Lecture 5:
Rasterization and Occlusion

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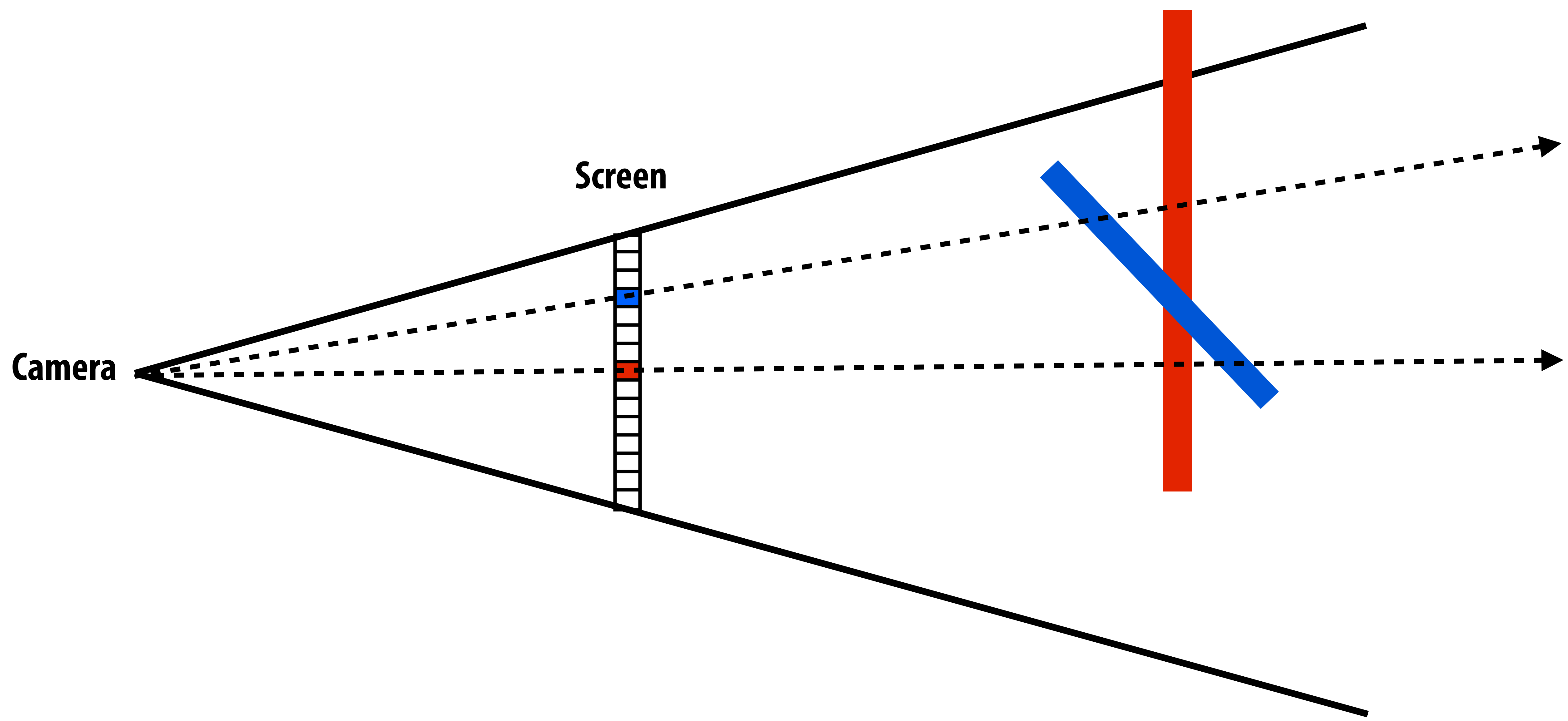
CMU 15-869: Graphics and Imaging Architectures (Fall 2011)

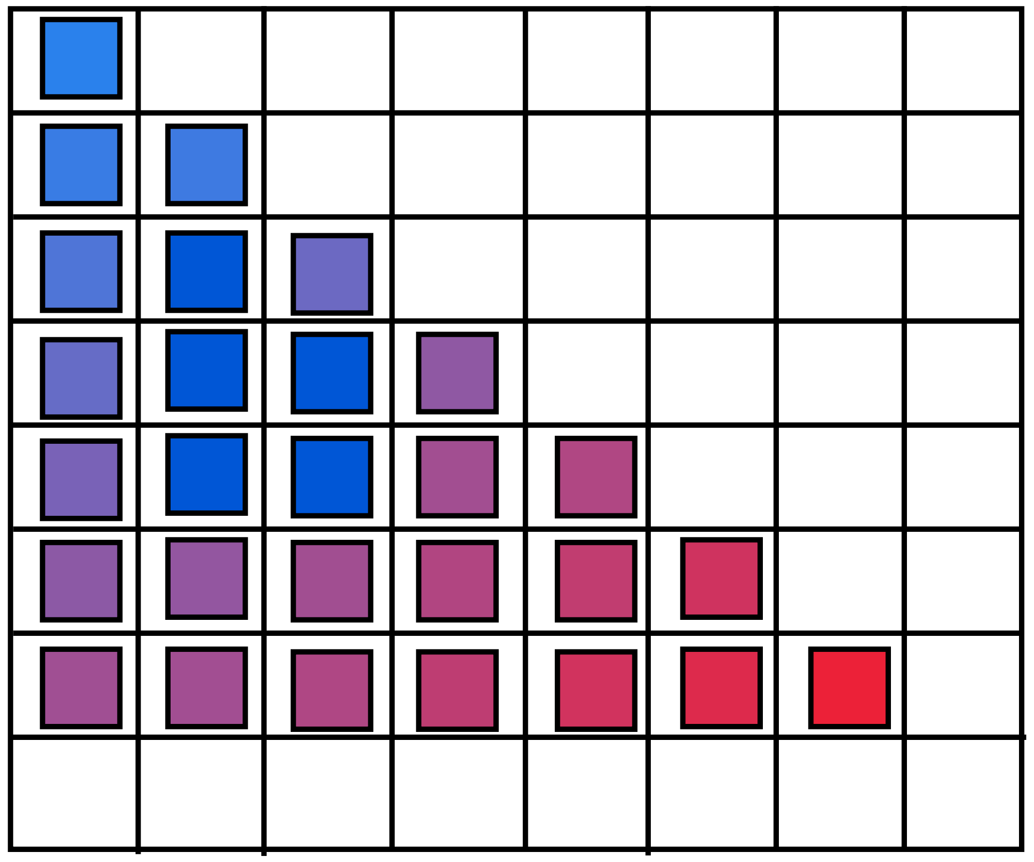
Visibility

- What scene geometry is visible within each screen pixel?
  - What geometry projects into a screen pixel? (screen coverage)
  - Which of this geometry is visible from the camera at that pixel? (occlusion)



Visibility on GPU: rasterization + Z-buffering

- The rasterizer converts a primitives (triangles) into fragments
  - Computes covered pixels (selection: what fragments get generated?)
  - Computes triangle attributes for fragment (attribute assignment: how is surface data is associated with the fragment?)



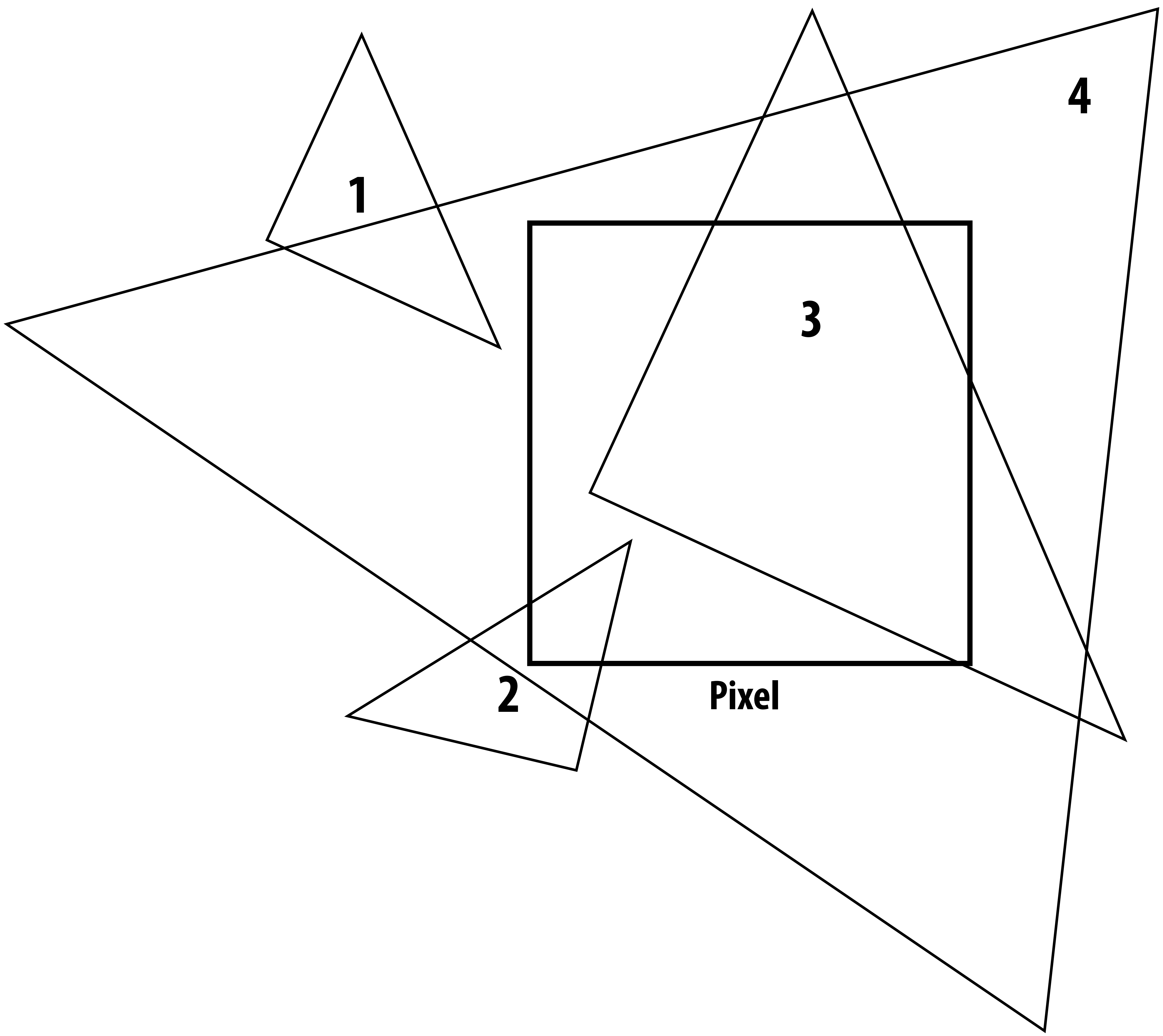
```
struct fragment
{
   float3 normal;      // interpolated application-defined attribs
   float2 texcoord1;   // (e.g., texture coordinates, surface normal)
   float2 texcoord2;

                       // pipeline-interpretted fields:

   int x, y;           // pixel position corresponding to fragment
   float depth;        // triangle depth for fragment
}
```

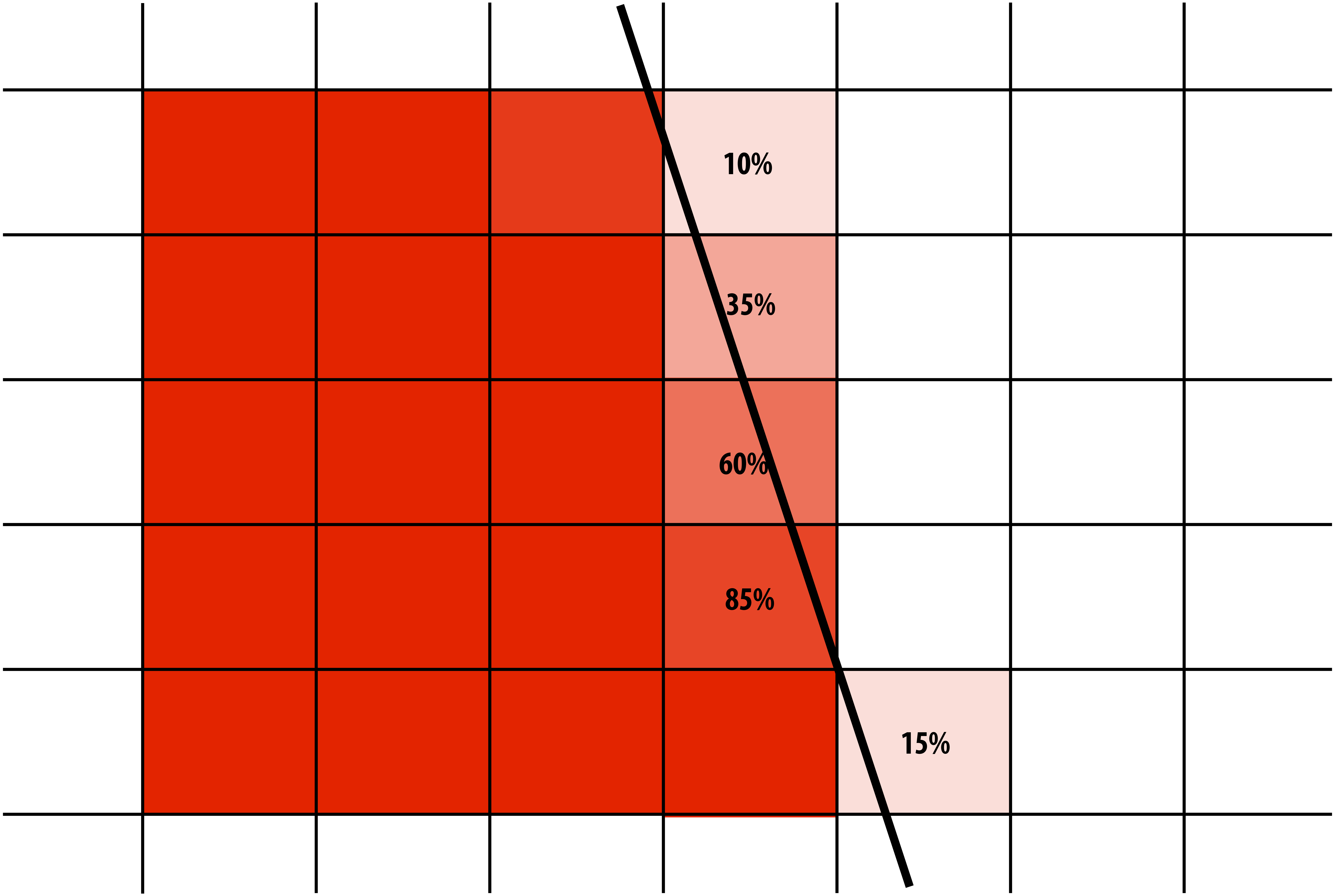
- Recall: frame-buffer operations stage handles occlusion using the Z-buffer algorithm
  - Although there are many optimizations (we will discuss some today)

