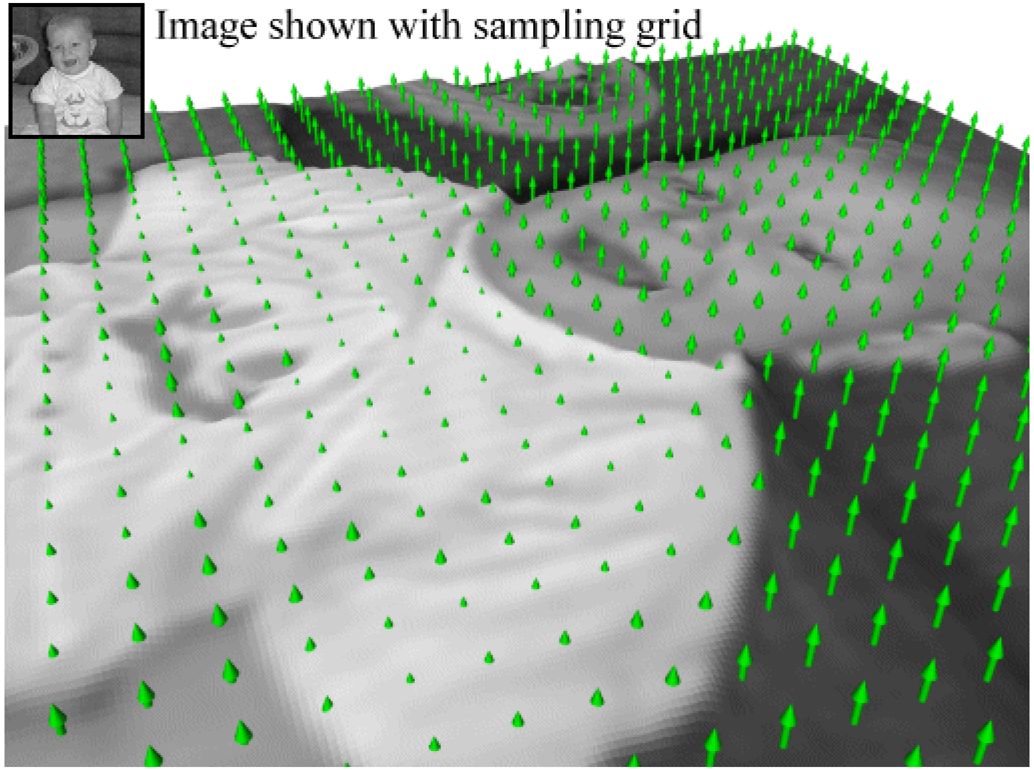
- simplest sampling is on a grid
- sample depends solely on value at grid points



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!

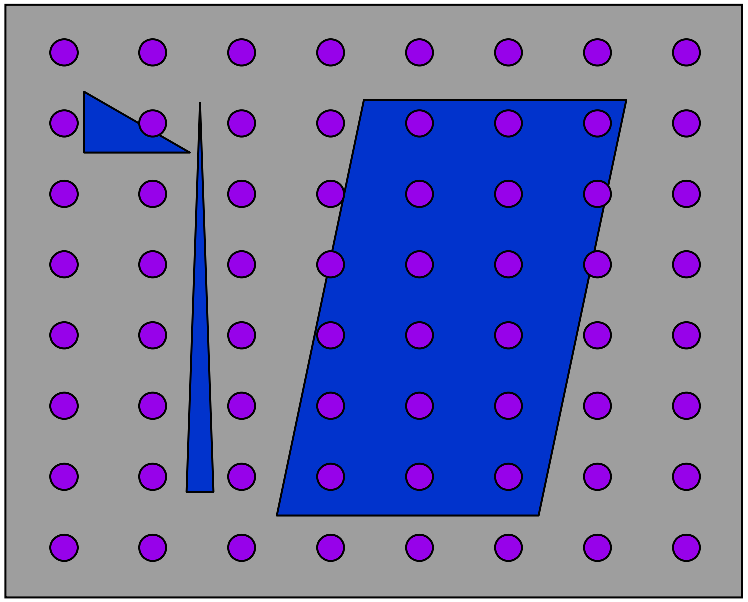
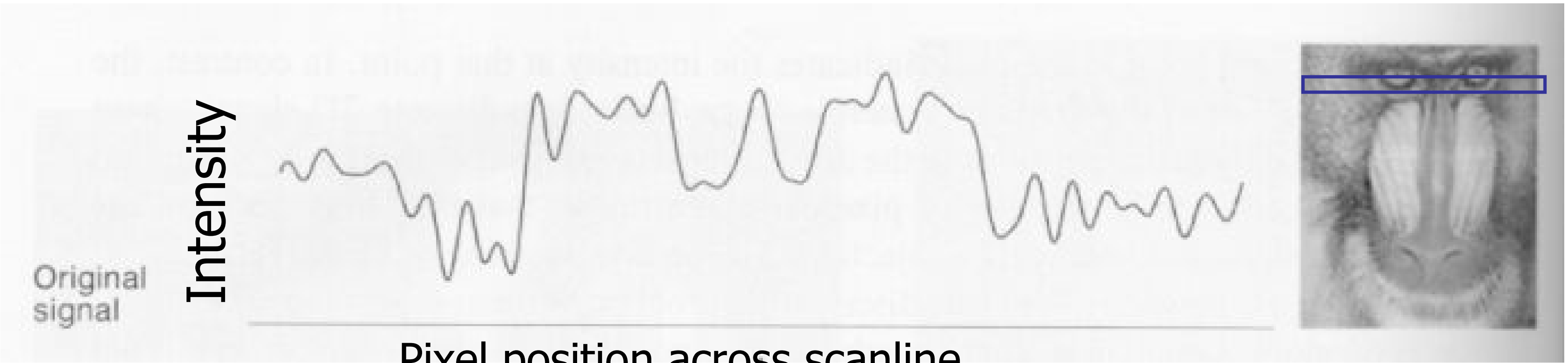


