graphics pipeline

graphics pipeline

- sequence of operations to generate an image using object-order processing
  - primitives processed one-at-a-time
  - software pipeline: e.g. Renderman
    - high-quality and efficiency for large scenes
  - hardware pipeline: e.g. graphics accelerators
    - lower-quality solution for interactive applications
- will cover algorithms of modern hardware pipeline
  - but evolve drastically every few years
  - we will only look at triangles

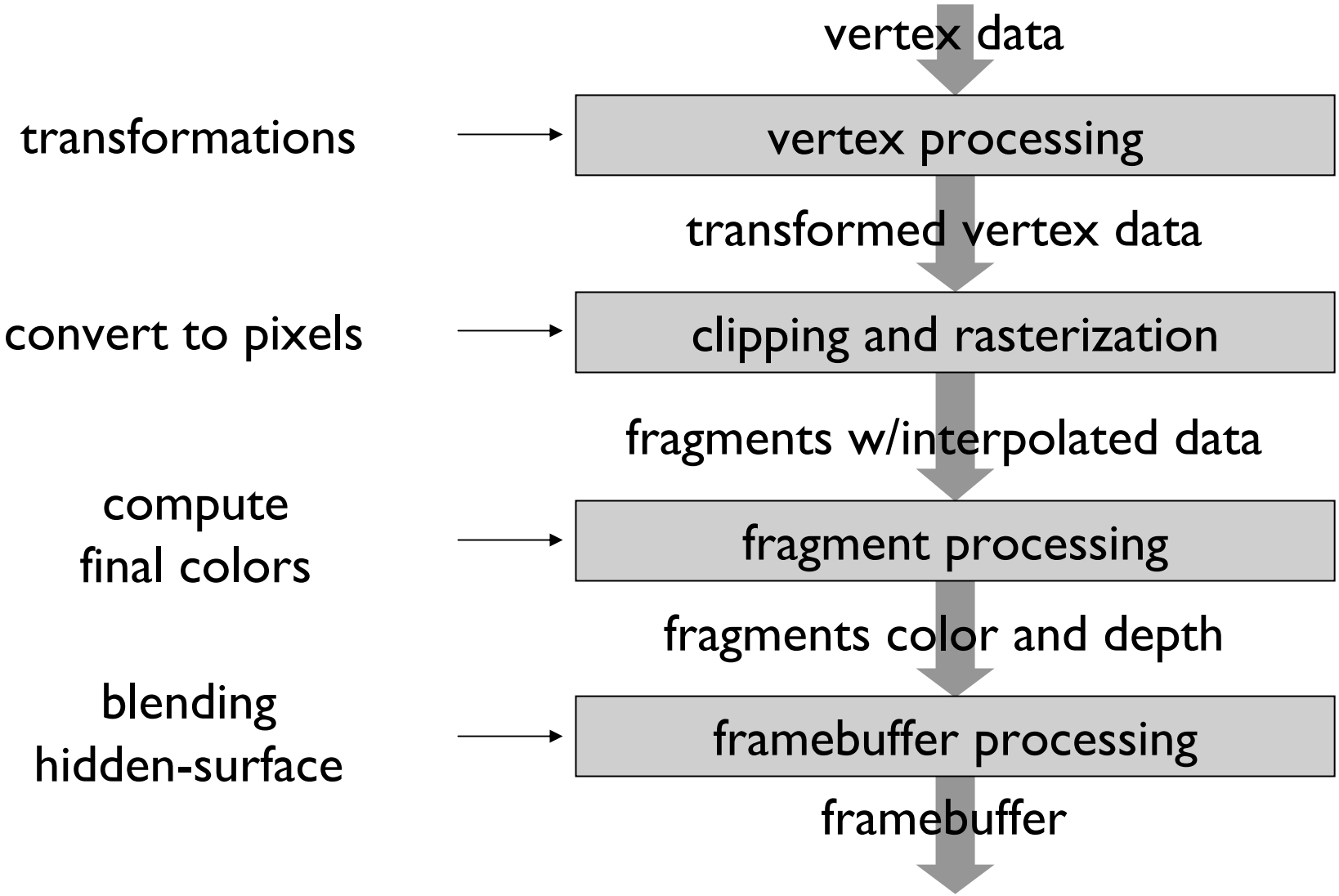
graphics pipeline

- handles only simple primitives by design
  - points, lines, triangles, quads (as two triangles)
  - efficient algorithm
- complex primitives by tessellation
  - complex curves: tessellate into line strips
  - curves surfaces: tessellate into triangle meshes
- “pipeline” name derives from architecture design
  - sequences of stages with defined input/output
  - easy-to-optimize, modular design

graphics pipeline

- object-local algorithm
  - processes only one-surface-at-a-time
- various effects have to be approximated
  - shadows: shadow volume and shadow maps
  - reflections: environment mapping
  - hard to implement
- advanced effects cannot be implemented
  - soft shadows
  - blurry reflections and diffuse-indirect illumination

graphics pipeline stages



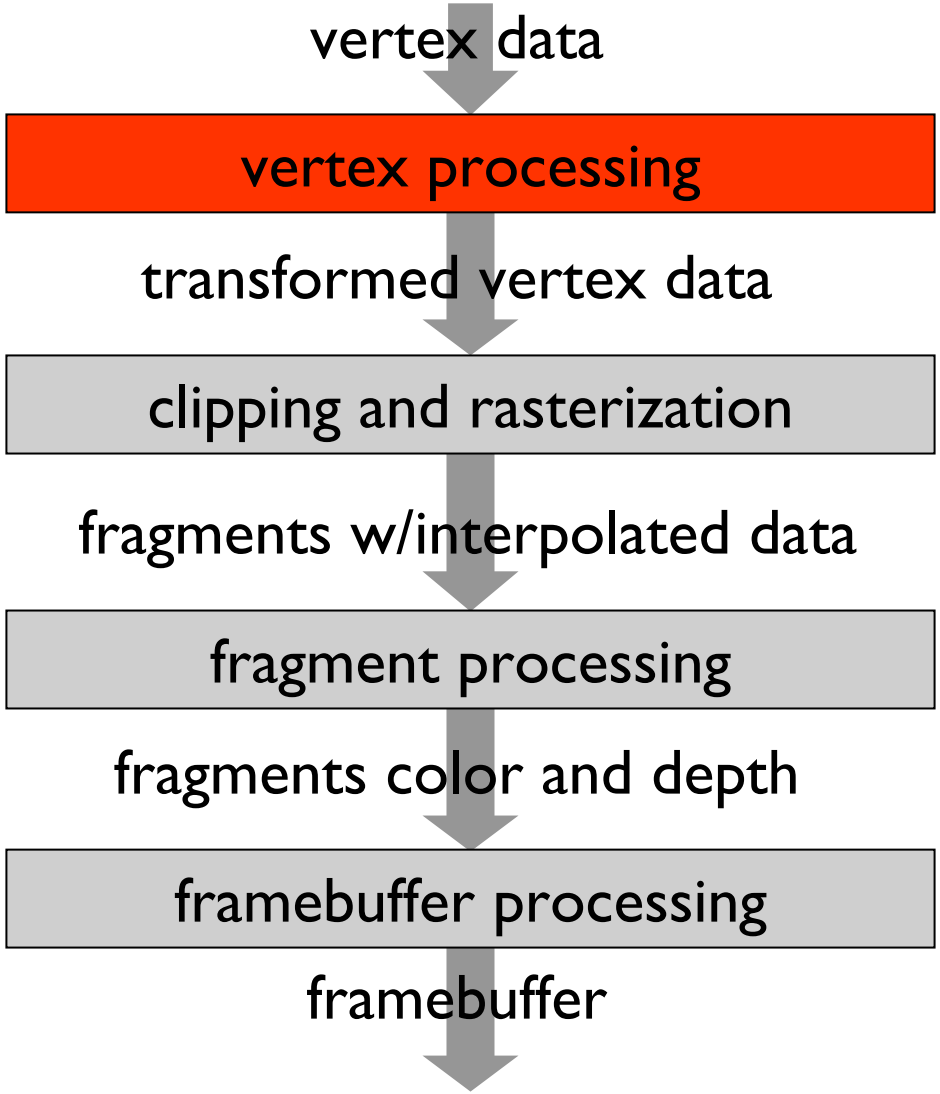
graphics pipeline stages

- vertex processing
  - input: vertex data (position, normal, color, etc.)
  - output: transformed vertices in homogeneous canonical view-volume, colors, etc.
  - applies transformation from object-space to clip-space
  - passes along material and shading data
- clipping and rasterization
  - turns sets of vertices into primitives and fills them in
  - output: set of fragments with interpolated data

graphics pipeline stages

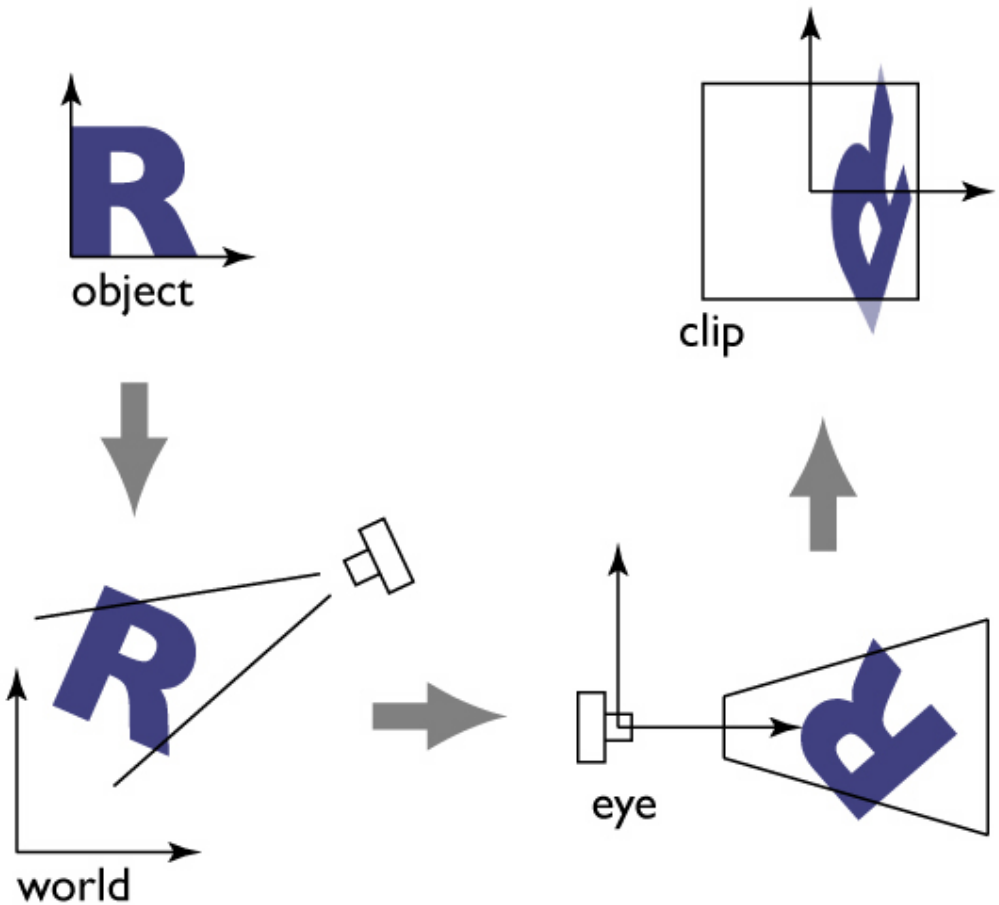
- fragment processing
  - output: final color and depth
  - traditionally mostly for texture lookups
    - lighting was computed for each vertex
  - today, computes lighting per-pixel
- framebuffer processing
  - output: final picture
  - hidden surface elimination
  - compositing via alpha-blending

