Lecture 8:

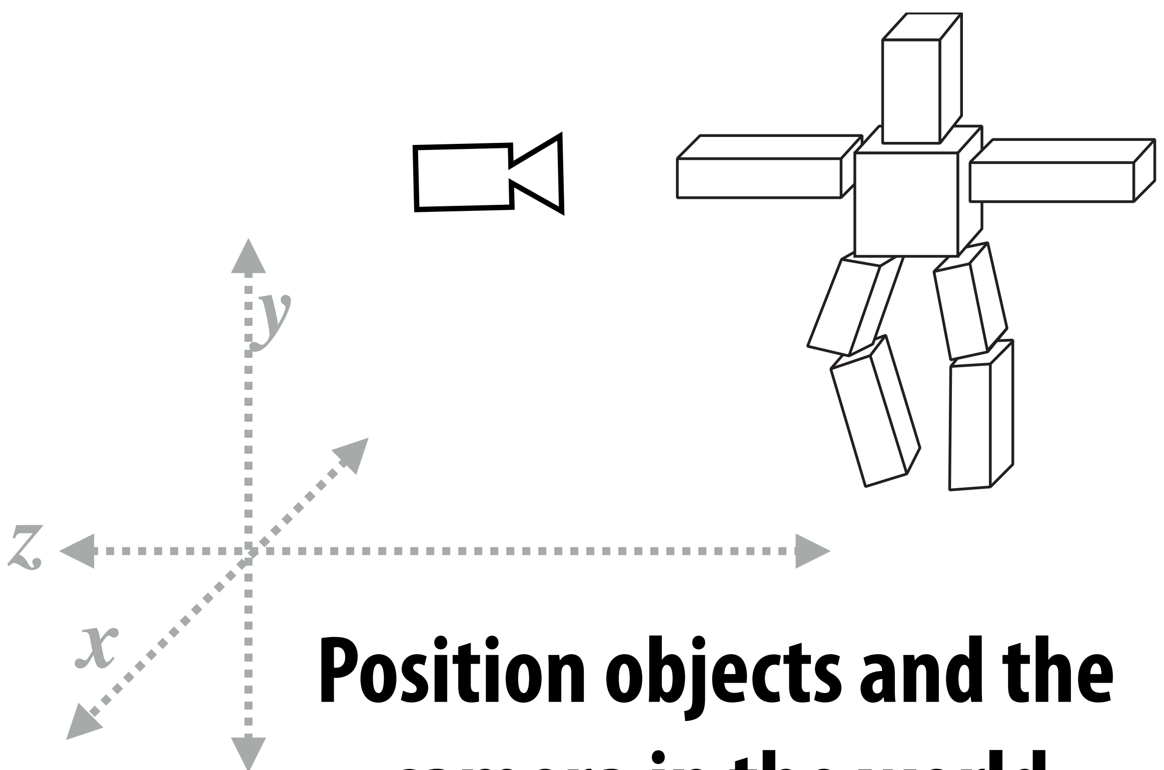
# The Rasterization Pipeline

## (and its implementation on GPUs)

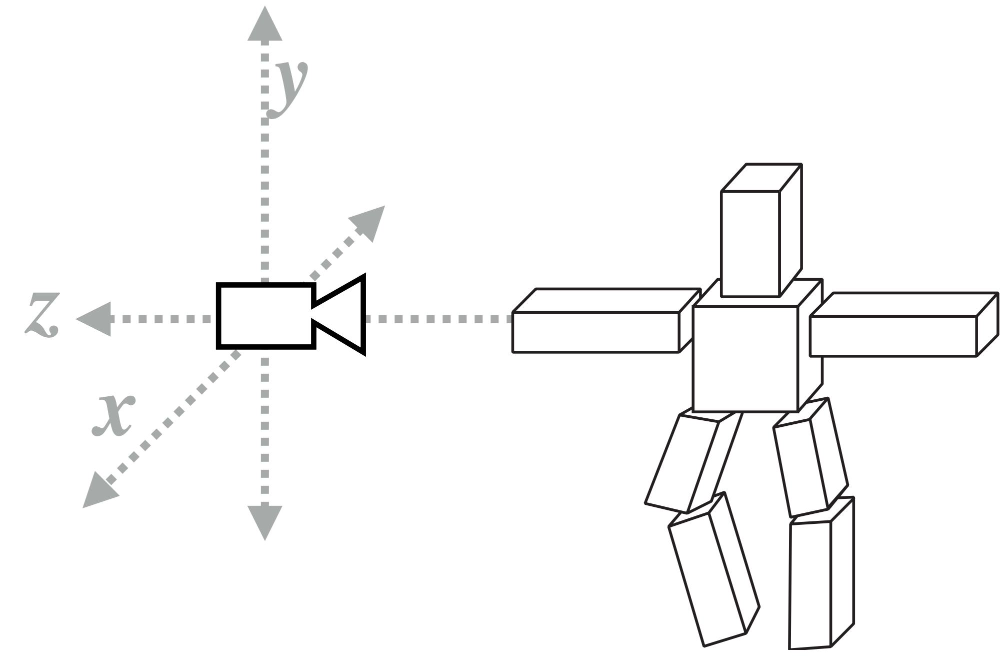
---

Computer Graphics
CMU 15-462/15-662, Spring 2018

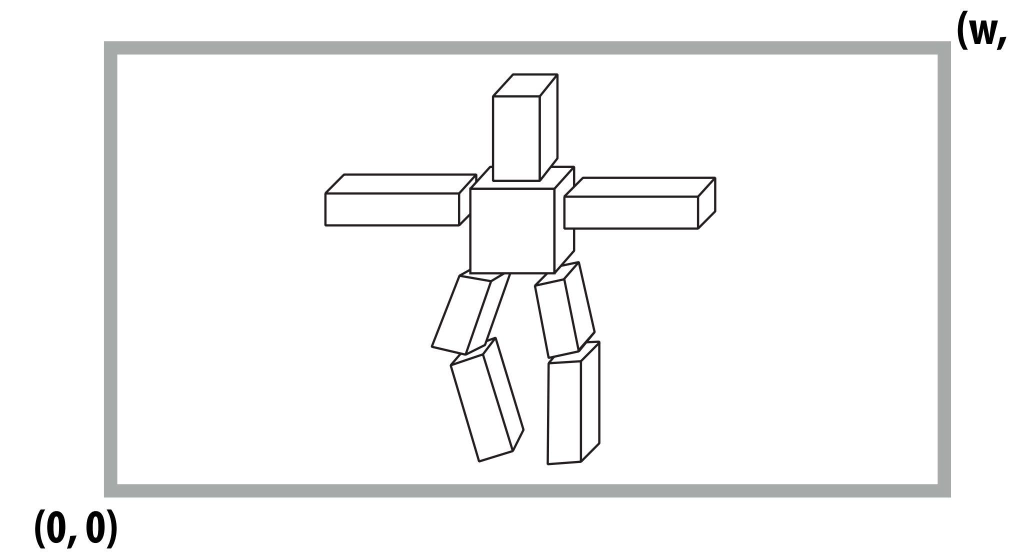
# What you know how to do (at this point in the course)



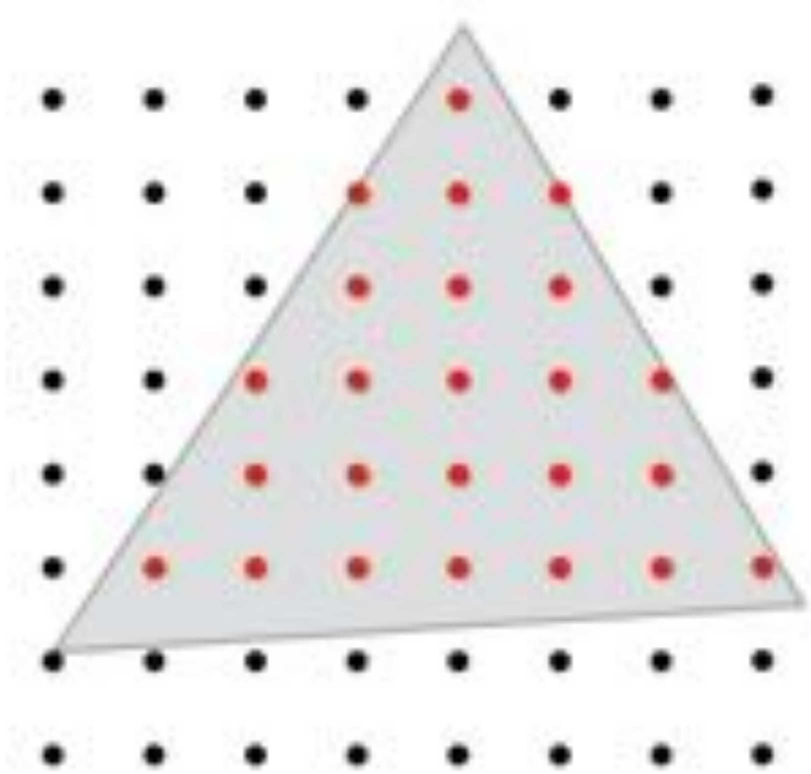

**Position objects and the camera in the world**




**Determine the position of objects relative to the camera**




**Project objects onto the screen**



**Sample triangle coverage**

**Compute triangle attribute values at covered sample points**

**Sample texture maps**

# What else do you need to know to render a picture like this?

## Surface representation

How to represent complex surfaces?

## Occlusion

Determining which surface is visible to the camera at each sample point

## Lighting/materials

Describing lights in scene and how materials reflect light.

# Course roadmap

## Drawing Things

Key concepts:
Sampling (and anti-aliasing)
Coordinate Spaces and Transforms

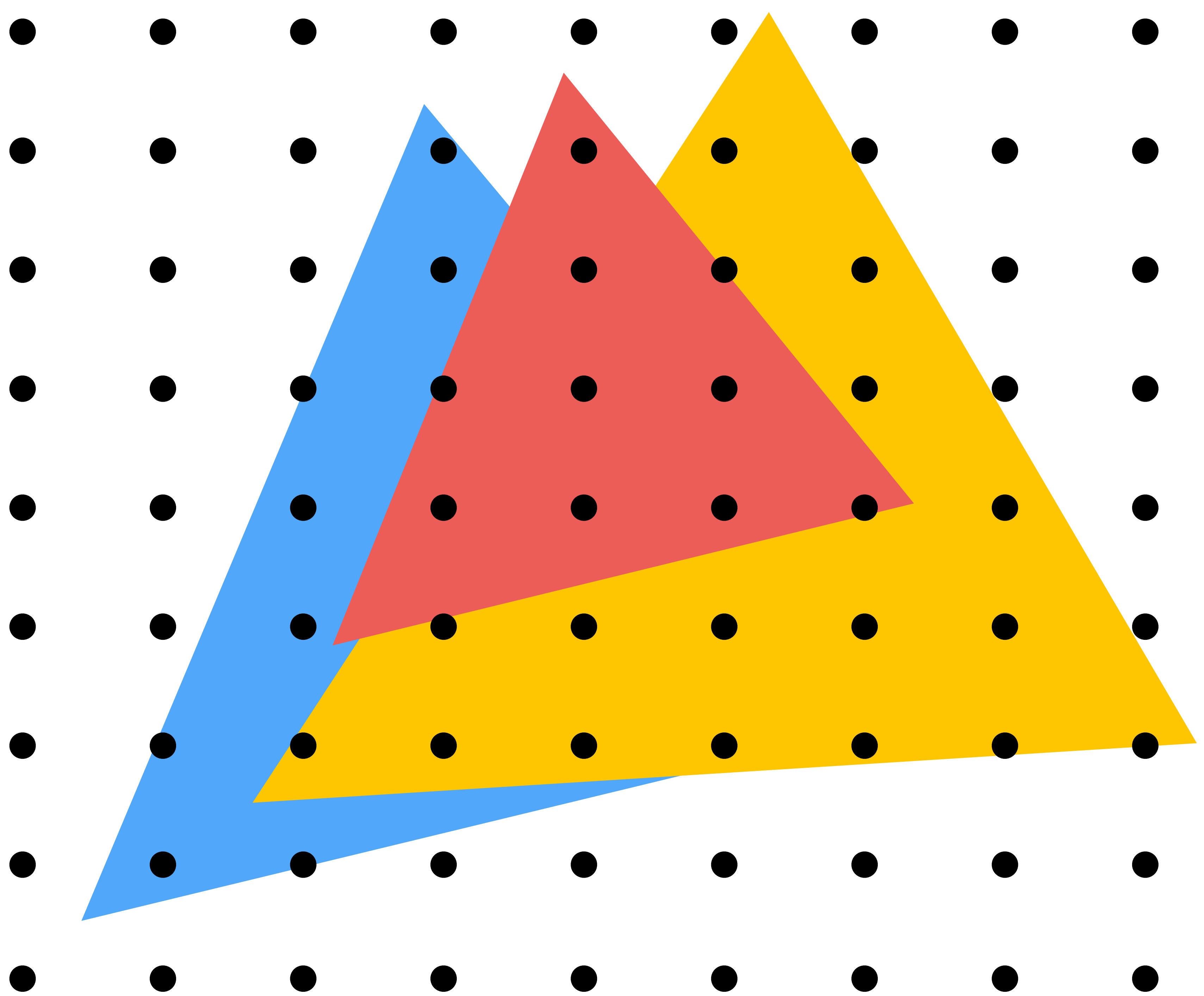
- Introduction
- Drawing a triangle (by sampling)
- Transforms and coordinate spaces
- Perspective projection and texture sampling
- Today: putting it all together: end-to-end rasterization pipeline

## Geometry

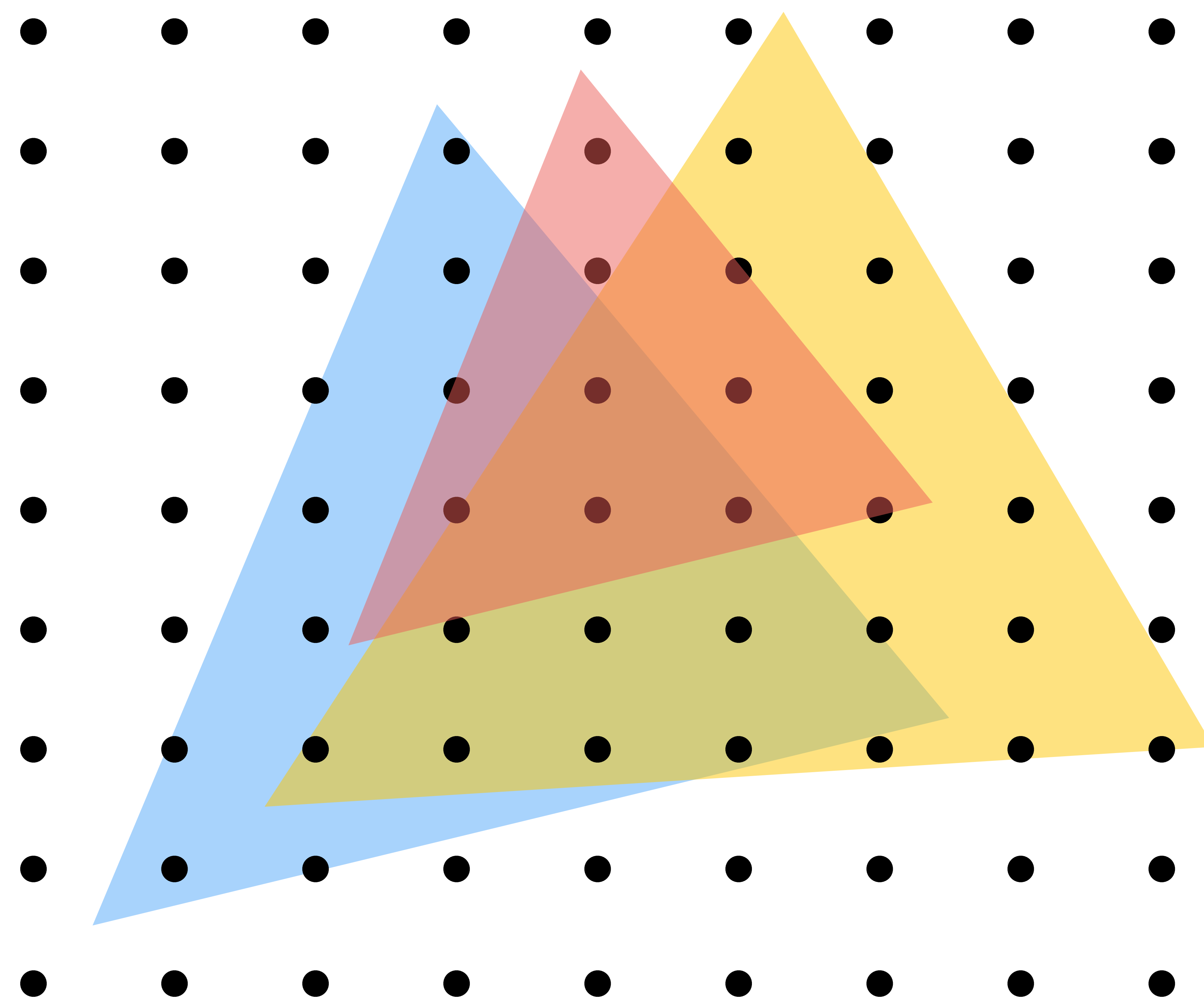
## Materials and Lighting

# Occlusion

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



Opaque Triangles



50% transparent triangles

# Review from last class

**Assume we have a triangle defined by the screen-space 2D position and distance ("depth") from the camera of each vertex.**

$$\begin{bmatrix}\mathbf{p}_{0x} & \mathbf{p}_{0y}\end{bmatrix}^T, \quad d_0$$

$$\begin{bmatrix}\mathbf{p}_{1x} & \mathbf{p}_{1y}\end{bmatrix}^T, \quad d_1$$

$$\begin{bmatrix}\mathbf{p}_{2x} & \mathbf{p}_{2y}\end{bmatrix}^T, \quad d_2$$

**How do we compute the depth of the triangle at covered sample point $(x, y)$?**

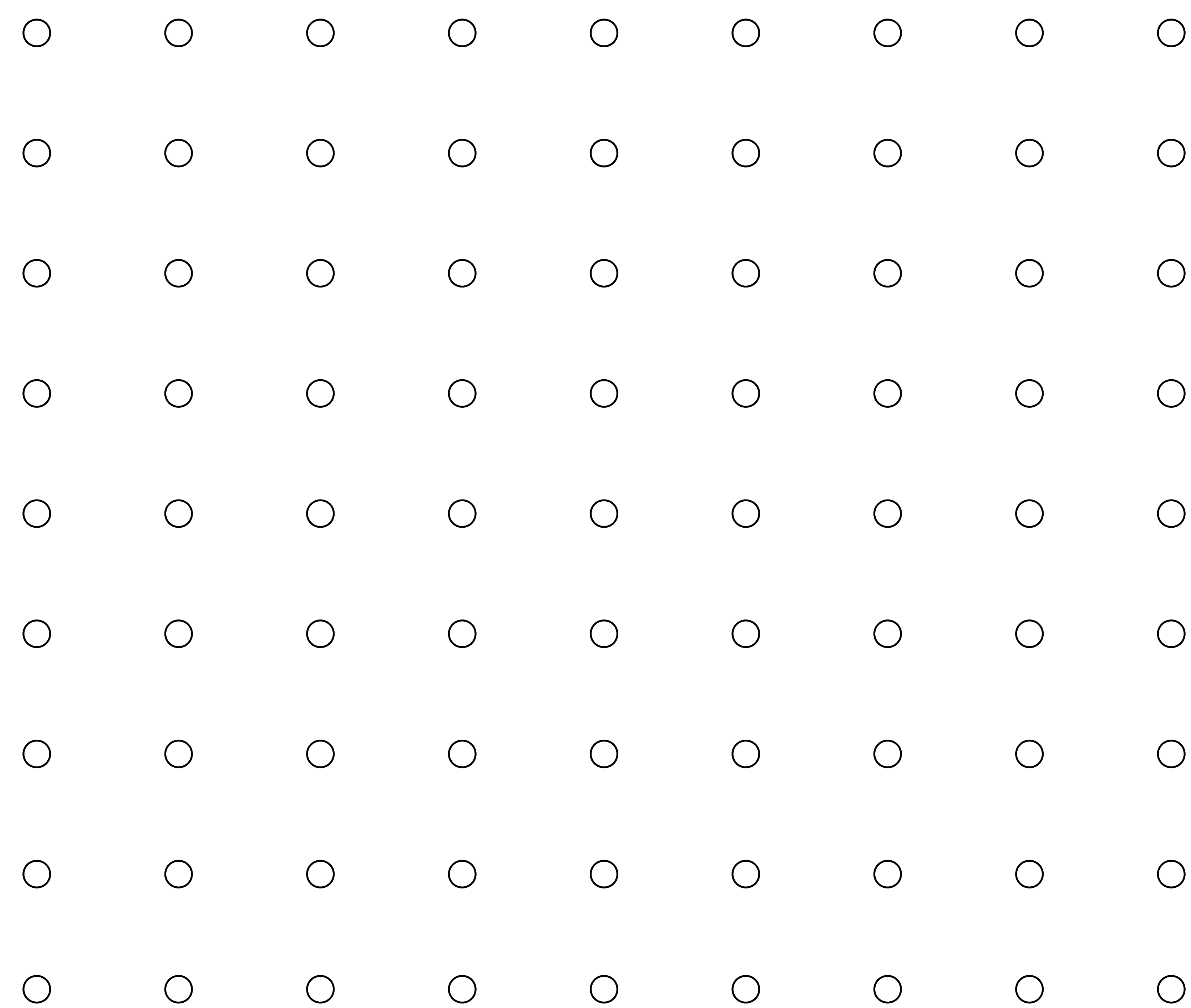
**Interpolate it just like any other attribute that varies linearly over the surface of the triangle.**

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

**For each coverage sample point, 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)** →



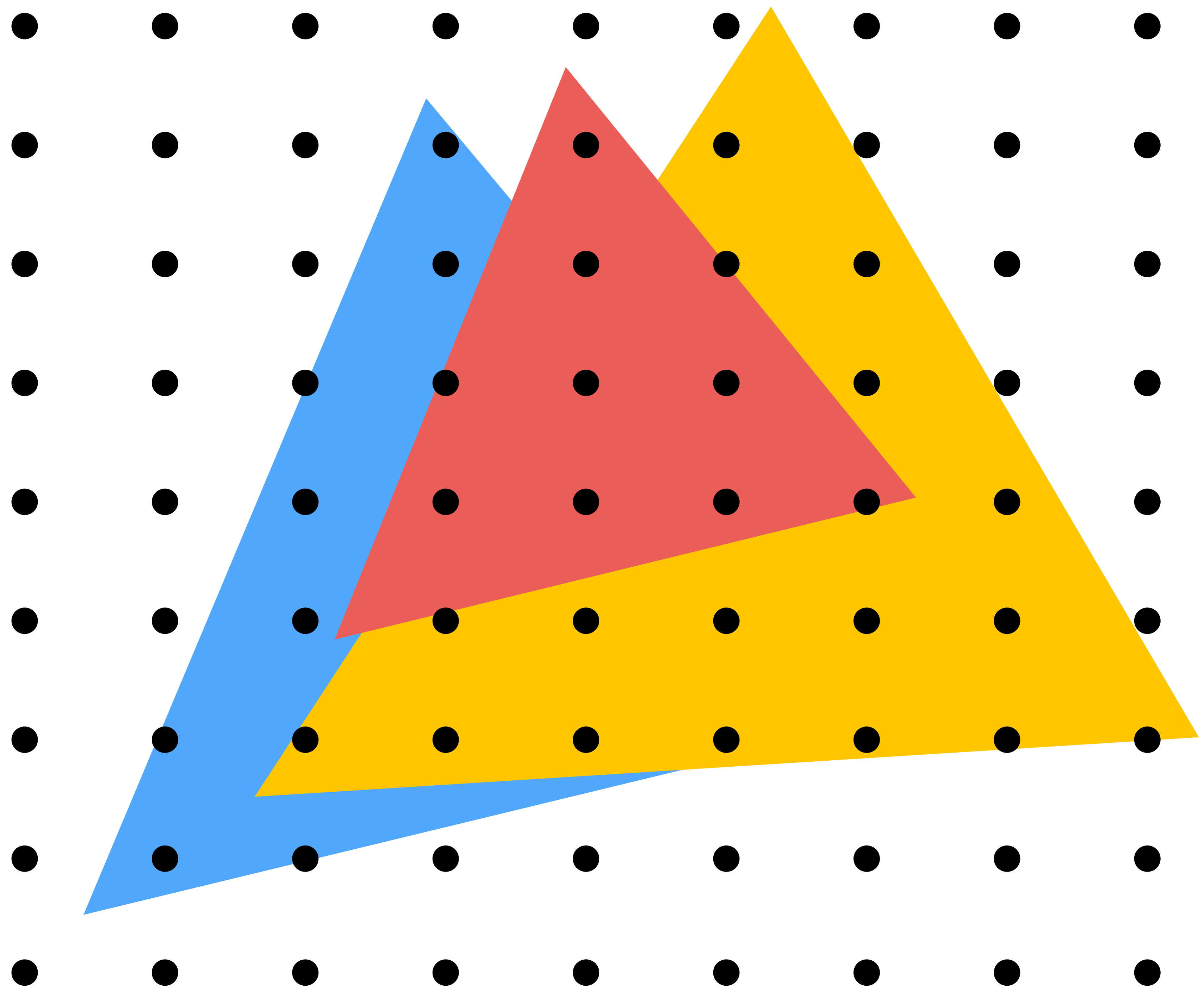
**Grayscale value of sample point used to indicate distance**

