Pipeline and Rasterization

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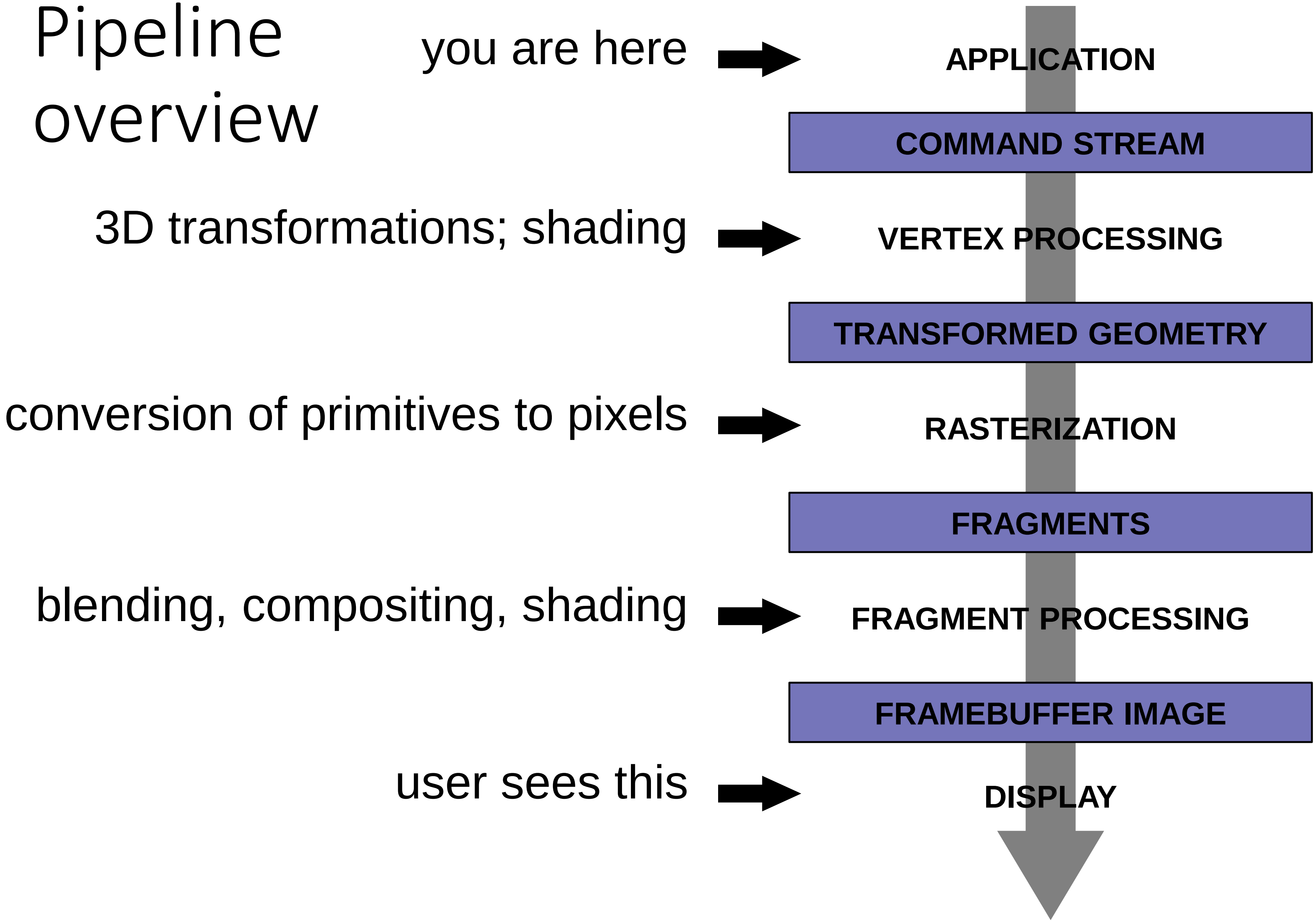
The graphics pipeline

- The standard approach to object-order graphics
- Many versions exist
  - software, e.g., Pixar's REYES architecture
    - many options for quality and flexibility
  - hardware, e.g., graphics cards in PCs
    - amazing performance: millions of triangles per frame
- We'll look at both the traditional OpenGL pipeline and also consider an abstract version of hardware pipeline
- "Pipeline" because of the many stages
  - very parallelizable
  - leads to remarkable performance of graphics cards (many times the flops of the CPU at 10% to 20% the clock speed)

Pipeline overview



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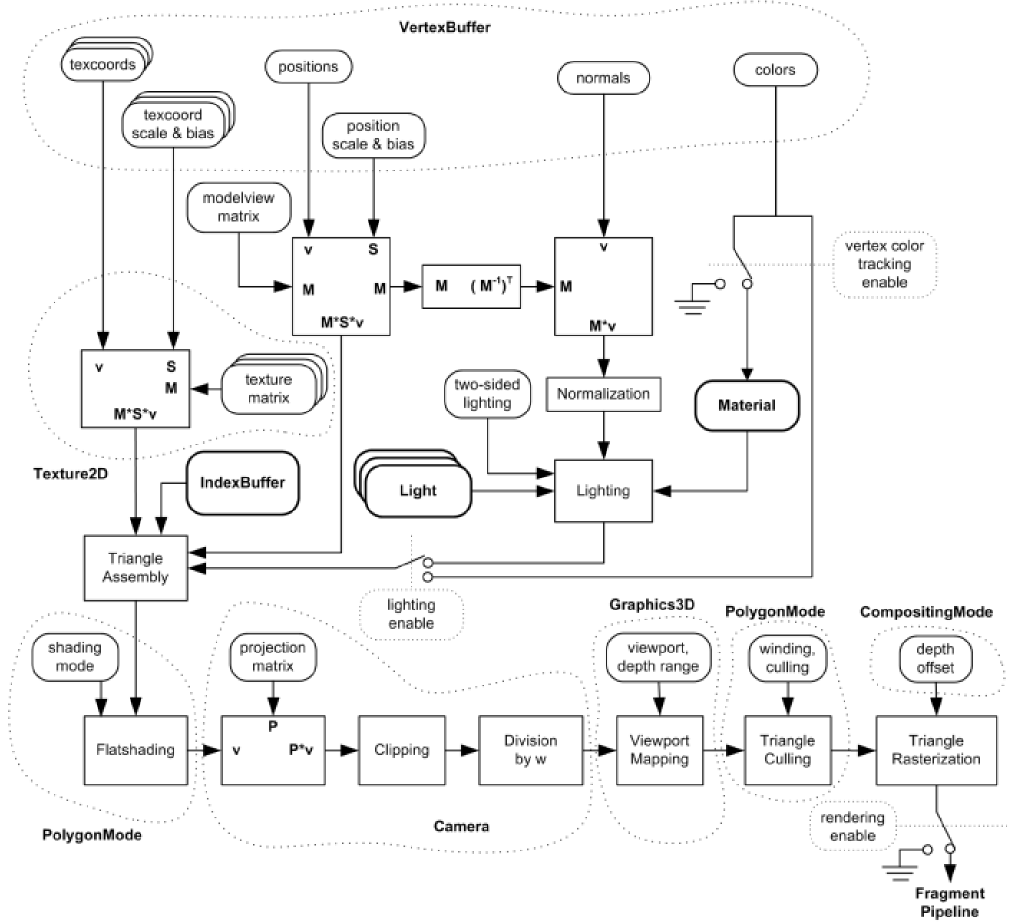
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PolygonMode
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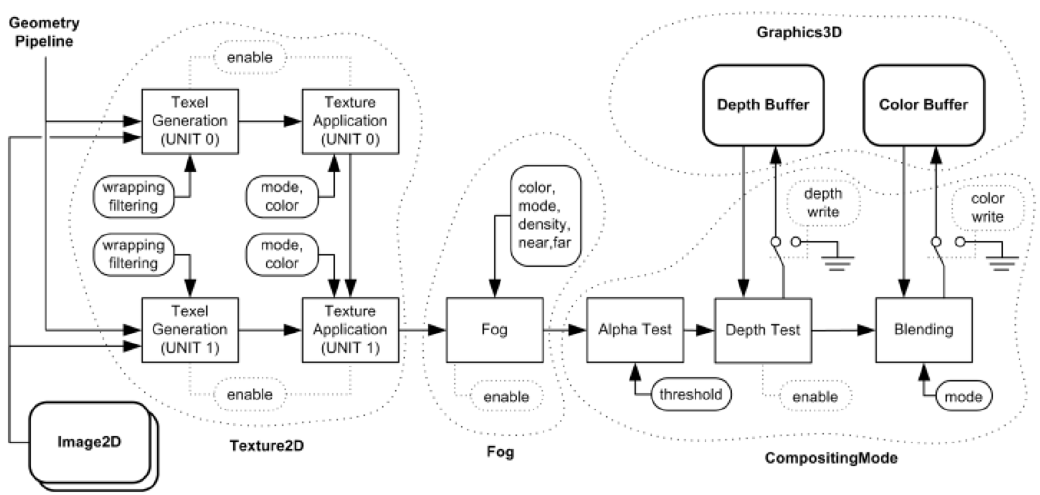
PolygonMode
Camera
Fragment Pipeline


