Lecture 8:

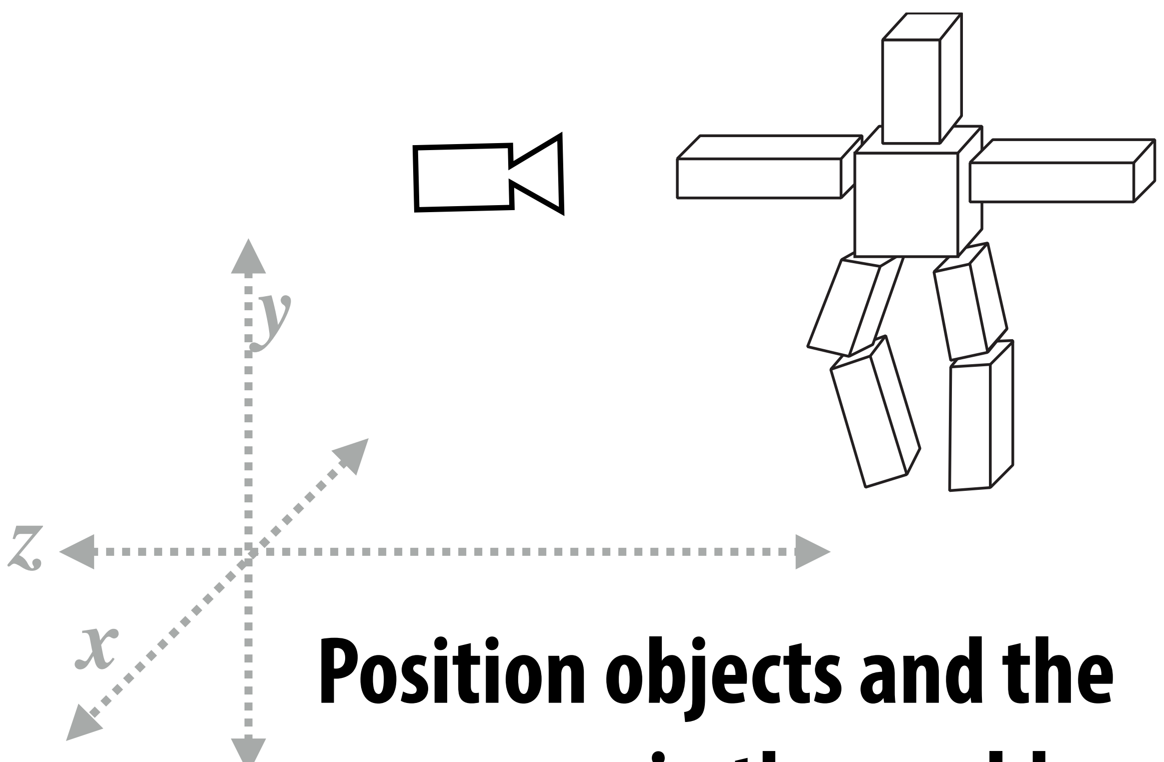
The Rasterization Pipeline

(and its implementation on GPUs)

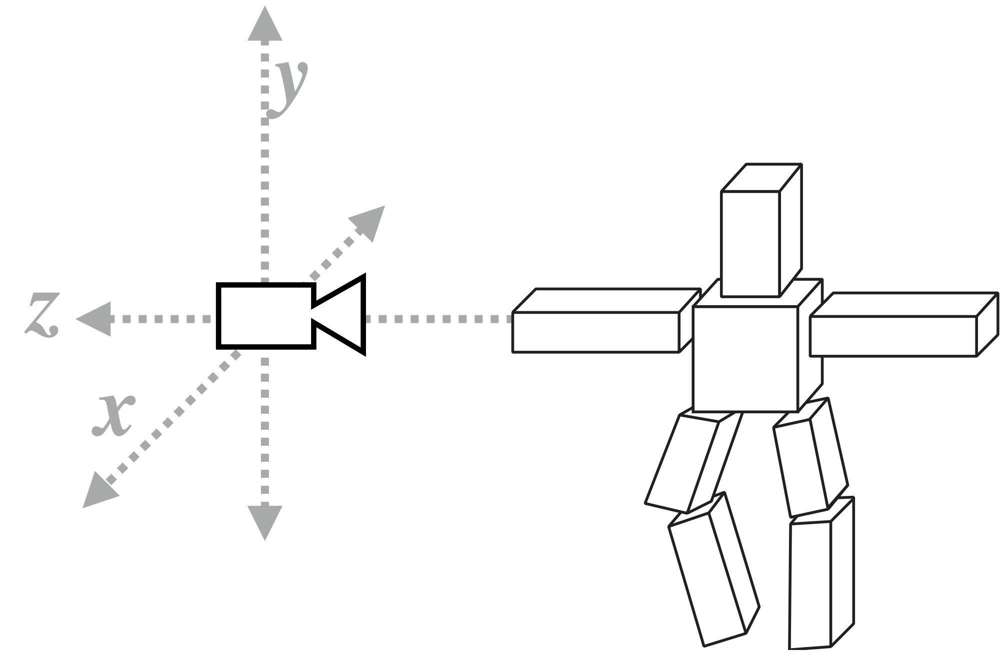
Computer Graphics

CMU 15-462/15-662, Fall 2017

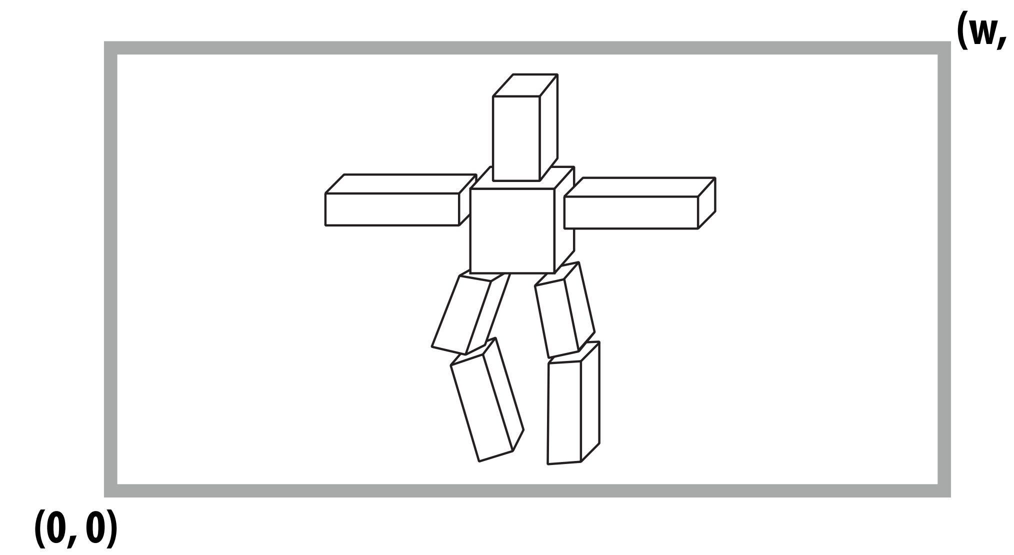
What you know how to do (at this point in the course)



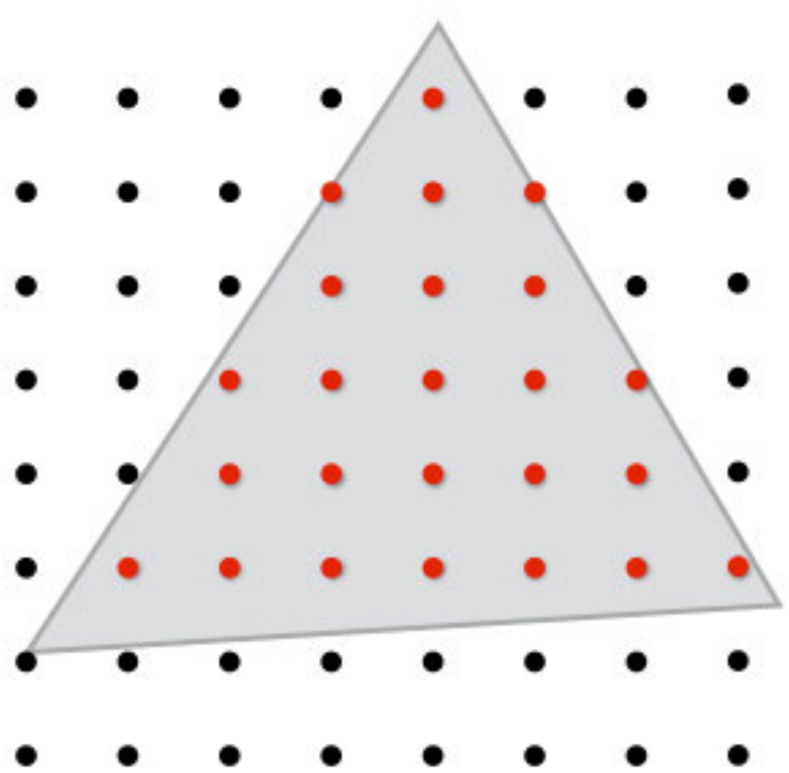
Position objects and the camera in the world



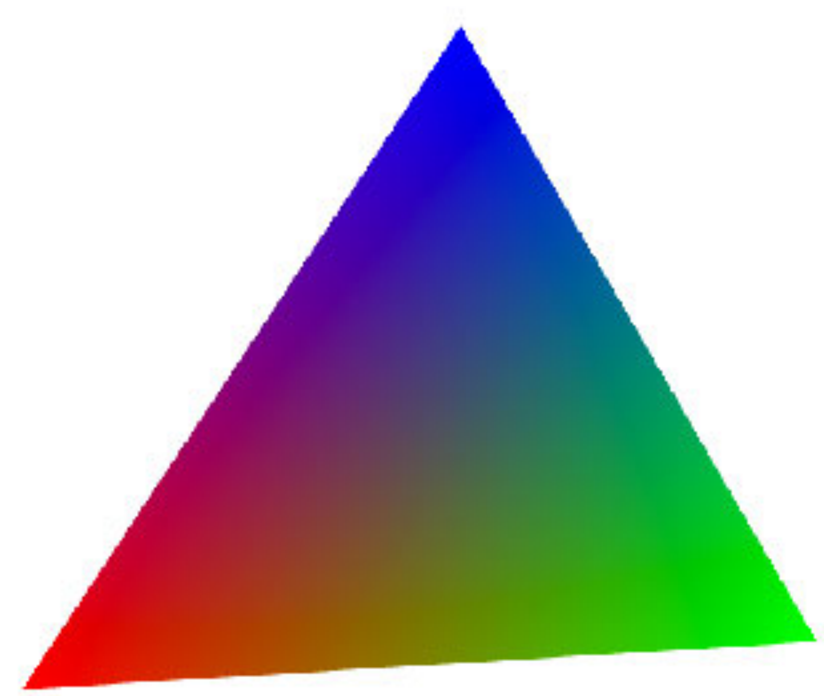
Determine the position of objects relative to the camera



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

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

Drawing Things

Key concepts:

Sampling (and anti-aliasing)

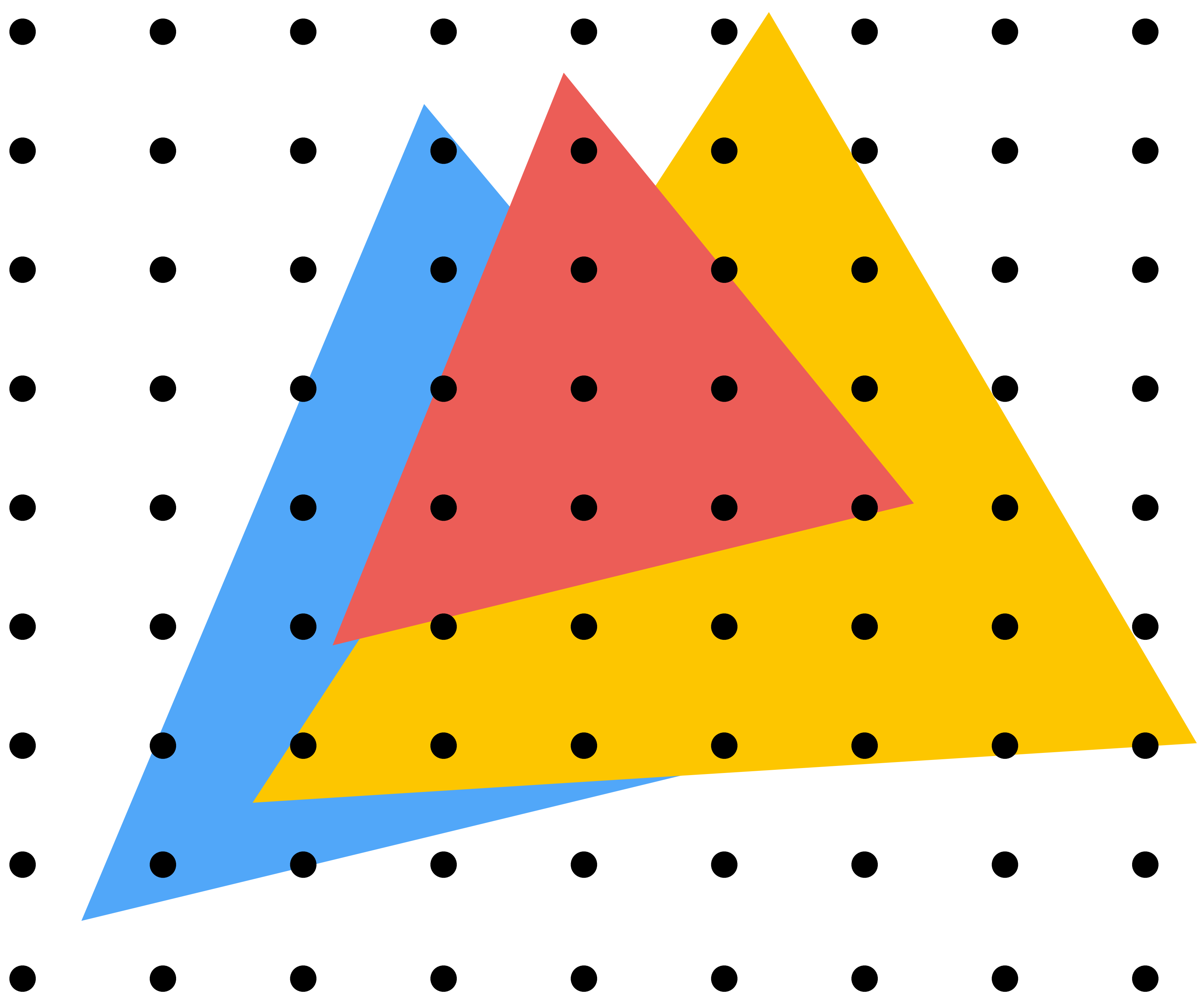
Coordinate Spaces and Transforms

Geometry

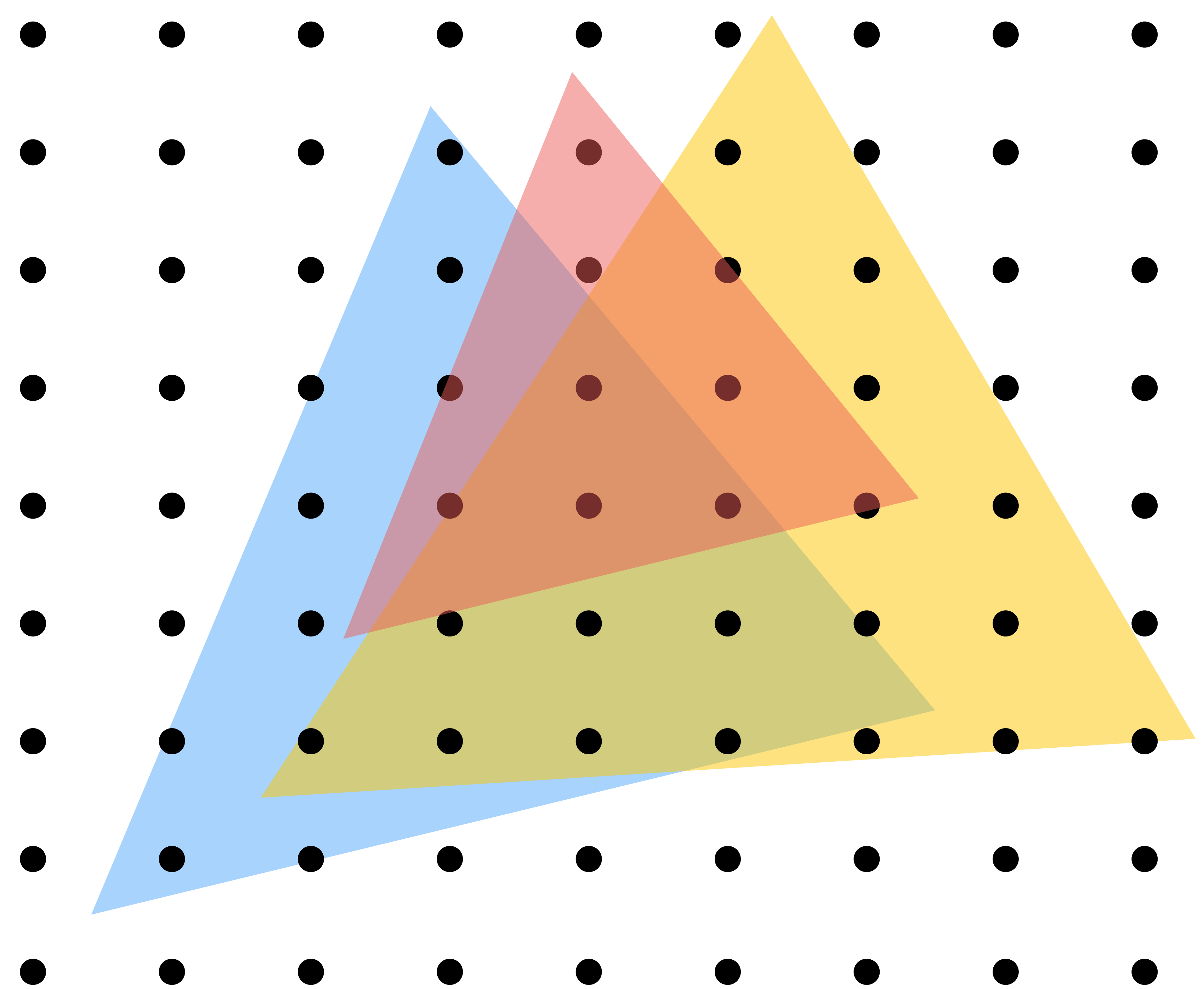
Materials and Lighting

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)?

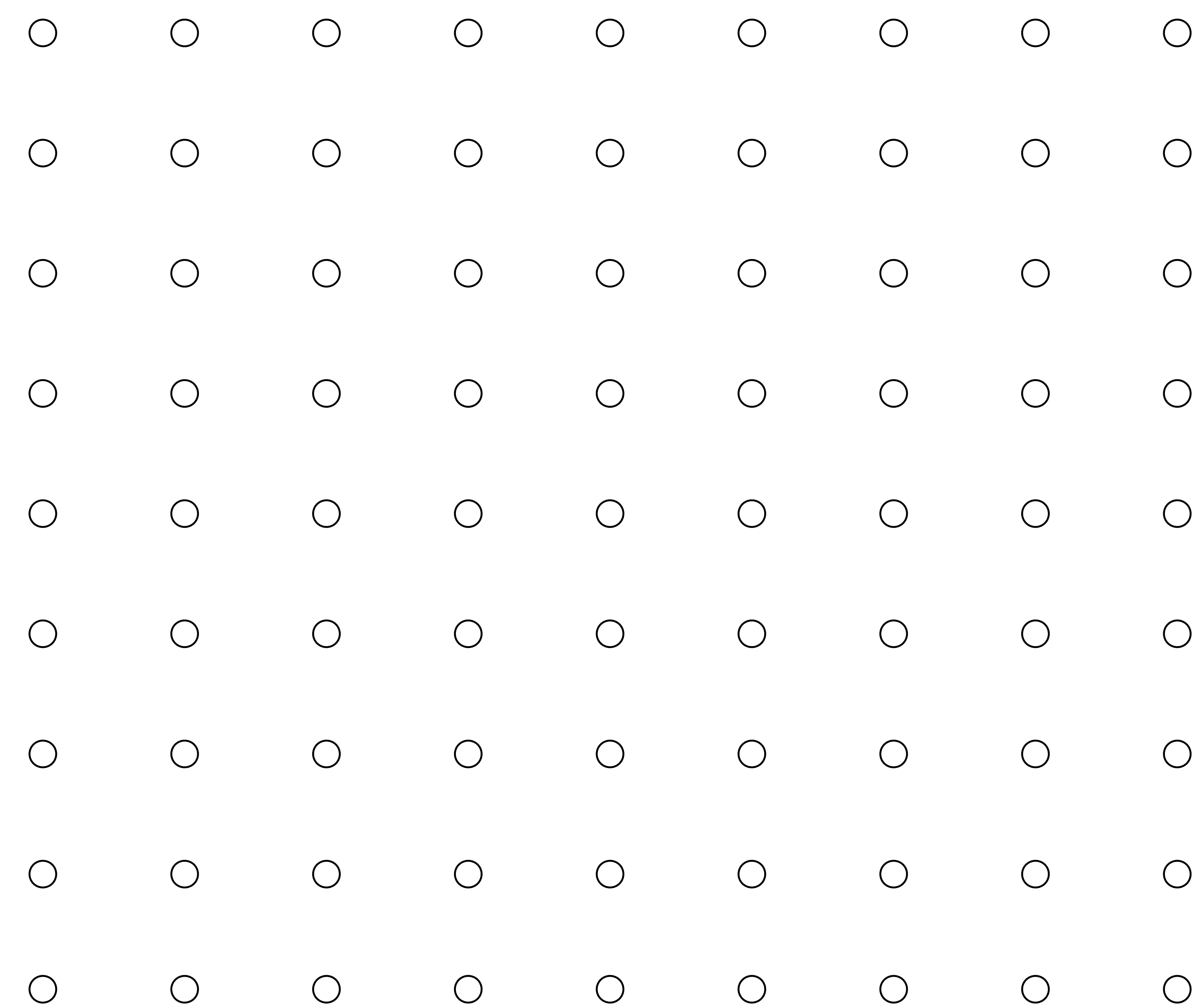
Interpolate it just like any other attribute that varies linearly over the surface of the triangle.

