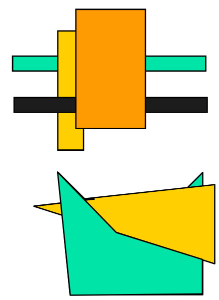
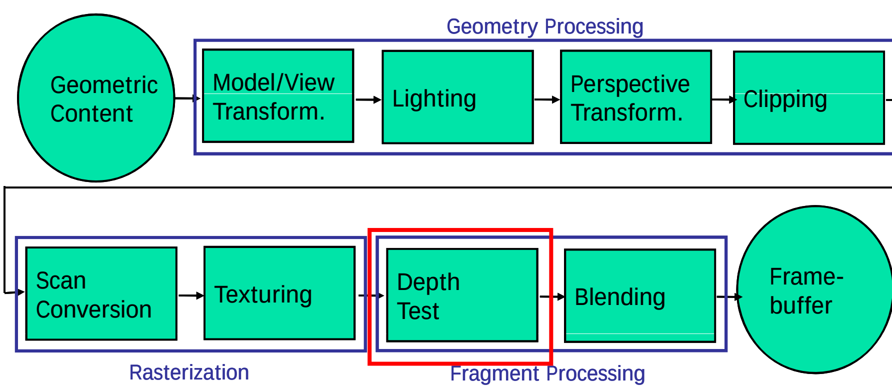
Chapter 10

Hidden Surface Removal/
Depth Test

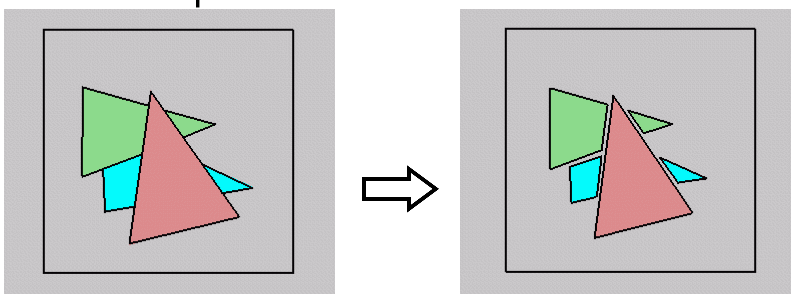


Rendering Pipeline



Occlusion

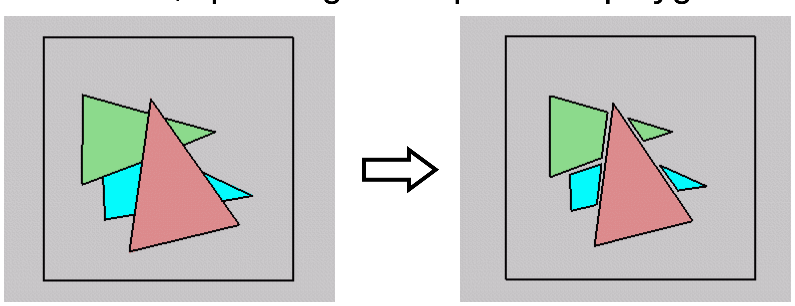
- For most interesting scenes, some polygons overlap



- 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 cyan, then green, then red
- Will this work in general?

Painter's Algorithm: Problems

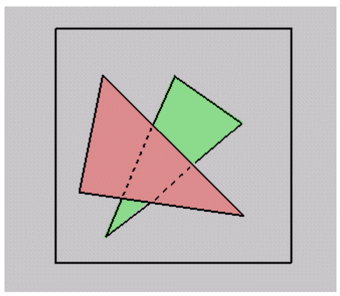
- Intersecting polygons present a problem
- Even non-intersecting polygons can form a cycle with no valid visibility order:

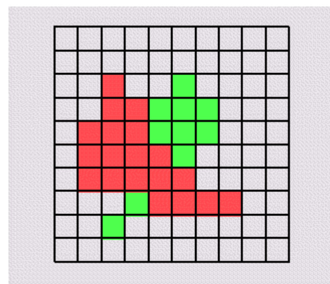
Hidden Surface Removal

- Object Space Methods:
  - Work in 3D before scan conversion
    - E.g. Painter's algorithm
  - Usually independent of resolution
    - Important to maintain independence of output device (screen/printer etc.)
- Image Space Methods:
  - Work on per-pixel/per fragment basis after scan conversion
  - Z-Buffer/Depth Buffer
  - Much faster, but resolution dependent

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
  - Also called depth buffer
  - Stores z value at each pixel
  - At frame beginning, initialize all pixel depths to ∞
- When scan converting: 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

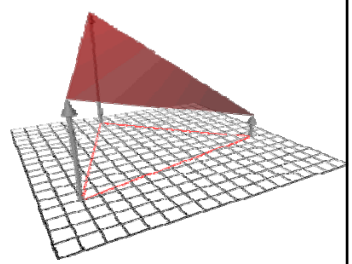
Z-Buffer

- 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
    }
  }
}
```

Interpolating Z

- Use barycentric coordinates
  - Interpolate z like other parameters
    - E.g. color
    - Use on of three formulas shown
      - Plane/edge walk/barycentric



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

- History:
  - Object space algorithms were proposed when memory was expensive
  - First 512x512 framebuffer was >$50,000!
