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
  - point, lines, triangles, quads (as two triangles)
  - efficient algorithm
- complex primitives by tessellation
  - complex curves: tessellate into line strips
  - complex 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

vertex data

transformations → **[vertex processing]**

transformed vertex data

convert to pixels → **[clipping and rasterization]**

fragments w/ interpolated data

compute final colors → **[fragment processing]**

fragments color and depth

blending hidden-surface → **[framebuffer processing]**

framebuffer

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 data

[vertex processing]

transformed vertex data

[clipping and rasterization]

fragments w/ interpolated data

[fragment processing]

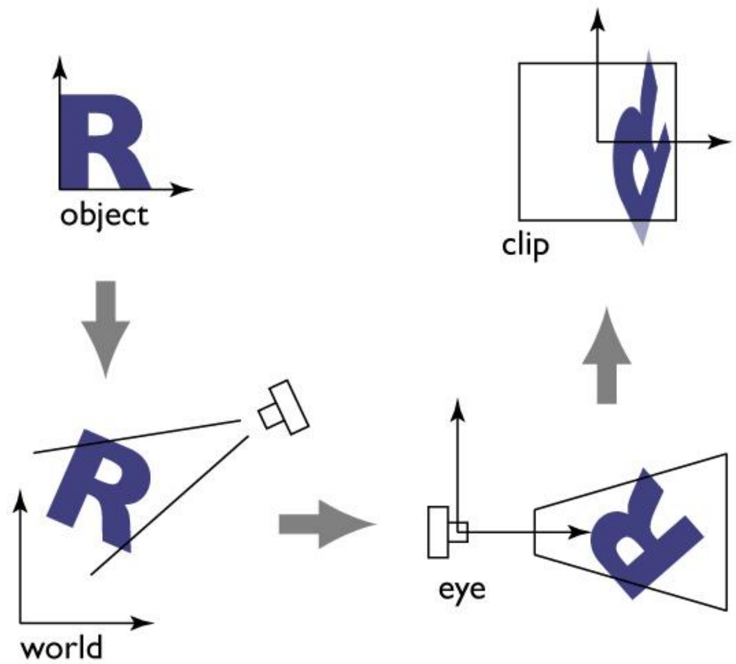
fragments color and depth

[framebuffer processing]

framebuffer

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

clipping and rasterization

vertex data

[vertex processing]

transformed vertex data

[clipping and rasterization]

fragments w/ interpolated data

[fragment processing]

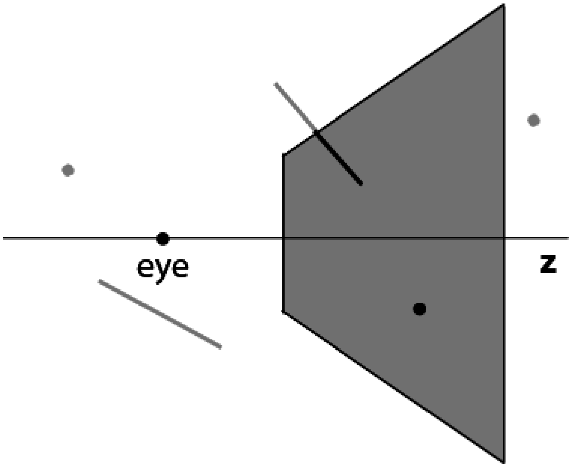
fragments color and depth

[framebuffer processing]

