Lecture 15:

The Real-Time 3D Graphics Pipeline Architecture

Visual Computing Systems

Stanford CS348V, Winter 2018

What is an “architecture”?

(not distinguishing between software or hardware architecture)

A system architecture is an abstraction

- **Entities (state)**
  - Registers, buffers, vectors, triangles, lights, pixels, images
- **Operations (that manipulate state)**
  - Add two registers, copy buffers, multiply vectors, blur images, draw triangles
- **Mechanisms for creating/destroying entities, expressing operations**
  - Execute machine instruction, make API call, express logic in a programming language

Notice the different levels of granularity/abstraction in my examples

Key course theme: choosing the right level of abstraction for system's needs

Decision impacts system's expressiveness/scope and potential for efficient implementation

Example: x86 architecture?

- **State:**
  - Maintained by execution context (registers, PC, VM mappings, etc.)
  - Contents of memory

- **Operations:**
  - x86 instructions (privileged and non-privileged)

Example: GPU compute architecture (as defined by CUDA)?

- **State:**
  - Execution context for all executing CUDA threads
  - Contents of global memory

- **Operations:**
  - Bulk launch N CUDA threads running of kernel K: `Launch(N, k)`
  - Individual instructions executed by CUDA thread

CUDA constructs (the kernel)

```
// CUDA kernel definition
__global__ void scale(float amount, float* a, float* b)
{
   int i = threadIdx.x;   // CUDA builtin: get thread id
   b[i] = amount * a[i];
}

// note: omitting array initialization via cudaMalloc()
float scale_amount;
float* input_array;
float* output_array;

// launch N CUDA threads, each thread executes kernel 'scale'
scale<<1,N>>(scale_amount, input_array, output_array);
```

Bulk thread launch: logically spawns N threads

Question: What should N be?

Question: Do you normally think of "threads" this way?

The 3D rendering task

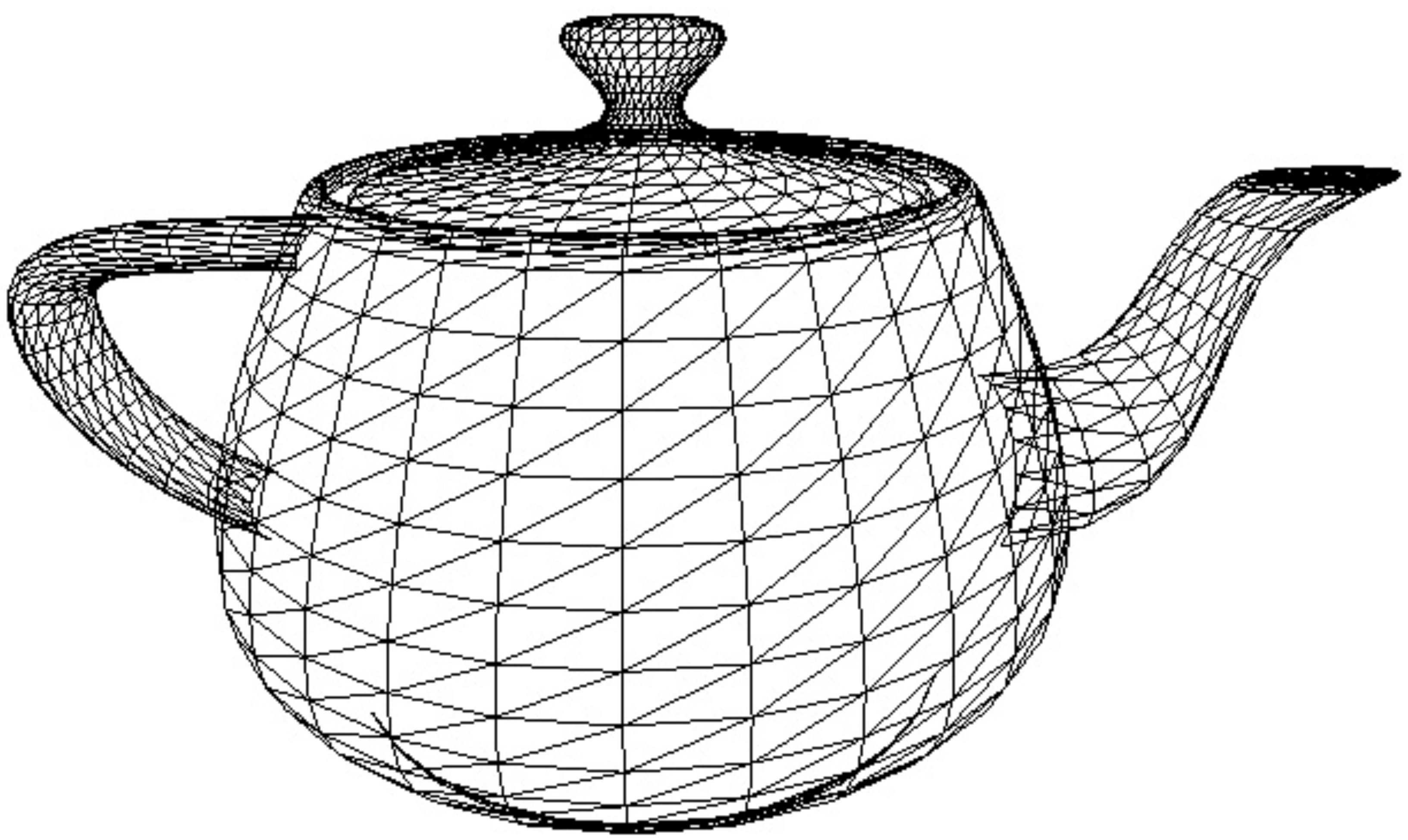


Image credit: Henrik Wann Jensen

Input: description of a scene

3D surface geometry (e.g., triangle meshes)
surface materials
lights
camera

Output: image

Problem statement: Determine how each geometric element contributes to the appearance of each output pixel in the image, given a description of a scene's surface properties and lighting conditions?

Goal: render very high complexity 3D scenes

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

Unreal Engine Kite Demo (Epic Games 2015)

Goal: render very high complexity 3D scenes

Ryse: Son of Rome (image credit: http://www.gamespot.com/ryse-son-of-rome/images/)

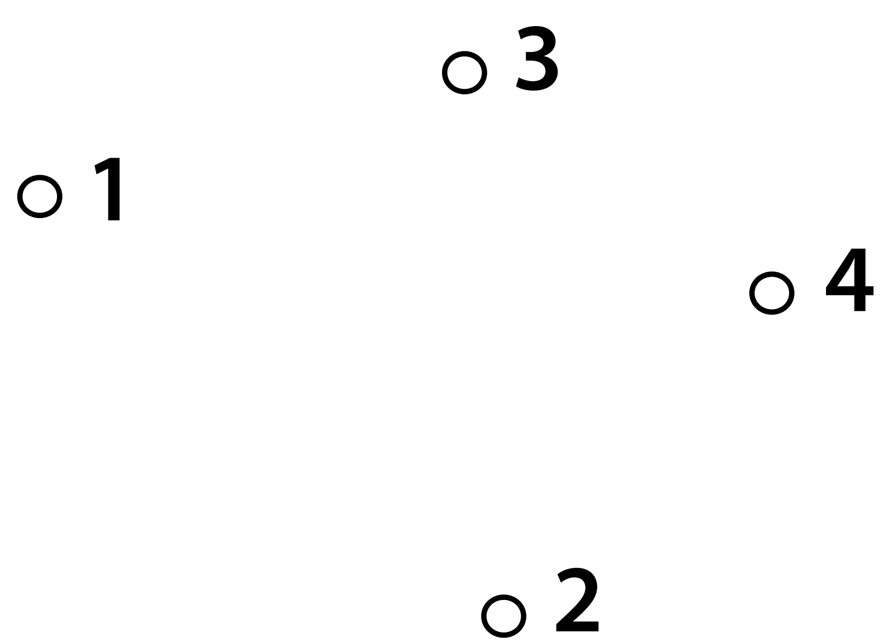
The real-time graphics pipeline architecture

(GPU-accelerated OpenGL/D3D graphics pipeline, from a systems perspective)

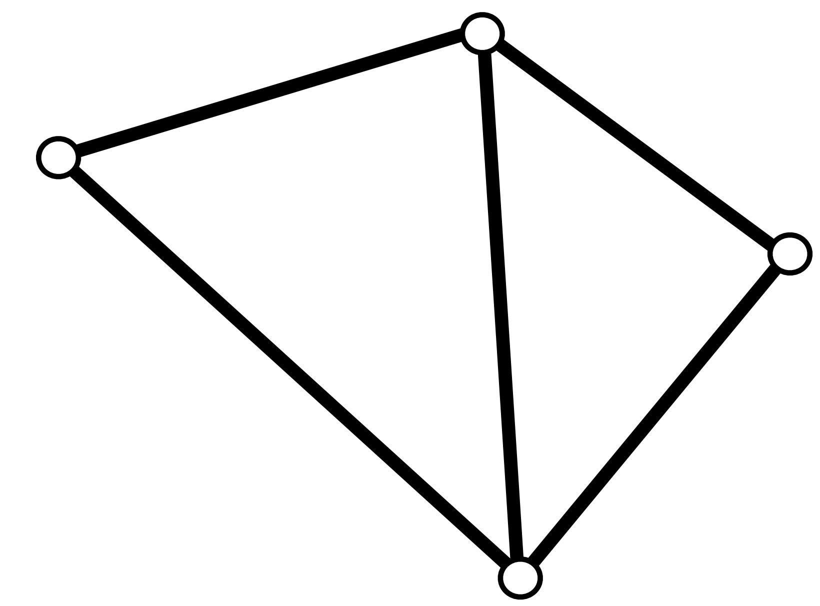
The graphics pipeline is an architecture for driving modern GPU execution

(Note to CUDA programmers: graphics pipeline was the original interface to GPU hardware. Compute mode execution came later…)

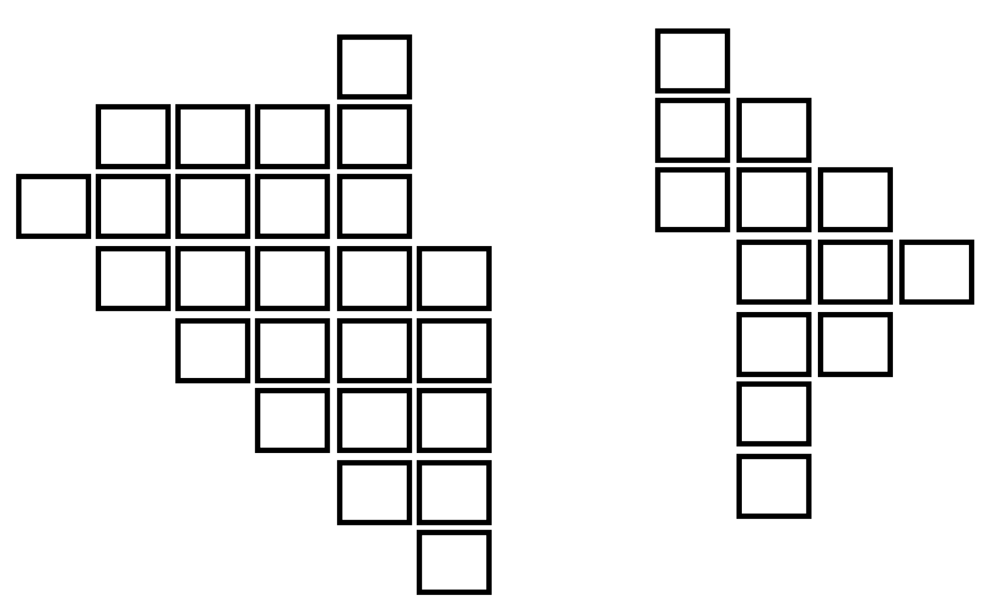
Real-time graphics pipeline entities



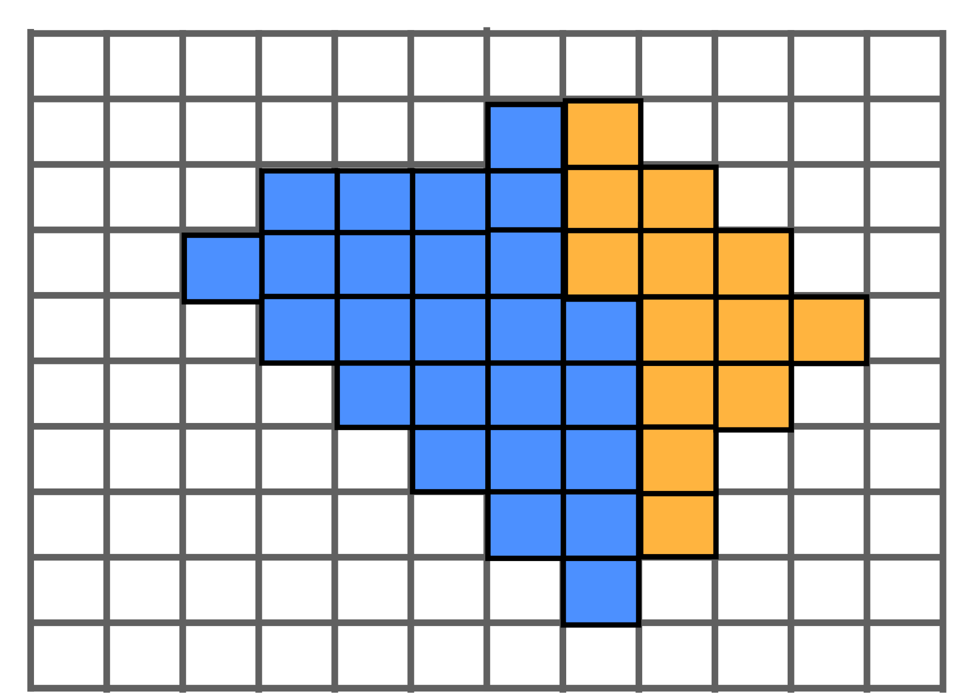
Vertices



Primitives
(triangles, points, lines)

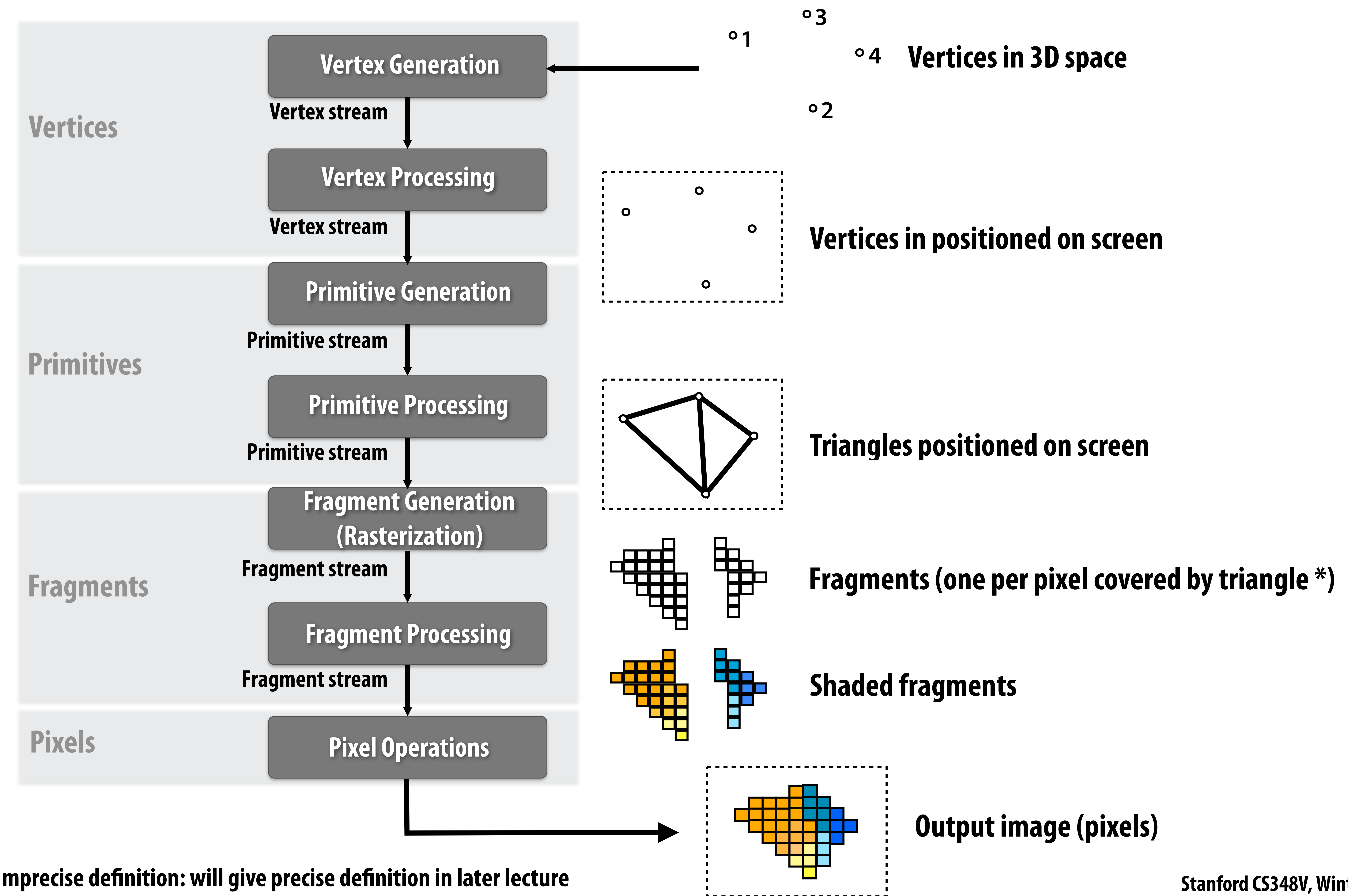


Fragments



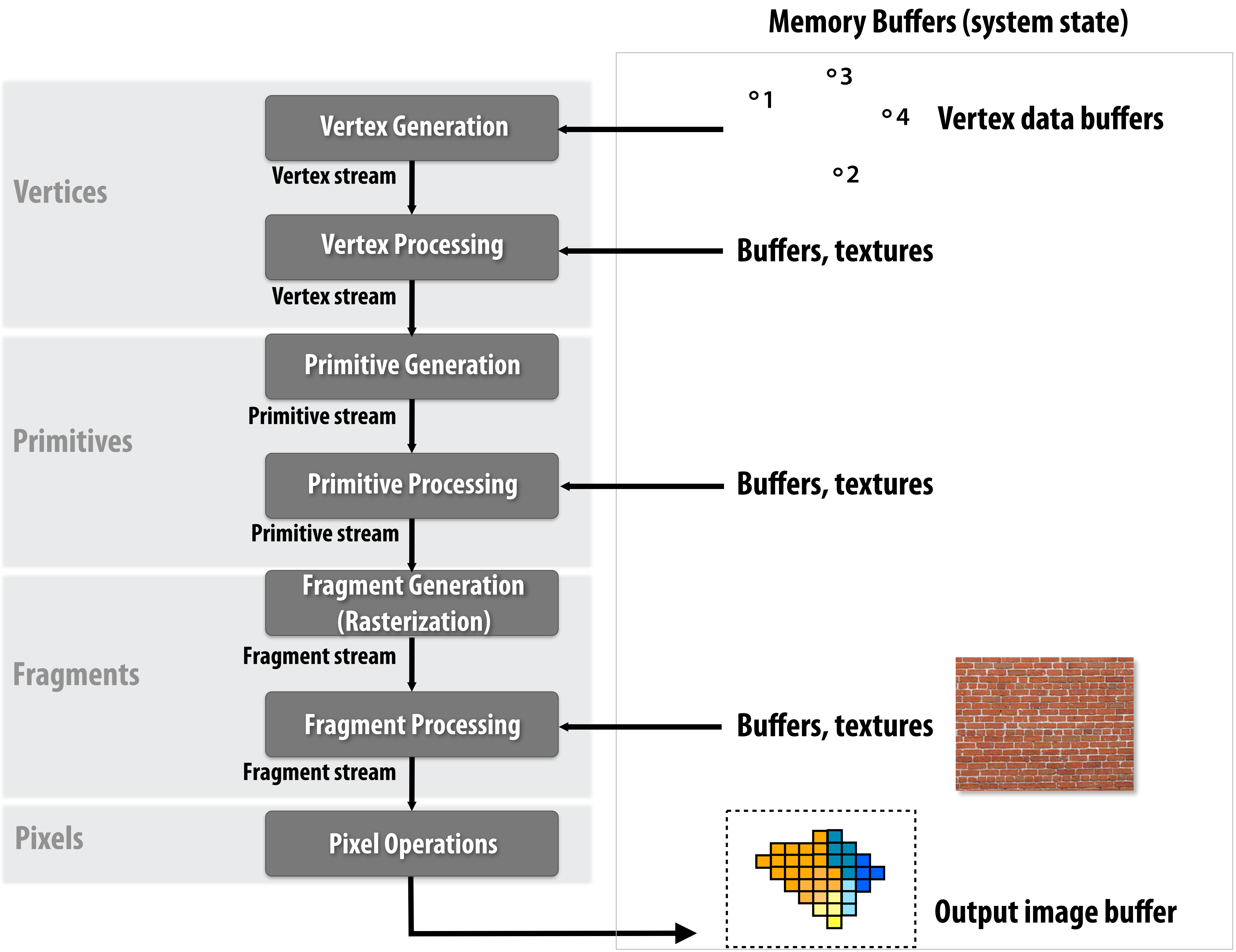
Pixels

Real-time graphics pipeline operations



* Imprecise definition: will give precise definition in later lecture

Real-time graphics pipeline state

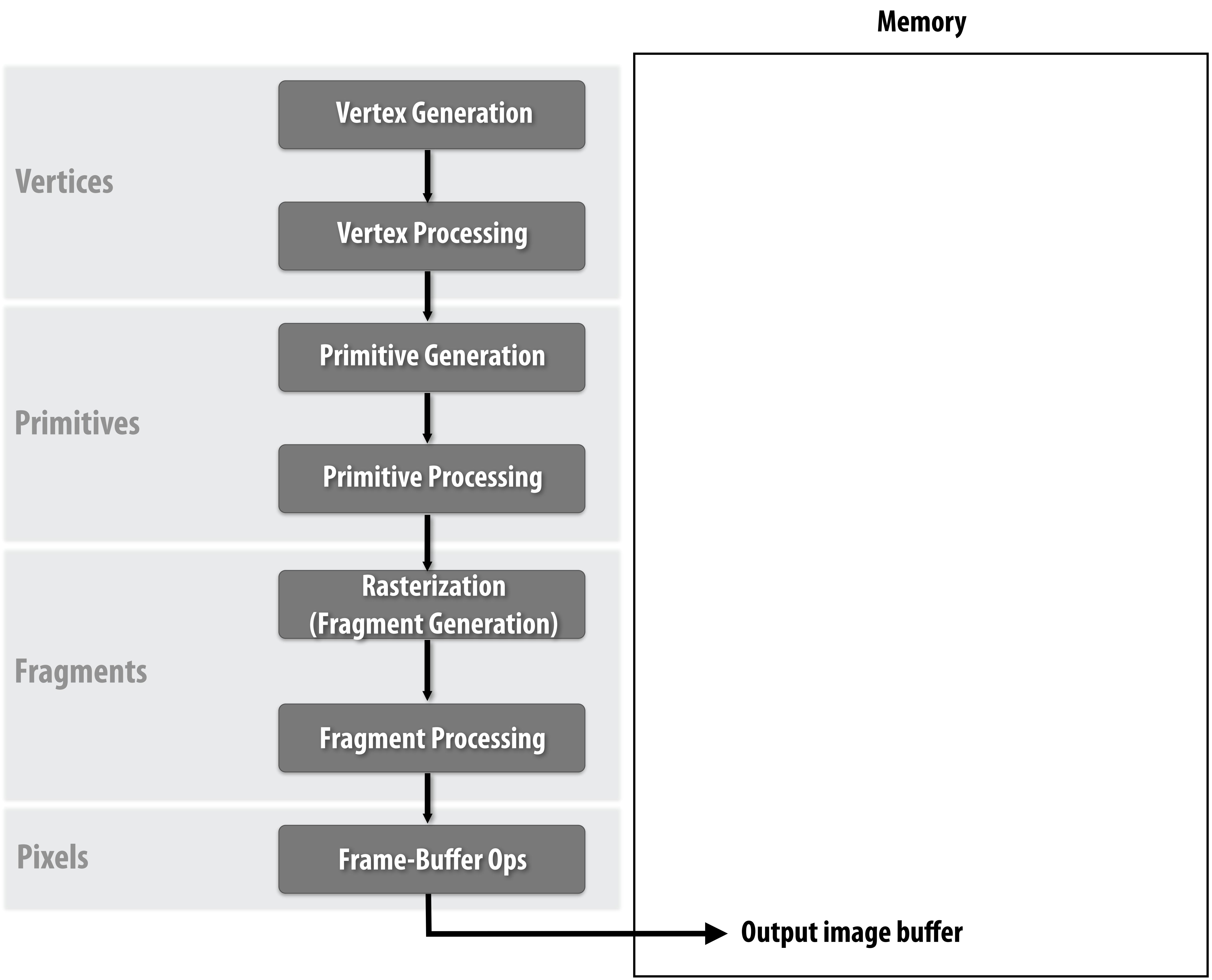


Issues to keep in mind during this overview*

- **Level of abstraction**
- **Orthogonality of abstractions**
- **How is the pipeline designed for performance/scalability?**
- **What the pipeline does and DOES NOT do**

*** These are great questions to ask yourself about any system you study**

The graphics pipeline

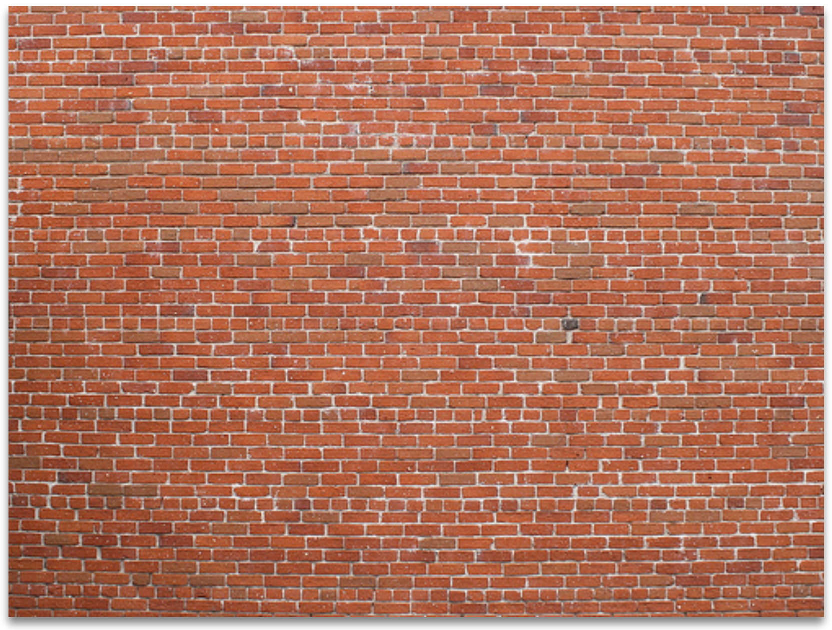


Command: draw these triangles!

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

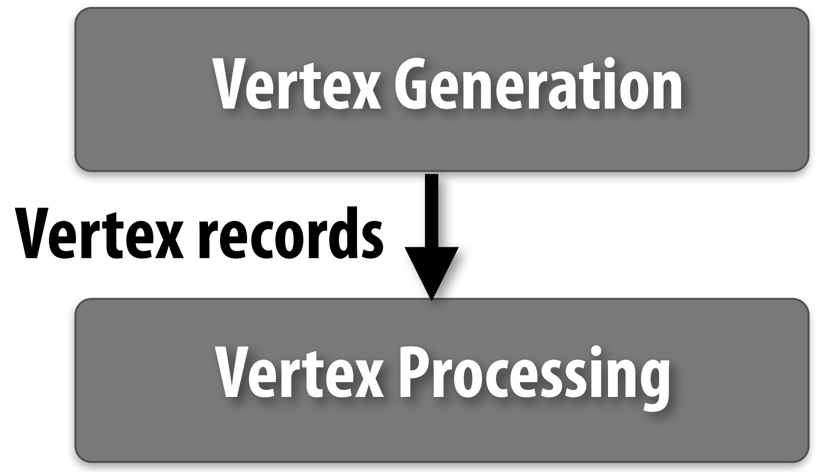
Object-to-camera-space transform: $\mathbf{T}$

Perspective projection transform $\mathbf{P}$

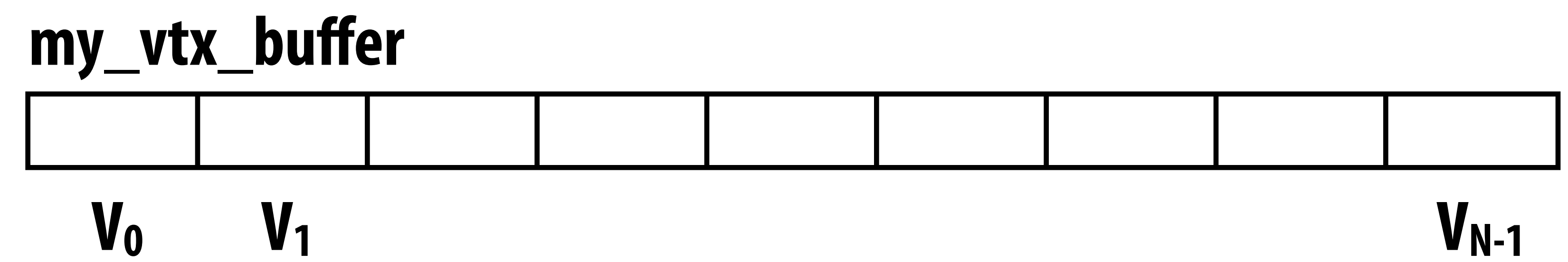
Size of output image (W, H)

Use depth test /update depth buffer: YES!

“Assembling” vertices

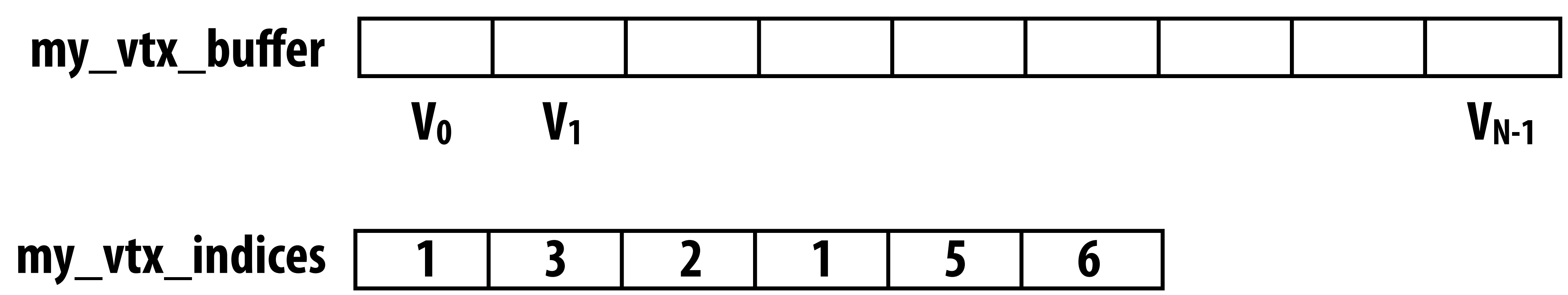


Contiguous version data version



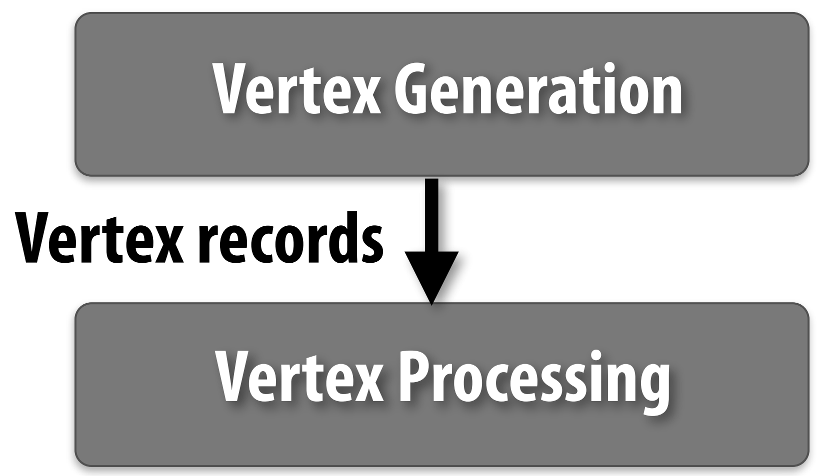

```
glBindBuffer(GL_ARRAY_BUFFER, my_vtx_buffer);
glDrawArrays(GL_TRIANGLES, 0, N);
```

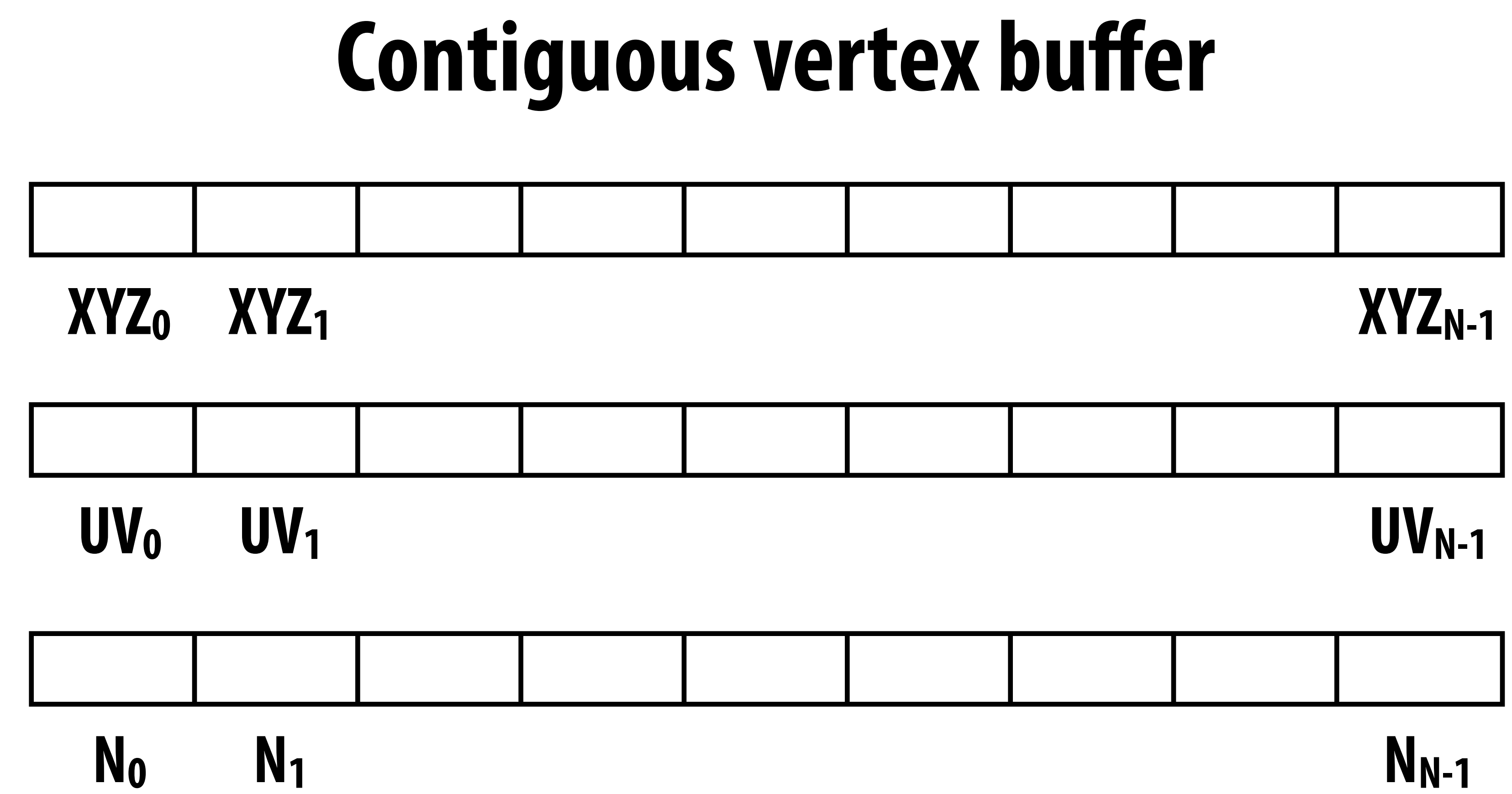
Indexed access version (“gather”)




```
glBindBuffer(GL_ARRAY_BUFFER, my_vtx_buffer);
glDrawElements(GL_TRIANGLES, 6, GL_UNSIGNED_INT,
               my_vtx_indices);
```

“Assembling” vertices



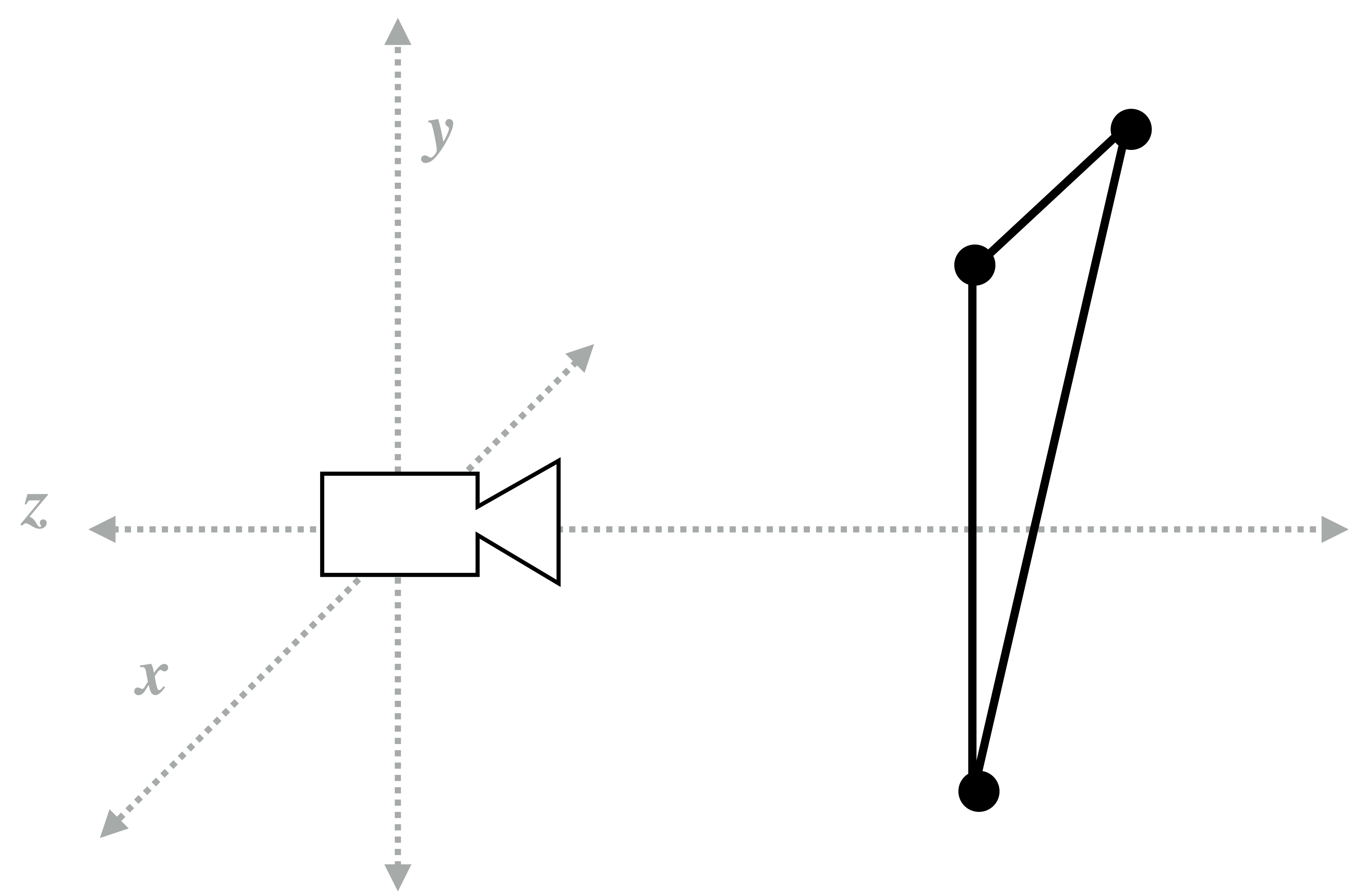


Output of vertex generation is a collection of vertex records.

