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Visibility Algorithms

Jiří Bittner

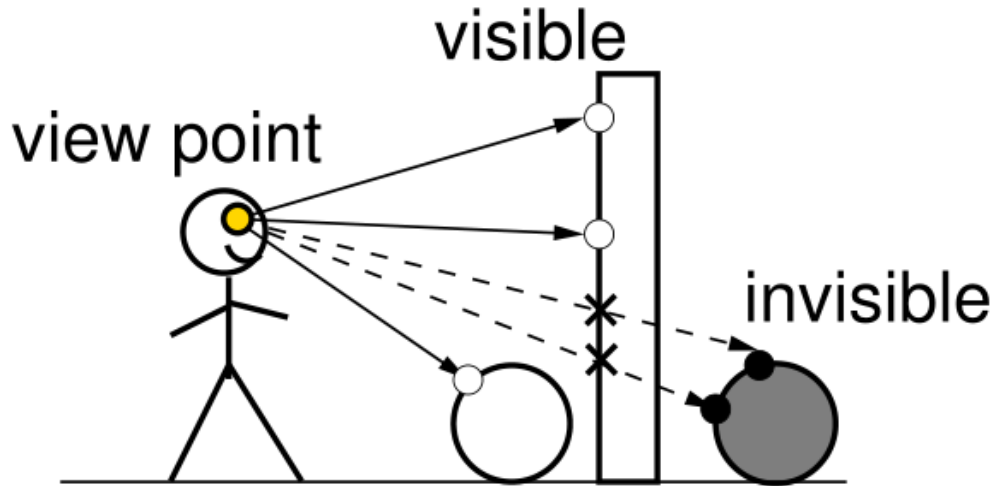
Outline

- Visibility in graphics
- Depth Buffer
- Ray Casting
- Painter's algorithm
- BSP Trees
- Warnock's Algorithm
- Specialized Visibility Algorithms

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Visibility - Introduction

- Points A,B visible \Leftrightarrow line segment AB does not intersect opaque object
- Example: visibility from a view point



Visibility in Computer Graphics

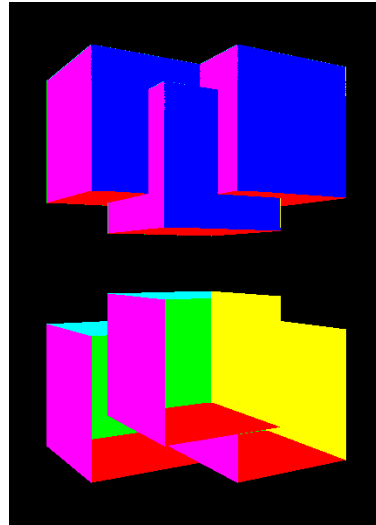
- Hidden surface removal
- Shadows
- Radiosity
- Ray Tracing
- Visibility culling

- Games / Multi-User Environments
- Streaming

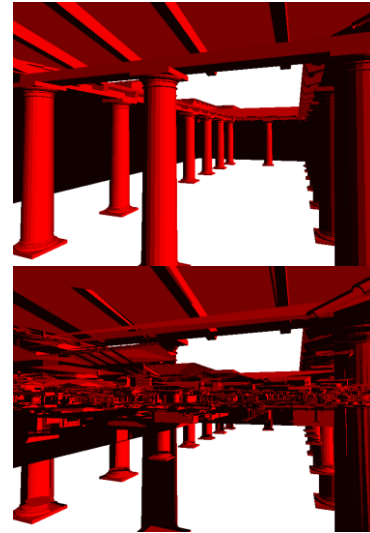
Hidden surface removal

- Creating “correct” 2D image of 3D scene
 - Finding visible objects and their visible parts
 - Eliminating invisible objects and invisible parts

ON



OFF



Visibility algorithms

- Raster algorithms (image space)
 - Solve visibility for pixels
 - For each pixel
 - Find nearest object projected to pixel
 - Shade the pixel using object color
 - Algorithms: z-buffer, ray casting, painters alg.
- Vector algorithms (object space)
 - Vector based description of visibility
 - For each object
 - Find object parts not hidden by others
 - Draw visible/invisible parts
 - Algorithms: Naylor, Weiler-Atherton, Roberts
 - CAD systems, technical drawings, special applications

Complexity: $O(P.N)$

P .. #pixels
N .. #objects

Complexity: $O(N^2)$

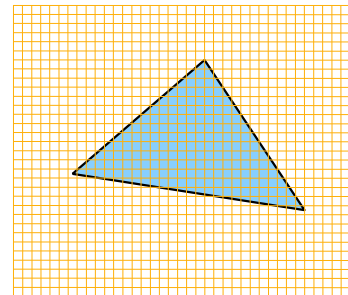
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Depth buffer (Z-buffer)

- Ed Catmull – 1975
 - Co-founder and president of Pixar
- Wolfgang Strasser - 1975
- For each pixel depth of the nearest object
- Process objects in **arbitrary order**
 1. Rasterize to fragments
 2. Compare depth of each fragment with z-buffer content
 3. If closer overwrite z-buffer and pixel color



Depth buffer – pseudocode

- Two arrays: `z_buffer`, `color_buffer`

```
Clear color_buffer;  
Set z-buffer to “infinity”;  
for (each object) {  
  for (each object pixel P[x,y]) {  
    if (z-buffer[x,y] > P[x,y].depth) {  
      z_buffer[x,y] = P[x,y].depth;  
      color_buffer[x,y] = P[x,y].color;  
    }  
  }  
}
```

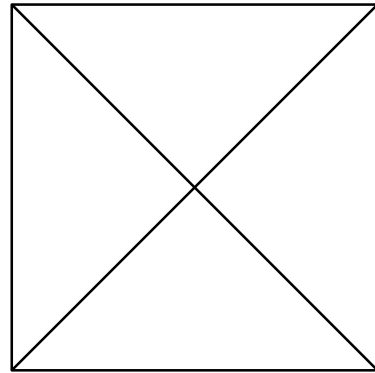
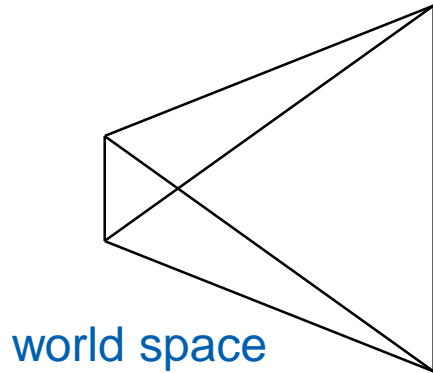
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Depth buffer - details