- Radical new approach at the time
  - The big idea:
    - Resolve visibility independently at each pixel

Depth Test Precision

- Reminder: projective transformation maps eye-space z to generic z-range (NDC)
- Simple example:

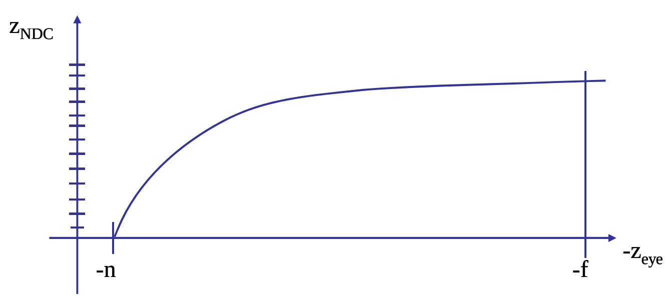
$$T\left(\begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}\right) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & a & b \\ 0 & 0 & -1 & 0 \end{bmatrix}\begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

- 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: $f{:}n < 1000$ for 24 bit depth buffer
- With 16 bits cannot discern cm differences in objects at 1 km distance

Z-Buffer Algorithm Questions

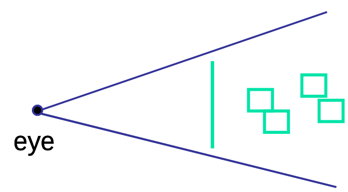
- How much memory does the Z-buffer use?
- Does the image rendered depend on the drawing order?
- Does the time to render the image depend on the drawing order?
- How does Z-buffer load scale with visible polygons? with framebuffer resolution?

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

Z-Buffer Cons

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



- Shared edges/overlaps handled inconsistently
  - *Ordering dependent*

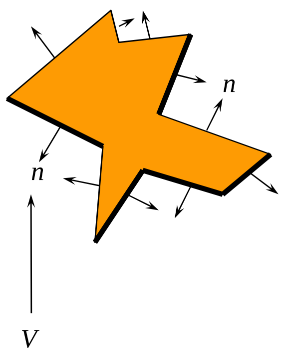
Z-Buffer Cons

- Requires “lots” of memory
  - (e.g. 1280x1024x32 bits)
- Requires fast memory
  - Read-Modify-Write in inner loop
- Hard to simulate transparent 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

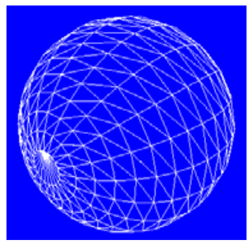
Object Space Algorithms

- 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

Back Face Culling (object space)



- In closed polyhedron you don't see object "back" faces
- Assumption
  - Normals of faces point *out* from the object



Back Face Culling

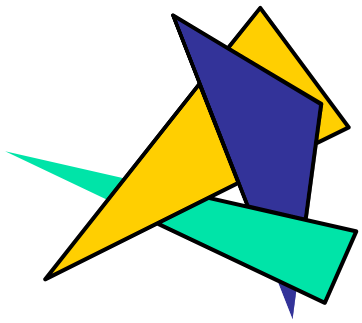
- Determine back & front faces using sign of inner product nv

$$n \cdot v = n_x v_x + n_y v_y + n_z v_z = \|n\| \cdot \|v\| \cos\theta$$

- In a convex object :
  - Invisible back faces
  - All front faces entirely visible ⇒ solves hidden surfaces problem
- In non-convex object:
  - Invisible back faces
  - Front faces can be visible, invisible, or partially visible

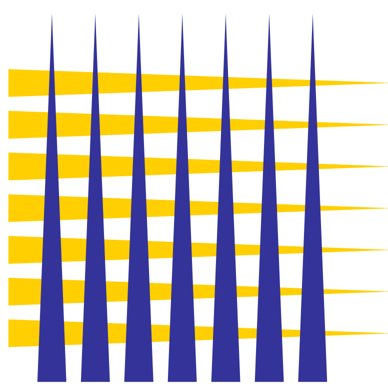
Object Space (Full) Visibility Algorithms

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



Object Space Visibility Algorithms

- What is the worst-case cost of computing the fragments for a scene composed of n polygons?
