

Computer Graphics

- Rasterization -

Philipp Slusallek

Rasterization

- **Definition**

- Given some 2D geometry (point, line, circle, triangle, polygon,...), specify which pixels of a raster display each primitive *covers*
 - Often also called “scan-conversion”
- Anti-aliasing: instead of only fully-covered pixels (single sample), specify what parts of a pixel is *covered* (multi/super-sampling)

- **Perspectives**

- OpenGL lecture: from an application programmer’s point of view
- This lecture: from a graphics package implementer’s point of view
- Looking at rasterization of (i) lines and (ii) polygons (areas)

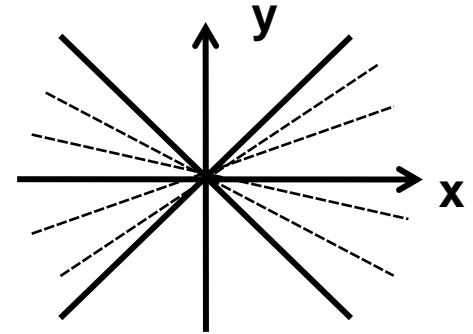
- **Usages of rasterization in practice**

- 2D-raster graphics, e.g. Postscript, PDF, SVG, ...
 - 3D-raster graphics, e.g. SW rasterizers (Mesa, OpenSWR), HW
 - 3D volume modeling and rendering
 - Volume operations (CSG operations, collision detection)
 - Space subdivision (spatial indices): construction and traversal
-

Rasterization

- **Assumptions**

- Pixels are sample **points** on a 2D integer grid
 - OpenGL: cell bottom-left, integer-coordinate
 - X11, Foley: at the cell center (we will use this)
- Simple raster operations
 - Just setting pixel values or not (binary decision)
 - More complex operations later: compositing/anti-aliasing
- Endpoints snapped to (sub-)pixel integer coordinates
 - Simple and consistent computations with fixed-point arithmetic
- Limiting to lines with gradient/slope $|m| \leq 1$ (mostly horizontal)
 - Separate handling of horizontal and vertical lines
 - For mostly vertical, swap x and y ($|1/m| \leq 1$), rasterize, swap back
 - Special cases in SW, trivial in HW :-)
- Line width is one pixel
 - $|m| \leq 1$: 1 pixel per column (X-driving axis)
 - $|m| > 1$: 1 pixel per row (Y-driving axis)



Lines: As Functions

- **Specification**

- Initial and end points: $(x_b, y_b), (x_e, y_e), (dx, dy) = (x_e - x_b, y_e - y_b)$
- Functional form: $y = mx + B$
- End points with integer coordinates \Rightarrow rational slope $m = dy/dx$

- **Goal**

- Find that pixel per column whose distance to the line is smallest

- **Brute-force algorithm**

- Assume that +X is the driving axis \rightarrow set pixel in every column

for $x_i = x_b$ to x_e

$$y_i = m * x_i + B$$

setPixel(x_i , Round(y_i)) // Round(y_i) = Floor($y_i + 0.5$)

- **Comments**

- Variables m and thus y_i need to be calculated in floating-point
 - Not well suited for direct HW implementation
 - A floating-point ALU is significantly larger in HW than integer
-

Lines: DDA

- **DDA: Digital Differential Analyzer**
 - Origin of incremental solvers for simple differential equations
 - The Euler method
 - Per time-step: $x' = x + dx/dt$, $y' = y + dy/dt$
 - **Incremental algorithm**
 - Choose $dt=dx$, then per pixel
 - $x_{i+1} = x_i + 1$
 - $y_{i+1} = m * x_{i+1} + B = m(x_i + 1) + B = (m * x_i + B) + m = y_i + m$
 - `setPixel(xi+1, Round(yi+1))`
 - **Remark**
 - Utilization of **coherence** through **incremental** calculation
 - Avoids the “costly” multiplication
 - Accumulates error over length of the line
 - Up to 4k additions on UHD!
 - Floating point calculations may be moved to fixed point
 - Must control accuracy of fixed point representation
 - Enough extra bits to hide accumulated error (>>12 bits for UHD)
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Lines: Bresenham (1963)