vertex processing



vertex processing

- transform vertices from model to clip space

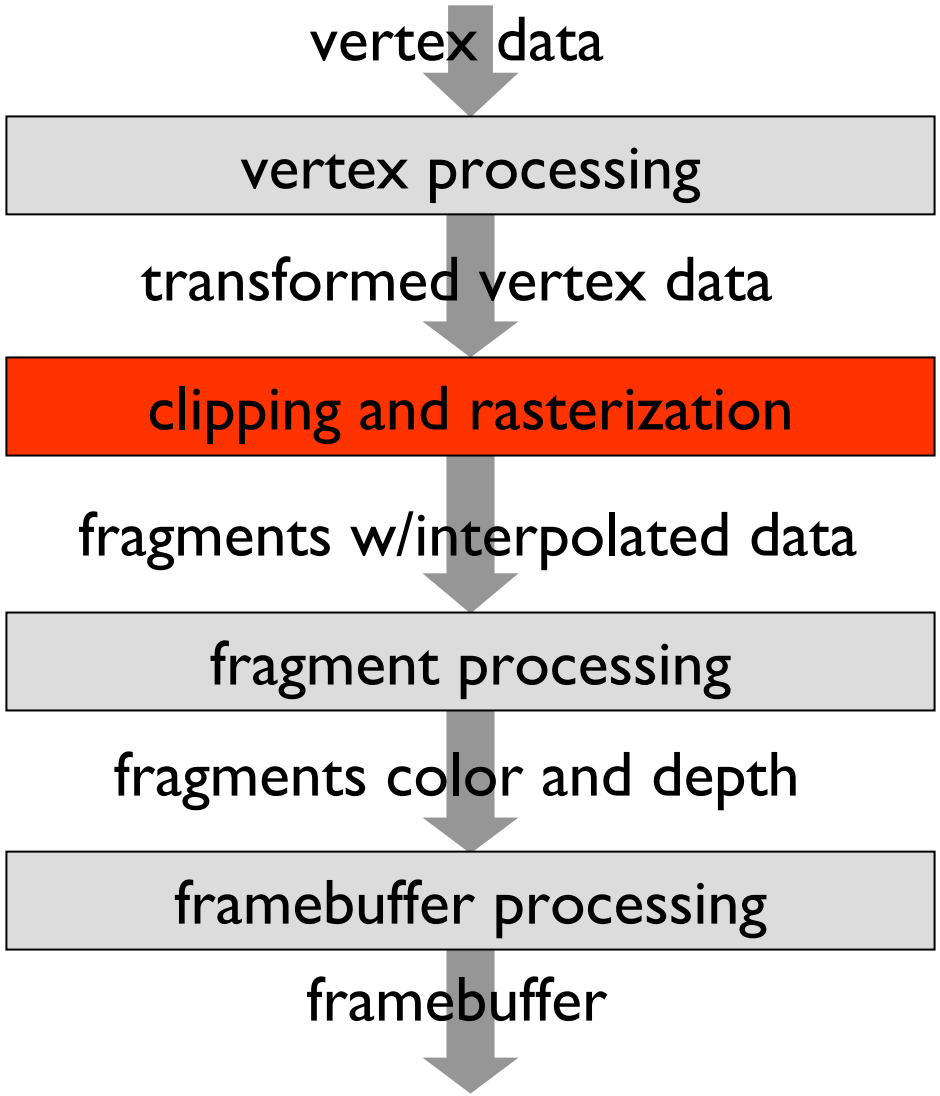


[Marschner 2004]

vertex processing

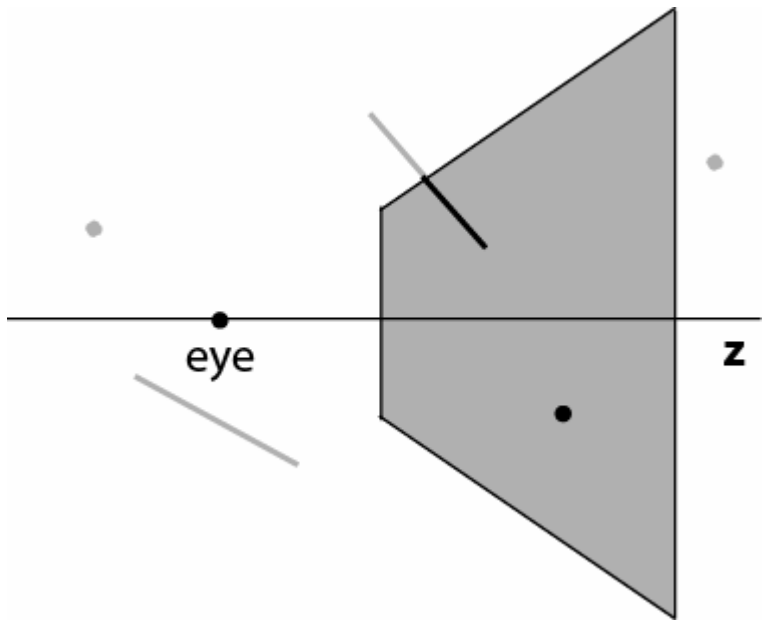
- other geometry tasks
  - deformation: skinning, mesh blending
  - low-quality lighting
  - pass other properties to next stages of pipeline
  - the only place to algorithmically alter shape
- programmable hardware unit
  - algorithm can be changed at run-time by application
  - only recent change

clipping and rasterization



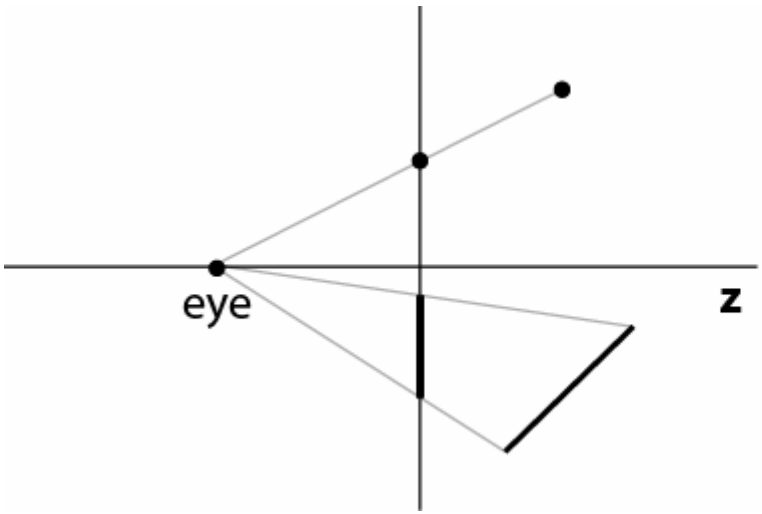
clipping

- remove (partial) objects not in the view frustum
  - efficiency: cull later stages of the pipeline
  - correctness: perspective transform can cause trouble
  - often referred as culling when full objects removed

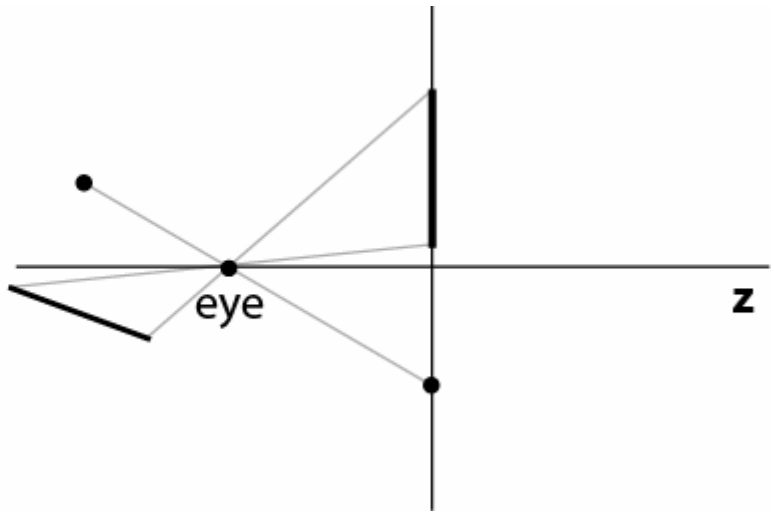


clipping to ensure correctness

in front of eye

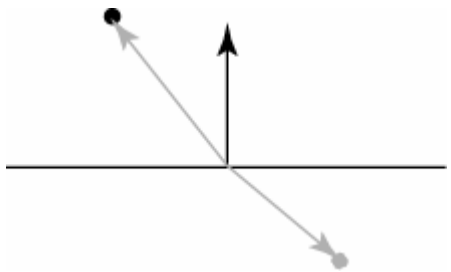


behind eye



point clipping

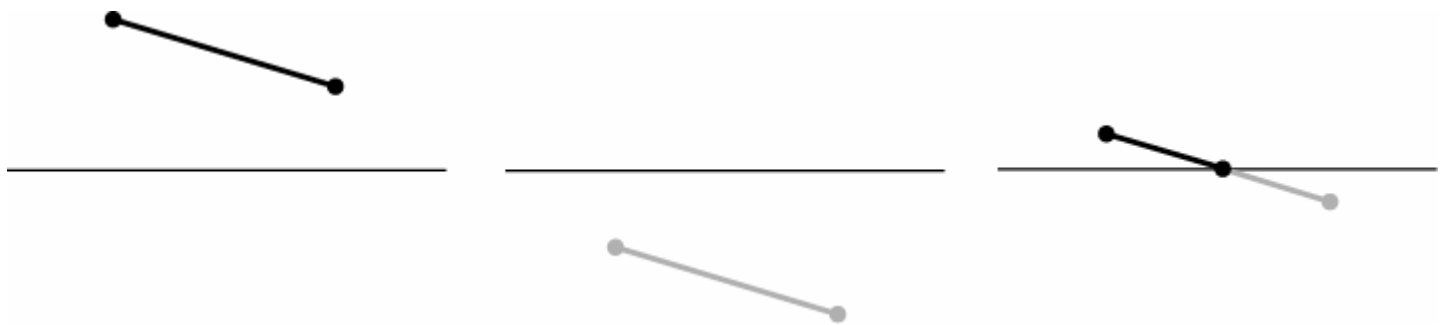
- point-plane clipping
  - test if the point is on the right side of the plane
  - by taking dot-product with the plane normal
  - can be performed in homogeneous coordinates



- point-frustum clipping
  - point-plane clipping for each frustum plane

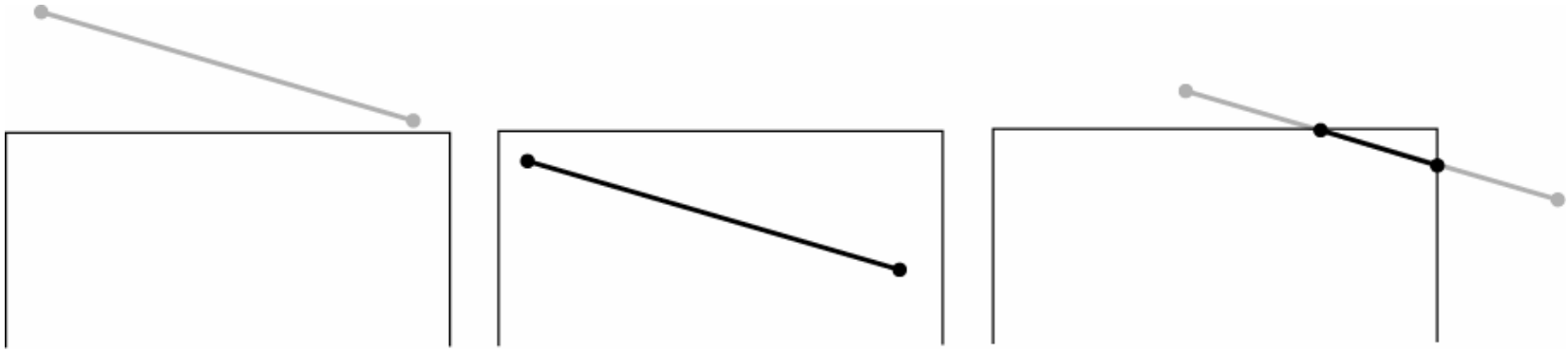
line clipping

- segment-plane clipping
  - test point-plane clipping for endpoints
  - if endpoints are clipped, clip whole segment
  - if endpoints are not clipped, accept whole segment
  - if one endpoint is clipped, clip segment
    - compute segment-plane intersection
    - create shorter segment



line clipping

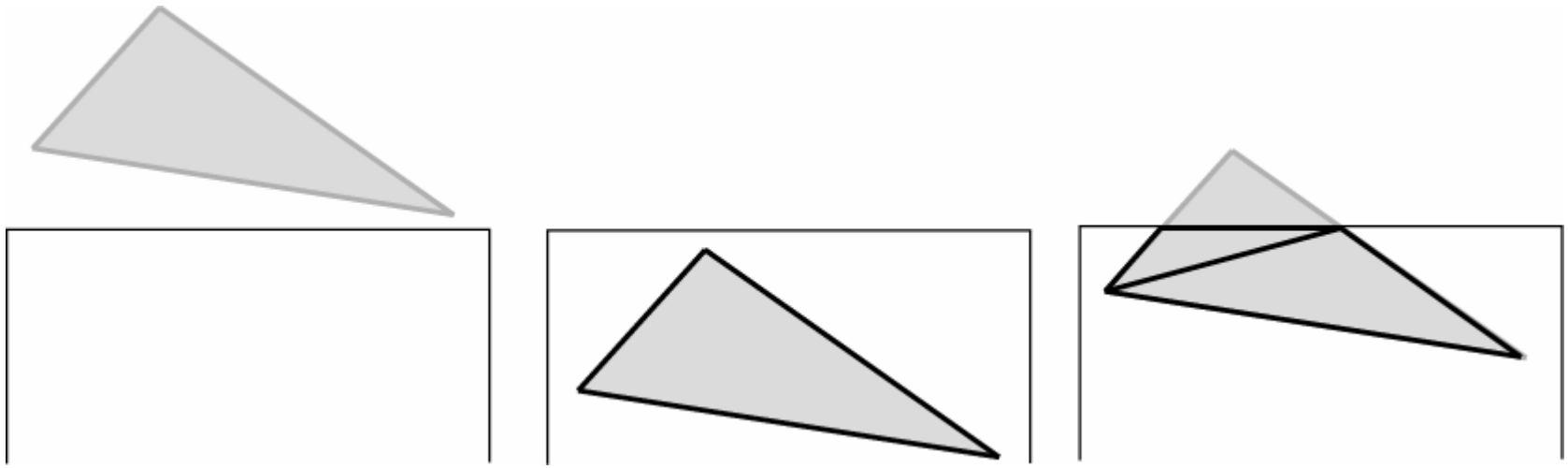
- segment-frustum clipping
  - clip against each plane incrementally
  - guarantee to create the correct segment



