Occlusion / Hidden Surface Removal / Depth Test

Wolfgang Heidrich

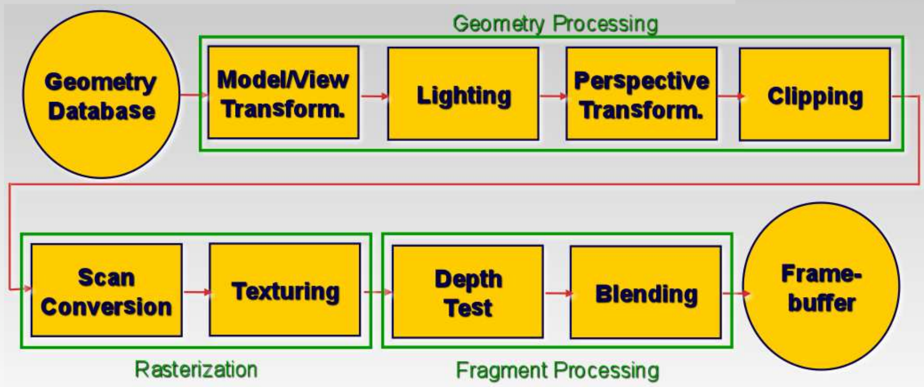
Course News

Assignment 2
- Due March 2

Homework 5
- Out today

Reading
- No new reading this week

The Rendering Pipeline



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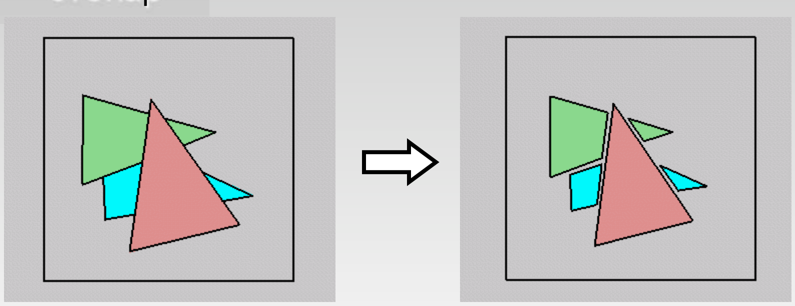
Occlusion

- For most interesting scenes, some polygons overlap



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

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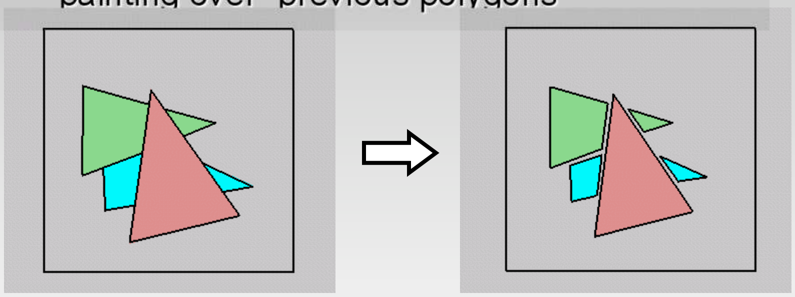
Painter's Algorithm

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



- Draw cyan, then green, then red

will this work in 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:

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

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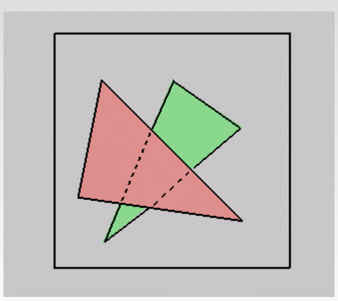
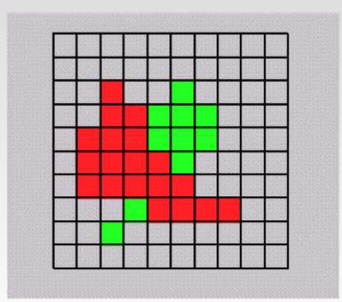
The Z-Buffer Algorithm

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





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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

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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