Geometry Pipeline
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Texel Generation (UNIT 0)
Texture Application (UNIT 0)
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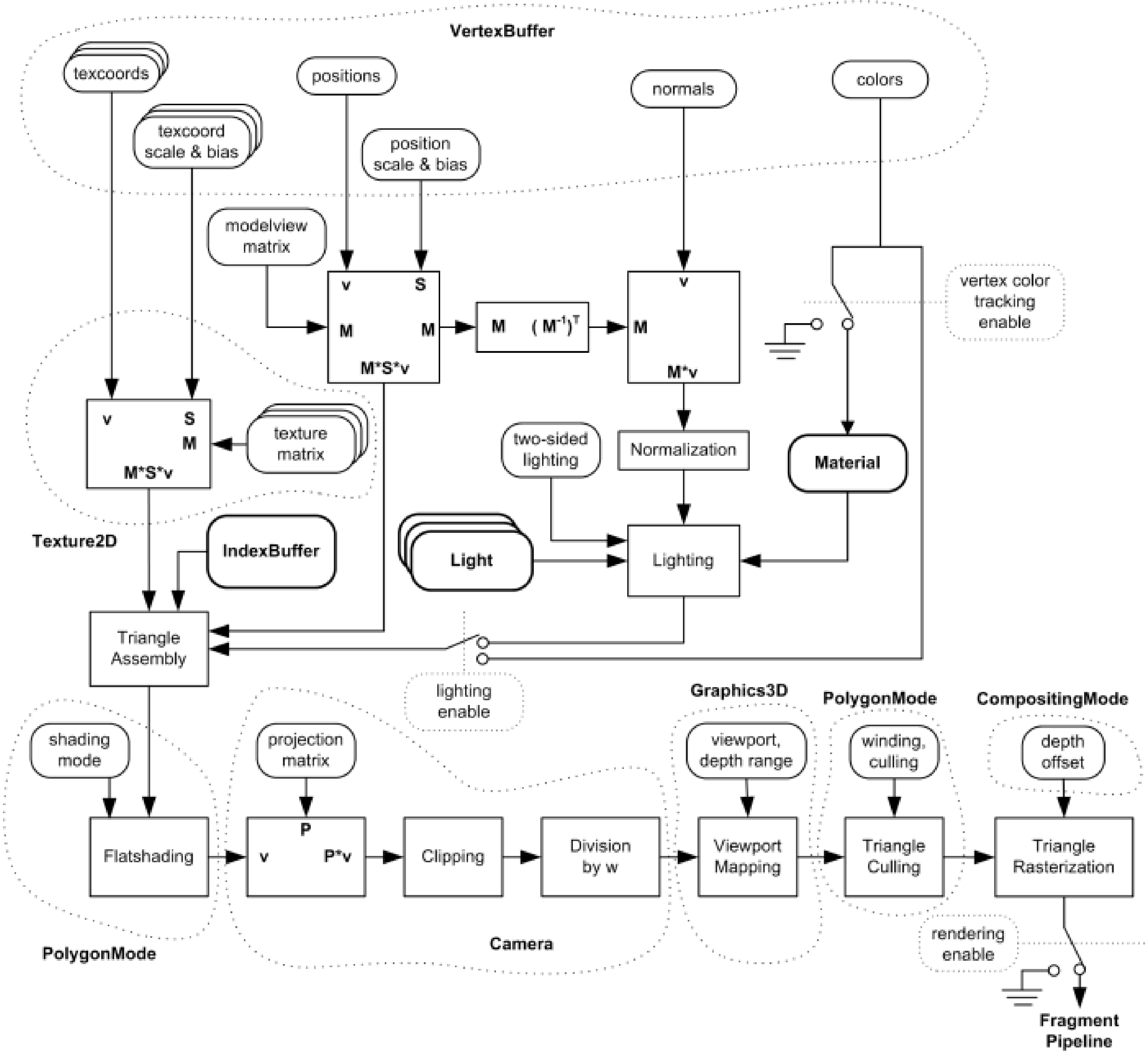
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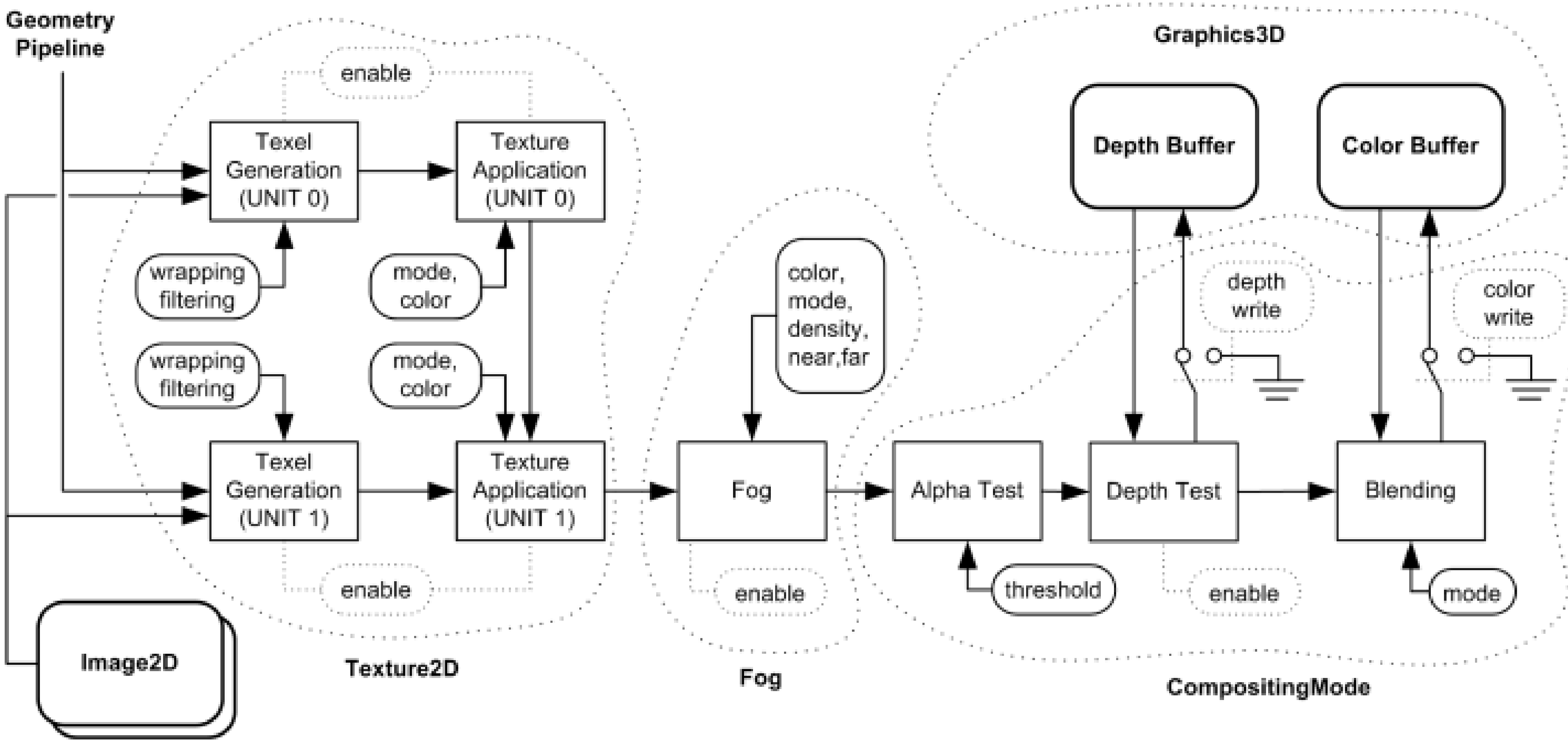
Fragment Pipeline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Texture Application (UNIT 1)
Fog
Alpha Test
Depth Test
Blending
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Image2D
Texture2D
Fog
CompositingMode

Primitives

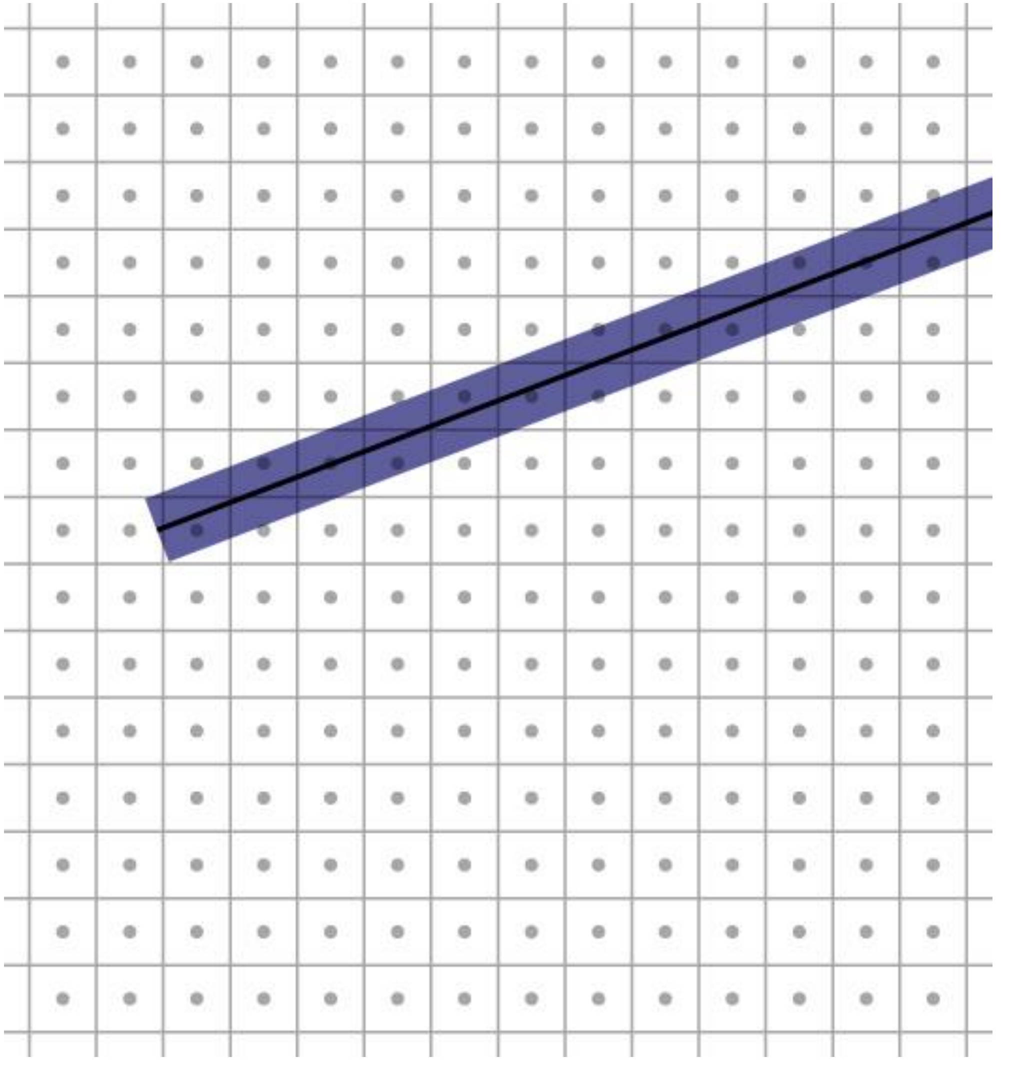
- Points
- Line segments (and chains, loops of line segments)
- Triangles (and strips and fans of adjacent triangles)
- And that’s all!
  - Curves? Approximate them with chains of line segments
  - Polygons? Break them up into triangles
  - Curved regions? Approximate them with triangles
- Trend has been toward minimal primitives
  - simple, uniform, repetitive: good for parallelism

Rasterization

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

Rasterizing lines

- Define line as a rectangle
- Specify by two endpoints
- Ideal image: black inside, white outside



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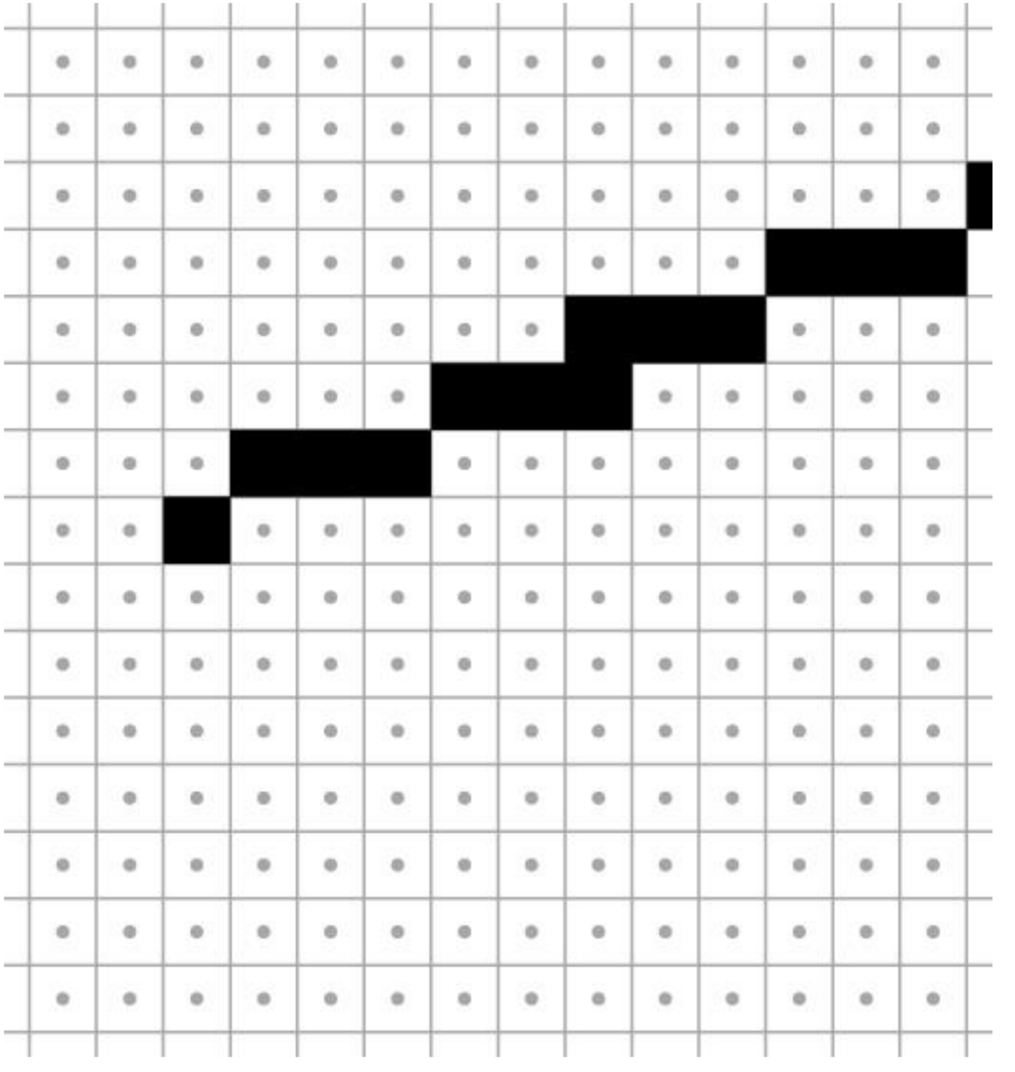
Point sampling

- Approximate rectangle by drawing all pixels whose centers fall within the line
- Problem: sometimes turns on adjacent pixels