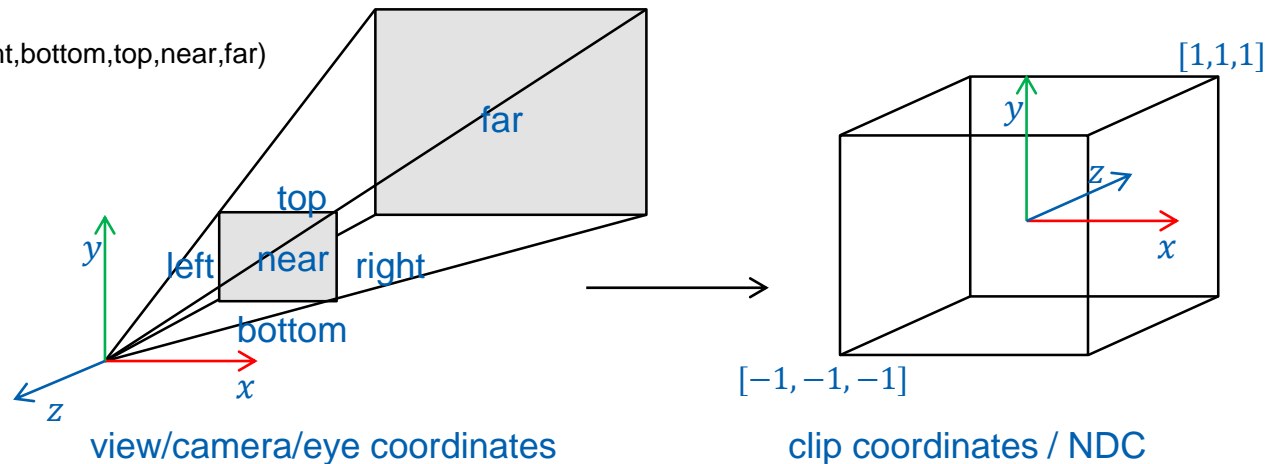
- Computing pixel depth - interpolation
- Linear interpolation of $z'' \sim 1/z$ (z'' - device coordinates)
- For perspective projection depth resolution is non-uniform
 - Nearer objects have higher depth resolution



- **z-fighting** when rendering farther objects

Perspective projection - OpenGL

- glFrustum(left,right,bottom,top,near,far)



$$M = \begin{bmatrix} \frac{2near}{right - left} & 0 & \frac{right + left}{right - left} & 0 \\ 0 & \frac{2near}{top - bottom} & \frac{top + bottom}{top - bottom} & 0 \\ 0 & 0 & \frac{near + far}{near - far} & \frac{2 far near}{near - far} \\ 0 & 0 & -1 & 0 \end{bmatrix}$$

Perspective projection

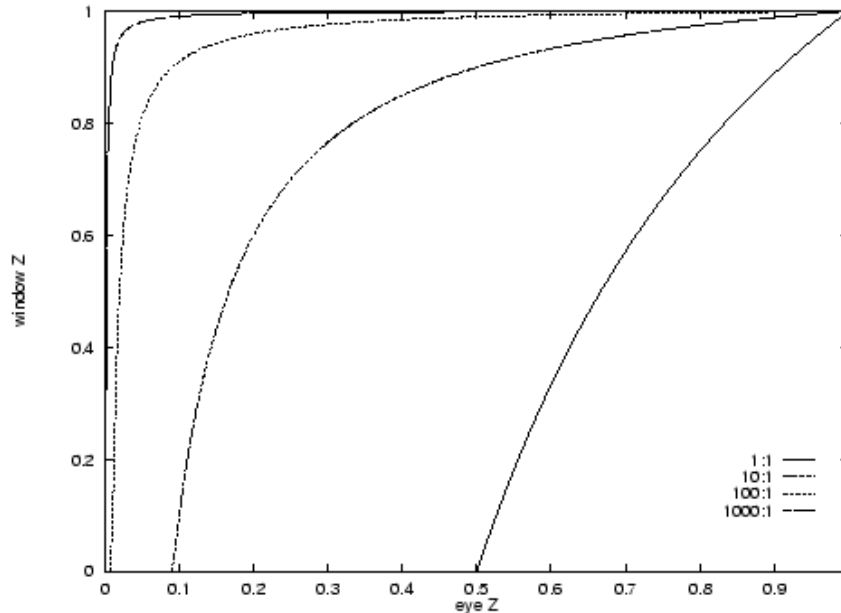
$$M = \begin{bmatrix} \frac{2near}{right - left} & 0 & \frac{right + left}{right - left} & 0 \\ 0 & \frac{2near}{top - bottom} & \frac{top + bottom}{top - bottom} & 0 \\ 0 & 0 & \frac{near + far}{near - far} & \frac{2 far near}{near - far} \\ 0 & 0 & -1 & 0 \end{bmatrix}$$

$$x' = \frac{2 near}{left - right} \frac{x}{z} - \frac{right + left}{right - left}$$

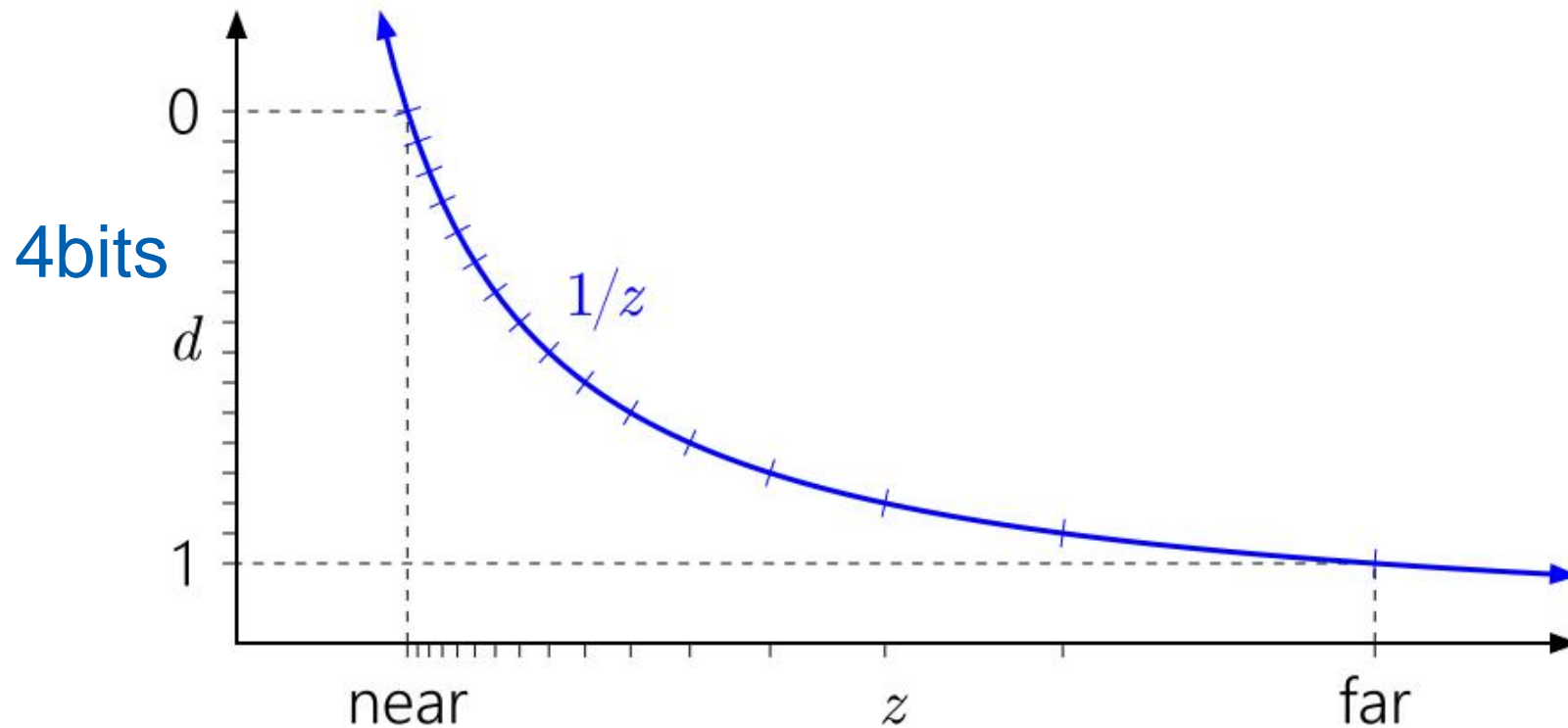
$$z' = \frac{near + far}{far - near} + \frac{2 far near}{far - near} \frac{1}{z}$$