Current architectures set a limit of 128 32-bit attributes per vertex.

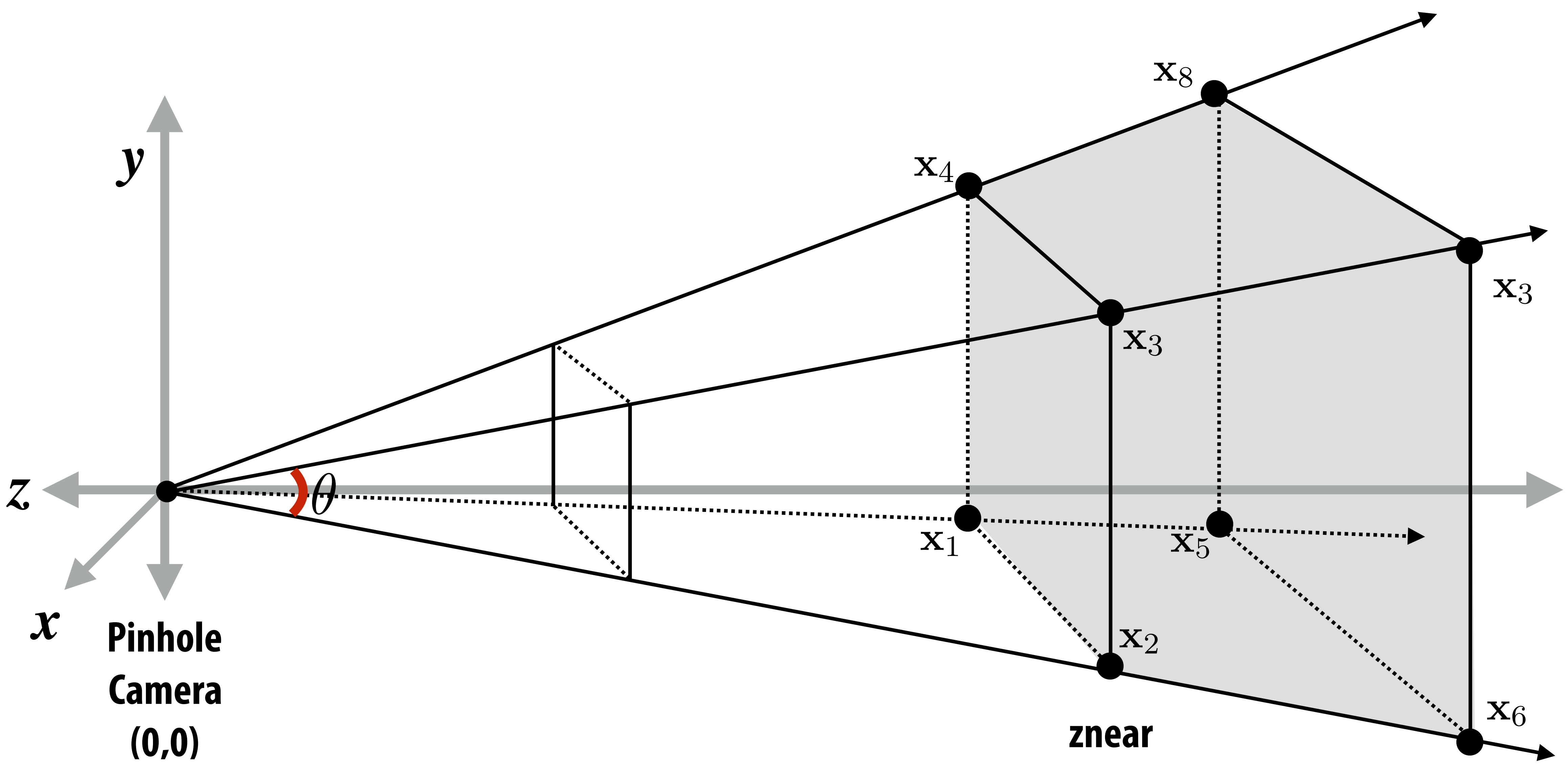
What the vertex processing kernel does

Transform triangle vertices from world-space coordinates into camera space coordinates

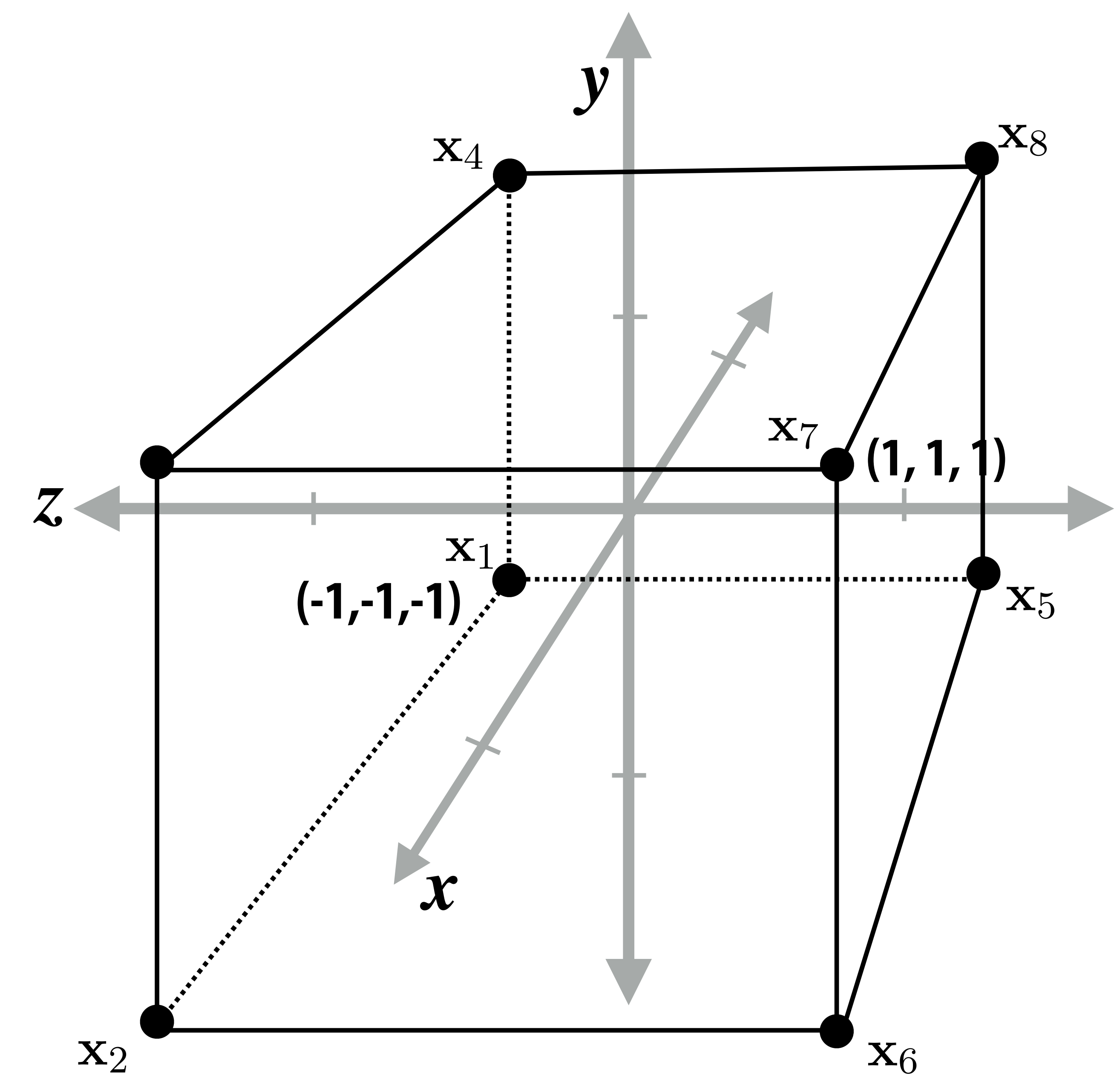


What the vertex processing kernel does

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

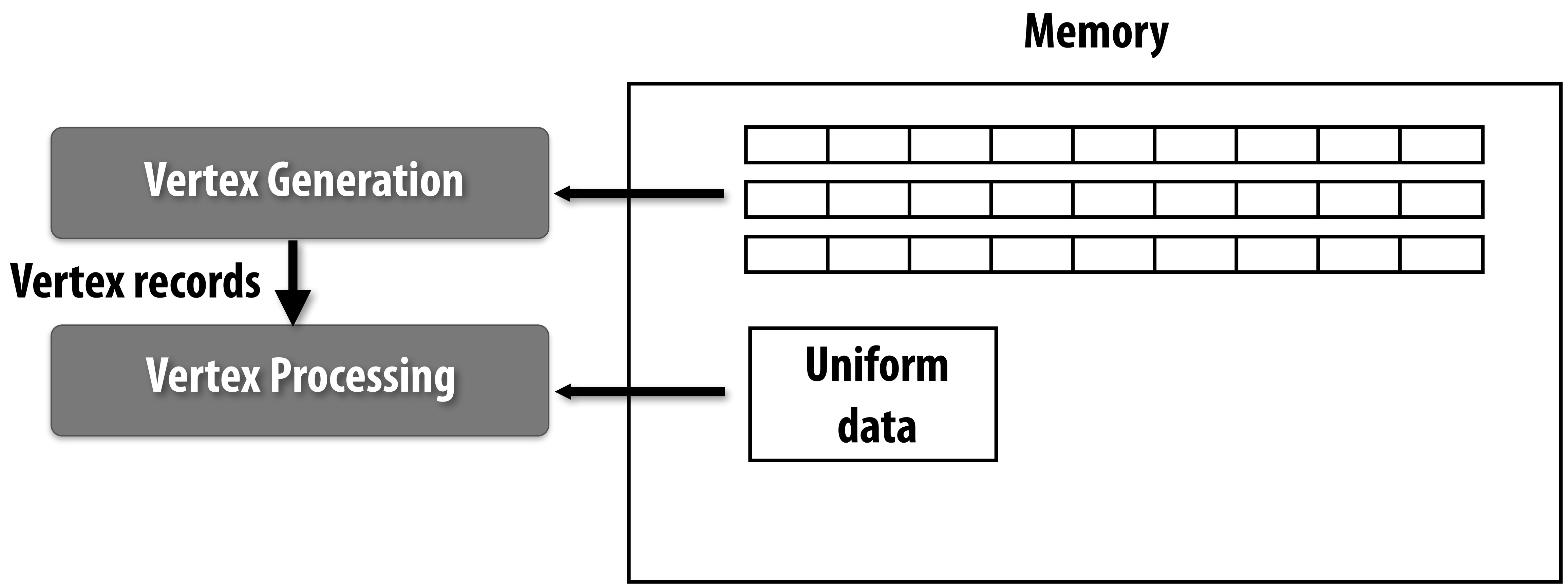


Camera-space positions: 3D



Normalized space positions

Vertex processing: inputs

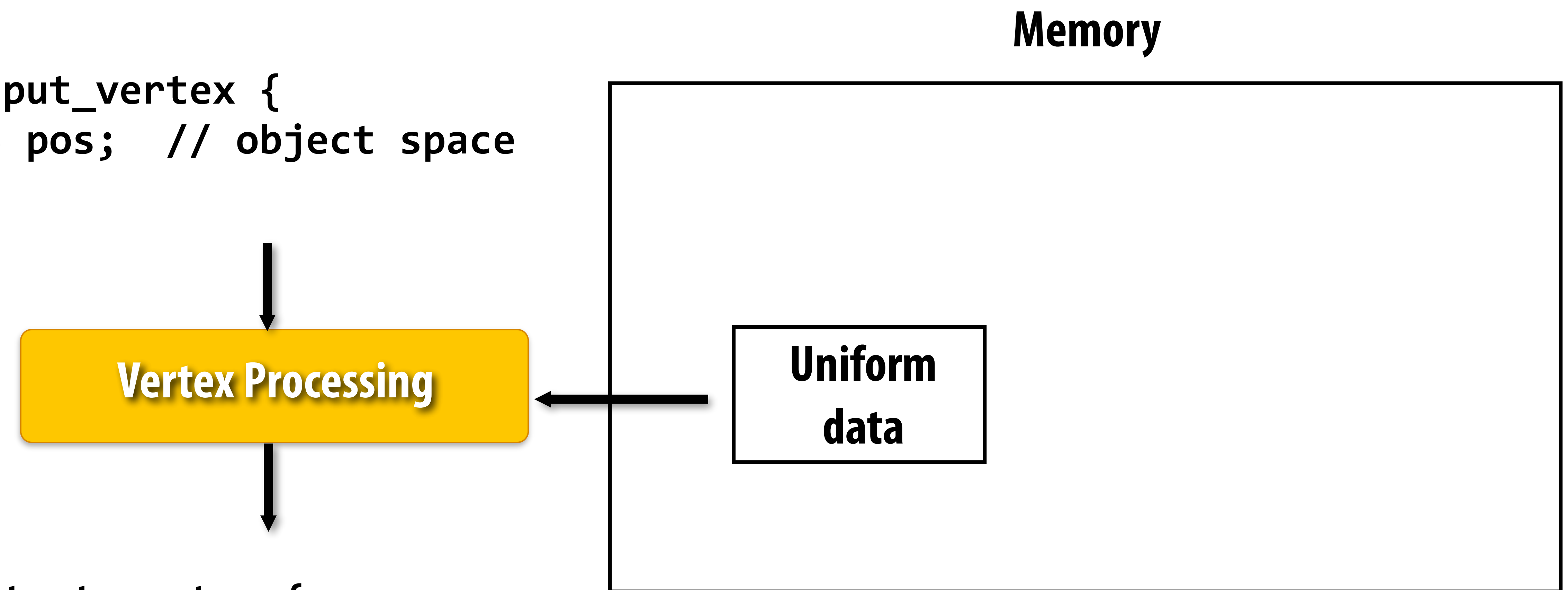


Uniform data: constant read-only data provided as input to every instance of the vertex shader
e.g., object-to-clip-space vertex transform matrix

Vertex processing operates on a stream of vertex records + read-only "uniform" inputs.

Vertex processing: inputs and outputs

```
struct input_vertex {
   float3 pos;  // object space
};
```




```
struct output_vertex {
   float3 pos; // NDC space
};
```

1 input vertex ⟶ 1 output vertex

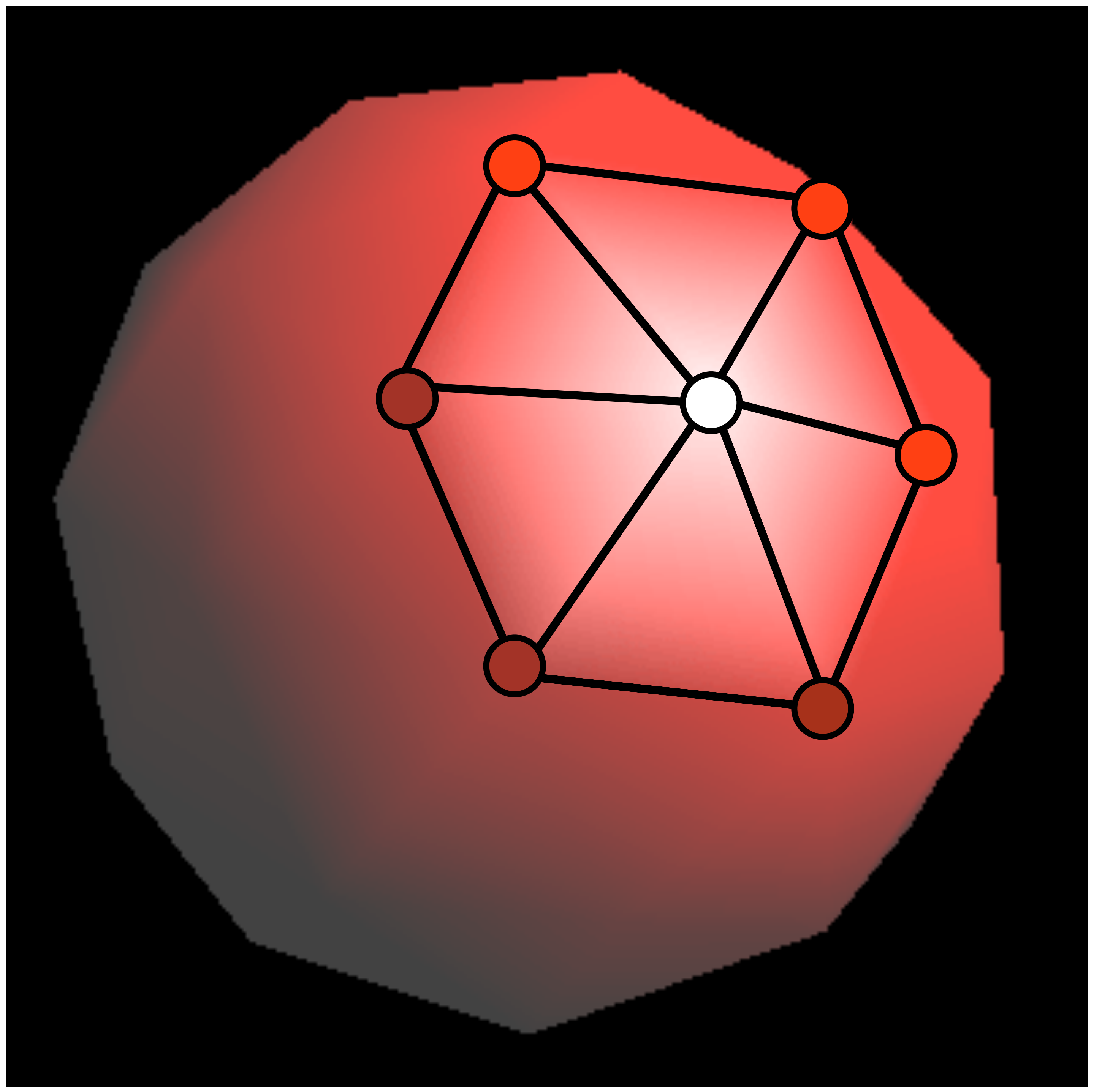
independent processing of each vertex

Vertex Shader Program *

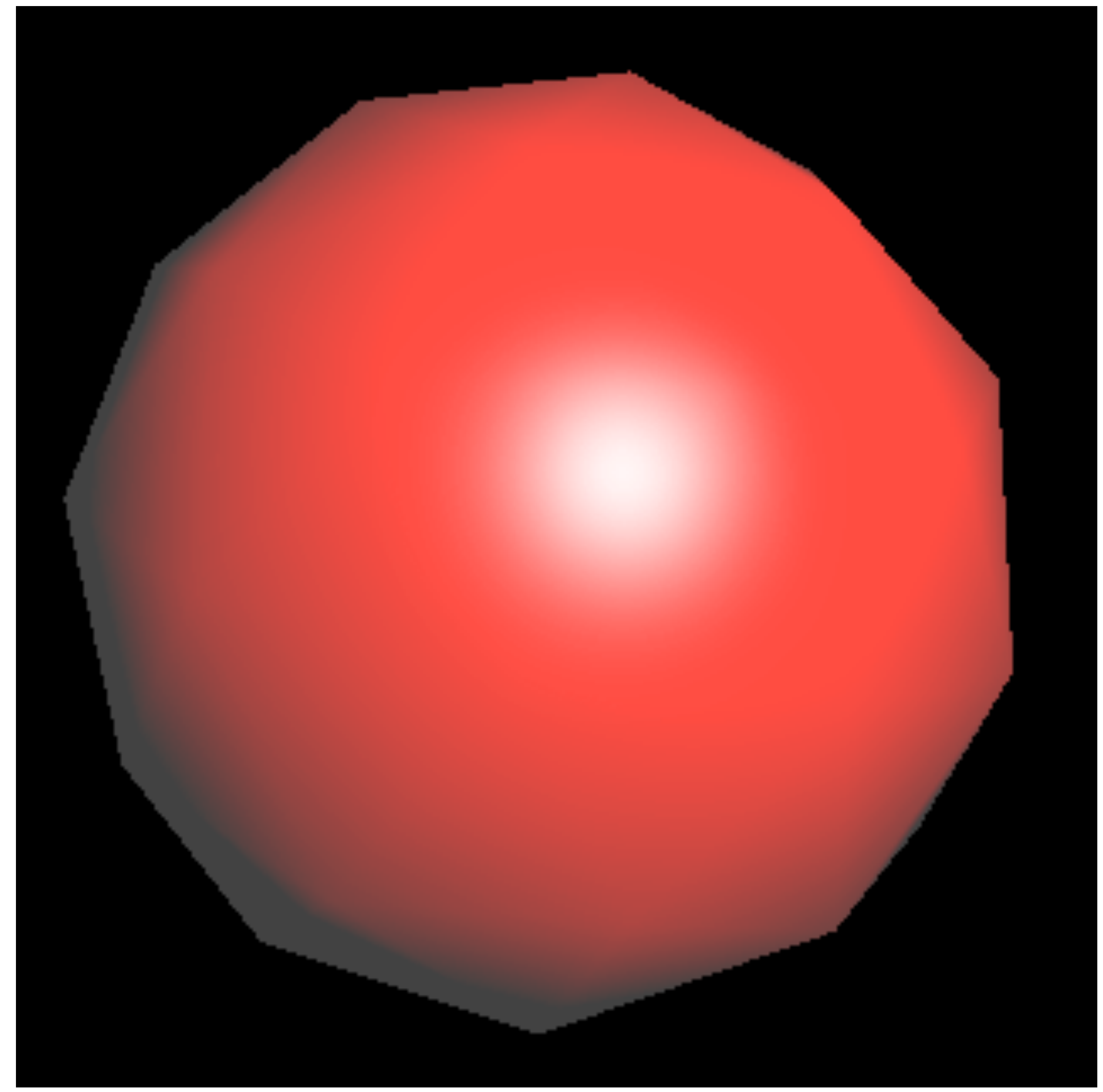
```
uniform mat4 my_transform;   // P * T

output_vertex my_vertex_program(input_vertex in) {
    output_vertex out;
    out.pos = my_transform * in.pos; // matrix-vector mult
    return out;
}
```

(* Note: this is pseudocode, not valid GLSL syntax)

Example per-vertex computation: lighting



Per-vertex lighting computation

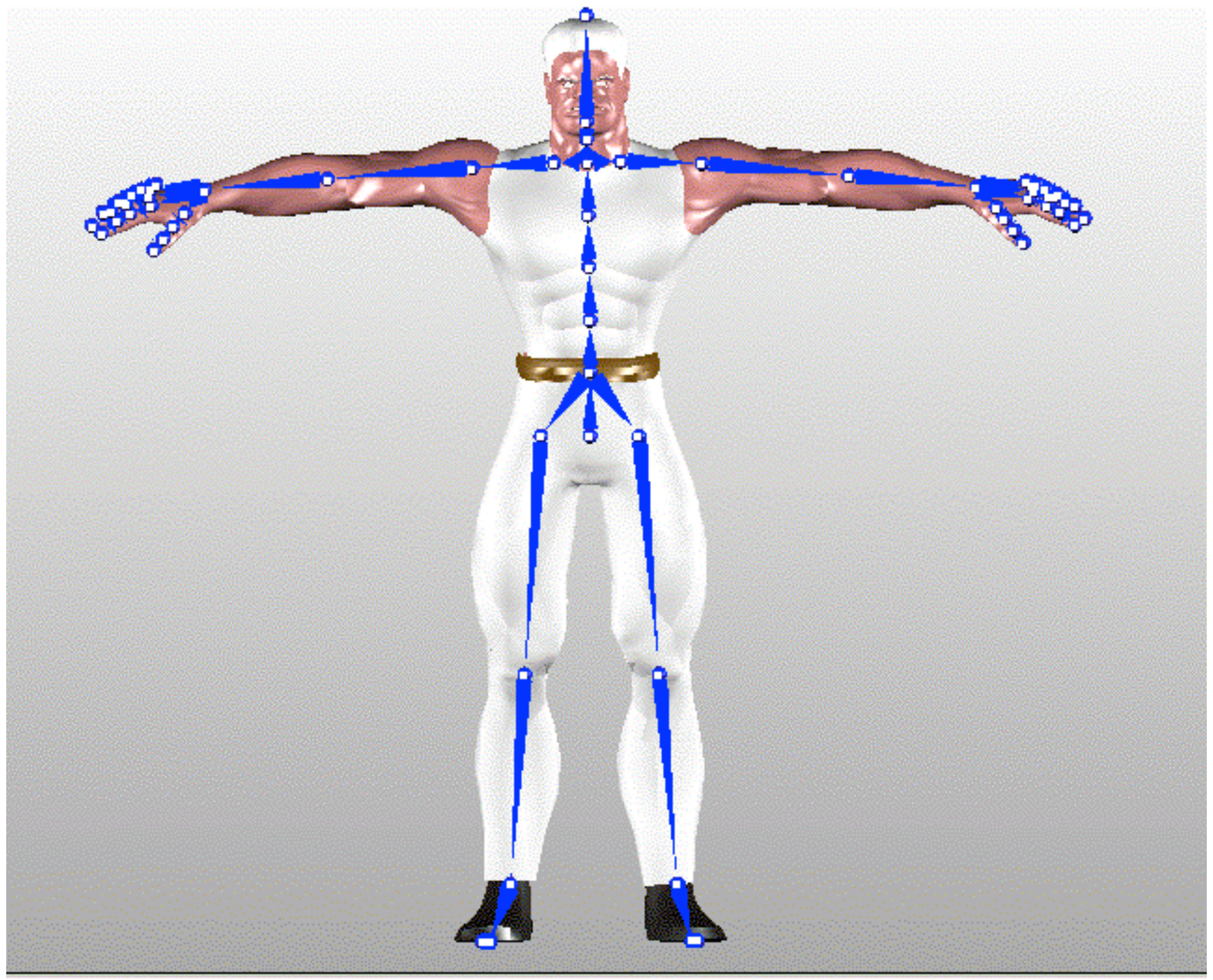


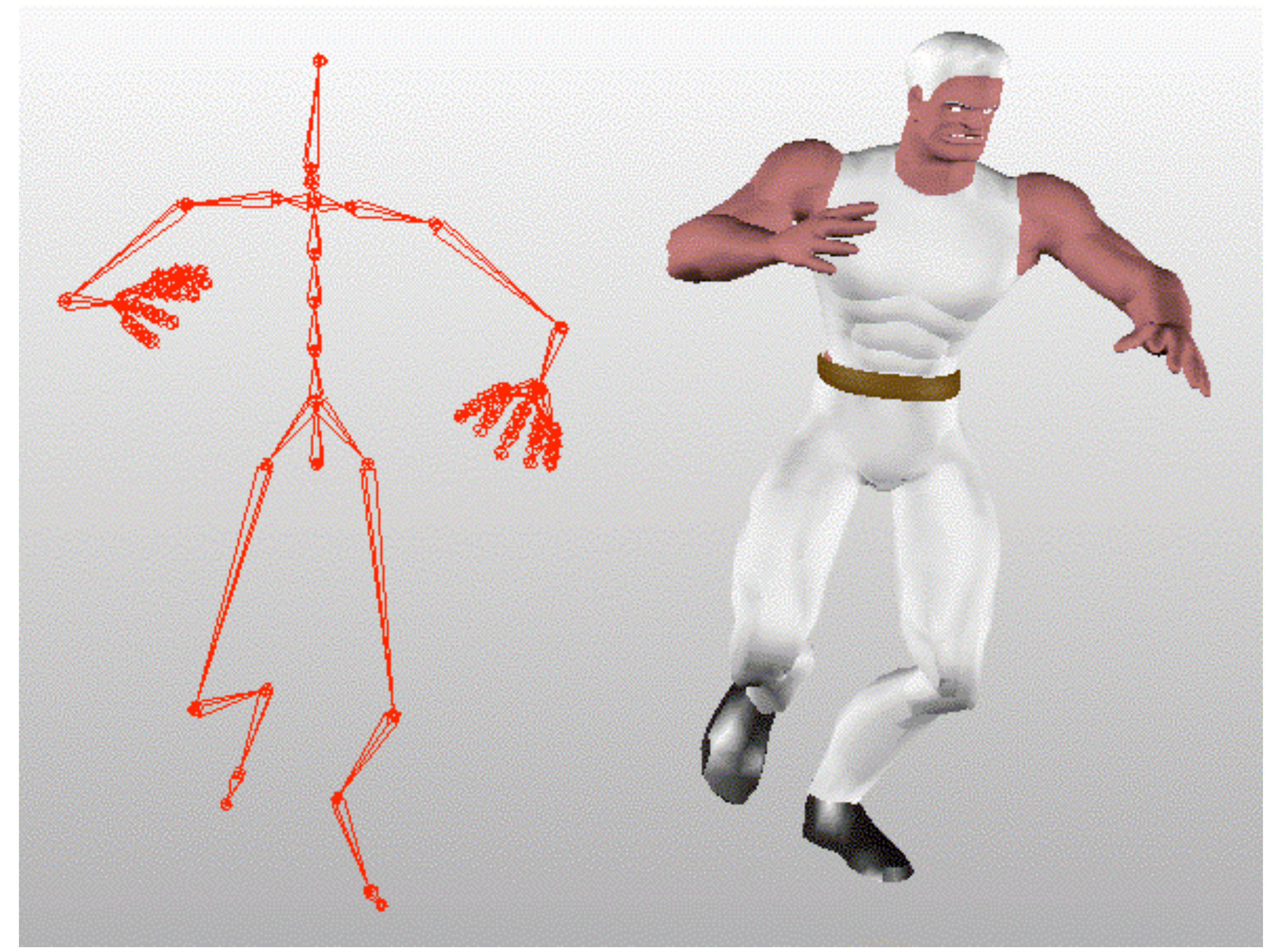
Per-vertex normal computation, per pixel lighting

Input per-vertex data: surface normal, surface color

Input uniform data: light direction, light color

Example per-vertex computation: skeletal animation via “skinning”





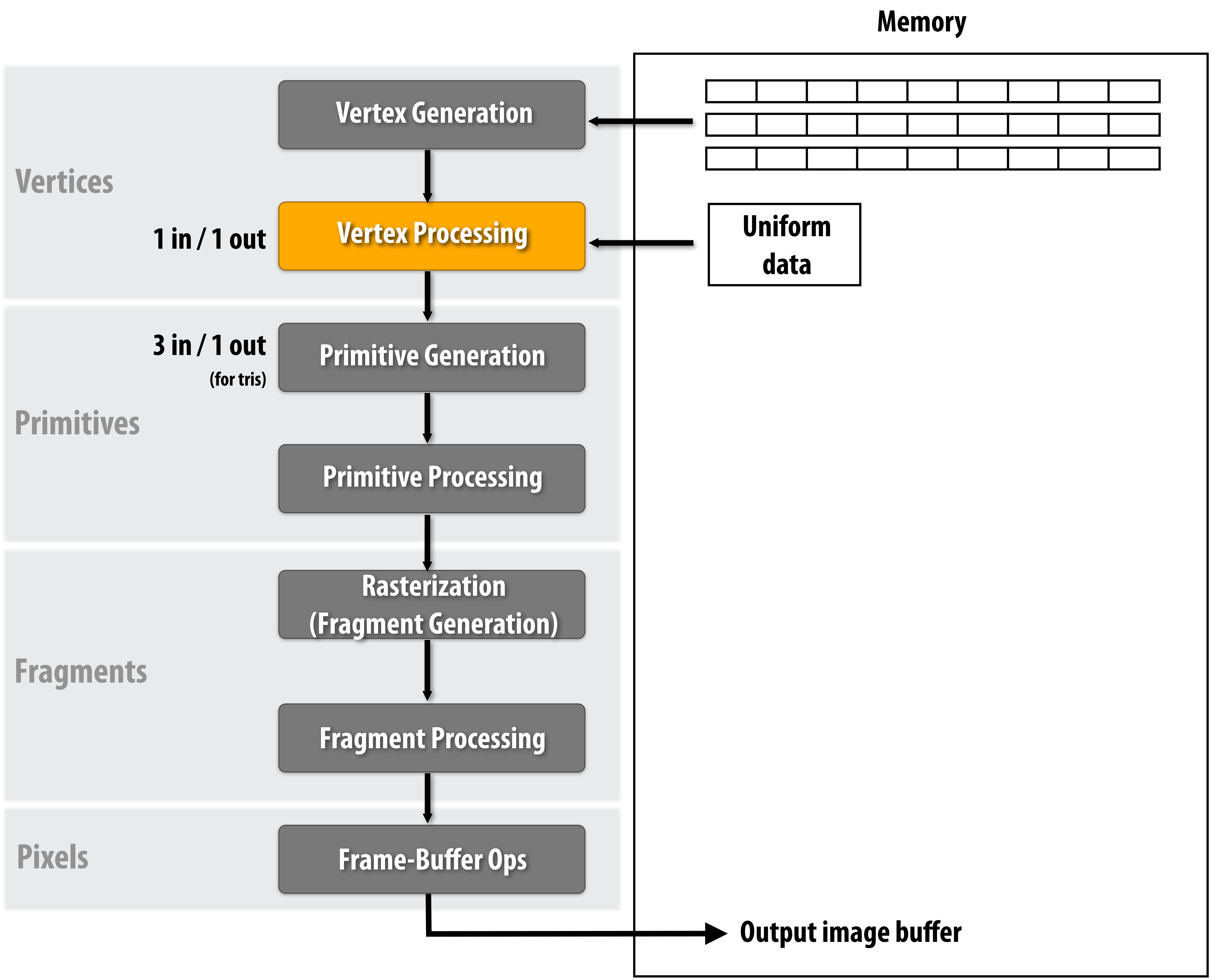
$$V_{skinned} = \sum_{b \in bones} w_b M_b V_{base}$$

Input per-vertex data: base vertex position (V_{base}) + blend coefficients (w_b)