**Black = small distance**

**White = large distance**

# Depth buffer example

# Example: rendering three opaque triangles



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

**Processing yellow triangle:**

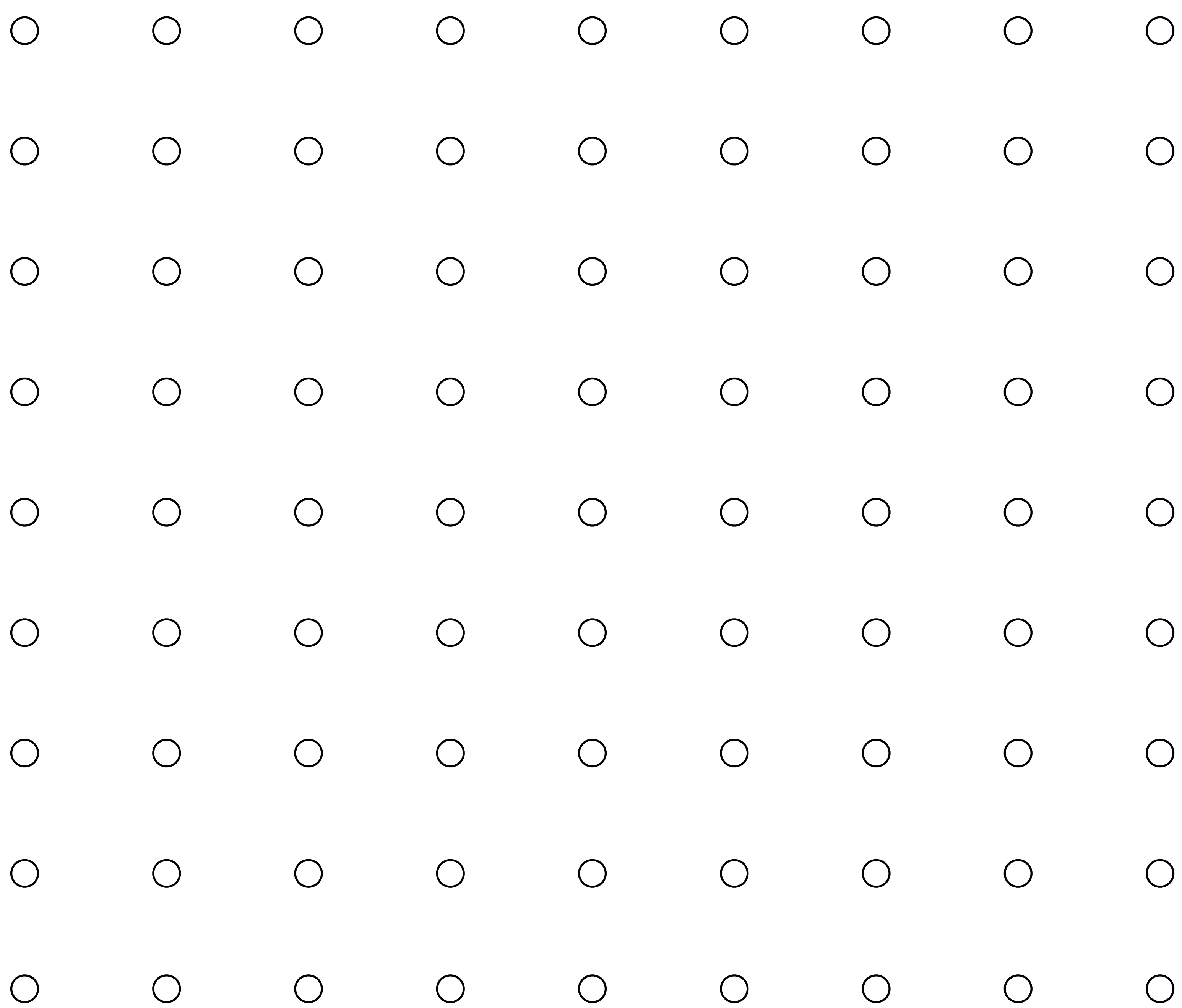
**depth = 0.5**

**Grayscale value of sample point used to indicate distance**

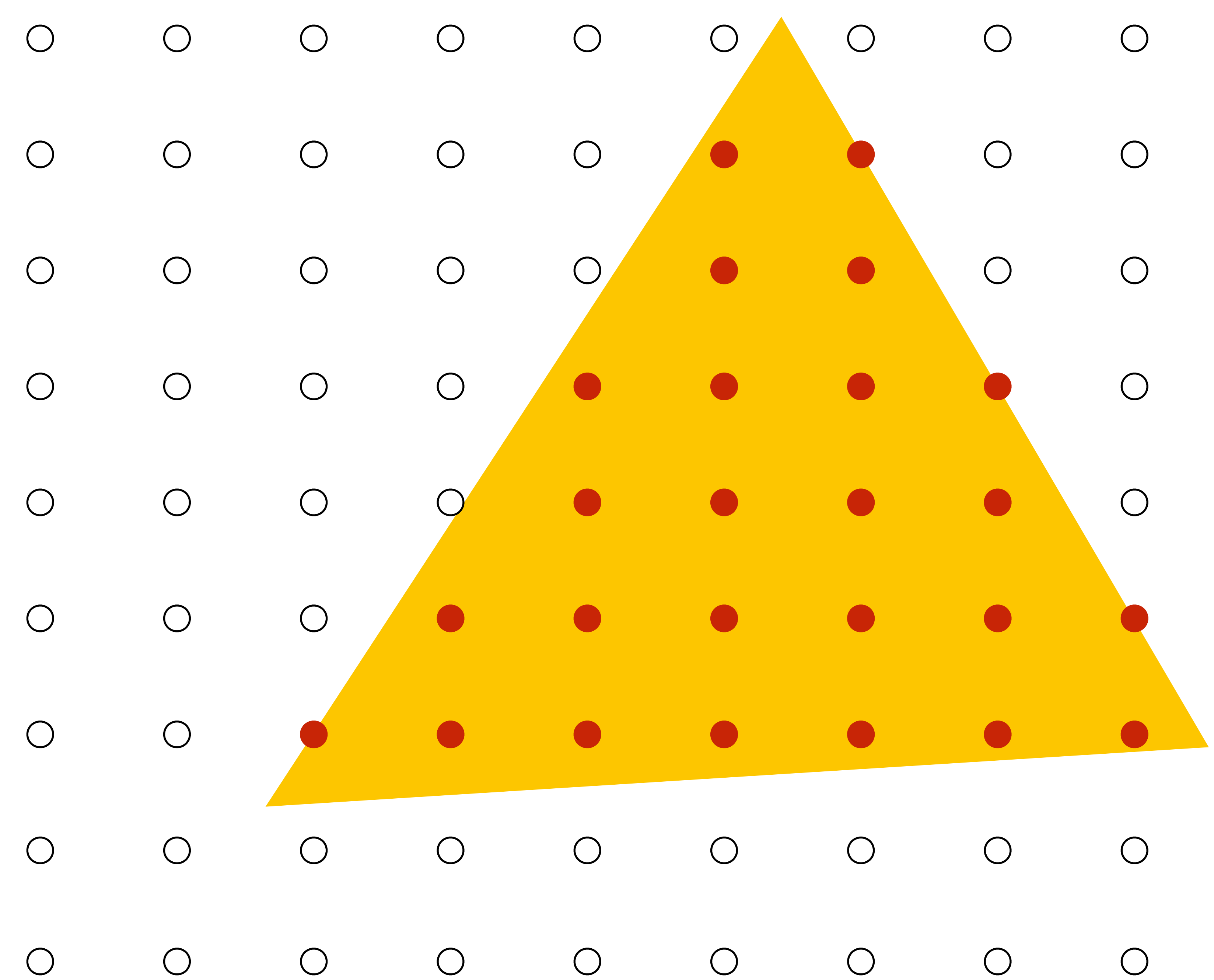
**White = large distance**

**Black = small distance**

**Red = sample passed depth test**



**Color buffer contents**



**Depth buffer contents**

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

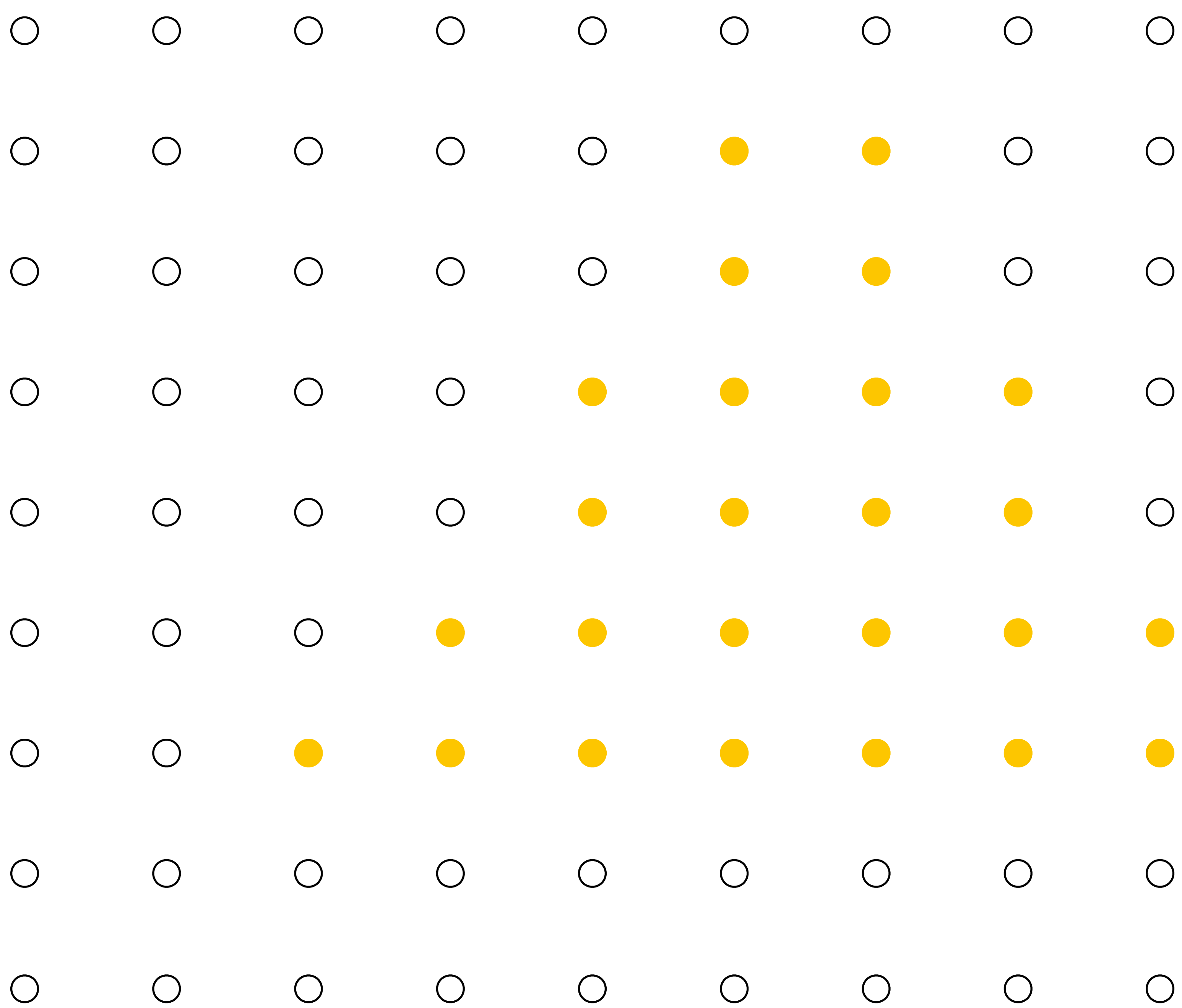
## After processing yellow triangle:

Grayscale value of sample point used to indicate distance

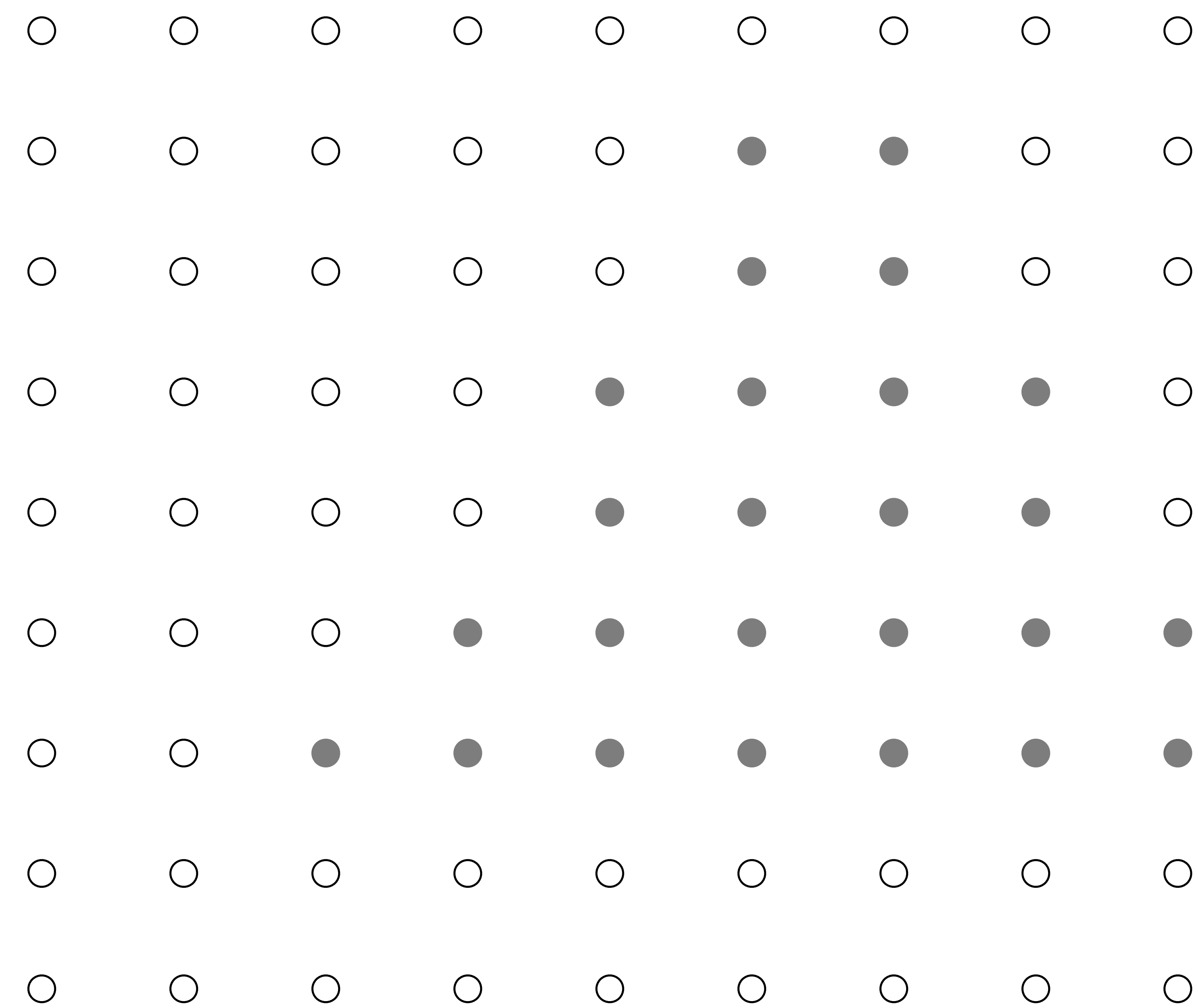
White = large distance

Black = small distance

Red = sample passed depth test



Color buffer contents



Depth buffer contents

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

**Processing blue triangle:**

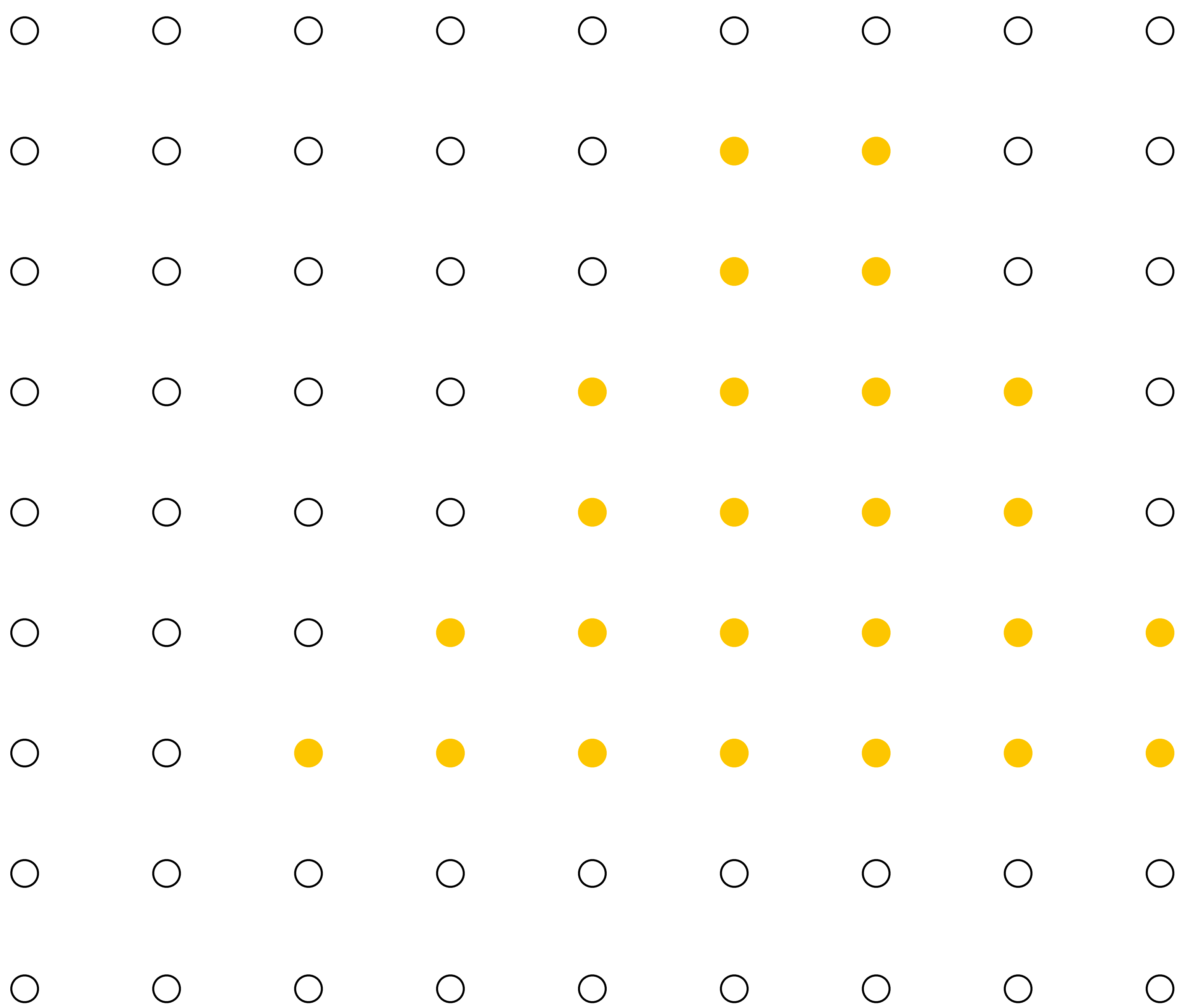
**depth = 0.75**

**Grayscale value of sample point used to indicate distance**

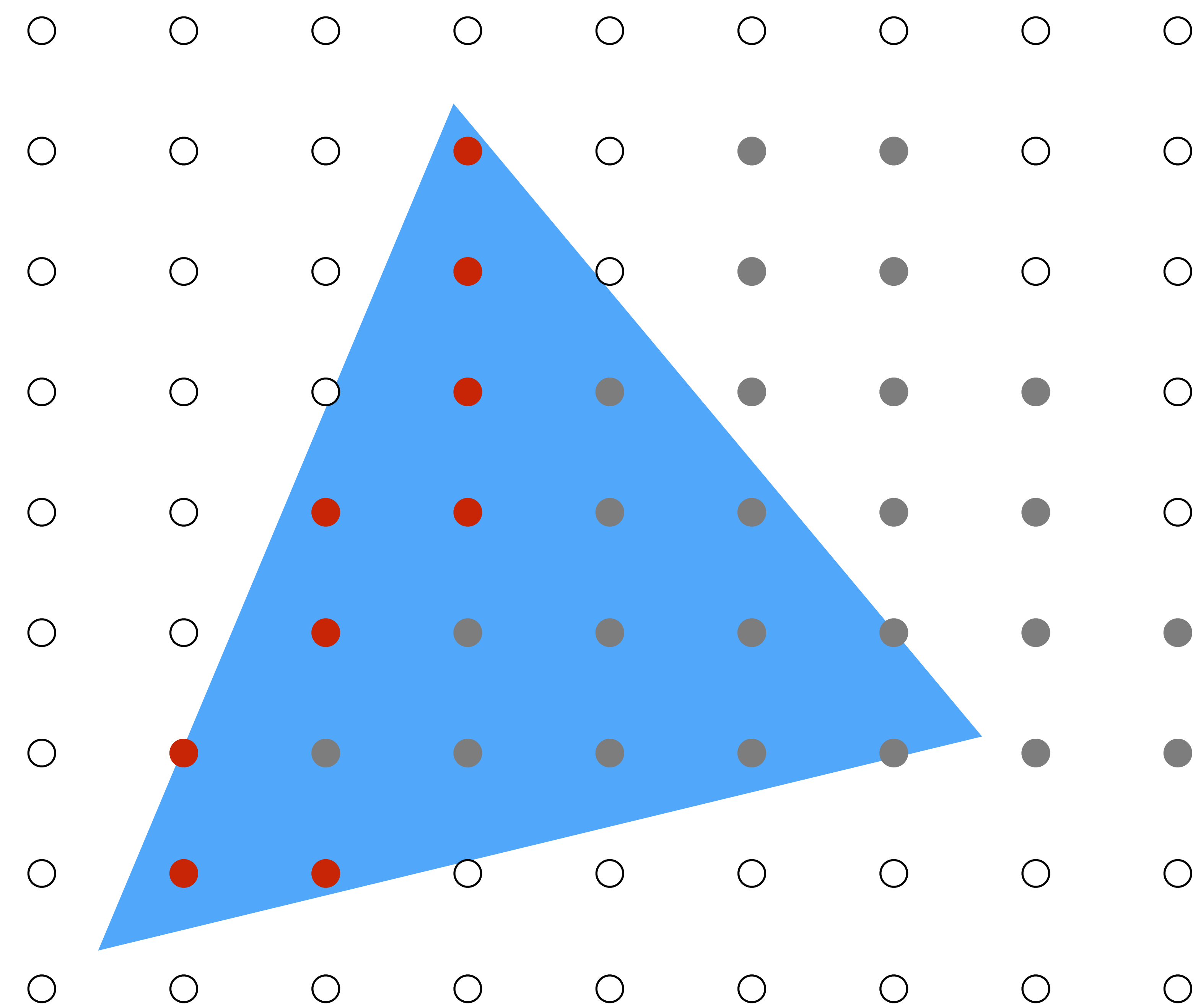
**White = large distance**

**Black = small distance**

**Red = sample passed depth test**



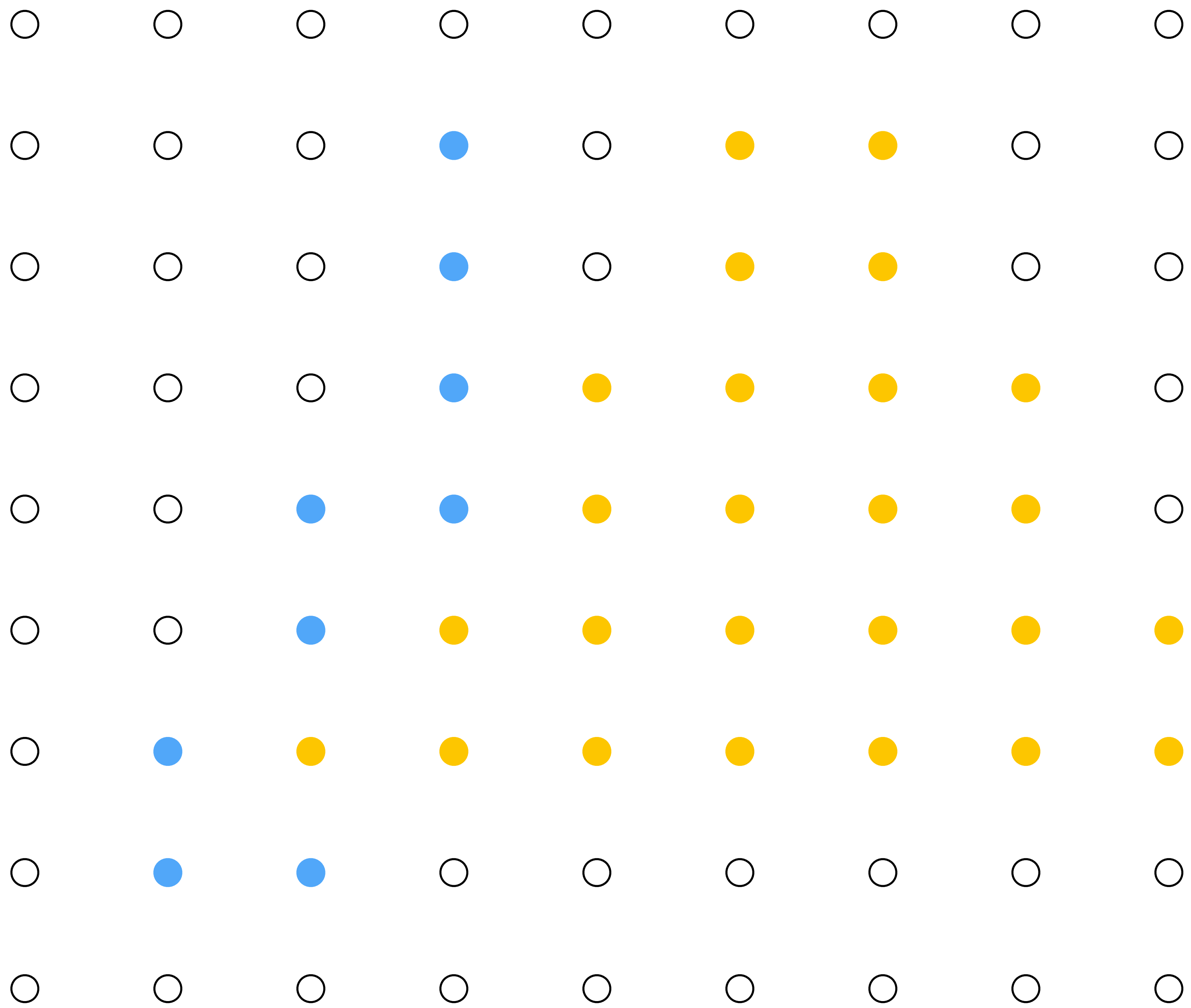
**Color buffer contents**



**Depth buffer contents**

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

**After processing blue triangle:**



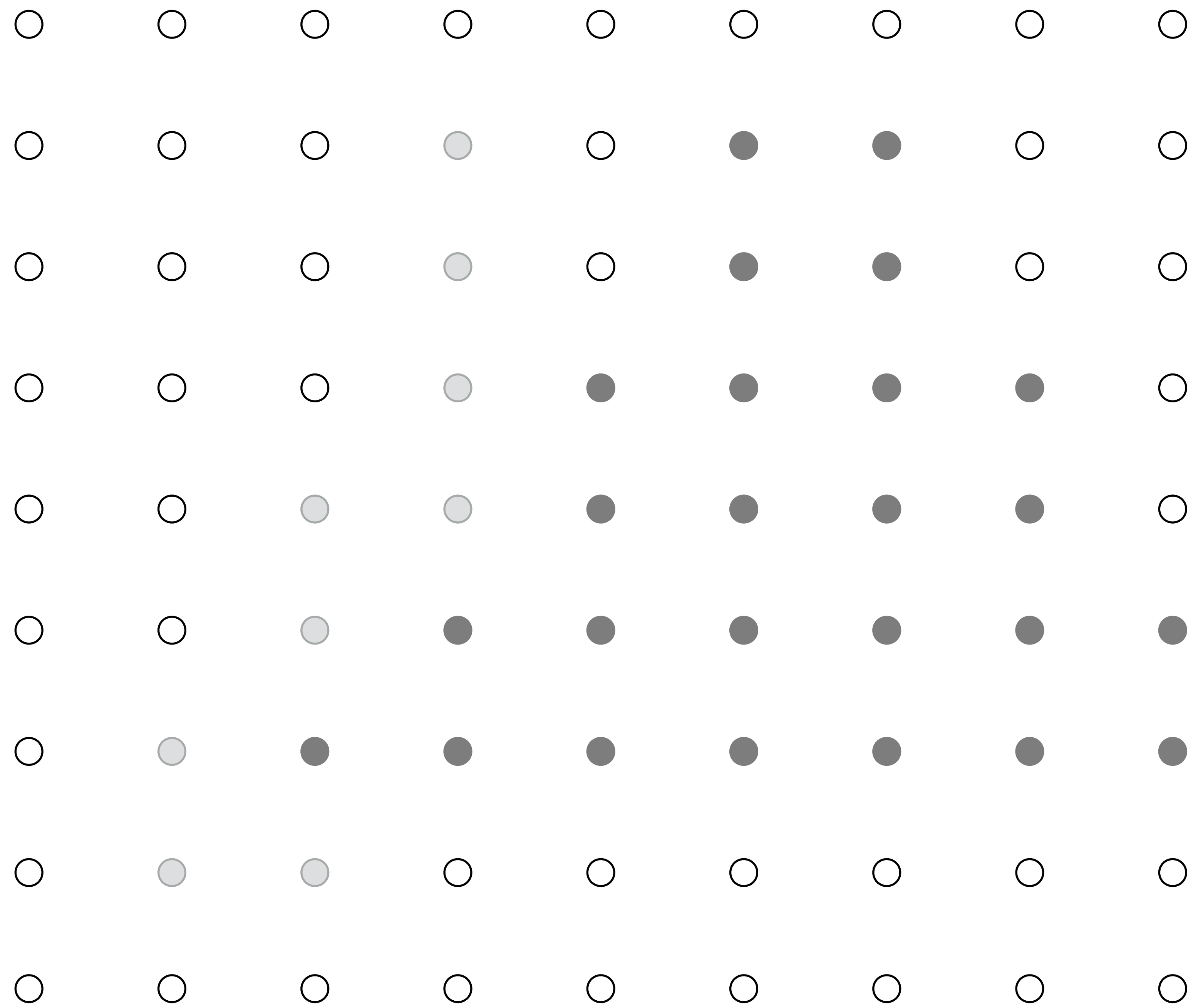
Color buffer contents

Grayscale value of sample point used to indicate distance

White = large distance

Black = small distance

Red = sample passed depth test



Depth buffer contents

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

**Processing red triangle:**

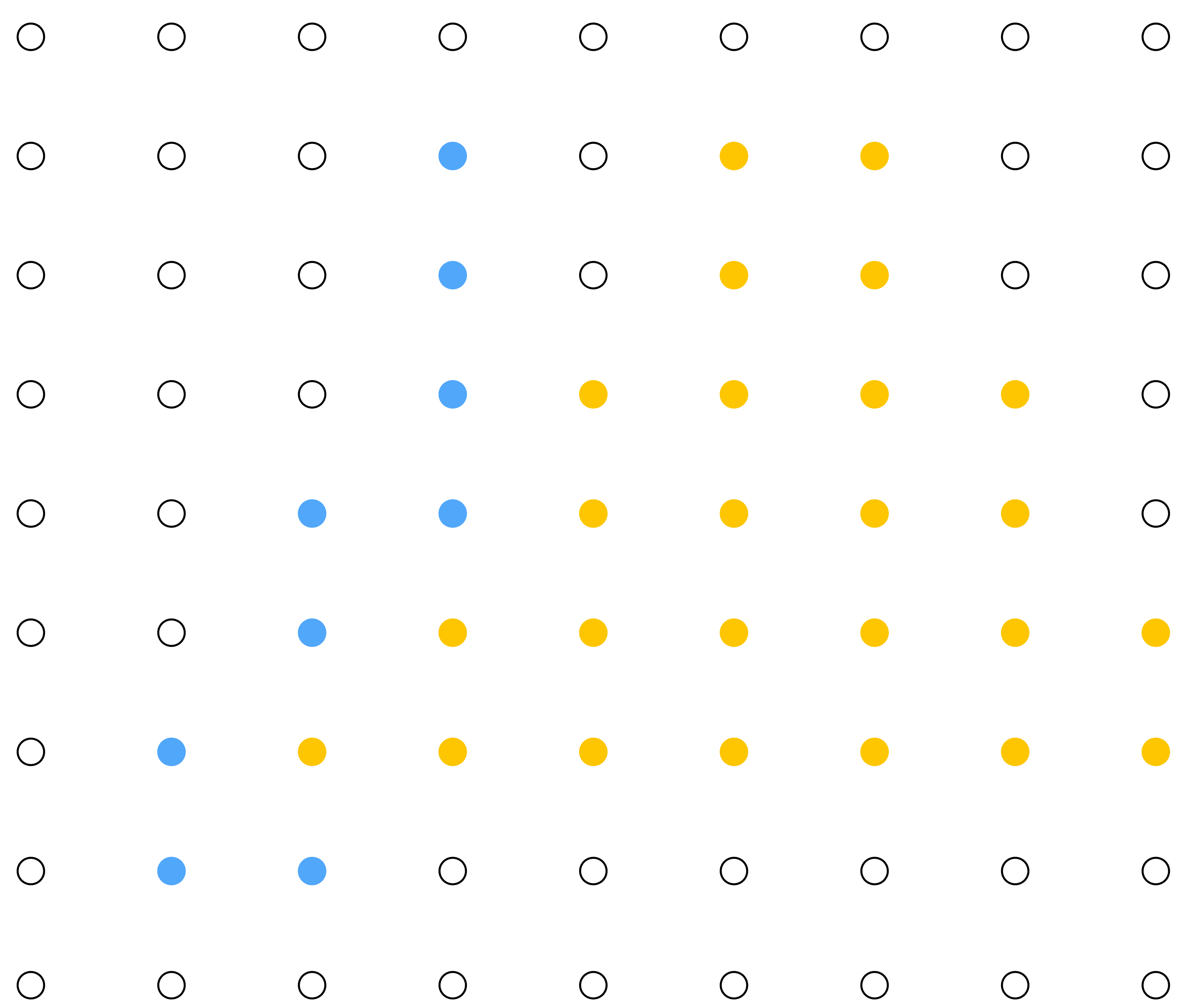
**depth = 0.25**

**Grayscale value of sample point used to indicate distance**

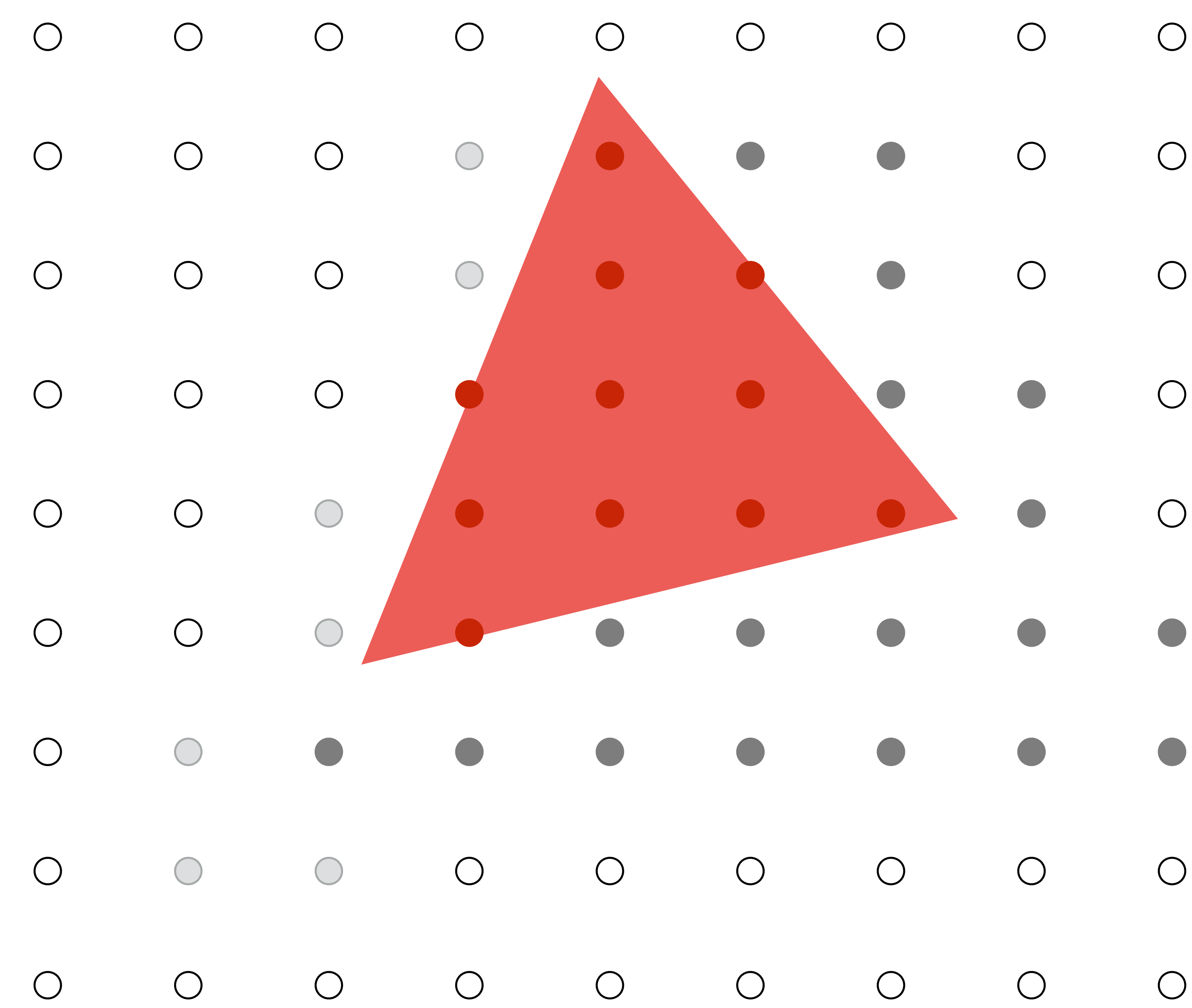
**White = large distance**

**Black = small distance**

**Red = sample passed depth test**



**Color buffer contents**



**Depth buffer contents**

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

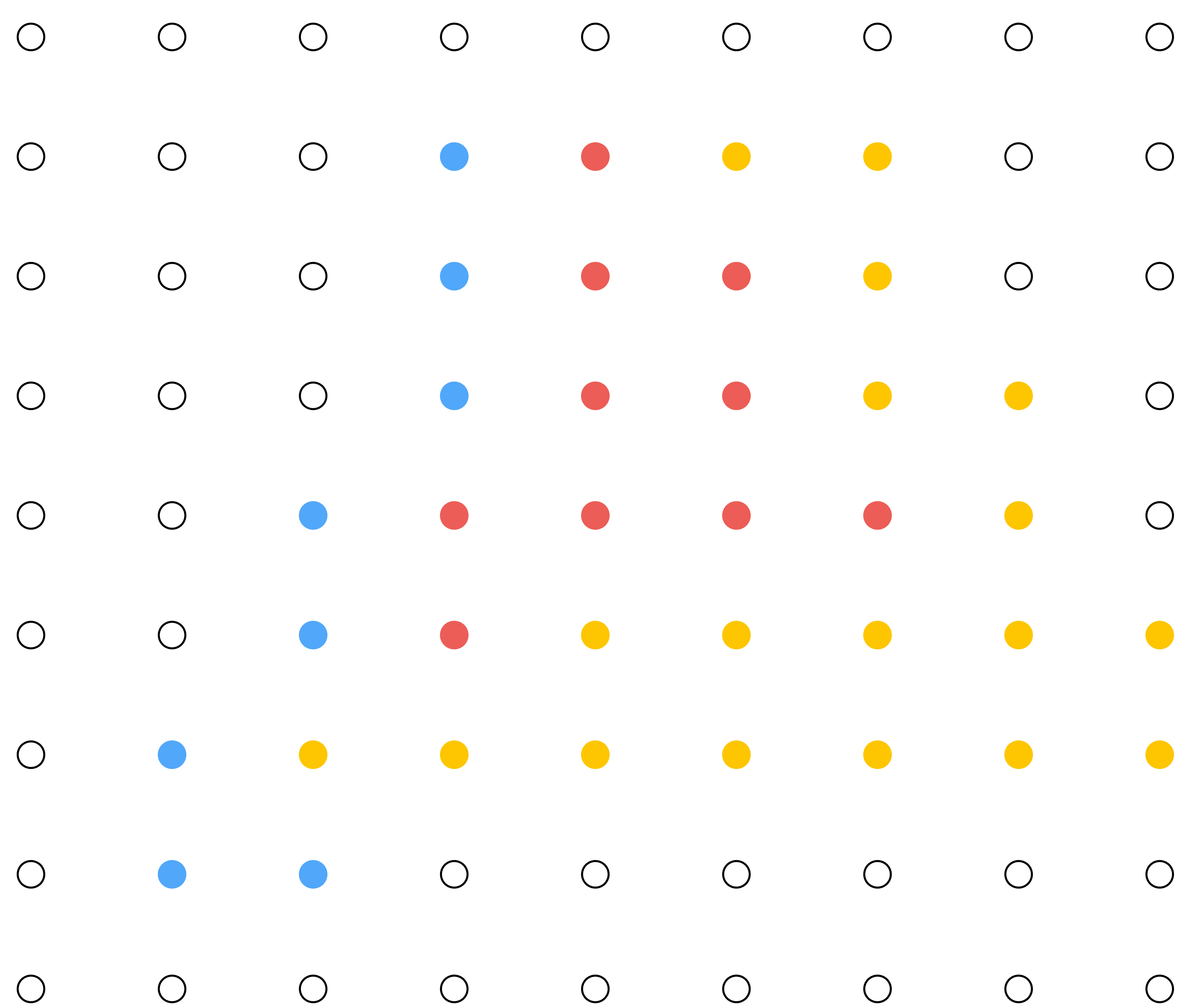
## After processing red triangle:

Grayscale value of sample point used to indicate distance

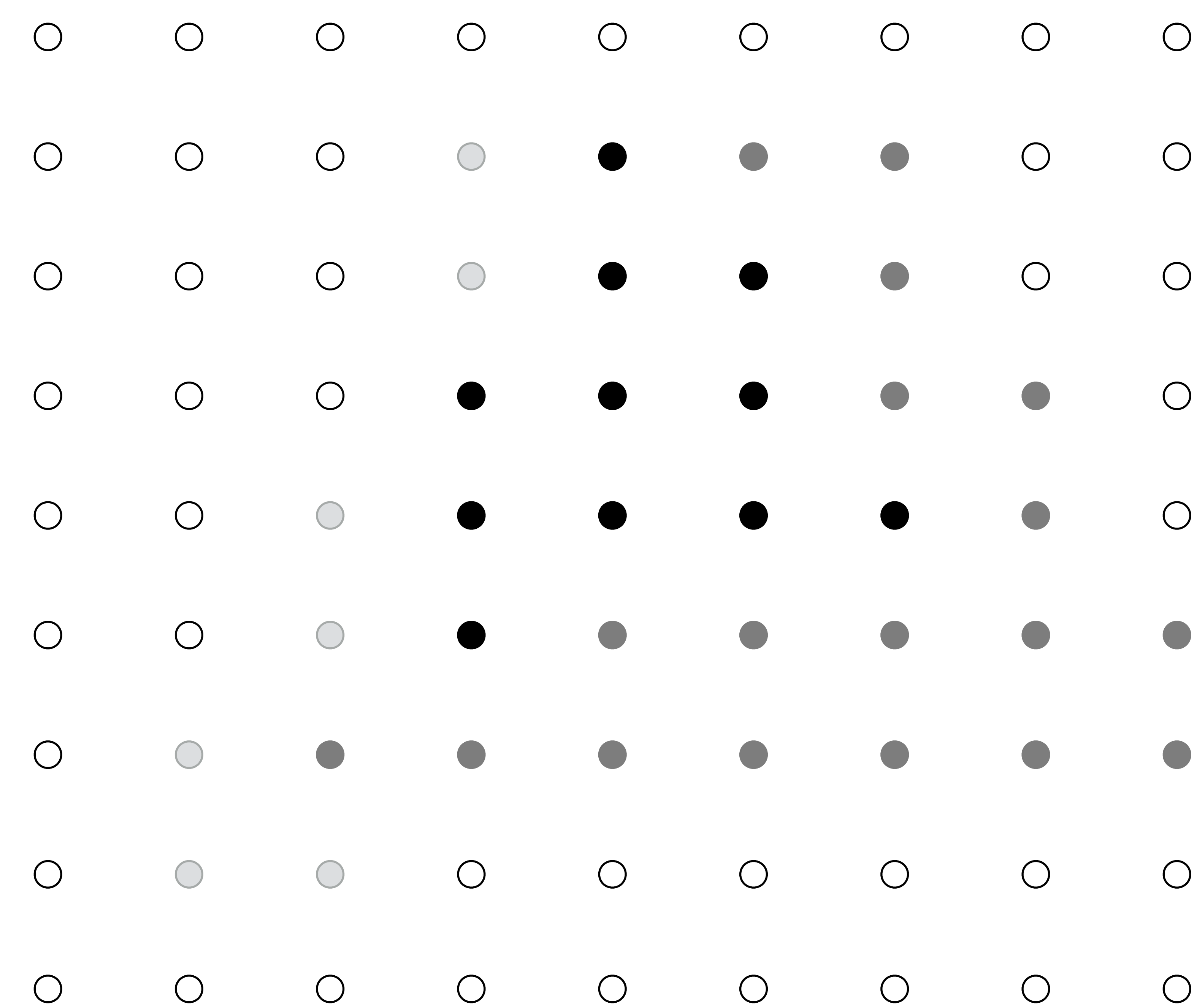
White = large distance

Black = small distance

Red = sample passed depth test



Color buffer contents



Depth buffer contents

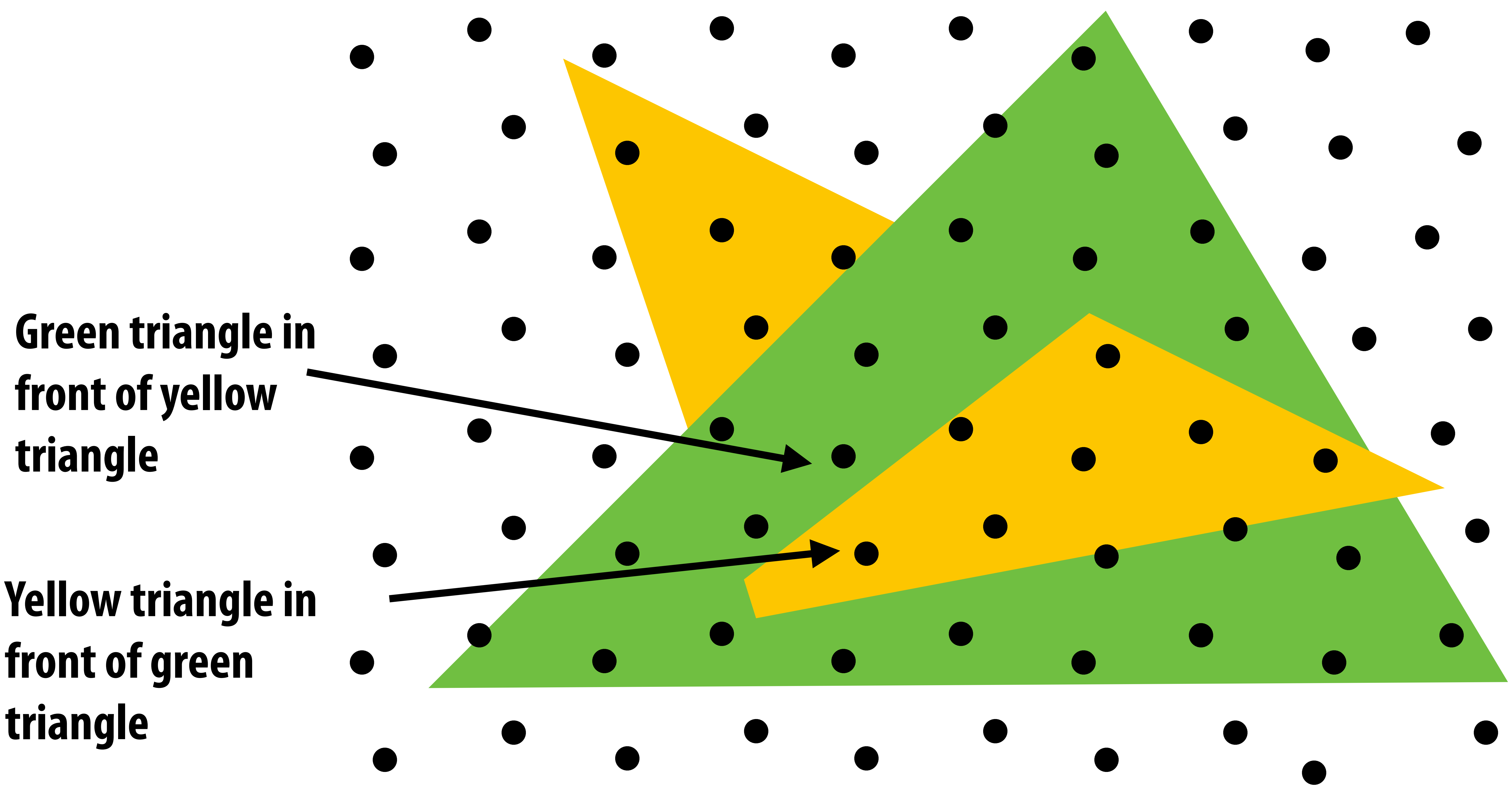
# Occlusion using the depth buffer

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


depth_test(tri_d, tri_color, x, y) {

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

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

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

# Does depth-buffer algorithm handle interpenetrating surfaces?

**Of course!**

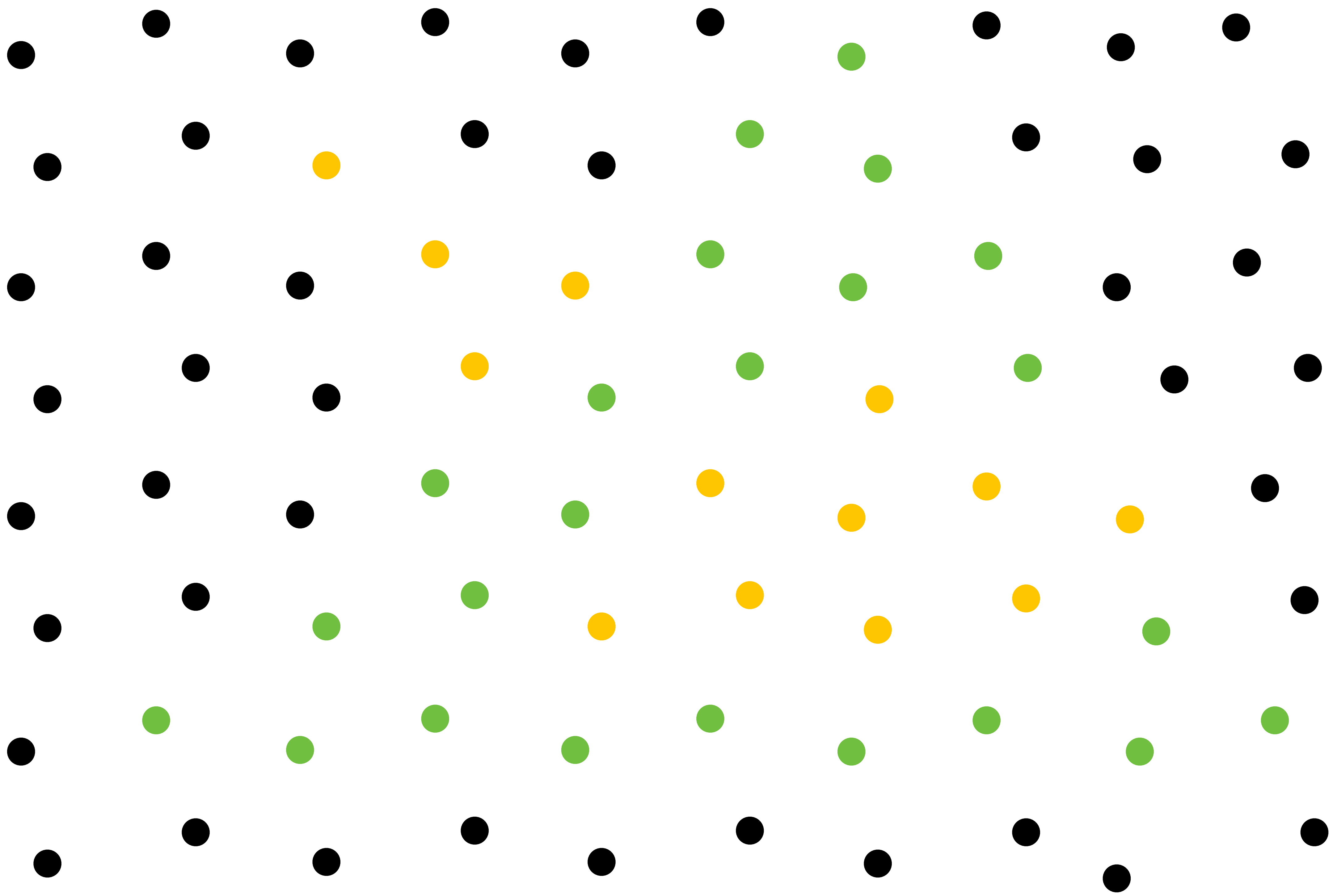
**Occlusion test is based on depth of triangles at a given sample point. The relative depth of triangles may be different at different sample points.**



# Does depth-buffer algorithm handle interpenetrating surfaces?

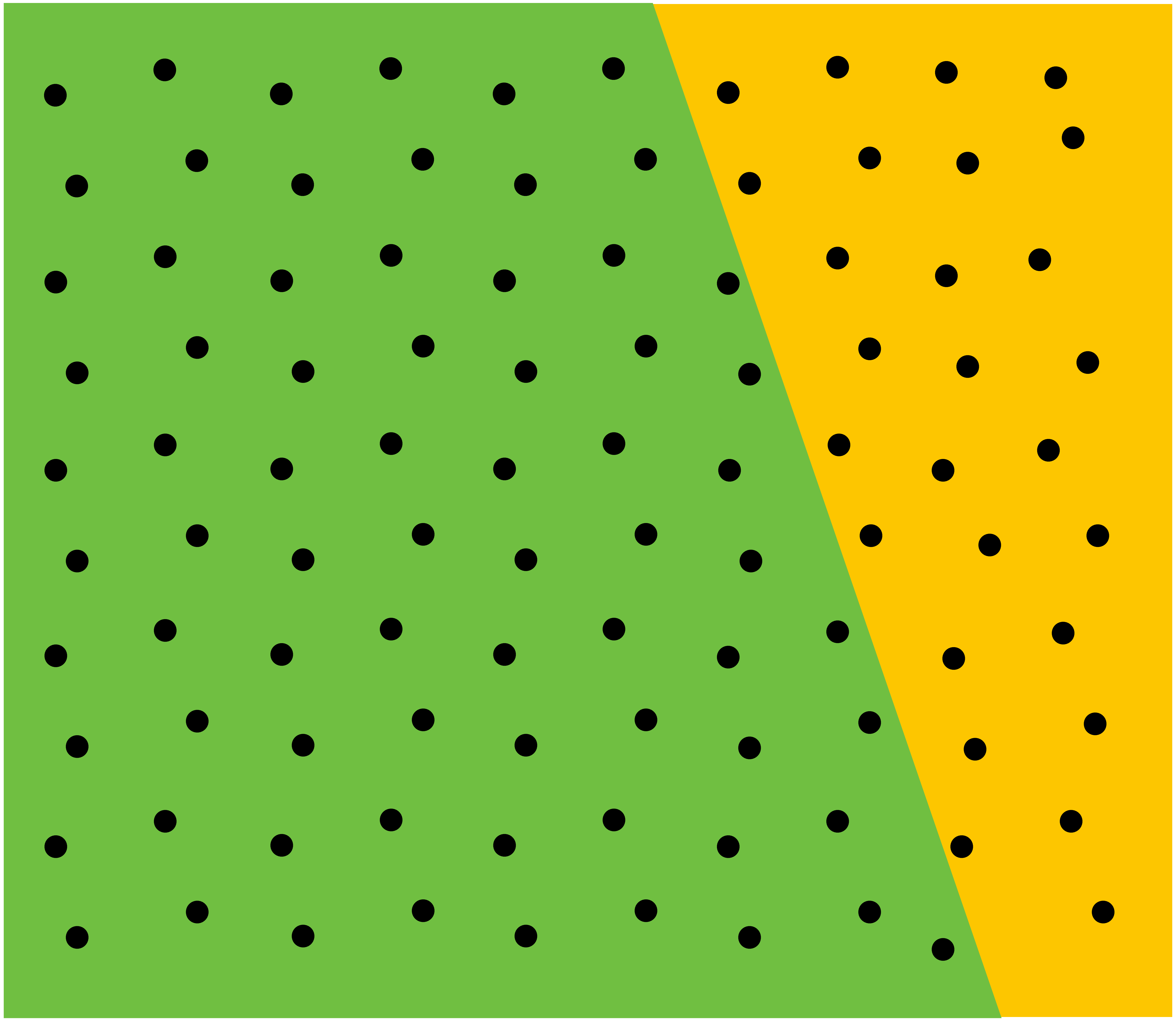
**Of course!**

**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.**



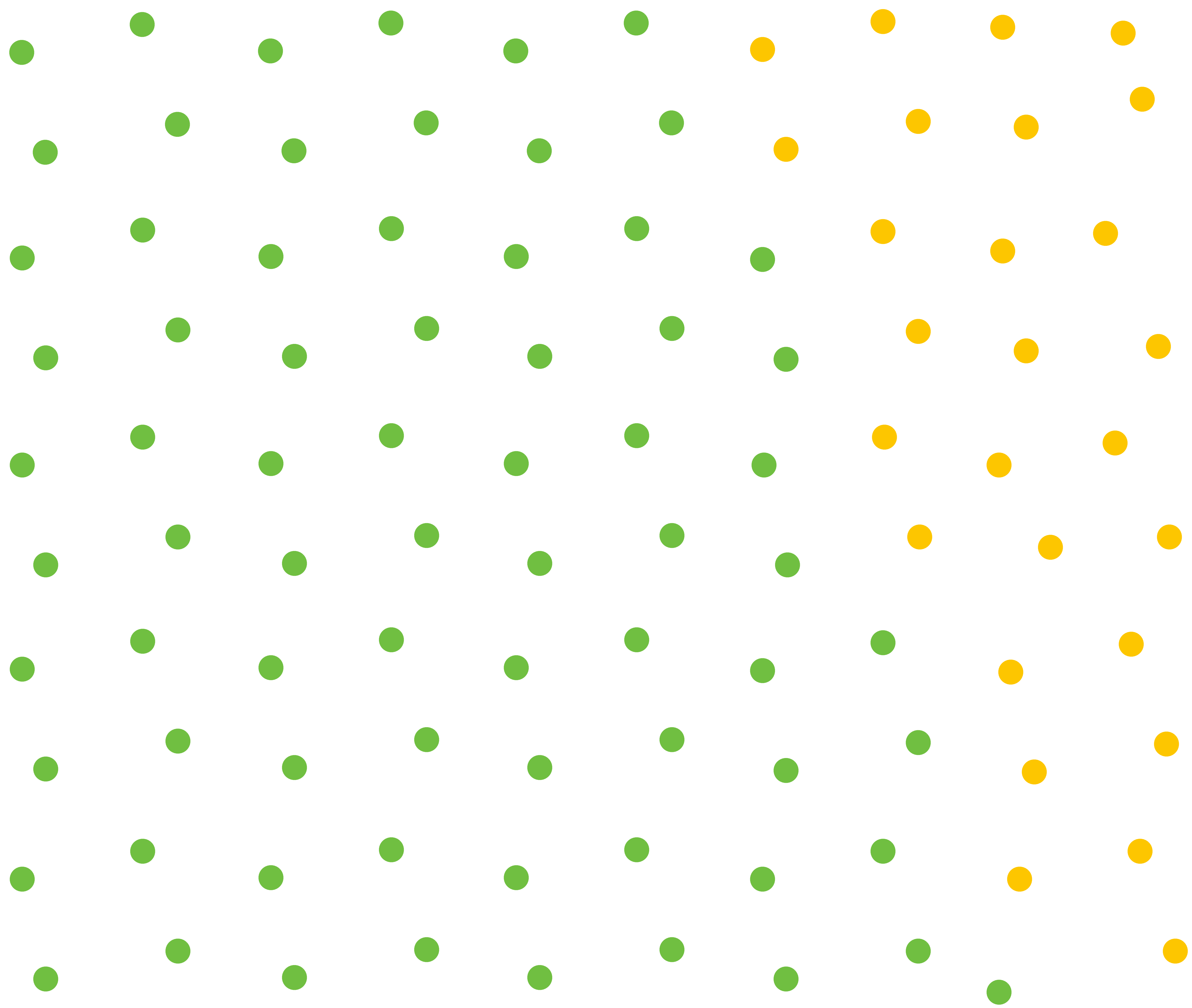
# Does depth buffer work with super sampling?

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

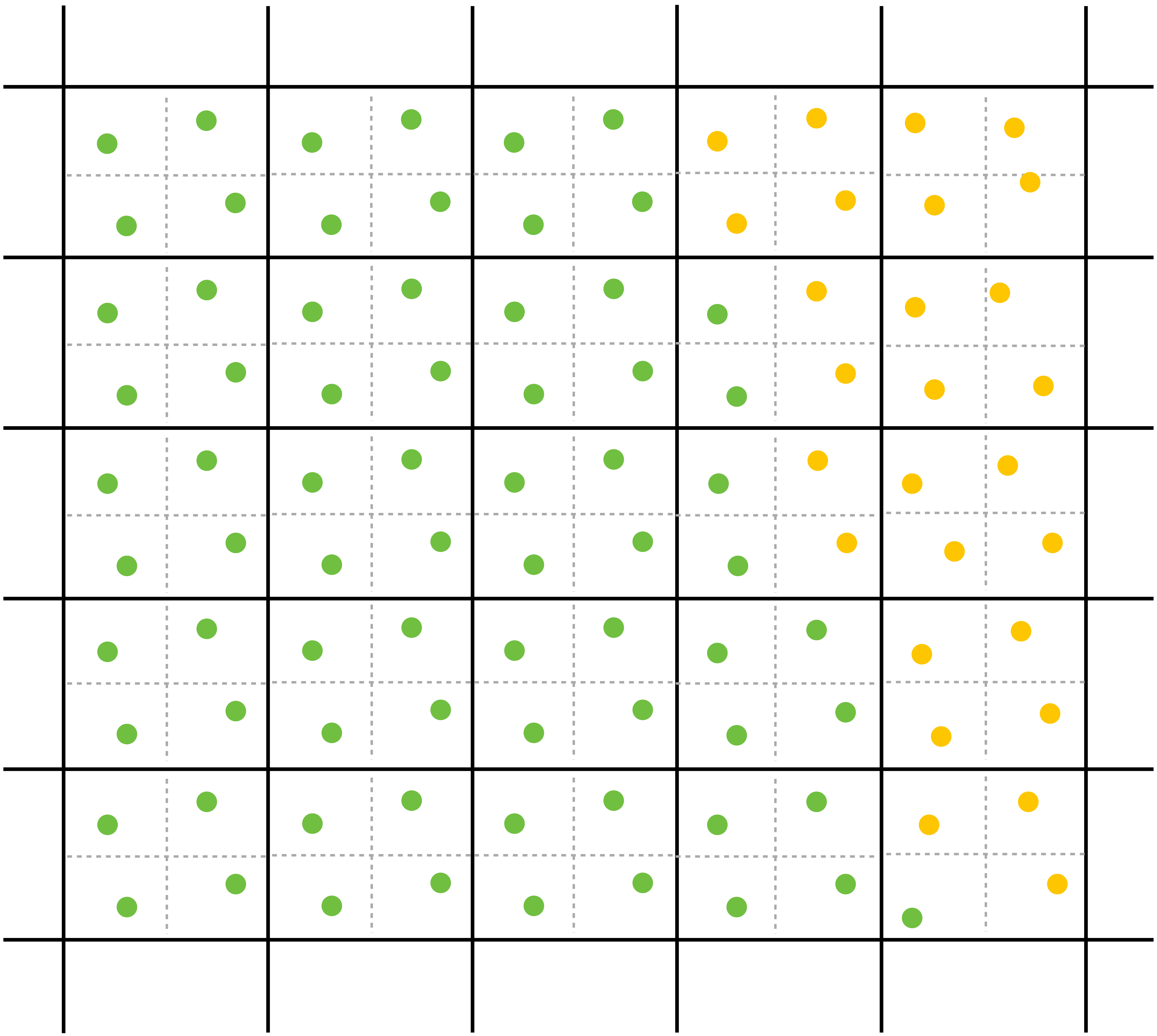


This example: green triangle occludes yellow triangle

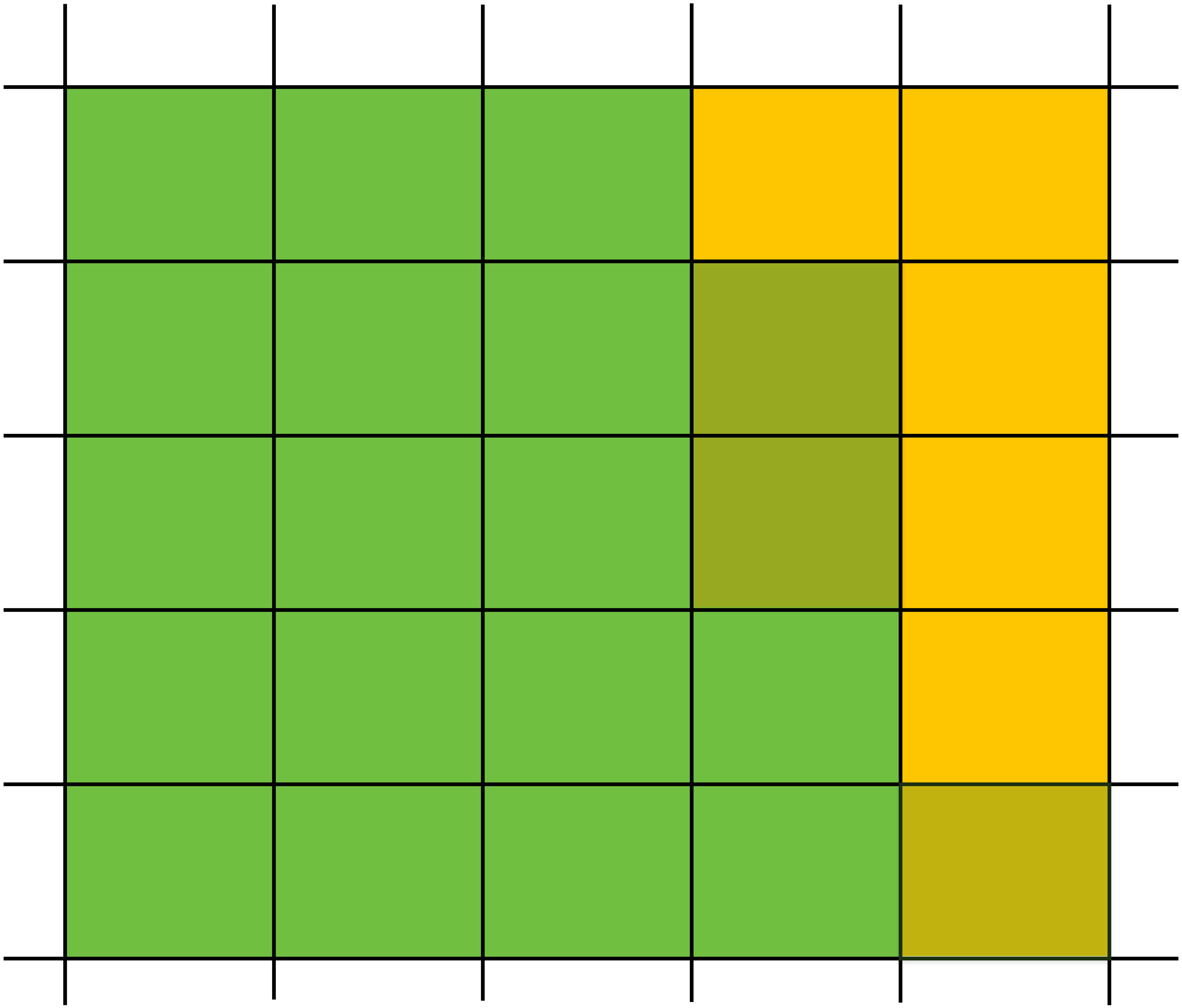
# Color buffer contents



# 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 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?**

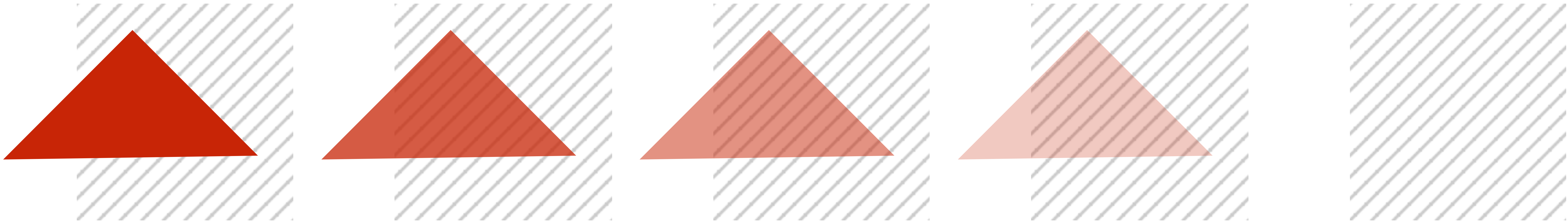
# Compositing

# Representing opacity as alpha

**Alpha describes the opacity of an object**

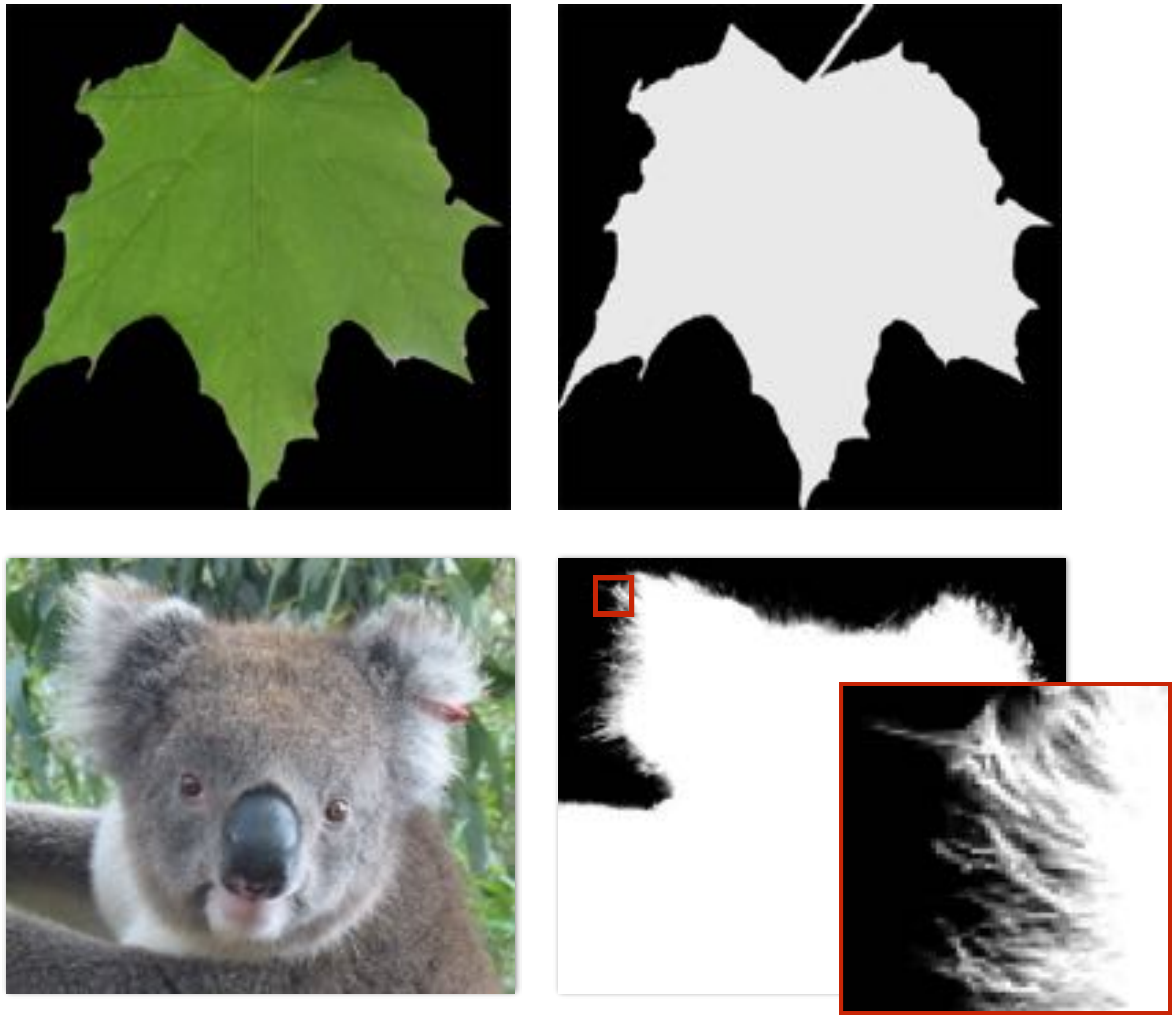
- Fully opaque surface: $\alpha = 1$
- 50% transparent surface: $\alpha = 0.5$
- Fully transparent surface: $\alpha = 0$