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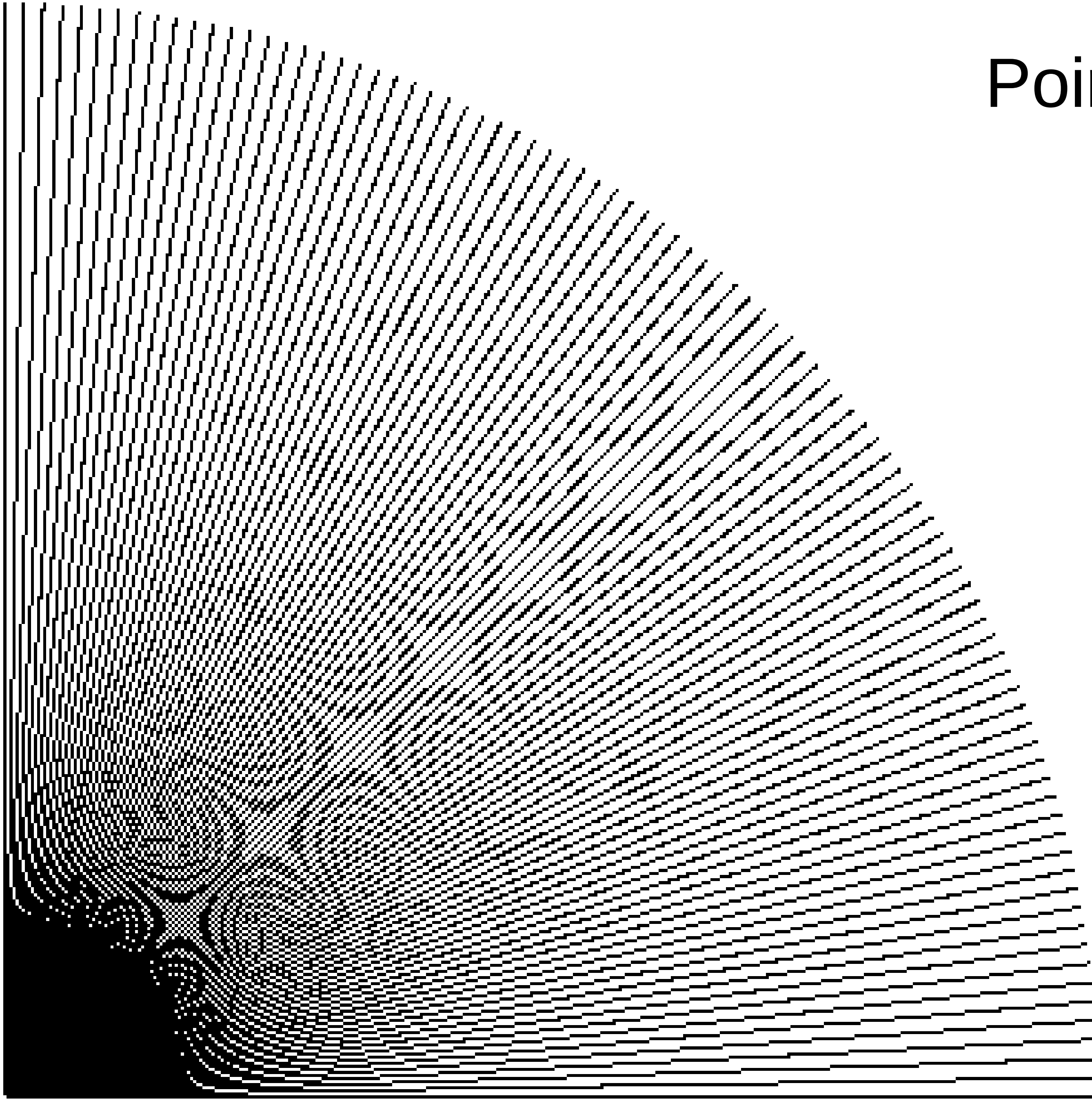

Point sampling in action

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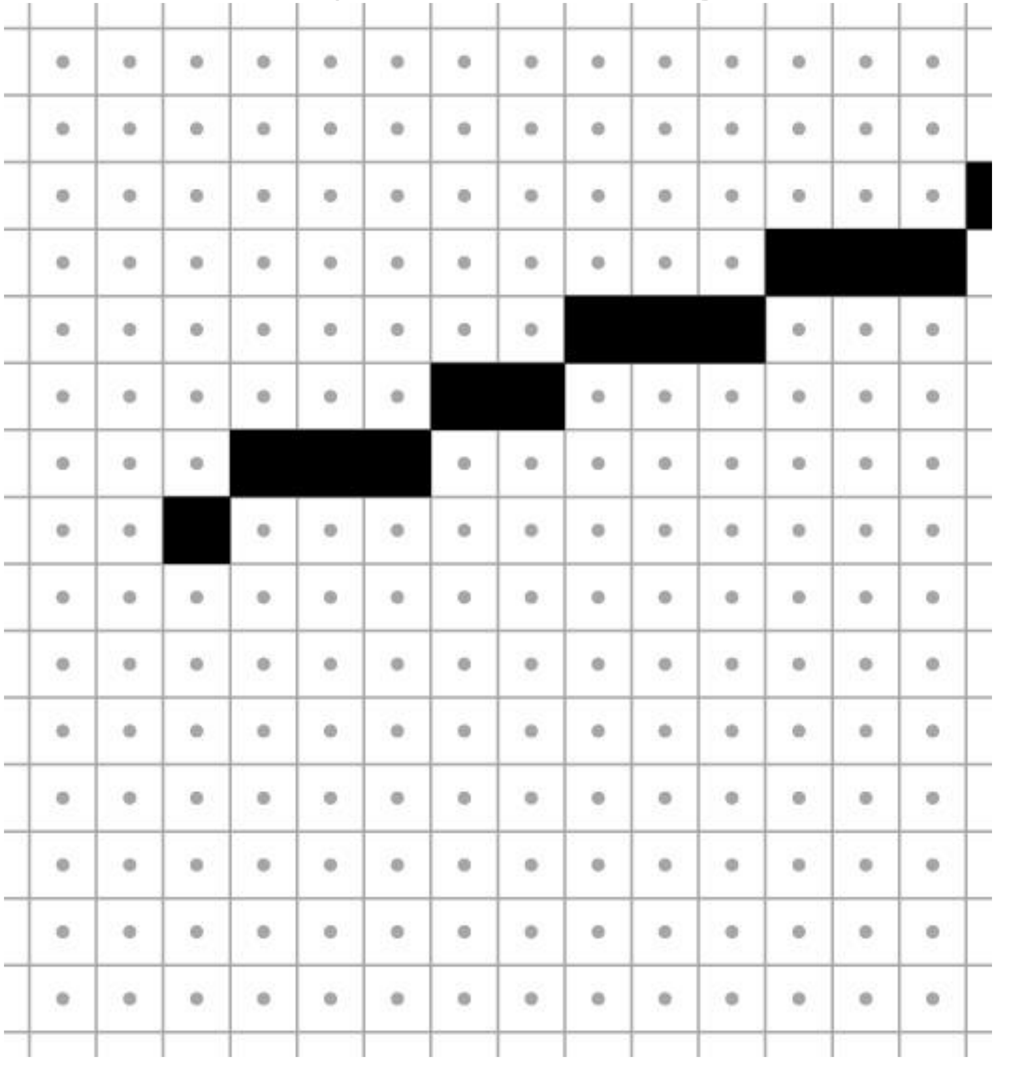
Bresenham lines (midpoint alg.)

- Point sampling unit width rectangle leads to uneven line width
- Define line width parallel to pixel grid
- That is, turn on the single nearest pixel in each column
- Note that 45 degree lines are now thinner



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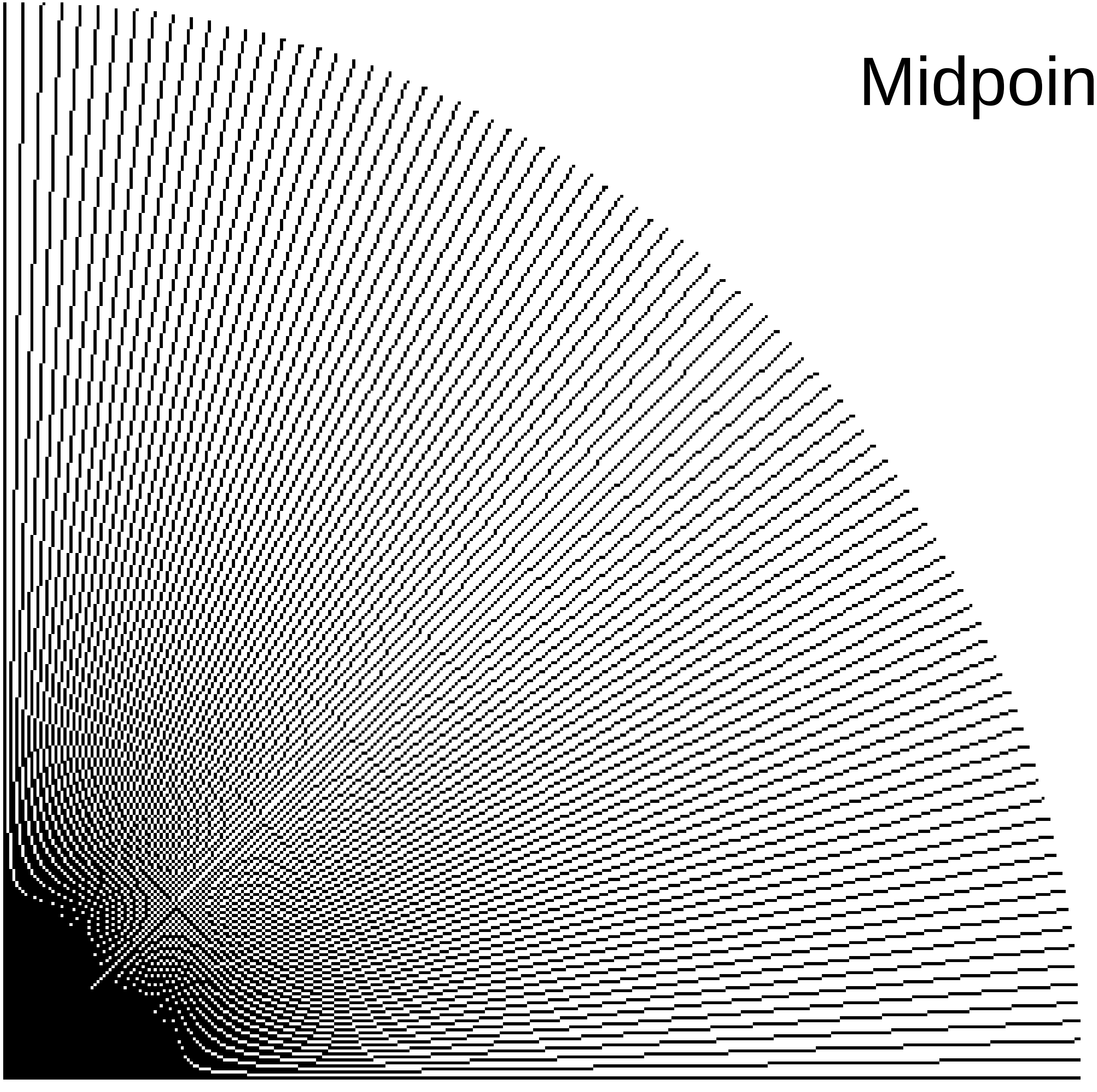
Midpoint algorithm in action