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) →



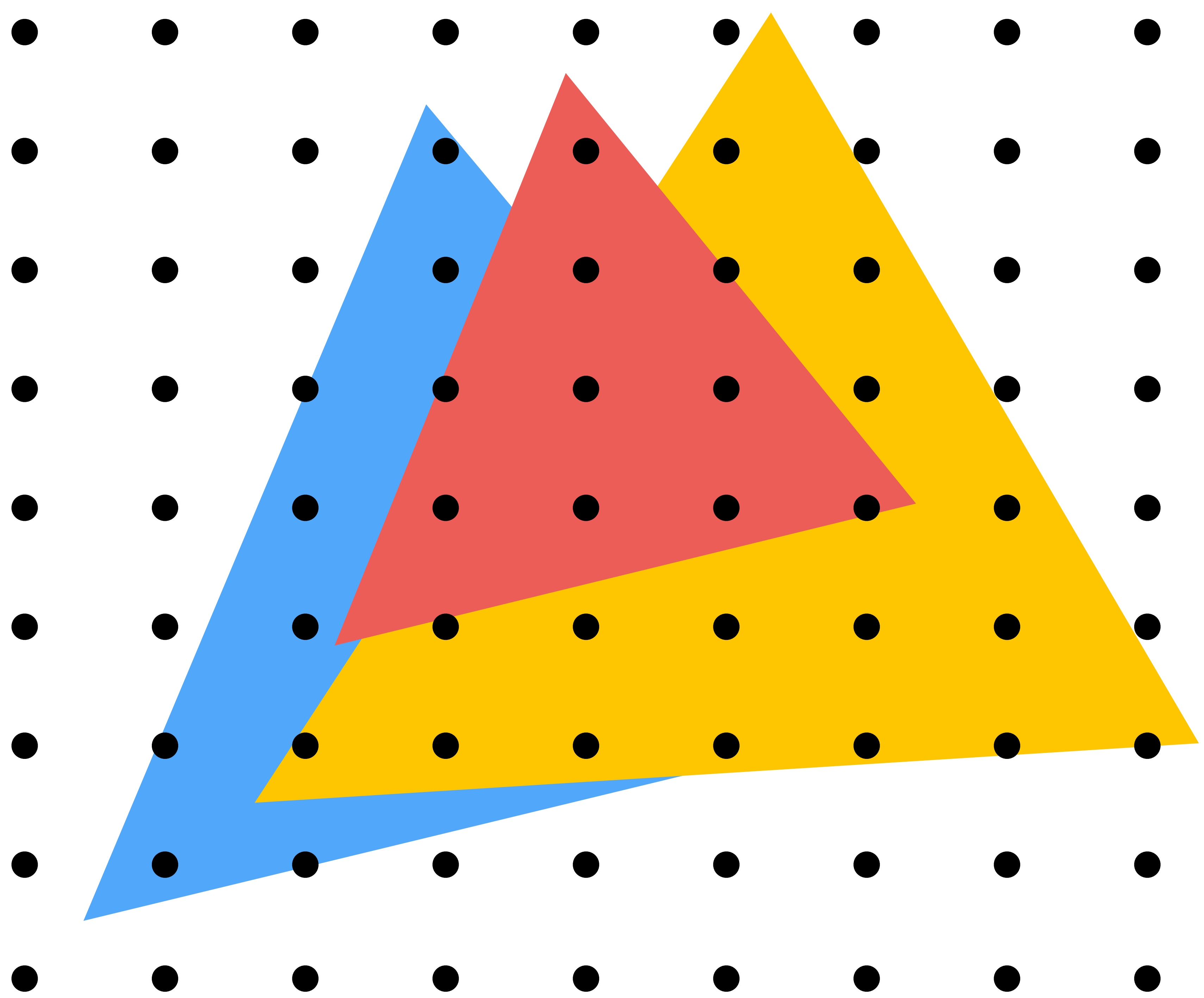
Grayscale value of sample point used to indicate distance

Black = small distance

White = large distance

Depth buffer example

Example: rendering three opaque triangles



Occlusion using the depth-buffer (Z-buffer)

Processing yellow triangle:

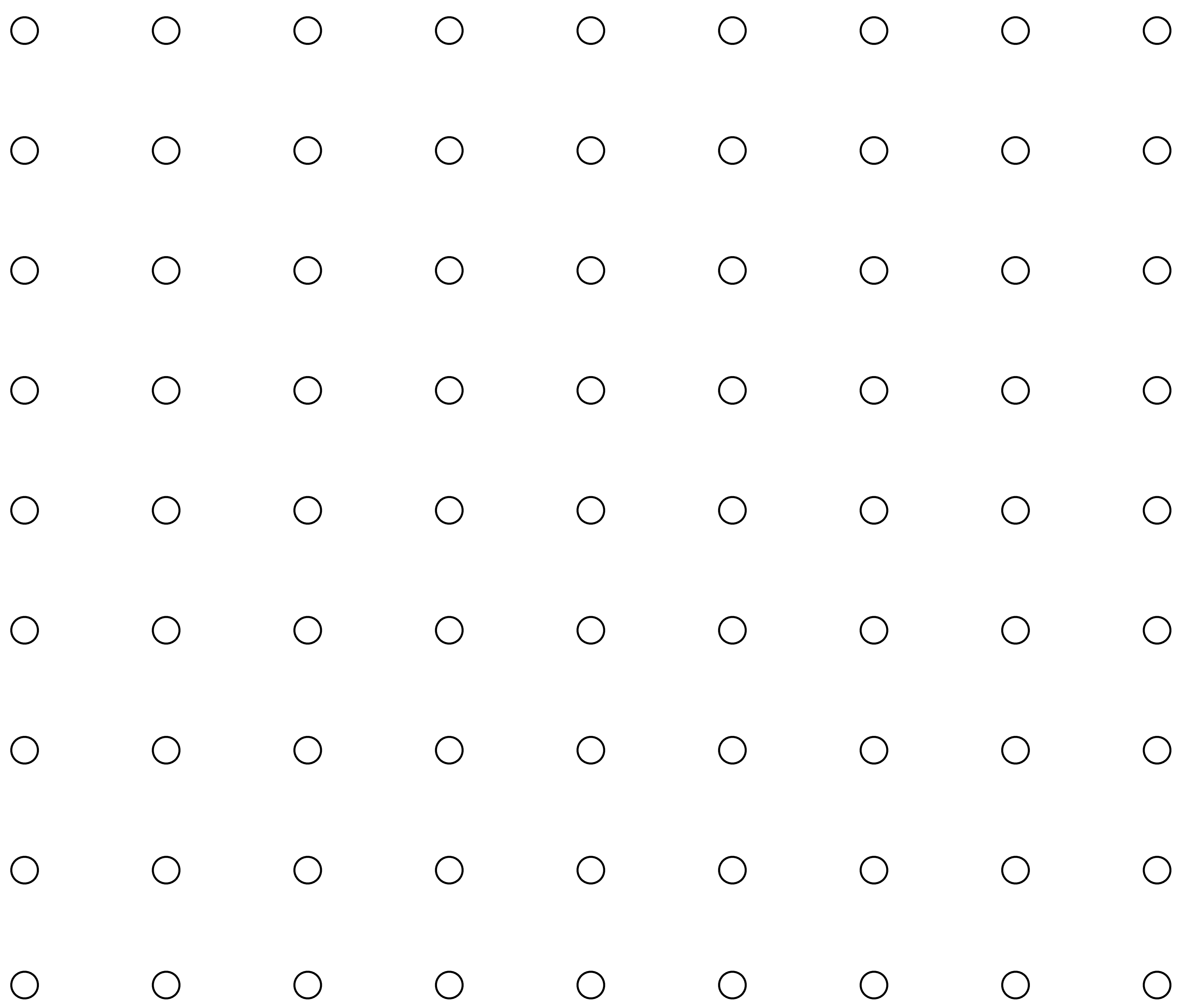
depth = 0.5

Grayscale value of sample point used to indicate distance

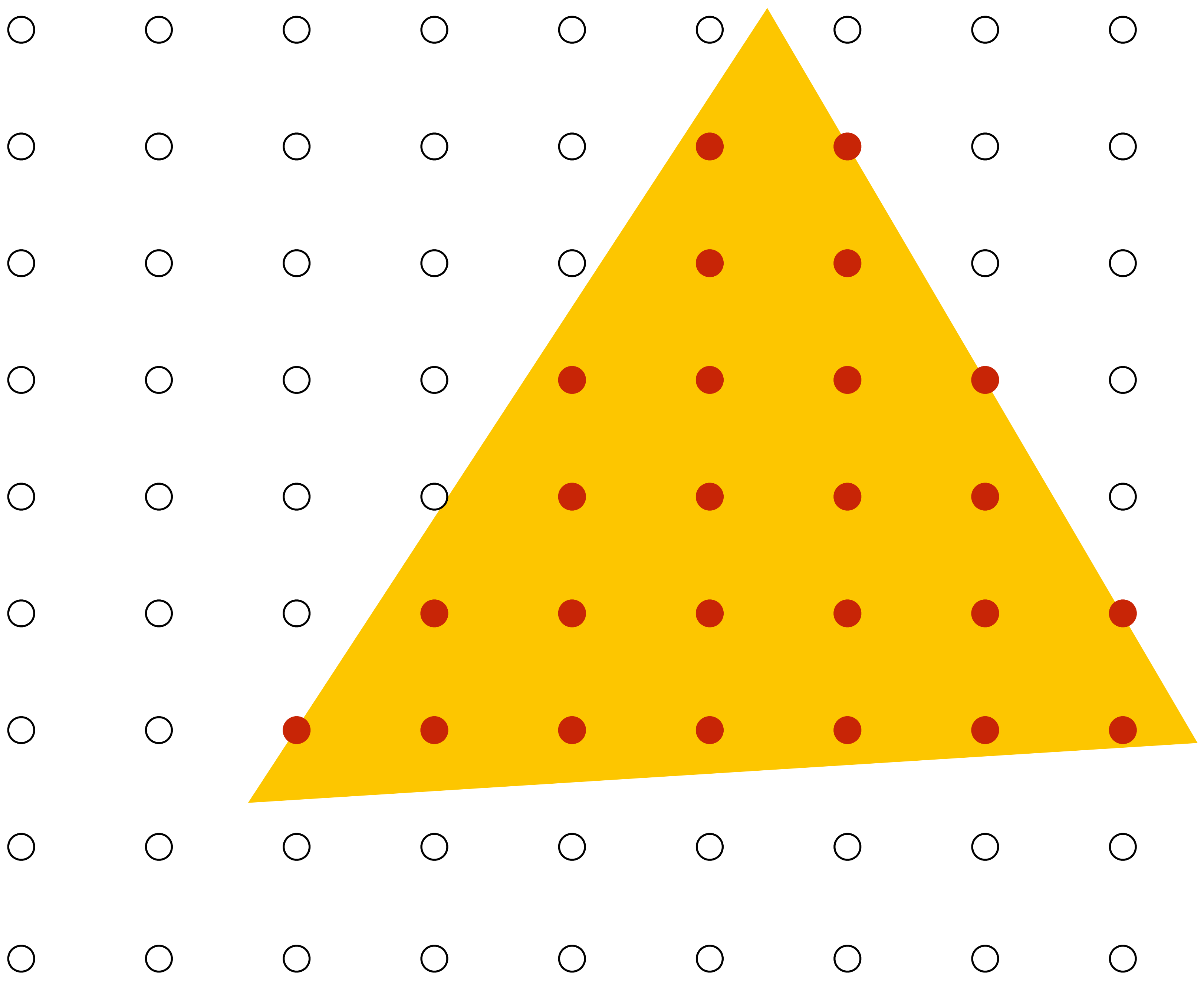
White = large distance

Black = small distance

Red = sample passed depth test



Color buffer contents



Depth buffer contents

Occlusion using the depth-buffer (Z-buffer)

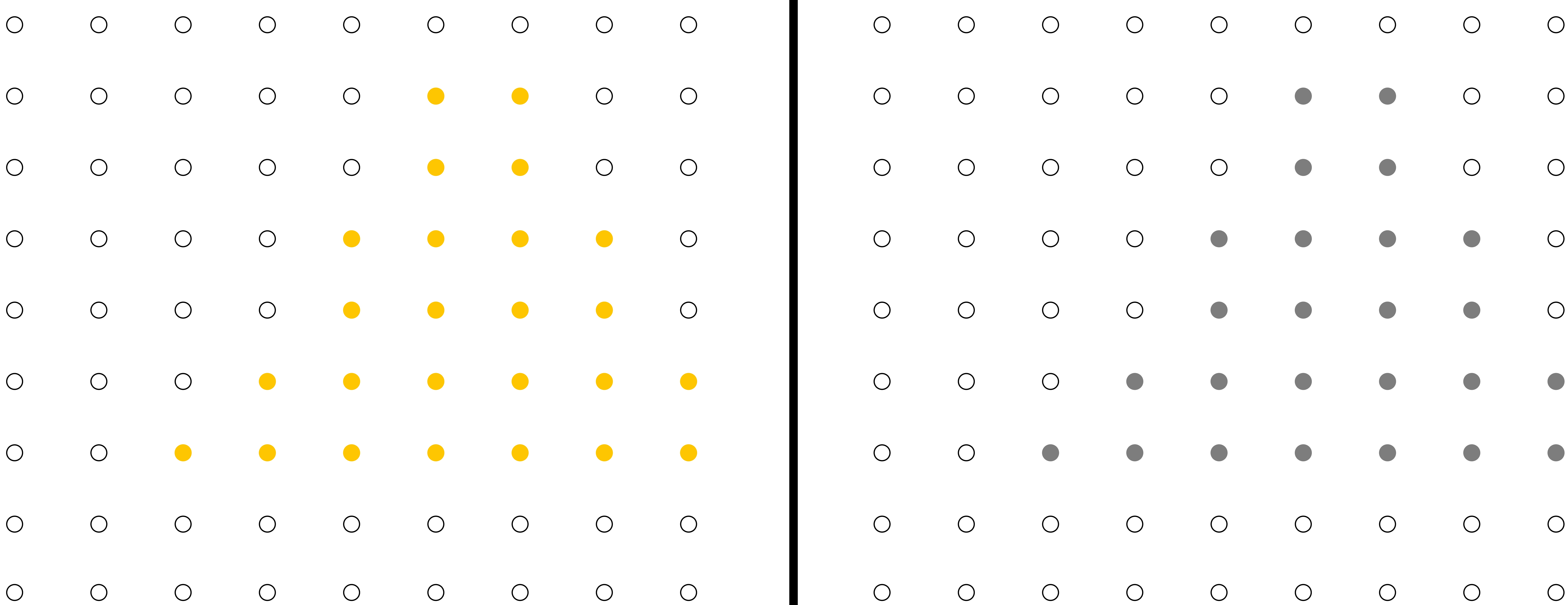
After processing yellow triangle:

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:

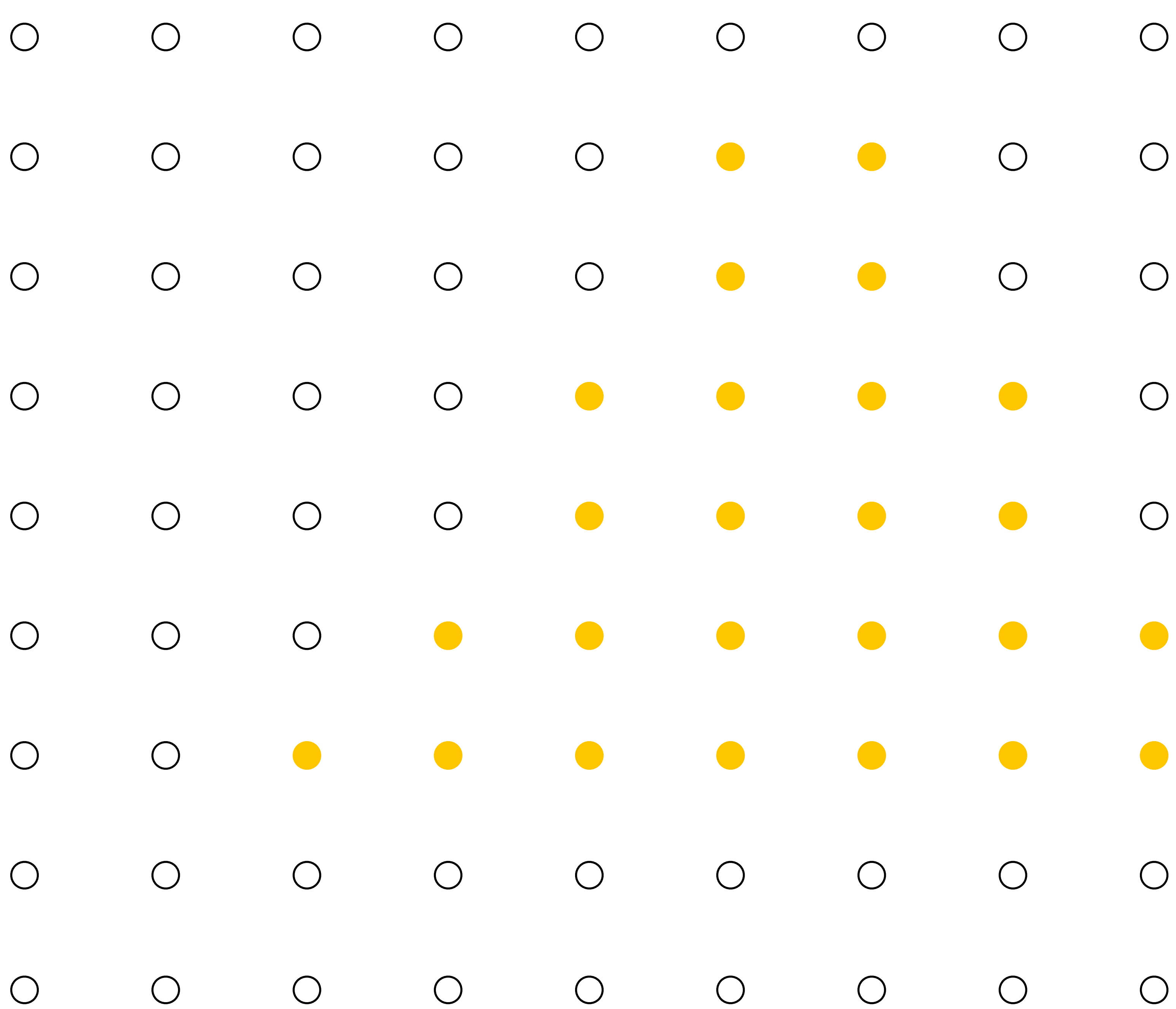
depth = 0.75

Grayscale value of sample point used to indicate distance

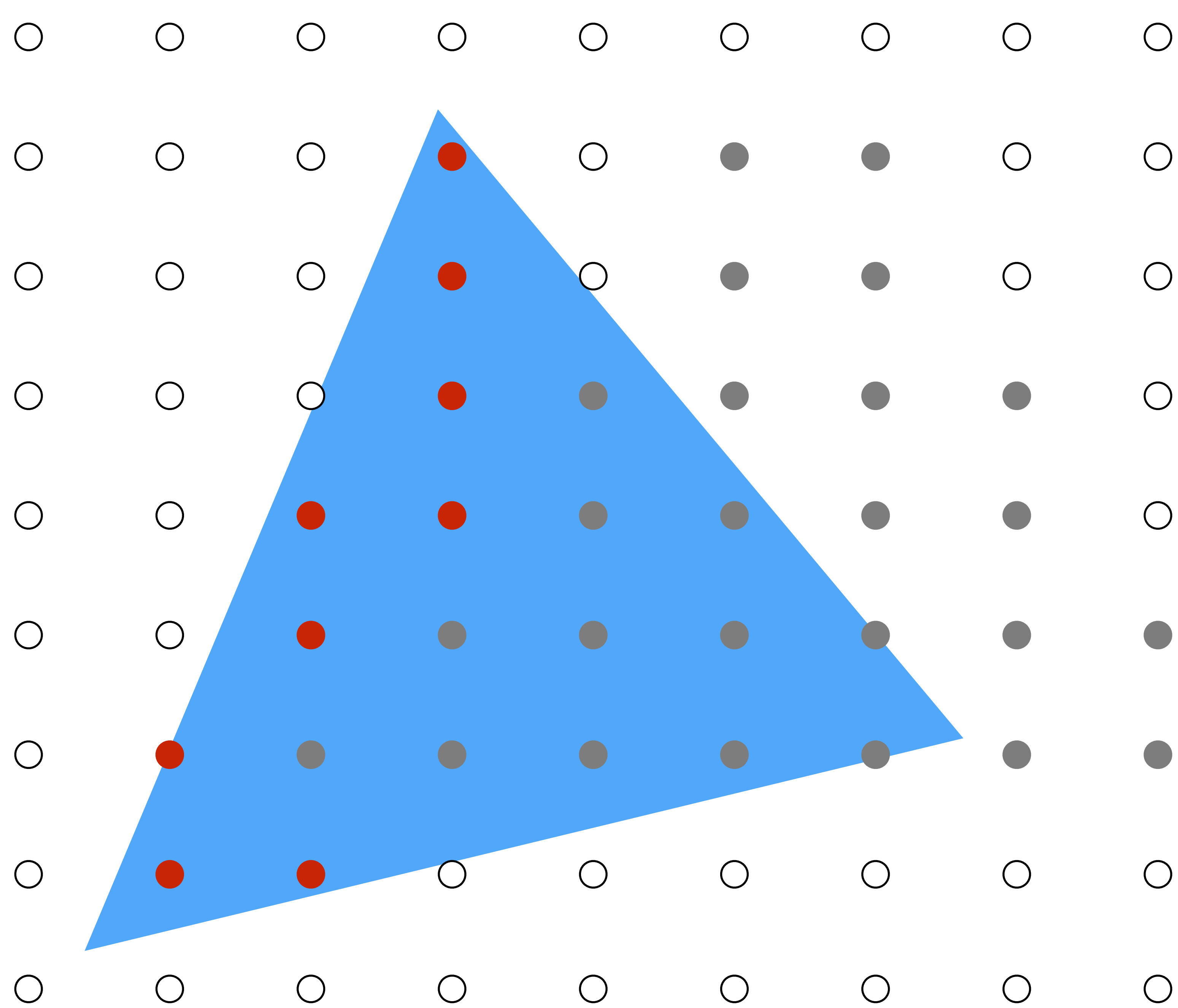
White = large distance

Black = small distance

Red = sample passed depth test



Color buffer contents



Depth buffer contents

Occlusion using the depth-buffer (Z-buffer)

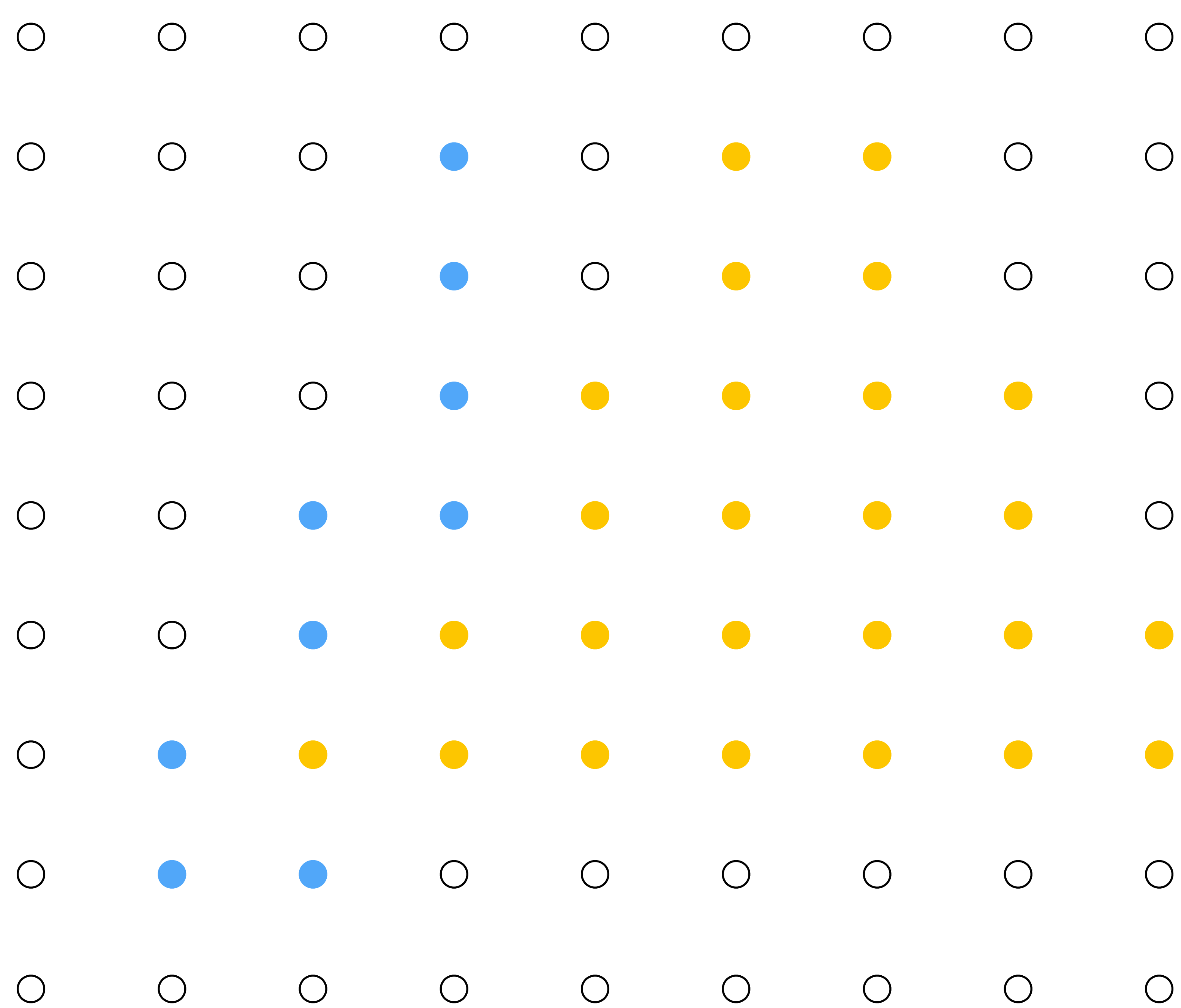
After processing blue triangle:

Grayscale value of sample point used to indicate distance

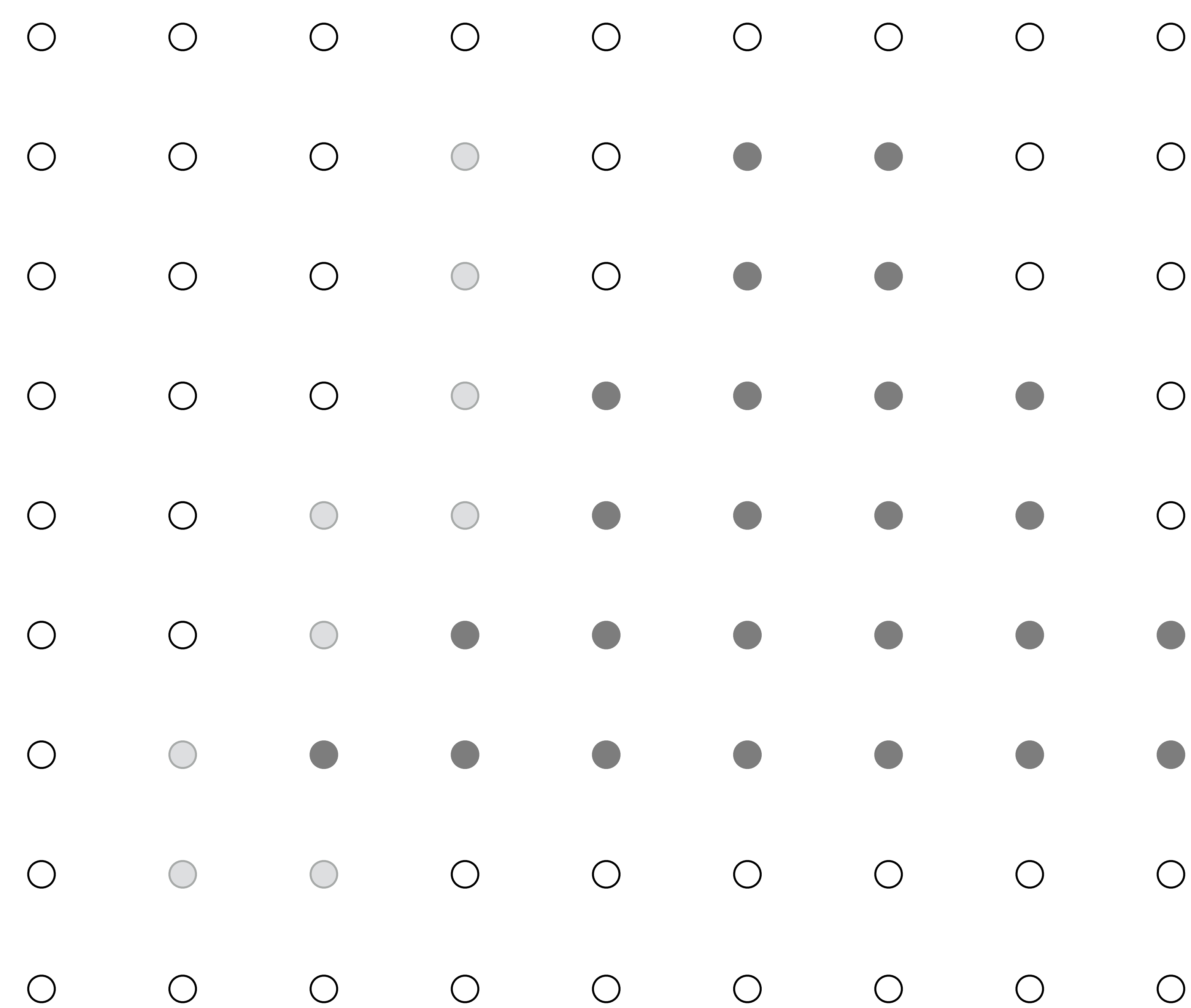
White = large distance

Black = small distance

Red = sample passed depth test



Color buffer contents

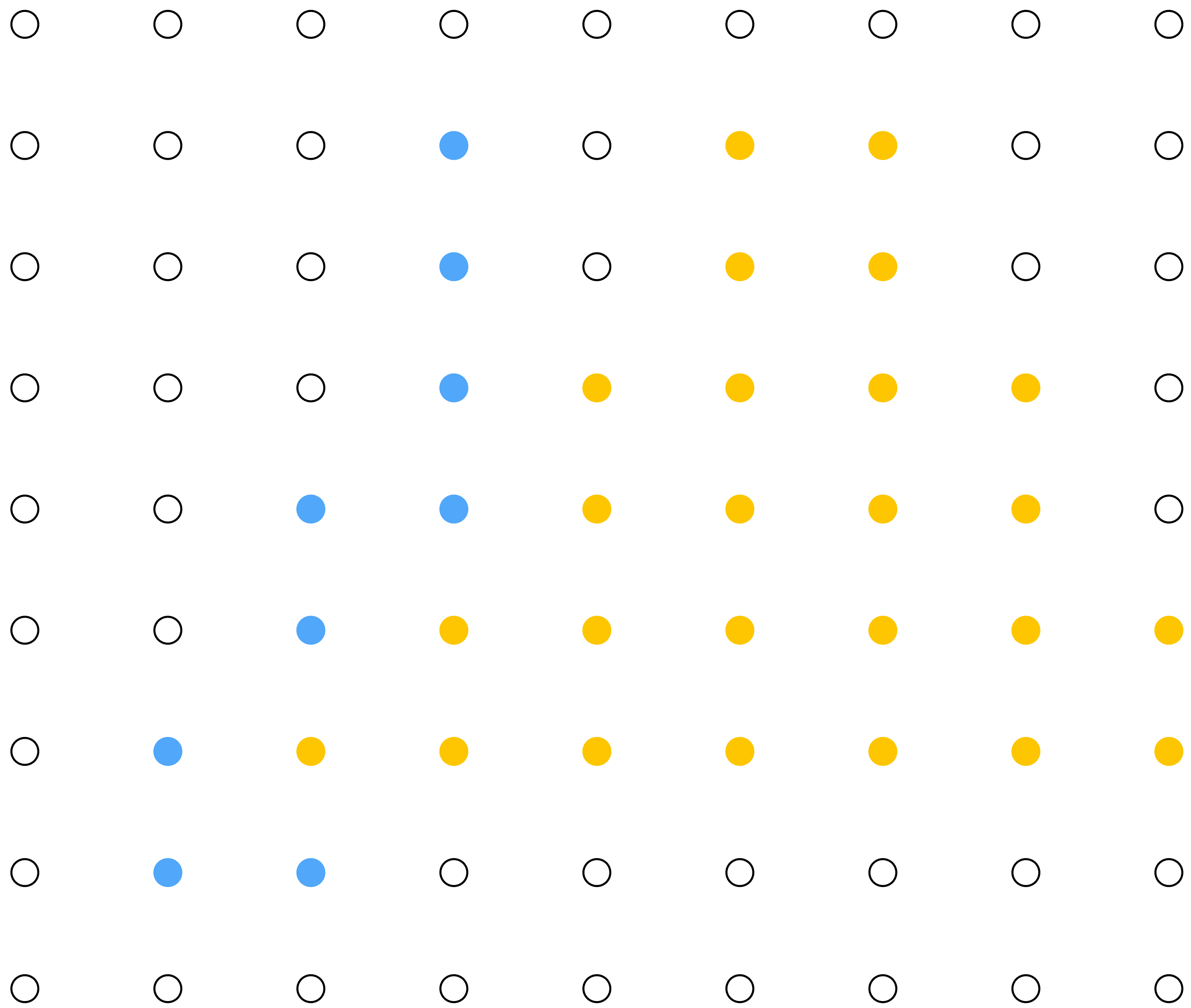


Depth buffer contents

Occlusion using the depth-buffer (Z-buffer)

Processing red triangle:

depth = 0.25



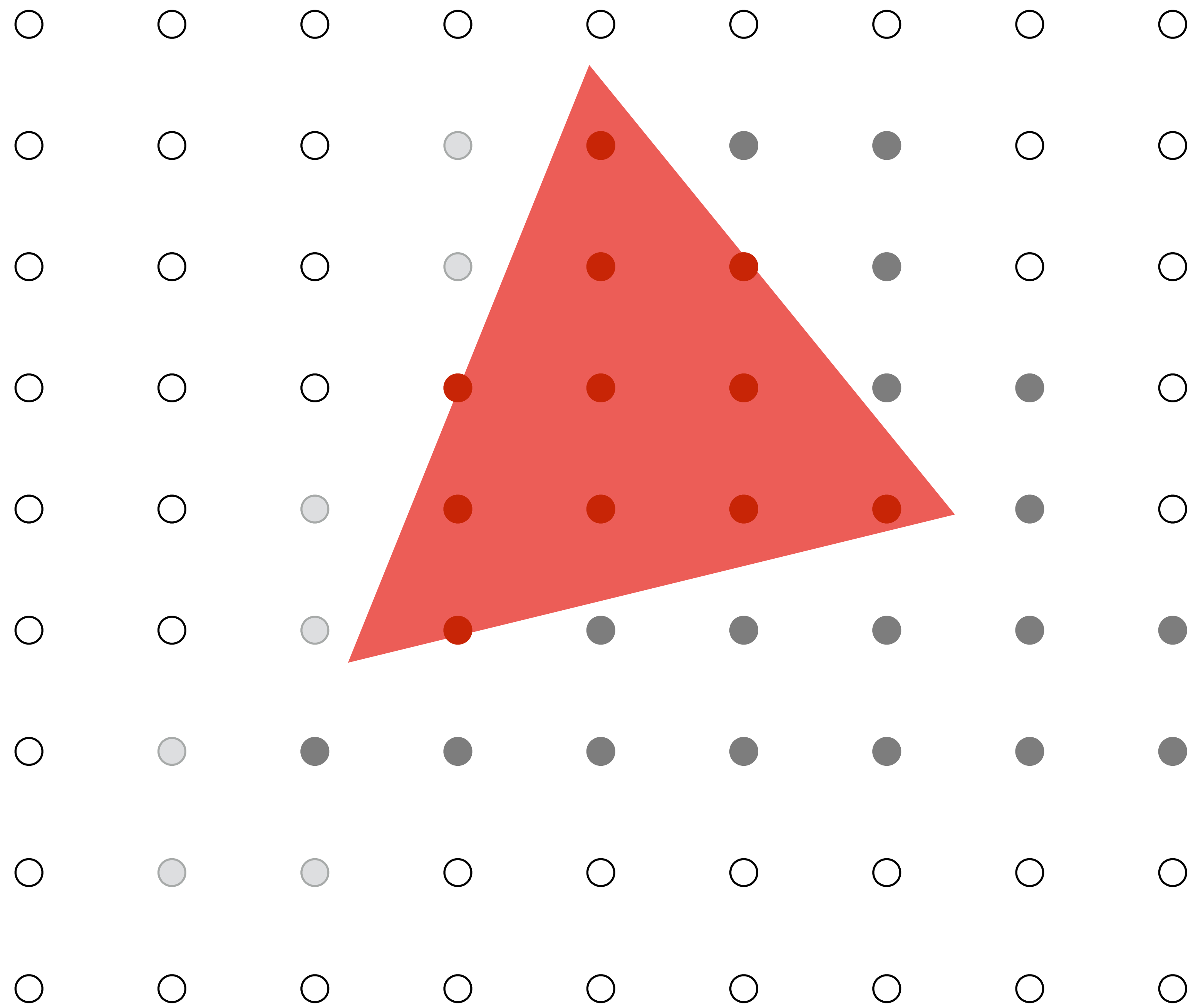
Color buffer contents

Grayscale value of sample point used to indicate distance

White = large distance

Black = small distance

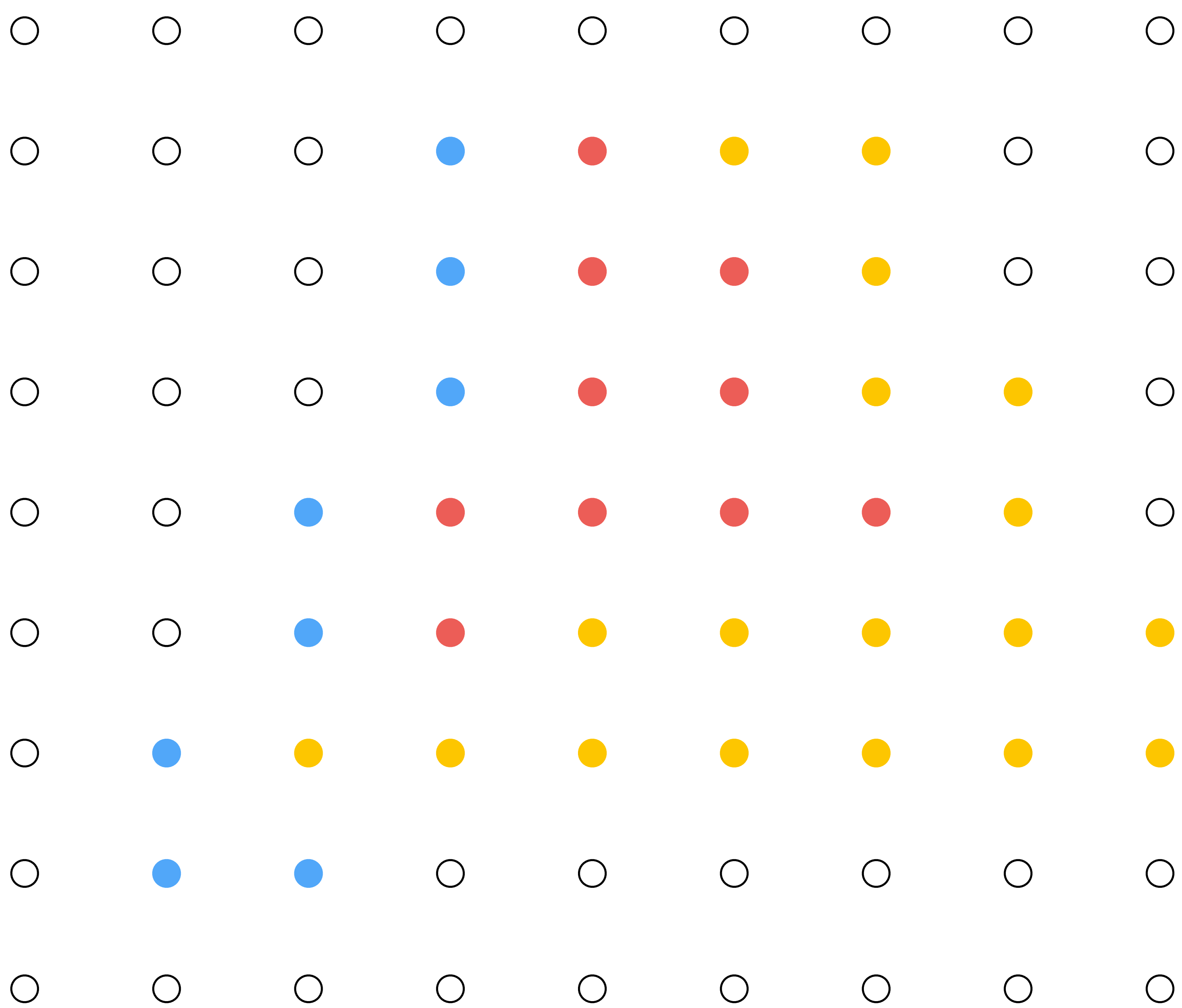
Red = sample passed depth test



Depth buffer contents

Occlusion using the depth-buffer (Z-buffer)

After processing red triangle:



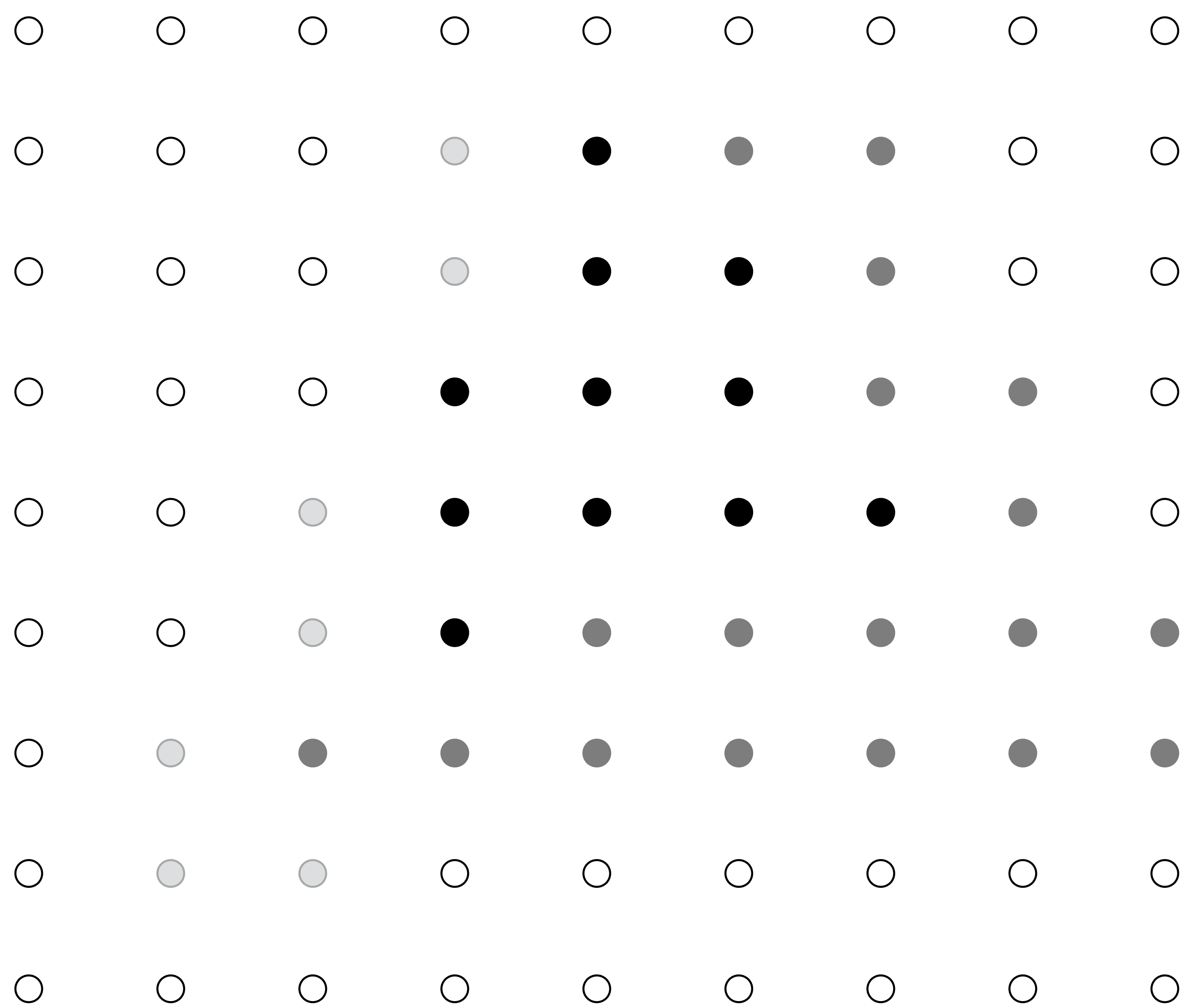
Color buffer contents

Grayscale value of sample point used to indicate distance

White = large distance

Black = small distance

Red = sample passed depth test



Depth buffer contents

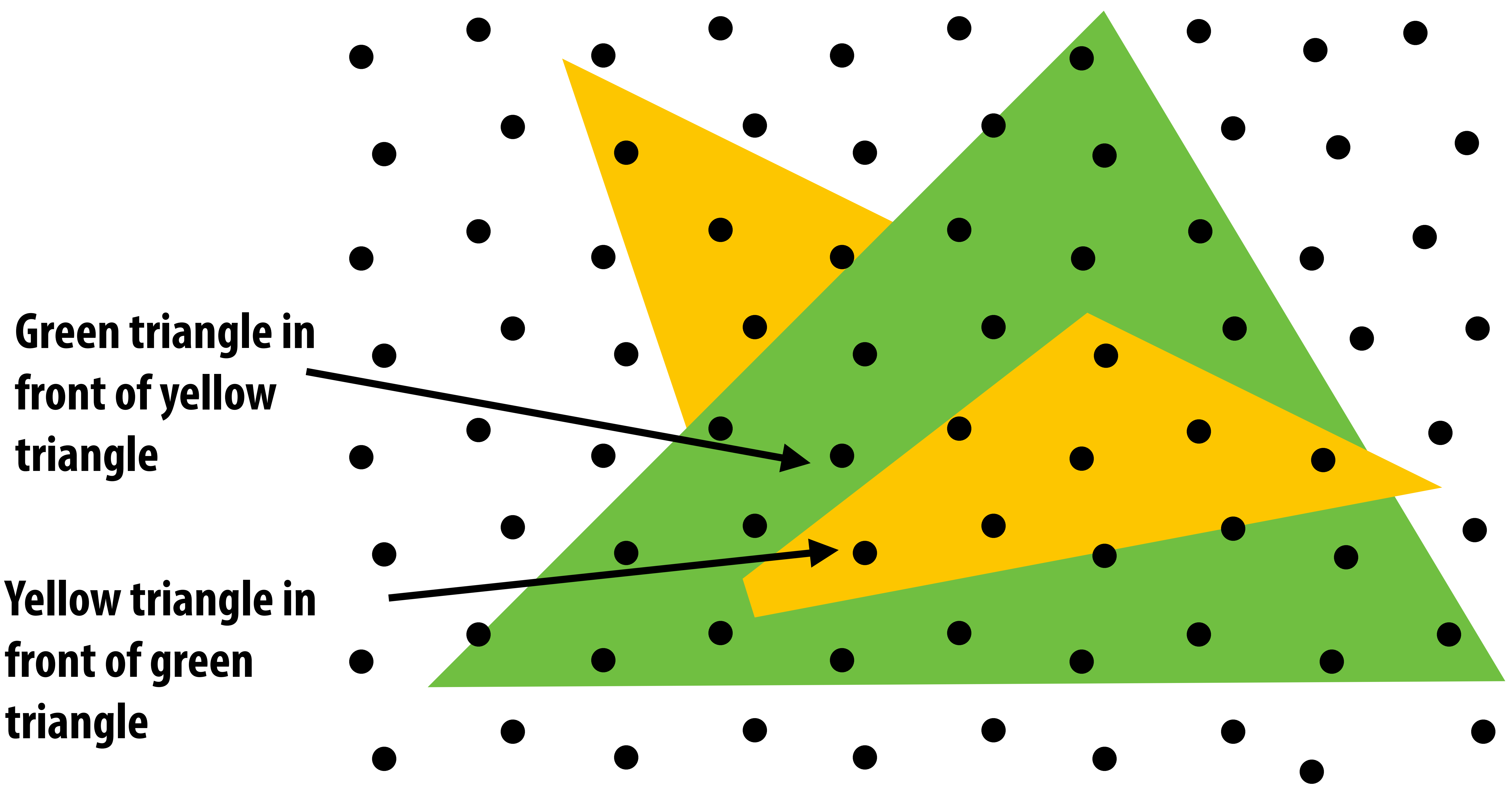
Occlusion using the depth buffer

```
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!

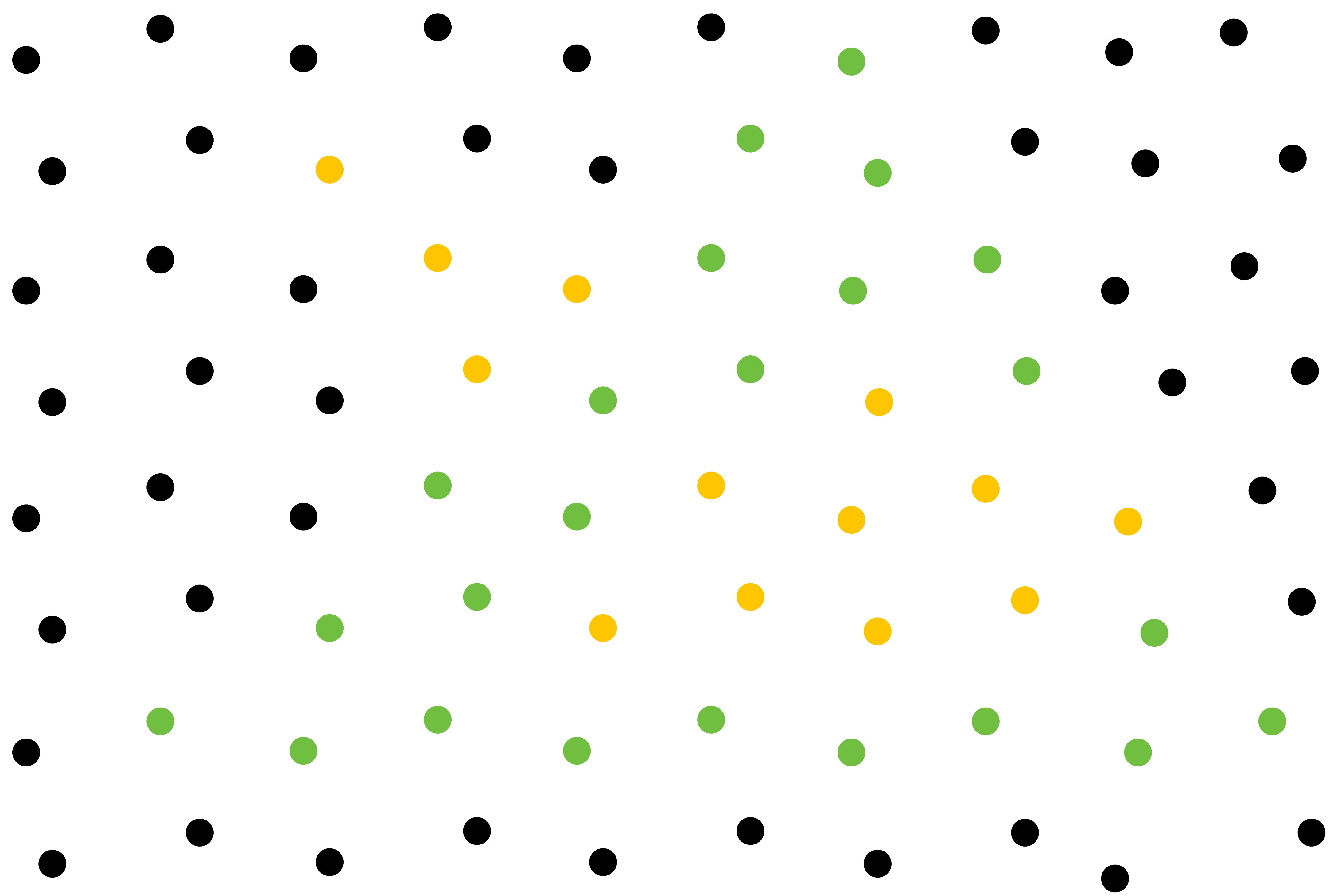
Occlusion test is based on depth of triangles at a given sample point. The relative depth of triangles may be different at different sample points.



Does depth-buffer algorithm handle interpenetrating surfaces?

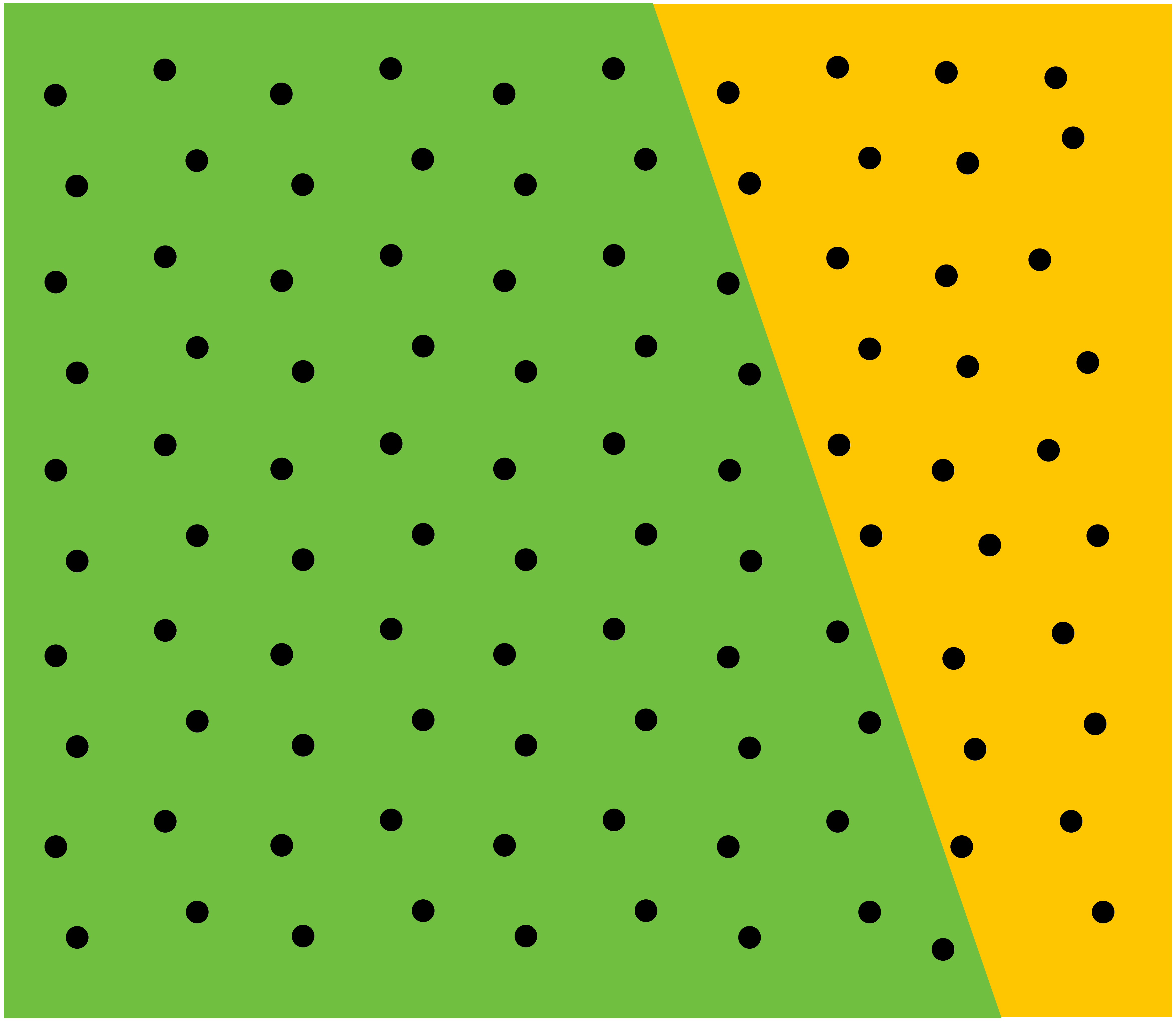
Of course!

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.



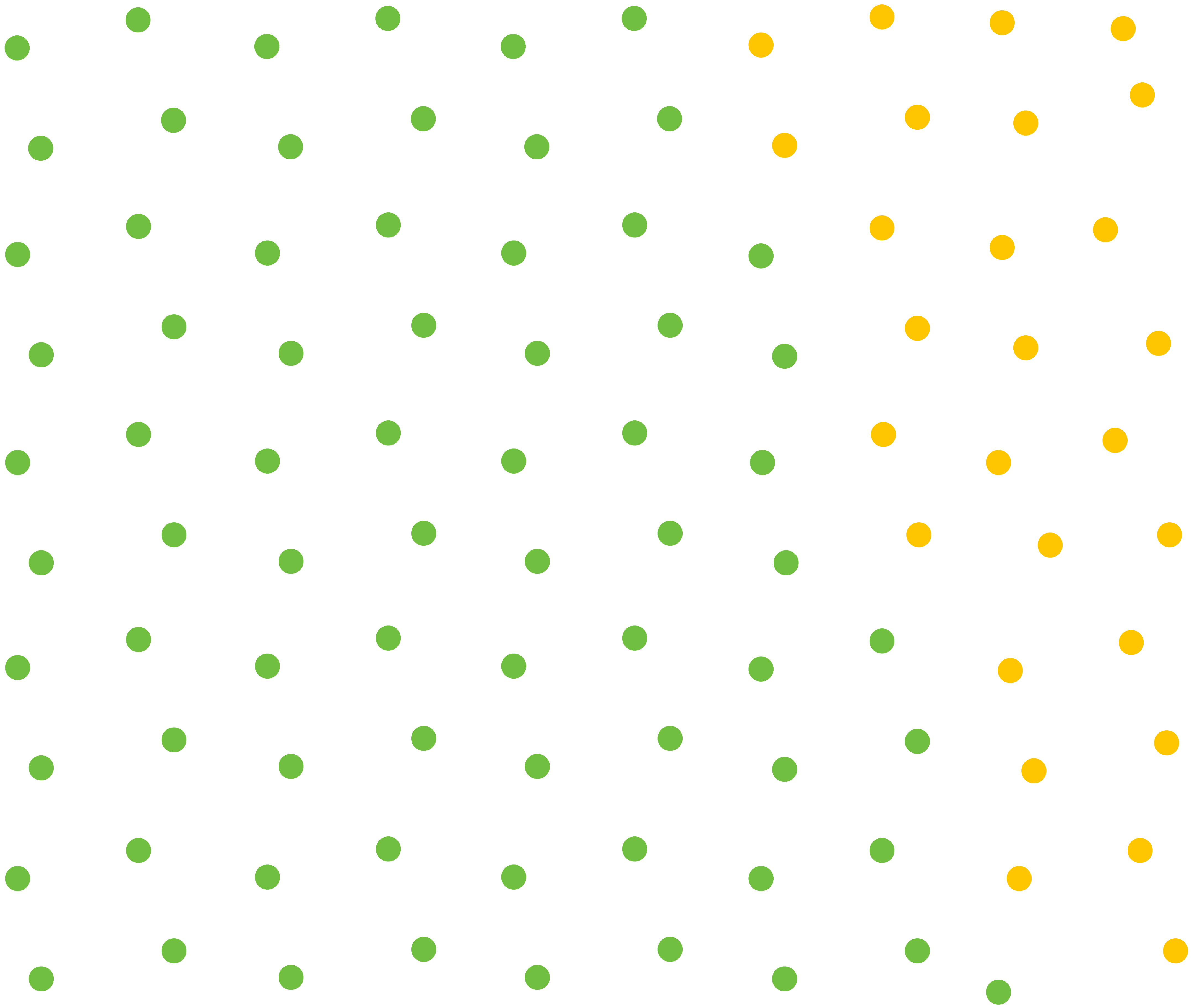
Does depth buffer work with super sampling?

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

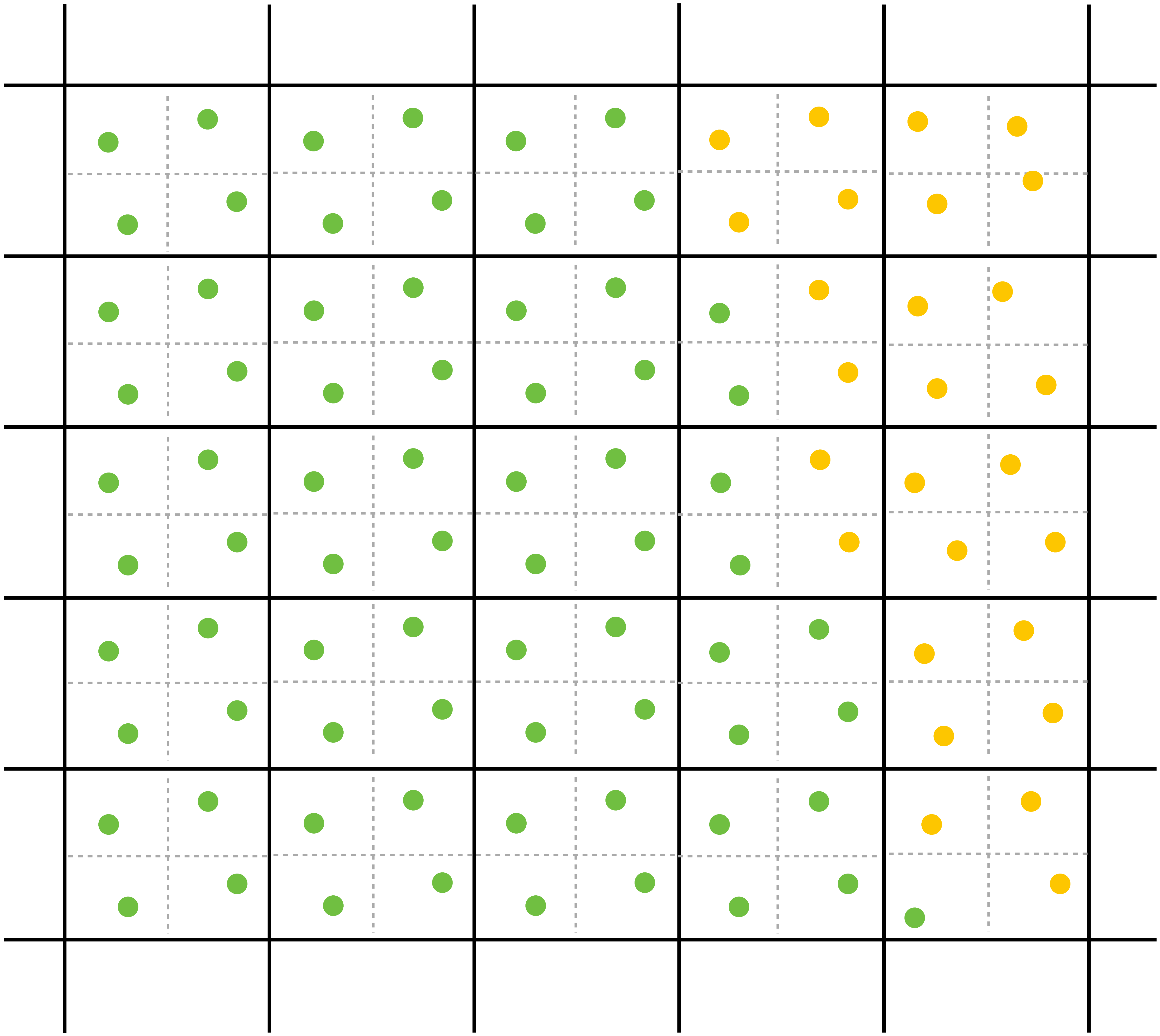


This example: green triangle occludes yellow triangle

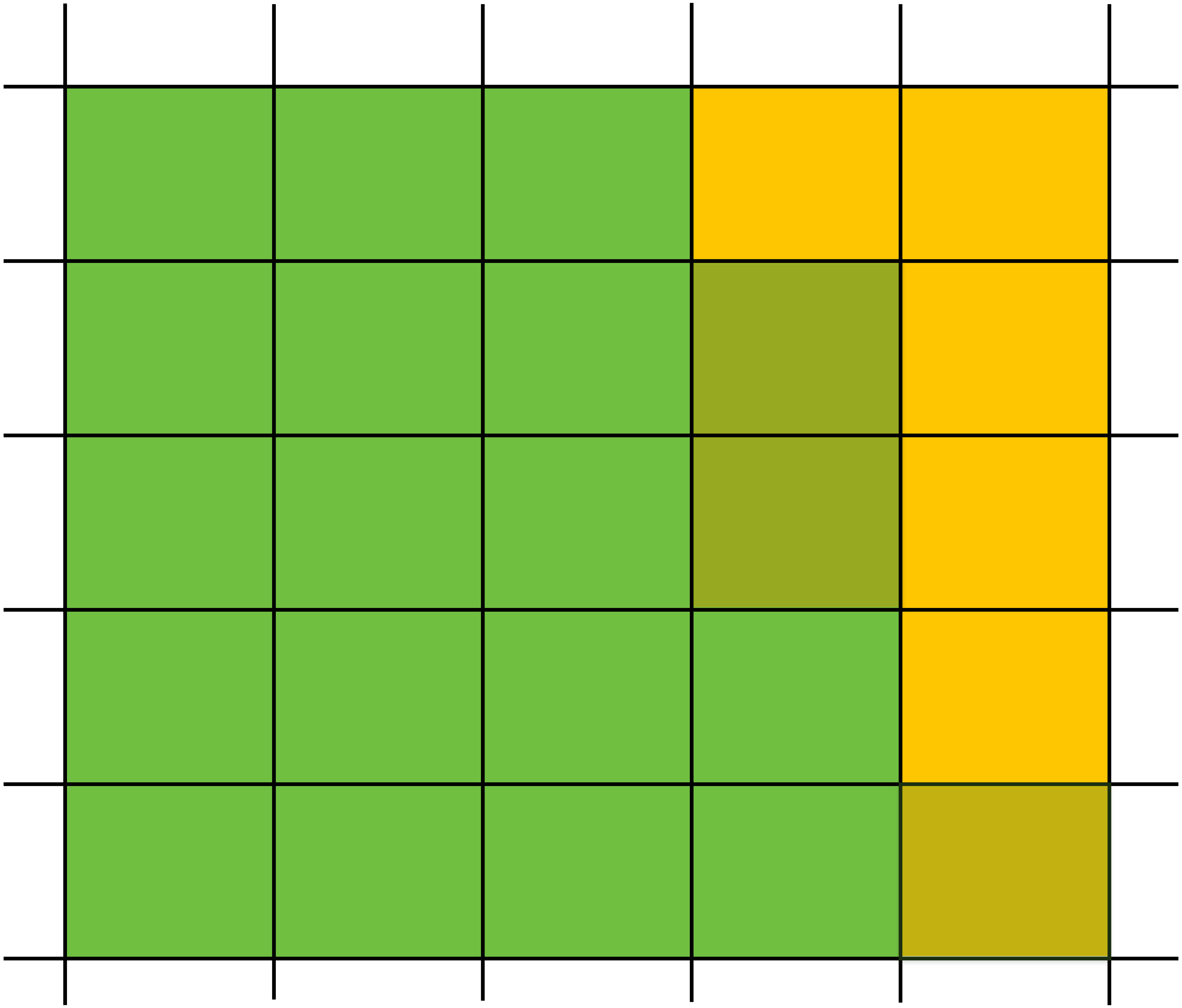
Color buffer contents



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?

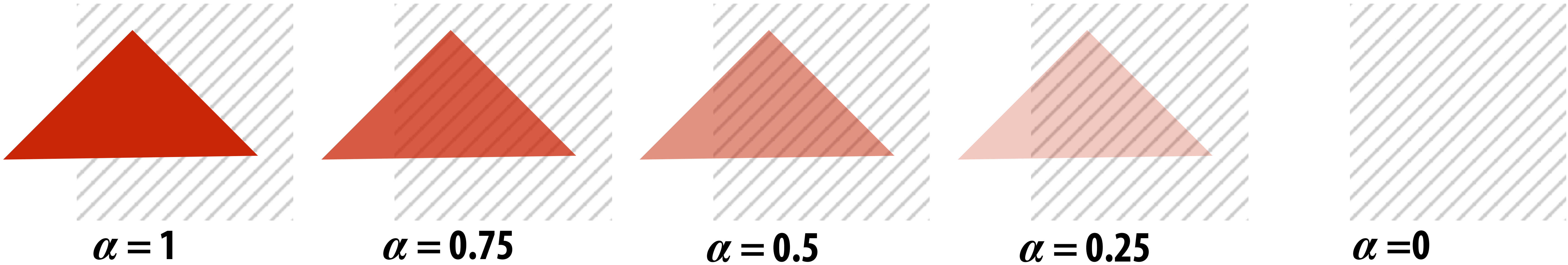
Compositing

Representing opacity as alpha

Alpha describes the opacity of an object

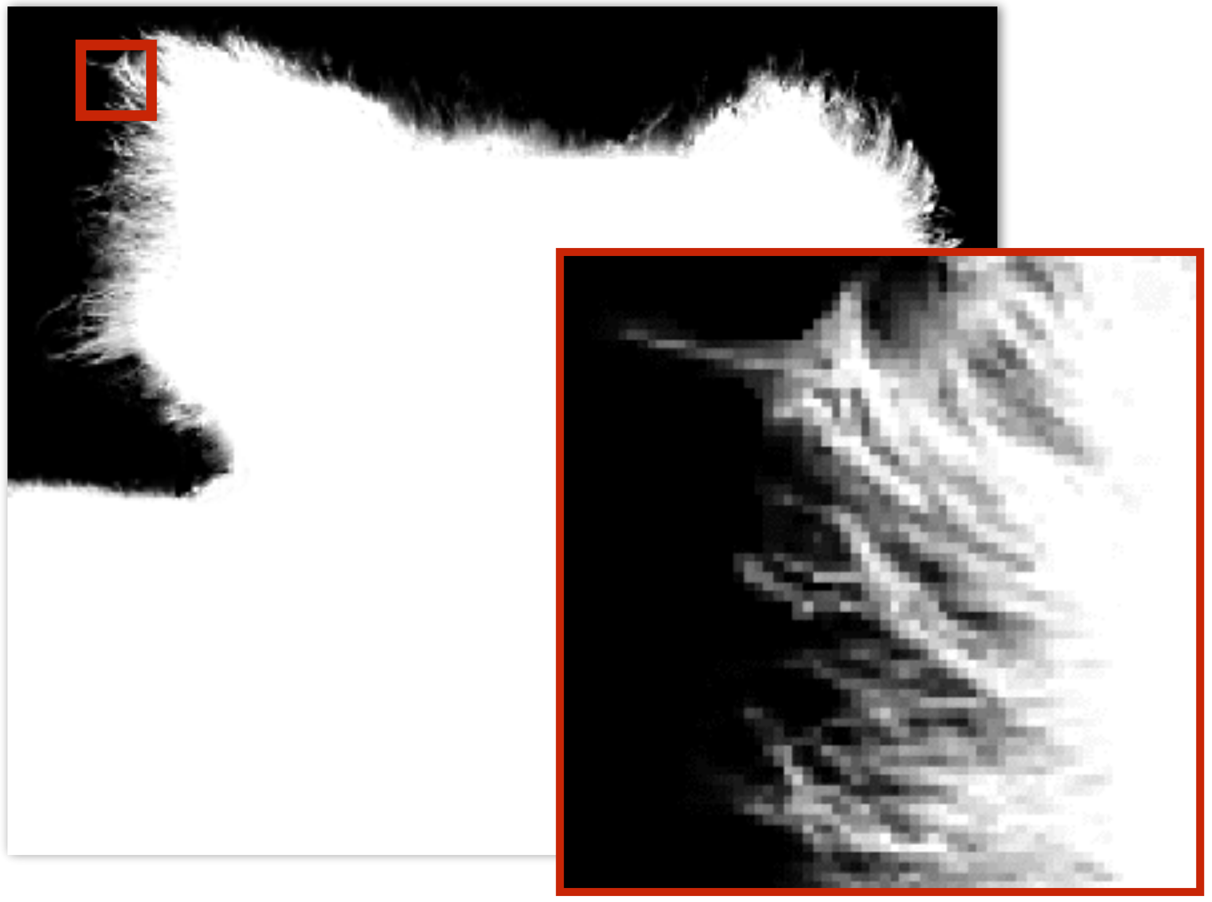
- **Fully opaque surface:** $\alpha = 1$
- **50% transparent surface:** $\alpha = 0.5$
- **Fully transparent surface:** $\alpha = 0$

Red triangle with decreasing opacity



Alpha: additional channel of image (rgba)

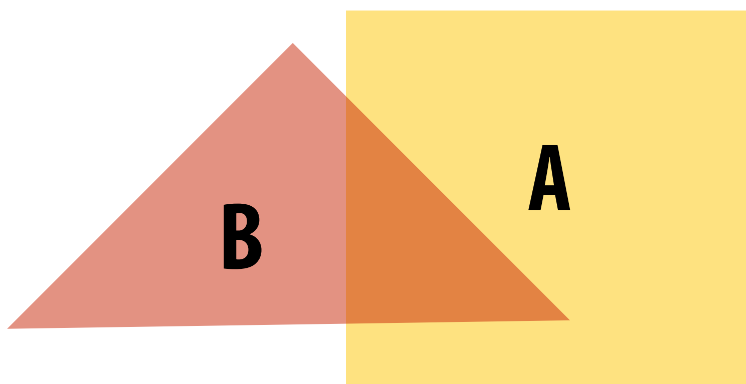


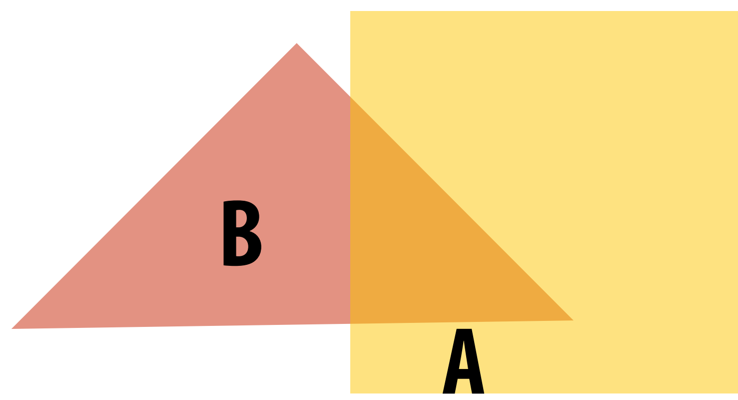
α of foreground object

Over operator:

Composite image B with opacity α_B <u>over</u> image A with opacity α_A