**Red triangle with decreasing opacity**



$\alpha = 1$ $\alpha = 0.75$ $\alpha = 0.5$ $\alpha = 0.25$ $\alpha = 0$

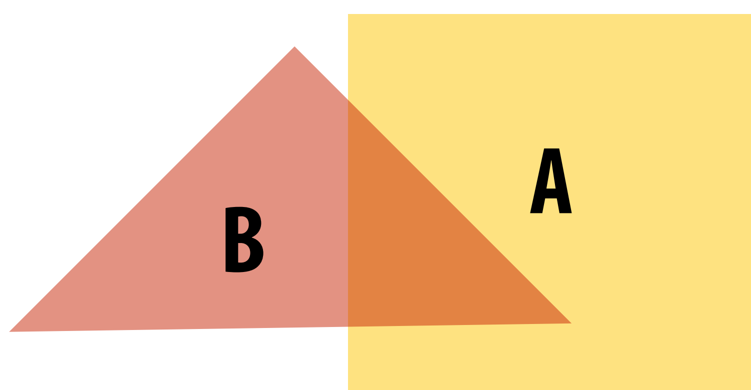
# Alpha: additional channel of image (rgba)



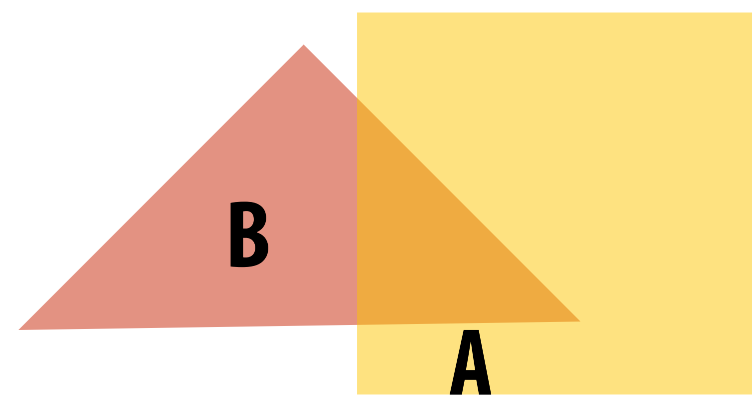
$\alpha$ of foreground object

# Over operator:

**Composite image B with opacity $\alpha_B$ <u>over</u> image A with opacity $\alpha_A$**



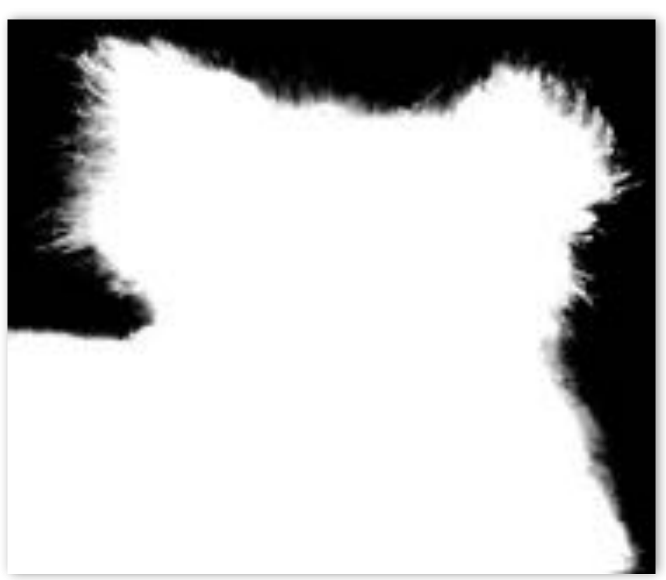

B over A




A over B

A over B != B over A

"Over" is not commutative

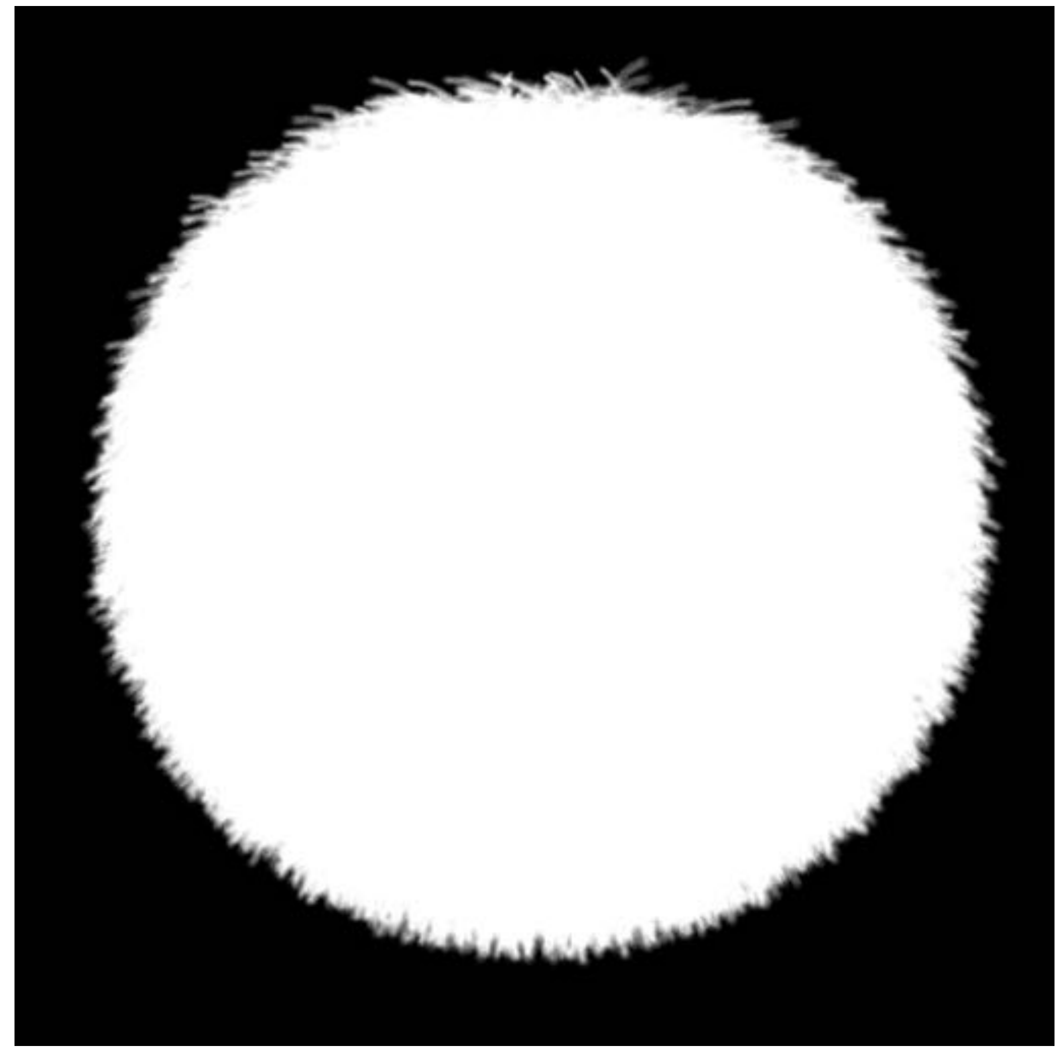


Koala over NYC

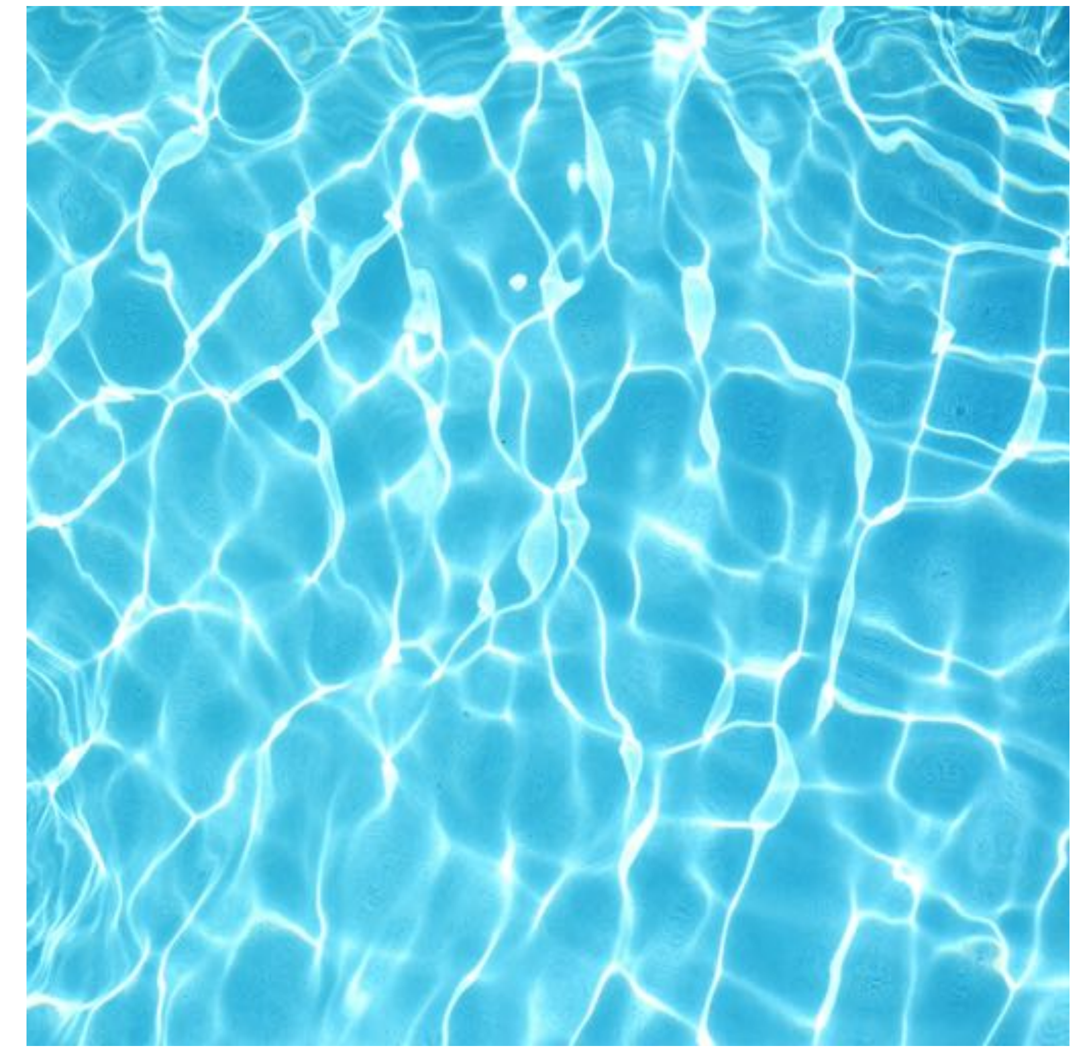
# Fringing

## 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?)

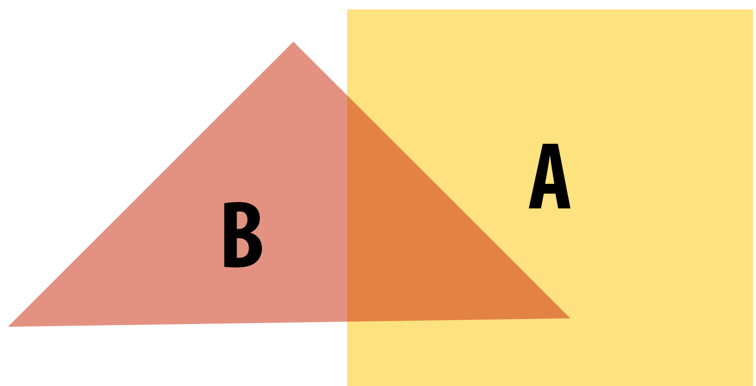
# Over operator: non-premultiplied alpha

**Composite image B with opacity $\alpha_B$ over image A with opacity $\alpha_A$**

**A first attempt:**

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

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

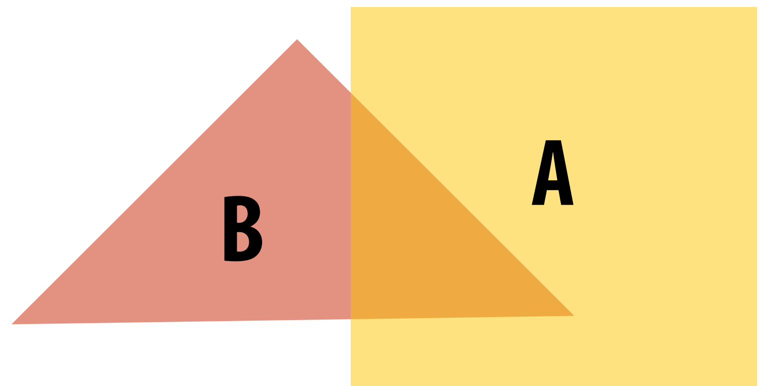



**B over A**

**Composited color:**

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

- $\alpha_B B$: Appearance of semi-transparent B
- $(1 - \alpha_B)$: What B lets through
- $\alpha_A A$: Appearance of semi-transparent A




**A over B**

**A over B != B over A**

**"Over" is not commutative**

# Over operator: premultiplied alpha

**Composite image B with opacity $\alpha_B$ over image A with opacity $\alpha_A$**

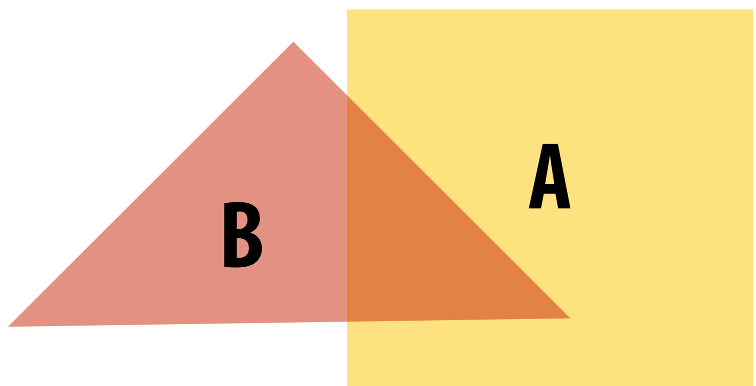
**Non-premultiplied alpha:**

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

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

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

← **two multiplies, one add (referring to vector ops on colors)**



**B over A**

**Premultiplied alpha:**

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

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

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

← **one multiply, one add**

**Composite alpha:**

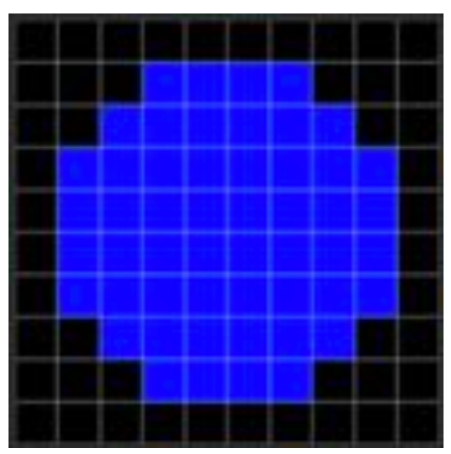
$$\alpha_C = \alpha_B + (1 - \alpha_B)\alpha_A$$

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

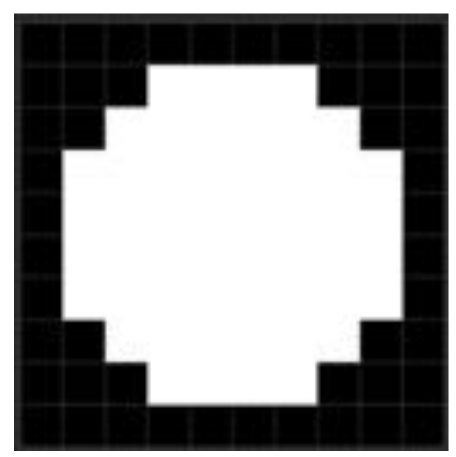
**Non-premultiplied alpha composites alpha differently than rgb.**

# A problem with non-premultiplied alpha

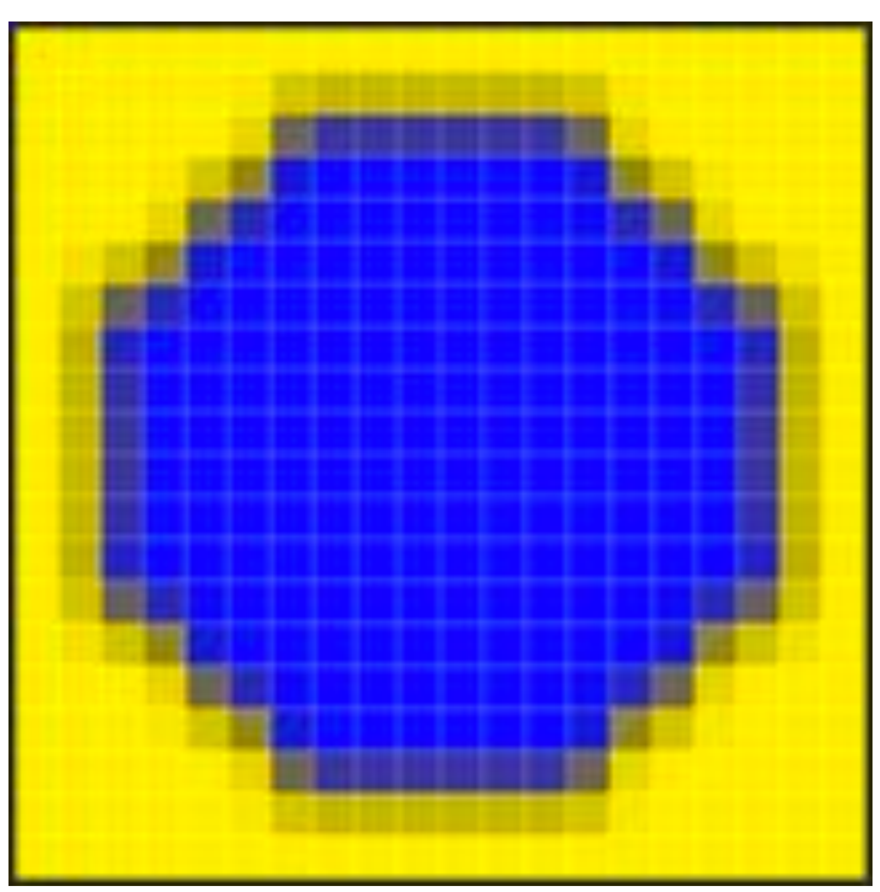
- Suppose we upsample an image w/ an alpha mask, then composite it onto a background
- How should we compute the interpolated color/alpha values?
- If we interpolate color and alpha separately, then blend using the non-premultiplied "over" operator, here's what happens:



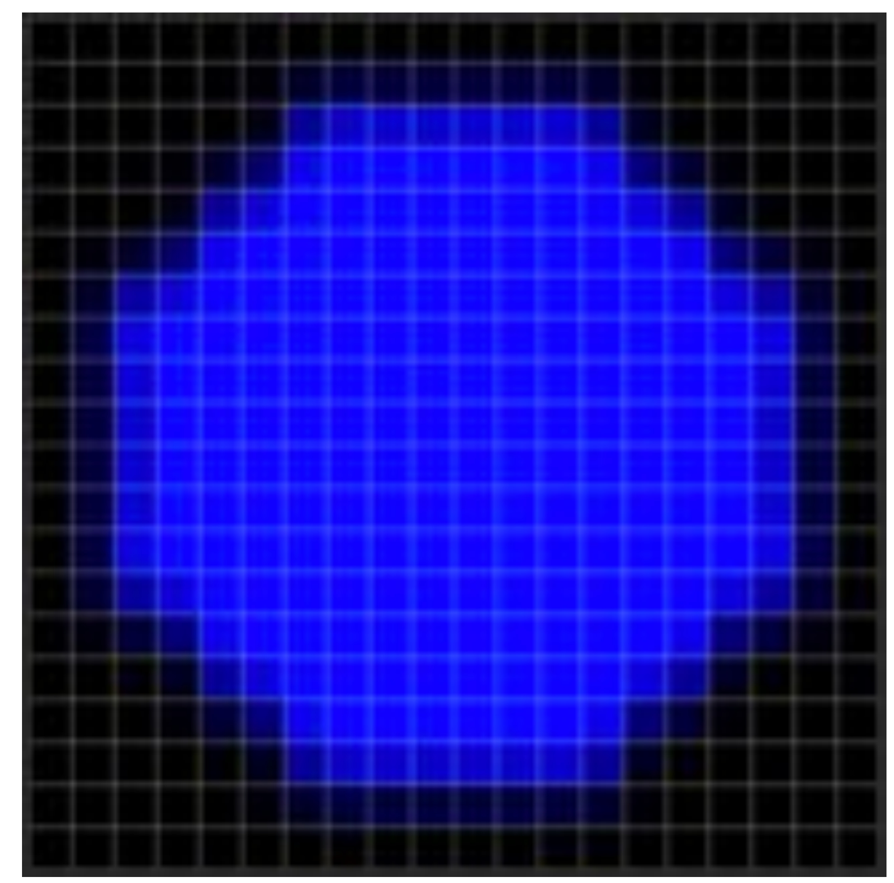
original color



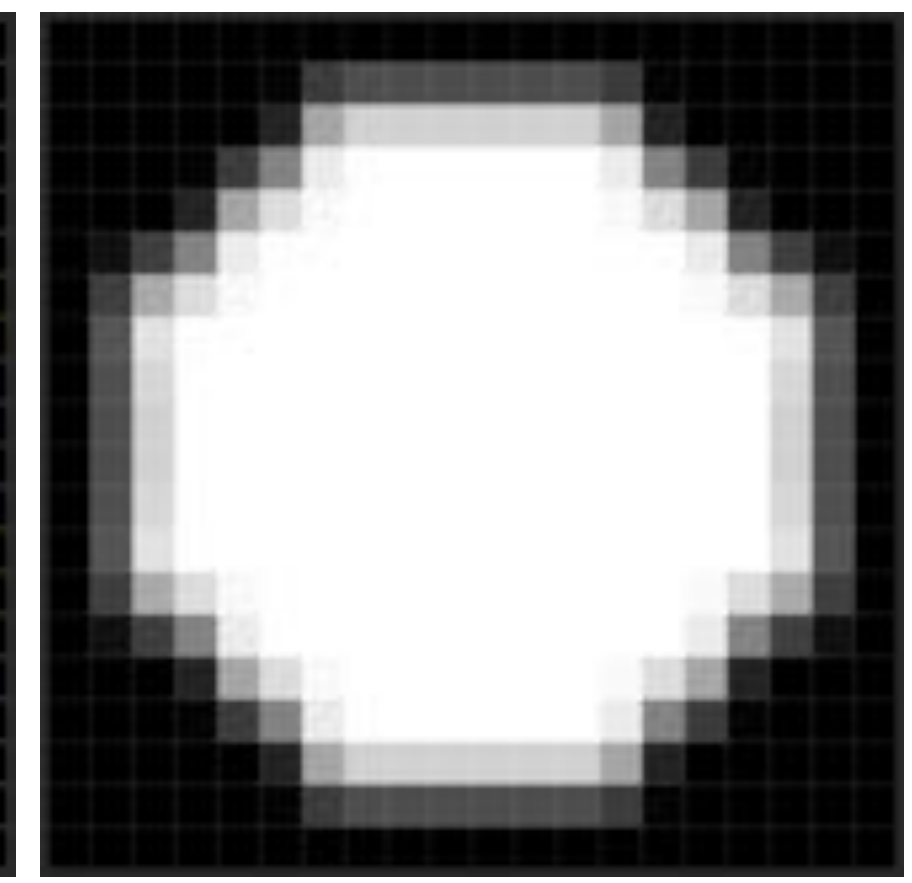
original alpha



composited onto yellow background



upsampled color

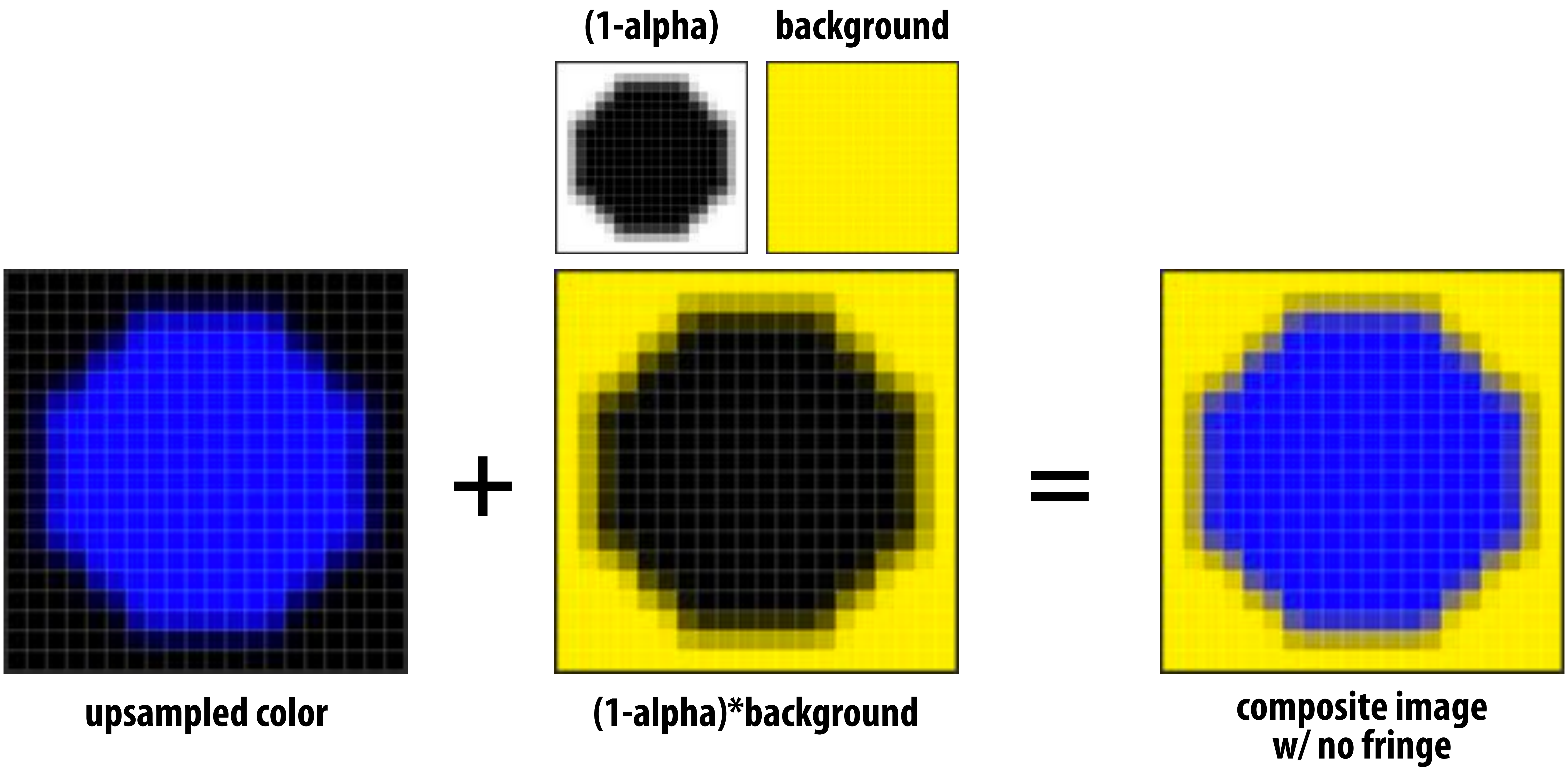


upsampled alpha

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

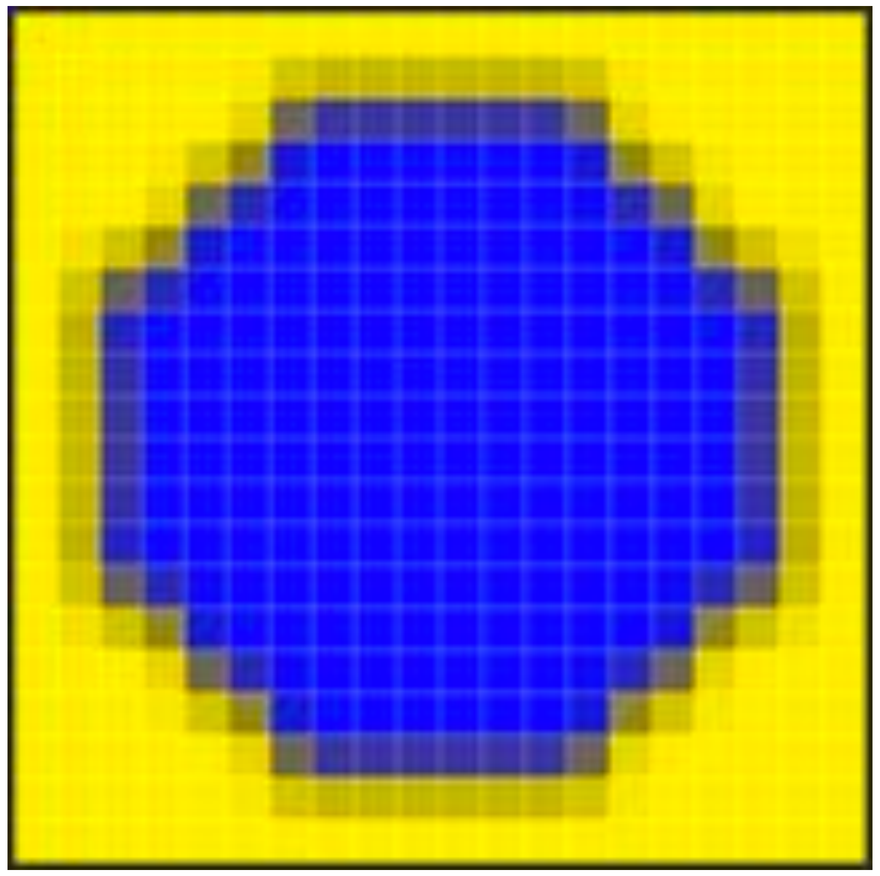
# Eliminating fringe w/ premultiplied "over"

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



# Eliminating fringe w/ premultiplied “over”

- If we instead use  the premultiplied “over” operation, we get the correct alpha:



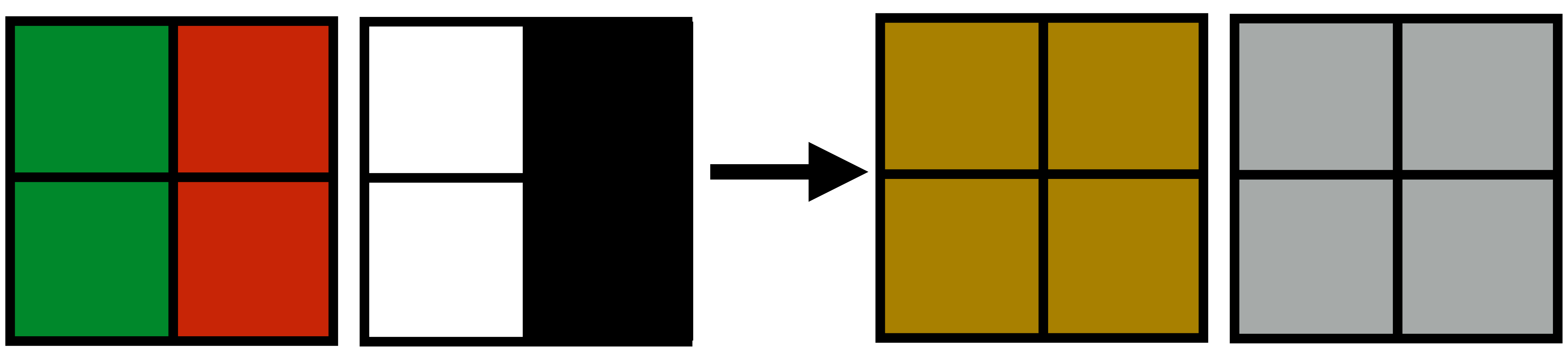
composite image
WITH fringe

# Similar problem with non-premultiplied alpha

## Consider pre-filtering (downsampling) a texture with an alpha matte

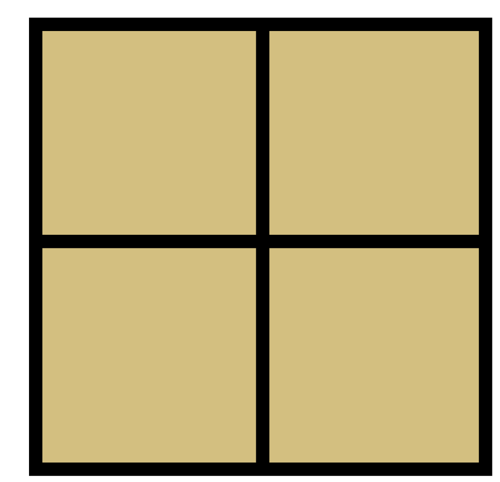

Desired filtered result

---



input color | input $\alpha$ | filtered color | filtered $\alpha$

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

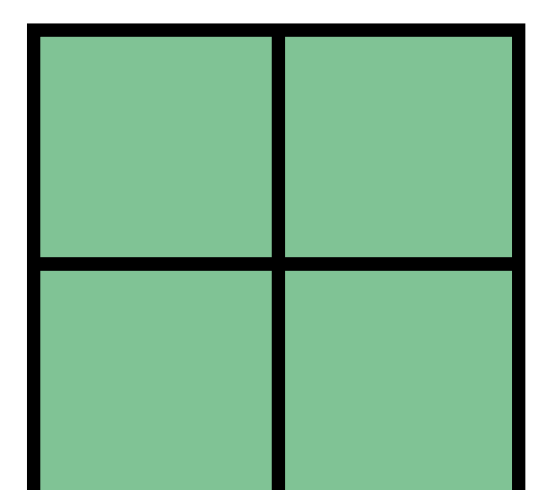


filtered result composited over white

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



# More problems: applying "over" repeatedly

**Composite image C with opacity $\alpha_C$ over B with opacity $\alpha_B$ over image A with opacity $\alpha_A$**

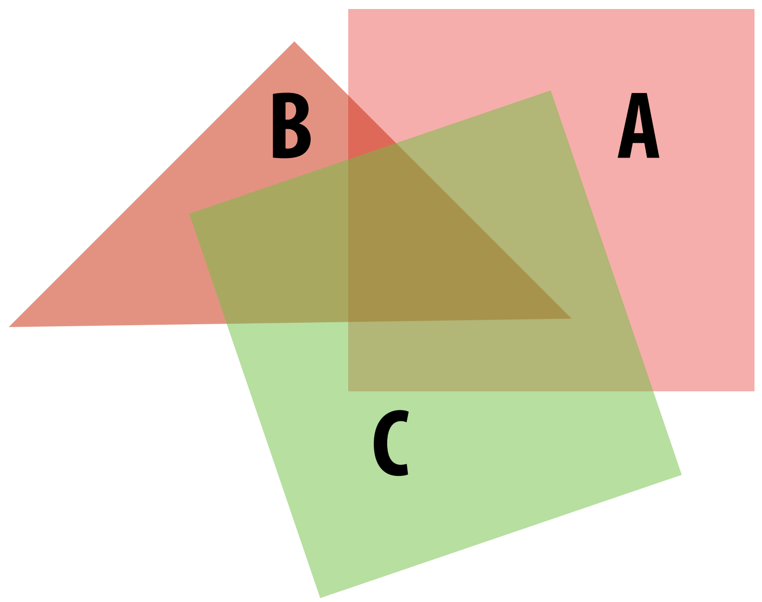
## Non-premultiplied alpha is not closed under composition:

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

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

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

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




C over B over A

## Consider result 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!

"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))`

**Q: What would be the correct UN-premultiplied RGBA for 50% red on top of 50% red?**

# Summary: advantages of premultiplied alpha

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

# Strategy for drawing semi-transparent primitives

**Assuming all primitives are semi-transparent, and RGBA values are encoded with premultiplied alpha, here's one strategy for creating a correctly rasterized image:**