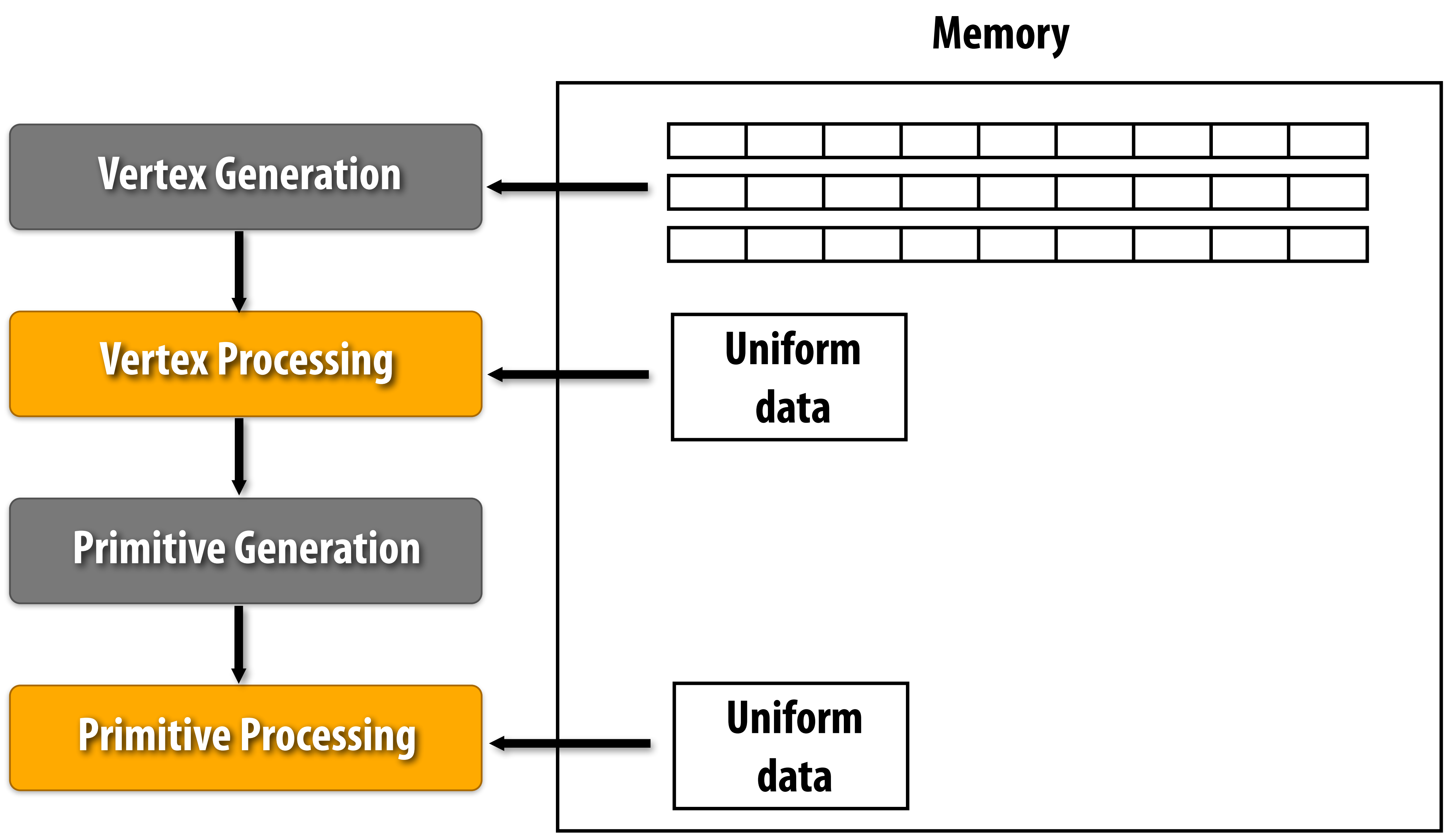
Input: uniform data: “bone” matrices (M_b) for current animation frame

Image credit: http://www.okino.com/conv/skinning.htm

Primitive generation: group vertices into primitives



Programmable primitive processing *



input vertices for 1 prim ⟶ output vertices for N prims **

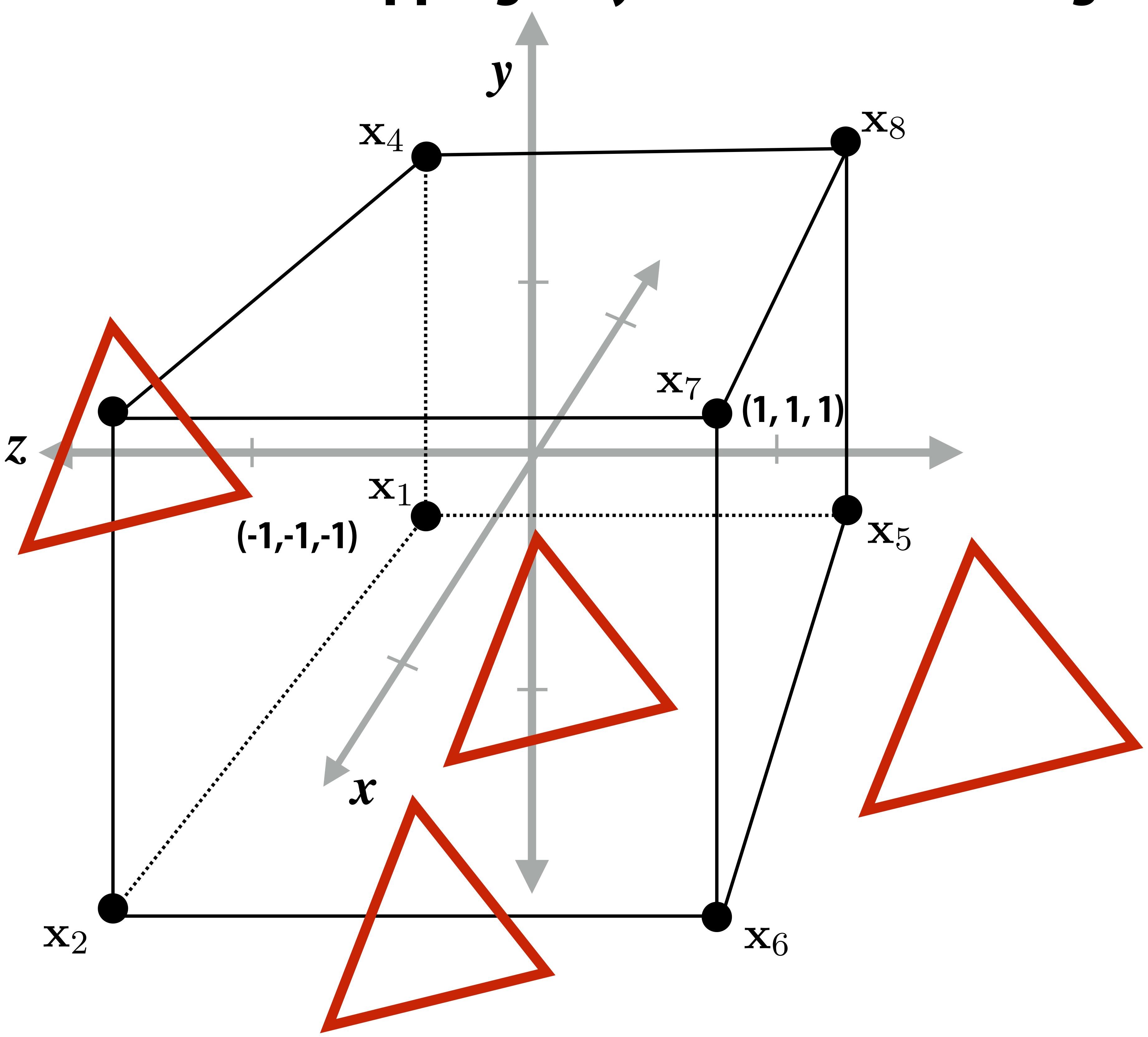
independent processing of each INPUT primitive

* "Geometry shader" in OpenGL/Direct3D terminology

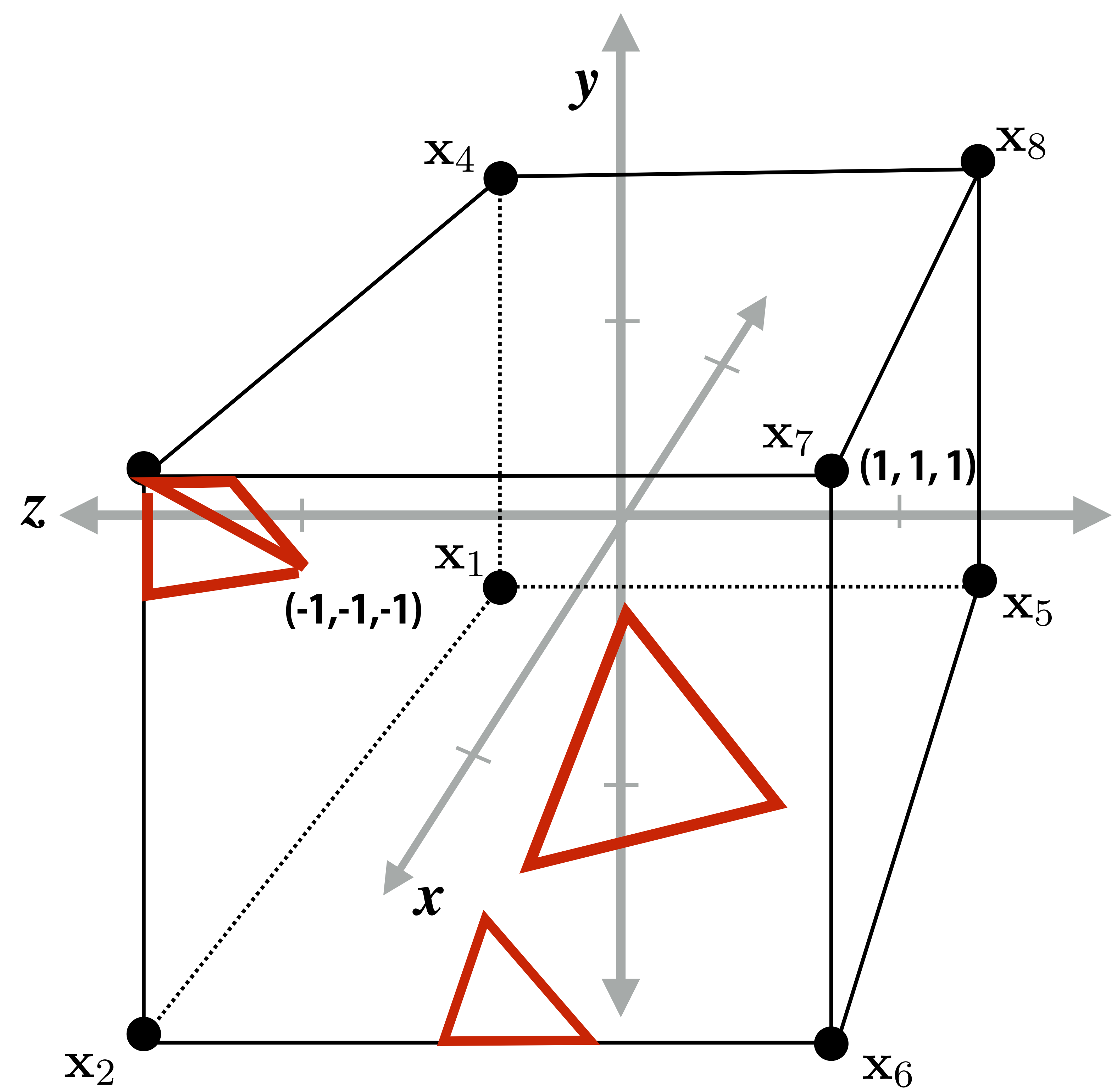
** Pipeline caps output at 1024 floats of output

Primitive processing: 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



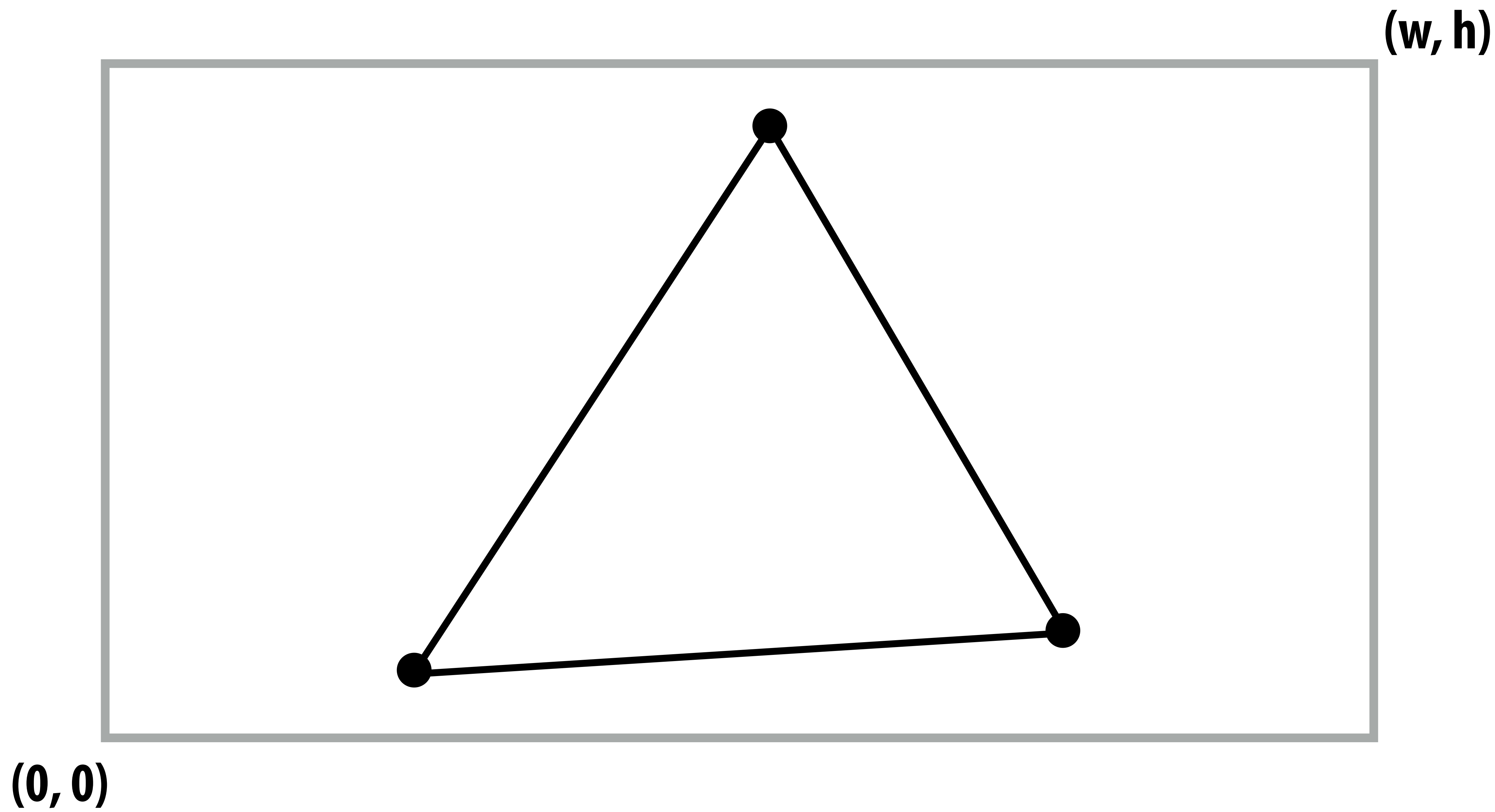
Triangles before clipping



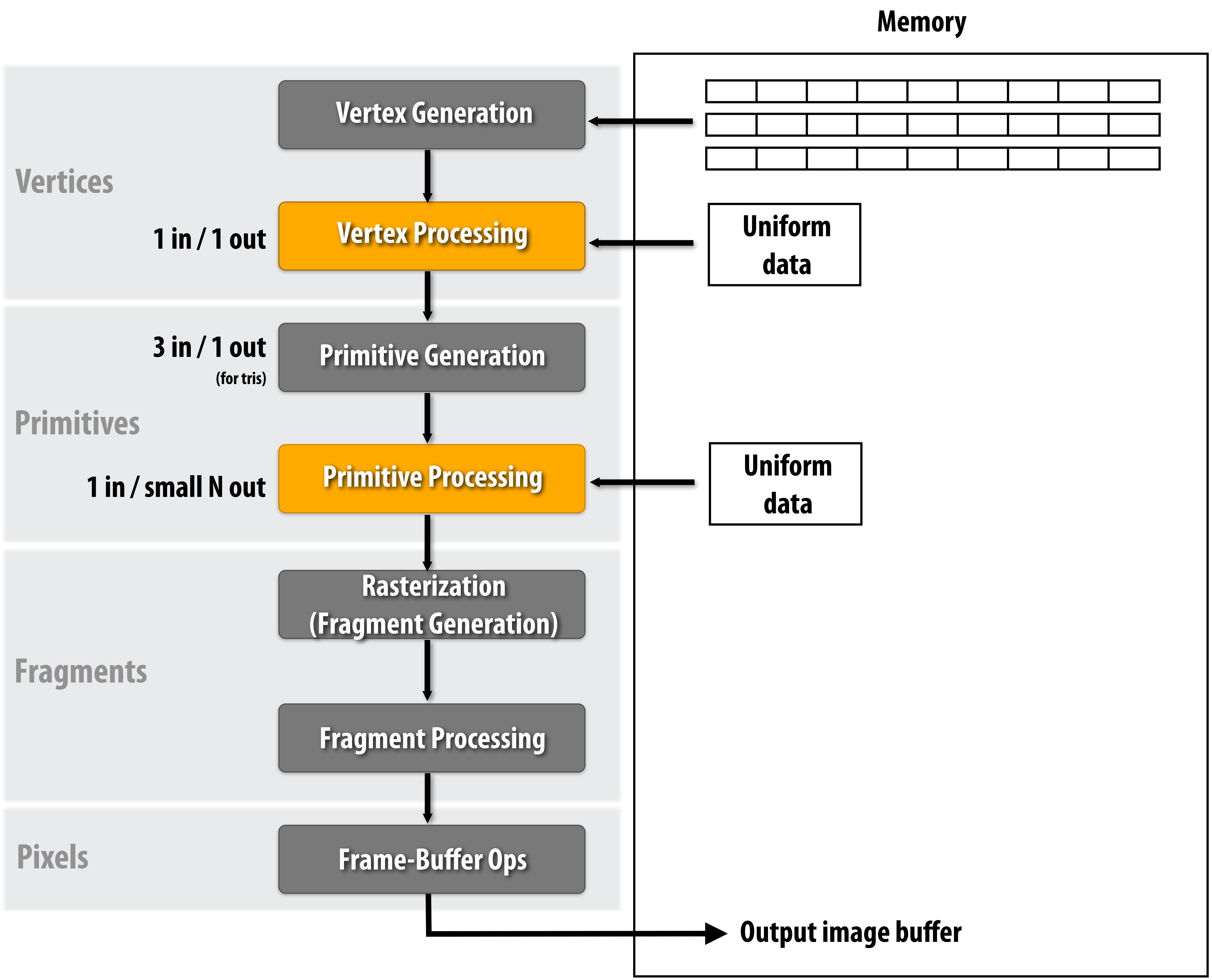
Triangles after clipping

Transform to screen coordinates

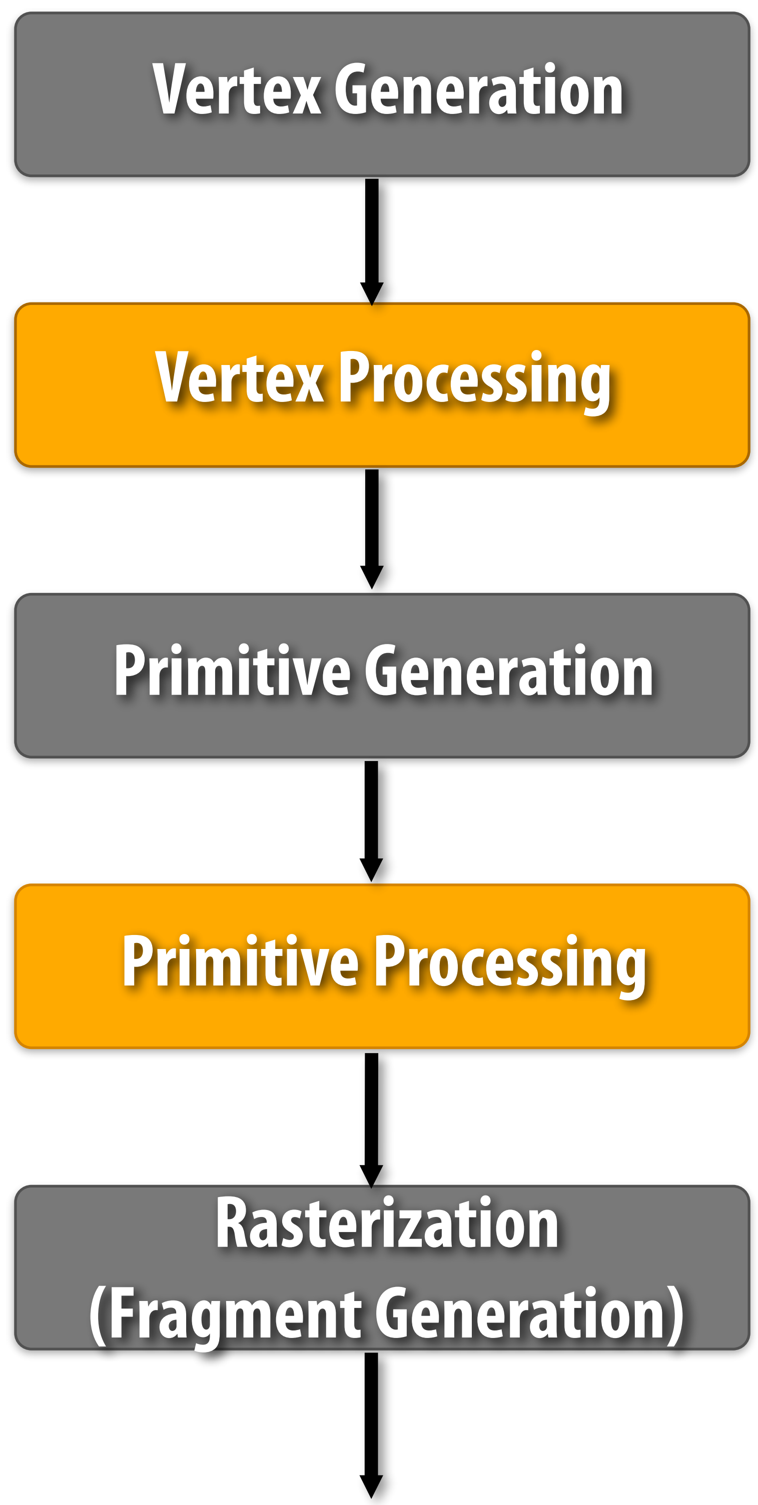
Transform vertex xy positions from normalized coordinates into screen coordinates (based on screen w,h)



The graphics pipeline

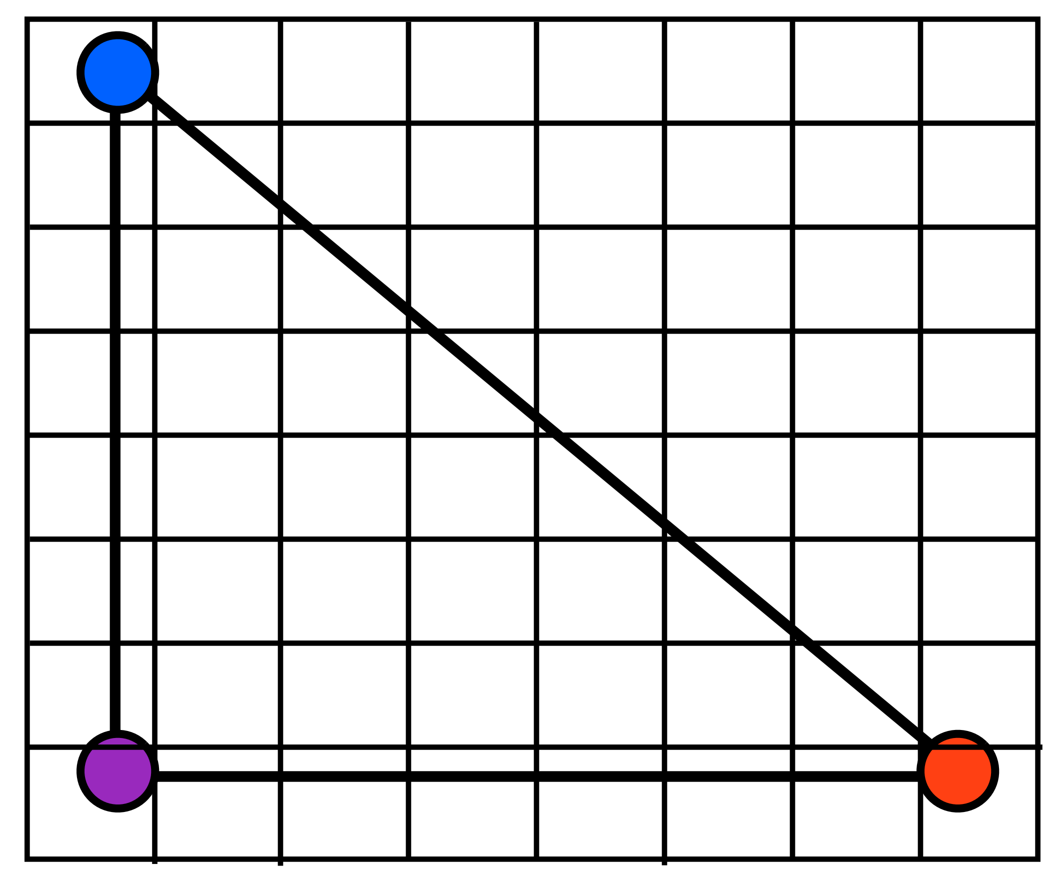


Rasterization (fragment generation)



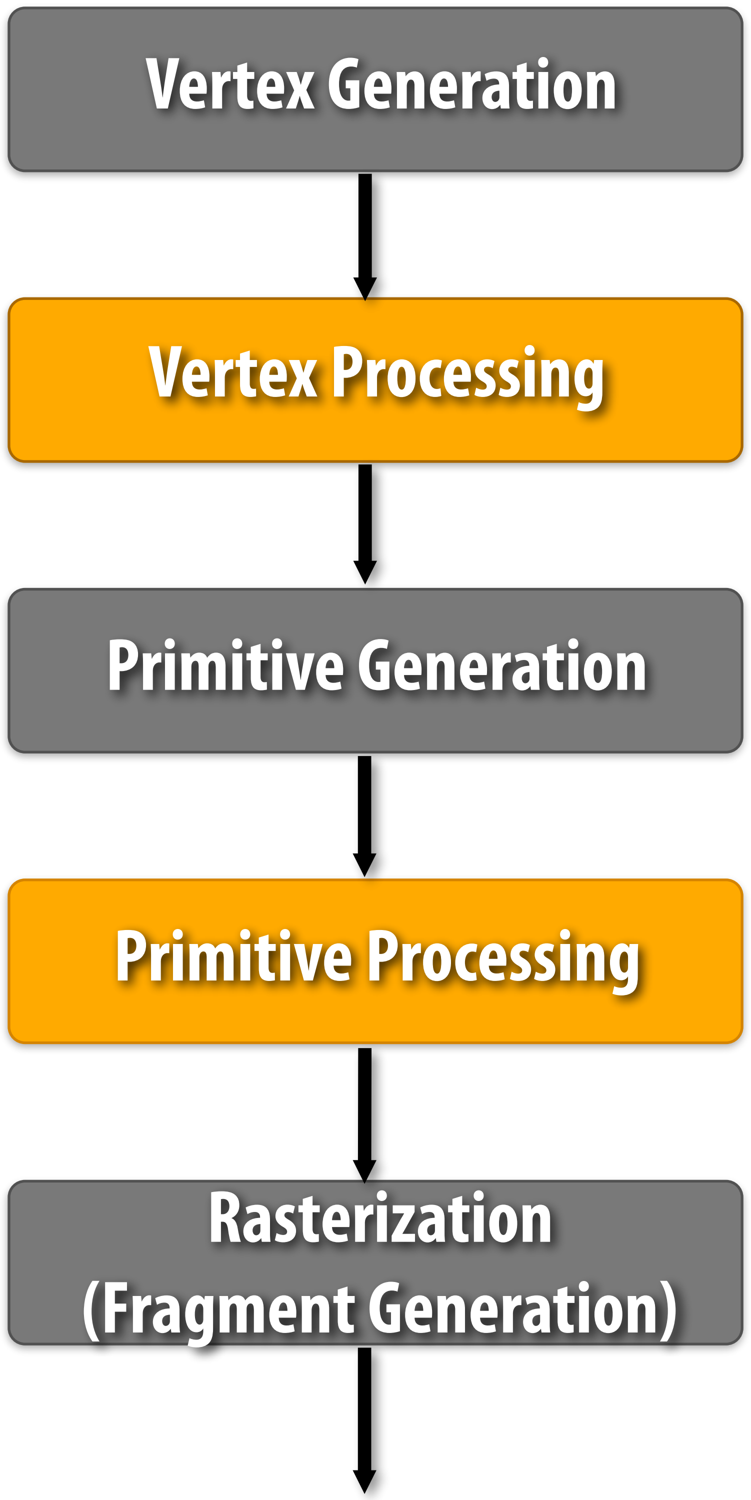
1 input prim ⟶ N output fragments

N is unbounded
(size of triangles varies greatly)



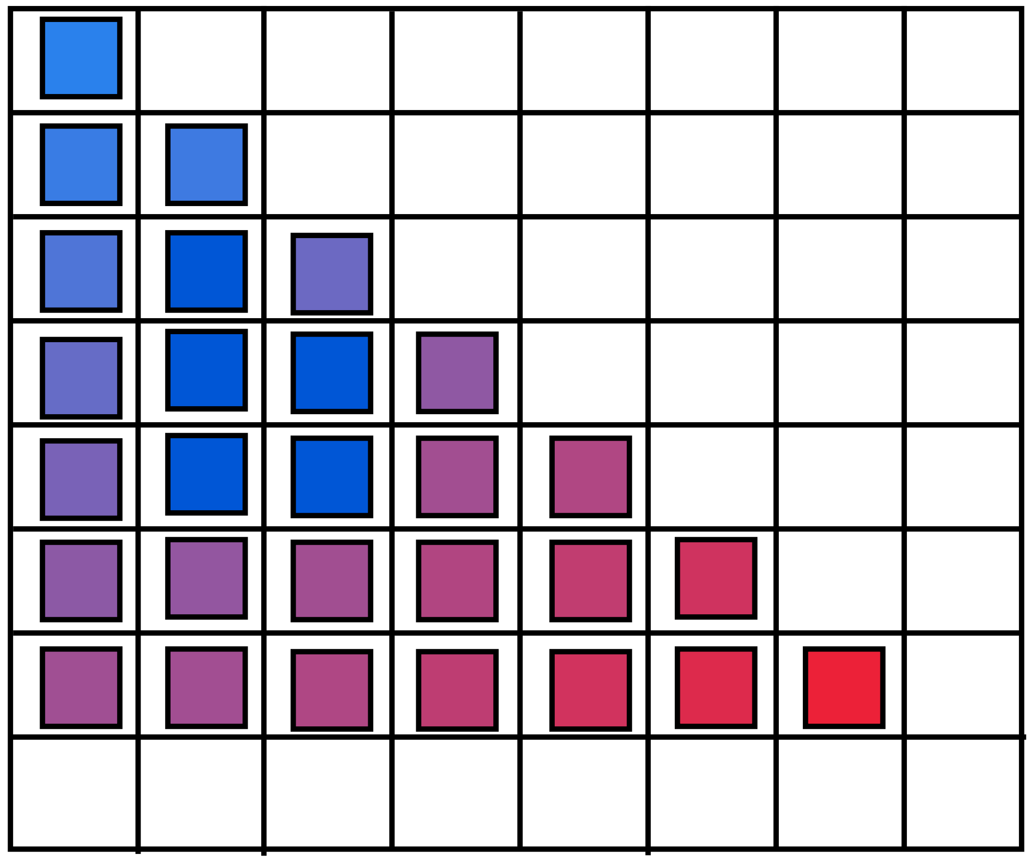
```
struct fragment       // note similarity to output_vertex from before
{
   float  x,y;        // screen pixel coordinates (sample point location)
   float  z;          // depth of triangle at sample point

   float3 normal;     // interpolated application-defined attribs
   float2 texcoord;   // (e.g., texture coordinates, surface normal)
};
```

Rasterization (fragment generation)



Compute covered pixels

Sample vertex attributes once per covered pixel



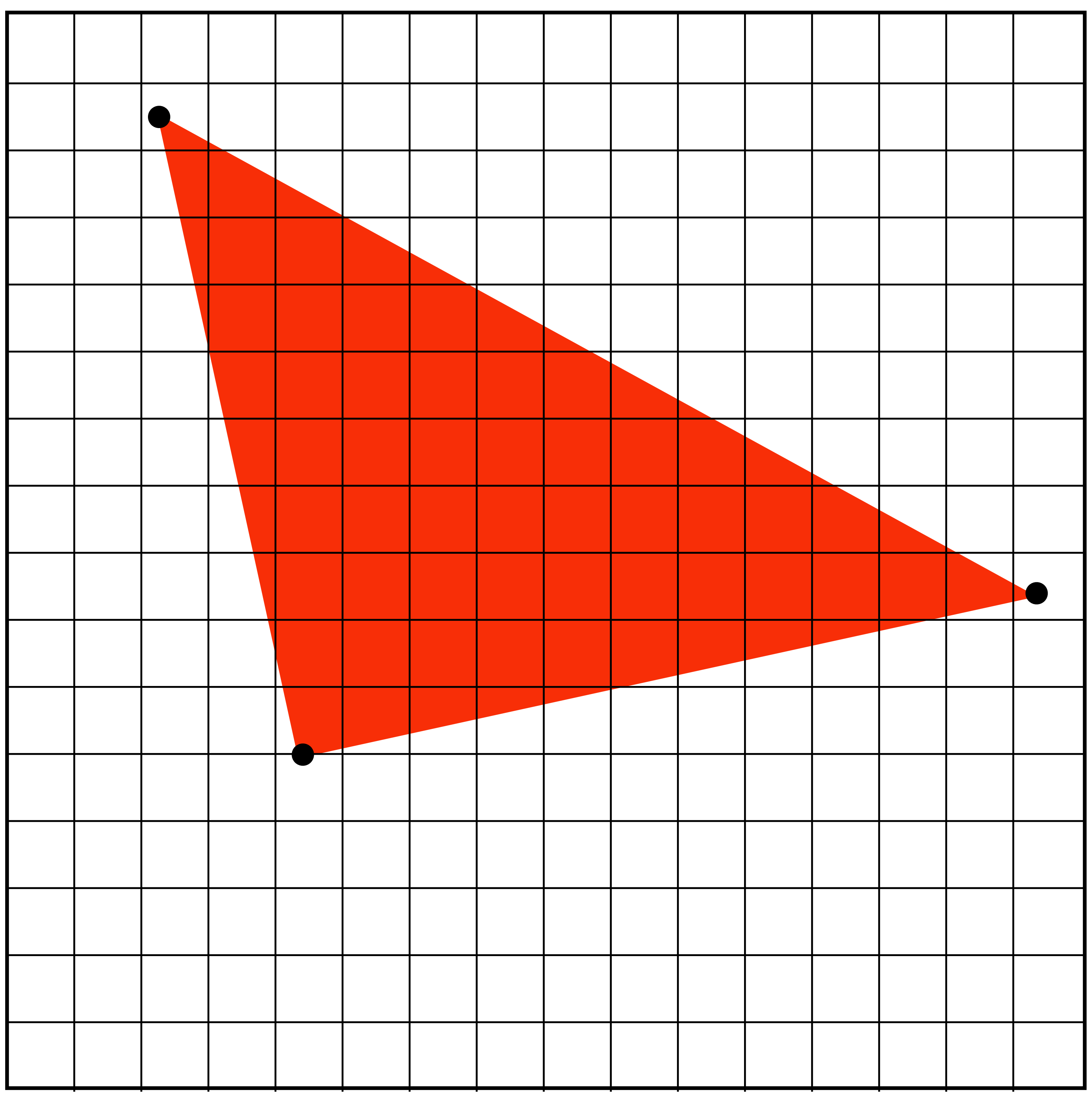
```
struct fragment      // note similarity to output_vertex from before
{
   float  x,y;       // screen pixel coordinates (sample point location)
   float  z;         // depth of triangle at sample point

   float3 normal;    // interpolated application-defined attribs
   float2 texcoord;  // (e.g., texture coordinates, surface normal)

}
```

Implementation of rasterization

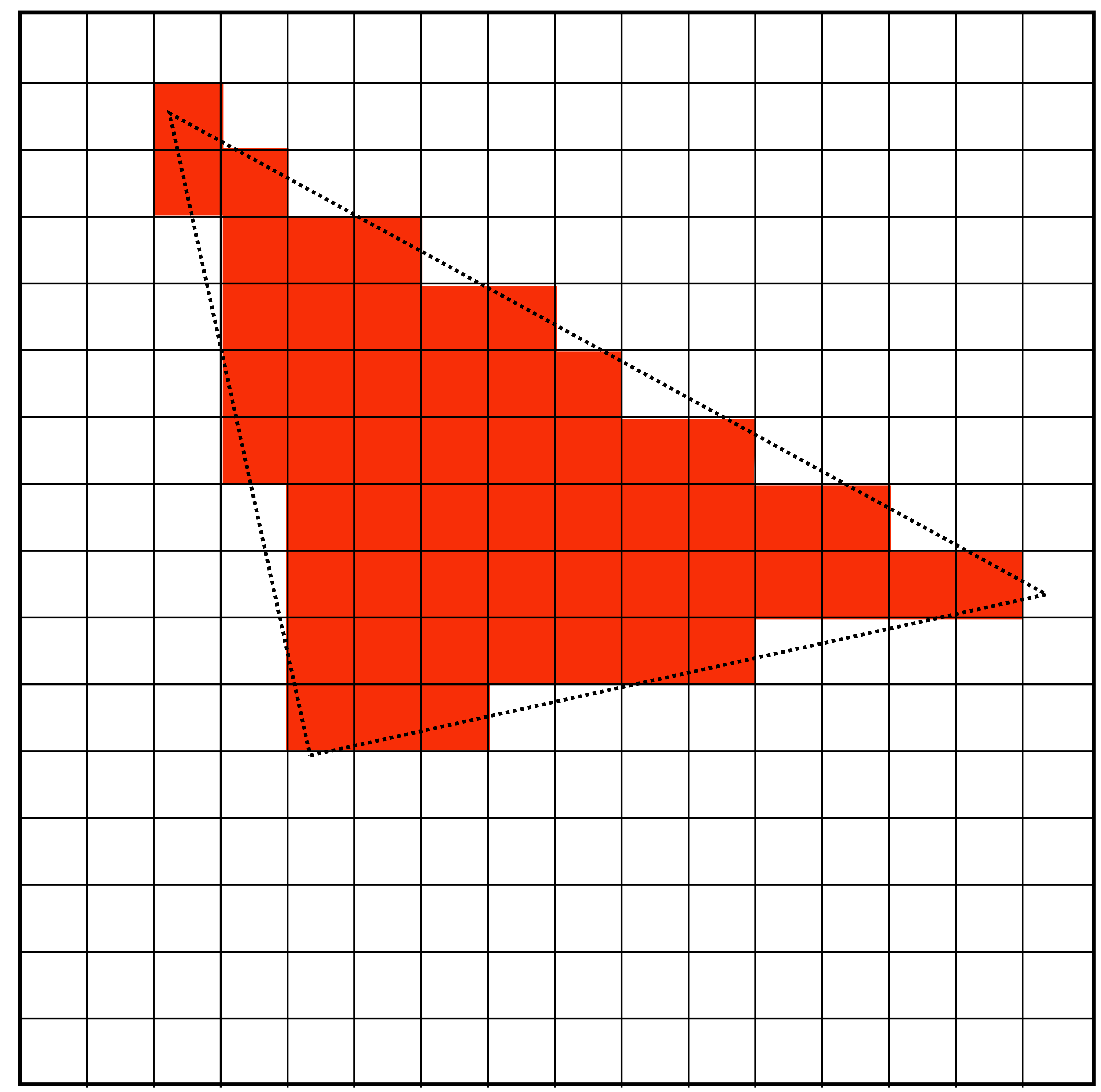
Computing triangle coverage

What pixels does the triangle overlap?