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

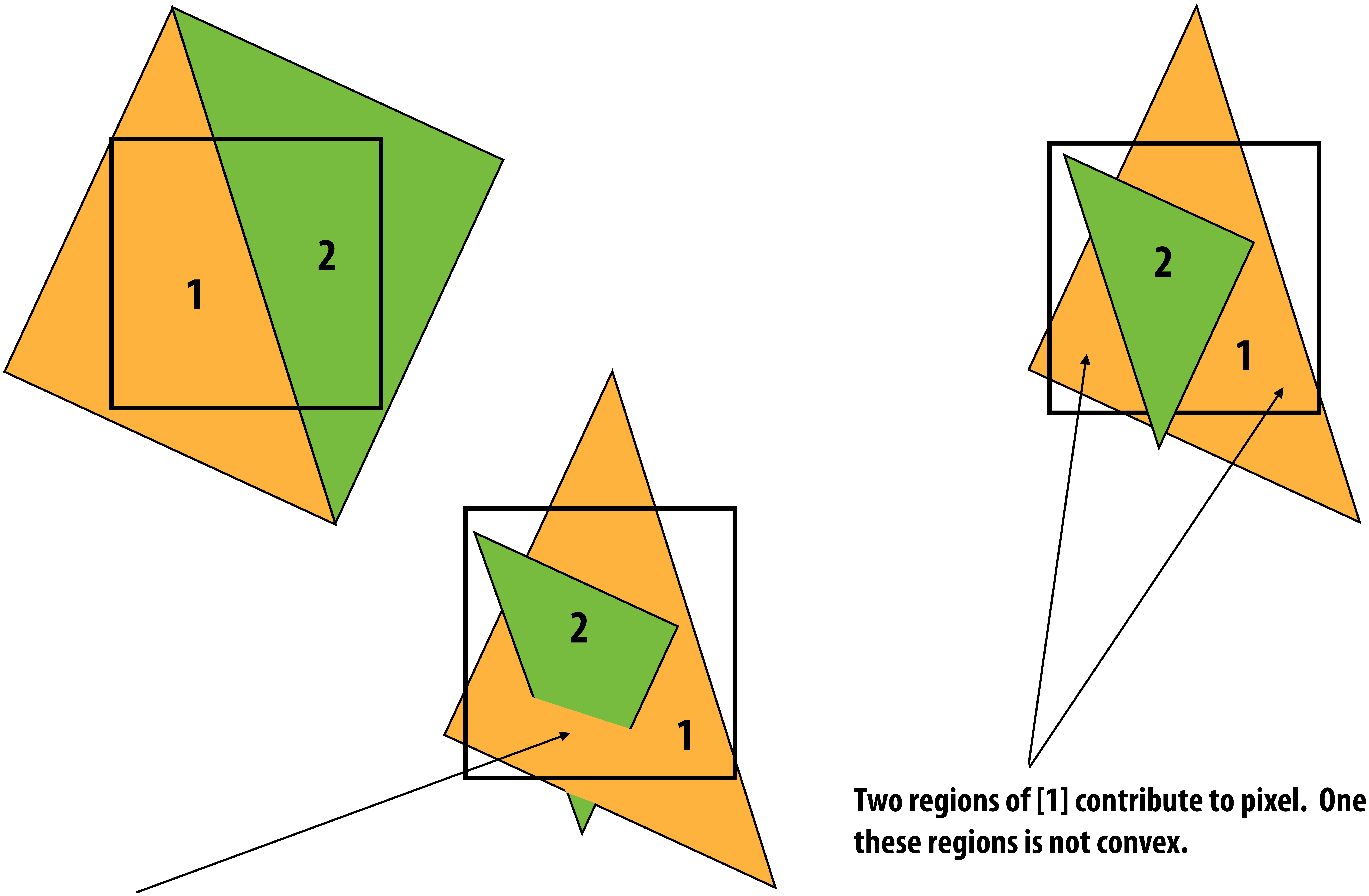


Integrate pixel coverage analytically

(A fragment is an area sample)



Analytical schemes get tricky when considering occlusion

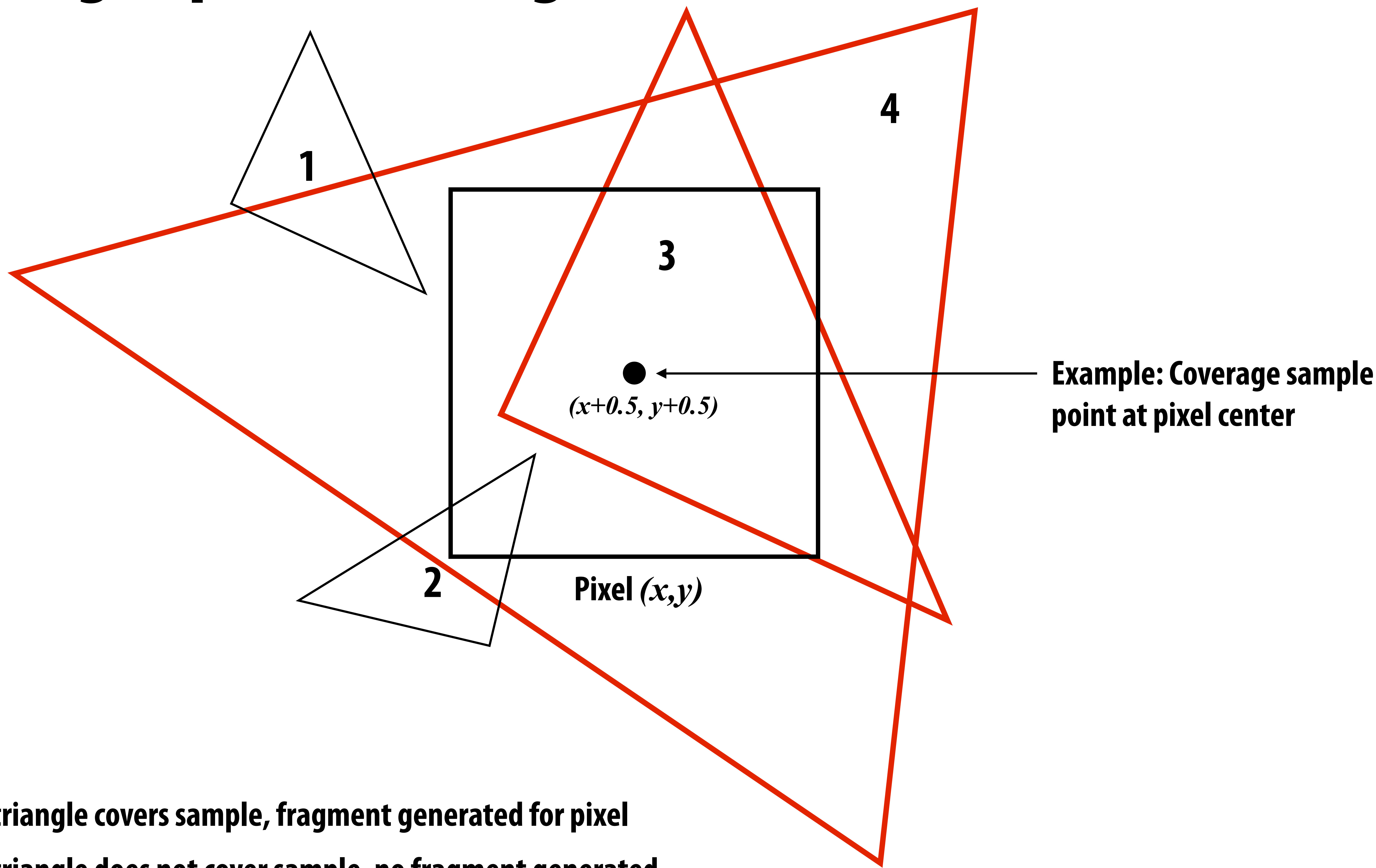


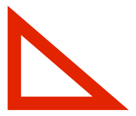
Interpenetration: even worse

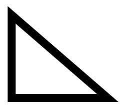
Two regions of [1] contribute to pixel. One of these regions is not convex.

Note: unbounded storage per pixel.