Depth distributions in z-buffer

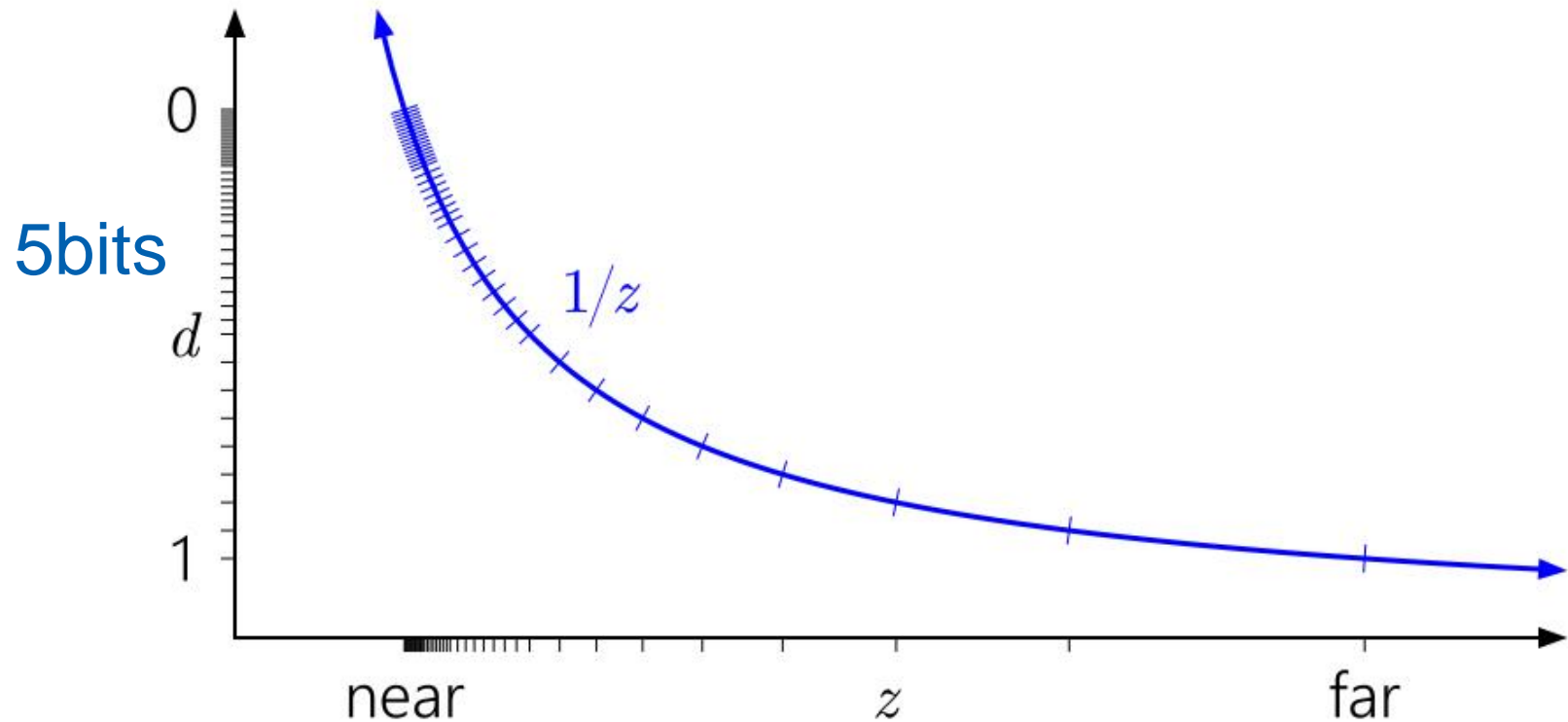
- Careful setting of near-far planes
 - near = 1 / far = 10 : 50% between 1.0 a 1.8
 - near = 0.01 / far = 10 : 90% between 0.01 – 0.1
 - Median = $2 \cdot \text{near} \cdot \text{far} / (\text{near} + \text{far})$



