The Graphics Pipeline

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Two approaches to rendering

Two approaches to rendering

```
for each object in the scene {
   for each pixel in the image {
      if (object affects pixel) {
         do something
      }
   }
}
```

object order
or
rasterization

Two approaches to rendering

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image order
or
ray tracing

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We did this first

image order
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ray tracing

Two approaches to rendering

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We'll do this now

object order
or
rasterization

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We did this first

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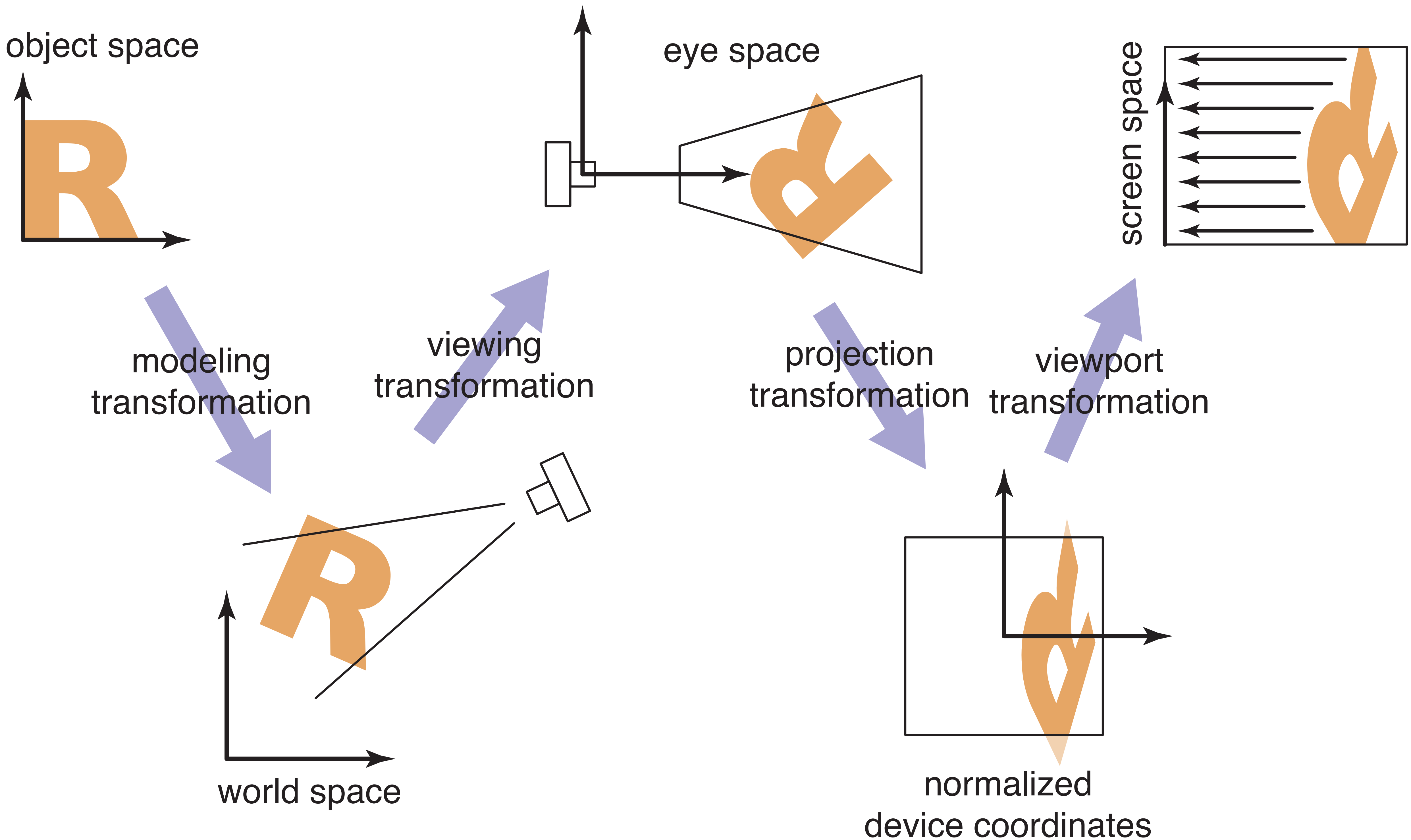
Overview

- **Standard sequence of transformations**
  - efficiently move triangles to where they belong on the screen
- **Rasterization**
  - how triangles are converted to fragments
- **Hidden surface removal**
  - efficiently getting the right surface in front
- **Graphics pipeline**
  - the efficient parallel implementation of object-order graphics

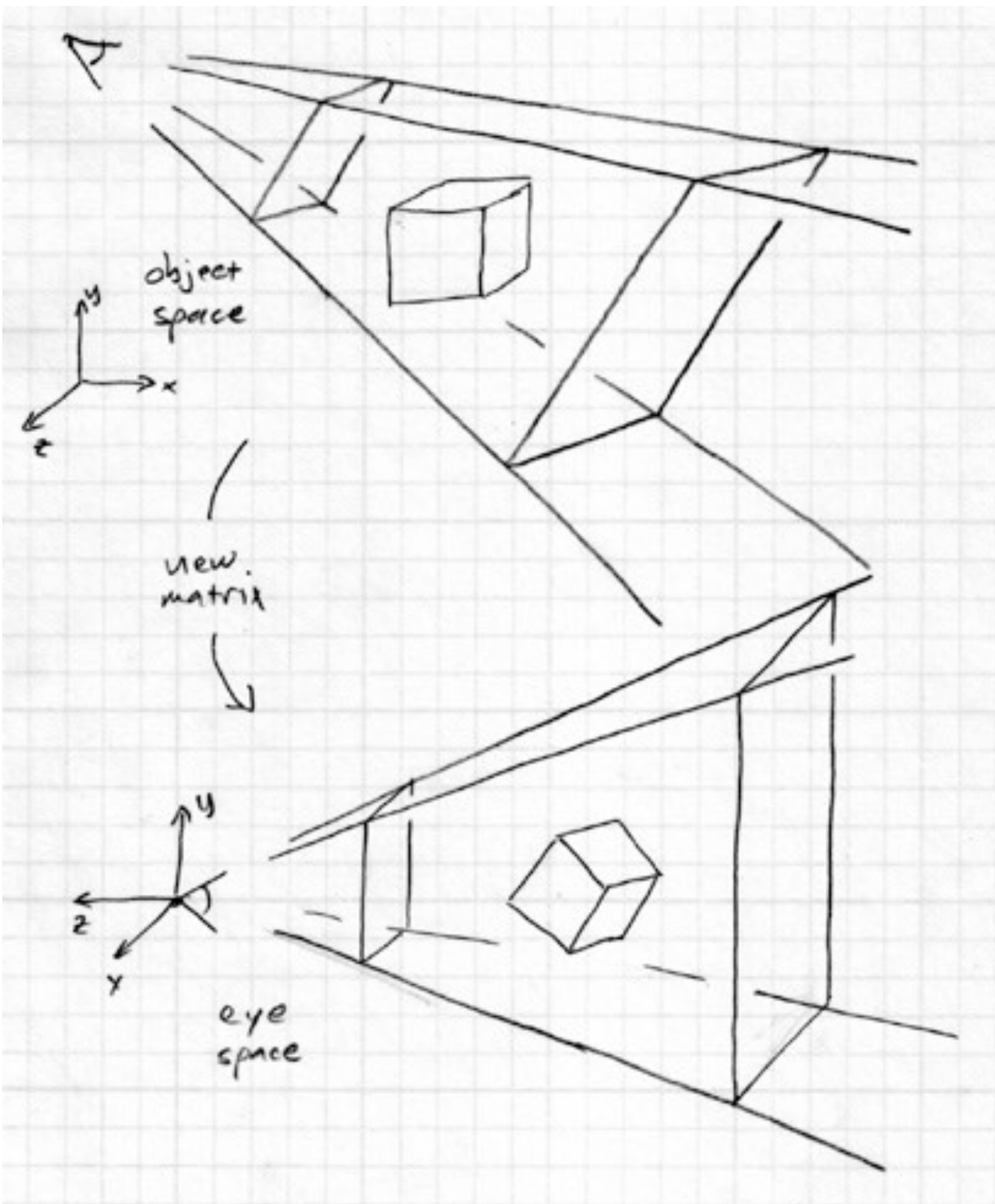
The Graphics Pipeline

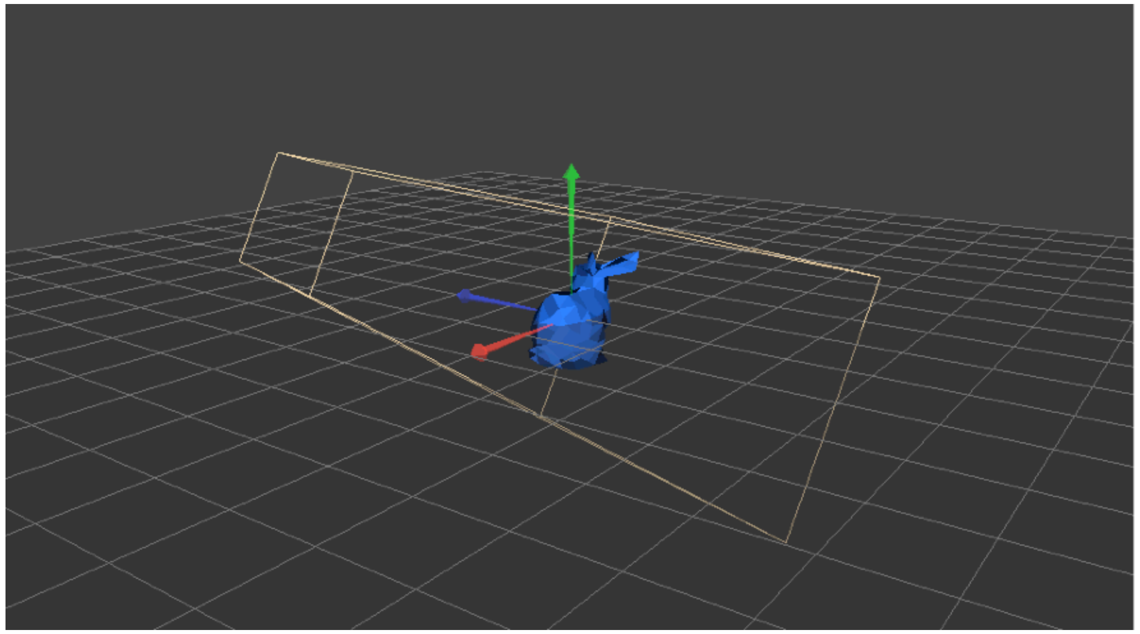
1. A standard sequence of transformations

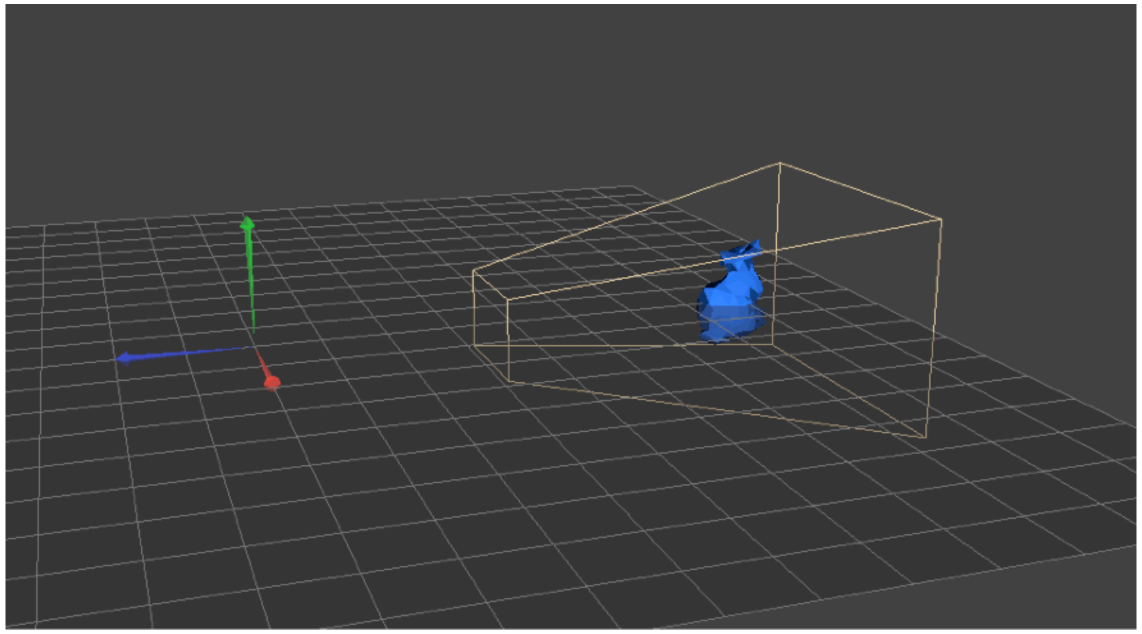

object space
eye space
screen space
modeling
transformation
viewing
transformation
projection
transformation
viewport
transformation
world space
normalized
device coordinates

Perspective viewing

Demo







The Graphics Pipeline

2. Rasterization

Rasterization

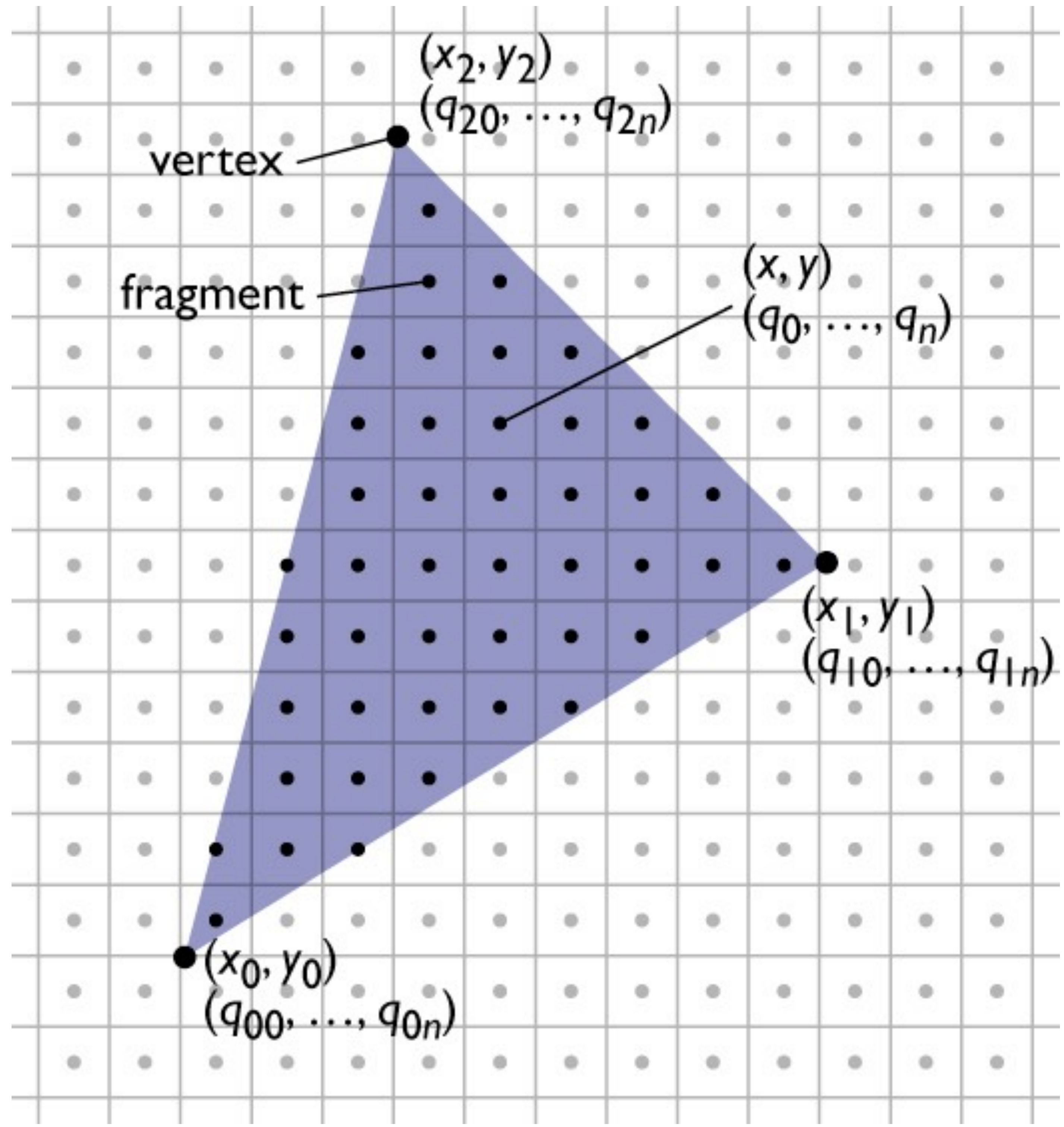
- **First job: enumerate the pixels covered by a primitive**
  – simple definition: pixels whose centers fall inside
- **Second job: interpolate values across the primitive**
  – e.g. colors computed at vertices
  – e.g. normals at vertices
  – e.g. texture coordinates

Rasterizing triangles

- **Input:**
  - three 2D points (the triangle's vertices in pixel space)
    - $(x_0, y_0); (x_1, y_1); (x_2, y_2)$
  - parameter values at each vertex
    - $q_{00}, \ldots, q_{0n}; q_{10}, \ldots, q_{1n}; q_{20}, \ldots, q_{2n}$
- **Output: a list of fragments, each with**
  - the integer pixel coordinates (x, y)
  - interpolated parameter values $q_0, \ldots, q_n$