Modern GPU fragment selection: point sample triangle-pixel coverage

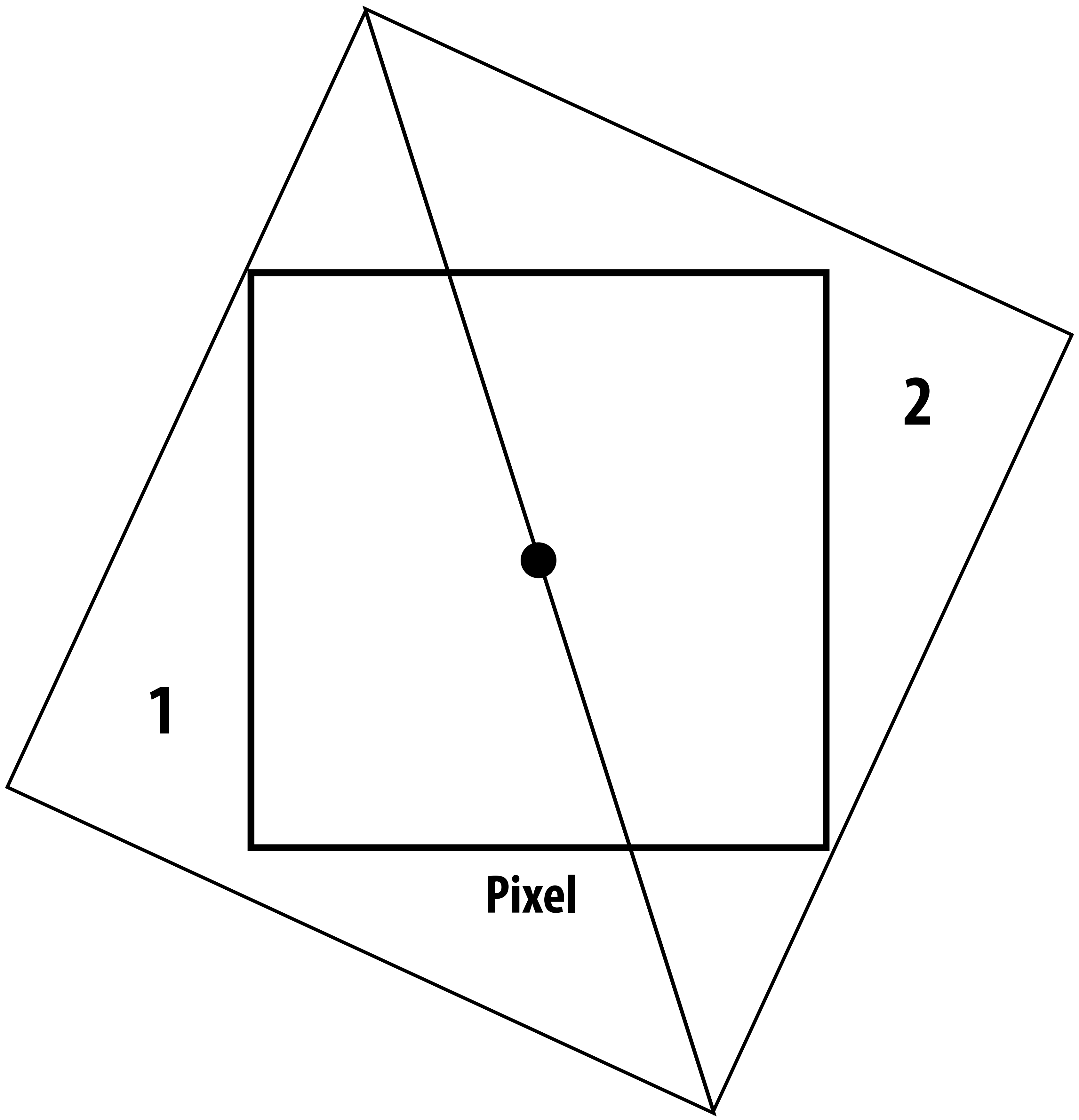


 = triangle covers sample, fragment generated for pixel

 = triangle does not cover sample, no fragment generated

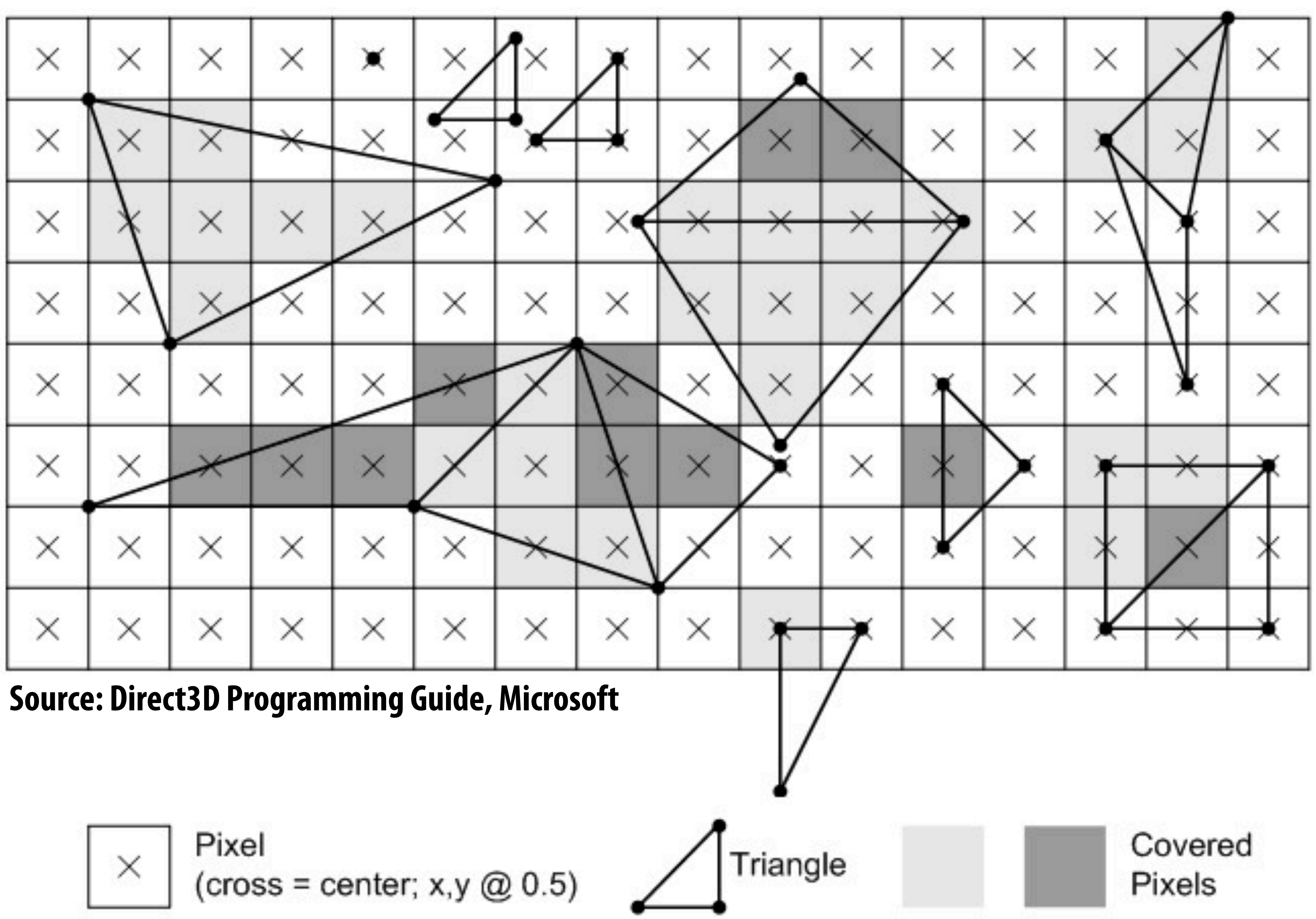
Edge cases (literally)

Is fragment generated for triangle 1? for triangle 2?



Edge rules

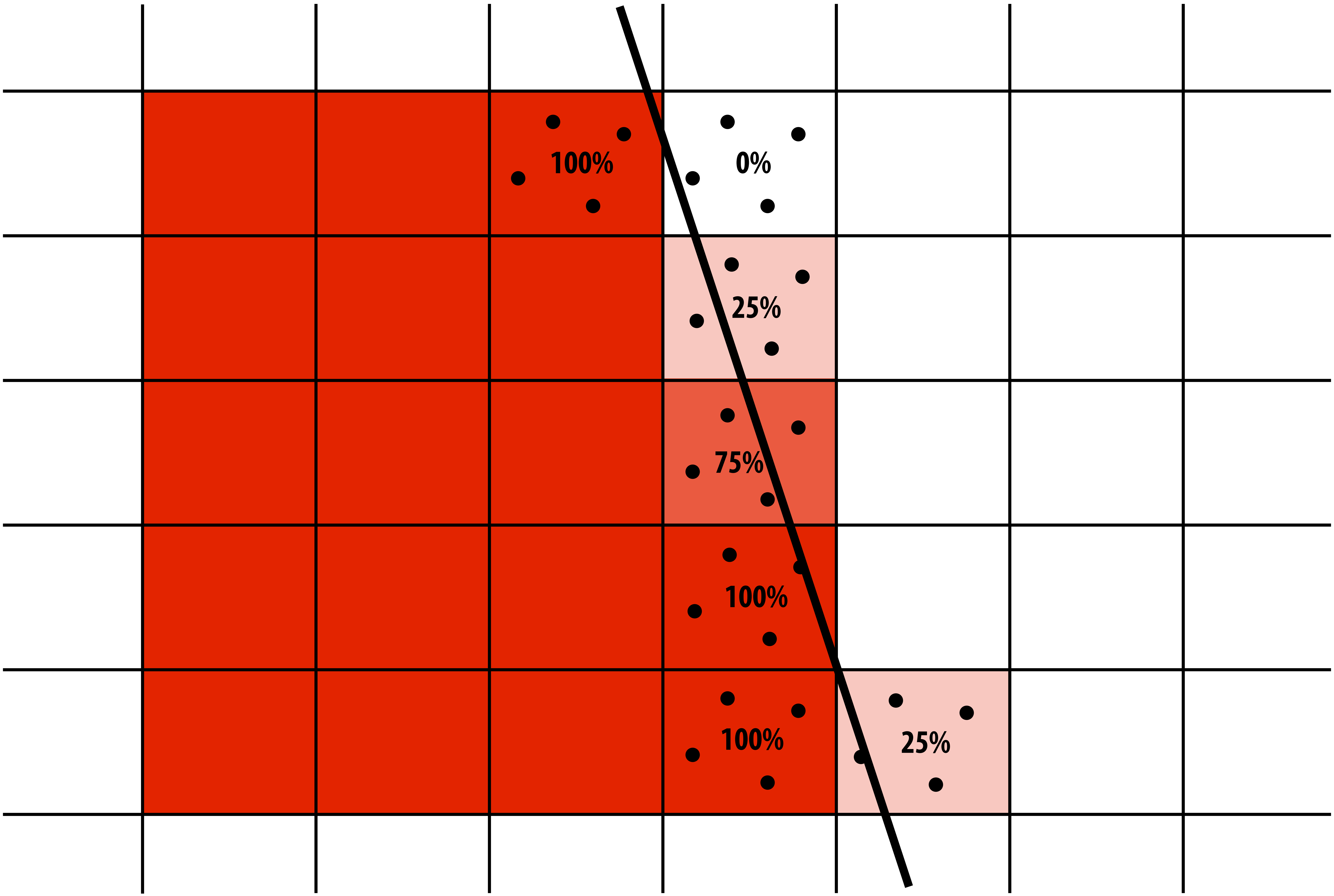
- Direct3D rules: when edge falls directly on sample, sample classified as within triangle if the edge is a "top edge" or "left edge"
  - Top edge: horizontal edge that is above all other edges
  - Left edge: an edge that is not exactly horizontal and is on the left side of the triangle. (triangle can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



Source: Direct3D Programming Guide, Microsoft

Super-sampling to anti-alias edges

(will discuss next time)



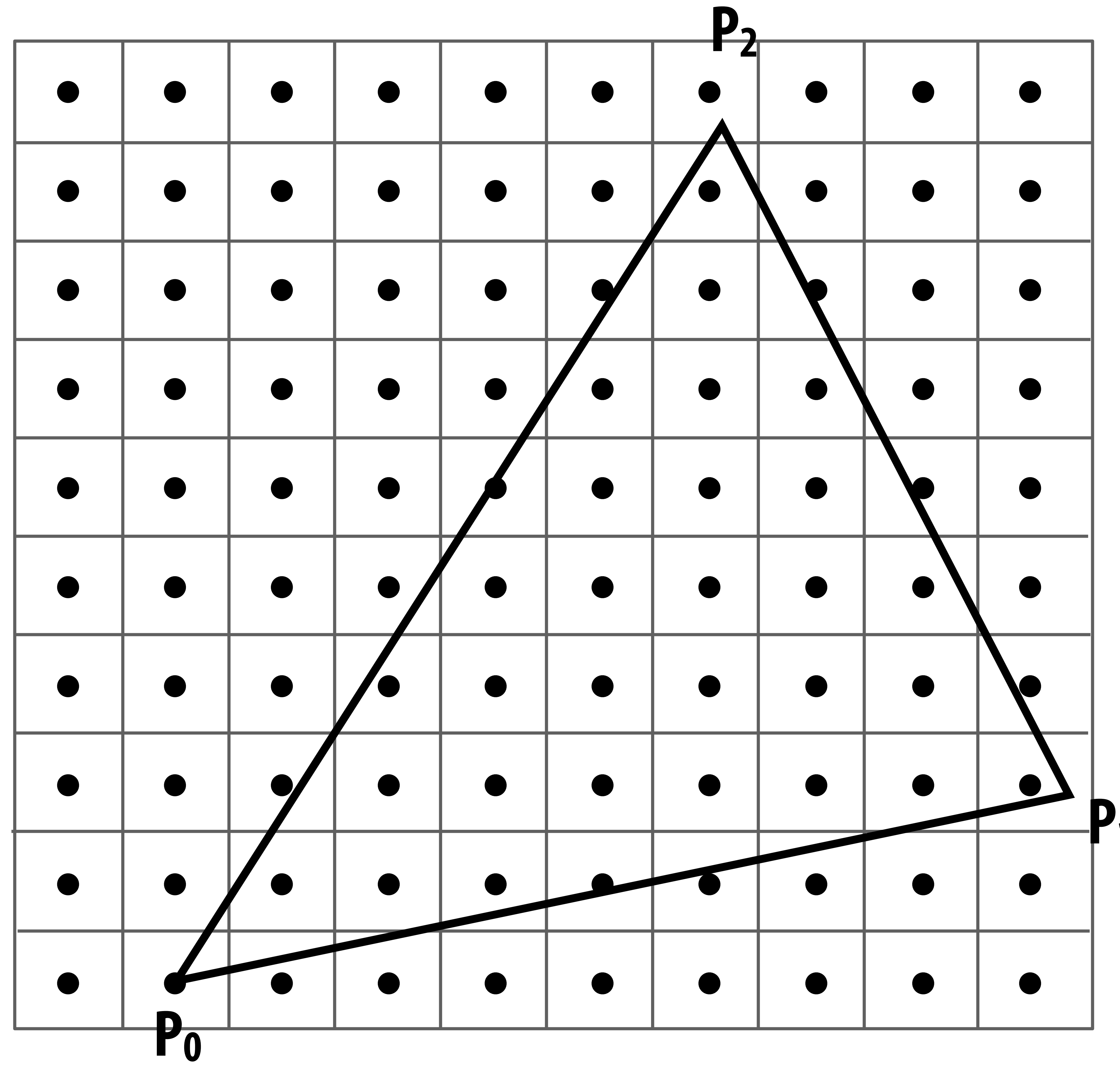
Point-in-triangle test

$P_i = (x_i/w_i, y_i/w_i, z_i/w_i) = (X_i, Y_i, Z_i)$

$dX_i = X_{i+1} - X_i$
$dY_i = Y_{i+1} - Y_i$

$E_i(x,y) = (x-X_i)\, dY_i - (y-Y_i)\, dY_i$
$\quad = A_i x + B_i y + C_i$

$E_i(x,y) = 0$: point on edge
$\quad > 0$: outside edge
$\quad < 0$: inside edge



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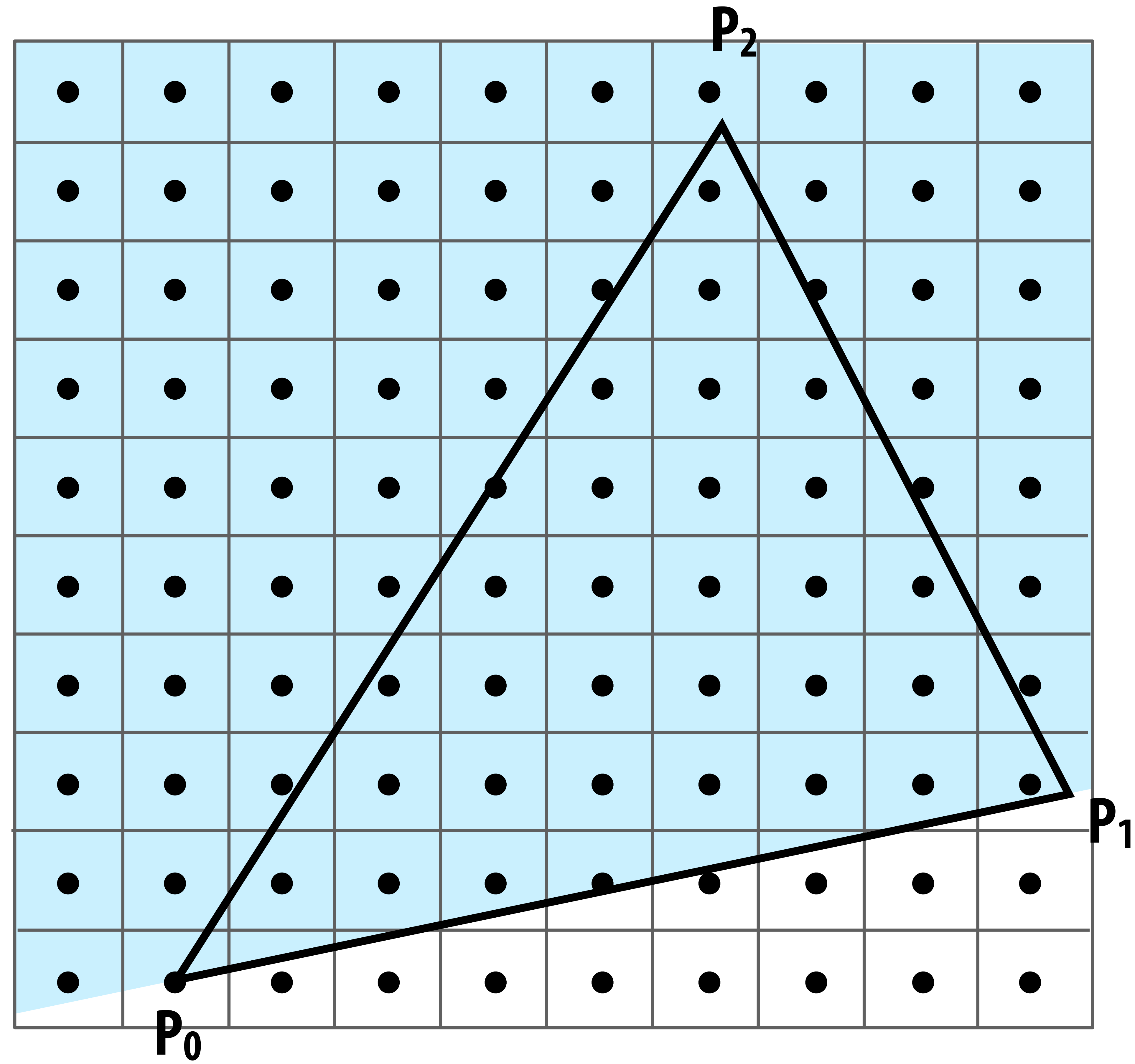

