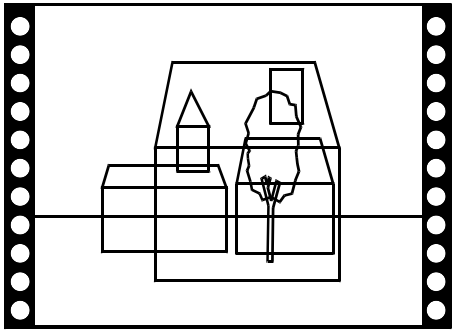
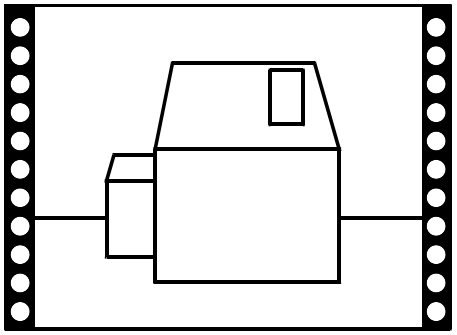
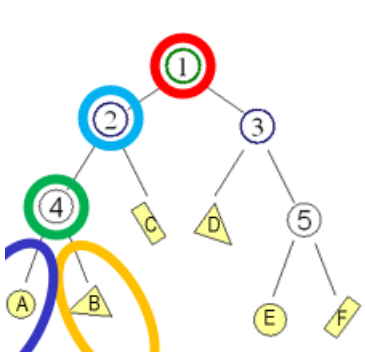
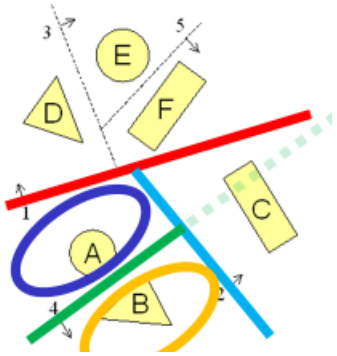
Visibility - CSE160 – Nov 10

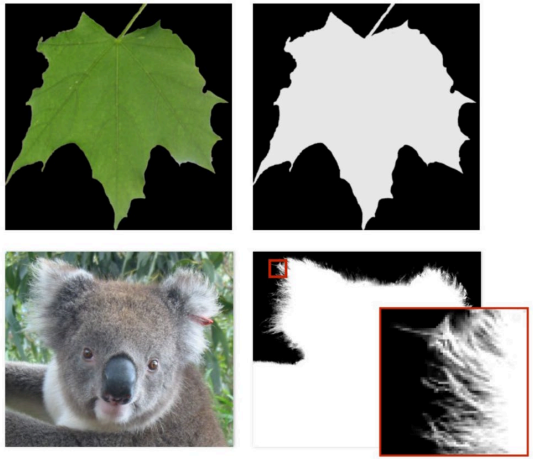
- Visibility Problem Statement
- Depth Buffer
- Compositing
- Back To Front: Painters Algorithm and BSP Trees
- From Vertices to Frame Buffer
- Administrative
- Q&A







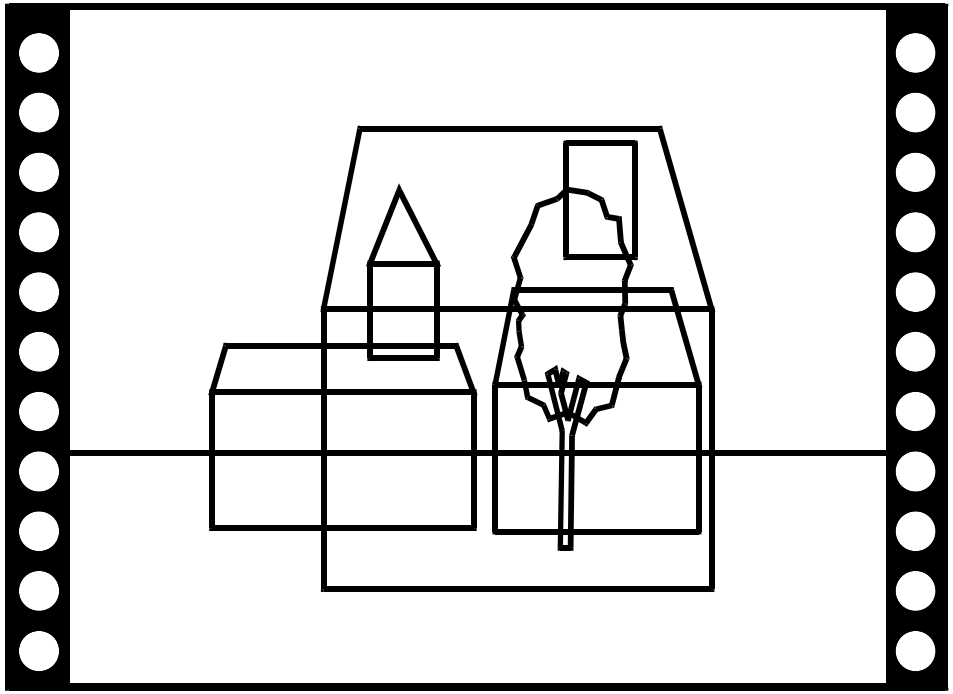


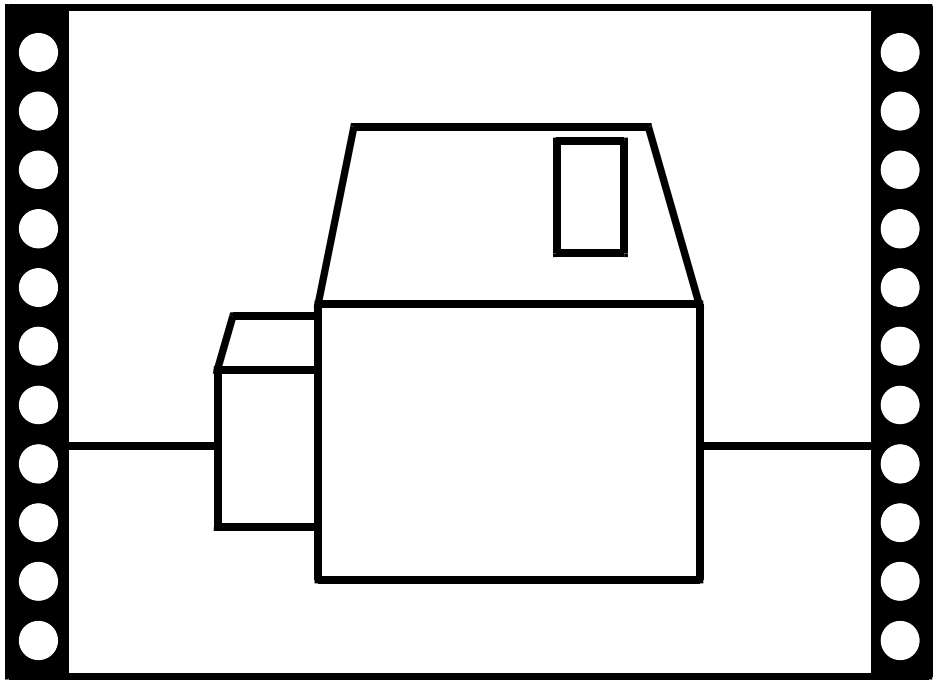


Visibility Problem Statement

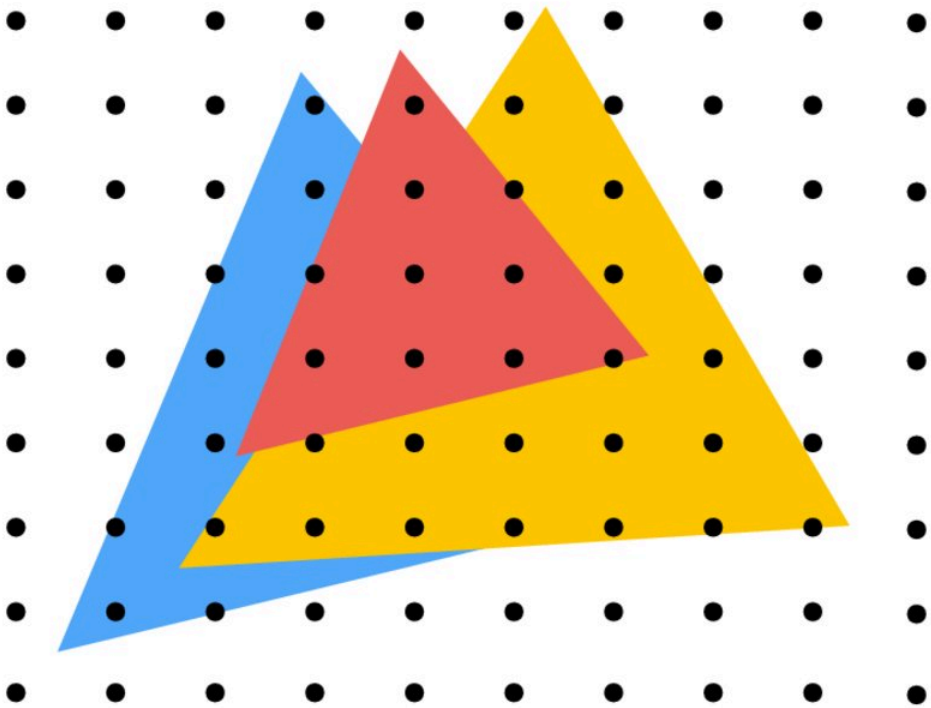
Visibility

- How do we know which parts are visible/in front?

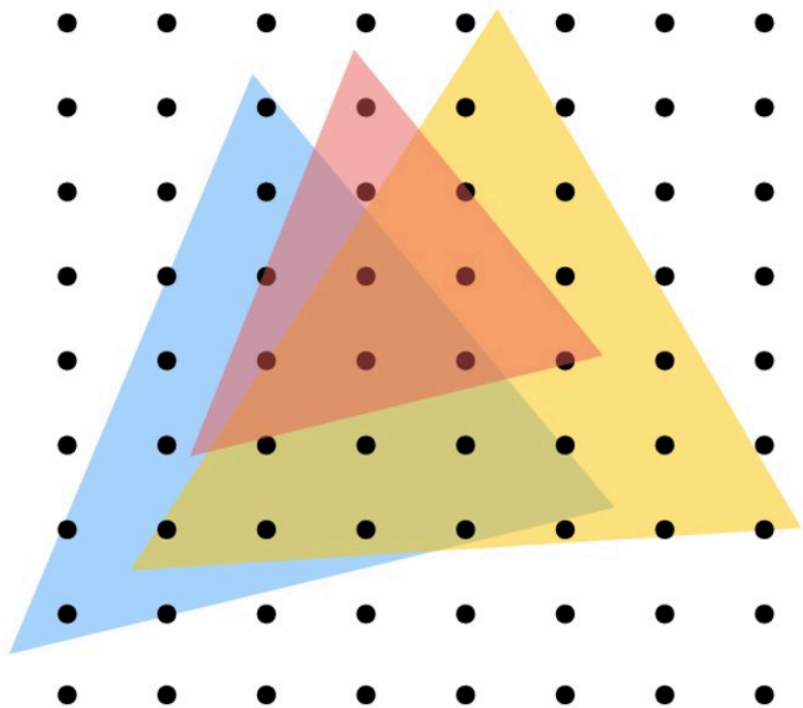




Occlusion: which triangle is visible at each covered sample point?



Opaque Triangles



50% transparent triangles

Depth Buffer

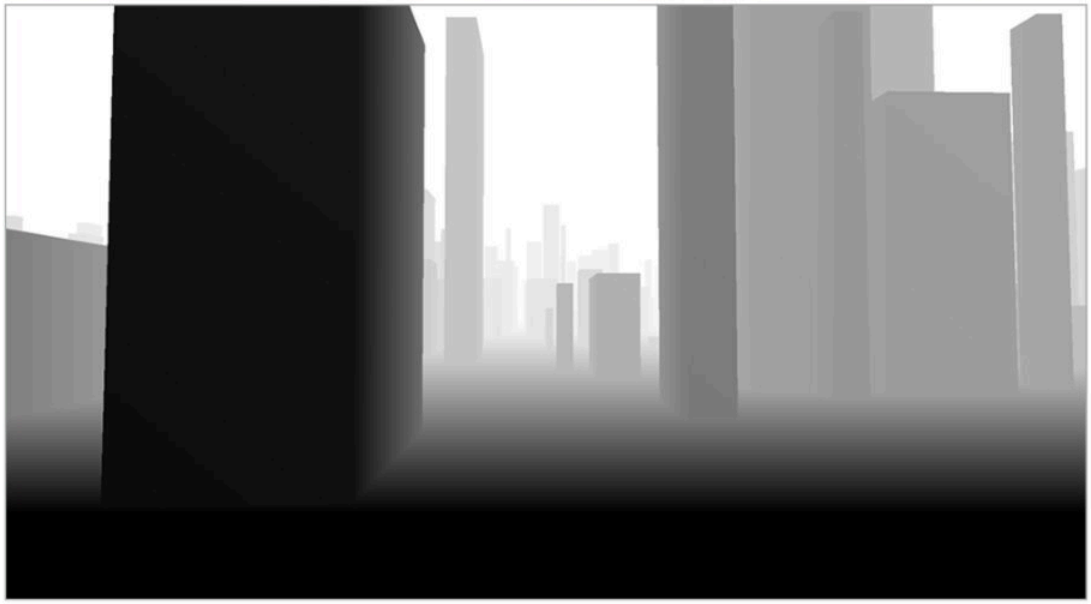
Depth buffer (aka "Z buffer")

Color buffer:

(stores color per sample… e.g., RGB)

Depth buffer:

(stores depth per sample)



Stores depth of closest surface drawn so far

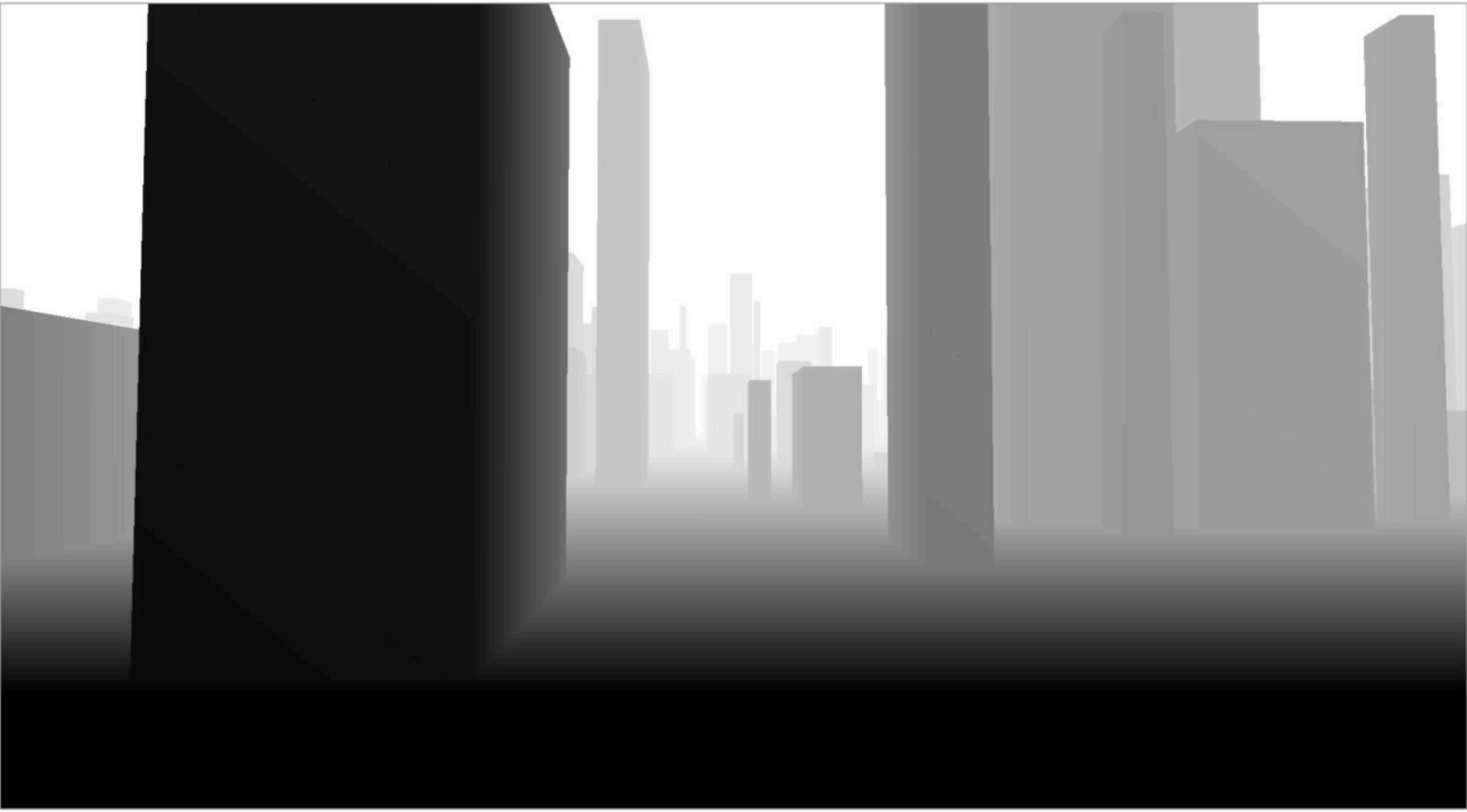
black = close depth

white = far depth

Depth buffer (a better look)

Color buffer (stores color measurement per sample, eg., RGB value per sample)

Depth buffer (a better look)



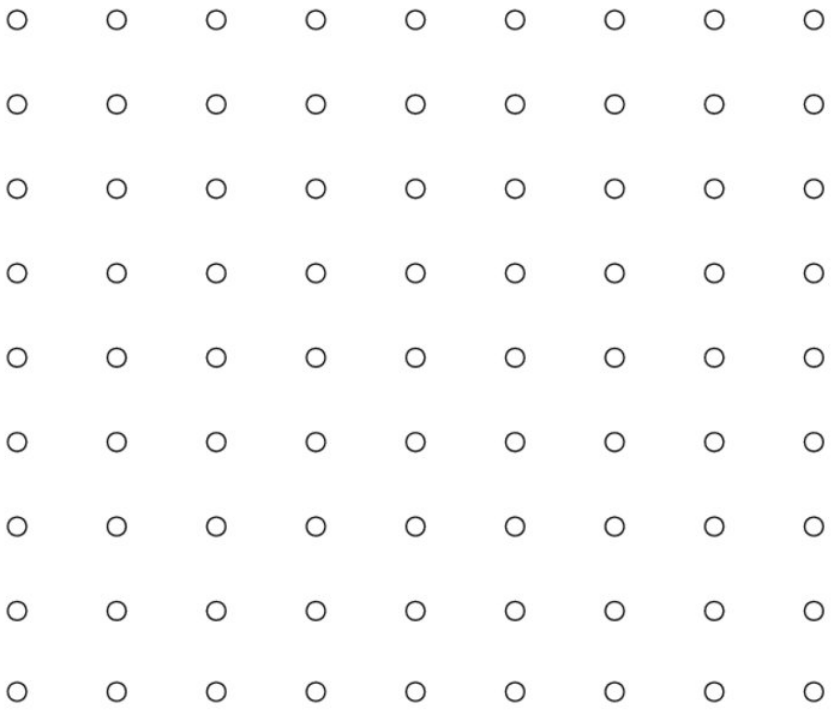
Corresponding depth buffer after rendering all triangles
(stores closest scene depth per sample)

Occlusion using the depth-buffer ("Z-buffer")

For each coverage sample point, the depth-buffer stores depth of closest triangle at this sample point that has been processed by the renderer so far.

Closest triangle at sample point (x,y) is triangle with minimum depth at (x,y)

Initial state of depth buffer before rendering any triangles (all samples store farthest distance)

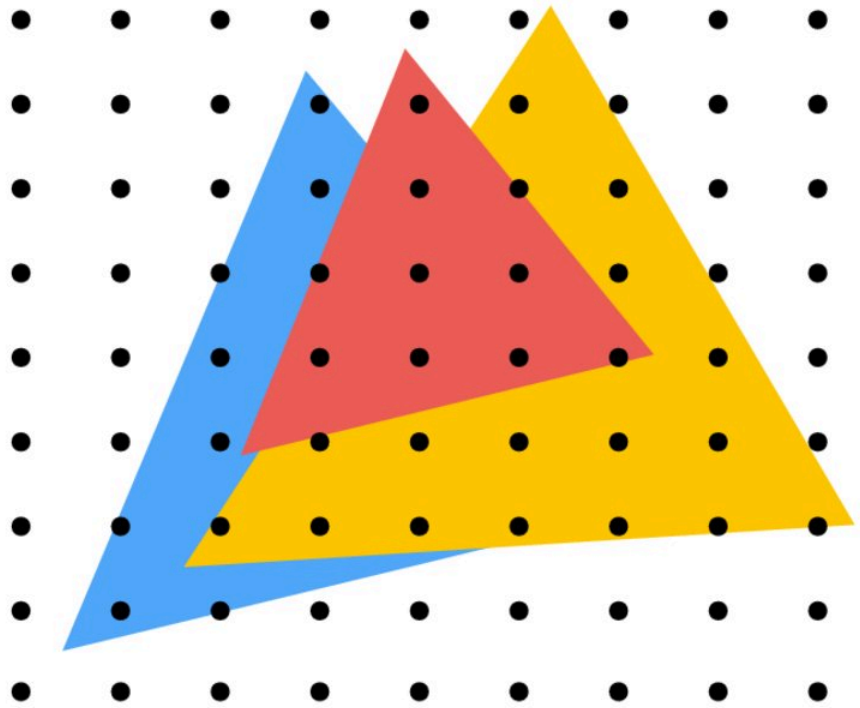


Grayscale value of sample point used to indicate distance

Black = small distance

White = large distance

Example: rendering three opaque triangles



Occlusion using the depth-buffer (Z-buffer)

Processing yellow triangle:

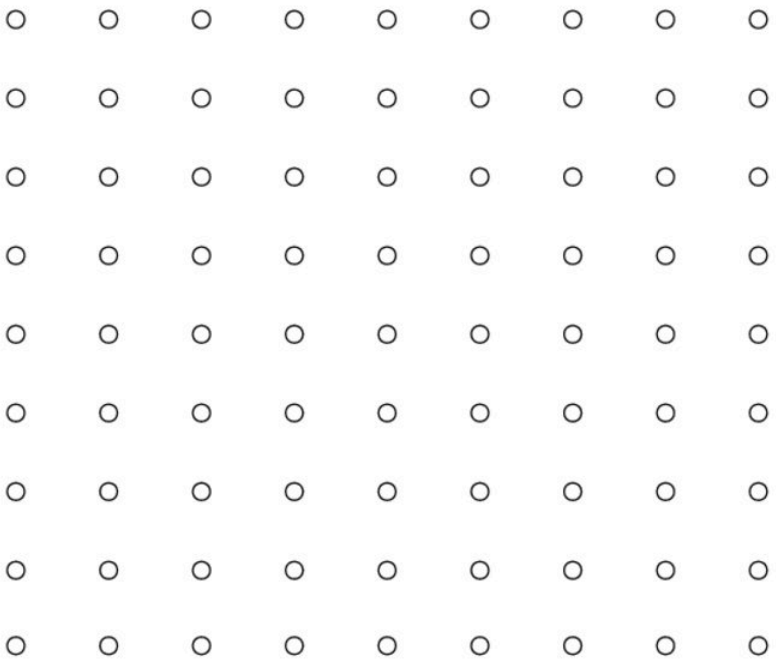
depth = 0.5

Grayscale value of sample point used to indicate distance

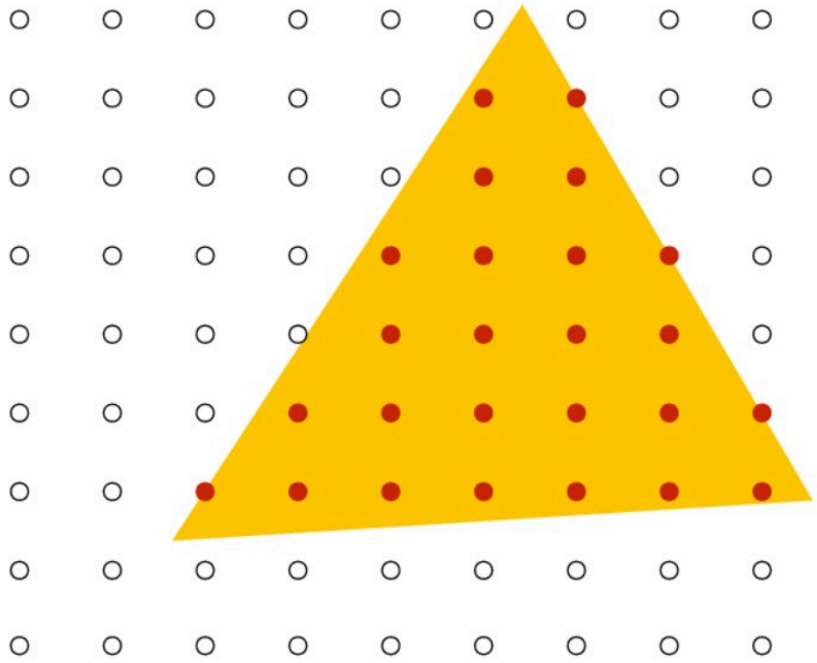
White = large distance

Black = small distance

Red = samples that pass depth test



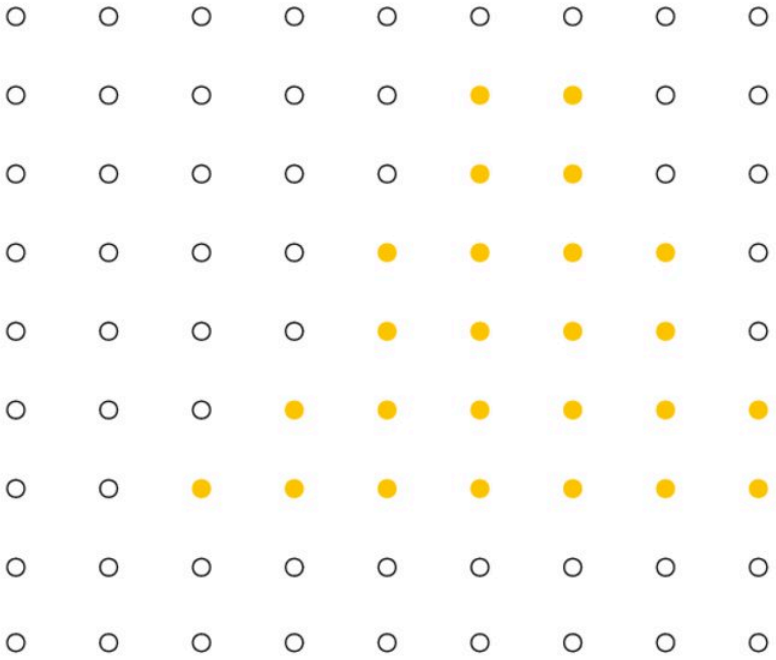
Color buffer contents



Depth buffer contents

Occlusion using the depth-buffer (Z-buffer)

After processing yellow triangle:



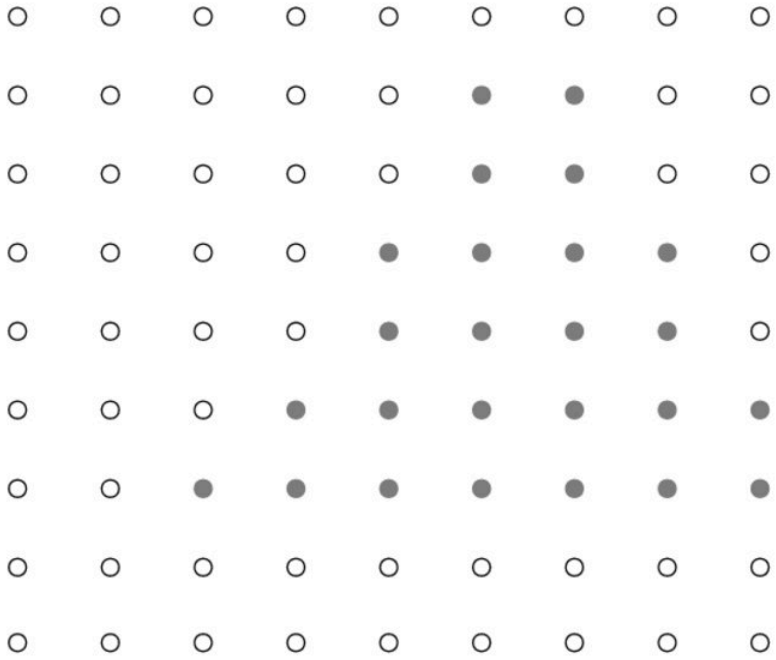
Color buffer contents

Grayscale value of sample point used to indicate distance

White = large distance

Black = small distance

Red = samples that pass depth test

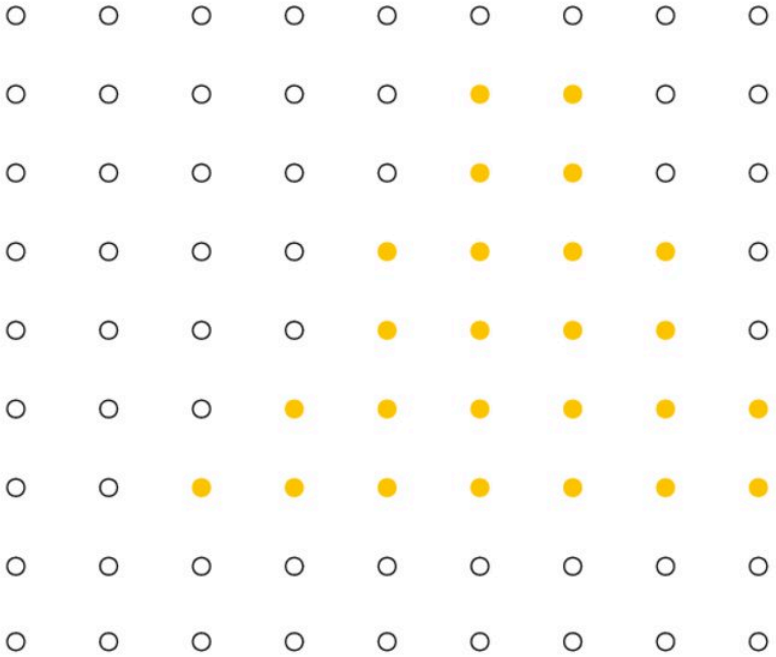


Depth buffer contents

Occlusion using the depth-buffer (Z-buffer)

Processing blue triangle:

depth = 0.75



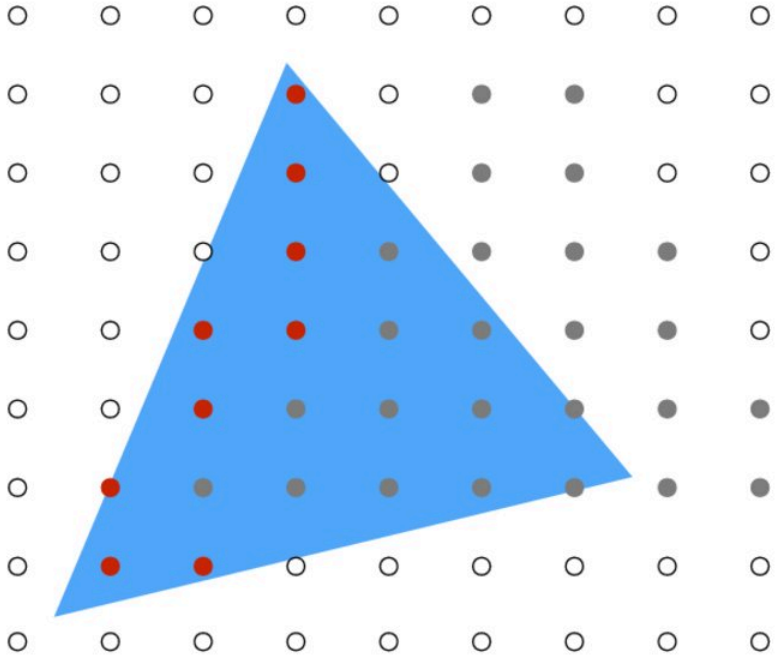
Color buffer contents

Grayscale value of sample point used to indicate distance

White = large distance

Black = small distance

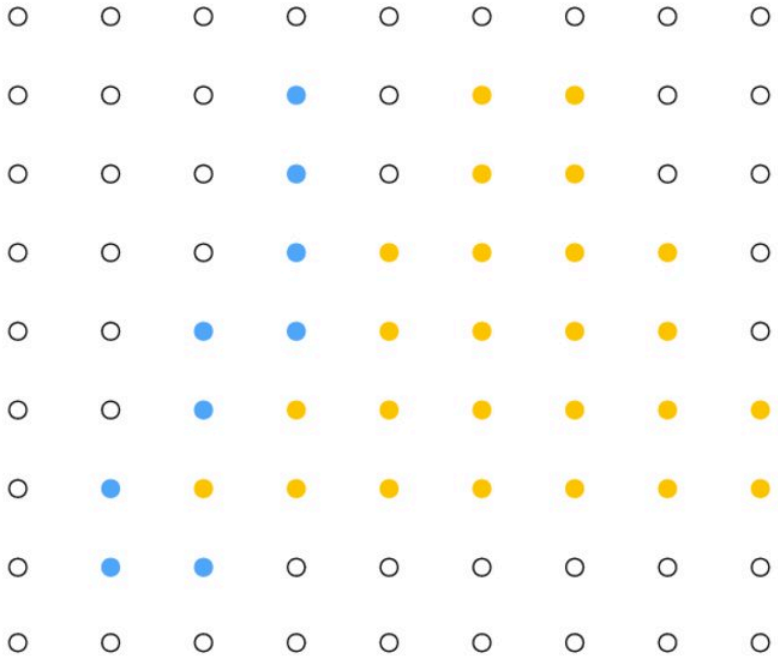
Red = samples that pass depth test



Depth buffer contents

Occlusion using the depth-buffer (Z-buffer)

After processing blue triangle:



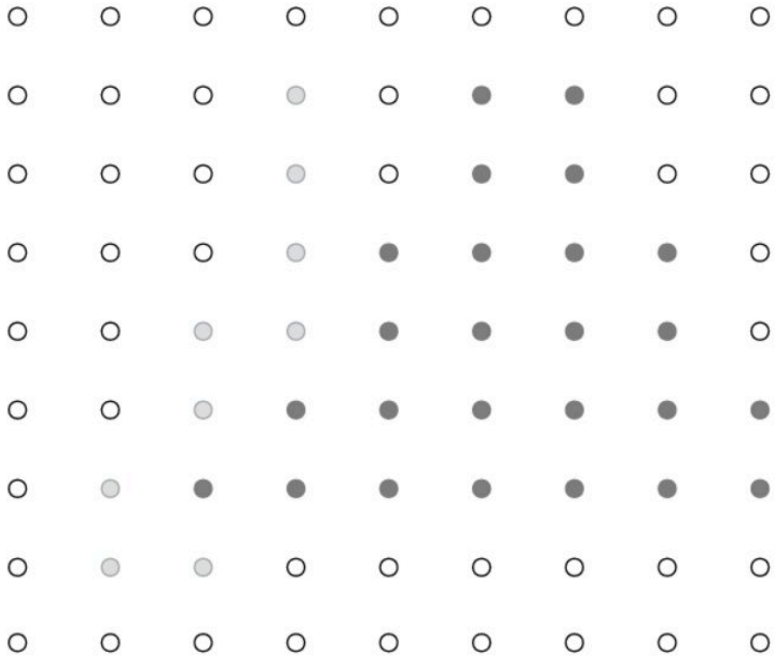
Color buffer contents

Grayscale value of sample point used to indicate distance

White = large distance

Black = small distance

Red = samples that pass depth test

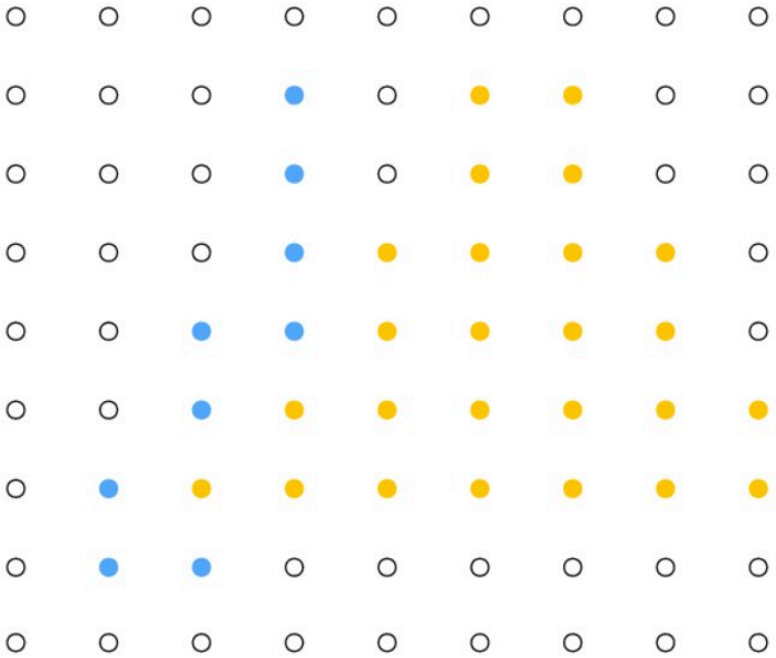


Depth buffer contents

Occlusion using the depth-buffer (Z-buffer)

Processing red triangle:

depth = 0.25



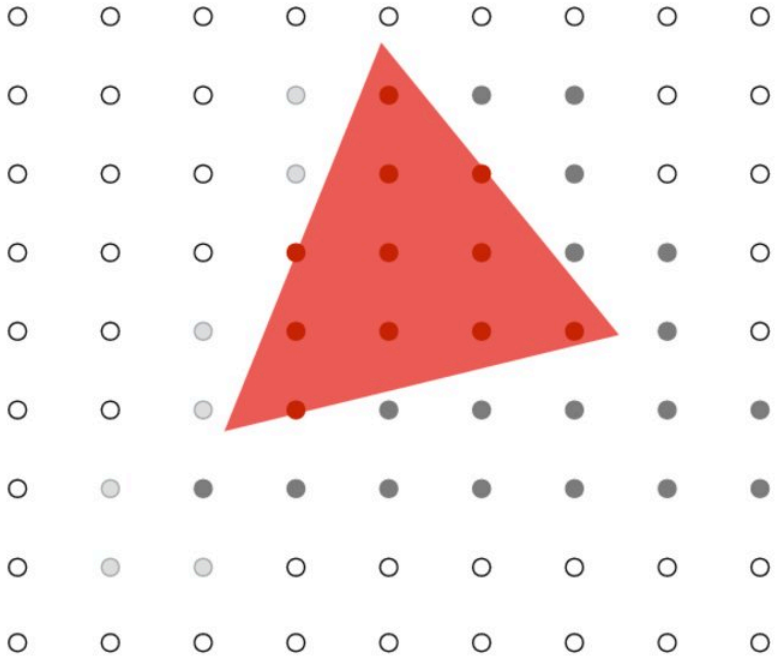
Color buffer contents

Grayscale value of sample point used to indicate distance

White = large distance

Black = small distance

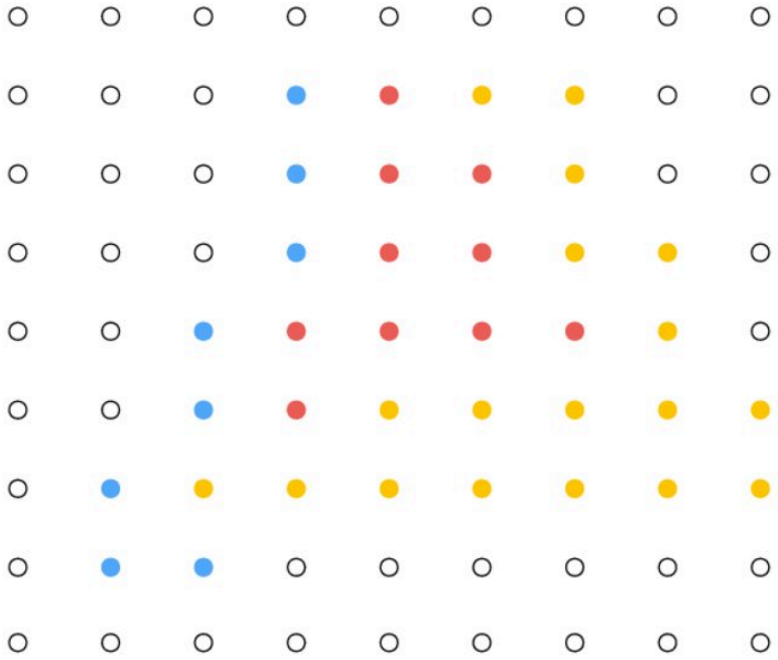
Red = samples that pass depth test



Depth buffer contents

Occlusion using the depth-buffer (Z-buffer)

After processing red triangle:



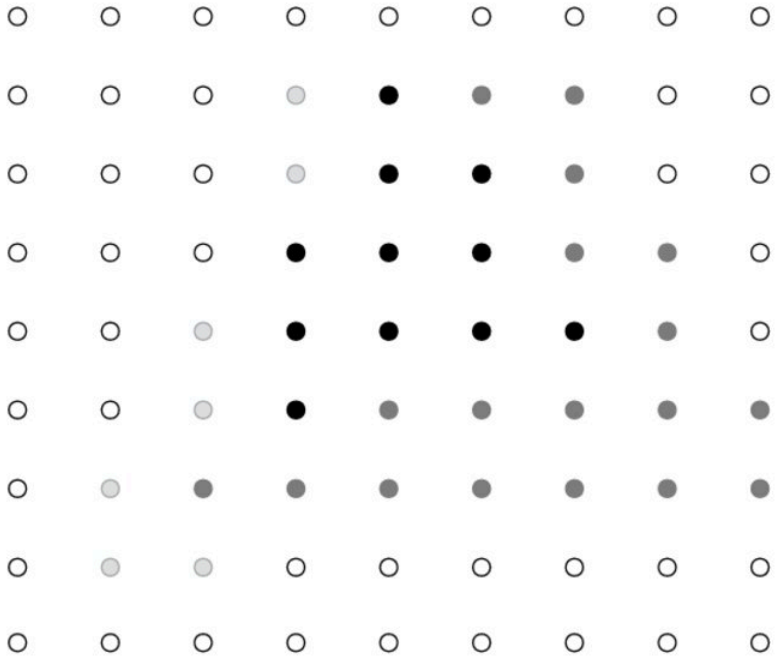
Color buffer contents

Grayscale value of sample point used to indicate distance

White = large distance

Black = small distance

Red = samples that pass depth test



Depth buffer contents

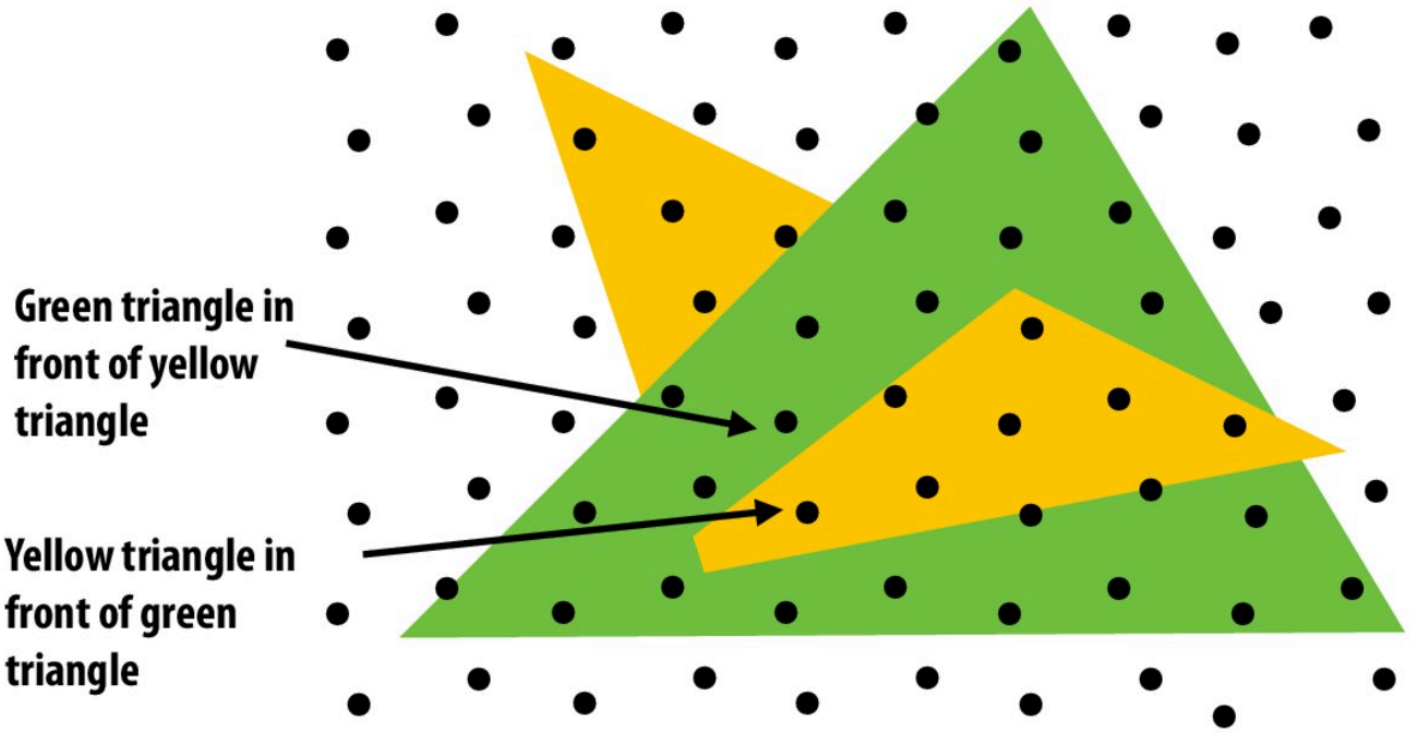
Occlusion using the depth buffer (opaque surfaces)

```
bool pass_depth_test(d1, d2) {
   return d1 < d2;
}


depth_test(tri_d, tri_color, x, y) {

  if (pass_depth_test(tri_d, depth_buffer[x][y]) {

    // triangle is closest object seen so far at this
    // sample point. Update depth and color buffers.

    depth_buffer[x][y] = tri_d;   // update depth_buffer
    color[x][y] = tri_color;      // update color buffer
  }
}
```

Does depth-buffer algorithm handle interpenetrating surfaces?

Of course!

Occlusion test is based on depth of triangles *at a given sample point.* The relative depth of triangles may be different at different sample points.