Image As Signal

- 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

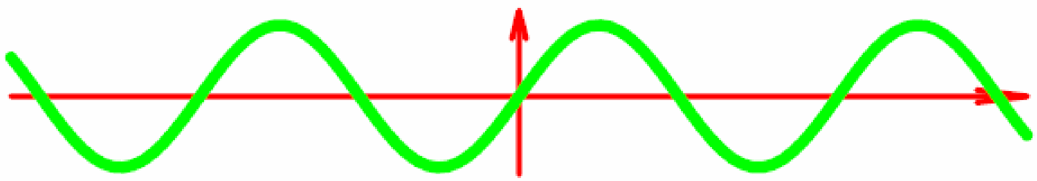
Sampling Theory

- 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

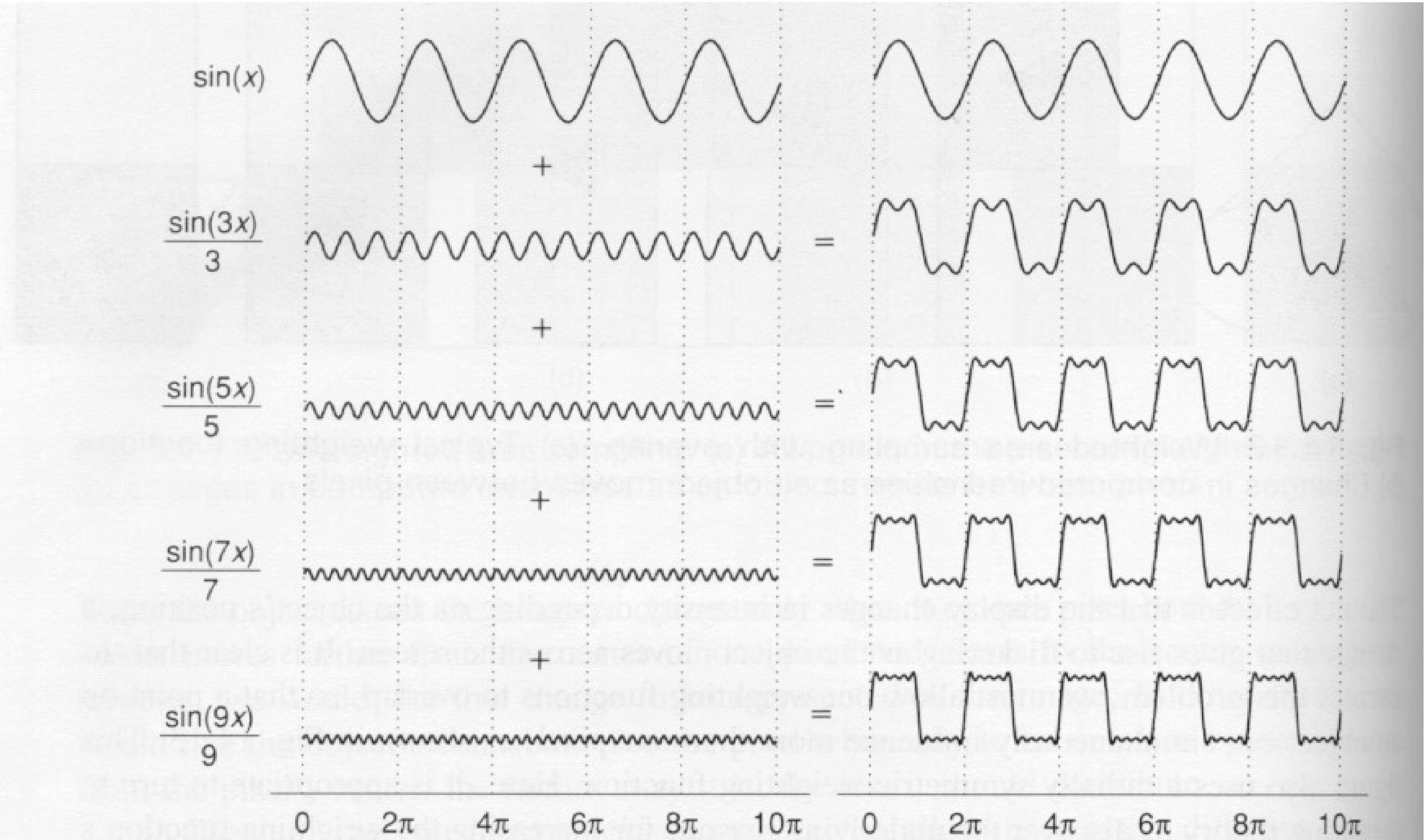
Sampling Theory in a Nutshell

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

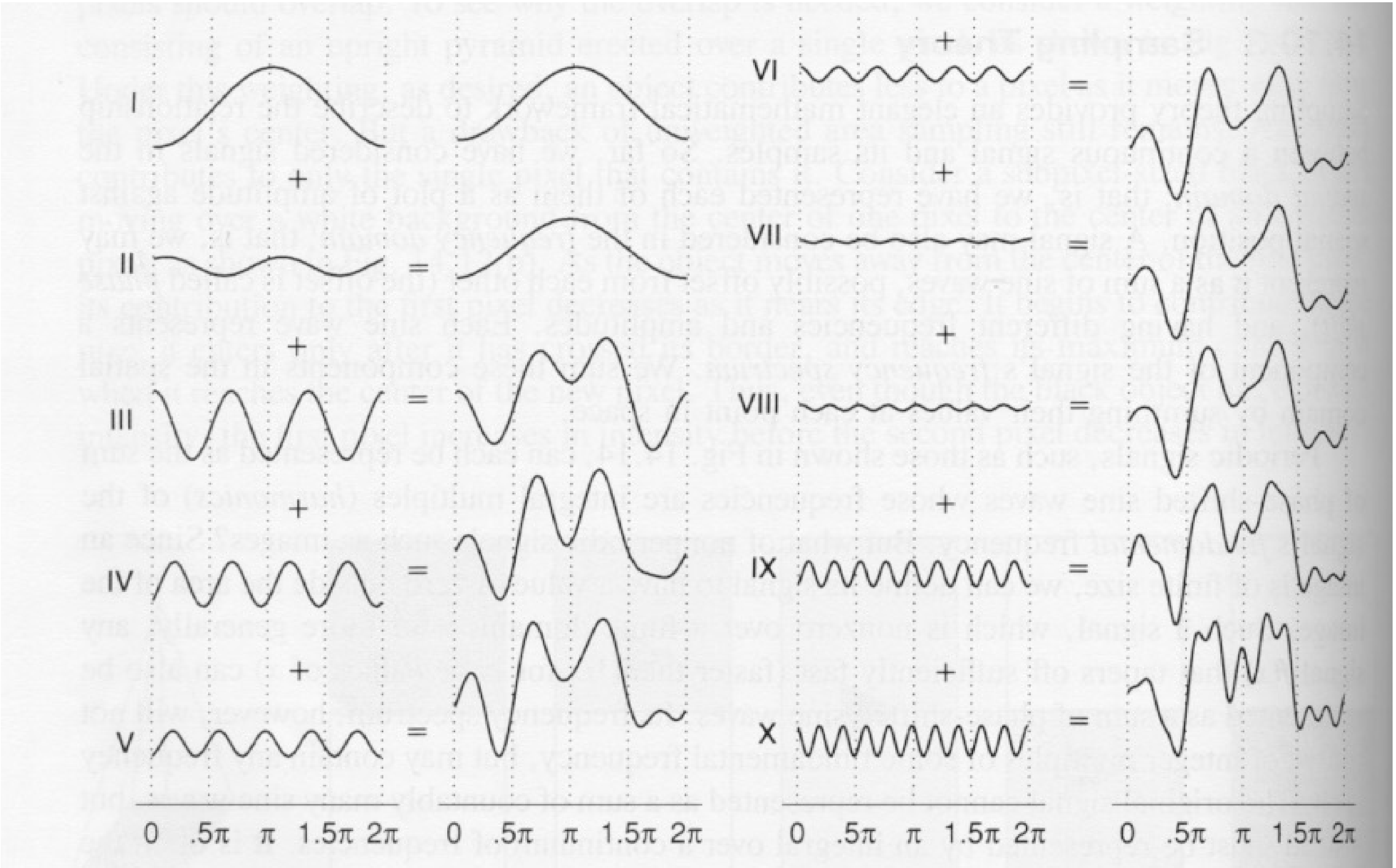
$\sin(t)$



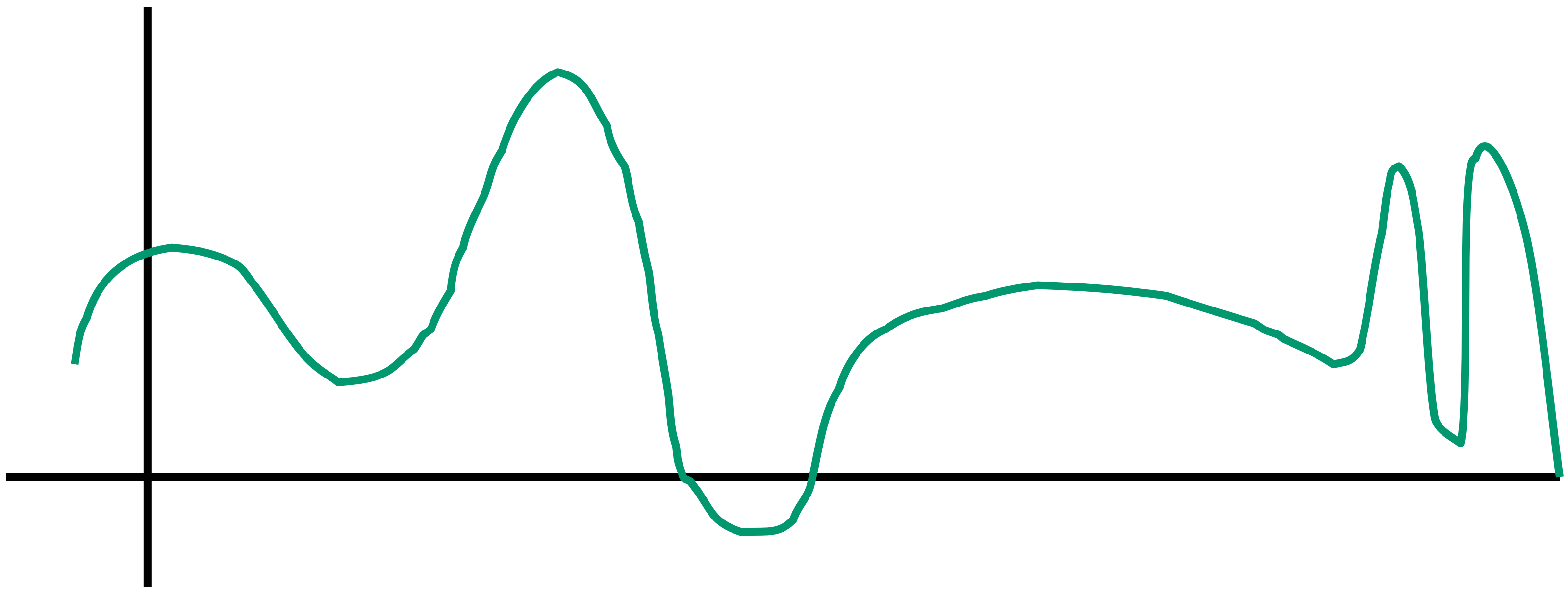
Summing Waves I



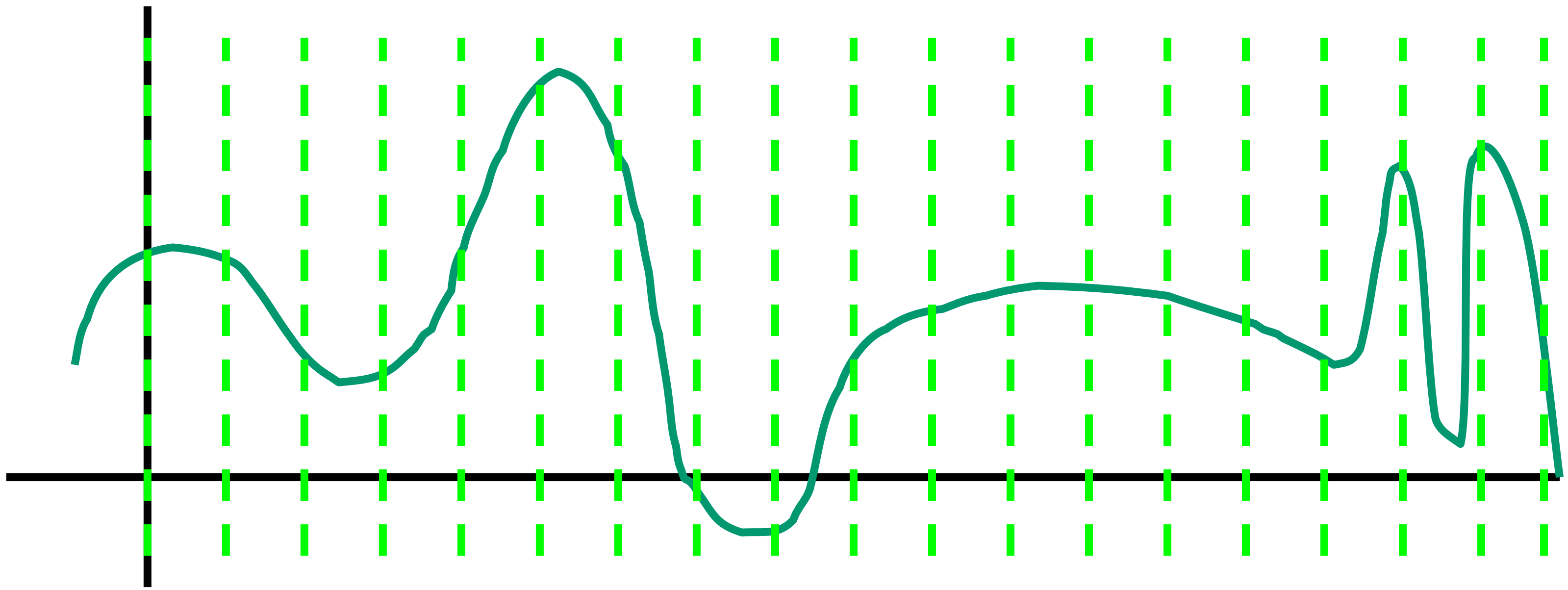
Summing Waves II



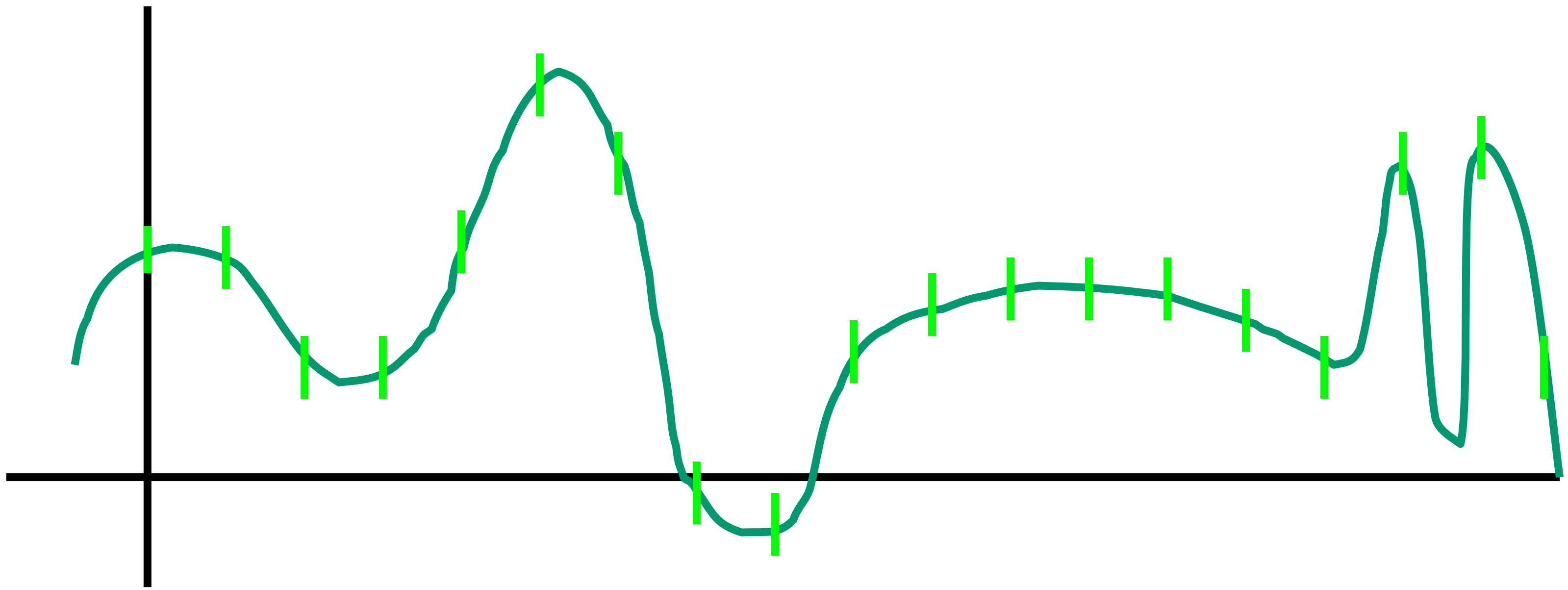
1D Sampling and Reconstruction



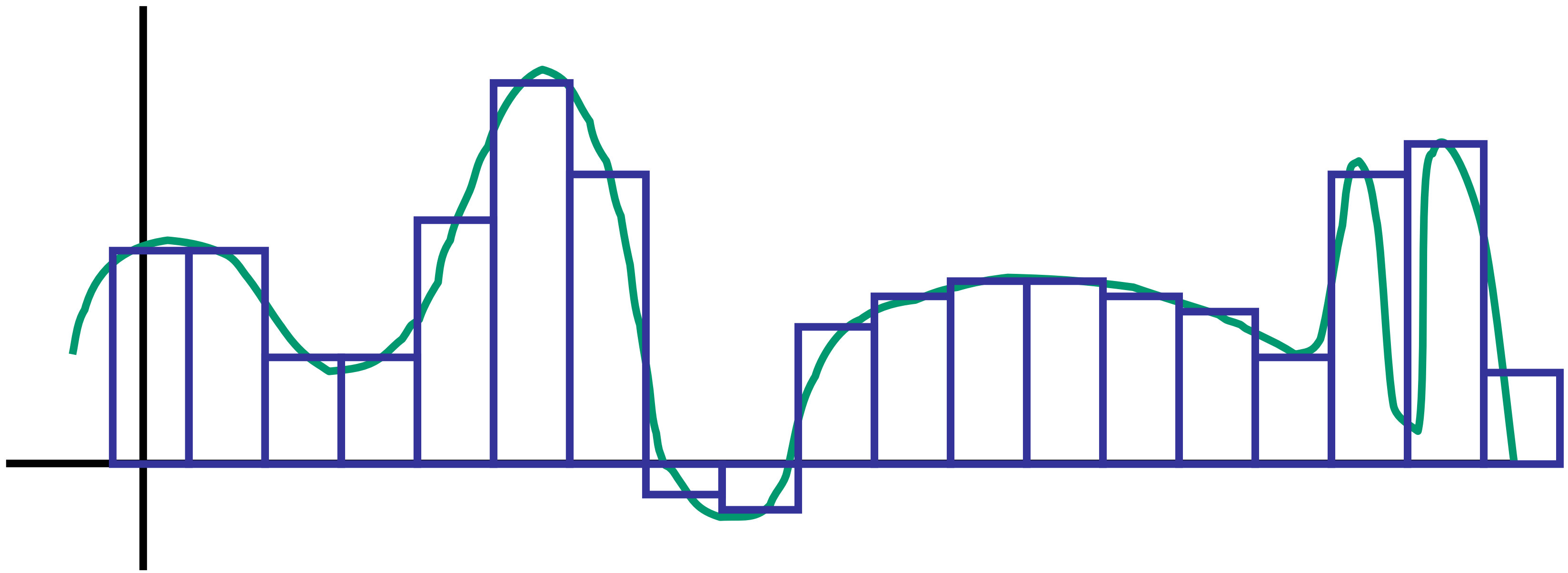
1D Sampling and Reconstruction



1D Sampling and Reconstruction

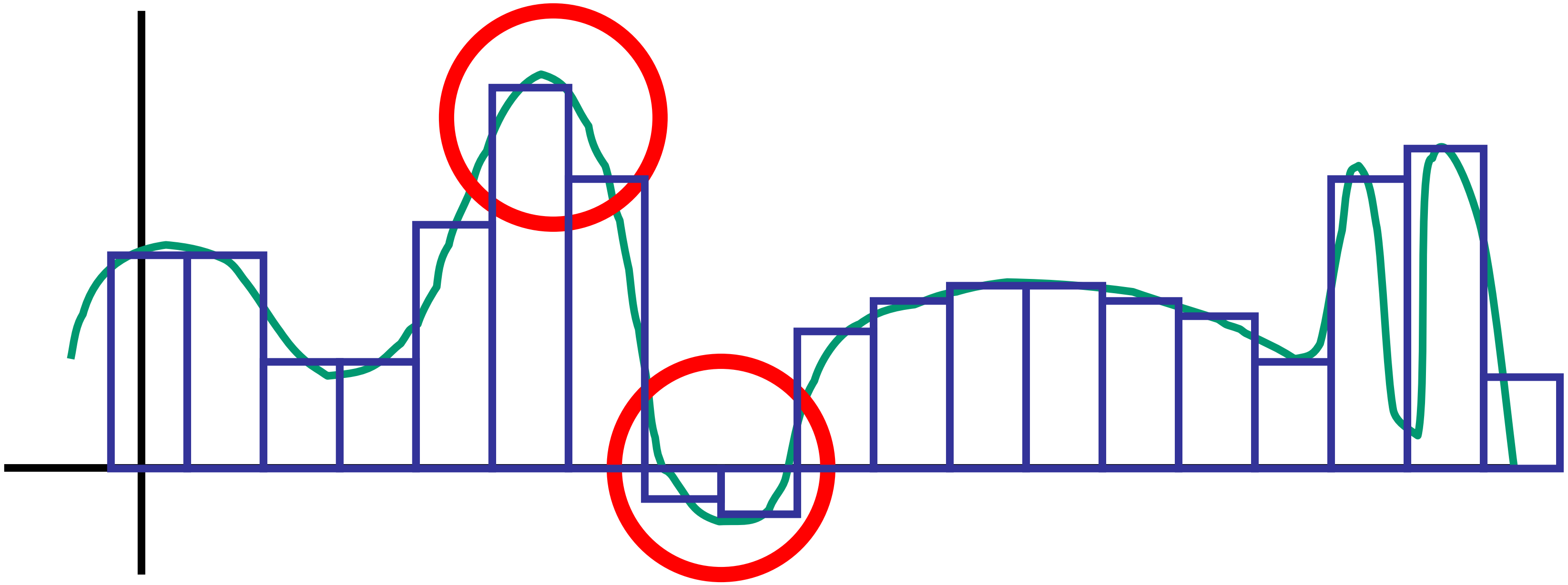


1D Sampling and Reconstruction



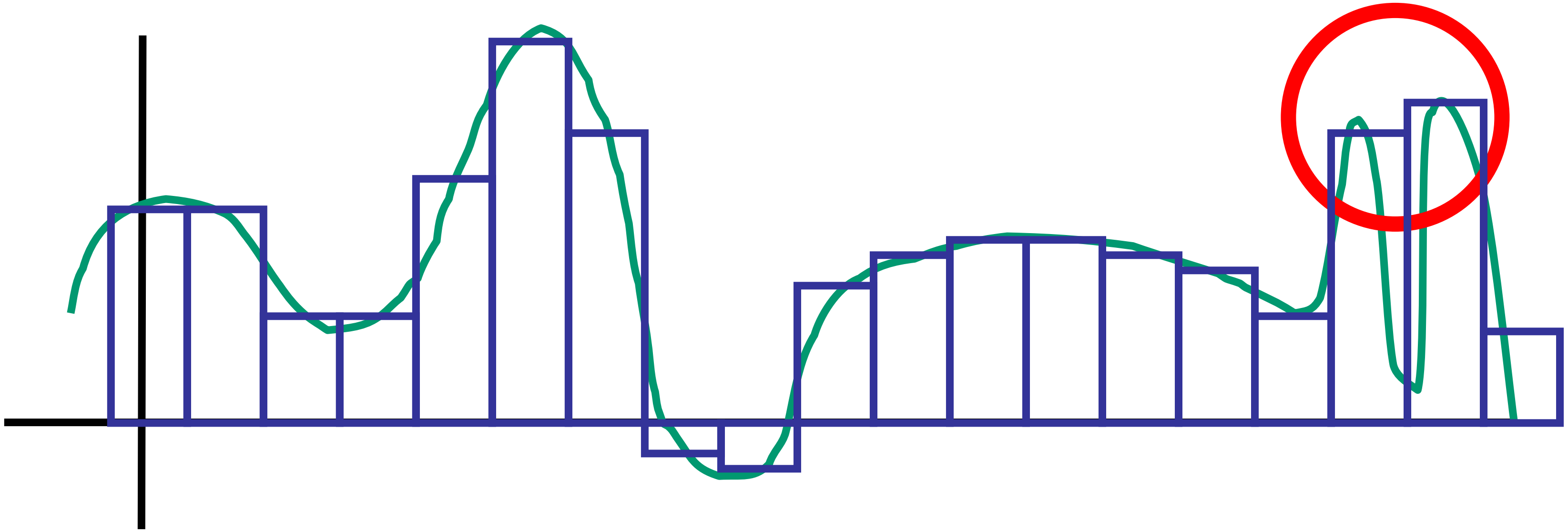
1D Sampling and Reconstruction

- 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

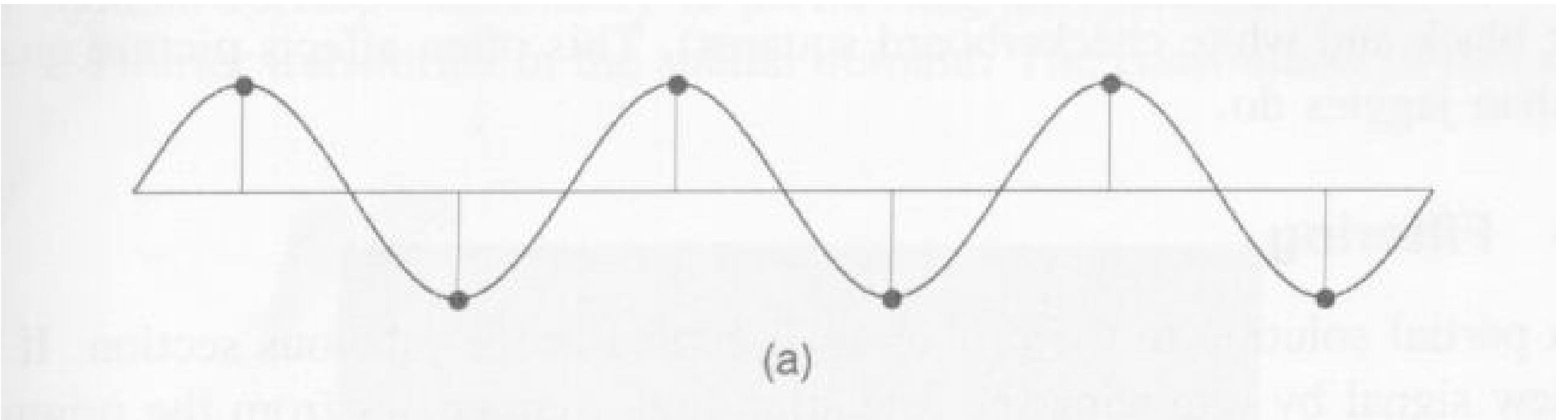
iff

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



(a)

Falling Below Nyquist Rate

- when sampling below Nyquist Rate, resulting signal looks like a lower-frequency one
  - this is aliasing!

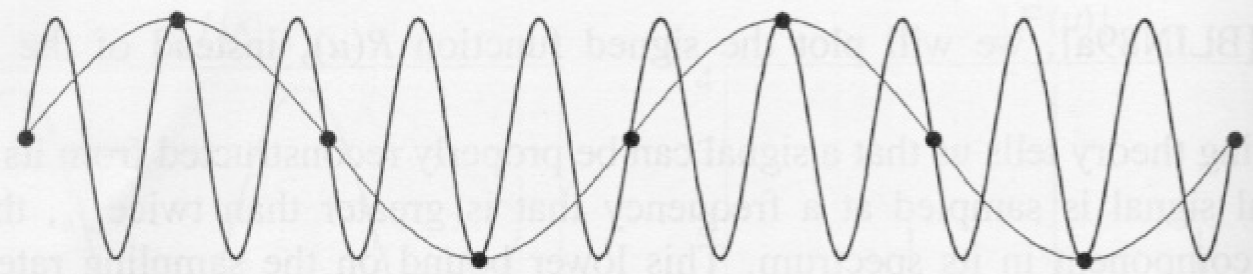
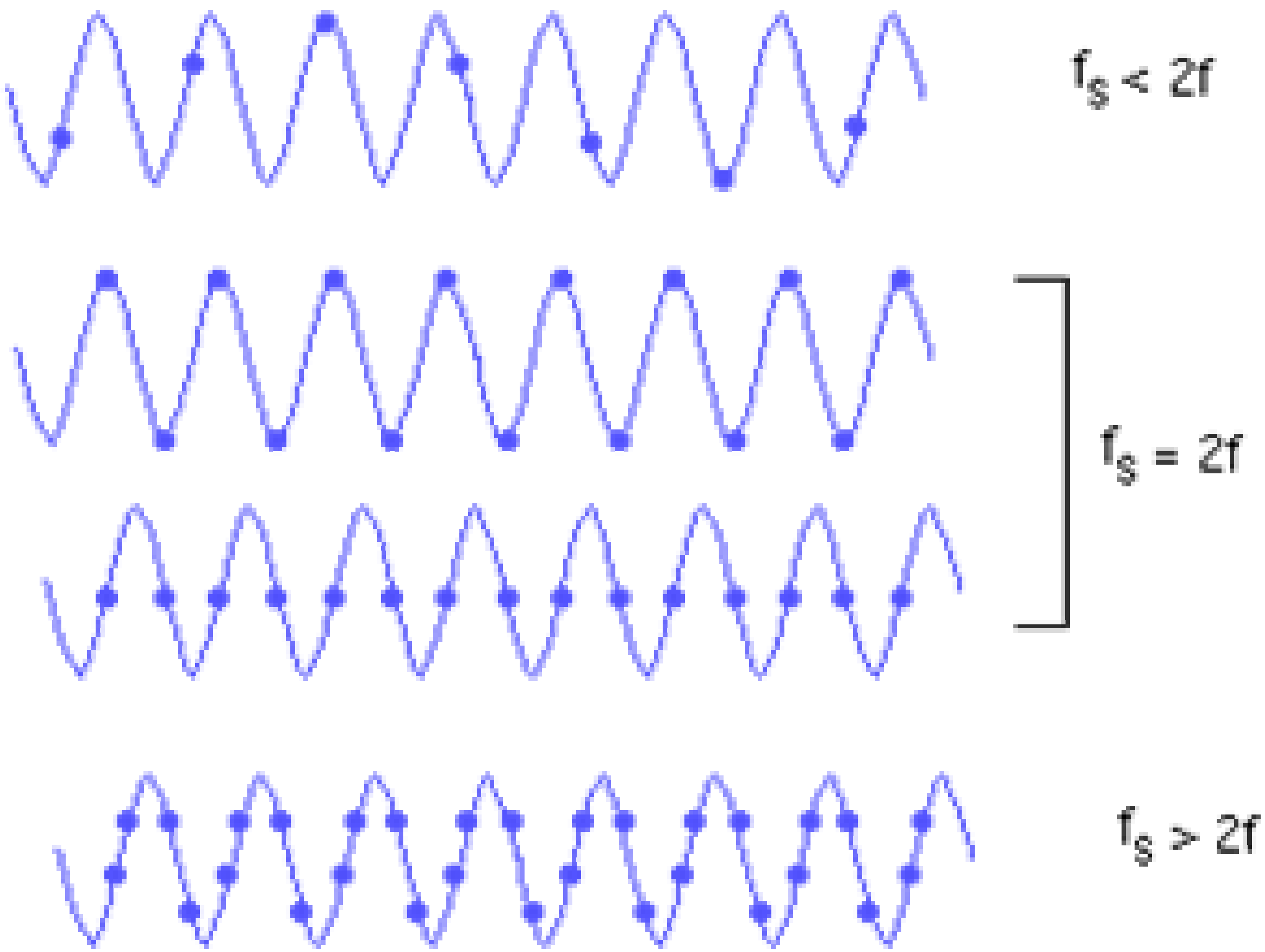


Fig. 14.17 Sampling below the Nyquist rate. (Courtesy of George Wolberg, Columbia University.)

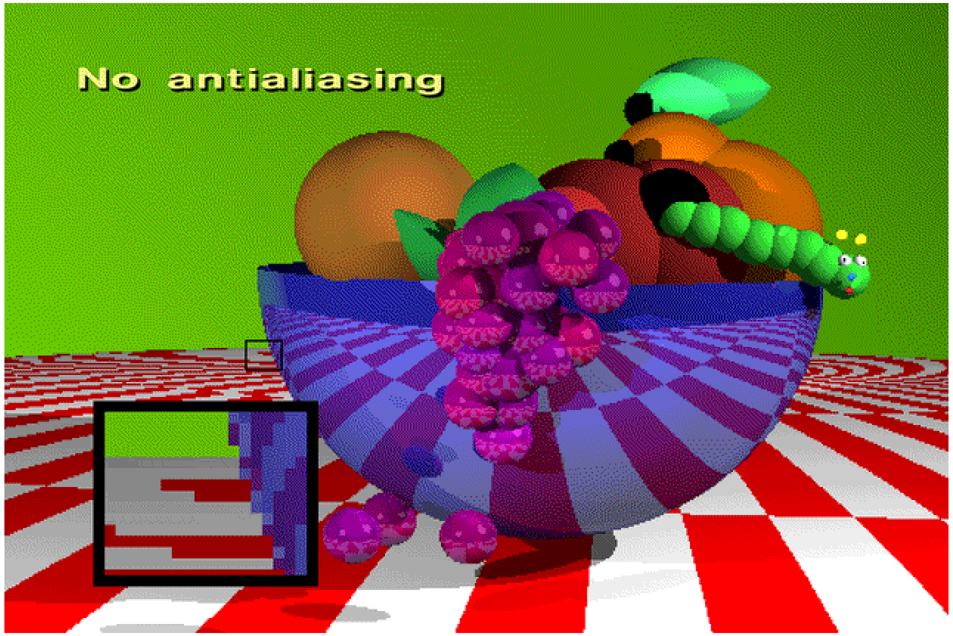
Nyquist Rate

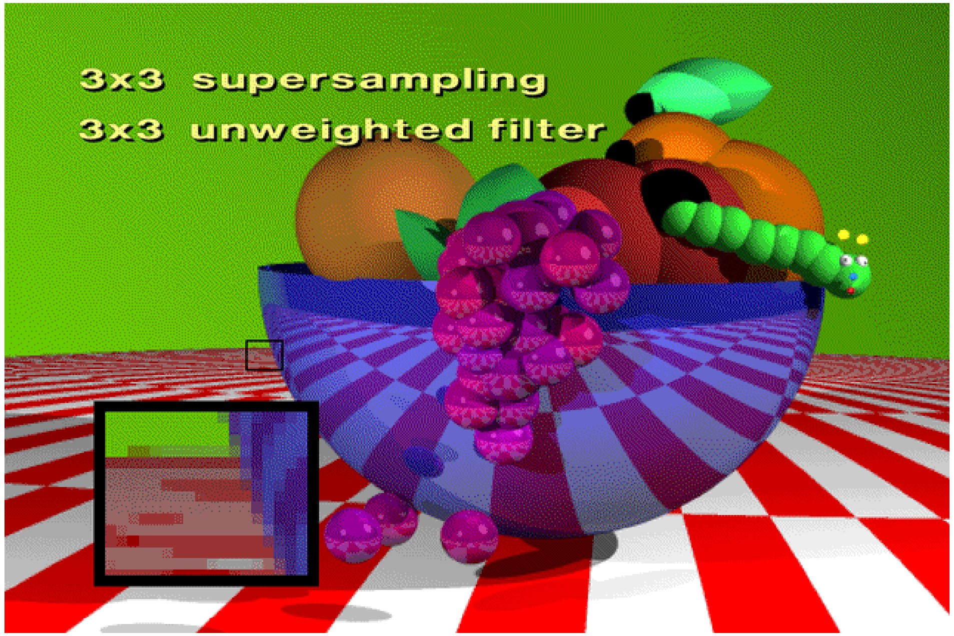


Aliasing

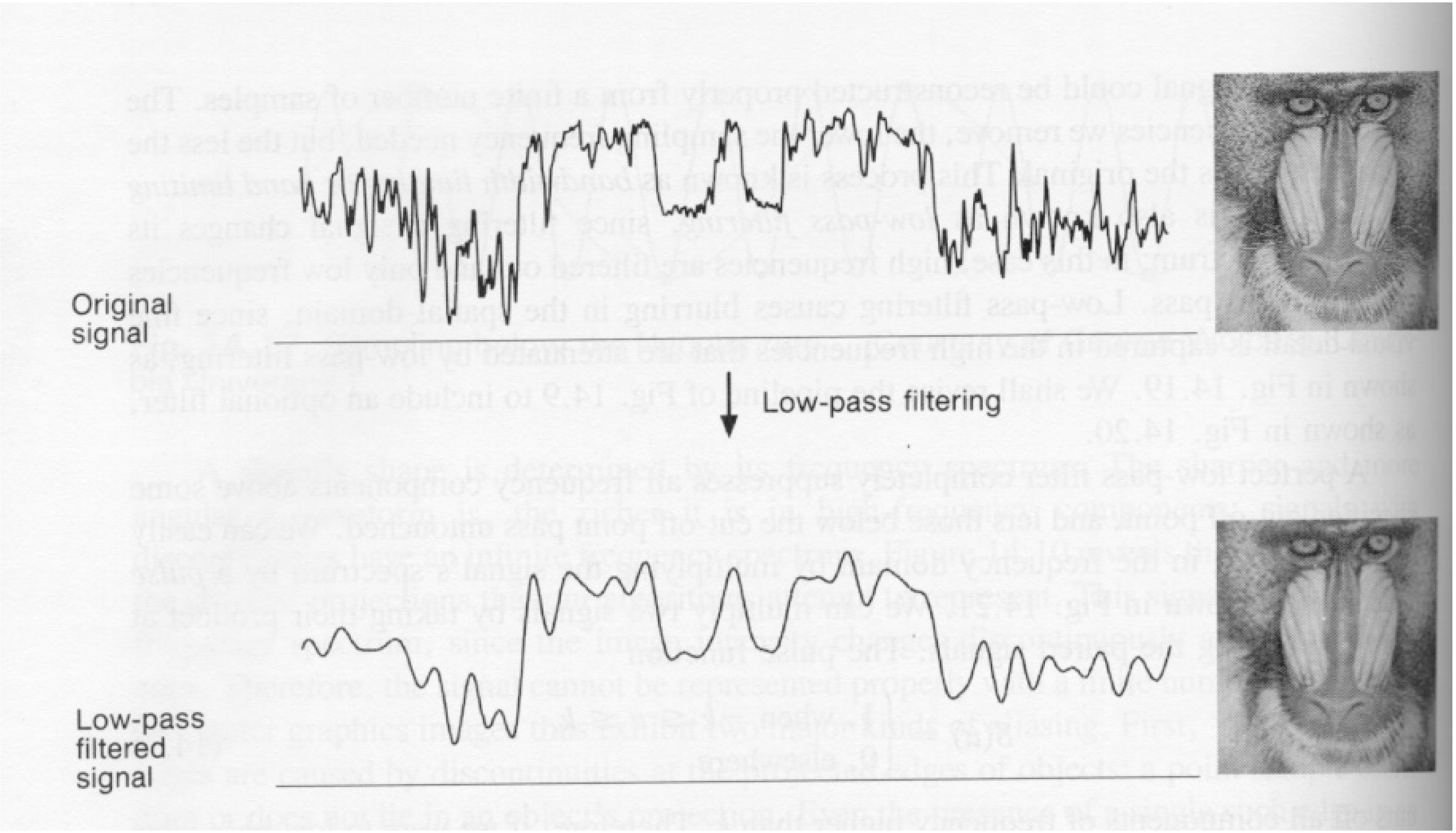
- incorrect appearance of high frequencies as low frequencies
- to avoid: antialiasing
  - supersample
    - sample at higher frequency
  - low pass filtering
    - remove high frequency function parts
    - aka prefiltering, band-limiting