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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
    }
  }
}
```

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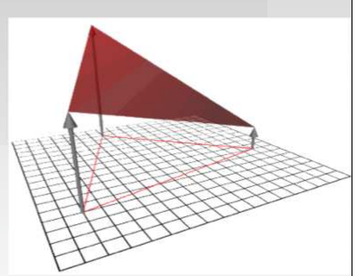
Interpolating Z

Edge walking

- Just interpolate Z along edges and across spans

Barycentric coordinates

- Interpolate z like other parameters
- E.g. color



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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***

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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:

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

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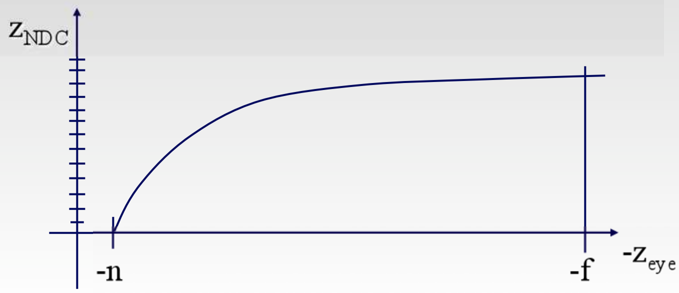
Depth Test Precision

- 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*



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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

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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?

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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

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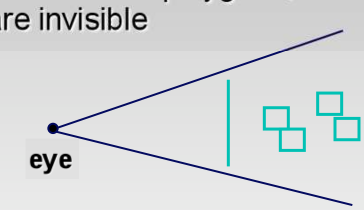
Z-Buffer Cons

Poor for scenes with high depth complexity

- Need to render all polygons, even if most are invisible



Shared edges are handled inconsistently

- *Ordering dependent*

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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*

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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

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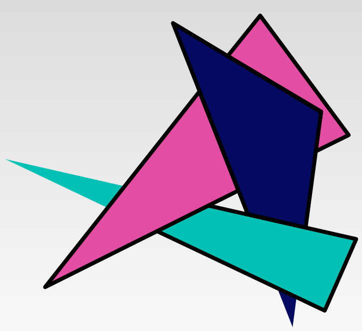
Object Space Visibility Algorithms

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



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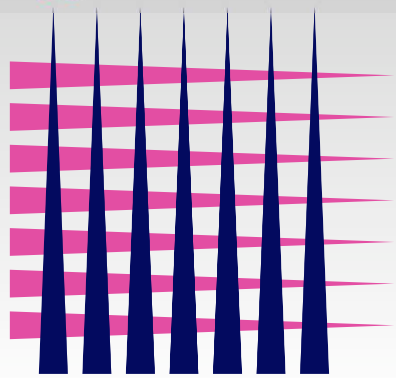
Object Space Visibility Algorithms

What is the minimum worst-case cost of computing the fragments for a scene composed of *n* polygons?

Answer:
$O(n^2)$



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Object Space 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 one:
  - Binary Space Partition (BSP) Trees
  - *Still in use today for ray-tracing, and in combination with z-buffer*

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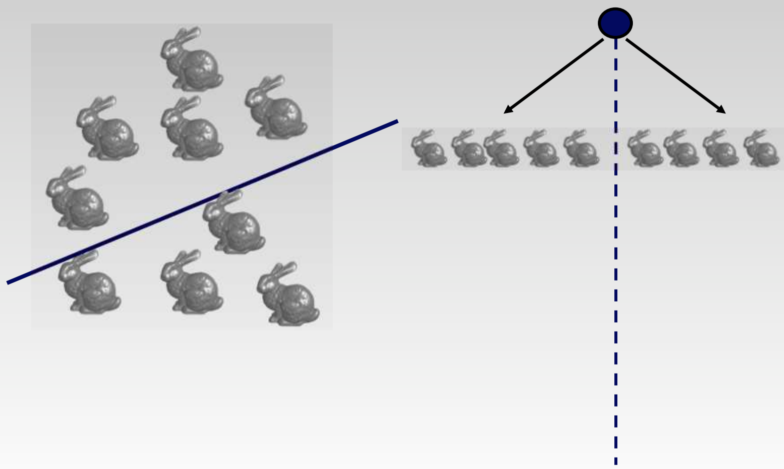
Binary Space Partition Trees (1979)

BSP Tree: partition space with binary tree of planes

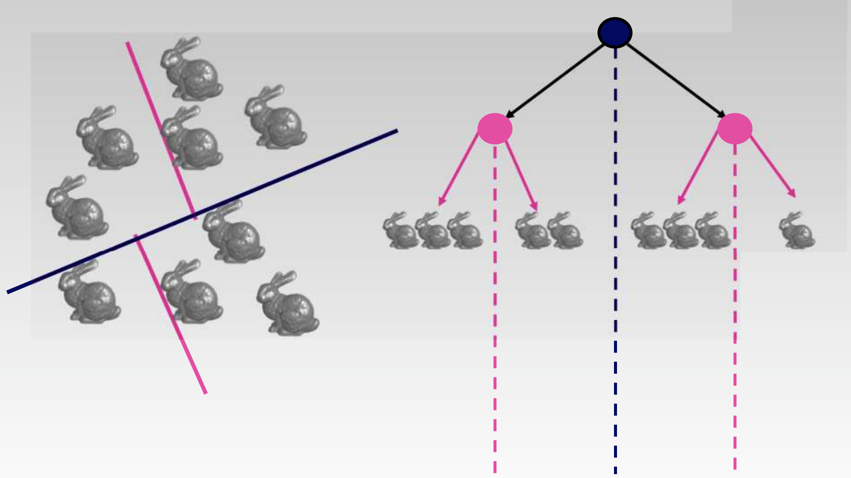
- Idea: divide space recursively into half-spaces by choosing splitting planes that separate objects in scene
- Preprocessing: create binary tree of planes
- Runtime: correctly traversing this tree enumerates objects from back to front

Creating BSP Trees: Objects

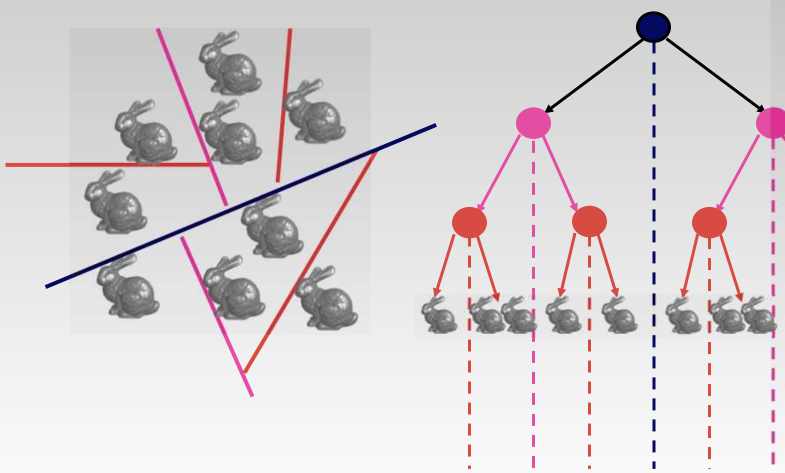
Creating BSP Trees: Objects



Creating BSP Trees: Objects



Creating BSP Trees: Objects



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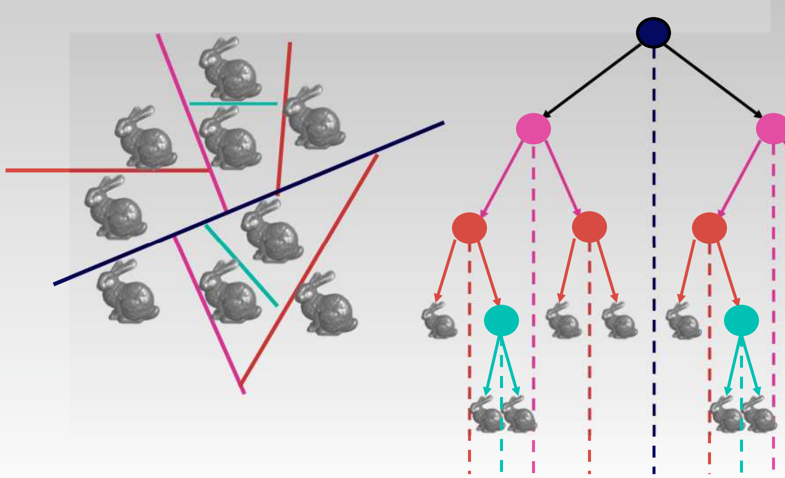
Creating BSP Trees: Objects



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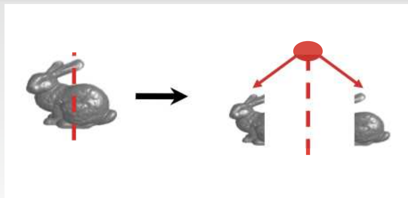
Splitting Objects

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



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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*

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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);
```