Rasterizing triangles

- **Summary**
  1. evaluation of linear functions on pixel grid
  2. functions defined by parameter values at vertices
  3. using extra parameters to determine fragment set



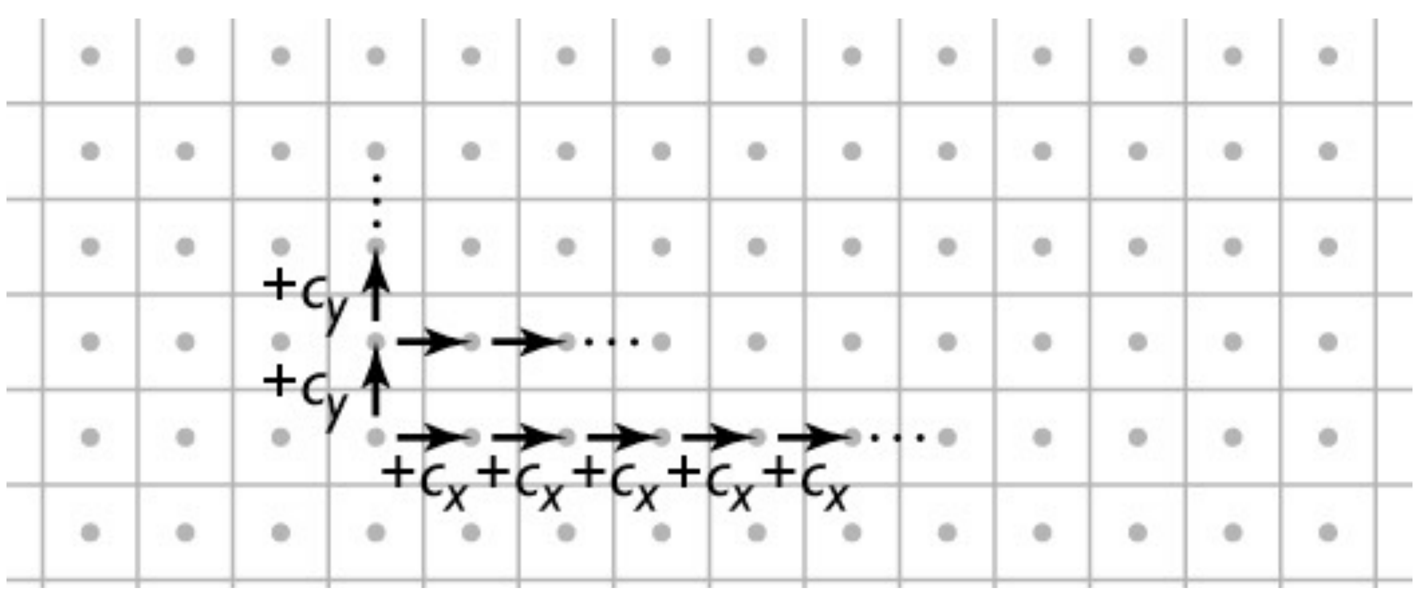
Incremental linear evaluation

- **A linear (affine, really) function on the plane is:**

$$q(x, y) = c_x x + c_y y + c_k$$

- **Linear functions are efficient to evaluate on a grid:**

$$q(x+1, y) = c_x(x+1) + c_y y + c_k = q(x, y) + c_x$$
$$q(x, y+1) = c_x x + c_y(y+1) + c_k = q(x, y) + c_y$$

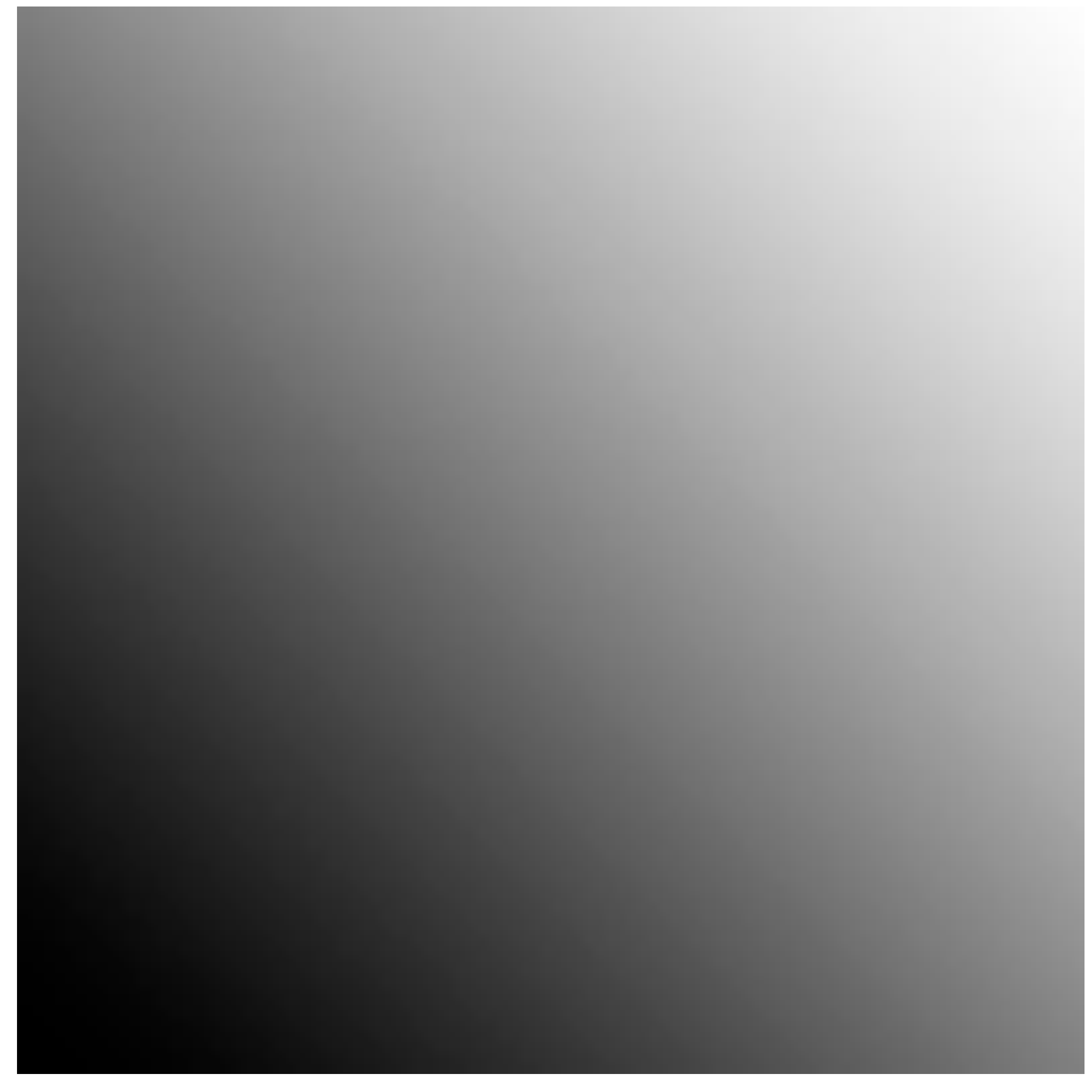


Incremental linear evaluation

```
linEval(xm, xM, ym, yM, cx, cy, ck) {

   // setup
   qRow = cx*xm + cy*ym + ck;

   // traversal
   for y = ym to yM {
      qPix = qRow;
      for x = xm to xM {
         output(x, y, qPix);
         qPix += cx;
      }
      qRow += cy;
   }
}
```

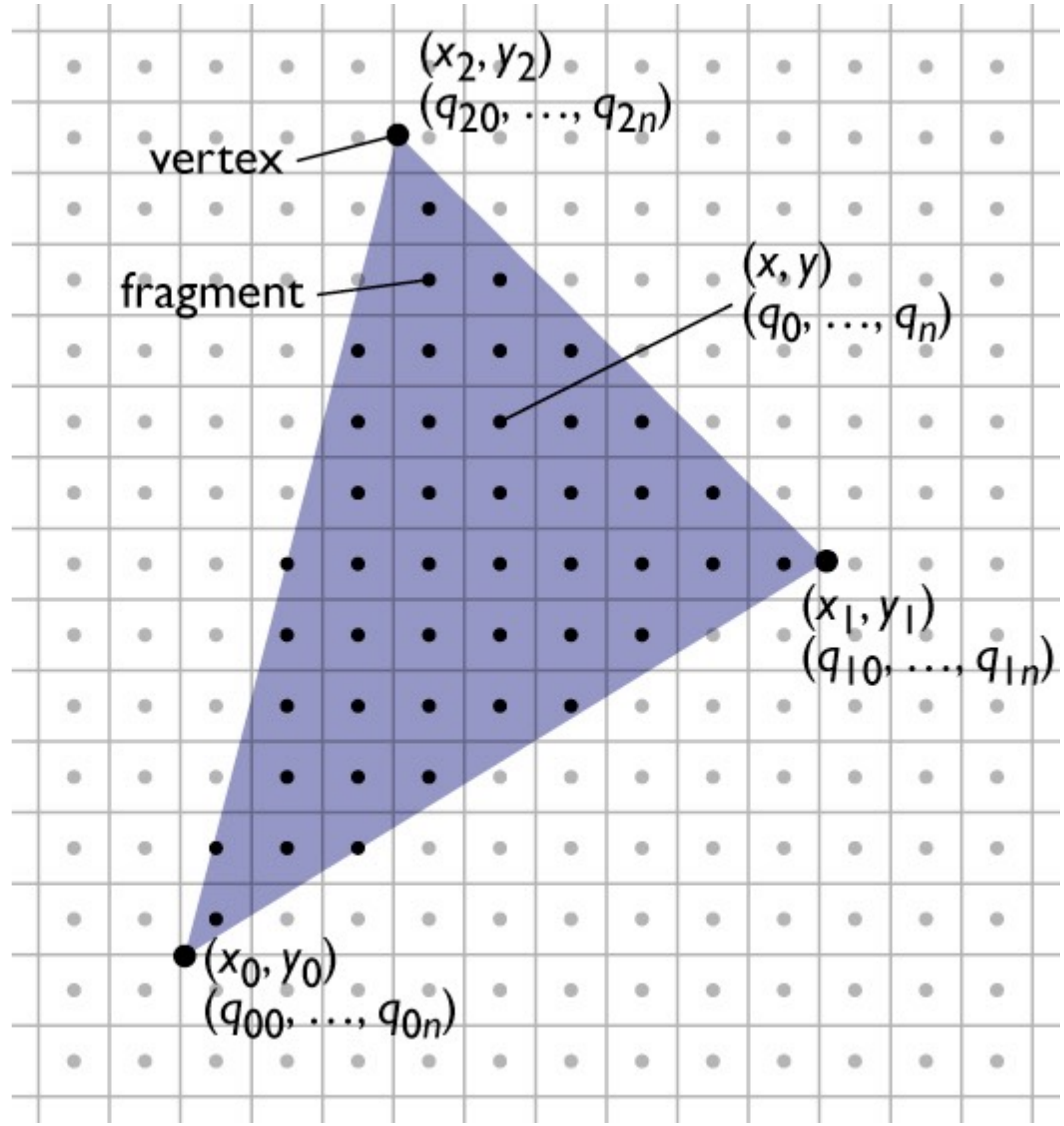


$c_x = .005; c_y = .005; c_k = 0$

(image size 100x100)

Rasterizing triangles

- **Summary**
  1 evaluation of linear functions on pixel grid
  2 functions defined by parameter values at vertices
  3 using extra parameters to determine fragment set



Defining parameter functions

- **To interpolate parameters across a triangle we need to find the c_x, c_y, and c_k that define the (unique) linear function that matches the given values at all 3 vertices**
  – this is 3 constraints on 3 unknown coefficients:

$$c_x x_0 + c_y y_0 + c_k = q_0$$
$$c_x x_1 + c_y y_1 + c_k = q_1$$
$$c_x x_2 + c_y y_2 + c_k = q_2$$

(each states that the function agrees with the given value at one vertex)

  – leading to a 3x3 matrix equation for the coefficients:

$$\begin{bmatrix} x_0 & y_0 & 1 \\ x_1 & y_1 & 1 \\ x_2 & y_2 & 1 \end{bmatrix} \begin{bmatrix} c_x \\ c_y \\ c_k \end{bmatrix} = \begin{bmatrix} q_0 \\ q_1 \\ q_2 \end{bmatrix}$$

(singular iff triangle is degenerate)

Defining parameter functions

- **More efficient version: shift origin to** (x_0, y_0)

$$q(x, y) = c_x(x - x_0) + c_y(y - y_0) + q_0$$

$$q(x_1, y_1) = c_x(x_1 - x_0) + c_y(y_1 - y_0) + q_0 = q_1$$

$$q(x_2, y_2) = c_x(x_2 - x_0) + c_y(y_2 - y_0) + q_0 = q_2$$

  – now this is a 2x2 linear system (since q_0 falls out):

$$\begin{bmatrix} (x_1 - x_0) & (y_1 - y_0) \\ (x_2 - x_0) & (y_2 - y_0) \end{bmatrix} \begin{bmatrix} c_x \\ c_y \end{bmatrix} = \begin{bmatrix} q_1 - q_0 \\ q_2 - q_0 \end{bmatrix}$$

  – solve using Cramer's rule (see textbook):

$$c_x = (\Delta q_1 \Delta y_2 - \Delta q_2 \Delta y_1)/(\Delta x_1 \Delta y_2 - \Delta x_2 \Delta y_1)$$

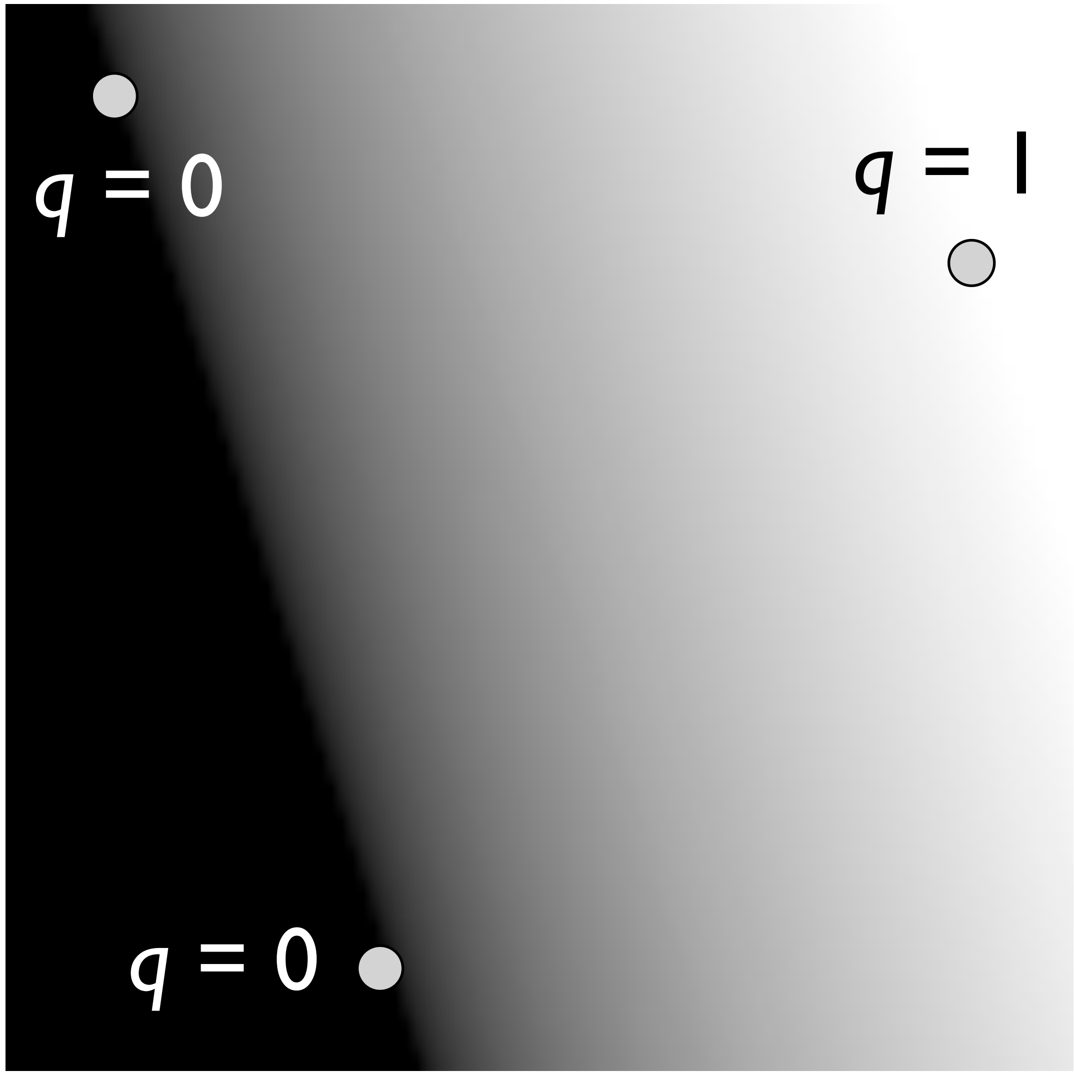
$$c_y = (\Delta q_2 \Delta x_1 - \Delta q_1 \Delta x_2)/(\Delta x_1 \Delta y_2 - \Delta x_2 \Delta y_1)$$