framebuffer

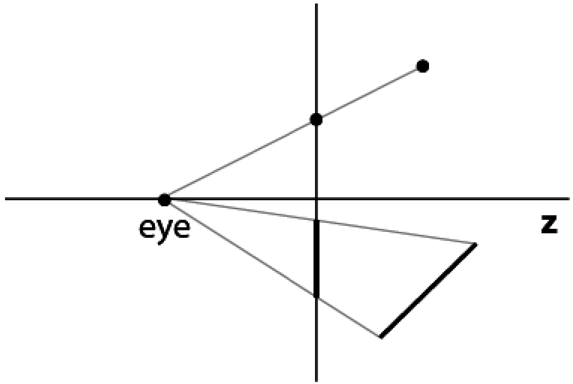
clipping and rasterization

- 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

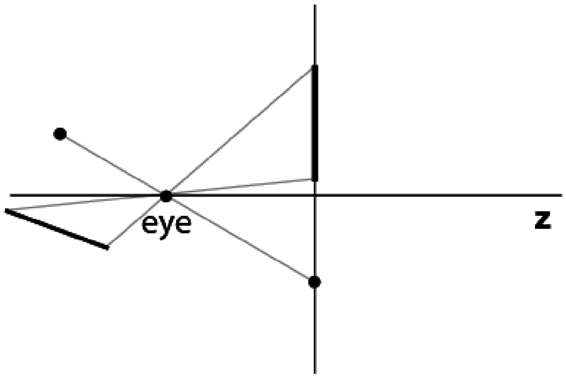


clipping to ensure correctness

in front of eye

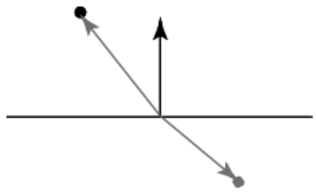


behind eye



point clipping

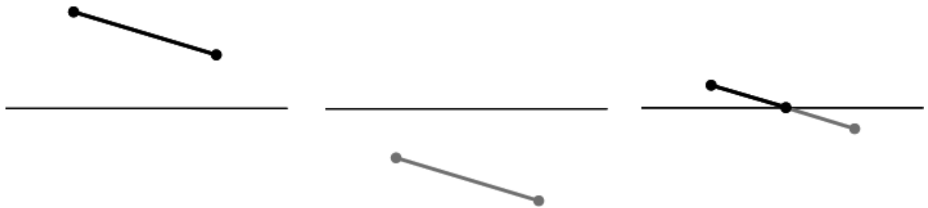
- point-plane clipping
  - test if the point is on the right side of the plane
  - by taking dot-product with the plane normal
  - can be performed in homogeneous coordinates



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

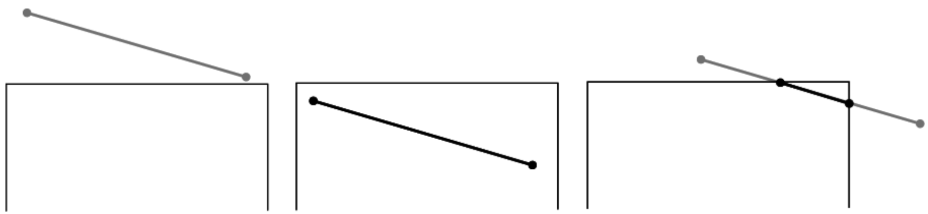
line clipping

- 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

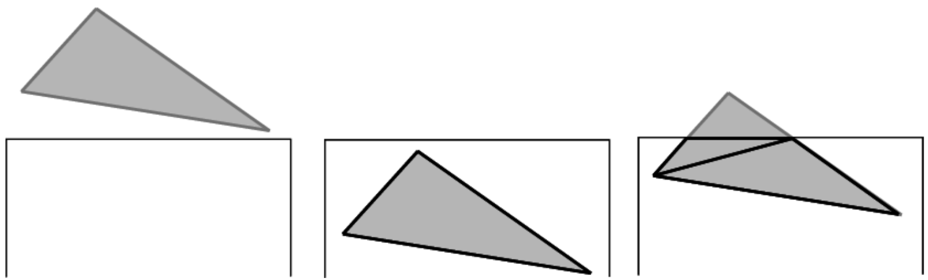
- segment-frustum clipping
  - clip against each plane incrementally
  - guarantee to create the correct segment



- 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

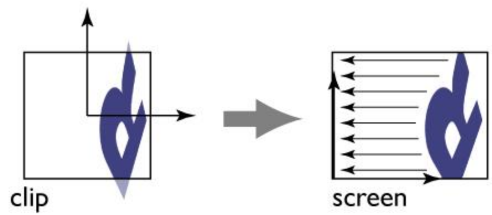


culling

- 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

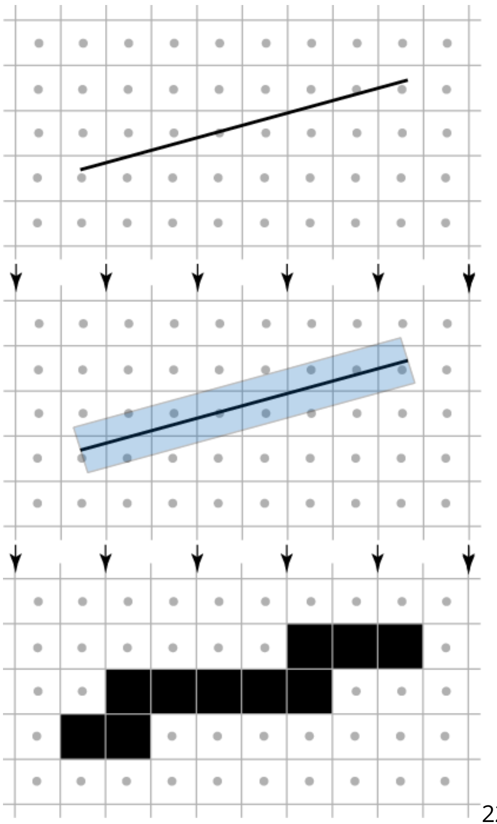
- approximate primitives into pixels
  - pixel centered at integer coordinates
- determine which pixels to turn on
  - no anti-aliasing (jaggies): pixel in the primitive
  - consider anti-aliasing for some primitives
  - input: vertex position in homogeneous coordinates
- interpolate values across primitive
  - color, 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