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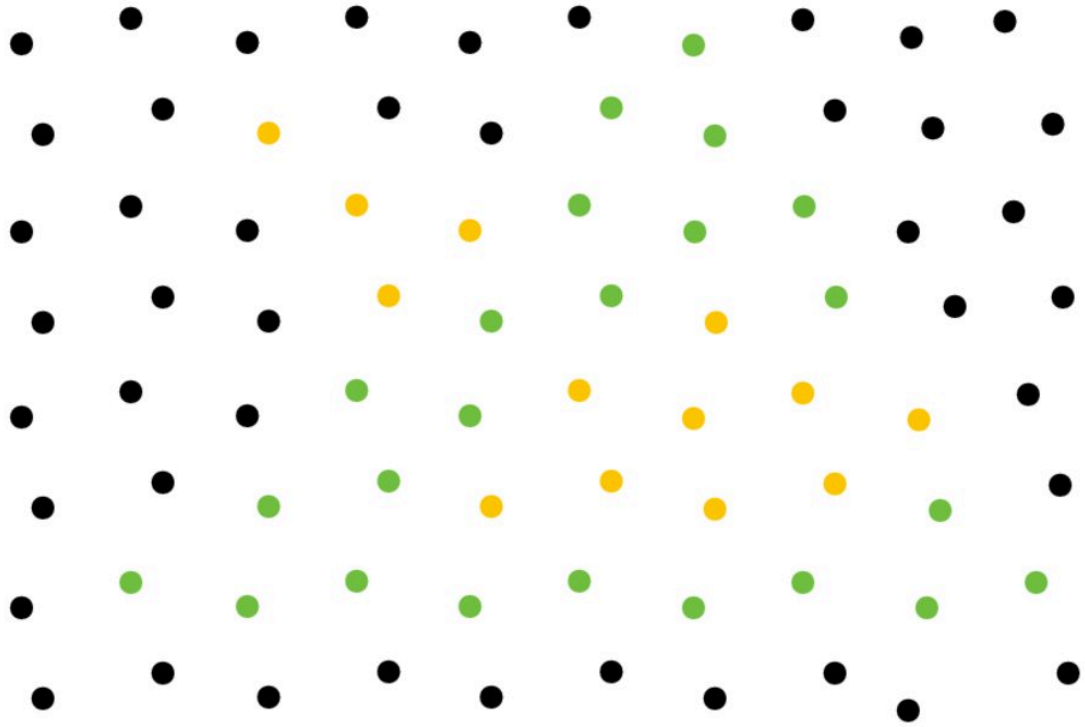
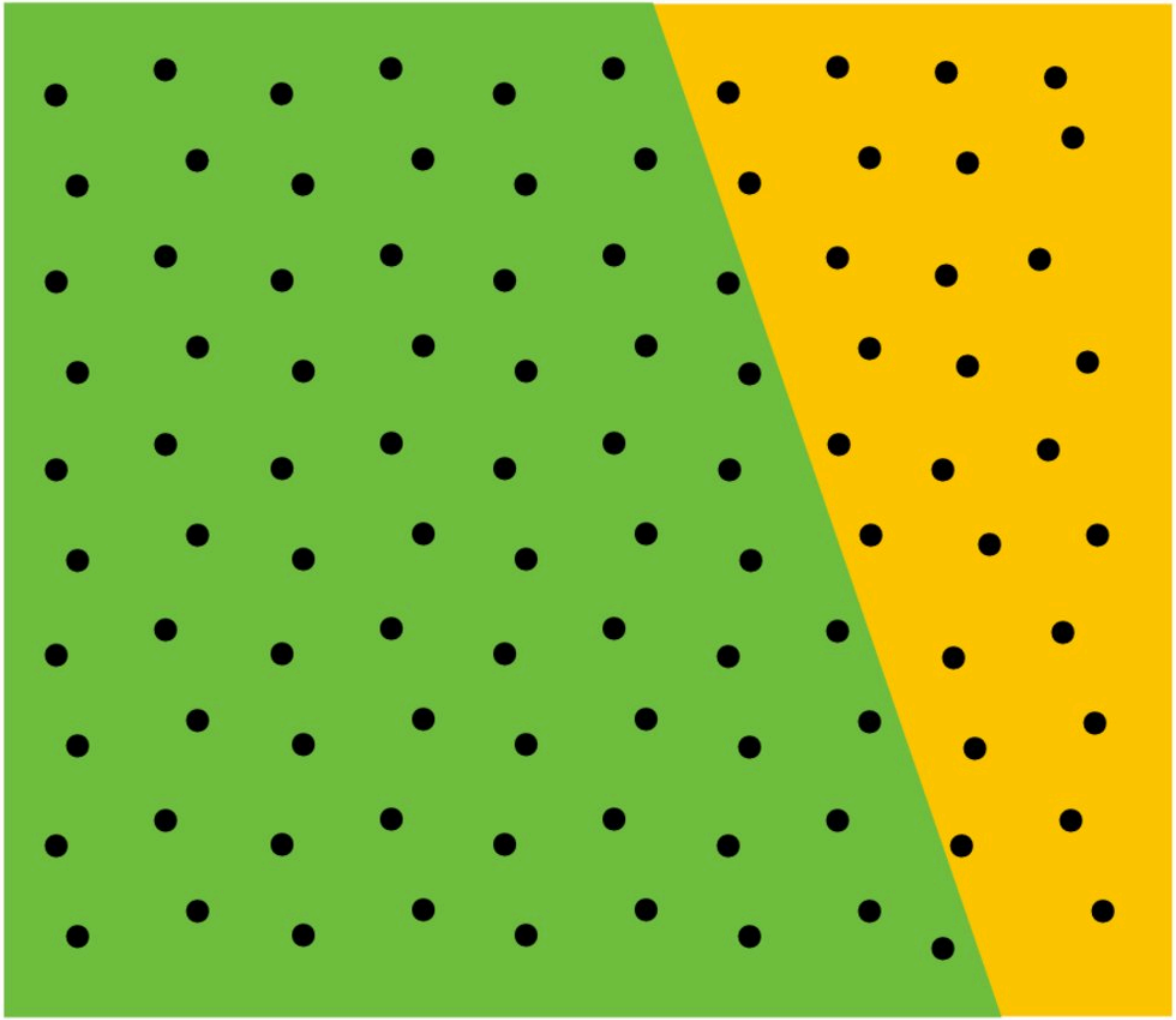


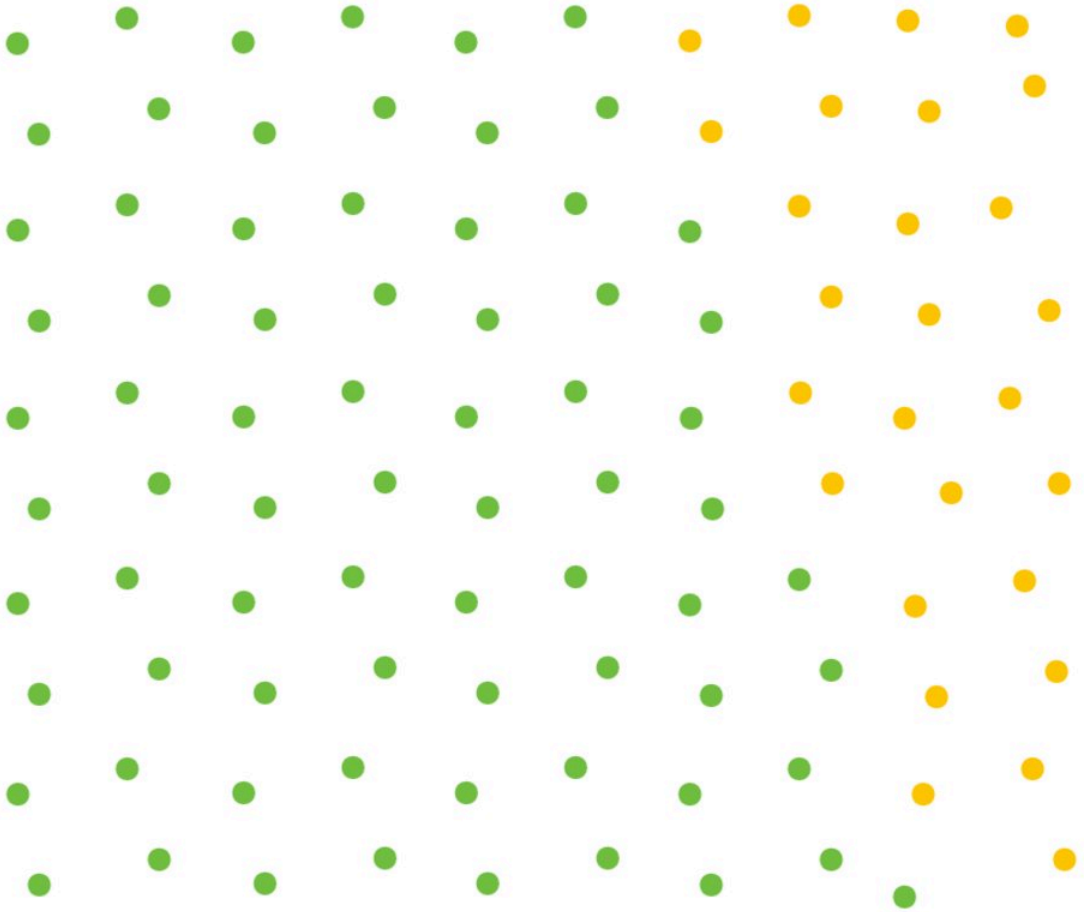
Does depth buffer work with super sampling?

Of course! Occlusion test is per sample, not per pixel!

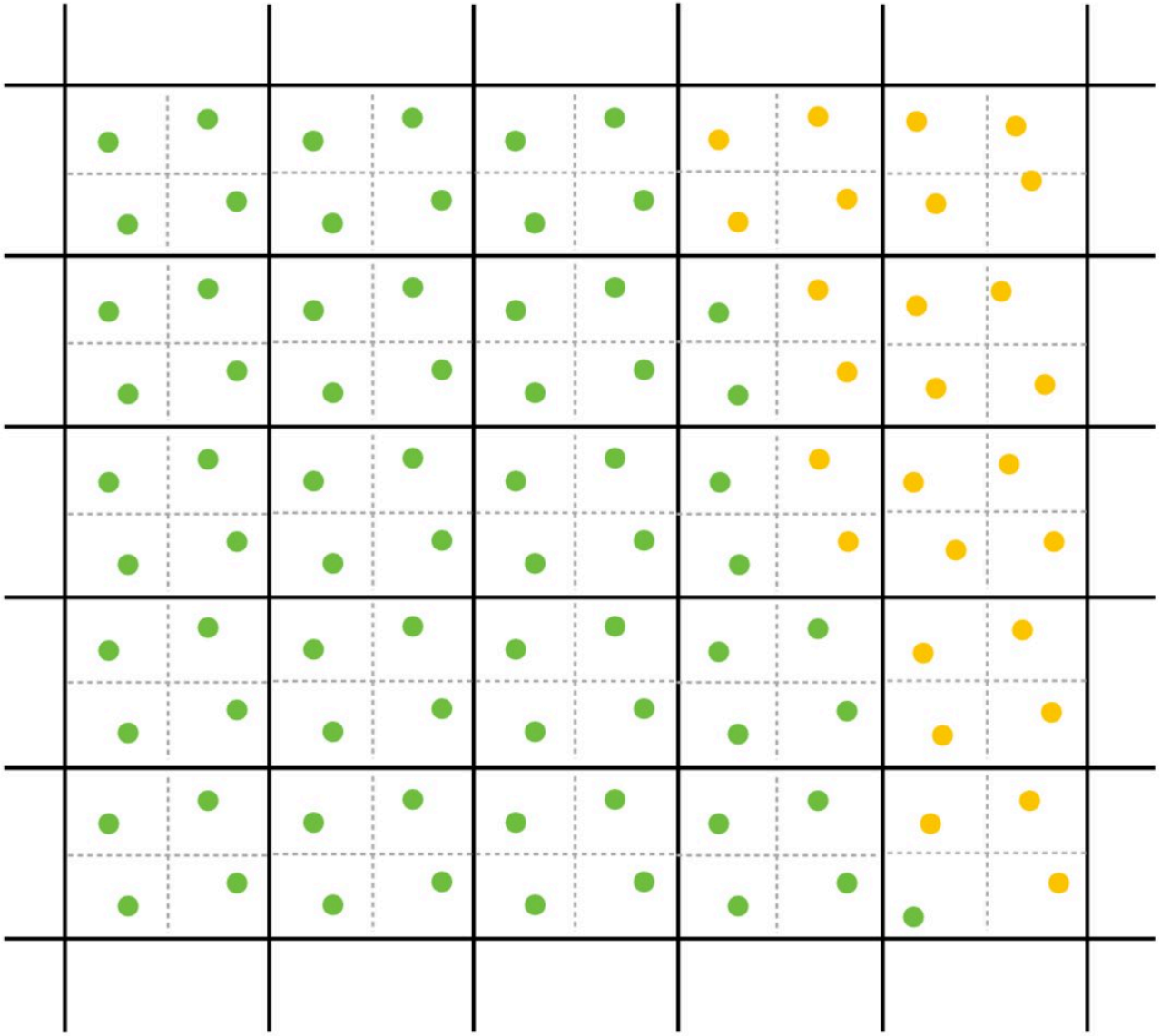


This example: green triangle occludes yellow triangle

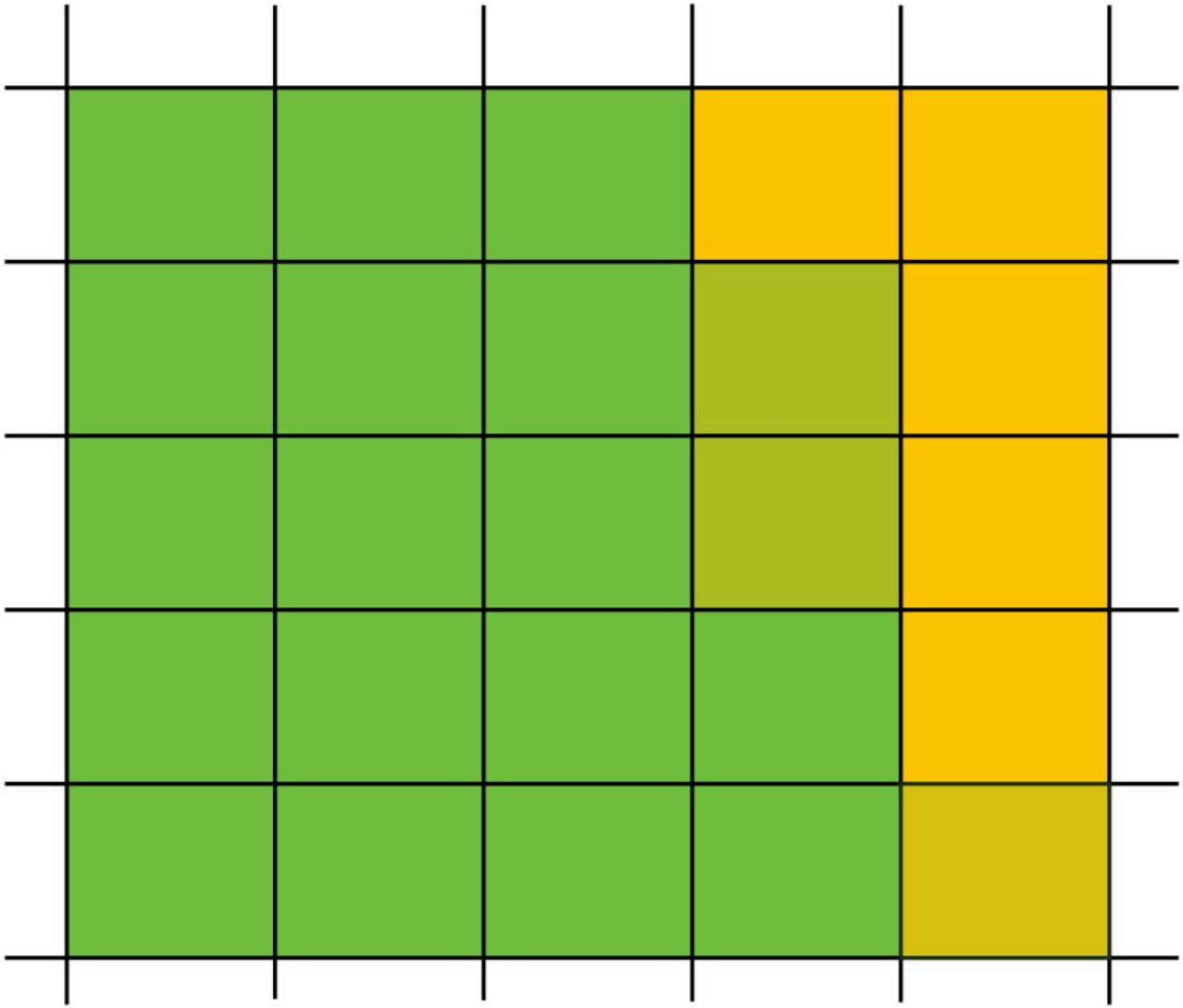
Color buffer contents



Color buffer contents (4 samples per pixel)



Final resampled result



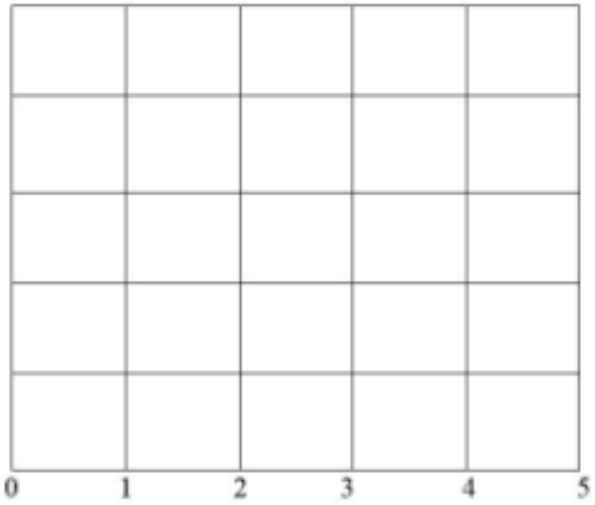
Note anti-aliasing of edge due to filtering of green and yellow samples.

Summary: occlusion using a depth buffer

- Store one depth value per coverage sample (not per pixel!)
- Constant space per sample
  - Implication: constant space for depth buffer
- Constant time occlusion test per covered sample
  - Read-modify write of depth buffer if "pass" depth test
  - Just a depth buffer read if "fail"
- Not specific to triangles: only requires that surface depth can be evaluated at a screen sample point

But what about semi-transparent surfaces?

What is the state of the Z-buffer after rendering this scene?
Z=0 is near. Z=9 is far.



There is a red square with corners at

(0, 0, 1),
(1, 0, 1),
(1, 1, 1),
(0, 1, 1).

There is a green square with corners at

(0,0,2)
(2,0,2)
(2,2,2)
(0,2,2)

A

9	9	9	9	9
9	9	9	9	9
9	9	9	9	9
2	2	9	9	9
1	2	9	9	9

B

9	9	9	9	9
9	9	9	9	9
9	9	9	9	9
2	2	9	9	9
2	2	9	9	9

C

0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
2	**2**	0	0	0
1	**2**	0	0	0

D

0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
2	**2**	0	0	0
2	**2**	0	0	0

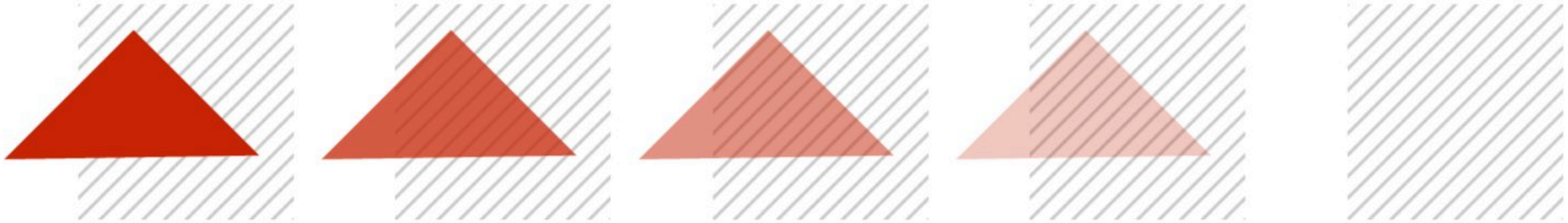
Compositing

Representing opacity as alpha

Alpha describes the opacity of an object

- **Fully opaque surface: $\alpha = 1$**
- **50% transparent surface: $\alpha = 0.5$**
- **Fully transparent surface: $\alpha = 0$**

Red triangle with decreasing opacity



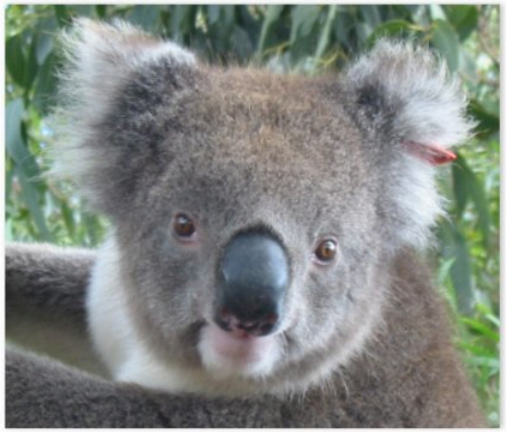
Alpha: coverage analogy

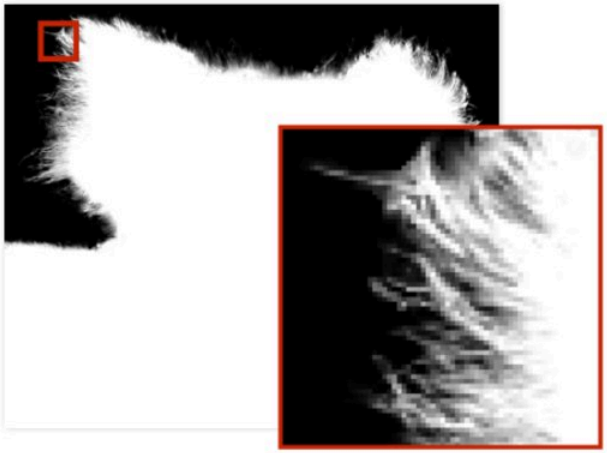
- Can think of alpha as describing the opacity of a semi-transparent surface
- Or… as partial coverage by fully opaque object
  - consider a screen door

$\alpha = 0.5$

(Squint at this slide and the scene on the left and the right will appear similar)

Alpha: additional channel of image (rgba)

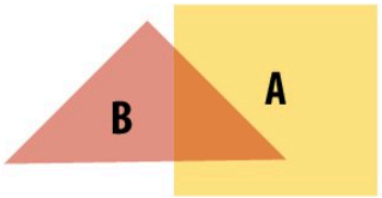




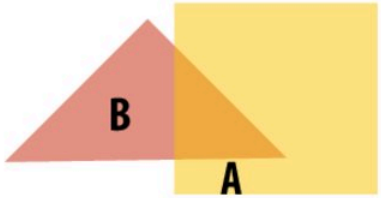
α of foreground object

Over operator:

Composite image B with opacity α_B over image A with opacity α_A



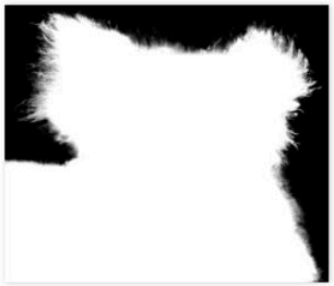
B over A

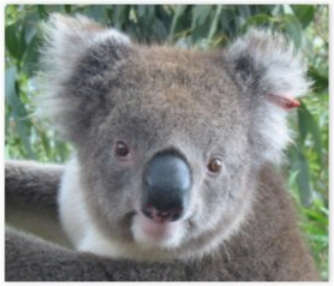


A over B

A over B != B over A

"Over" is not commutative





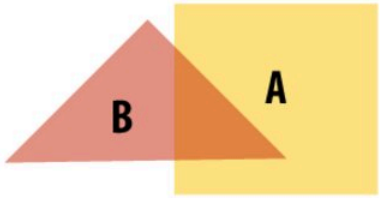
Koala over NYC

Over operator: non-premultiplied alpha

Composite image B with opacity α_B over image A with opacity α_A

First attempt: (represent colors as 3-vectors, alpha separately)

$$A = \begin{bmatrix} A_r & A_g & A_b \end{bmatrix}^T$$
$$B = \begin{bmatrix} B_r & B_g & B_b \end{bmatrix}^T$$



B over A

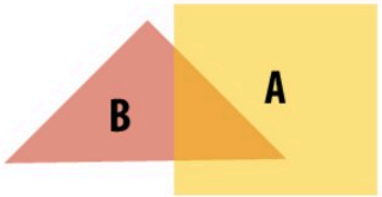
Composited color:

Appearance of semi-transparent A

$$C = \alpha_B B + (1 - \alpha_B)\alpha_A A$$

Appearance of semi-transparent B

What B lets through



A over B

A over B != B over A

"Over" is not commutative

Composite alpha:

$$\alpha_C = \alpha_B + (1 - \alpha_B)\alpha_A$$

Premultiplied alpha

- **Represent (potentially transparent) color as a 4-vector where RGB values have been premultiplied by alpha**

$$A' = \begin{bmatrix} \alpha_A A_r & \alpha_A A_g & \alpha_A A_b & \alpha_A \end{bmatrix}^T$$

Example: 50% opaque red

[0.5, 0.0, 0.0, 0.5]

Example: 75% opaque magenta

[0.75, 0.0, 0.75, 0.75]

Over operator: using premultiplied alpha

Composite image B with opacity α_B over image A with opacity α_A

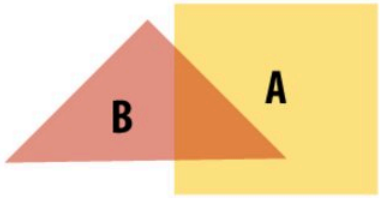
Non-premultiplied alpha representation:

$$A = \begin{bmatrix} A_r & A_g & A_b \end{bmatrix}^T$$

$$B = \begin{bmatrix} B_r & B_g & B_b \end{bmatrix}^T$$

$$C = \alpha_B B + (1 - \alpha_B)\alpha_A A$$ ← two multiplies, one add

(referring to vector ops on colors)



B over A

Composite alpha:

$$\alpha_C = \alpha_B + (1 - \alpha_B)\alpha_A$$

Premultiplied alpha representation:

$$A' = \begin{bmatrix} \alpha_A A_r & \alpha_A A_g & \alpha_A A_b & \alpha_A \end{bmatrix}^T$$

$$B' = \begin{bmatrix} \alpha_B B_r & \alpha_B B_g & \alpha_B B_b & \alpha_B \end{bmatrix}^T$$

$$C' = B + (1 - \alpha_B)A$$ ← one multiply, one add

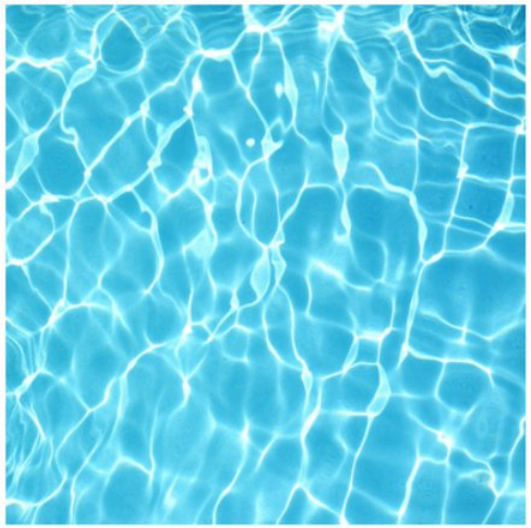
Notice premultiplied alpha composites alpha just like how it composites rgb.