Supersampling





Low-Pass Filtering



Low-Pass Filtering

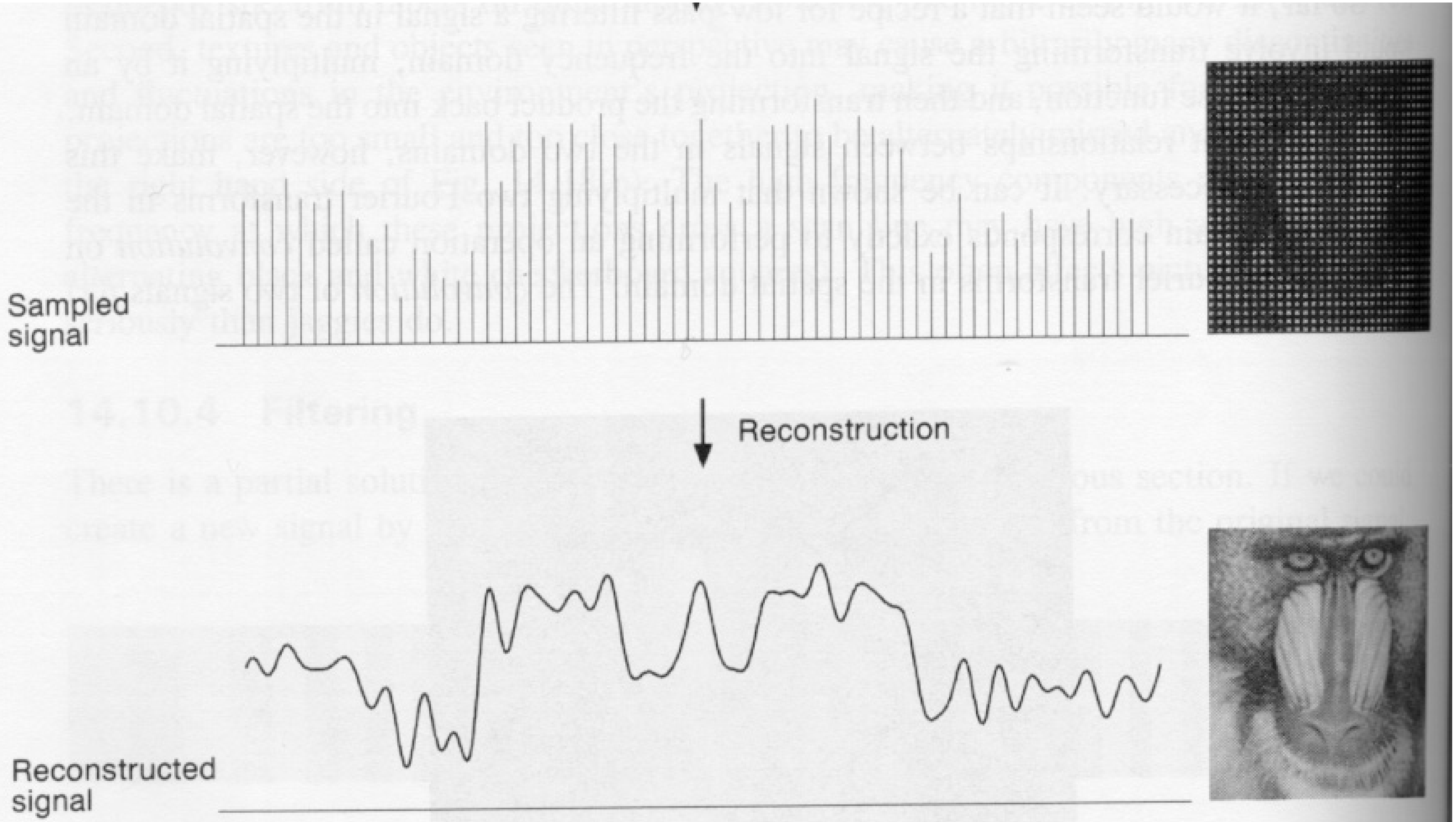
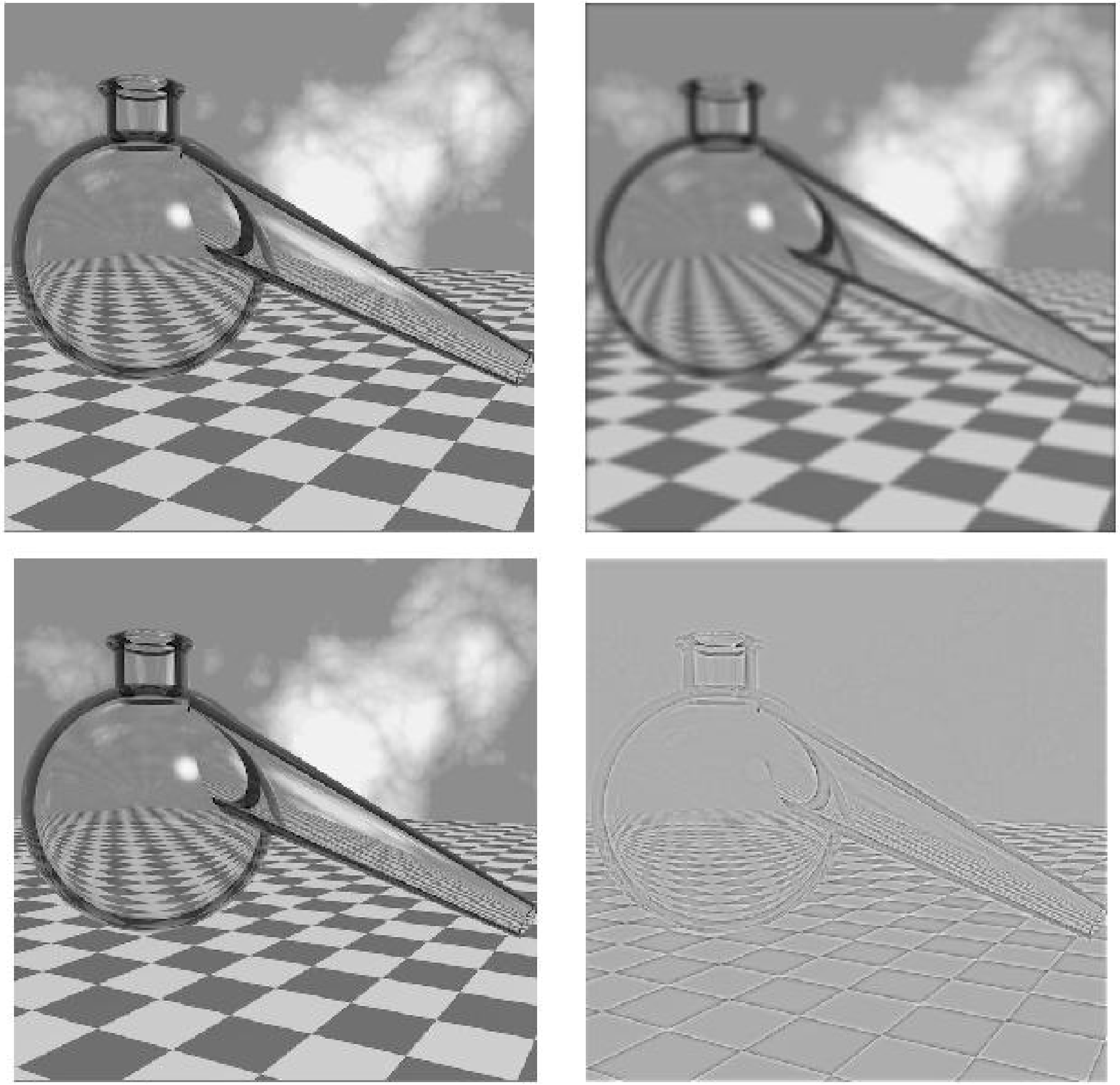


Fig. 14.20 The sampling pipeline with filtering. (Courtesy of George Wolberg, Columbia University.)

Filtering

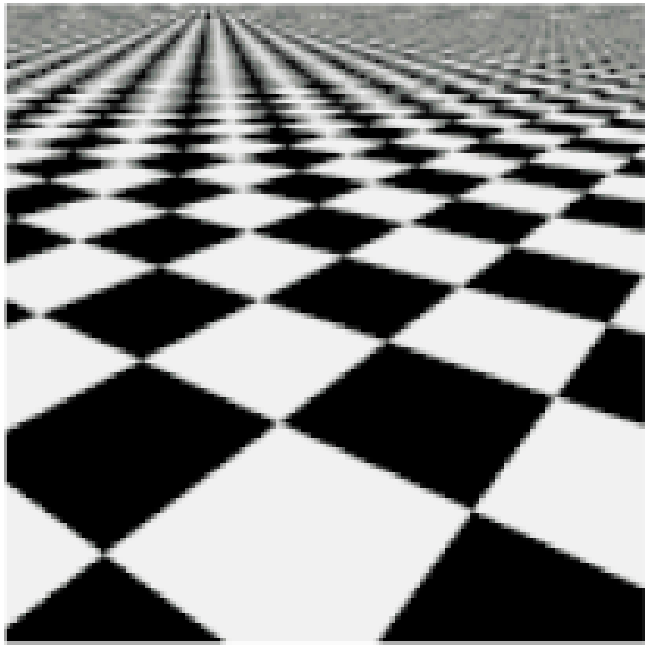
- low pass
  - blur
- high pass
  - edge finding



Previous Antialiasing Example

- texture mipmapping: low pass filter

(a)



(b)

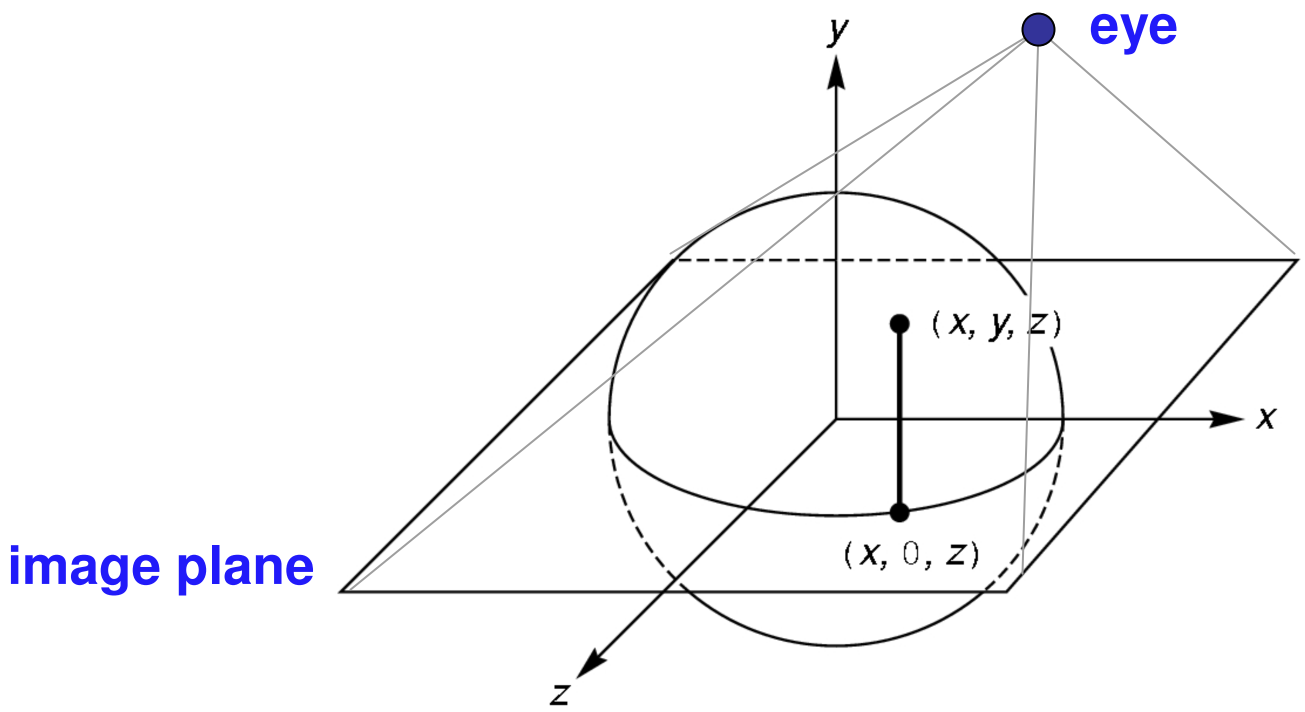
Virtual Trackball

Virtual Trackball

- interface for spinning objects around
  - drag mouse to control rotation of view volume
- rolling glass trackball
  - center at screen origin, surrounds world
  - hemisphere "sticks up" in z, out of screen
  - rotate ball = spin world

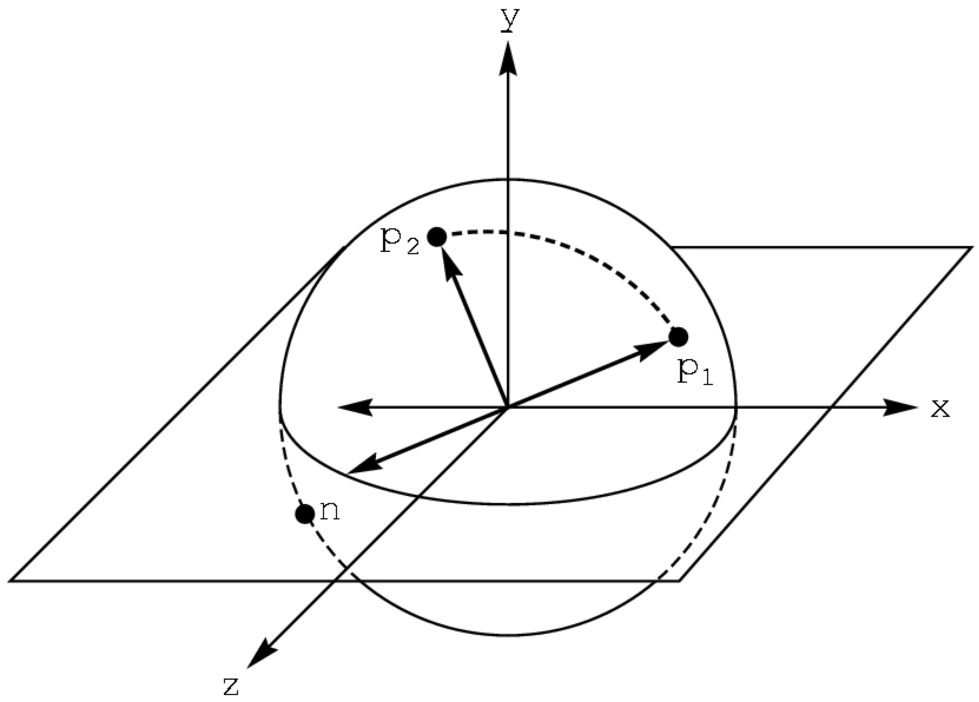
Virtual Trackball

- know screen click: (x, 0, z)
- want to infer point on trackball: (x,y,z)
  - ball is unit sphere, so ||x, y, z|| = 1.0
  - solve for y



Trackball Rotation

- correspondence:
  - moving point on plane from (x, 0, z) to (a, 0, c)
  - moving point on ball from $\mathbf{p_1}$ =(x, y, z) to $\mathbf{p_2}$ =(a, b, c)
- correspondence:
  - translating mouse from $\mathbf{p_1}$ (mouse down) to $\mathbf{p_2}$ (mouse up)
  - rotating about the axis $\mathbf{n} = \mathbf{p_1} \times \mathbf{p_2}$



Trackball Computation

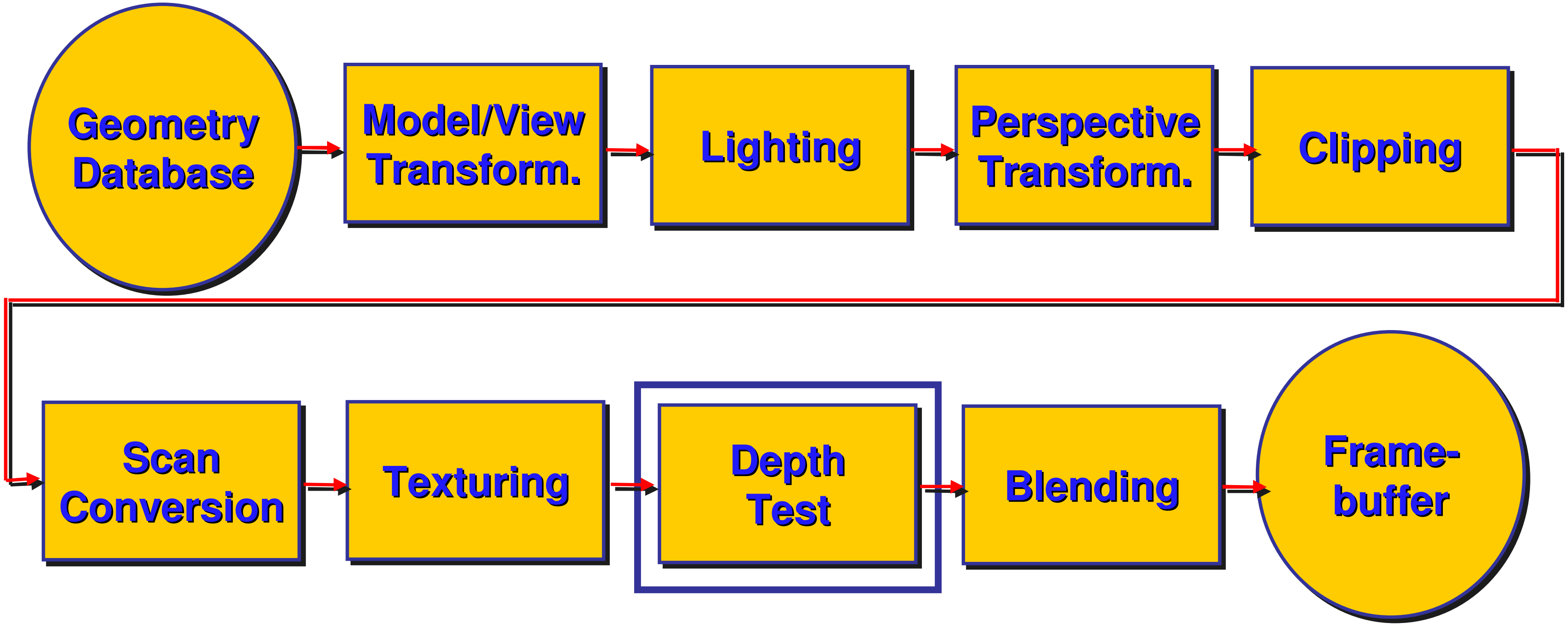
- user defines two points
  - place where first clicked $\mathbf{p_1} = (x, y, z)$
  - place where released $\mathbf{p_2} = (a, b, c)$
- create plane from vectors between points, origin
  - axis of rotation is plane normal: cross product
    - $(\mathbf{p_1} - \mathbf{o}) \times (\mathbf{p_2} - \mathbf{o})$: $\mathbf{p_1} \times \mathbf{p_2}$ if origin = (0,0,0)
  - amount of rotation depends on angle between lines
    - $\mathbf{p_1} \cdot \mathbf{p_2} = |\mathbf{p_1}|\ |\mathbf{p_2}| \cos \theta$
    - $|\mathbf{p_1} \times \mathbf{p_2}| = |\mathbf{p_1}|\ |\mathbf{p_2}| \sin \theta$
- compute rotation matrix, use to rotate world

Visibility

Reading

- FCG Chapter 7

Rendering Pipeline



Covered So Far

- modeling transformations
- viewing transformations
- projection transformations
- clipping
- scan conversion
- lighting
- shading

- we now know everything about how to draw a polygon on the screen, except *visible surface determination*

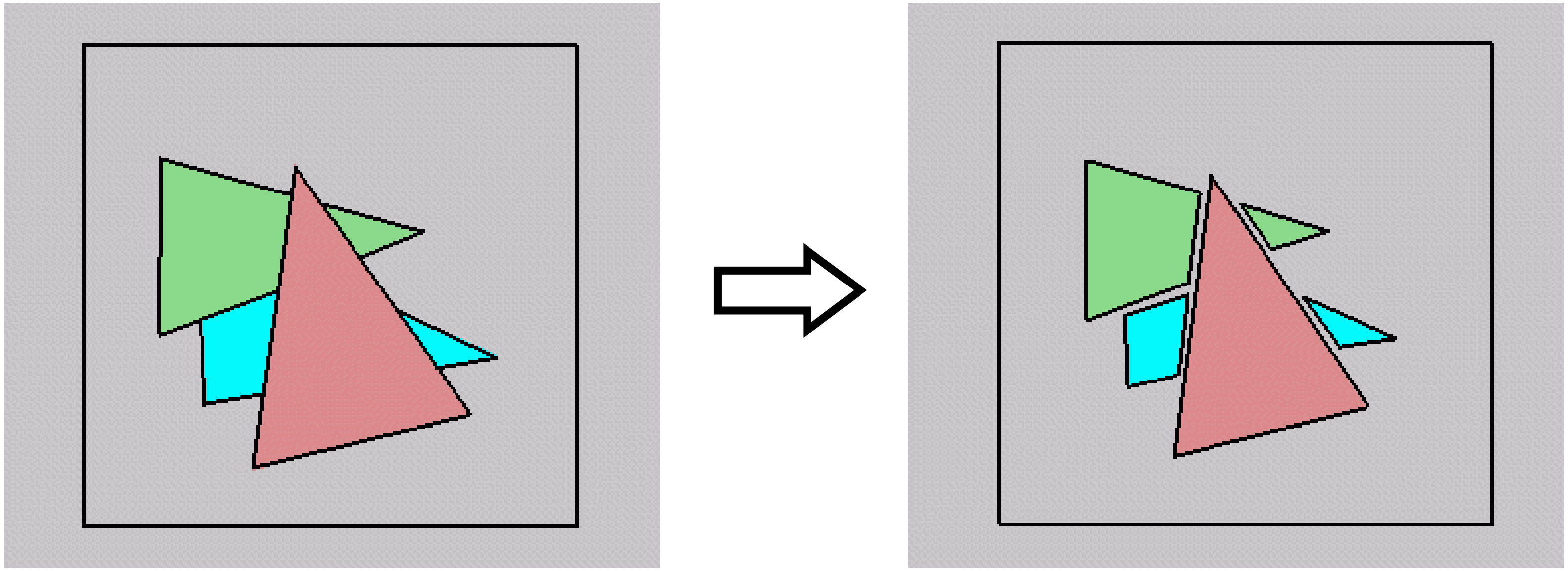
Invisible Primitives

- *why might a polygon be invisible?*
  - polygon outside the *field of view / frustum*
    - solved by clipping
  - polygon is *backfacing*
    - solved by backface culling
  - polygon is *occluded* by object(s) nearer the viewpoint
    - solved by hidden surface removal
- for efficiency reasons, we want to avoid spending work on polygons outside field of view or backfacing
- for efficiency and correctness reasons, we need to know when polygons are occluded

Hidden Surface Removal

Occlusion

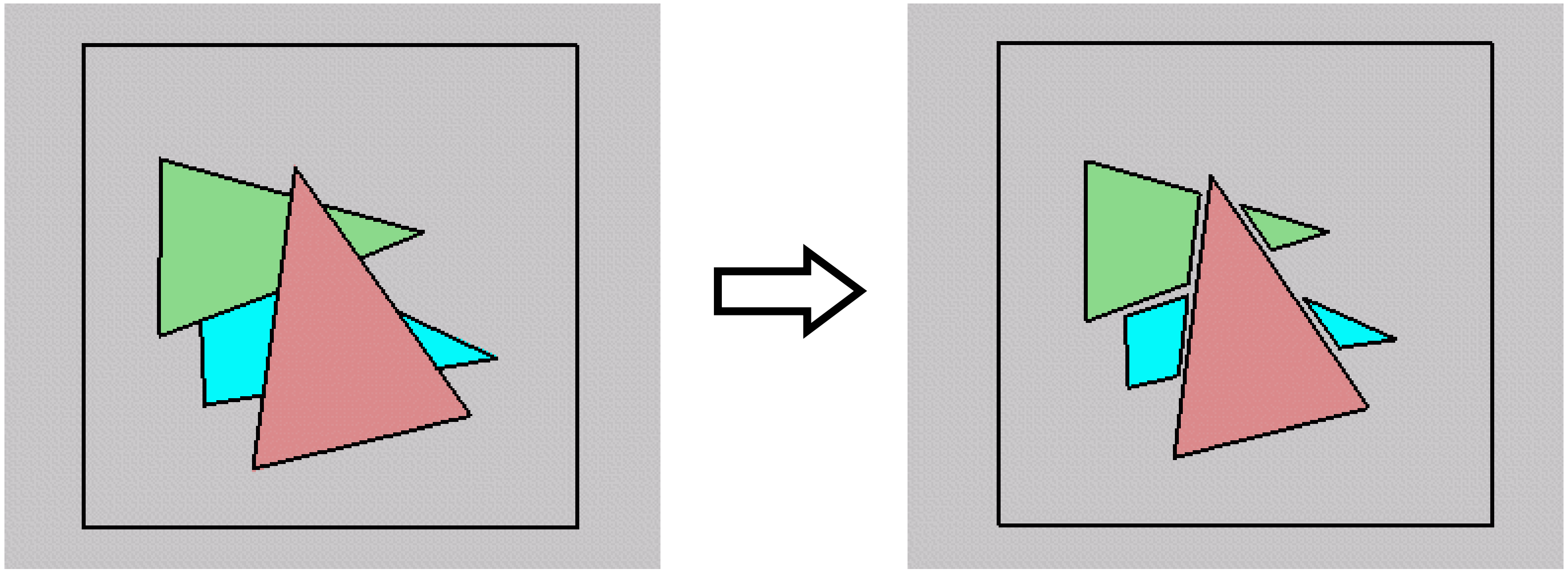
- for most interesting scenes, some polygons overlap



- to render the correct image, we need to determine which polygons occlude which

Painter's Algorithm

- simple: render the polygons from back to front, "painting over" previous polygons



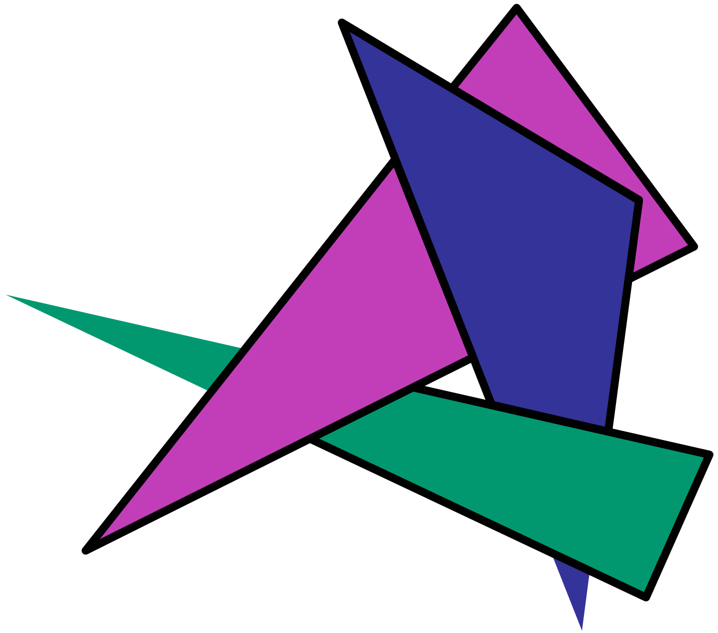
  - draw blue, then green, then orange
- will this work in the general case?