- Answer: $O(n^2)$



Object Space Visibility Algorithms

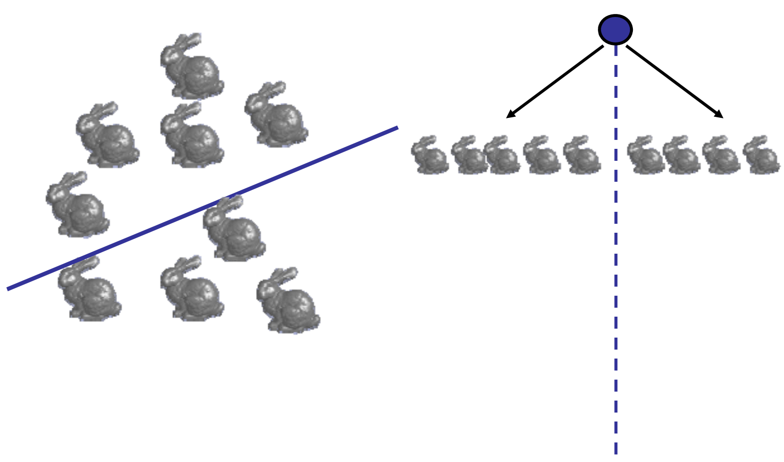
- Not optimal for our "cheap" memory rendering pipeline setup
  - But very useful for other tasks (e.g. RayTracing) or to speed pipeline rendering for static scenes
- Example:
  - Binary Space Partition (BSP) Trees

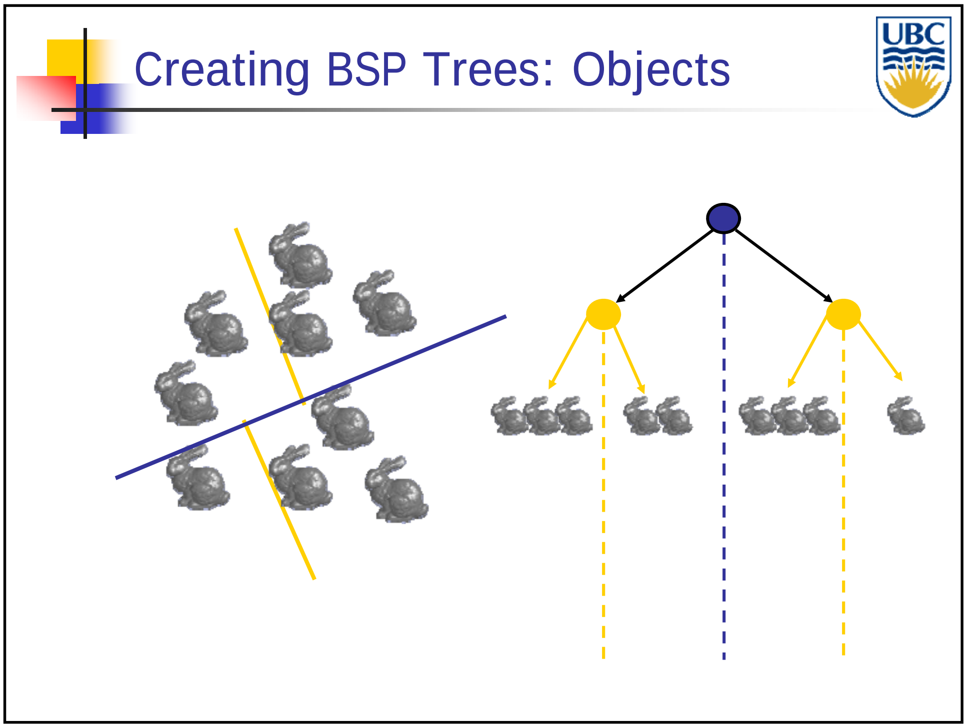
Binary Space Partition Trees

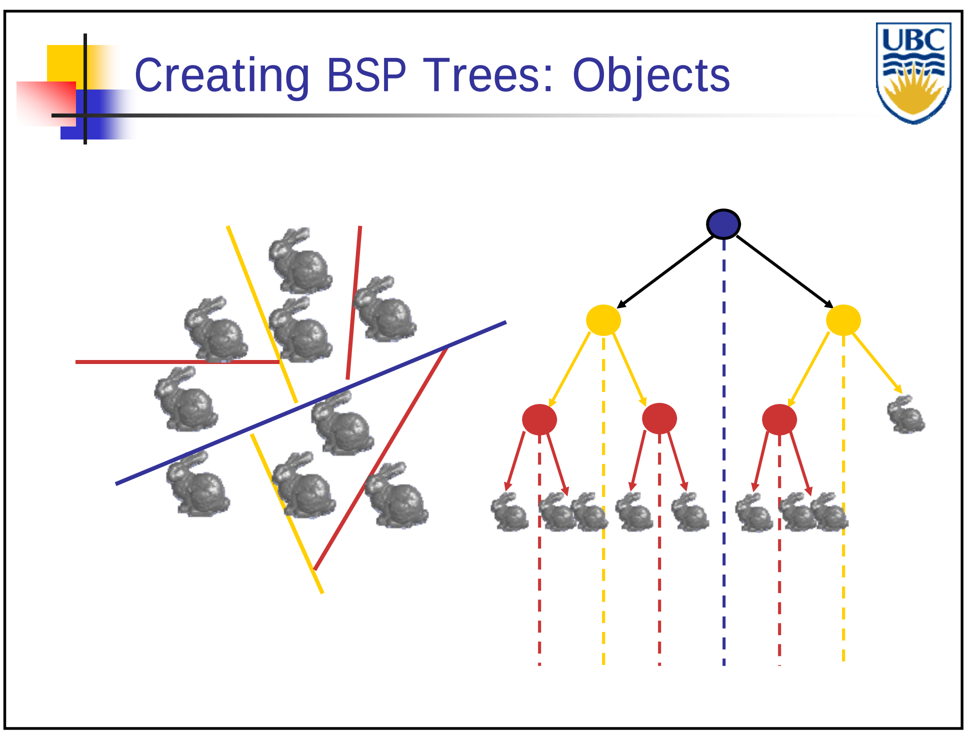
- BSP Tree: partition space with binary tree of planes