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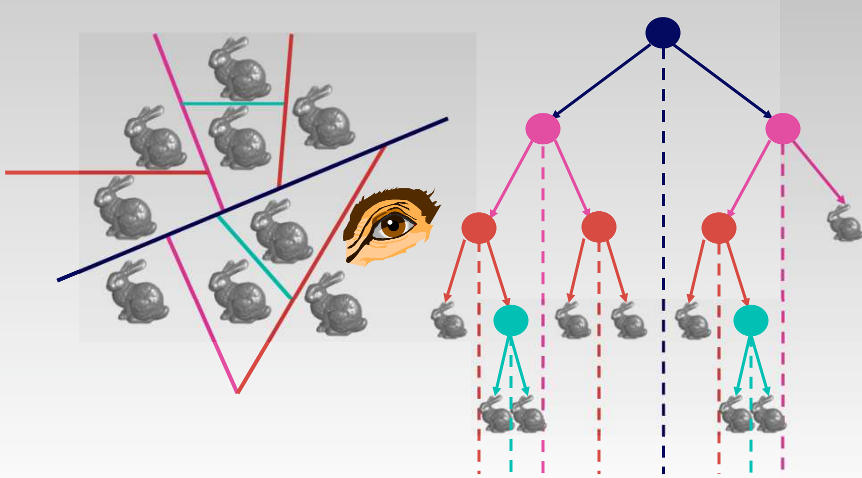
BSP Trees : Viewpoint A