Painter's Algorithm: Problems

- *intersecting polygons* present a problem
- even non-intersecting polygons can form a cycle with no valid visibility order:

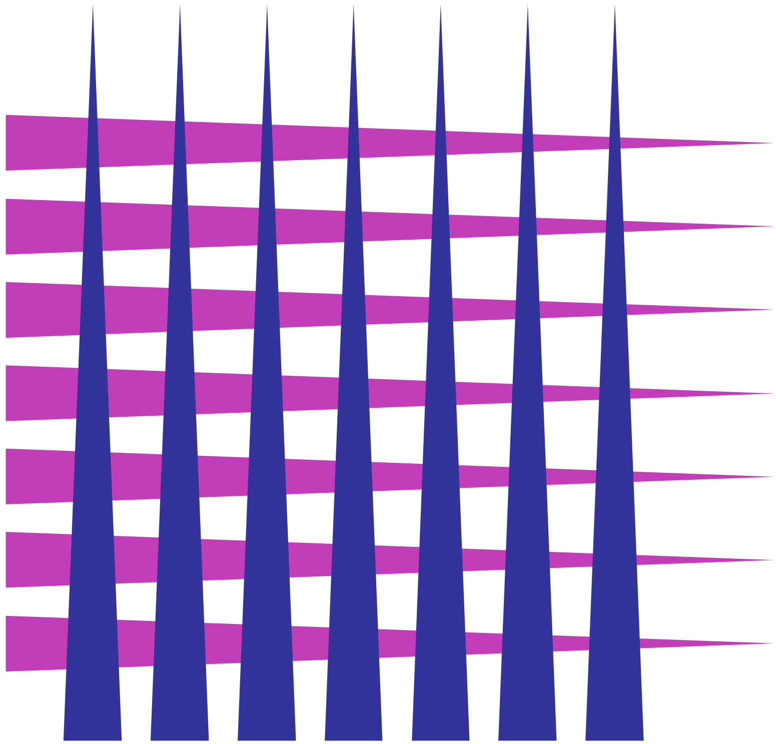
Analytic Visibility Algorithms

- early visibility algorithms computed the set of visible polygon *fragments* directly, then rendered the fragments to a display:



Analytic Visibility Algorithms

- *what is the minimum worst-case cost of computing the fragments for a scene composed of* n *polygons?*
- answer: $O(n^2)$



Analytic Visibility Algorithms

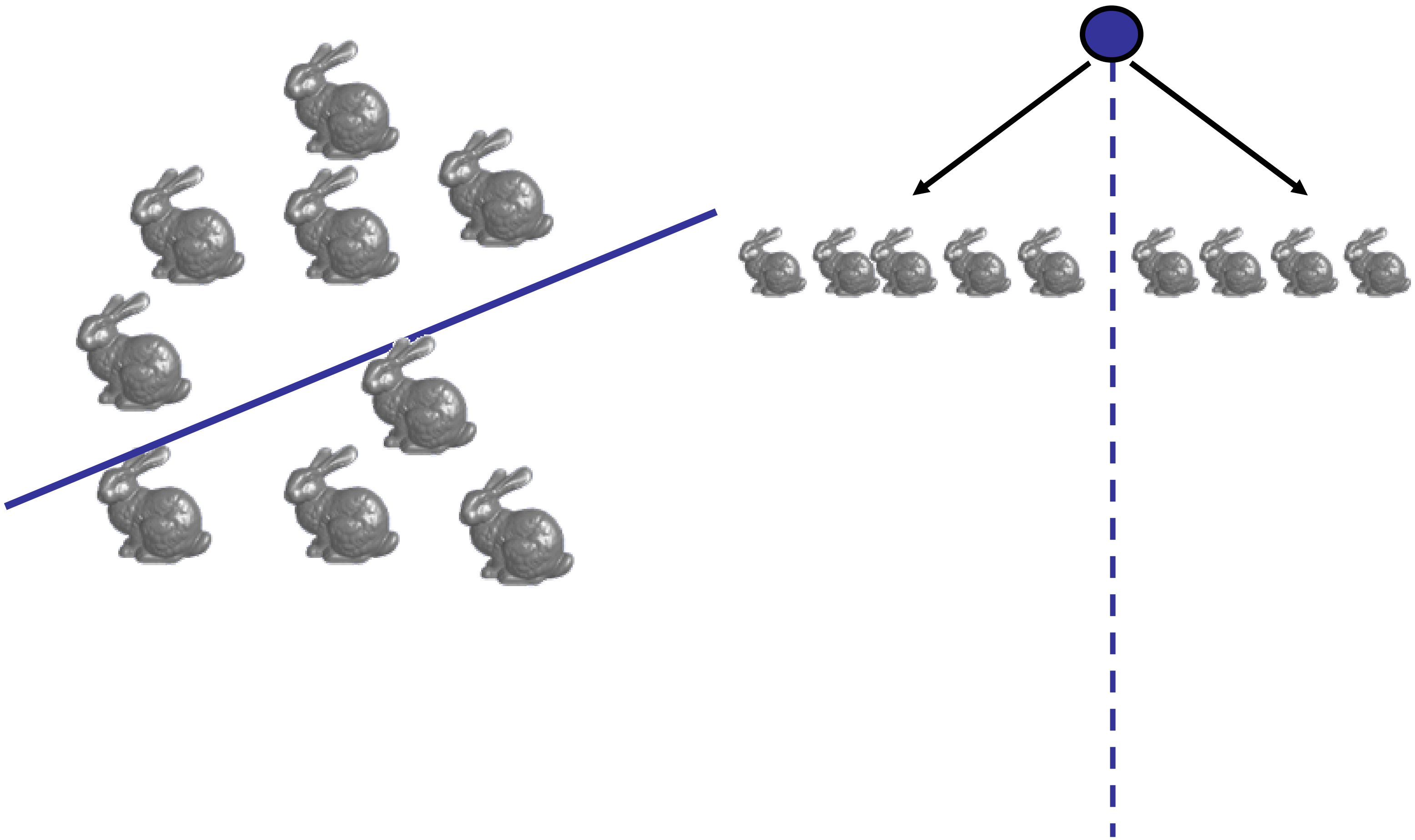
- so, for about a decade (late 60s to late 70s) there was intense interest in finding efficient algorithms for hidden surface removal
- we'll talk about two:
  - *Binary Space Partition (BSP) Trees*
  - *Warnock's Algorithm*

Binary Space Partition Trees (1979)

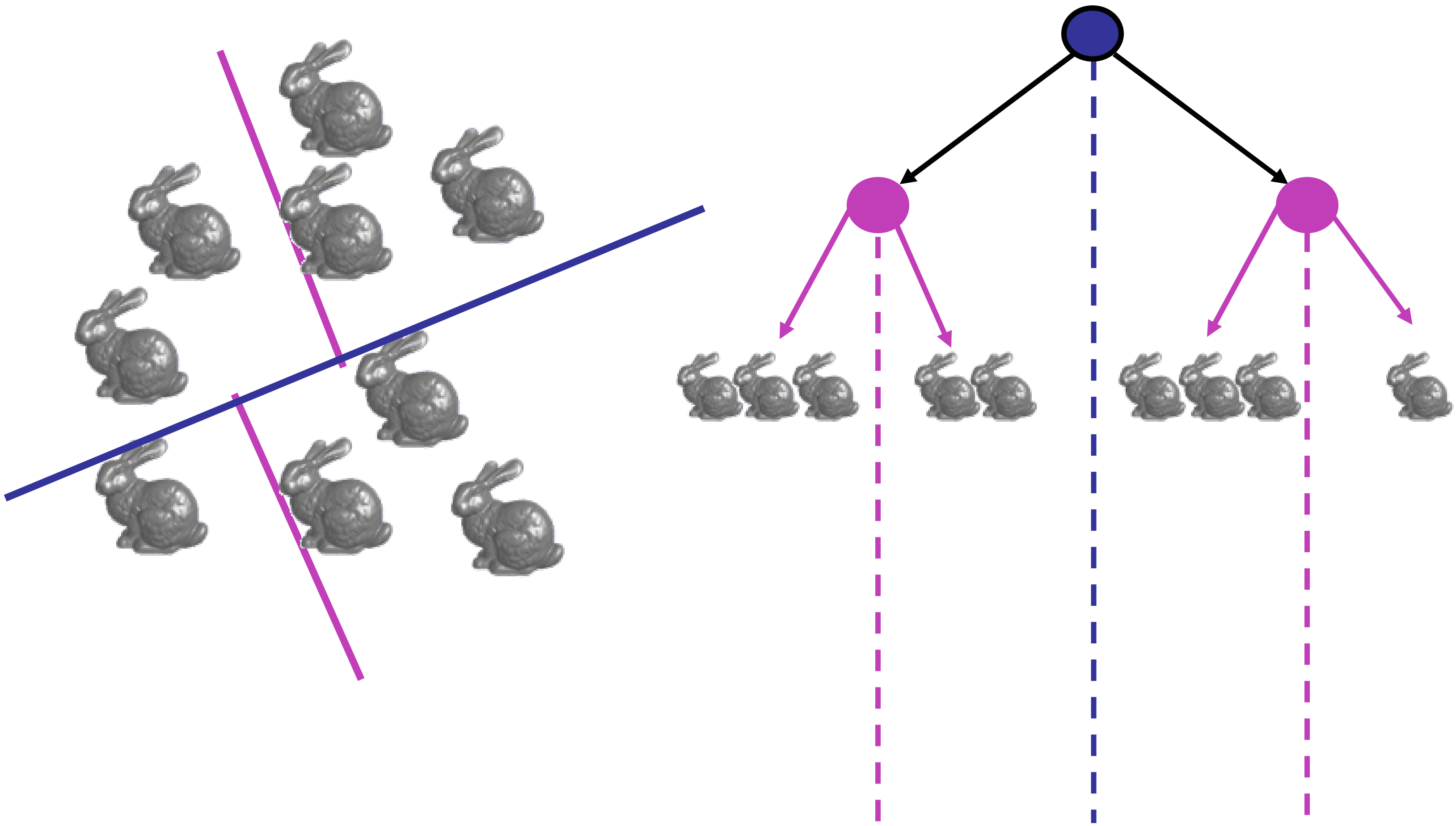
- BSP Tree: partition space with binary tree of planes
  - idea: divide space recursively into half-spaces by choosing splitting planes that separate objects in scene
  - preprocessing: create binary tree of planes
  - runtime: correctly traversing this tree enumerates objects from back to front

Creating BSP Trees: Objects

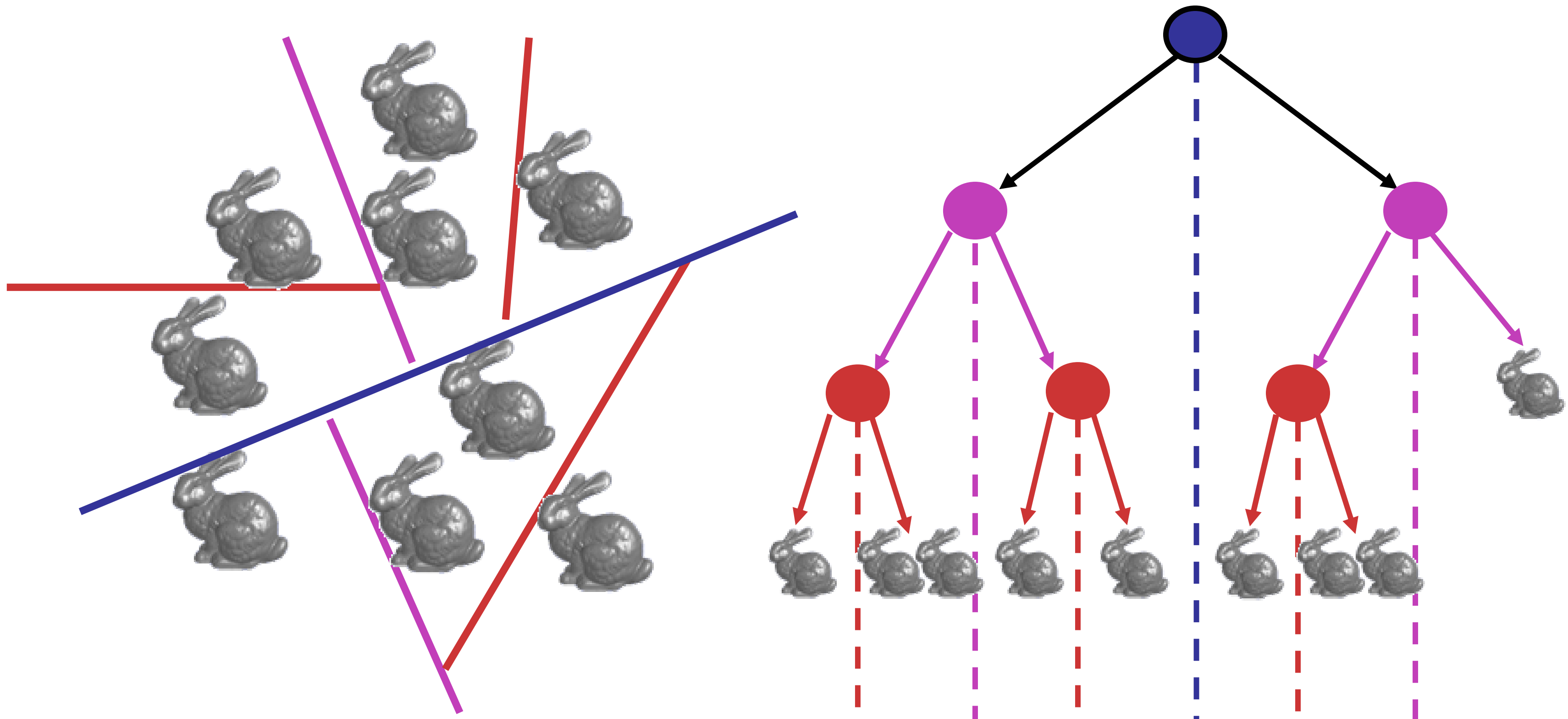
Creating BSP Trees: Objects



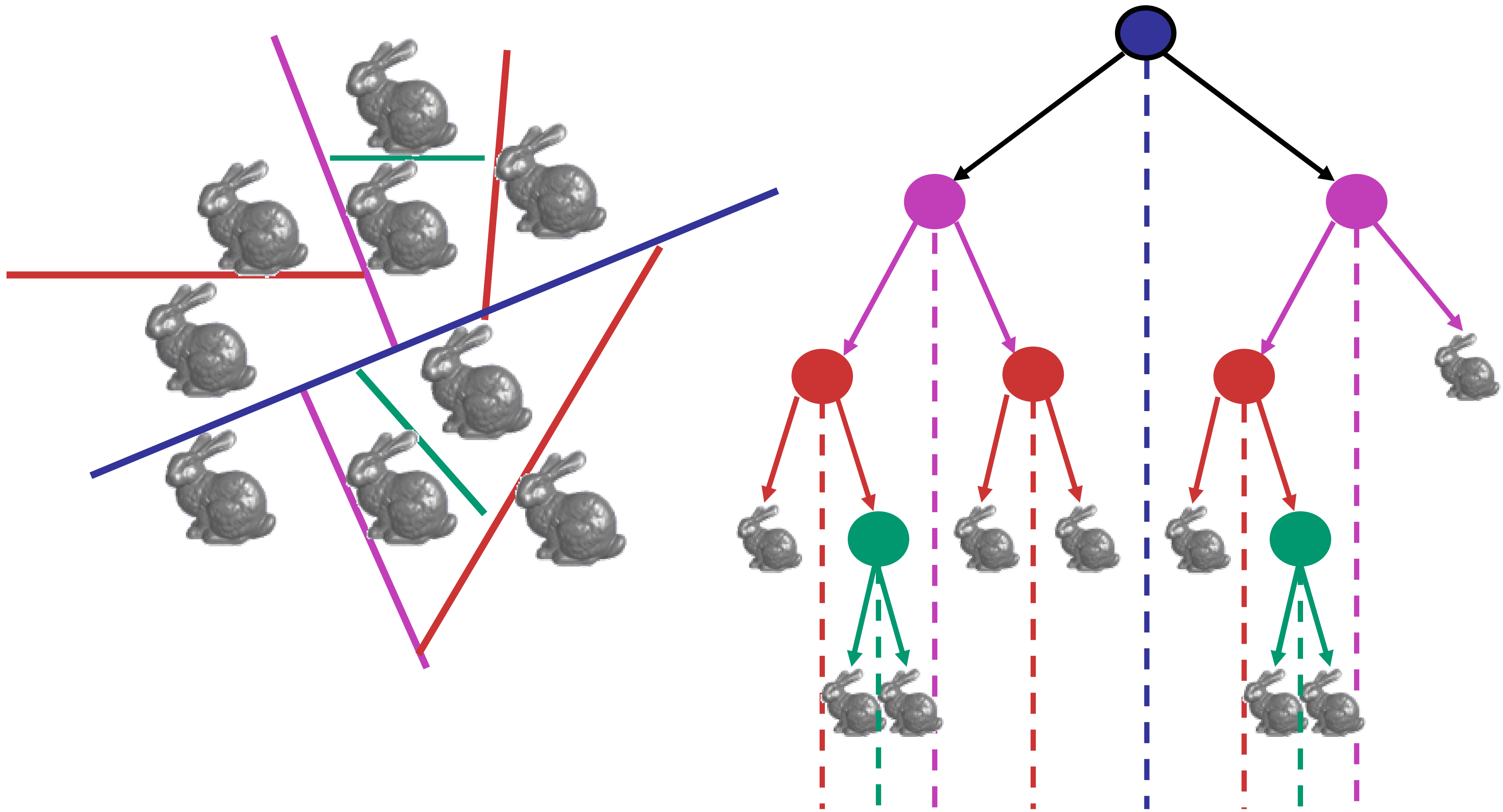
Creating BSP Trees: Objects



Creating BSP Trees: Objects

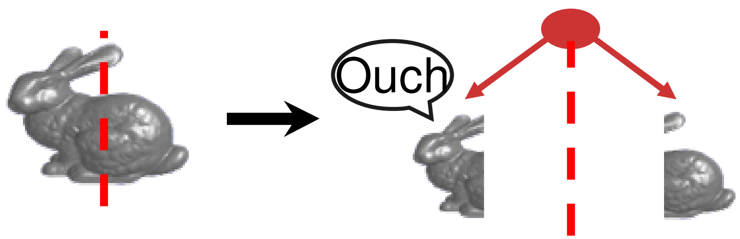


Creating BSP Trees: Objects



Splitting Objects

- no bunnies were harmed in previous example
- but what if a splitting plane passes through an object?
  - split the object; give half to each node



Traversing BSP Trees

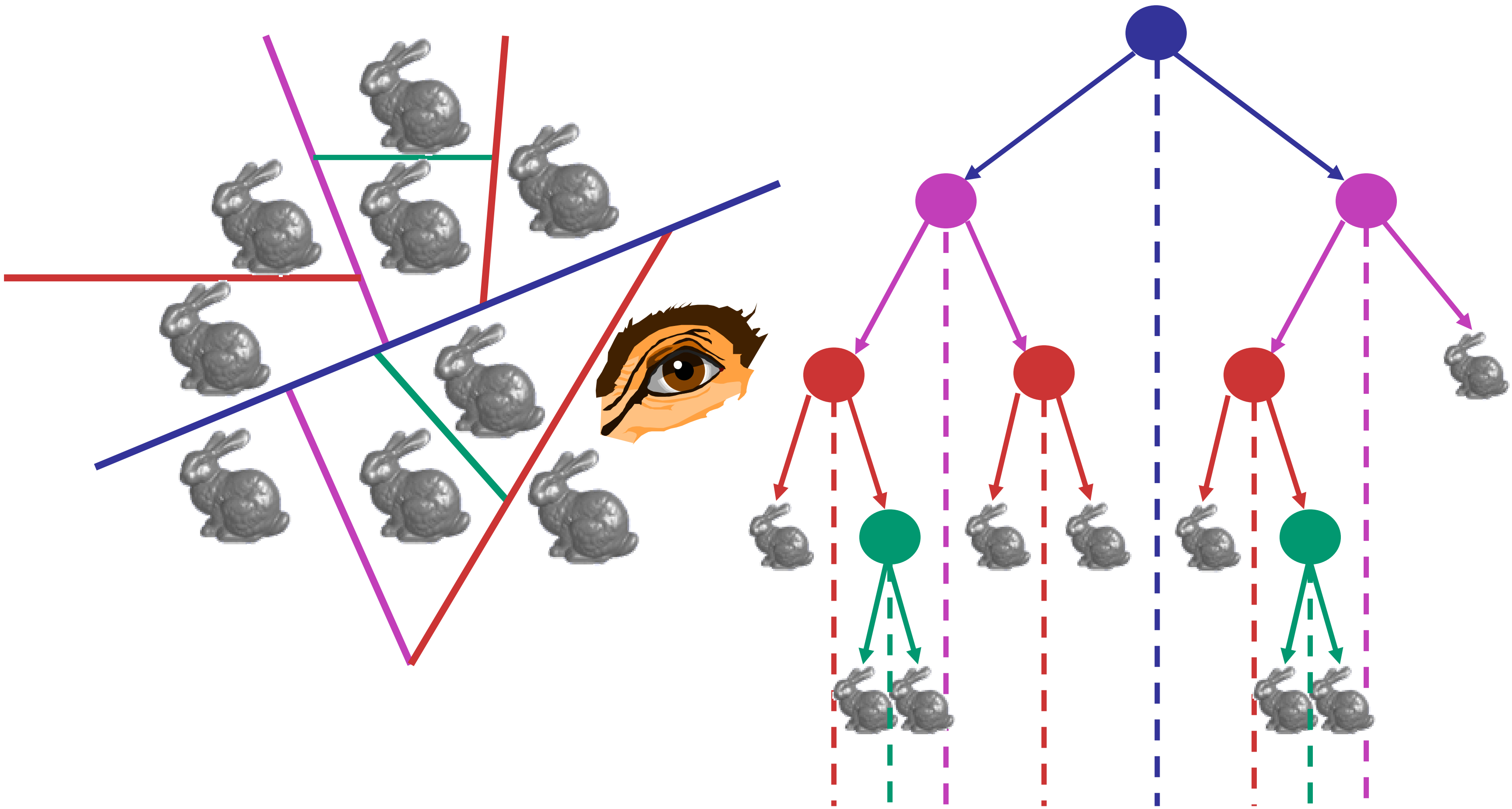
- tree creation independent of viewpoint
  - preprocessing step
- tree traversal uses viewpoint
  - runtime, happens for many different viewpoints
- each plane divides world into near and far
  - for given viewpoint, decide which side is near and which is far
    - check which side of plane viewpoint is on independently for each tree vertex
    - tree traversal differs depending on viewpoint!
  - recursive algorithm
    - recurse on far side
    - draw object
    - recurse on near side