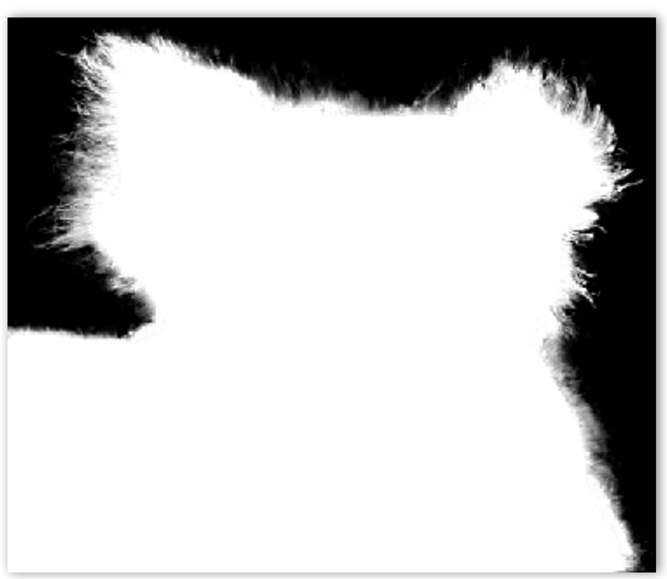
B over A

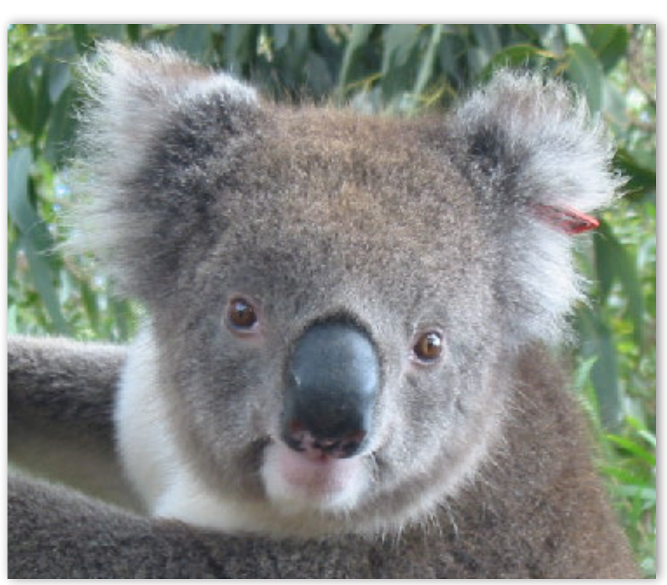


A over B

A over B != B over A

"Over" is not commutative



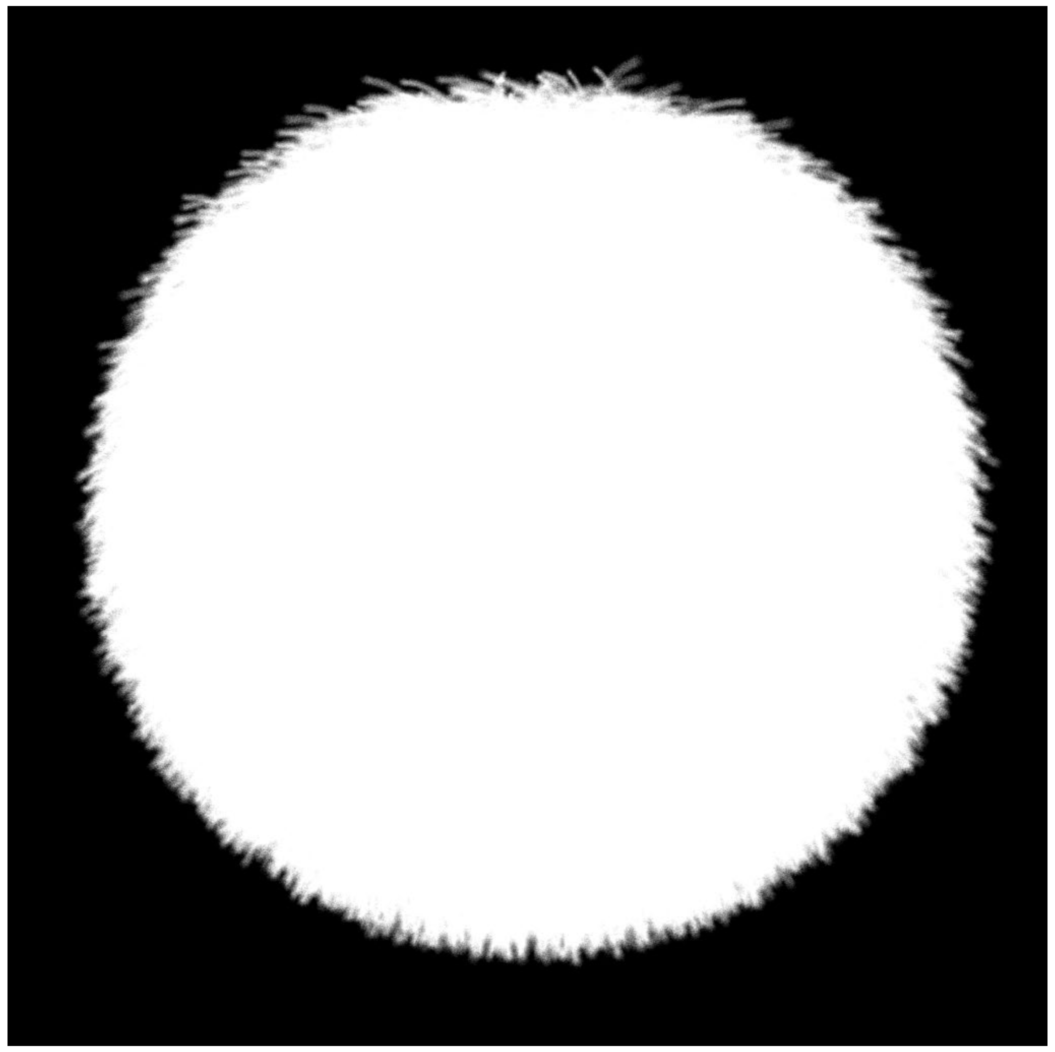


Koala over NYC

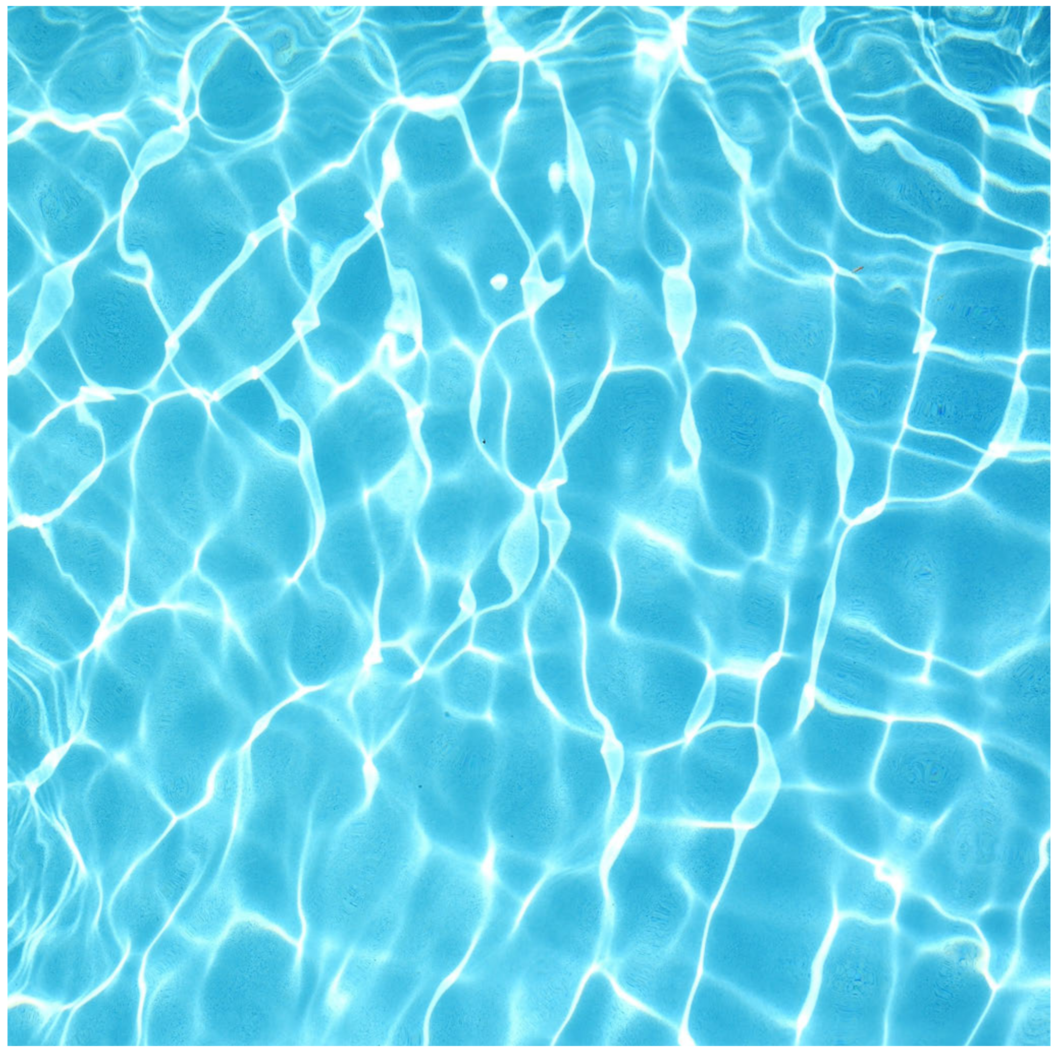
Fringing

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

foreground color



foreground alpha



background color

fringing

no fringing

No fringing

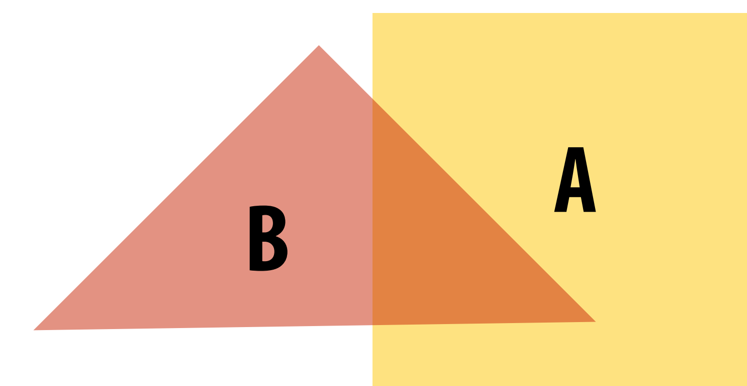
Fringing (…why does this happen?)

Over operator: non-premultiplied alpha

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

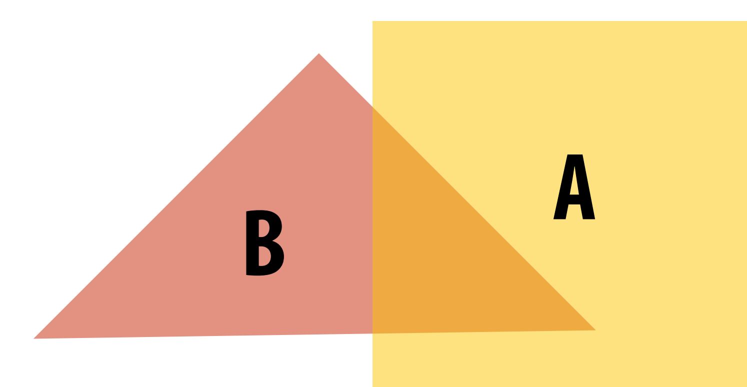
Composited color:

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

Over operator: premultiplied alpha

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

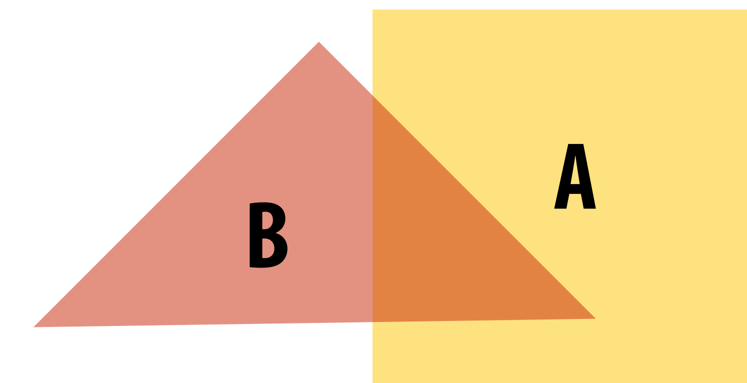
Non-premultiplied alpha:

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

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

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

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:

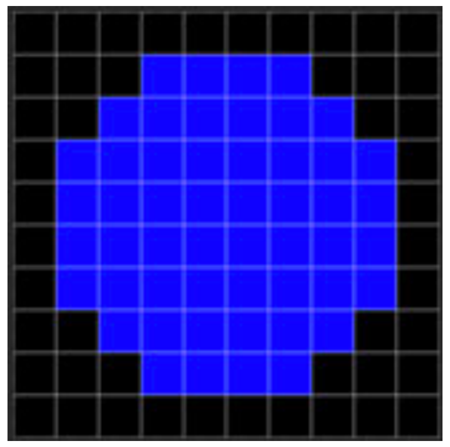
$$\alpha_C = \alpha_B + (1 - \alpha_B)\alpha_A$$

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

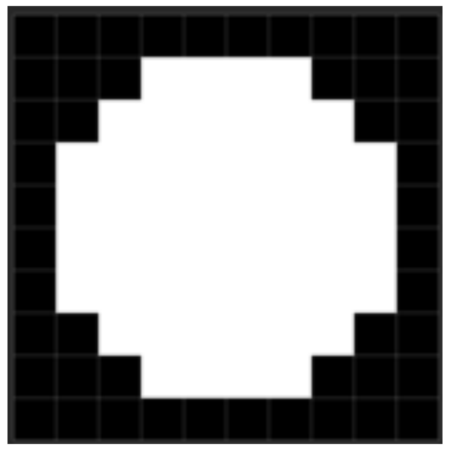
Non-premultiplied alpha composites alpha differently than rgb.

A problem with non-premultiplied alpha

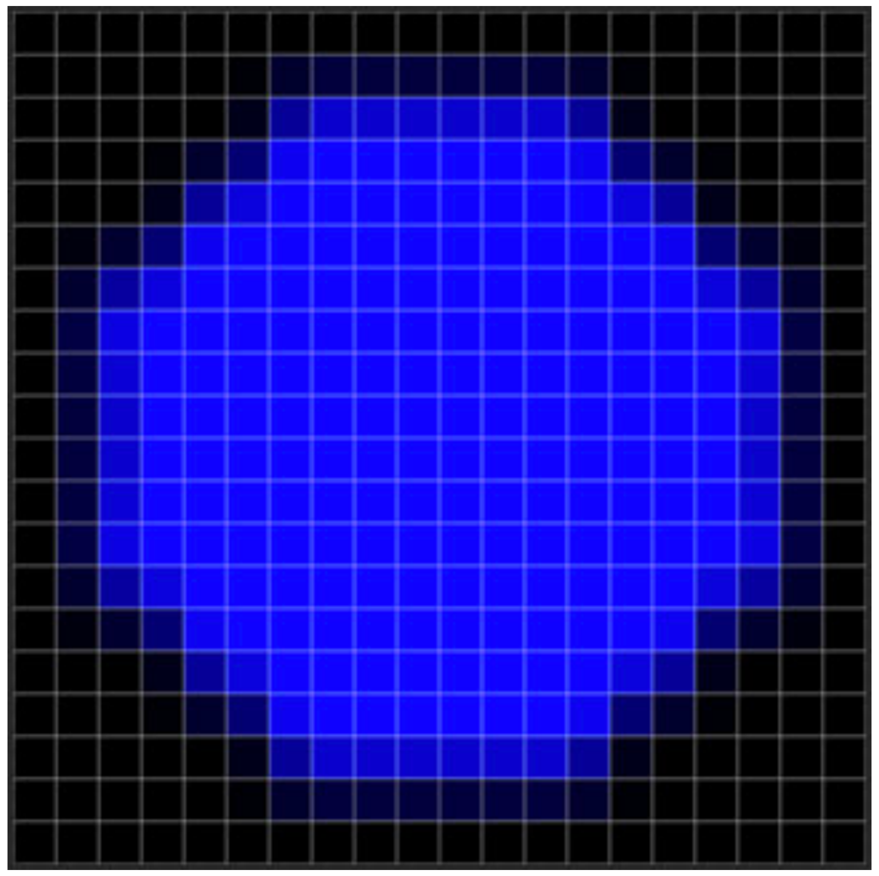
- Suppose we upsample an image w/ an alpha mask, then composite it onto a background
- How should we compute the interpolated color/alpha values?
- If we interpolate color and alpha separately, then blend using the non-premultiplied "over" operator, here's what happens:



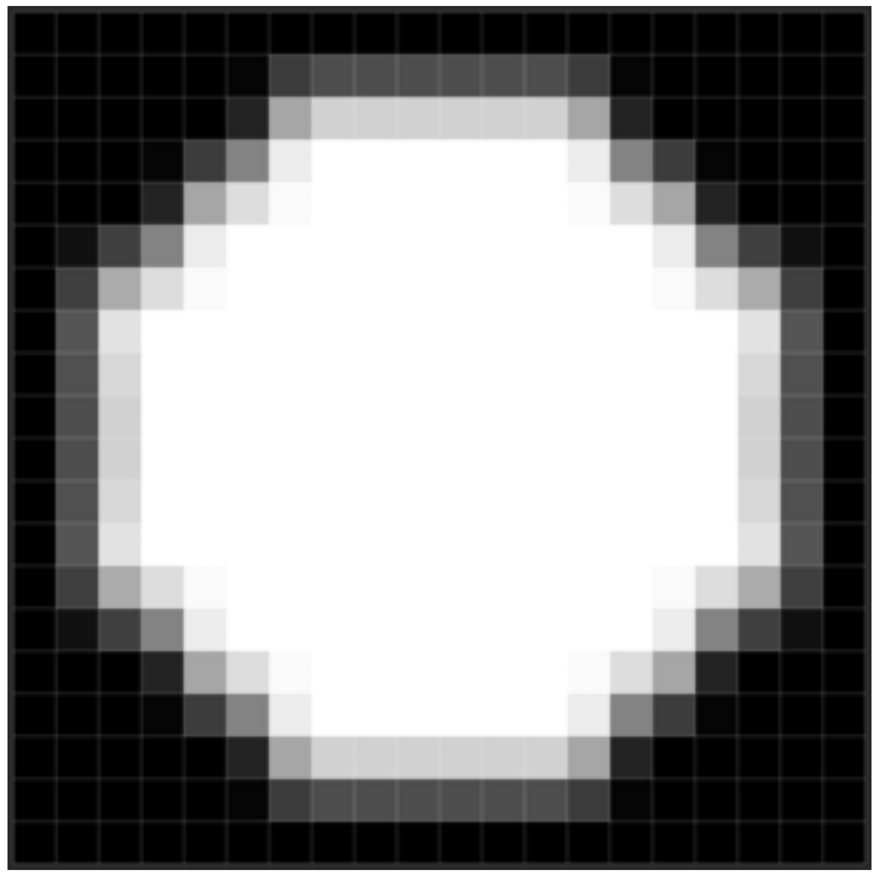
original color



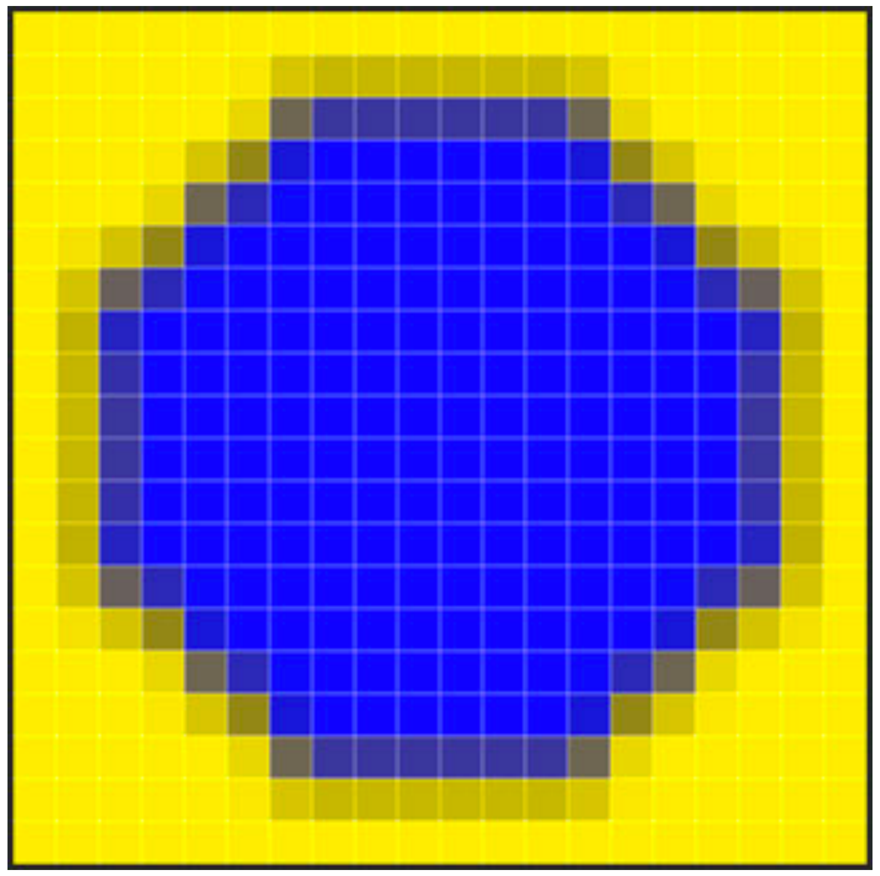
original alpha



upsampled color



upsampled alpha

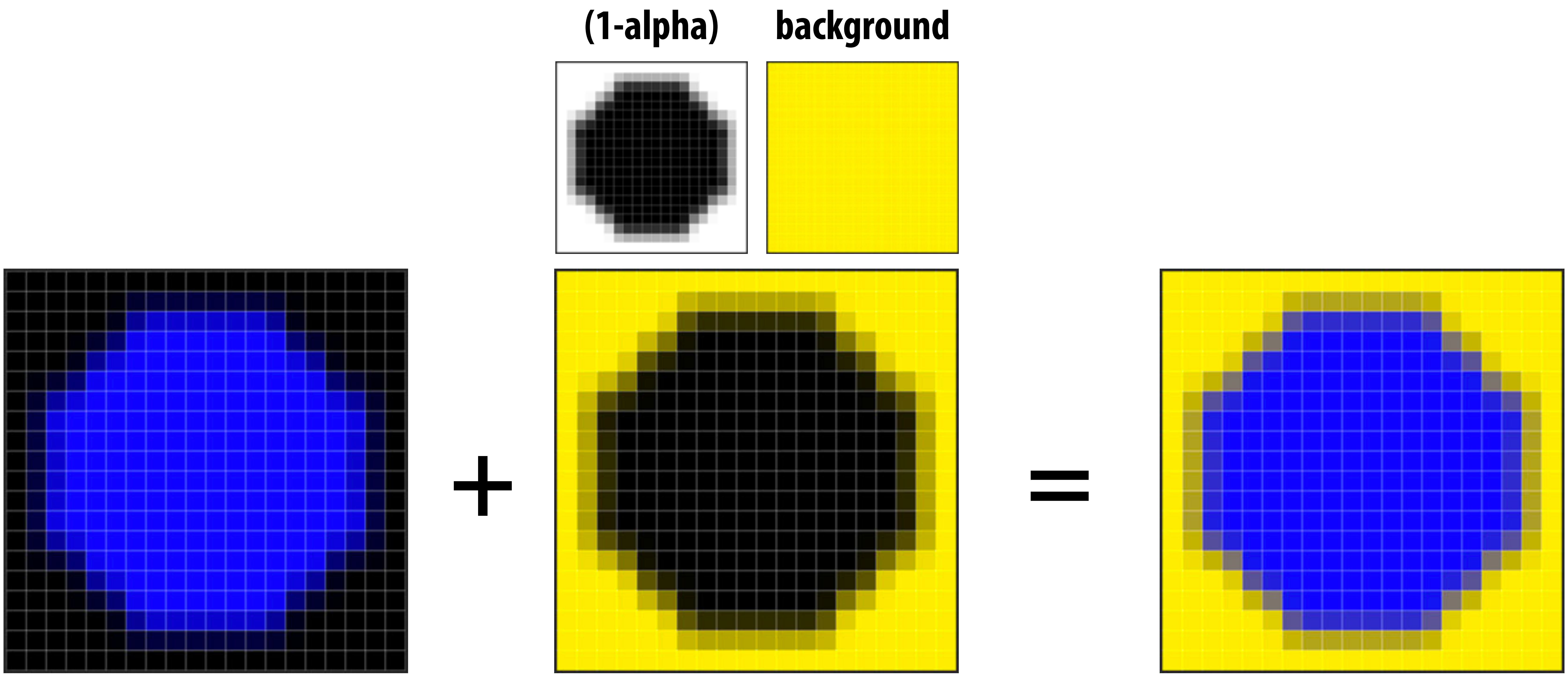


composited onto yellow background

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:



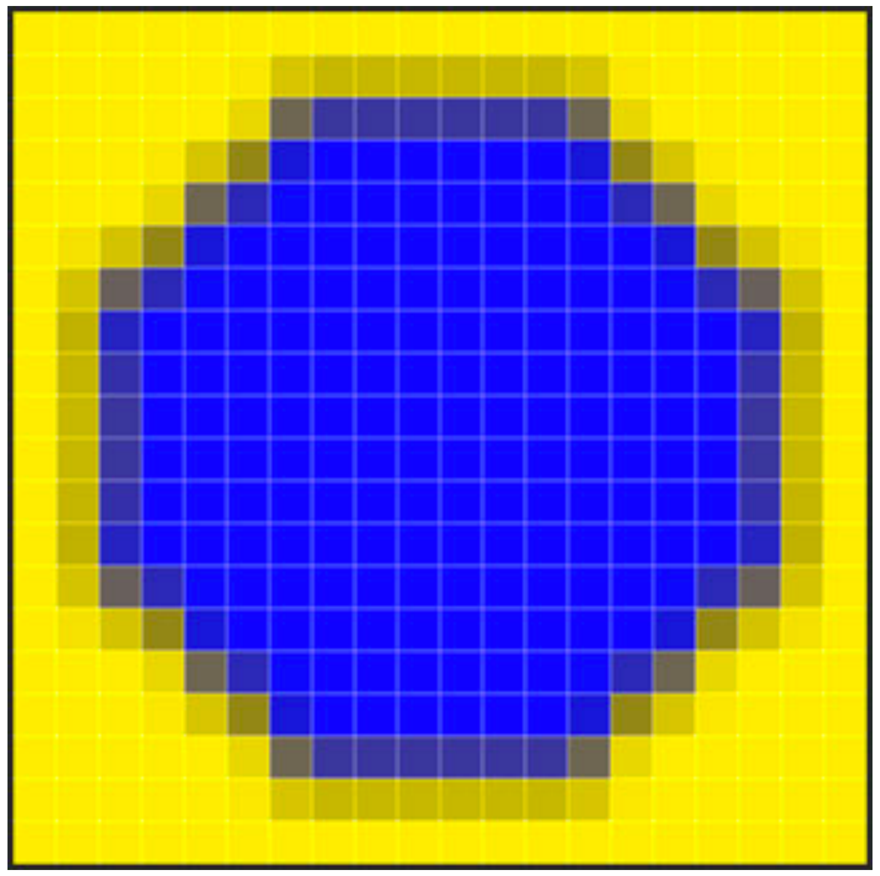
upsampled color

(1-alpha)*background

composite image
w/ no fringe

Eliminating fringe w/ premultiplied "over"

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

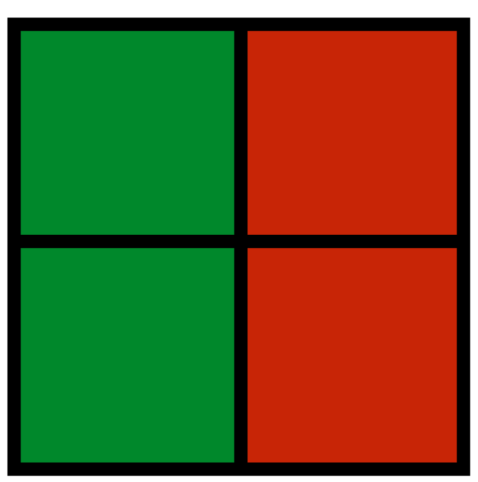


composite image
WITH fringe

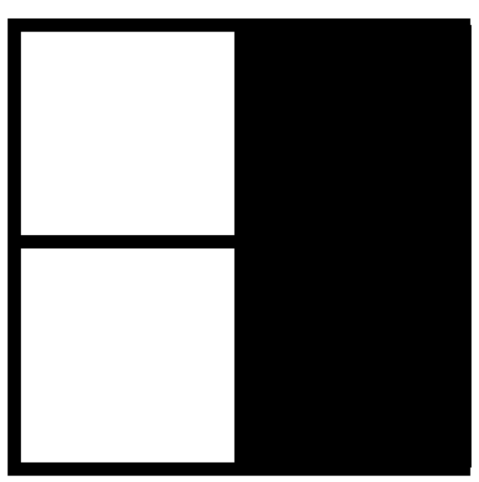
Similar problem with non-premultiplied alpha

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

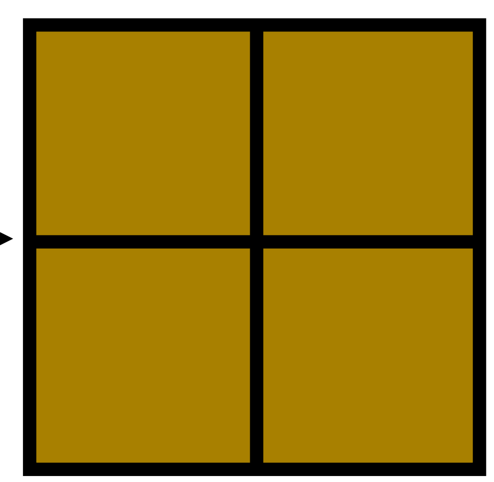
Desired filtered result



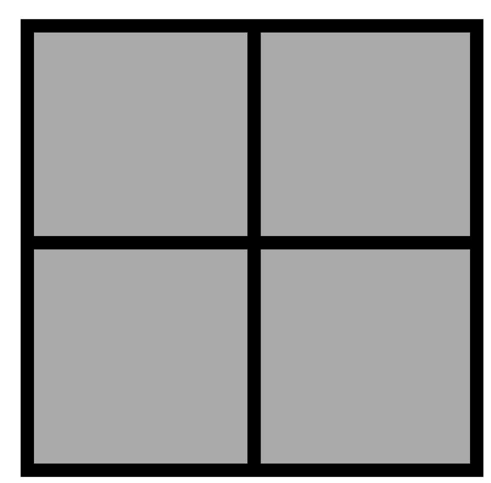
input color



input α

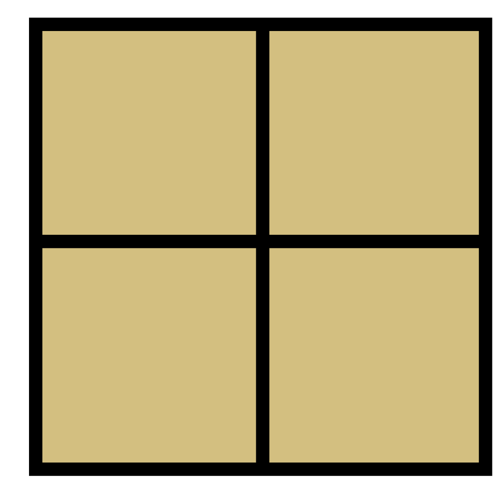


filtered color



filtered α

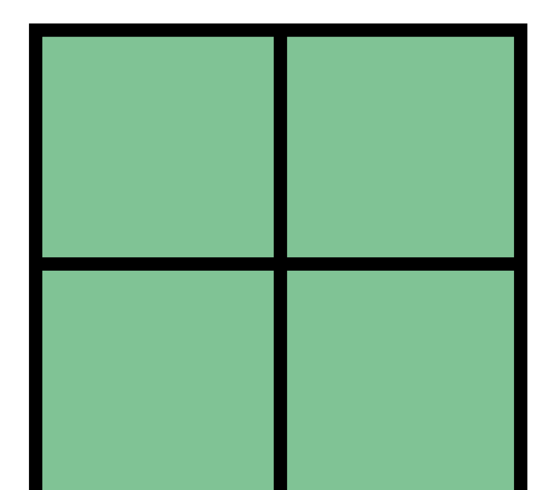
Downsampling non-premultiplied alpha image results in 50% opaque brown)



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

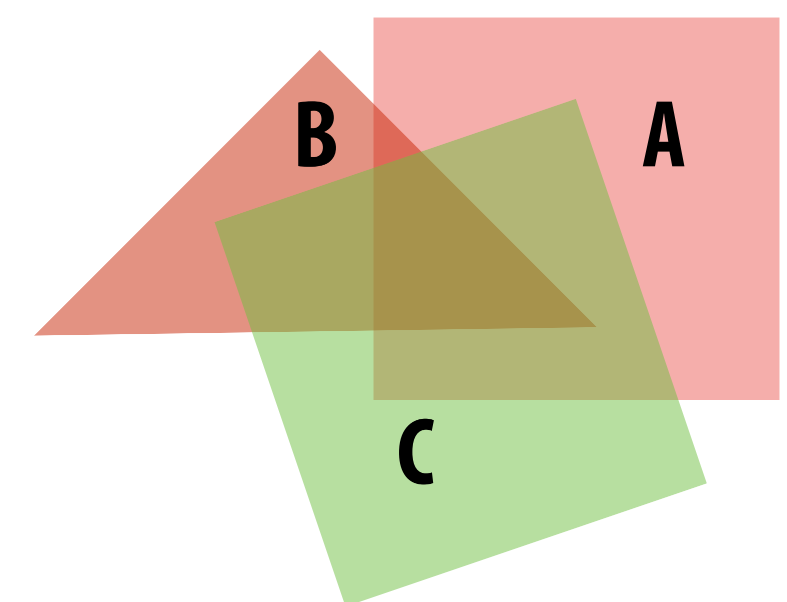
Non-premultiplied alpha is not closed under composition:

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

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

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

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



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 + (1-c1.a) * c2;
}

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(tri_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

