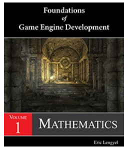
GPU Font Rendering

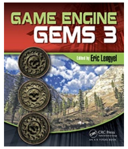
Current State of the Art

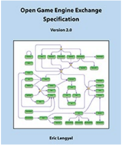
Eric Lengyel, Ph.D.
Terathon Software

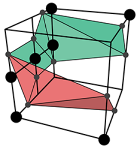
About the speaker

- Working in game/graphics dev since 1994
  - Previously at Sierra, Apple, Naughty Dog
- Current projects:
  - Slug Library, C4 Engine, The 31st, FGED









About this talk

- Unicode
- Glyphs
- TrueType
- Font Rendering
- Typography

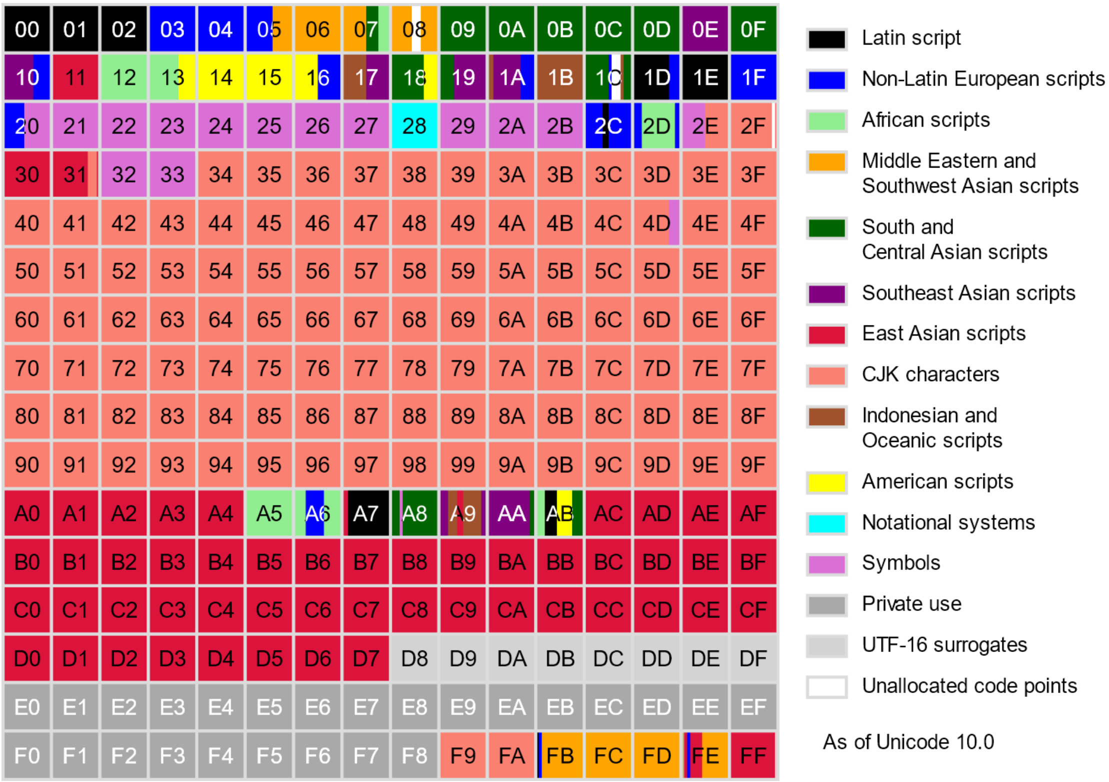
Unicode

- Defines character codes
- Originally 16-bit
- Now has range 0x000000 – 0x10FFFF
- Divided into 17 “planes”

Basic Multilingual Plane

- 0x0000 – 0xFFFF
- First 128 code points are ASCII
- Lots of other common scripts/languages
- Lots of common symbols