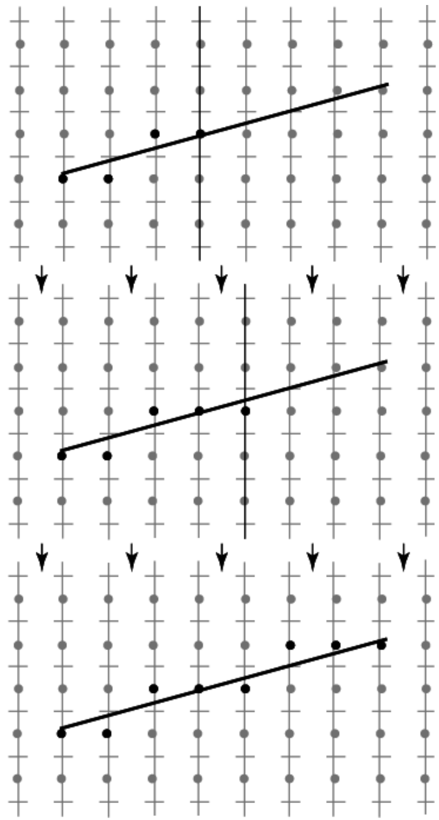
- represent line as rectangle
- approximated by all pixel within the line
  - for each pixel center, test if inside the rectangle
- inefficient
  - many inside tests
- inaccurate
  - thickness not constant



midpoint line rasterization

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

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



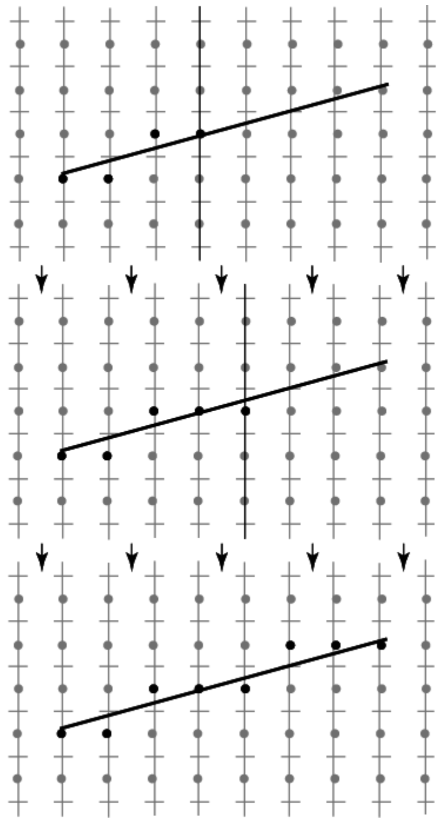
optimizing midpoint line rasterization

- evaluating y is slow
- use incremental difference, DDA

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

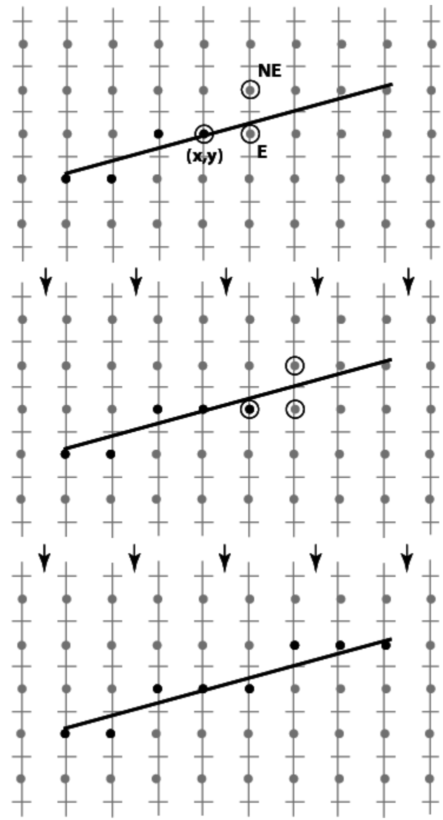
$$y(x+1) = y(x) + m$$

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



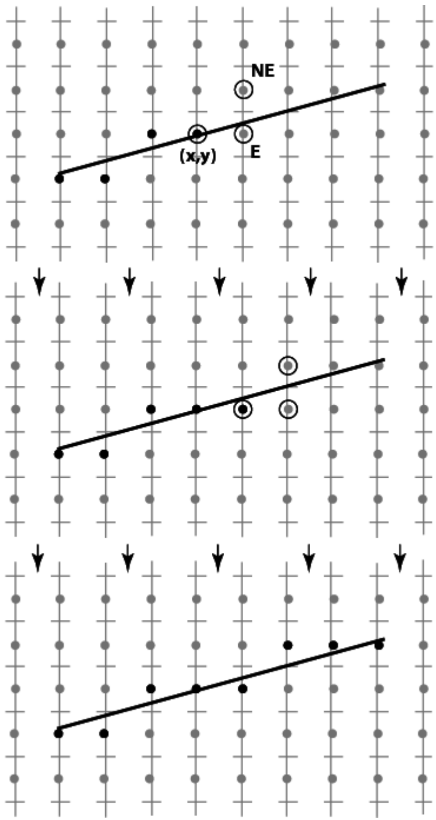
bresenham's line rasterization

- 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: $d = d + m - 1$
  - E: $d = d + m$
- can use integers only