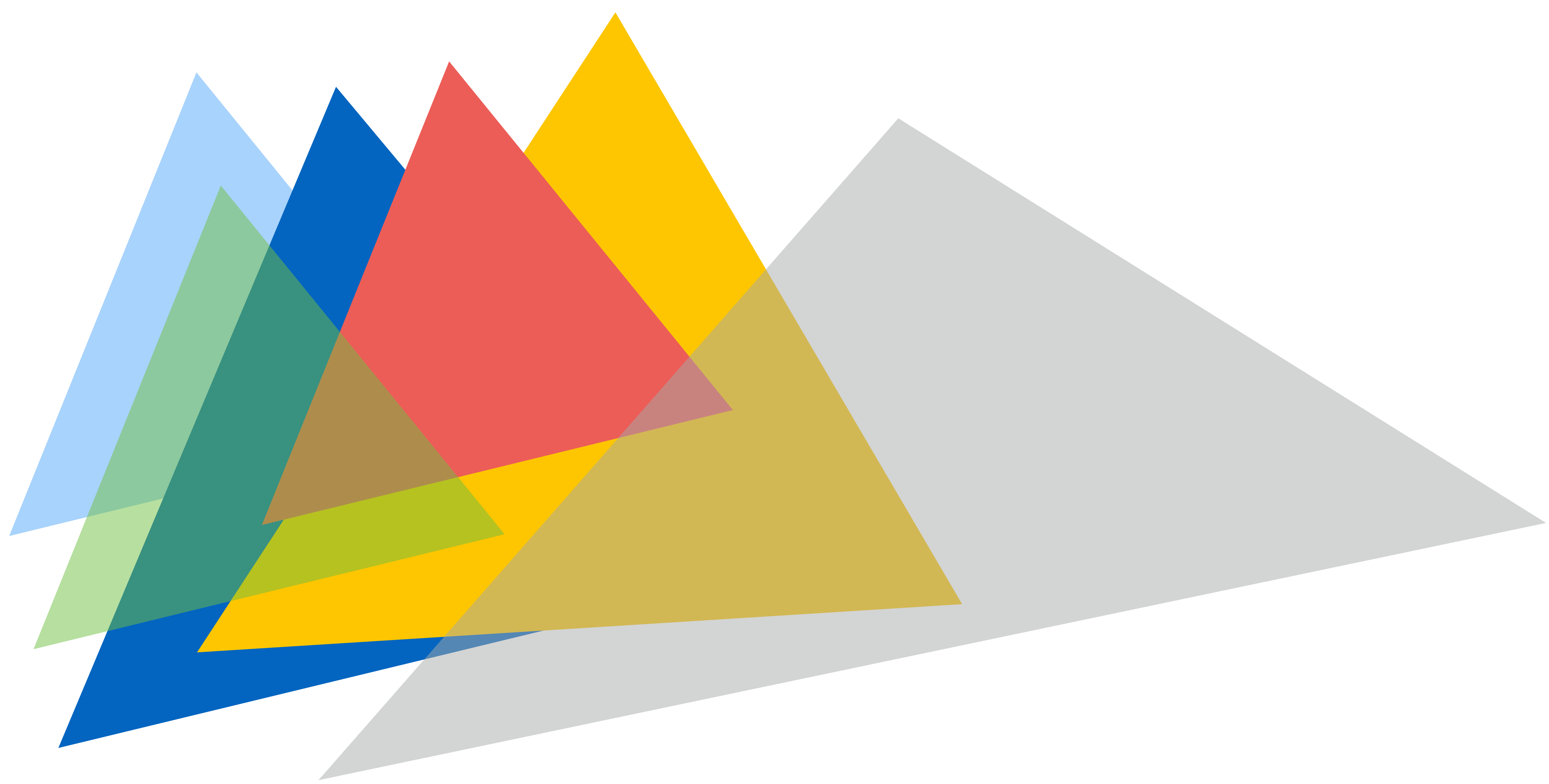
Now what if we have a mixture of opaque and transparent triangles?

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!

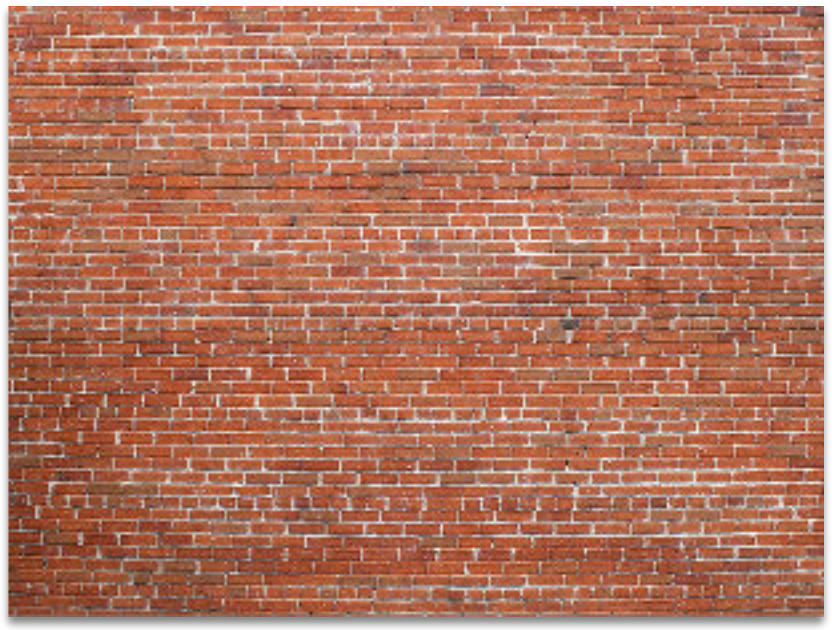
Inputs:

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: $\mathbf{T}$

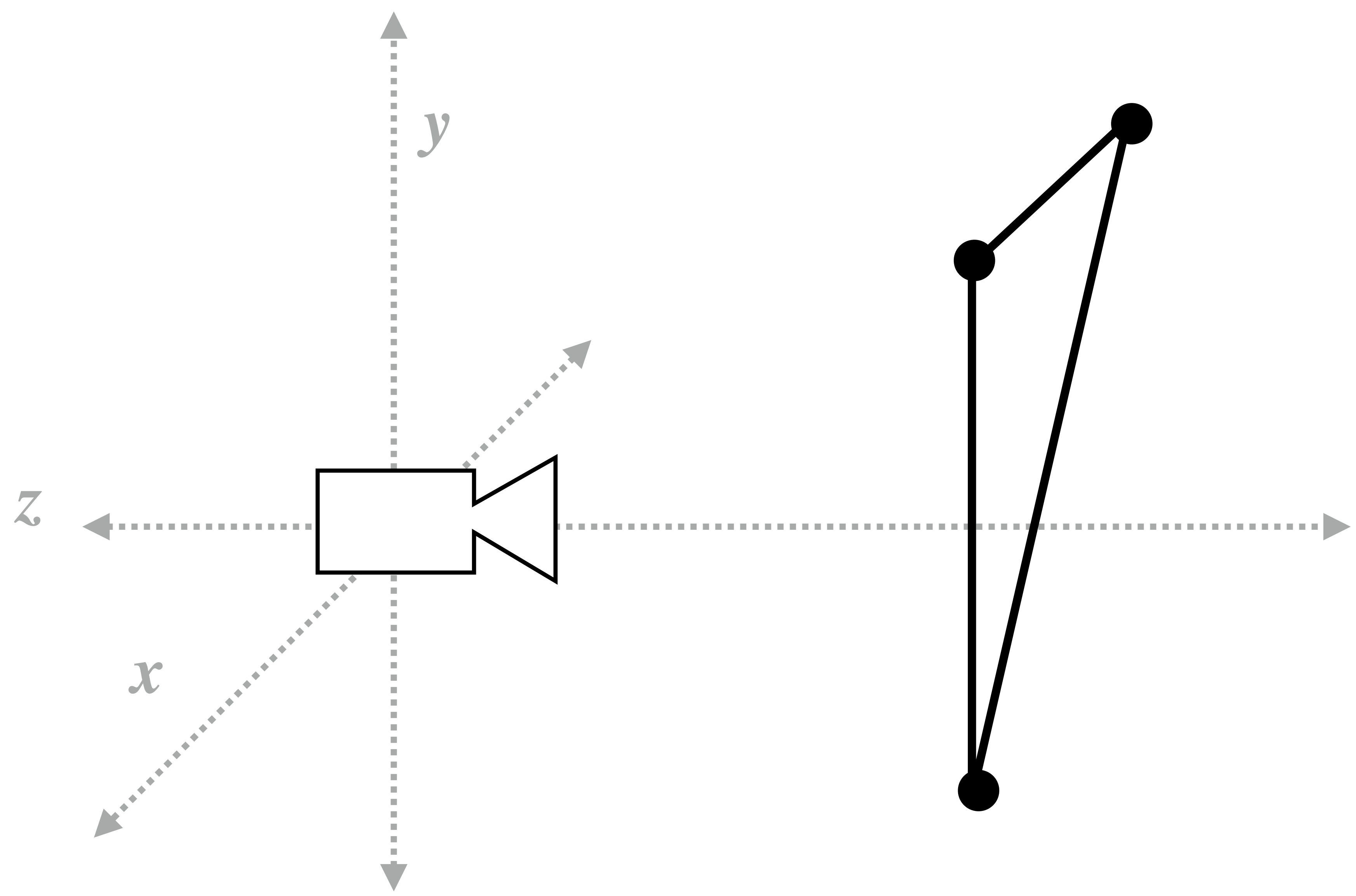
Perspective projection transform $\mathbf{P}$

Size of output image (W, H)

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

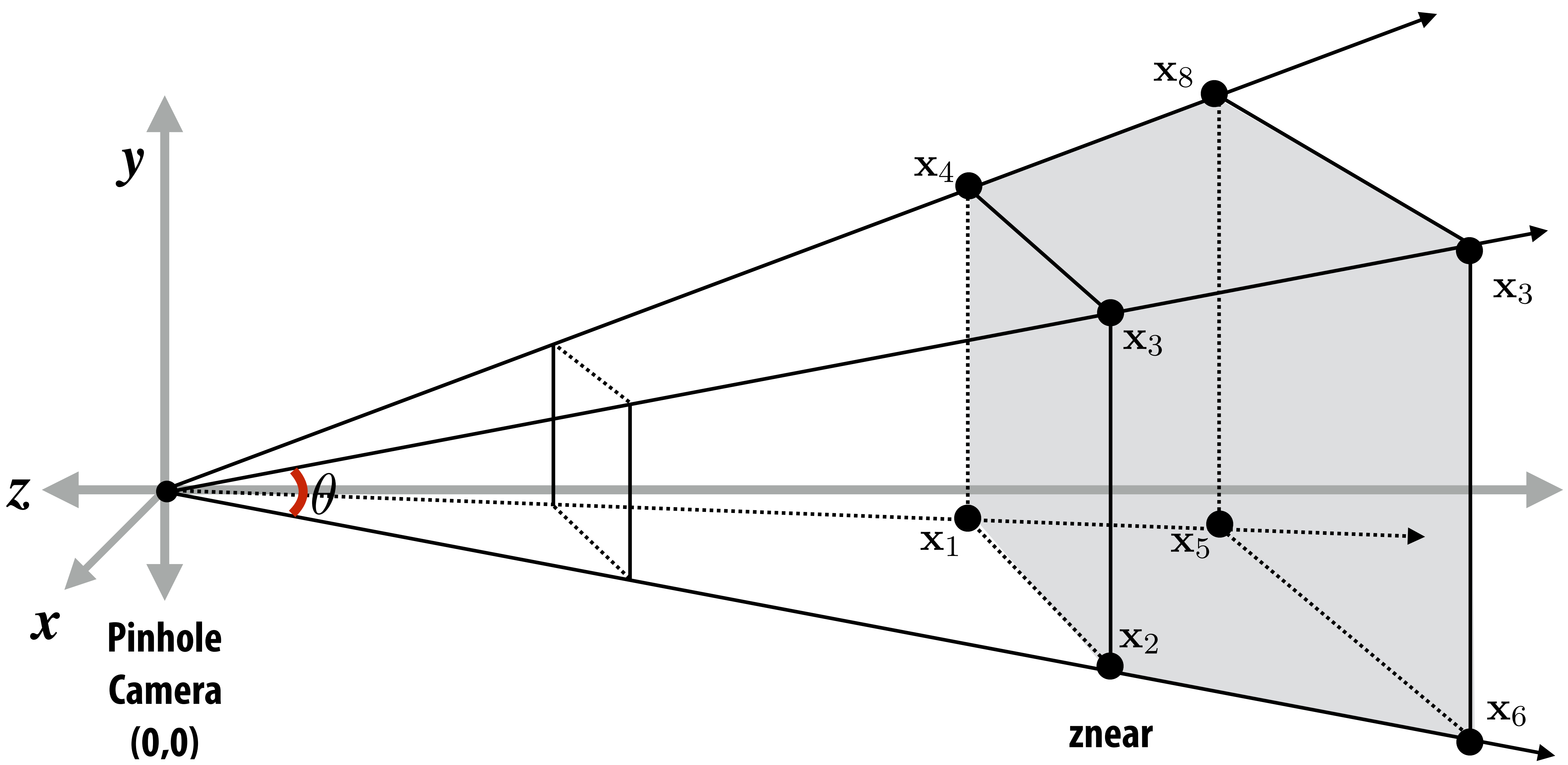
Step 1:

Transform triangle vertices into camera space

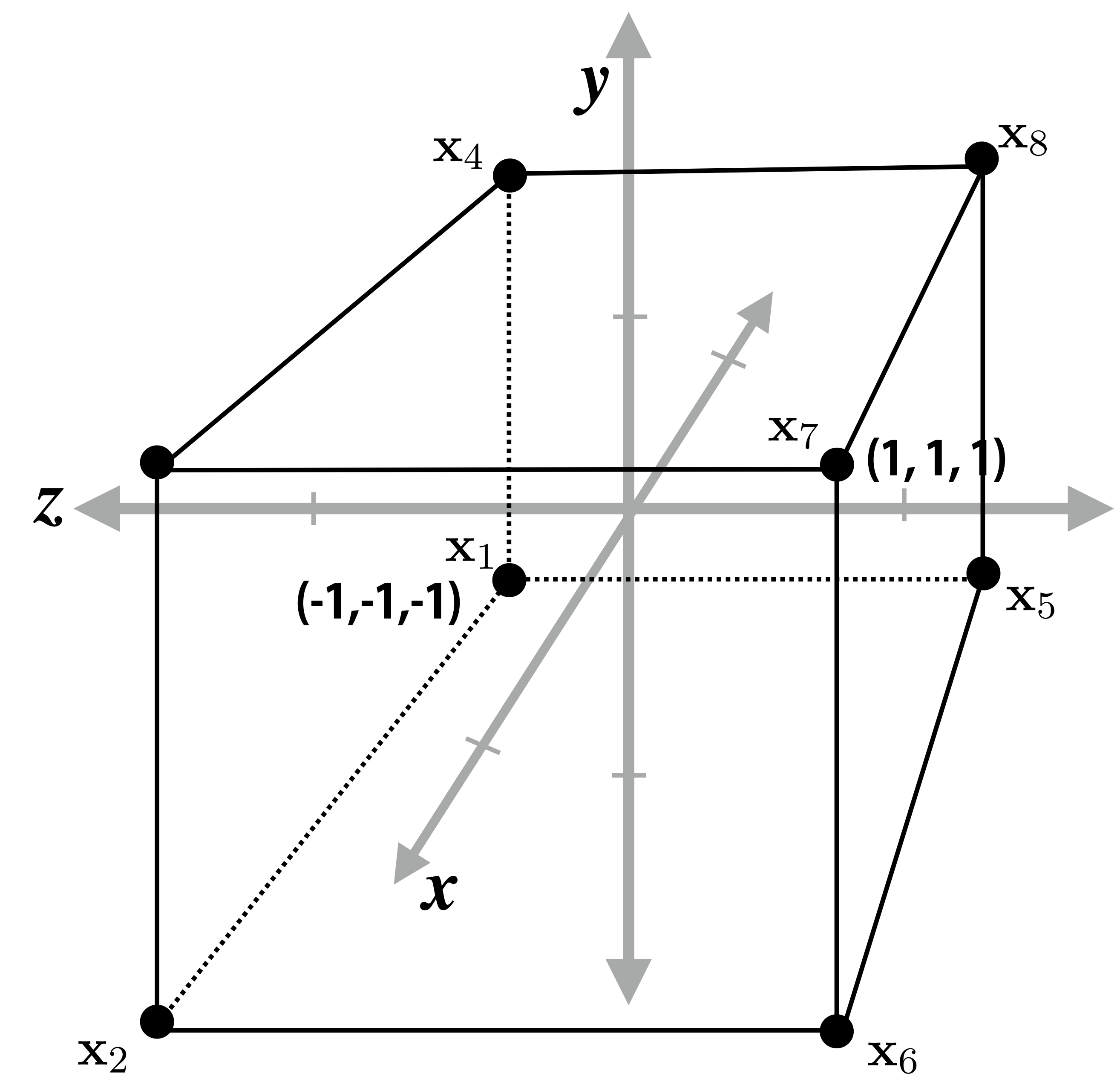


Step 2:

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



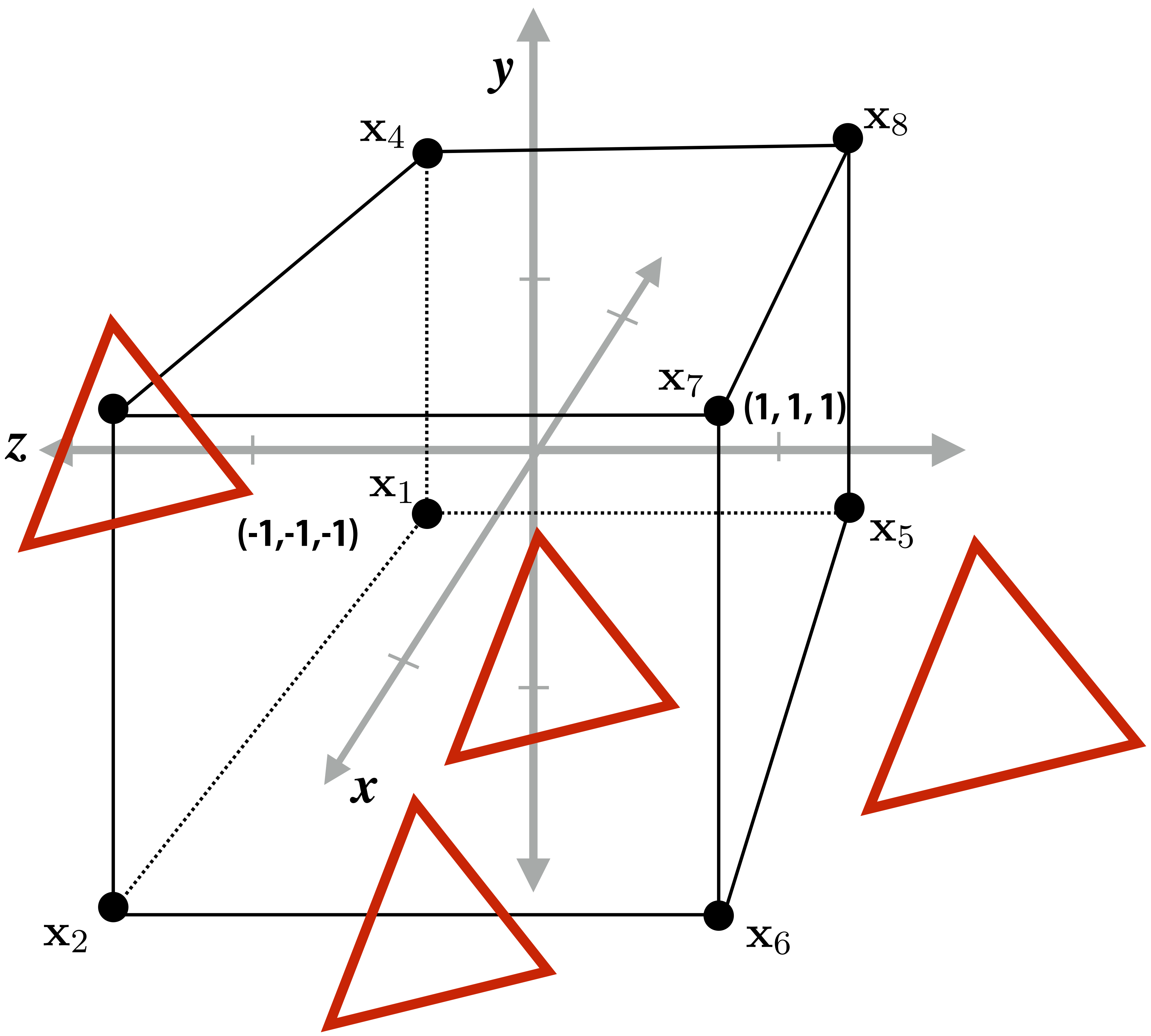
Camera-space positions: 3D



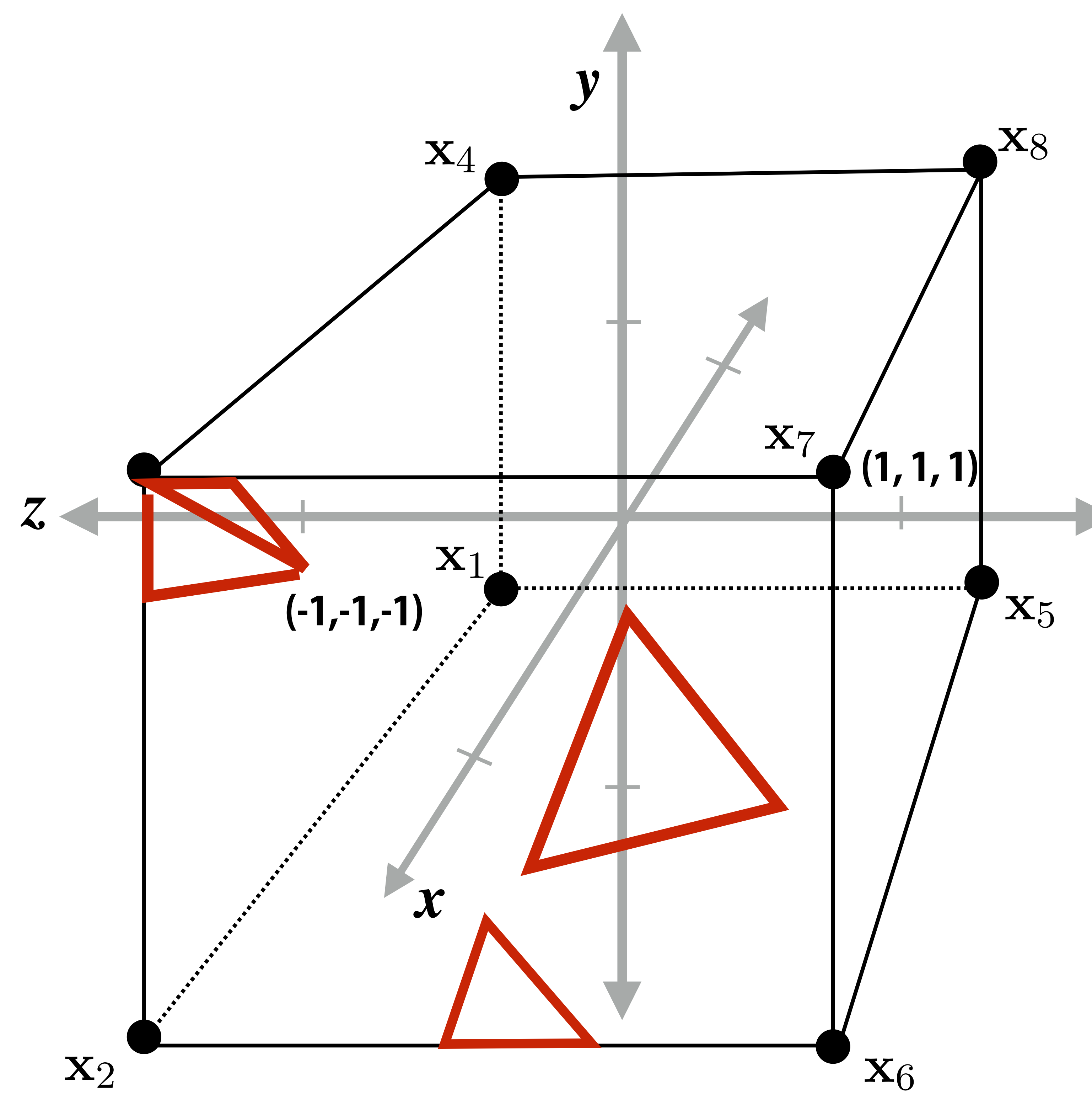
Normalized space positions

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)**



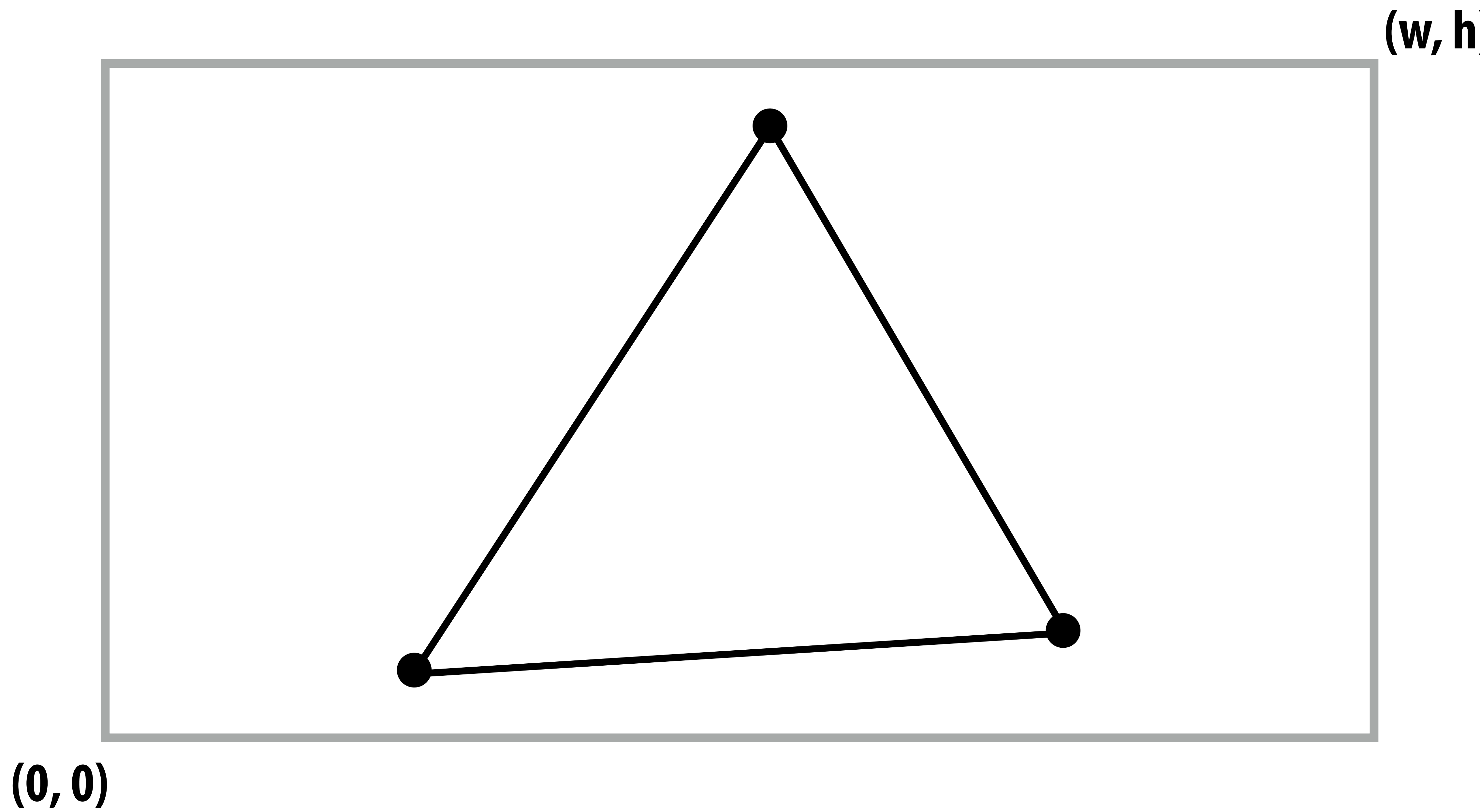
Triangles before clipping



Triangles after clipping

Step 4: transform to screen coordinates

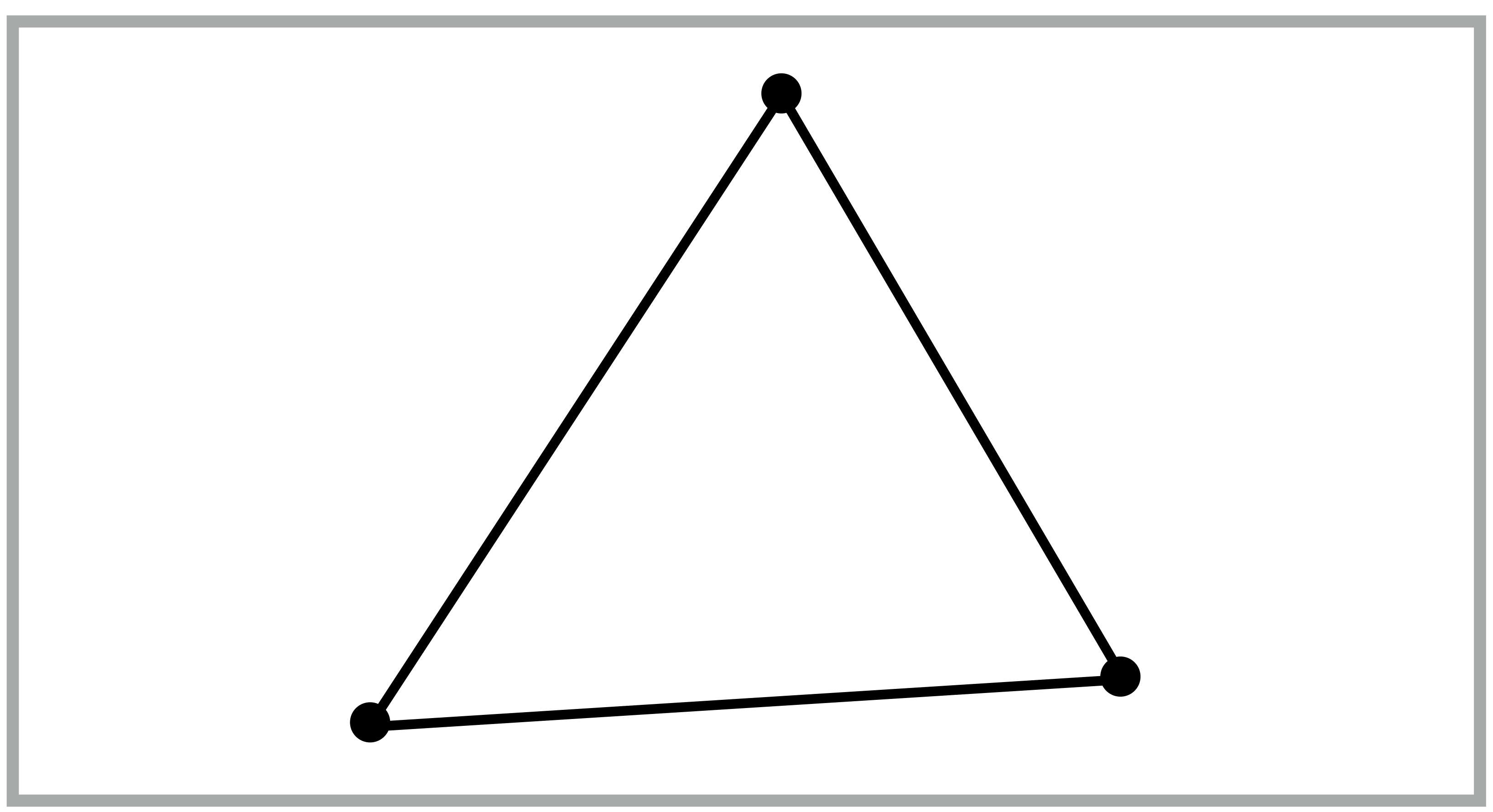
Perform homogeneous divide, transform vertex xy positions from normalized coordinates into screen coordinates (based on screen w,h)



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.**



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

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

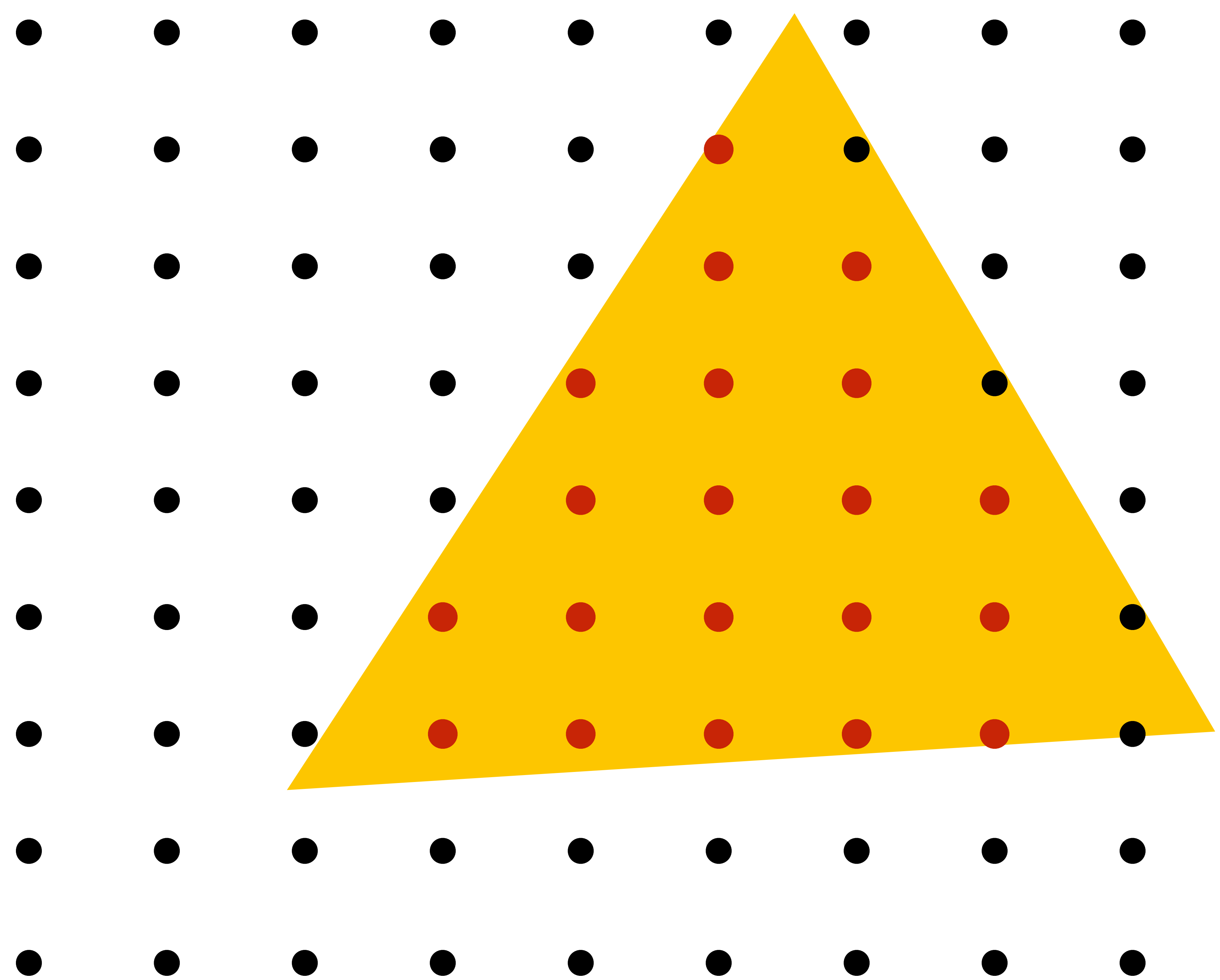
$$\mathbf{E}_{20}(x, y)$$

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

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

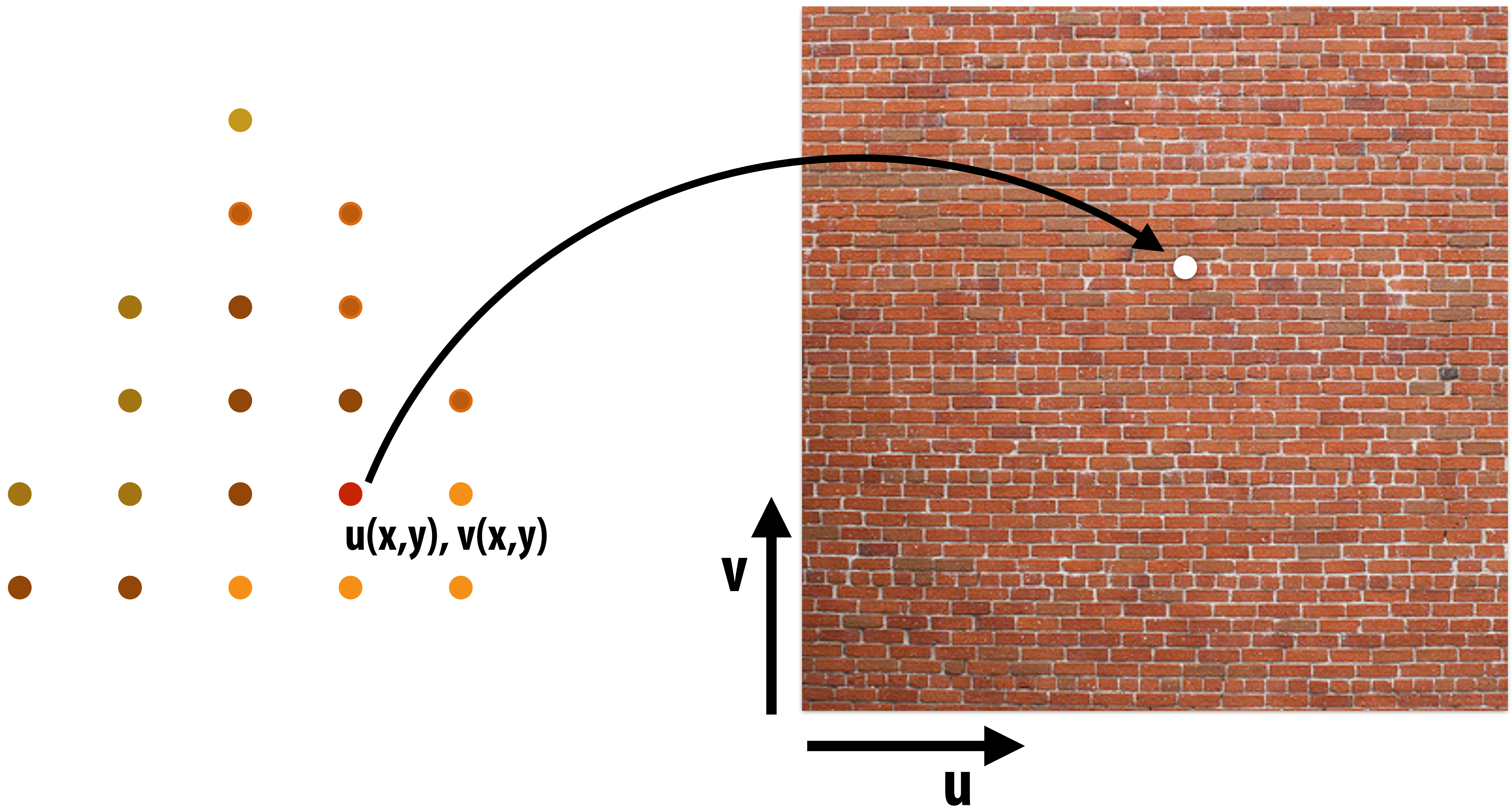
Step 6: sample coverage

Evaluate attributes z, u, v at all covered samples