- more efficient algorithms available
  - previous incremental approach might try too hard
  - provide early rejection for common cases
  - so, only clip when necessary

polygon clipping

- convex polygons similar to line clipping
  - clip each point in sequence
    - remove outside points
    - create new points on boundary
  - clipped triangles are not necessarily triangles



culling

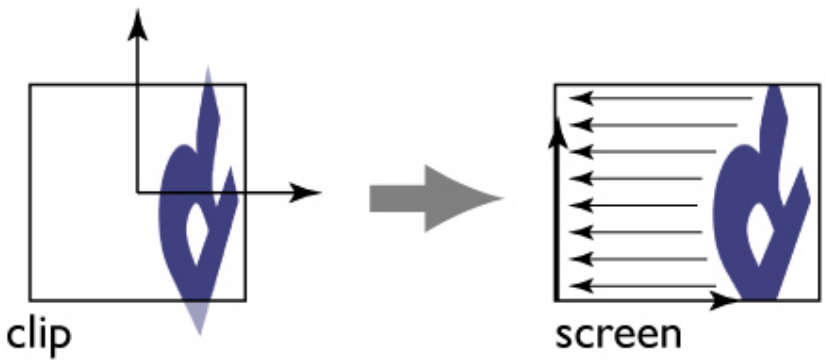
- further optimize by rejecting “useless” triangles

- backface culling
  - if triangle face is oriented away from camera, cull it
  - only ok for closed surfaces

- early z-culling
  - if triangle is behind existing scene, cull it
  - uses z-buffer introduced later on

viewport transformation

- transform the canonical view volume to the pixel coordinates of the screen
- also rescale z in the [0..1] range
  - we will see later why
- perspective divide is often performed here



[Marschner 2004]

rasterization

- approximate primitives into pixels
  - pixel centered at integer coordinates
- determine which pixels to turn on
  - no antialiasing (jaggies): pixel in the primitive
  - consider antialiasing for some primitives
  - input: vertex position in homogenous coordinates
- interpolate values across primitive
  - colors, normals, position at vertices
  - input: any vertex property

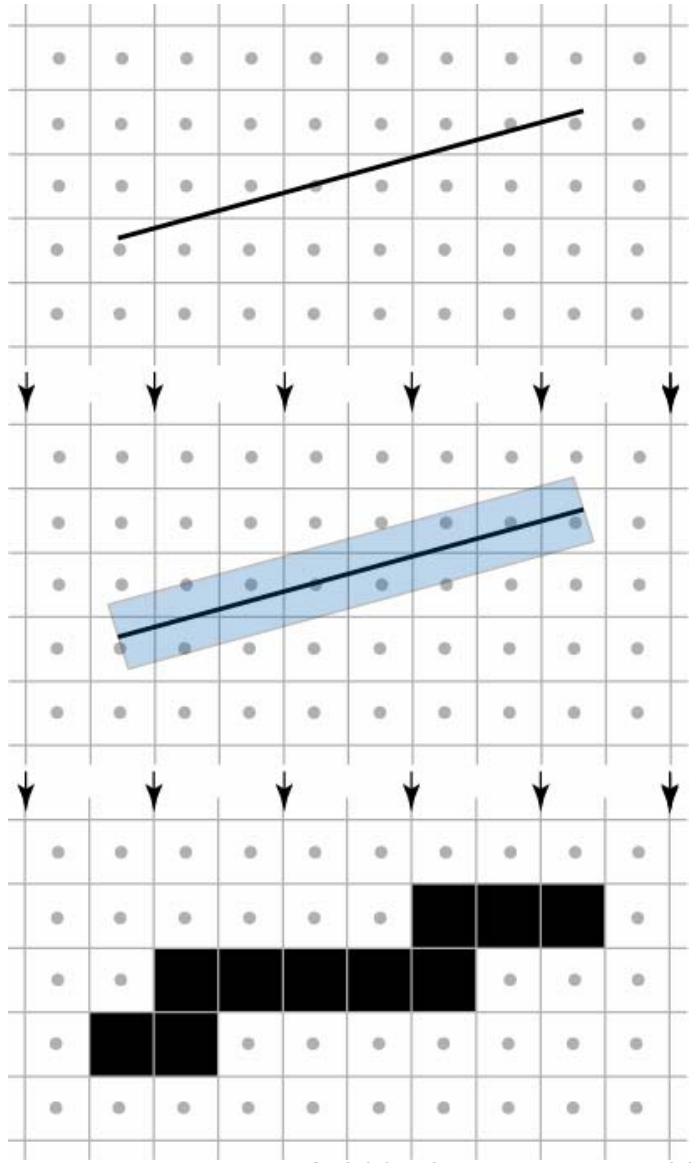
line rasterization

- approximate line with a collection of pixels
- desirable properties
  - uniform thickness and brightness
  - continuous appearance (no holes)
  - efficiency
  - simplicity (for hardware implementation)

- line equation: $y = mx + b$
  - in this lecture, for simplicity, assume m in [0,1)

point-sampled line rasterization

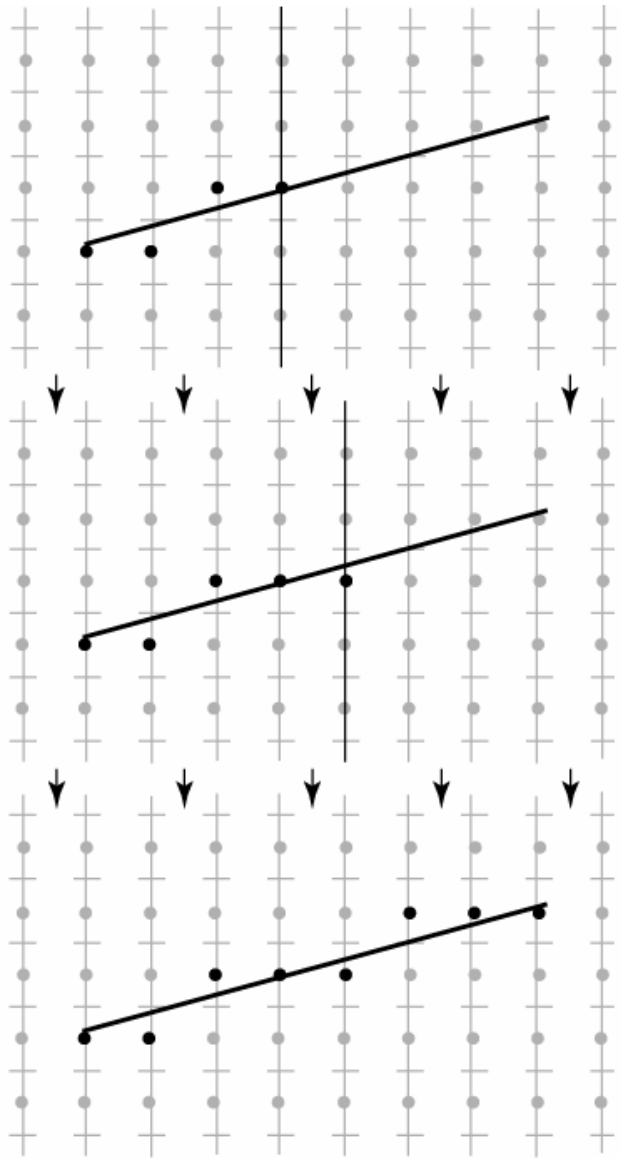
- represent line as rectangle
- approximated by all pixel within the line
  - for each pixel center, test if inside the rectangle
- inefficient
  - many inside tests
- inaccurate
  - thickness not constant



midpoint line rasterization

- for each column
  only turn on closest pixel
- simple algorithm
  - given line equation
  - eval. eq. for each column
  - between endpoints

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



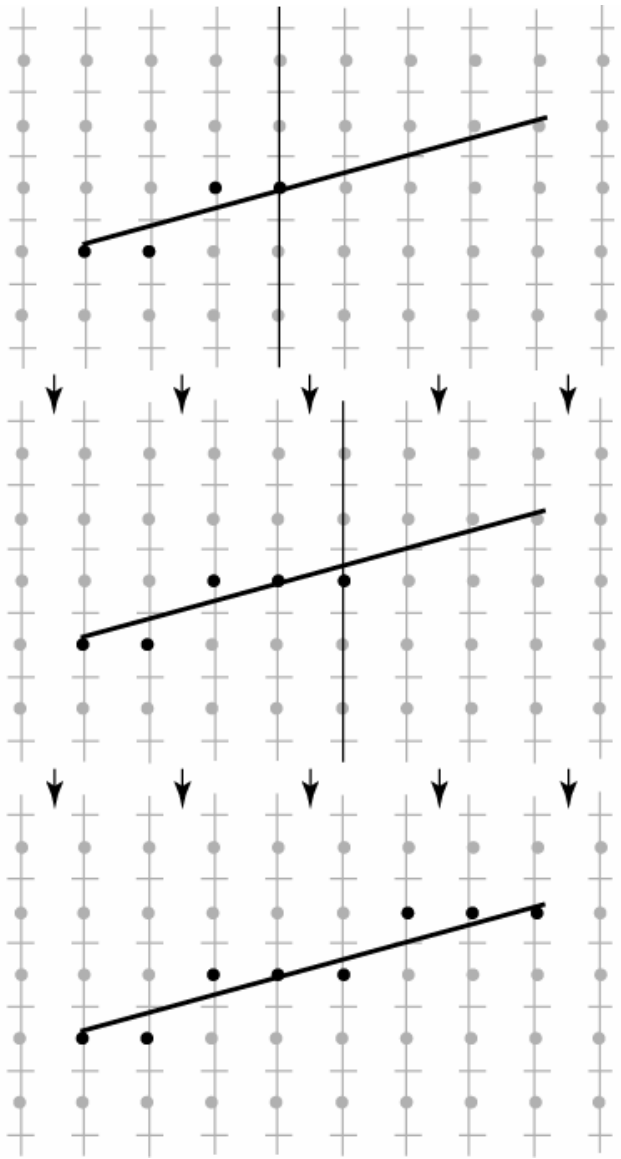
optimizing midpoint line rasterization

- evaluating *y* is slow
- use incremental difference, DDA

$$m = \Delta y / \Delta x$$

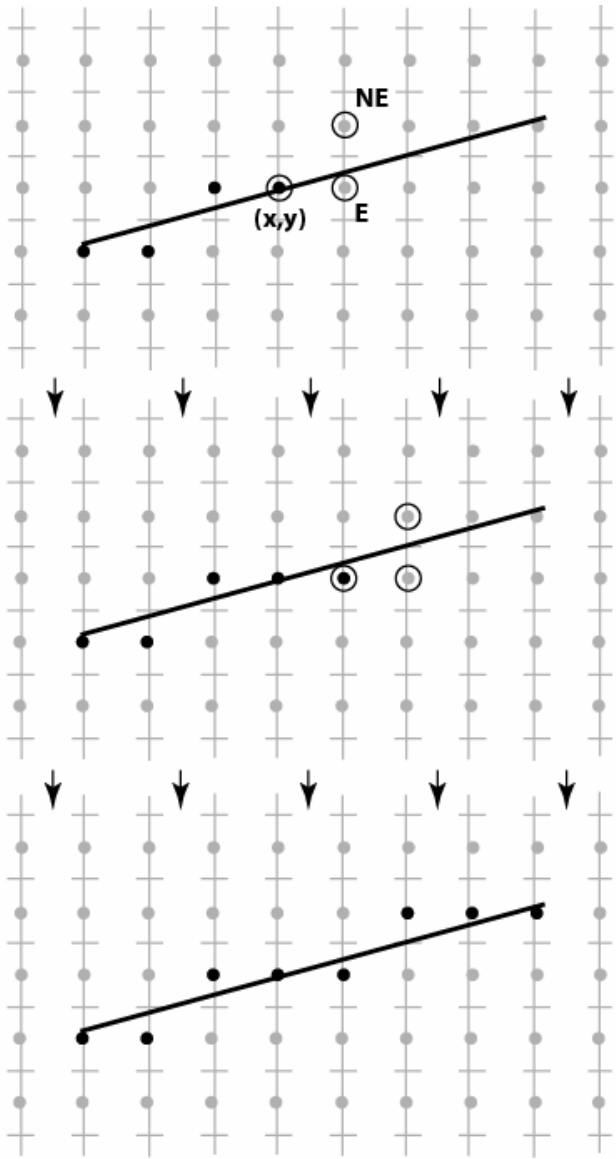
$$y(x+1) = y(x) + m$$

```
x = ceil(x0)
y = m*x + b
while x < floor(x1)
    write(x, round(y), 1)
    y += m
    x += 1
```