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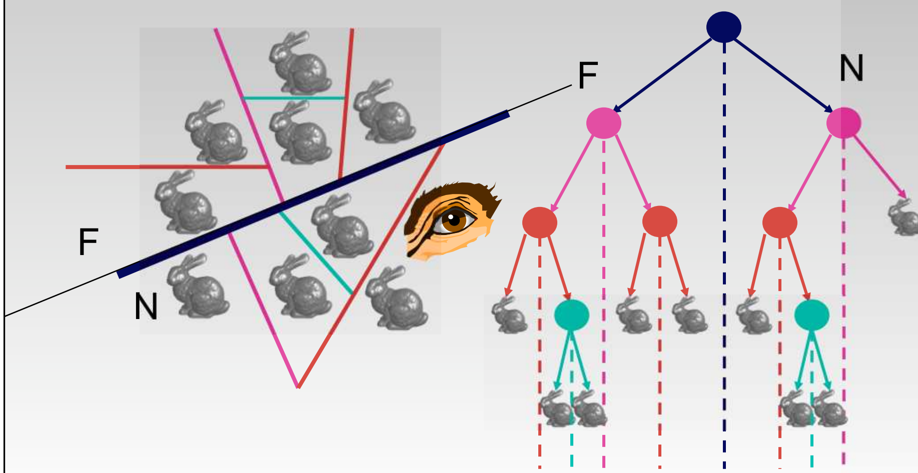
BSP Trees : Viewpoint A



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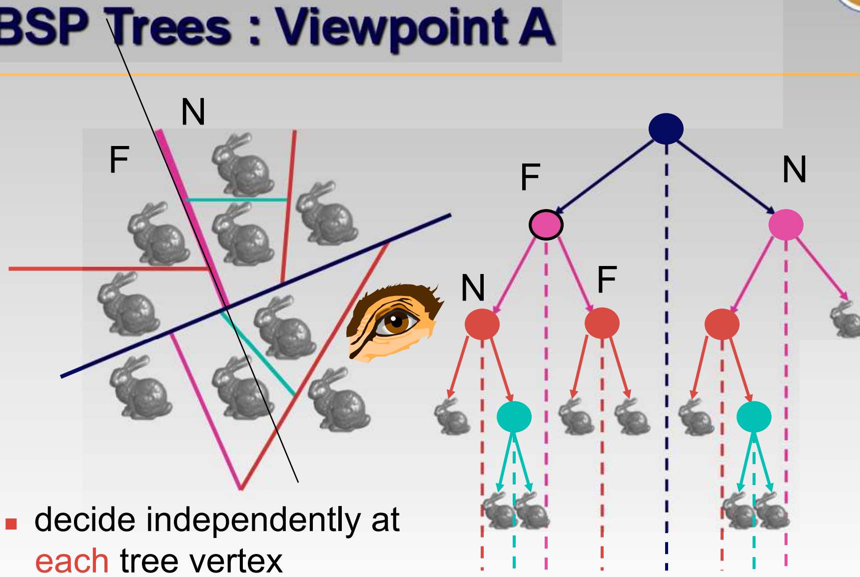
BSP Trees : Viewpoint A



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

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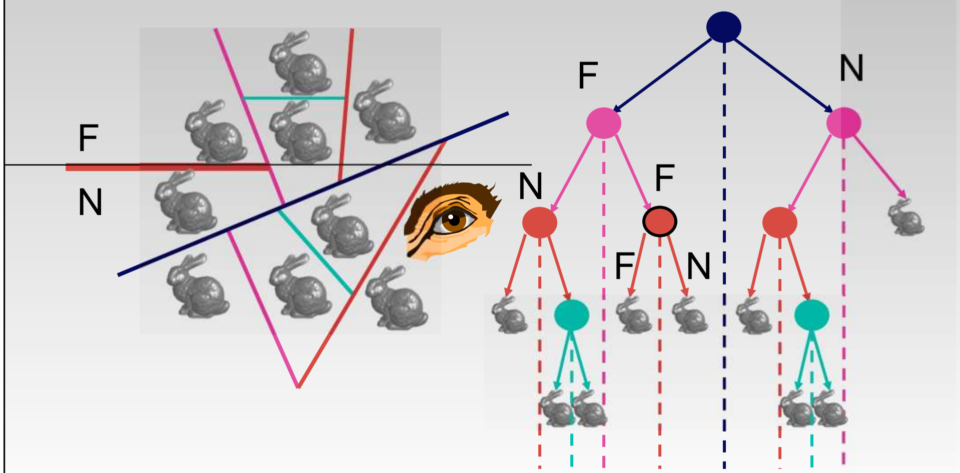
BSP Trees : Viewpoint A