Depth Precision Issues - Example



Depth Precision Issues - Example

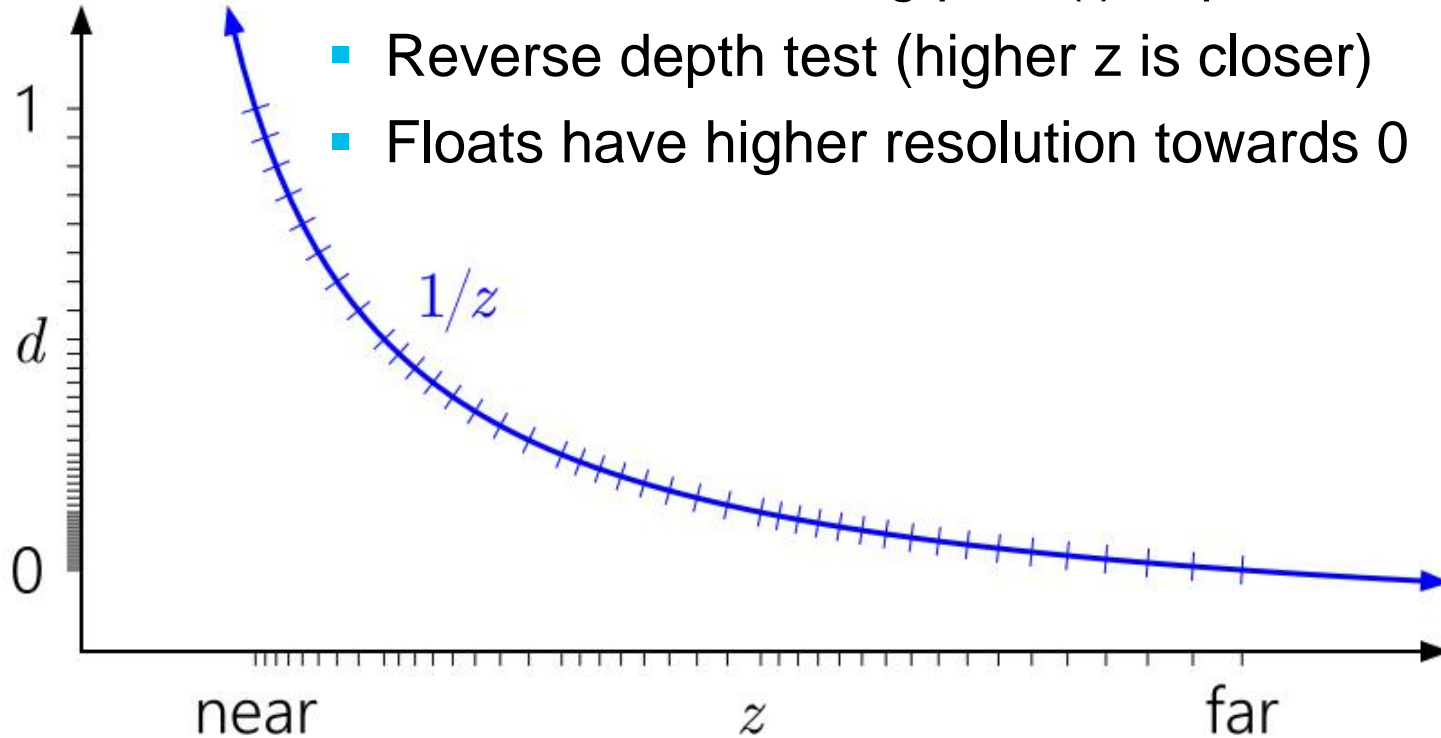


Resolving Z-fighting

- Careful settings of near(!) and far planes
- Rendering close and far objects
 - Several passes, updating near/far
 - combine using stencil
- W-buffer
 - stores eye space z, linear depth distribution
 - reciprocal of z_i' for each pixel
- Reverse z
 - Lapidous and Jiao. Optimal depth buffer for low-cost graphics hardware. HWWS '99.
 - <https://developer.nvidia.com/content/depth-precision-visualized>

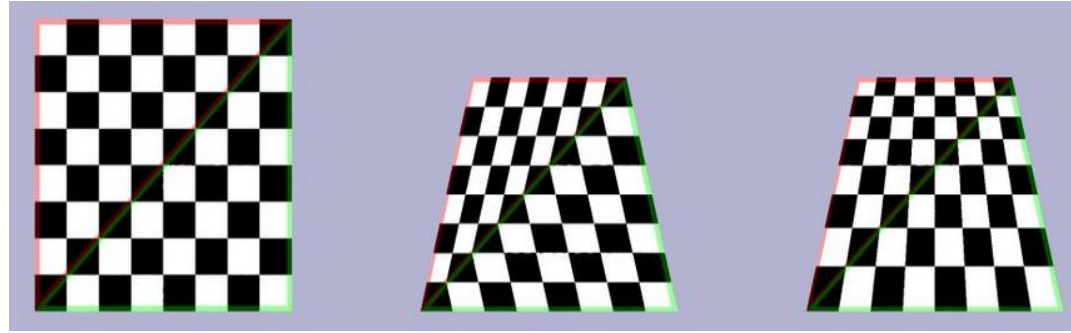
Reverse Z

- Use $1-z'$ and floating point(!) depth buffer
- Reverse depth test (higher z is closer)
- Floats have higher resolution towards 0



Perspectively correct interpolation

- LERP in screen space
 - non linear in object space (hyperbola) !
- Solution for color
 - Compute $c' = c/z$ and $z' = 1/z$
 - LERP of c' and z'
 - For each pixel $c_i = c'_i / z'_i$
- The same for texture coordinates u, v (!)
- Note: OpenGL stores $1/z$ in w' component after persp. divide
 - Compute $w' = 1/z$ and $c' = c * w'$
 - LERP of c' and w'
 - For each pixel $c_i = c'_i / w'_i$



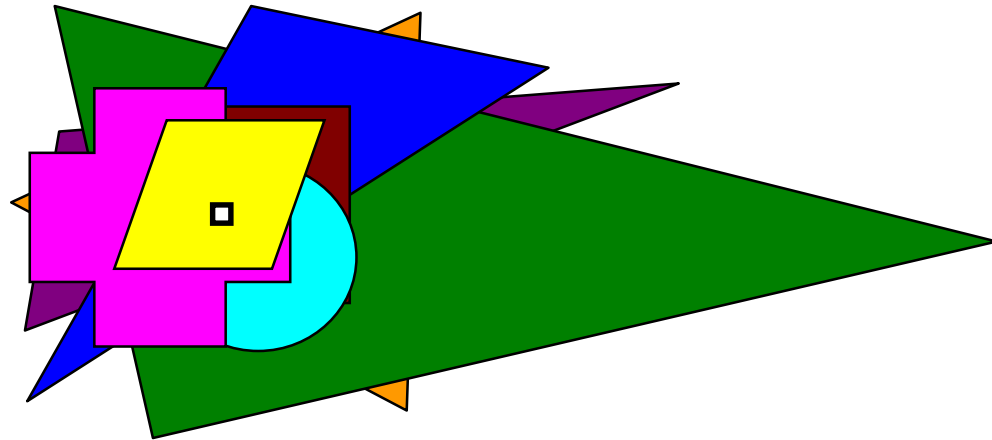
Depth buffer - properties

- **Benefits**
 - Simplicity
 - No preprocessing or sorting
 - Easy parallelization and HW implementation
- **Issues**
 - Pixel overdraw
 - Mapping depth to z-buffer bit range
 - Transparent objects
 - Alias

Quiz – number of overdraws

- 10 polygons project to pixel in random order
- What is the average number of overdraws?