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

update_color_buffer( x, y, sample_color, sample_depth )
{
   if (pass_depth_test(sample_depth, zbuffer[x][y]) {
       // (how) should we update depth buffer here??
       color[x][y] = over(sample_color, color[x][y]);
   }
}
```

**Q: What is the assumption made by this implementation?**

**Triangles must be rendered in back to front order!**

# Putting it all together

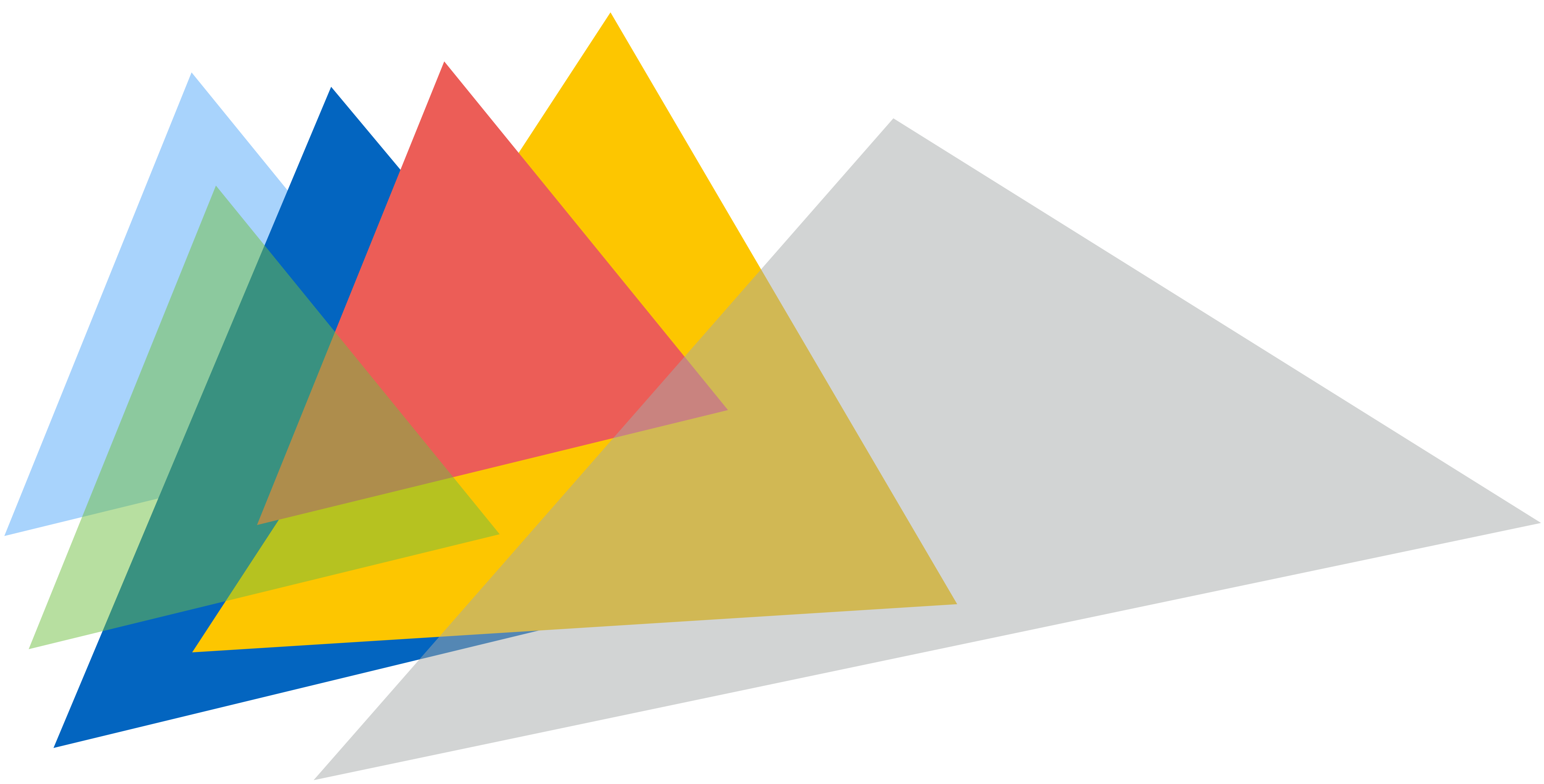
## Now what if we have a mixture of opaque and transparent triangles?

**Step 1: render opaque primitives (in any order) 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



# End-to-end rasterization pipeline
# (“real-time graphics pipeline”)

# Goal: turn these inputs into an image!

## 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:** $\mathbf{T}$

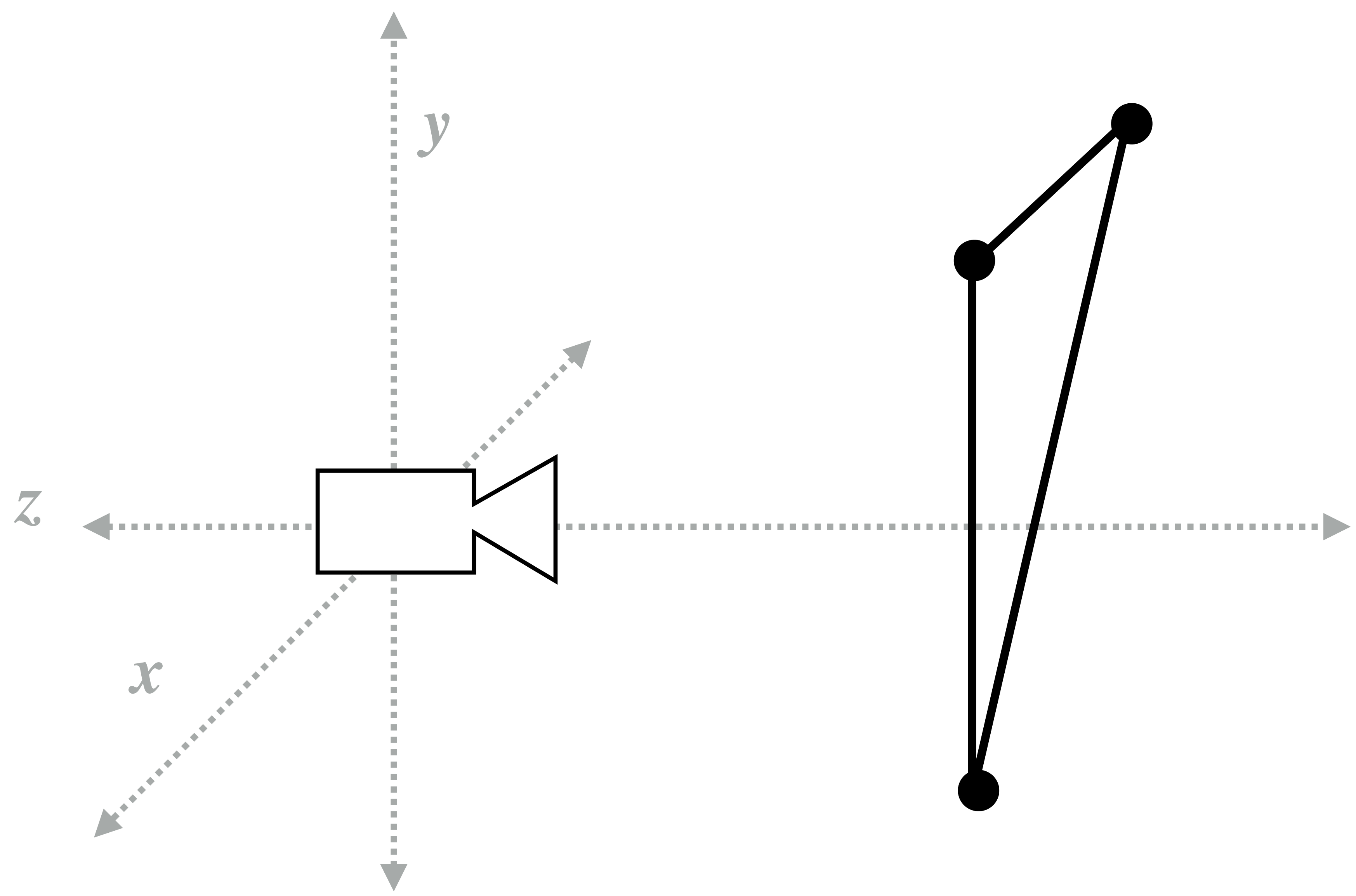
**Perspective projection transform** $\mathbf{P}$

**Size of output image (W, H)**

**At this point we should have all the tools we need, but let's review…**

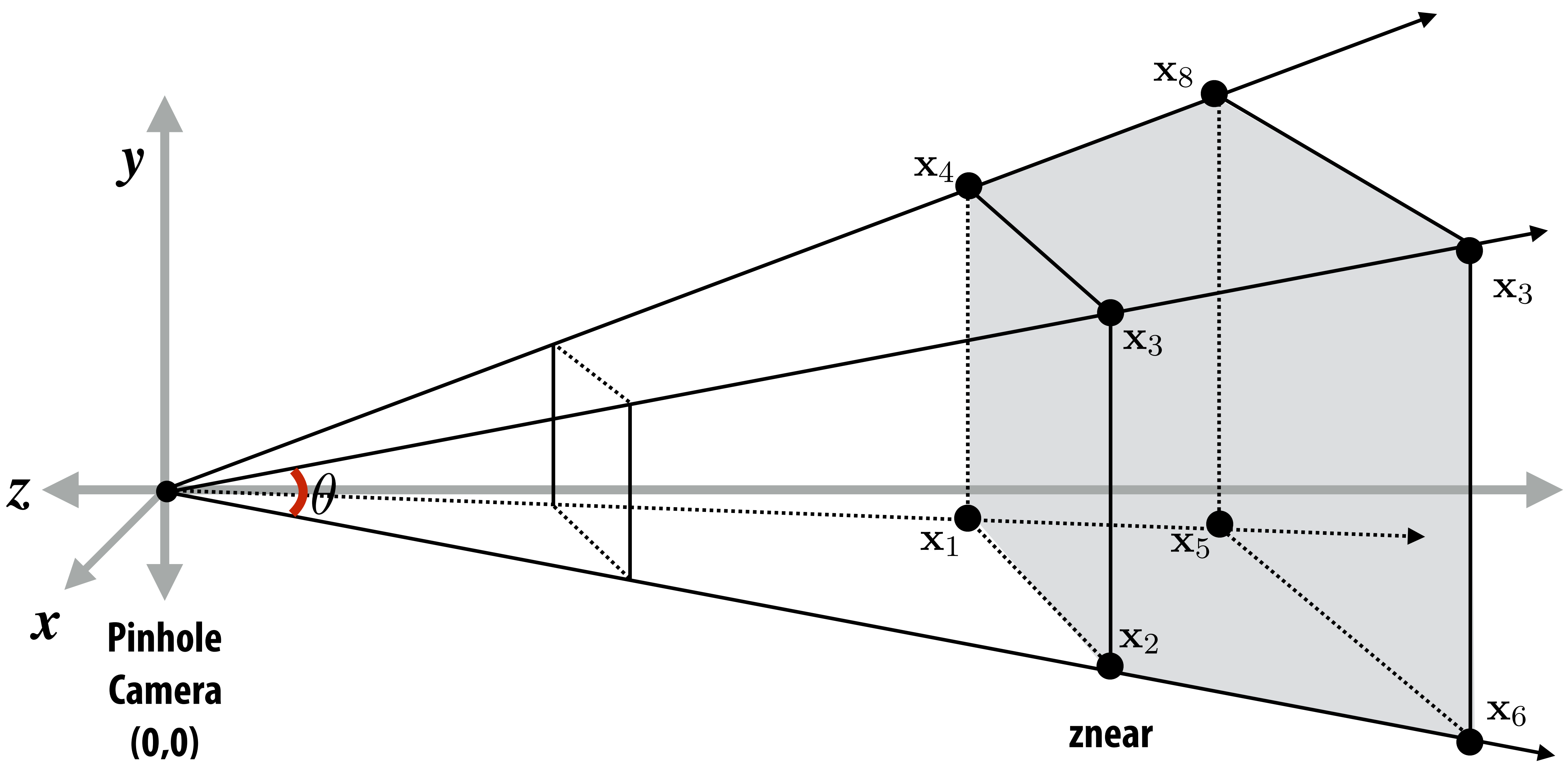
# Step 1:

## Transform triangle vertices into camera space

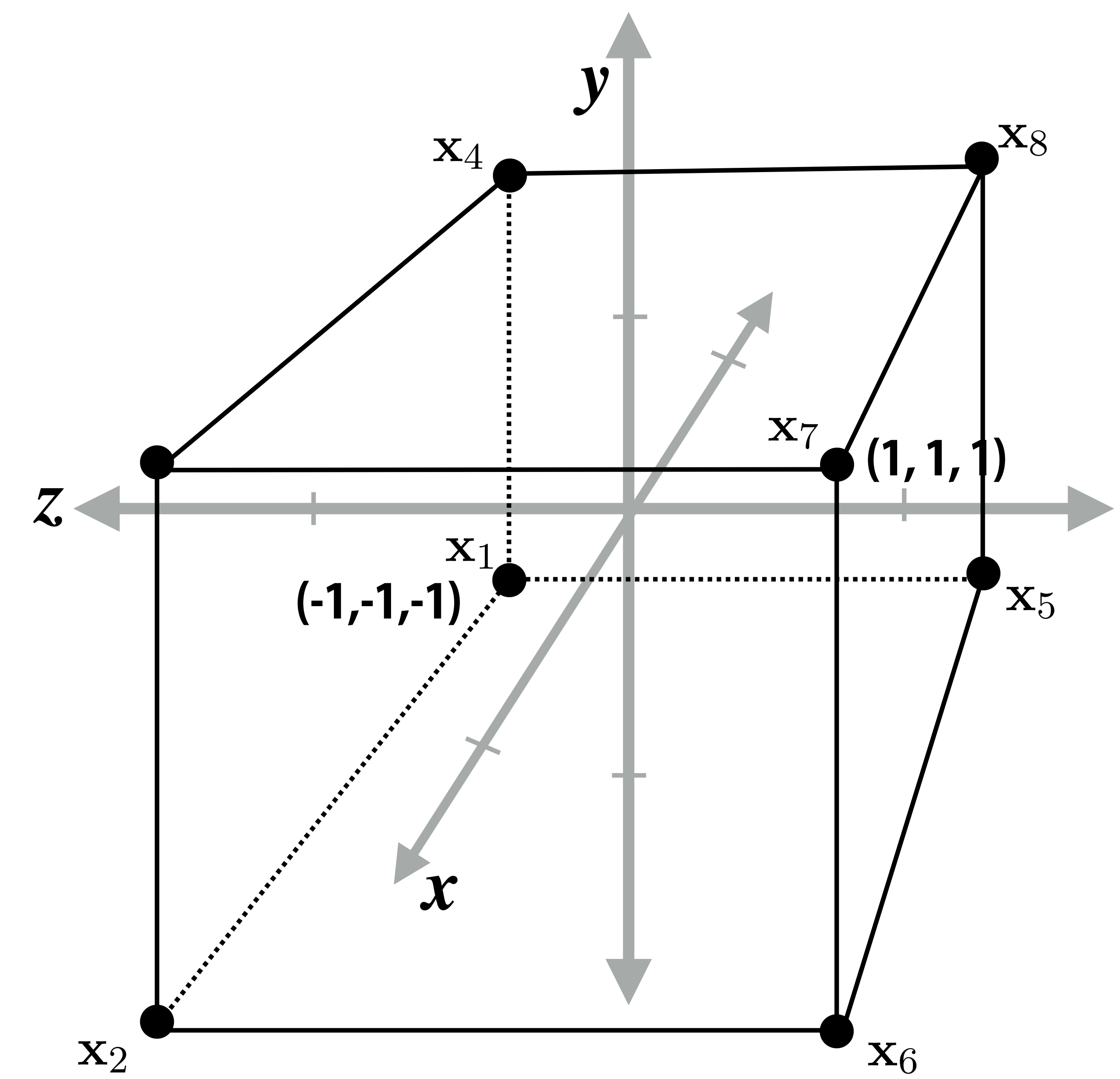


# Step 2:

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



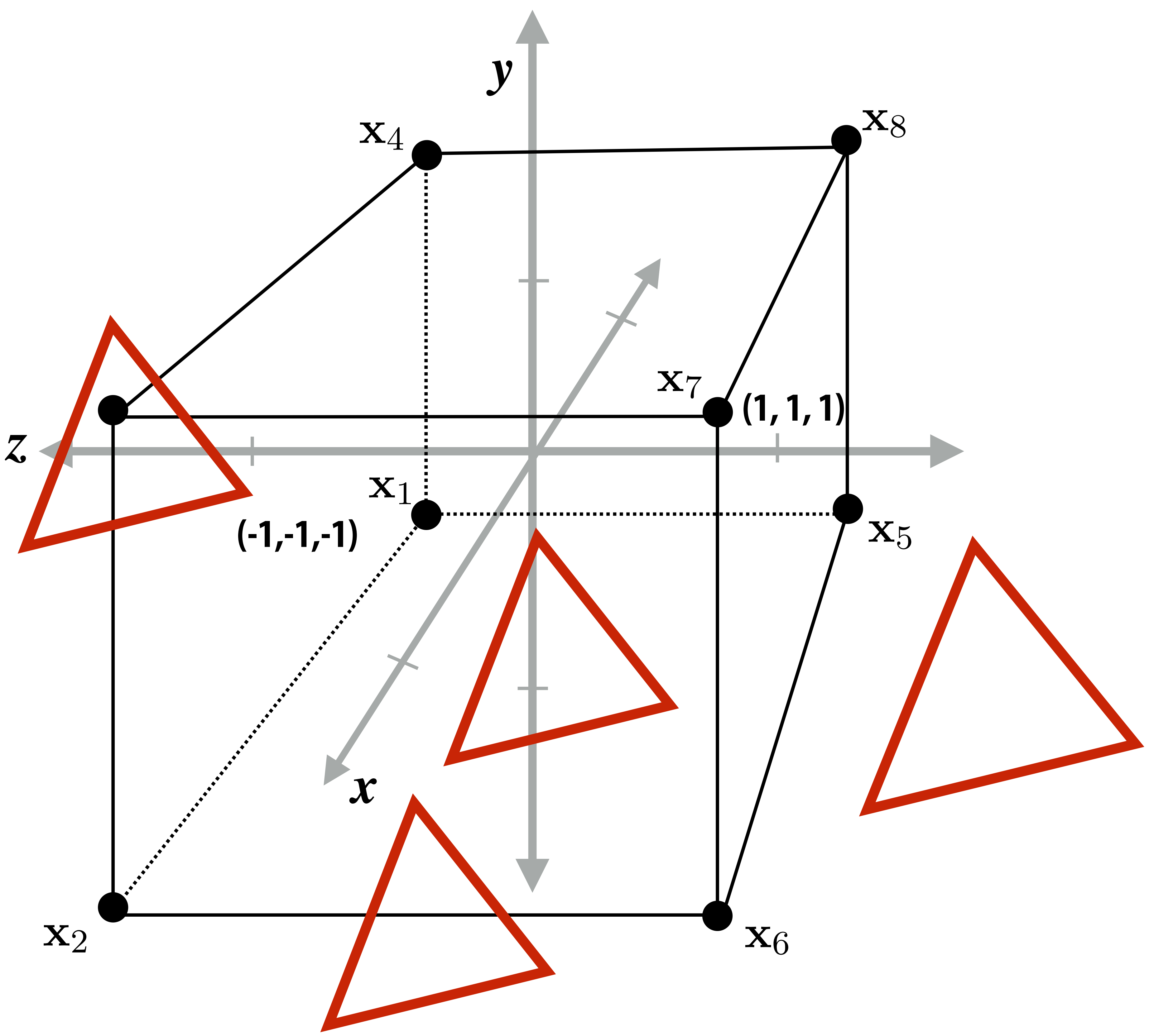

**Camera-space positions: 3D**



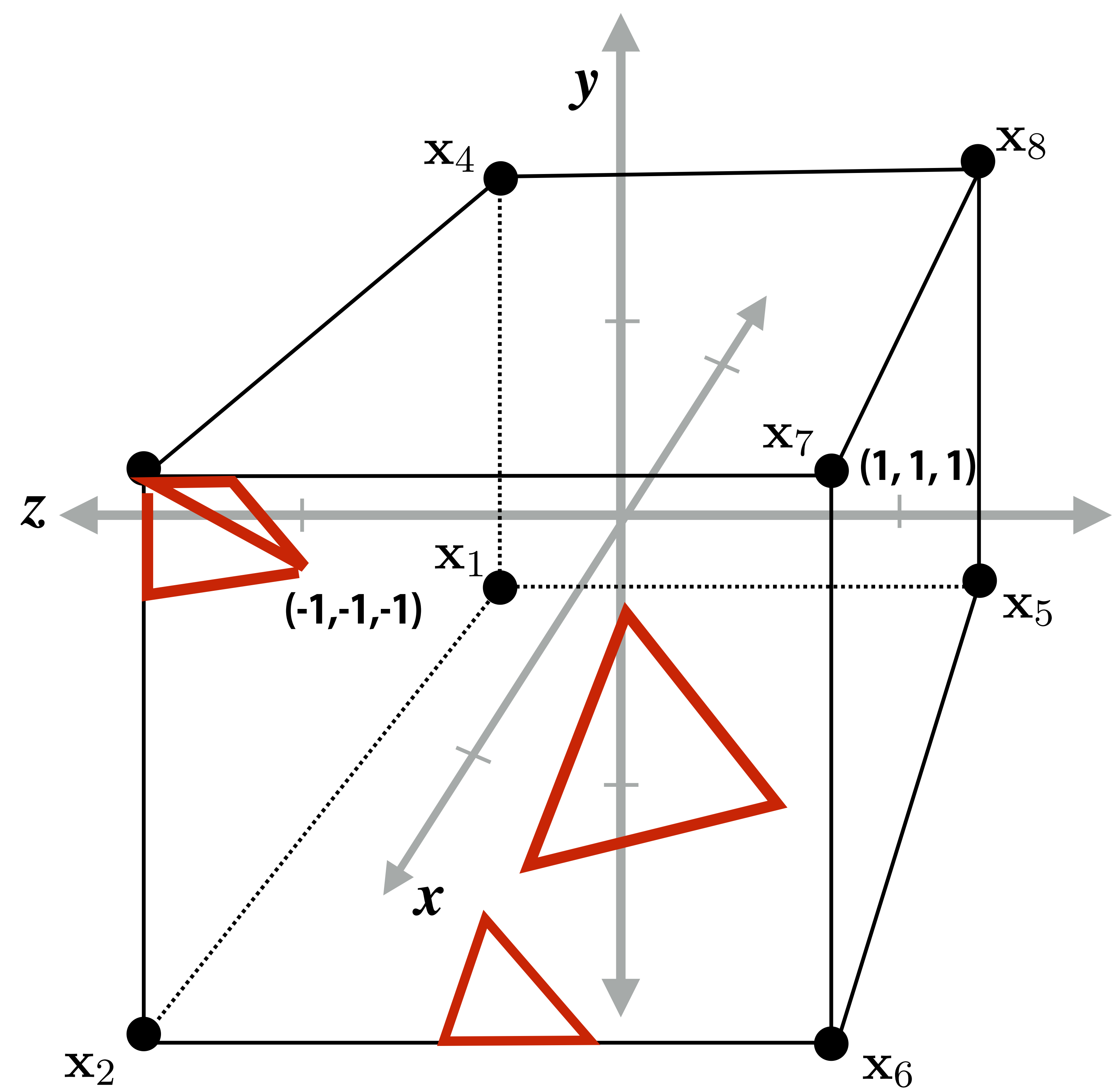

**Normalized space positions**

# 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**
  - **(possibly generating new triangles)**



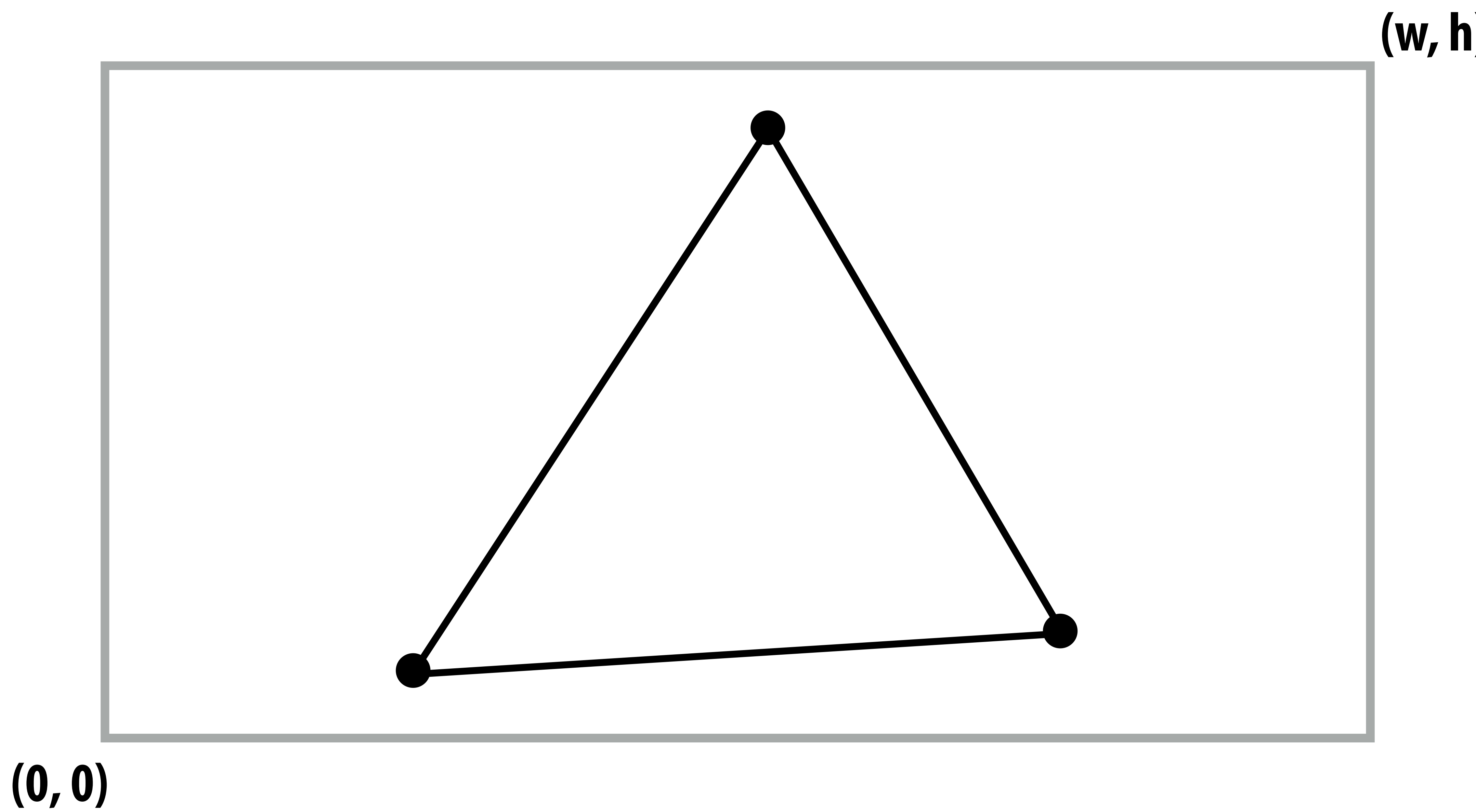

**Triangles before clipping**




**Triangles after clipping**

# Step 4: transform to screen coordinates

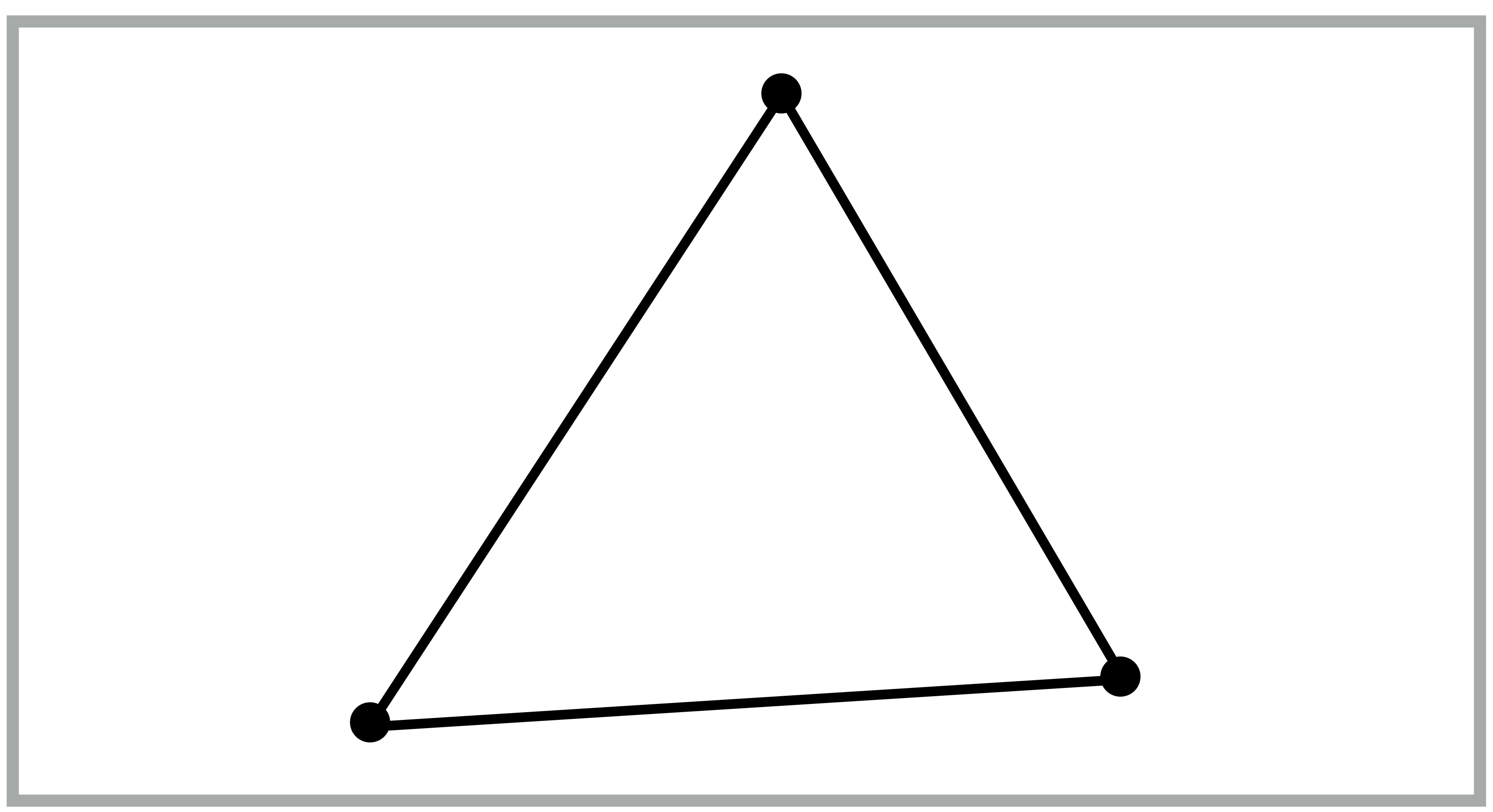
**Perform homogeneous divide, transform vertex xy positions from normalized coordinates into screen coordinates (based on screen w,h)**



# Step 5: setup triangle (triangle preprocessing)

**Before rasterizing triangle, can compute a bunch of data that will be used by all fragments, e.g.,**

- **triangle edge equations**
- **triangle attribute equations**
- **etc.**



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

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

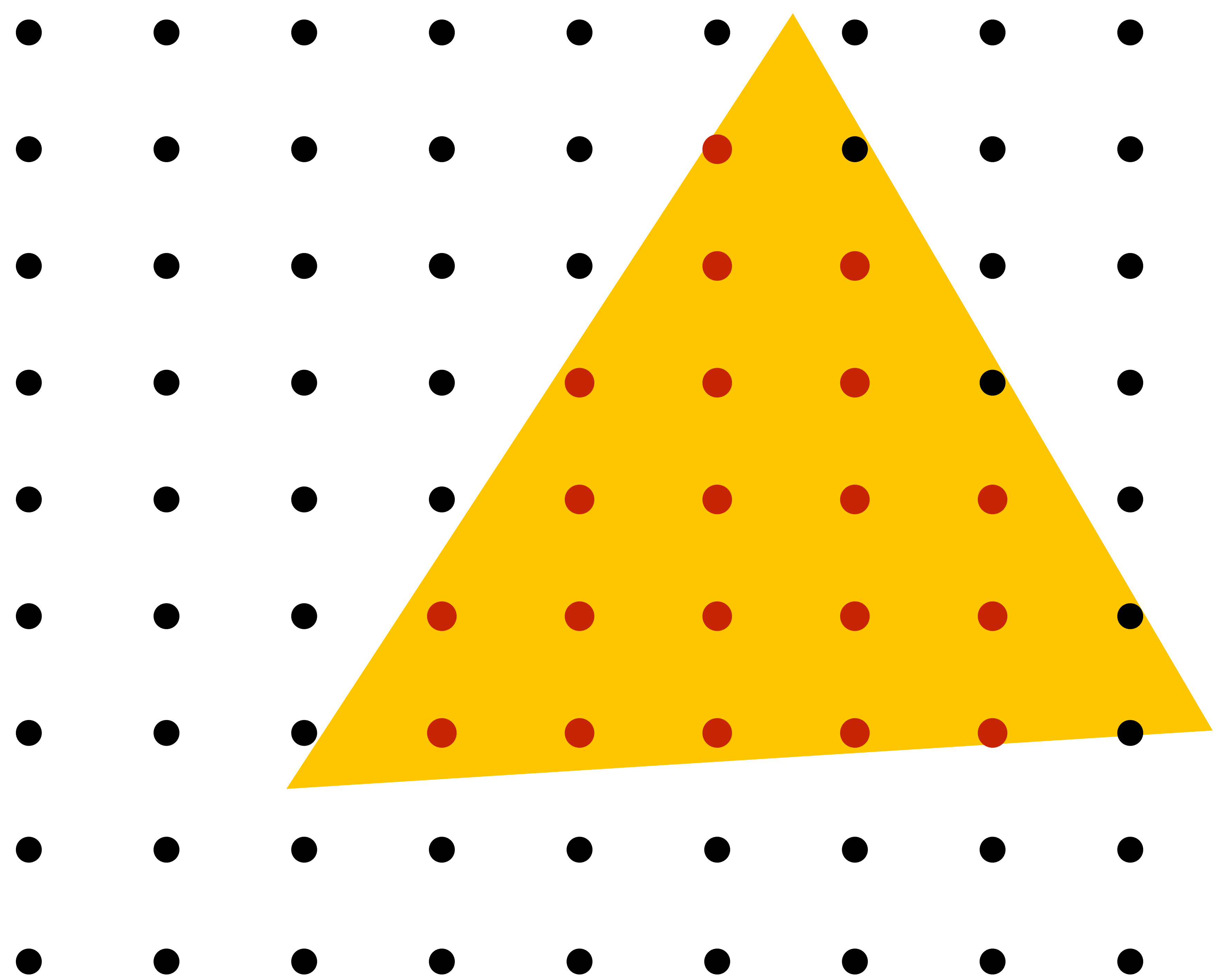
$$\mathbf{E}_{20}(x, y)$$

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

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

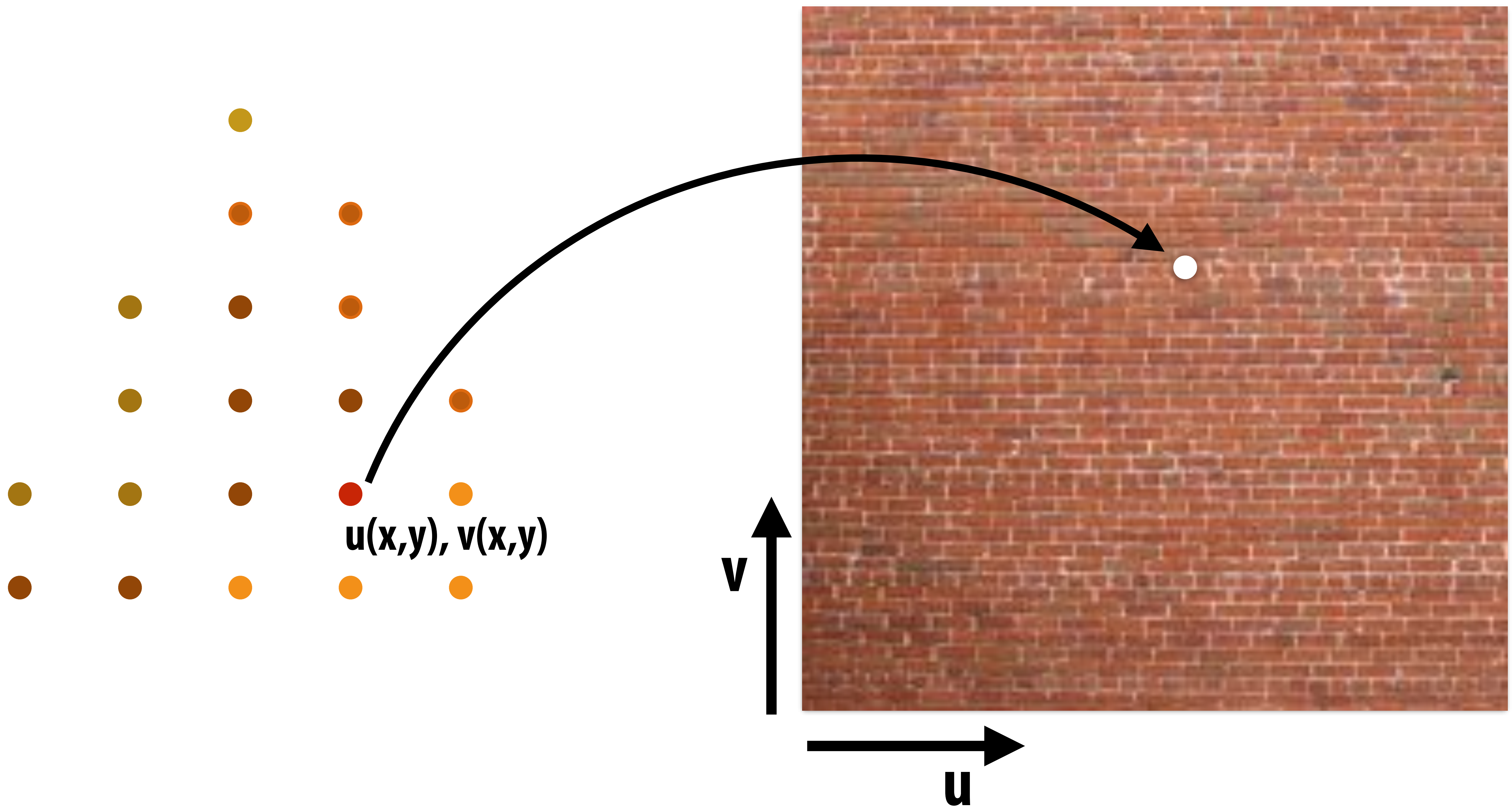
# Step 6: sample coverage

## Evaluate attributes z, u, v at all covered samples



# Step 6: compute triangle color at sample point

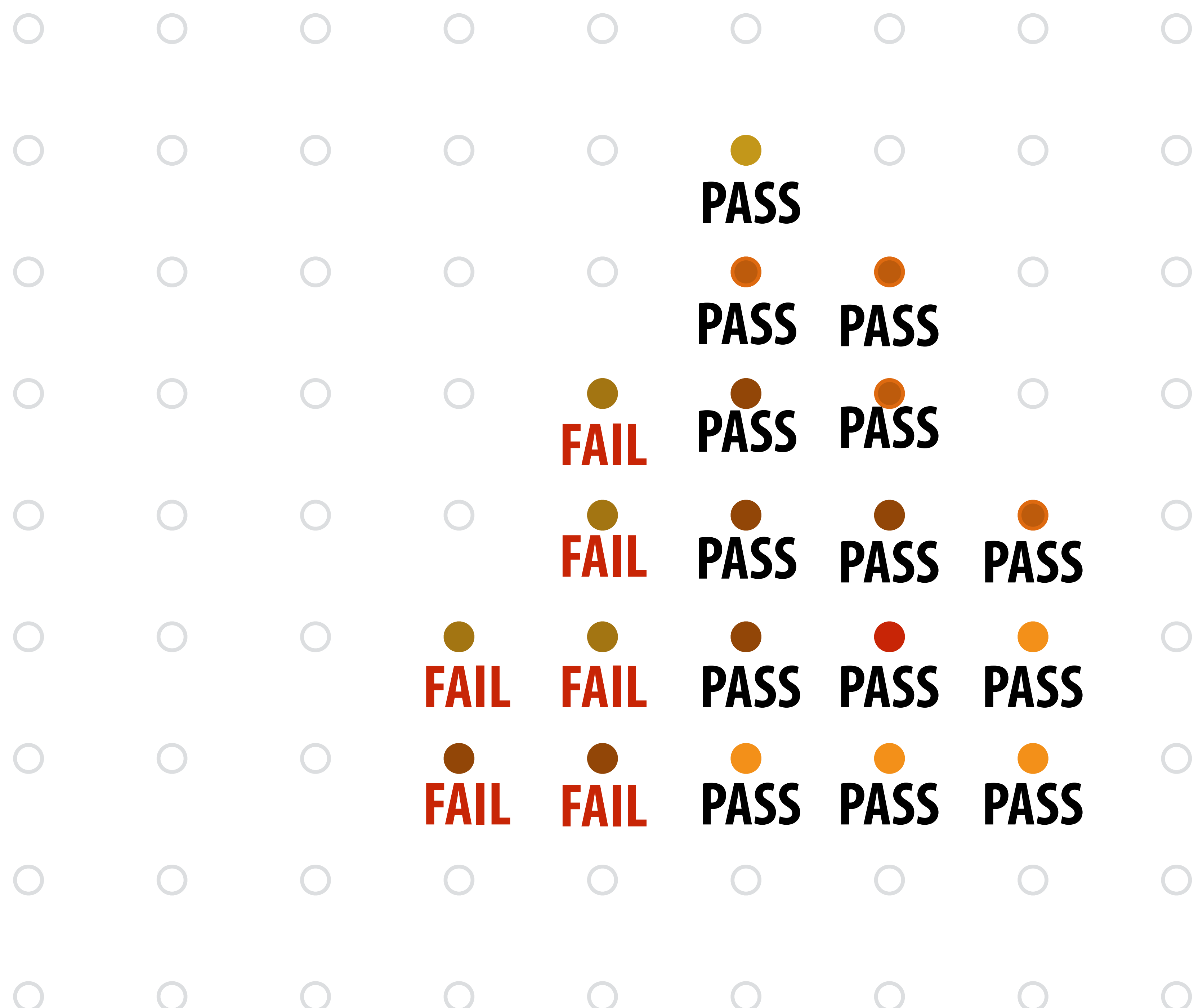
## e.g., sample texture map *



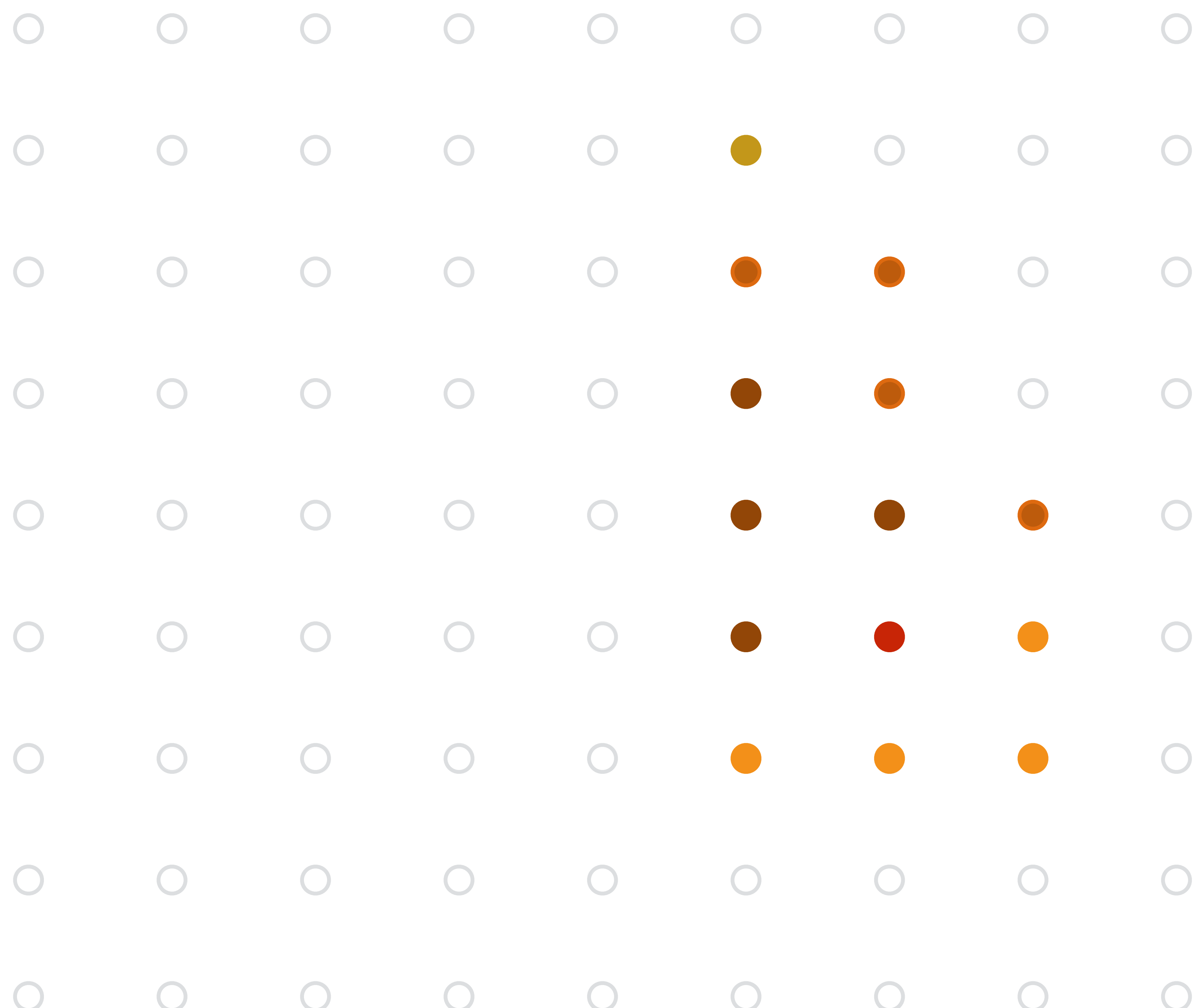

* So far, we've only described computing triangle's color at a point by interpolating per-vertex colors, or by sampling a texture map. Later in the course, we'll discuss more advanced algorithms for computing its color based on material properties and scene lighting conditions.

# Step 7: perform depth test (if enabled)

## Also update depth value at covered samples (if necessary)

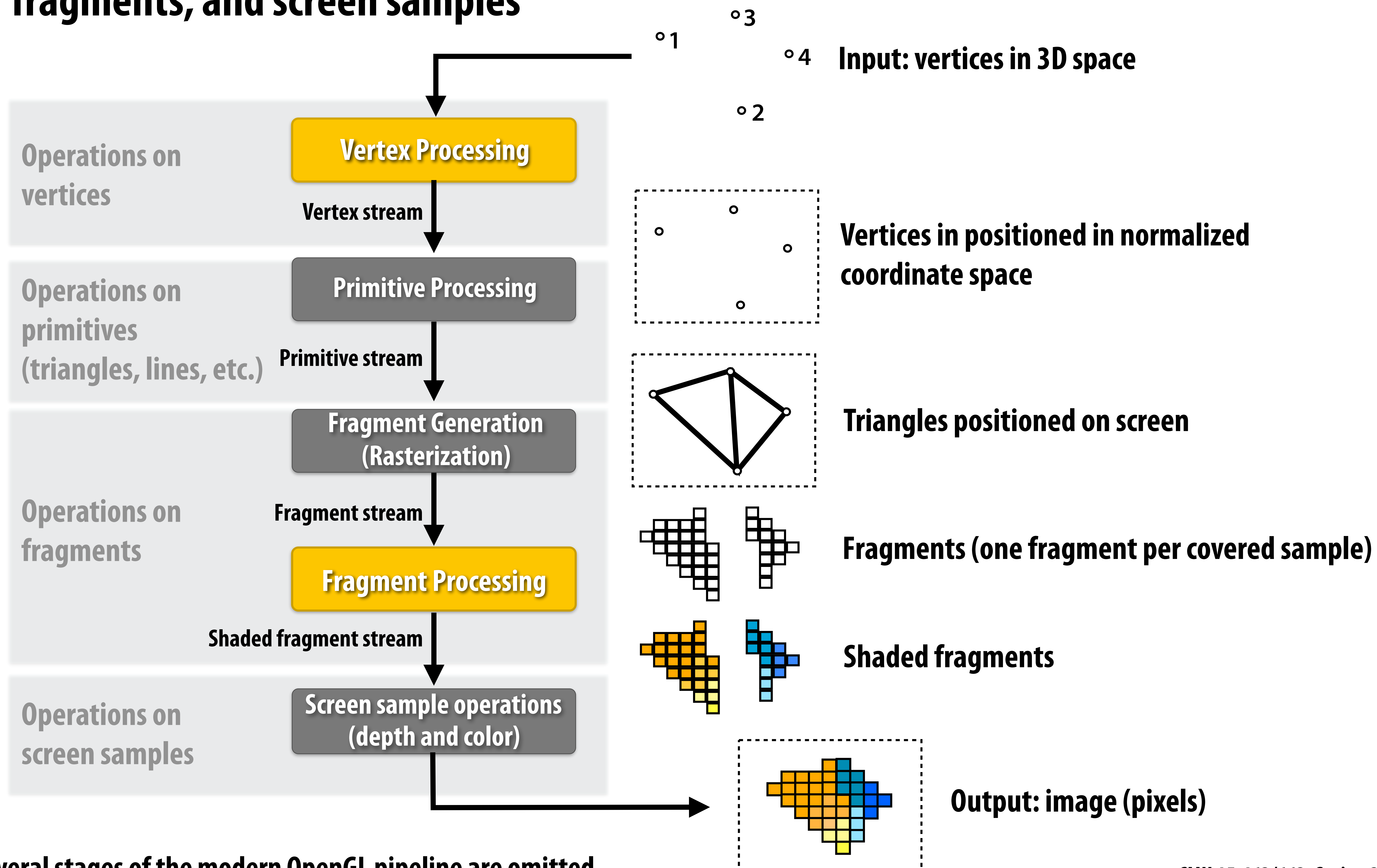


# Step 8: update color buffer (if depth test passed)



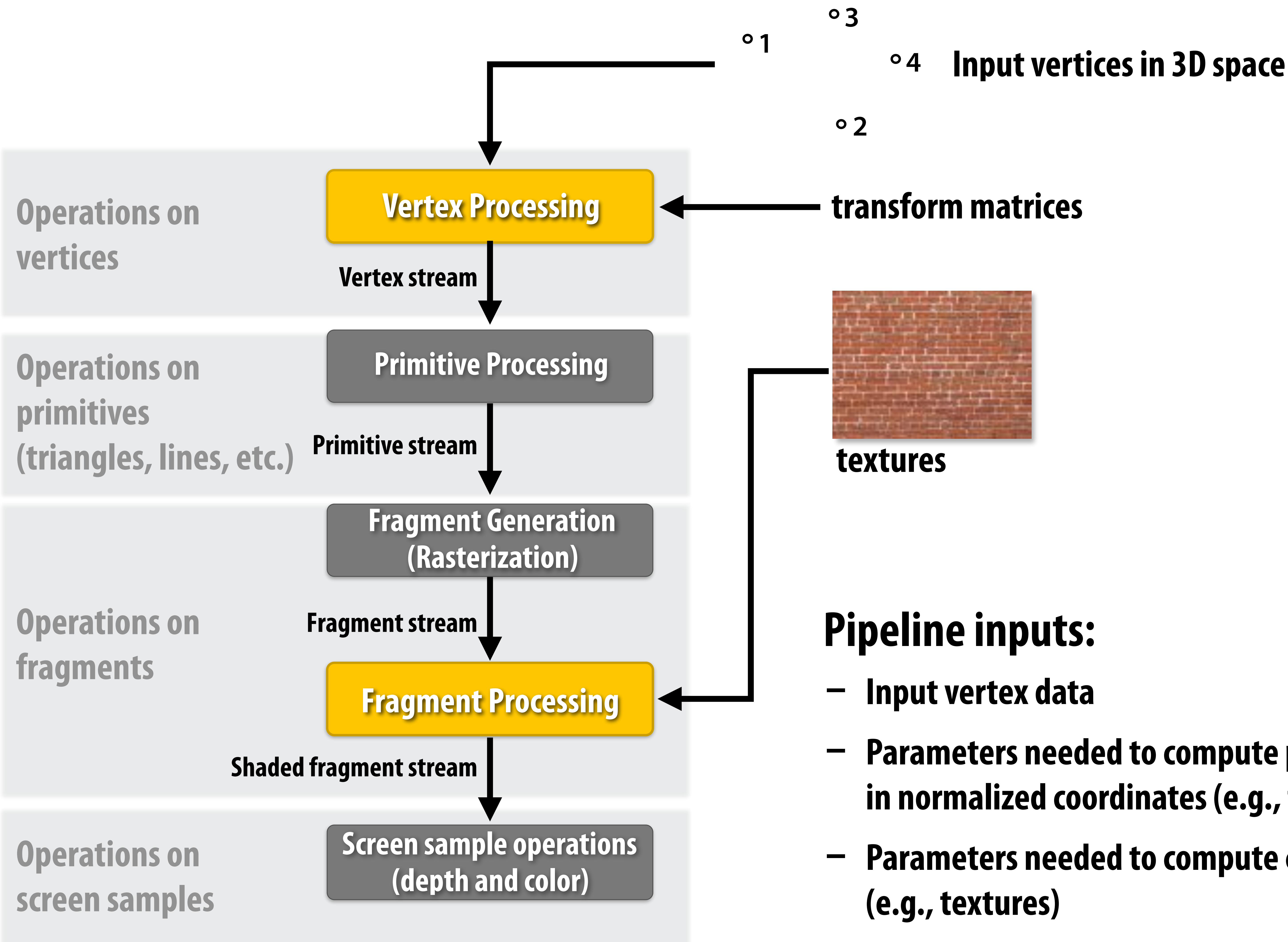
# OpenGL/Direct3D graphics pipeline *

**Structures rendering computation as a series of operations on vertices, primitives, fragments, and screen samples**




* Several stages of the modern OpenGL pipeline are omitted

# OpenGL/Direct3D graphics pipeline *




## Pipeline inputs:

- Input vertex data
- Parameters needed to compute position on vertices in normalized coordinates (e.g., transform matrices)
- Parameters needed to compute color of fragments (e.g., textures)
- "Shader" programs that define behavior of vertex and fragment stages

* several stages of the modern OpenGL pipeline are omitted

# Shader programs

## Define behavior of vertex processing and fragment processing stages
## Describe operation on a single vertex (or single fragment)

### Example GLSL fragment shader program