Traversing BSP Trees

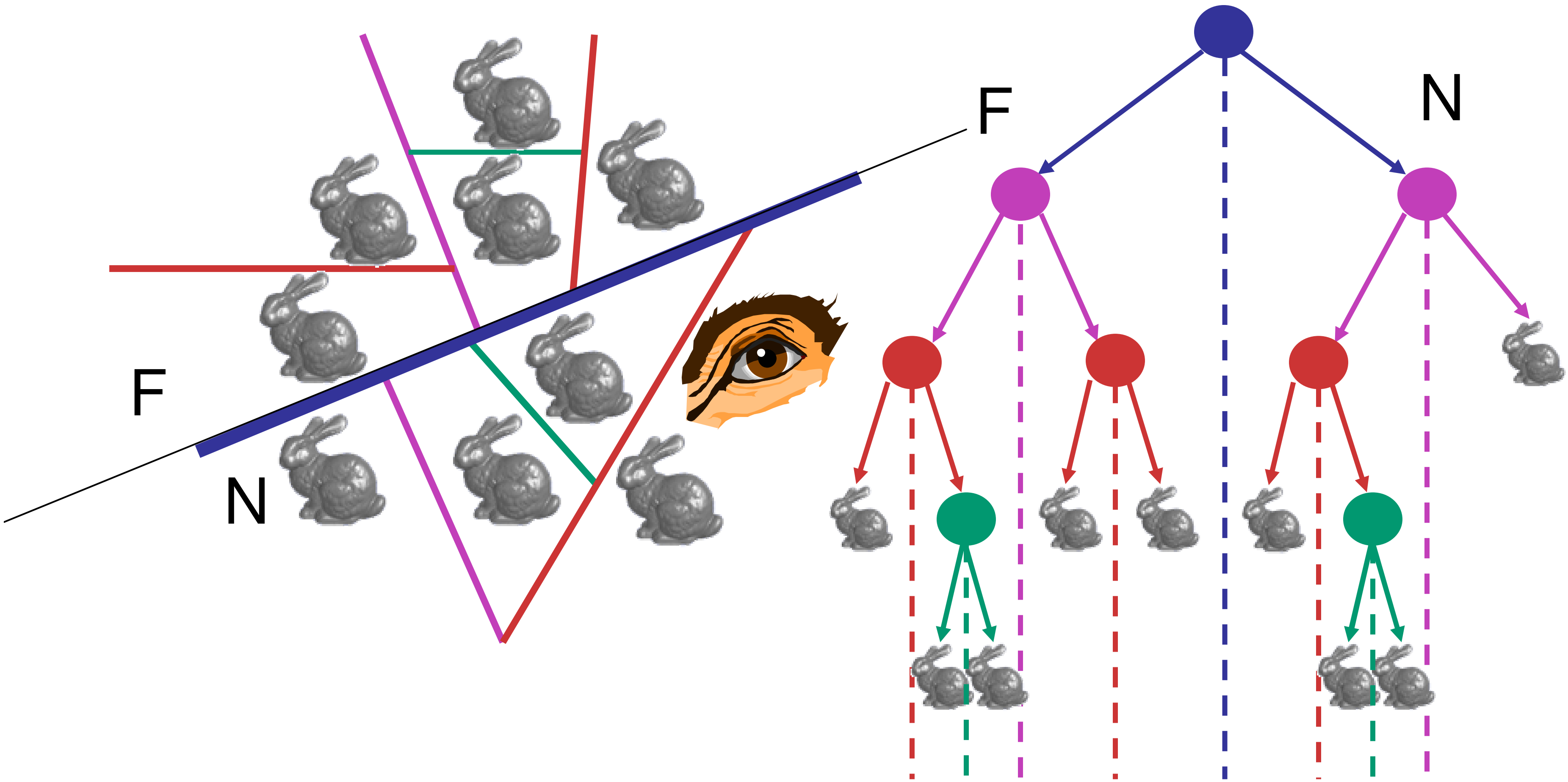
query: given a viewpoint, produce an ordered list of (possibly split) objects from back to front:

```
renderBSP(BSPtree *T)
  BSPtree *near, *far;
  if (eye on left side of T->plane)
     near = T->left; far = T->right;
  else
     near = T->right; far = T->left;
  renderBSP(far);
  if (T is a leaf node)
     renderObject(T)
  renderBSP(near);
```

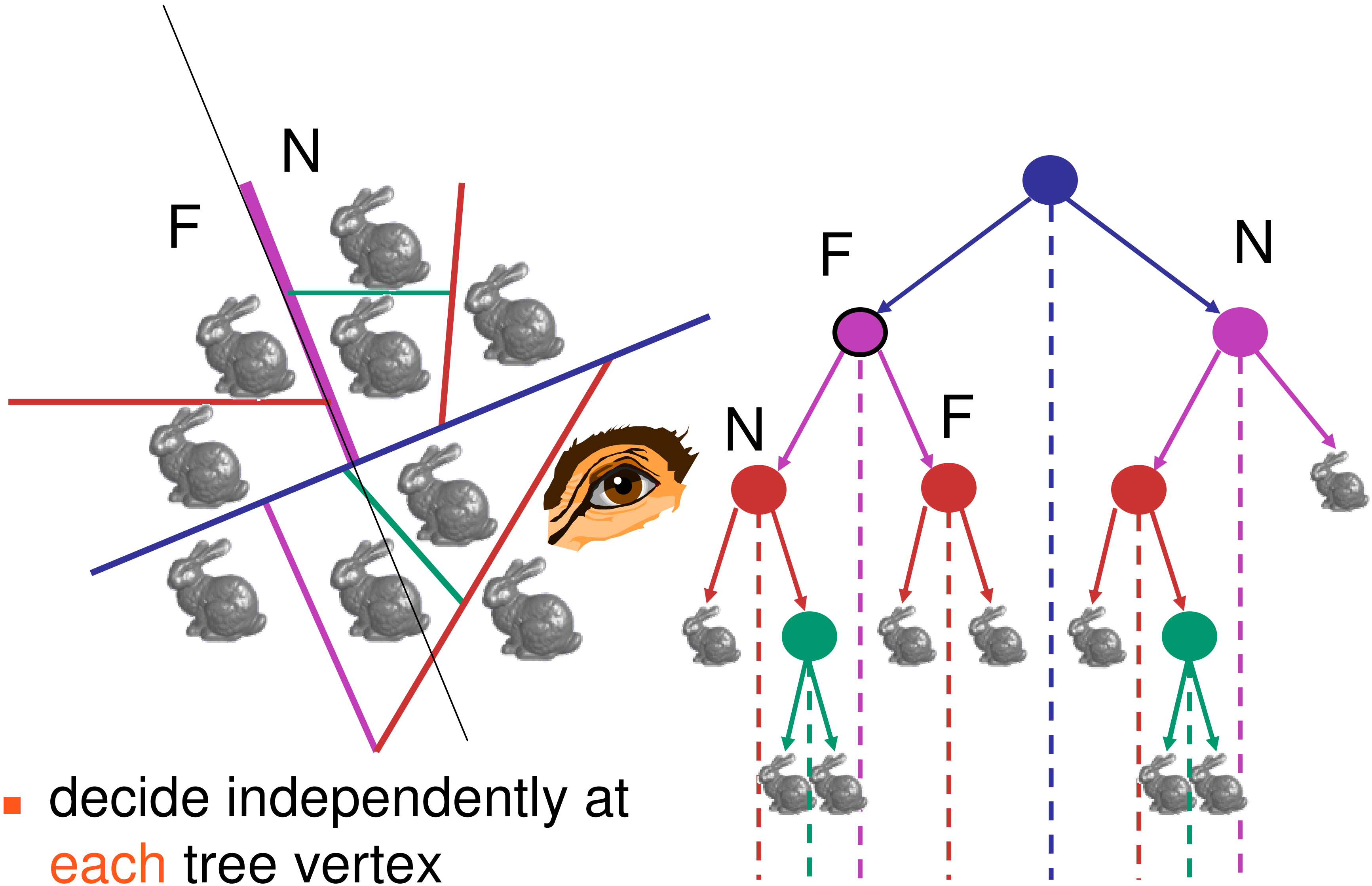
BSP Trees : Viewpoint A



BSP Trees : Viewpoint A

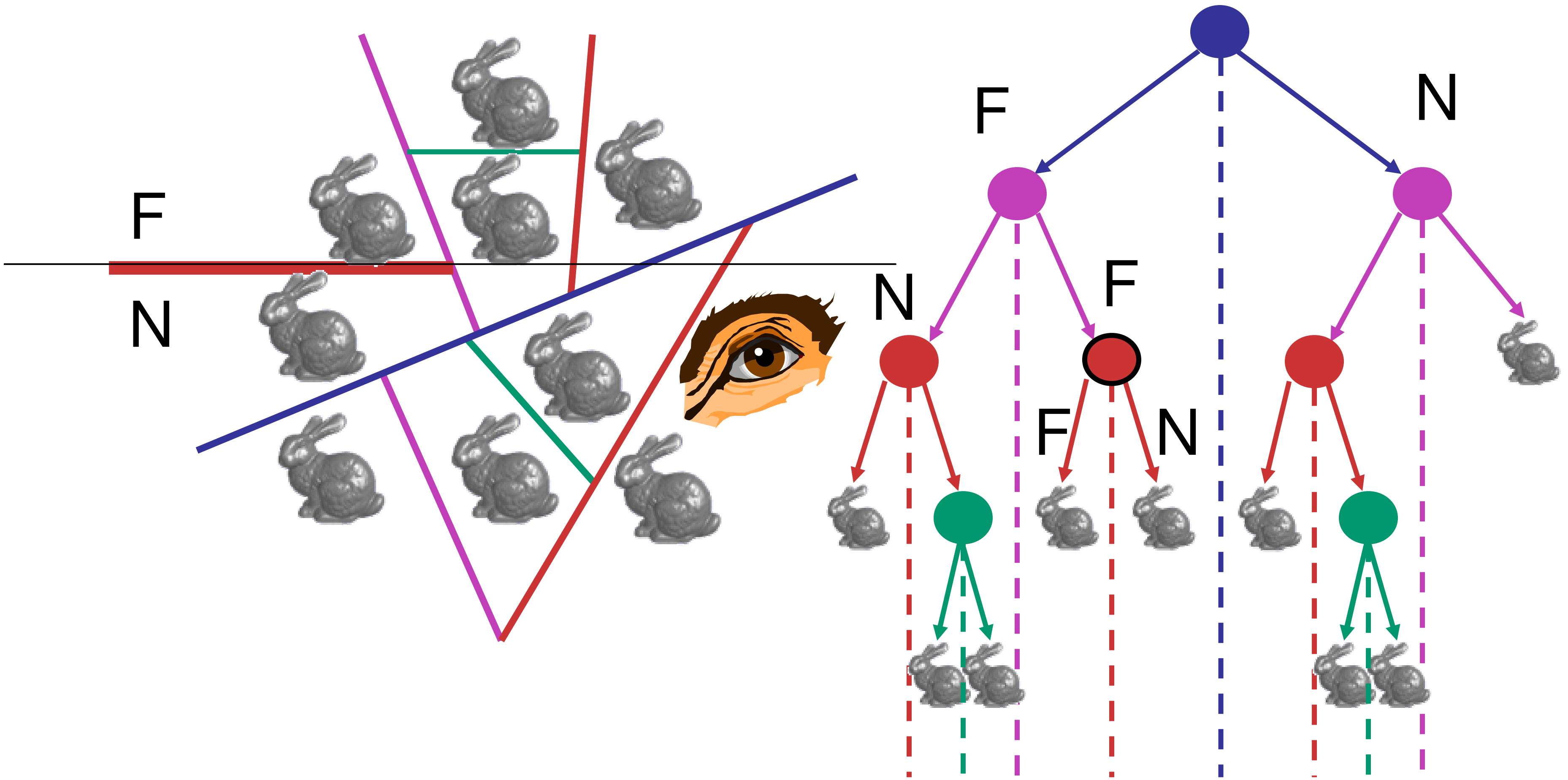


BSP Trees : Viewpoint A

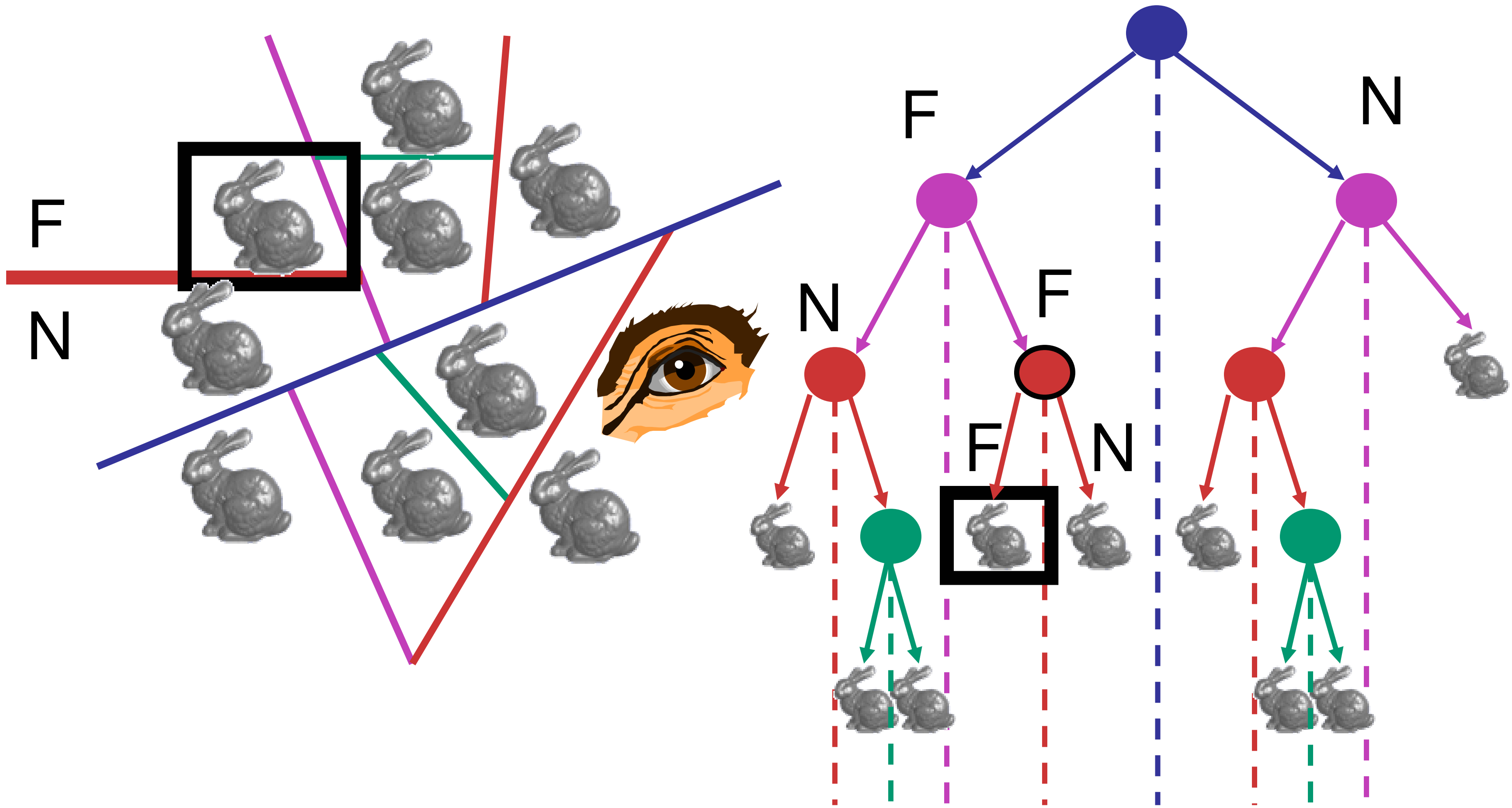


- decide independently at each tree vertex
  - not just left or right child!