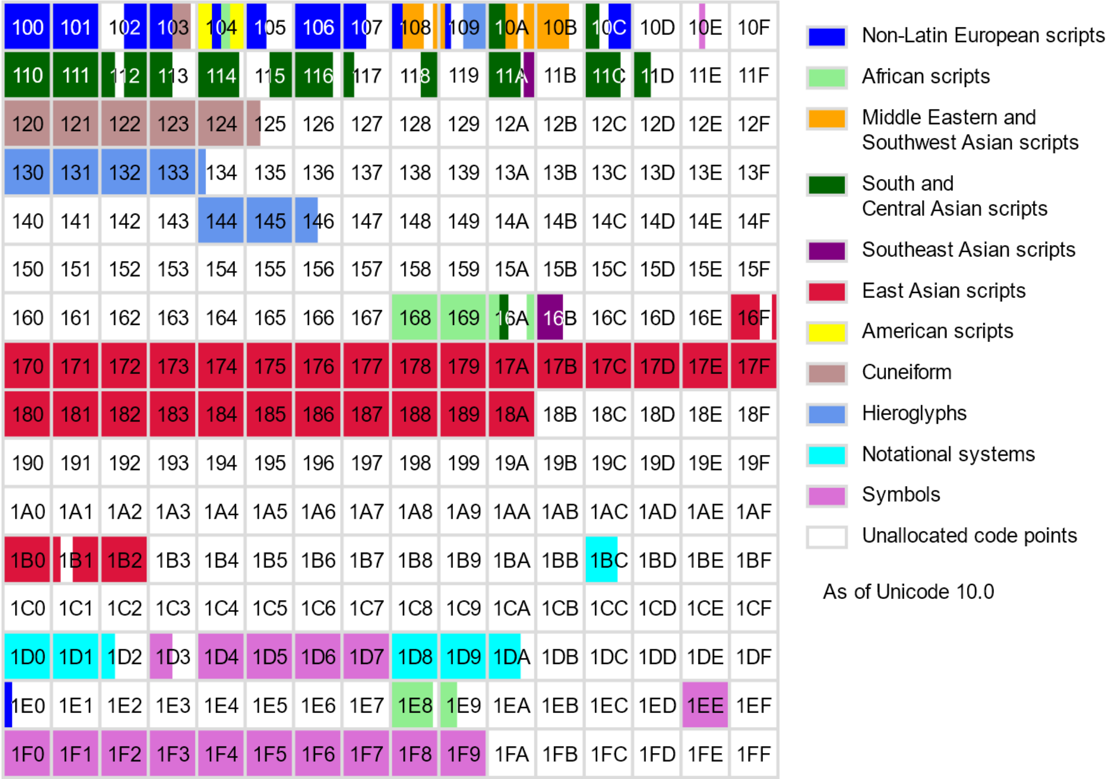
Basic Multilingual Plane



Supplementary Multilingual Plane

- 0x010000 – 0x01FFFF
- Rare characters from many languages
- Rare scripts like Cuneiform and Hieroglyphs
- Mathematical symbols and bold / italic
- Emoticons 👩‍🔬

Supplementary Multilingual Plane



As of Unicode 10.0

Supplementary Ideographic Plane

- 0x020000 – 0x02FFFF
- Less common CJK ideographs

Supplementary Ideographic Plane

Other Planes

- Planes 0x03 – 0x0D unused
- Plane 0x0E contains special tags and variation selectors
- Planes 0x0F and 0x10 for private use only

Character Encoding

- ASCII
- UCS-2 (Universal Coded Character Set)
  - Always 16 bits per character
- UTF-16
  - 16 bits or 32 bits per character
- UTF-32
  - Always 32 bits per character

UTF-8

- 1 – 4 bytes per character
  - Using variable-length encoding
- Values 0x00 – 0x7F identical to ASCII
- High bit set indicates part of multi-byte sequence

UTF-8

- 1 byte: 0x00 – 0x7F
- 2 bytes: 0x0080 – 0x07FF
- 3 bytes: 0x0800 – 0xFFFF
- 4 bytes: 0x010000 – 0x10FFFF