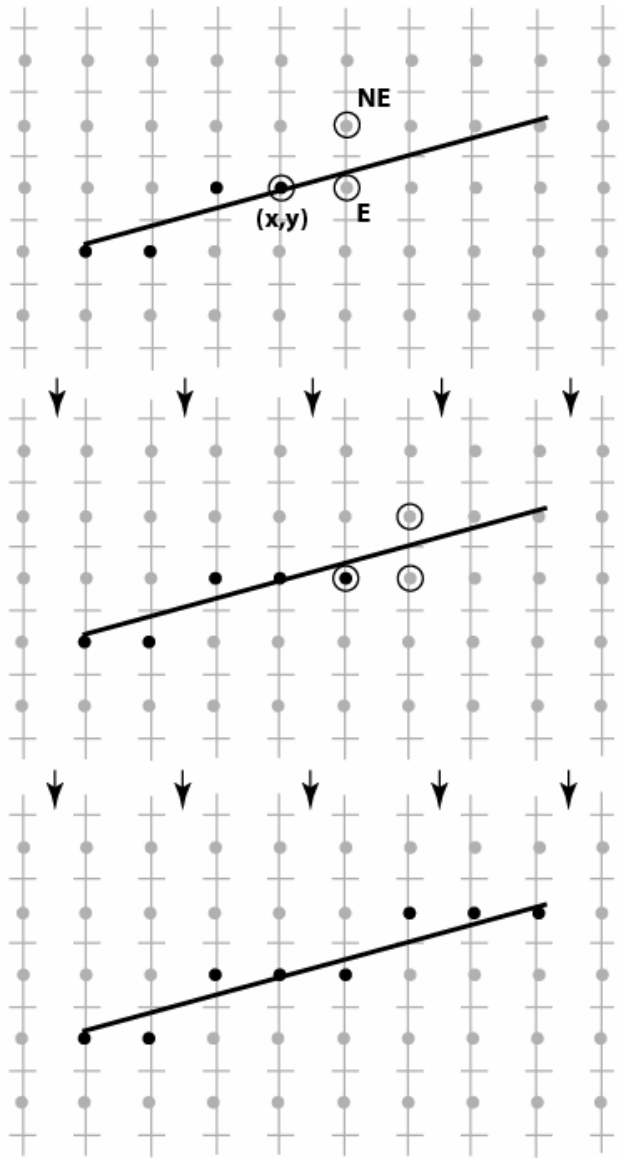
bresenham's line rasterization

- at each pixel (x_p,y_p), only two options: E(x_p+1,y_p) or NE(x_p+1,y_p+1)
- $d = (x_p + 1)m + b - y_p$
  - if d > 0.5 then NE
  - else E
- can evaluate *d* using incremental differences
  - NE: *d* += *m* - 1
  - E: *d* += *m*
- can use integers only



bresenham's line rasterization

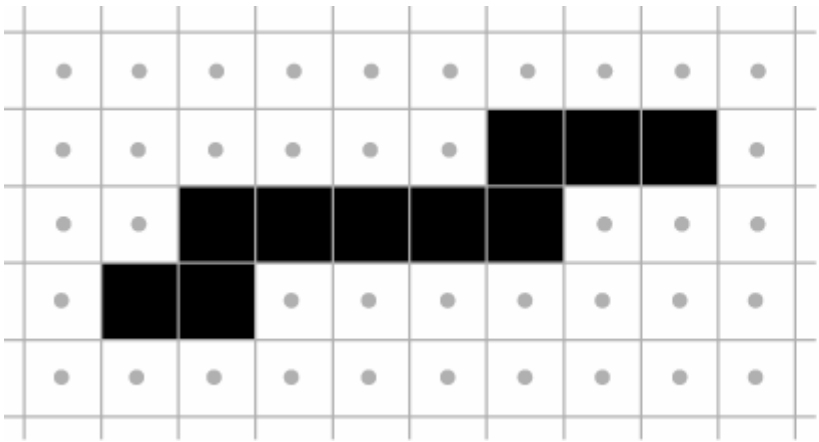
```
x = ceil(x0)
y = round(m*x + b)
d = m*(x+1)+b-y
while x < floor(x1)
    write(x, y, 1)
    x += 1
    d += m
    if d > 0.5
        y += 1
        d -= 1
```



midpoint vs. point-sampled line

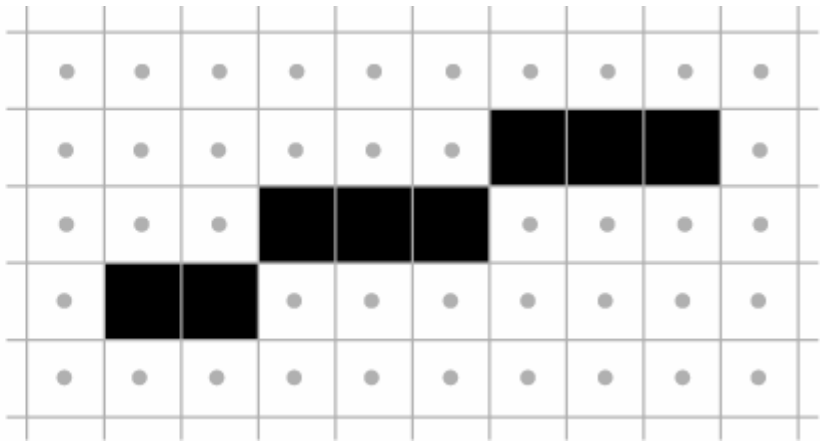
point-sampled

varying thickness



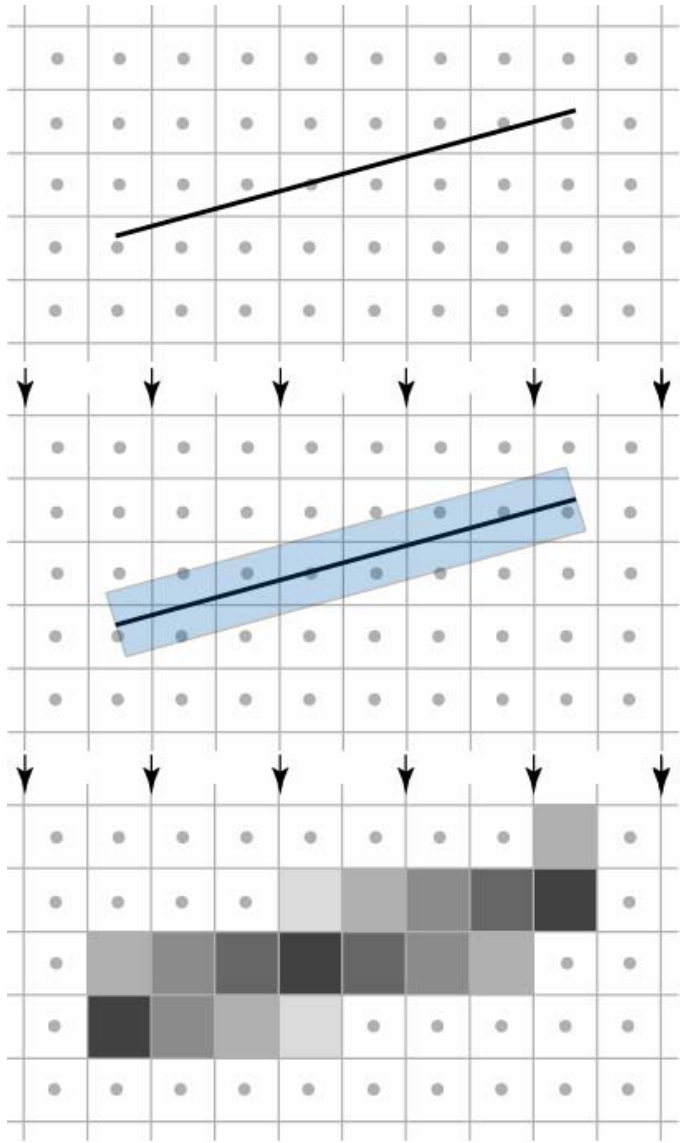
midpoint

same thickness



antialiased line rasterization

- for each pixel, color is the ratio of the area covered by the line
- need to touch multiple pixels per column
- can be done efficiently by precomputation and lookup tables
  - area only depends on line to pixel distance

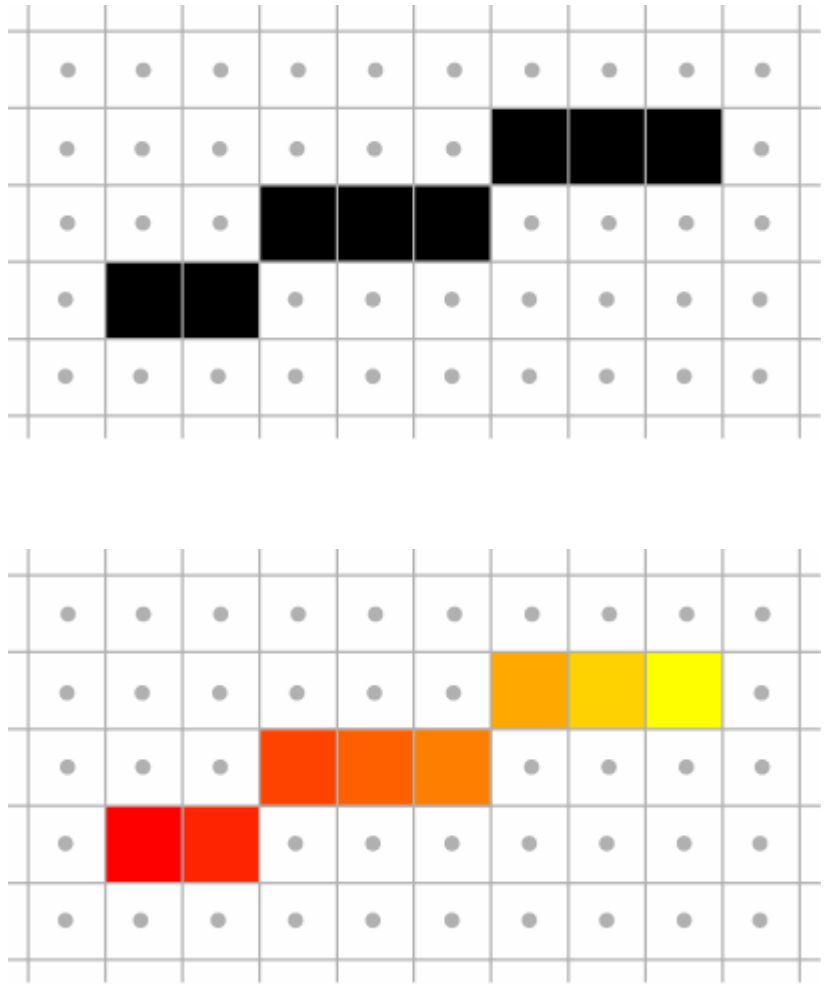


interpolating parameters along a line

- often associate params q_i at line vertices
  - colors, alphas
- linearly interpolate q_i

$$q_i(s) = q_{i0} \cdot (1 - s) + q_{i1} \cdot s$$

  - s is fractional distance along the line
  - can be done using incremental differences