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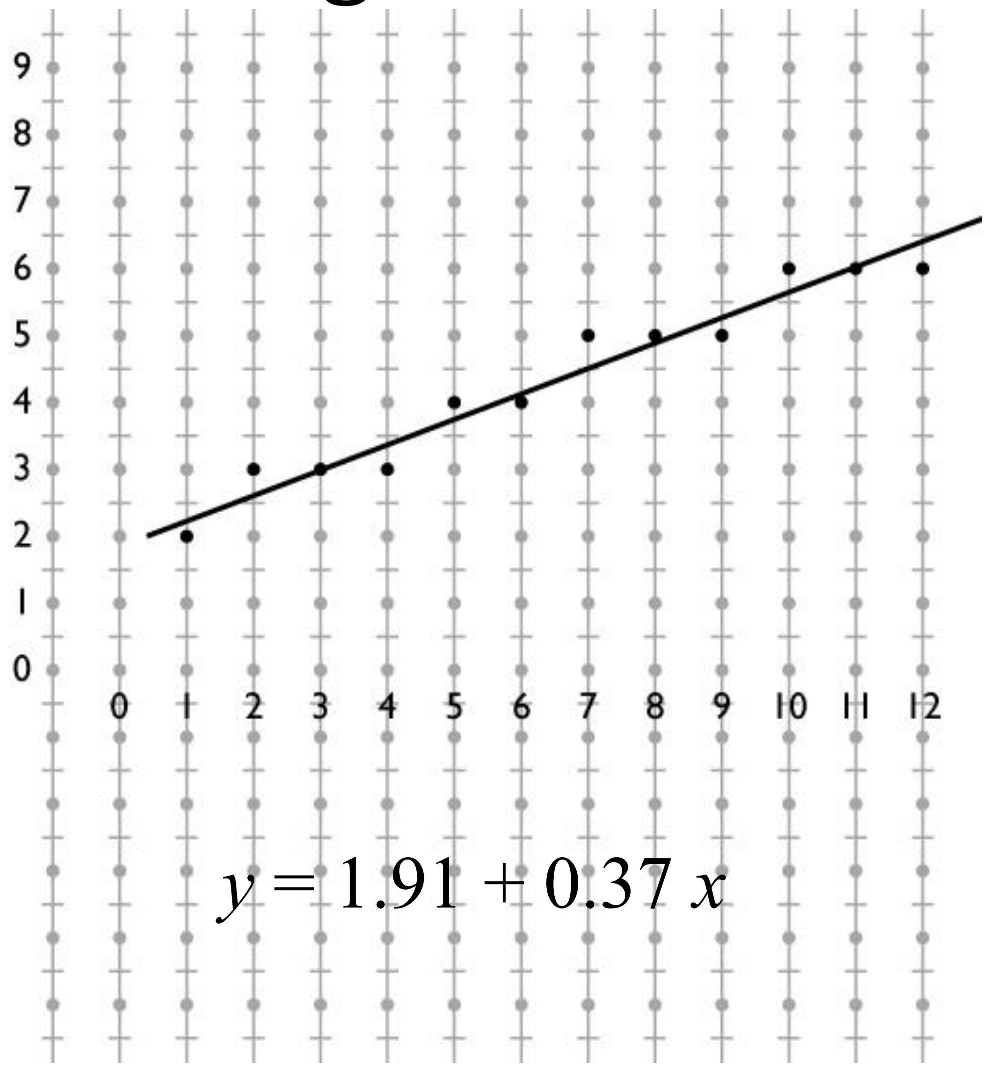
Algorithms for drawing lines

- line equation:
  $y = b + m\,x$
- **Simple algorithm:** evaluate line equation per column
- Without loss of generality, assume,
  $x_0 < x_1; \quad 0 \le m \le 1$

```
for x = ceil(x0) to floor(x1)
     y = b + m*x
     output(x, round(y))
```



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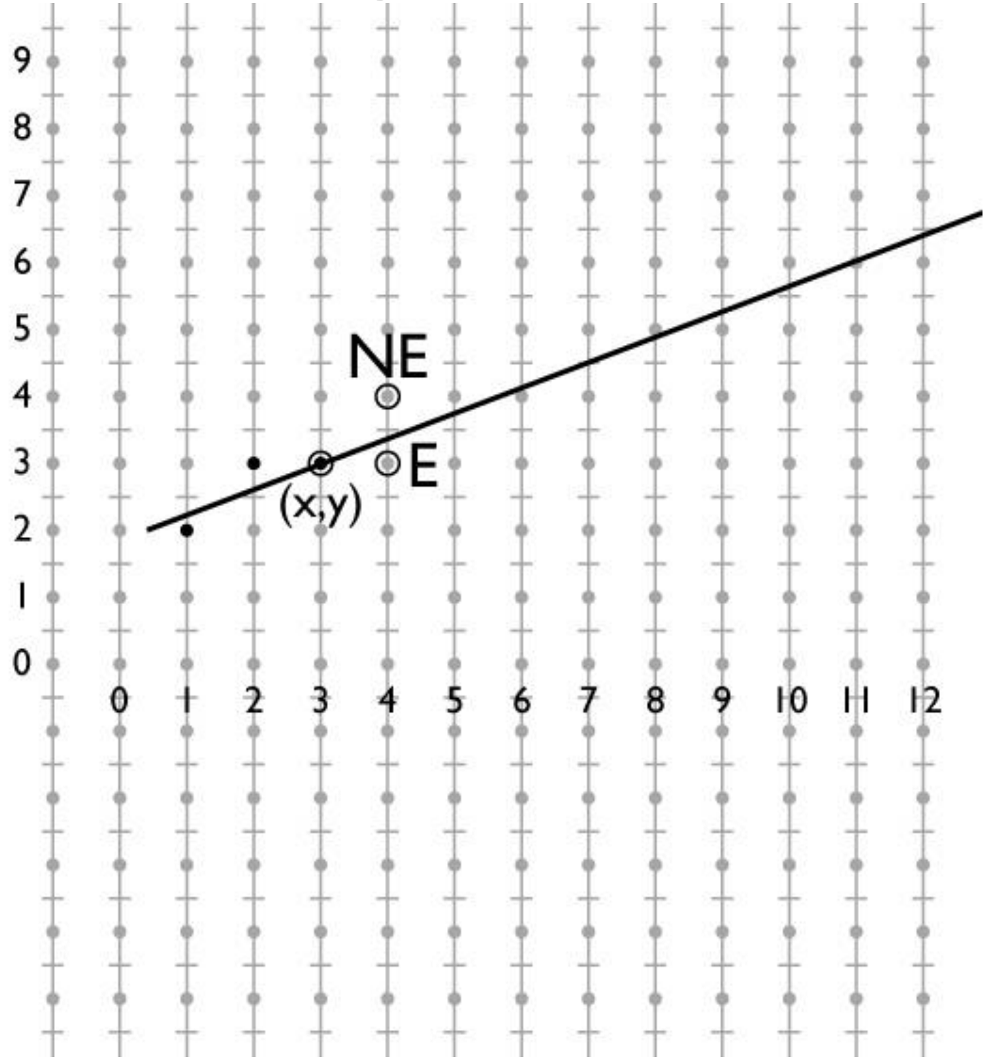
Optimizing line drawing

- Multiplying and rounding is **slow**
- At each pixel the only options are E and NE
- $d = m(x + 1) + b - y$
- $d > 0.5$ **decides** between E and NE



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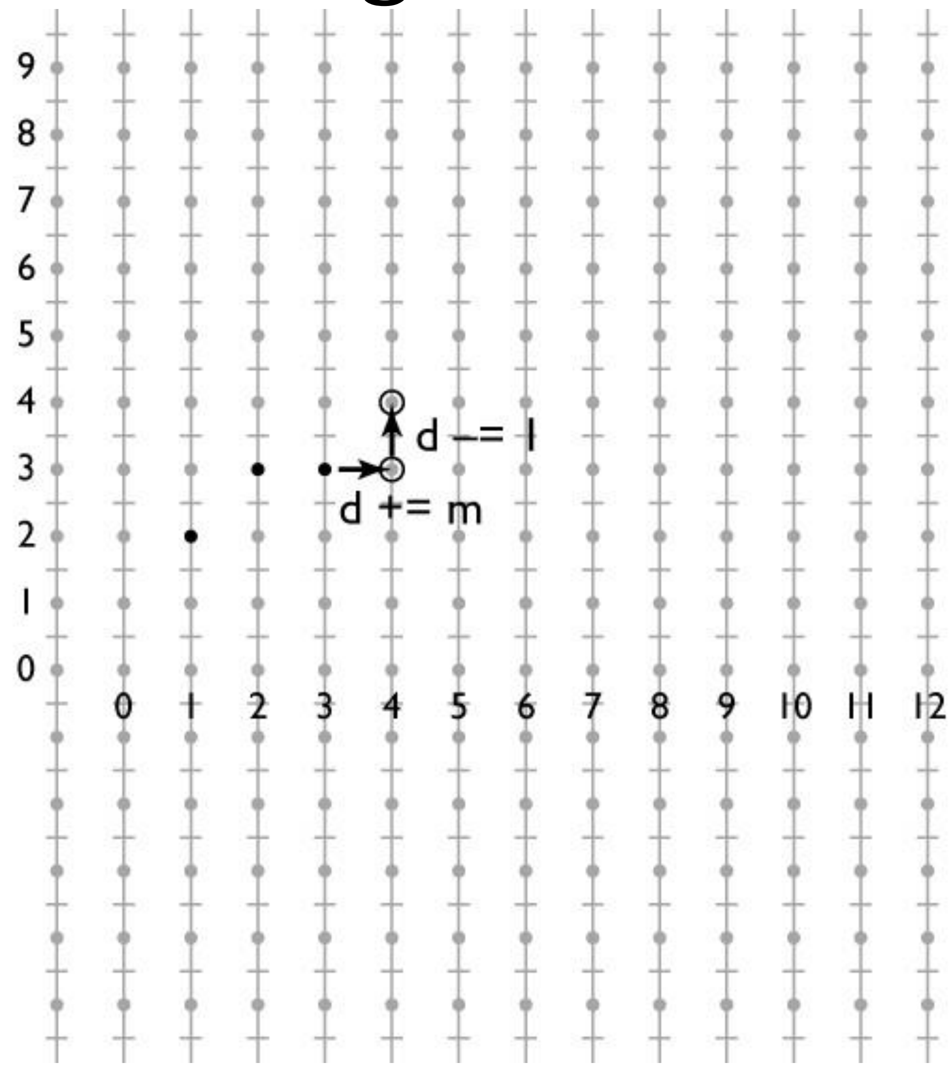
Optimizing line drawing

- $d = m(x+1) + b - y$
- Only need to update d for integer steps in x and y
- Do that with addition
- Known as “DDA” (digital differential analyzer)



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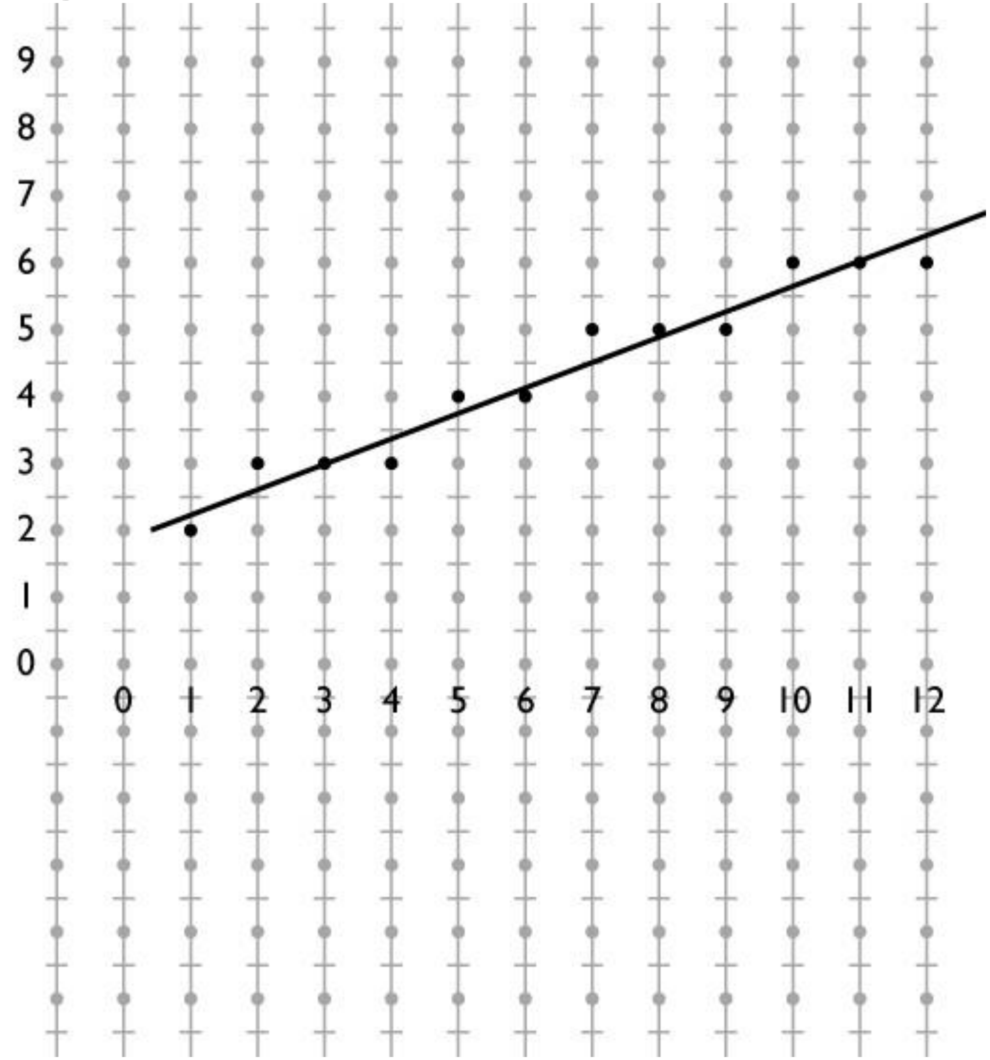
Midpoint line algorithm

```
x = ceil(x0)
y = round(m*x + b)
d = m*(x + 1) + b – y
while x < floor(x1)
     if d > 0.5
          y += 1
          d –= 1
     x += 1
     d += m
     output(x, y)
```



Bresenham's algorithm for drawing lines does this using only integer operations in the inner loop.