Glyphs

- Fonts contain glyphs
- Glyphs have font-specific internal numbering
- Fonts contain tables that map character codes (Unicode values) to glyph indexes

Glyphs

- Fonts typically contain many more glyphs that are not directly mapped from characters
  - Type variations
  - Alternate styles
  - Ligatures, ZWJ sequences
  - Initial, medial, final forms (Arabic)
- More about these later

TrueType

- Contains resolution-independent representations of glyph outlines
- Has character-to-glyph mappings
- Usually contains several other tables with typographic information (e.g., kerning)

Glyph Outline

- Glyph defined by one or more closed contours
- Each contour defined by continuous sequence of quadratic Bézier curves
- Winding number determines whether a given point is inside the glyph

Winding Number

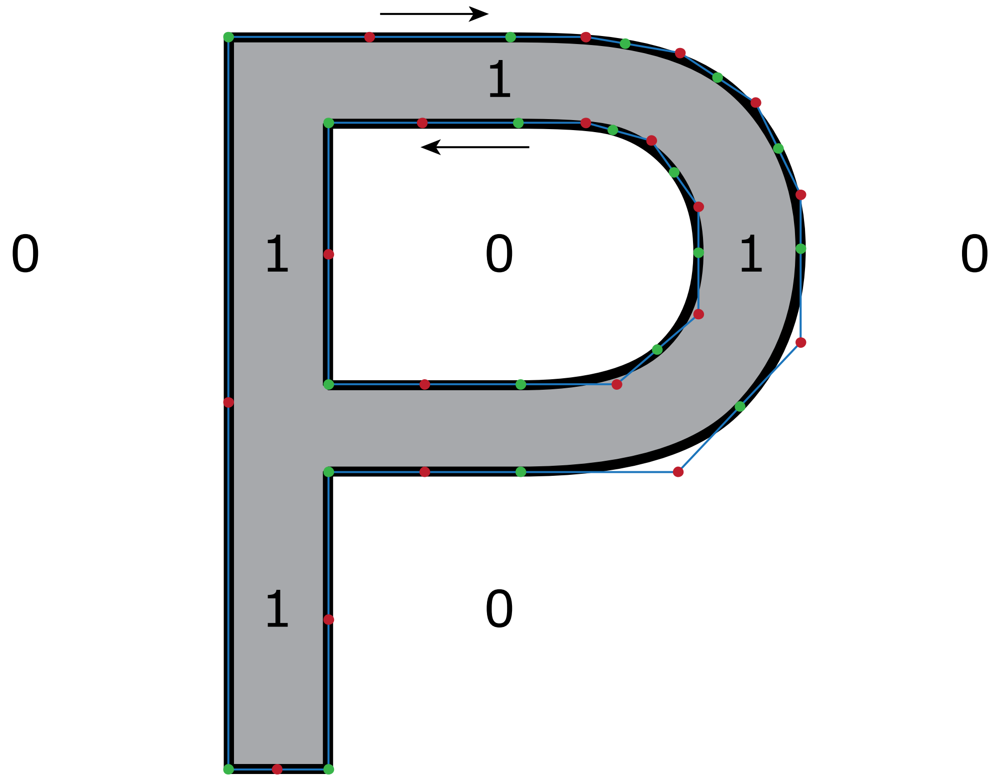
- Contours defining outer edge of glyph wound in one direction (either CW or CCW is okay)

- Contours defining a hole in the glyph wound in the opposite direction

Winding Number

- Count number of positive loops for outer contours
- Subtract number of negative loops for inner contours
- Nonzero means point inside glyph boundary