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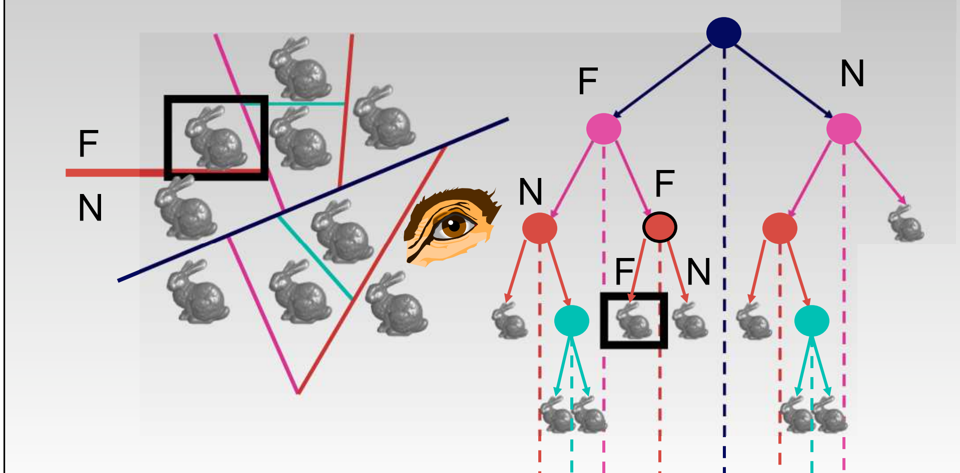
BSP Trees : Viewpoint A



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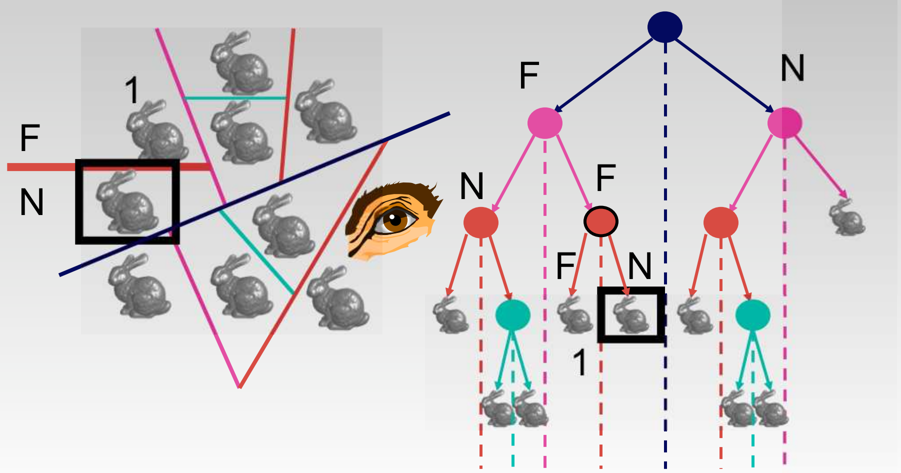
BSP Trees : Viewpoint A



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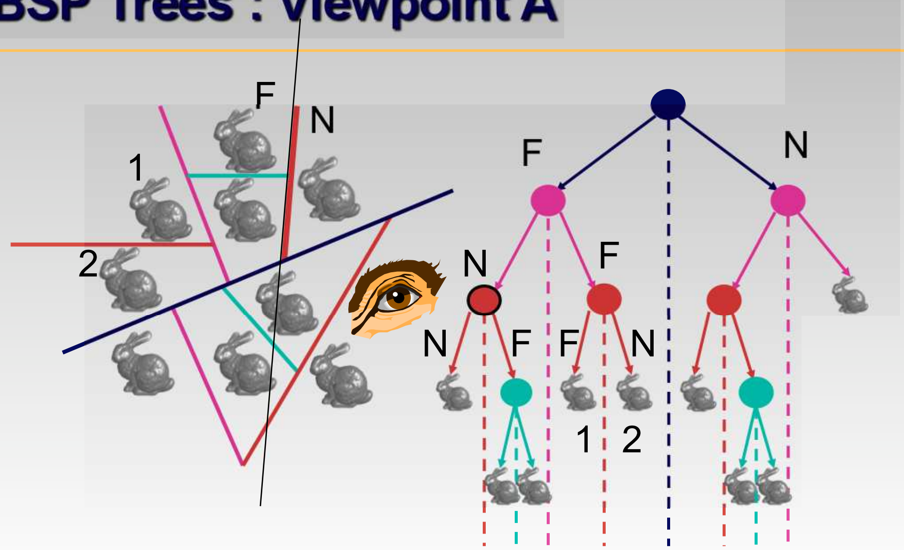
BSP Trees : Viewpoint A