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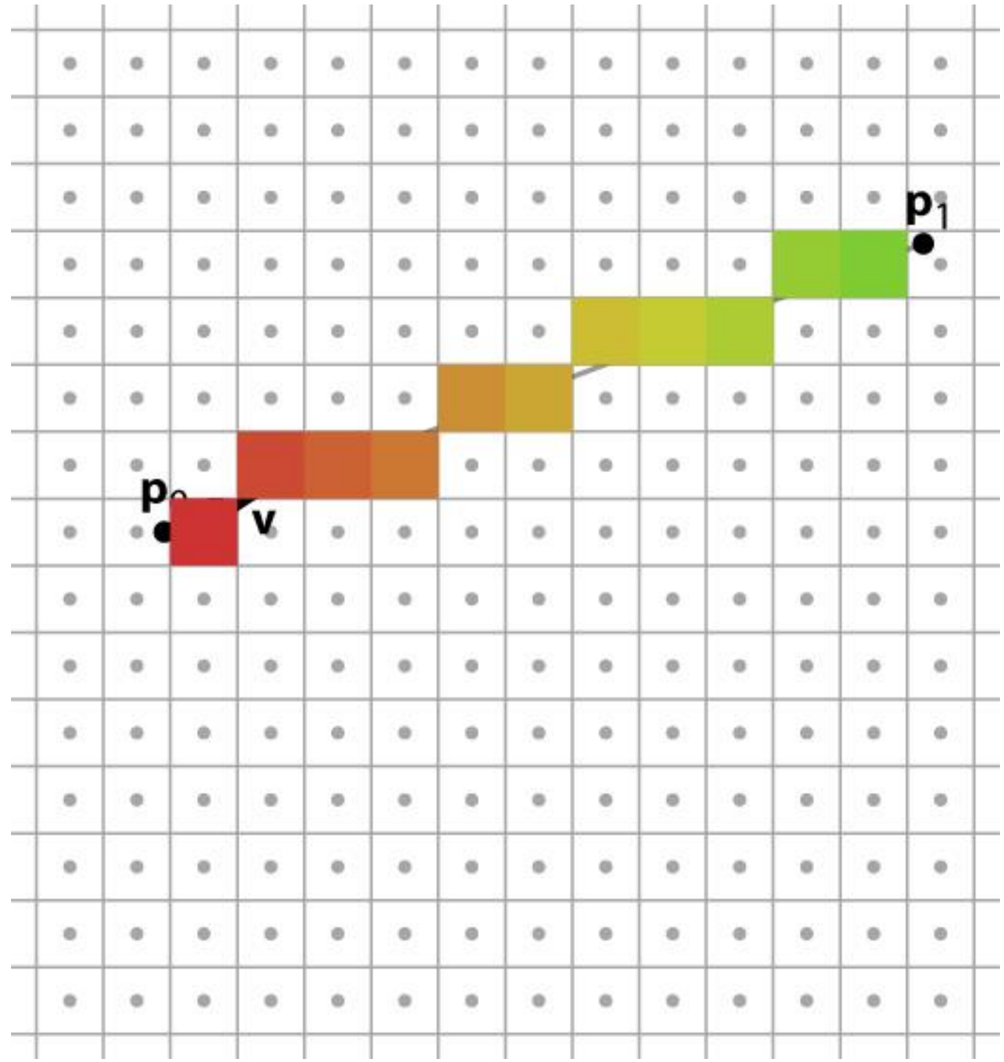
Linear interpolation

- We often attach attributes to vertices
  - e.g., computed diffuse color of a hair being drawn using lines
  - want color to vary smoothly along a chain of line segments
- Recall basic definition
  - 1D: $f(x) = (1 - \alpha)\, y_0 + \alpha\, y_1$
    where $\alpha = (x - x_0) / (x_1 - x_0)$
- In the 2D case of a line segment, alpha is just the fraction of the distance from (x_0, y_0) to (x_1, y_1)

Linear interpolation

- Pixels are not exactly on the line
- Define 2D function by projection on line
    - this is linear in 2D
    - therefore can use DDA to interpolate



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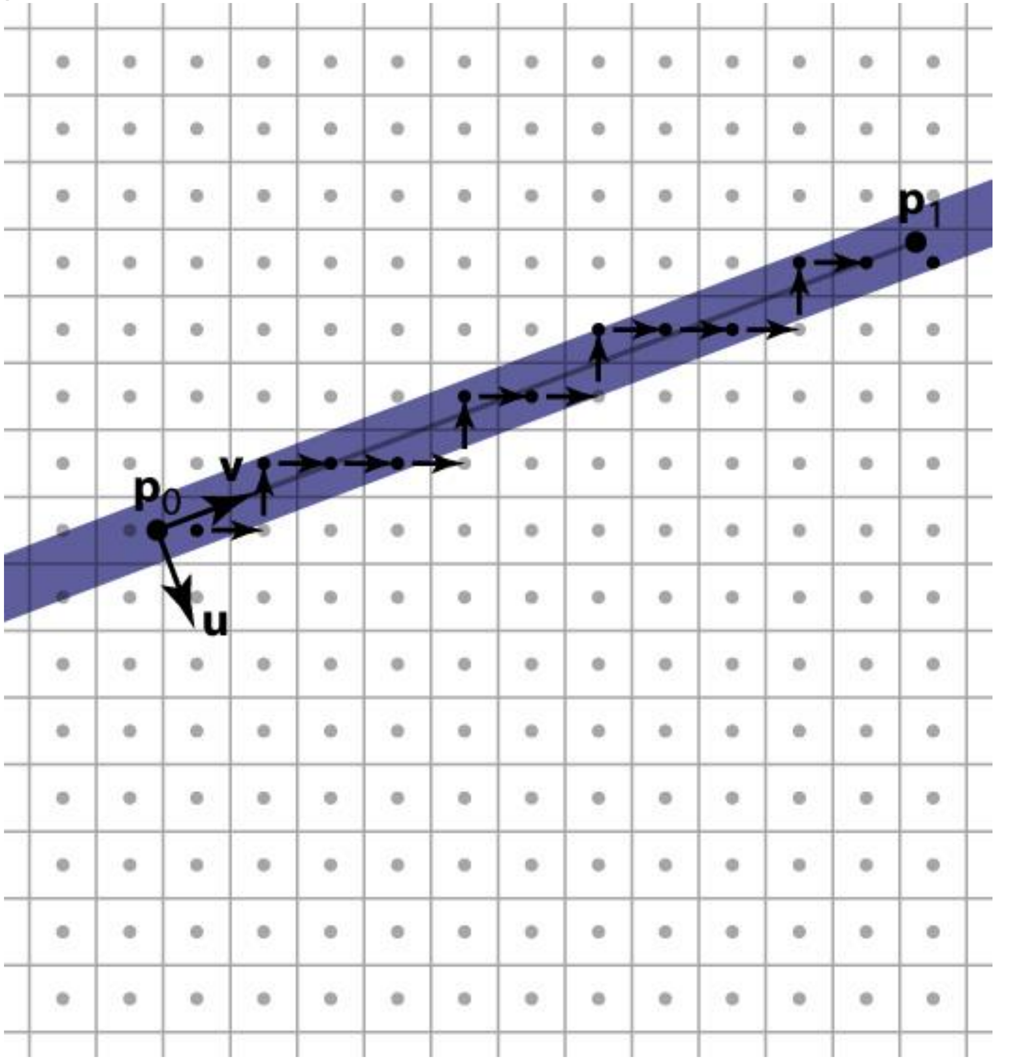
Alternate interpretation

- We are updating d and α as we step from pixel to pixel
  - d tells us how far from the line we are
    α tells us how far along the line we are
- So d and α are coordinates in a coordinate system oriented to the line

Alternate interpretation

- View loop as visiting all pixels the line passes through
  - Interpolate d and α for each pixel
  - Only output fragment if the pixel is in band
- This makes linear interpolation the primary operation



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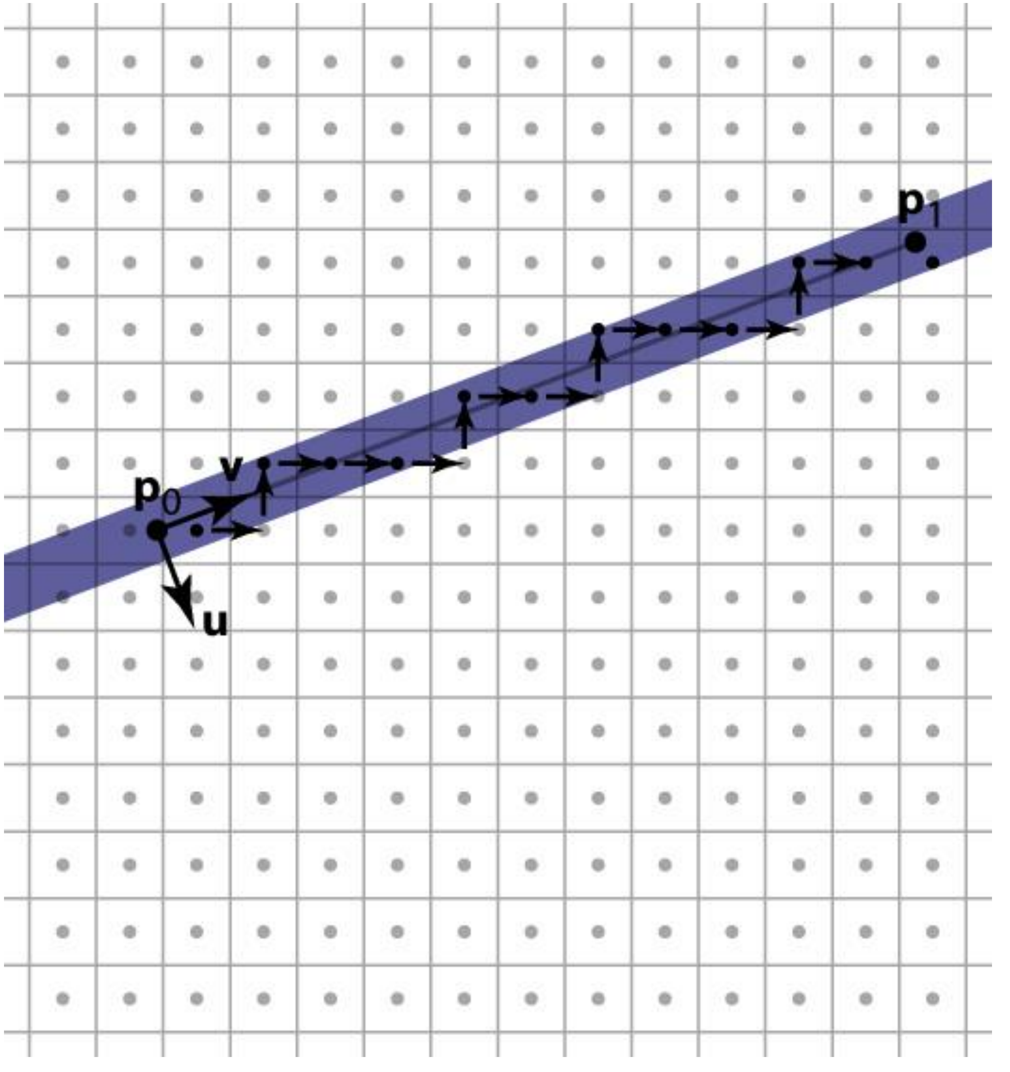
Pixel-walk line rasterization

```
x = ceil(x0)
y = round(m*x + b)
d = m*x + b – y
while x < floor(x1)
  if d > 0.5
    y += 1; d –= 1;
  else
    x += 1; d += m;
  if –0.5 < d ≤ 0.5
    output(x, y)
```



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Rasterizing triangles

- The most common case in most applications
  - with good antialiasing can be the only case
  - some systems render a line as two skinny triangles
- Triangle represented by three vertices
- Simple way to think of algorithm follows the pixel-walk interpretation of line rasterization
  - walk from pixel to pixel over (at least) the polygon's area
  - evaluate linear functions as you go
  - use those functions to decide which pixels are inside