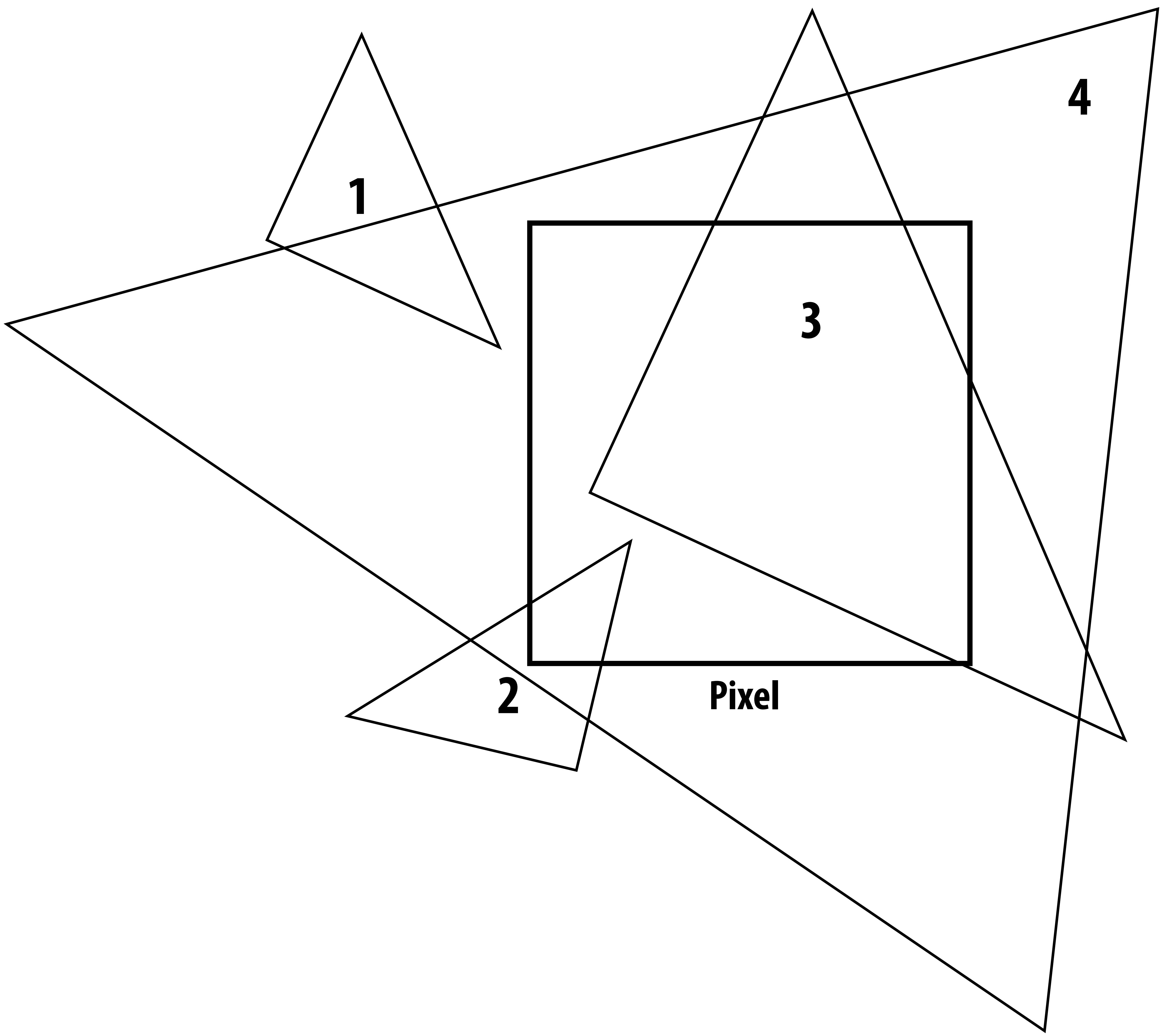
Input:
projected position of triangle vertices: P_0, P_1, P_2



Output:
set of pixels "covered" by the triangle



What does it mean for a pixel to be covered by a triangle?

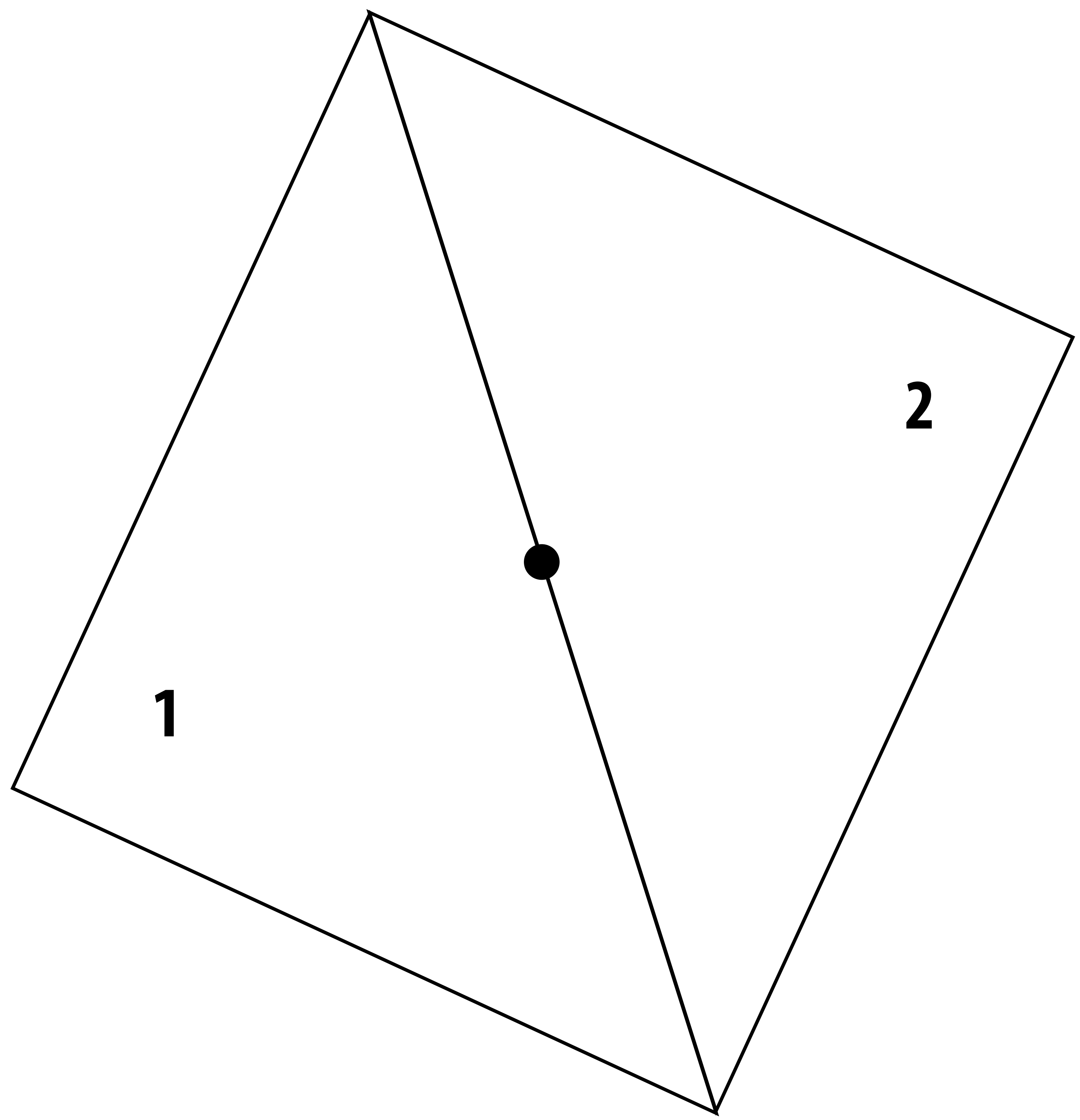


Sampling 2D triangle coverage signal

$$\text{coverage(x,y)} = \begin{cases} 1 & \text{if the triangle contains point (x,y)} \\ 0 & \text{otherwise} \end{cases}$$

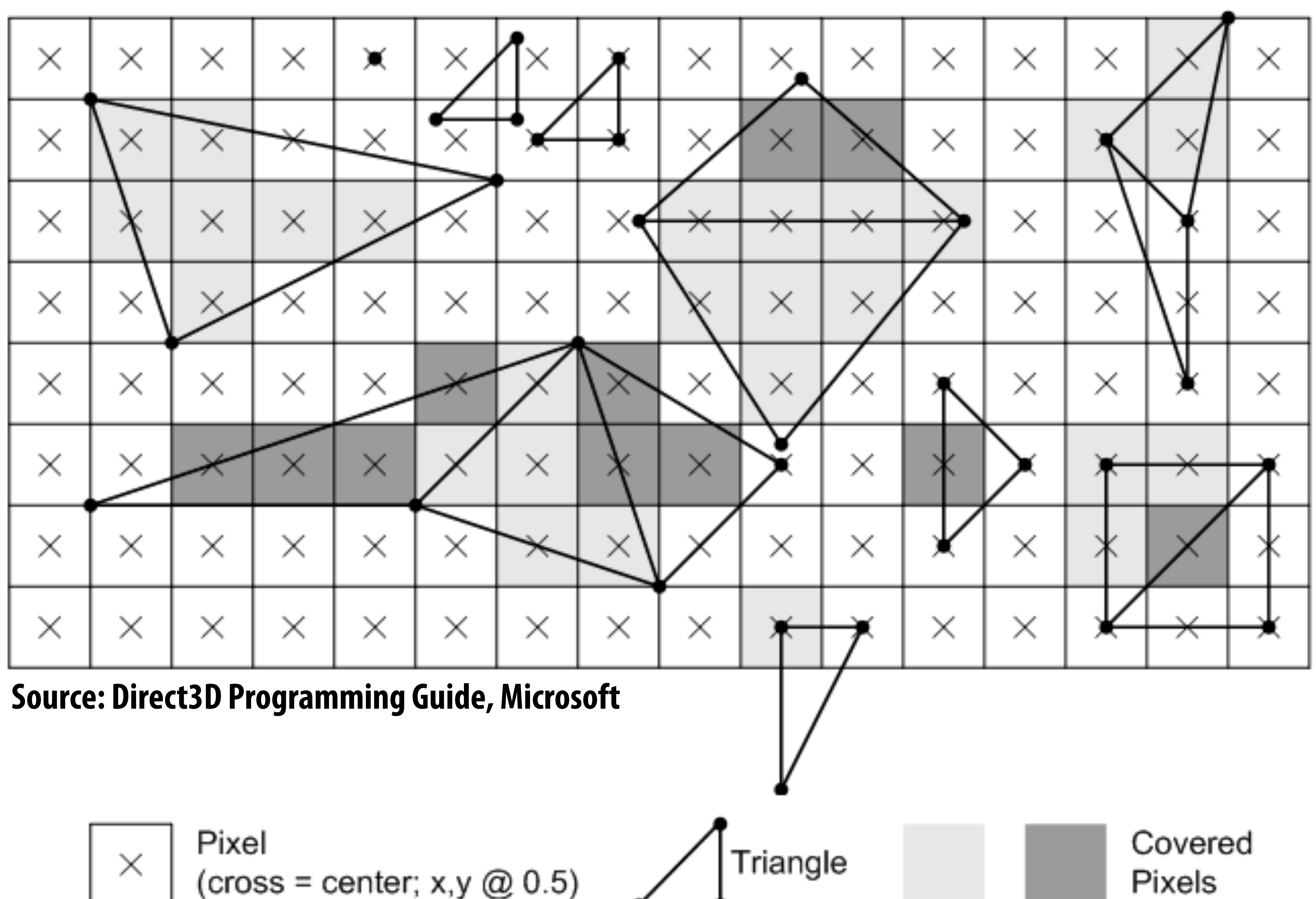
Edge cases (literally)

Is this sample point covered by triangle 1? or triangle 2? or both?



Edge rules

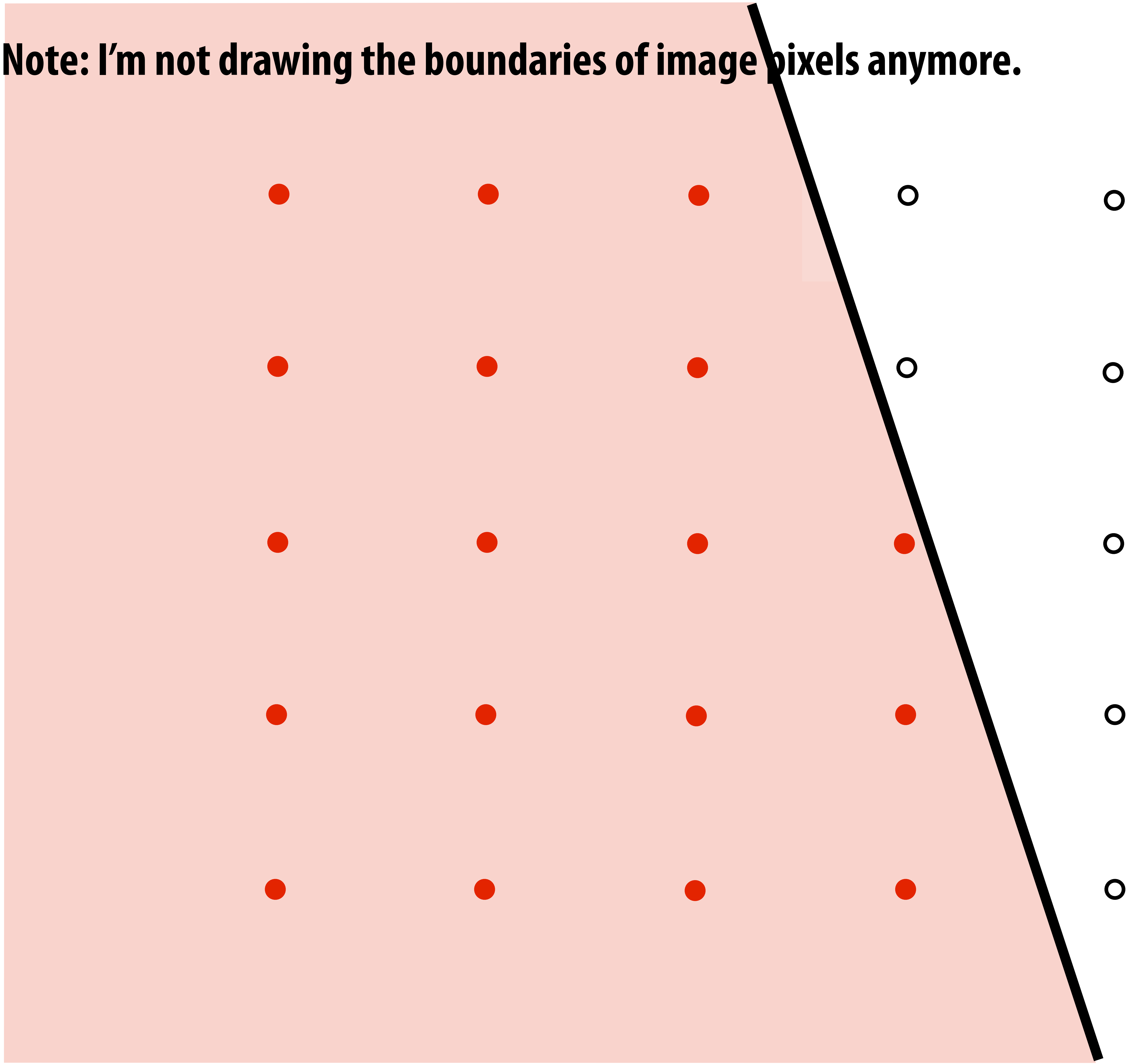
- Direct3D rules: when edge falls directly on sample, sample classified as within triangle if the edge is a "top edge" or "left edge"
    - Top edge: horizontal edge that is above all other edges
    - Left edge: an edge that is not exactly horizontal and is on the left side of the triangle. (triangle can have one or two left edges)



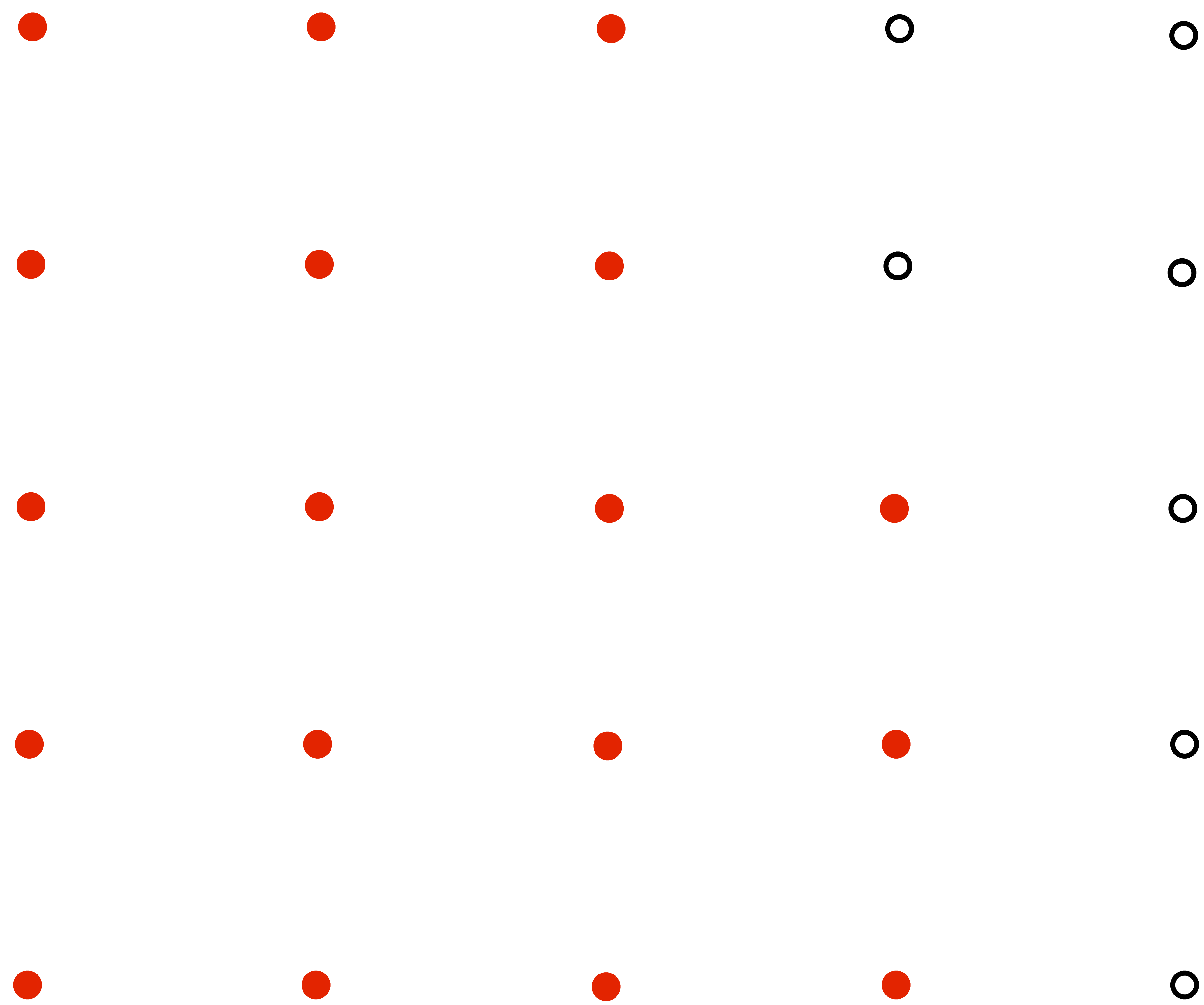
Source: Direct3D Programming Guide, Microsoft

Results of sampling triangle coverage

Note: I'm not drawing the boundaries of image pixels anymore.



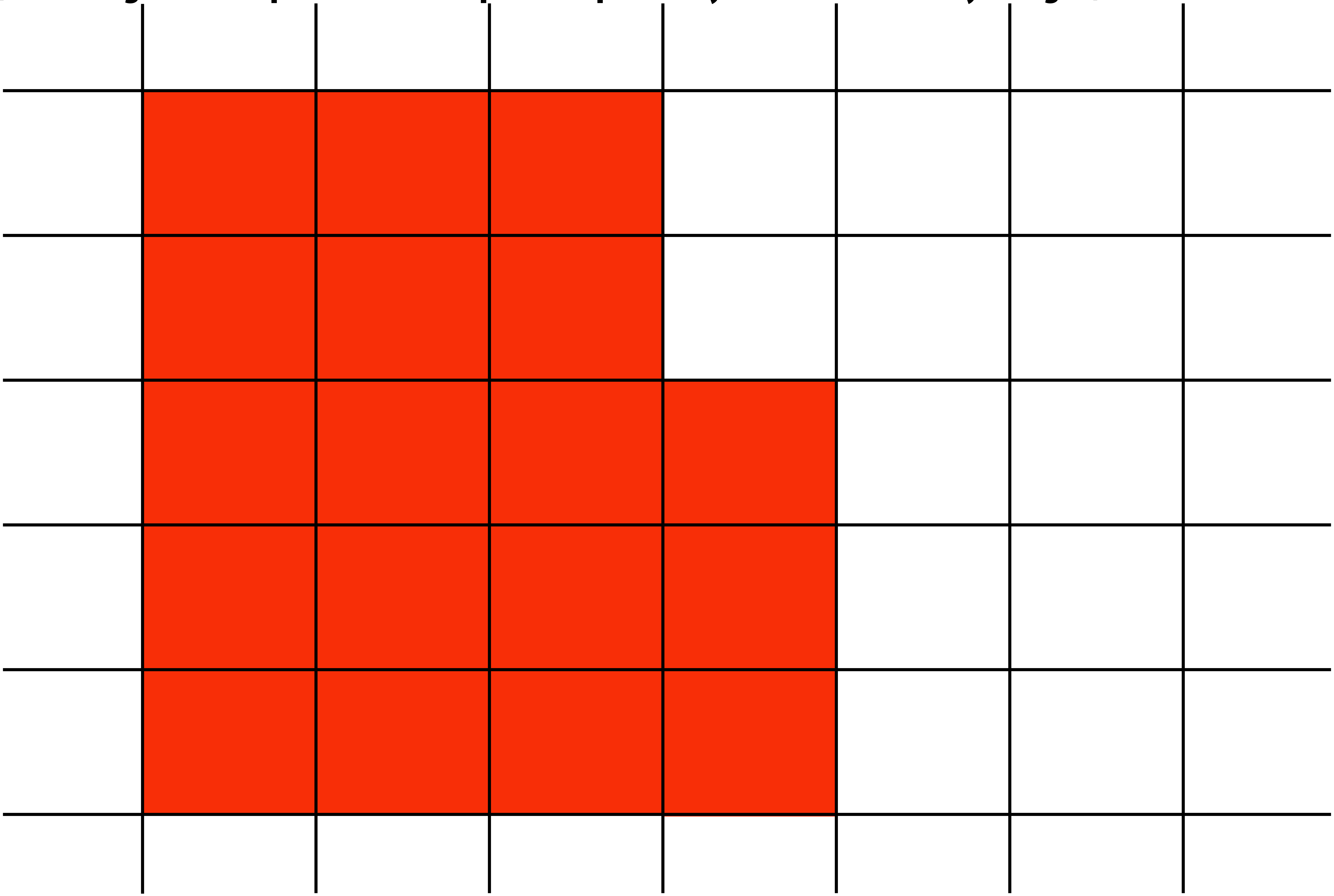
I have a sampled signal, now I want to display it on a screen



So if we send the display this…

We might see this when we look at the screen

(assuming a screen pixel emits a square of perfectly uniform intensity of light)



Recall: the real coverage signal was this

Note: I'm not drawing the boundaries of image pixels anymore.

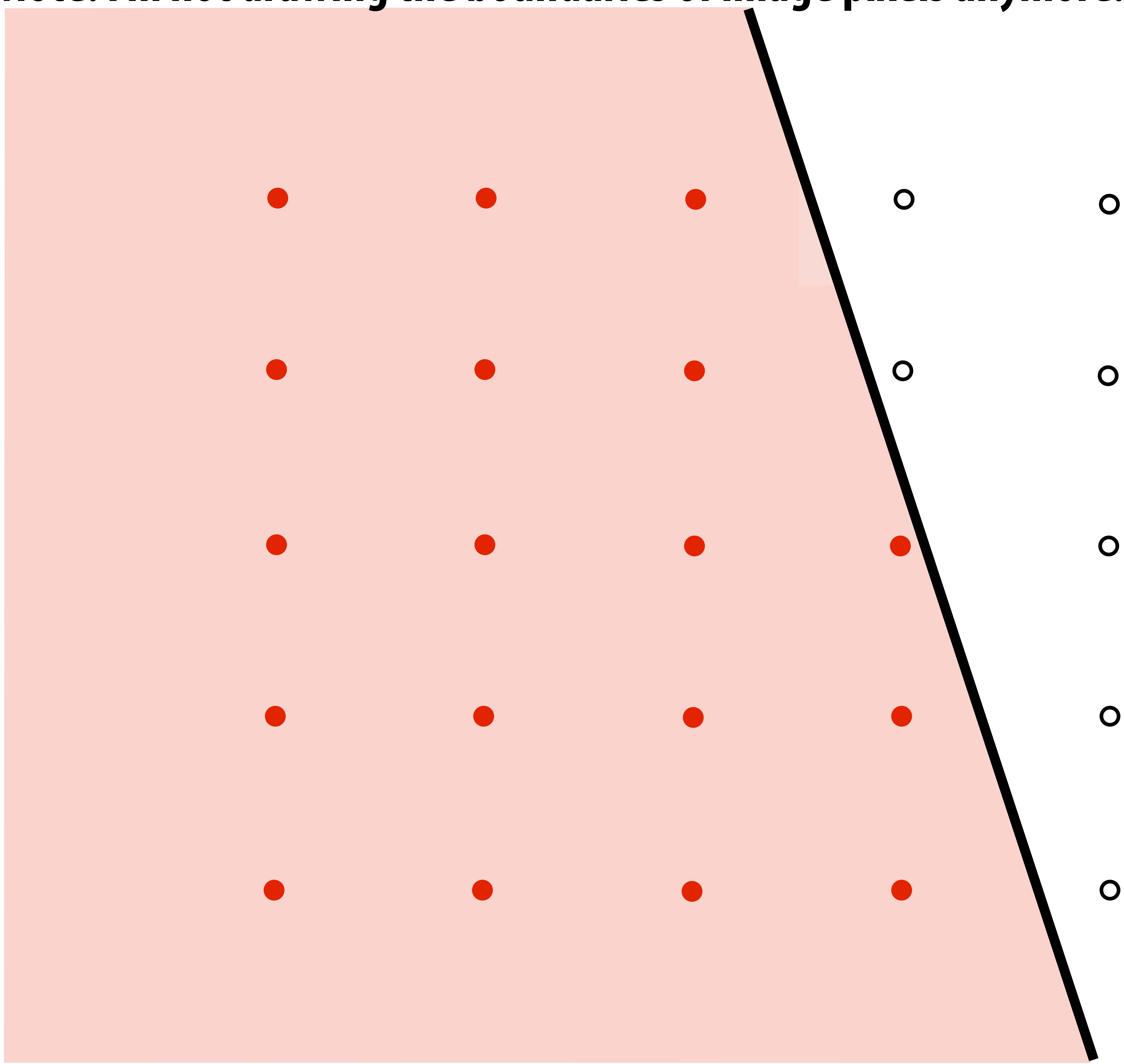
Problem: aliasing

- Undersampling high frequency signal results in aliasing
  - "Jaggies" in a single image
  - "Roping" or "shimmering" in an animation

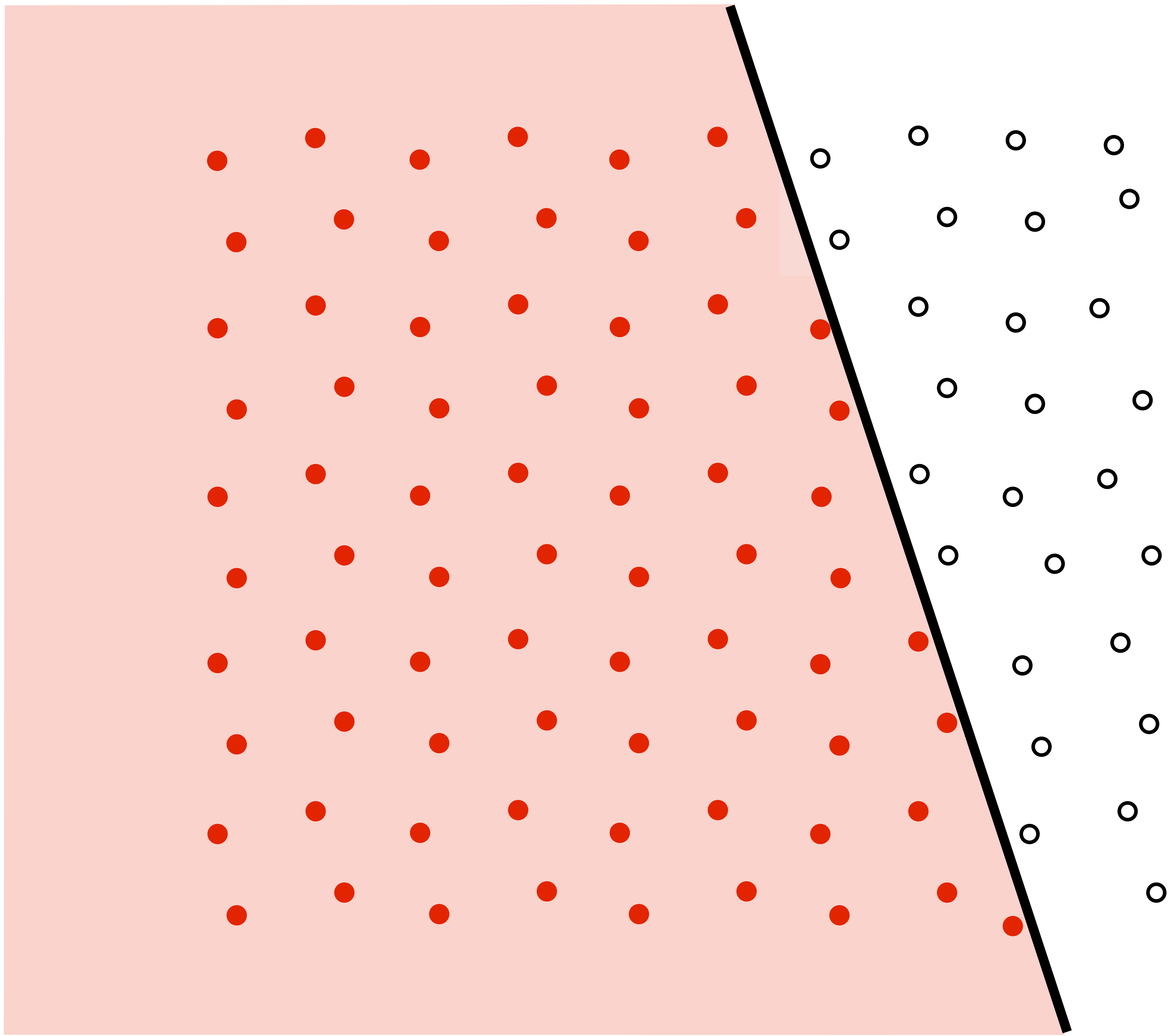
- High frequencies exist in coverage signal because of triangle edges

Initial coverage sampling rate (1 sample per pixel)

Note: I'm not drawing the boundaries of image pixels anymore.