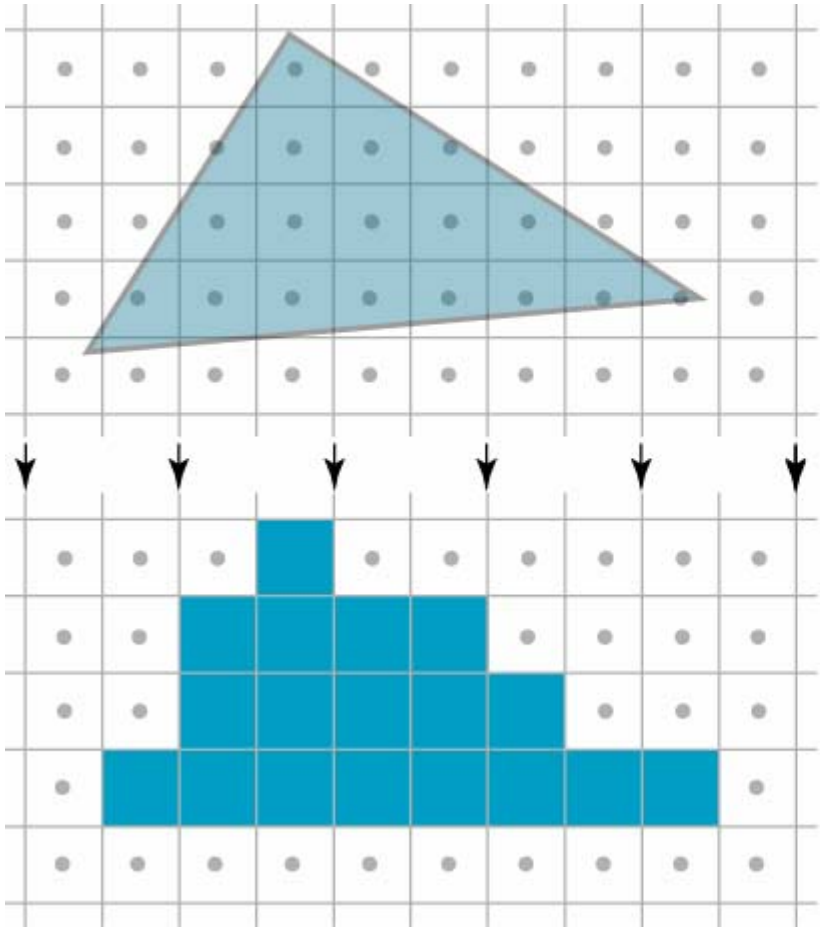


triangle rasterization

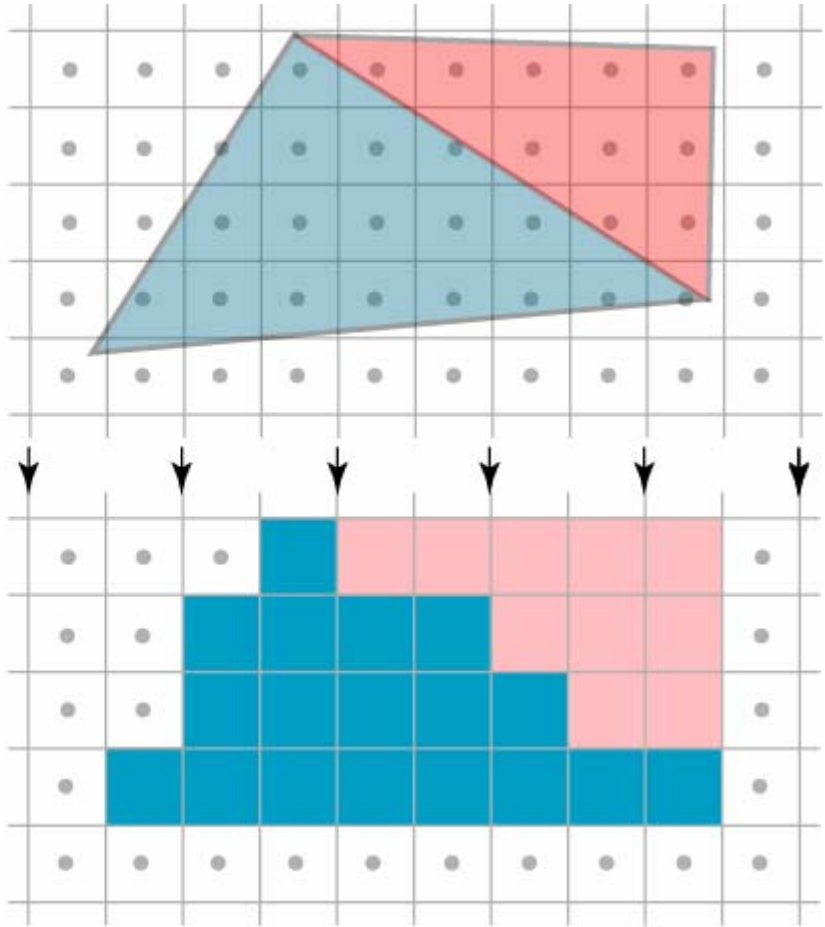
- most common operation in graphics pipelines
  - can be the only one: turn everything into triangles
- input: 2D triangle with vertex attributes
  - 2d vertex coordinates: $\{(x_0,y_0), (x_1,y_1), (x_2,y_2)\}$
  - other attributes: $\{q_{i0},q_{i1},q_{i2}\}$
- output: list of fragments with interpol. attributes
  - list of pixel coordinates that are to be drawn
  - linearly interpolated vertex attributes

triangle rasterization

one triangle



consistent triangles



brute force triangle rasterization

- foreach pixel in image
  - determine if inside triangle
  - interpolate attributes
- use baricentric coordinates
- optimize by only checking triangle bounding box

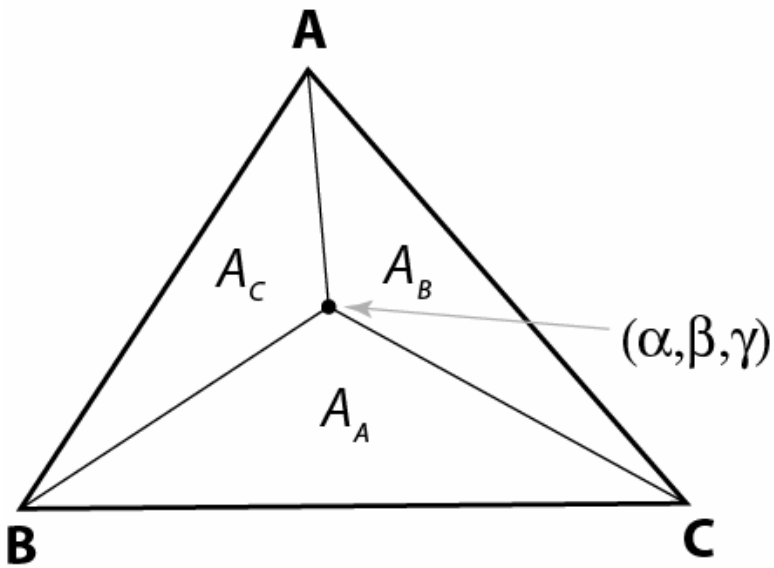
triangle baricentric coordinates

$$\mathbf{p} = \alpha\,\mathbf{a} + \beta\,\mathbf{b} + \gamma\,\mathbf{c} \qquad \alpha + \beta + \gamma = 1$$

- analytic interpretation
  - coordinate system on the triangle

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

- geometric interpretation
  - relative areas
  - relative distances



- also useful for ray-triangle intersection

brute force triangle rasterization

for each pixel (x,y) in triangle bounding box

compute (α,β,γ)

if (α,β,γ) in $[0,1]^3$

$q_i = \alpha \bullet q_{i0} + \beta \bullet q_{i1} + \gamma \bullet q_{i2}$

write(x,y,$\{q_i\}$)

- can be made incremental as in line drawing
- more efficient options exists, but …

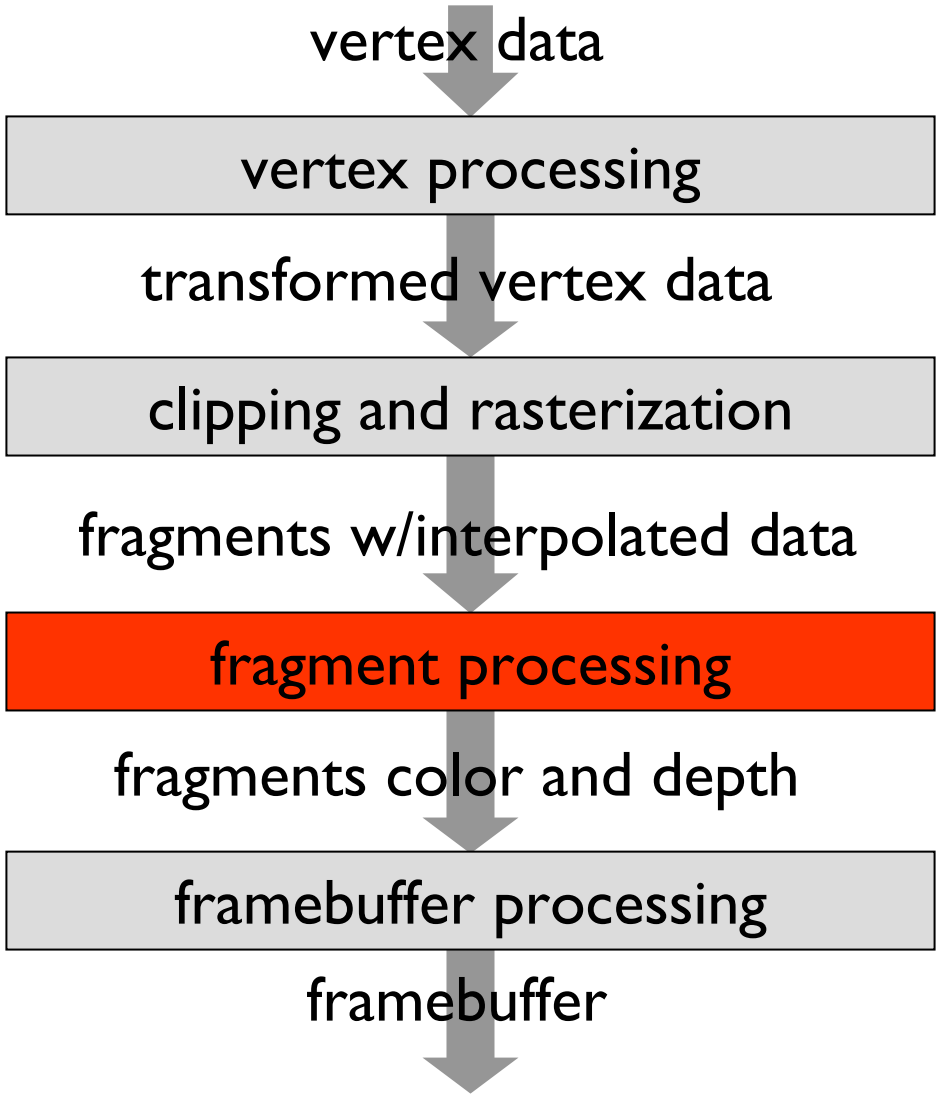
triangle rasterization on hardware

- old hardware: optimized for large triangles
  - use smart algorithm
    - clip triangle to screen window
    - setup initial values
    - interpolate
  - hard to parallelize, high set up cost
- modern hardware: optimized for small triangles
  - use incremental brute force algorithm
    - only clip against near plane for correctness
    - work with clipped bounding box
  - easily parallelizable, little setup cost
    - use tiles in image plane

rasterization take home message

- complex but efficient set of algorithms
  - lots of small little details that matters for correctness
- no clear winner
  - architecture: parallel vs. serial
  - input: e.g. size of triangles
  - amortization: one-time vs. step-by-step cost
- complex algorithms have often hidden costs
  - verify if they can be amortized
- loops are expensive: optimize as you can