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 $q_0, \ldots, q_n$

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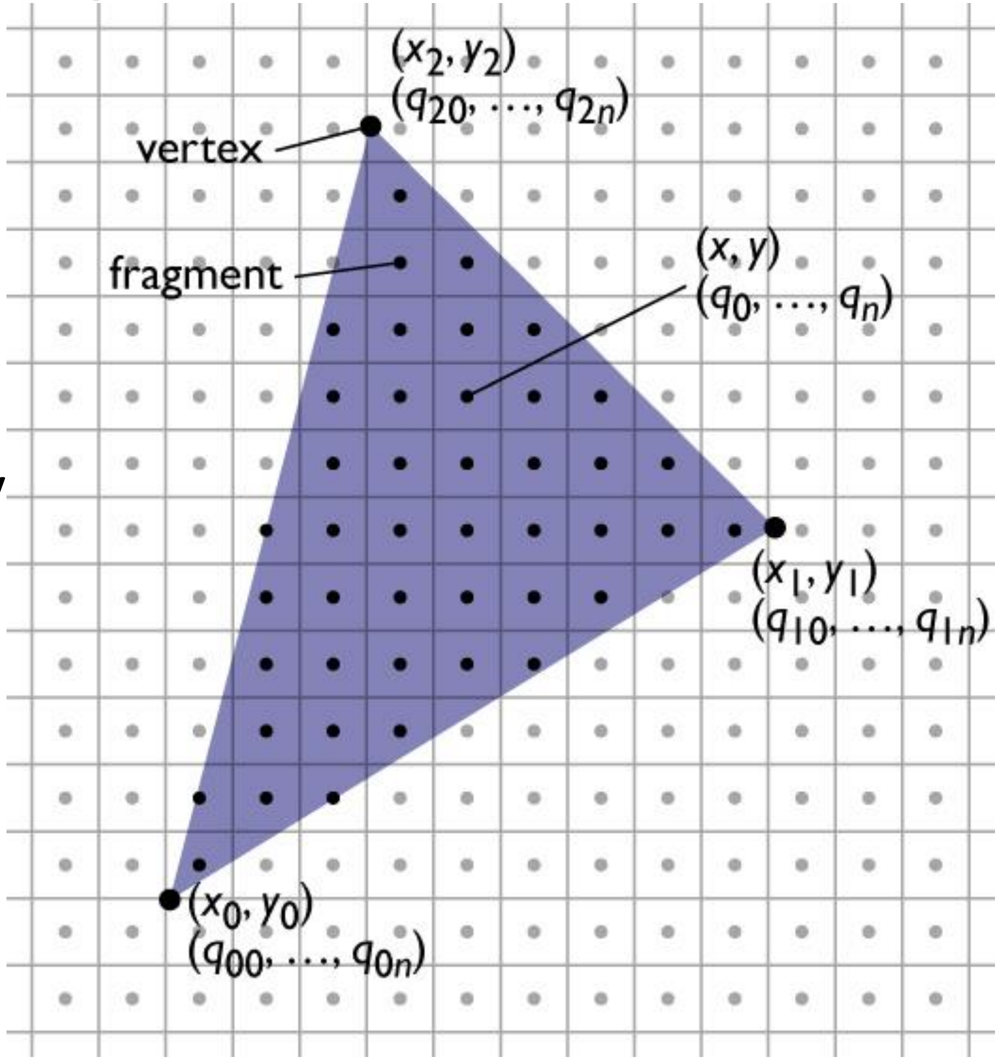
Rasterizing triangles

- 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



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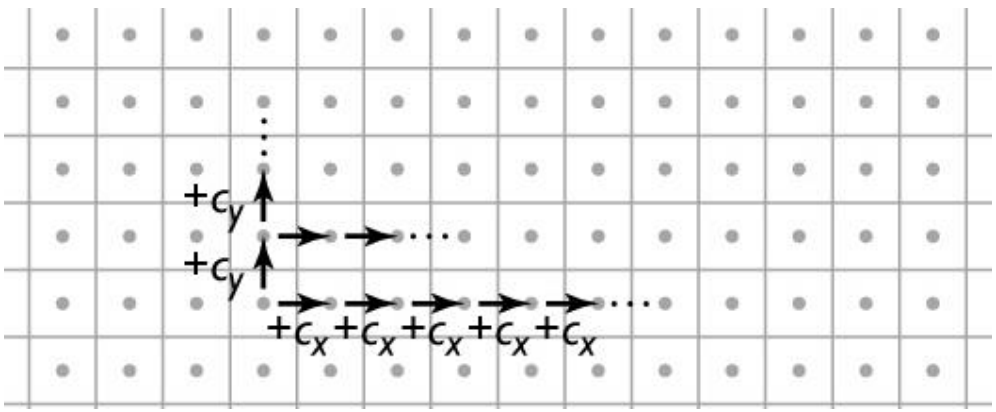
Consider…
Incremental linear evaluation

- 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:

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



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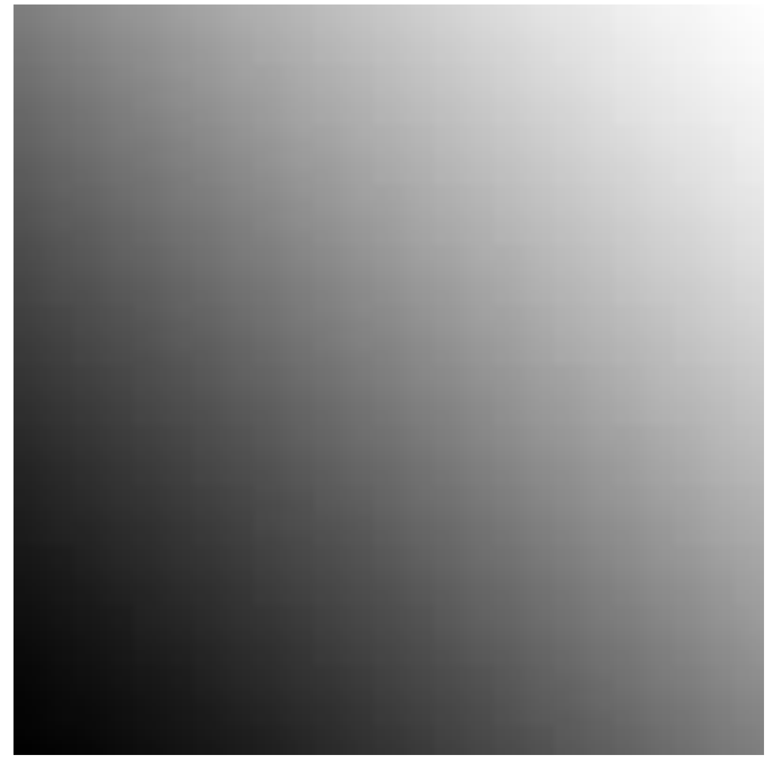
Incremental linear evaluation

```
linEval(xl, xh, yl, yh, cx, cy, ck) {

    // setup
    qRow = cx*xl + cy*yl + ck;

    // traversal
    for y = yl to yh {
        qPix = qRow;
        for x = xl to xh {
            output(x, y, qPix);
            qPix += cx;
        }
        qRow += cy;
    }
}
```



$c_x = .005;\ c_y = .005;\ c_k = 0$
(image size 100x100)

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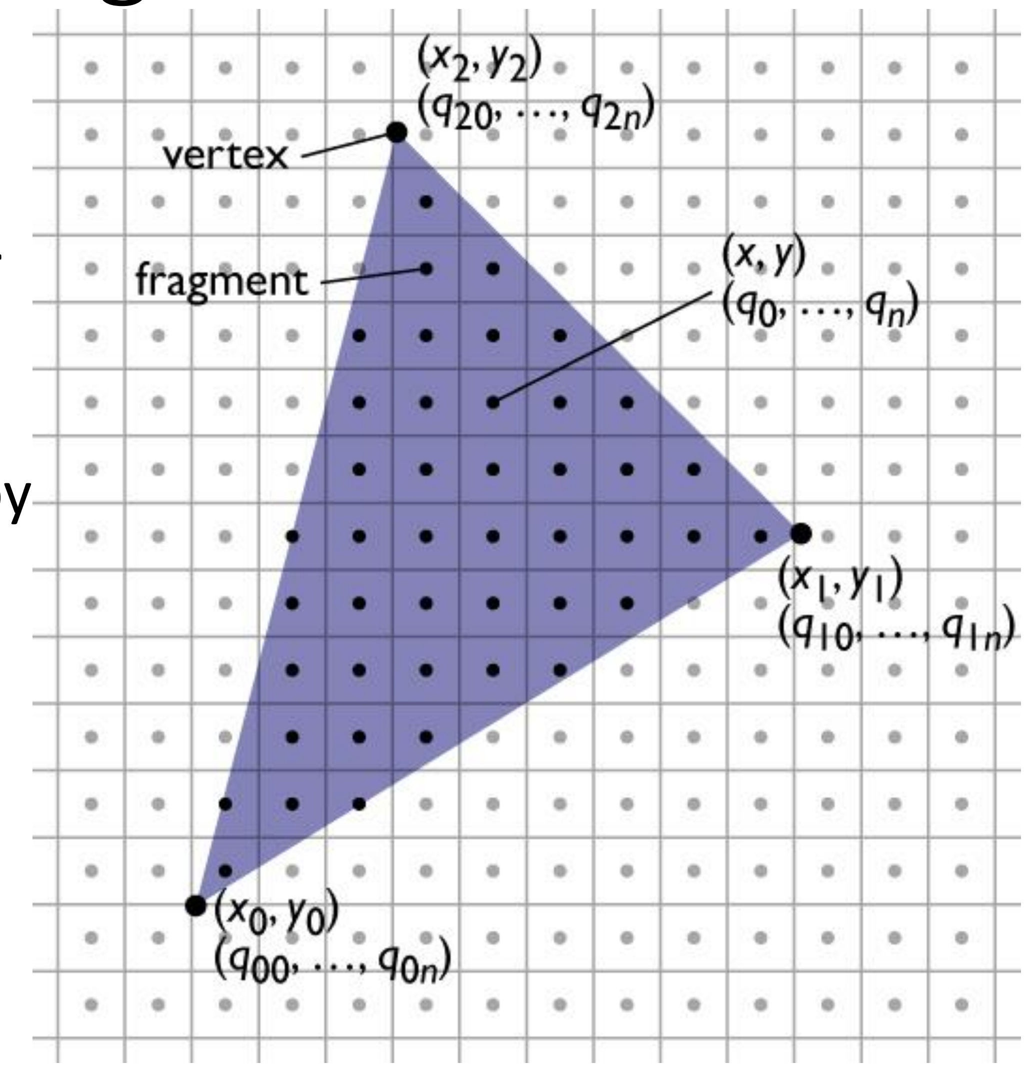
Rasterizing triangles

- 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 Shirley):

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

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

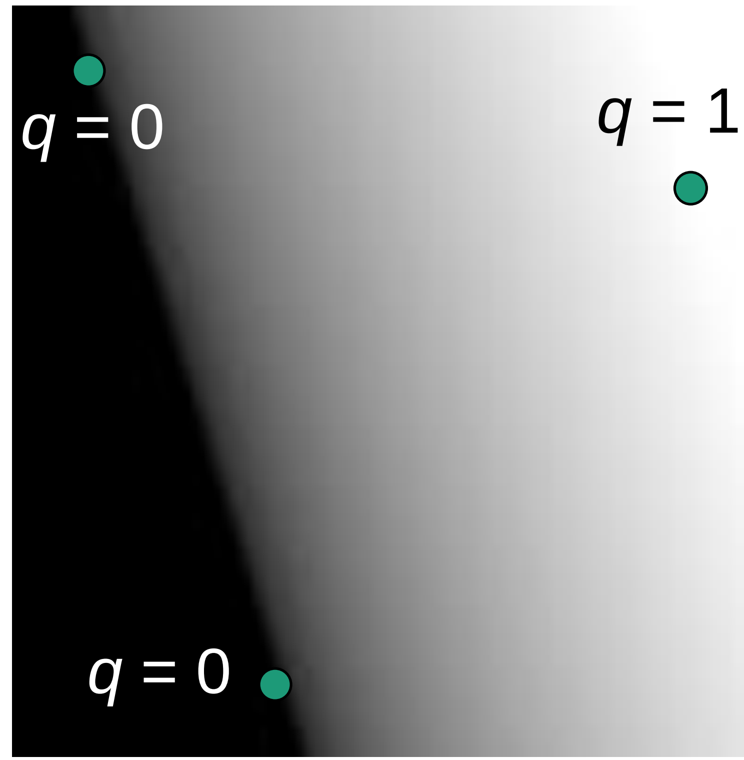
Last Class?

```
linInterp(xl, xh, yl, yh, 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*(xl-x0) + cy*(yl-y0) + q0;

  // traversal (same as before)
  for y = yl to yh {
    qPix = qRow;
    for x = xl to xh {
      output(x, y, qPix);
      qPix += cx;
    }
    qRow += cy;
  }
}
```