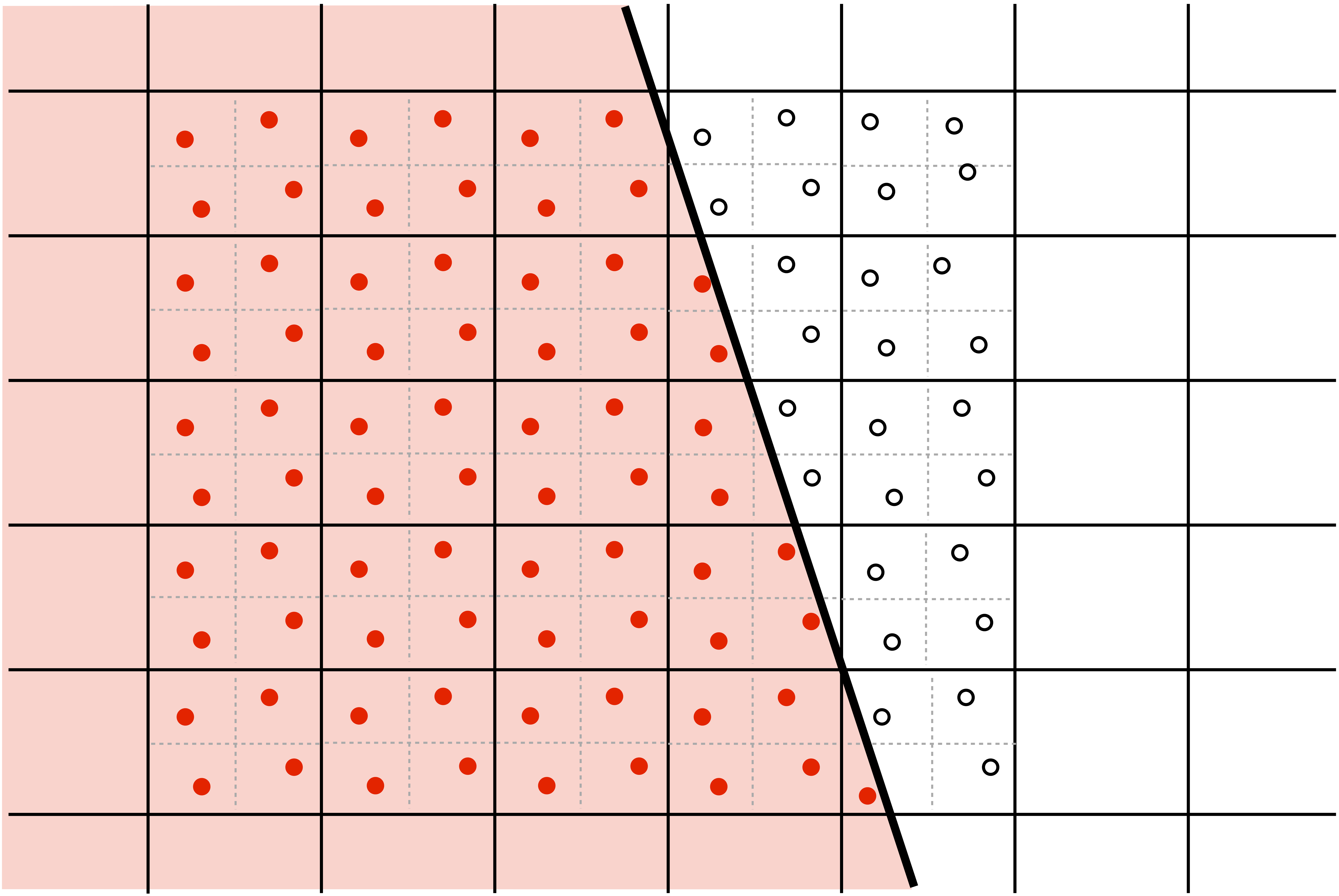


Increase density of sampling coverage signal



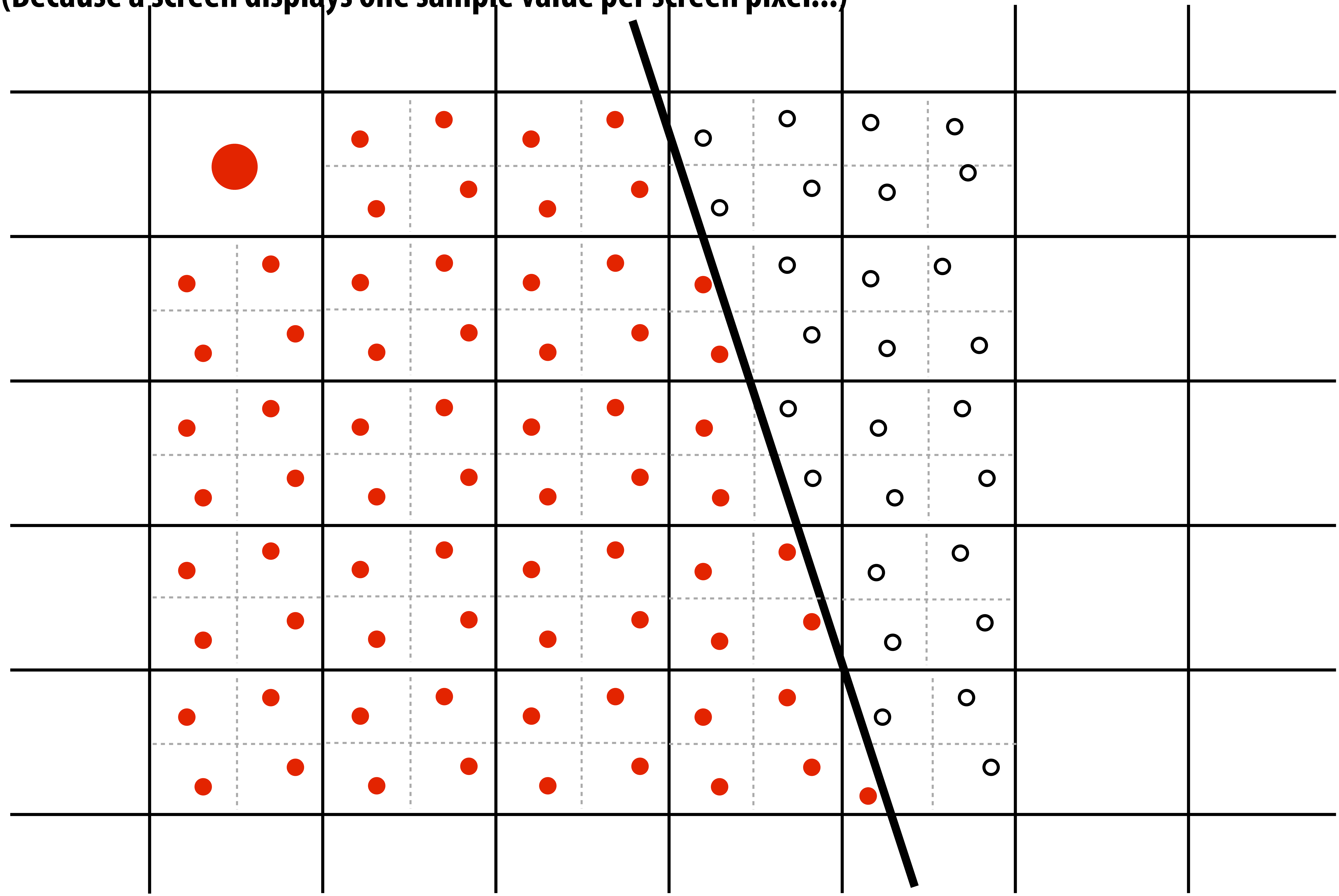
Supersampling

Example: stratified sampling using four samples per pixel

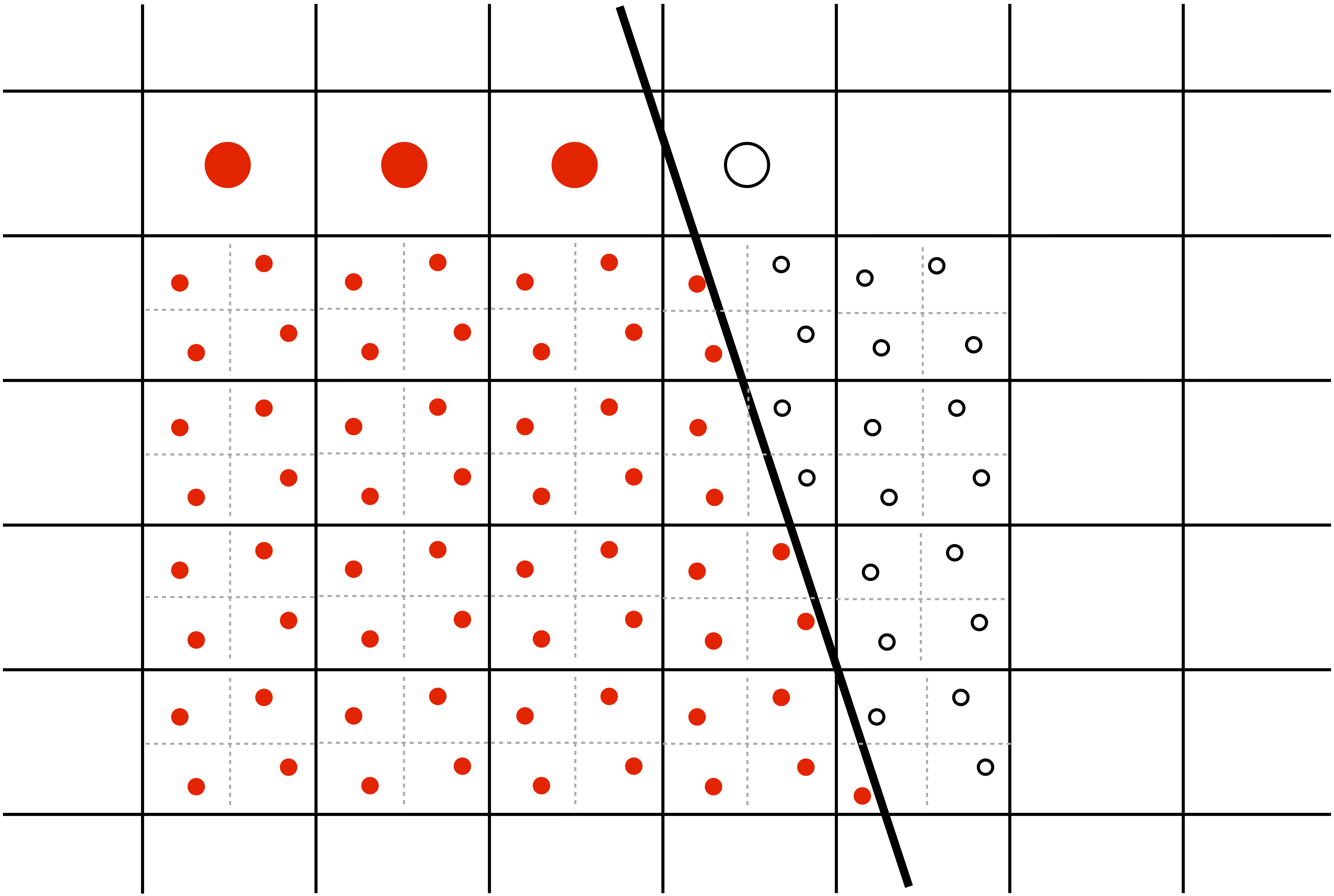


Resample to display's pixel resolution

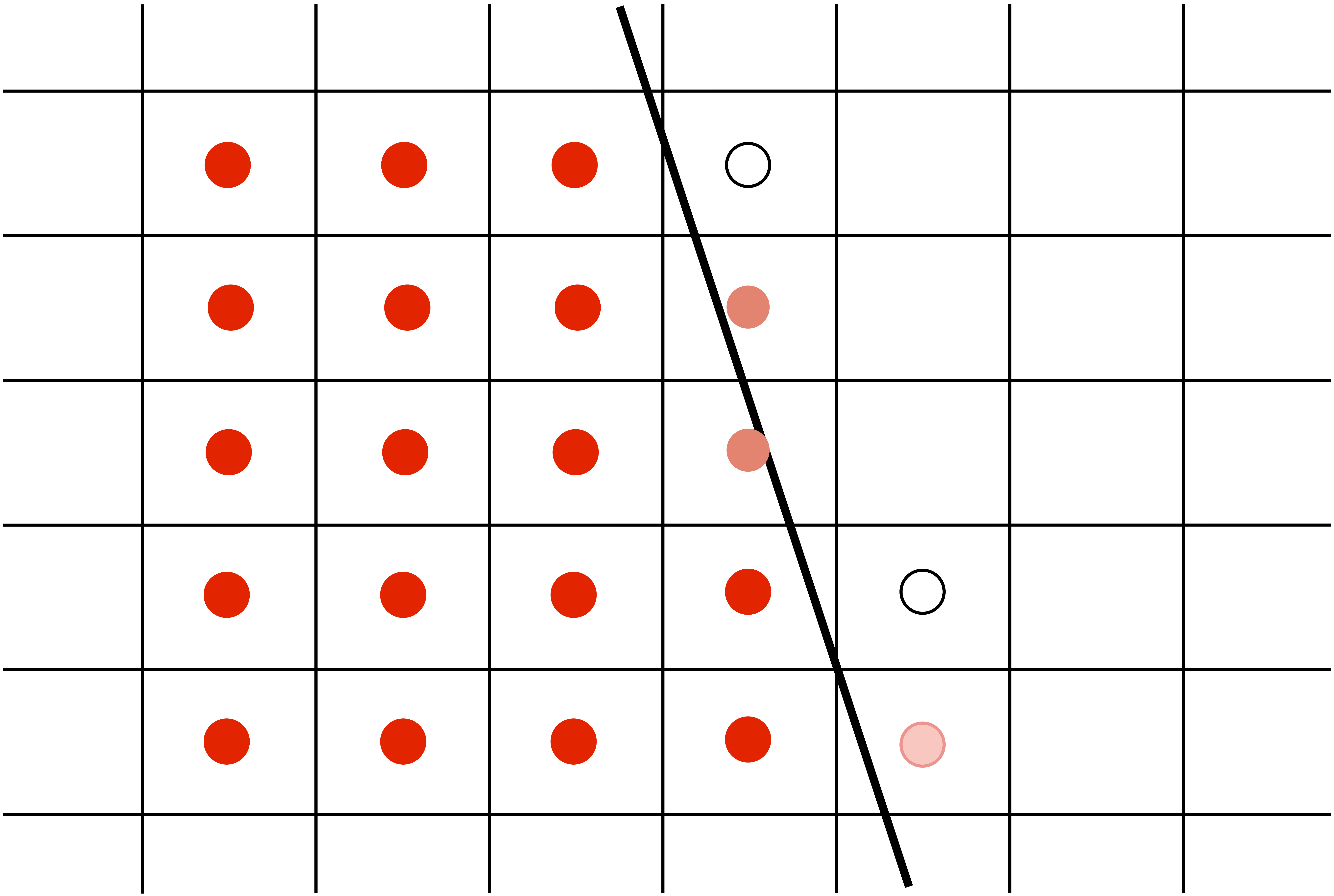
(Because a screen displays one sample value per screen pixel...)



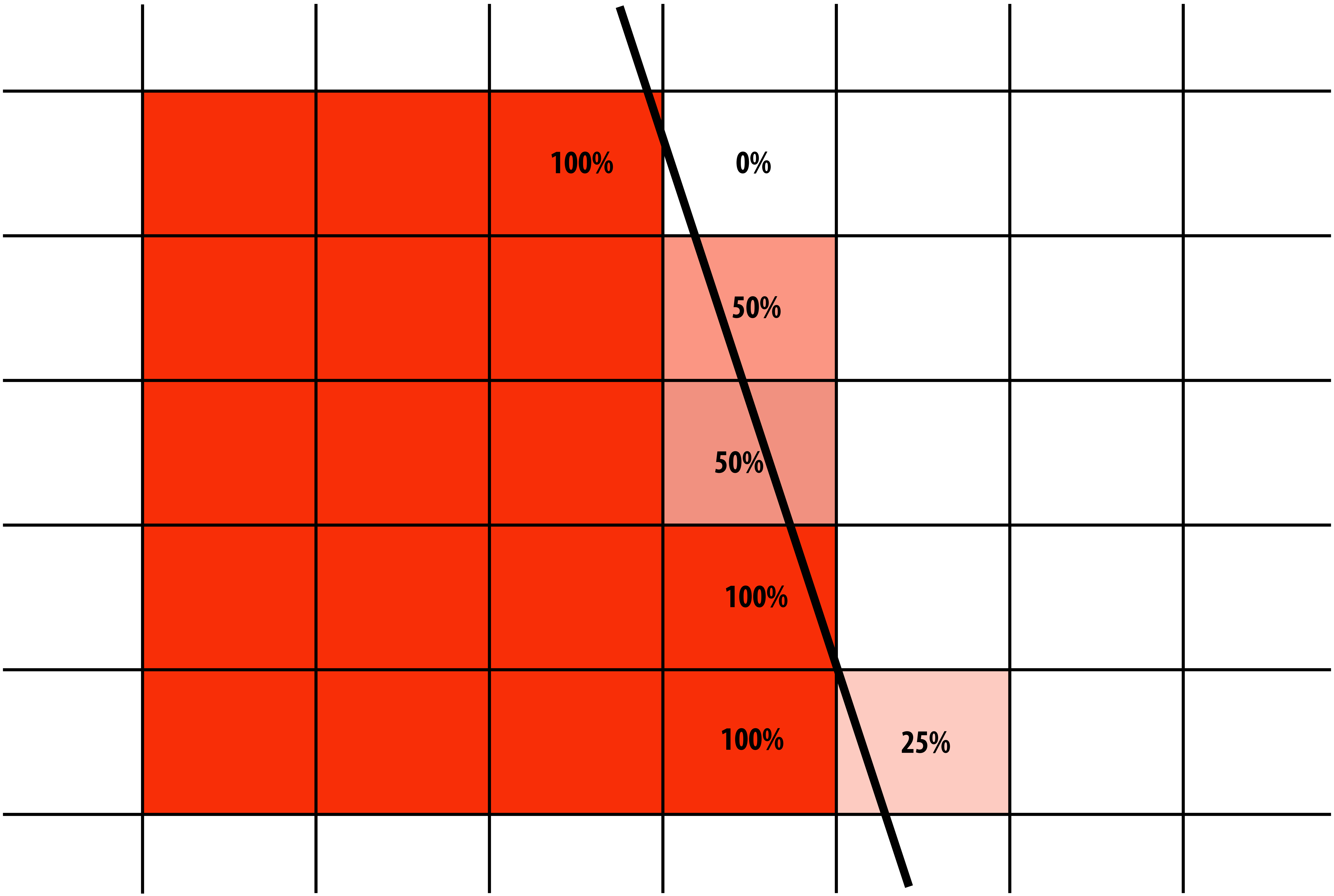
Resample to display's pixel rate (box filter)



Resample to display's pixel rate (box filter)



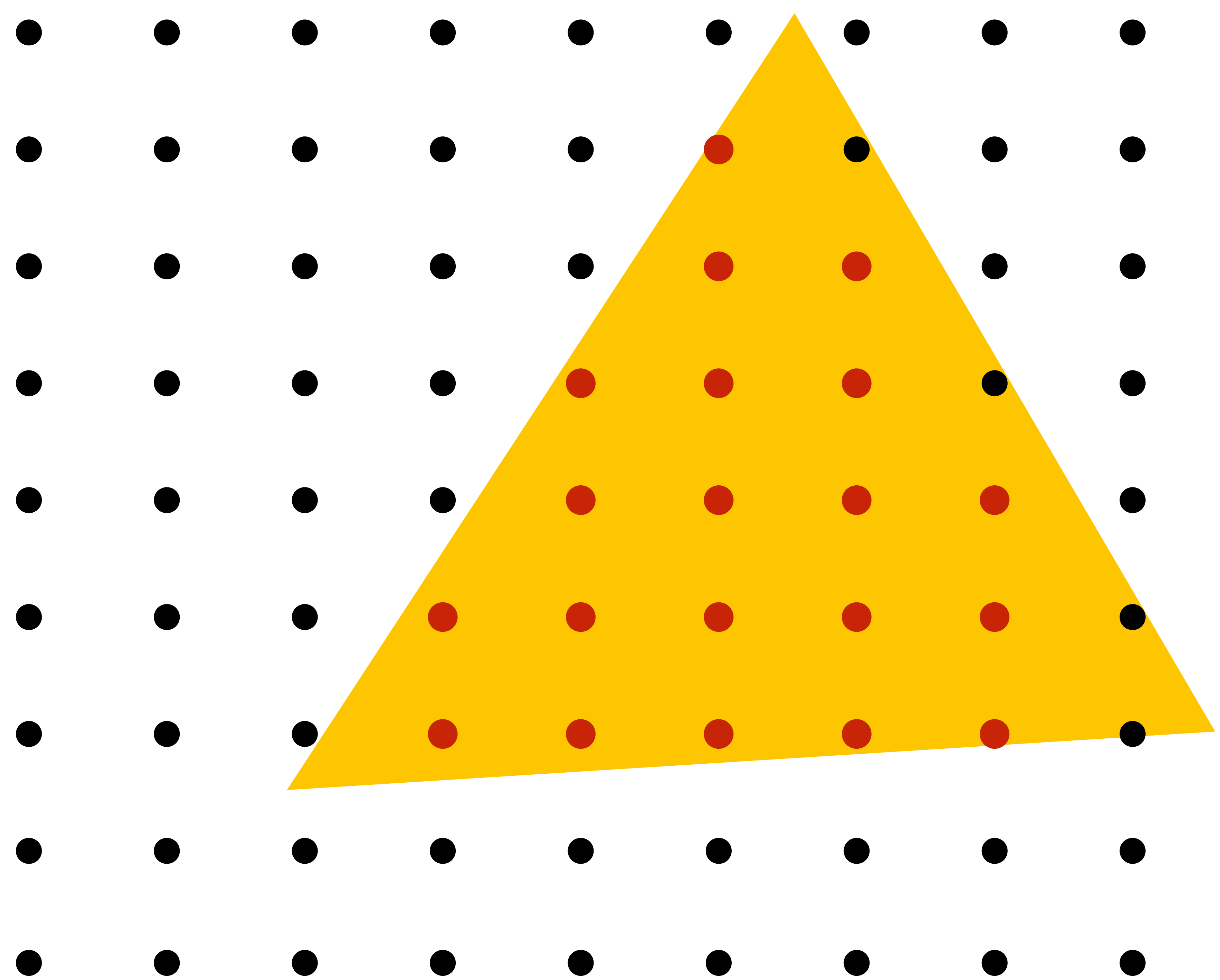
Displayed result (note anti-aliased edges)



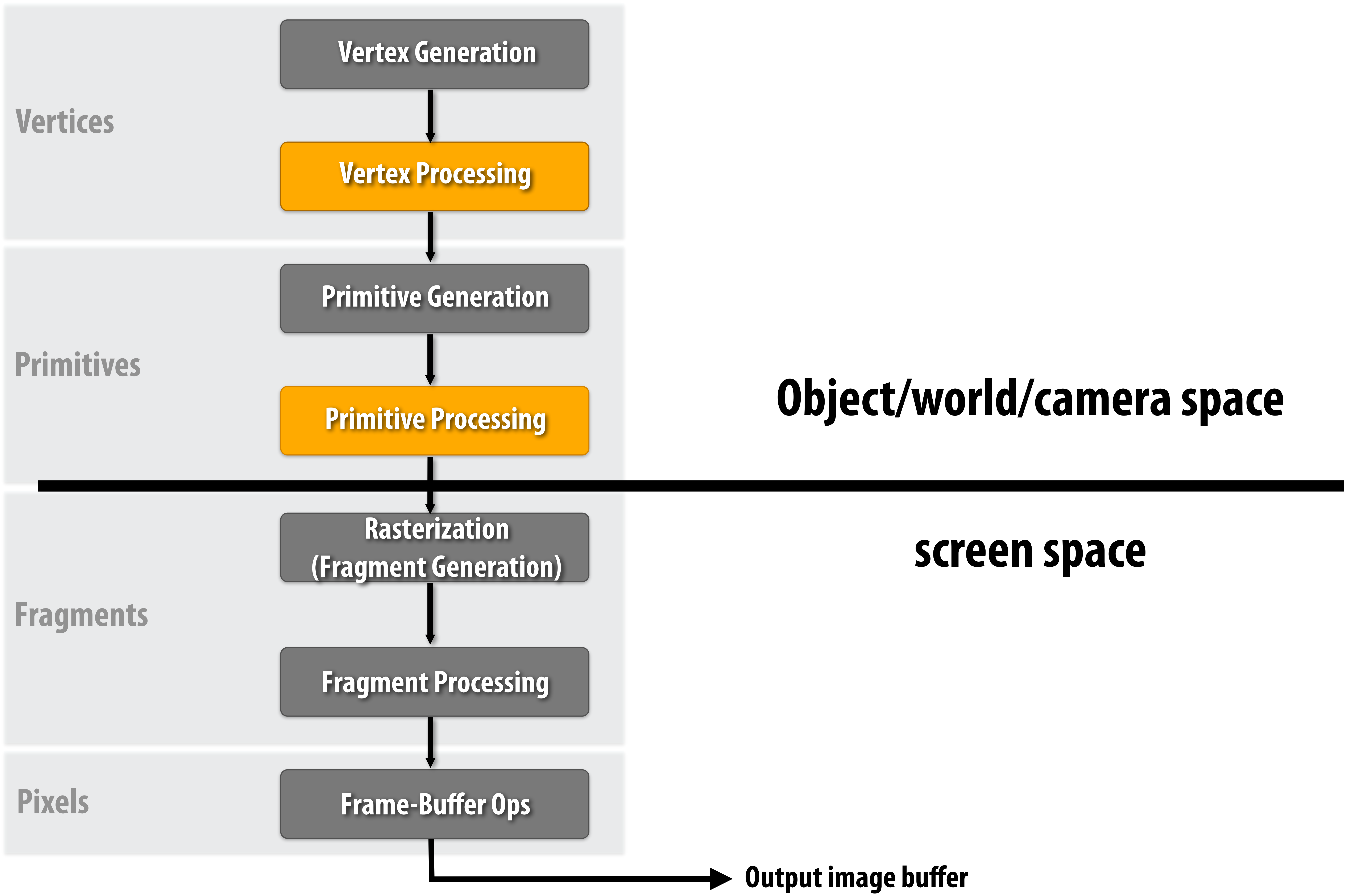
End:
Implementation of rasterization

Fragment generation: sampling coverage

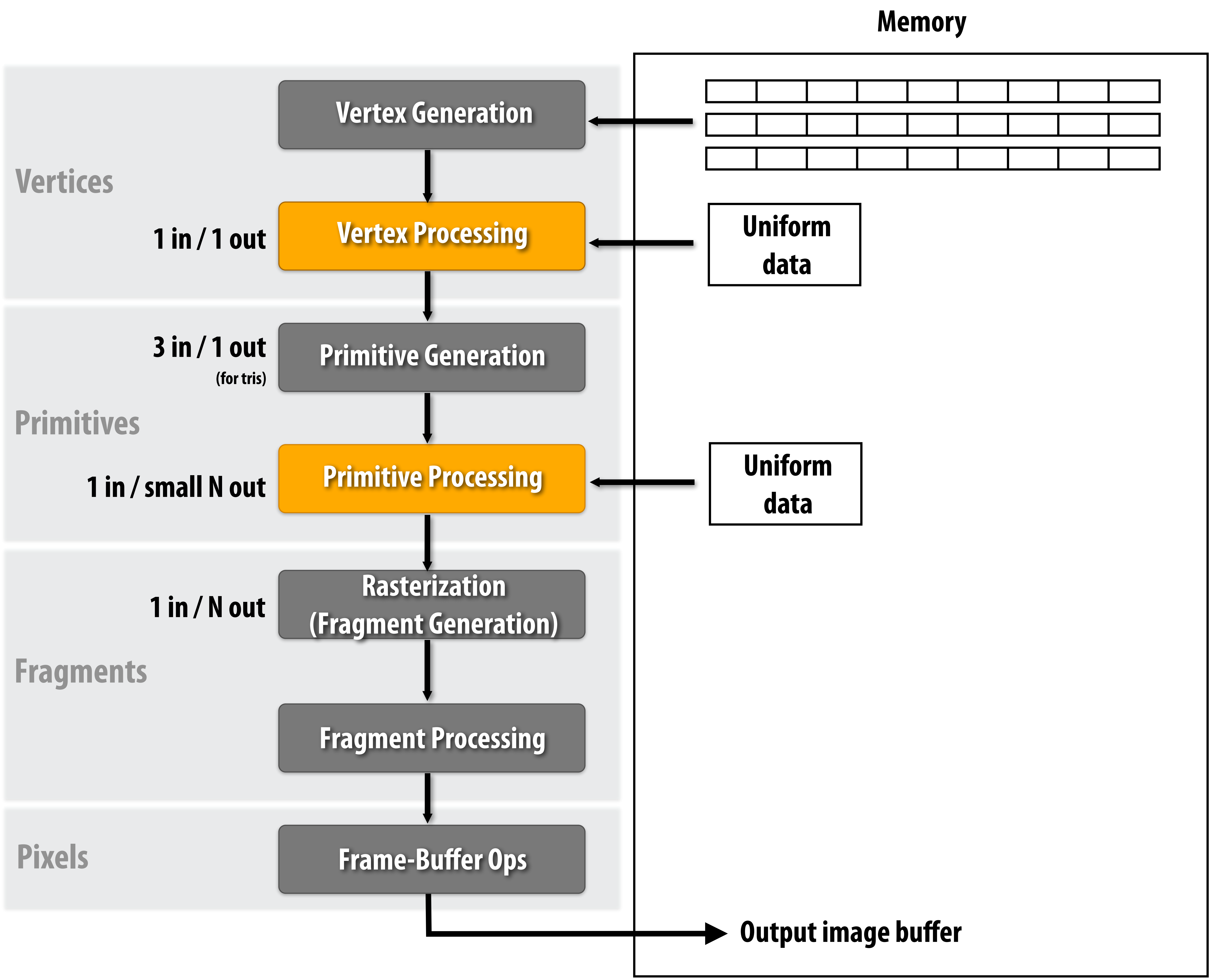
Evaluate attributes (depth, u, v) at all covered samples



The graphics pipeline

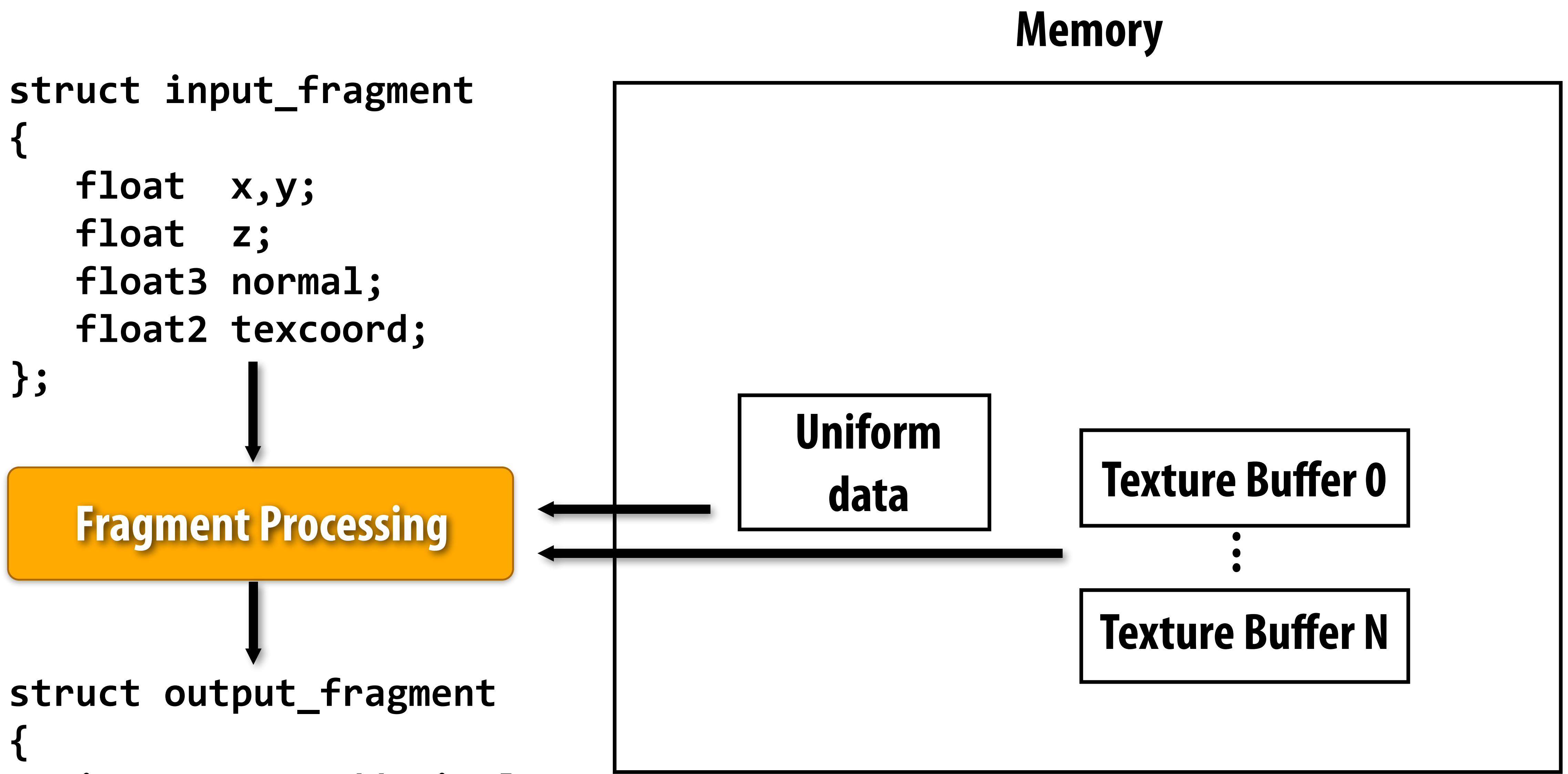


The graphics pipeline



Fragment processing

```
struct input_fragment
{
   float  x,y;
   float  z;
   float3 normal;
   float2 texcoord;
};
```

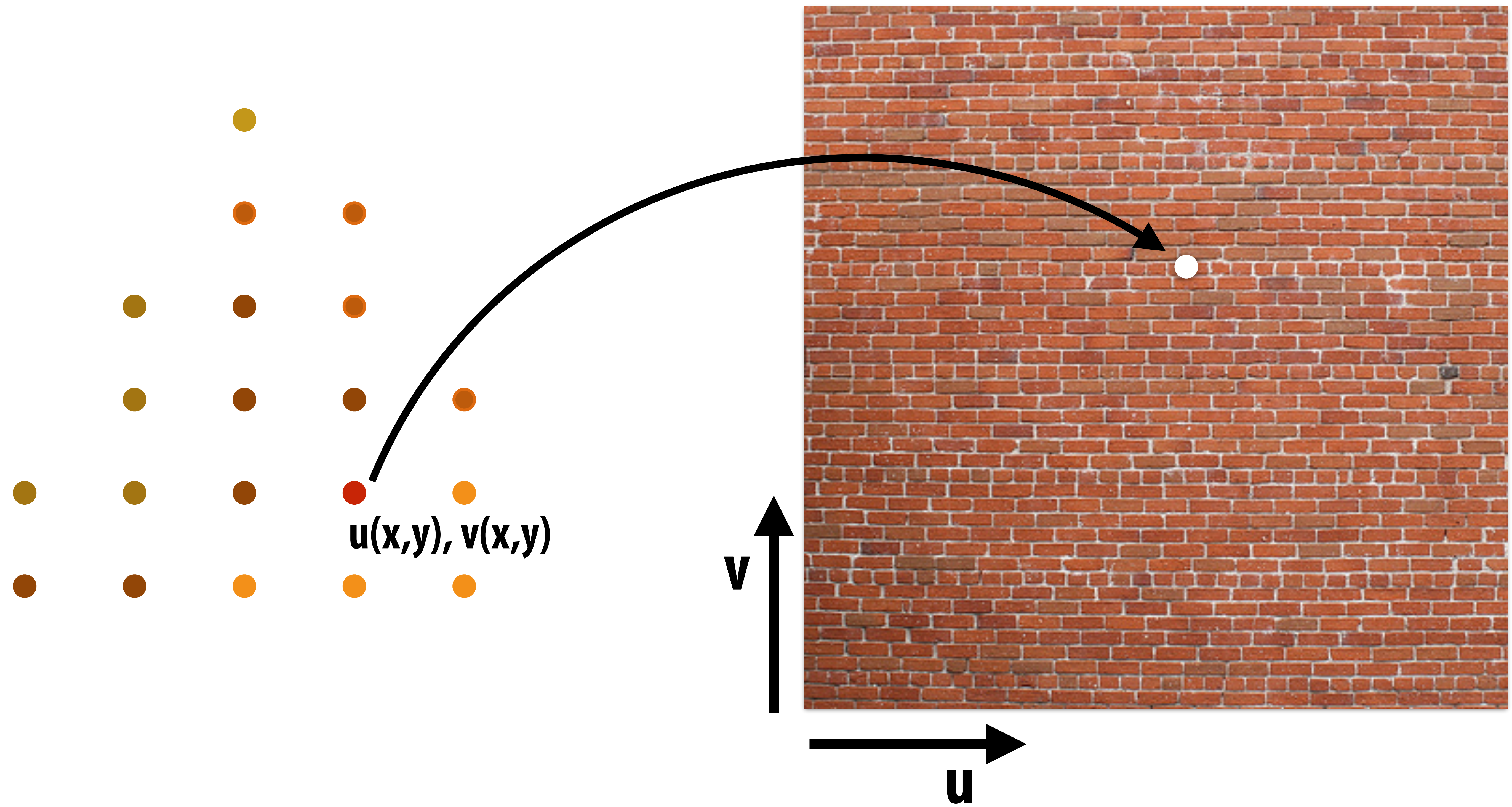



```
struct output_fragment
{
   int    x,y; // pixel
   float  z;
   float4 color;
};
```