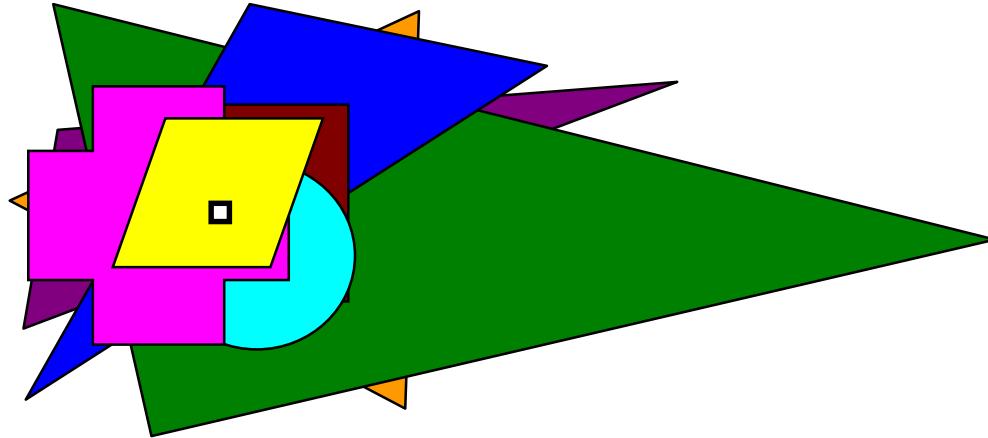
- a) 3
- b) 5.5
- c) 7



Source: Eric Haines - Subtle Tools

Intuitive answer

- Front-to-back 1x, back-to-front 10x
- So the average is 5.5 overdraws



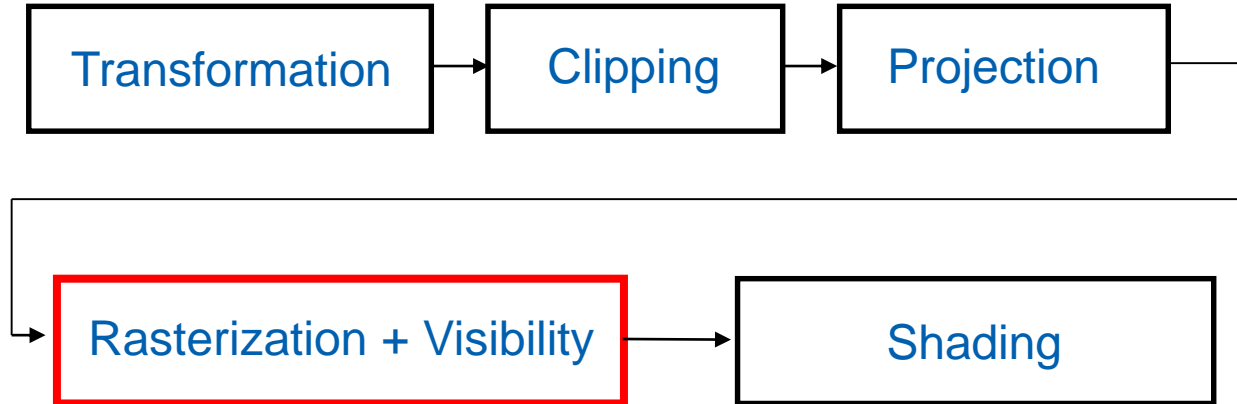
Correct answer

- The first polygon must cause overflow: 1
- The second is either back or front
 - Chance of overflow: $\frac{1}{2}$
- Third polygon
 - $\frac{1}{3}$ chance that it is the closest and causes overflow
- Harmonic series: $1 + \frac{1}{2} + \frac{1}{3} + \dots + \frac{1}{10} = 2.9289$

1 poly	1x
4 polys	2.08x
11 polys	3.02x
31 polys	4.03x
83 polys	5.00x
12,367 polys	10.00x

Aproximation for big N
 $\text{overflow}(N) = \ln(N) + 0.57721$

Depth buffer in image pipeline



Depth buffer in OpenGL

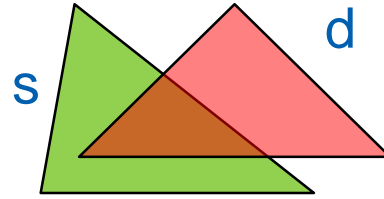
- `glutInitDisplayMode (... | GLUT_DEPTH | ...);`
- `glEnable(GL_DEPTH_TEST);`
- `glDepthFunc(GL_LESS);`
- `glClear(GL_DEPTH_BUFFER_BIT);`
- `glDepthMask(mask);`
 - `GL_TRUE` read/write
 - `GL_FALSE` read only

Depth buffer and transparent objects

- Draw all non-transparent objects using z-buffer
- Sort all transparent objects back-to-front
- Render transparent objects with alpha-blending
 - OpenGL:
 - `glDepthMask(GL_FALSE);`
 - `glBlendFunc(gl.ONE, gl.ONE_MINUS_SRC_ALPHA);`
 - `glEnable(GL_BLEND);`
- Depth peeling
 - Iterative rendering layer by layer
 - Additional depth check: if $z(\text{current_layer}) \geq z(\text{prev_layer}) \rightarrow$ cull
 - Use “shadow test + alpha test” (Everitt 2001)

Alpha blending – Over & Under operator

- $C=(r, g, b, \alpha)$
- α opacity
 - $\alpha = 0$ transparent
 - $\alpha = 1$ opaque



$$C = \alpha_s C_s + (1 - \alpha_s) C_d$$

s over d

$$C = \alpha_s (1 - \alpha_d) C_s + \alpha_d C_d$$
$$\alpha = \alpha_s (1 - \alpha_d) + \alpha_d$$

s under d

Depth buffer – Questions

- Should we draw back to front or front to back? And should we care?
- How to increase depth resolution?
- When to perform the depth test?
- How to handle transparent objects?

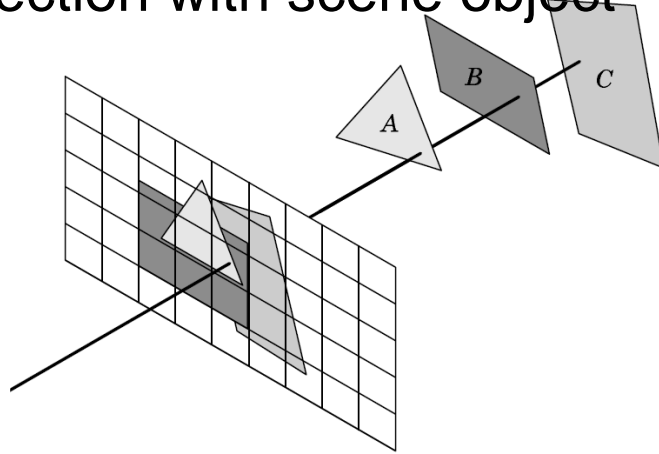
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Ray casting

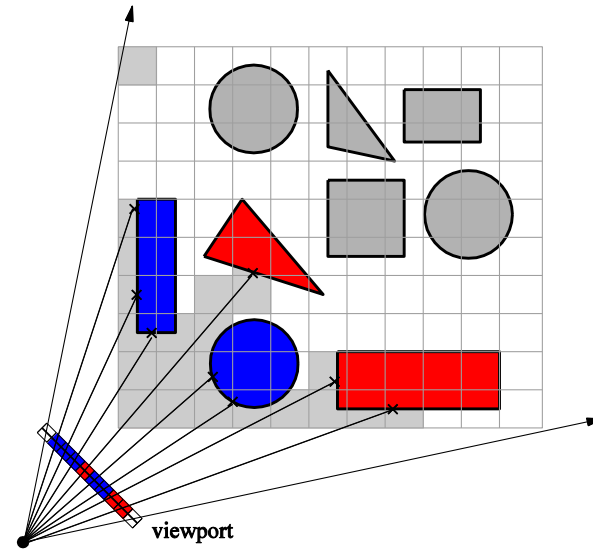
- Cast ray for each image pixel [Appel68]
- Find the nearest intersection with scene object



- Complexity
 - Naive: $O(R \cdot N)$
 - With spatial data structure: $O(R \cdot \log N)$

Accelerated ray casting

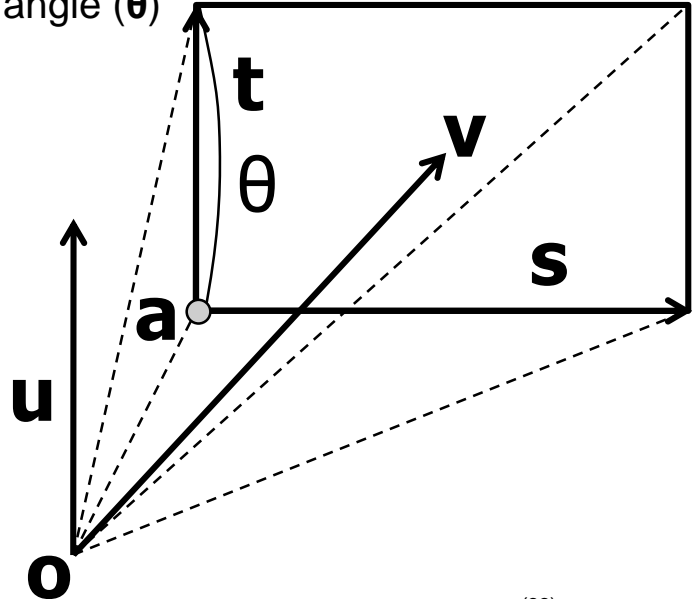
- Step 1: construct spatial DS
 - Preprocessing
 - BVH, kD-tree, octree, 3D grid
- Step 2: find the nearest intersection
 - Walk through cells intersected by the ray
 - Intersection found: terminate