- Idea: divide space recursively into half-spaces by choosing splitting planes that separate objects in scene
  - Now we can define partial view order between halves
- Preprocessing: create binary tree of planes
- Runtime: correctly traversing this tree enumerates objects from back to front

Creating BSP Trees: Objects

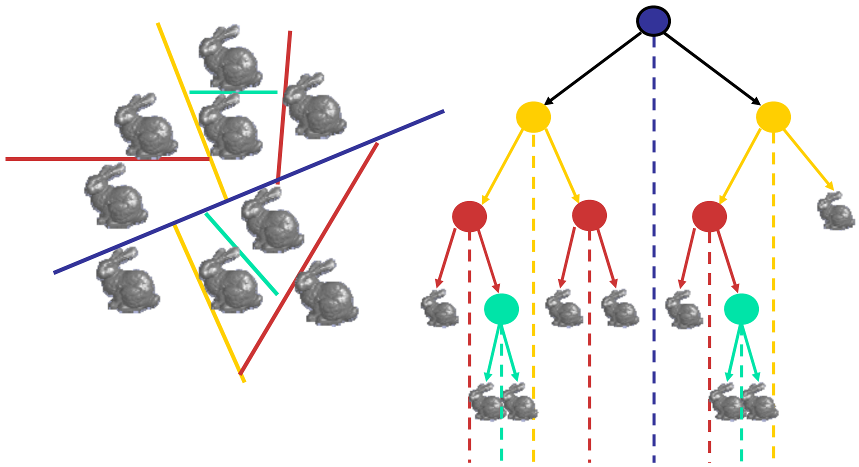
Creating BSP Trees: Objects




Creating BSP Trees: Objects
UBC

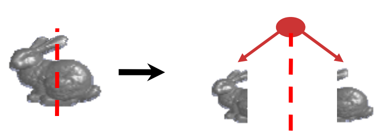

Creating BSP Trees: Objects
UBC

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