- **DDA analysis**

- Critical point: decision whether we need rounding up or down

- **Idea**

- Integer-based decision through implicit functions
- Implicit line equation

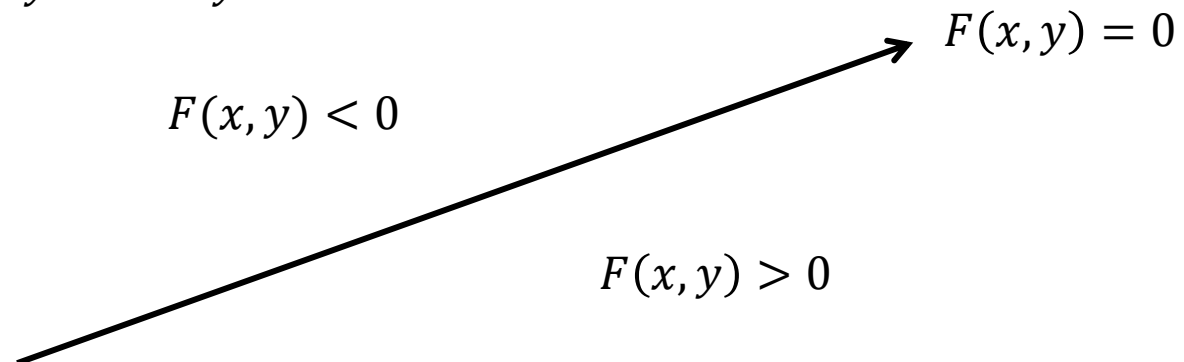
- $F(x, y) = ax + by + c = 0$

- Here with $y = mx + B = \frac{dy}{dx}x + B \Rightarrow 0 = dyx - dx y + B dx$

- $a = dy, \quad b = -dx, \quad c = Bdx$

- Results in

- $F(x, y) = dyx - dx y + dx B = 0$

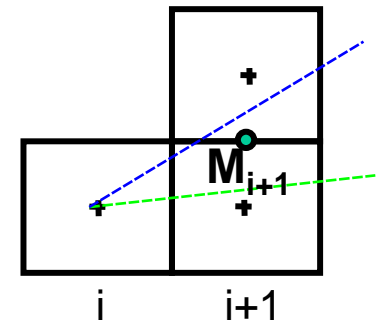


Lines: Bresenham

- **Decision variable d (the midpoint formulation)**

- Assume we are at $x=i$, calculating next step at $x=i+1$
- Measures the vertical distance of midpoint from line:

$$\begin{aligned}d_{i+1} &= F(M_{i+1}) = F(x_i + 1, y_i + 1/2) \\ &= a(x_i + 1) + b(y_i + 1/2) + c\end{aligned}$$



- **Preparations for the next pixel**

IF ($d_{i+1} \leq 0$) // Increment in x only

$$d_{i+2} = d_{i+1} + a = d_{i+1} + dy \quad // \text{Incremental calculation}$$

ELSE // Increment in x and y

$$d_{i+2} = d_{i+1} + a + b = d_{i+1} + dy - dx$$

$$y = y + 1$$

ENDIF

$$x = x + 1$$

Lines: Integer Bresenham

- **Initialization**

- $d_1 = F\left(x_b + 1, y_b + \frac{1}{2}\right) = a(x_b + 1) + b\left(y_b + \frac{1}{2}\right) + c$

- $= ax_b + by_b + c + a + \frac{b}{2} = F(x_b, y_b) + a + \frac{b}{2} = a + \frac{b}{2}$

- Because $F(x_b, y_b)$ is zero by definition (line goes through (x_b, y_b))
 - Pixel is always set (but check consistency rules → later)