Defining parameter functions

```
linInterp(xm, xM, ym, yM, x0, y0, q0,
        x1, y1, q1, x2, y2, q2) {

   // setup
   det = (x1−x0)*(y2−y0) – (x2−x0)*(y1−y0);
   cx = ((q1−q0)*(y2−y0) – (q2−q0)*(y1−y0)) / det;
   cy = ((q2−q0)*(x1−x0) – (q1−q0)*(x2−x0)) / det;
   qRow = cx*(xm−x0) + cy*(ym−y0) + q0;

   // traversal (same as before)
   for y = ym to yM {
      qPix = qRow;
      for x = xm to xM {
         output(x, y, qPix);
         qPix += cx;
      }
      qRow += cy;
   }
}
```

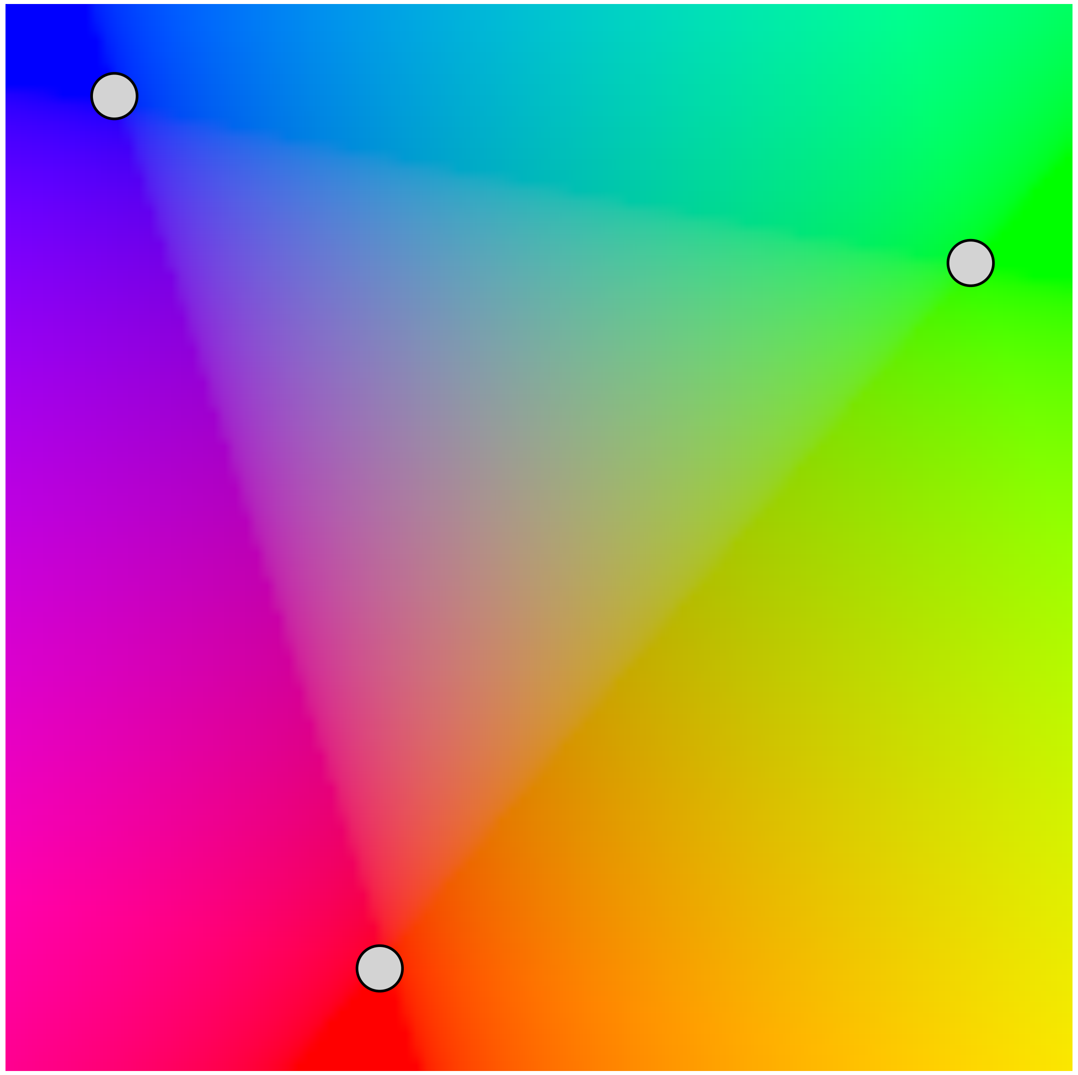


Interpolating several parameters

```
linInterp(xm, xM, ym, yM, n, x0, y0, q0[],
        x1, y1, q1[], x2, y2, q2[]) {

    // setup
    for k in 0 to n
        // compute cx[k], cy[k], qRow[k]
        // from q0[k], q1[k], q2[k]

    // traversal
    for y = ym to yM {
        for k = 0 to n, qPix[k] = qRow[k];
        for x = xm to xM {
            output(x, y, qPix);
            for k = 0 to n, qPix[k] += cx[k];
        }
        for k = 0 to n, qRow[k] += cy[k];
    }
}
```



Rasterizing triangles

- **Summary**
  1 evaluation of linear functions on pixel grid
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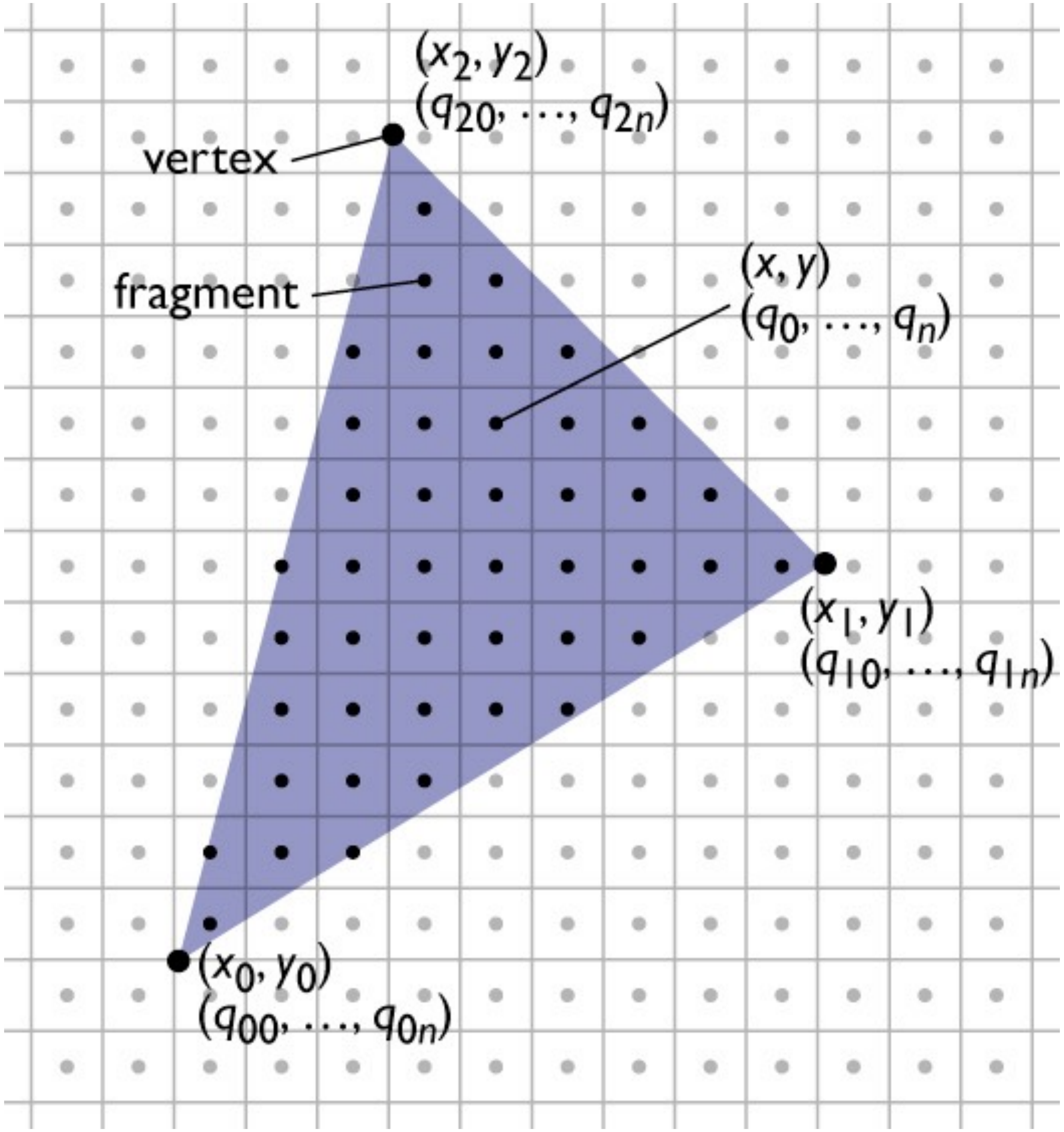
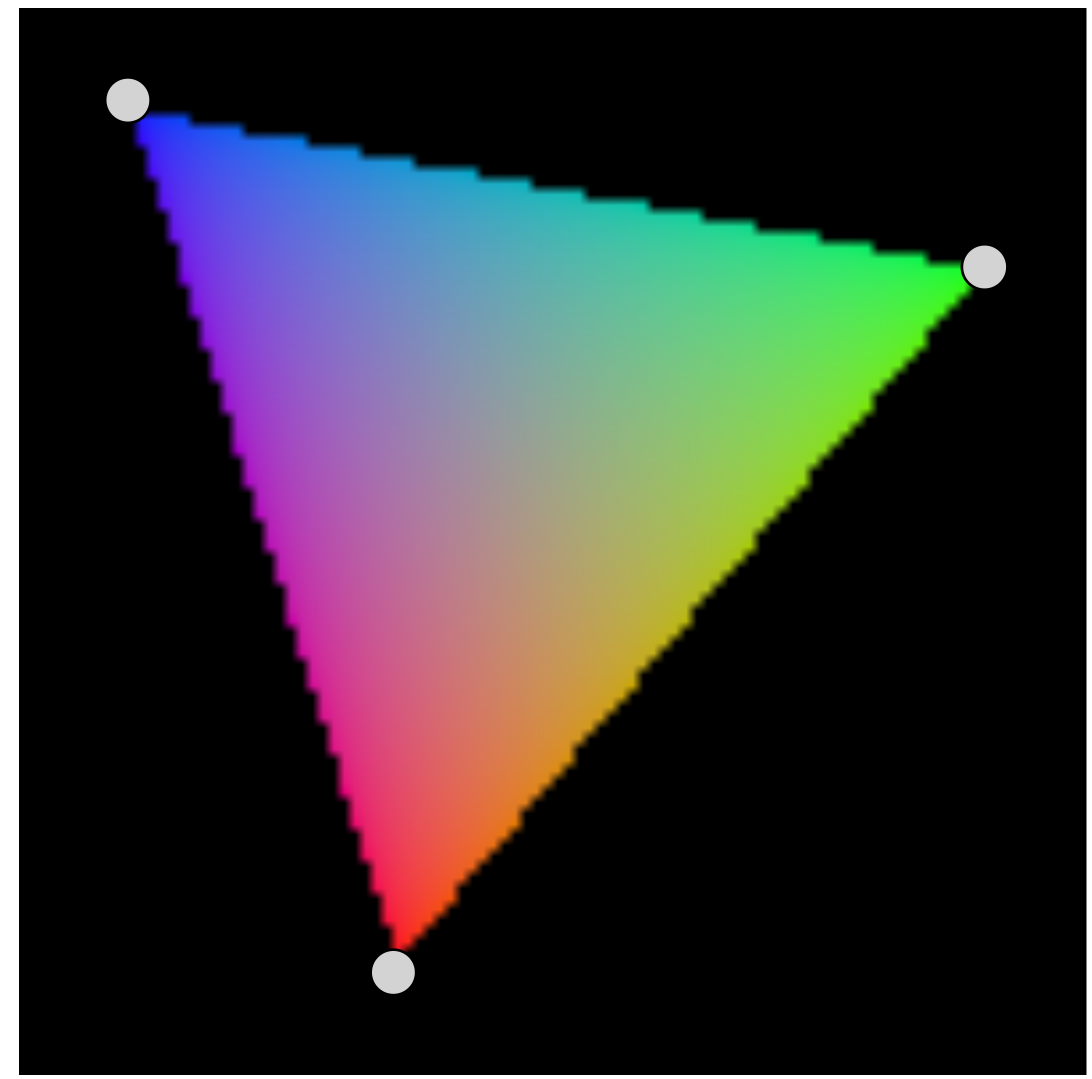


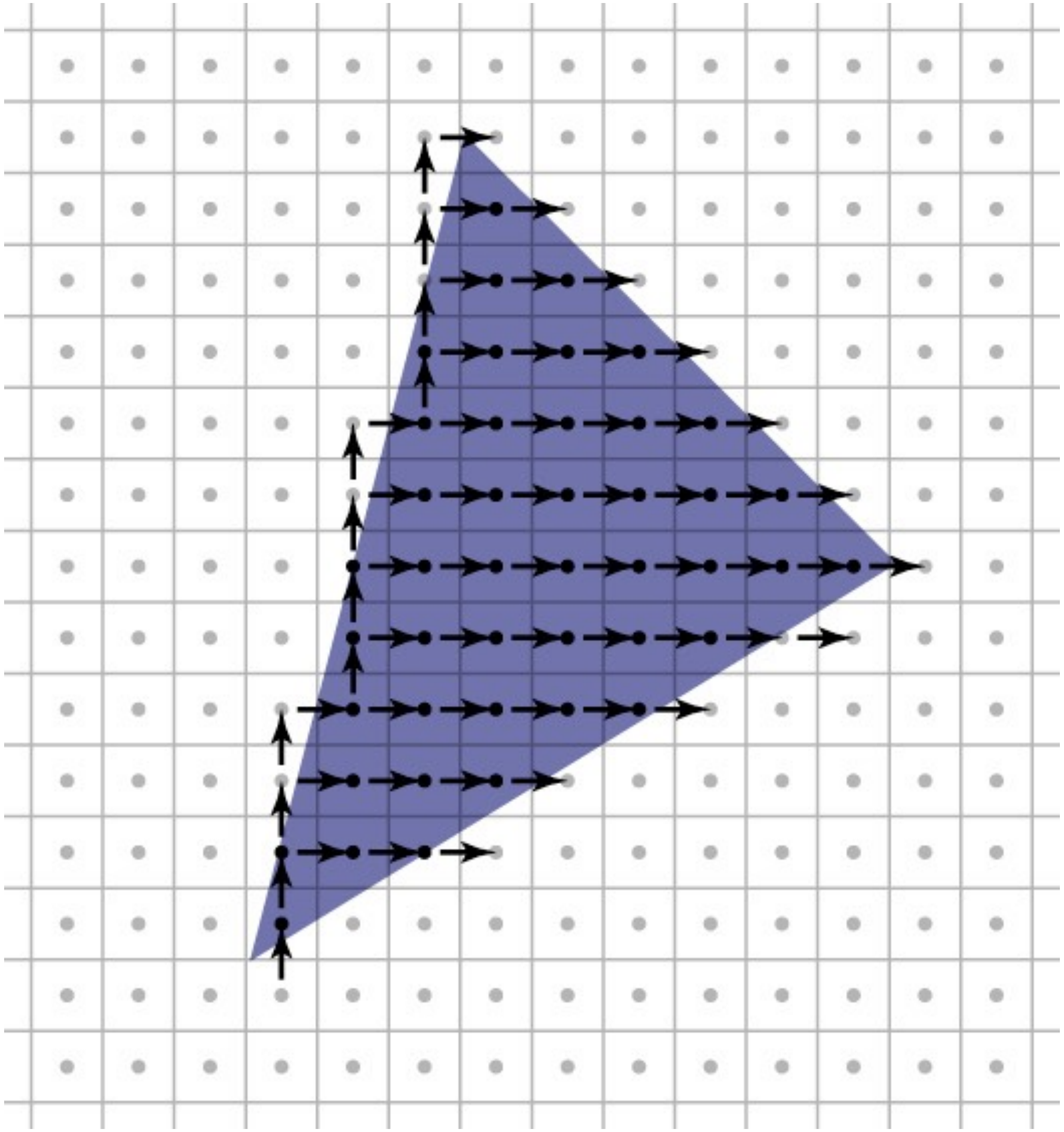
Clipping to the triangle

- **Interpolate three barycentric coordinates across the plane**
  - recall each barycentric coord is 1 at one vert. and 0 at the other two
- **Output fragments only when all three are > 0.**



Pixel-walk (Pineda) rasterization

- **Conservatively visit a superset of the pixels you want**
- **Interpolate linear functions**
- **Use those functions to determine when to emit a fragment**