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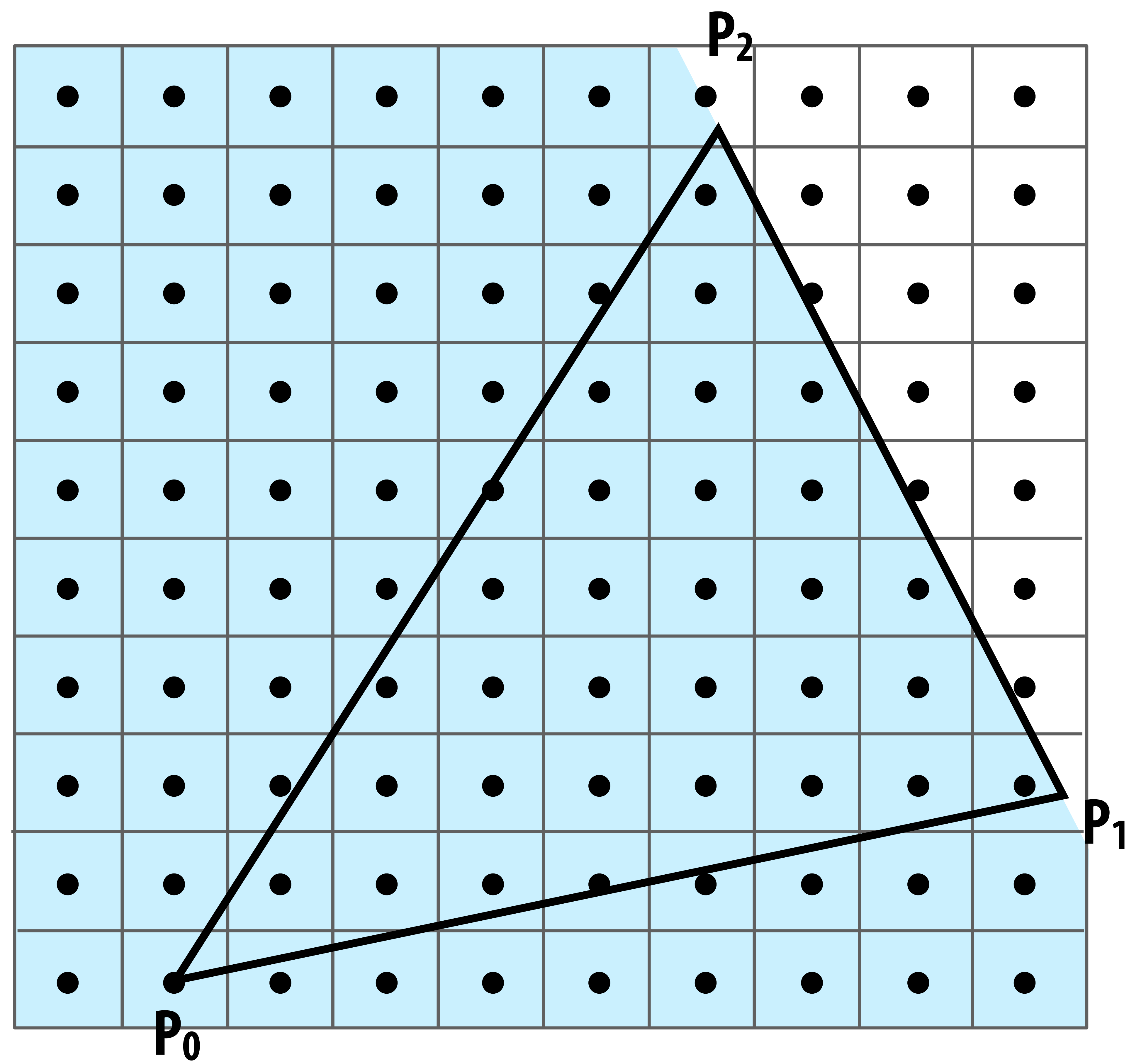

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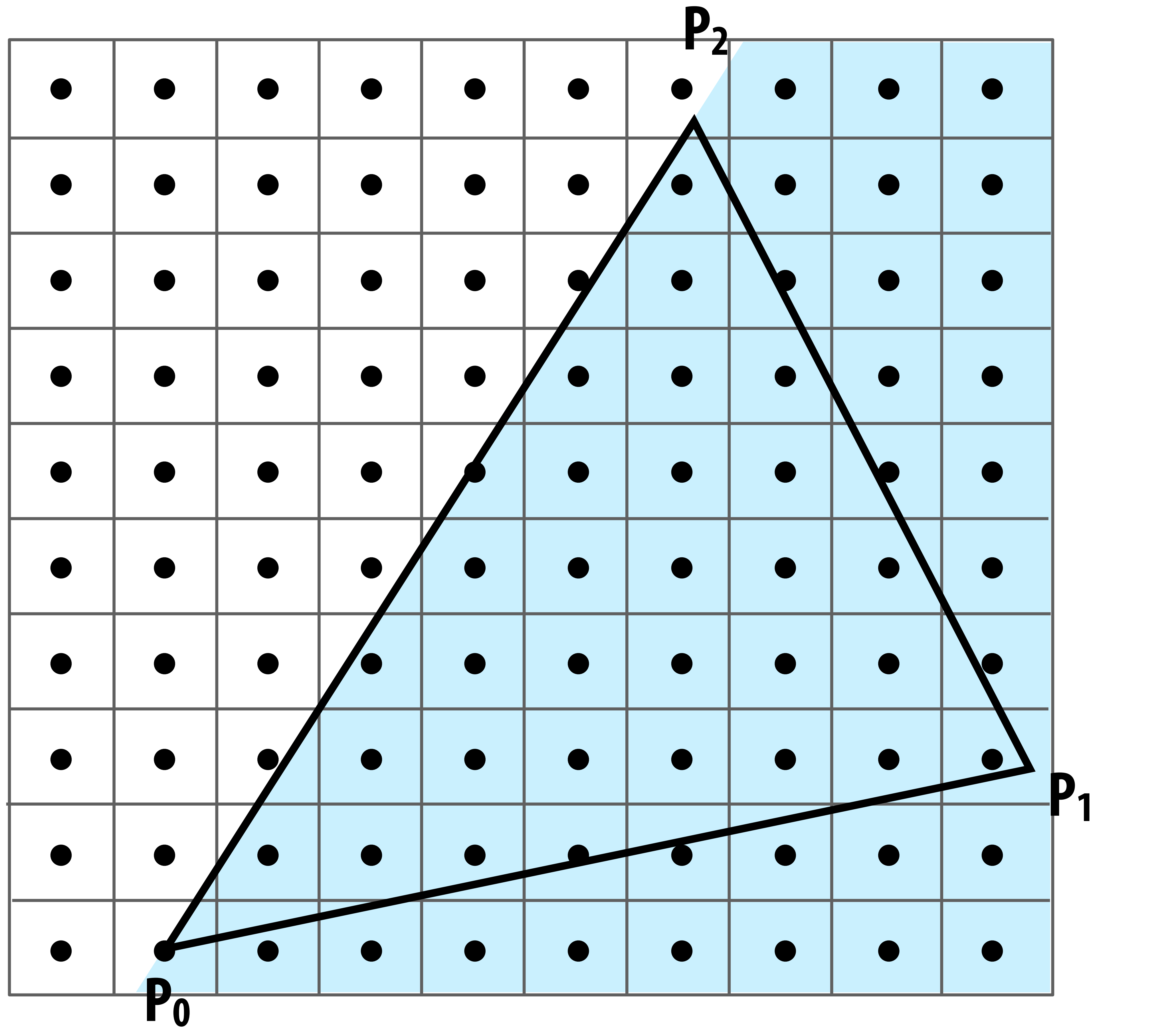

Point-in-triangle test

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$$E_i(x,y) = (x - X_i)\, dY_i - (y - Y_i)\, dY_i$$
$$= A_i\, x + B_i\, y + C_i$$

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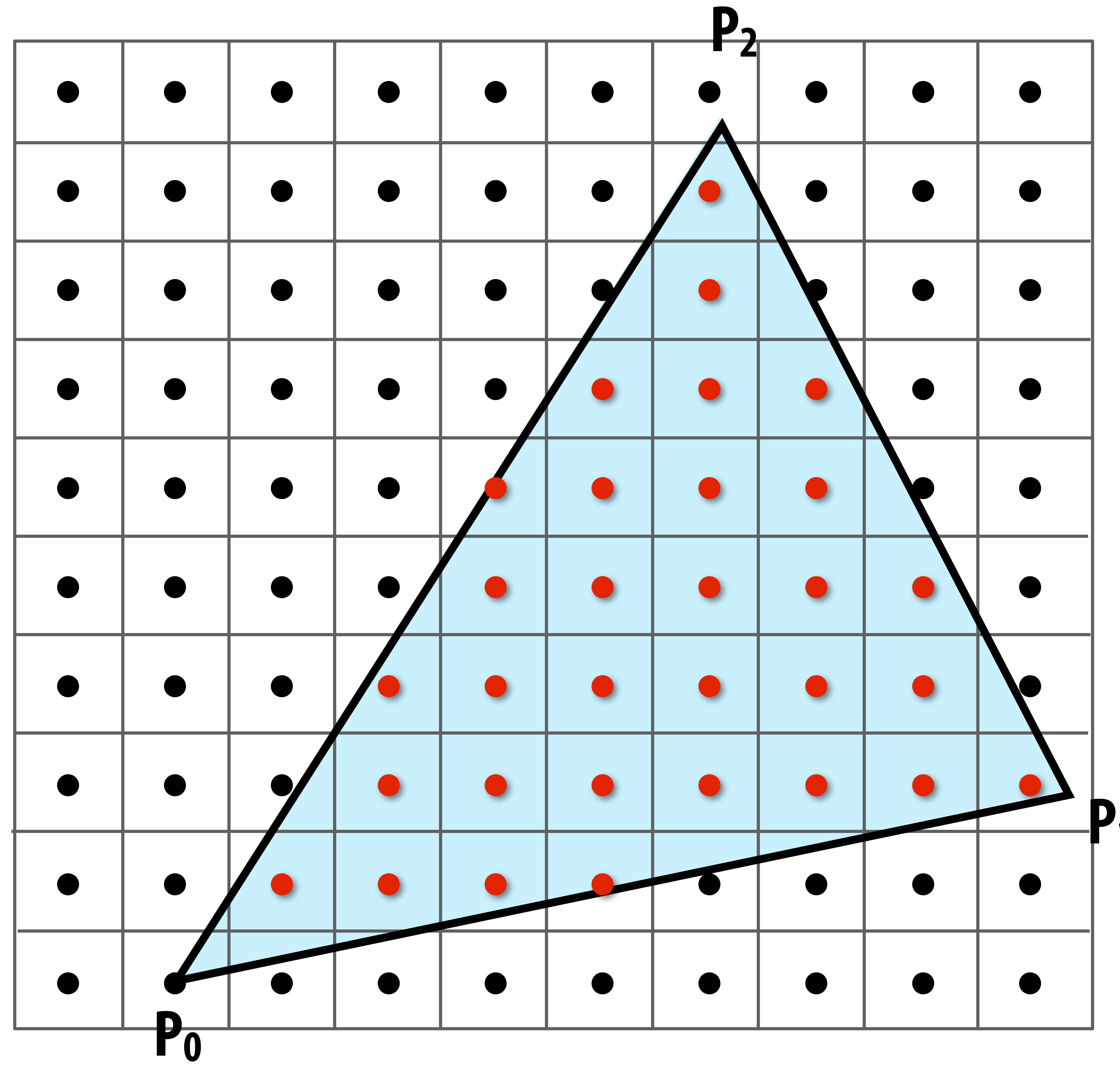

Incremental triangle traversal

$P_i = (x_i/w_i, y_i/w_i, z_i/w_i) = (X_i, Y_i, Z_i)$

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$= A_i x + B_i y + C_i$

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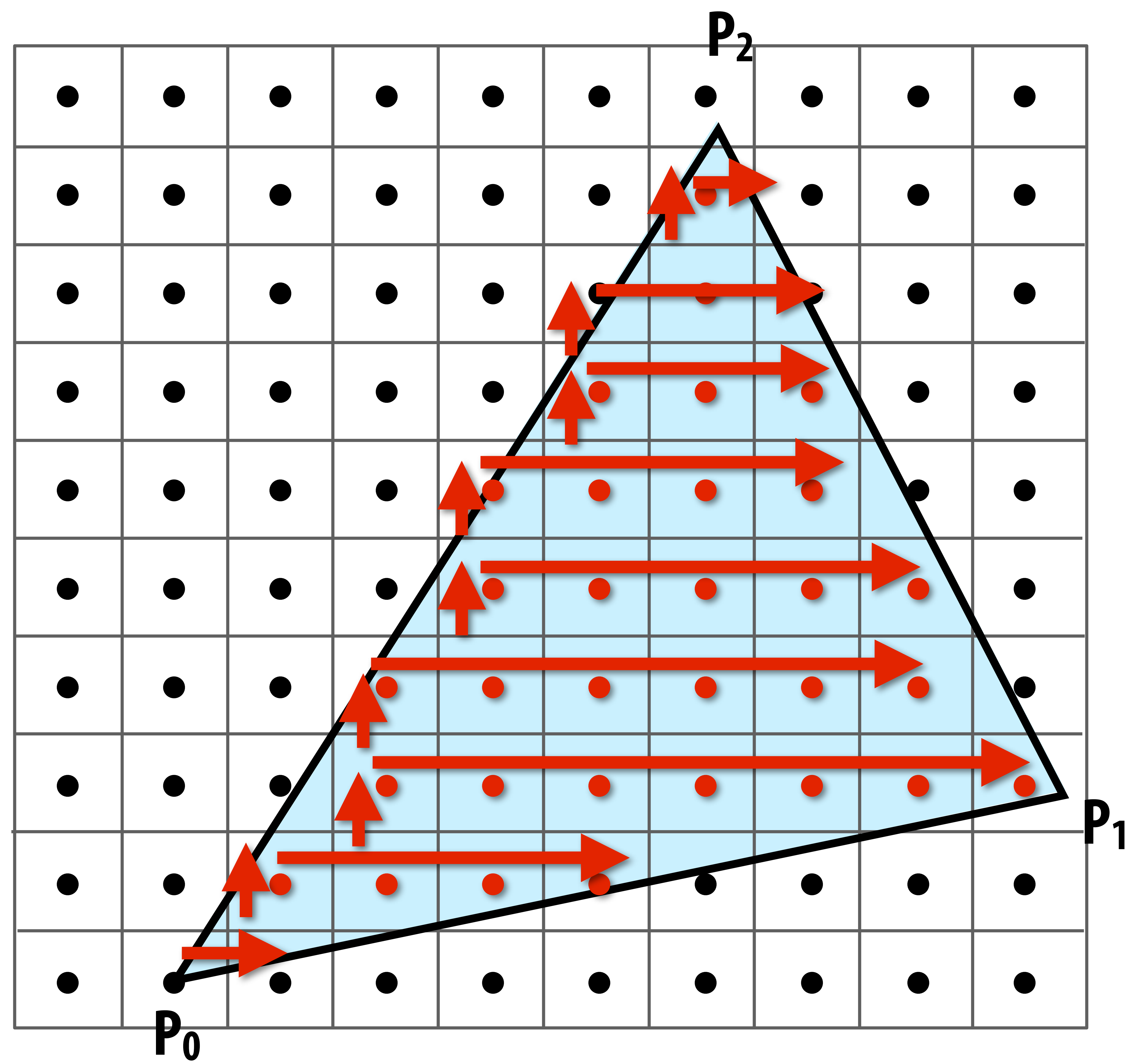
Note incremental update:

$dE_i(x+1,y) = E_i(x,y) + dY_i = E_i(x,y) + A_i$
$dE_i(x,y+1) = E_i(x,y) + dX_i = E_i(x,y) + B_i$



Incremental update saves computation:
One addition per edge, per sample test

Note: many traversals possible: backtrack, zig-zag, Hilbert/Morton curves (locality maximizing)

Modern hierarchical traversal

Traverse triangle as before, but in blocks

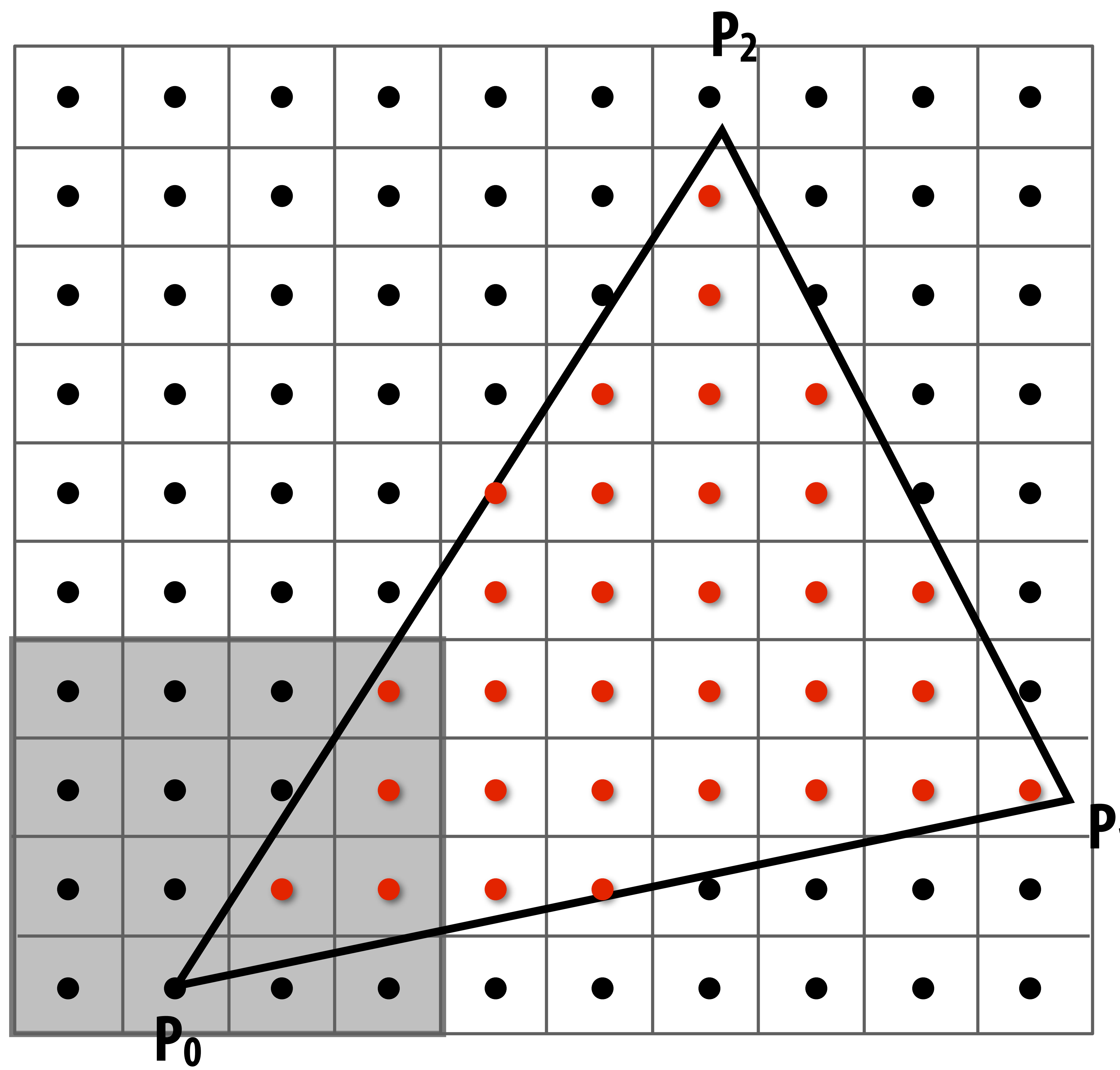
Test all samples in block against triangle in parallel (data-parallellism)

Can be implemented as multi-level hierarchy.

Advantages:

- Simplicity of wide parallel execution overcomes cost of extra point-in-triangle tests (recall: most triangles cover many samples, especially when super-sampling coverage)
- Can skip sample testing work (early outs): entire block not in triangle, entire block entirely within triangle
- Important for early Z cull (later in this lecture)

Another modern approach: Hierarchical Recursive Descent.
(See Mike Abrash's Dr. Dobbs article in readings)



Attribute assignment

- How are fragment attributes (color, normal, texcoords) computed?
  - Point sample attributes as well. (e.g., at pixel center)
  - Must compute $A(x,y)$ for all attributes

Computing a plane equation for an attribute:

Attribute values at three vertices: A_0, A_1, A_2
Projected positions of three vertices: (X_0, Y_0), (X_1, Y_1), (X_2, Y_2)
$A(x,y) = ax + by + c$

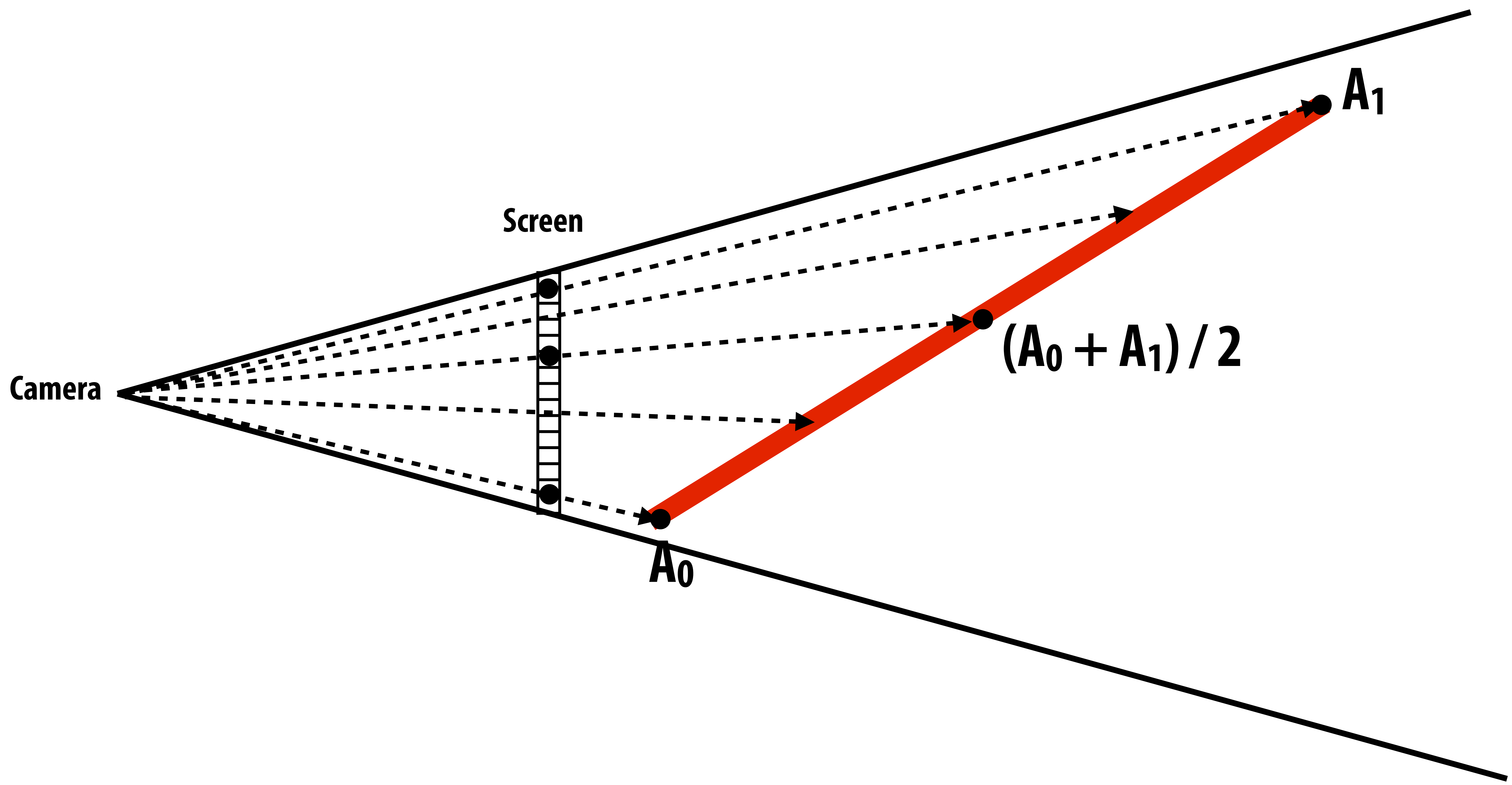
$A_0 = aX_0 + bY_0 + c$
$A_1 = aX_1 + bY_1 + c$
$A_2 = aX_2 + bY_2 + c$

3 equations, 3 unknowns. Solve for a,b,c **

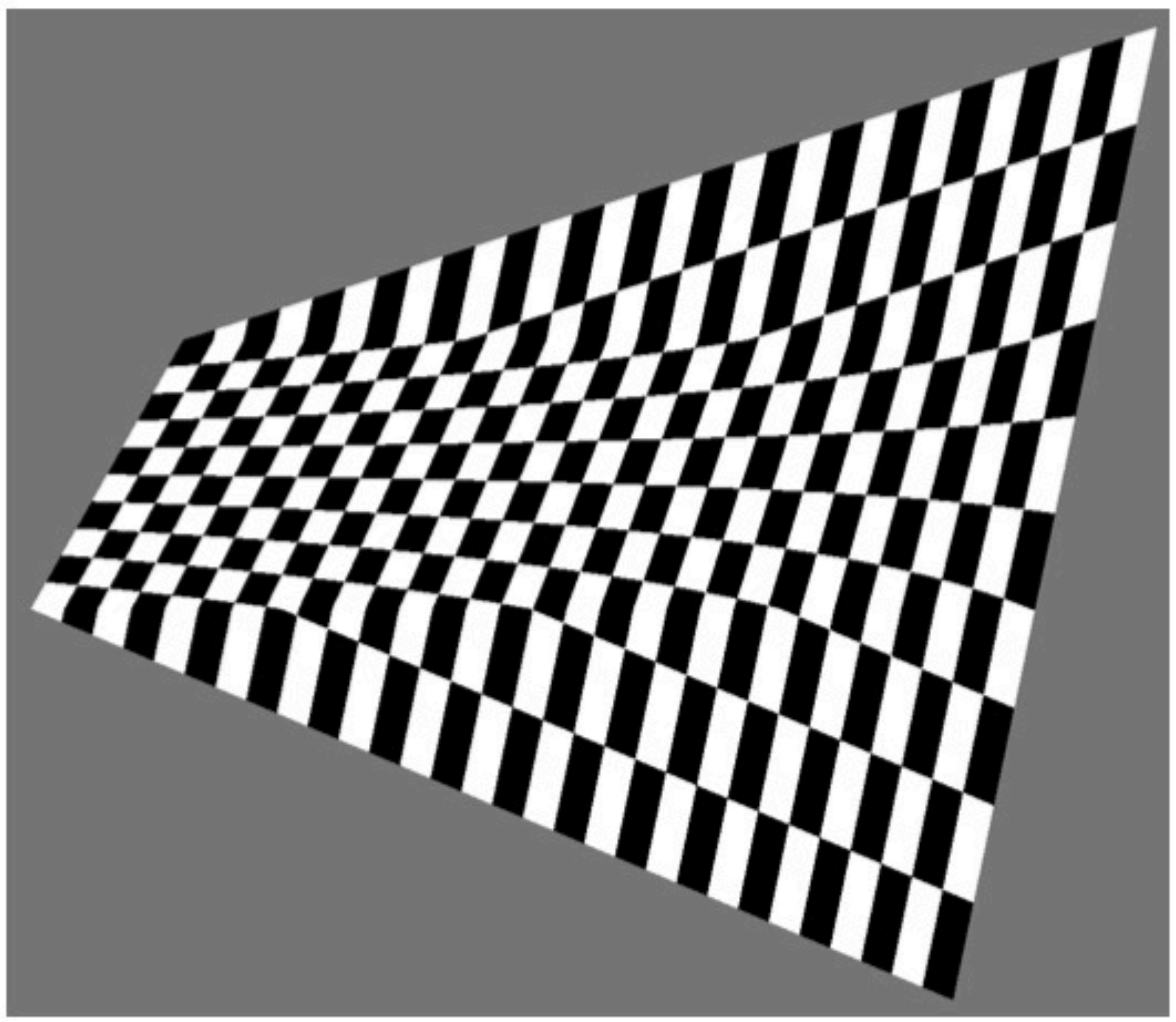
** Discard zero-area triangles before getting here (recall we computed area in back-face culling)