Ray Casting – Generating (Primary) Rays

- Implicit camera parameters
 - MVP matrix inversion
- Explicit knowledge of camera parameters
 - position (\mathbf{o}), view direction (\mathbf{v}), up vector (\mathbf{u}), view angle (θ)

1. Compute view coordinate system: \mathbf{a} , \mathbf{s} , \mathbf{t}
2. Ray through pixel x , y (image size width \times height):
ray_origin = \mathbf{o} ;
ray_dir = $\text{Normalize}(\mathbf{a} + x/\text{width} * \mathbf{s} + y/\text{height} * \mathbf{t} - \mathbf{o})$;



Ray casting - properties

- Benefits

- Flexibility (adaptive raster, ray tracing)
- Efficient culling of occluded objects

- Drawbacks

- Lower use of coherence
- Requires spatial DS
 - Issue for dynamic scenes and HW implementation

Z-buffer vs. Ray Casting

	Scan-line coherence	Requires preprocessing	Efficient handling of occluded objects
Z-buffer	yes +	no +	no -
Ray casting	no -	yes -	yes +

Z-buffer better for dynamic scenes with low occlusion

Ray casting better for complex highly occluded scenes

Z-buffer GPU optimizations

- Z-cull
 - z_{\min}, z_{\max} for 8x8 pixel blocks
 - If $\text{tri}_{z_{\min}} > \text{tile}_{z_{\max}}$ discard
- Early-z test (for each pixel)
 - Apply z-test before shader execution
 - On newer GPUs used by default
 - Switched off when modifying “z” in shader
- HW occlusion queries, conditional rendering

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Painter's algorithm

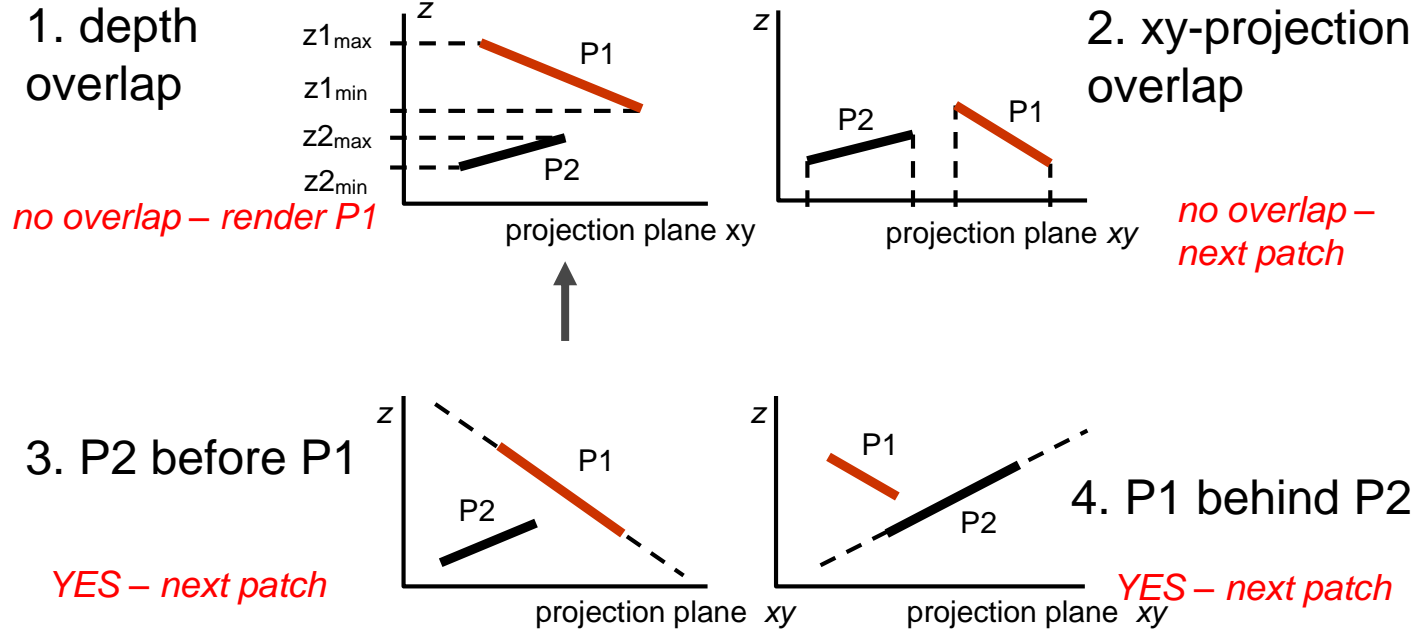
- Rendering back to front
- Farther patches overwritten by closer ones
- Used in 2D drawing tools (layers)

- In 3D without explicit ordering more complicated
- Depth sort algorithm [Newell72]

Depth Sort Painter's algorithm

- Sort patches using z_{\max} of each patch
- Farthest patch = candidate for rendering (P1)
- Series of tests to confirm the candidate using remaining patches

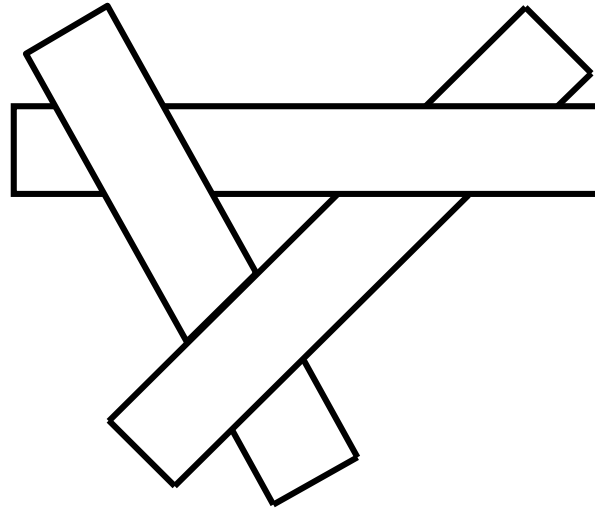
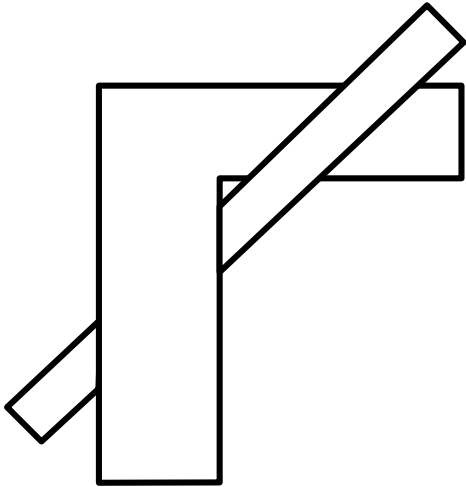
Depth Sort Painter's algorithm – cont.