Glyph Outline / Winding Number



Font Rendering in Games

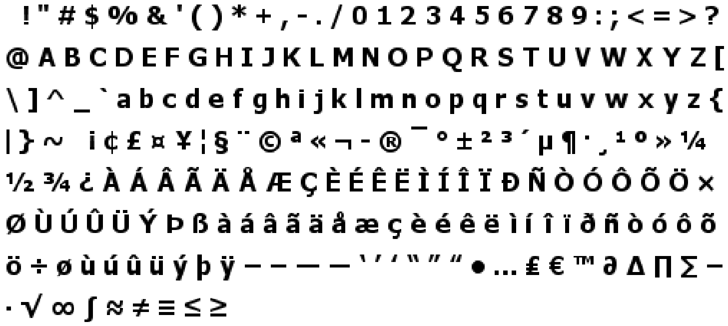
- Text rendered in lots of places
  - GUI: Buttons, menus, ...
  - HUD: Score, health, ammo, ...
  - In scene: Signs, labels, computer screens, ...
  - Debug info: Console, stats, timings, ...

GPU Font Rendering: Current State of the Art

Basic GPU Font Rendering

- Rasterize each glyph on CPU and store results in a texture map called an “atlas”
- Can be done for multiple font sizes at once
- Packing methods can vary in sophistication

Font Atlases



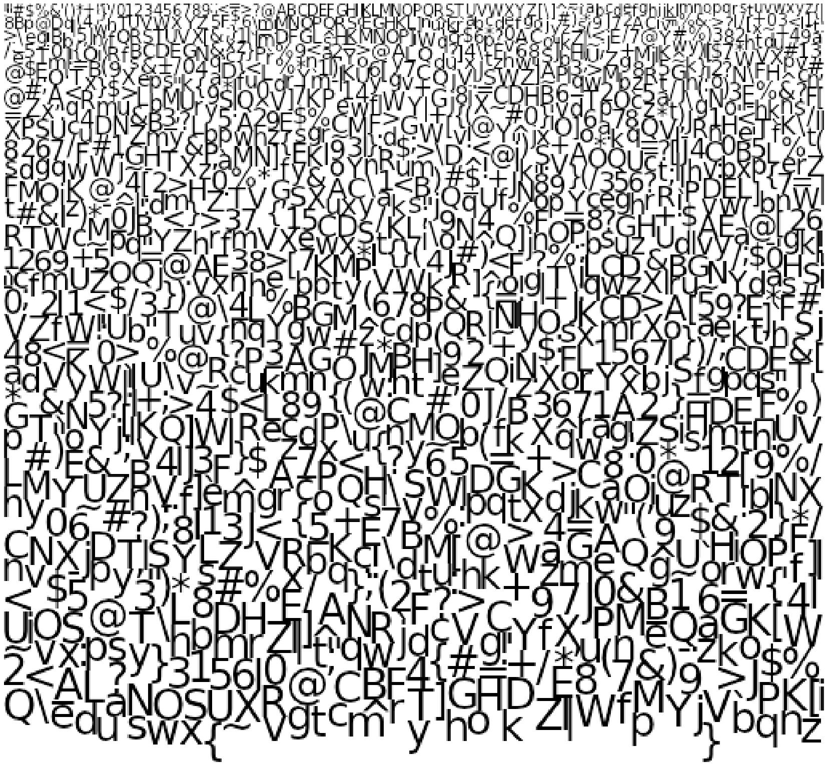


Image credit: freetype-gl

Font Atlases

- Render one quad for each glyph
- Texture map the glyph’s image from the atlas
- Very simple and stupid fast

Font Atlases

- Very limited quality
- Only looks good at originally rendered size
- Magnification looks terrible

Font Atlases

- Minification also problematic
- Mipmaps work to a degree
- Glyphs must be surrounded by empty space in atlas to prevent bleeding into neighbors

Signed Distance Fields

- Instead of storing glyph images in atlas, store distance to glyph outline at each point