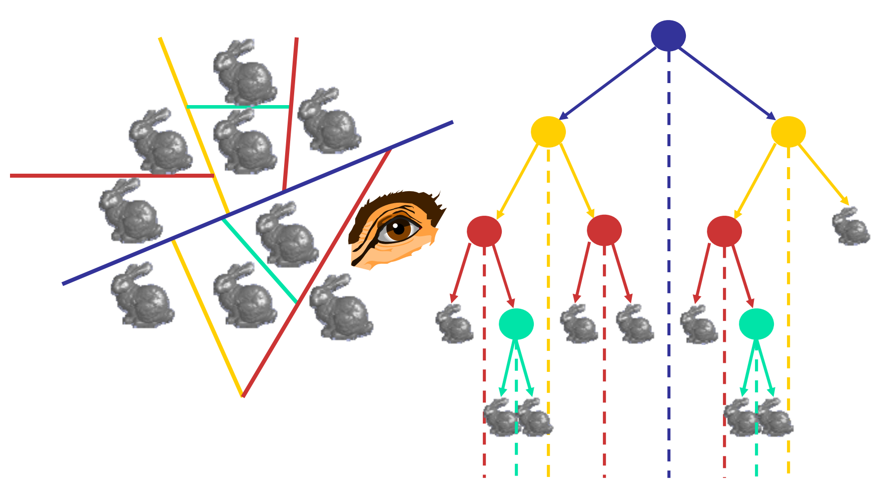
Traversing BSP Trees

- 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

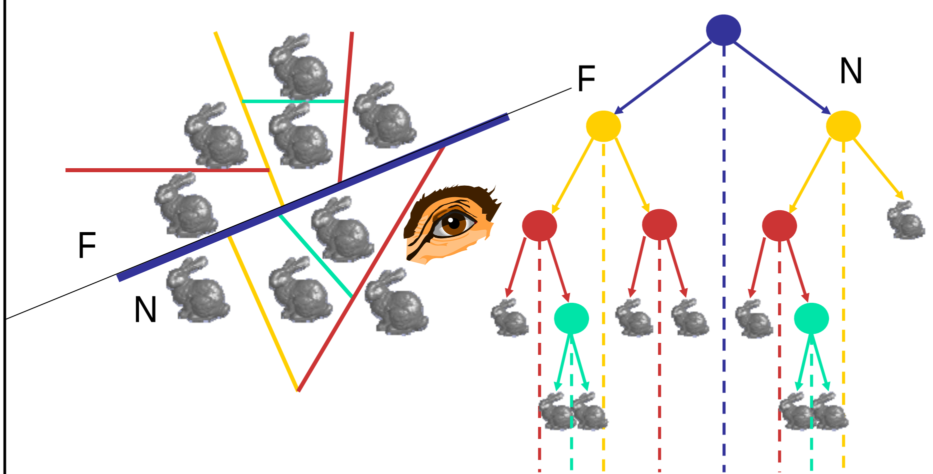
Traversing BSP Trees

```
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);
```

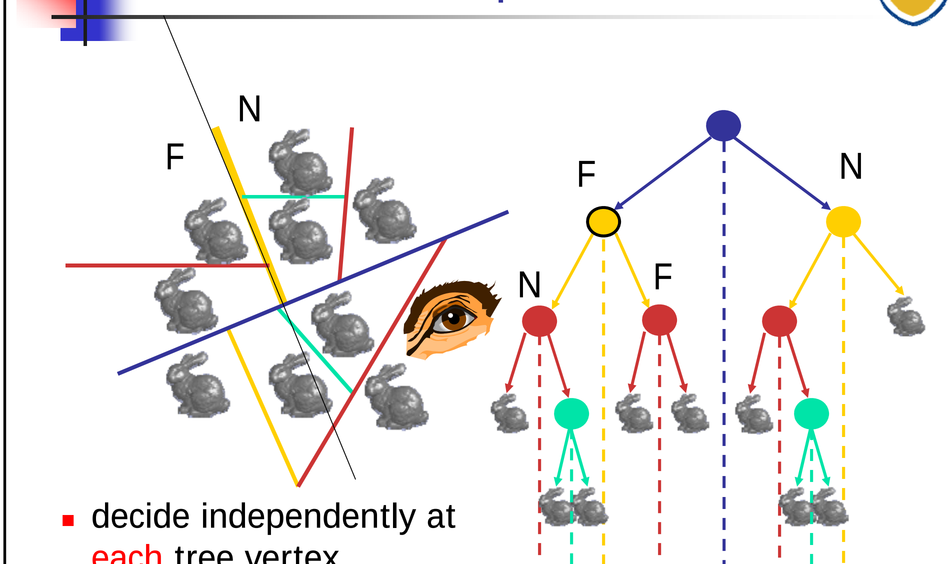
BSP Trees : Viewpoint A



BSP Trees : Viewpoint A

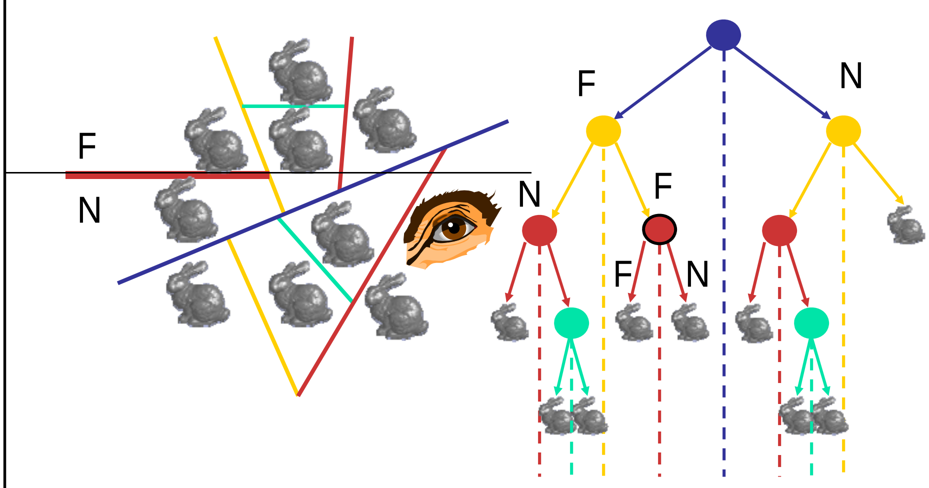


BSP Trees : Viewpoint A

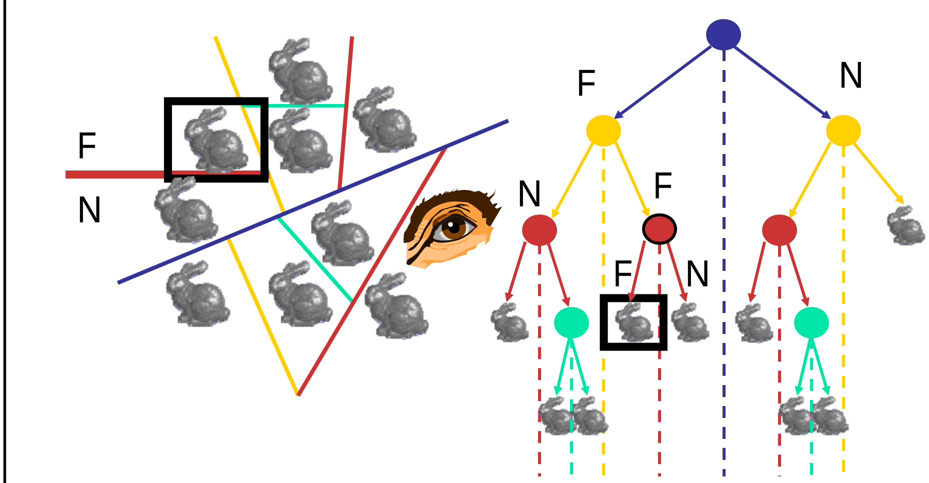


- decide independently at each tree vertex
  - not just left or right child!