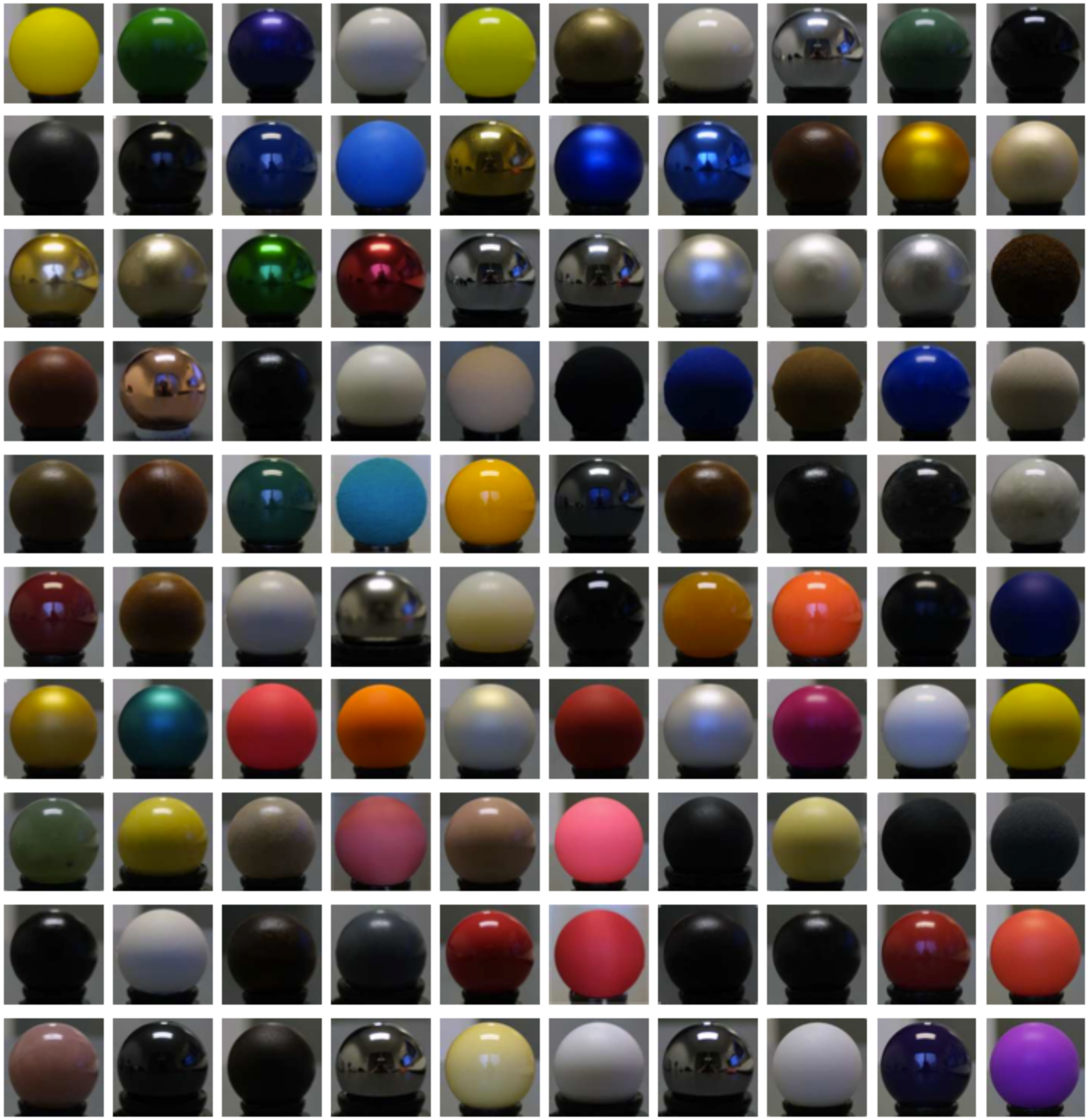
```
texture my_texture;

output_fragment my_fragment_program(input_fragment in)
{
    output_fragment out;
    float4 material_color = sample(my_texture, in.texcoord);

    for (each light L in scene)
    {
        out.color += shade(L) // compute reflectance towards camera due to L
    }
    return out;
}
```

Example per-fragment operation: computing fragment color

e.g., sample texture map



Many different materials in the world



Tabulated BRDFs

Images from Matusik et al. SIGGRAPH 2003

Materials

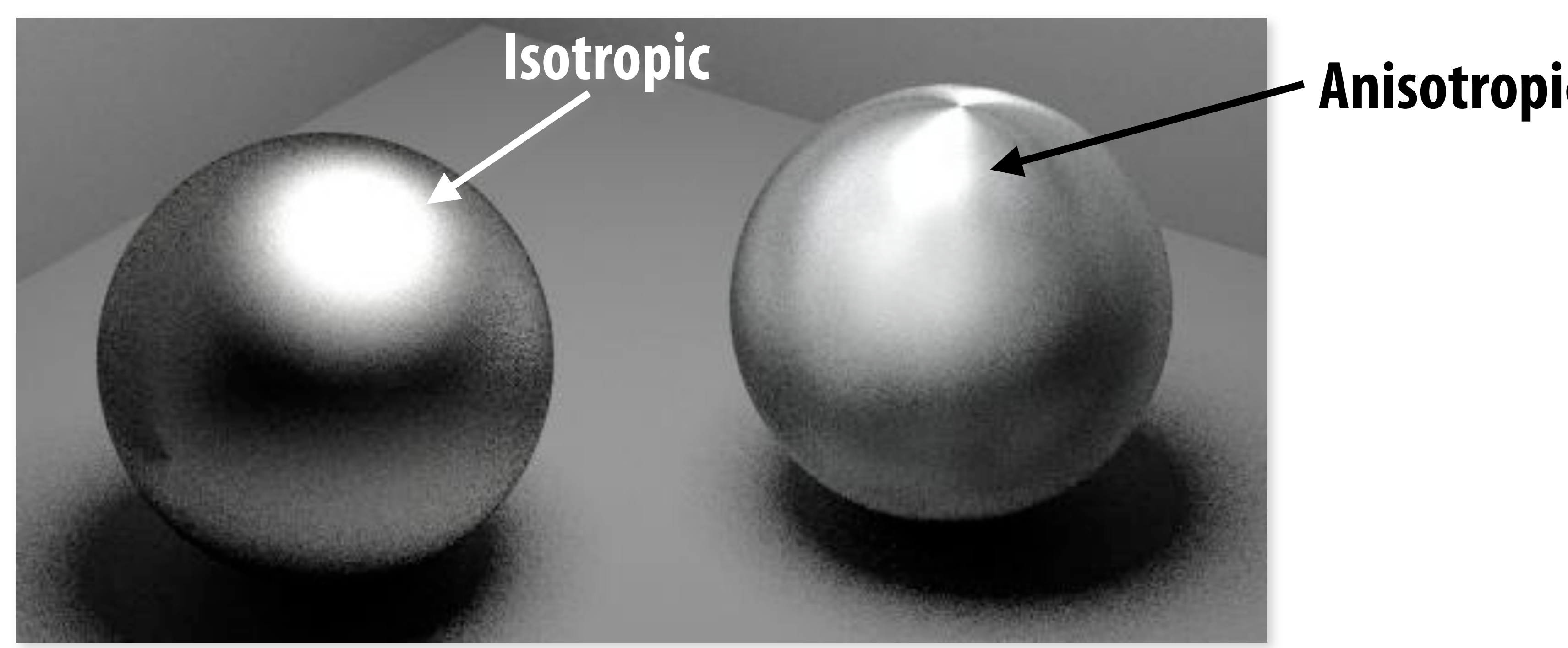
[Image credit: Jakob et al. 2014]

More complex materials

[Images from Lafortune et al. 97]

Fresnel reflection: reflectance is a function of viewing angle (notice higher reflectance near grazing angles)

[Images from Westin et al. 92]



Anisotropic reflection: reflectance depends on azimuthal angle (e.g., oriented microfacets in brushed steel)

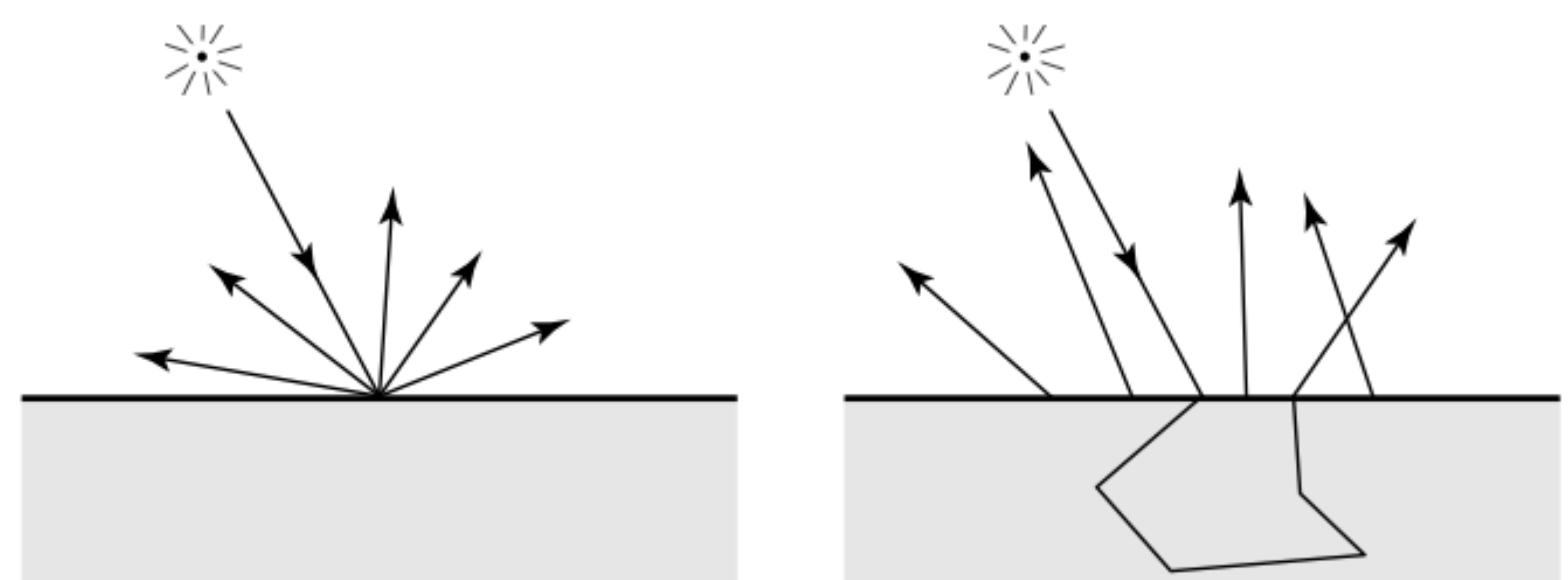
Subsurface scattering materials

[Wann Jensen et al. 2001]

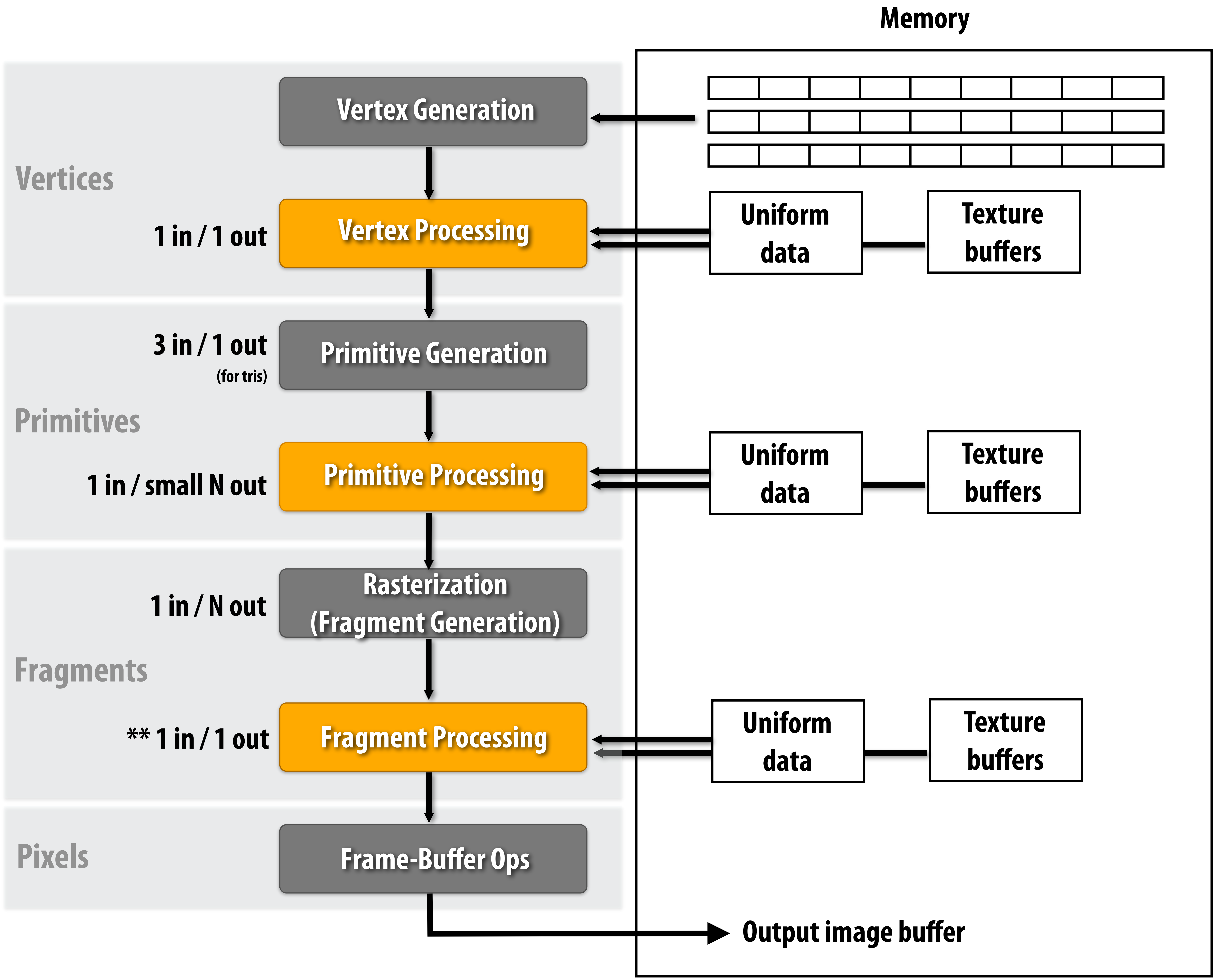
BRDF

BSSRDF

- Account for scattering inside surface
- Light exits surface from different location it enters
  - Very important to appearance of translucent materials (e.g., skin, foliage, marble)



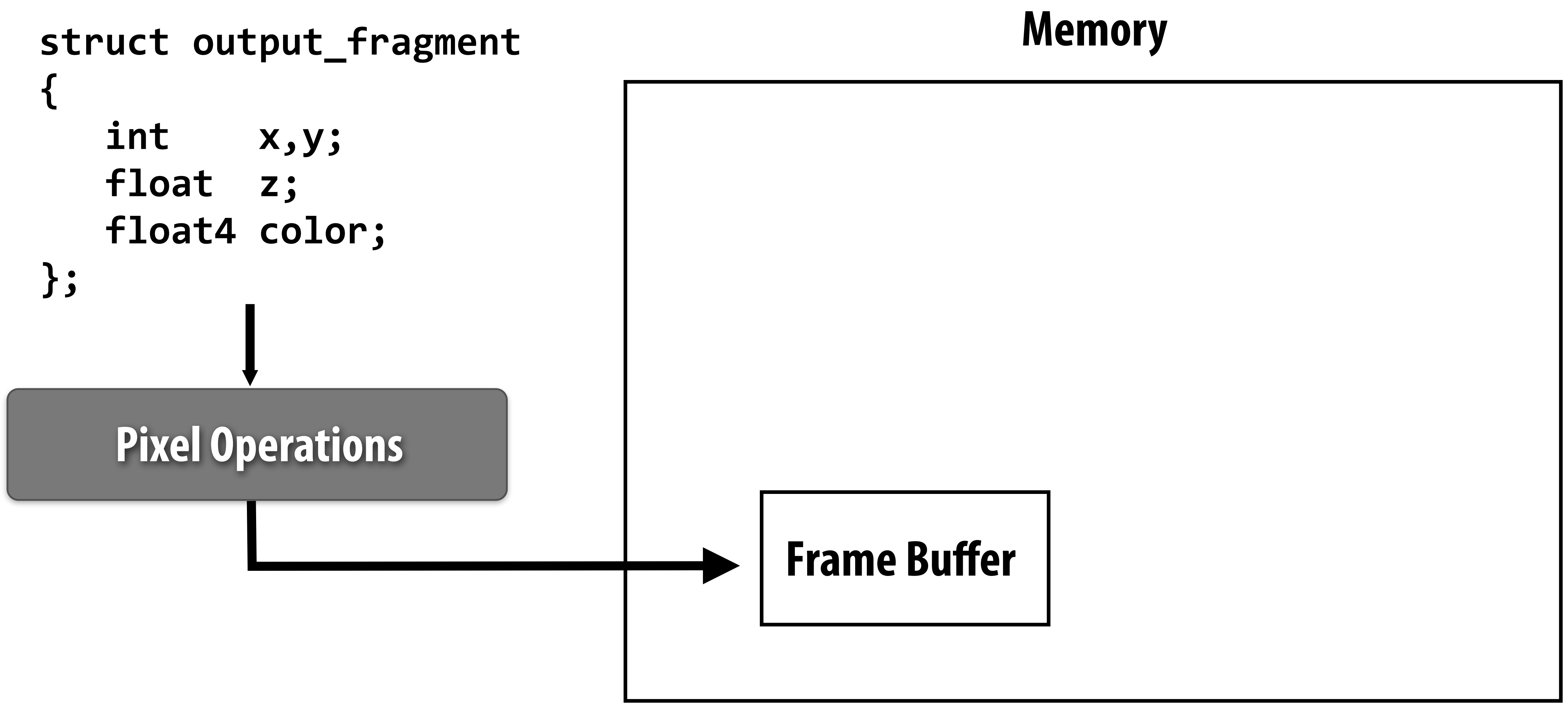
The graphics pipeline



** can be 0 out

Frame-buffer operations

```
struct output_fragment
{
   int    x,y;
   float  z;
   float4 color;
};
```



- **Key responsibilities:**
  - Accumulate/blend fragment color into frame buffer based on "depth test"

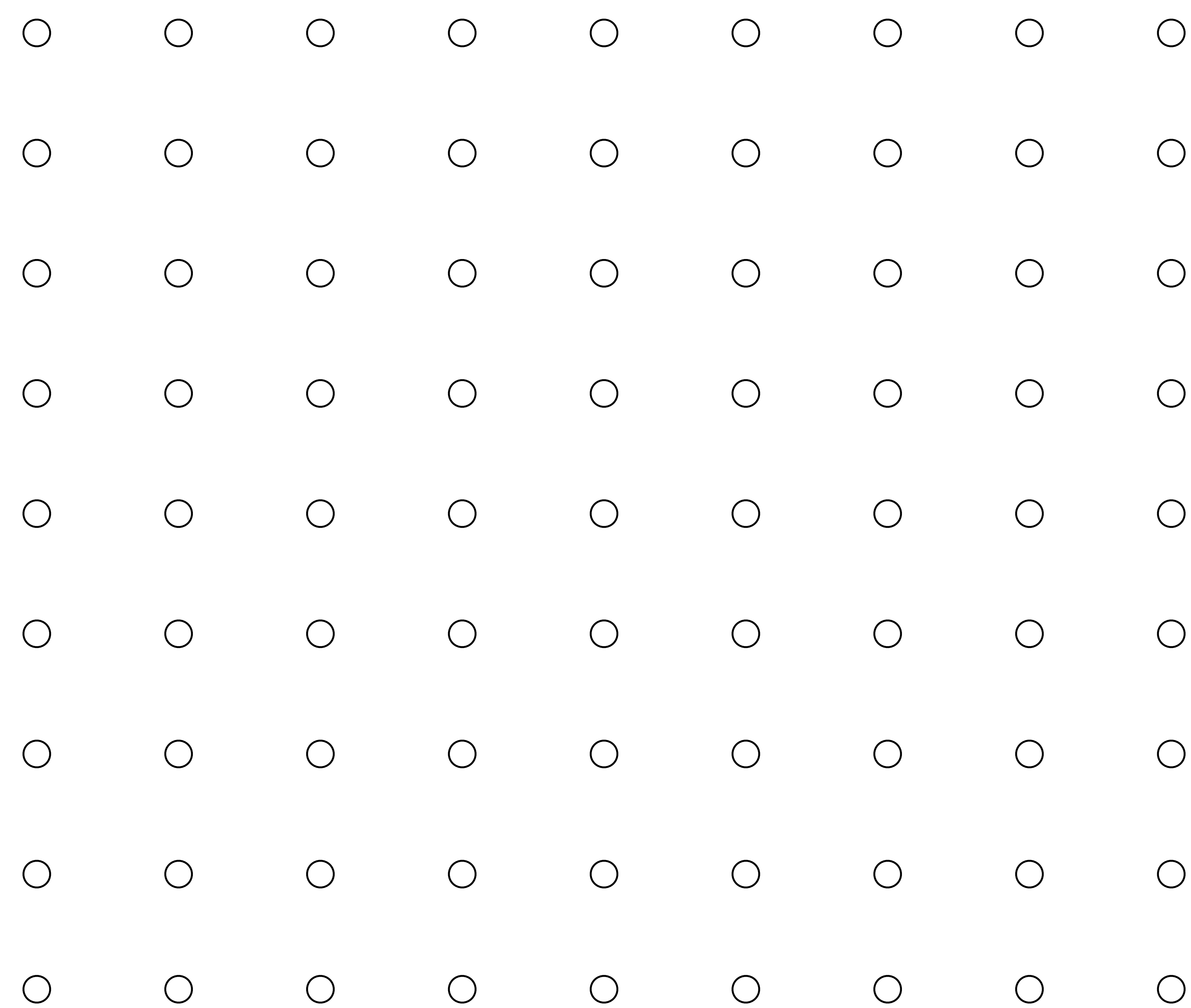
Implementation of depth testing

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)



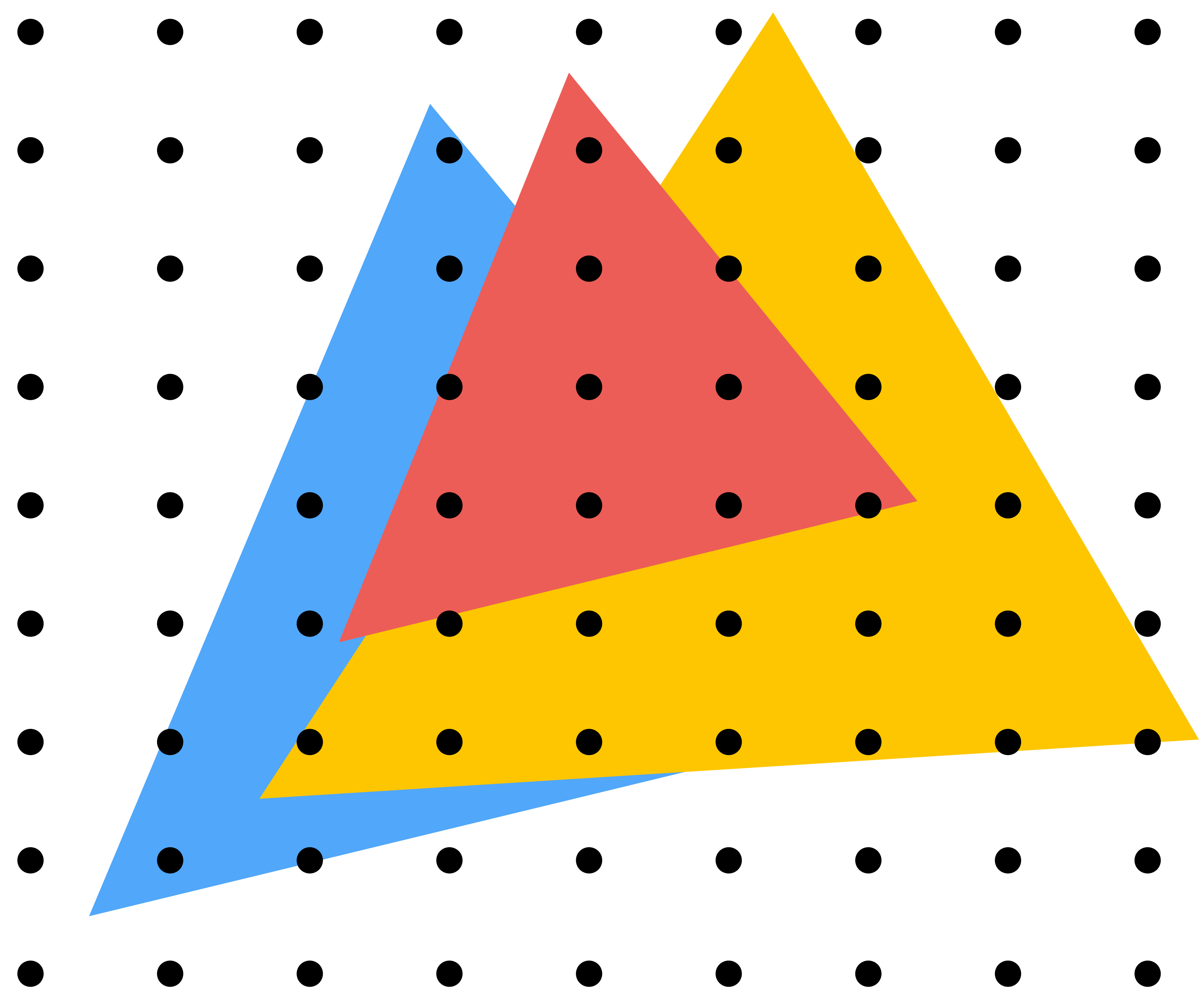
Grayscale value of sample point used to indicate distance

Black = small distance

White = large distance

Depth buffer example

Example: rendering three opaque triangles



Occlusion using the depth-buffer (Z-buffer)

Processing yellow triangle:

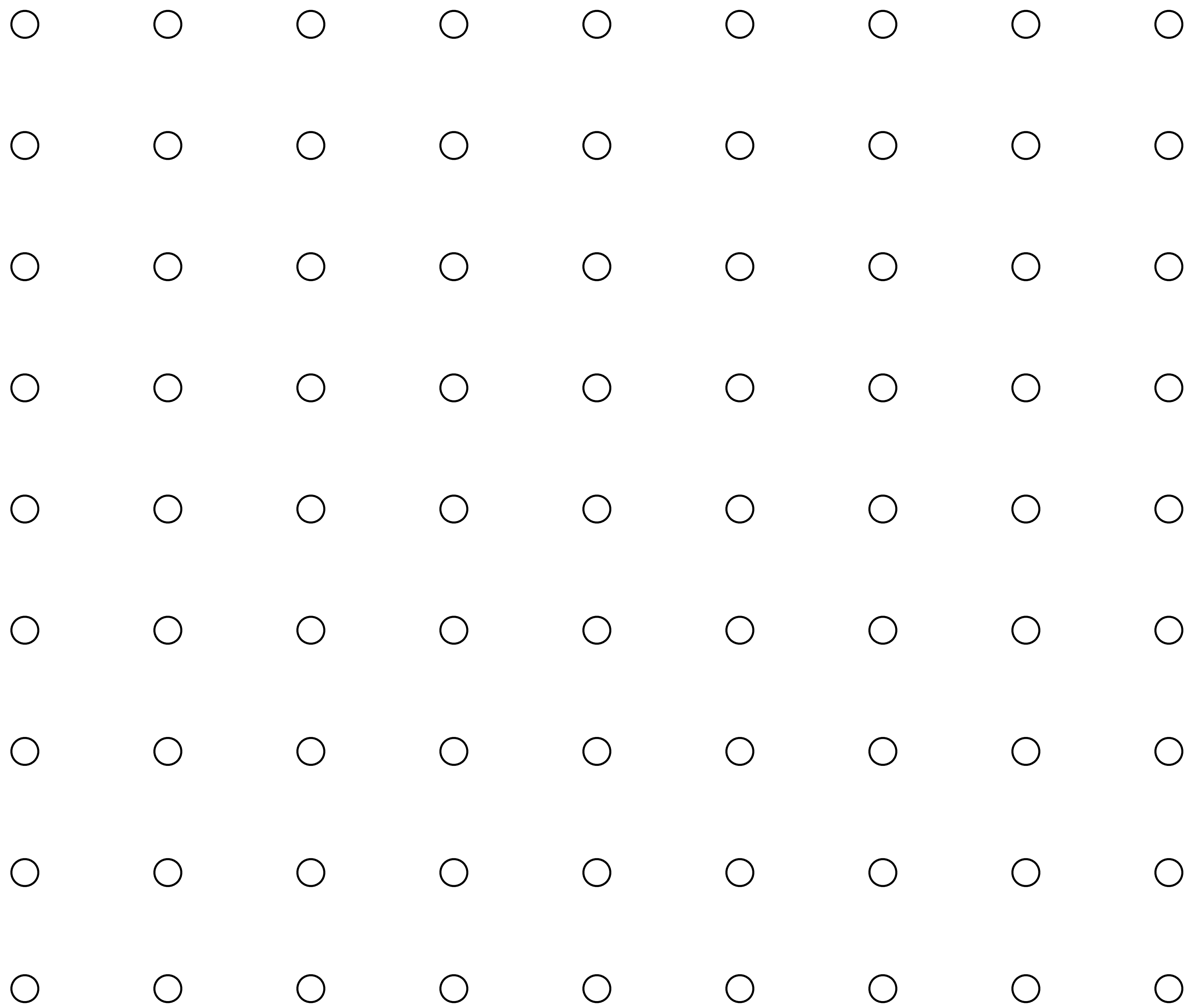
depth = 0.5

Grayscale value of sample point used to indicate distance

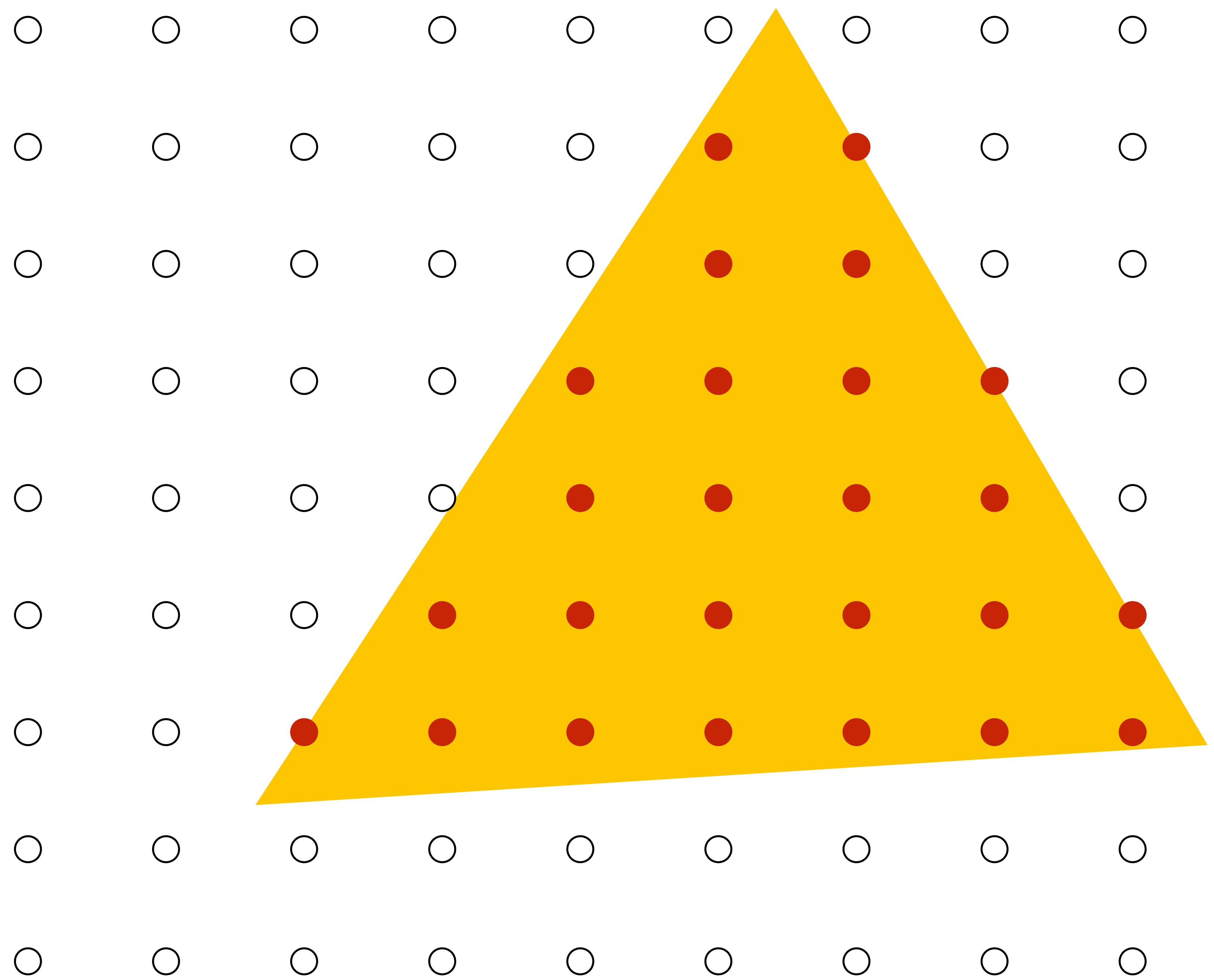
White = large distance

Black = small distance

Red = sample passed depth test



Color buffer contents



Depth buffer contents

Occlusion using the depth-buffer (Z-buffer)

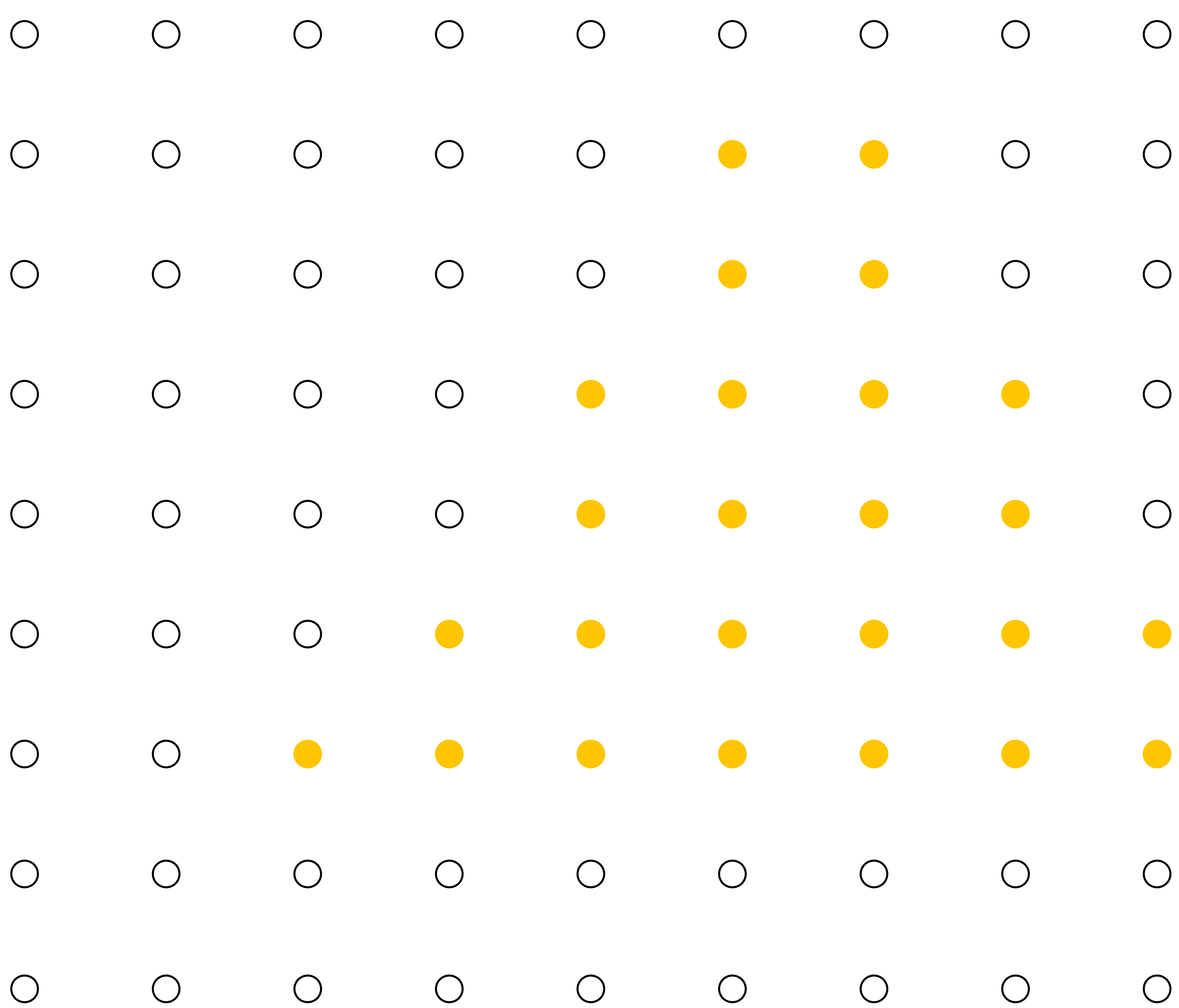
After processing yellow triangle:

Grayscale value of sample point used to indicate distance

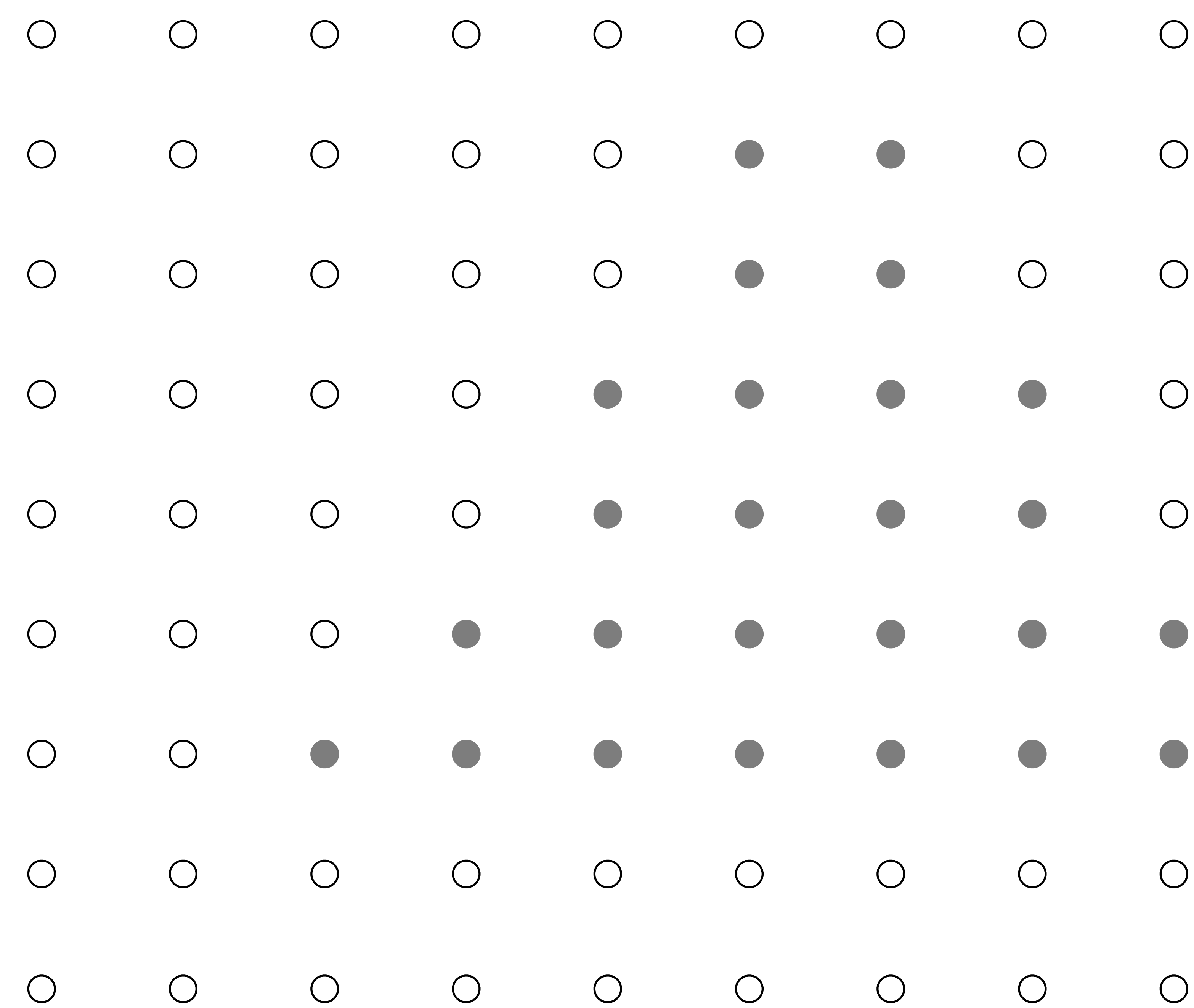
White = large distance

Black = small distance

Red = sample passed depth test



Color buffer contents

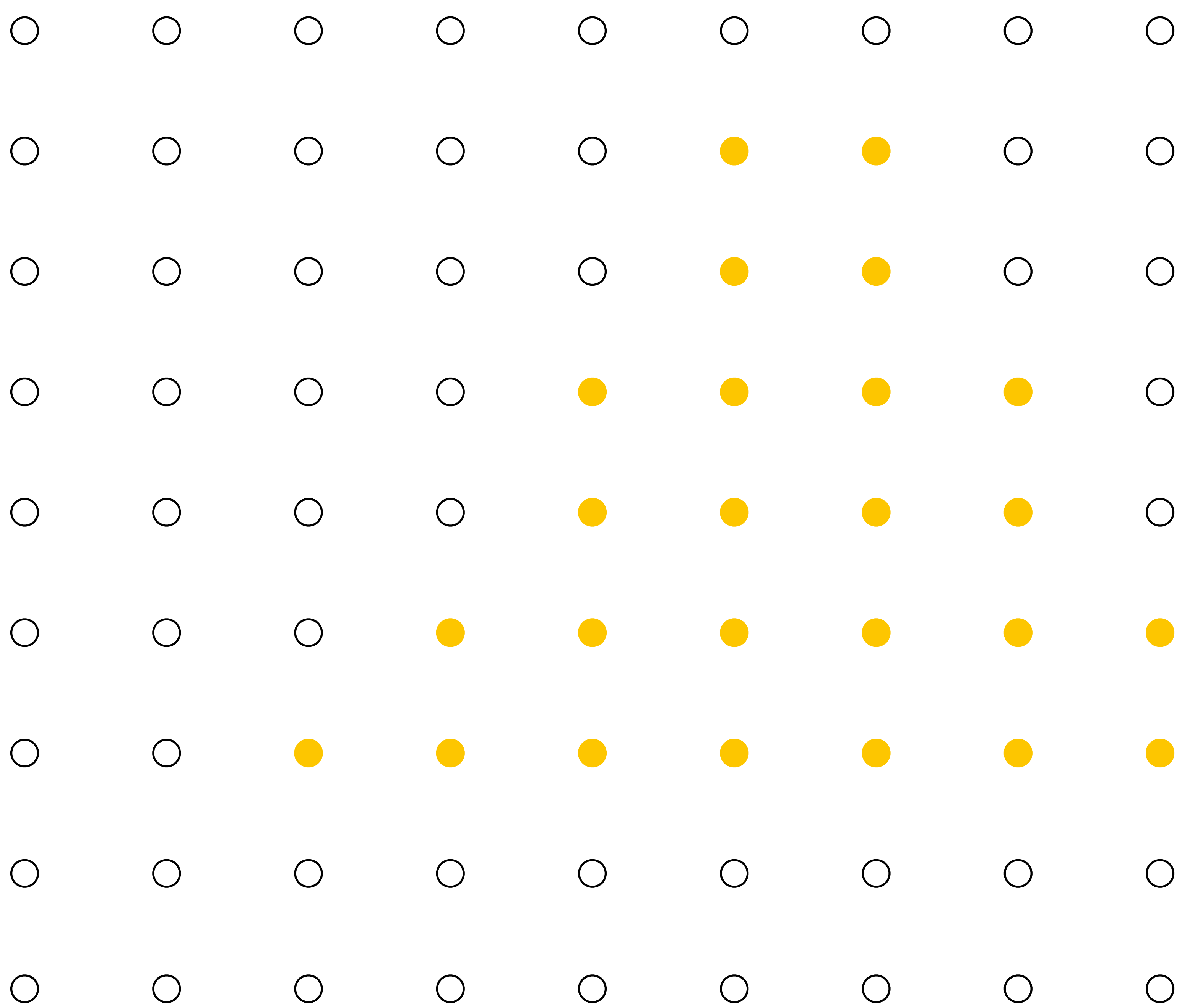


Depth buffer contents

Occlusion using the depth-buffer (Z-buffer)

Processing blue triangle:

depth = 0.75



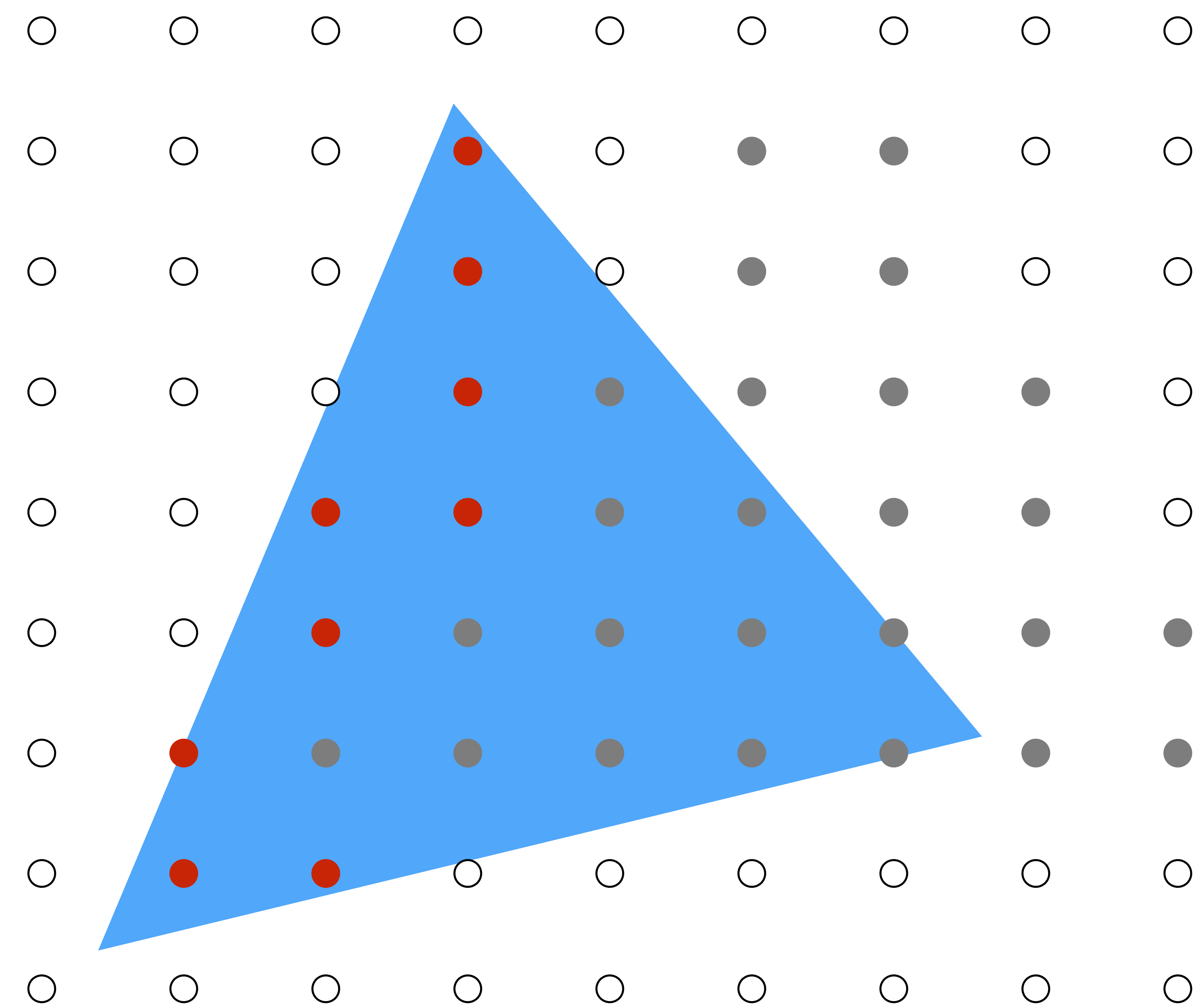
Color buffer contents

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)

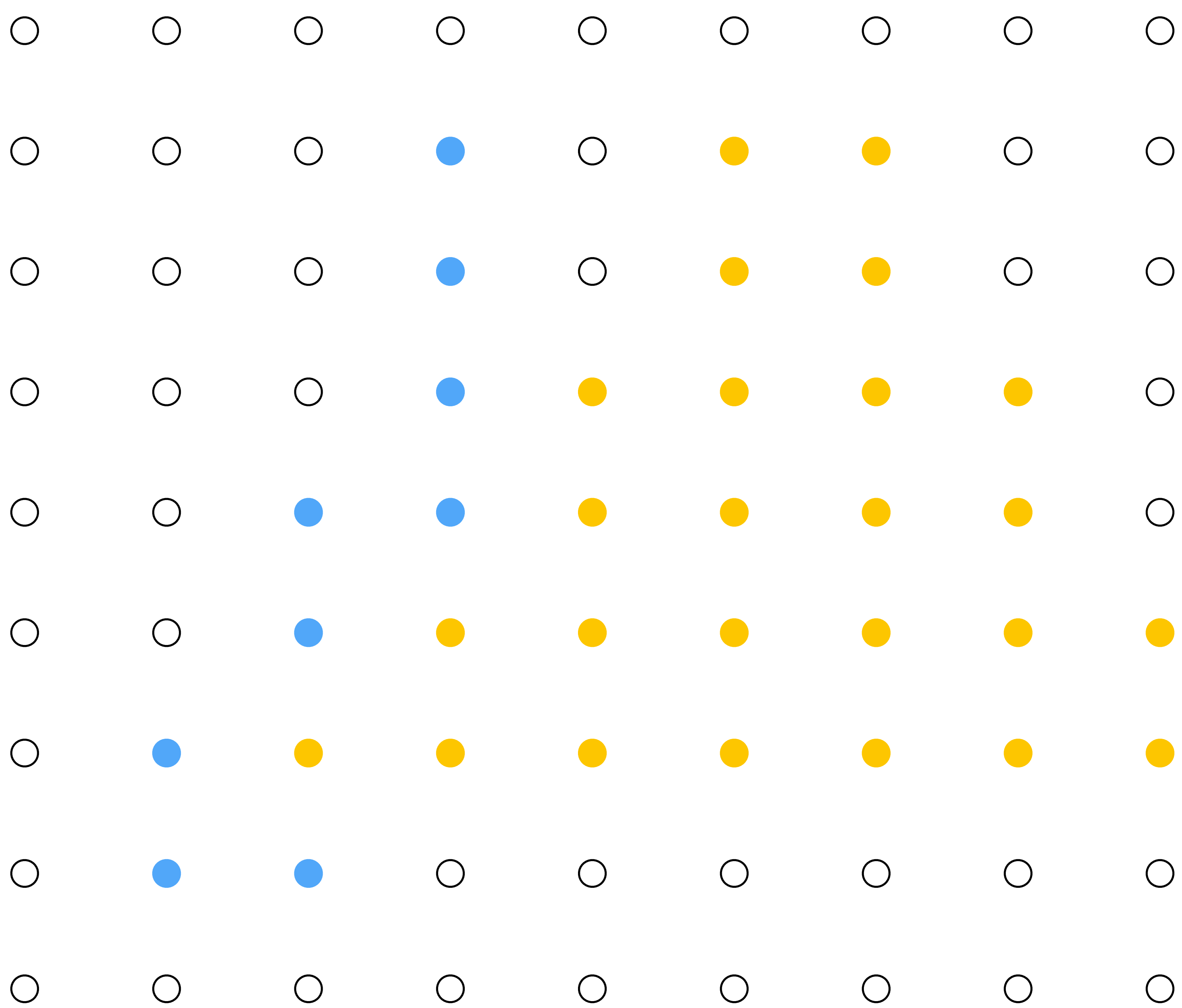
After processing blue triangle:

Grayscale value of sample point used to indicate distance

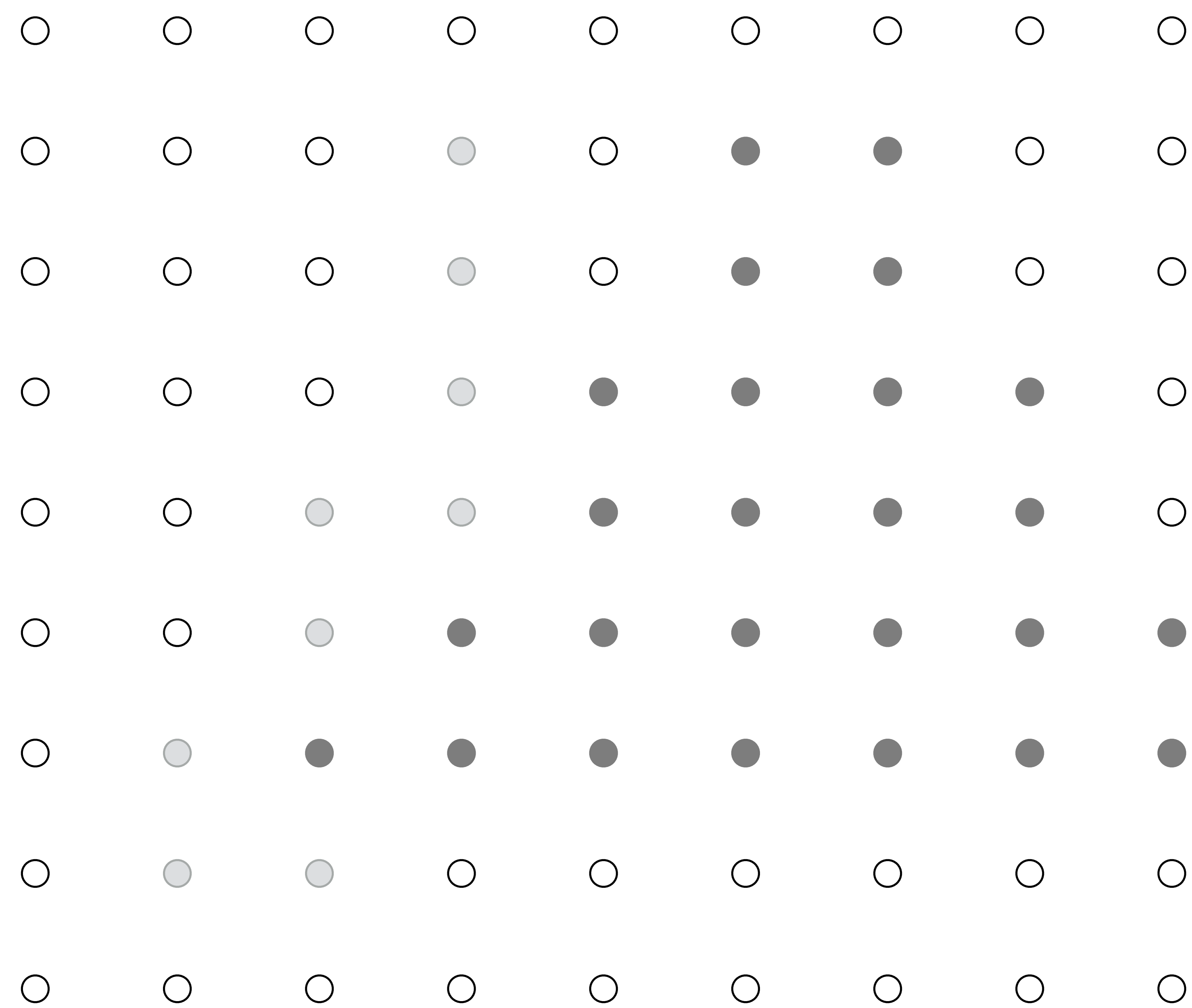
White = large distance

Black = small distance

Red = sample passed depth test



Color buffer contents



Depth buffer contents

Occlusion using the depth-buffer (Z-buffer)

Processing red triangle:

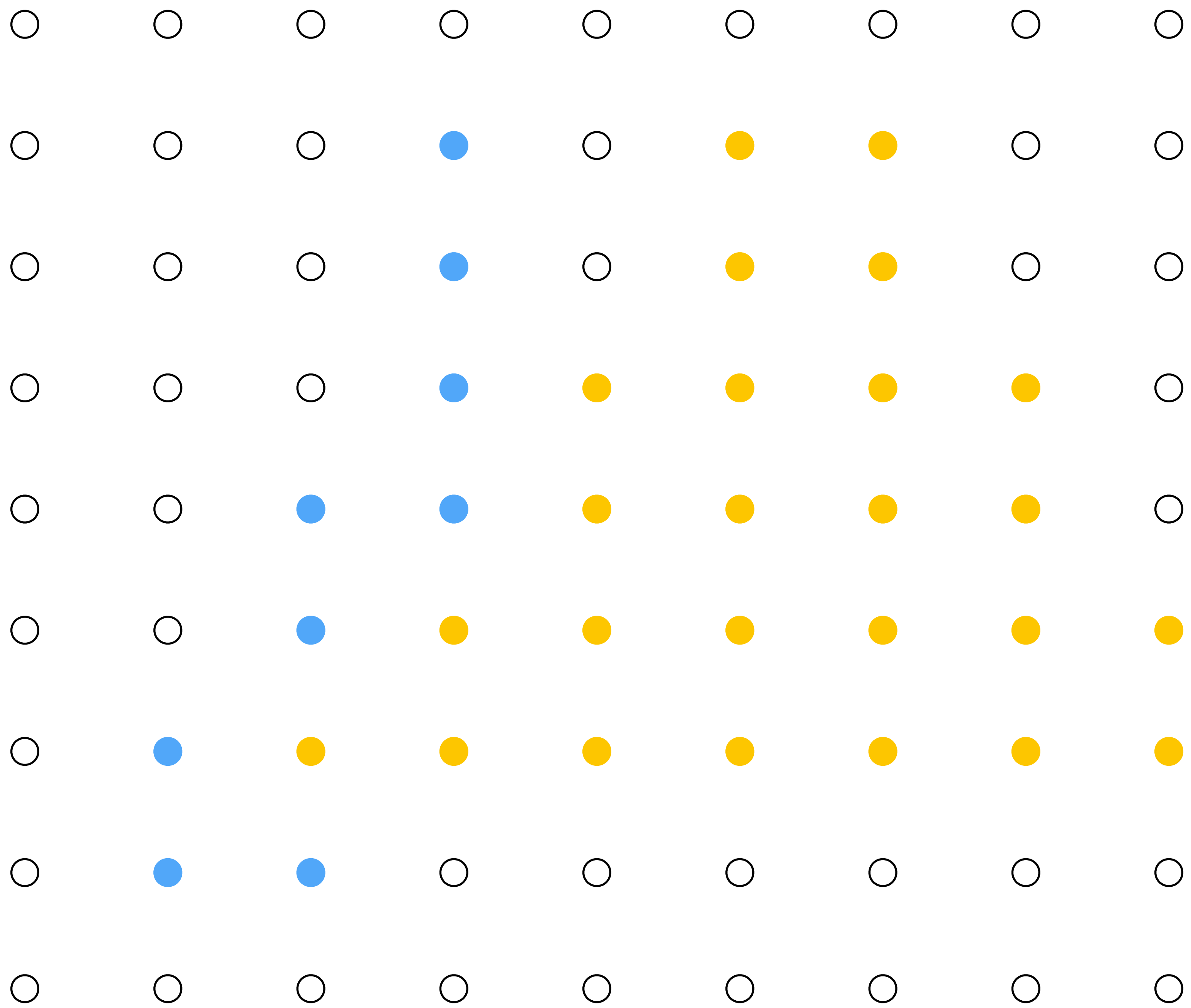
depth = 0.25

Grayscale value of sample point used to indicate distance

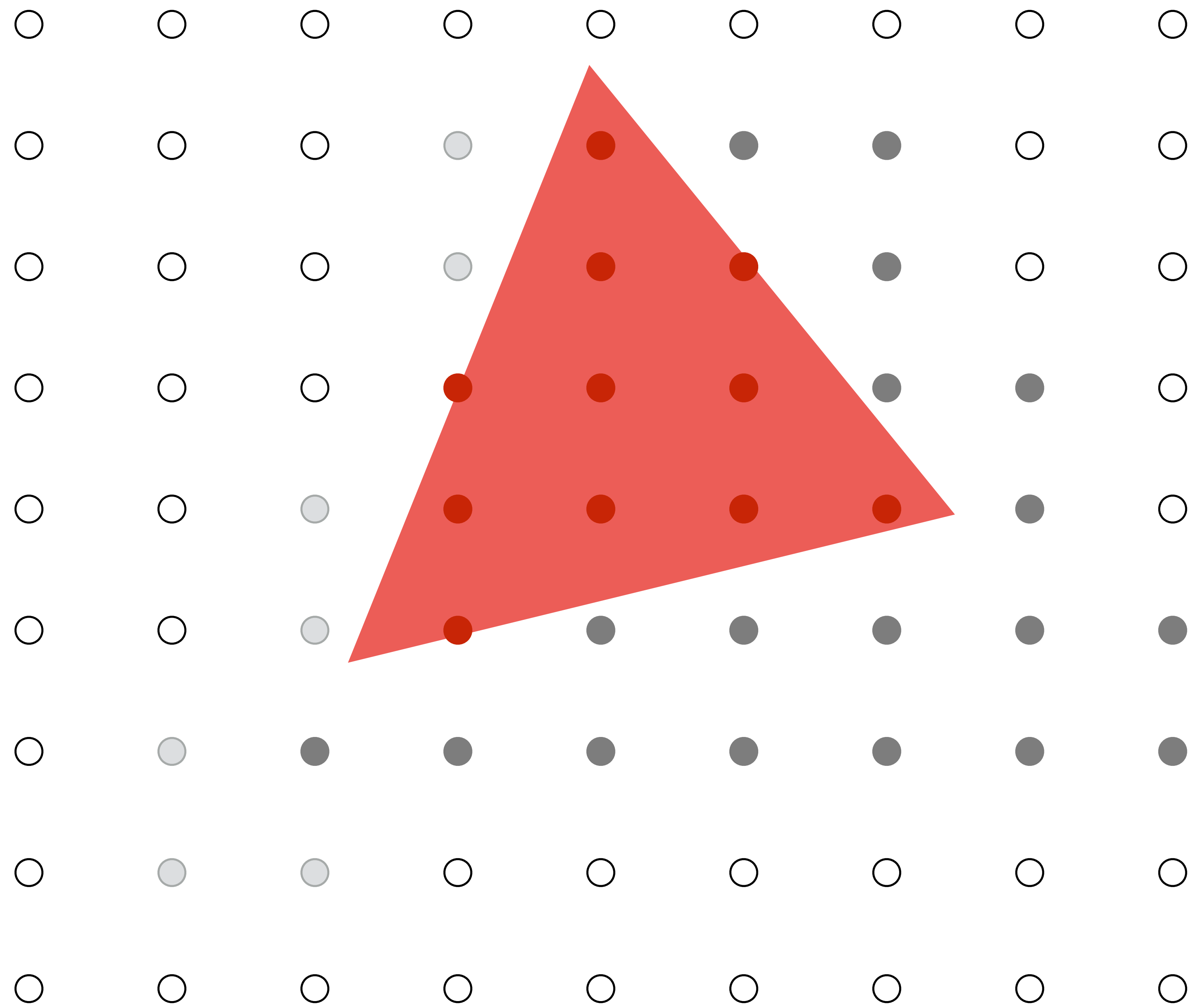
White = large distance

Black = small distance

Red = sample passed depth test



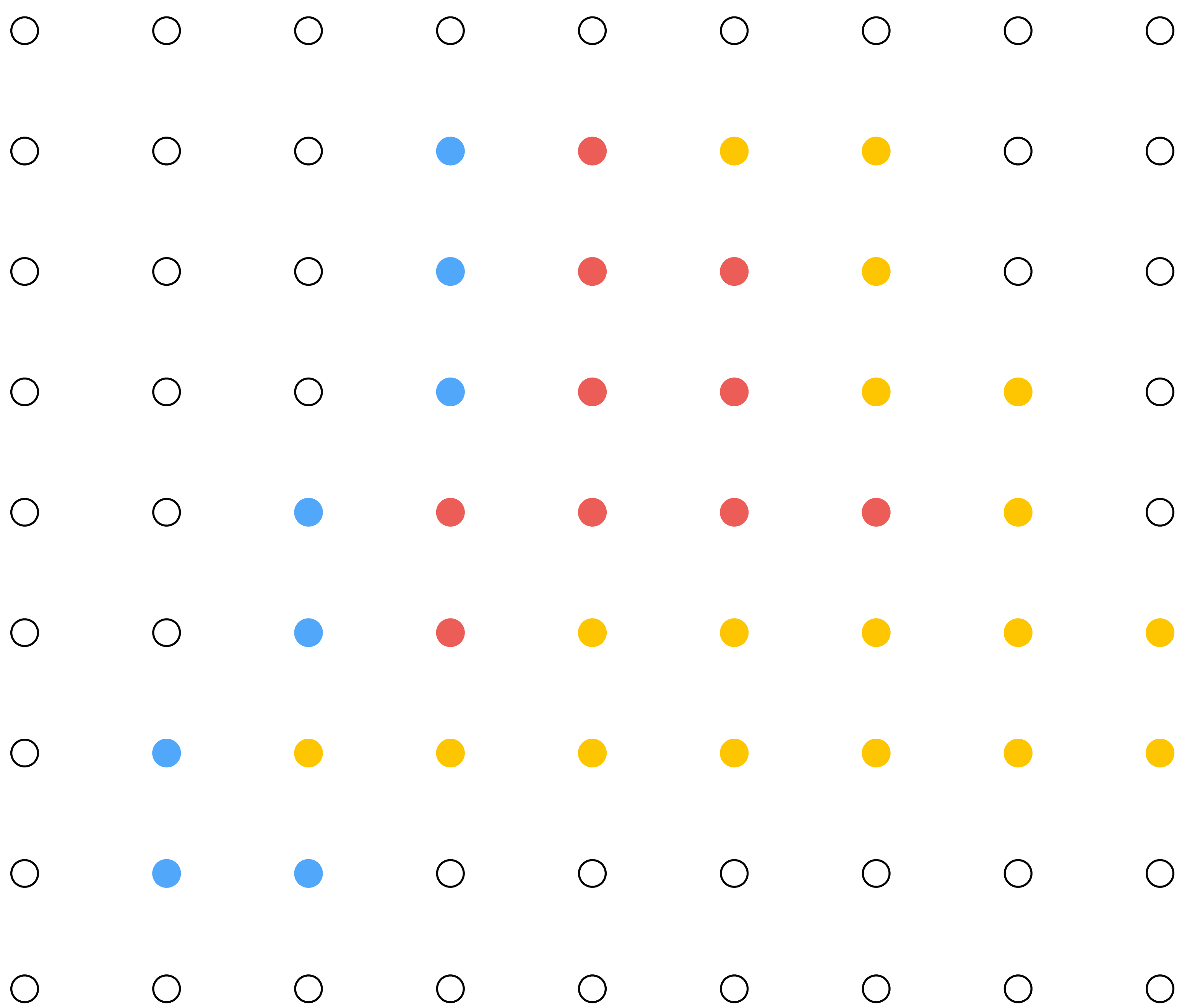
Color buffer contents



Depth buffer contents

Occlusion using the depth-buffer (Z-buffer)

After processing red triangle:



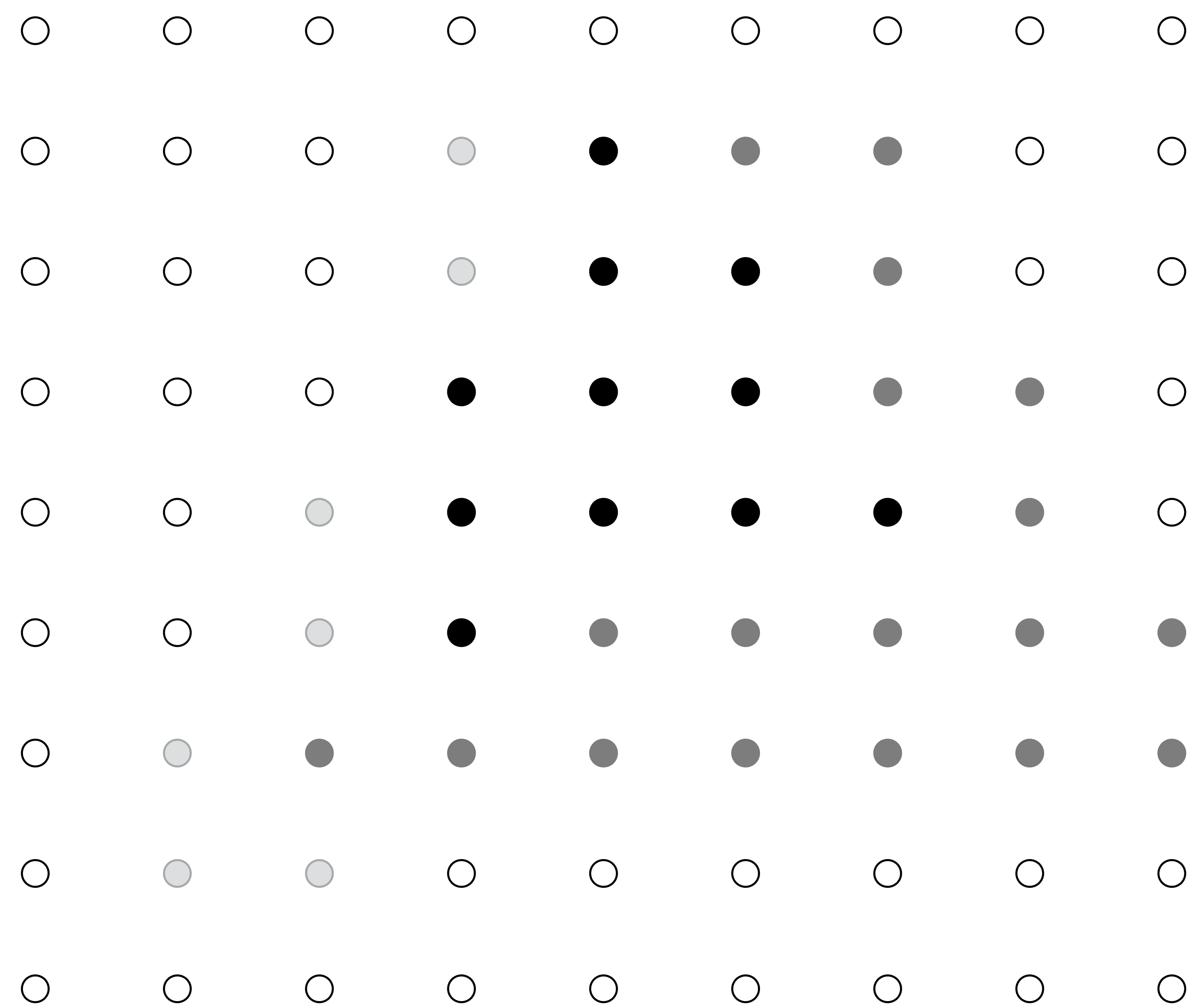
Color buffer contents

Grayscale value of sample point used to indicate distance

White = large distance

Black = small distance

Red = sample passed depth test



Depth buffer contents

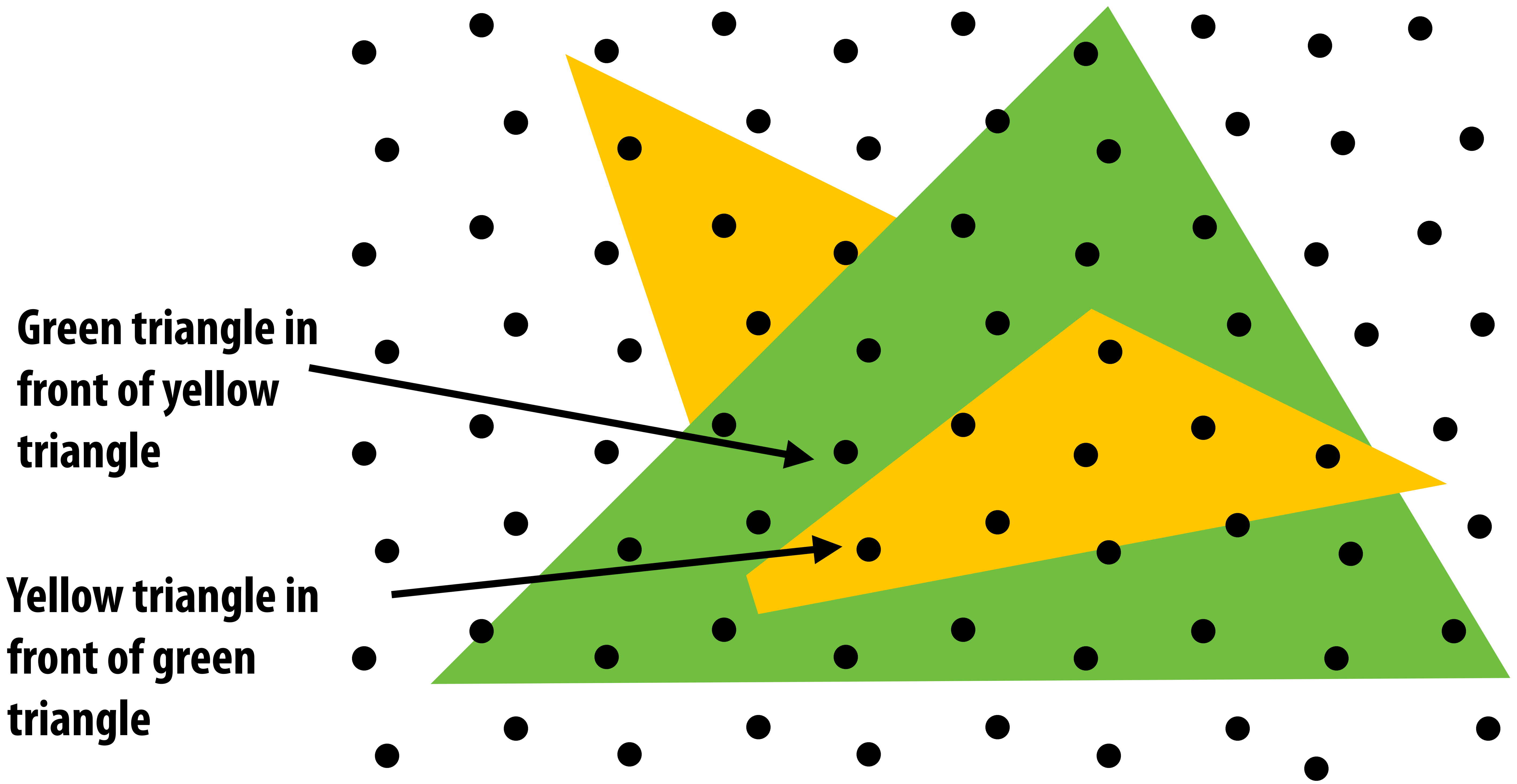
Occlusion using the depth buffer

```
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!

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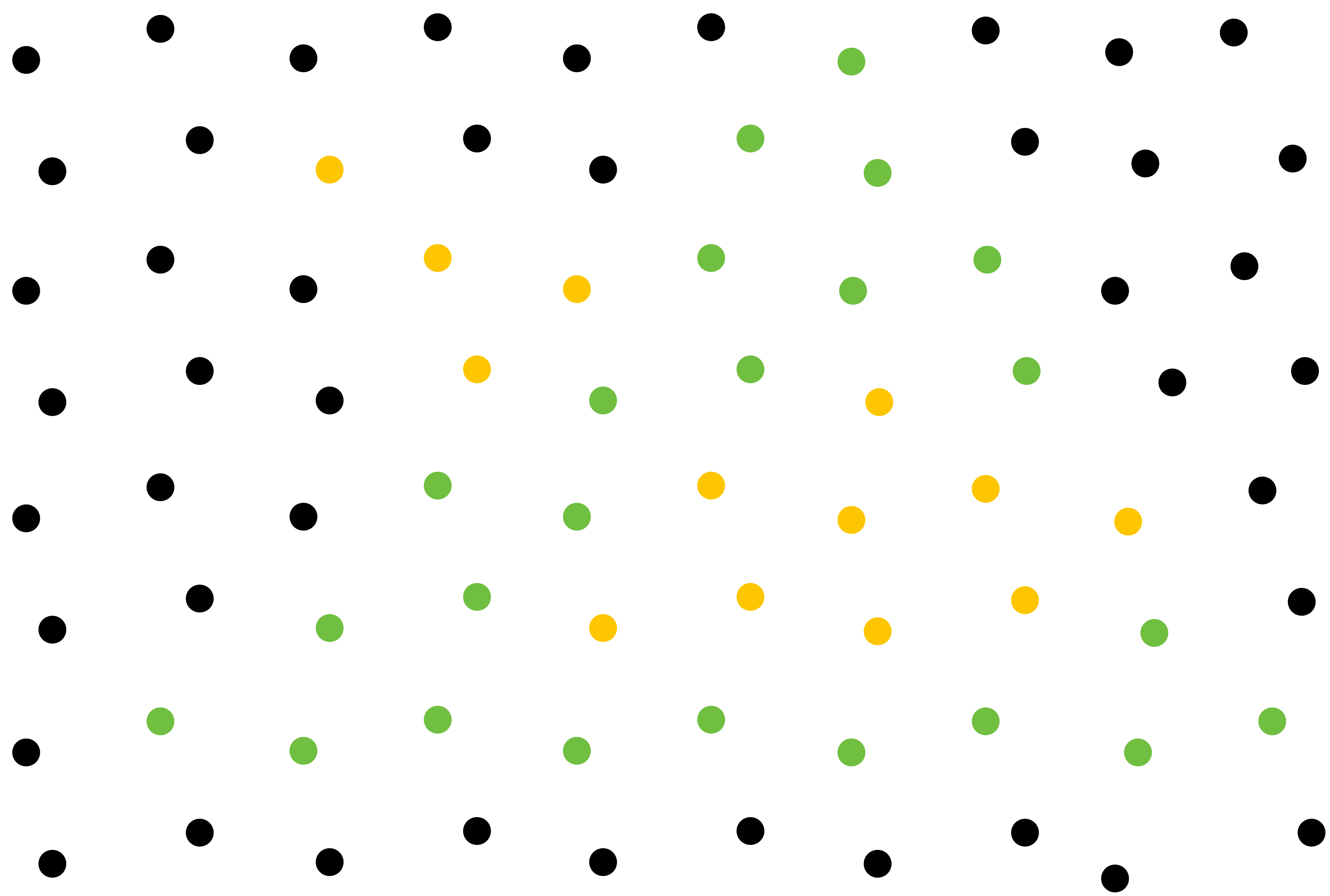


Summary: occlusion using a depth buffer

- Store one depth value per coverage sample (not per pixel!)

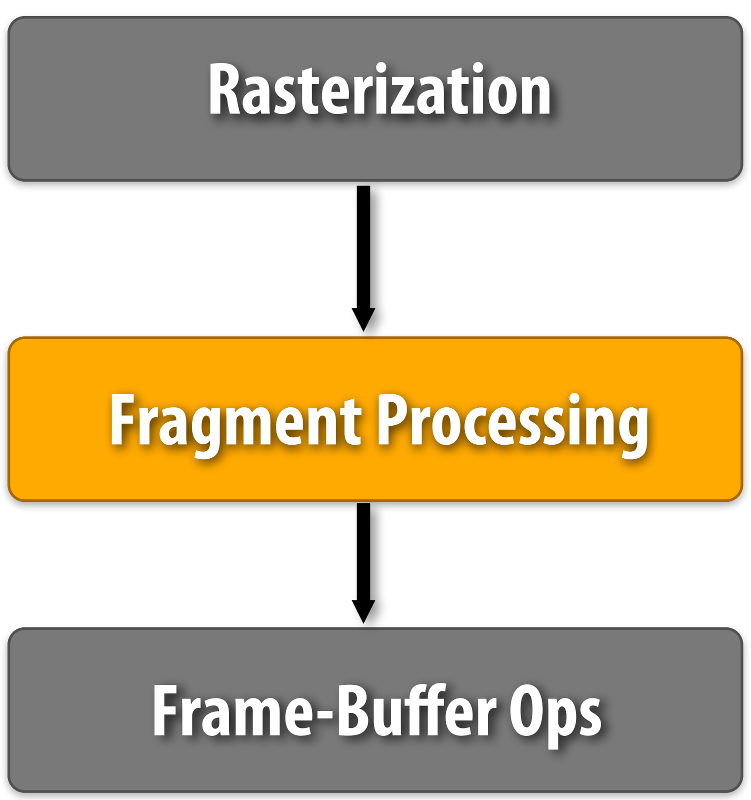
- Constant space per sample
  - Implication: constant space for depth buffer

- Constant time occlusion test per covered sample
  - Read-modify write of depth buffer if "pass" depth test
  - Just a read if "fail"

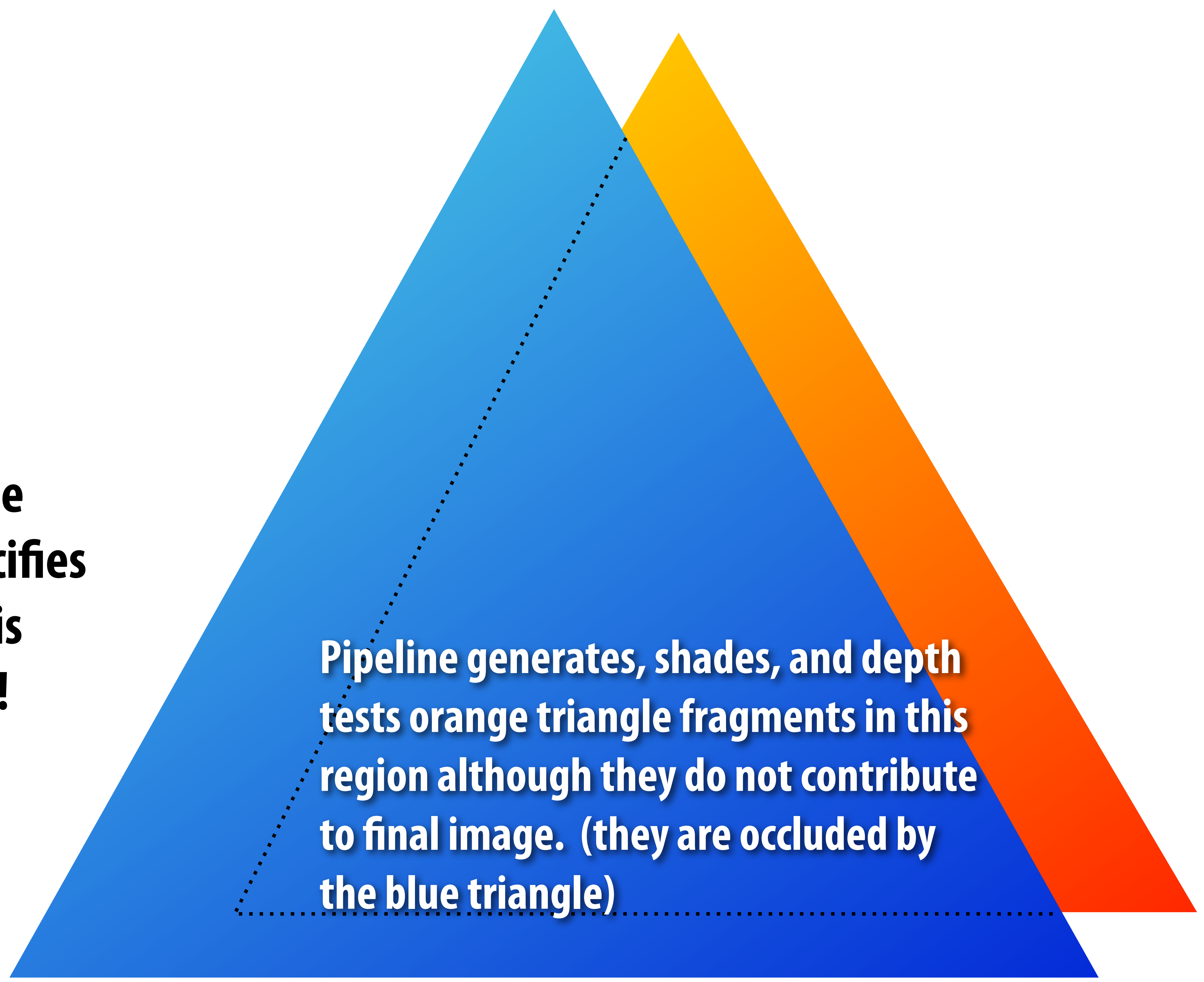
- Not specific to triangles: only requires that surface depth can be evaluated at a screen sample point

Early occlusion-culling ("early Z")

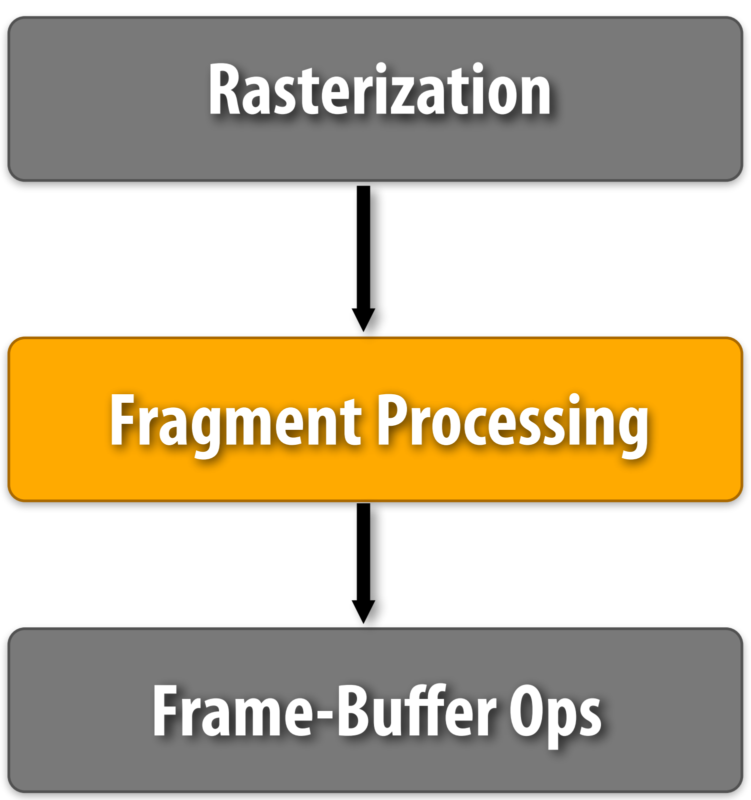
Idea: GPU discards fragments that are known to not contribute to image as early as possible in the pipeline



Graphics pipeline abstraction specifies that depth test is performed here!



Early occlusion-culling ("early Z")



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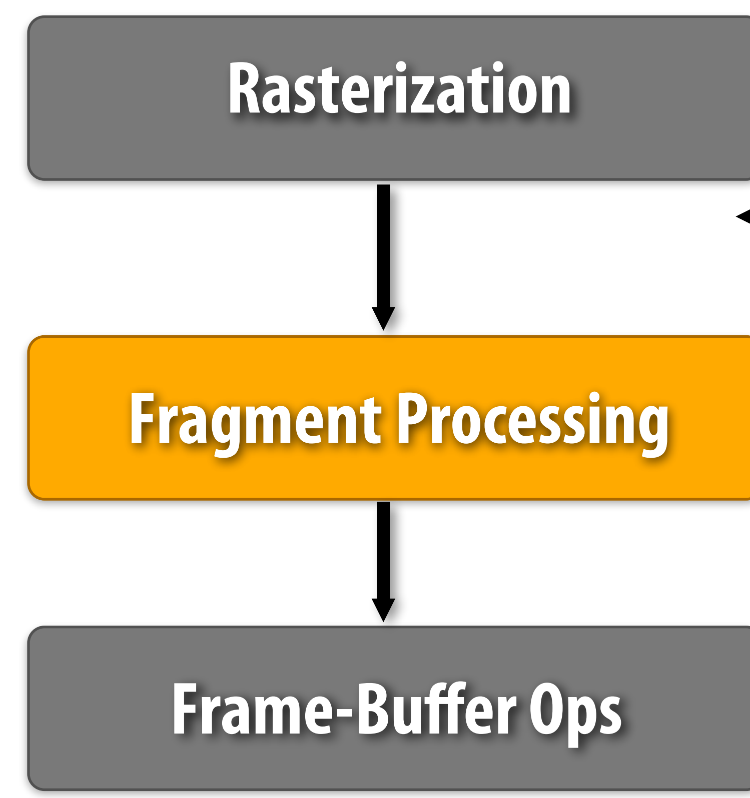


Optimization: reorder pipeline operations: perform depth test immediately following rasterization and <u>before</u> fragment shading

A GPU implementation detail: not reflected in the graphics pipeline abstraction

Key assumption: occlusion results do not depend on fragment shading

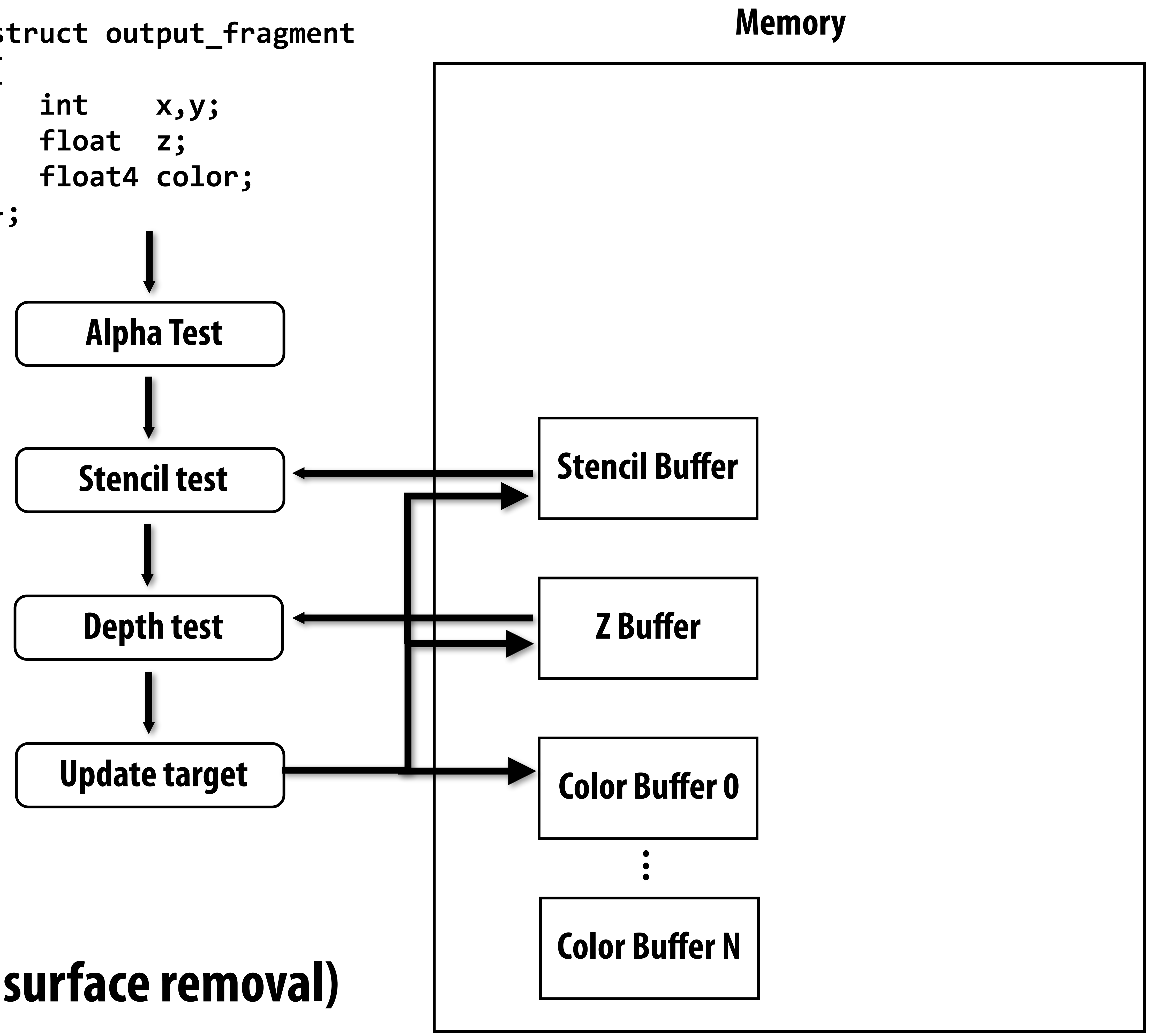
- Example operations that prevent use of this early Z optimization: enabling alpha test, fragment shader modifies fragment's Z value

Note: early Z only provides benefit if closer triangle is rendered by application first!
(application developers are encouraged to submit geometry in as close to front-to-back order as possible)

End:
Implementation of depth testing

Frame-buffer operations (full view)

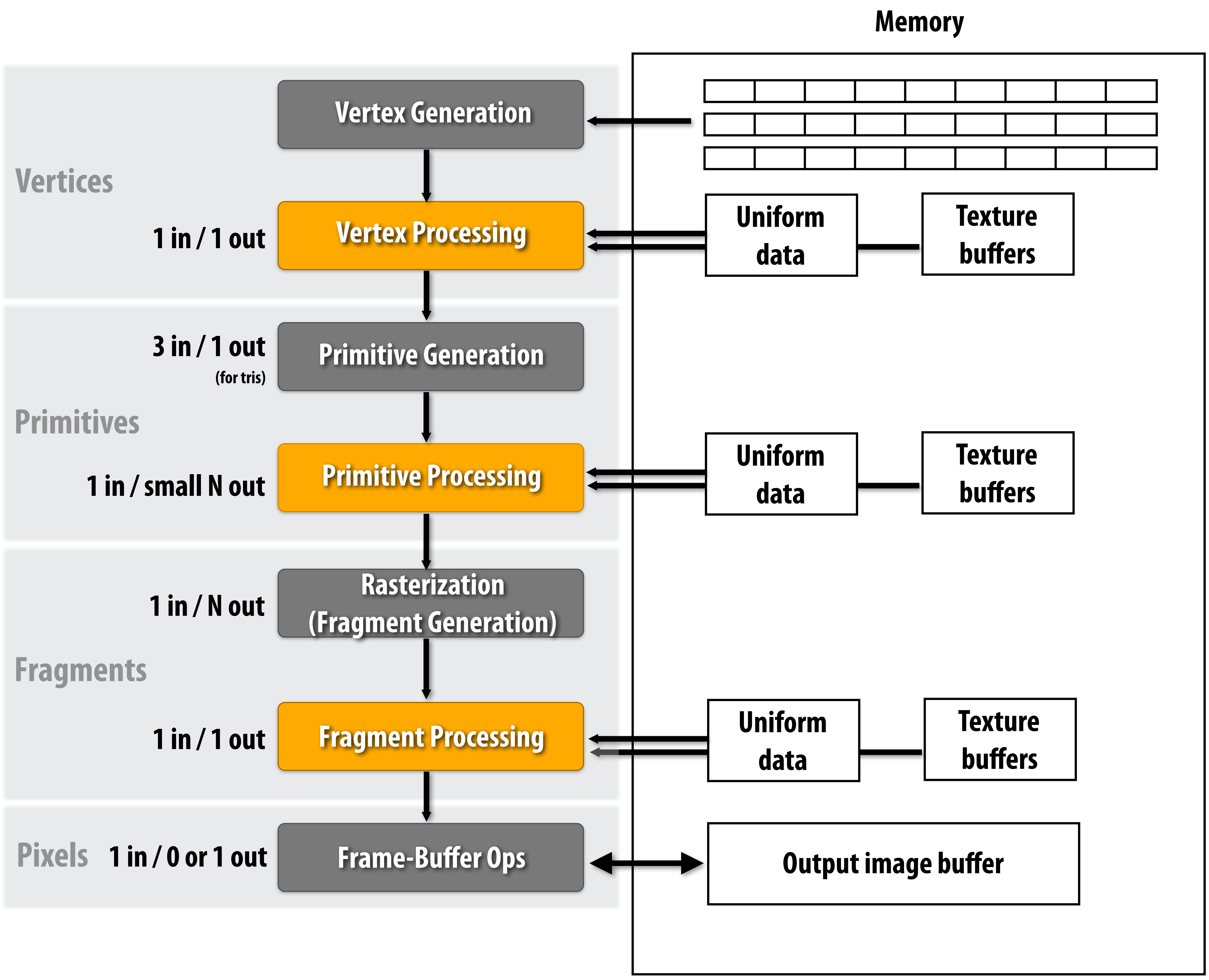
```
struct output_fragment
{
   int    x,y;
   float  z;
   float4 color;
};
```



Depth test (hidden surface removal)

```
if (fragment.z < zbuffer[fragment.x][fragment.y])
{
    zbuffer[fragment.x][fragment.y] = fragment.z;
    color_buffer[fragment.x][fragment.y] = blend(color_buffer[fragment.x][fragment.y], fragment.color);
}
```

The graphics pipeline



Programming the graphics pipeline

- Issue draw commands ⟶ output image contents change

Command Type	Command
State change	Bind shaders, textures, uniforms
Draw	Draw using vertex buffer for object 1
State change	Bind new uniforms
Draw	Draw using vertex buffer for object 2
State change	Bind new shader
Draw	Draw using vertex buffer for object 3
State change	Change depth test function
State change	Bind new shader
Draw	Draw using vertex buffer for object 4

Note: efficiently managing stage changes is a major challenge in implementations

A series of graphics pipeline commands

State change (set "red" shader)

Draw

State change (set "blue" shader)

Draw

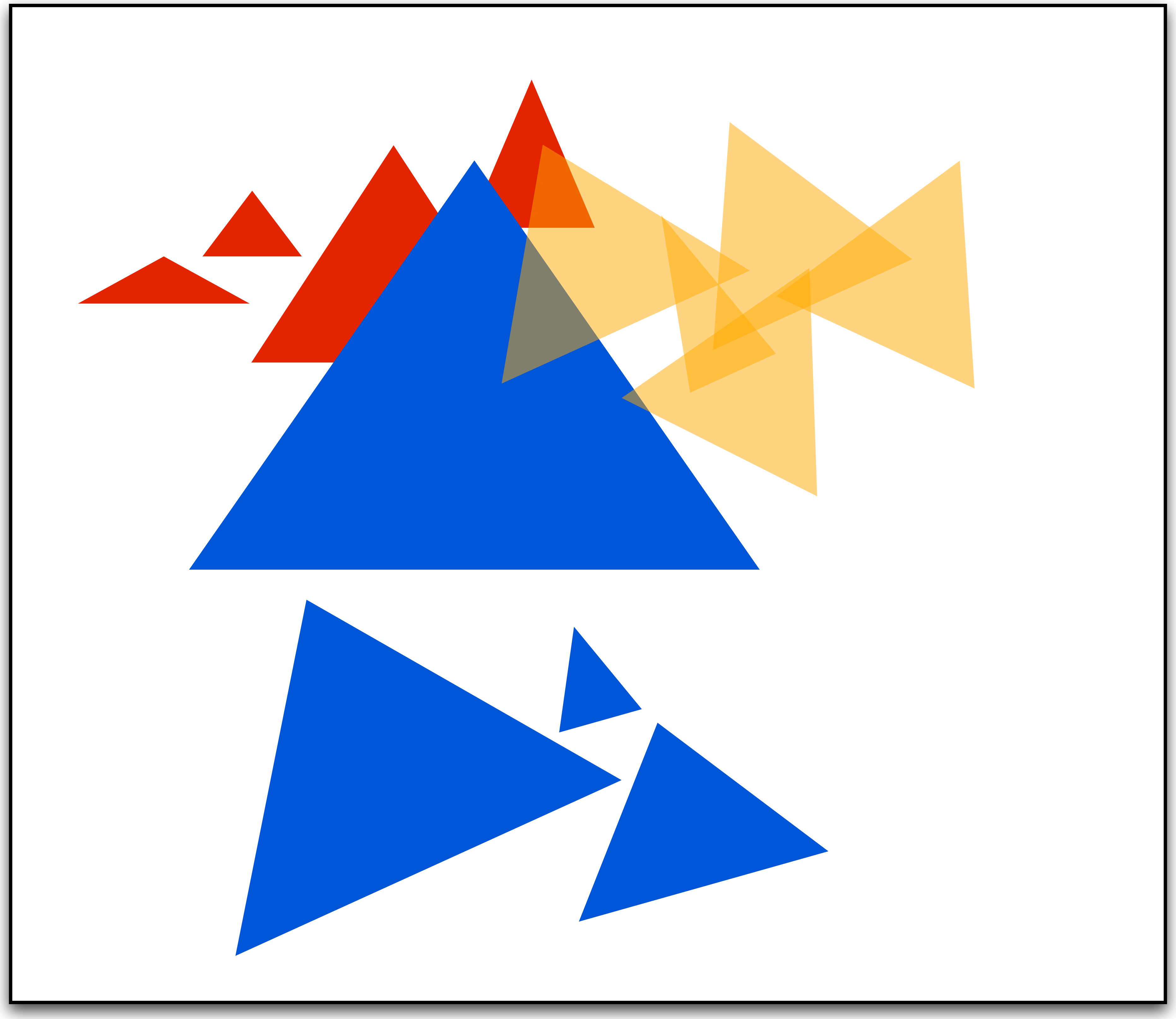
Draw

Draw

State change (change blend mode)

State change (set "yellow" shader

Draw



Feedback loop 1: use output image as input texture in later draw command

- Issue draw commands ⟶ output image contents change

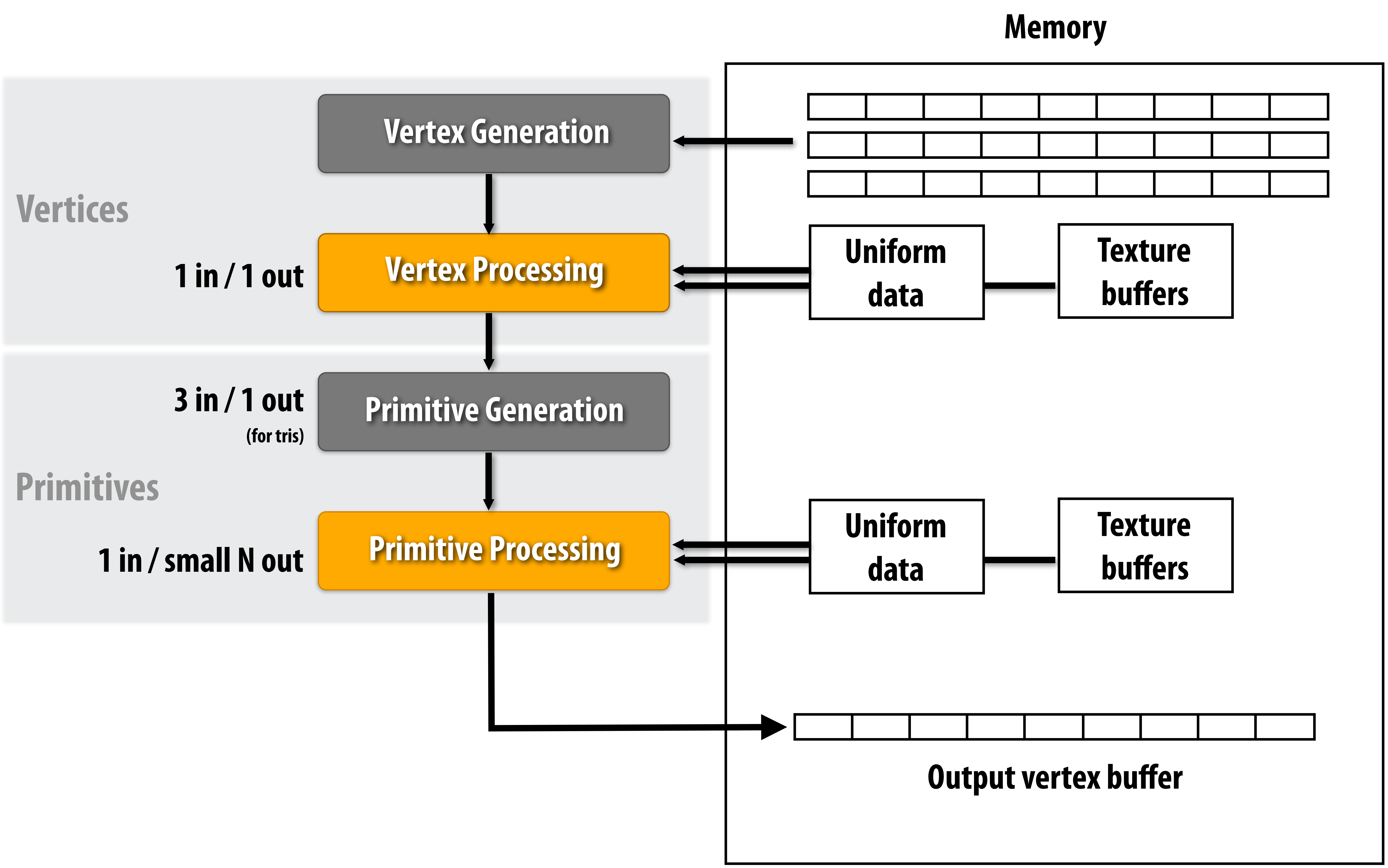
Command Type	Command
Draw	Draw using vertex buffer for object 5
Draw	Draw using vertex buffer for object 6
State change	Bind contents of output image as texture 1
Draw	Draw using vertex buffer for object 5
Draw	Draw using vertex buffer for object 6
	⋮

Rendering to textures for later use is key technique when implementing:

- Shadows
- Environment mapping
- Post-processing effects

Feedback loop 2: output intermediate geometry for use in later draw command

- Issue draw commands ⟶ output image contents change



Analyzing the design of the graphics pipeline

- **Level of abstraction**

- **Orthogonality of abstractions**

- **How is pipeline designed for performance/scalability?**

- **What the pipeline does and DOES NOT do**

*** These are great questions to ask yourself about any system we discuss in this course**

Level of abstraction

- Imperative abstraction, not declarative
  - Application code specifies: "draw these triangles, using this fragment shader, with depth testing on".
  - It does not specify: "draw a cow made of marble on a sunny day"

- Programmable stages provide application large amount of flexibility (e.g., to implement wide variety of materials and lighting techniques)

- Configurable (but not programmable) pipeline structure: application can turn stages on and off, create feedback loops

- Abstraction is low enough to allow application to implement many techniques, but high enough to abstract over radically different GPU implementations (NVIDIA, AMD, Intel GPUs, mobile GPUs, etc.)

Orthogonality of abstractions

- All vertices treated the same regardless of primitive type
  - Result: vertex programs are oblivious to primitive types
  - The same vertex program works for triangles and lines

- All primitives are converted into fragments for per-pixel shading and frame-buffer operations
  - Fragment programs are oblivious to source primitive type and the behavior of the vertex program *
  - Z-buffer is a common representation used to perform occlusion for any primitive that can be converted into fragments

* Almost oblivious. Vertex shader must make sure it passes along all inputs required by the fragment shader

What the pipeline DOES NOT do (non-goals)

- **Modern graphics pipeline has no concept of lights, materials, geometric modeling transforms**
  - Only streams of records processed by application defined kernels: vertices, primitives, fragments, pixels
  - And pipeline state (input/output buffers, "shaders", and fixed-function configuration parameters)
  - Applications implement lights, materials, etc. using these basic abstractions
- The graphics pipeline has no concept of a scene
- It is just a virtual machine that executes pipeline state change and primitive drawing commands

Pipeline design facilitates performance/scalability

- [Reasonably] low level: low abstraction distance to implementation
- Constraints on pipeline structure:
  - Constrained data flow between stages
  - Fixed-function stages for common and difficult to parallelize tasks
  - Shaders: independent processing of each data element (enables data parallelism)
- Provide frequencies of computation (per vertex, per primitive, per fragment)
  - Application can choose to perform work at the rate required
- Keep it simple:
  - Only a few common intermediate representations
    - Triangles, points, lines
    - Fragments, pixels
  - Z-buffer algorithm computes visibility for any primitive type
- "Immediate-mode system": pipeline processes primitives as it receives them (as opposed to buffering the entire scene)
  - Leave global optimization of <u>how</u> to render scene to the application

Perspective from Kurt Akeley

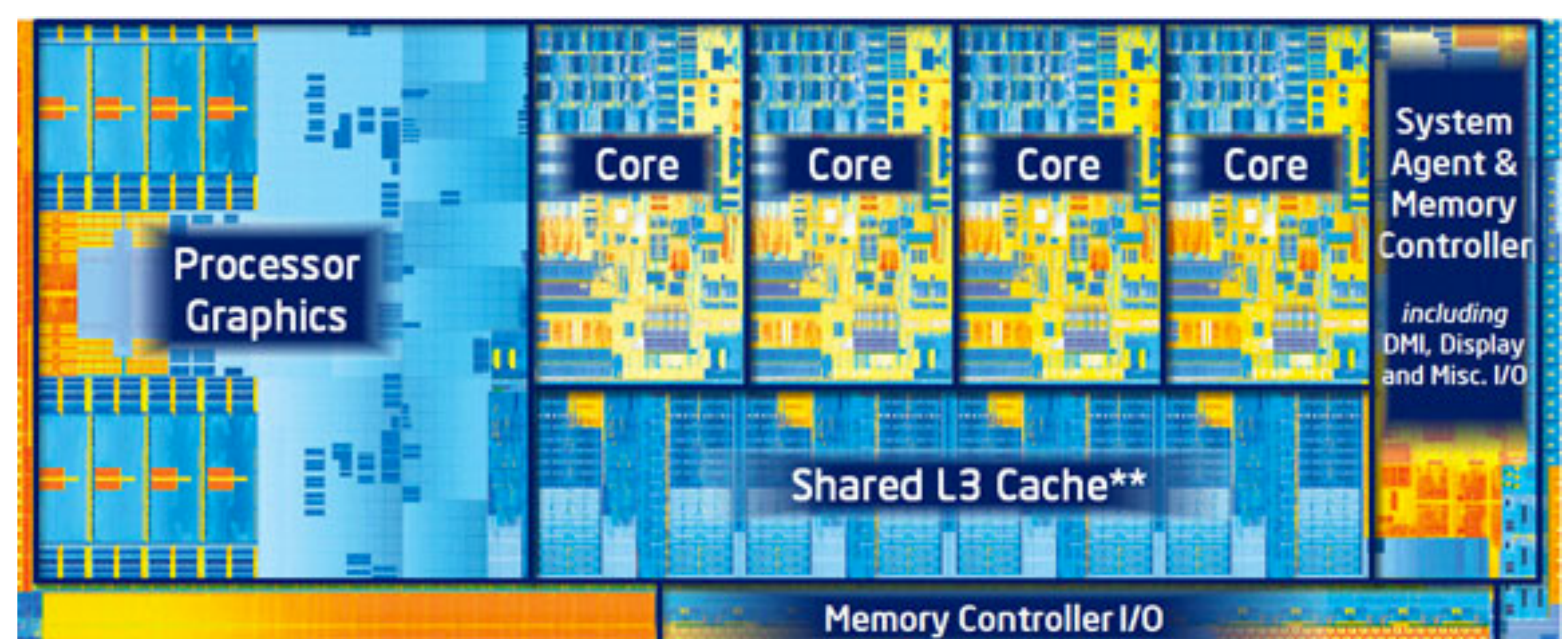
- Does the system meet original design goals, and then do much more than was originally imagined?

- If so, the design is a good one!
  - Simple, orthogonal concepts often produce this amplifier effect

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 many TFLOPs of performance for executing vertex and fragment shader programs

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