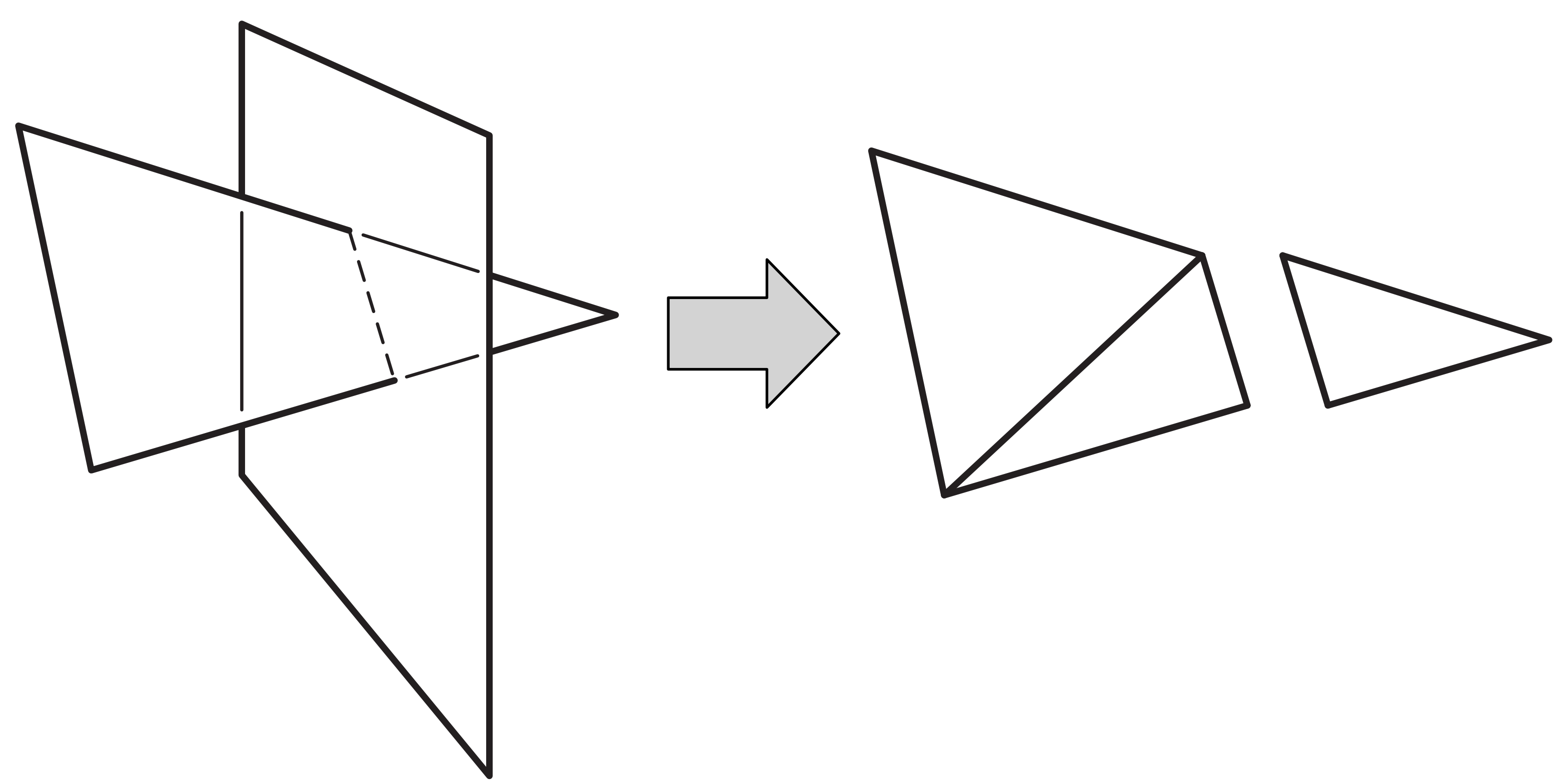


Clipping

- **Rasterizer tends to assume triangles are on screen**
  - particularly problematic to have triangles crossing the plane $z = 0$
- **After projection, before perspective divide**
  - clip against the planes $x/w, y/w, z/w = 1, -1$ (6 planes)
  - primitive operation: clip triangle against axis-aligned plane

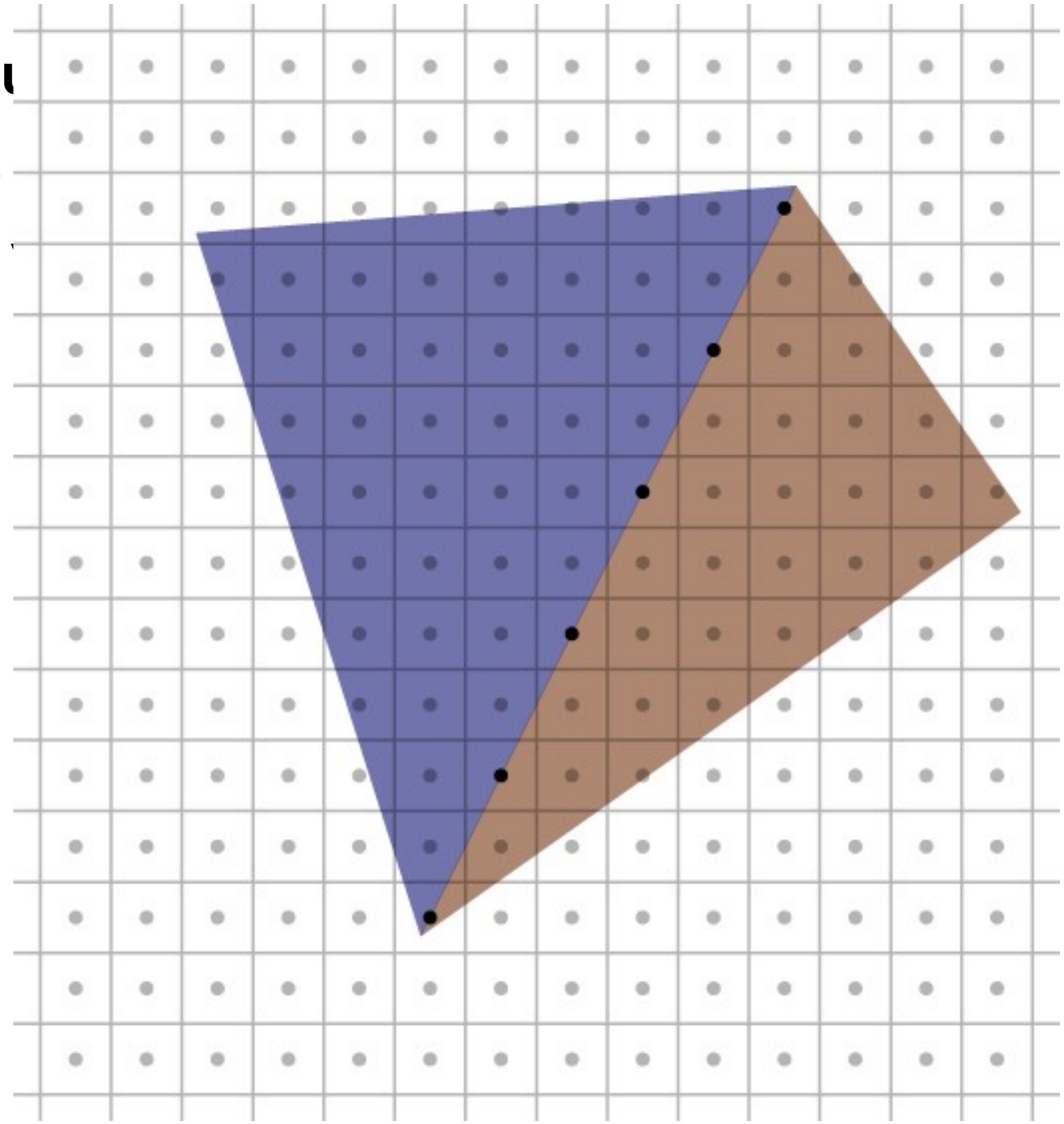
Clipping a triangle against a plane

- **4 cases, based on sidedness of vertices**
  - all in (keep)
  - all out (discard)
  - one in, two out (one clipped triangle)
  - two in, one out (two clipped triangles)



Rasterizing triangles: edge cases

- **Exercise caution with rou**
  - need to visit these pixels
  - but it's important not to

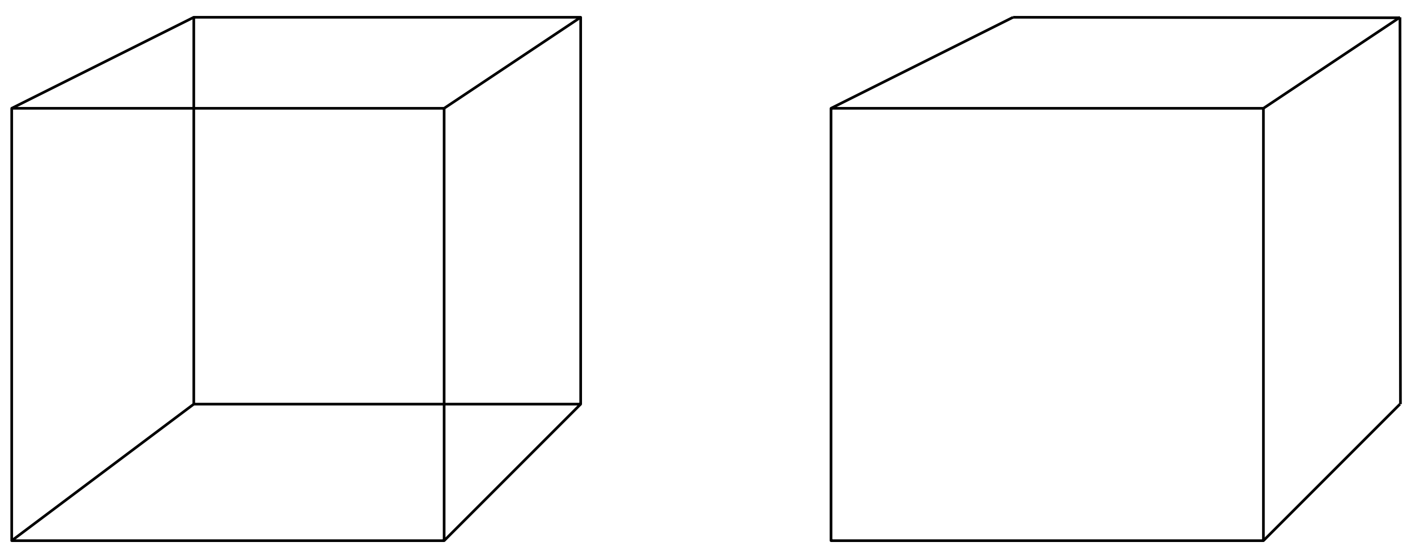


The Graphics Pipeline

3. Hidden surface removal

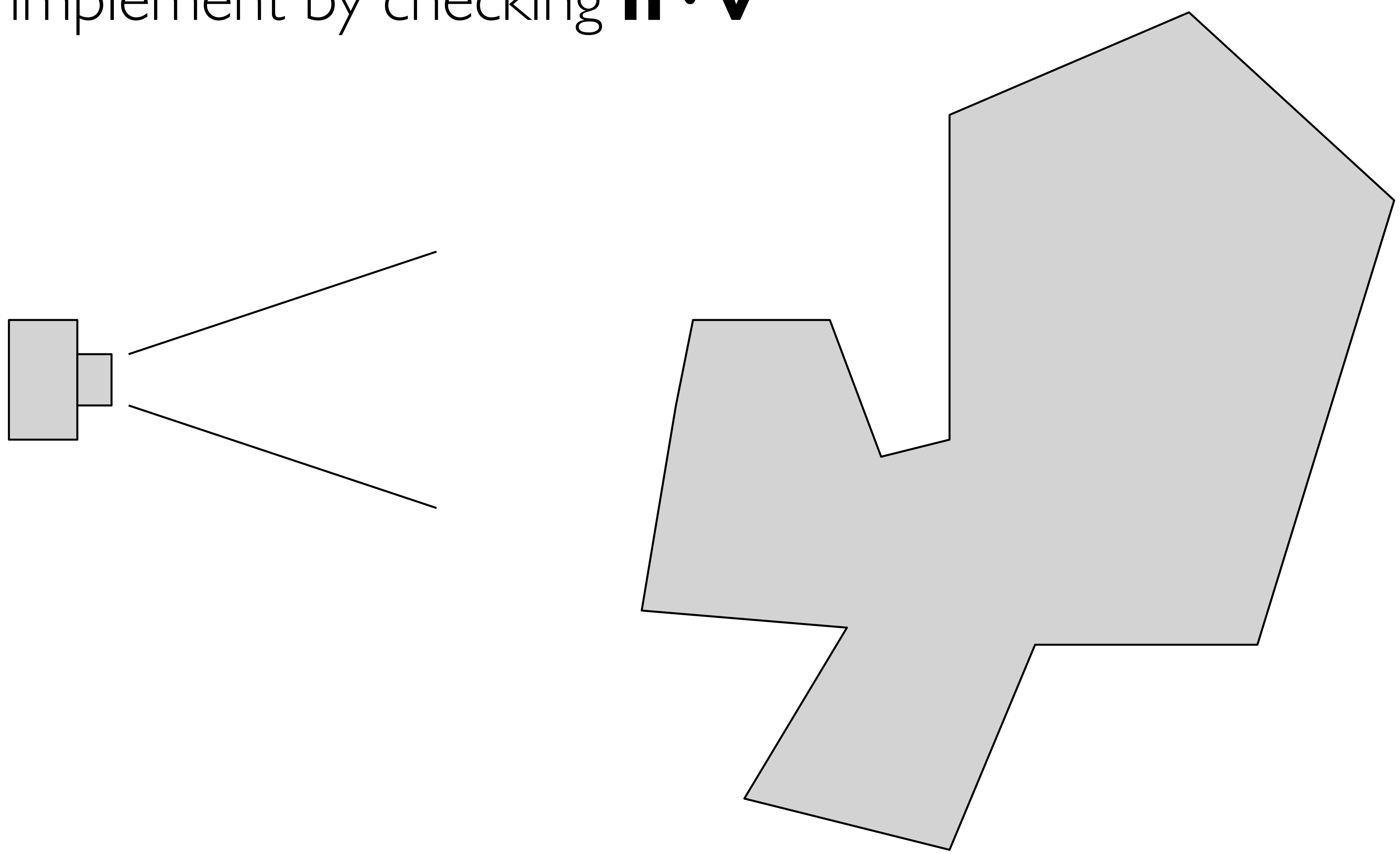
Hidden surface elimination

- **We have discussed how to map primitives to image space**
  - projection and perspective are depth cues
  - occlusion is another very important cue



Back face culling

- **For closed shapes you will never see the inside**
  - therefore only draw surfaces that face the camera
  - implement by checking $\mathbf{n} \cdot \mathbf{v}$



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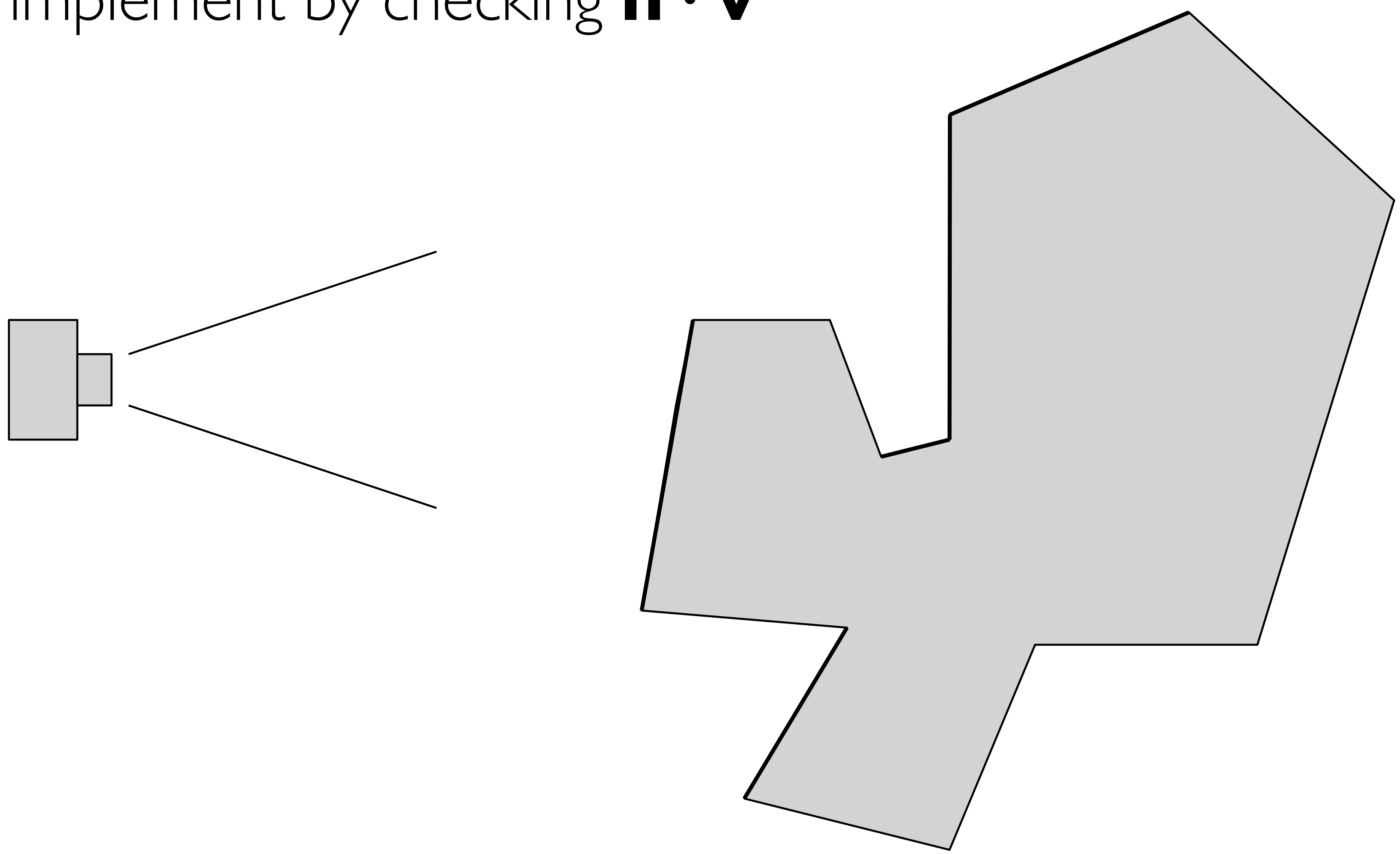