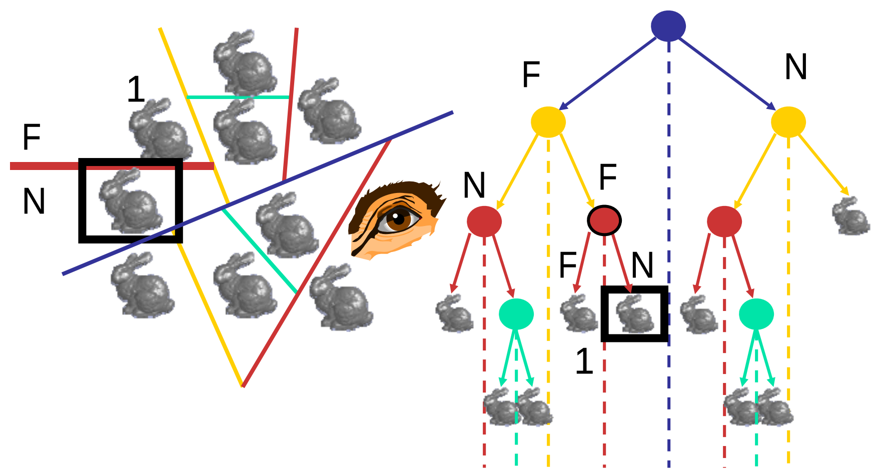
BSP Trees : Viewpoint A



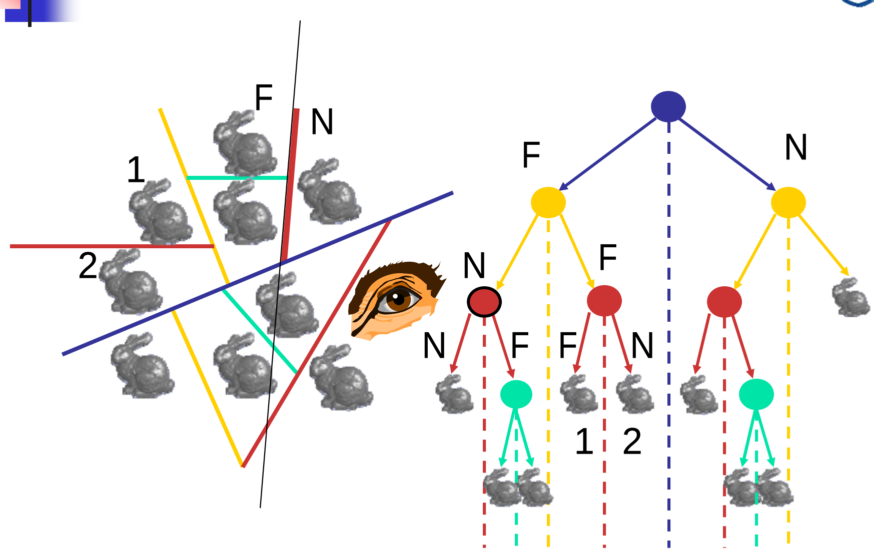
BSP Trees : Viewpoint A



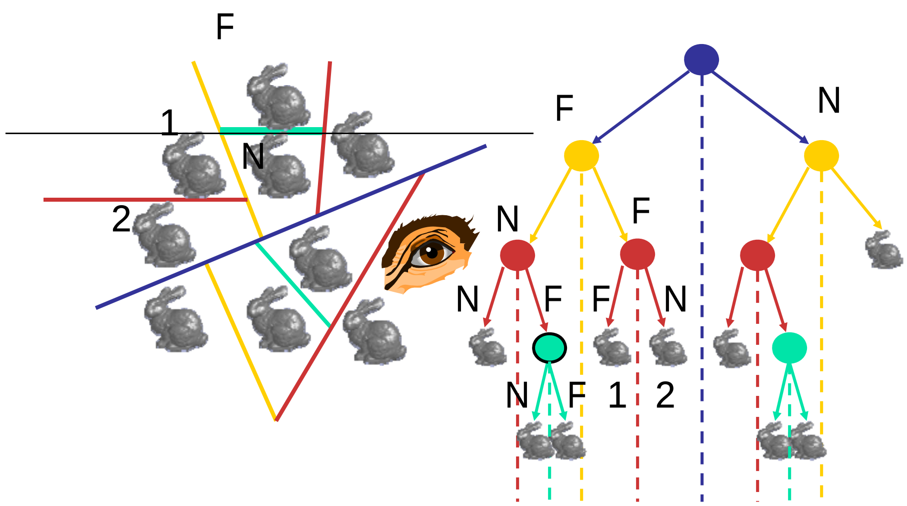
BSP Trees : Viewpoint A



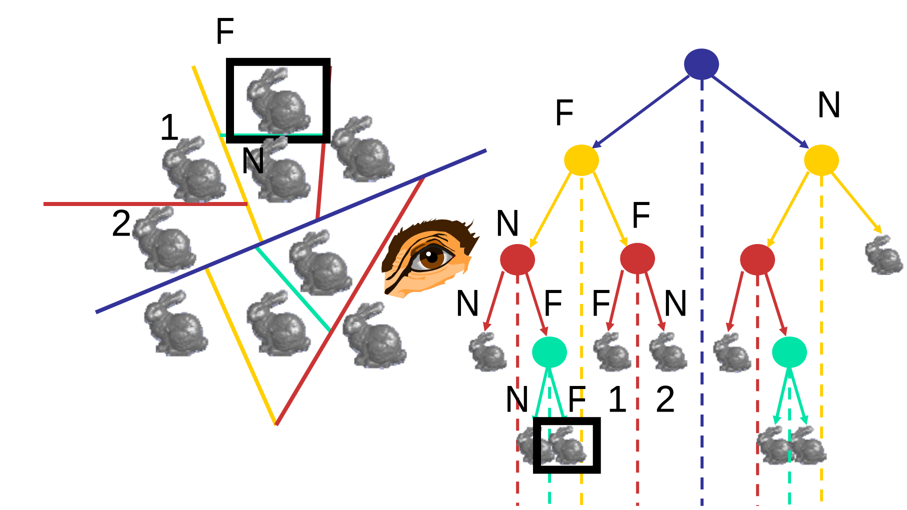
BSP Trees : Viewpoint A



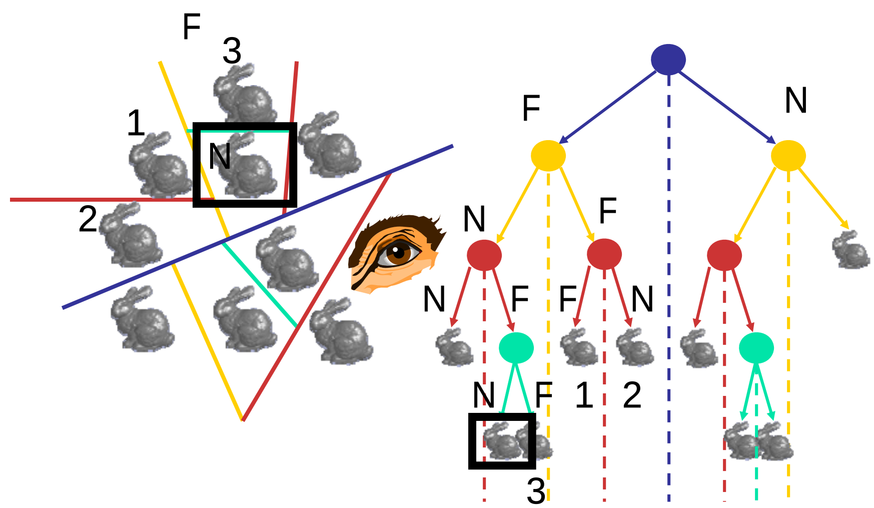
BSP Trees : Viewpoint A



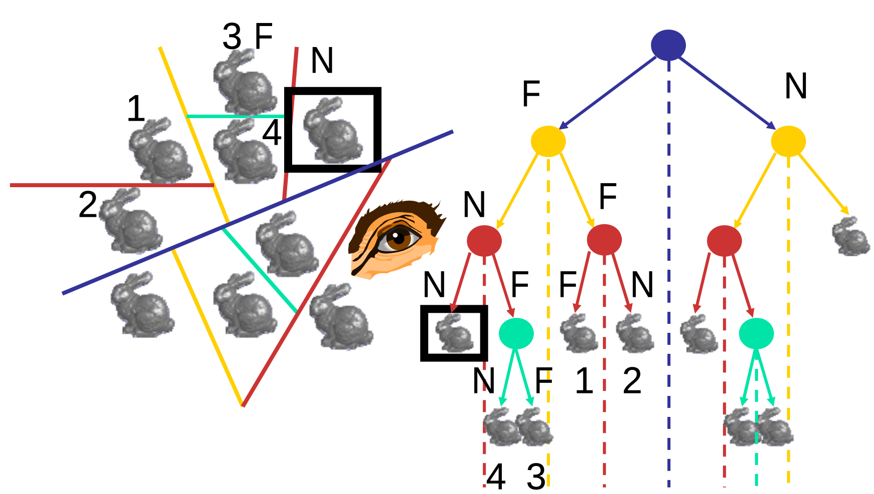