bresenham's line rasterization

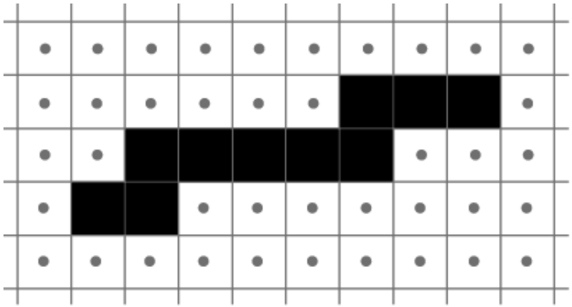
```
x = ceil(x0)
y = round(m*x + b)
d = m*(x + 1) + b - y
while x < floor(x1)
    write(x, y, 1)
    x += 1
    d += m
    if d > 0.5
        y += 1
        d -= 1
```



midpoint vs. point-sampled line

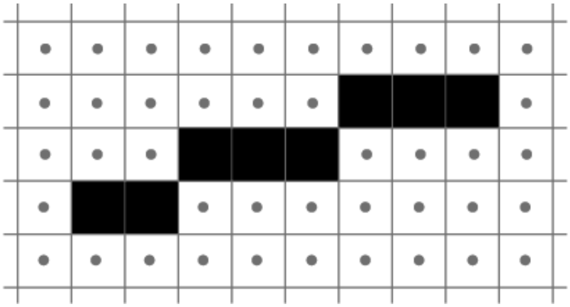
point-sampled

varying thickness



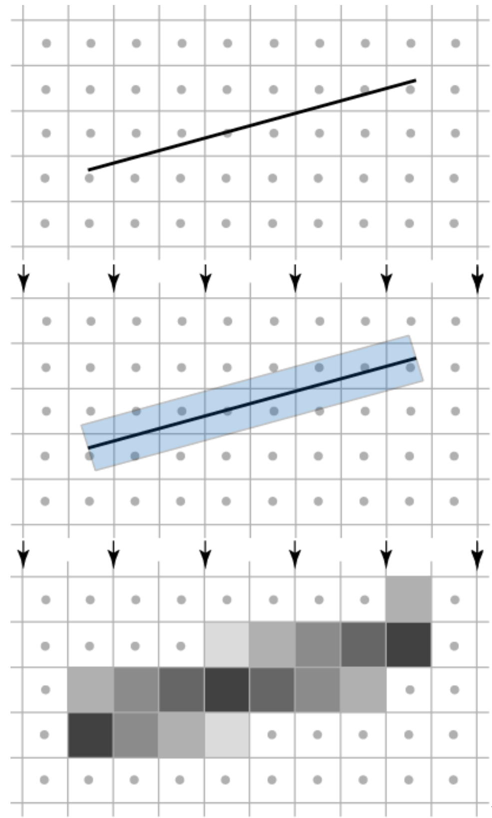
midpoint

same thickness



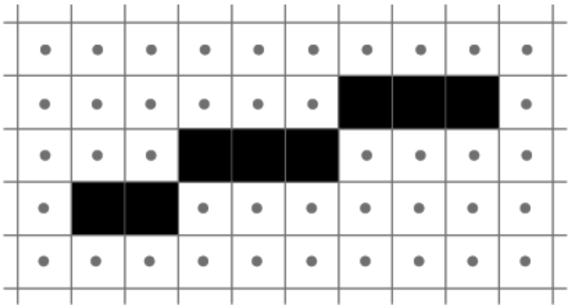
antialiased line rasterization

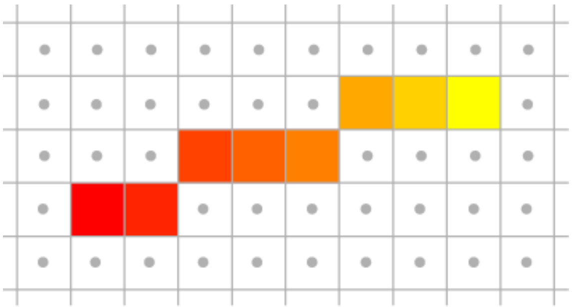
- for each pixel, color is the ratio of the area covered by the line
- need to touch multiple pixels per column
- can be done efficiently by precomputation and lookup tables
  - area only depends on line to pixel distance