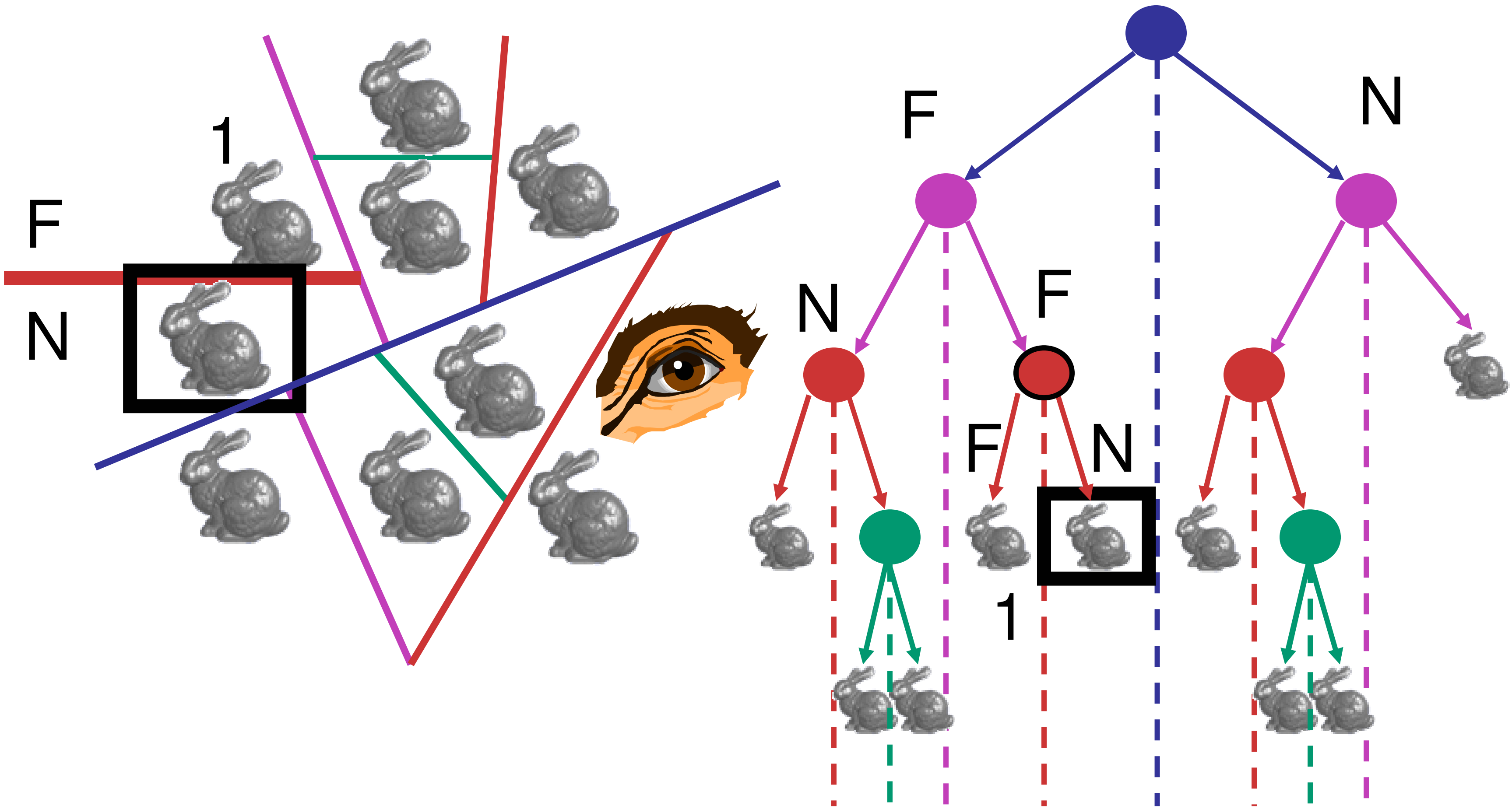
BSP Trees : Viewpoint A



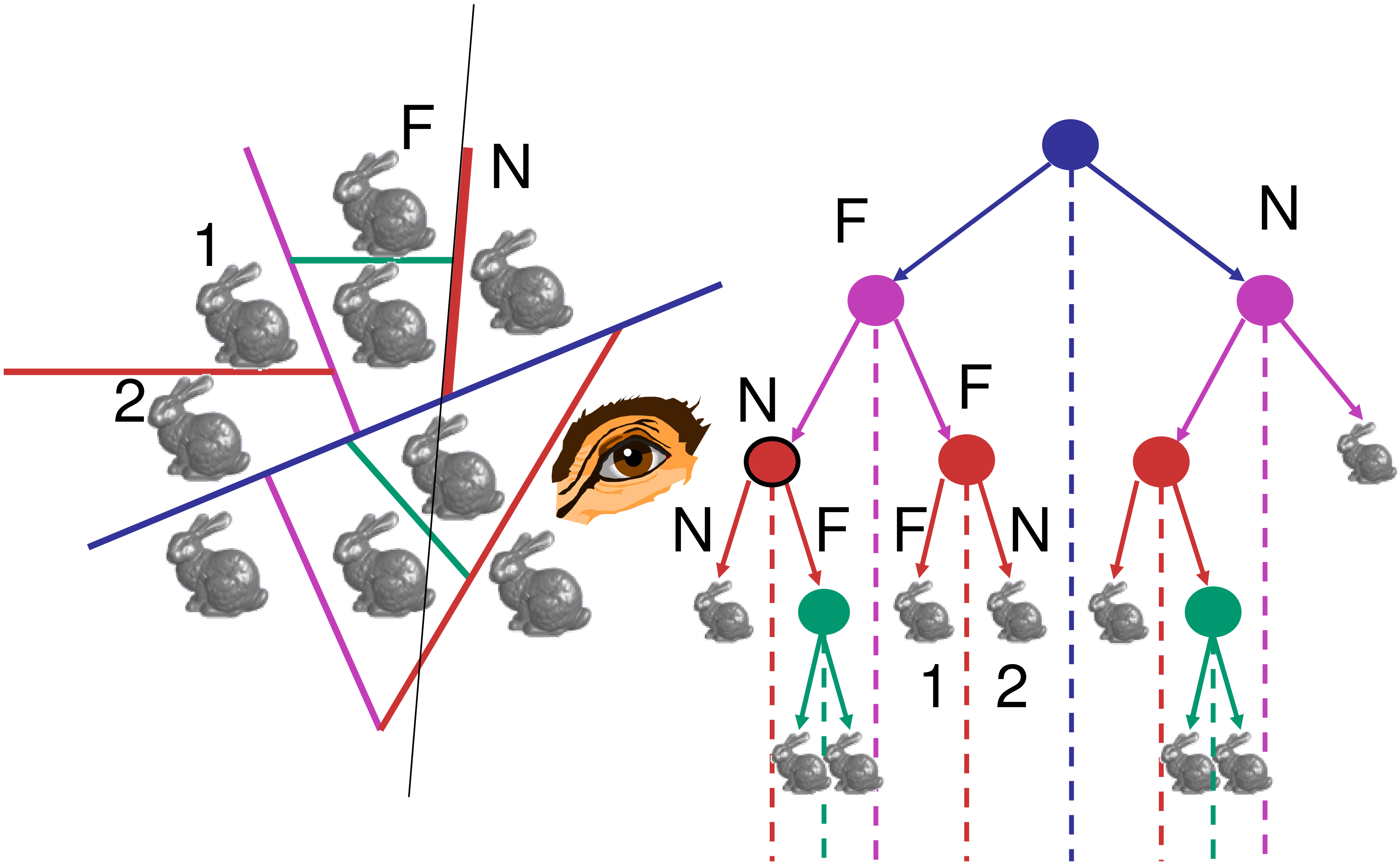
BSP Trees : Viewpoint A



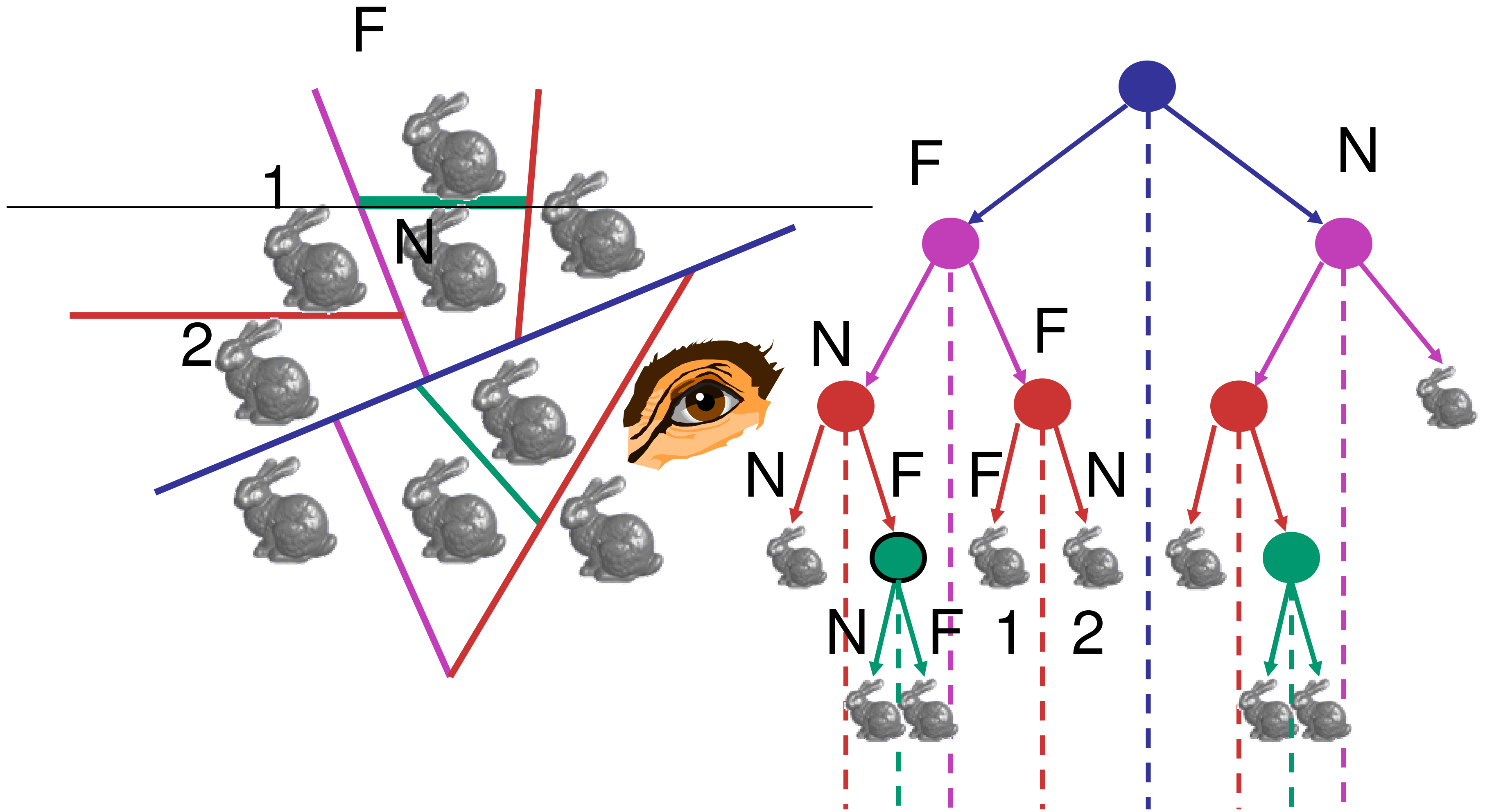
BSP Trees : Viewpoint A



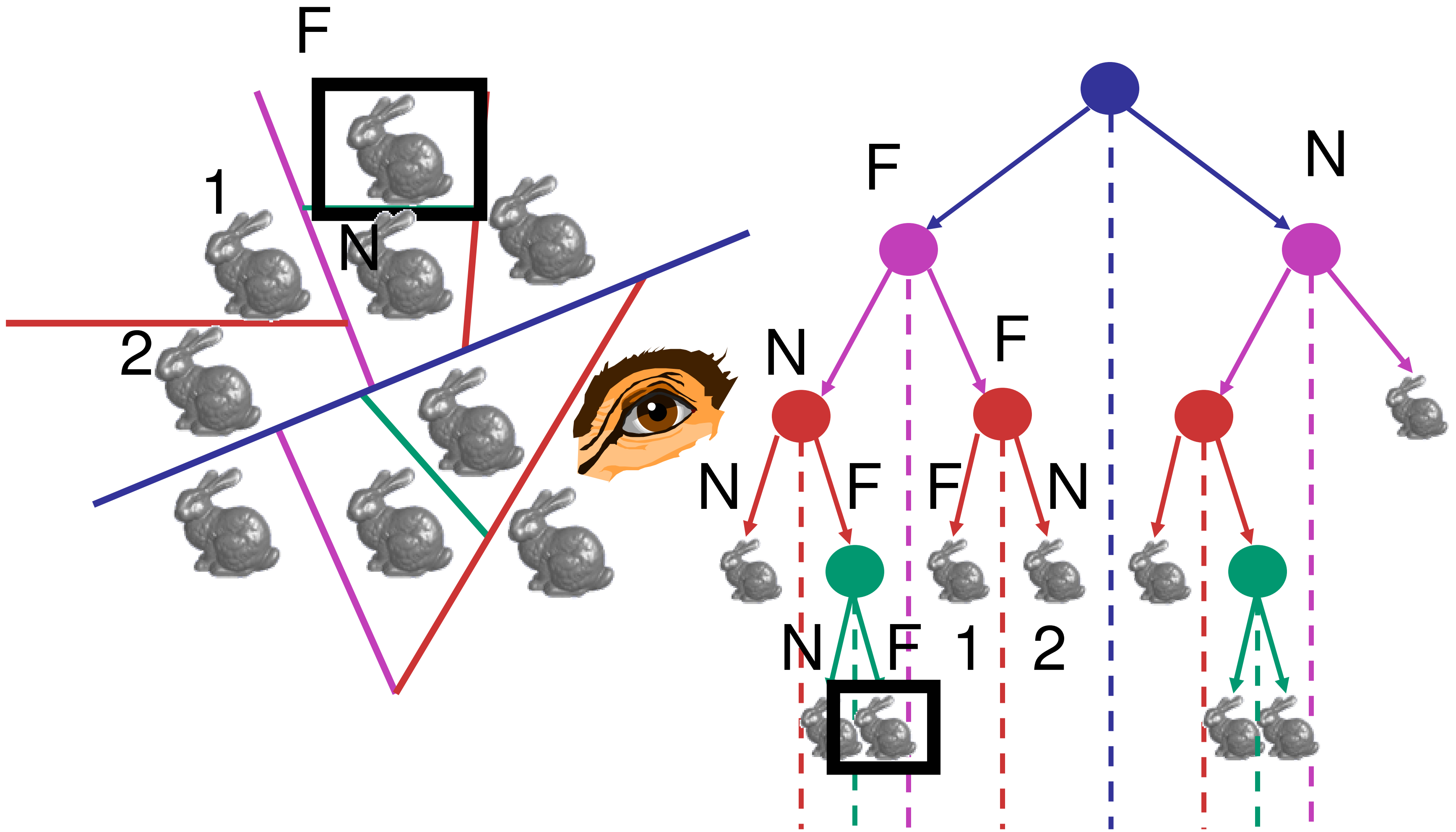
BSP Trees : Viewpoint A



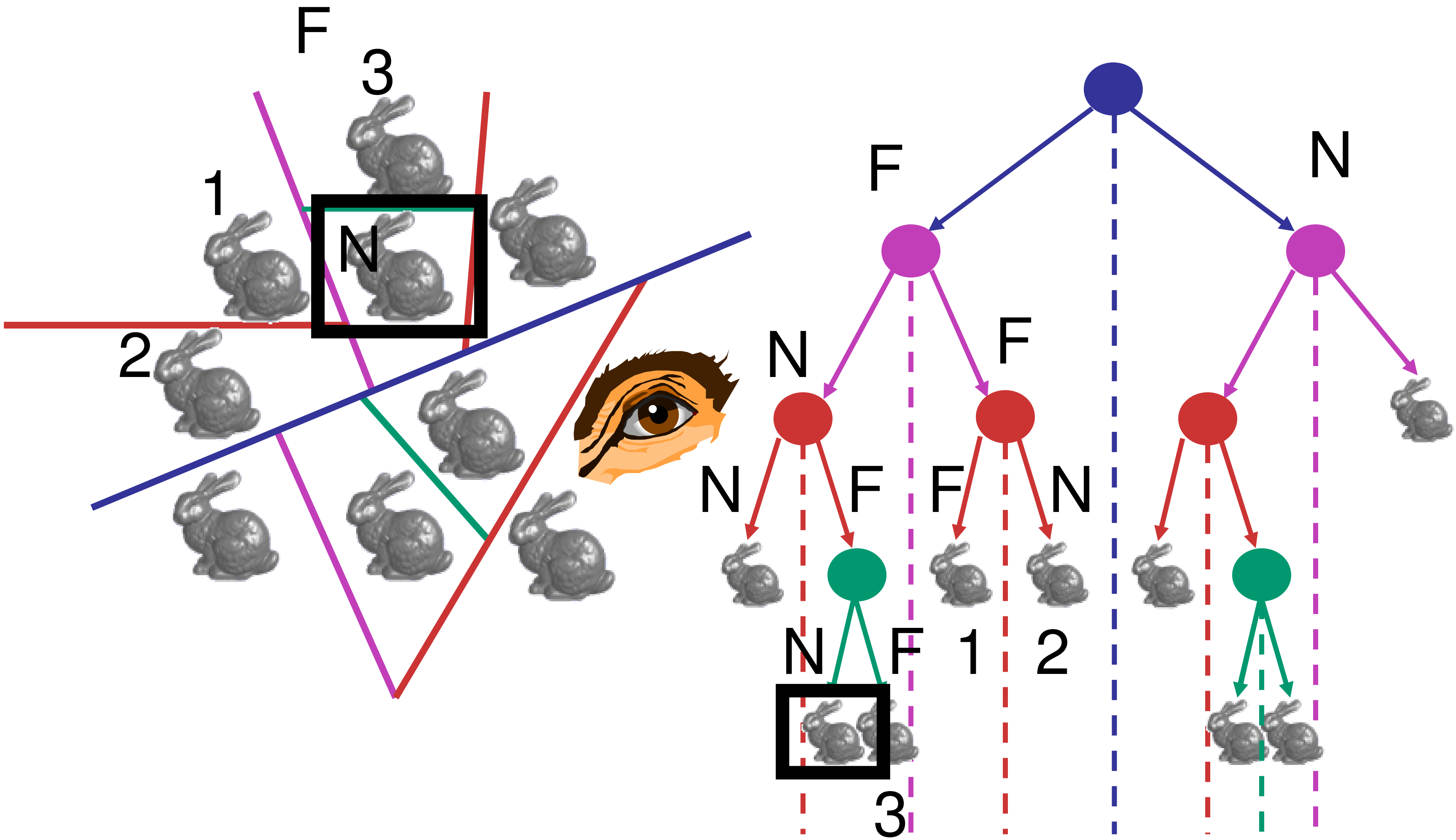
BSP Trees : Viewpoint A



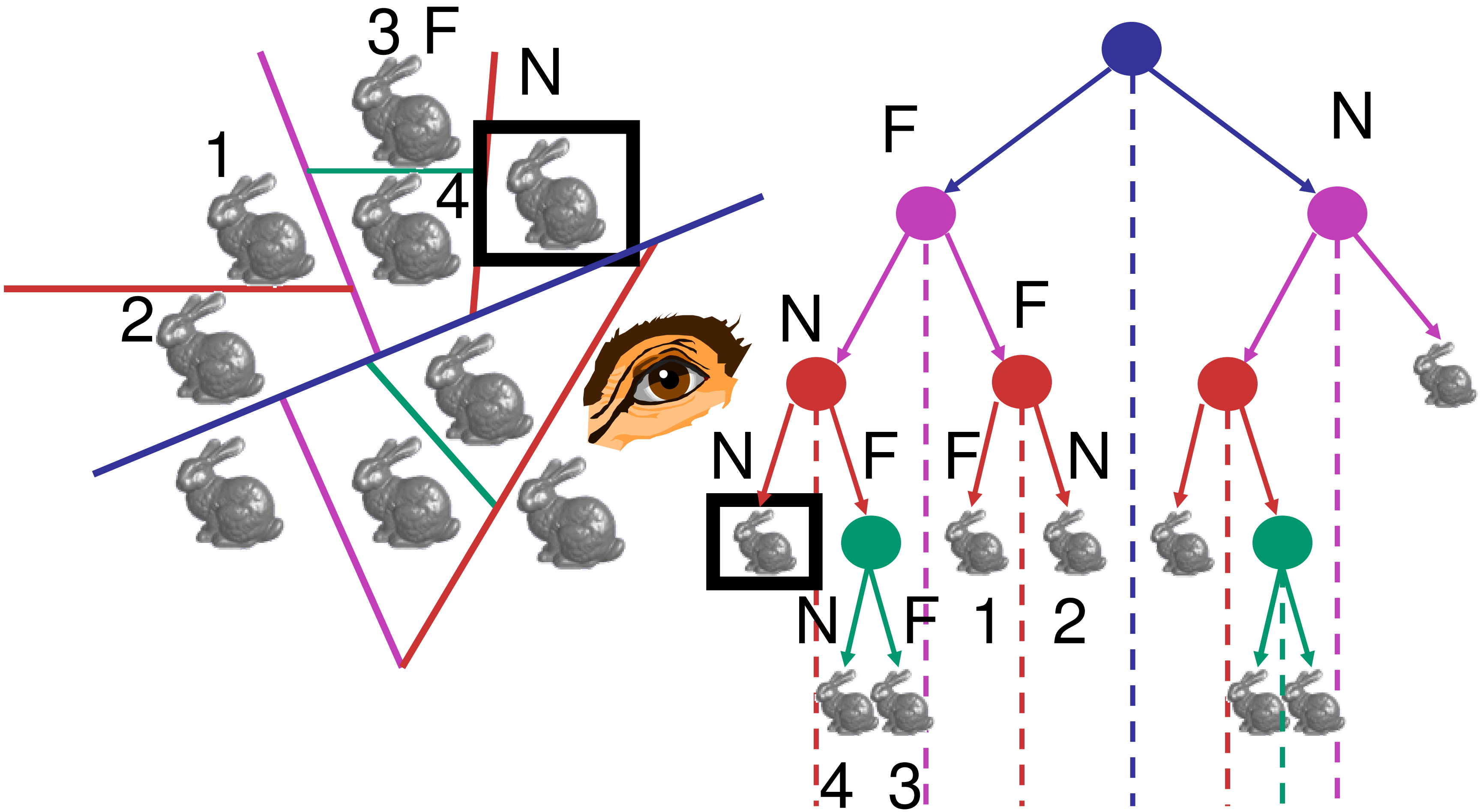
BSP Trees : Viewpoint A



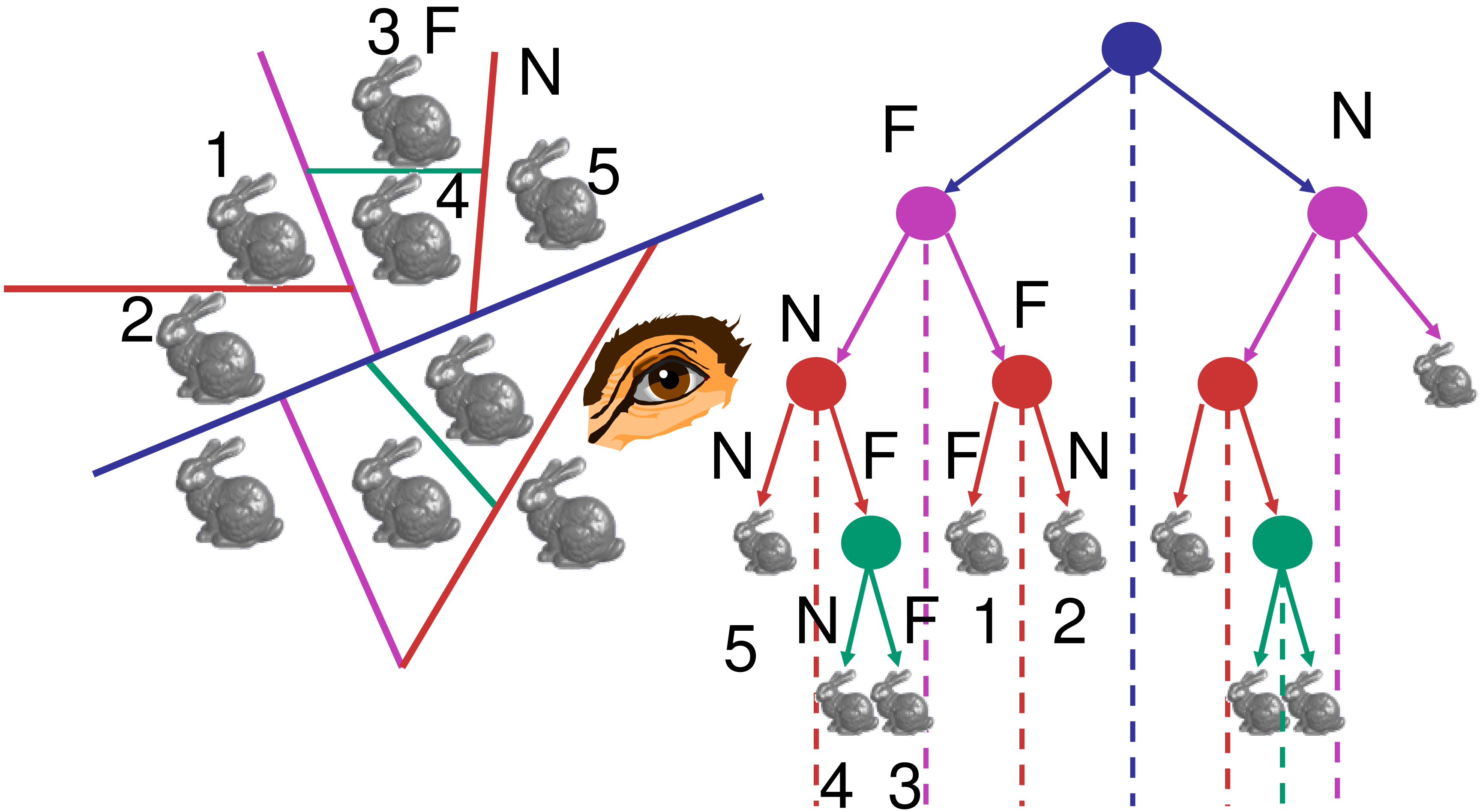
BSP Trees : Viewpoint A



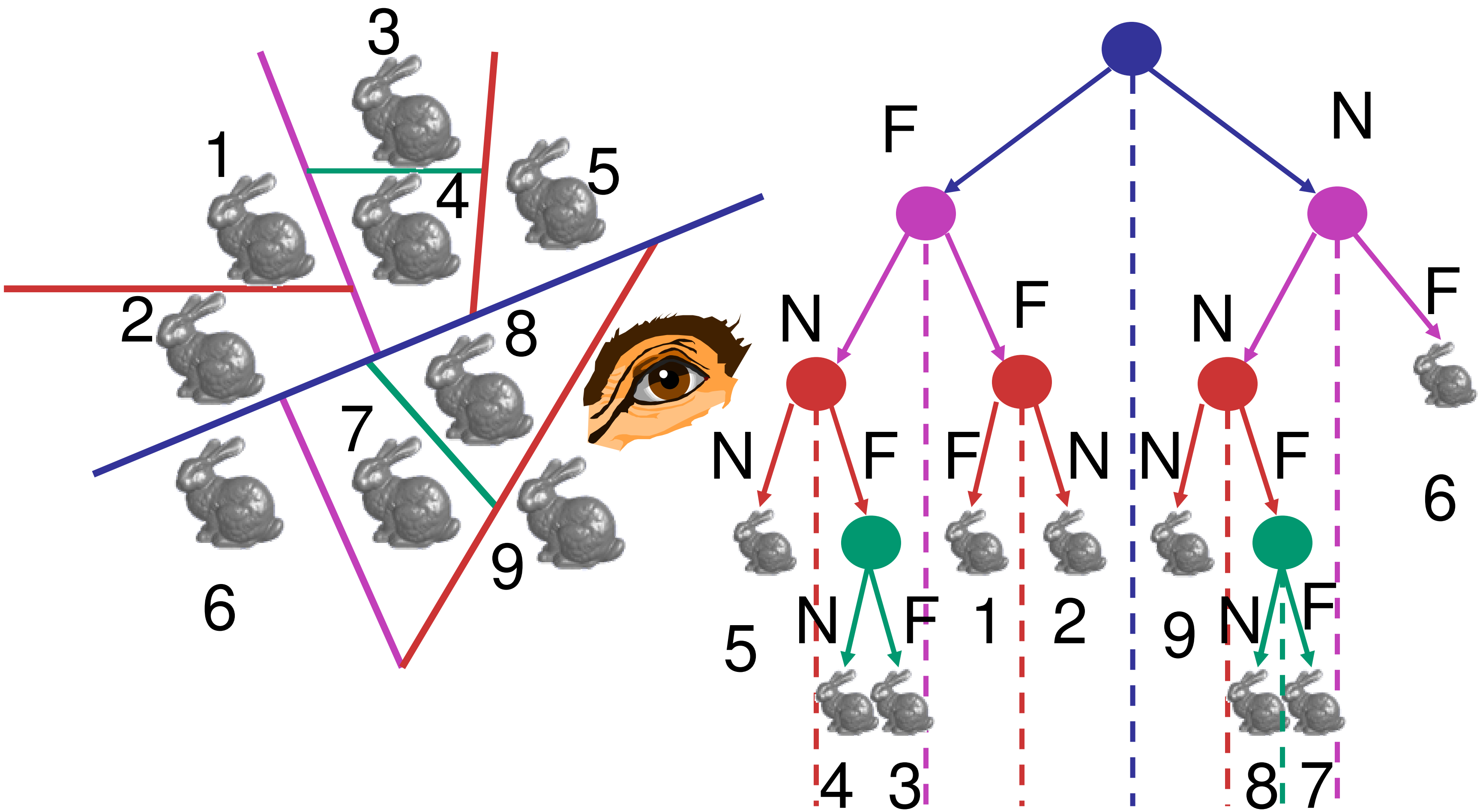
BSP Trees : Viewpoint A



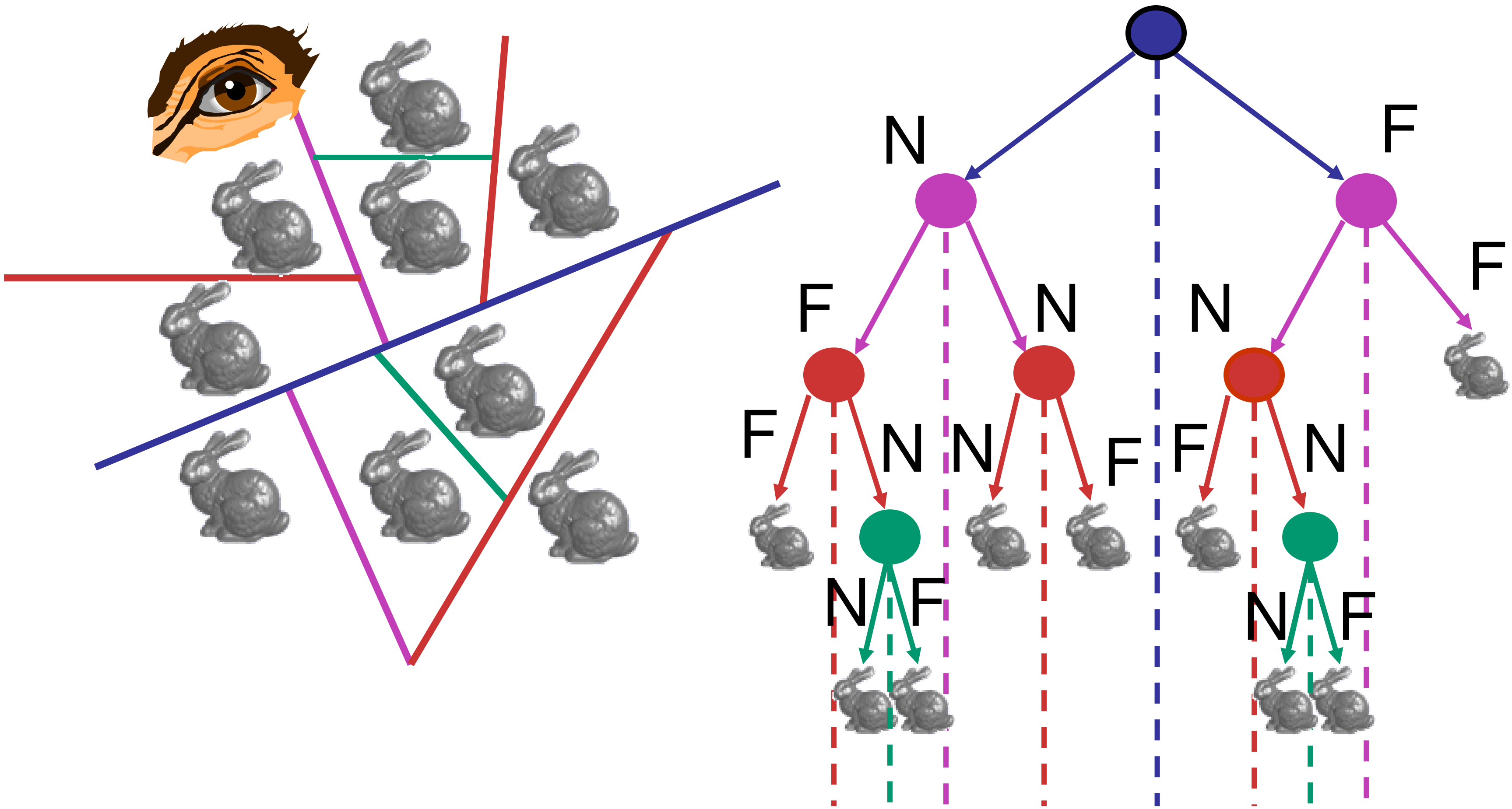
BSP Trees : Viewpoint A



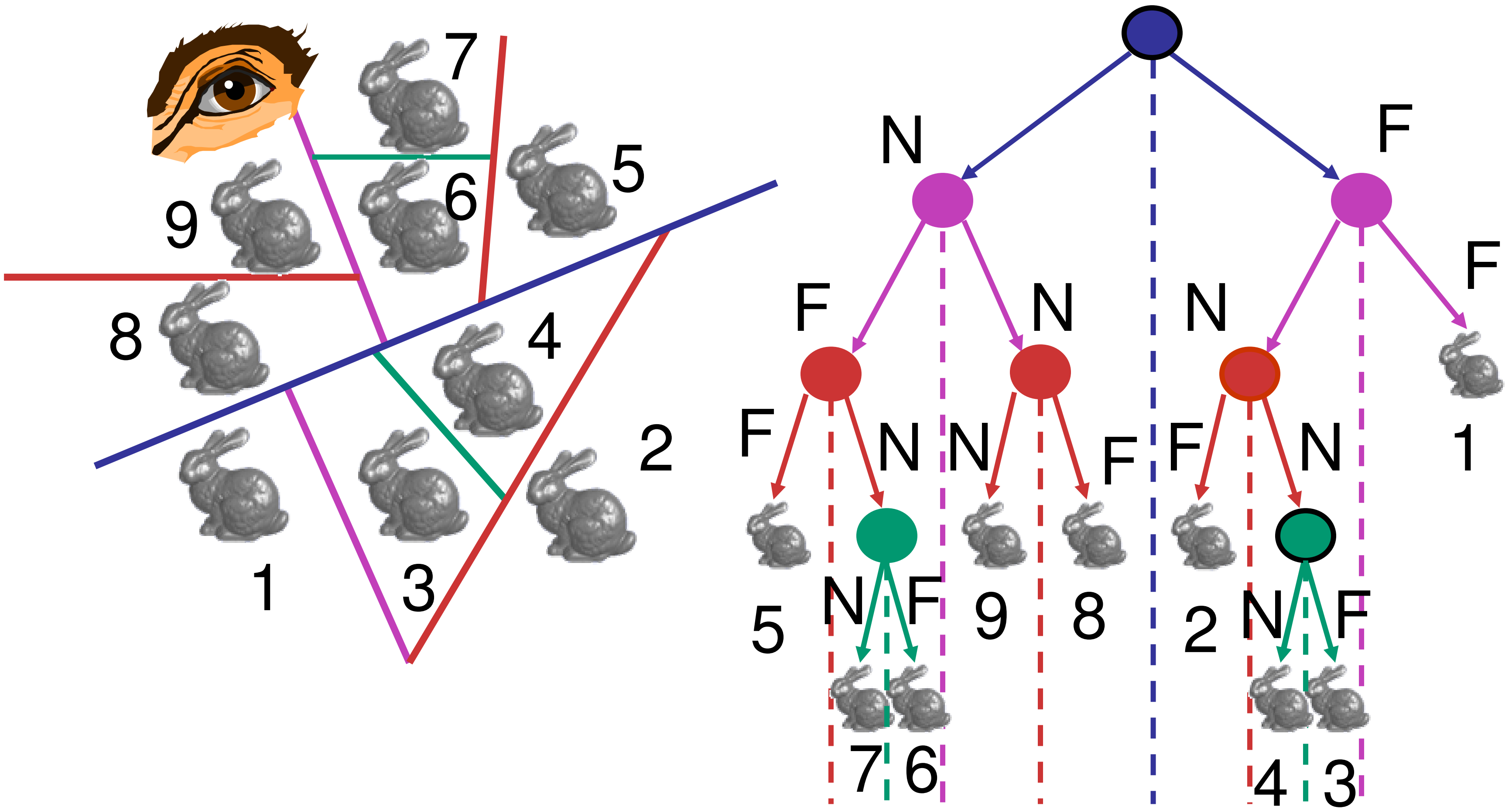
BSP Trees : Viewpoint A



BSP Trees : Viewpoint B



BSP Trees : Viewpoint B

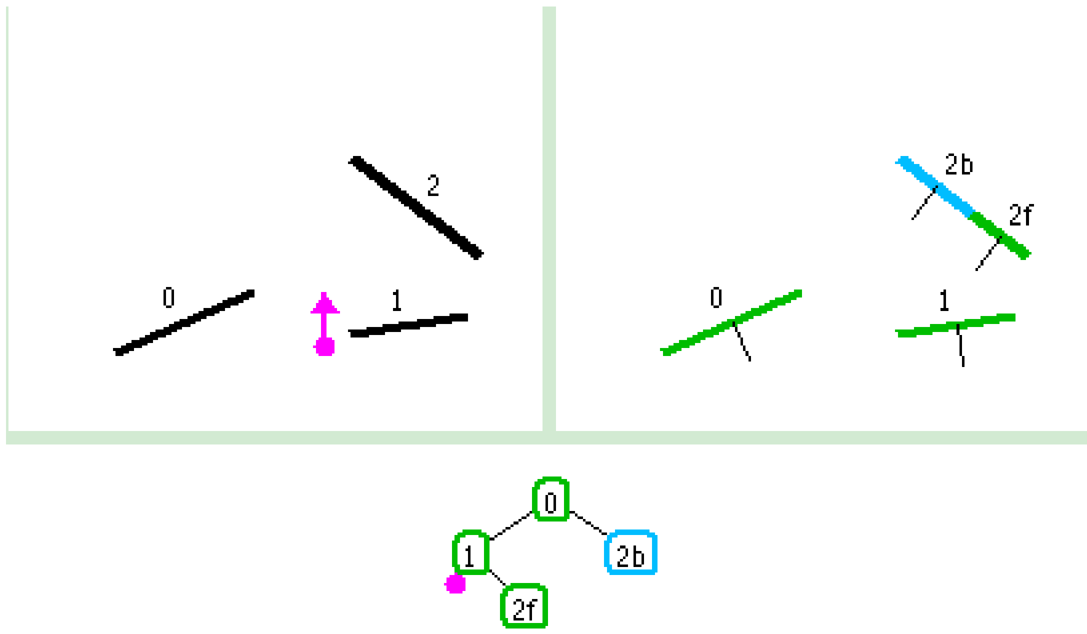


BSP Tree Traversal: Polygons

- split along the plane defined by any polygon from scene
- classify all polygons into positive or negative half-space of the plane
  - if a polygon intersects plane, split polygon into two and classify them both
- recurse down the negative half-space
- recurse down the positive half-space

BSP Demo

- useful demo:
  http://symbolcraft.com/graphics/bsp



Summary: BSP Trees

- pros:
  - simple, elegant scheme
  - correct version of painter's algorithm back-to-front rendering approach
  - was very popular for video games (but getting less so)
- cons:
  - slow to construct tree: O(n log n) to split, sort
  - splitting increases polygon count: $O(n^2)$ worst-case
  - computationally intense preprocessing stage restricts algorithm to static scenes

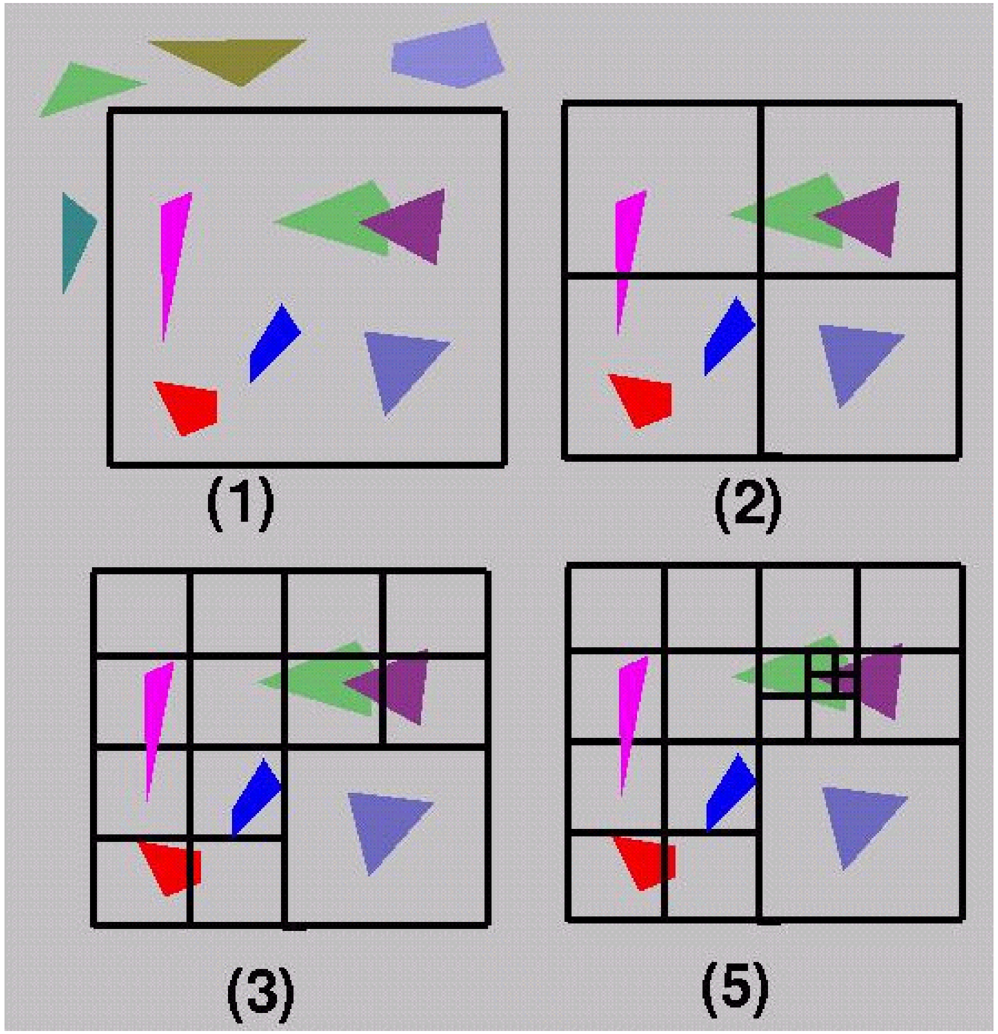
Warnock's Algorithm (1969)

- based on a powerful general approach common in graphics
  - if the situation is too complex, subdivide

- BSP trees was object space approach
- Warnock is image space approach

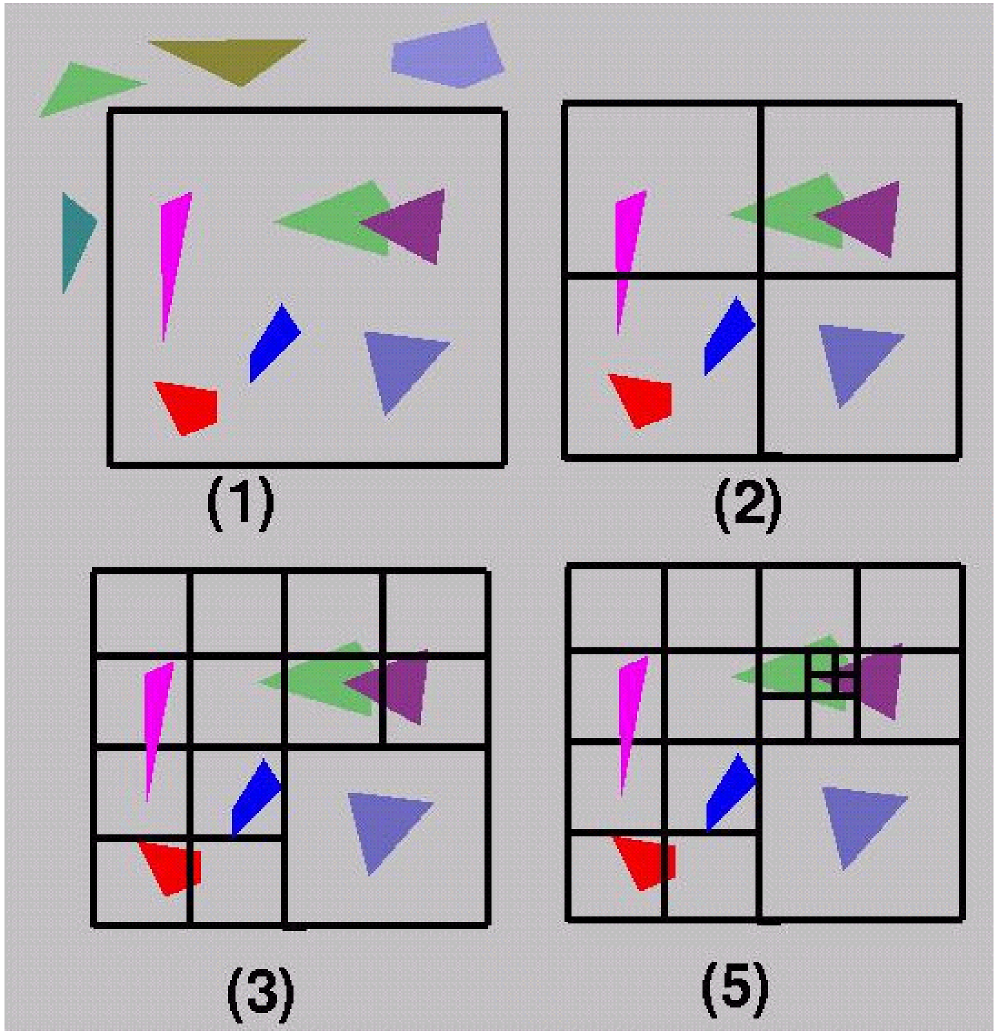
Warnock's Algorithm

- start with root viewport and list of all objects
- recursion:
  - clip objects to viewport
  - if only 0 or 1 objects
    - done
  - else
    - subdivide to new smaller viewports
    - distribute objects to new viewpoints
    - recurse



Warnock's Algorithm

- termination
  - viewport is single pixel
  - explicitly check for object occlusion



Warnock's Algorithm

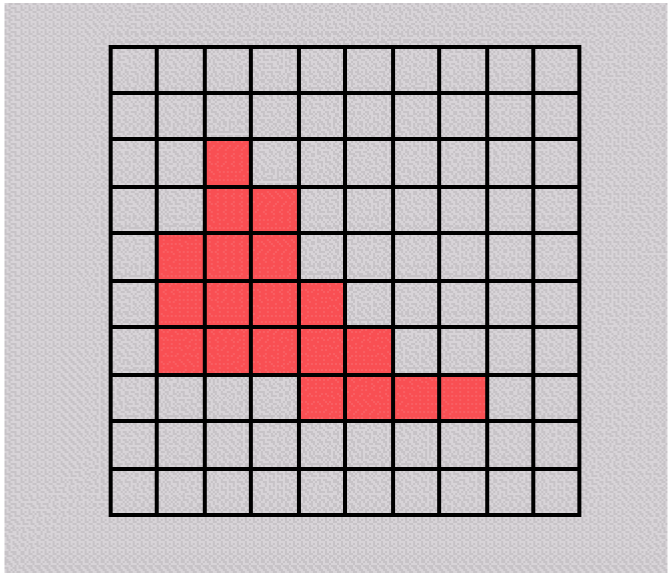
- pros:
  - very elegant scheme
  - extends to any primitive type
- cons:
  - hard to embed hierarchical schemes in hardware
  - complex scenes usually have small polygons and high depth complexity (number of polygons that overlap a single pixel)
    - thus most screen regions come down to the single-pixel case

The Z-Buffer Algorithm (mid-70's)

- both BSP trees and Warnock's algorithm were proposed when memory was expensive
  - first 512x512 framebuffer was >$50,000!
- Ed Catmull proposed a radical new approach called z-buffering.
- the big idea:
  - resolve visibility independently at each pixel

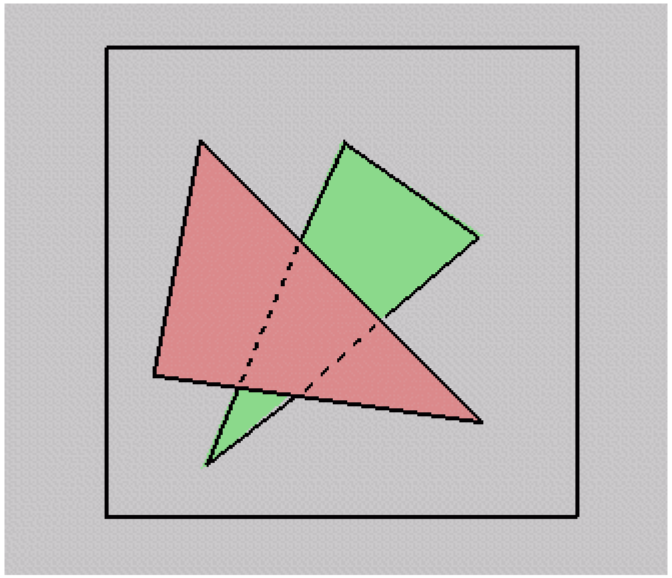
The Z-Buffer Algorithm

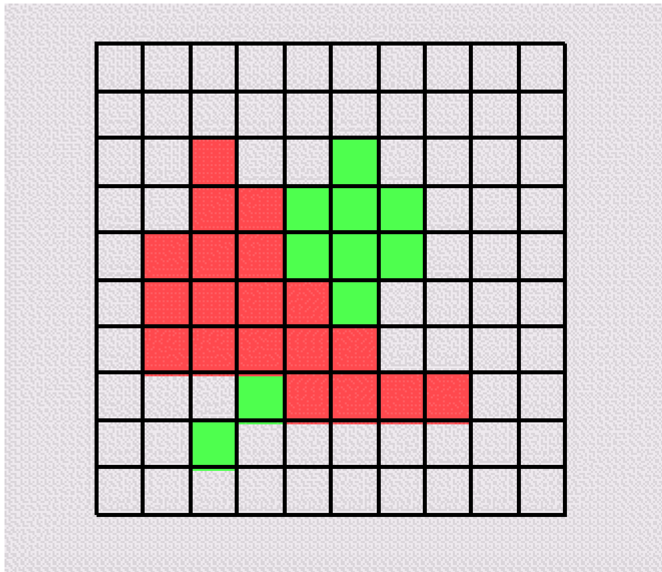