- **Elimination of fractions**

- Any positive scale factor maintains the sign of $F(x, y)$
 - $2F(x_b, y_b) = 2(ax_b + by_b + c) \rightarrow d_{start} = 2a + b$

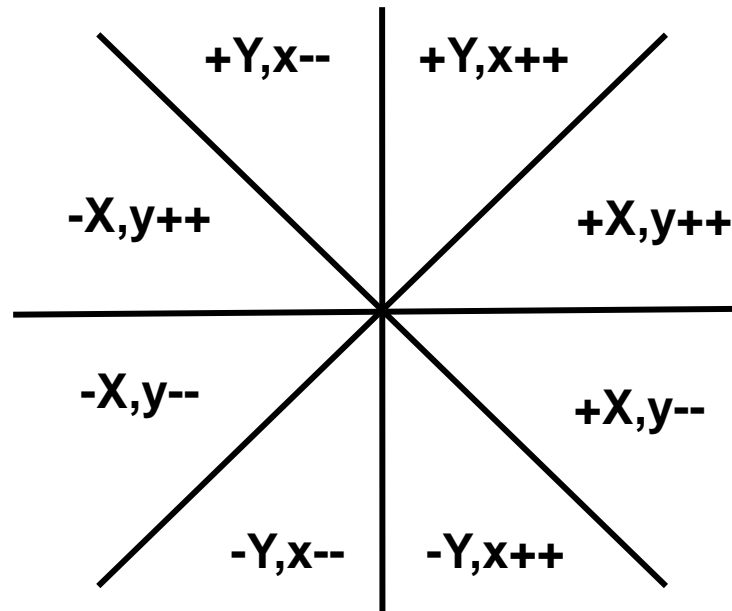
- **Observation:**

- When the start and end points have integer coordinates then $b = -dx$ and $a = dy$ are also integers
 - Floating point computation can be eliminated
 - **No accumulated error!!**

Lines: Arbitrary Directions

- **8 different cases**

- Driving (active) axis: $\pm X$ or $\pm Y$
- Increment/decrement of y or x , respectively

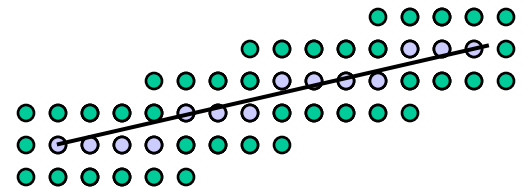
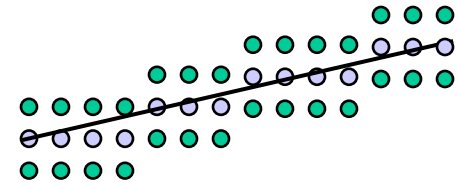


Thick Lines

- **Pixel replication**



- Problems with even-numbered widths
- Varying intensity of a line as a function of slope

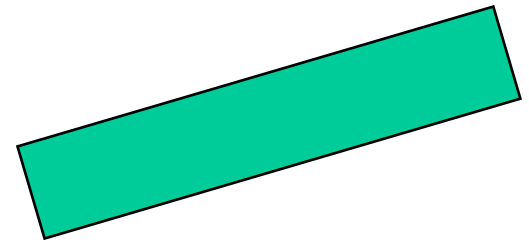


- **The moving pen**

- For some pen footprints the thickness of a line might change as a function of its slope
- Should be as “round” as possible

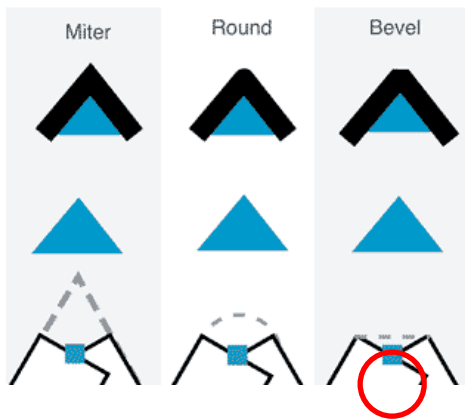
- **Real Solution: Draw 2D area**

- Allows for anti-aliasing and fractional width
- Main approach these days!