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



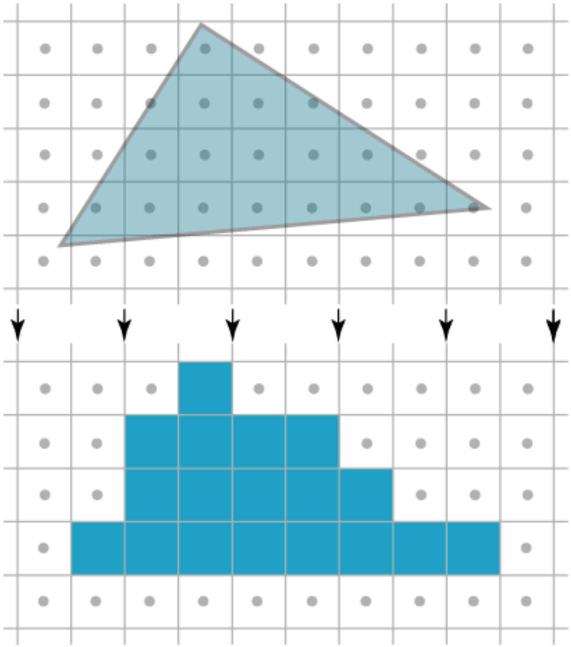


triangle rasterization

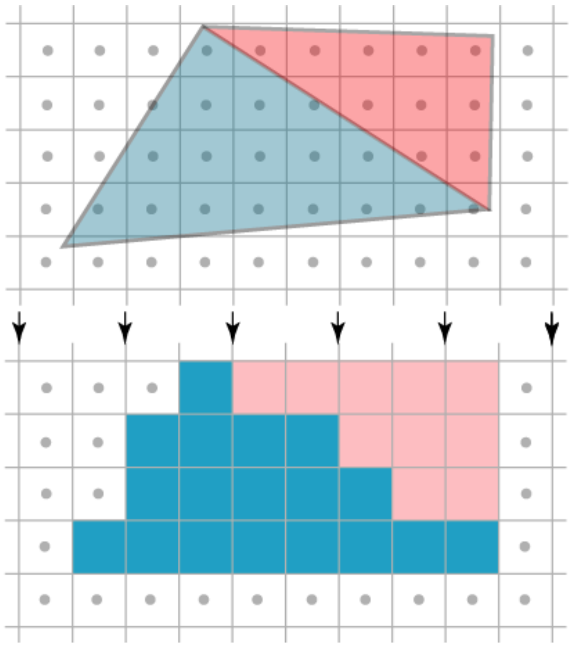
- most common operation in graphics pipelines
  - can be the only one: turn everything into triangles
- input: 2D triangle with vertex attributes
  - 2D vertex coordinates: $\{(x_0, y_0), (x_1, y_1), (x_2, y_2)\}$
  - other attributes: $\{q_{i0}, q_{i1}, q_{i2}\}$
- output: list of fragments with interpolated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

triangle rasterization

one triangle



consistent triangles

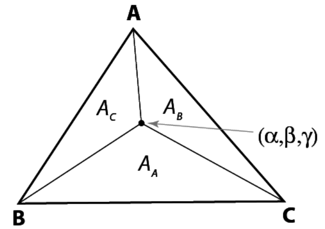


brute force triangle rasterization

- for each 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 of 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

```
foreach pixel(x,y) in triangle bounding box
    compute(alpha, beta, gamma)
    if(alpha,beta,gamma) in [0,1]^3
        qi = alpha*qi0 + beta*qi1 + gamma*qi2
        write(x, y, {qi})
```

- can be made incremental as in line drawing
- more efficient options exist, but...

triangle rasterization on hardware

- old hardware: optimized for large triangles
  - use smart algorithm
    - clip triangle to screen window
    - set up initial values
    - interpolate
  - hard to parallelize, high set up cost

triangle rasterization on hardware

- 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 set up cost
        - use tiles in image plane

rasterization take-home message

- complex but efficient set of algorithms
  - lots of small little details that matter 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 often have hidden costs
  - verify if they can be amortized
- loops are expensive: optimize as you can

fragment processing

vertex data

[vertex processing]

transformed vertex data

[clipping and rasterization]

fragments w/ interpolated data

[fragment processing]

fragments color and depth

[framebuffer processing]

framebuffer

fragment processing

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

framebuffer processing

vertex data

[vertex processing]

transformed vertex data

[clipping and rasterization]

fragments w/ interpolated data

[fragment processing]

fragments color and depth

[framebuffer processing]