```
uniform sampler2D myTexture;
uniform vec3 lightDir;
varying vec2 uv;
varying vec3 norm;

void diffuseShader()
{
  vec3 kd;
  kd = texture2d(myTexture, uv);
  kd *= clamp(dot(-lightDir, norm), 0.0, 1.0);
  gl_FragColor = vec4(kd, 1.0);
}
```

Program parameters (myTexture, lightDir)

Per-fragment attributes (interpolated by rasterizer) (uv, norm)

Sample surface albedo (reflectance color) from texture

Modulate surface albedo by incident irradiance (incoming light)

Shader outputs surface color

**Shader function executes once per fragment.**

**Outputs color of surface at sample point corresponding to fragment.**

(this shader performs a texture lookup to obtain the surface's material color at this point, then performs a simple lighting computation)

# Goal: render very high complexity 3D scenes

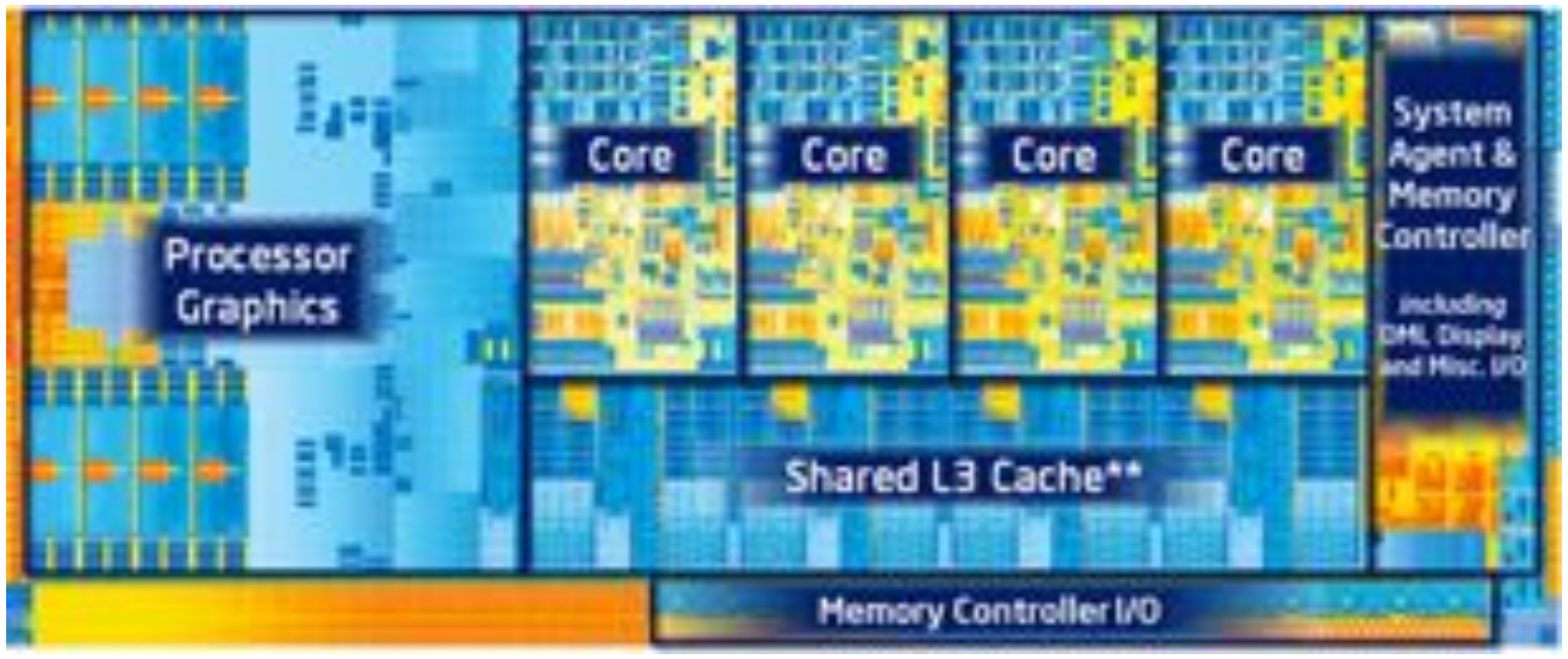
- 100's of thousands to millions of triangles in a scene
- Complex vertex and fragment shader computations
- High resolution screen outputs (2-4 Mpixel + supersampling)
- 30-60 fps

Unreal Engine Kite Demo (Epic Games 2015)

# Graphics pipeline implementation: GPUs

## Specialized processors for executing graphics pipeline computations


Discrete GPU card
(NVIDIA GeForce Titan X)

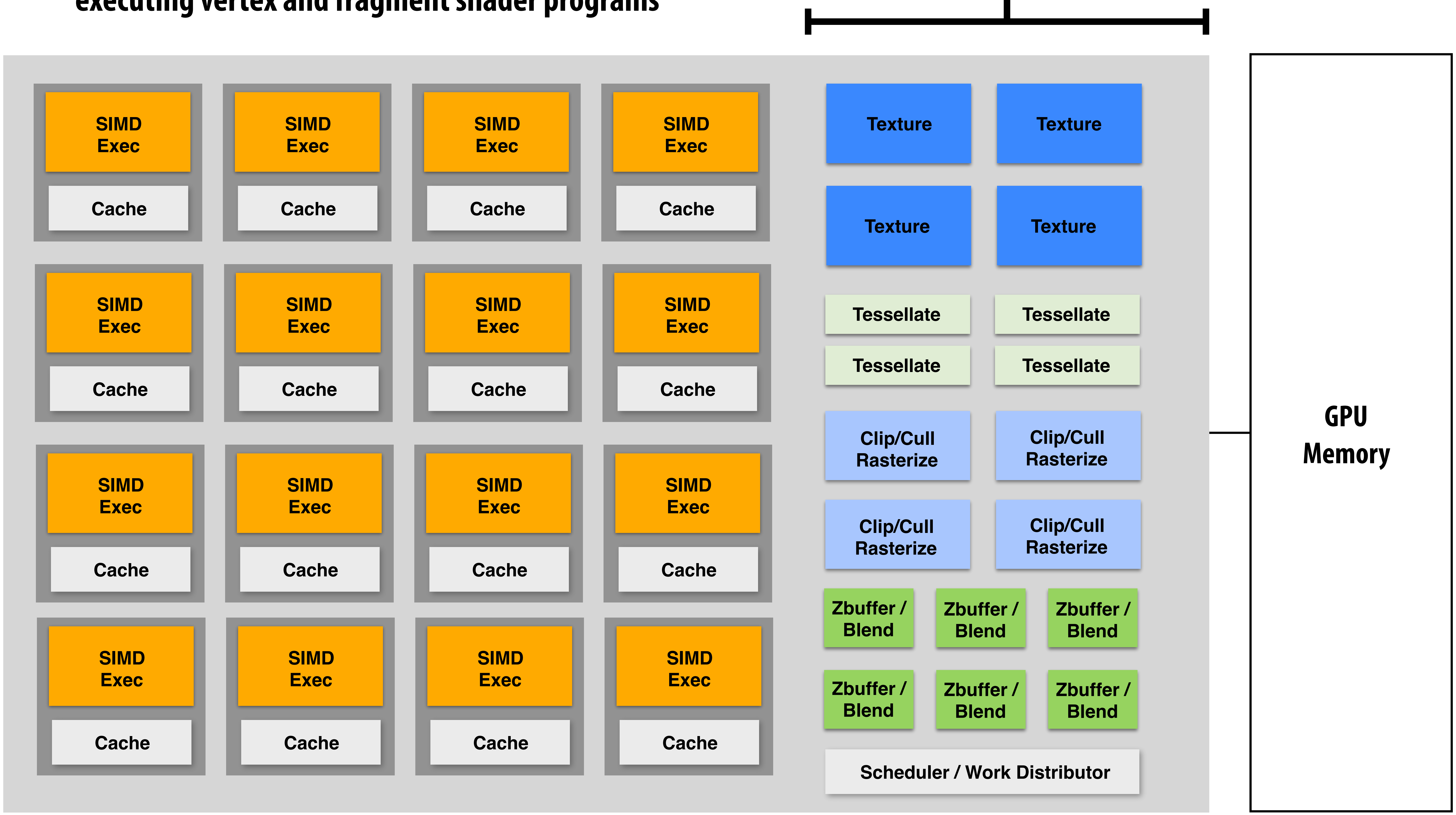



Integrated GPU: part of modern Intel CPU die

# GPU: heterogeneous, multi-core processor

Modern GPUs offer ~2-4 TFLOPs of performance for executing vertex and fragment shader programs

T-OP's of fixed-function compute capability over here



# Summary

- Occlusion resolved independently at each screen sample using the depth buffer
- Alpha compositing for semi-transparent surfaces
  - Premultiplied alpha forms simply repeated composition
  - “Over” compositing operations is not commutative: requires triangles to be processed in back-to-front (or front-to-back) order
- Graphics pipeline:
  - Structures rendering computation as a sequence of operations performed on vertices, primitives (e.g., triangles), fragments, and screen samples
  - Behavior of parts of the pipeline is application-defined using shader programs.
  - Pipeline operations implemented by highly, optimized parallel processors and fixed-function hardware (GPUs)