Fringing

Poor treatment of color/alpha can yield dark "fringing":

foreground color

foreground alpha



background color

fringing

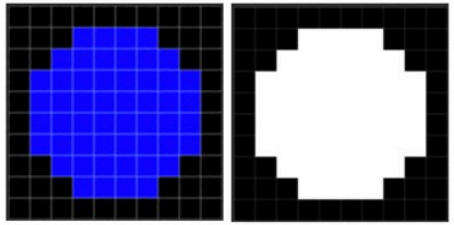
no fringing

No fringing

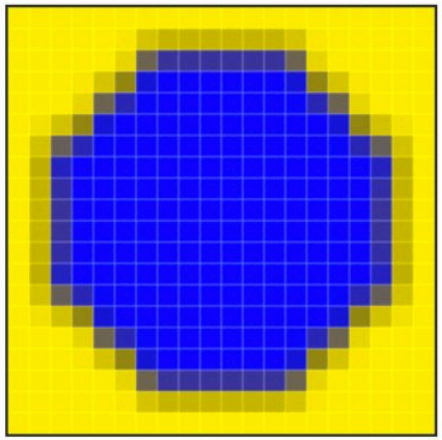
Fringing (…why does this happen?)

A problem with non-premultiplied alpha

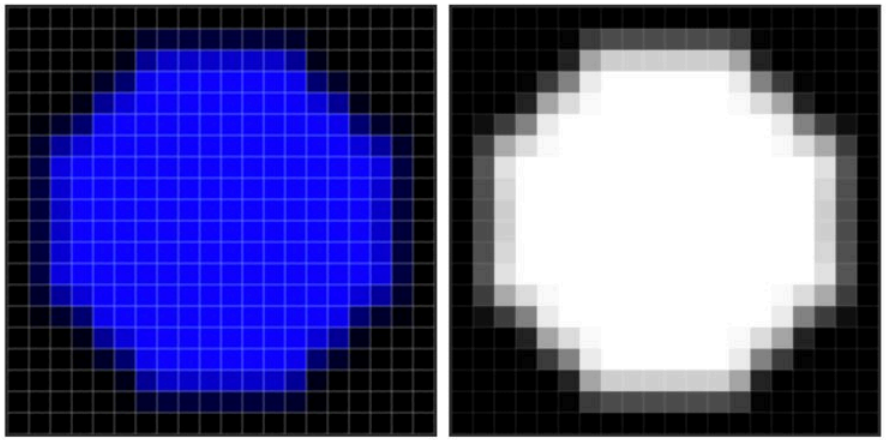
- Suppose we upsample an image w/ an alpha mask, then composite it onto a background
- How should we compute the interpolated color/alpha values?
- If we interpolate color and alpha separately, then blend using the non-premultiplied "over" operator, here's what happens:



original color | original alpha



composited onto yellow background

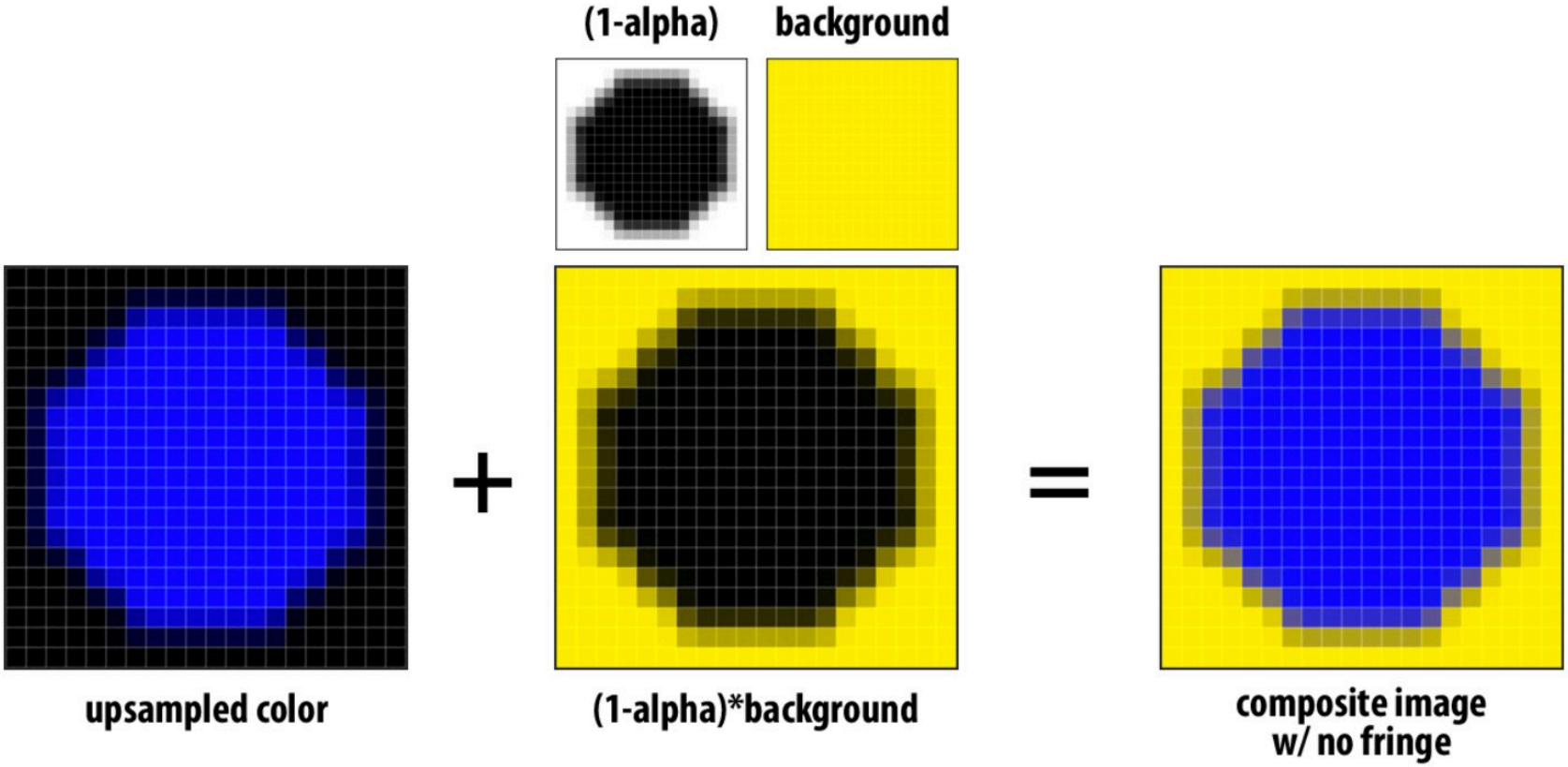


upsampled color | upsampled alpha

Notice black "fringe" that occurs because we're blending, e.g., 50% blue pixels using 50% alpha, rather than, 100% blue pixels with 50% alpha.

Eliminating fringe w/ premultiplied "over"

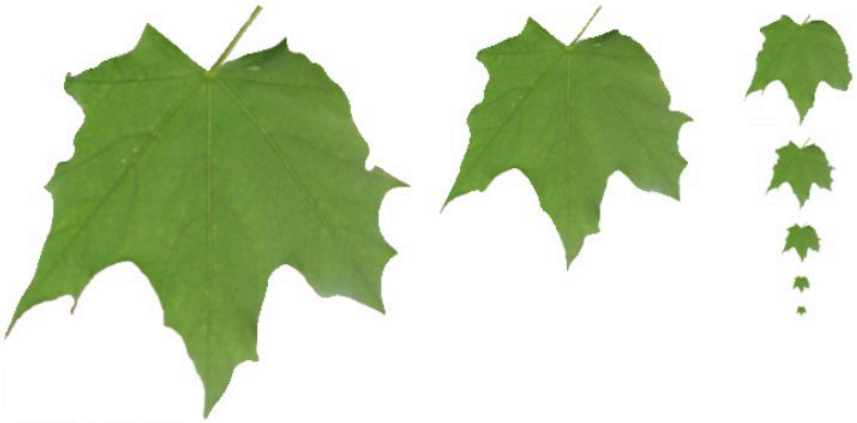
If we instead use the premultiplied "over" operation, we get the correct alpha:

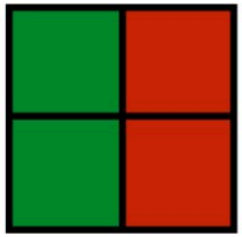


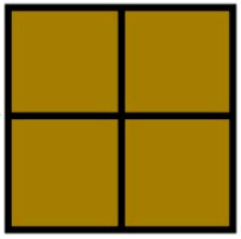
Another problem with non-premultiplied alpha

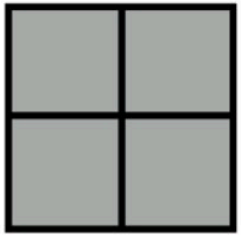
Consider pre-filtering a texture with an alpha matte

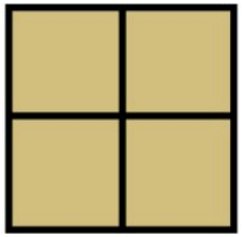
Desired filtered result









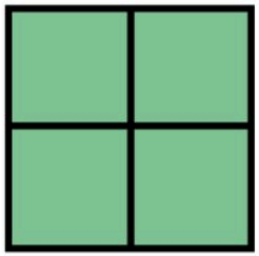


input color | input α | filtered color | filtered α | filtered result composited over white

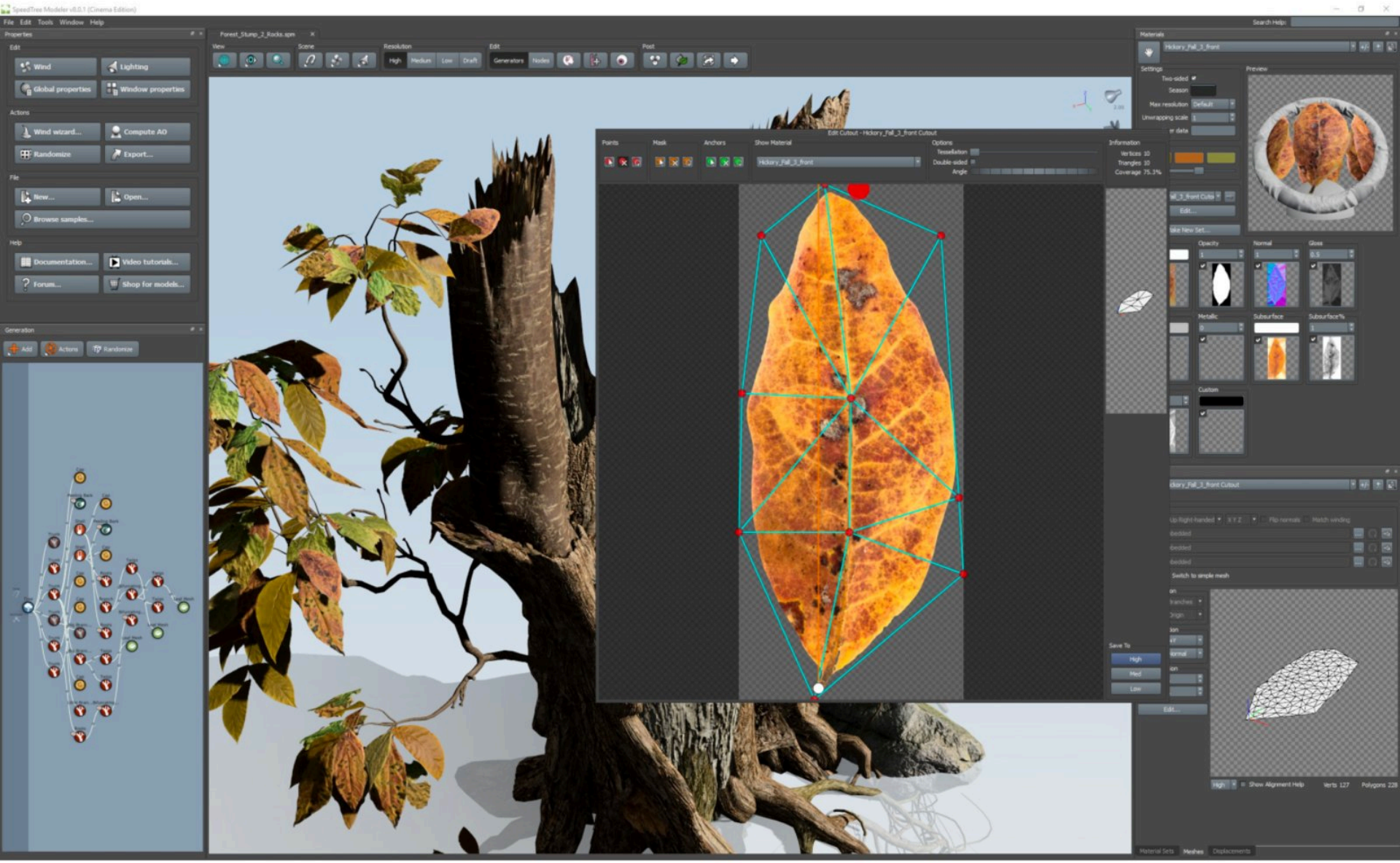
Downsampling non-premultiplied alpha image results in 50% opaque brown)

$0.25 * ((0, 1, 0, 1) + (0, 1, 0, 1) + (0, 0, 0, 0) + (0, 0, 0, 0)) = (0, 0.5, 0, 0.5)$

Result of filtering premultiplied image



Common use of textures with alpha: foliage



[Image credit: SpeedTree Cinema 8]

Foliage example

[Image credit: SpeedTree Cinema 8]

Another problem: applying "over" repeatedly

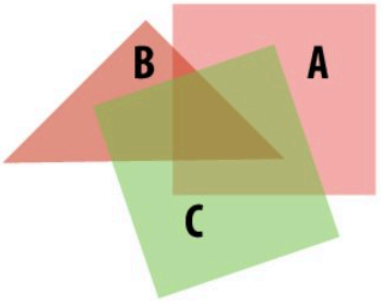
Consider composite image C with opacity α_C over B with opacity α_B over image A with opacity α_A

$$A = \begin{bmatrix} A_r & A_g & A_b \end{bmatrix}^T$$

$$B = \begin{bmatrix} B_r & B_g & B_b \end{bmatrix}^T$$

$$C = \alpha_B B + (1 - \alpha_B)\alpha_A A$$

$$\alpha_C = \alpha_B + (1 - \alpha_B)\alpha_A$$



C over B over A

Consider first step of of compositing 50% red over 50% red:

$$C = \begin{bmatrix} 0.75 & 0 & 0 \end{bmatrix}^T$$

$$\alpha_C = 0.75$$

Wait… this result is the premultiplied color!

So "over" for non-premultiplied alpha takes non-premultiplied colors to premultiplied colors ("over" operation is not closed)

Cannot compose "over" operations on non-premultiplied values:

```
over(C, over(B, A))
```

There is a closed form for non-premultiplied alpha:

$$C = \frac{1}{\alpha_C}(\alpha_B B + (1 - \alpha_B)\alpha_A A)$$

Summary: advantages of premultiplied alpha

- Simple: compositing operation treats all channels (rgb and a) the same
- Closed under composition
- Better representation for filtering textures with alpha channel
- More efficient than non-premultiplied representation: "over" requires fewer math ops

Color buffer update: semi-transparent surfaces

Assume: color buffer values and tri_color are represented with premultiplied alpha

```
over(c1, c2) {
   return c1 + (1-c1.a) * c2;
}

update_color_buffer(tri_z, tri_color, x, y) {
   // Note: no depth check, no depth buffer update
   color[x][y] = over(tri_color, color[x][y]);
}
```

What is the assumption made by this implementation?

Triangles must be rendered in back to front order!

What if triangles are rendered in front to back order?

Modify code: `over(color[x][y], tri_color)`

Putting it all together *

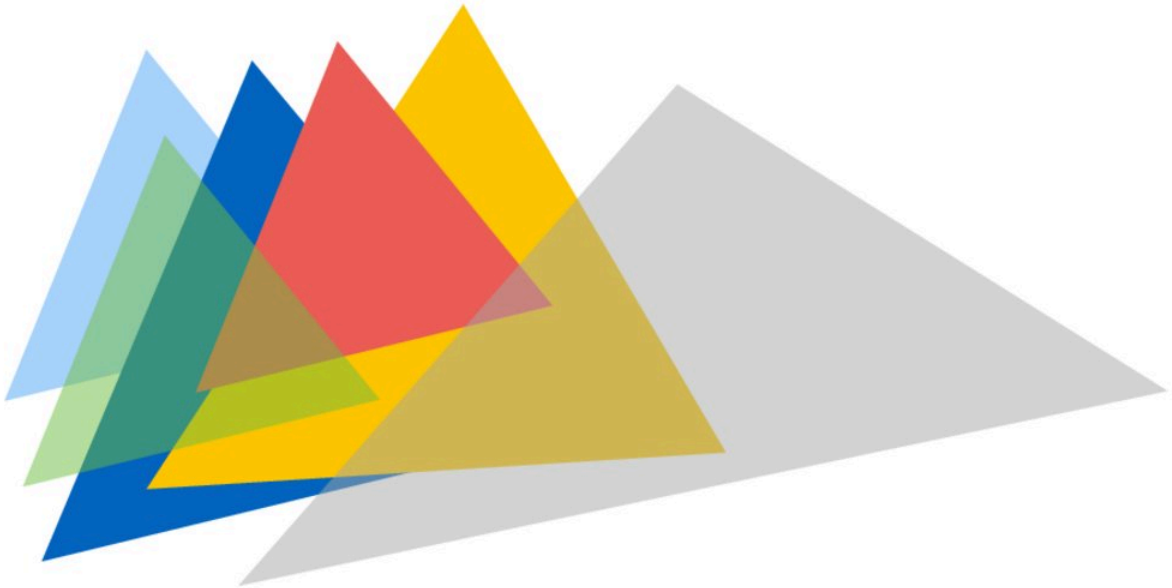
Consider rendering a mixture of opaque and transparent triangles

Step 1: render opaque surfaces using depth-buffered occlusion

If pass depth test, triangle overwrites value in color buffer at sample

Step 2: disable depth buffer update, render semi-transparent surfaces in back-to-front order.

If pass depth test, triangle is composited OVER contents of color buffer at sample



*** If this seems a little complicated, you will enjoy the simplicity of using ray tracing algorithm for rendering. More on this later in the course, and in CS348B**

Combining opaque and semi-transparent triangles

Assume: color buffer values and tri_color are represented with premultiplied alpha

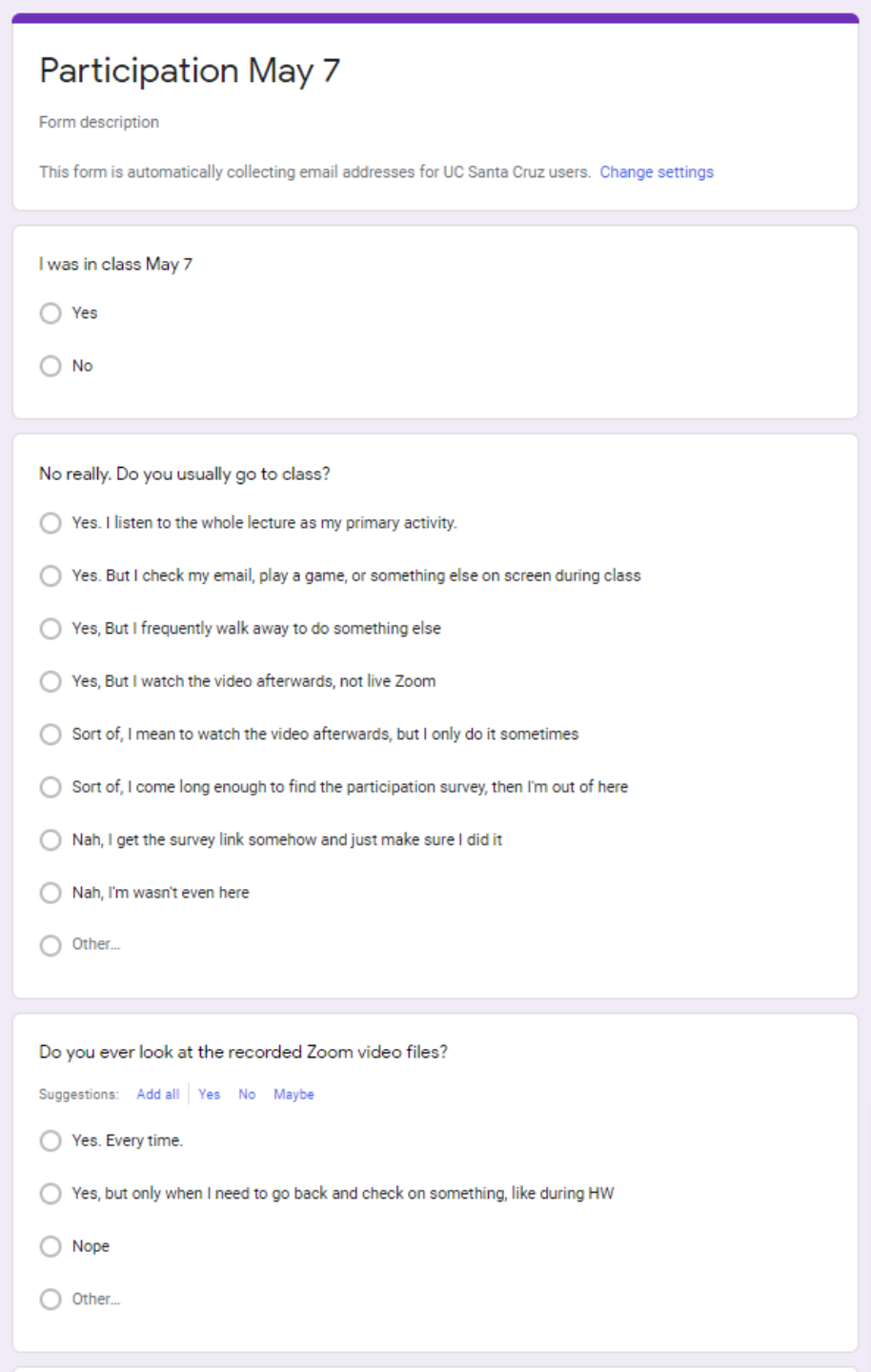
```
// phase 1: render opaque surfaces
update_color_buffer(tri_z, tri_color, x, y) {
   if (pass_depth_test(tri_z, zbuffer[x][y]) {
      color[x][y] = tri_color;
      zbuffer[x][y] = tri_z;
   }
}


// phase 2: render semi-transparent surfaces
update_color_buffer(tri_z, tri_color, x, y) {

   if (pass_depth_test(tri_z, zbuffer[x][y]) {
       // Note: no depth buffer update
       color[x][y] = over(tri_color, color[x][y]);
  }
}
```

Participation Survey

- http://tiny.cc/160-1110



Participation May 7

Form description

This form is automatically collecting email addresses for UC Santa Cruz users. Change settings

I was in class May 7

- Yes
- No

No really. Do you usually go to class?