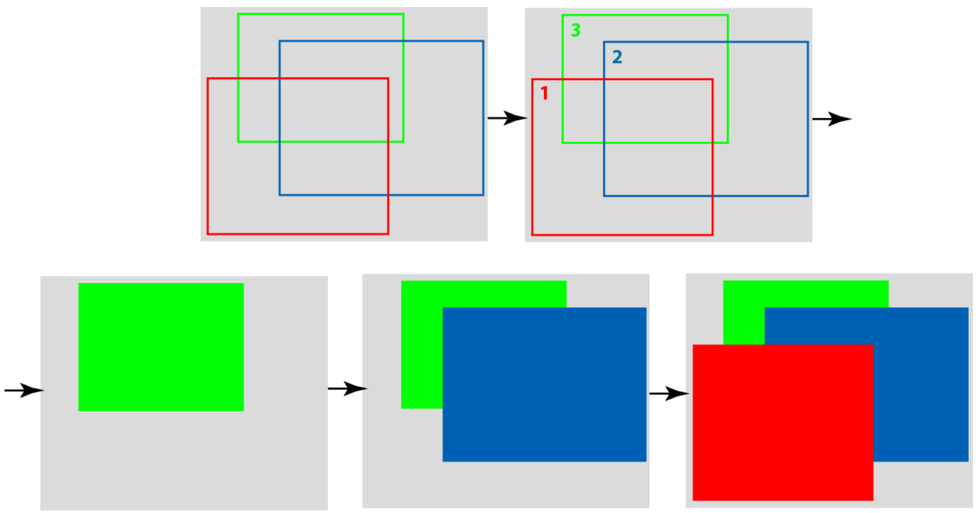
framebuffer

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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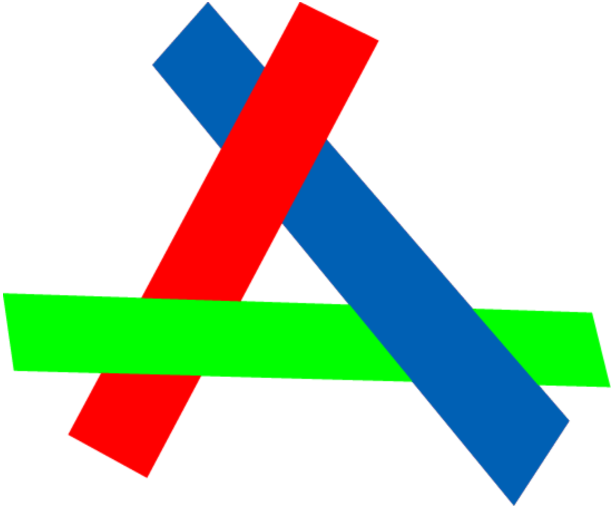
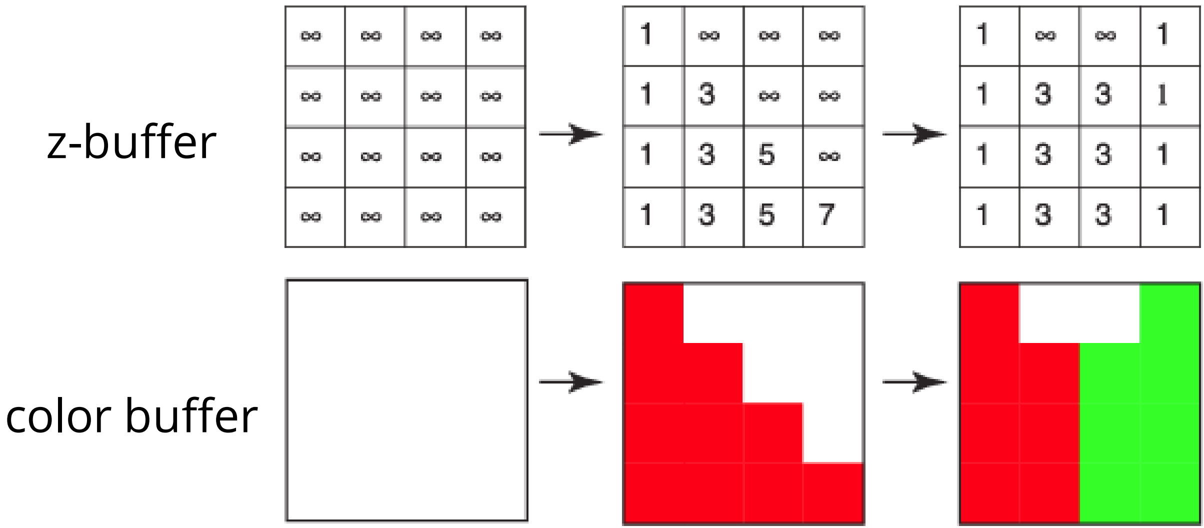


hidden surface removal - z buffer

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

hidden surface removal - z buffer

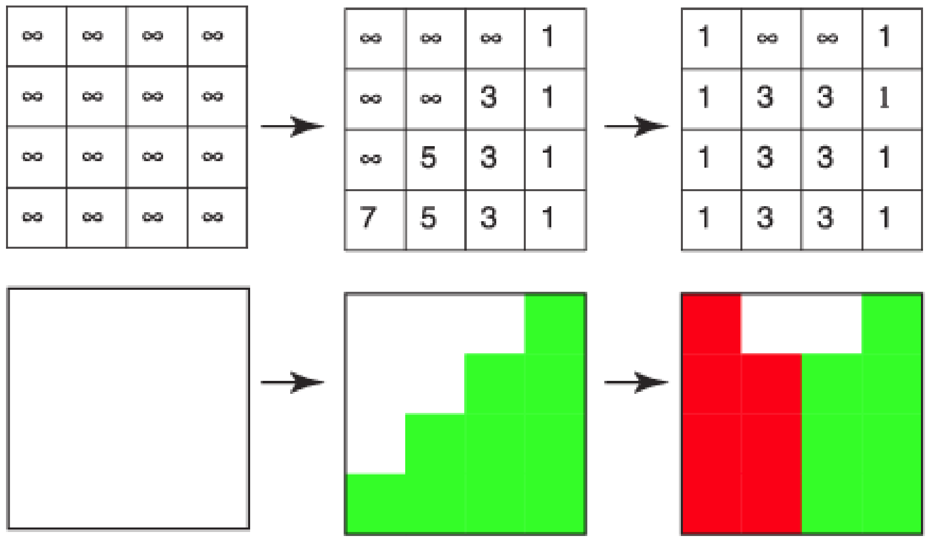


[adapted from Shirley]