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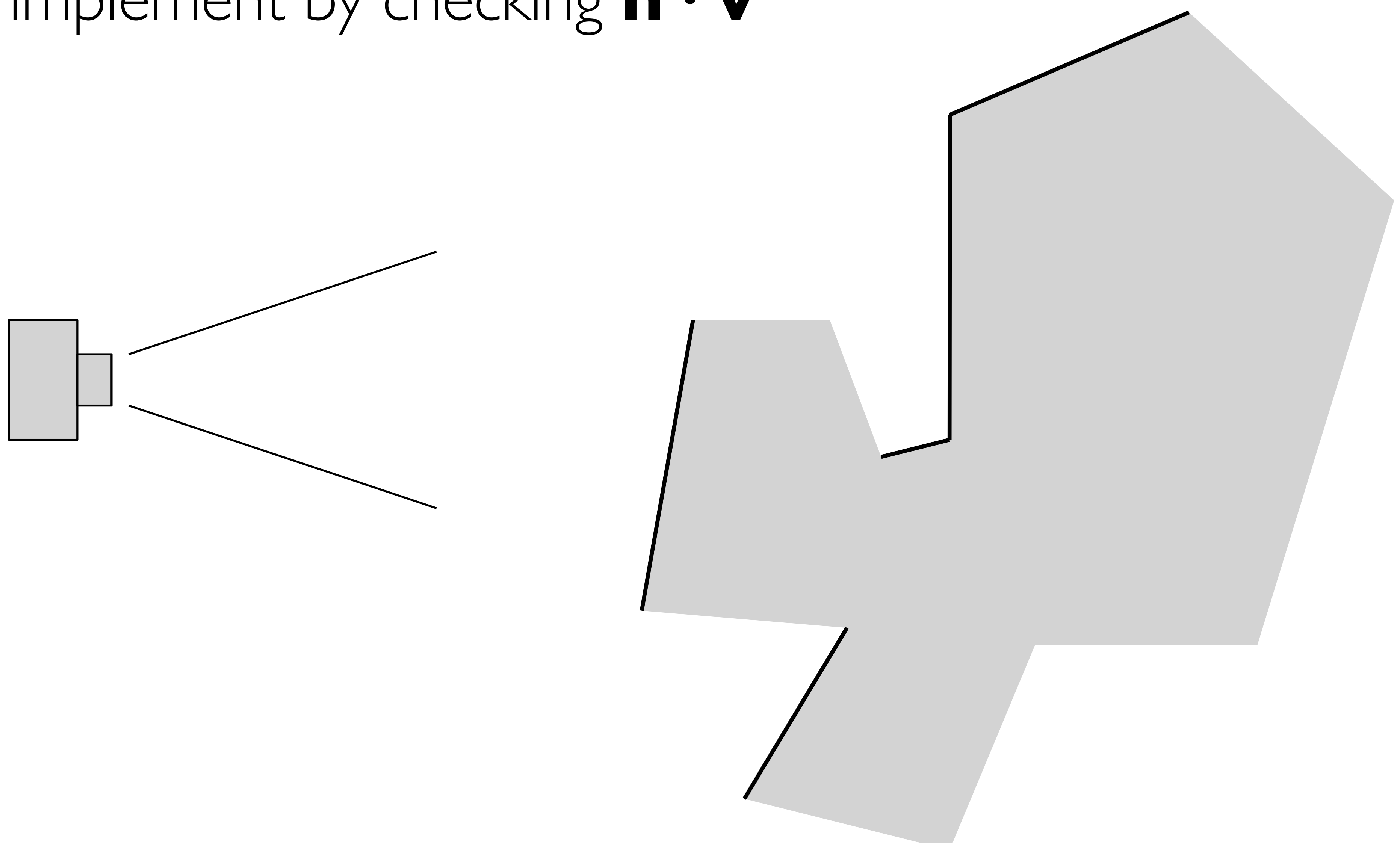

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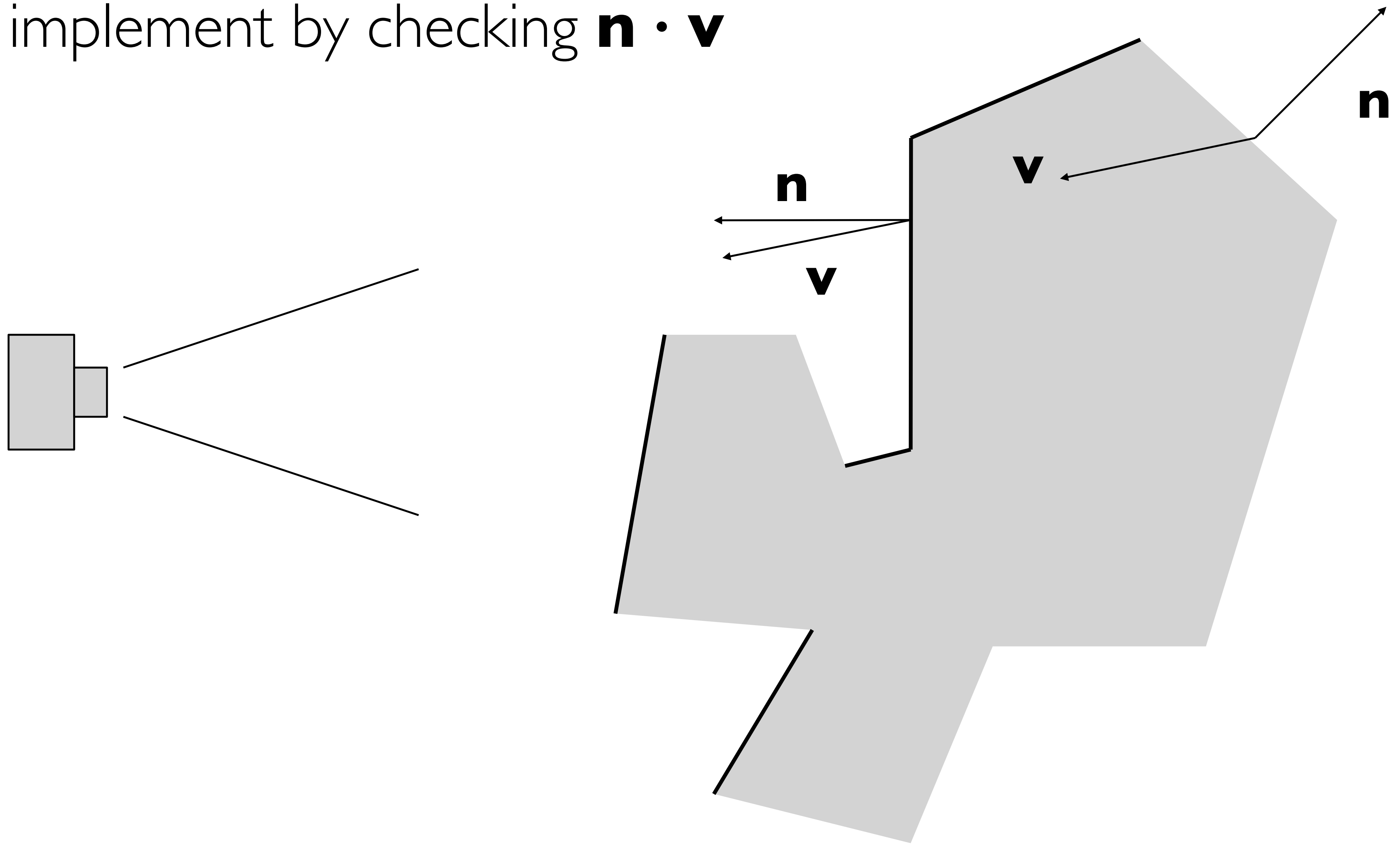

Painter's algorithm

- **Simplest way to do hidden surfaces**
- **Draw from back to front, use overwriting in framebuffer**

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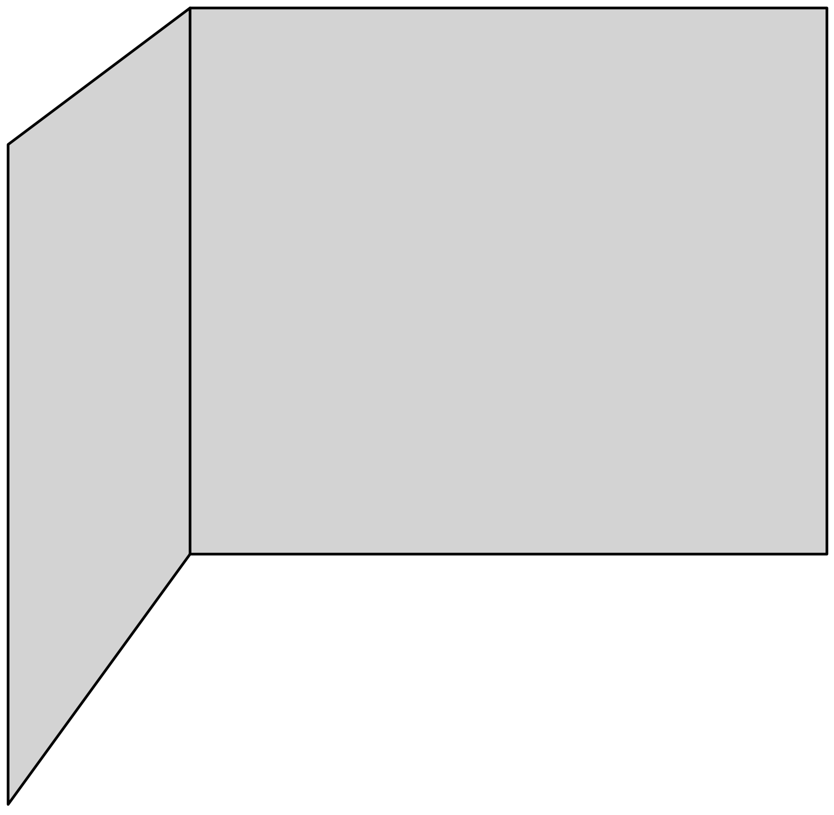

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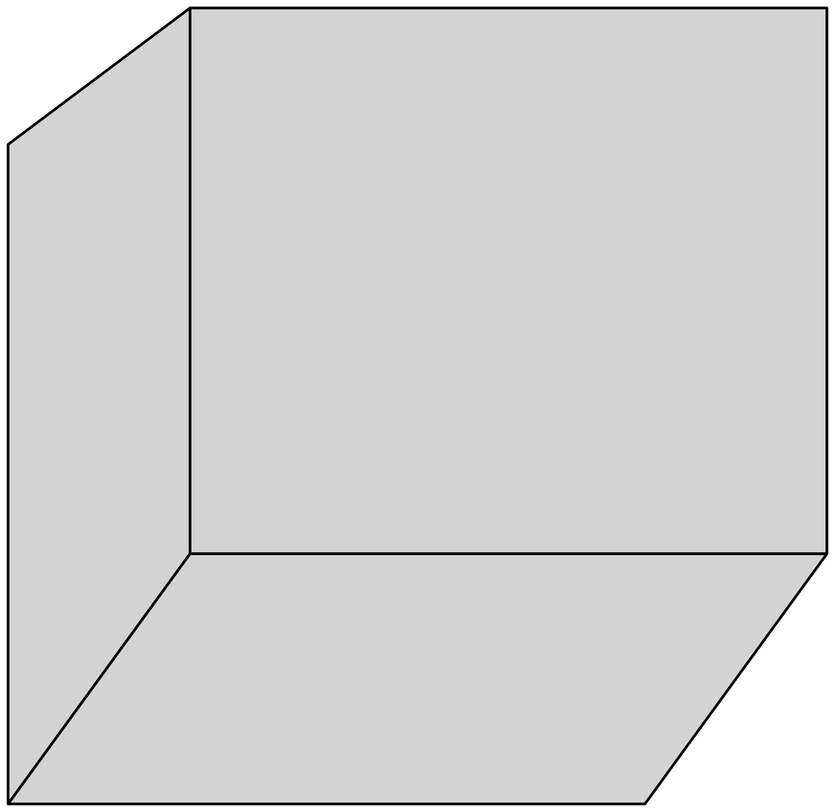

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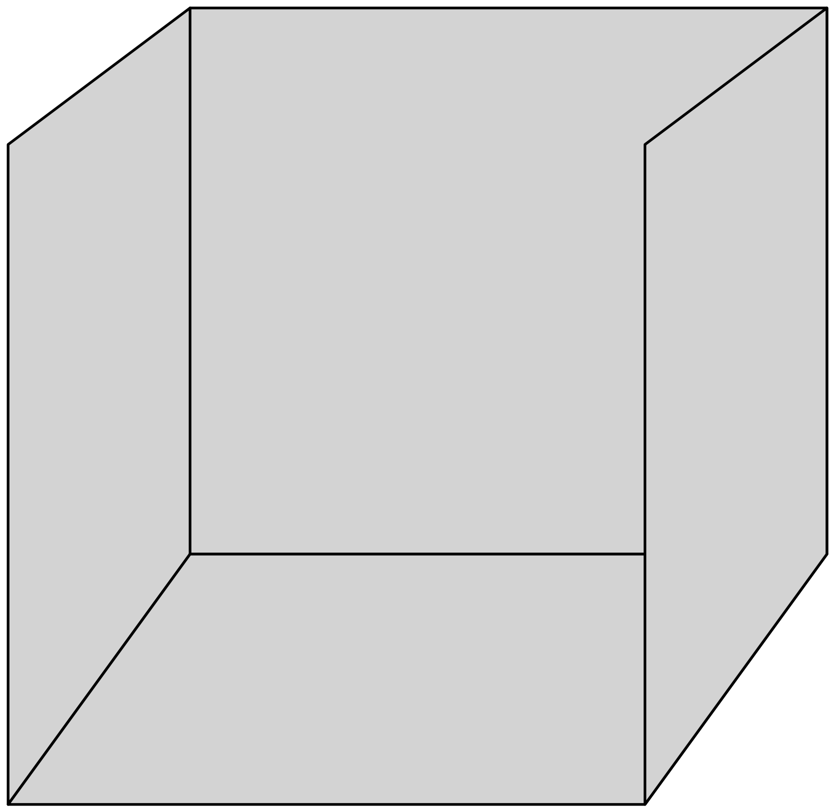

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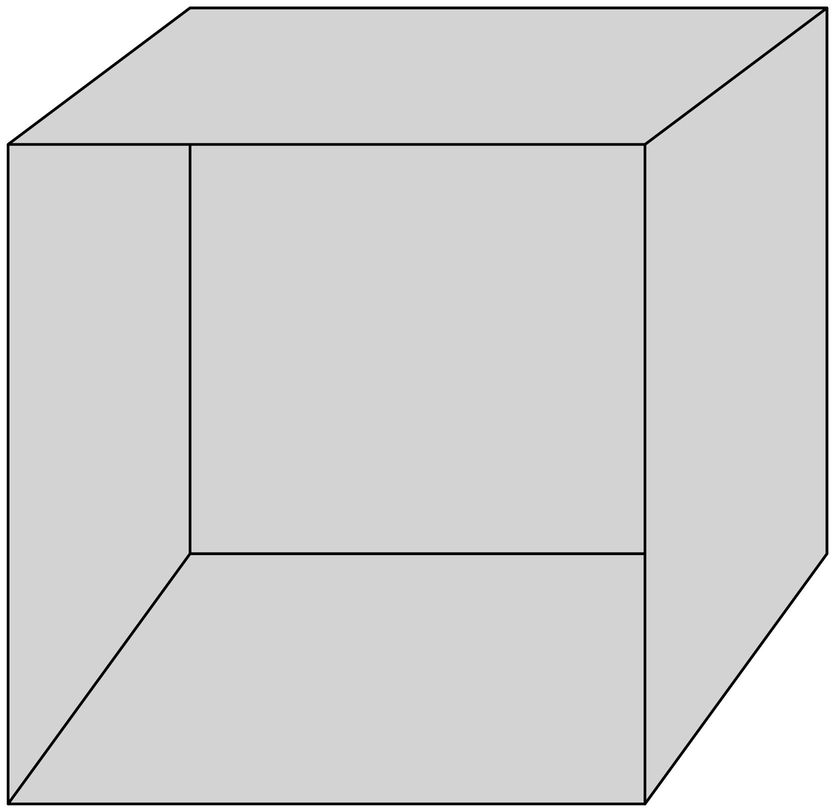