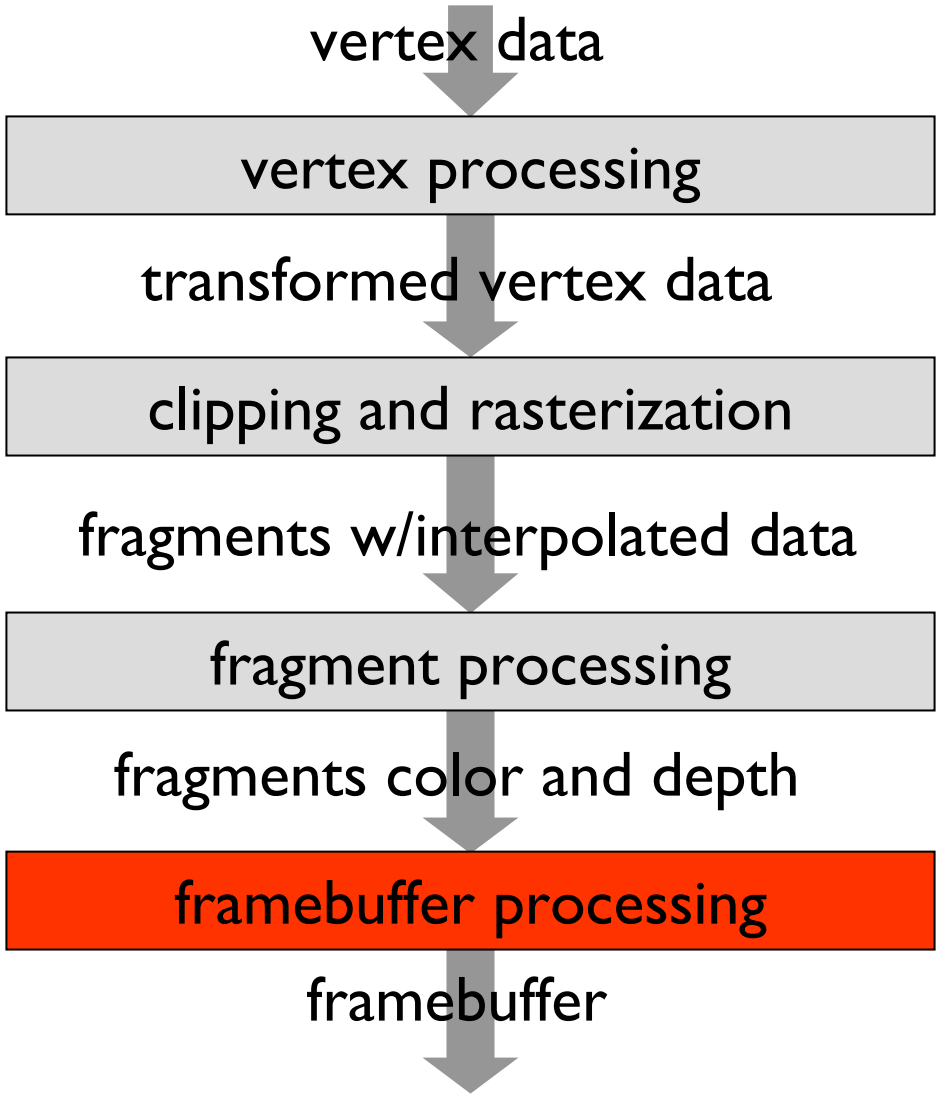
fragment processing



fragment processing

- compute final fragment colors, alphas and depth
  - depth is often untouched if no special effects
  - final lighting computations
  - lots of texture mapping: see later
- programmable hardware unit
  - algorithm can be changed at run-time by application
  - only recent change

framebuffer processing

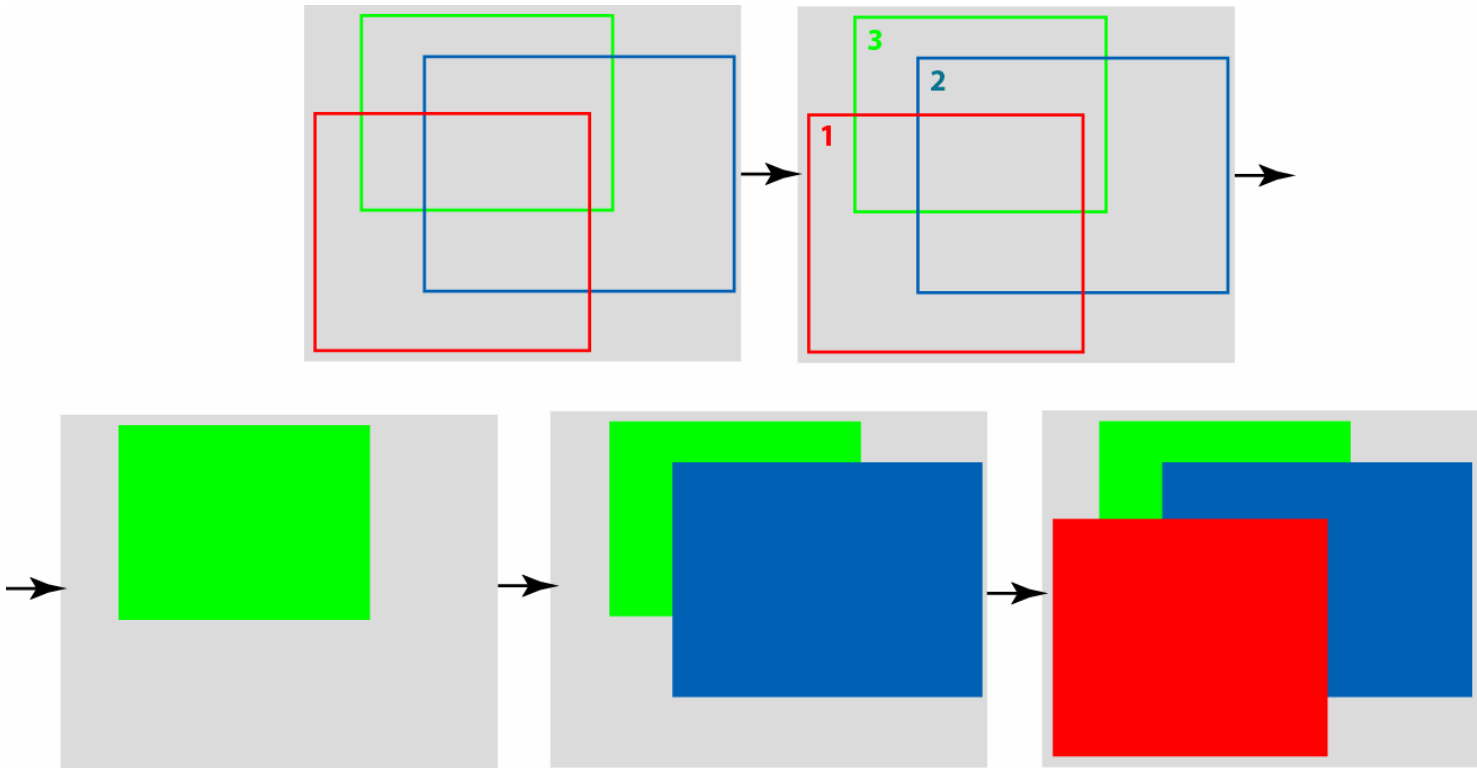


framebuffer processing

- hidden surface elimination
  - decides which surfaces are visible
- framebuffer blending
  - composite transparent surfaces if necessary

hidden surface removal – painter alg.

- sort objects back to front
- draw in sorted order
- does not work in many cases



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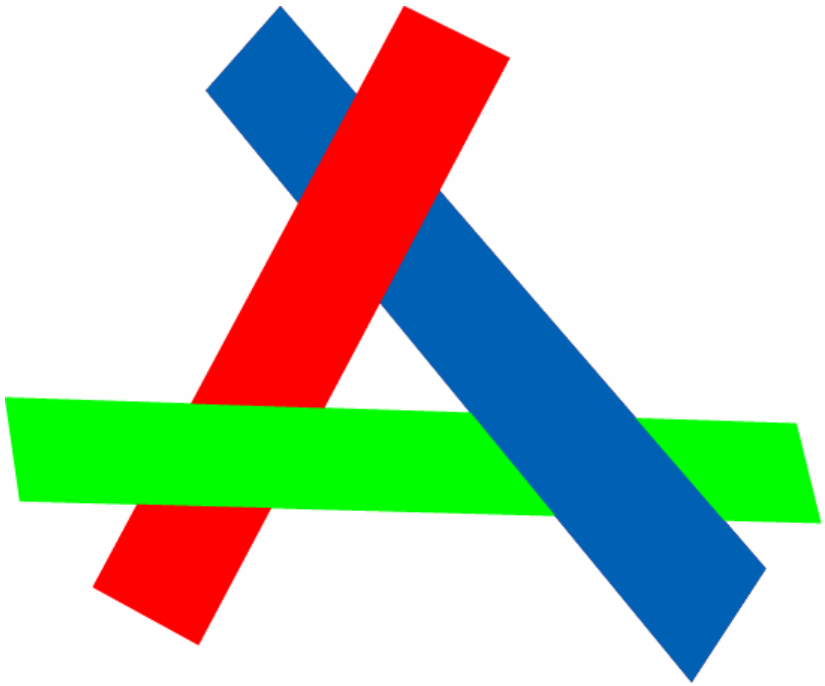
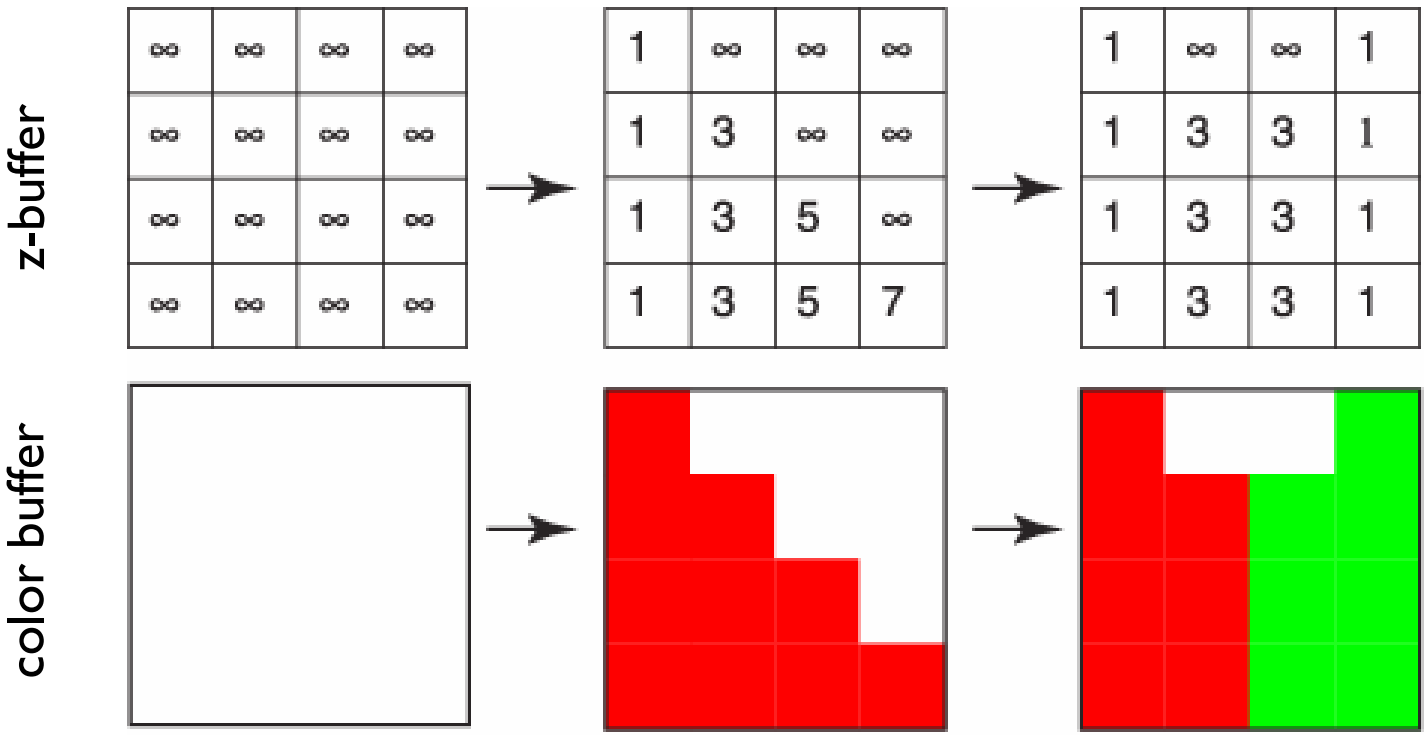