Tests failed: swap (P2 = new candidate)

Cycle of candidates

- Can be detected using counter for candidate
- Solved by cutting the patch



Painter's algorithm - properties

- **Benefits**
 - No depth buffer needed
 - Simplified version: easy implementation
- **Issues**
 - Overdraw
 - Correct depth order
 - Self intersections of patches not allowed

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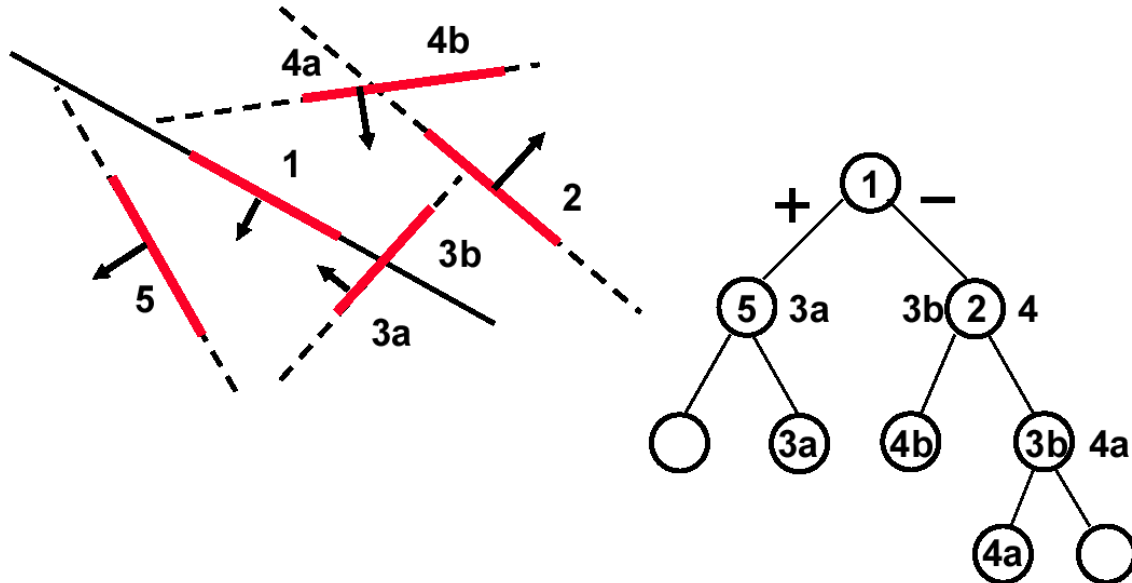
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Binary Space Partitioning (*BSP*)

- View independent sorting of the scene [Fuchs80]
- Two phases
 - BSP tree construction (1x)
 - Tree traversal and rendering (as painter's alg.)

BSP Tree Construction

- Recursive splitting by planes
- Planes typically defined using scene polygons



Rendering with BSP tree

```
void RenderBSP (Node S)
if (camera in front of S.plane) {
    RenderBSP (S.back);
    Render(S.polygons);
    RenderBSP (S.front);
}
else {
    RenderBSP (S.front);
    Render(S.polygons);
    RenderBSP (S.back);
}
}
```

BSP tree and Z-buffer

- Reduce number of overdraws
- Traverse front-to-back (reverse order compared to painter's alg.)
- Alternatives to BSP tree
 - kD tree, octree, BVH

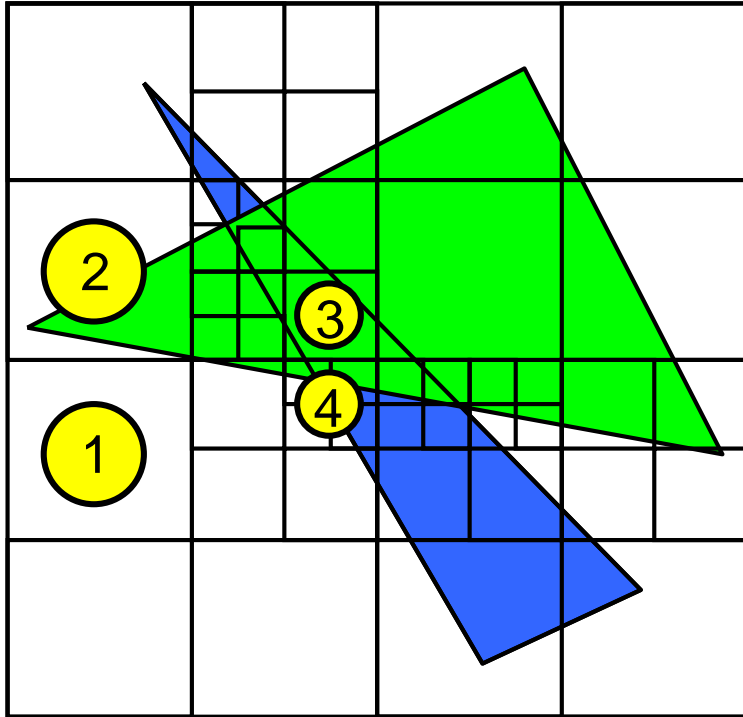
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Image Subdivision – Warnock's alg.

- Recursive fast rectangle clipping tests
- Recursion terminates in pixel /subpixel



Divide and Conquer [Warnock69]

1. No object: *background color*
2. One object: *render*
3. More objects, one closest: *render closest*
4. *Recursively subdivide*

Scan-line Algorithms

- Sort primitives by scan lines (Y)
- Compute spans: intersections of primitives and scan lines
- Elementary spans: intersection of spans
- Sort elementary spans (X)
- Find the closest object for each elementary span (Z)
- [Watkins70]
 - Bubble sort for X and Y
 - $O(\log n)$ search for Z

Outline

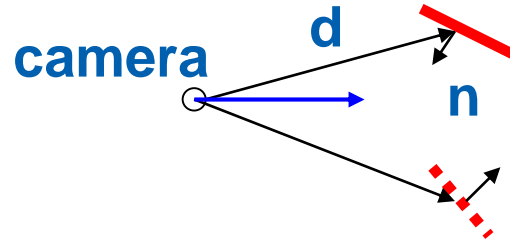
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Back-face Culling