- Yes. I listen to the whole lecture as my primary activity.
- Yes. But I check my email, play a game, or something else on screen during class
- Yes, But I frequently walk away to do something else
- Yes, But I watch the video afterwards, not live Zoom
- Sort of, I mean to watch the video afterwards, but I only do it sometimes
- Sort of, I come long enough to find the participation survey, then I'm out of here
- Nah, I get the survey link somehow and just make sure I did it
- Nah, I'm wasn't even here
- Other...

Do you ever look at the recorded Zoom video files?

Suggestions: Add all | Yes No Maybe

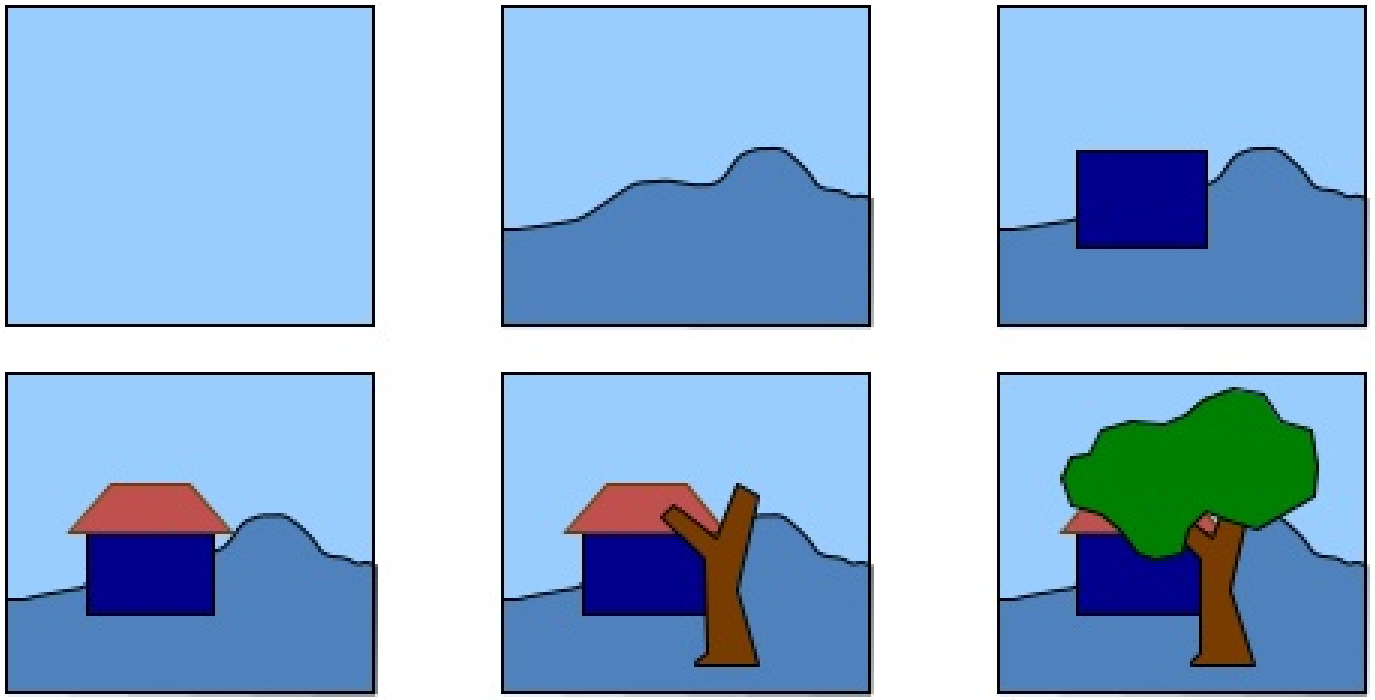
- Yes. Every time.
- Yes, but only when I need to go back and check on something, like during HW
- Nope
- Other...

Back To Front: Painters Algorithm and BSP Trees

Painter's Algorithm

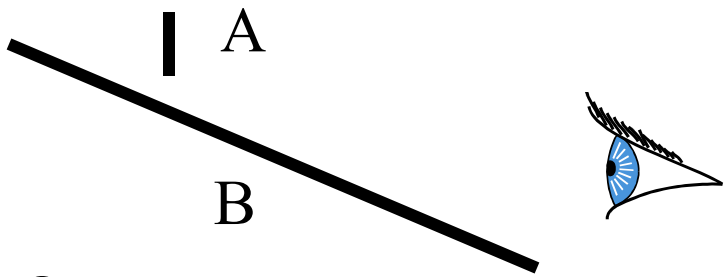
Draw surfaces from back (farthest away) to front (closest):

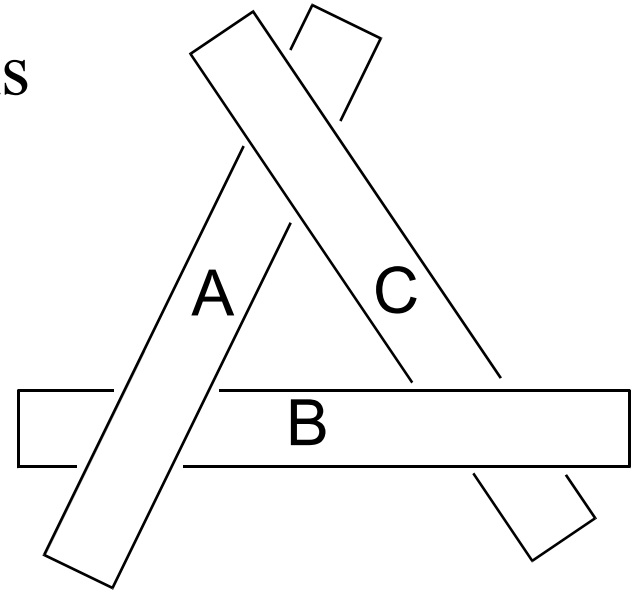
- Sort surfaces/polygons by their depth (*z* value)
- Draw objects in order (farthest to closest)
- Closer objects paint over the top of farther away objects



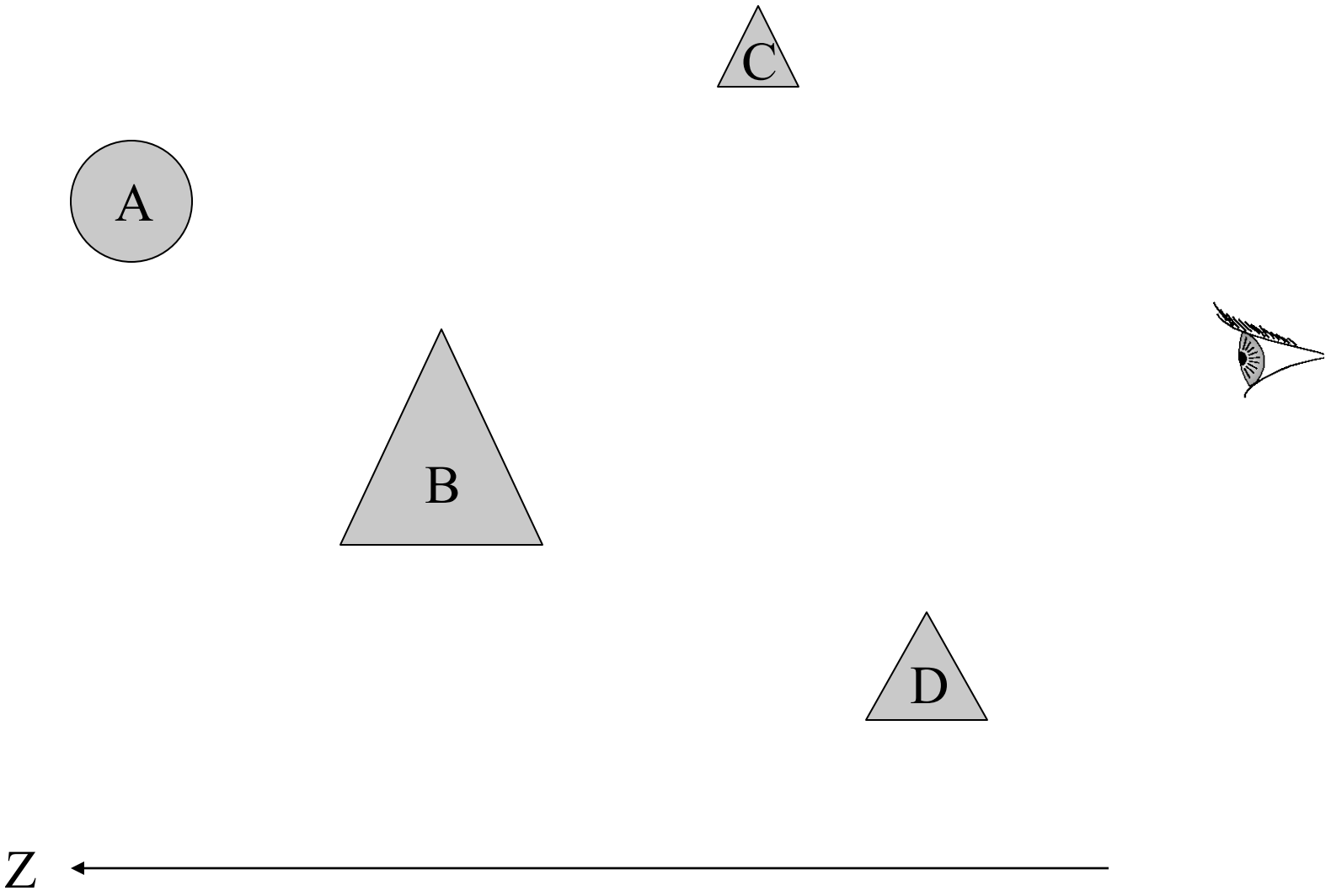
Painter's algorithm

- Draw back-to-front
- How do we sort objects?
- Can we always sort objects?
  - No, there can be cycles
  - Requires to split polygons

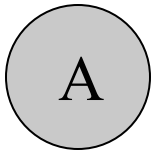


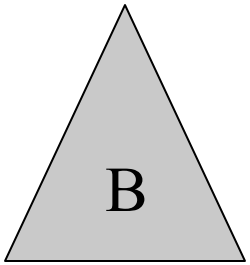


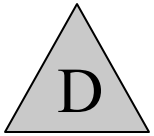
Worse, there is no single sort: ABCD?

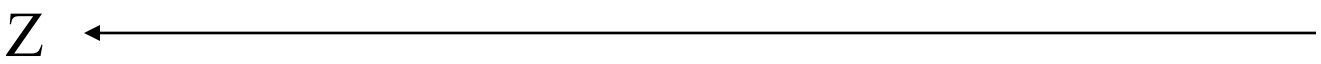


Camera moved : ABCD?
Resort every frame?



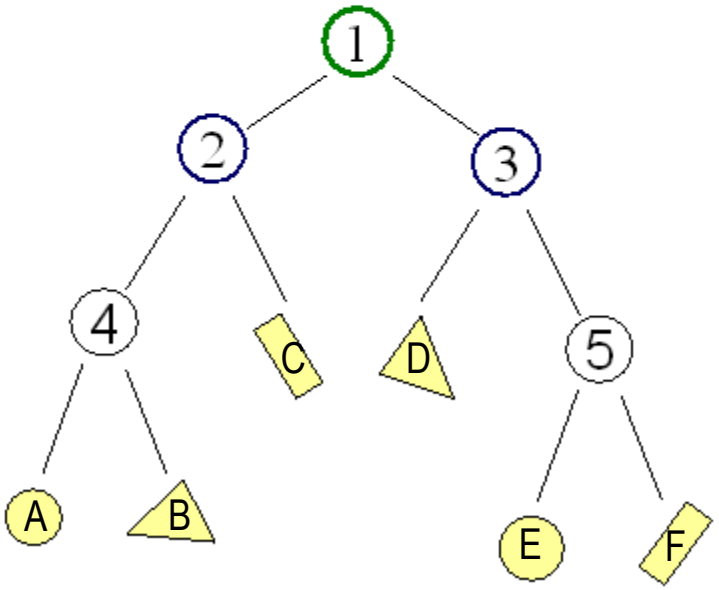


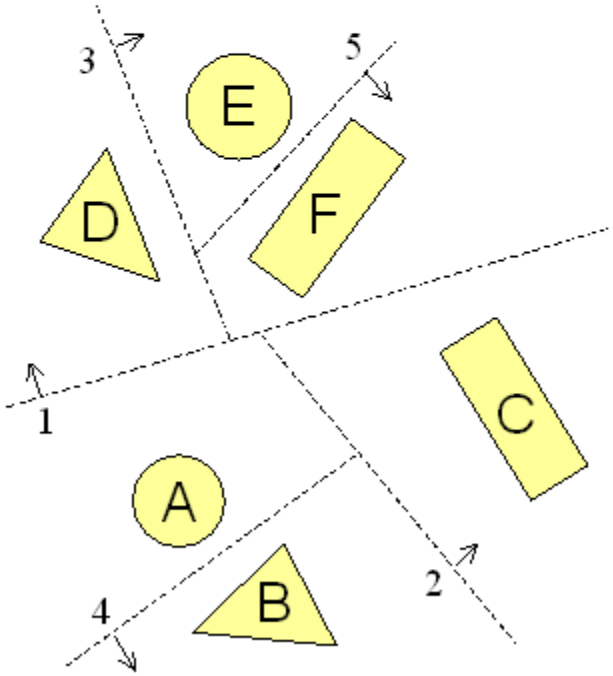




Binary Space Partition (BSP) Tree

- Recursively partition space by planes
  - Every cell is a convex polyhedron





Binary Space Partition (BSP) Tree

- Recursively partition space by planes
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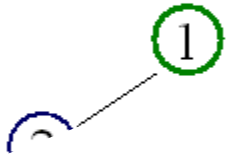
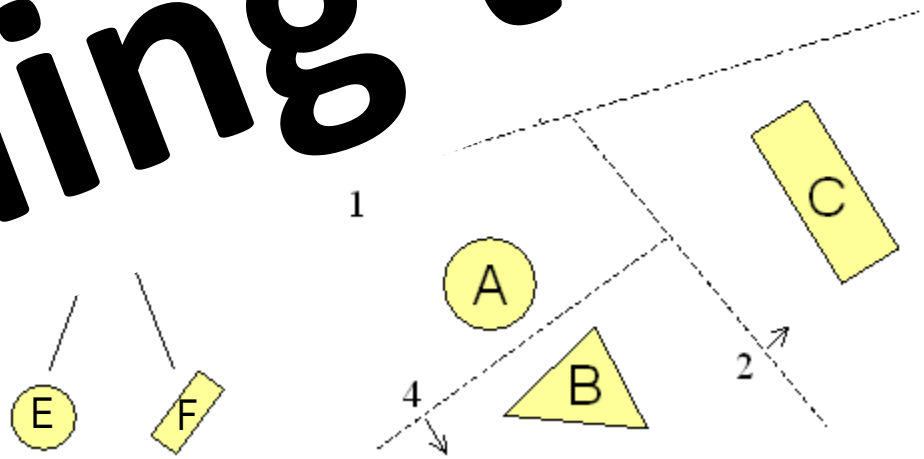
Building the tre





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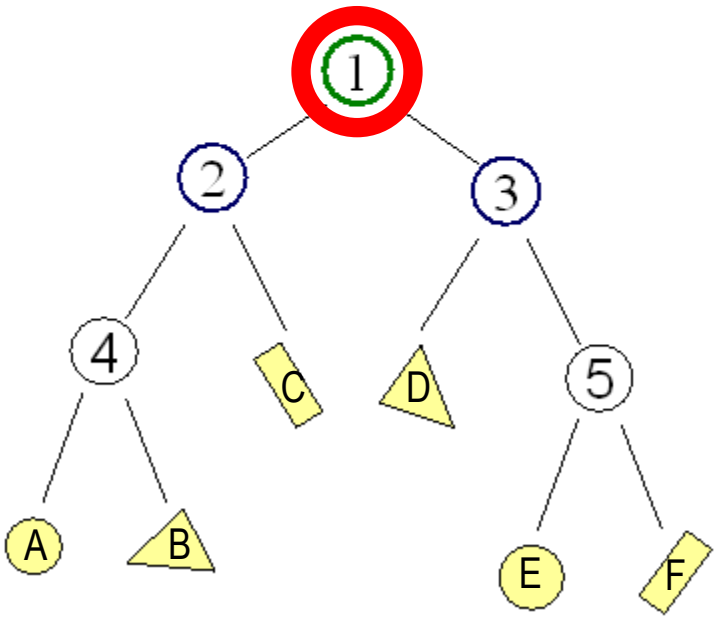

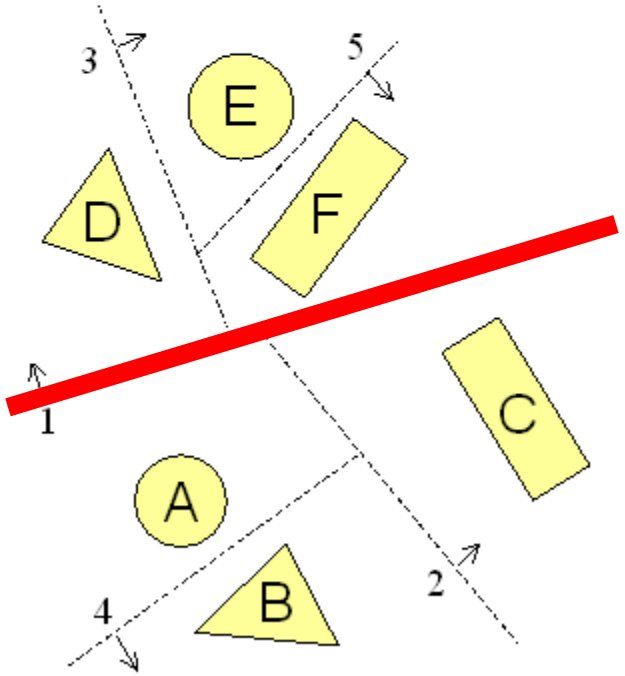

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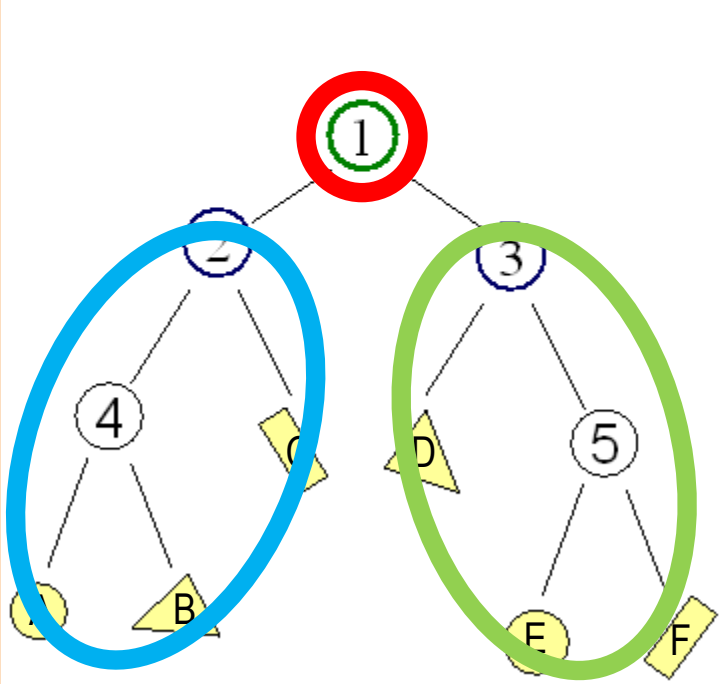

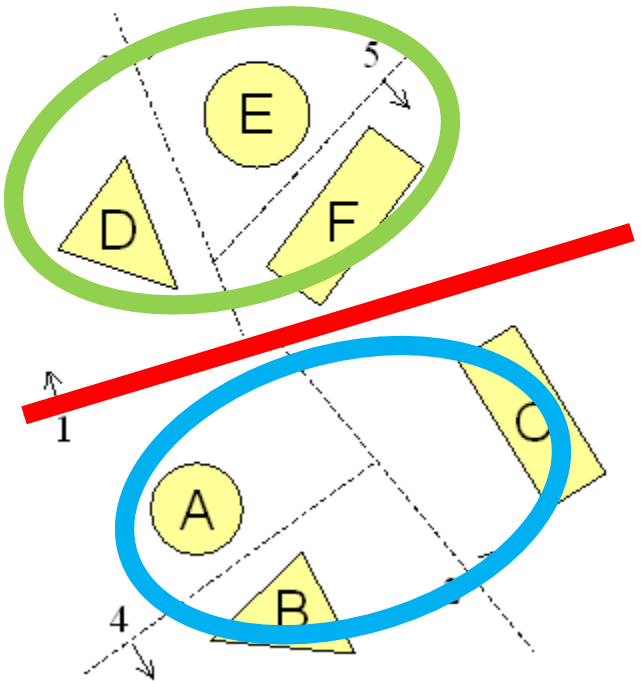

Binary Space Partition (BSP) Tree

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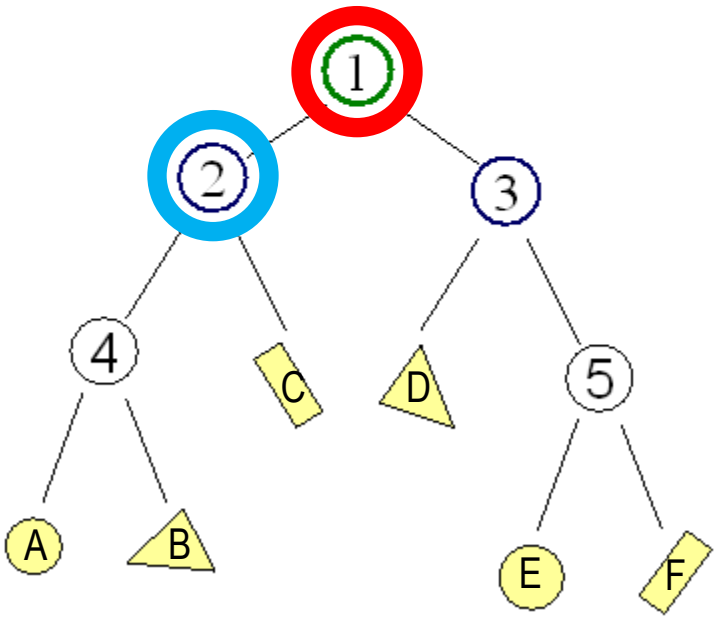