hidden surface removal – z buffer

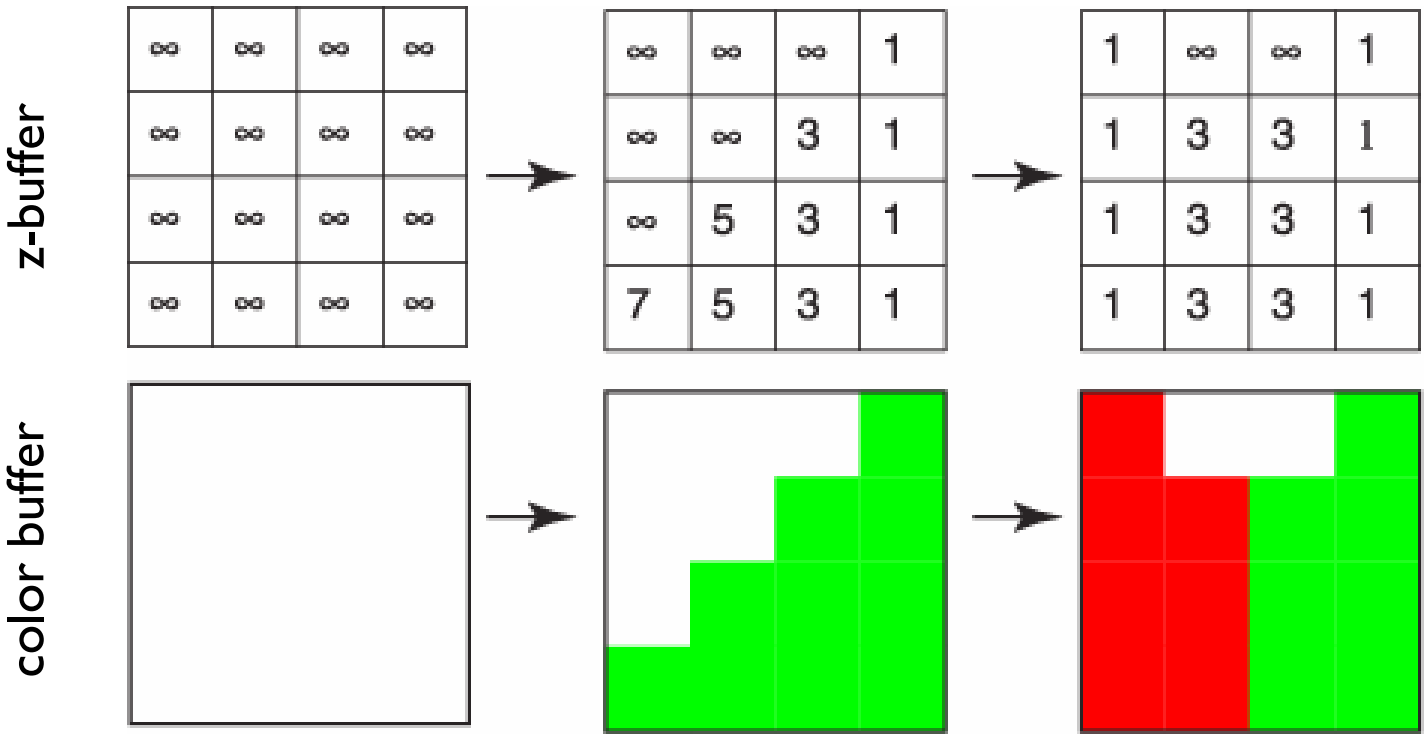
- brute force algorithm
- for each pixel, keep distance to closest object
- foreach object, rasterize updating pixels if distance is closer
  - opaque objects: works in every case
  - transparent objects: cannot properly composite

hidden surface removal – z buffer



[adapted from Shirley]

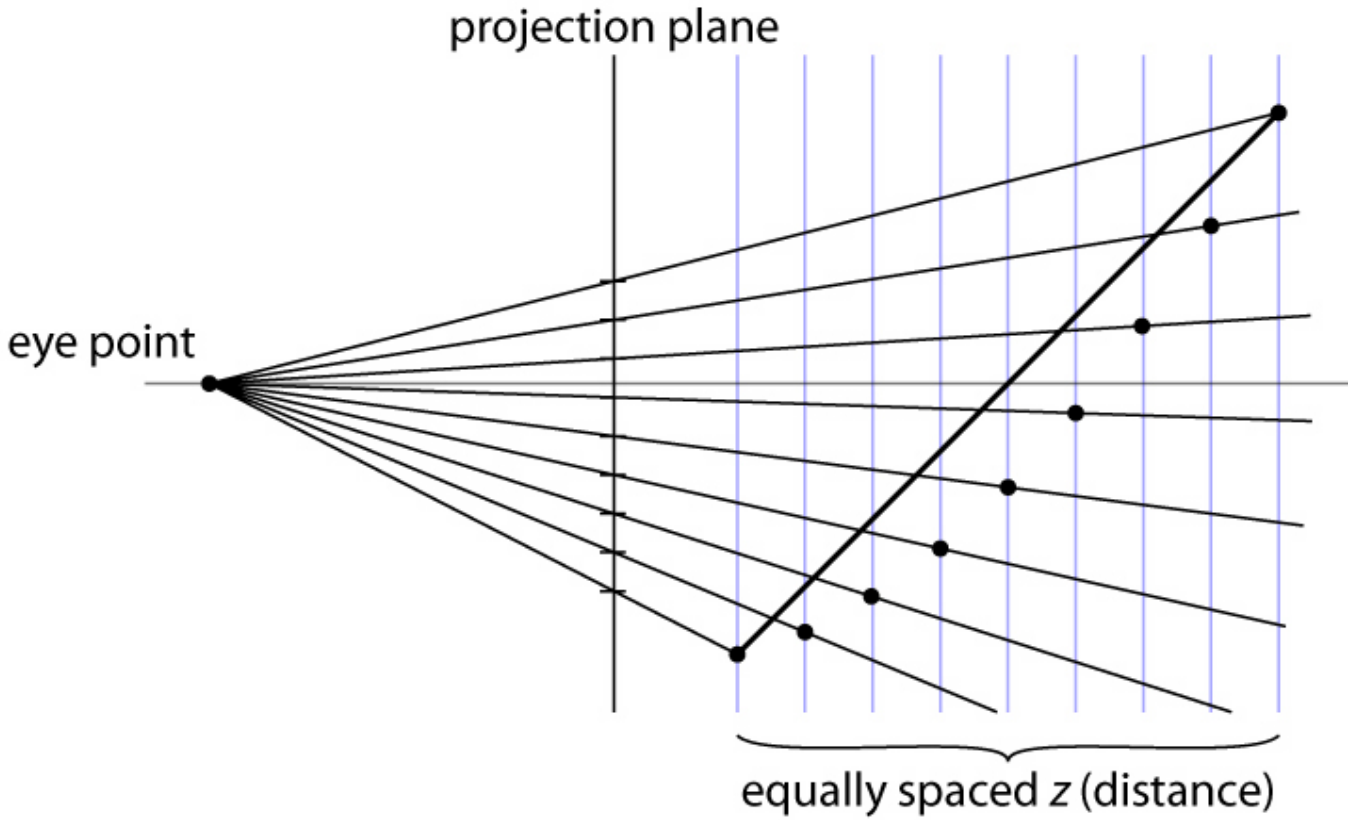
hidden surface removal – z buffer



[adapted from Shirley]

which z distance

- use z value after homogenues xform
  - linear interpolation works
  - storage non-linear: more precision around near frame



[Marschner 2004]

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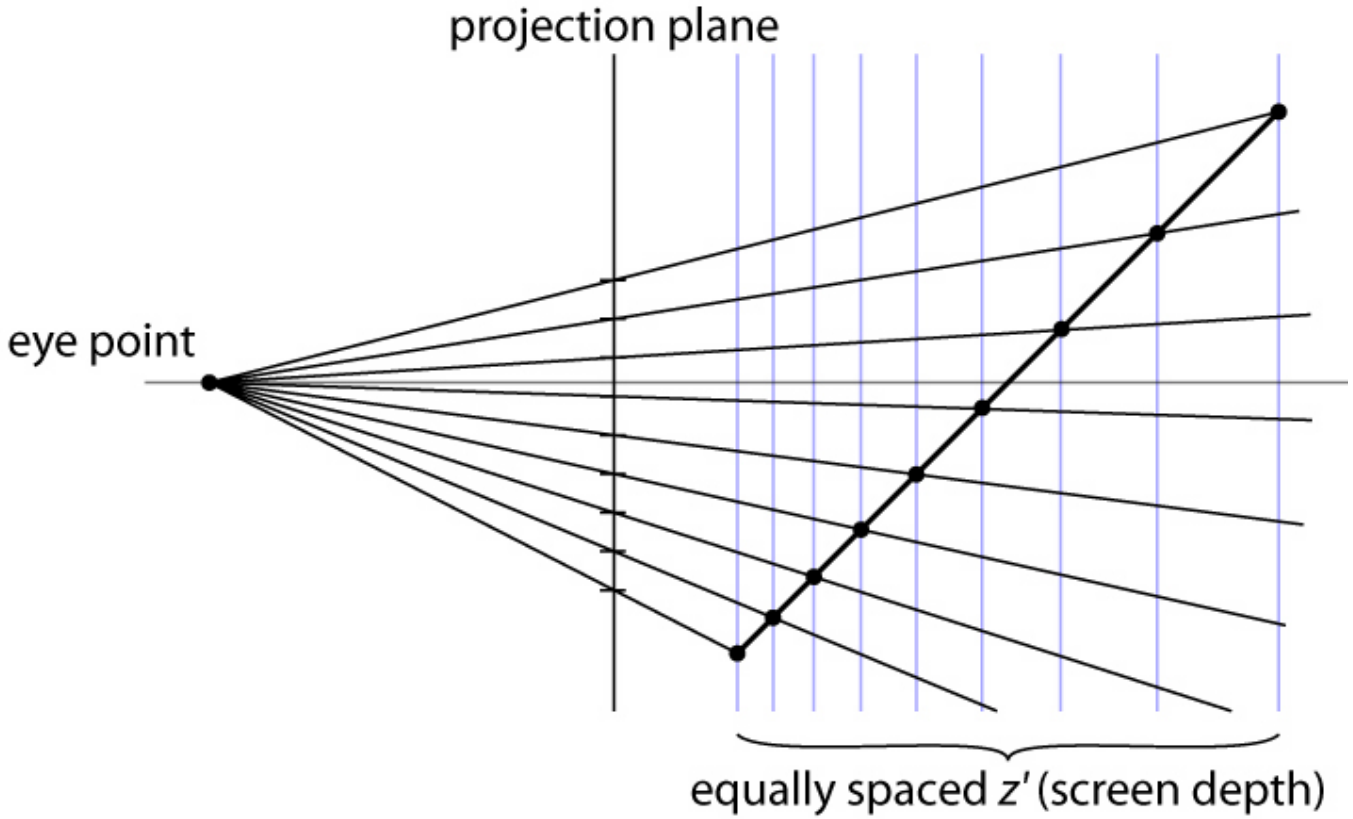


[Marschner 2004]

hidden surface removal – raycasting

- foreach ray, find intersection to closest surface
  - works for opaque and transparent objects
- loops over pixels and then over surfaces
  - inefficient
  - would like to loop over surfaces only once

hidden surface removal - scanline

- for each scanline, sort primitives
  - incremental rasterization
  - sorting can be done in many ways
  - needs complex data structures
  - works for opaque and transparent objects

hidden surface removal - REYES

- foreach primitives, turn into small grids of quads
- hit-test quads by ray-casting
- keep list of sorted list hit-points per pixel
  - like z-buffer but uses a list
  - works for opaque and transparent objects
- hybrid between raycast and z-buffer
  - very efficient for high complexity
    - when using appropriate data-structures
  - solves many other problems we will encounter later

framebuffer processing

- hidden surface elimination using Z-buffer

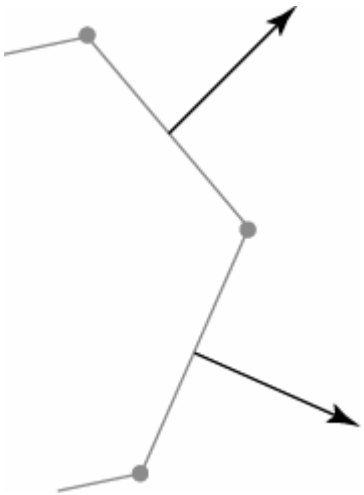
- framebuffer blending using α-compositing
  - but cannot sort fragments properly
  - incorrect transparency blending
  - need to presort transparent surfaces only
    - like painter's algorithm, so not correct in many cases

lighting computation

- where to evaluate lighting?
  - flat: at vertices but do not interpolate colors
  - Gourand: at vertices, with interpolated color
  - Phong: at fragments, with interpolated normals