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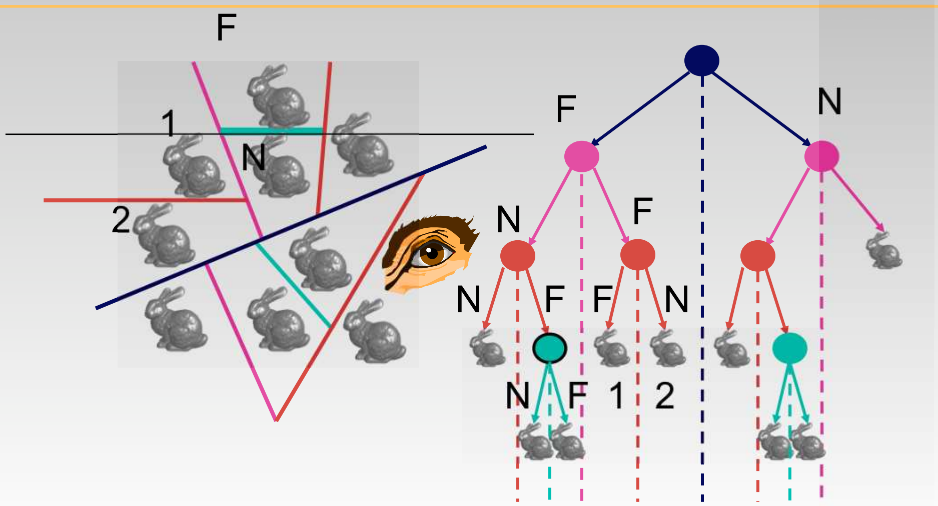
BSP Trees : Viewpoint A



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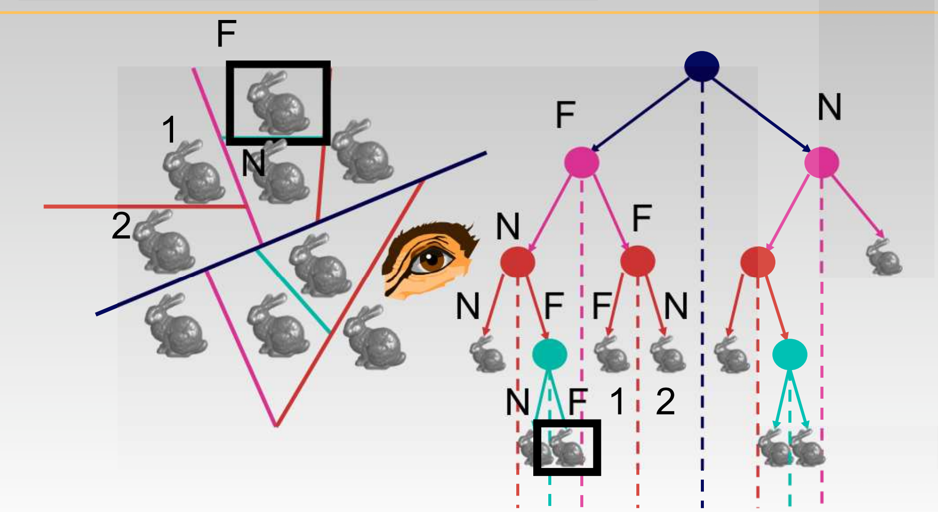
BSP Trees : Viewpoint A