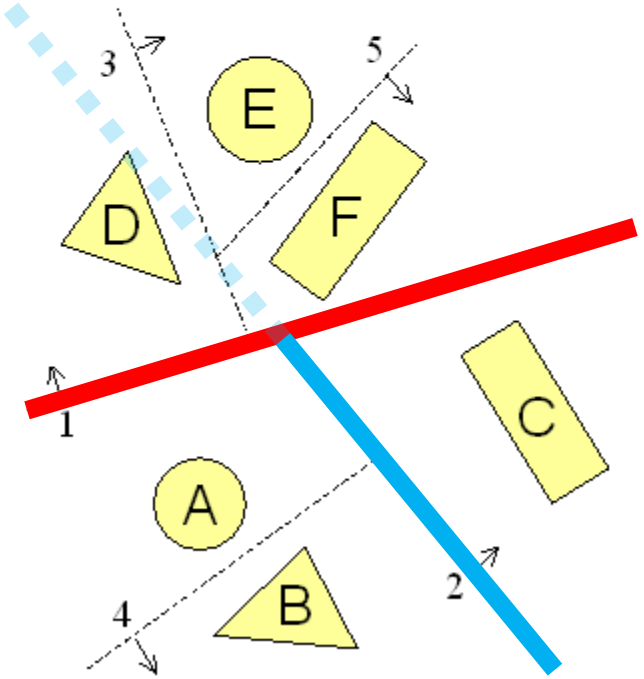

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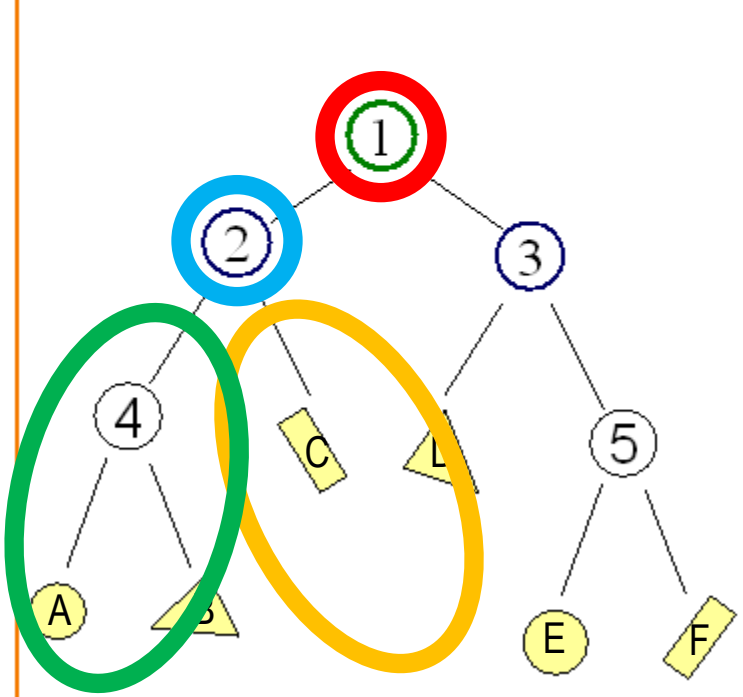

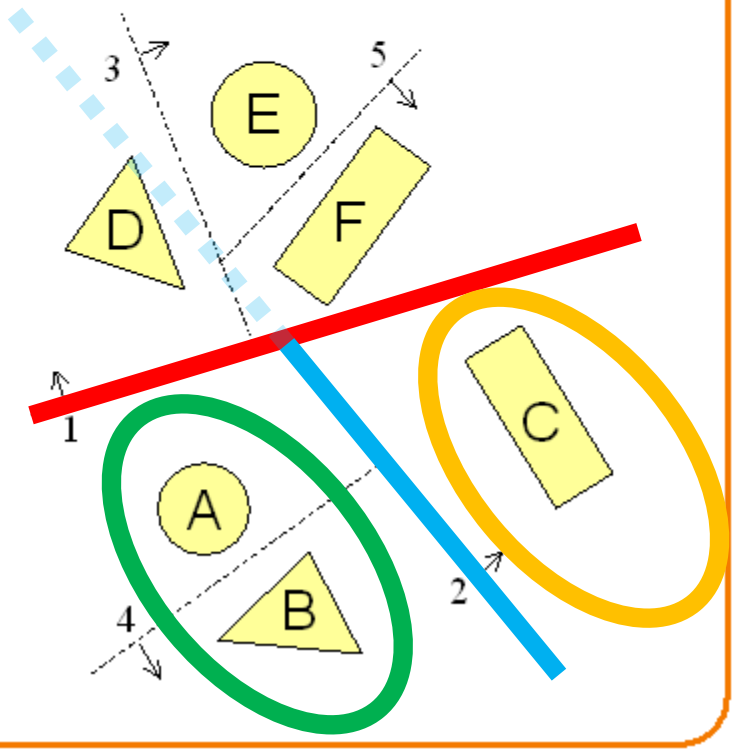

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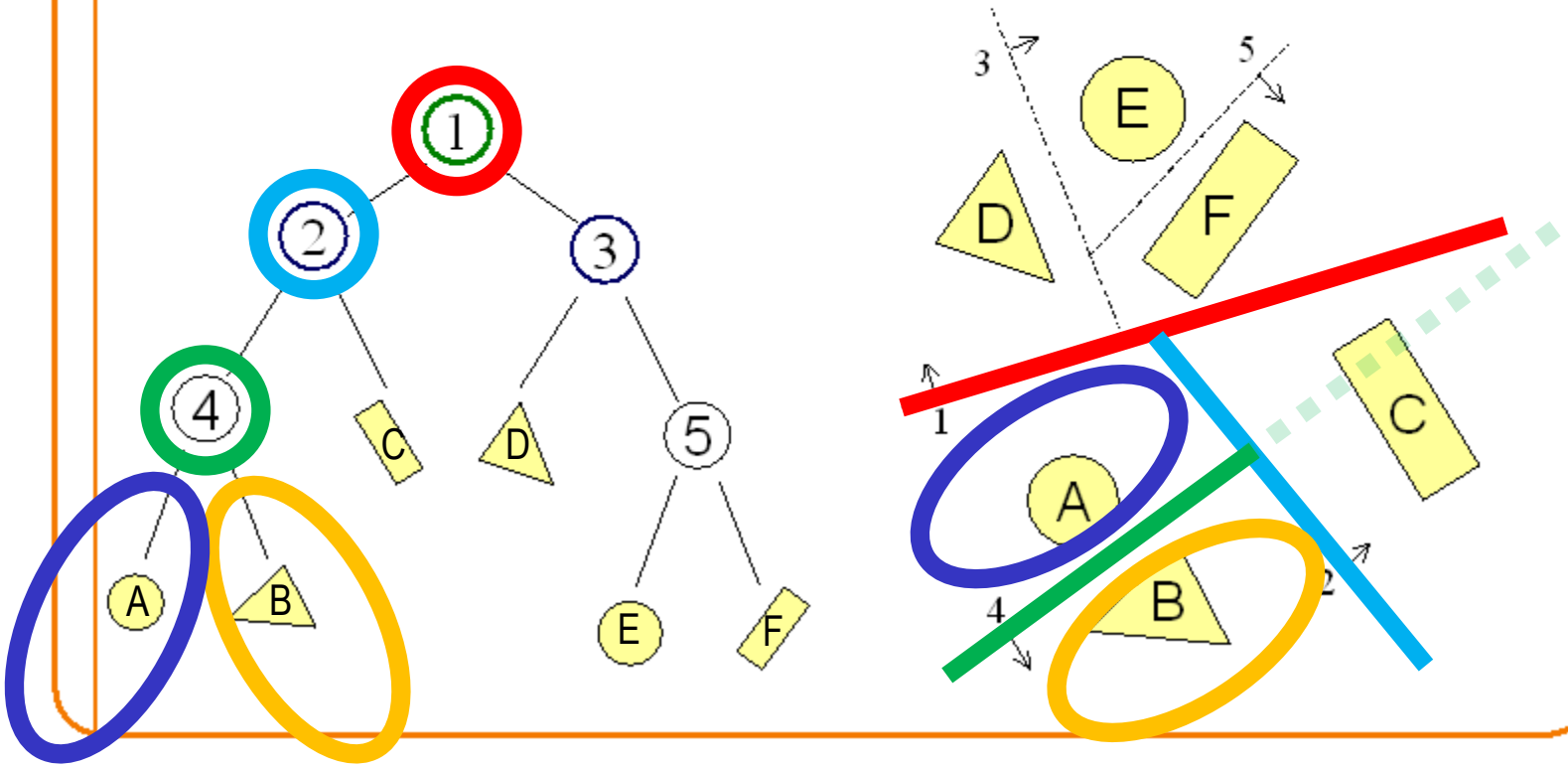

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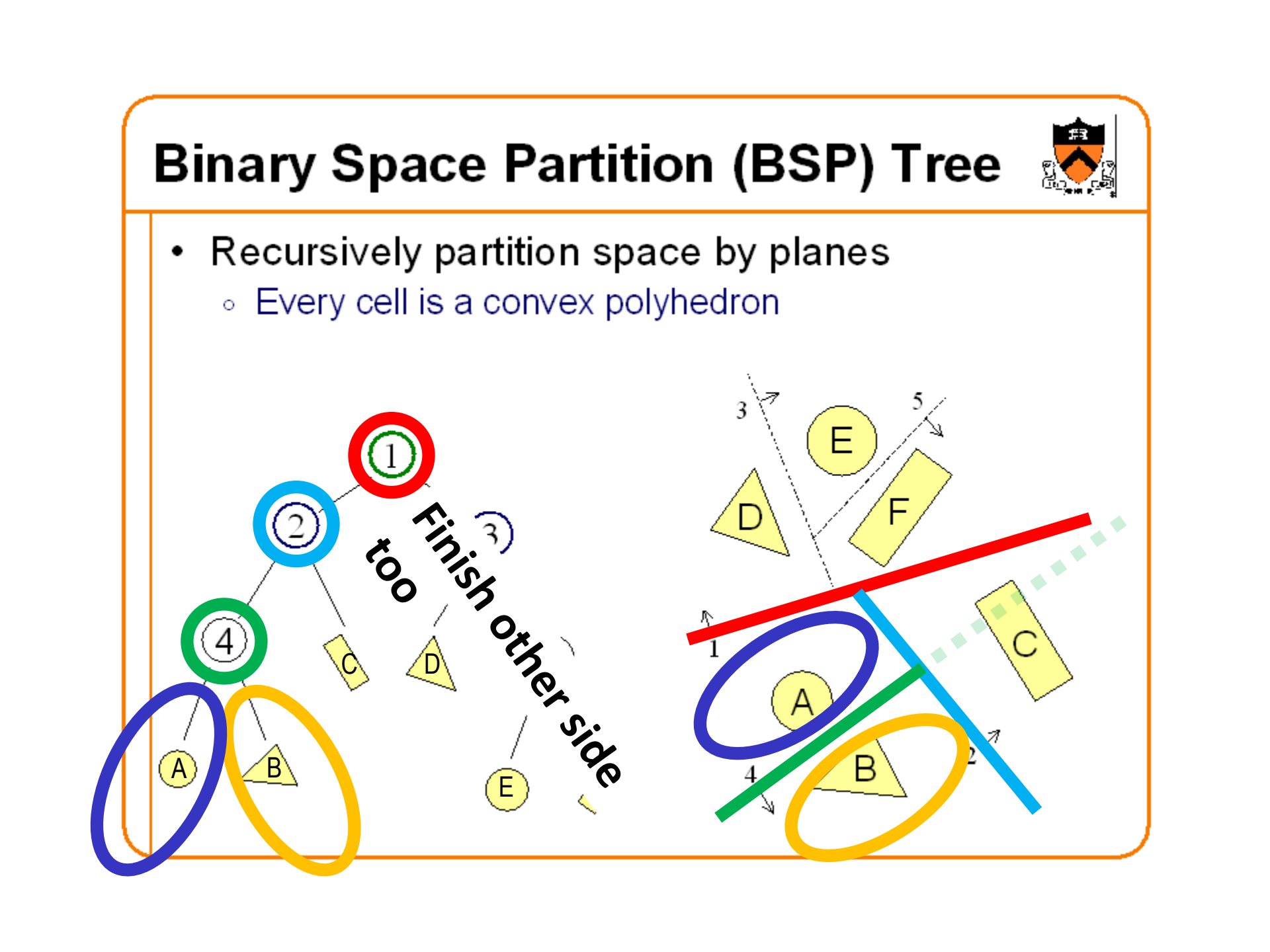

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Binary Space Partition (BSP) Tree

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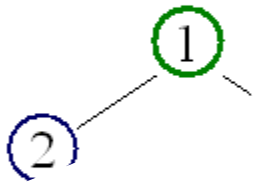
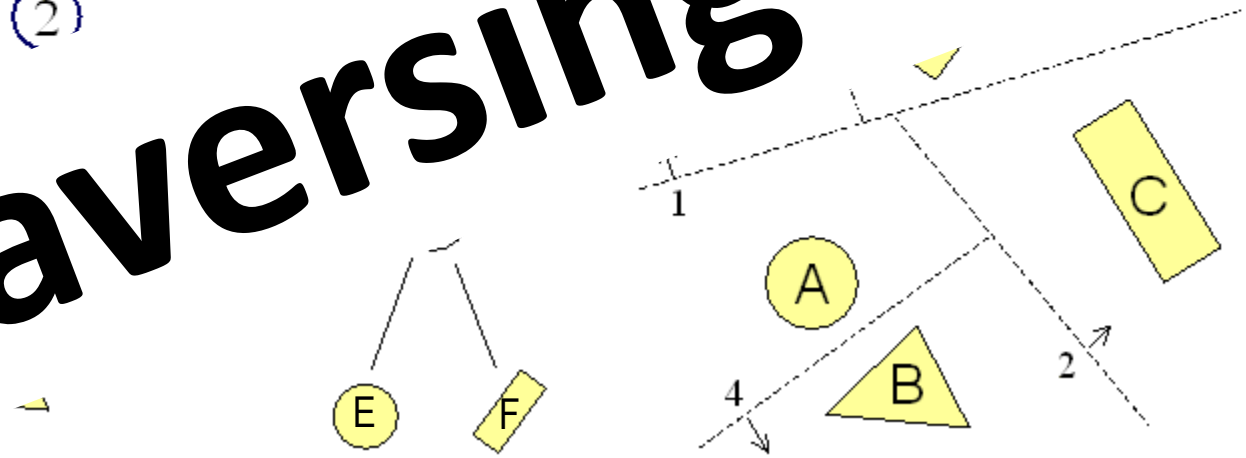
Traversing the tre





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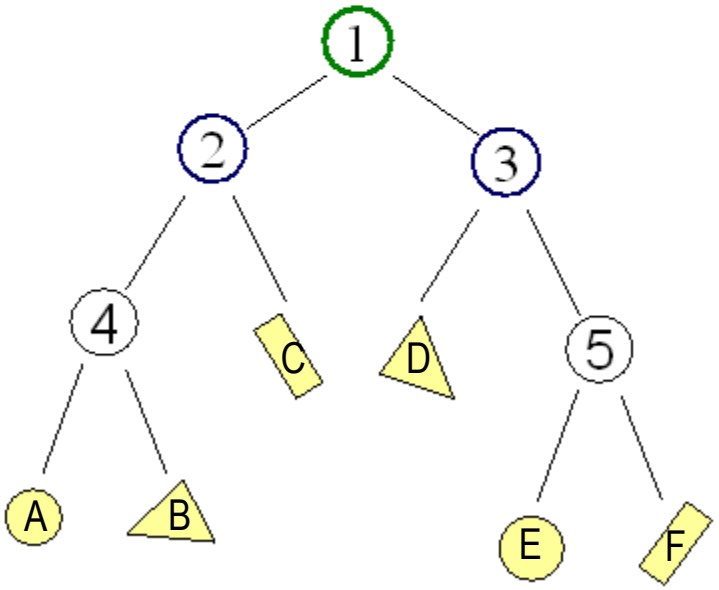

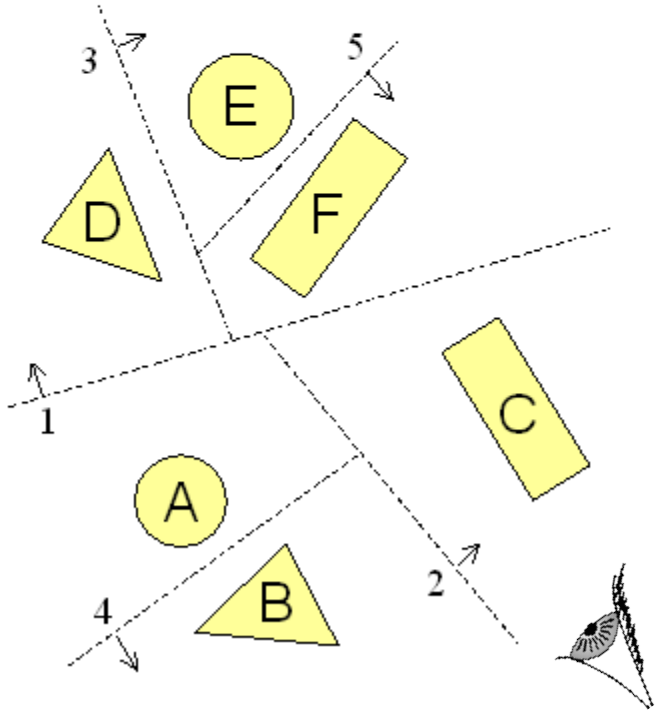

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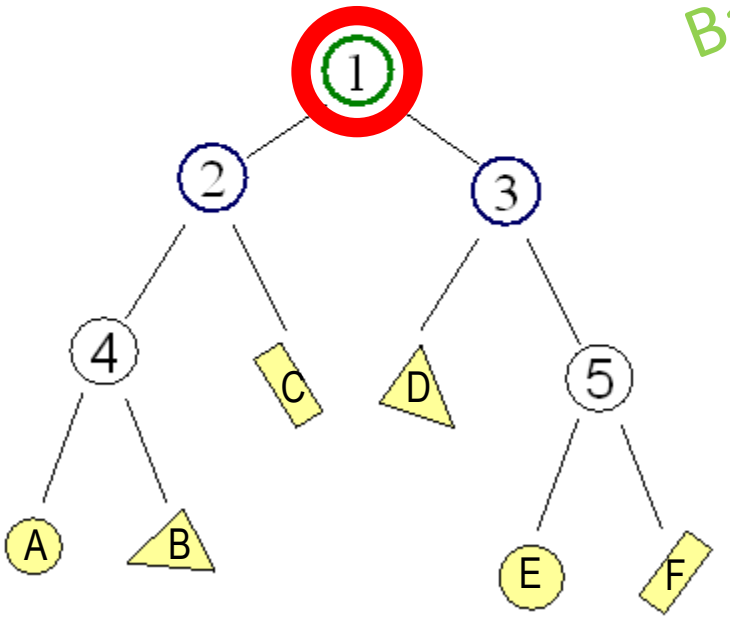

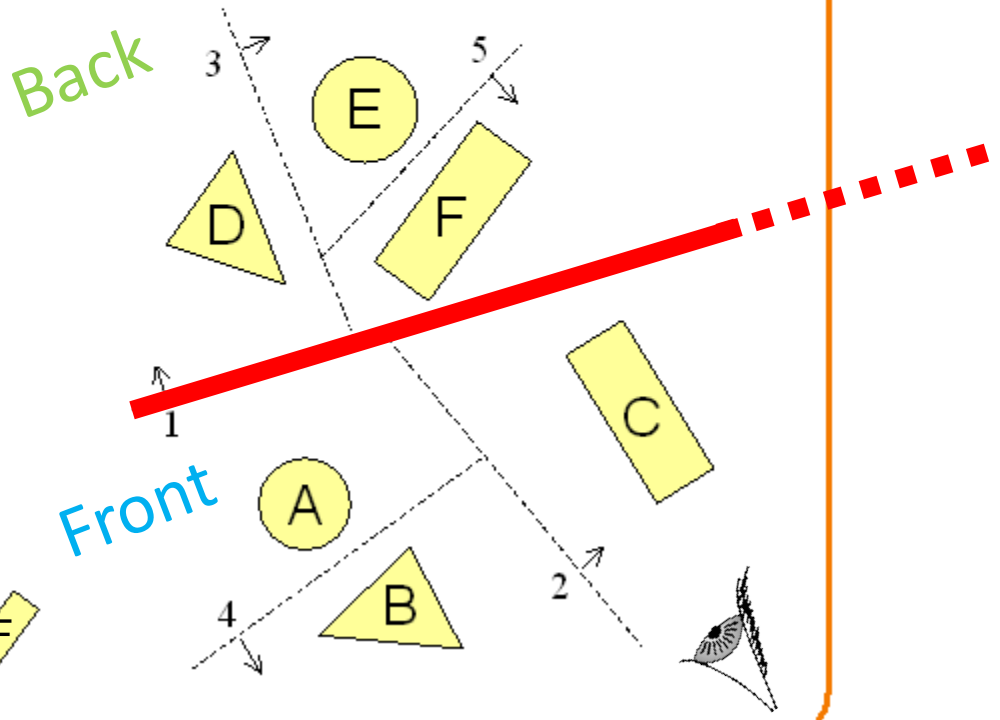

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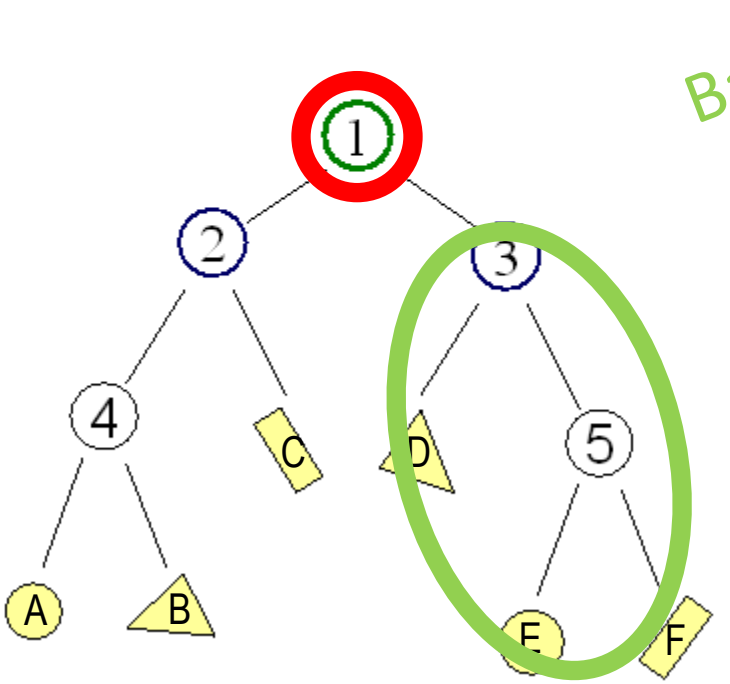