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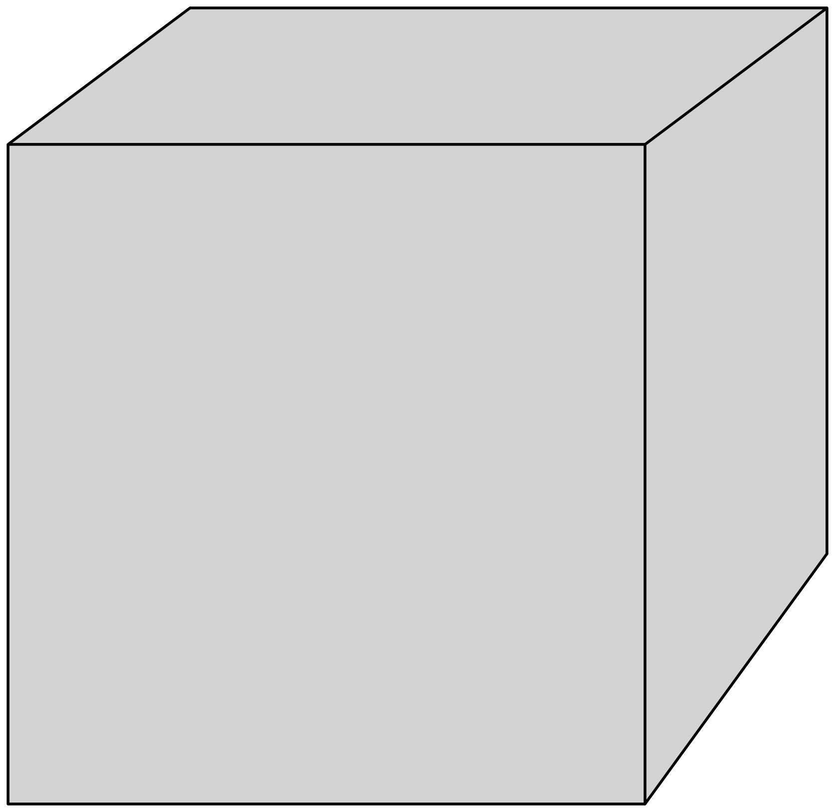
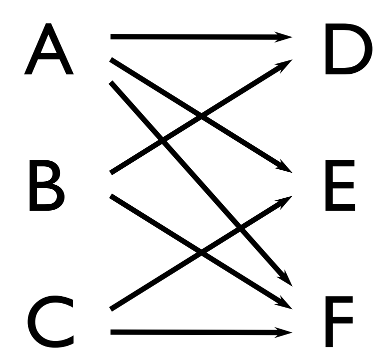
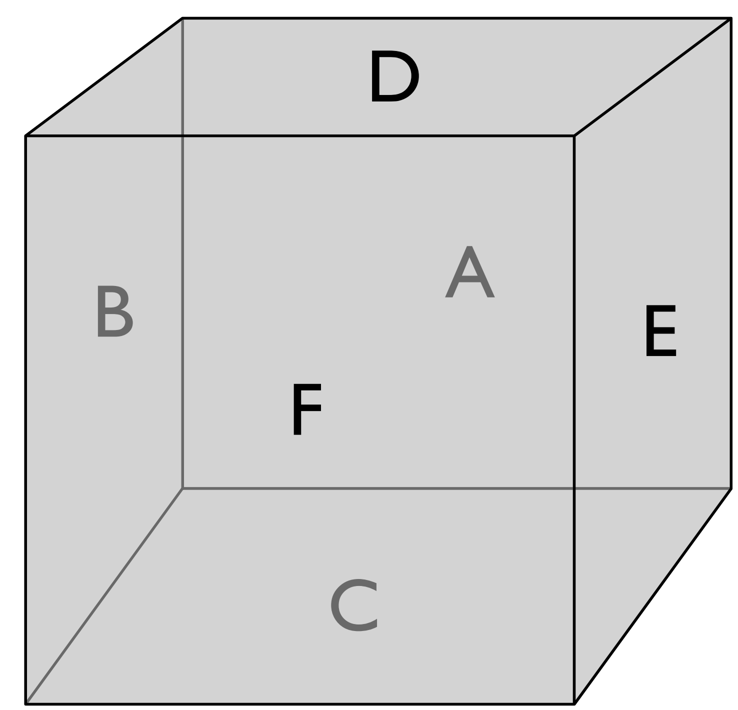


Painter's algorithm

- **Amounts to a topological sort of the graph of occlusions**
  - that is, an edge from A to B means A sometimes occludes B
  - any sort is valid
    - ABCDEF
    - BADCFE
  - if there are cycles there is no sort





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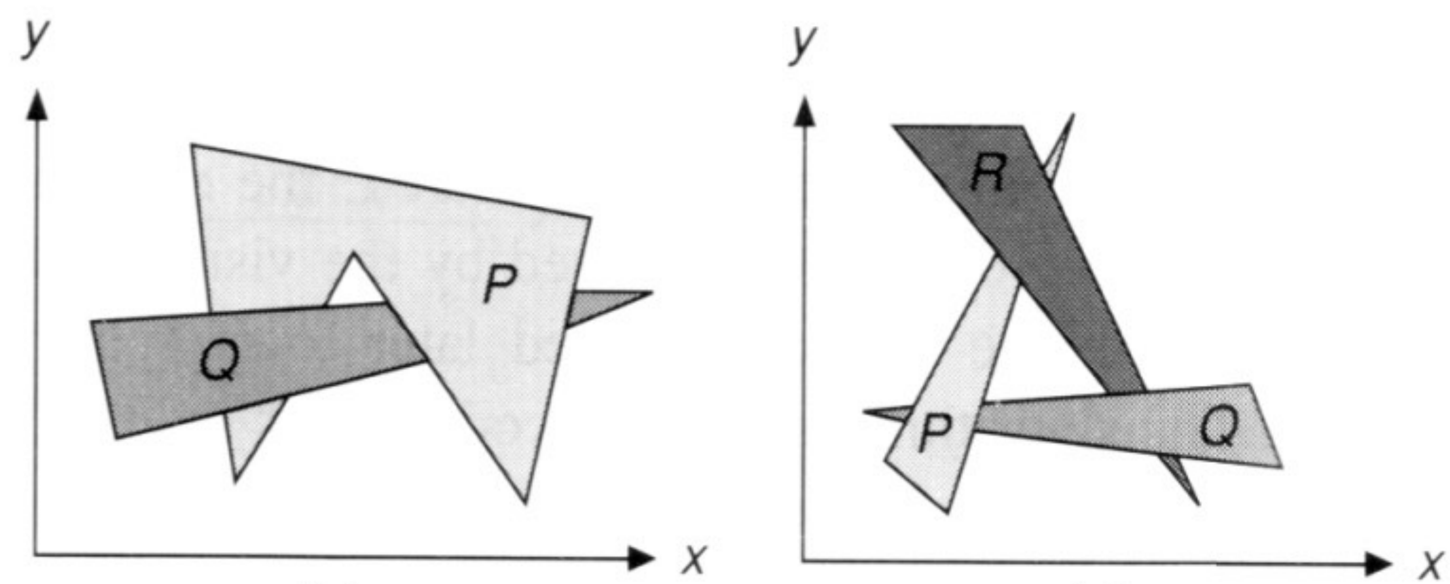
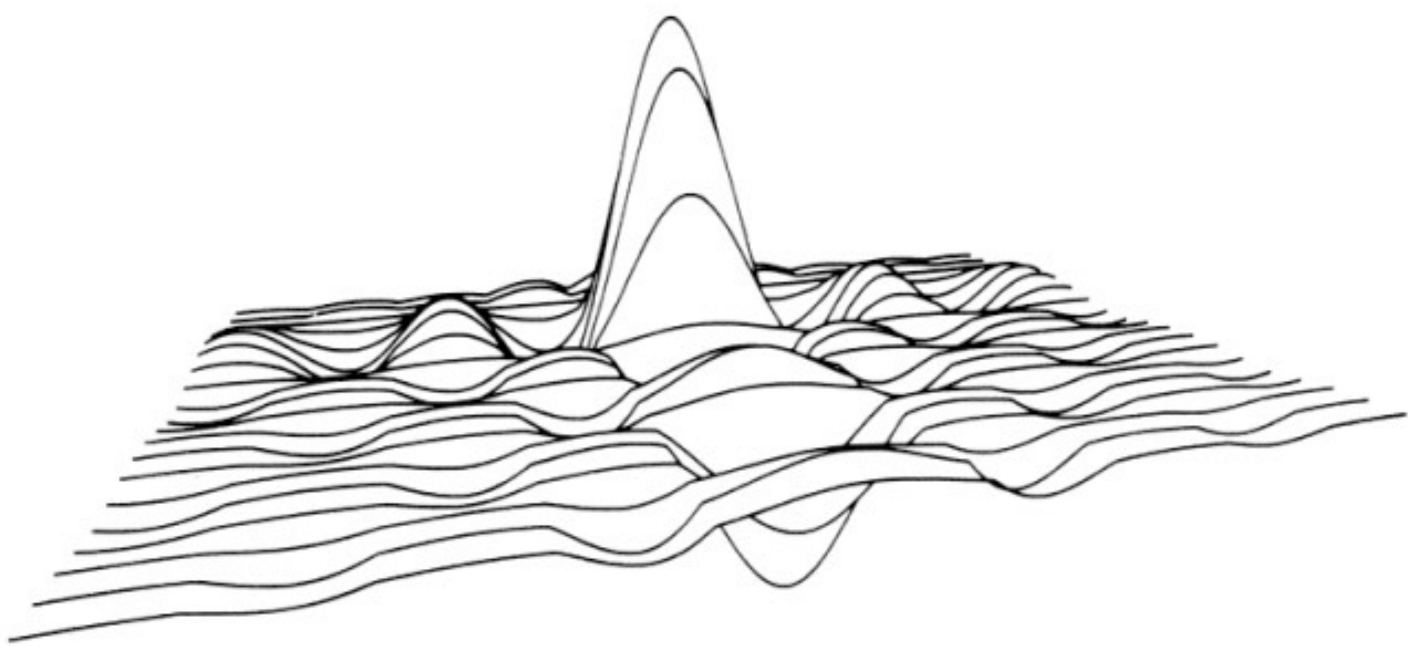


(b)
(c)

[Foley et al.]

Painter's algorithm

- **Useful when a valid order is easy to come by**
- **Compatible with alpha blending**

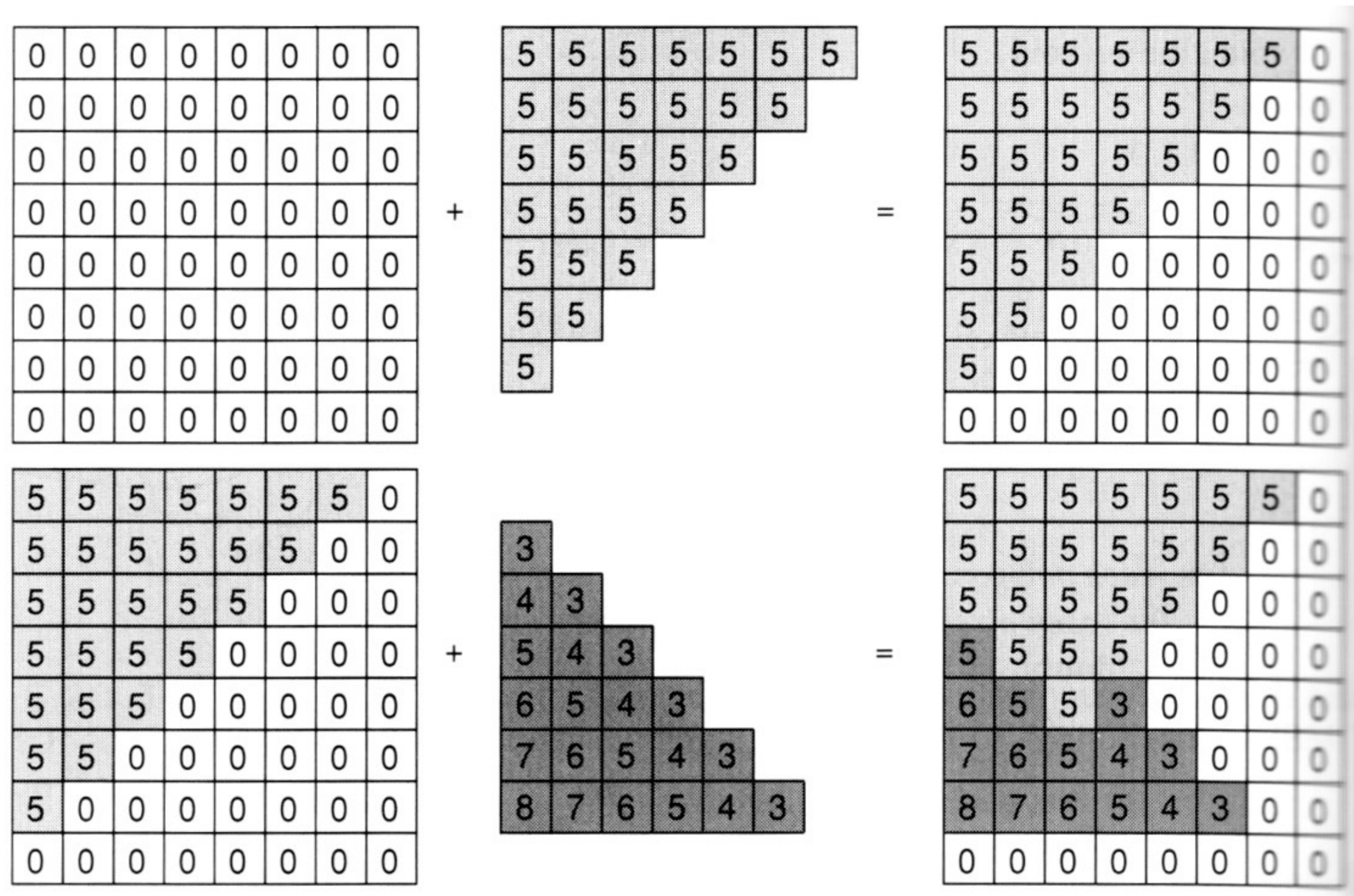


[Foley et al.]

The **z** buffer

- **In many (most) applications maintaining a *z* sort is too expensive**
  – changes all the time as the view changes
  – many data structures exist, but complex
- **Solution: draw in any order, keep track of closest**
  – allocate extra channel per pixel to keep track of closest depth so far
  – when drawing, compare object's depth to current closest depth and discard if greater
  – this works just like any other compositing operation

The **z** buffer



[Foley et al.]

– another example of a memory-intensive brute force approach that works and has become the standard

The Graphics Pipeline

4. The rasterization pipeline

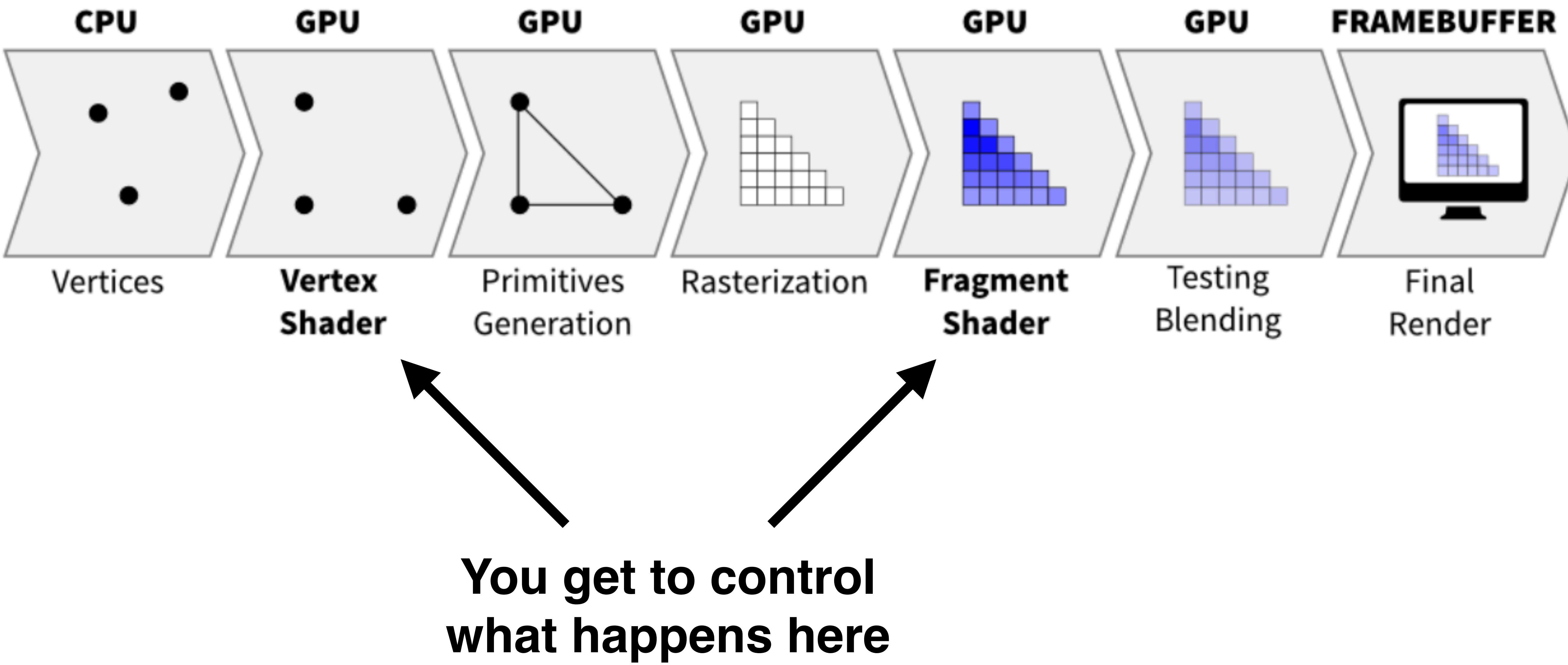
The graphics pipeline

- **The standard approach to object-order graphics**
- **Many versions exist**
  - software, e.g. Pixar's REYES architecture
    - many options for quality, flexibility, scalability
  - hardware, e.g. graphics cards in PCs
    - amazing performance: millions of triangles per frame
- **We'll focus on an abstract version of hardware pipeline**
- **"Pipeline" because of the many stages**
  - very parallelizable workload
  - leads to remarkable performance of graphics cards (many times the flops of the CPU at ~1/2 the clock speed)

Primitives

- **Points**
- **Line segments**
  - and chains of connected line segments
- **Triangles**
- **And that's all!**
  - Curves? Approximate them with chains of line segments
  - Polygons? Break them up into triangles
  - Curved surfaces? Approximate them with triangles
- **Trend over the decades: toward minimal primitives**
  - simple, uniform, repetitive: good for parallelism