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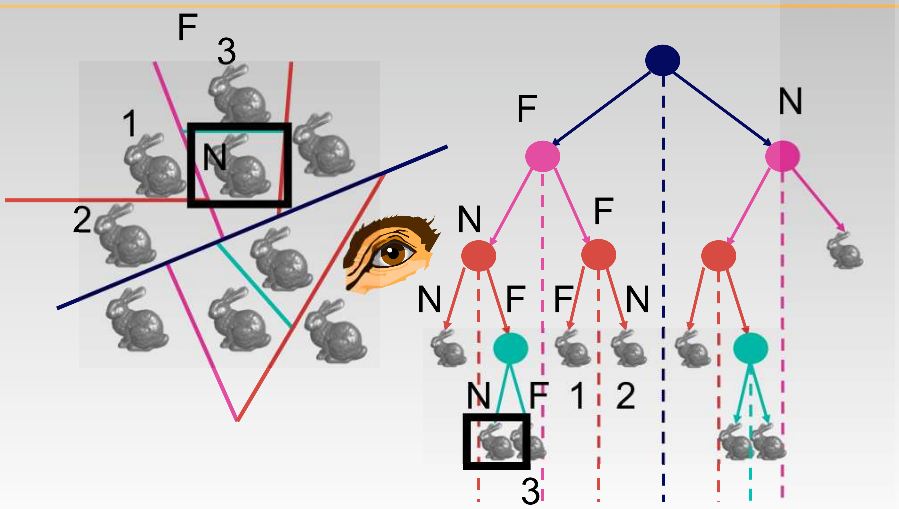
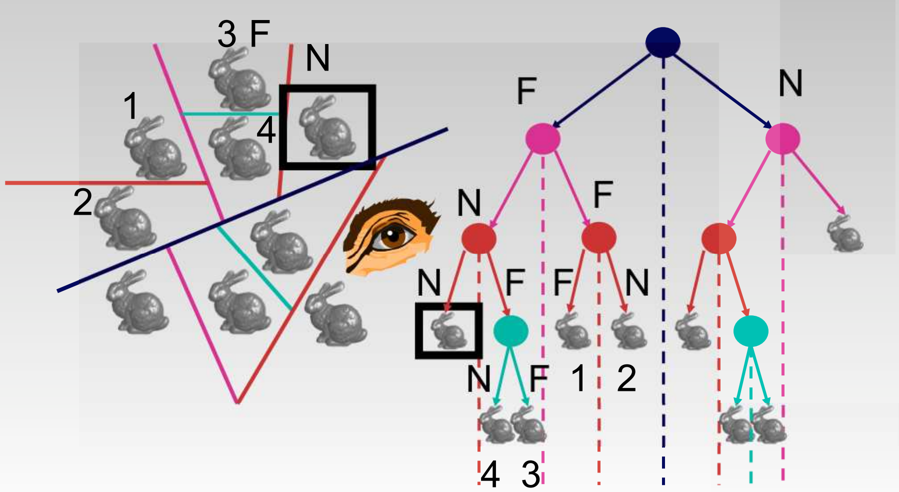
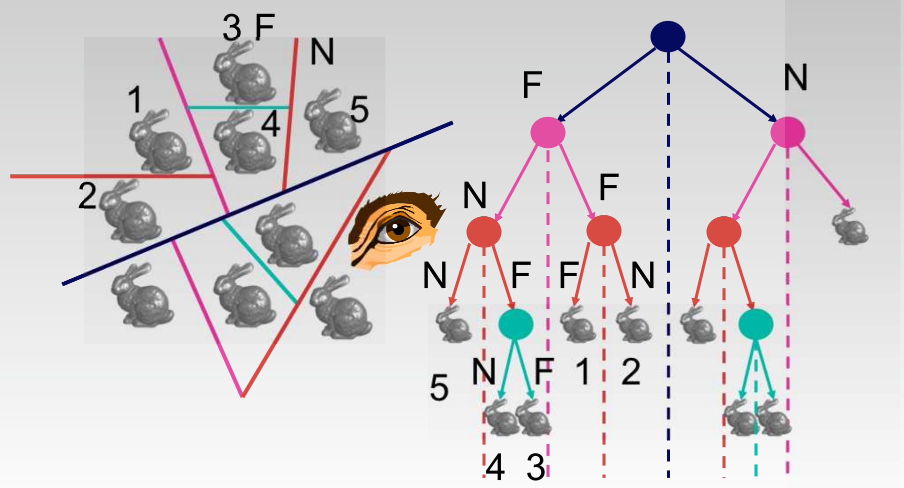
BSP Trees : Viewpoint A