Handling Start and End Points

- **End points handling (not available in current OpenGL)**
 - Joining: handling of joints between lines
 - Bevel: connect outer edges by straight line
 - Miter: join by extending outer edges to intersection
 - Round: join with radius of half the line width
 - Capping: handling of end point
 - Butt: end line orthogonally at end point
 - Square: end line with oriented square
 - Round: end line with radius of half the line width
 - Avoid **overdraw** when lines join



Bresenham: Circle

- **Eight different cases, here +X, y--**

Initialization: $x = 0, y = R$

$$F(x,y) = x^2 + y^2 - R^2$$

$$d = F(x+1, y-1/2)$$

IF $d < 0$

$$d = F(x+2, y-1/2)$$

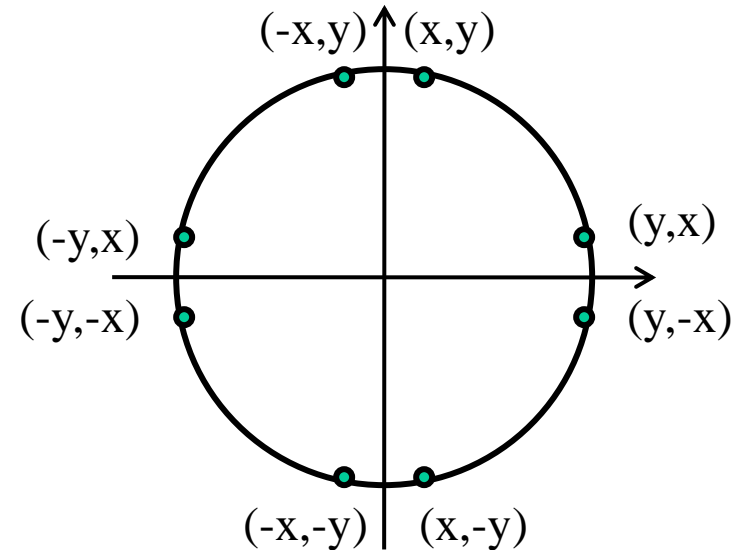
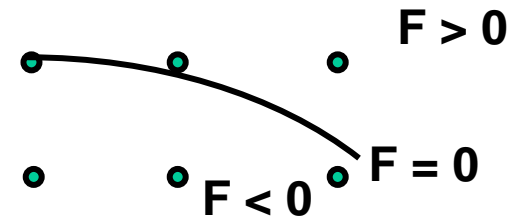
ELSE IF $d > 0$

$$d = F(x+2, y-3/2)$$

$$y = y-1$$

ENDIF

$$x = x+1$$



- Works because slope is smaller than 1
- **Eight-way symmetry: only one 45° segment is needed to determine all pixels in a full circle**