Defining parameter functions

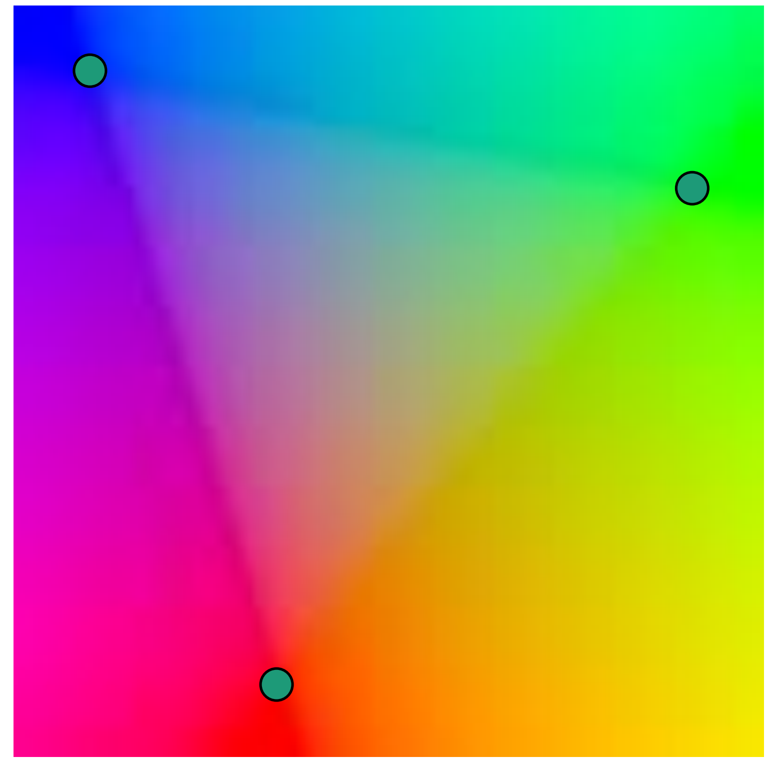


Interpolating several parameters

```
linInterp(xl, xh, yl, yh, n, x0, y0, q0[], x1, y1, q1[], x2, y2, q2[]) {

  // setup
  for k = 0 to n-1
    // compute cx[k], cy[k], qRow[k]
    // from q0[k], q1[k], q2[k]

  // traversal
  for y = yl to yh {
    for k = 1 to n, qPix[k] = qRow[k];
    for x = xl to xh {
      output(x, y, qPix);
      for k = 1 to n, qPix[k] += cx[k];
    }
    for k = 1 to n, qRow[k] += cy[k];
  }
}
```



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Rasterizing triangles

- Summary
  1. evaluation of linear functions on pixel grid
  2. functions defined by parameter values at vertices
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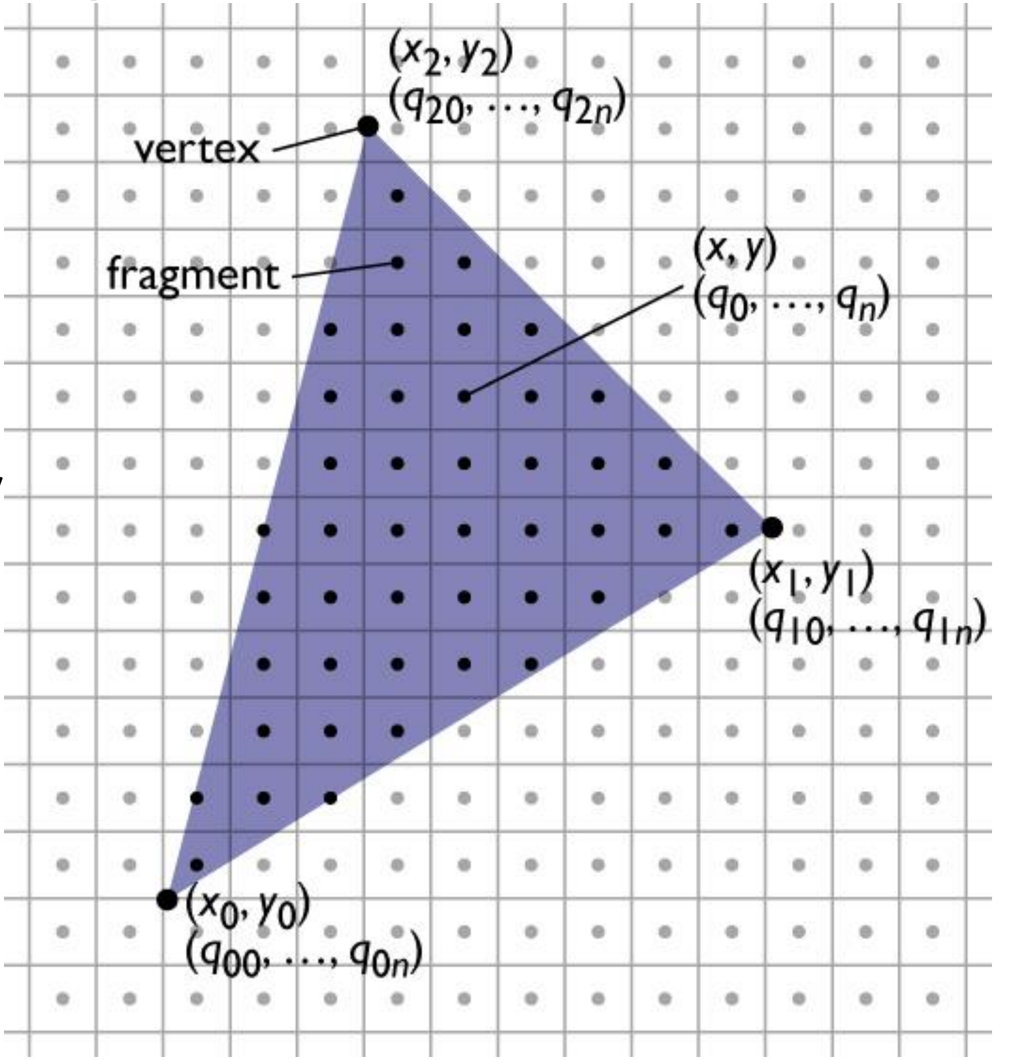

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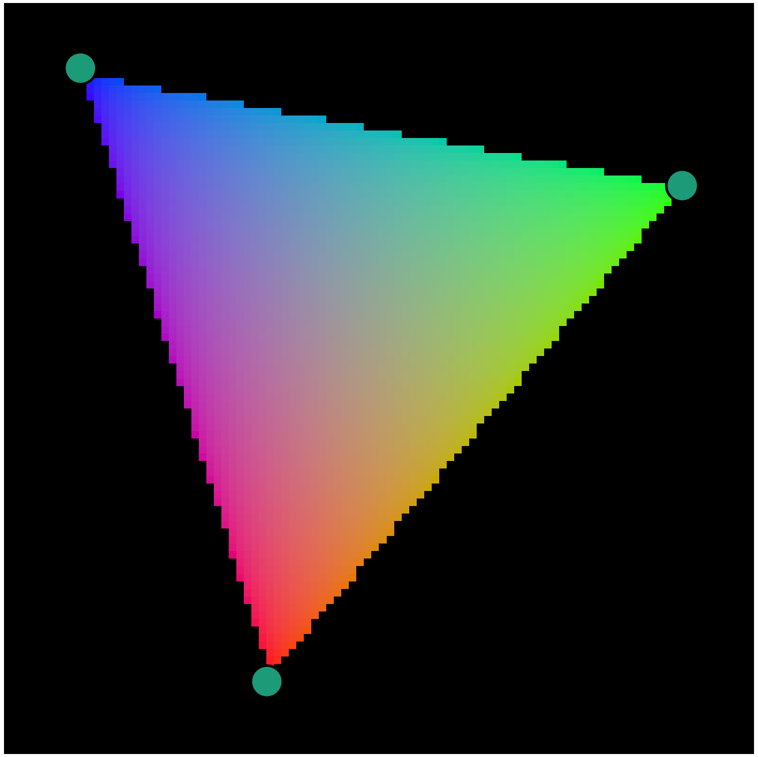
Clipping to the triangle

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



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Barycentric coordinates

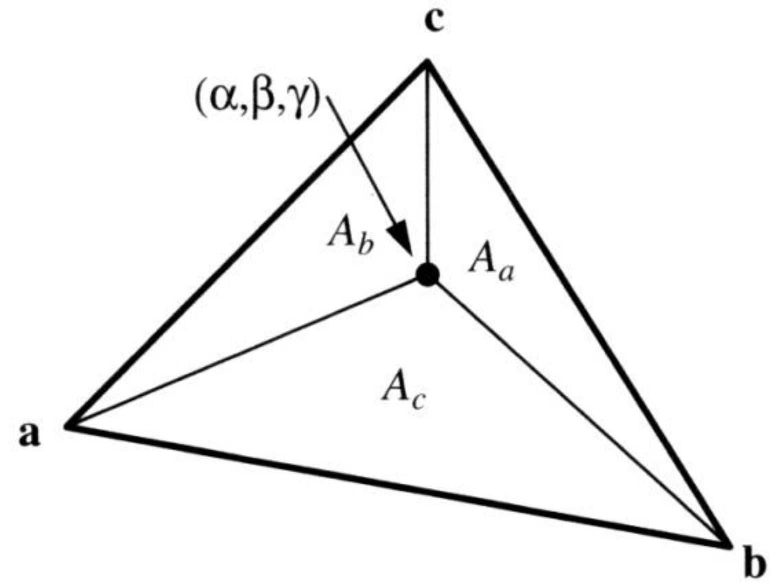
- A coordinate system for triangles
  - algebraic viewpoint:

$$\mathbf{p} = \alpha\mathbf{a} + \beta\mathbf{b} + \gamma\mathbf{c}$$

$$\alpha + \beta + \gamma = 1$$

  - geometric viewpoint (areas)
- Triangle interior test:

$$\alpha > 0; \quad \beta > 0; \quad \gamma > 0$$



[Shirley 2000]

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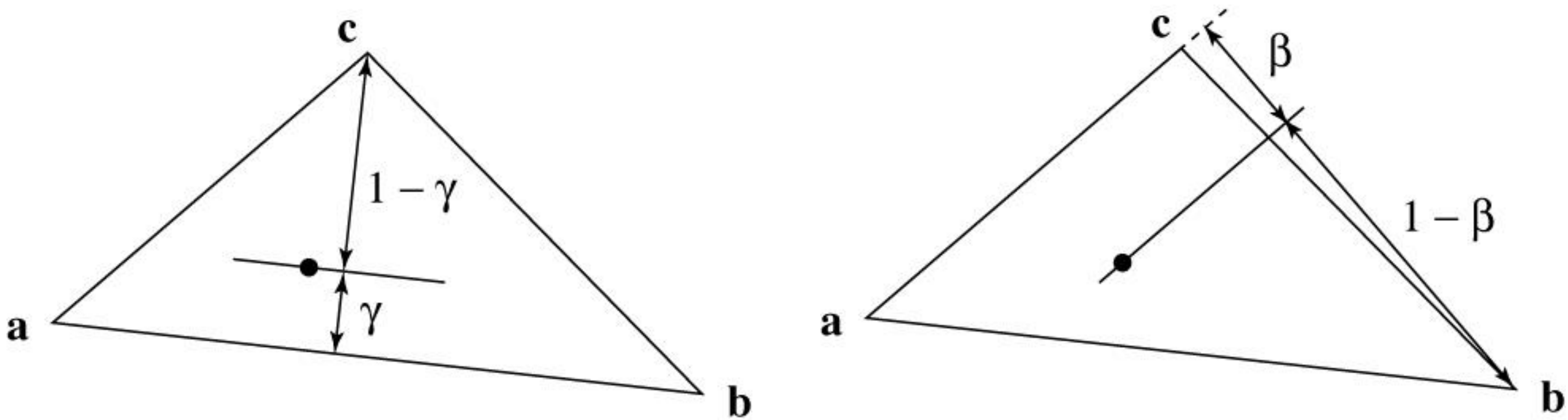
Barycentric coordinates

- A coordinate system for triangles
  - geometric viewpoint: distances (also area ratios, blackboard)