Programmable shading



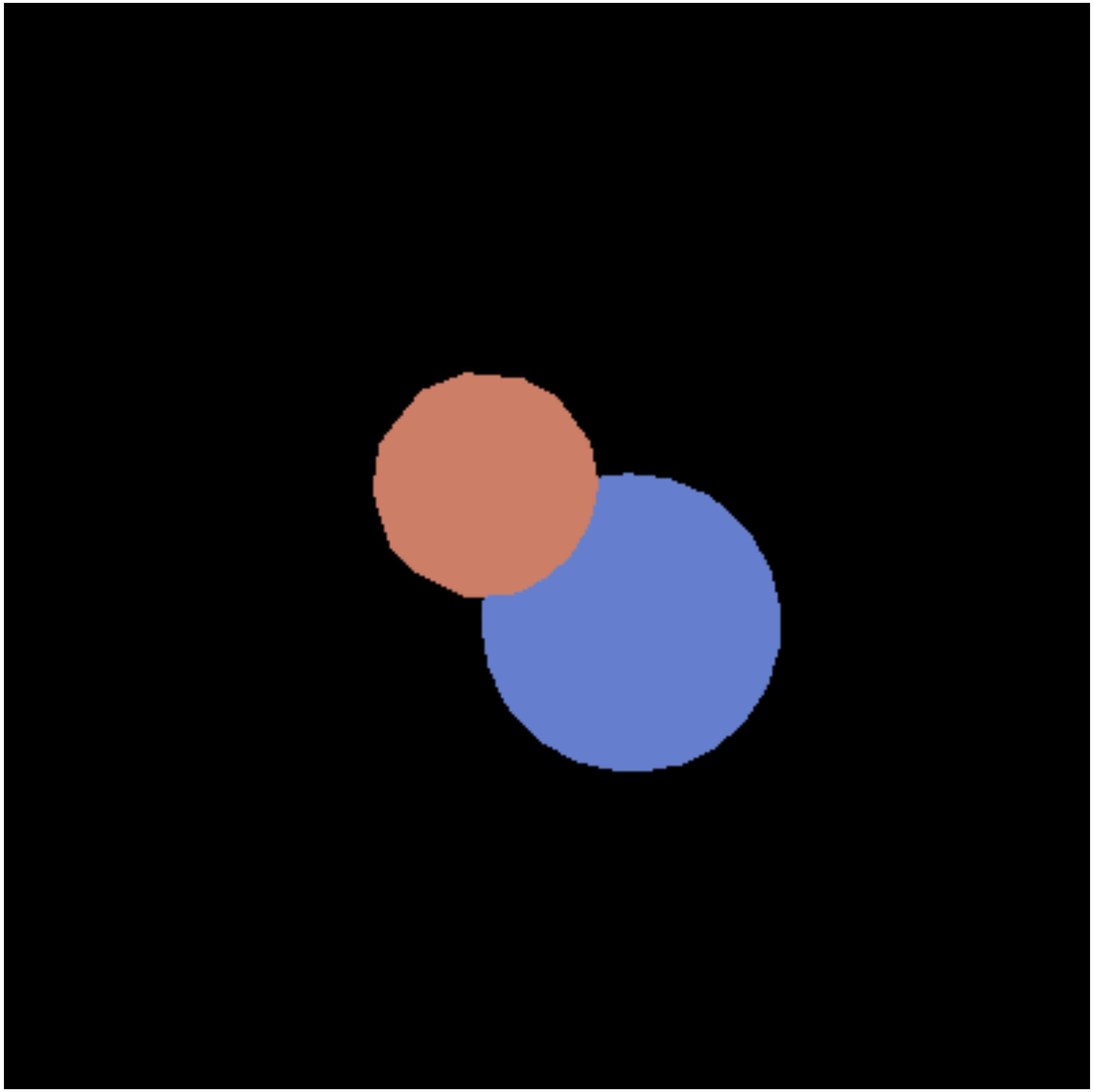
Francesco Andreussi?

Pipeline for minimal operation

Demo

- **Vertex stage (input: position / vtx)**
  – transform position (object to screen space)
- **Rasterizer**
  – nothing (extra) to interpolate
- **Fragment stage (output: color)**
  – write a fixed color to color planes
  – (color is a "uniform" quantity that is infrequently updated)

Result of minimal pipeline

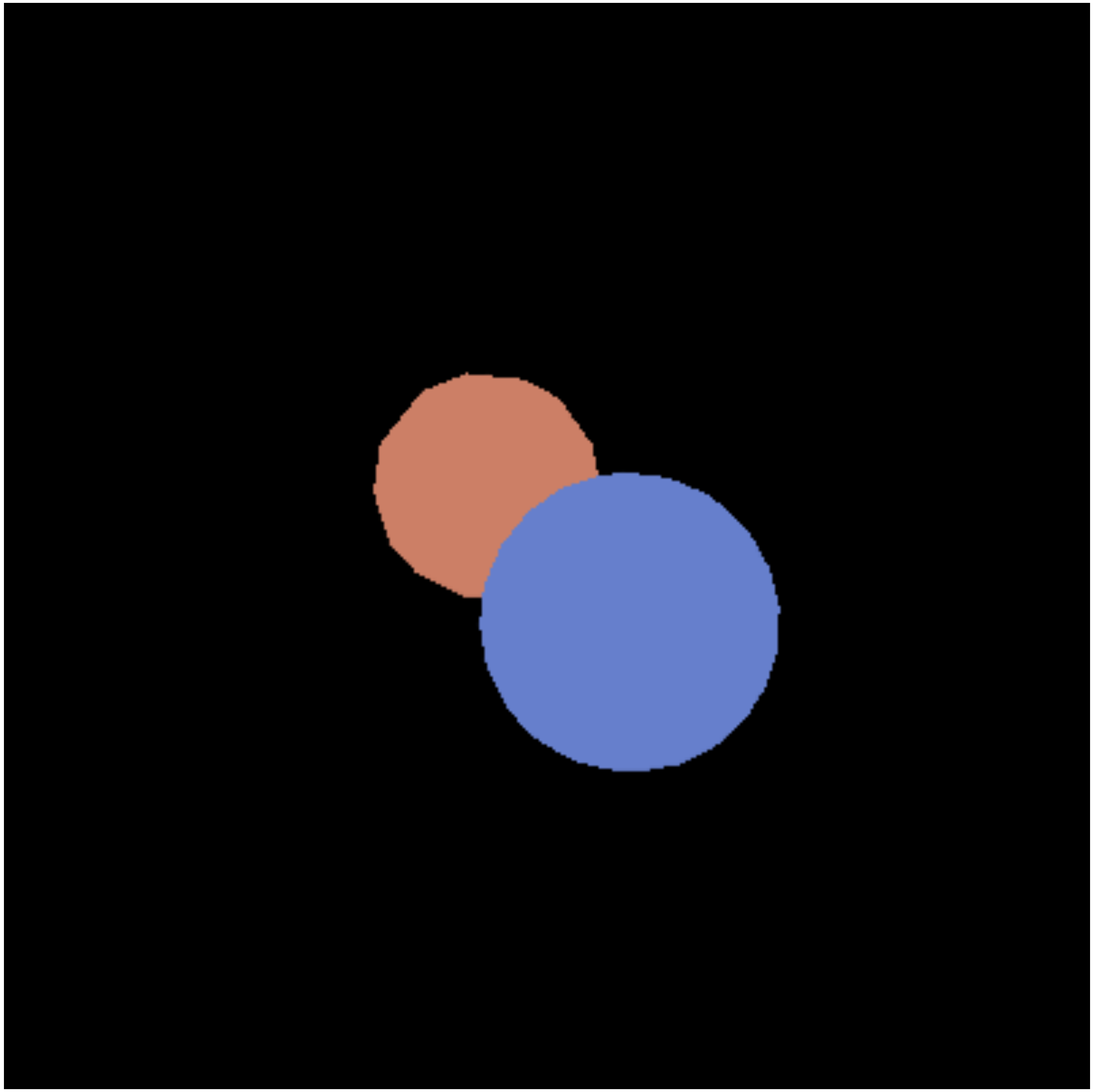


Pipeline for basic z-buffer

Demo

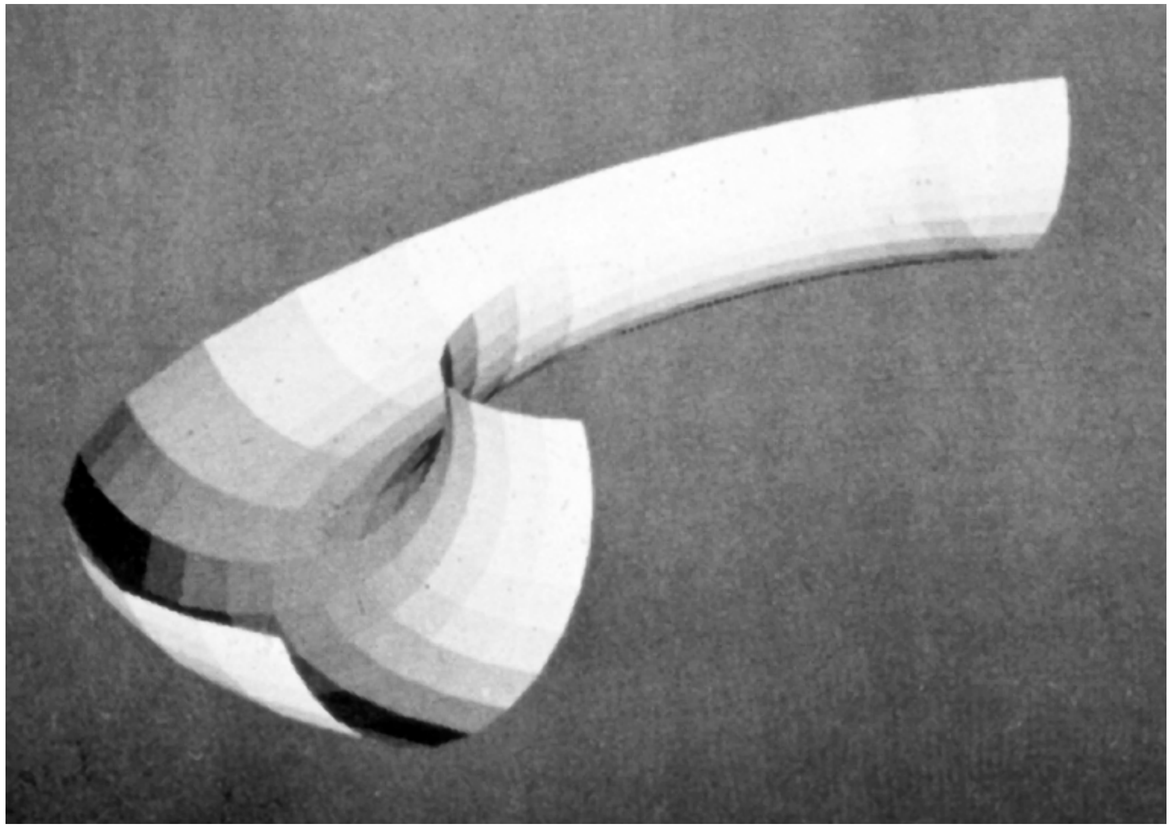
- **Vertex stage (input: position / vtx)**
  - transform position (object to screen space)
- **Rasterizer**
  - interpolated parameter: z' (screen z)
- **Fragment stage (output: color, z')**
  - write fixed color to color planes only if interpolated $z' <$ current z'

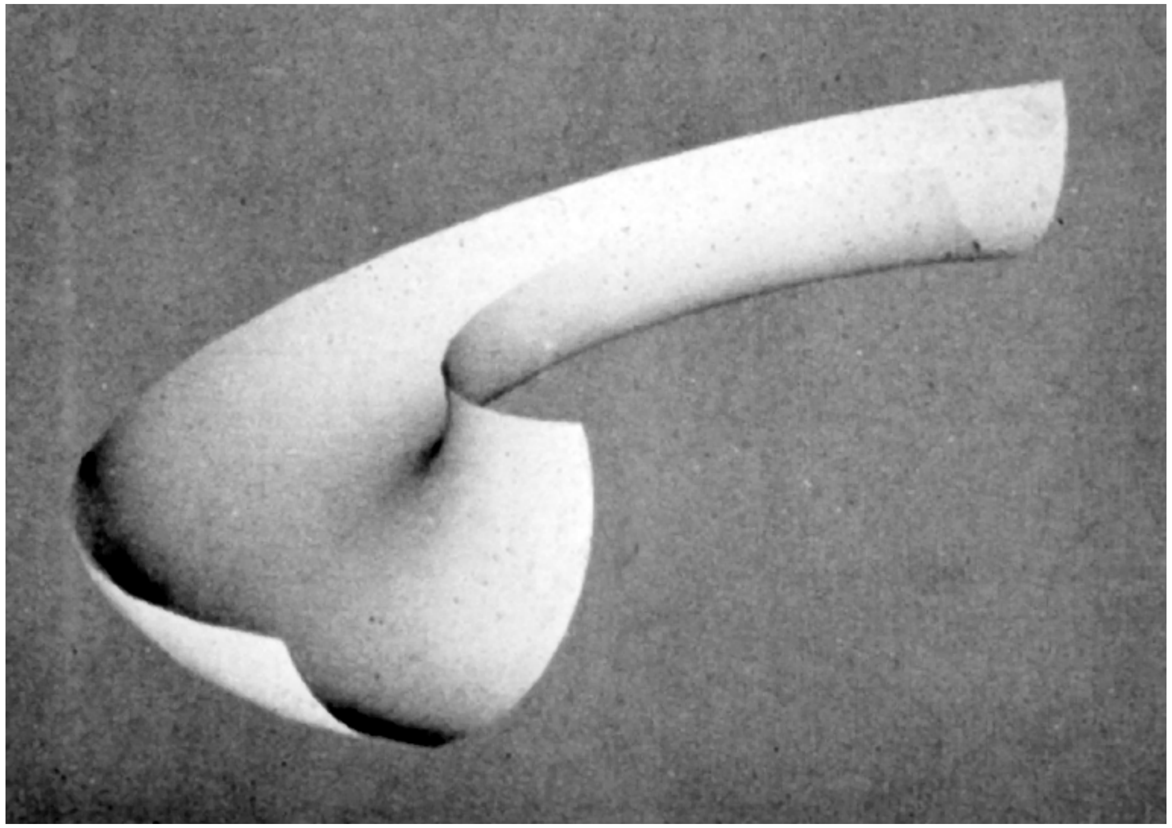
Result of z-buffer pipeline



Gouraud shading

- **Often we're trying to draw smooth surfaces, so facets are an artifact**
  - compute colors at vertices using vertex normals
  - interpolate colors across triangles
  - "Gouraud shading"
  - "Smooth shading"





[Gouraud thesis]

Pipeline for Gouraud shading

Demo

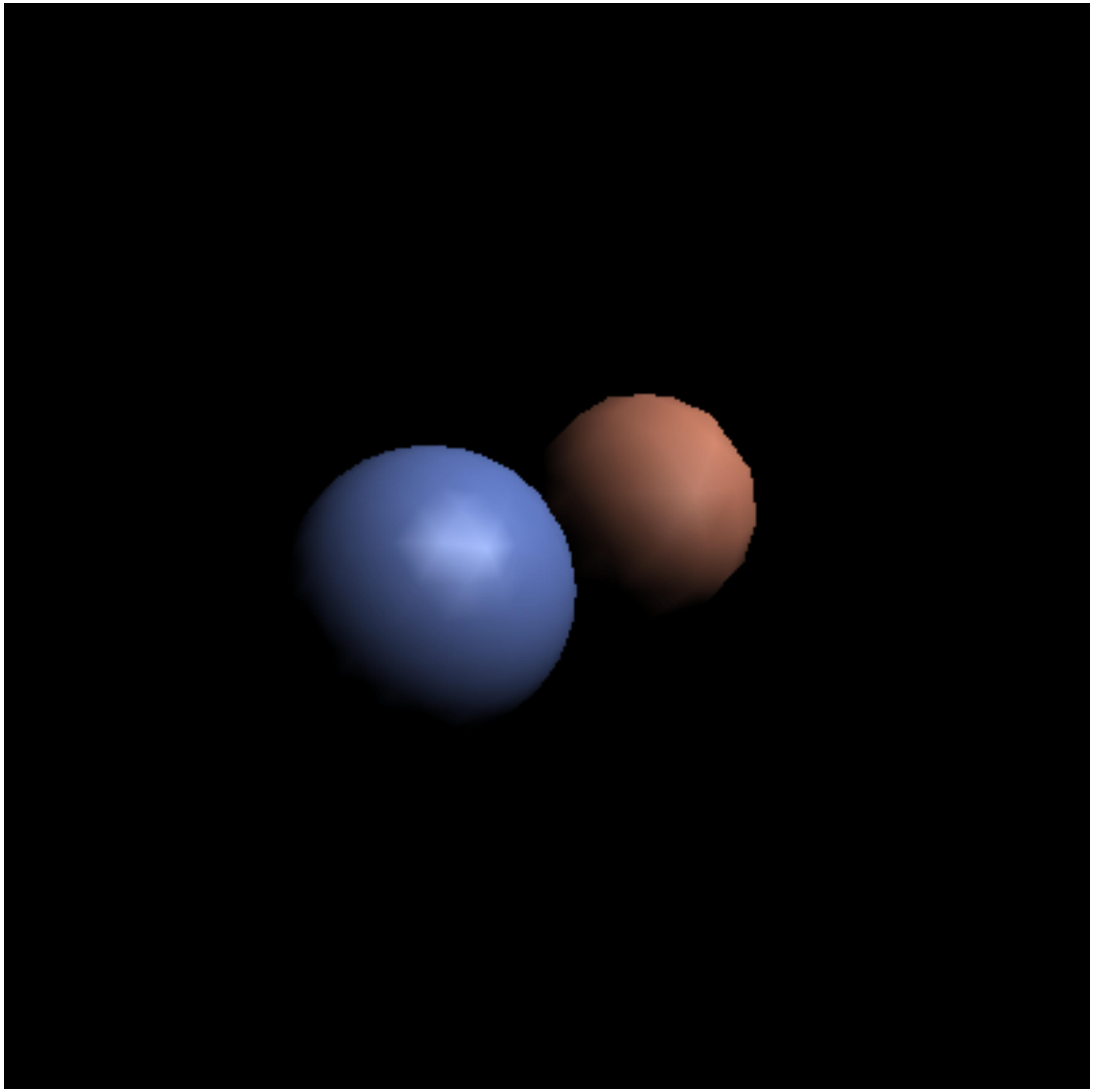
- **Vertex stage (input: position and normal / vtx)**
  - transform position and normal (object to eye space)
  - compute shaded color per vertex (using fixed diffuse color)
  - transform position (eye to screen space)
- **Rasterizer**
  - interpolated parameters: z' (screen z); r, g, b color
- **Fragment stage (output: color, z')**
  - write to color planes only if interpolated $z' <$ current z'