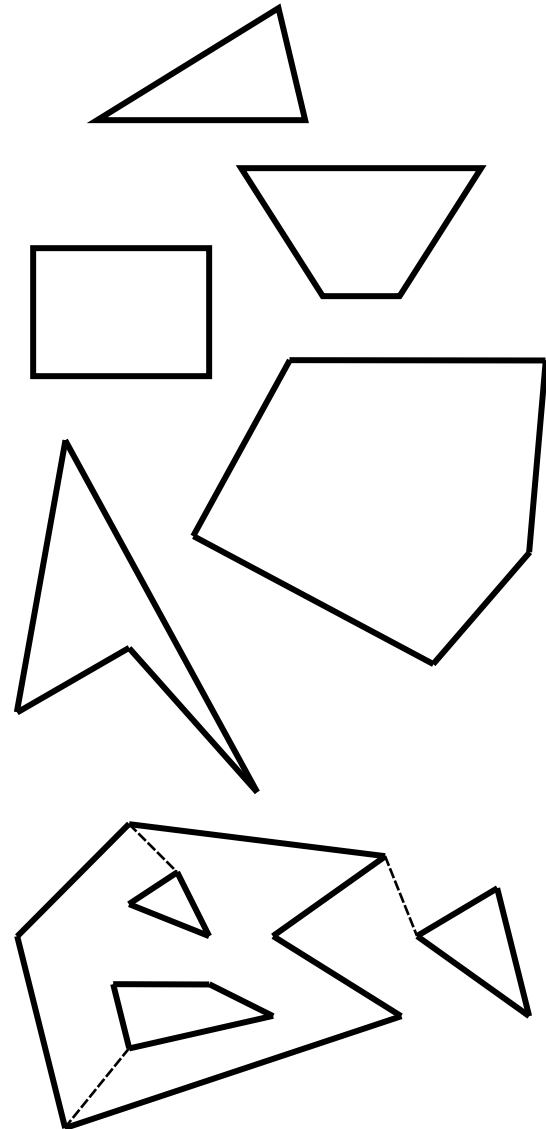
Reminder: Polygons

- **Types**

- Triangles
- Trapezoids
- Rectangles
- Convex polygons
- Concave polygons
- Arbitrary polygons
 - Holes
 - Overlapping

- **Two approaches**

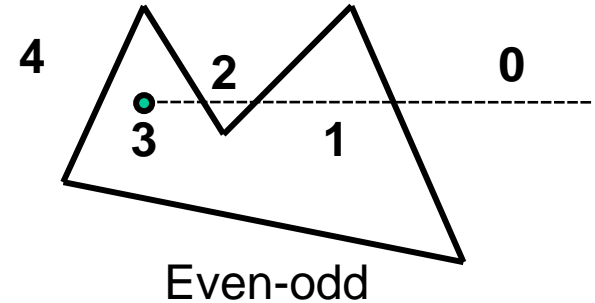
- Polygon tessellation into triangles
 - Only option for OpenGL
 - Must mark internal edges so they are not drawn for outlines
- Direct scan-conversion
 - Mostly in early SW algorithms



Inside-Outside Tests

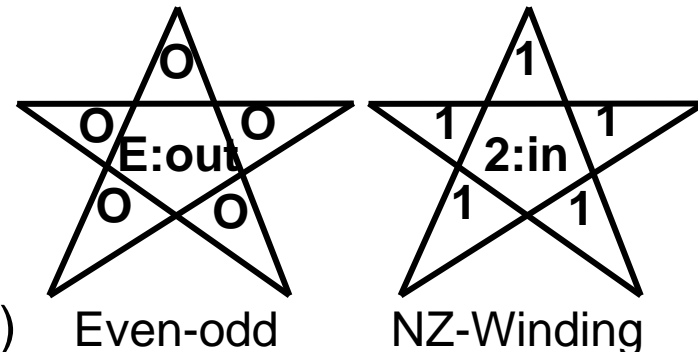
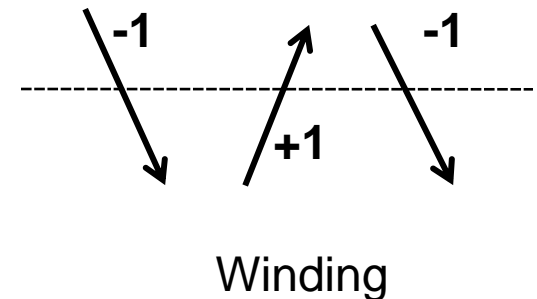
- **What is the interior of a polygon?**

- Jordan curve theorem
 - „Any continuous **simple** closed curve in the plane, separates the plane into two disjoint regions, the inside and the outside, one of which is bounded.“