Perspective correct interpolation

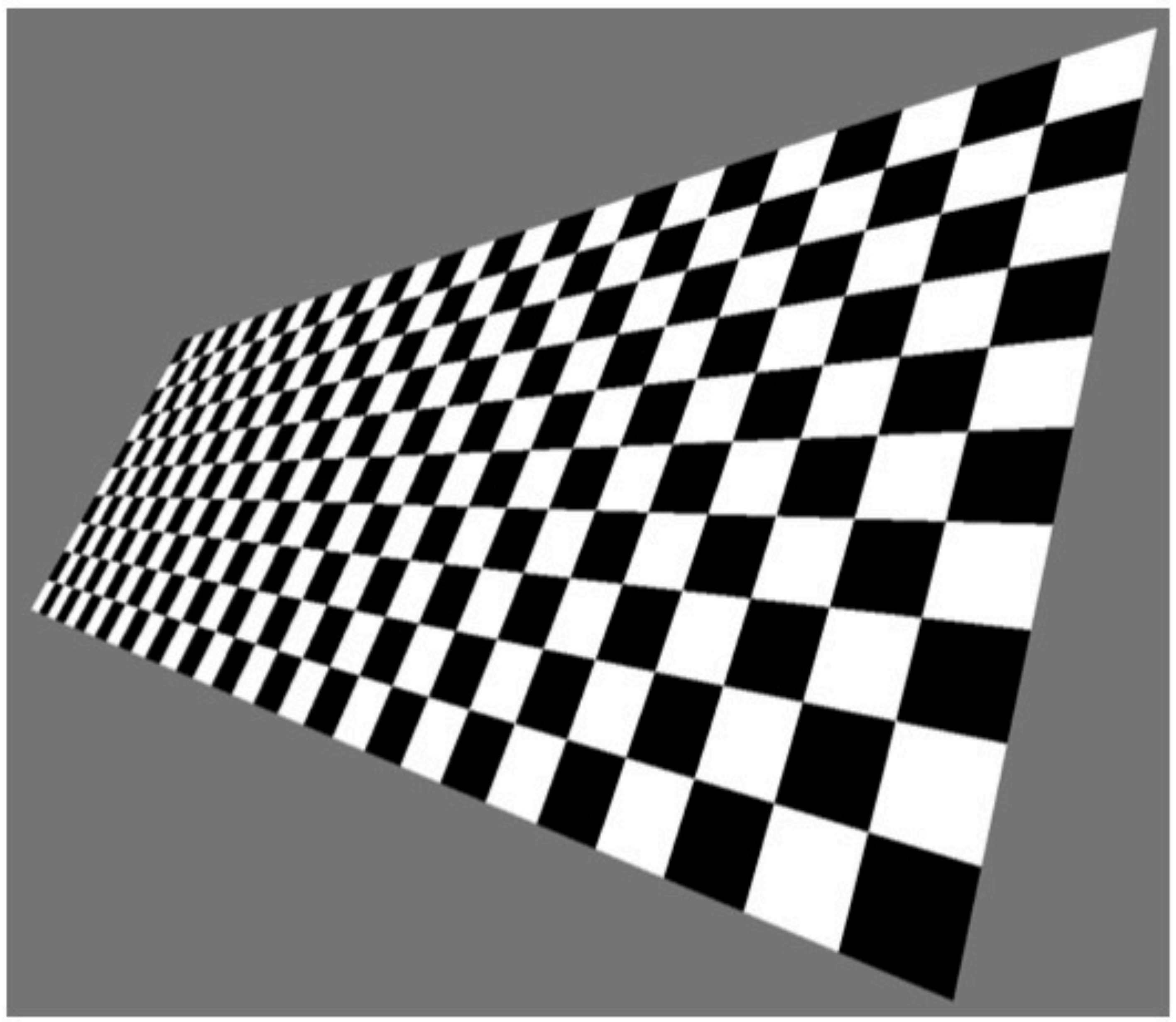
Attribute values are linear on triangle in 3D, but not linear in projected screen XY



Perspective-correct interpolation



Linear screen interpolation of (u,v)



Perspective-correct interpolation of (u,v)

[images from Heckbert and Moreton 1991]

Perspective correct interpolation

Attribute values are linear on triangle in 3D, but not linear in projected screen XY

But... projected values (A/w) are linear in screen XY: compute plane equations from A/w

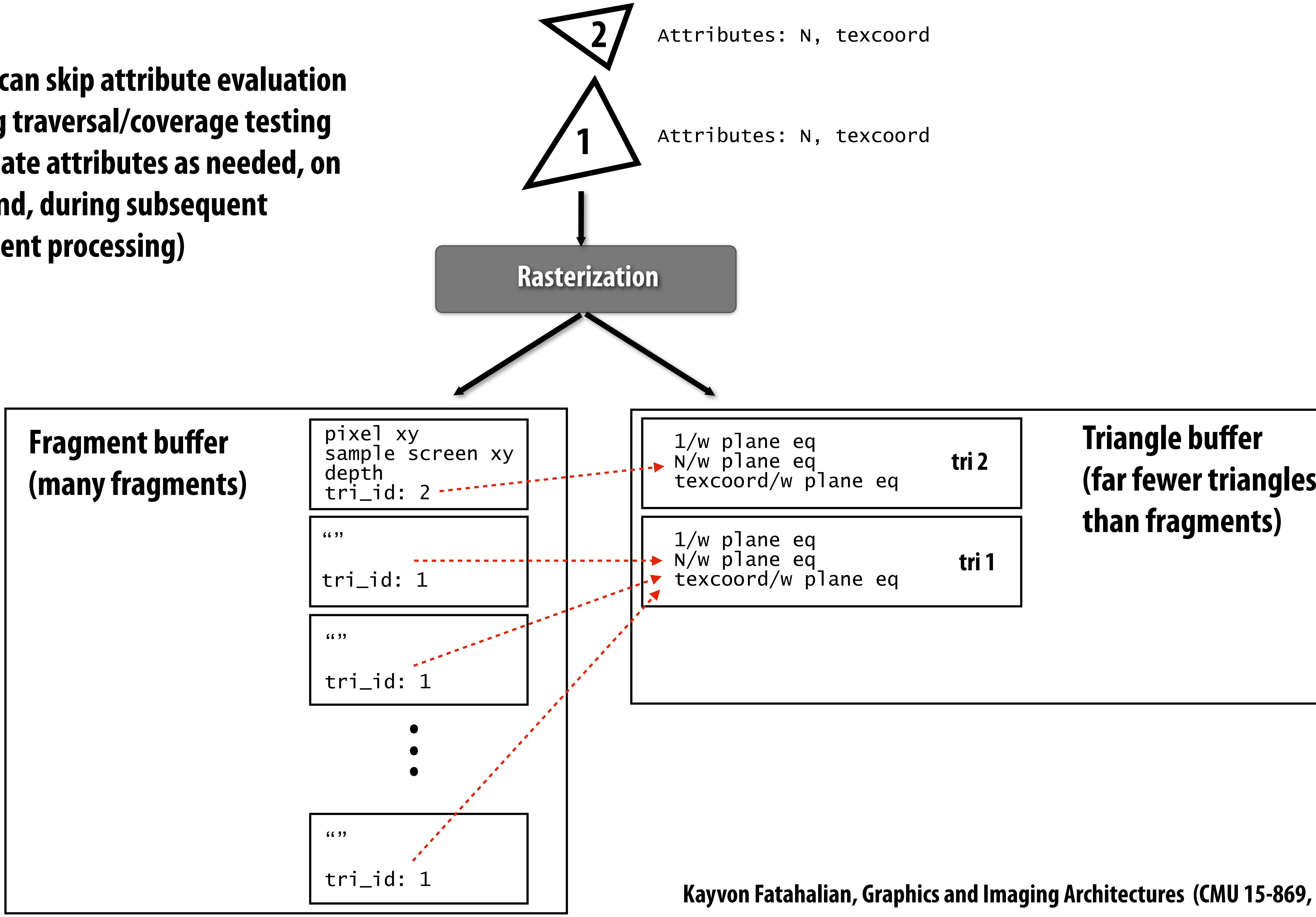
For each generated fragment:

- **evaluate $^1/_w(x,y)$ (from precomputed plane equation)**
- **reciprocate to get $w(x,y)$**
- **for each attribute**
  - **evaluate $^A/_w(x,y)$ (from precomputed plane equation)**
  - **multiply result by $w(x,y)$ to get $A(x,y)$**

Storage optimization:
store plane equations separate from fragments

(very useful for large triangles)

Note: can skip attribute evaluation during traversal/coverage testing (evaluate attributes as needed, on demand, during subsequent fragment processing)



Rasterization

- Triangle setup:
  - Transform clip space vertex positions to screen space
  - Convert positions to fixed point (Direct3D specifies 8 bits of subpixel precision**)
  - Compute edge equations
  - Compute plane equations for all vertex attributes and Z
- Traverse
  - Compute covered fragments using edge tests
  - Emit fragments (also emit per-triangle data as necessary)

** Note 1: limited precision can be a good thing: can limit really acute triangles (they snap to 0 area)

** Note 2: limited precision can be a bad thing: precision limits in (x,y) can limit precision in Z (see Akeley and Su, 2006)

Recall: z-buffer for occlusion

- **Z-buffer stores depth of scene at <u>each coverage sample</u>**
  - Each sample, not just each pixel
  - In practice, usually stores z/w
- **Triangles are planar: each triangle has exactly one depth at each sample (consistent ordering of fragments for each sample) ** ✓**
- **After fragment processing (shading) ...**

```
if (fragment.depth < z_buffer[fragment.x][fragment.y])
{
   color_buffer[fragment.x][fragment.y].rgba =
       blend(color_buffer[fragment.x][fragment.y].rgba, fragment.rgba);
   z_buffer[fragment.x][fragment.y] = fragment.depth;
}
```

- **Constant time occlusion test per fragment ✓**
- **Constant space per coverage sample ✓**

** assumes edge-on triangles have been discarded

Z-buffer for occlusion

- High bandwidth requirements (particularly when super-sampling)
  - Number of Z-buffer reads/writes depends on:
    - depth complexity of the scene
    - order triangles are provided to the graphics pipeline (if depth test fails, don't write Z or rgba)

- Bandwidth estimate:
  - 60 Hz * 2 MPixel image * avg. depth complexity 4 (assume replace 50%, 32-bit Z) = 2.8 GB/s
  - If super-sampling, multiply by 4 or 8x
  - 5 shadow maps per frame (1 MPixel, not super-sampled): additional 8.6 GB/s
  - Note: this does not include color buffer bandwidth

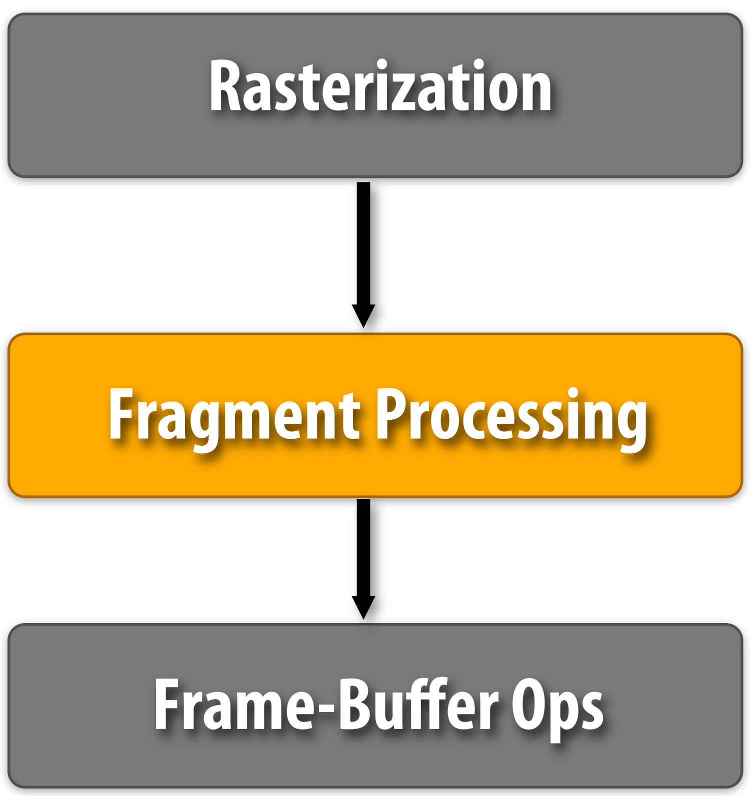
- Modern GPU implementations employ caching, compression
  - Recall sort-middle chunked: Z-buffer for current tile always on chip, can (sometimes) skip write of final Z values to memory (Z-buffer bandwidth = 0)