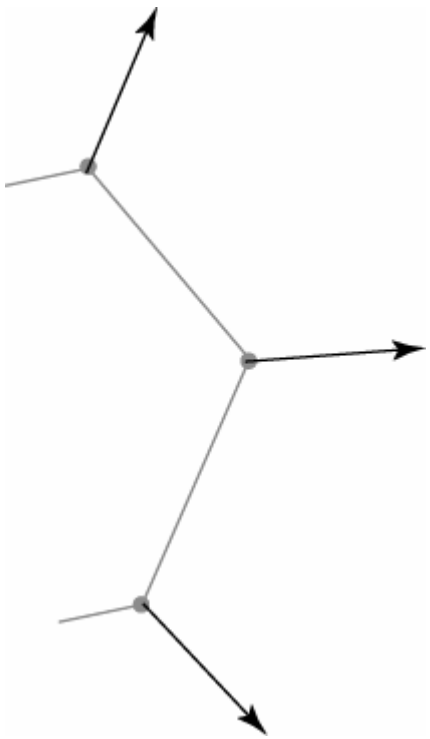
lighting computation – flat shading

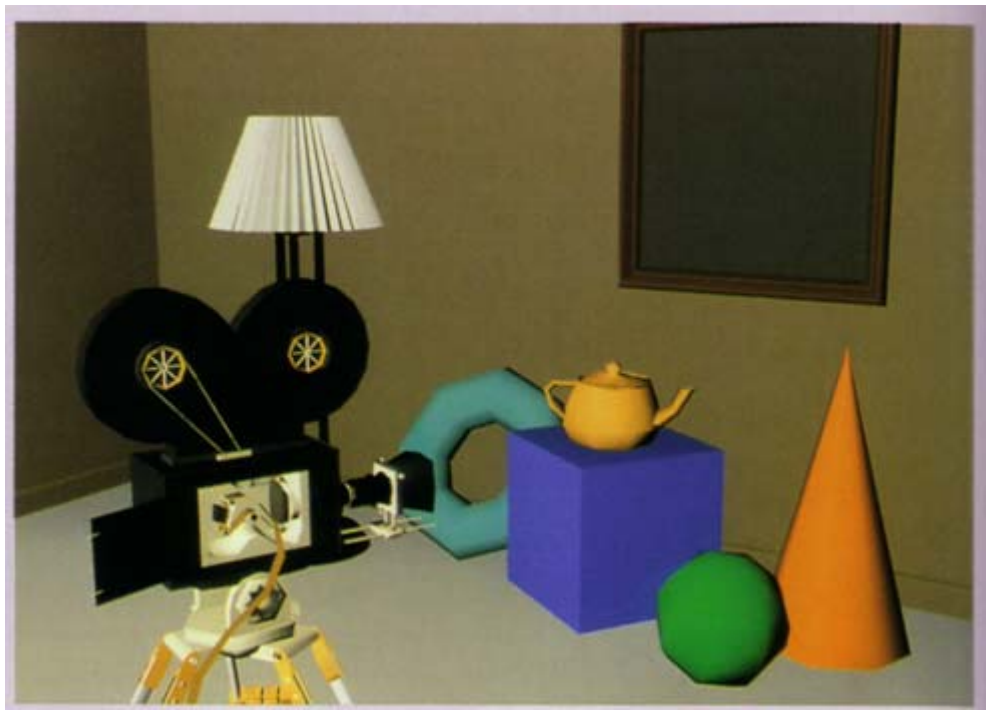
- compute using normals of the triangle
  - same as in raytracing
- flat and faceted look
- correct: no geometrical inconsistency



lighting computation – Gouraud shading

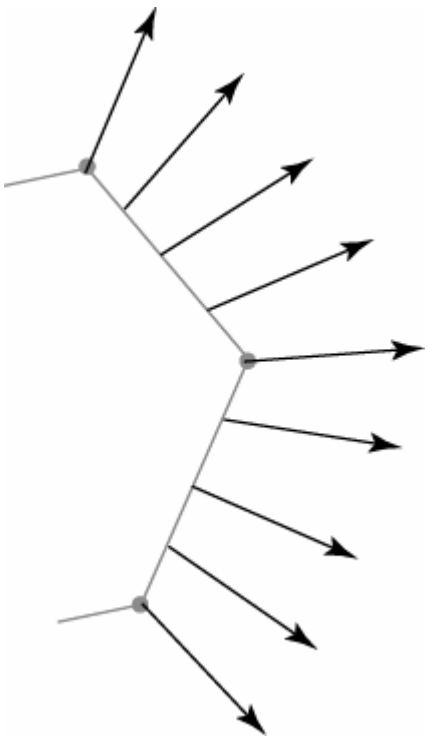
- compute light at vertex position
  - with vertex normals
- interpolate colors linearly over the triangle





lighting computation – Phong shading

- interpolate normals per-pixels: shading normals
- compute lighting for each pixel
  - lighting depends less on tessellation



lighting computation – Phong shading

Gouraud

artifacts in highlights

Phong

good highlights

lighting computation

- per-pixel lighting is becoming ubiquitous
  - much more robust
  - move lighting from vertex to fragment processing
    - new hardware architectures allows for this
    - we introduce Gouraud for historical reasons
  - raytracing can have this by using shading normals
- shading normals introduce inconsistencies
  - lights can come from "below" the surface

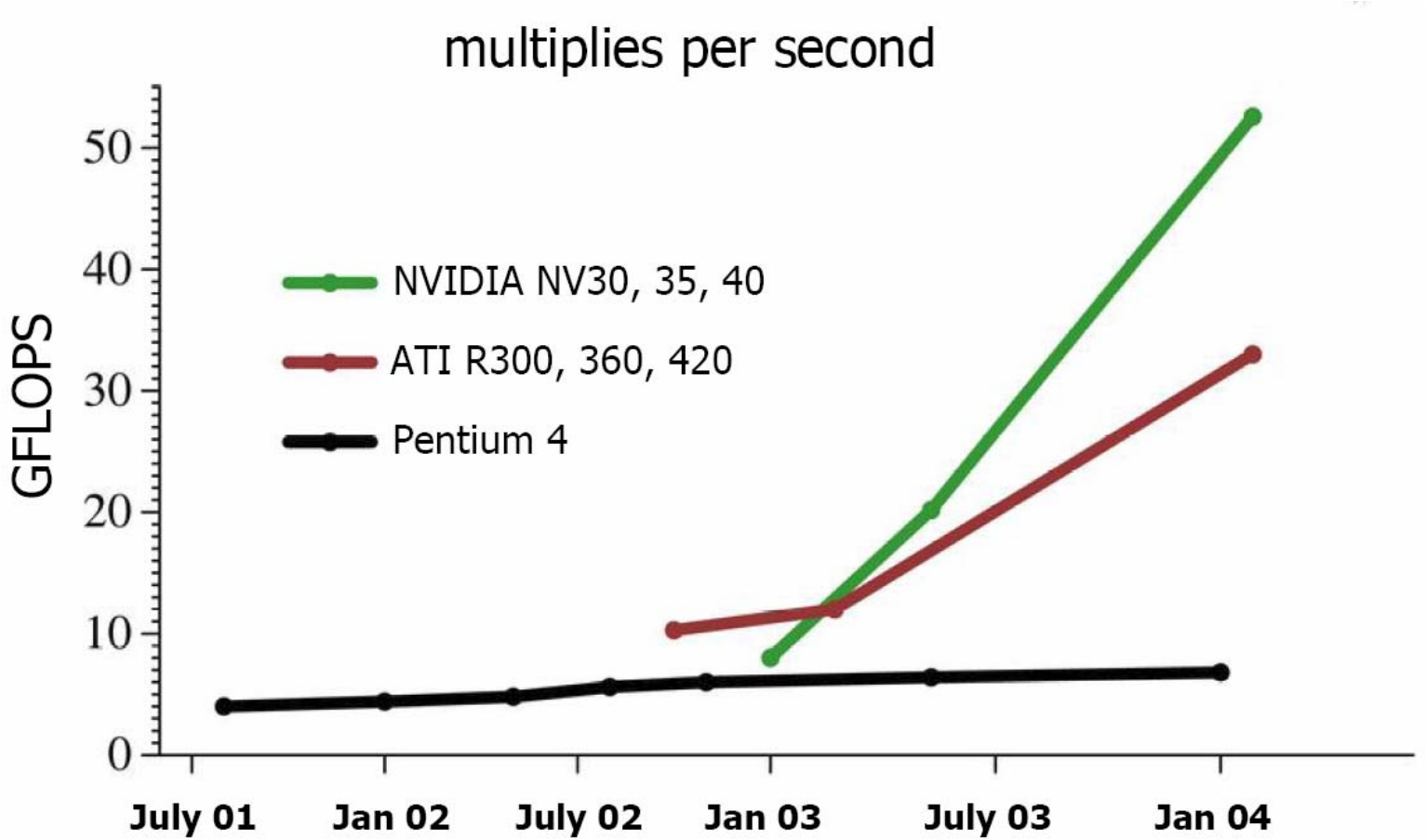
why graphics pipelines?

- simple algorithms can be mapped to hardware
- high performance using on-chip parallel execution
  - highly parallel algorithms
  - memory access tends to be coherent
  - one-object at a time

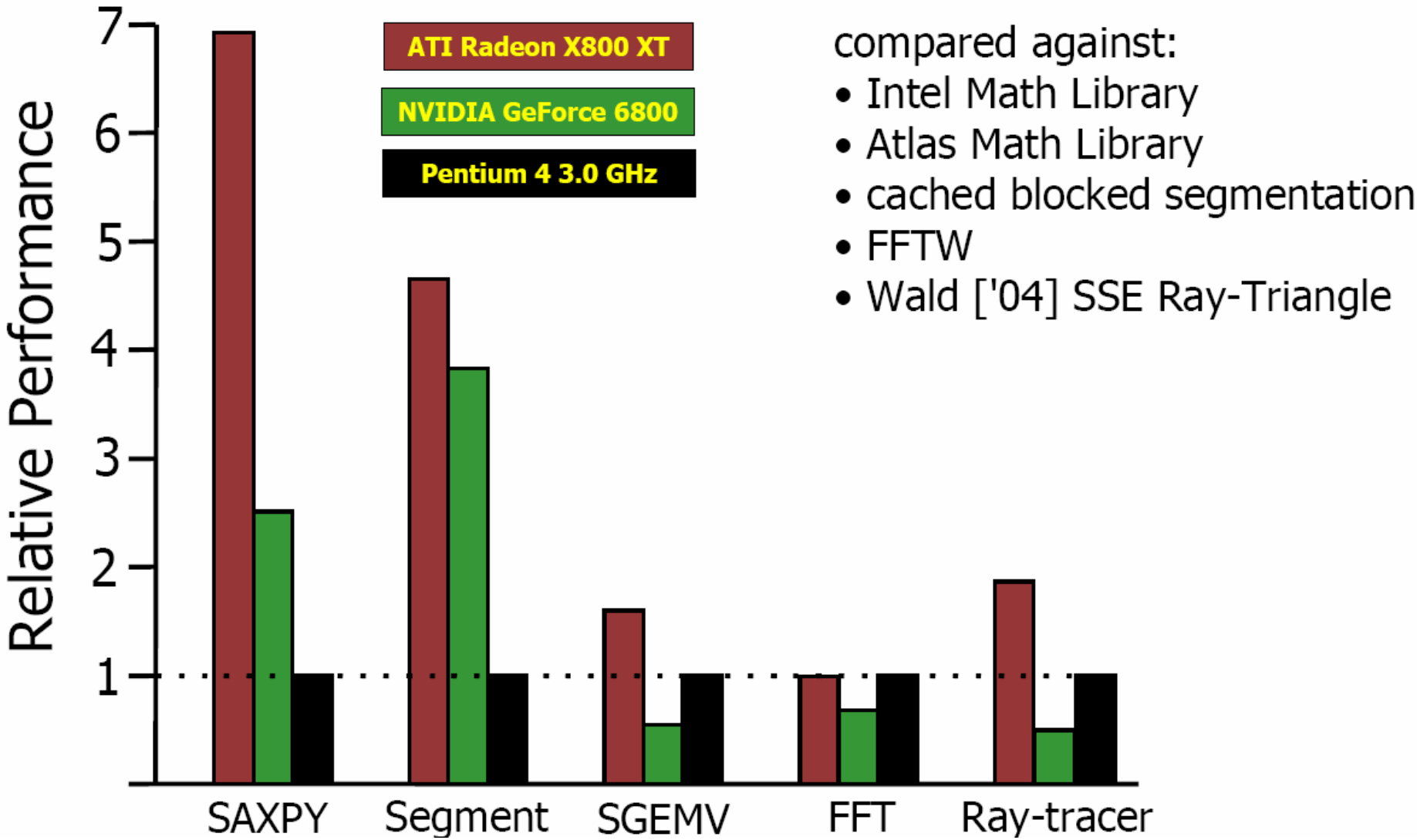
graphics pipeline architecture

- multiple arithmetic units
  - NVidia Geforce 7800: 8 vertex units, 24 pixel units
- very small caches
  - not needed since memory access are very coherent
- fast memory architecture
  - needed for color/z-buffer traffic
- restricted memory access patterns
  - no read-modify-write
  - bound to change hopefully
- easy to make fast: this is what Intel would love!
- research into using for scientific computing

graphics pipeline performance



graphics pipeline performance



graphics pipelines vs. raytracing

raycasting

- foreach pixel
  foreach object
- project pixels onto objects
- discretize first
- access objects many times
  - scene must fit in memory
- very general solution
- O(log(n)) w/accel. struct.
  - but constant very high

graphics pipeline

- foreach object
  foreach pixel
- project objects onto pixels
- discretize last
- access objects once
  - image must fit in memory
- hard for complex effects
- O(n) or lower sometimes
  - but constant very small