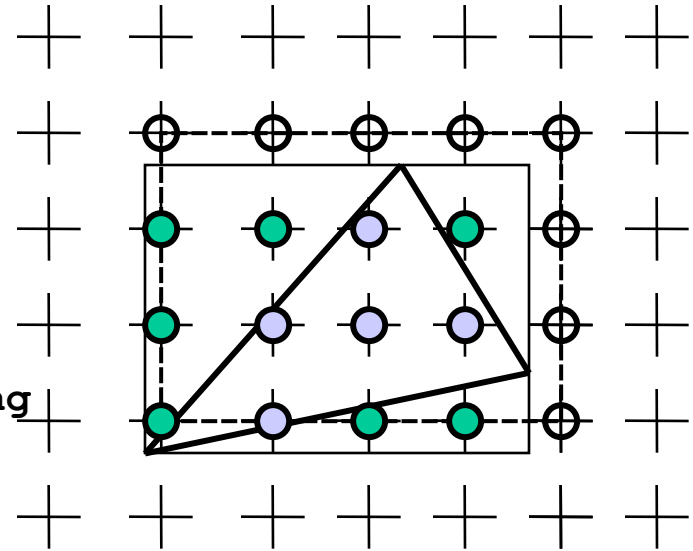
- **What to do with *non-simple* polygons?**

- Even-odd rule (odd parity rule)
 - Counting the number of edge crossings with a ray starting at the queried point **P** till infinity
 - Inside, if the number of crossings is odd
- (Non-zero) winding number rule
 - Counts # times polygon wraps around **P**
 - Signed intersections with a ray
 - Inside, if the number is not equal to zero
- Differences only in the case of non-simple curves (e.g. self-intersection)



Triangle Rasterization

```
Raster3_box(vertex v[3])
{
    int x, y;
    bbox b;
    bound3(v, &b);
    for (y = b.ymin; y < b.ymax; y++)
        for (x = b.xmin; x < b.xmax; x++)
            if (inside(v, x, y)) // upcoming
                fragment(x, y);
}
```



- **Brute-force algorithm**

- Iterate over all pixels within bounding box

- **Possible approaches for dealing with scissoring**

- Scissoring: Only draw on AA-Box of the screen (region of interest)
 - Test triangle for overlap with scissor box, otherwise discard
 - Use intersection of scissor and bounding box, otherwise as above
 - Important if clipping only against enlarged region!
-

Rasterization w/ Edge Functions

- **Approach (Pineda, '88)**

- Implicit edge functions for every edge

$$F_i(x, y) = ax + by + c$$

- Point is *inside* triangle, if every

$$F_i(x, y) \text{ has the same sign}$$

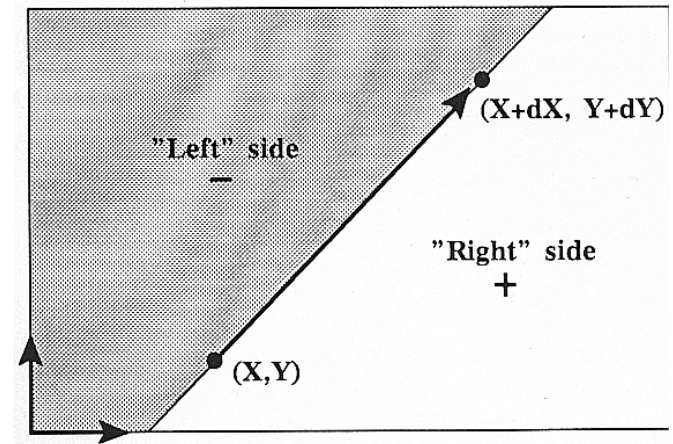
- Perfect for parallel evaluation at many points

- Particularly with wide SIMD machines (GPUs, SIMD CPU instructions)

- Requires “triangle setup”: Computation of edge function (a, b, c)
- Evaluation can also be done in homogeneous coordinates