Step 6: compute triangle color at sample point

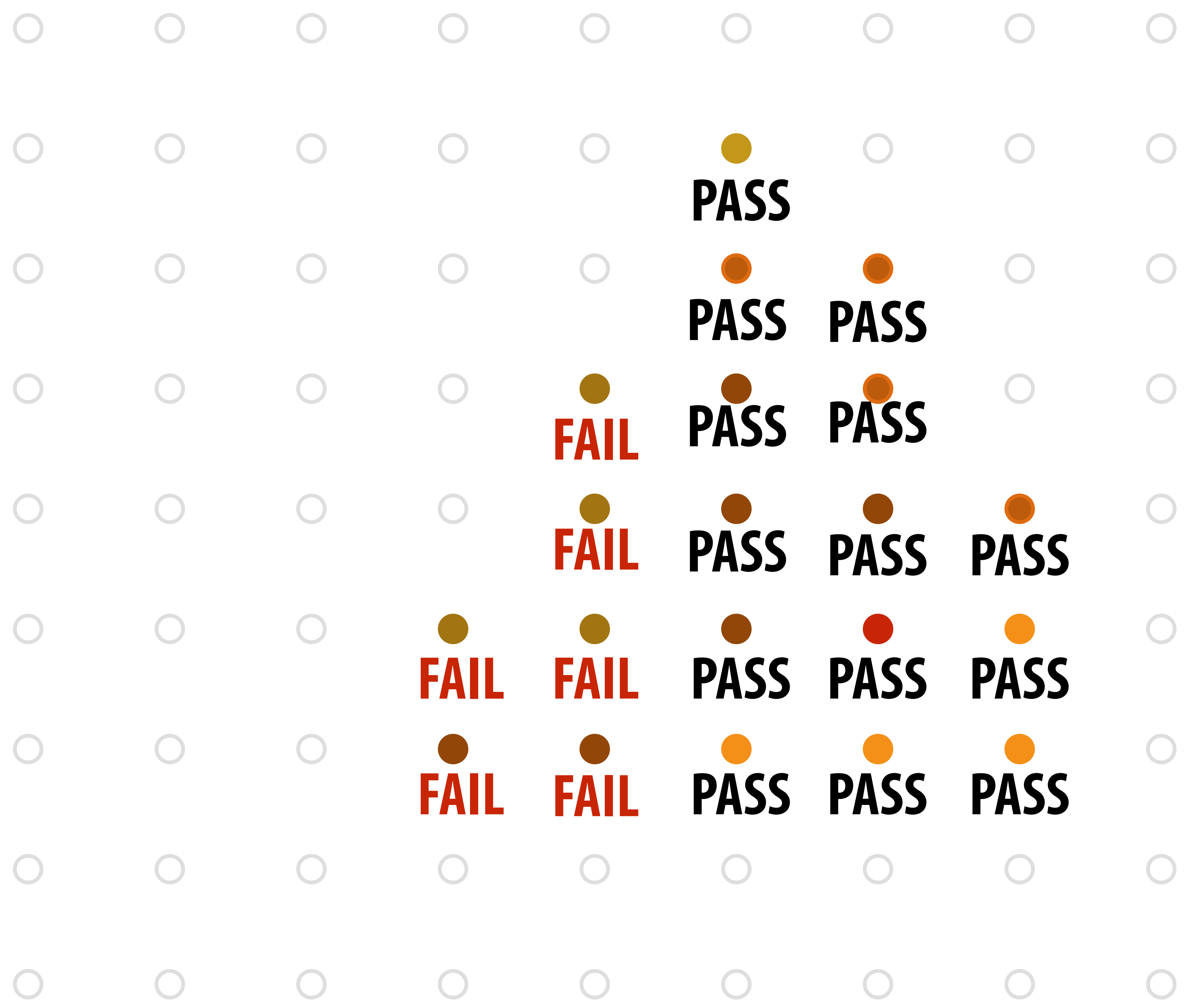
e.g., sample texture map *



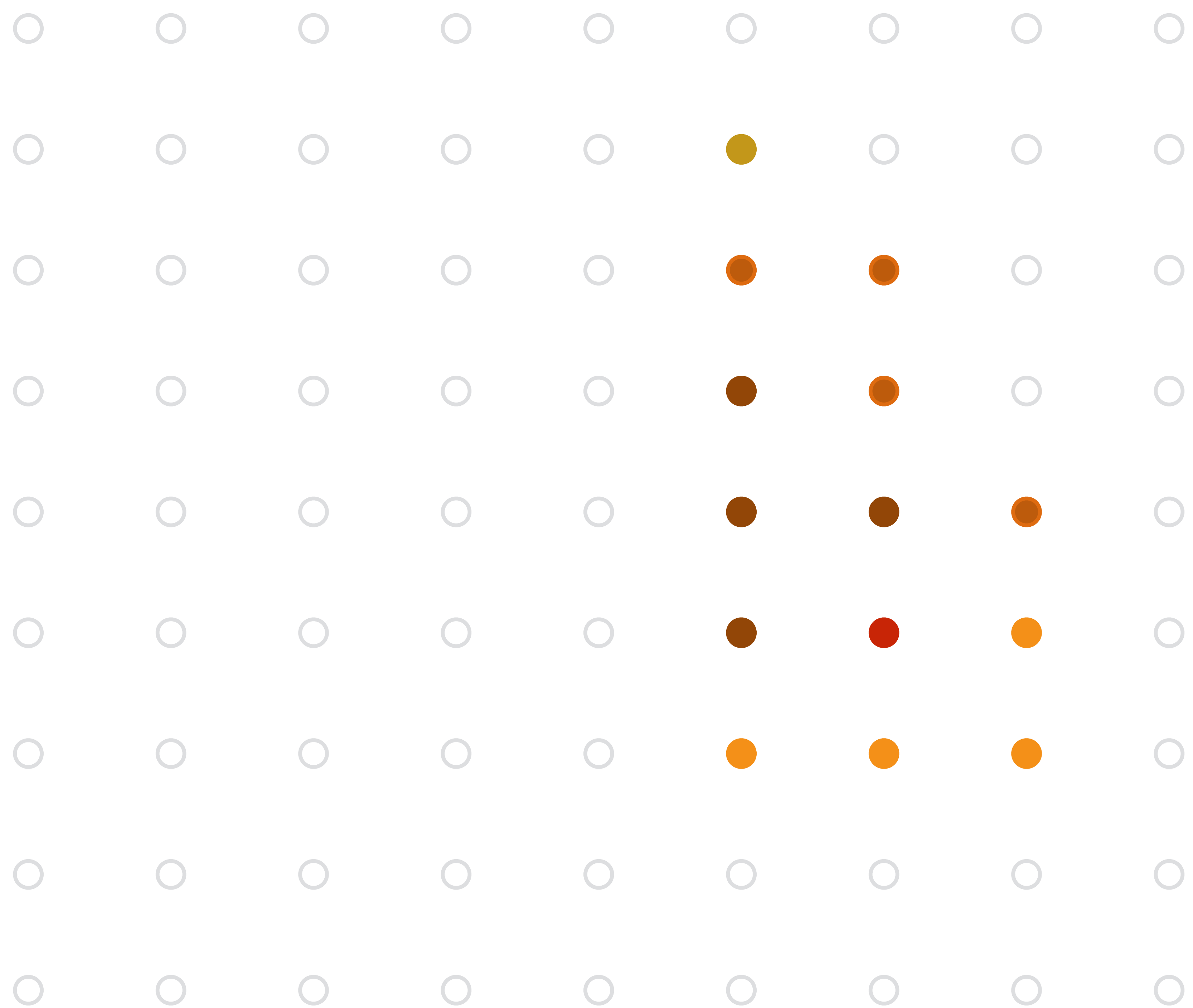
* So far, we've only described computing triangle's color at a point by interpolating per-vertex colors, or by sampling a texture map. Later in the course, we'll discuss more advanced algorithms for computing its color based on material properties and scene lighting conditions.

Step 7: perform depth test (if enabled)

Also update depth value at covered samples (if necessary)

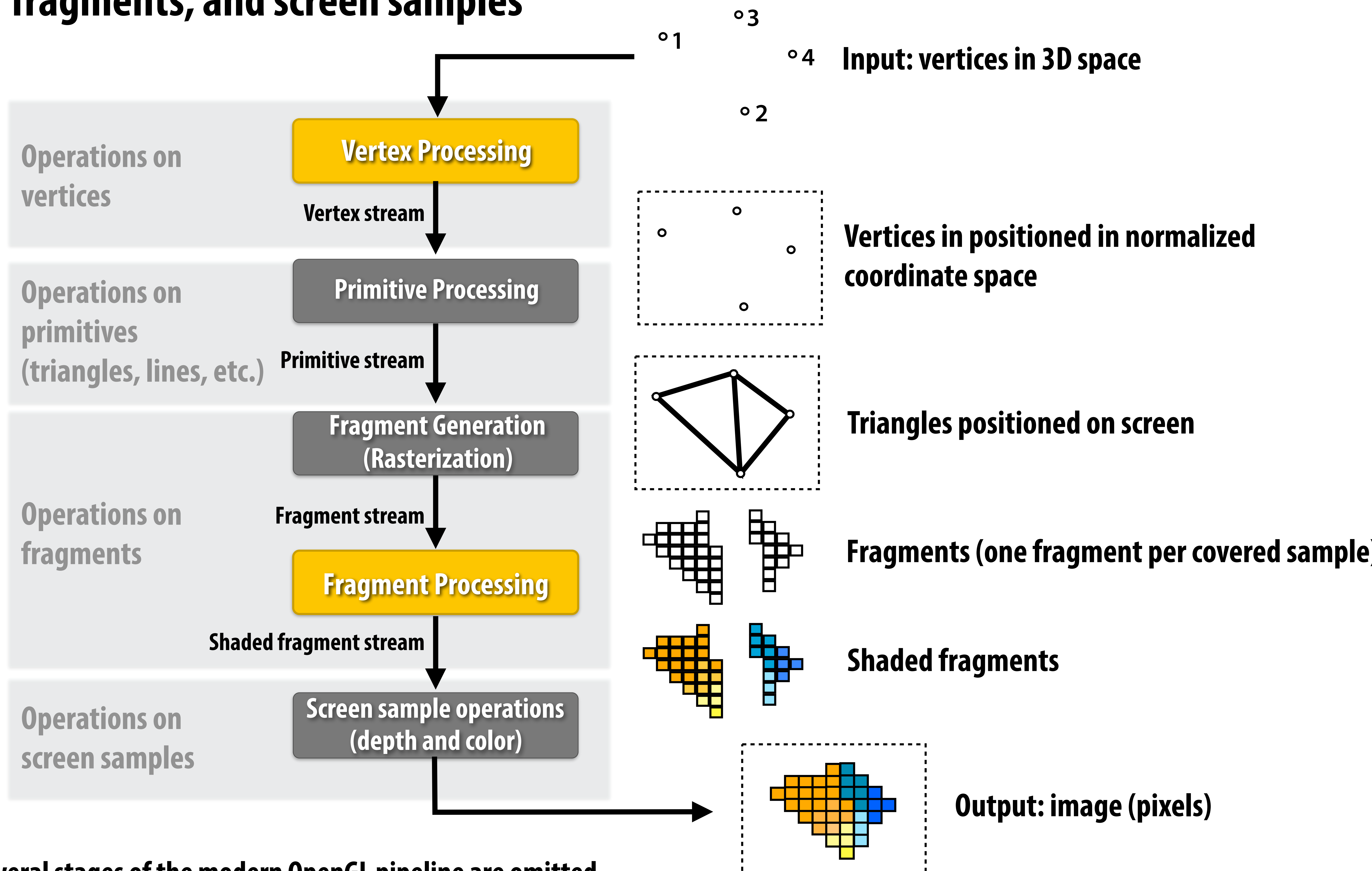


Step 8: update color buffer (if depth test passed)



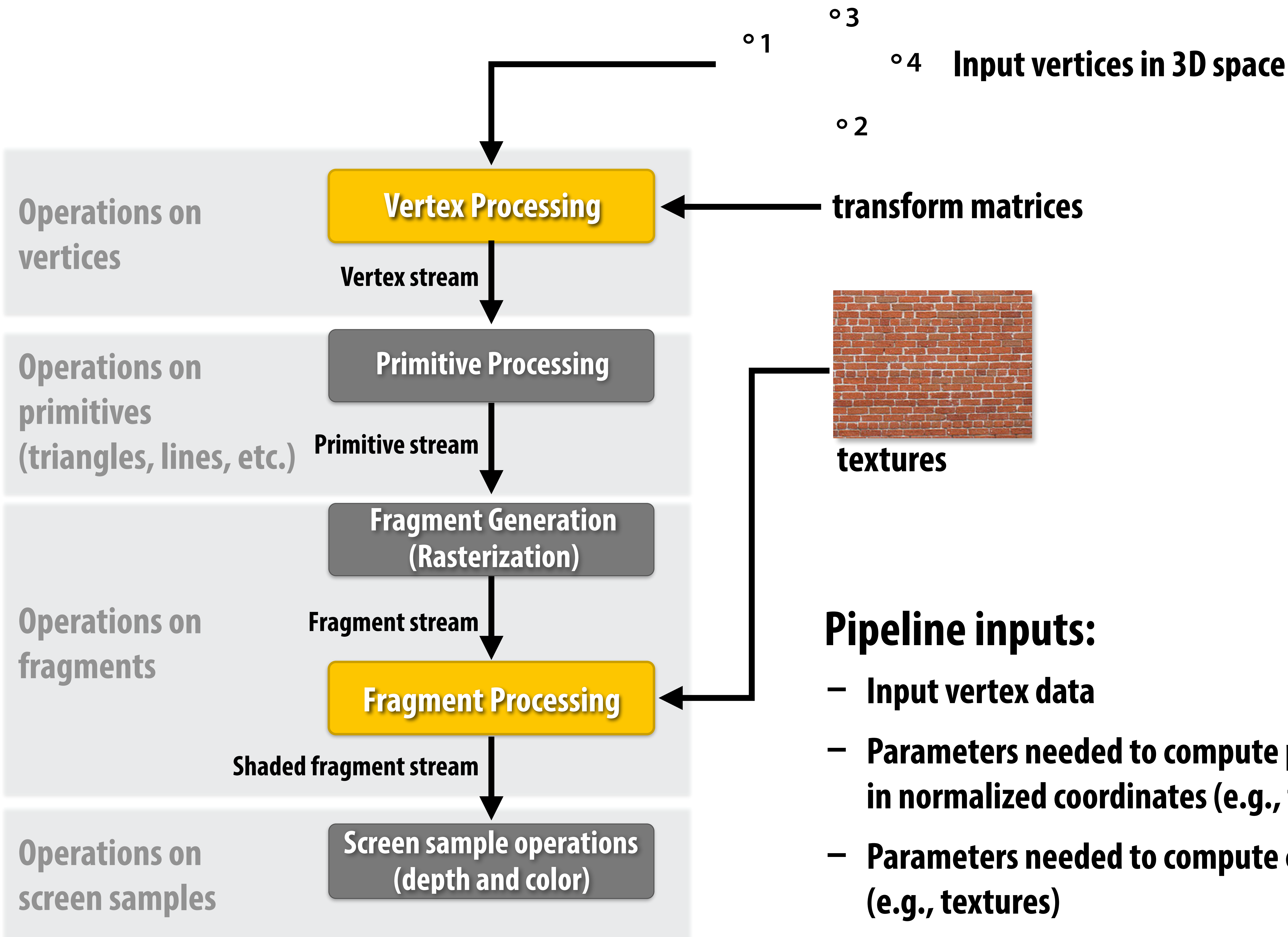
OpenGL/Direct3D graphics pipeline *

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

Per-fragment attributes (interpolated by rasterizer)

Sample surface albedo (reflectance color) from texture

Shader outputs surface color

Modulate surface albedo by incident irradiance (incoming light)

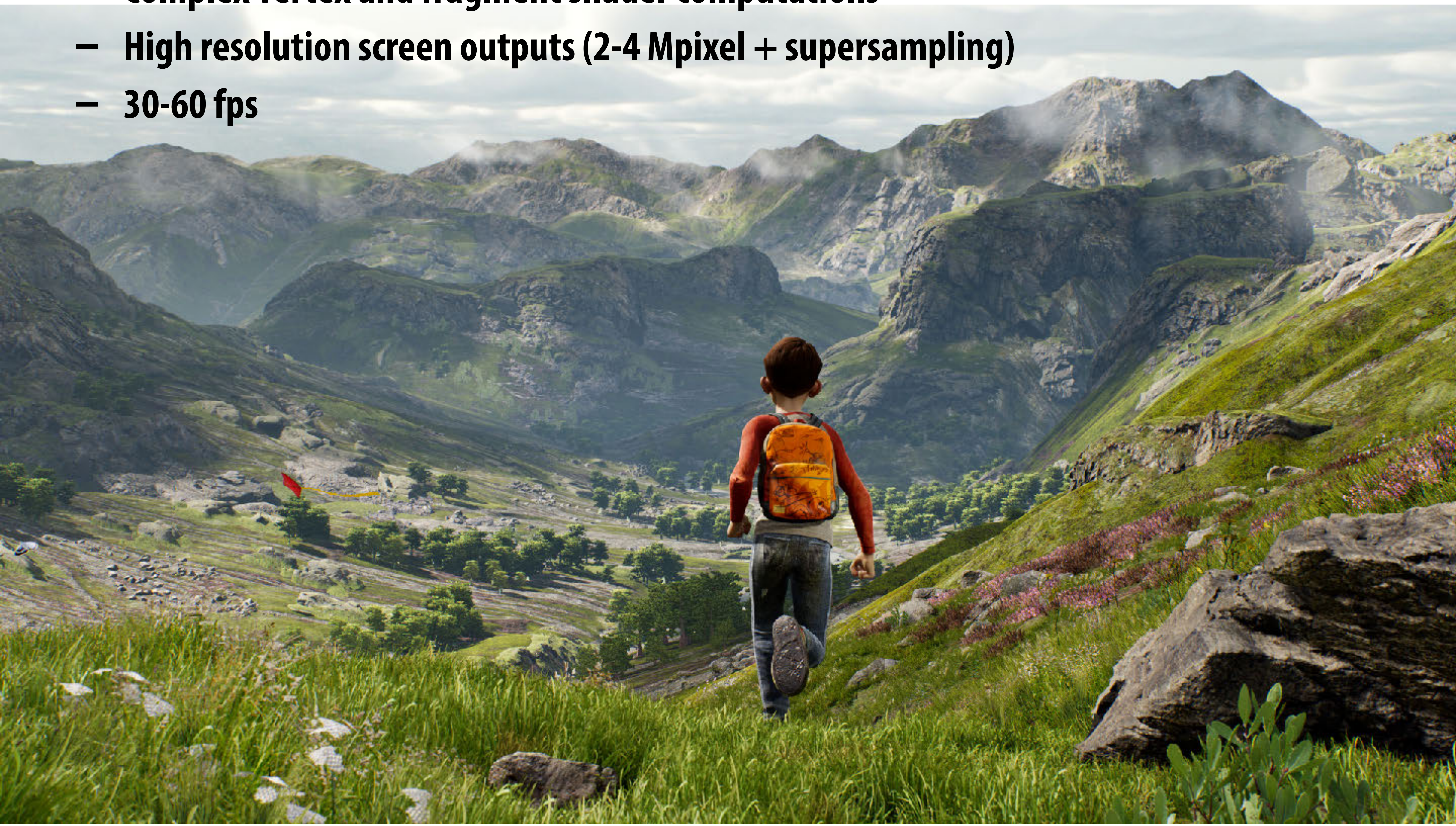
Shader function executes once per fragment.

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

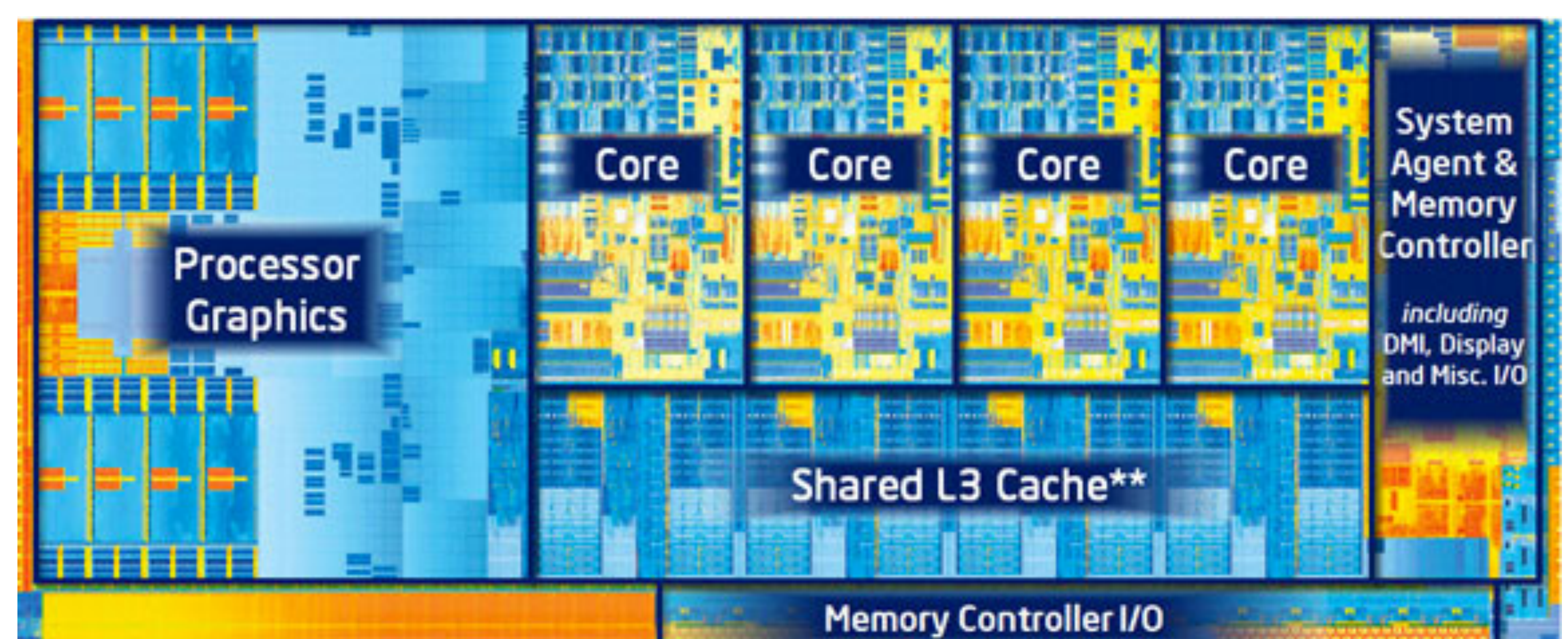


Unreal Engine Kite Demo (Epic Games 2015)

Graphics pipeline implementation: GPUs

Specialized processors for executing graphics pipeline computations

Discrete GPU card
(NVIDIA GeForce Titan X)

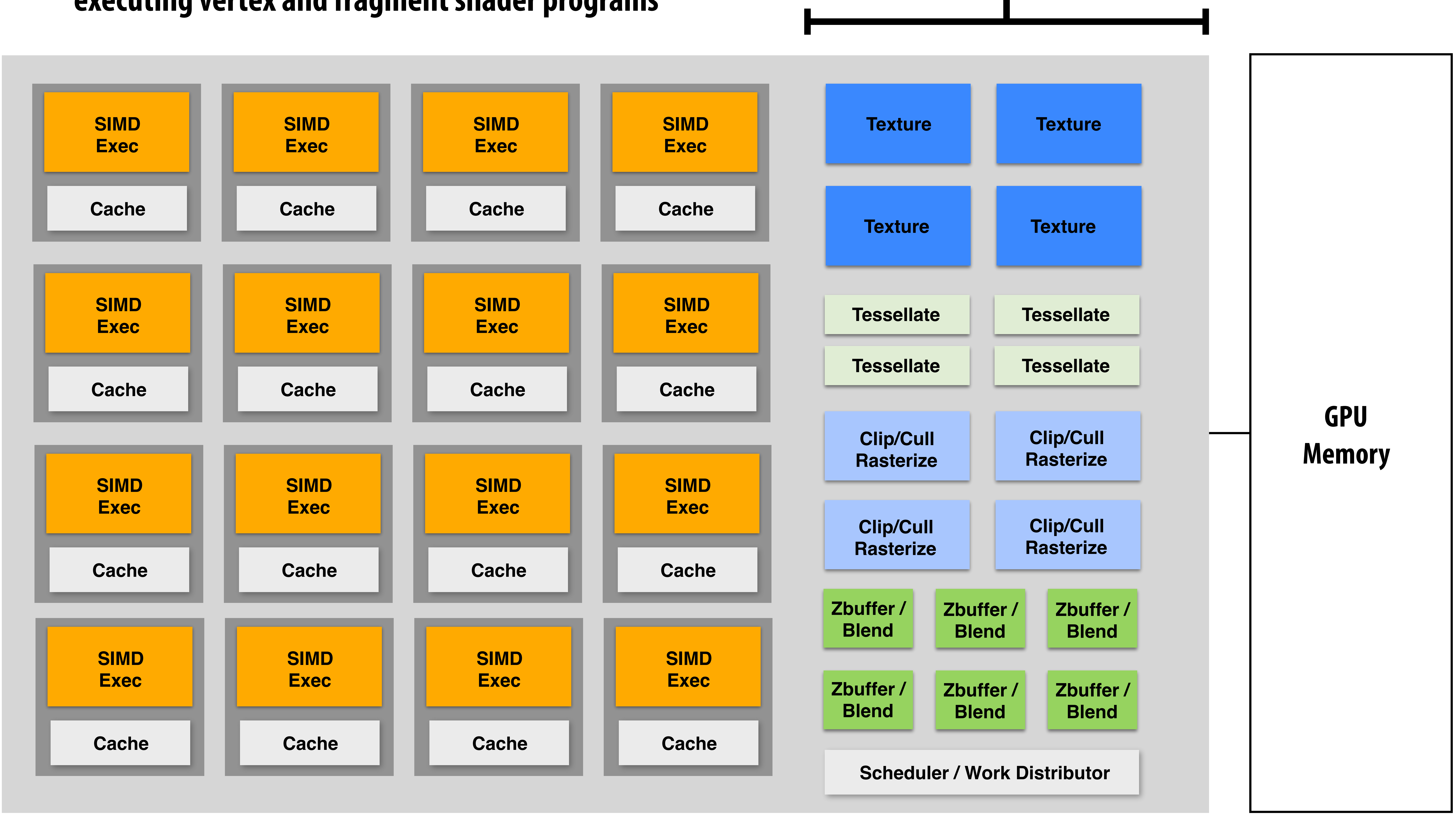


Integrated GPU: part of modern Intel CPU die

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



This part (mostly) not used by CUDA/OpenGL; raw graphics horsepower still greater than compute!

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)