BSP Trees : Viewpoint A



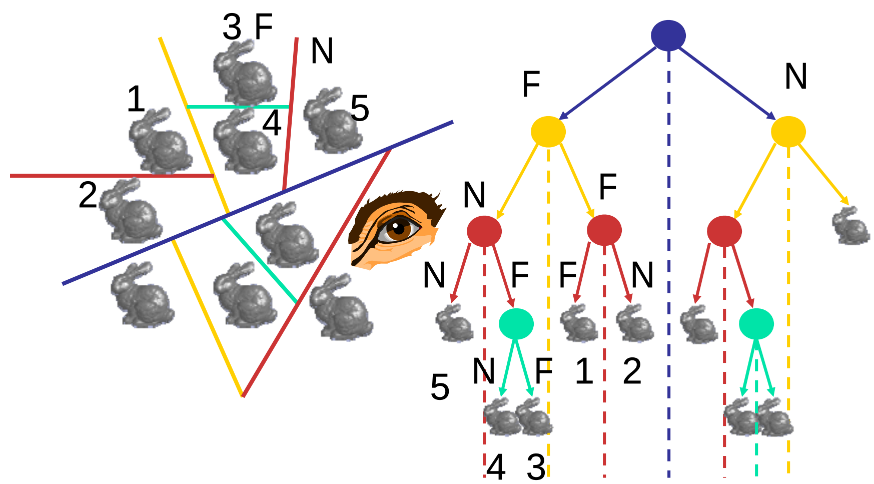
BSP Trees : Viewpoint A



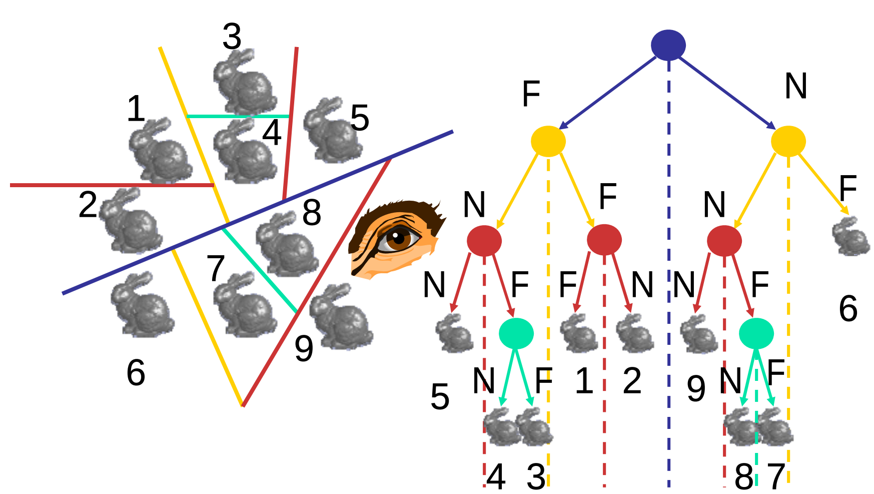
BSP Trees : Viewpoint A



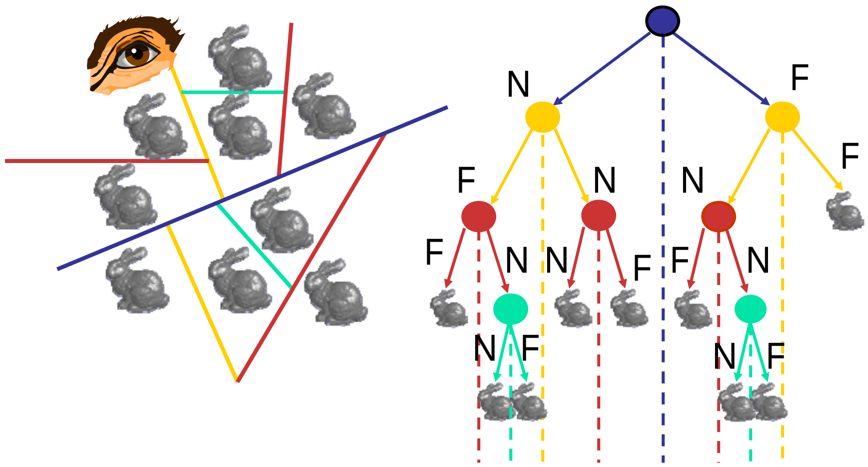
BSP Trees : Viewpoint A



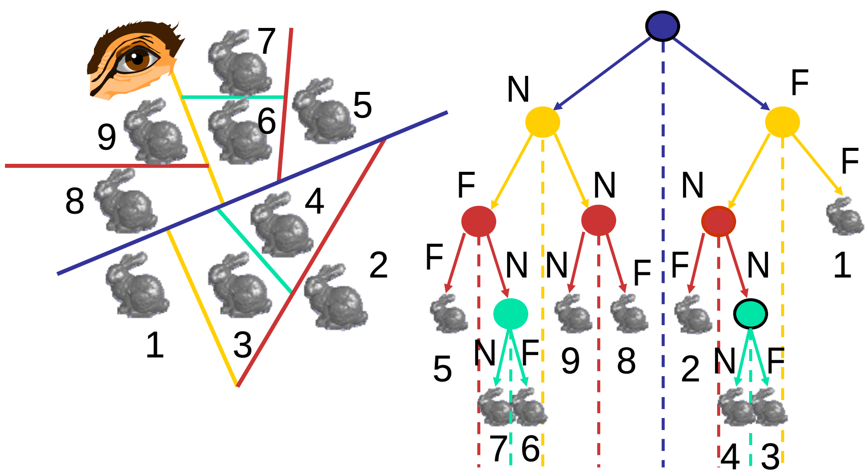
BSP Trees : Viewpoint A



BSP Trees : Viewpoint B



BSP Trees : Viewpoint B

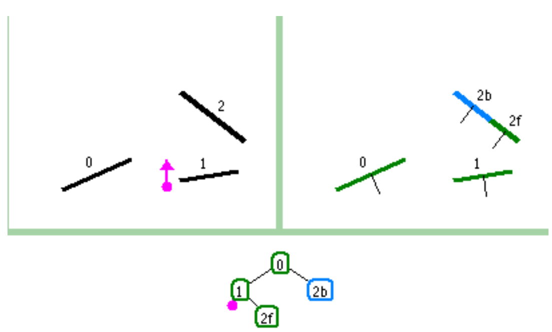


BSP Tree Traversal: Polygons

- 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
  - Still very popular for video games (but getting less so)
- Cons:
  - Slow(ish) to construct tree: O(n log n) to split, sort
  - Splitting increases polygon count: O(n2) worst-case
  - Computationally intense preprocessing stage restricts algorithm to static scenes