- **Hierarchical approach**

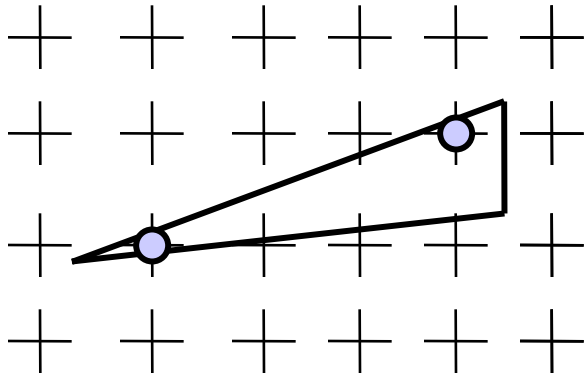
- Can be used to efficiently check large rectangular blocks of pixels
 - Divide screen into tiles/bins (possibly at several levels)
 - Evaluate F at tile corners
 - Recurse only where necessary, possibly until subpixel level



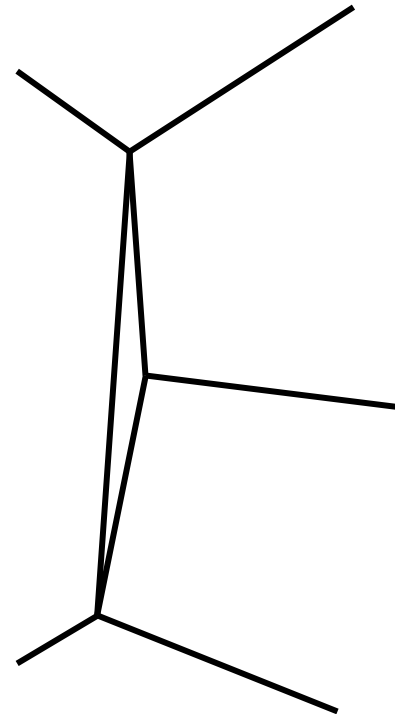
Gap and T-Vertices

- **Observations**

- Pixels set can be non-connected
- May have overlap and gaps at T-edges



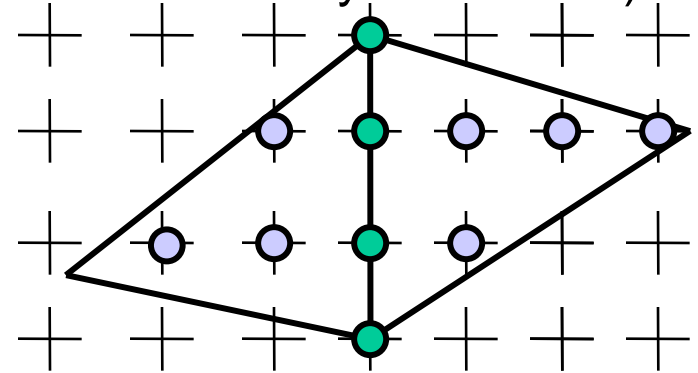
Non-connected pixels: OK



Not OK: Model must be changed

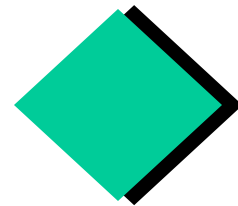
Problem on Edges

- **Consistency: edge singularity (shared by 2 triangles)**
 - What if term $d = ax+by+c = 0$ (pixel centers lies exactly on the line)
 - For $d \leq 0$: pixels would get set twice
 - Problem with some algorithms
 - Transparency, XOR, CSG, ...
 - Missing pixels for $d < 0$ (set by no tri.)



- **Solution: “shadow” test**

- Pixels are not drawn on the right and bottom edges
- Pixels are drawn on the left and upper edges
 - Evaluated via derivatives a and b
- Testing for all edges also solves problem at vertices



```
inside(value d, value a, value b)
{
    // ax + by + c = 0
    return (d < 0) || (d == 0 && !shadow(a, b));
}
shadow(value a, value b)
{
    return (a > 0) || (a == 0 && b > 0);
}
```