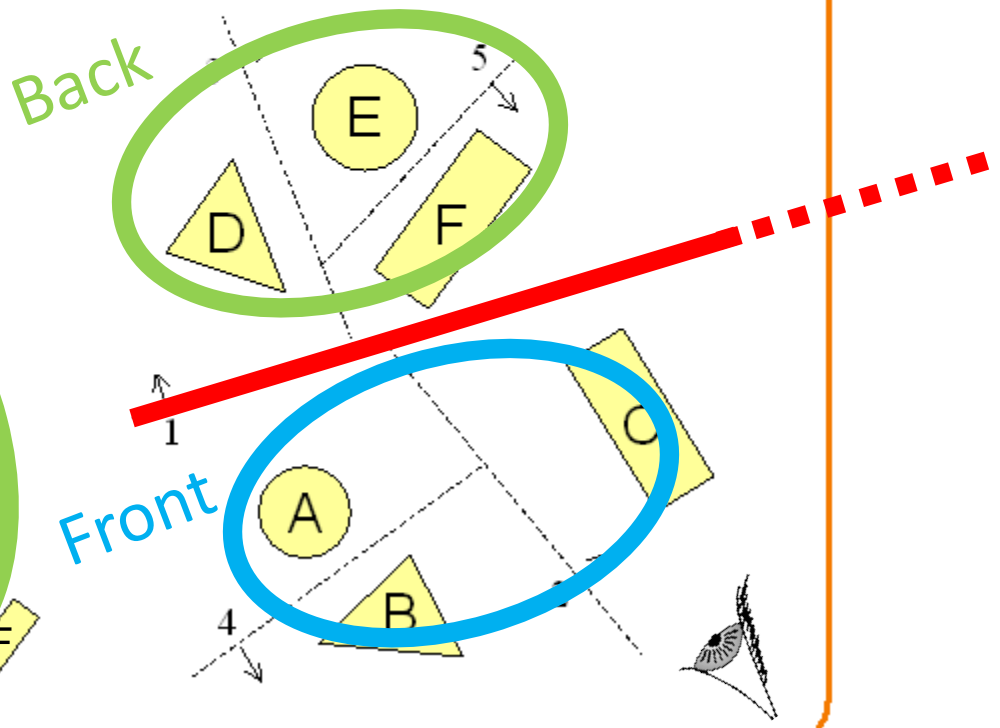

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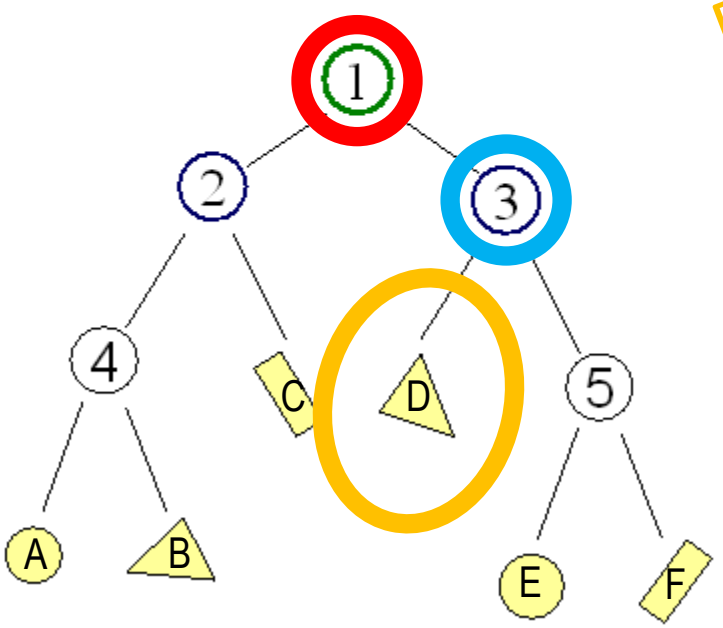
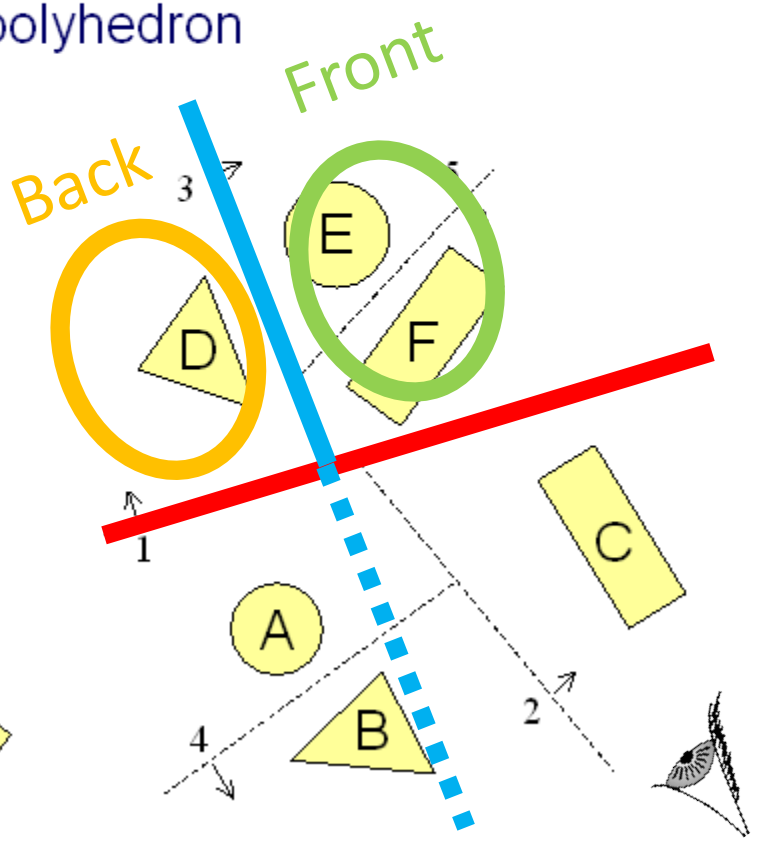
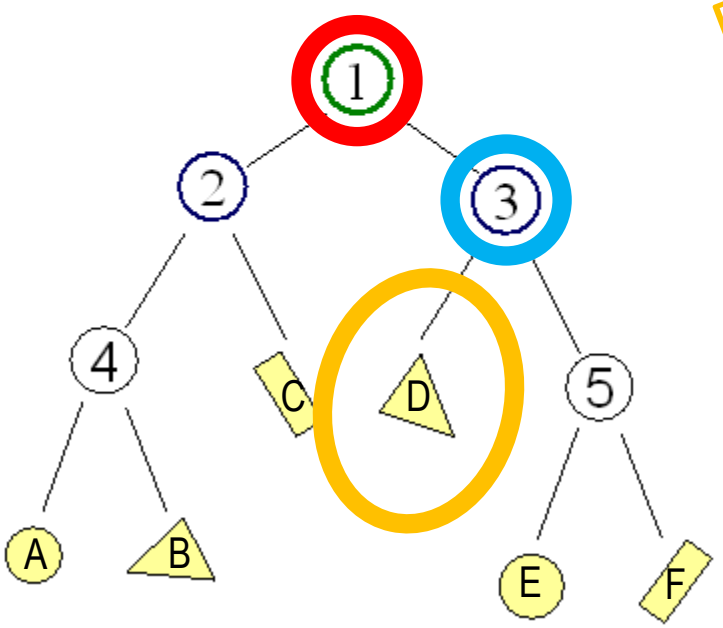
  - Every cell is a convex polyhedron

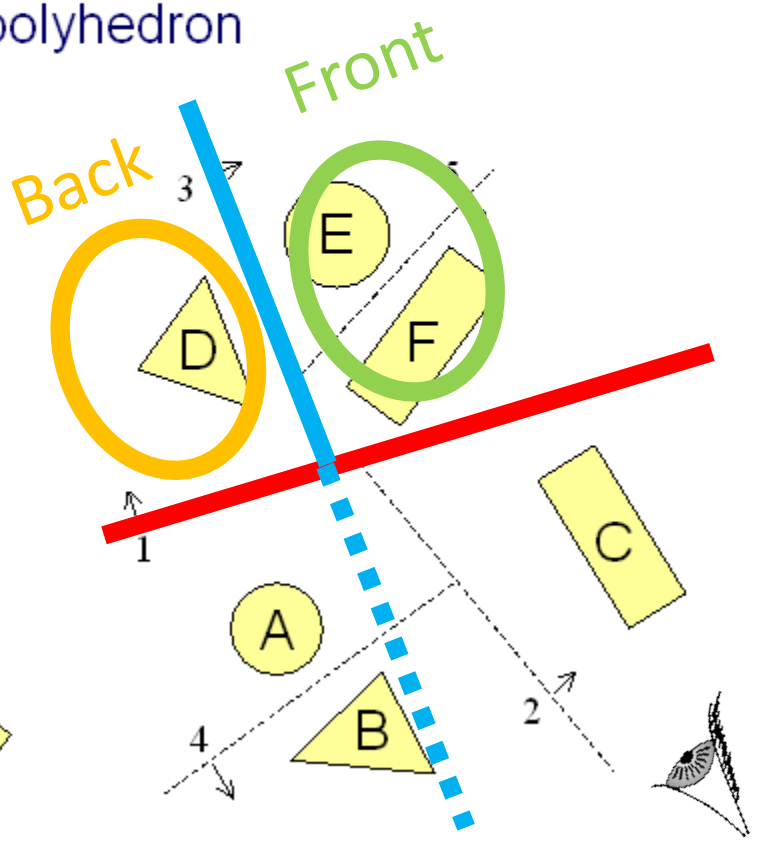




Binary Space Partition (BSP) Tree

- Recursively partition space by planes
  - Every cell is a convex polyhedron

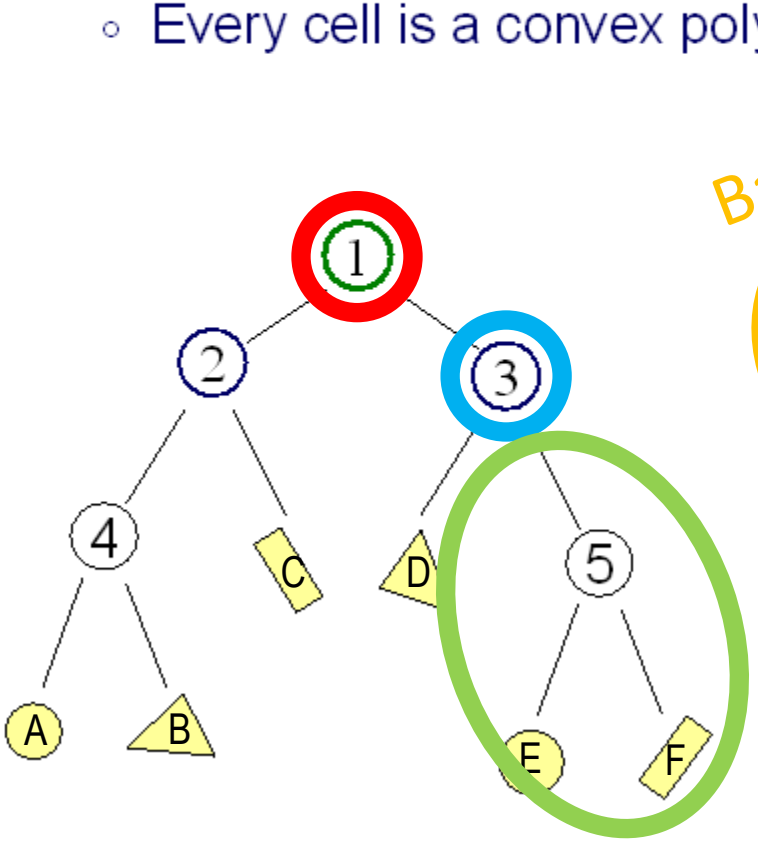


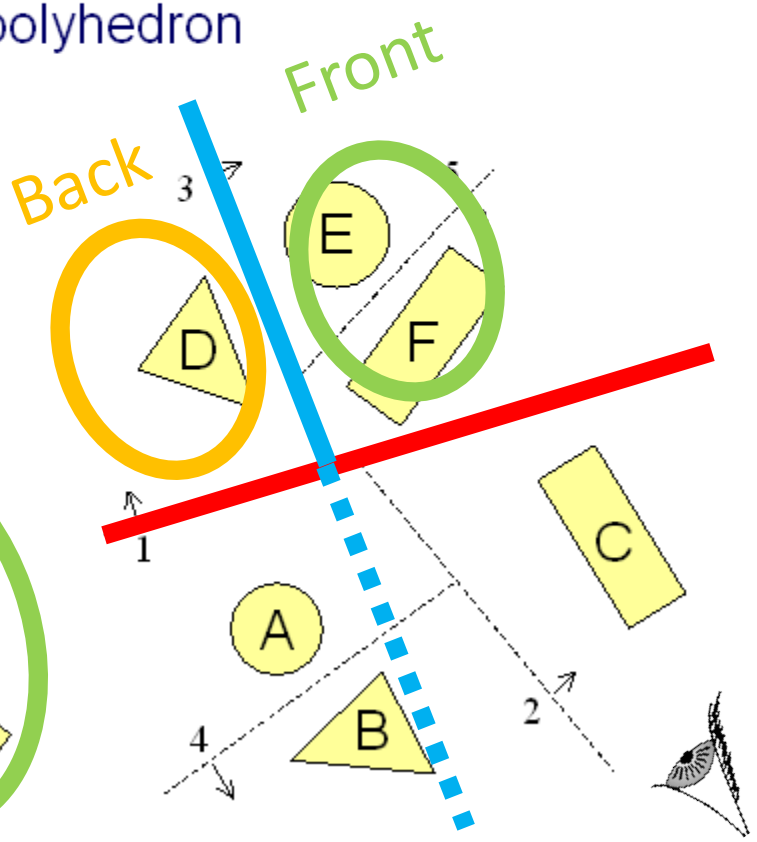


Drawing order: D,

Binary Space Partition (BSP) Tree

- Recursively partition space by planes
  - Every cell is a convex polyhedron

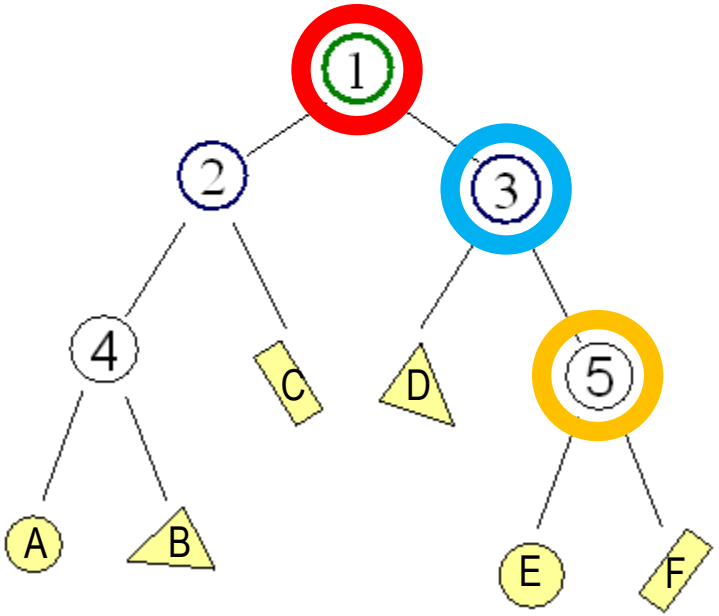


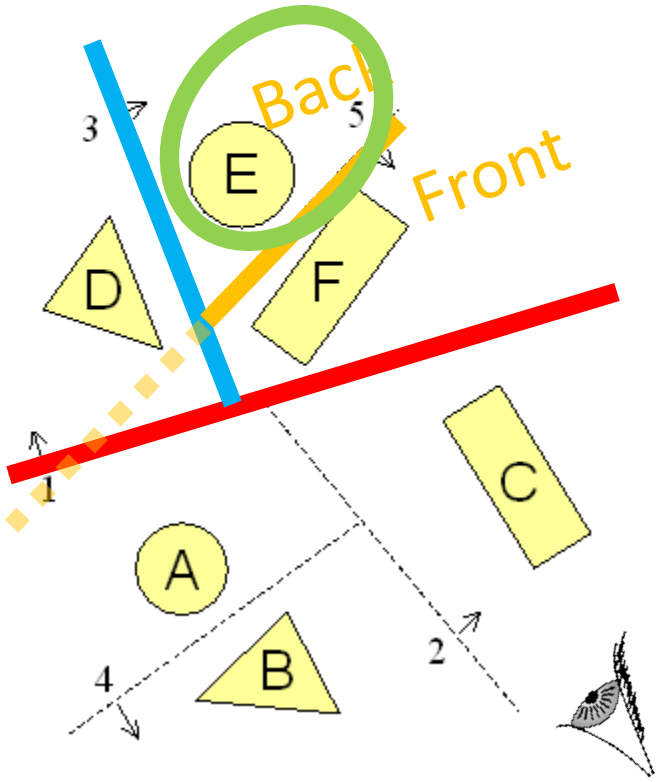


Drawing order: D, (EF)

Binary Space Partition (BSP) Tree

- Recursively partition space by planes
  - Every cell is a convex polyhedron

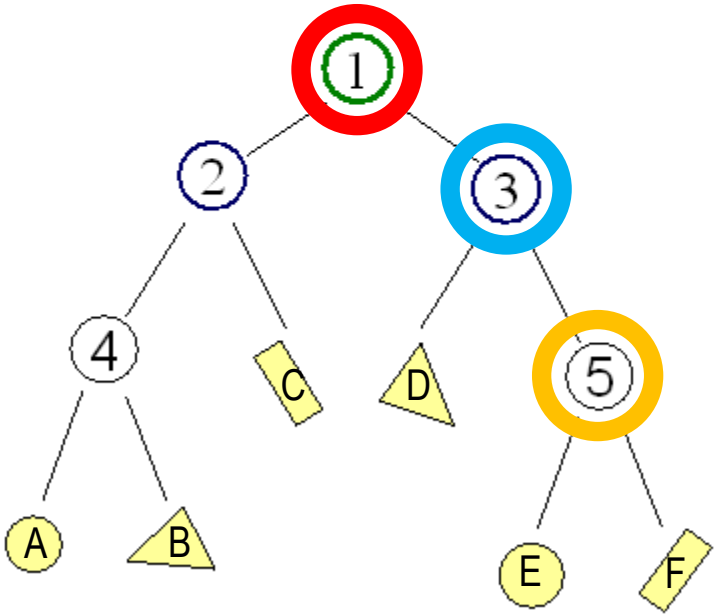


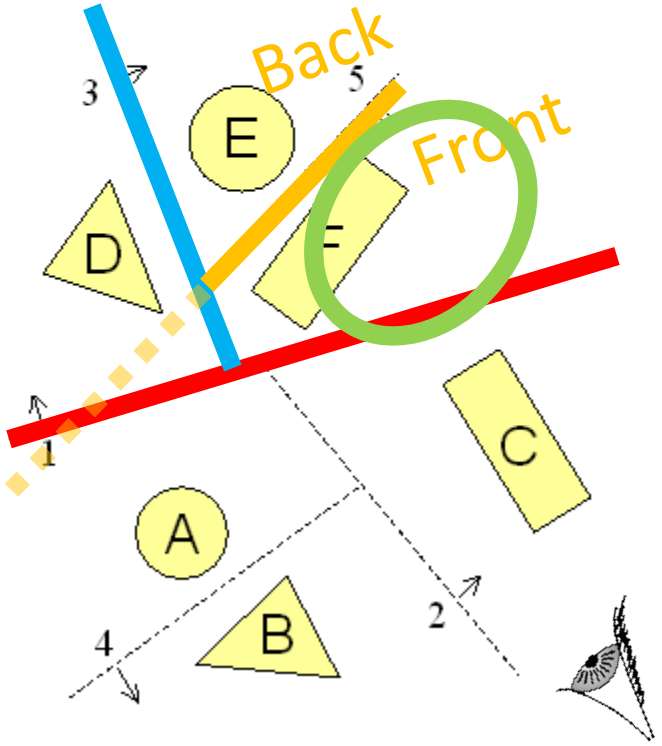


Drawing order: D, E,

Binary Space Partition (BSP) Tree

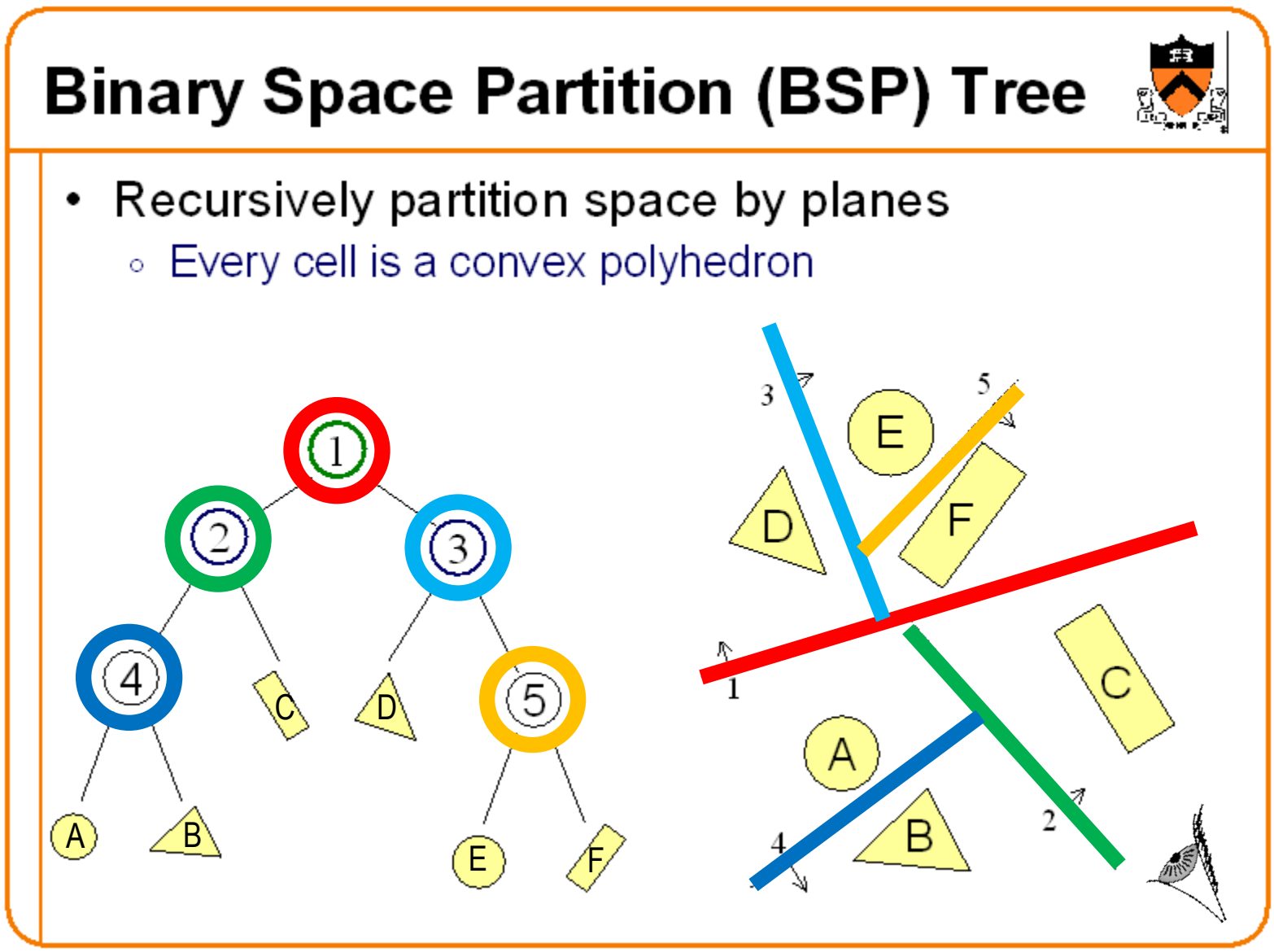
- Recursively partition space by planes
  - Every cell is a convex polyhedron





Drawing order: D, E, F

Binary Space Partition (BSP) Tree



- Recursively partition space by planes
  - Every cell is a convex polyhedron

Drawing order: D, E, F , A, B, C

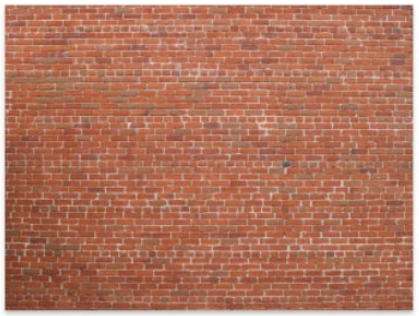
From Vertices to Frame Buffer

Command: draw these triangles!