Z-buffer compression

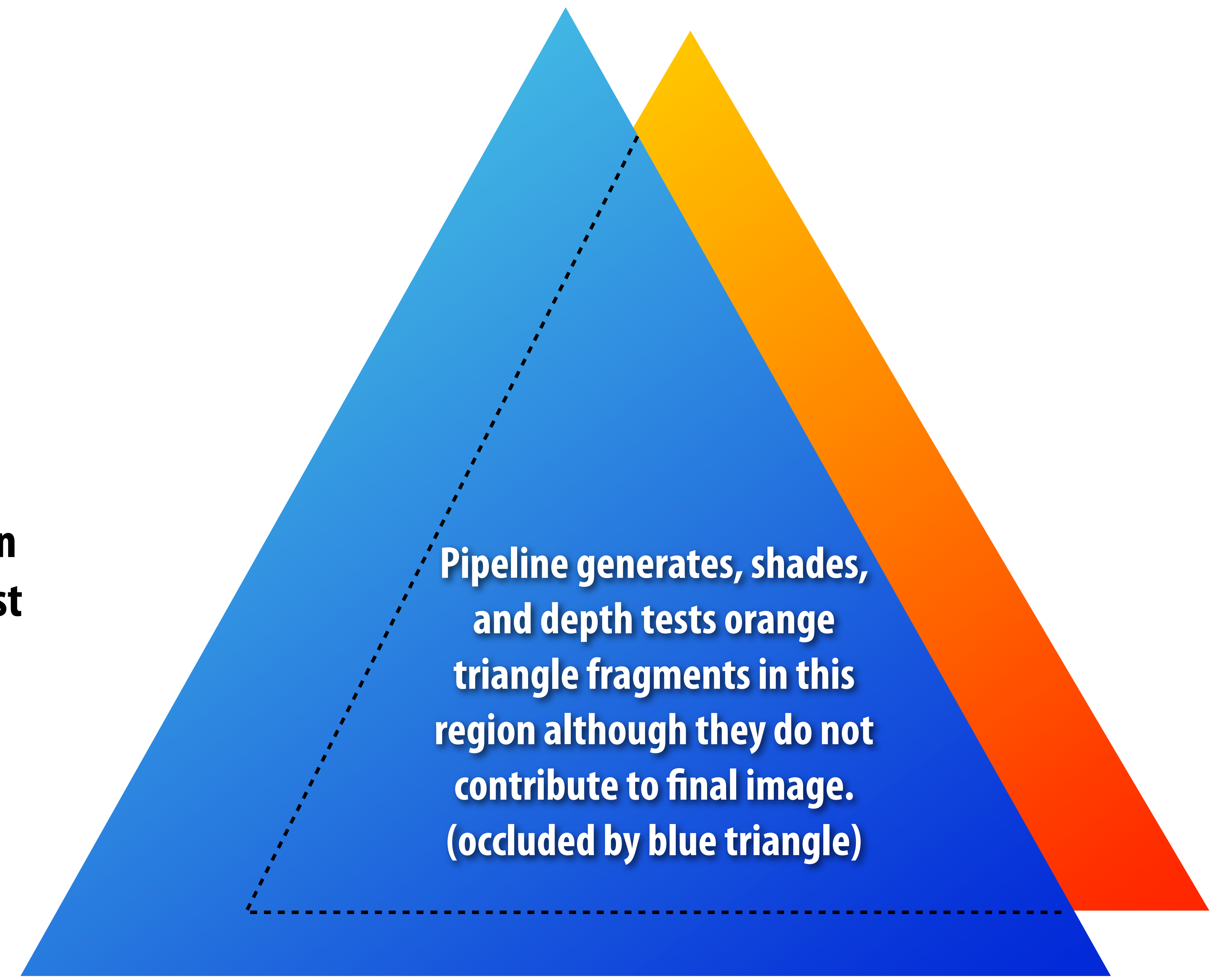
- Modern GPUs implement some form of lossless Z-buffer compression

- Very large compression ratios possible by exploiting screen coherence in depth values
  - Store plane equation for Z for an entire tile of pixels (possible when triangle covers tile)
  - Store base + low precision offsets for each sample in a tile

Early Z-culling ("early Z")

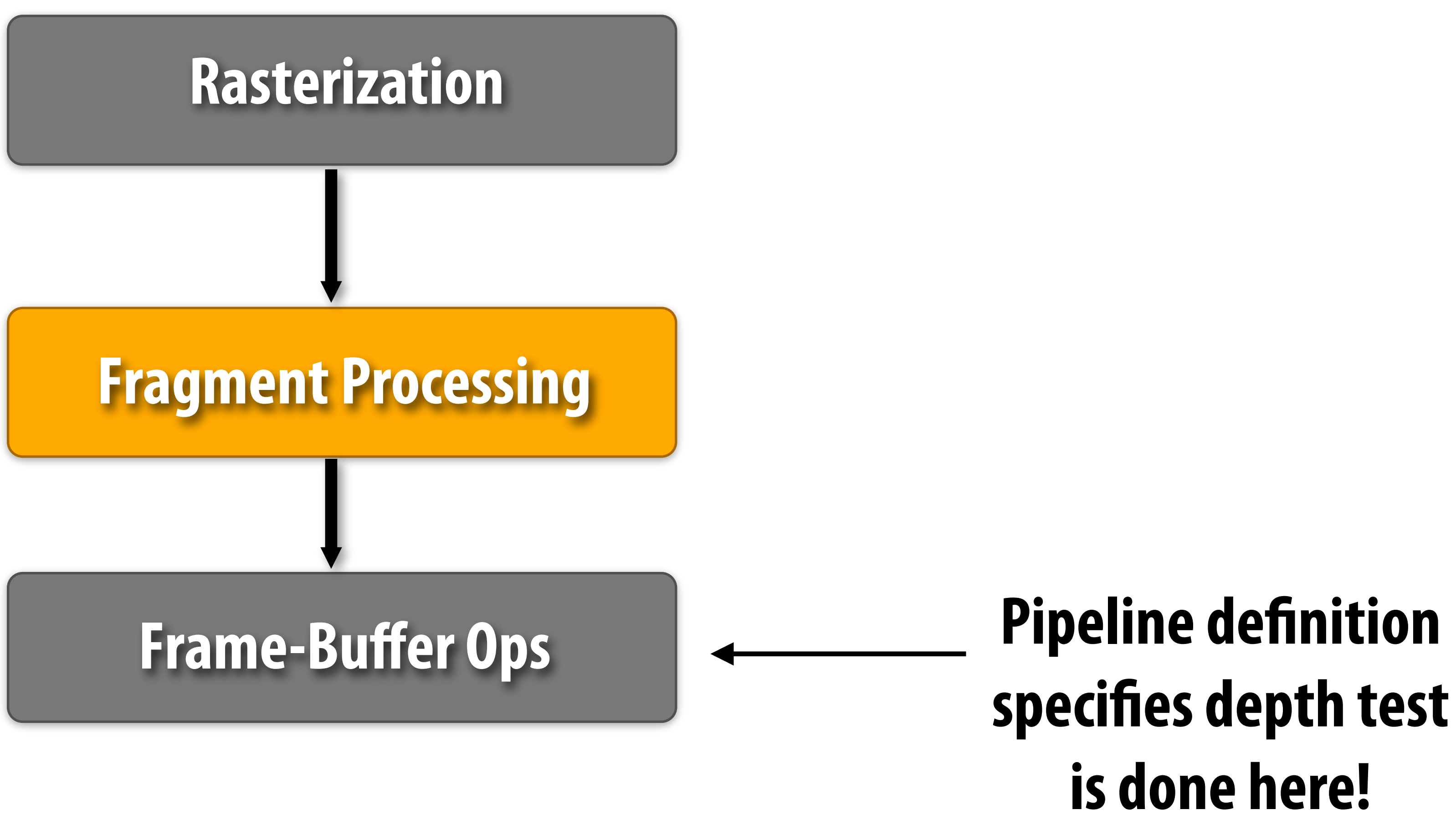


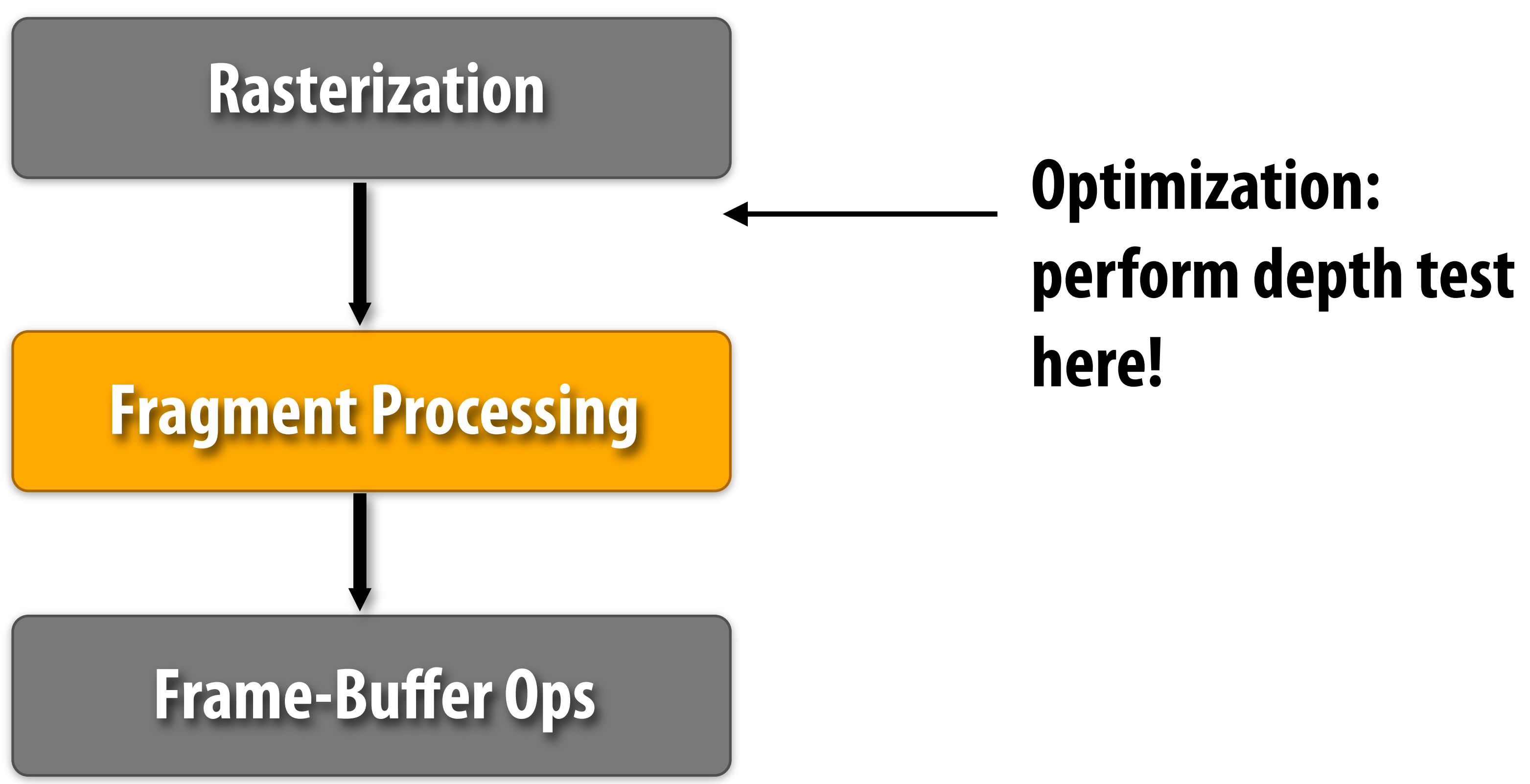
Pipeline definition specifies depth test is done here!



Goal: discard useless fragments from pipeline as soon as possible

Early Z-culling ("early Z")





Constraint: occlusion cannot depend on shading

e.g., pipeline alpha test enabled, fragment shader modifies Z

Note: Only provides benefit if blue triangle is rendered by application first.

Early Z

- **Perform depth test after rasterization, prior to fragment shading**
- **Reduces fragment processing work**
  - Amount of reduction dependent on triangle ordering
  - Ideal: front-to-back order
- **Does not reduce Z-buffer bandwidth (same Z reads and writes still occur)**
- **Common trick: "Z-prepass"**
  - Two rendering passes
    1. Render all scene geometry, with fragment processing disabled (pre-populate the Z-buffer)
    2. Re-render scene with shading enabled
  - Overhead of processing geometry twice vs. maximal early Z culling

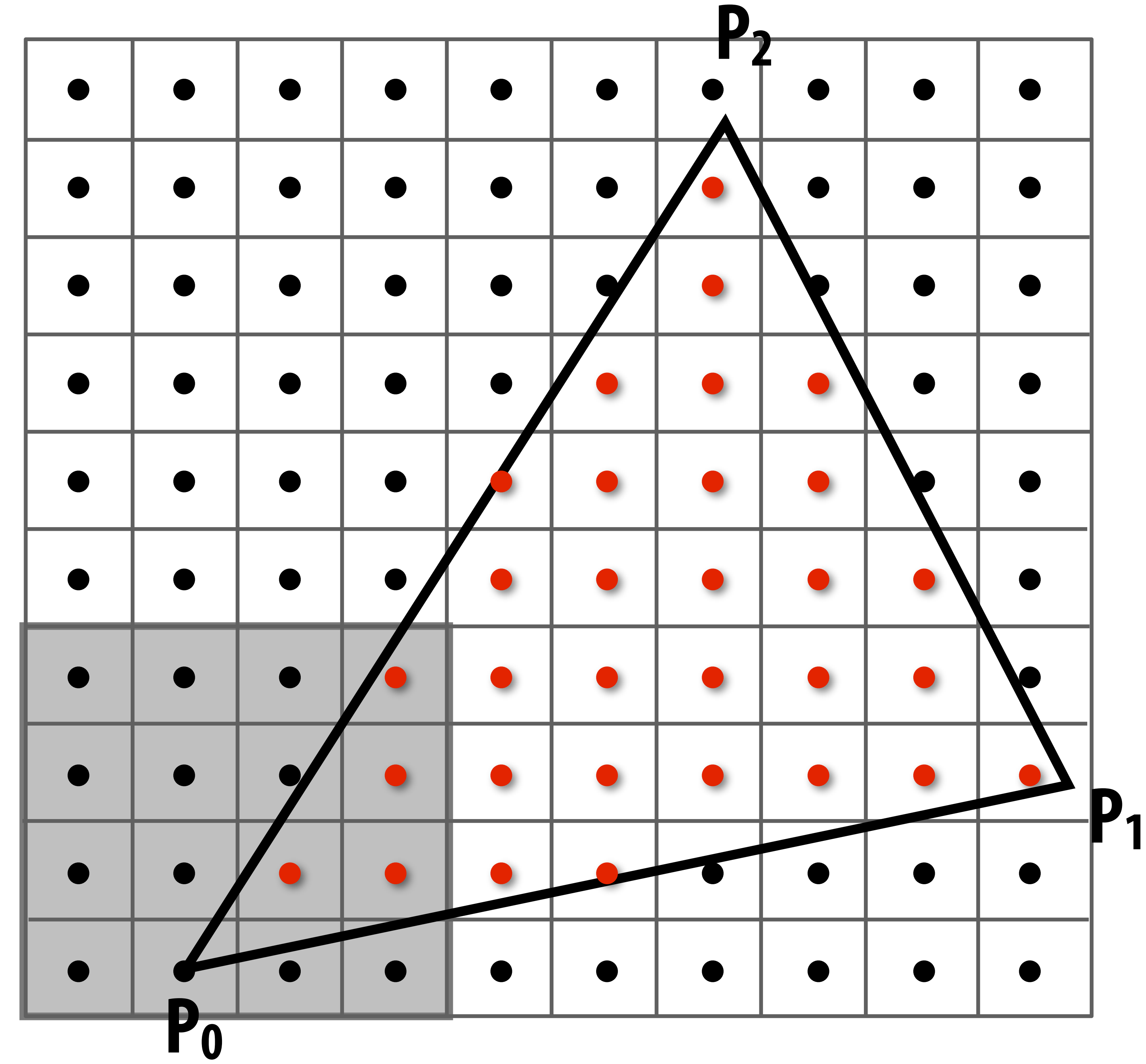
Hierarchical early Z: "hi-Z"