- we know how to rasterize polygons into an image discretized into pixels:



The Z-Buffer Algorithm

- what happens if multiple primitives occupy the same pixel on the screen?
  - which is allowed to paint the pixel?





The Z-Buffer Algorithm

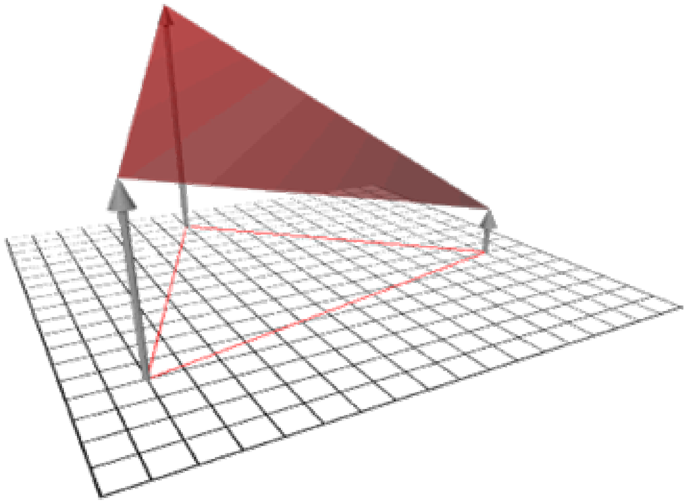
- idea: retain depth after projection transform
  - each vertex maintains z coordinate
    - relative to eye point
  - can do this with canonical viewing volumes

The Z-Buffer Algorithm

- augment color framebuffer with Z-buffer or depth buffer which stores Z value at each pixel
  - at frame beginning, initialize all pixel depths to ∞
  - when rasterizing, interpolate depth (Z) across polygon
  - check Z-buffer before storing pixel color in framebuffer and storing depth in Z-buffer
  - don’t write pixel if its Z value is more distant than the Z value already stored there

Interpolating Z

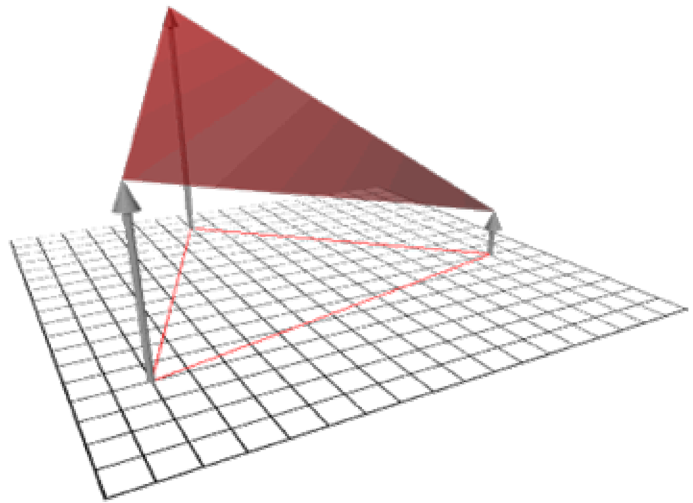
- edge equations: Z just another planar parameter:
  - $z = (-D - Ax - By) / C$
  - if walking across scanline by (D_x)
    $z_{new} = z_{old} - (A/C)(D_x)$



- total cost:
  - 1 more parameter to increment in inner loop
  - 3x3 matrix multiply for setup

Interpolating Z

- edge walking
  - just interpolate Z along edges and across spans
- barycentric coordinates
  - interpolate Z like other parameters



Z-Buffer

- store (r,g,b,z) for each pixel
  - typically 8+8+8+24 bits, can be more

```
for all i,j {
 Depth[i,j] = MAX_DEPTH
 Image[i,j] = BACKGROUND_COLOUR
}
for all polygons P {
  for all pixels in P {
    if (Z_pixel < Depth[i,j]) {
      Image[i,j] = C_pixel
      Depth[i,j] = Z_pixel
    }
  }
}
```

Depth Test Precision

- reminder: projective transformation maps eye-space *z* to generic *z*-range (NDC)
- simple example:

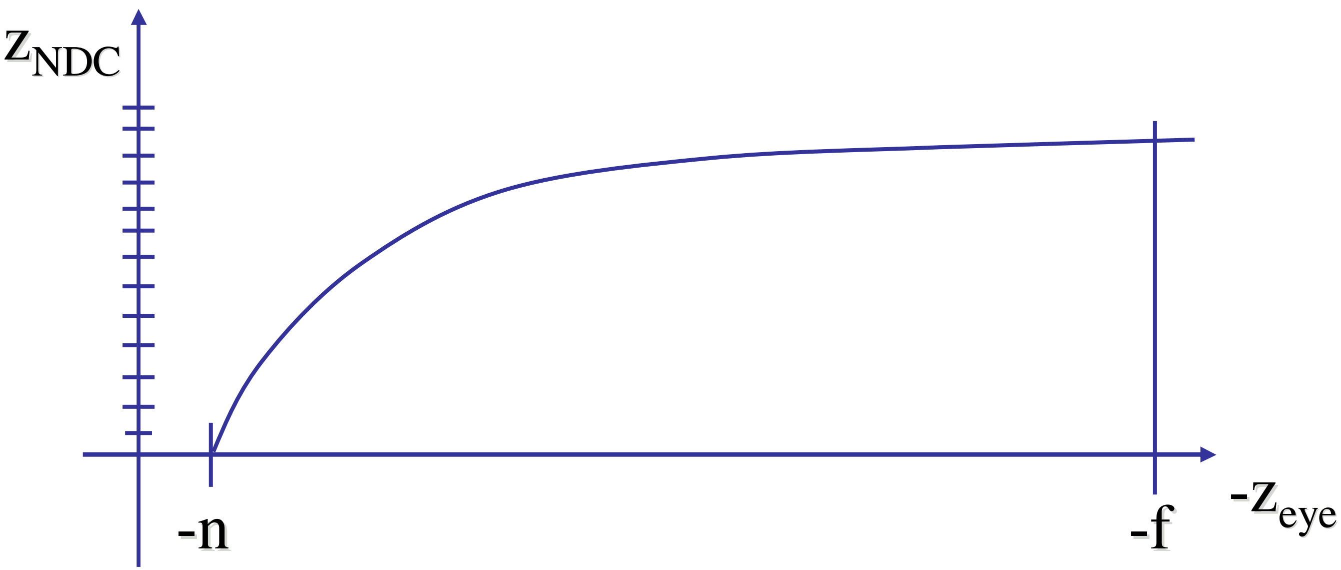
$$T\left(\begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}\right) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & a & b \\ 0 & 0 & -1 & 0 \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

- thus:

$$z_{NDC} = \frac{a \cdot z_{eye} + b}{z_{eye}} = a + \frac{b}{z_{eye}}$$

Depth Test Precision

- therefore, depth-buffer essentially stores 1/z, rather than z!
- issue with integer depth buffers
  - high precision for near objects
  - low precision for far objects



Depth Test Precision

- low precision can lead to depth fighting for far objects
  - two different depths in eye space get mapped to same depth in framebuffer
  - which object "wins" depends on drawing order and scan-conversion
- gets worse for larger ratios $f{:}n$
  - *rule of thumb:* $\mathrm{f{:}n} < 1000$ *for 24 bit depth buffer*
- with 16 bits cannot discern millimeter differences in objects at 1 km distance

Z-Buffer Algorithm Questions

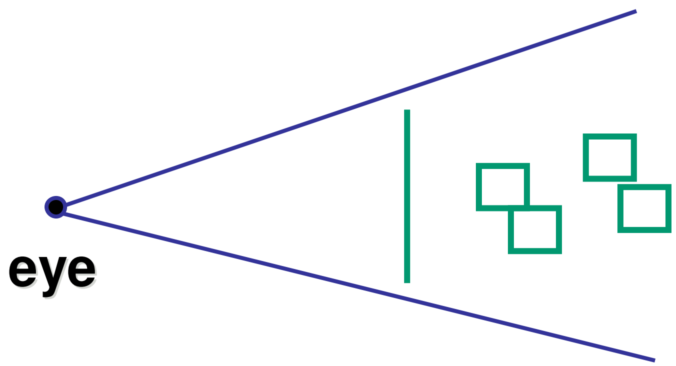
- how much memory does the Z-buffer use?
- does the image rendered depend on the drawing order?
- does the time to render the image depend on the drawing order?
- how does Z-buffer load scale with visible polygons? with framebuffer resolution?