Inputs:

```
list_of_positions = {
    v0x, v0y, v0z,
    v1x, v1y, v1x,
    v2x, v2y, v2z,
    v3x, v3y, v3x,
    v4x, v4y, v4z,
    v5x, v5y, v5x   };
```

```
list_of_texcoords = {
    v0u, v0v,
    v1u, v1v,
    v2u, v2v,
    v3u, v3v,
    v4u, v4v,
    v5u, v5v   };
```



Texture map

Object-to-camera-space transform: $\mathbf{T}$

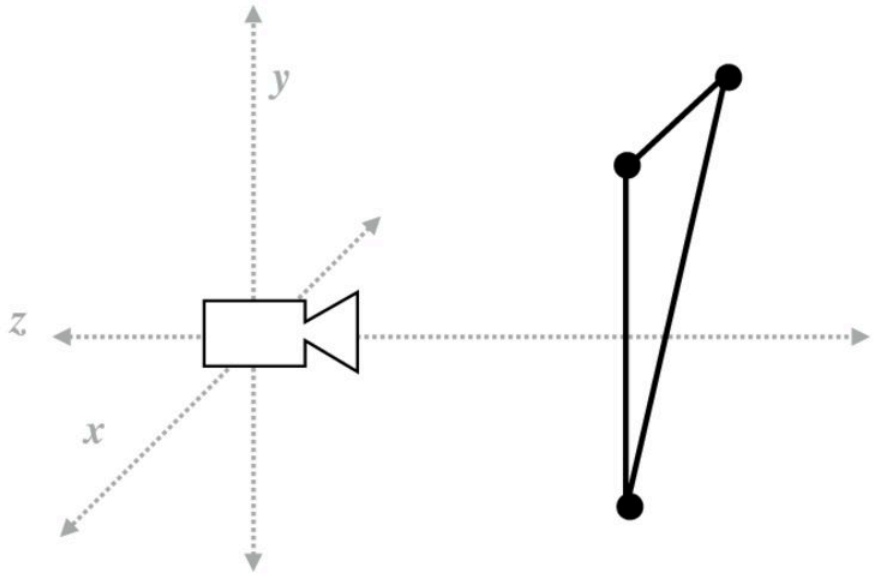
Perspective projection transform $\mathbf{P}$

Size of output image (W, H)

Use depth test /update depth buffer: YES!

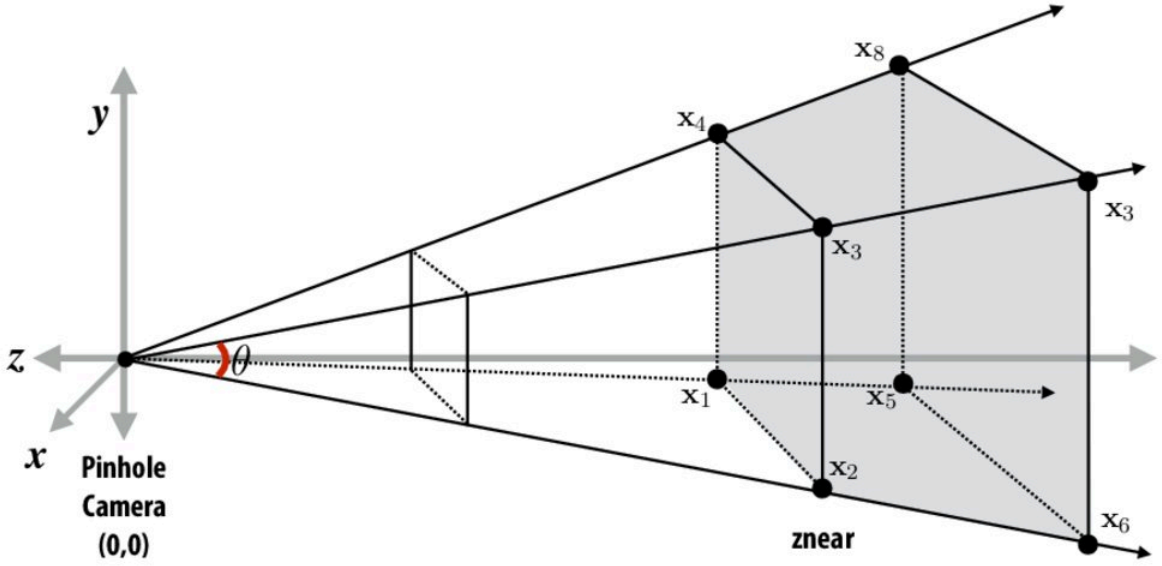
Step 1:

Transform triangle vertices into camera space (apply modeling and camera transform)

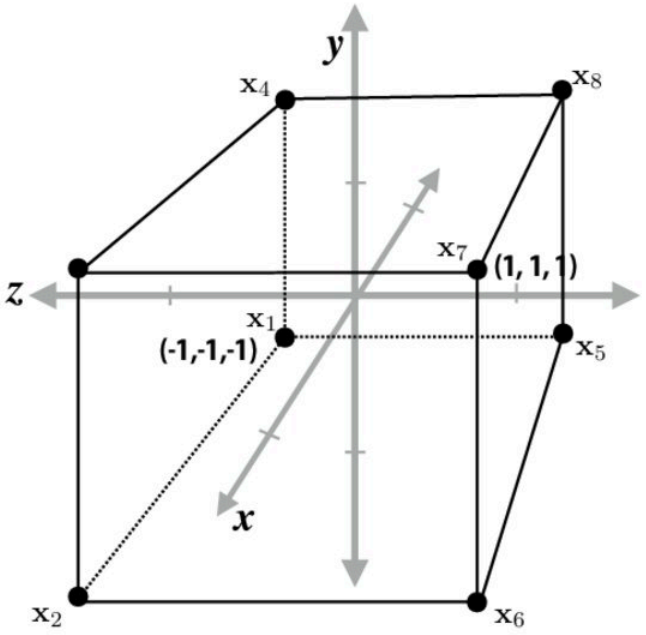


Step 2:

Apply perspective projection transform to transform triangle vertices into normalized coordinate space



Camera-space positions: 3D



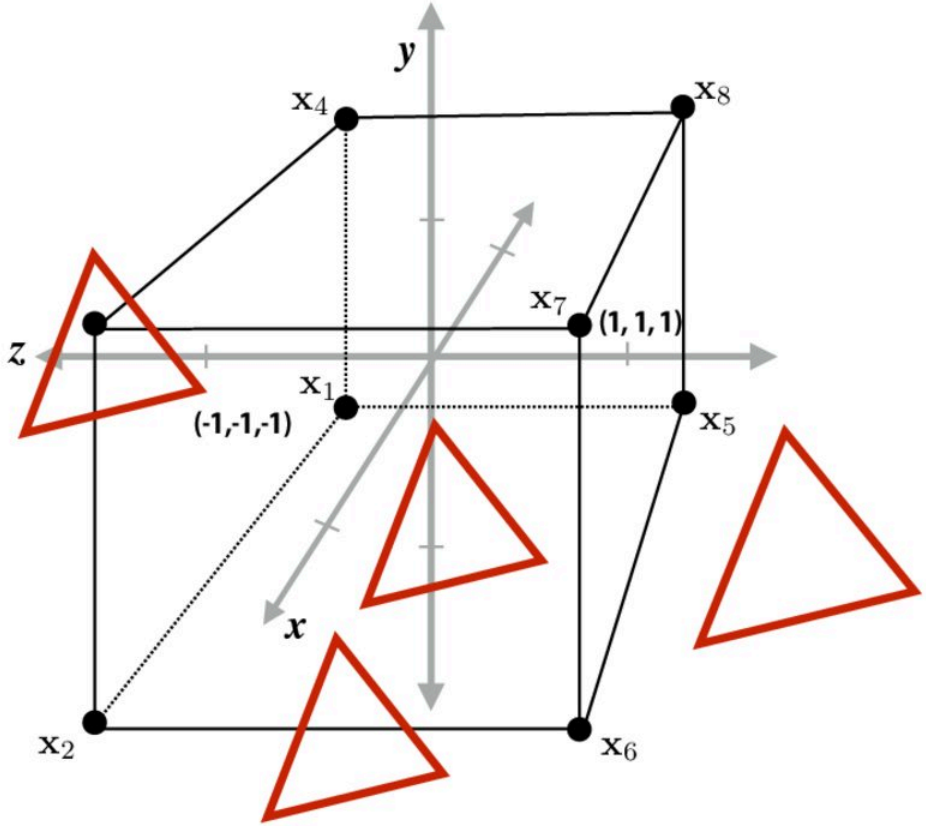
Normalized space positions

Note: I'm illustrating normalized 3D space after the homogeneous divide, it is more accurate to think of this volume in 3D-H space as defined by:

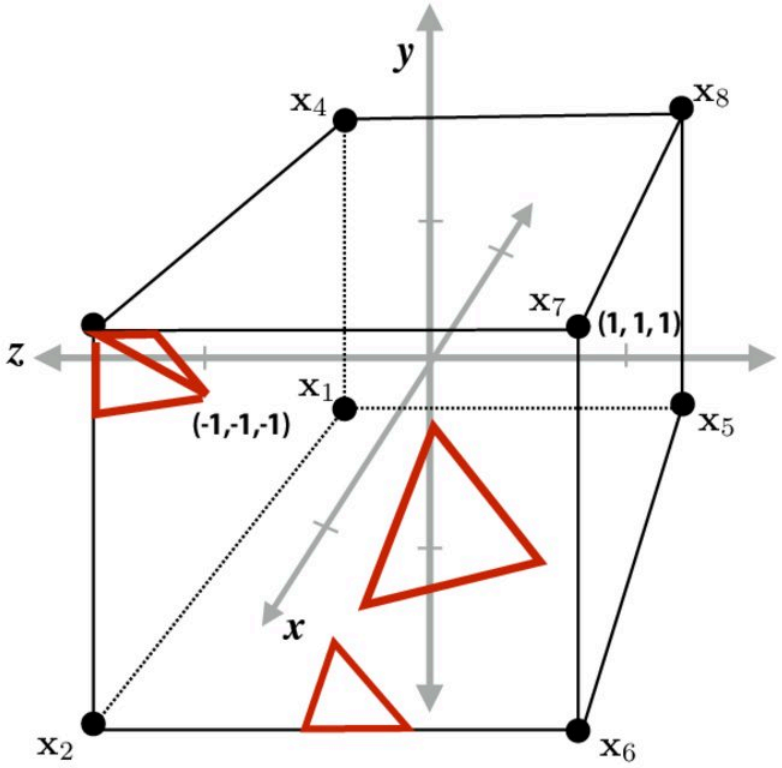
(-w, -w, -w, w) and (w, w, w, w)

Step 3: clipping

- Discard triangles that lie complete outside the unit cube (culling)
  - They are off screen, don't bother processing them further
- Clip triangles that extend beyond the unit cube to the cube
  - Note: clipping may create more triangles



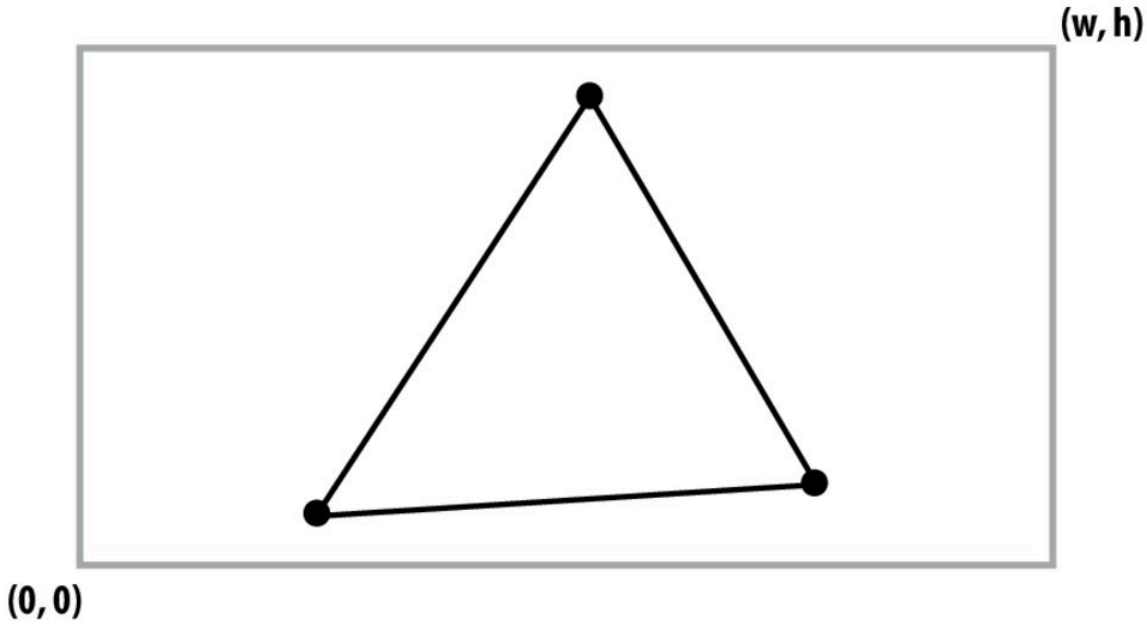
Triangles before clipping



Triangles after clipping

Step 4: transform to screen coordinates

Transform vertex xy positions from normalized coordinates into screen coordinates (based on screen w,h)



Step 5: setup triangle (triangle preprocessing)

Compute triangle edge equations

Compute triangle attribute equations

$$\mathbf{E}_{01}(x,y) \qquad \mathbf{U}(x,y)$$

$$\mathbf{E}_{12}(x,y) \qquad \mathbf{V}(x,y)$$

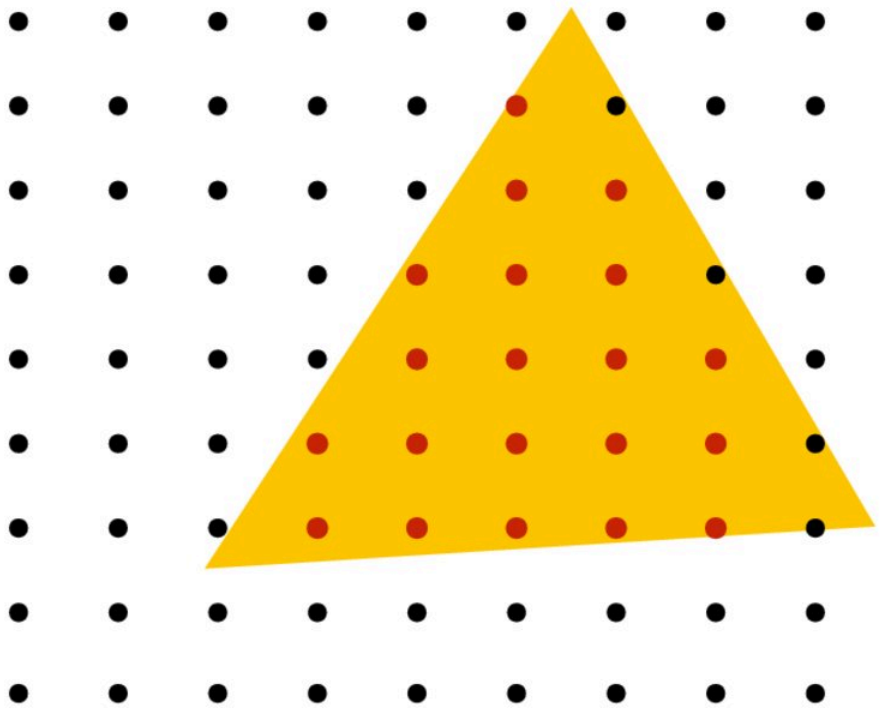
$$\mathbf{E}_{20}(x,y)$$

$$\frac{1}{\mathbf{w}}(x,y)$$

$$\mathbf{Z}(x,y)$$

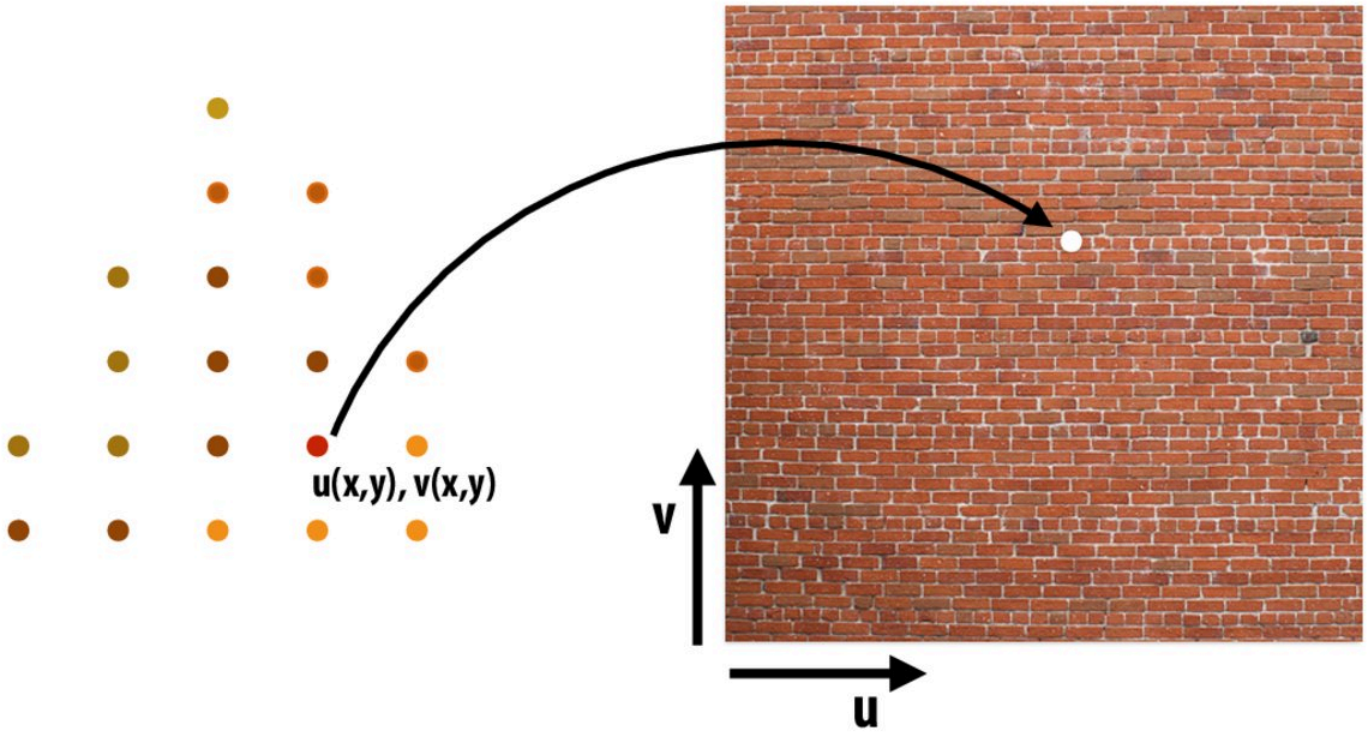
Step 6: sample coverage

Evaluate attributes z, u, v at all covered samples



Step 6: compute triangle color at sample point

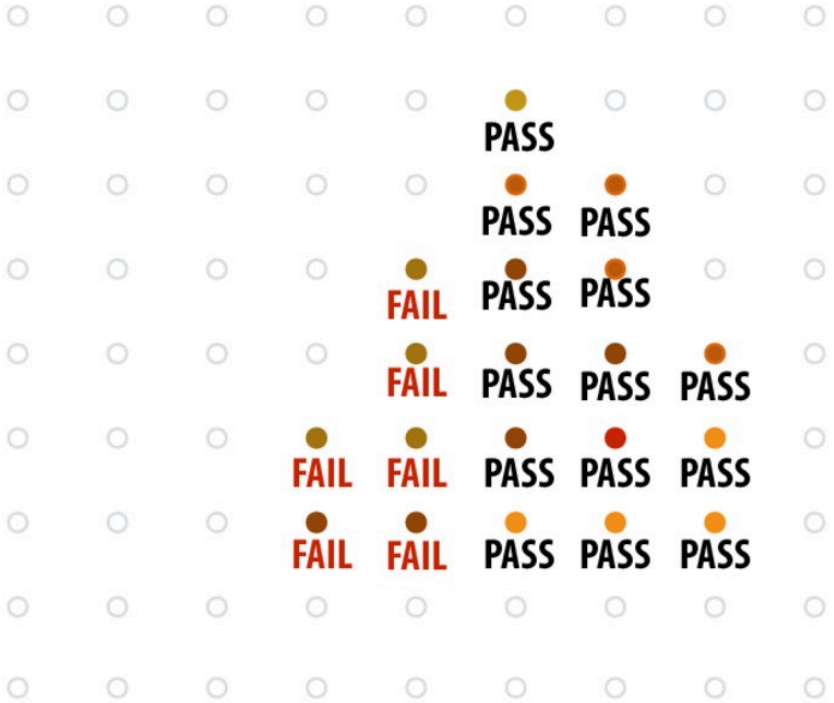
e.g., sample texture map *



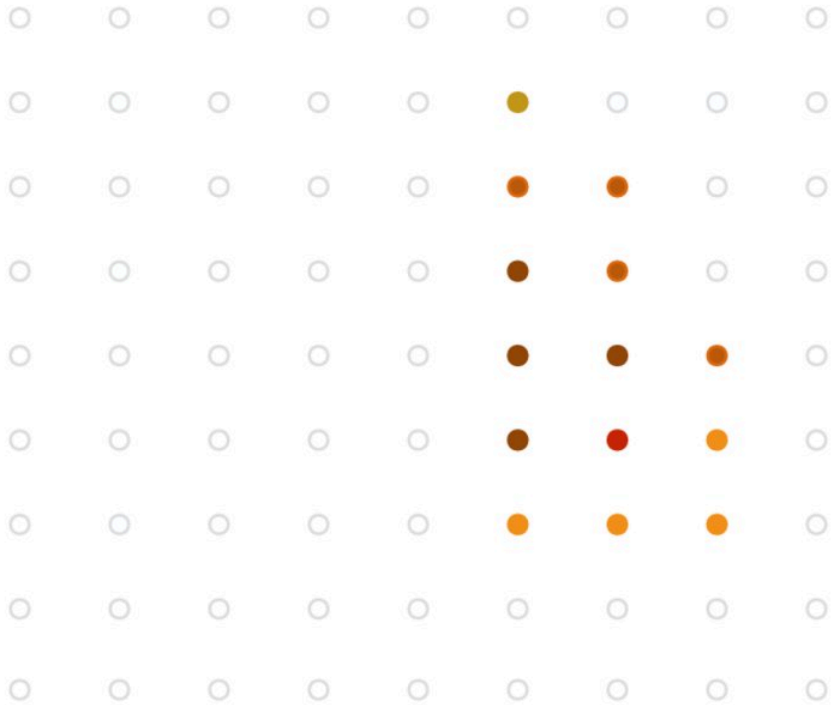
* So far, we've only described computing triangle's color at a point by interpolating per-vertex colors, or by sampling a texture map. Later in the course, we'll discuss more advanced algorithms for computing its color based on material properties and scene lighting conditions.

Step 7: perform depth test (if enabled)

Also update depth value at covered samples (if necessary)



Step 8: update color buffer (if depth test passed)



Step 9:

- Repeat steps 1-8 for all triangles in the scene!

Administrative

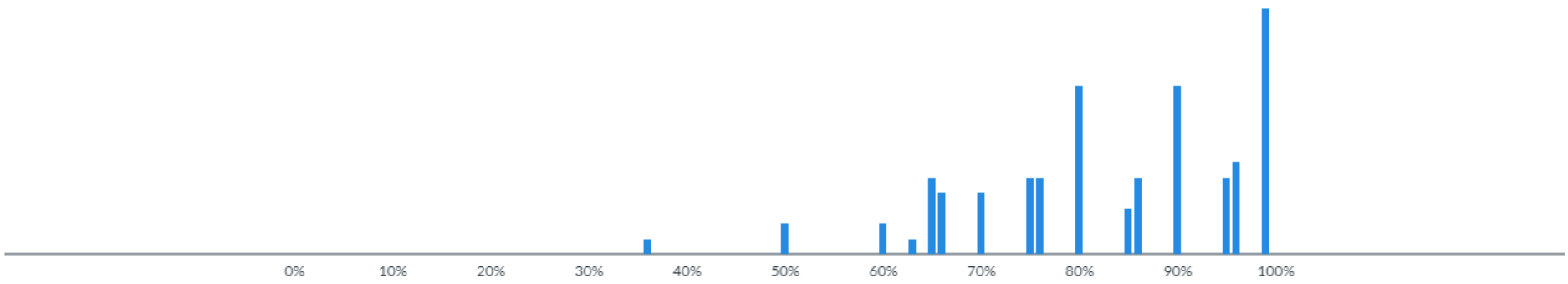
Due Dates

- Due Yesterday
  - HW 3 (Color+Texture)
- Due tomorrow
  - Quiz 3
- Due next Monday
  - Lab Assignment 3 (Blocky World)

Quiz 2 statistics

Quiz 2 - Transformations & Modeling

100%	37%	83%	1.399	53:54	0
High Score	Low Score	Mean Score	Standard Deviation	Mean Elapsed Time	Cronbach's Alpha



Data Last Updated: Nov 10, 2020

Q&A

End