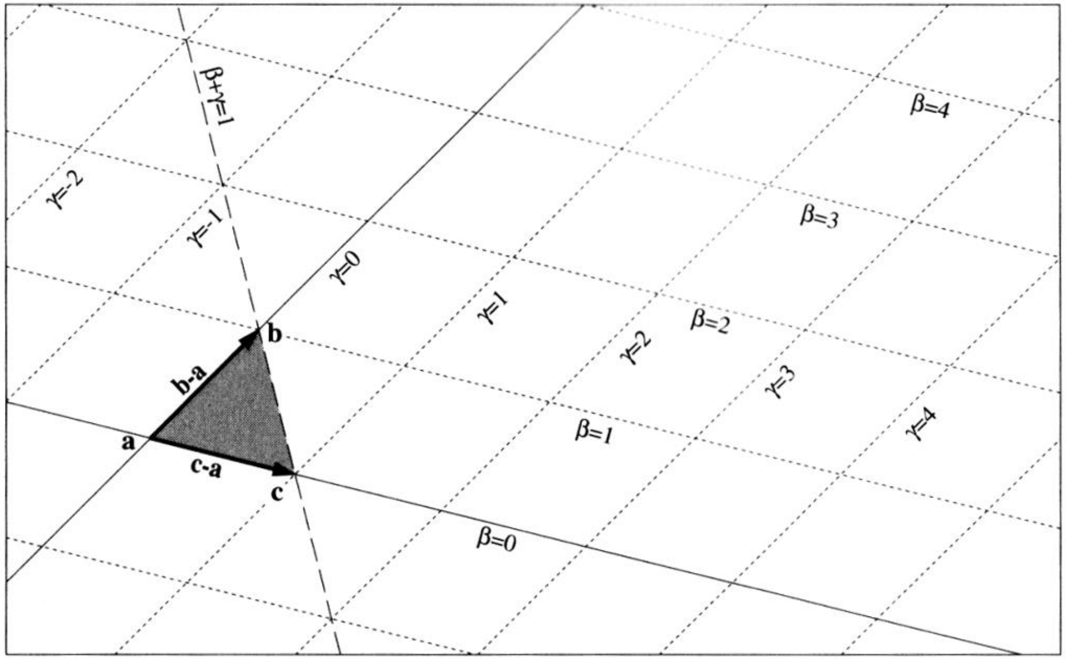
  - linear viewpoint: basis of edges

$$\alpha = 1 - \beta - \gamma$$

$$\mathbf{p} = \mathbf{a} + \beta(\mathbf{b} - \mathbf{a}) + \gamma(\mathbf{c} - \mathbf{a})$$

Barycentric coordinates

- Linear viewpoint: basis for the plane



[Shirley 2000]

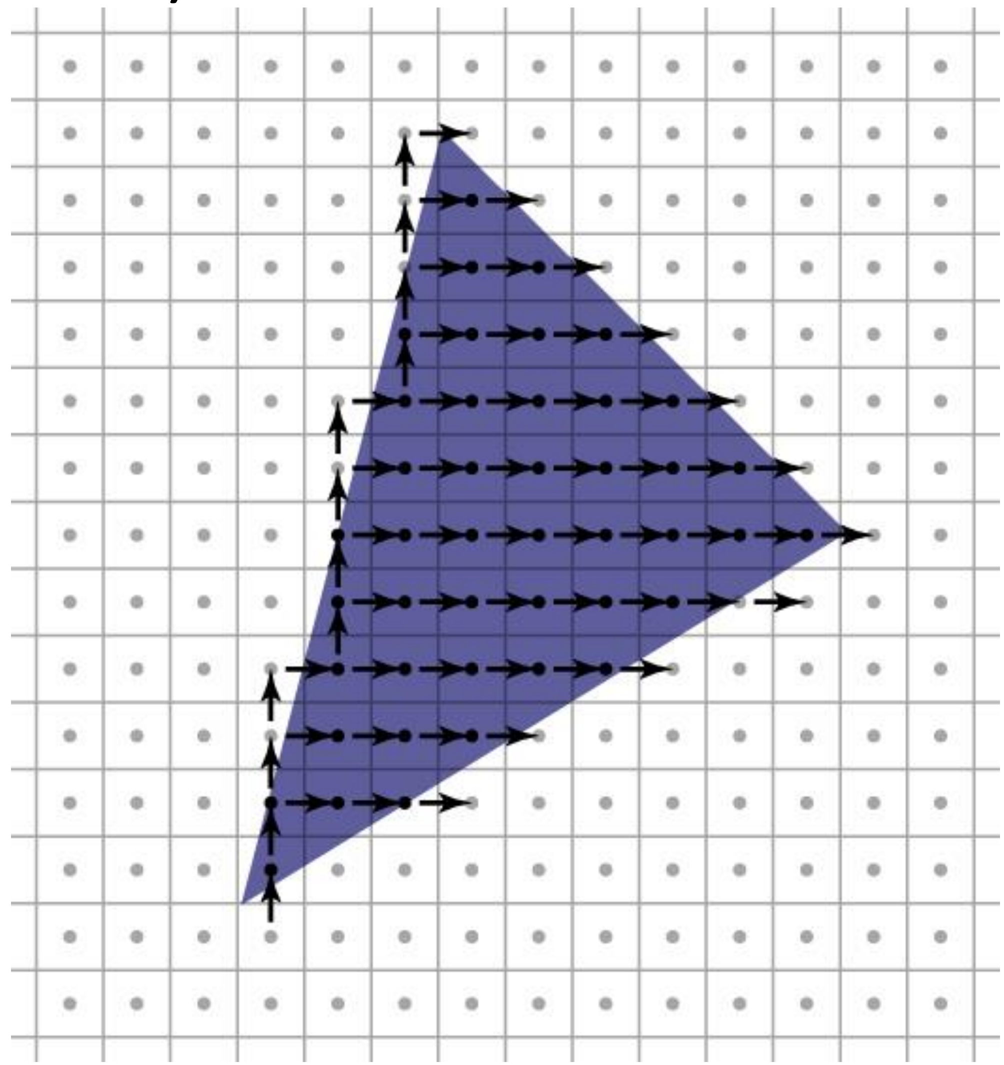
  - in this view, the triangle interior test is just
    $\beta > 0; \quad \gamma > 0; \quad \beta + \gamma < 1$

Walking edge equations

- We need to update values of the three edge equations with single-pixel steps in x and y
- Edge equation already in form of dot product
- components of vector are the increments

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



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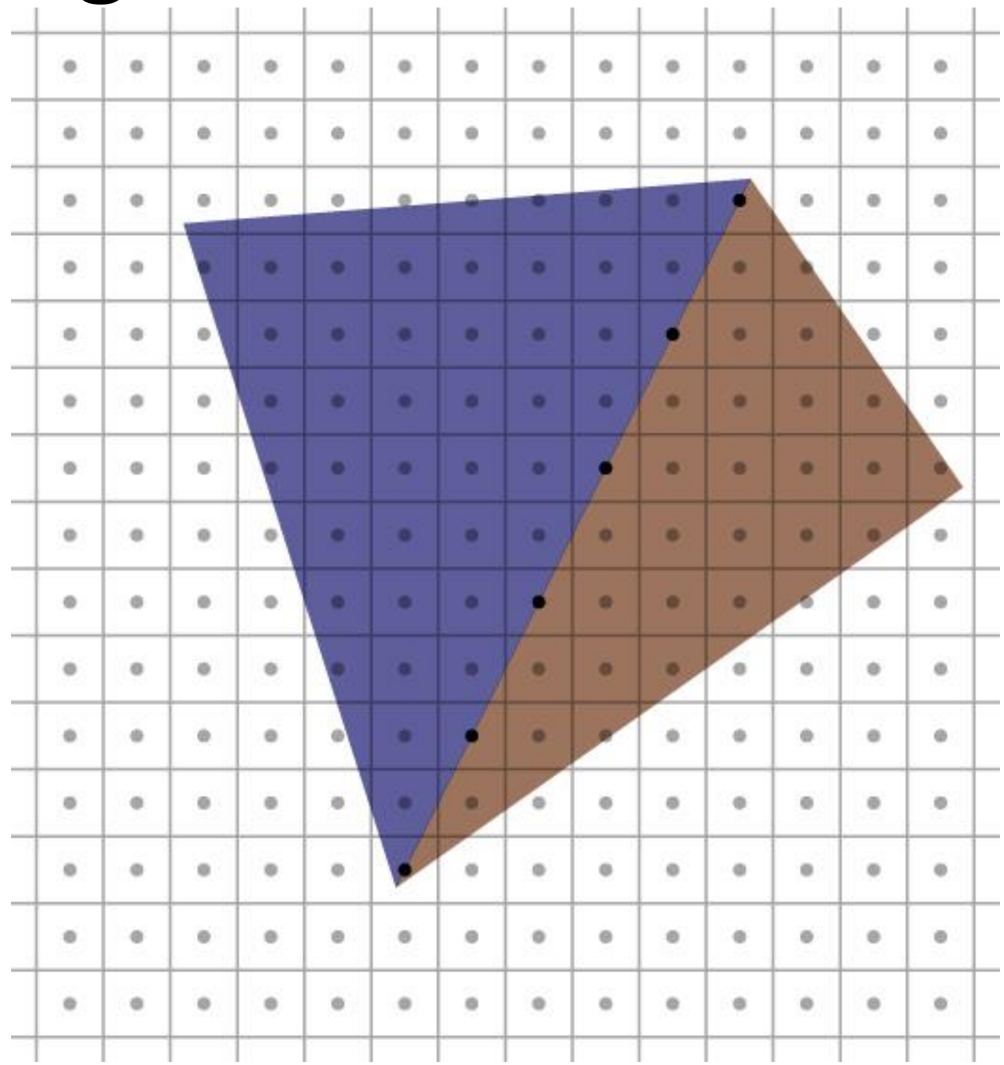
Rasterizing triangles

- Exercise caution with rounding and arbitrary decisions
  - need to visit these pixels once
  - but it's important not to visit them twice! (for instance, when drawing partially transparent surfaces)



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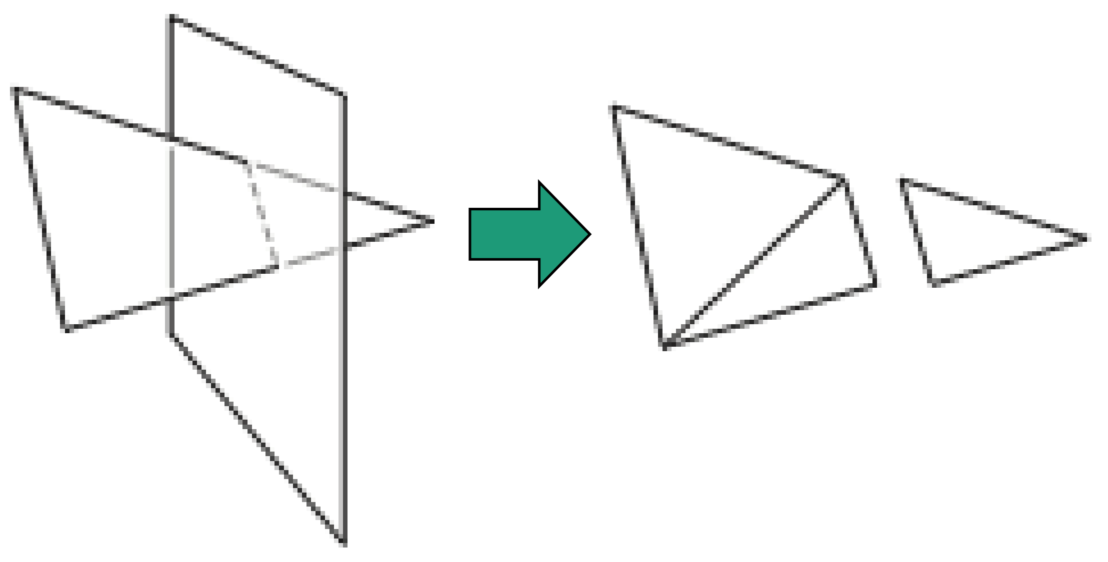
Clipping

- 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 $x, y, z = 1, -1$ (6 planes)
  - primitive operation: clip triangle against axis-aligned plane
  - *Homogeneous clip coordinates*

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)



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Tessellation

polygons into triangles…

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Review and more information

- Chapter 8 the graphics pipeline
  - 8.1 Rasterization
  - 8.1.3 and 8.1.4 contain more details on clipping, but we haven’t discussed this in any depth
- See also Chapter 2, miscellaneous math
  - 2.7 Triangles and Barycentric coordinates

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