Ray Tracing vs. Rasterization

- **In-Triangle test (for common origin)**
 - Rasterization:
 - Project to 2D, clip
 - Set up 2D edge functions, evaluate for each sample (using 2D point)
 - Ray tracing:
 - Set up 3D edge functions, evaluate for each sample (using direction)
 - The ray tracing test can also be used for rasterization in 3D
 - Avoids projection & clipping
 - **Enumerating scene primitives**
 - Rasterization (simple):
 - Sequentially enumerate them all in any order
 - Rasterization (advanced):
 - Build (coarse) spatial index (typically on application side)
 - Traverse with view frustum (large)
 - Possibly one frustum for every image tile separately, when using *tiled rendering*
 - Ray Tracing:
 - Build (detailed) spatial index
 - Traverse with (infinitely thin) ray or with some (typically small) frustum
 - Both approaches can benefit greatly from spatial index!
-

Ray Tracing vs. Rasterization (II)

- **Binning**

- Test to (hierarchically) find pixels likely to be covered by a primitive
- Rasterization:
 - Great speedup due to very large view frustum (many pixels)
- Ray tracing (frustum tracing)
 - Can speed up, depending on frustum size [Benthin'09]
- Ray Tracing (single/few rays)
 - Not needed

- **Conclusion**

- Both algorithms can use the same in-triangle test
 - In 3D, requires floating point, but boils down to 2D computation
- Both algorithms can benefit from spatial index
 - Benefit depends on relative cost of in-triangle test (HW vs. SW)
- Both algorithms can benefit from 2D binning to find relevant samples
 - Benefit depends on ratio of covered/uncovered samples per frustum

- **Both approaches are very similar**

- Different organization (size of frustum, binning)
 - There is no reason RT needs to be slower for primary rays (exc. FP)
-

HW-Supported Ray Tracing (finally)

Imagination-Grafikchip: 5 Mal schneller als GeForce GTX 980 Ti beim Raytracing

heise online 11.01.2016 17:25 Uhr Martin Fischer

vorlesen



Fünf Mal schneller als eine GeForce GTX 980 Ti soll die Mobil-GPU PowerVR GR6500 sein, allerdings nur bei bestimmten Raytracing-Anwendungen.

Die Mobil-Grafikeinheit PowerVR GR6500 soll fünf Mal schneller arbeiten als Nvidias GeForce GTX 980 Ti bei nur einem Zehntel der Leistungsaufnahme; allerdings nur bei bestimmten Raytracing-Anwendungen.

HW-Supported Ray Tracing (finally)

Druckversion - Nvidia GeForce RTX 2070-2080-2080-Ti-Raytracing-Be...

https://www.heise.de/newsticker/meldung/Nvidia-GeForce-RTX-2070-2080-2080-Ti-Raytracing-Be...


Apps Private Lehrstuhl Uni IVCI DFKI CISPA MPI MPI-SWS Weitere Lesezeichen

«zurück zum Artikel

heise online

Nvidia GeForce RTX 2070, 2080, 2080 Ti: Raytracing stolzen Preisen

20.08.2018 19:51 Uhr
Martin Fischer



Intel's new Xe GPU will have hardware-accelerated ray tracing




August 13, 2020 Intel has now confirmed that the Xe-HPG microarchitecture exists and that it will have ray tracing.

AMD unveils three Radeon 6000 graphics cards with ray tracing and RTX-beating performance

The RX 6800, 6800 XT and 6900 XT are coming soon.

News by **Will Judd**, Senior Staff Writer, Digital Foundry
Updated on 28 October 2020



It's time for **BIG NAVI**, as AMD has unveiled their new Radeon graphics cards: the \$579 RX 6800, \$649 RX 6800 XT and \$999 RX 6900 XT. AMD claims that the cards should meet or beat Nvidia's flagship RTX 30-series graphics cards, all the way up to the \$1499 RTX 3090, often at lower price and while consuming less power. The 6000-series cards are also the first desktop AMD GPUs to support real-time ray tracing, variable rate shading and other DirectX 12 Ultimate features. All in all, it's an exciting package for AMD fans - and would-be Nvidia users that might have become frustrated with poor RTX 30-series availability.

besonders effizient bei Raytracing-Berechnungen

eration vorgestellt. Die beiden High-End-Modelle