hidden surface removal - z buffer

z-buffer

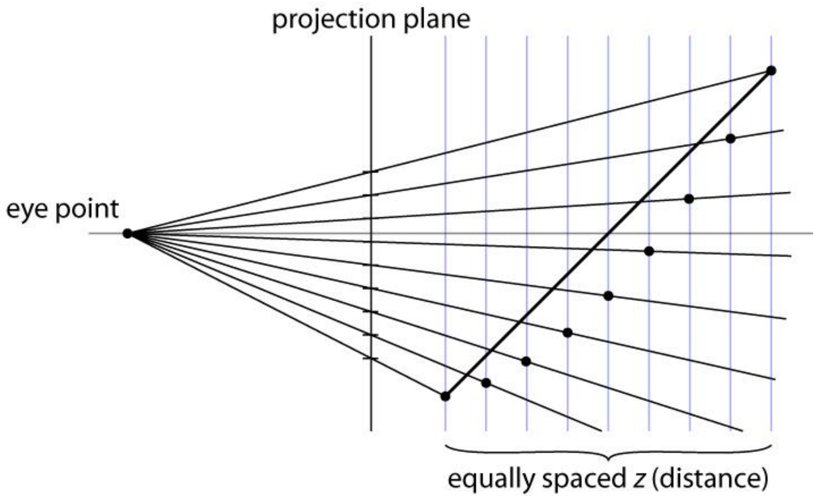
color buffer



[adapted from Shirley]

which z distance

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



[Marschner 2004]

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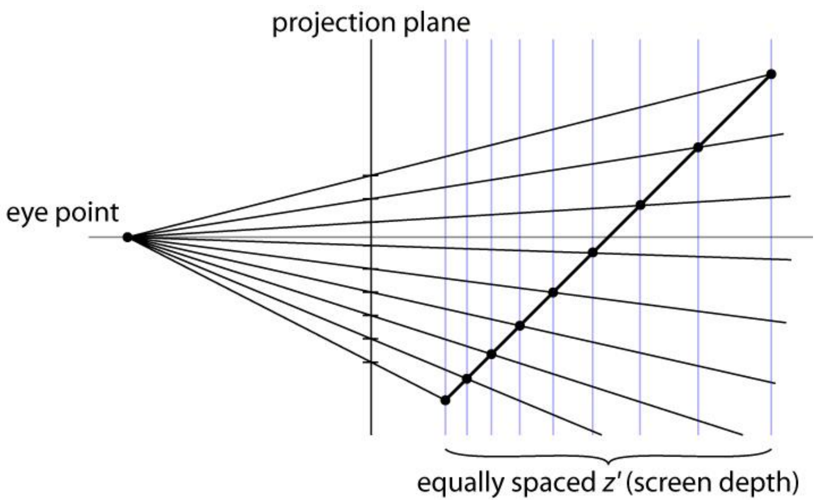


[Marschner 2004]

hidden surface removal - raycasting

- for each 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

- for each primitives, turn into small grids of quads
- hit-test quads by ray-casting
- keep list of sorted 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

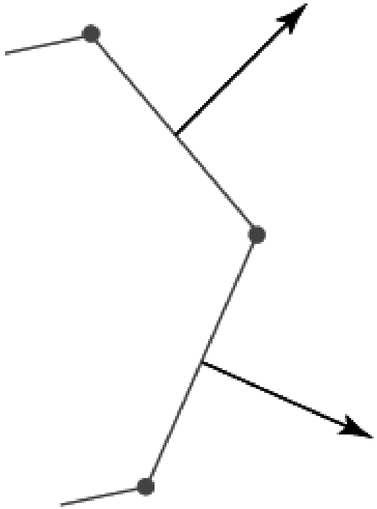
- hidden surface elimination using Z-buffer
- framebuffer blending using α-compositing
  - but cannot sort fragments properly
  - incorrect transparency blending
  - need to presort transparent surfaces only
    - like painter's algorithm, so not correct in many cases

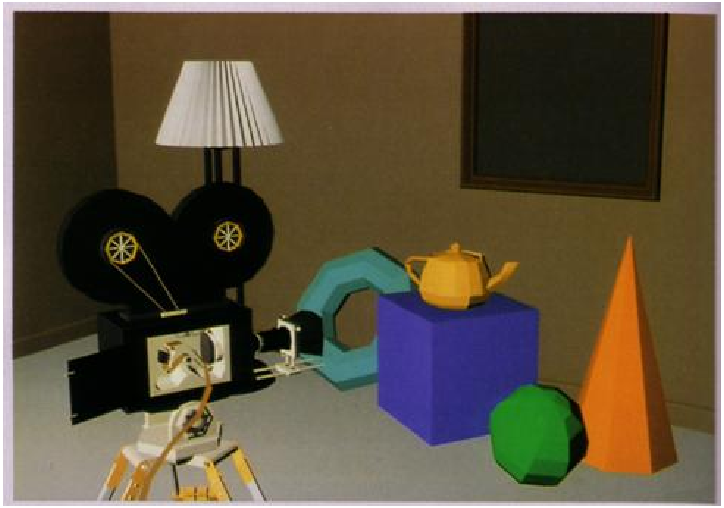
lighting computation

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

lighting computation - flat shading

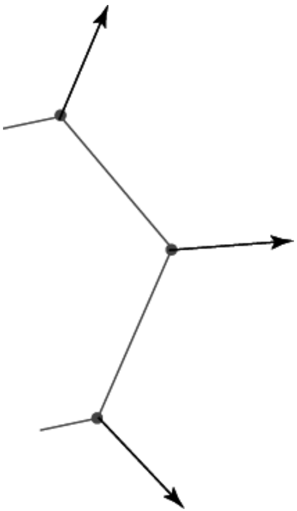
- compute using normals of the triangle
  - same as in raytracing
- flat and faceted look
- correct: no geometrical inconsistency