Recall hierarchical traversal during rasterization

For each screen tile, compute farthest value in the z-buffer: `z_far`

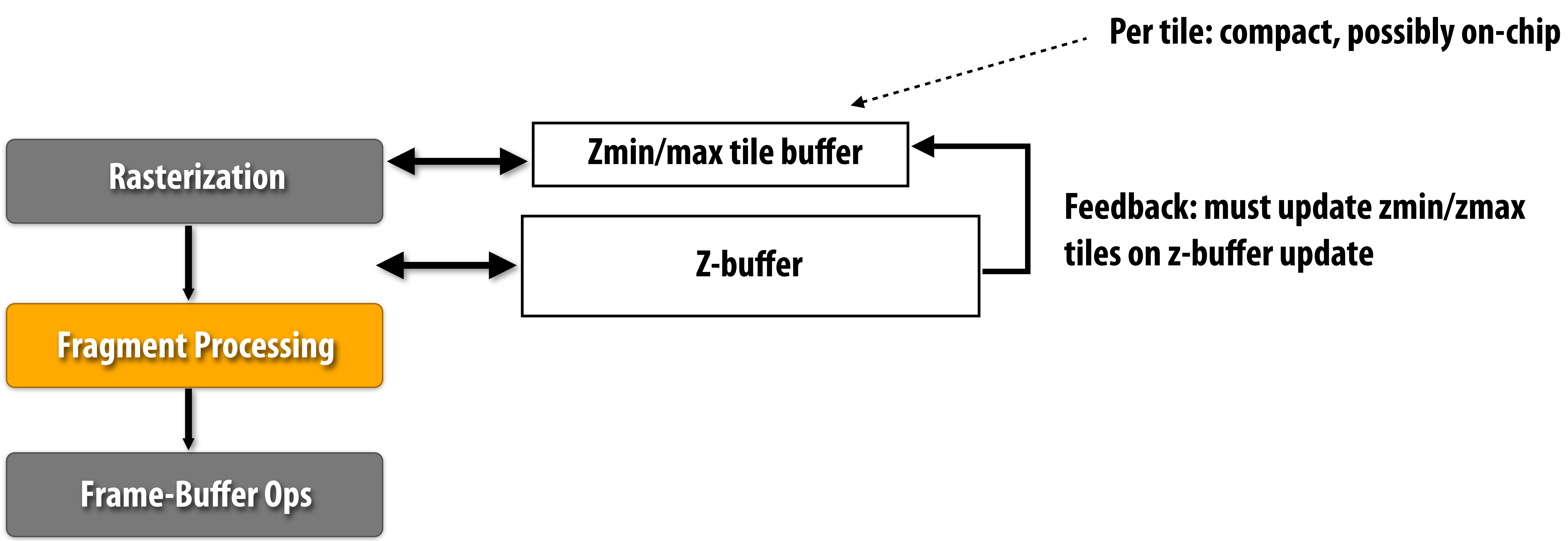
During traversal, for each tile:

1. Compute closest point on triangle in tile: `tri_near` (using Z plane equation)
2. If `tri_near` > `z_far`, then triangle is occluded in this tile. Proceed immediately to next tile. (no fragments generated)



Note, if z-buffer also stores `z_near` for each tile and `tri_far` < `z_near`, then all depth tests for triangle in tile will pass. (no need to check individual per-sample depth values later)

Hierarchical + early Z-culling



Remember: these are GPU implementation optimizations. They are not reflected in the pipeline abstraction

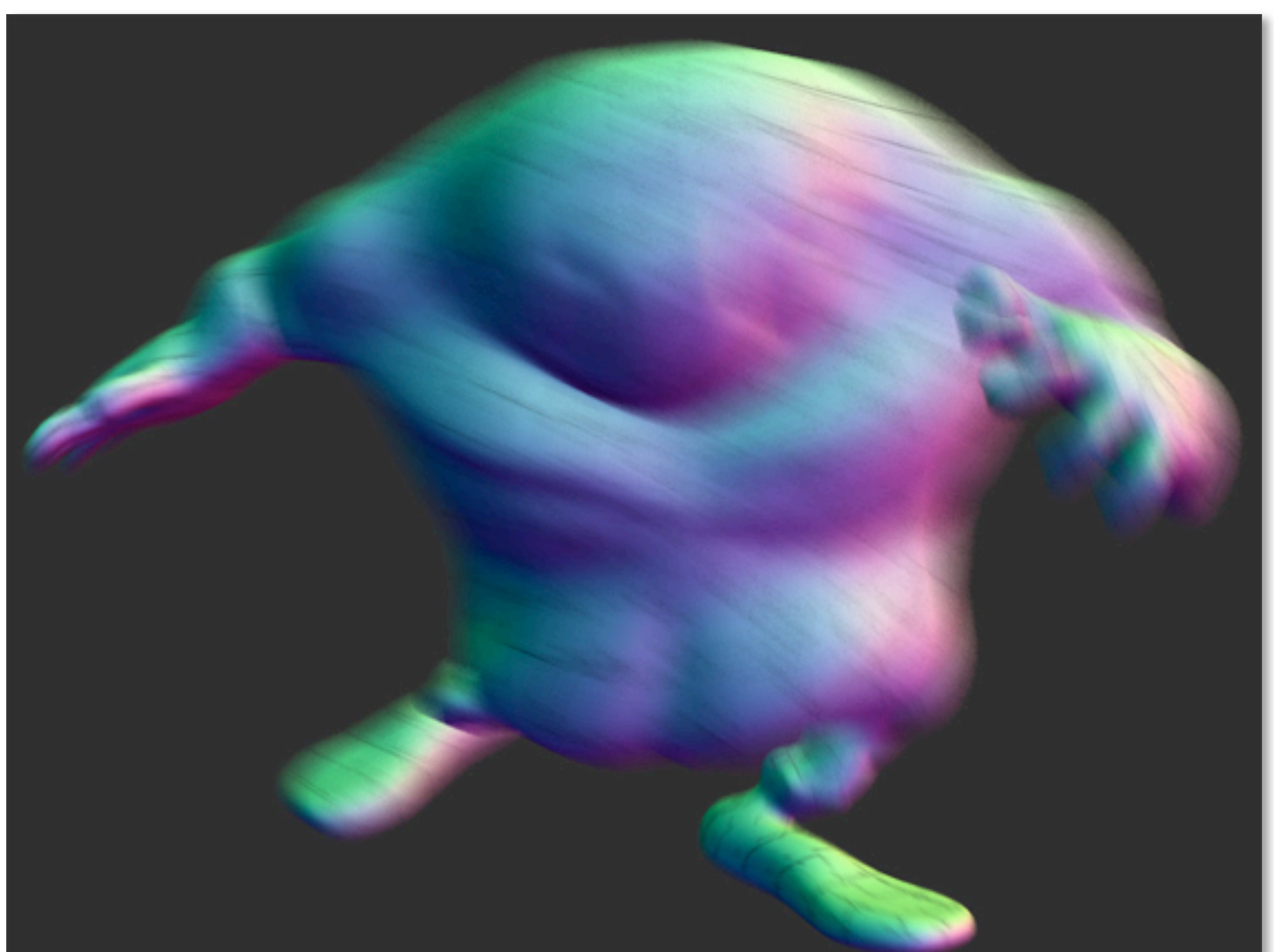
Hierarchical Z

- Perform depth test at tile granularity prior to sampling coverage
  - Reduces rasterization work
  - Reduces required Z-buffer bandwidth
  - <u>Does not</u> reduce fragment processing work more than early Z (conservative optimization: will discard a subset of the fragments early Z does)

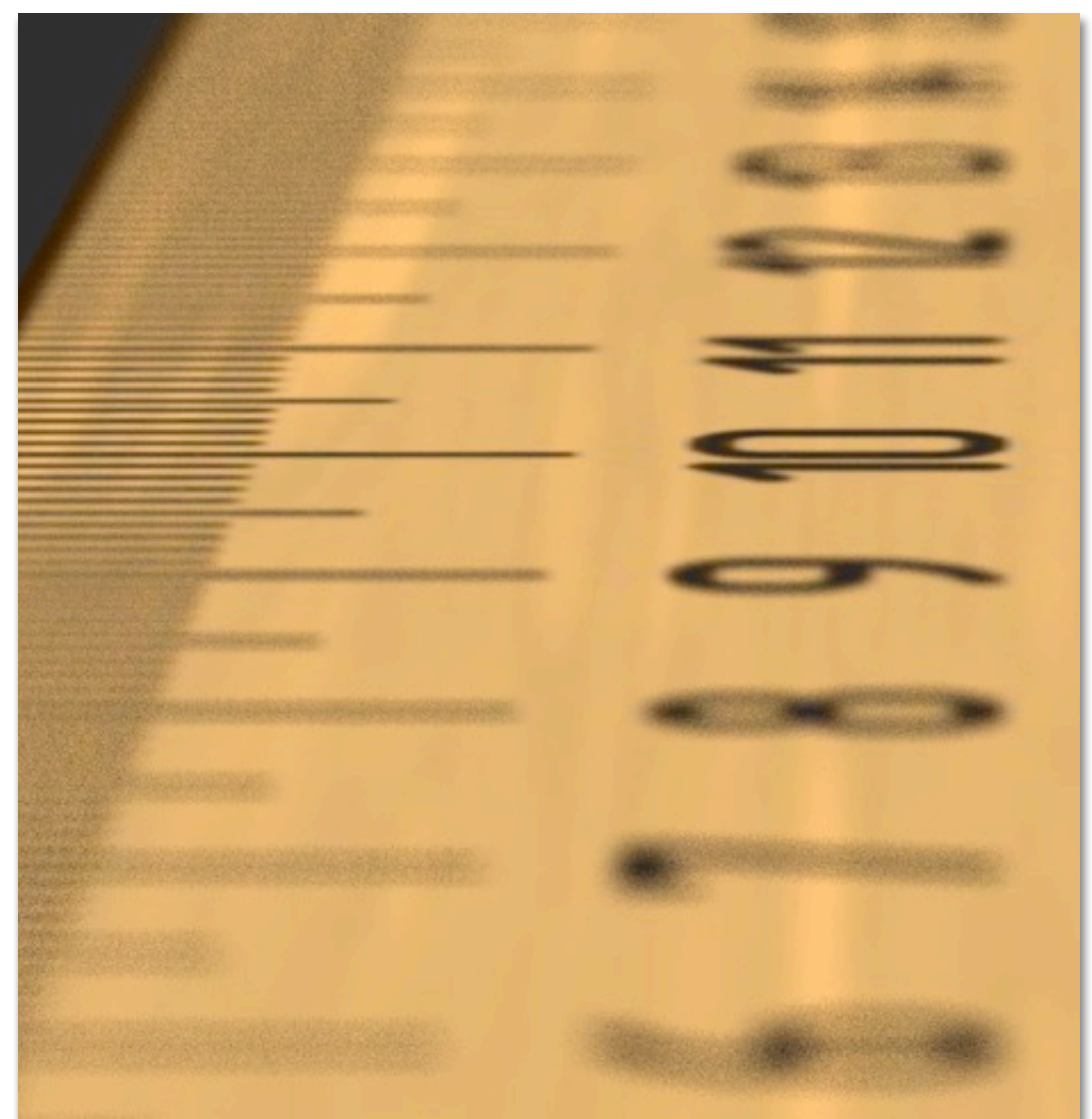
Modern research topic

- **Accurate camera simulation in real-time rendering**
  - Visibility algorithms discussed today simulate image formation by virtual pinhole camera, with infinite shutter
  - Real cameras have finite apertures, finite exposure duration
  - Visibility computation requires integration over time and lens aperture (high computational cost + diminished spatial coherence)

Time integration: motion blur



Lens integration: defocus blur



Readings

Rasterization Techniques:

- M. Olano and T. Greer, *Triangle Scan Conversation Using 2D Homogeneous Coordinates*. Graphics Hardware 97
- M. Abrash, Rasterization on Larrabee, Dr. Dobbs Portal. May 1, 2009
  http://drdobbs.com/high-performance-computing/217200602
- Take a look at source code for NVIDIA CUDA rasterizer:
  http://research.nvidia.com/publication/high-performance-software-rasterization-gpus

Hierarchical Z-Buffering:

- N. Greene et al., *Hierarchical Z-Buffer Visibility*. SIGGRAPH 93
- S. Morien, *ATI Radeon HyperZ Technology*. Hot 3D Presentation, Graphics Hardware 2000

Z-Buffer Precision:

- K. Akeley and J. Su, *Minimum Triangle Separation for Correct Z-Buffer Occlusion*, Eurographics 2006

Recent Rasterization Topics:

- K. Fatahalian et al., *Data-parallel Rasterization of Micropolygons with Motion and Defocus Blur.* High Performance Graphics 2009
- S. Laine et al., *Clipless Dual-Space Bounds for Faster Stochastic Rasterization*. SIGGRAPH 2011
- G. Johnson et al. *The Irregular Z-buffer: Hardware Acceleration for Irregular Data Structures*. Transactions on Graphics (4), 2005

Also Highly Recommended:

- A. R. Smith, *A Pixel is Not a Little Square*. Microsoft Technical Memo, 1995