Non-diffuse Gouraud shading

- **Can apply Gouraud shading to any illumination model**
  - it's just an interpolation method
- **Results are not so good with fast-varying models (like specular reflection)**
  - problems with any highlights smaller than a triangle

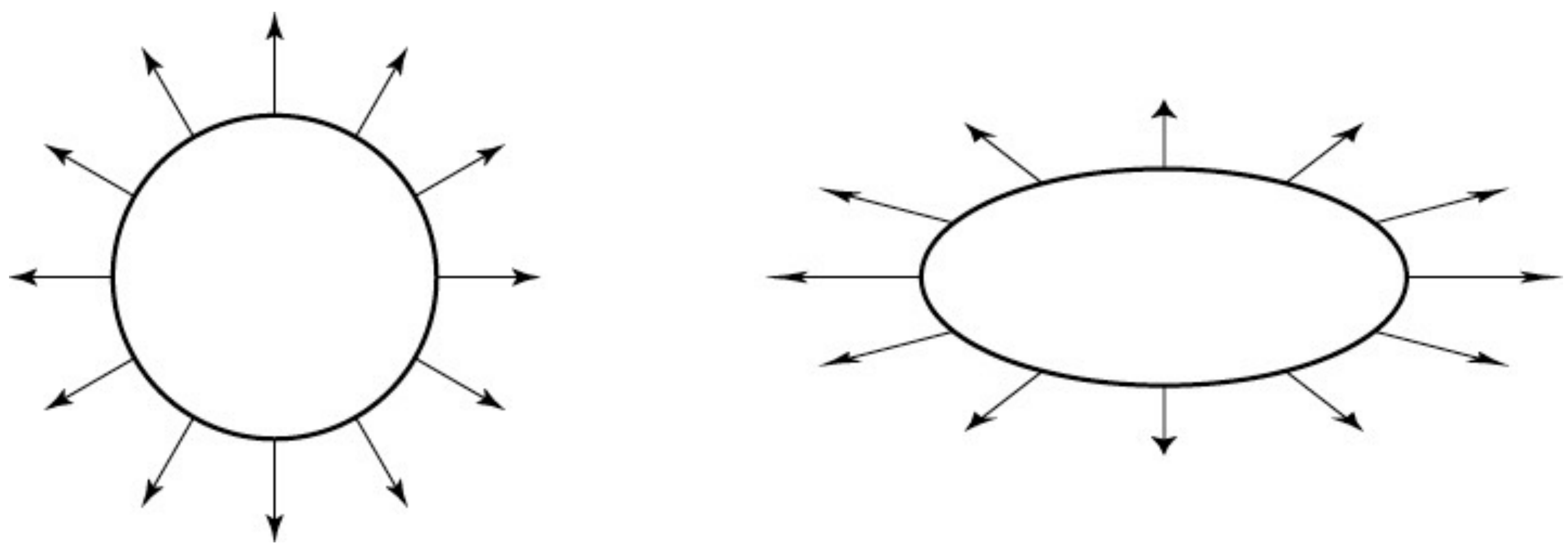
[Foley et al.]

Result of Gouraud shading pipeline



Transforming normal vectors

- **Transforming surface normals**
  - differences of points (and therefore tangents) transform OK
  - normals do not --> use inverse transpose matrix



have: $\mathbf{t} \cdot \mathbf{n} = \mathbf{t}^T \mathbf{n} = 0$
want: $M\mathbf{t} \cdot X\mathbf{n} = \mathbf{t}^T M^T X \mathbf{n} = 0$
so set $X = (M^T)^{-1}$
then: $M\mathbf{t} \cdot X\mathbf{n} = \mathbf{t}^T M^T (M^T)^{-1} \mathbf{n} = \mathbf{t}^T \mathbf{n} = 0$

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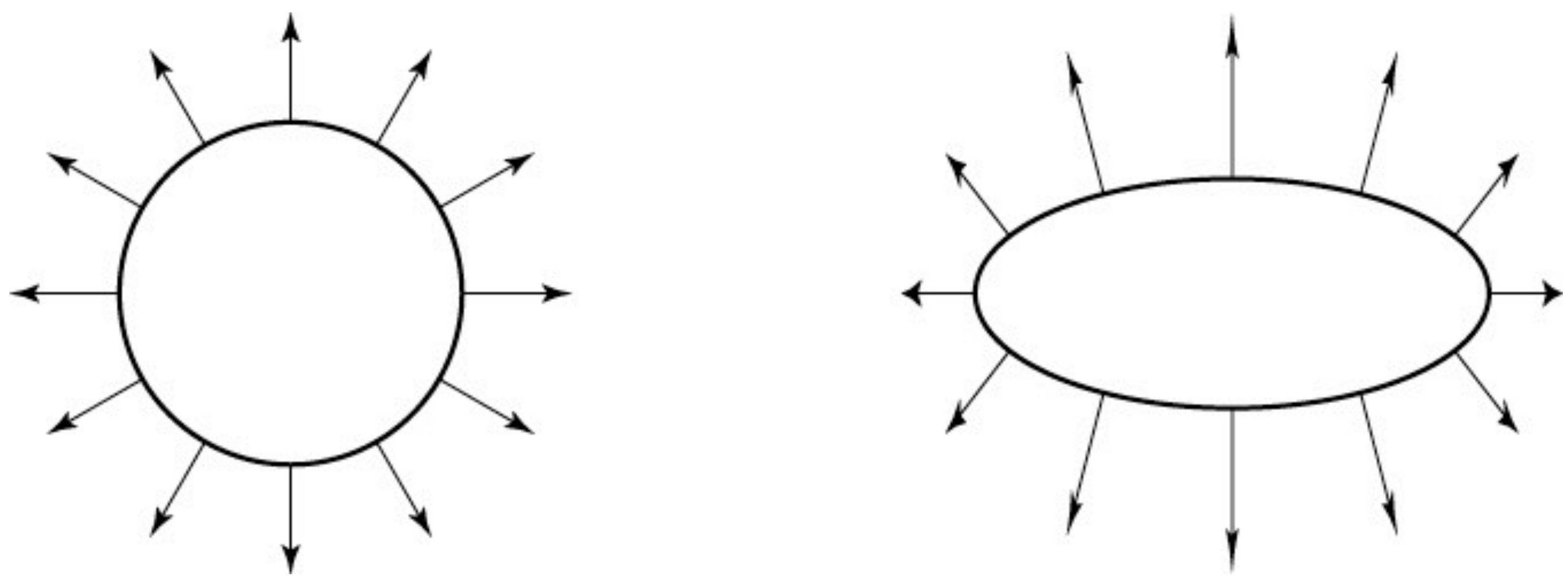

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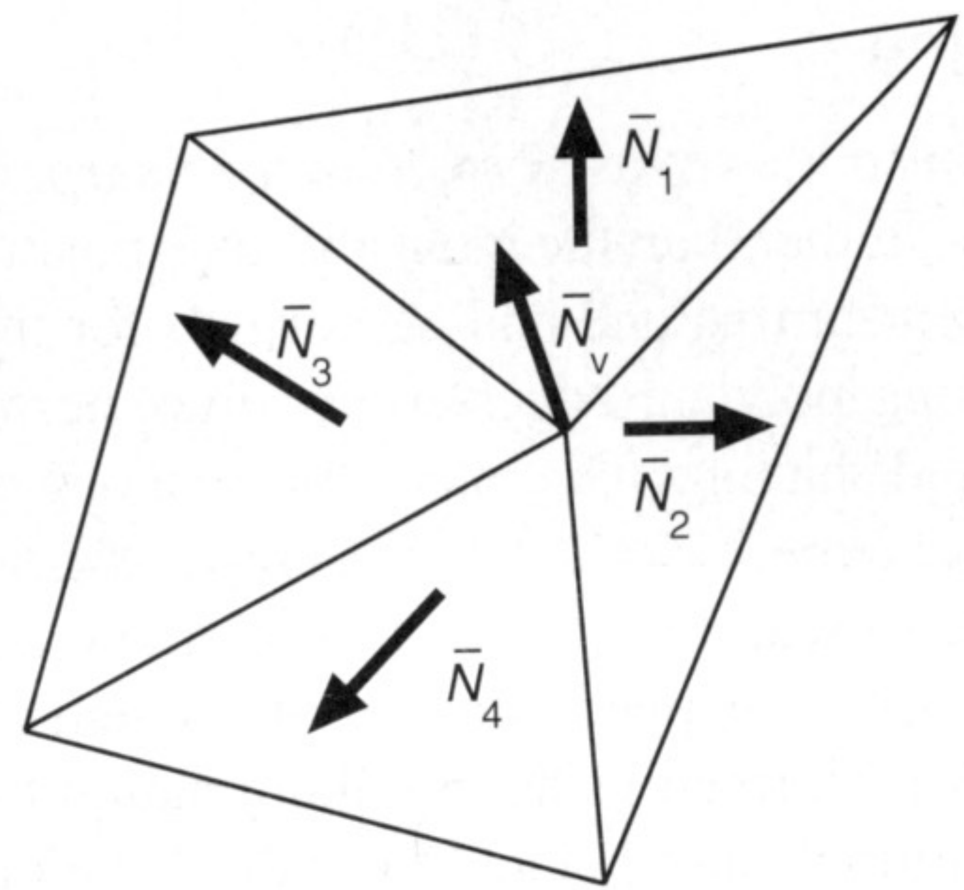
Vertex normals

- **Need normals at vertices to compute Gouraud shading**
- **Best to get vtx. normals from the underlying geometry**
  – e. g. spheres example
- **Otherwise have to infer vtx. normals from triangles**
  – simple scheme: average surrounding face normals

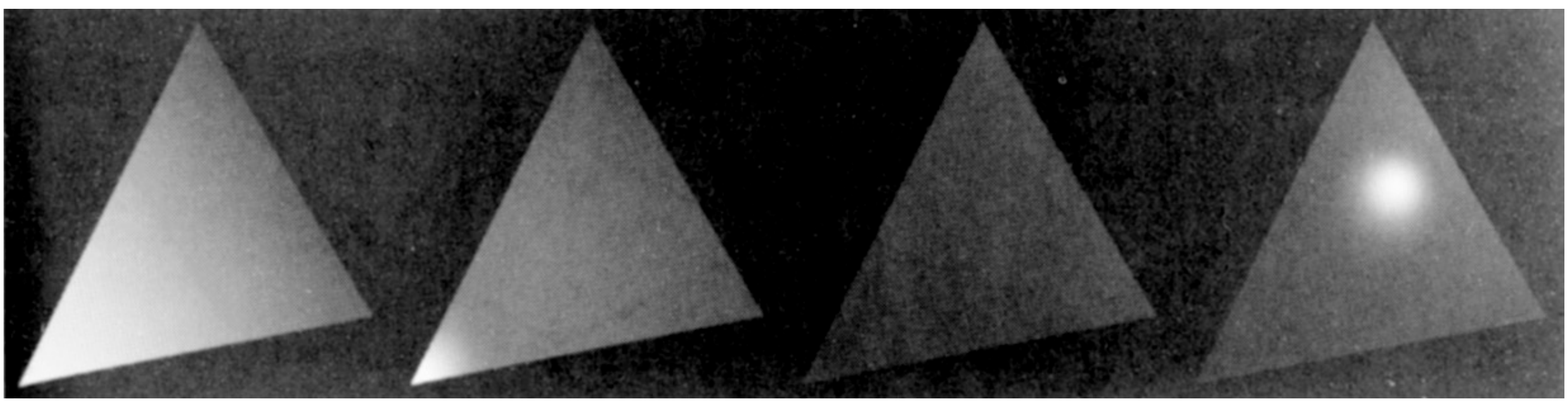
$$N_v = \frac{\sum_i N_i}{\|\sum_i N_i\|}$$



[Foley et al.]

Per-pixel (Phong) shading

- **Get higher quality by interpolating the normal**
  - just as easy as interpolating the color
  - but now we are evaluating the illumination model per pixel rather than per vertex (and normalizing the normal first)
  - in pipeline, this means we are moving illumination from the vertex processing stage to the fragment processing stage

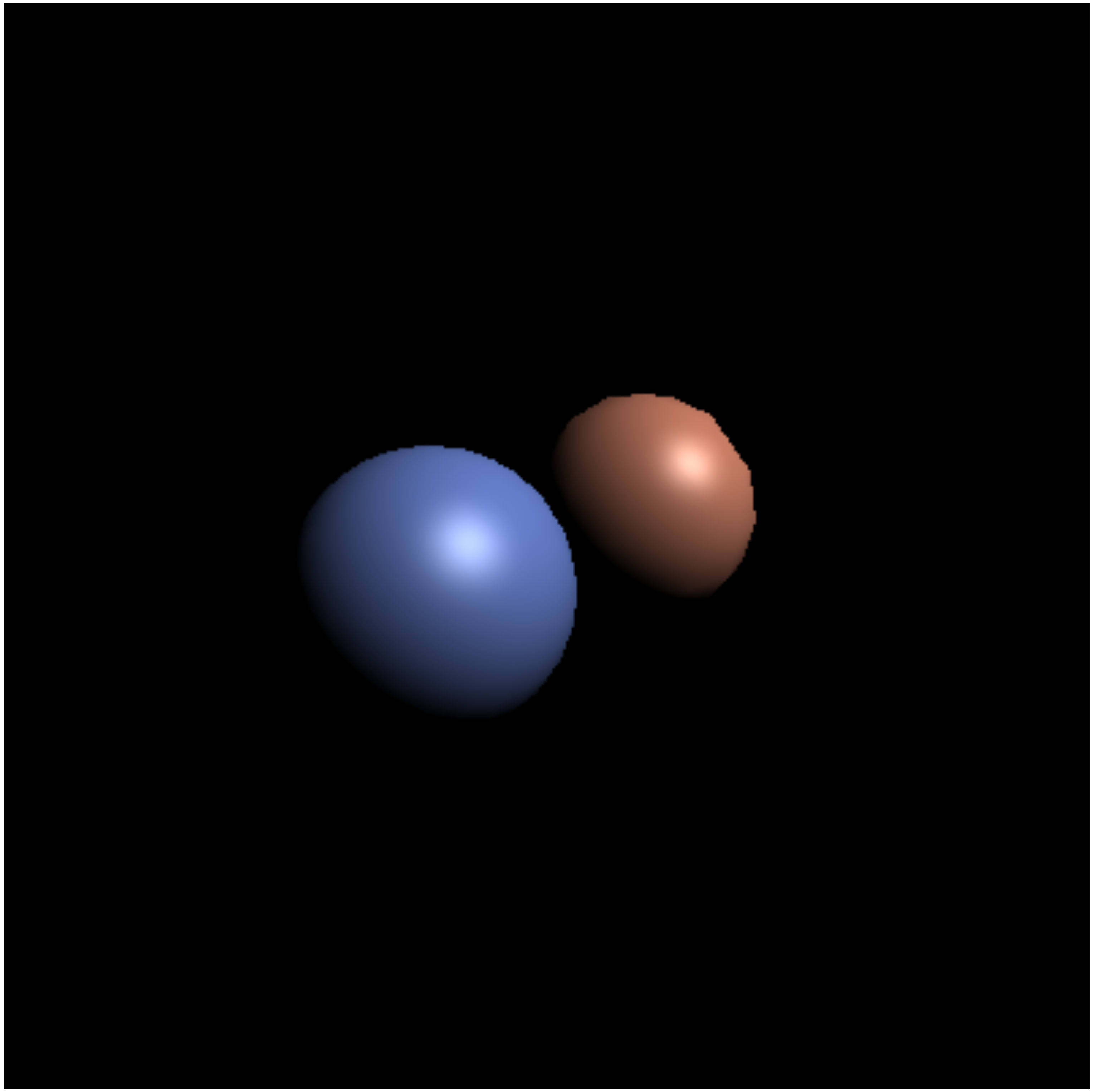


Pipeline for per-pixel shading

Demo

- **Vertex stage (input: position and normal / vtx)**
  - transform position and normal (object to eye space)
  - transform position (eye to screen space)
- **Rasterizer**
  - interpolated parameters: z' (screen z); x, y, z normal
- **Fragment stage (output: color, z')**
  - compute shading using fixed color and interpolated normal
  - write to color planes only if interpolated $z' <$ current z'

Result of per-pixel shading pipeline



Programming hardware pipelines

- **Modern hardware graphics pipelines are flexible**
  - programmer defines exactly what happens at each stage
  - do this by writing *shader programs* in domain-specific languages called *shading languages*
  - rasterization is fixed-function, as are some other operations (depth test, many data conversions, …)
- **One example: OpenGL and GLSL (GL Shading Language)**
  - several types of shaders process primitives and vertices; most basic is the *vertex program*
  - after rasterization, fragments are processed by a *fragment program*

GLSL Shaders