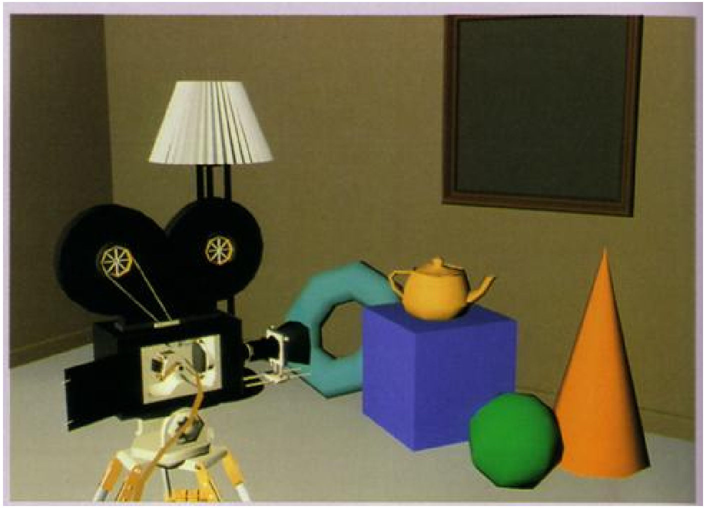




lighting computation - gouraud shading

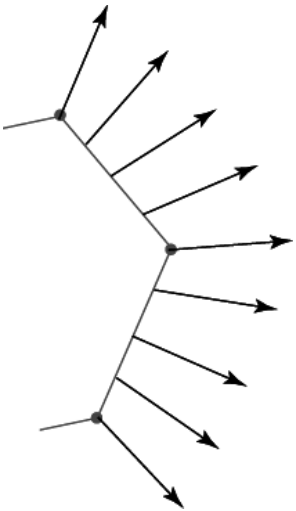
- compute light at vertex position
  - with vertex normals
- interpolate colors linearly over the triangle





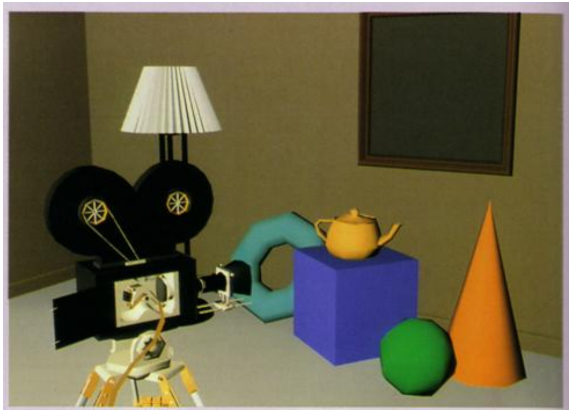
lighting computation - phong shading

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



lighting computation comparison

Gouraud



artifacts in highlights

Phong

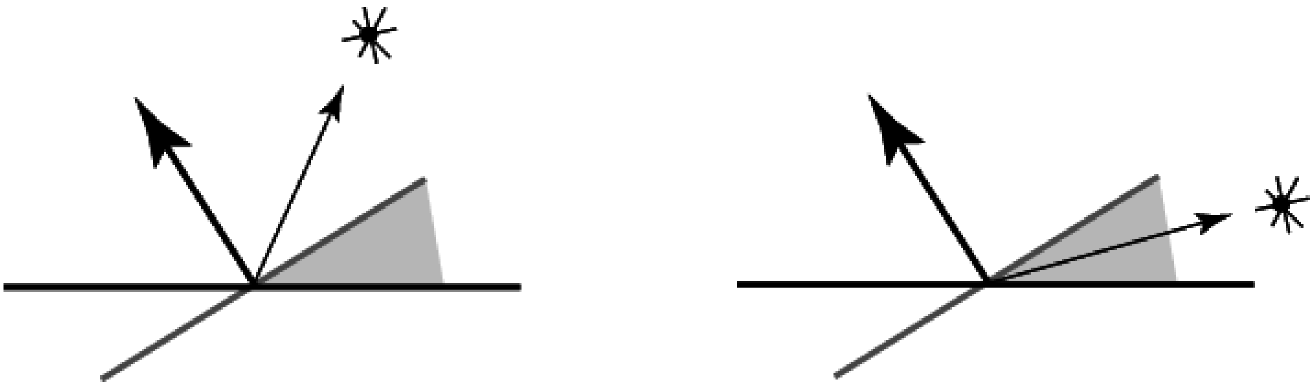
good highlights

lighting computation

- per-pixel lighting is becoming ubiquitous
  - much more robust
  - move lighting from vertex to fragment processing
    - new hardware architectures allow for this
    - we introduce Gouraud for historical reasons
  - raytracing can have this by using shading normals

lighting computation

- 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 GTX Titan: 2688 stream processors
- very small caches
  - not needed since memory accesses 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 pipelines vs. raytracing

raycasting

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

graphics pipeline

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