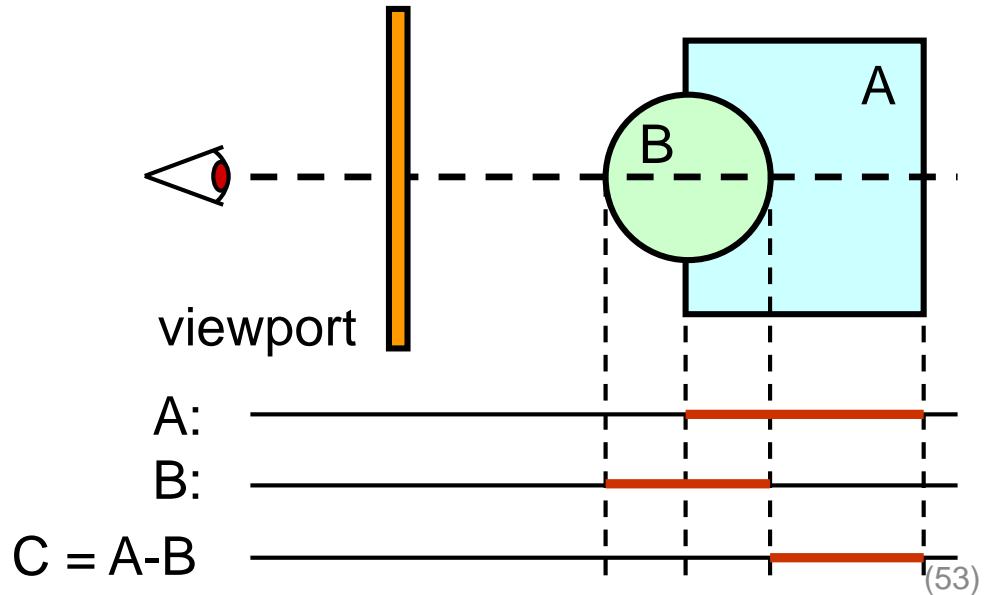
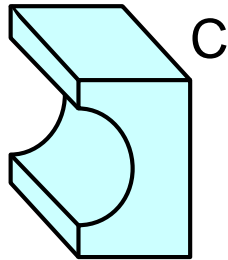
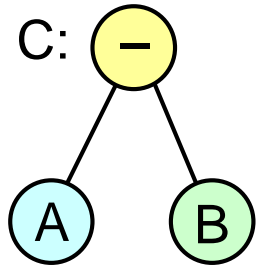
- Eliminates ~ 50% polygons
- If $d \cdot n > 0$: cull
- In NDC: just check for sign of n'_z
 - Computed from transformed vertices (not shading normal)
- OpenGL:

```
glFrontFace(GL_CCW);  
glCullFace(GL_FRONT);  
glEnable(GL_CULL_FACE);
```



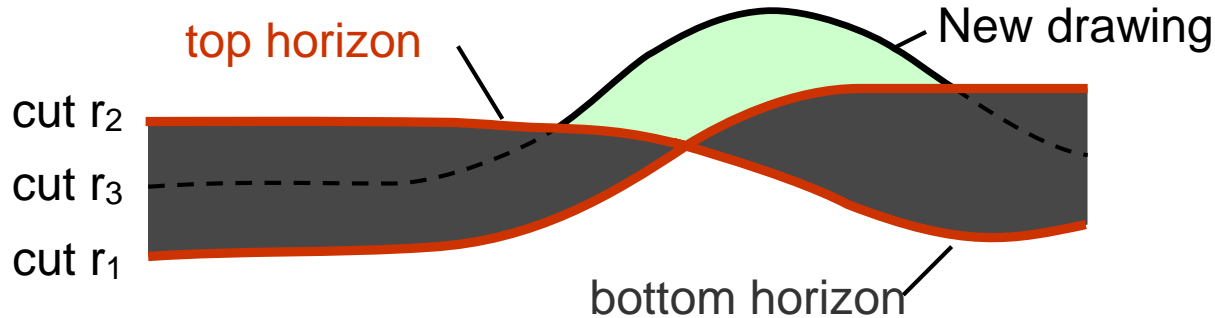
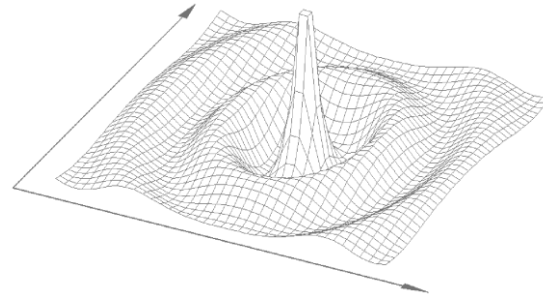
Direct rendering of CSG models

- Specialized ray casting
- Intervals of ray/object intersections
- Solving set operations = set operations on intervals



Floating horizon algorithm

- Graphs of functions $z = f(x,y)$
- Terrains (height field)
- Algorithm outline
 - Render front-to-back
 - Keep bottom and top horizon



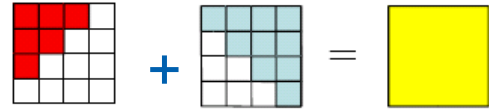
A-Buffer

- Antialiasing, correct transparency
 - [Carpenter84], Lucasfilm: “The Road To Point Reyes”
 - Later used in RenderMan (Pixar)
- Ordered list of primitives for each pixel
- Storing not just depth
 - transparency, coverage, object ID, normal,...
- Polygon rasterization
 - Non-transparent polygon covers the whole pixel – add to list and **remove** farther ones
 - Transparent polygon or partial pixel coverage – insert to list, **do not remove** farther ones

A-Buffer

- Rendering pass

- For each pixel process the list front-to-back
- Composition (subpixel rasterization, coverage mask 4x4)
- Similar to MSAA



- Benefits

- More general than z-buffer
- Used in production rendering
- Handles transparency

Loren Carpenter. 1984. The A -buffer, an antialiased hidden surface method. SIGGRAPH '84.

Other buffers...

A-buffer - Carpenter, 1984
G-buffer - Saito & Takahashi, 1991
M-buffer - Schneider & Rossignac, 1995
P-buffer - Yuan & Sun, 1997
T-buffer - Hsiung, Thibadeau & Wu, 1990
W-buffer - 3dfx, 1996?
Z-buffer - Catmull, 1973 (?)
ZZ-buffer - Salesin & Stolfi, 1989

Accumulation Buffer - Haerberli & Akeley, 1990
Area Sampling Buffer - Sung, 1992
Back Buffer - Baum, Cohen, Wallace & Greenberg, 1986
Close Objects Buffer - Telea & van Overveld, 1997
Color Buffer
Compositing Buffer - Lau & Wiseman, 1994
Cross Scan Buffer - Tanaka & Takahashi, 1994
Delta Z Buffer - Yamamoto, 1991
Depth Buffer - 1984
Depth-Interval Buffer - Rossignac & Wu, 1989
Double Buffer - 1993

Escape Buffer - Hepting & Hart, 1995
Frame Buffer - Kajjiya, Sutherland & Cheadle, 1975
Hierarchical Z-Buffer - Greene, 1993
Item Buffer - Weghorst, Hooper & Greenberg, 1984
Light Buffer - Haines & Greenberg, 1986
Mesh Buffer - Deering, 1995
Normal Buffer - Curington, 1985
Picture Buffer - Ollis & Borgwardt, 1988
Pixel Buffer - Peachey, 1987
Ray Distribution Buffer - Shinya, 1994
Ray-Z-Buffer - Lamparter, Muller & Winckler, 1990
Refreshing Buffer - Basil, 1977
Sample Buffer - Ke & Change, 1993
Shadow Buffer - GIMP, 1999
Sheet Buffer - Mueller & Crawfis, 1998
Stencil Buffer - 1997?
Super Buffer - Gharachorloo & Pottle, 1985
Super-Plane Buffer - Zhou & Peng, 1992
Triple Buffer
Video Buffer - Scherson & Punte, 1987
Volume Buffer - Sramek & Kaufman, 1999

Source: Eric Haines - Is the Hardware Z-Buffer Doomed?

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Questions?