Z-Buffer Pros

- simple!!!
- easy to implement in hardware
  - hardware support in all graphics cards today
- polygons can be processed in arbitrary order
- easily handles polygon interpenetration
- enables deferred shading
  - rasterize shading parameters (e.g., surface normal) and only shade final visible fragments

Z-Buffer Cons

- poor for scenes with high depth complexity
  - need to render all polygons, even if most are invisible



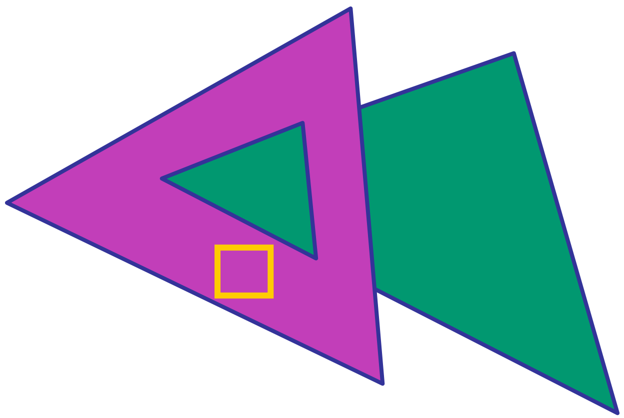
- shared edges are handled inconsistently
  - *ordering dependent*

Z-Buffer Cons

- requires lots of memory
  - (e.g. 1280x1024x32 bits)
- requires fast memory
  - Read-Modify-Write in inner loop
- hard to simulate translucent polygons
  - we throw away color of polygons behind closest one
  - works if polygons ordered back-to-front
    - extra work throws away much of the speed advantage

Hidden Surface Removal

- two kinds of visibility algorithms
  - object space methods
  - image space methods



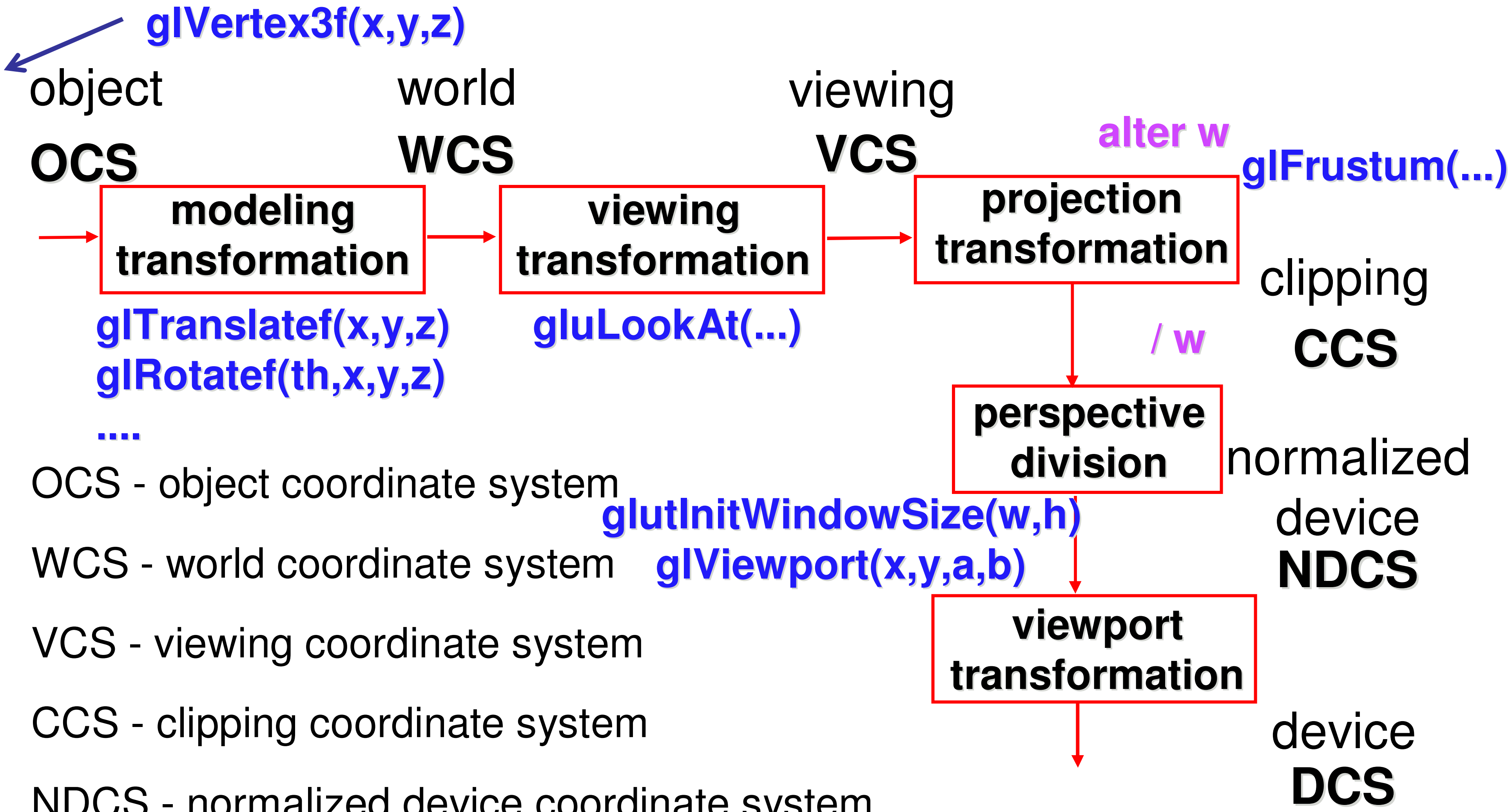
Object Space Algorithms

- determine visibility on object or polygon level
  - using camera coordinates
- resolution independent
  - explicitly compute visible portions of polygons
- early in pipeline
  - after clipping
- requires depth-sorting
  - painter's algorithm
  - BSP trees

Image Space Algorithms

- perform visibility test for in screen coordinates
  - limited to resolution of display
  - Z-buffer: check every pixel independently
  - Warnock: check up to single pixels if needed
- performed late in rendering pipeline

Projective Rendering Pipeline



OCS - object coordinate system

WCS - world coordinate system

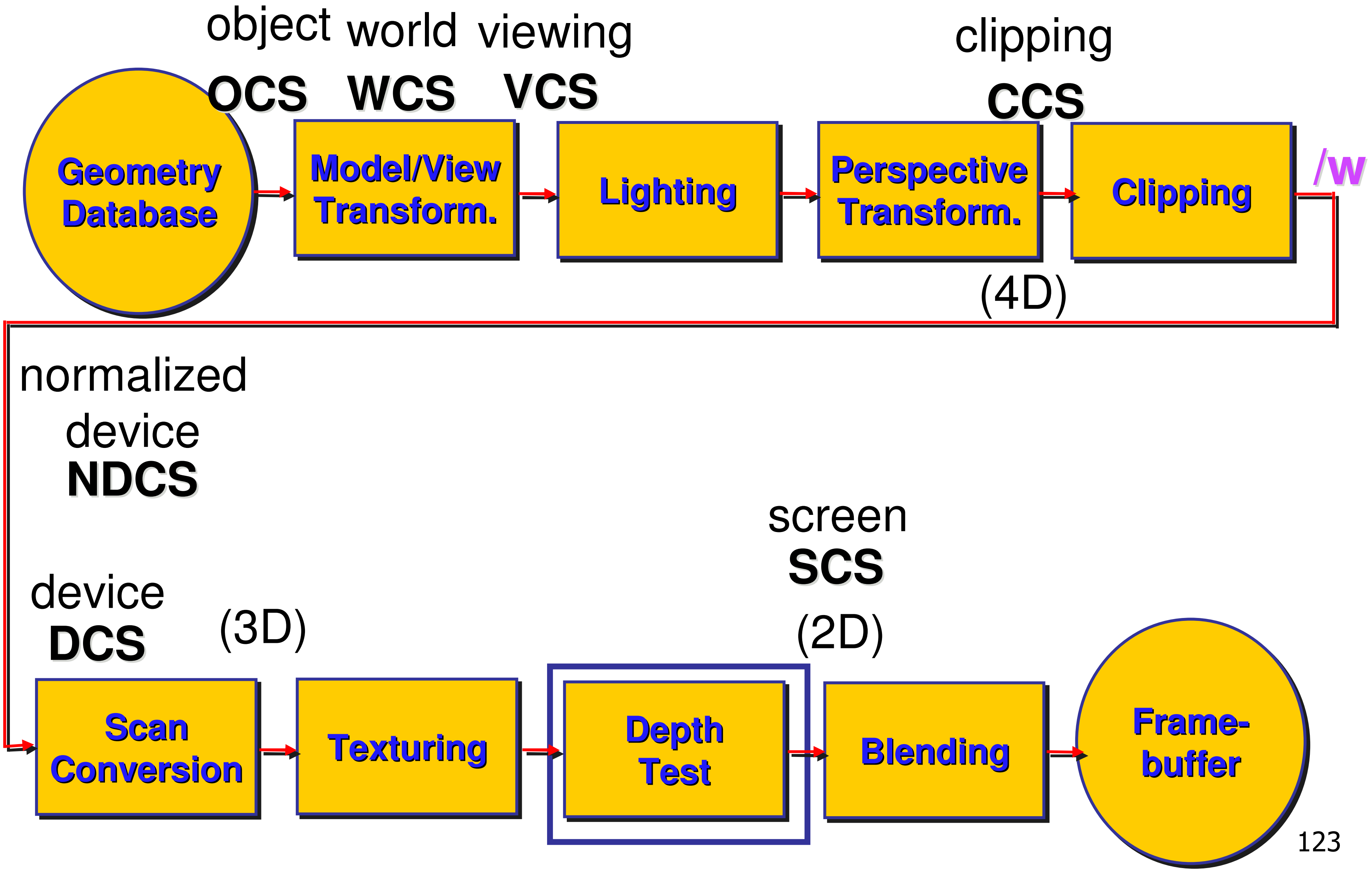
VCS - viewing coordinate system

CCS - clipping coordinate system

NDCS - normalized device coordinate system

DCS - device coordinate system

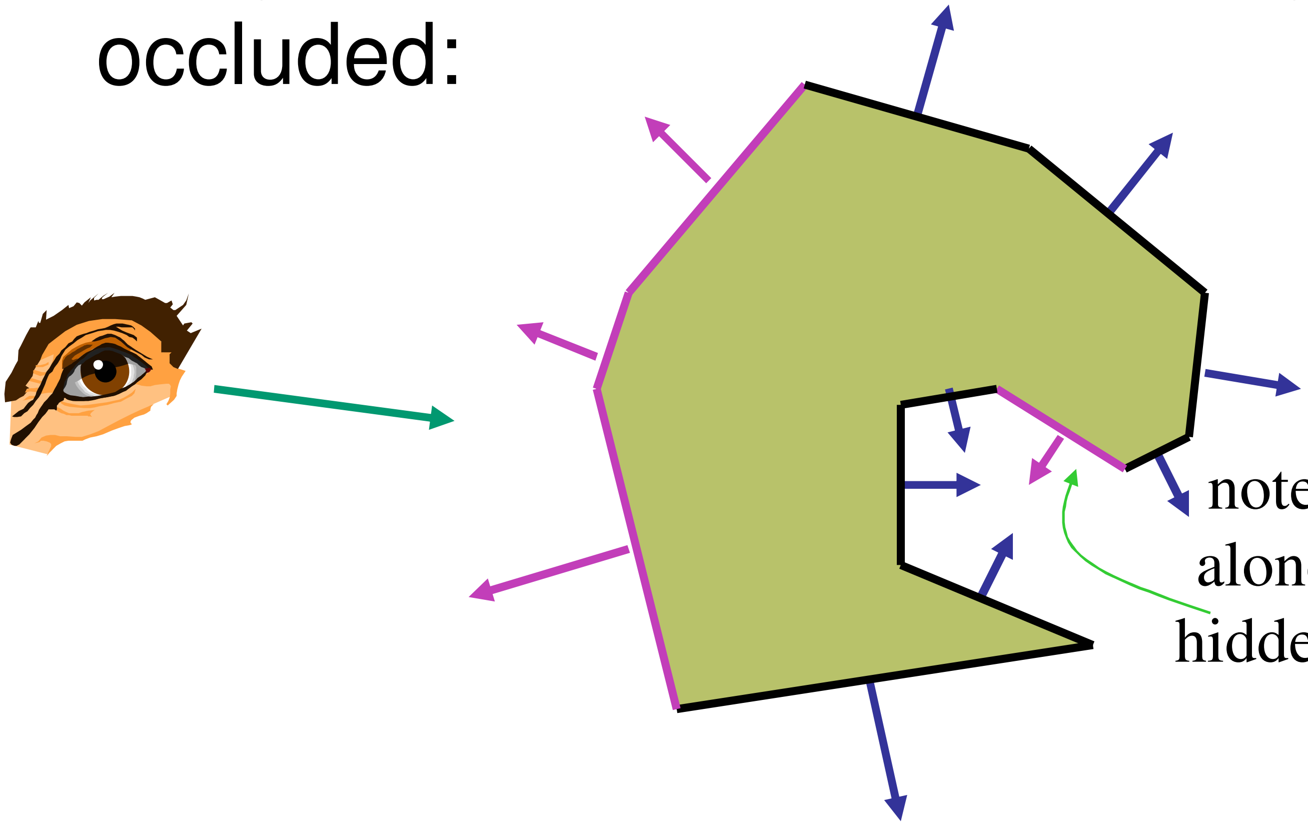
Rendering Pipeline



Backface Culling

Back-Face Culling

- on the surface of a closed orientable manifold, polygons whose normals point away from the camera are always occluded:



note: backface culling alone doesn't solve the hidden-surface problem!

Back-Face Culling

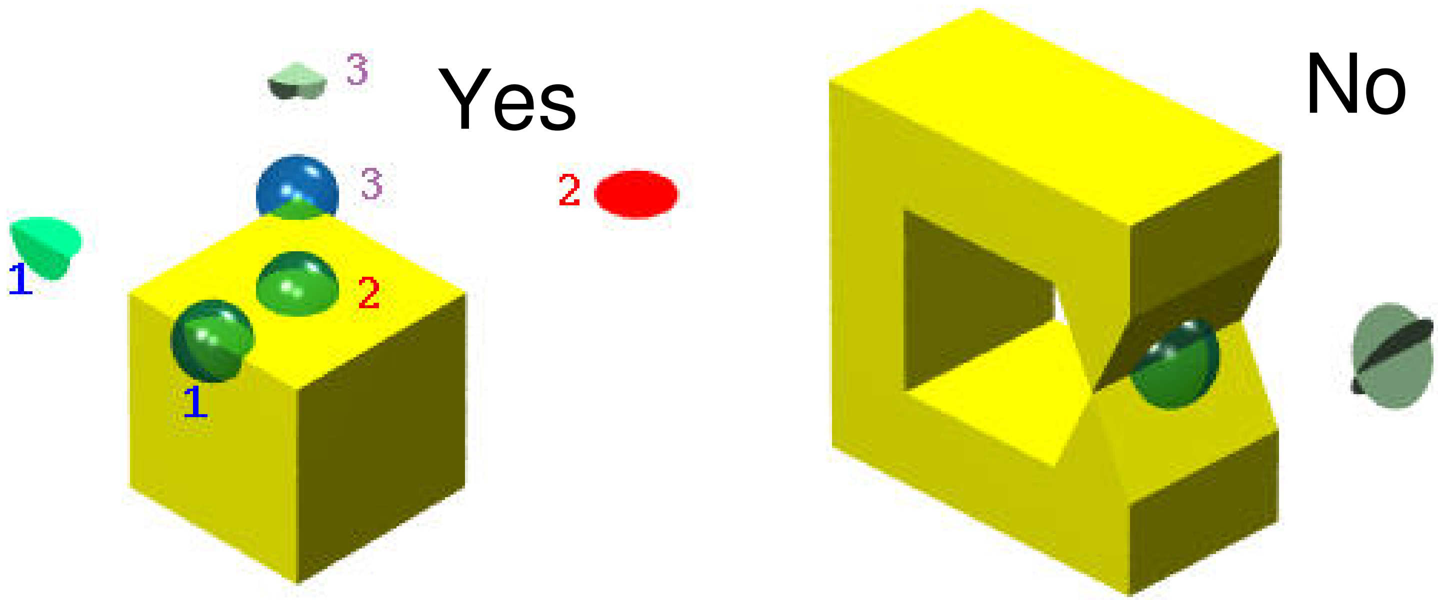
- not rendering backfacing polygons improves performance
  - by how much?
    - reduces by about half the number of polygons to be considered for each pixel
  - optimization when appropriate

Back-Face Culling

- most objects in scene are typically “solid”
- rigorously: orientable closed manifolds
  - orientable: must have two distinct sides
    - cannot self-intersect
    - a sphere is orientable since has two sides, 'inside' and 'outside'.
    - a Mobius strip or a Klein bottle is not orientable
  - closed: cannot “walk” from one side to the other
    - sphere is closed manifold
    - plane is not

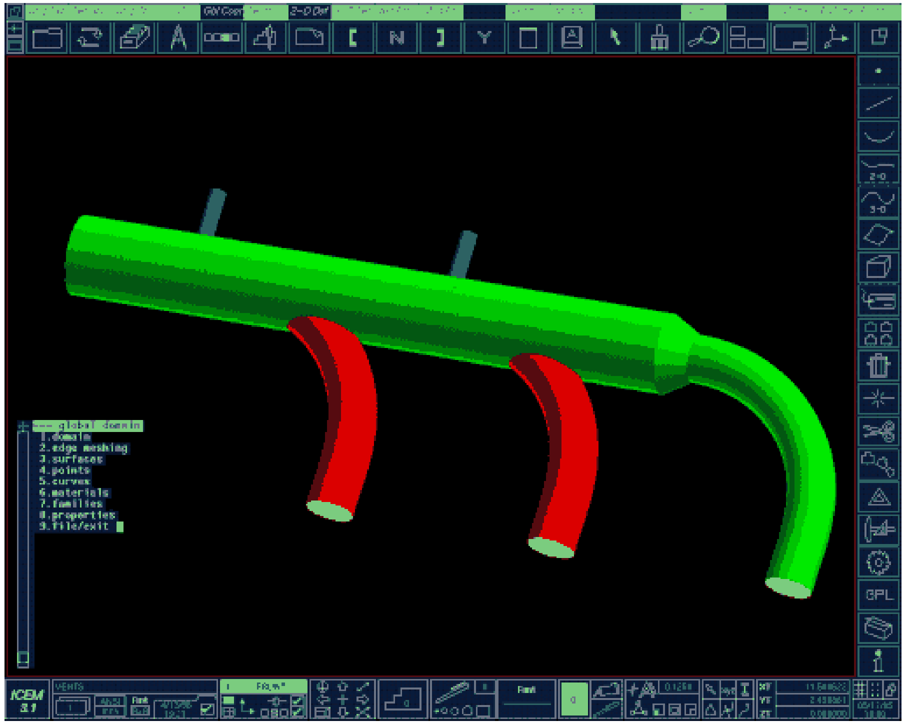
Back-Face Culling

- most objects in scene are typically "solid"
- rigorously: orientable closed manifolds
  - manifold: local neighborhood of all points isomorphic to disc
  - boundary partitions space into interior & exterior



Manifold

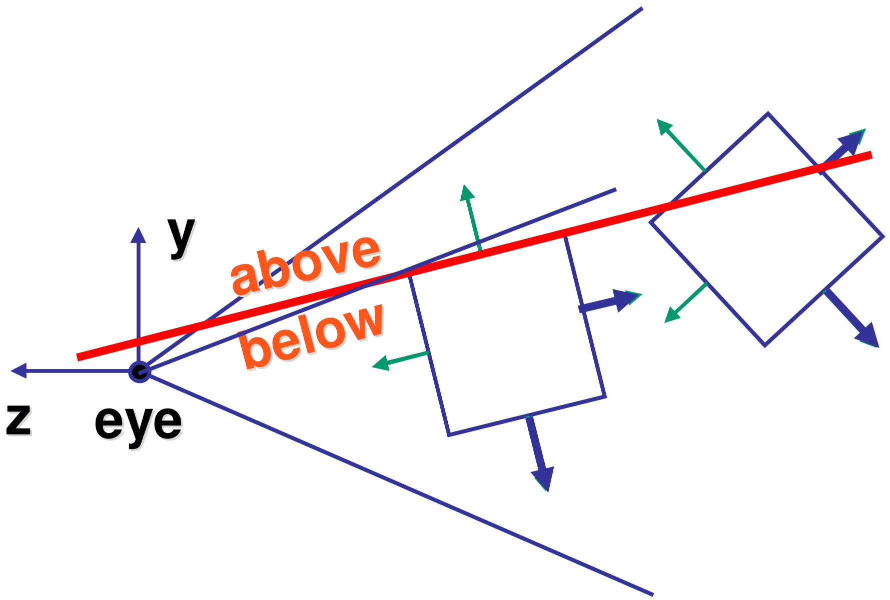
- examples of *manifold* objects:
  - sphere
  - torus
  - well-formed CAD part



Back-Face Culling

- examples of non-manifold objects:
  - a single polygon
  - a terrain or height field
  - polyhedron w/ missing face
  - anything with cracks or holes in boundary
  - one-polygon thick lampshade

Back-face Culling: VCS



first idea:

cull if $N_Z < 0$

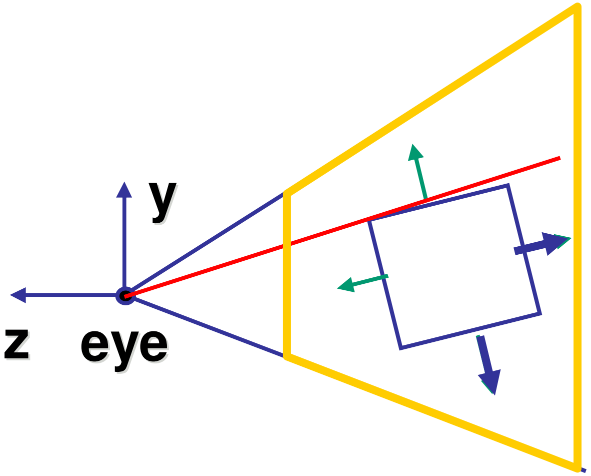
sometimes
misses polygons that
should be culled

better idea:

cull if eye is below polygon plane

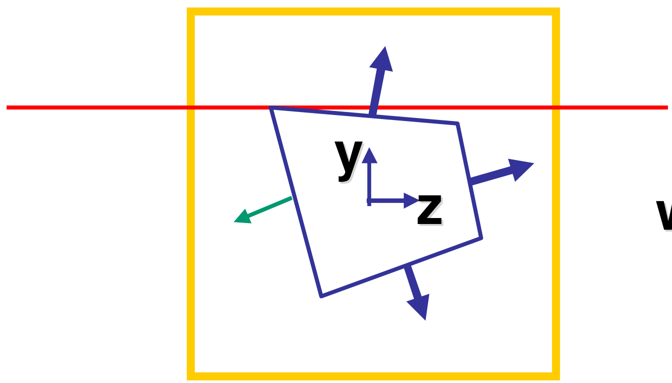
Back-face Culling: NDCS

VCS



NDCS

eye



works to cull if $N_Z > 0$