BSP Trees : Viewpoint A



BSP Trees : Viewpoint A



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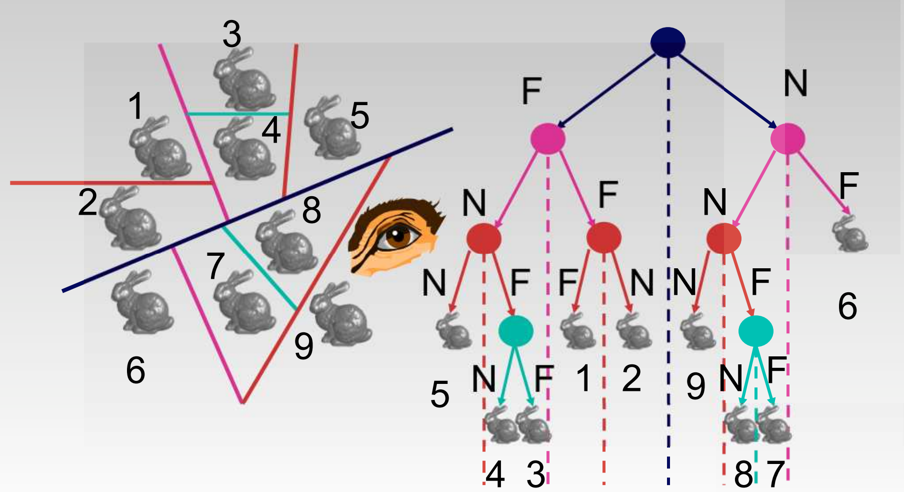
BSP Trees : Viewpoint A



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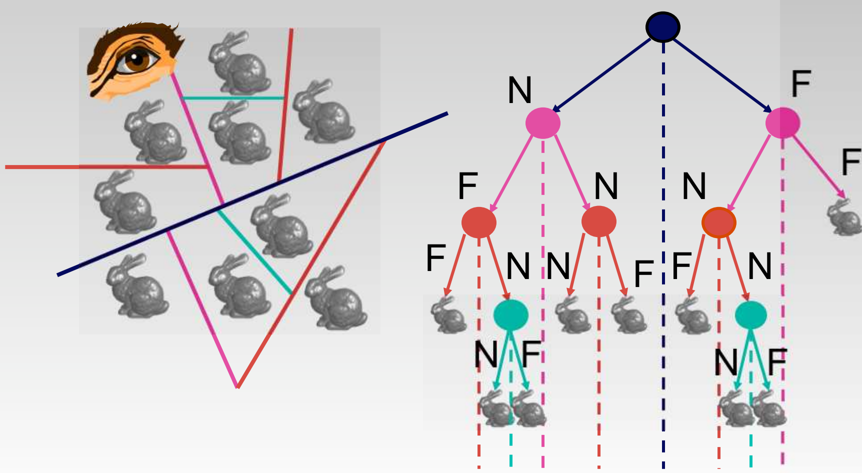
BSP Trees : Viewpoint B



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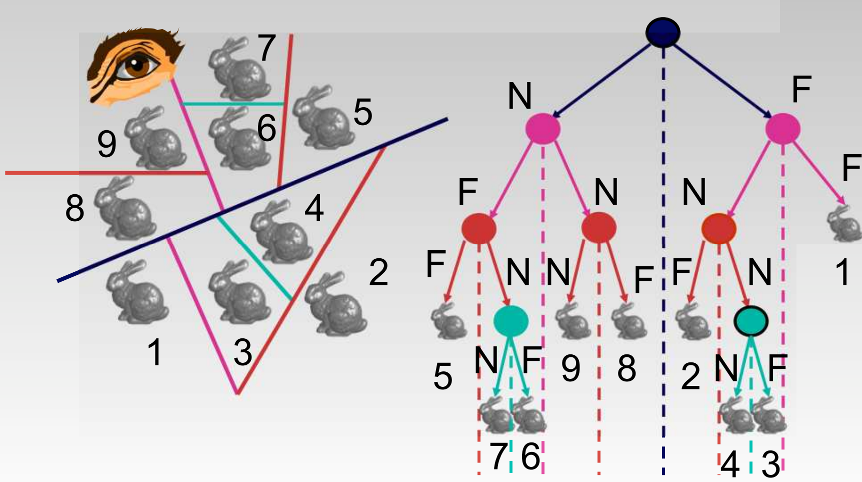
BSP Trees : Viewpoint B



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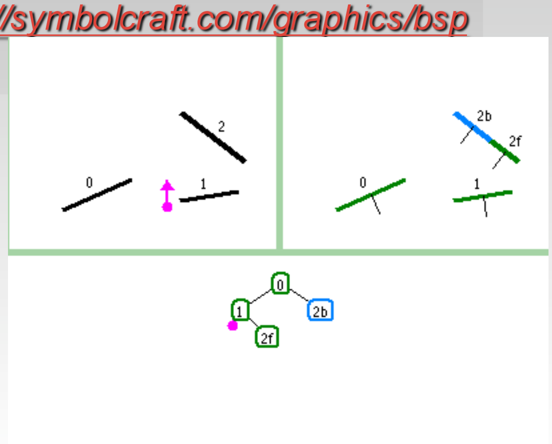
BSP Tree Traversal: Polygons

- 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: $O(n^2)$ worst-case
- Computationally intense preprocessing stage restricts algorithm to static scenes

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Coming Up:

Wednesday

- Blending

Friday / next week

- Texture mapping

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