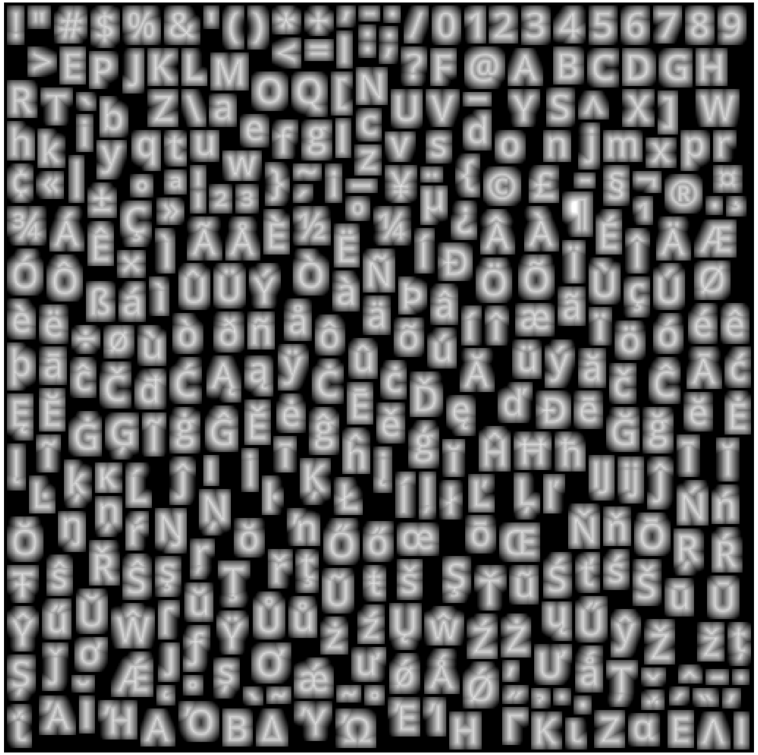


Image credit: Konstantin Käfer, “Drawing Text with Signed Distance Fields in Mapbox GL”, 2014.

Signed Distance Fields

- Render linear coverage by scaling distance to pixel units and clamping
- Requires derivatives in pixel shader and extra computation
- Still very fast

Signed Distance Fields

- Addresses magnification problem
- Also allows good perspective rendering

Image credit: Chris Green, "Improved Alpha-Tested Magnification for Vector Textures and Special Effects", 2007.

Signed Distance Fields

- Need high resolution to capture glyph details
- Sharp corners always rounded off
  - Can be addressed with multiple distance channels
- Minification becomes bigger problem
  - Because one distance value can't account for multiple curves in scaled-down field

Signed Distance Fields

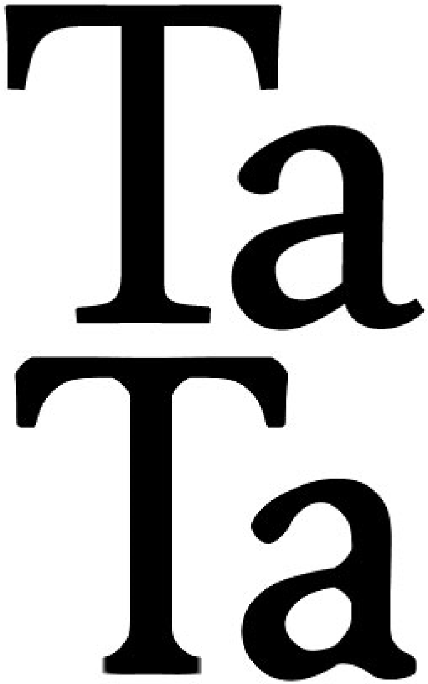


Image credit: David Rosen, “High-quality text rendering”, 2013.

Resolution Independence

- Render directly from original outline data
  - Control points for quadratic Bézier curves
- No more texture atlases!
  - No resolution-dependent approximation
  - Impossible to lose detail

Loop-Blinn Method

- Creates a triangulation for each glyph using its outline control points
- Each triangle corresponds to one Bézier curve
- Simple calculation based on interpolated texture coordinates yields inside/outside state

Loop-Blinn Method

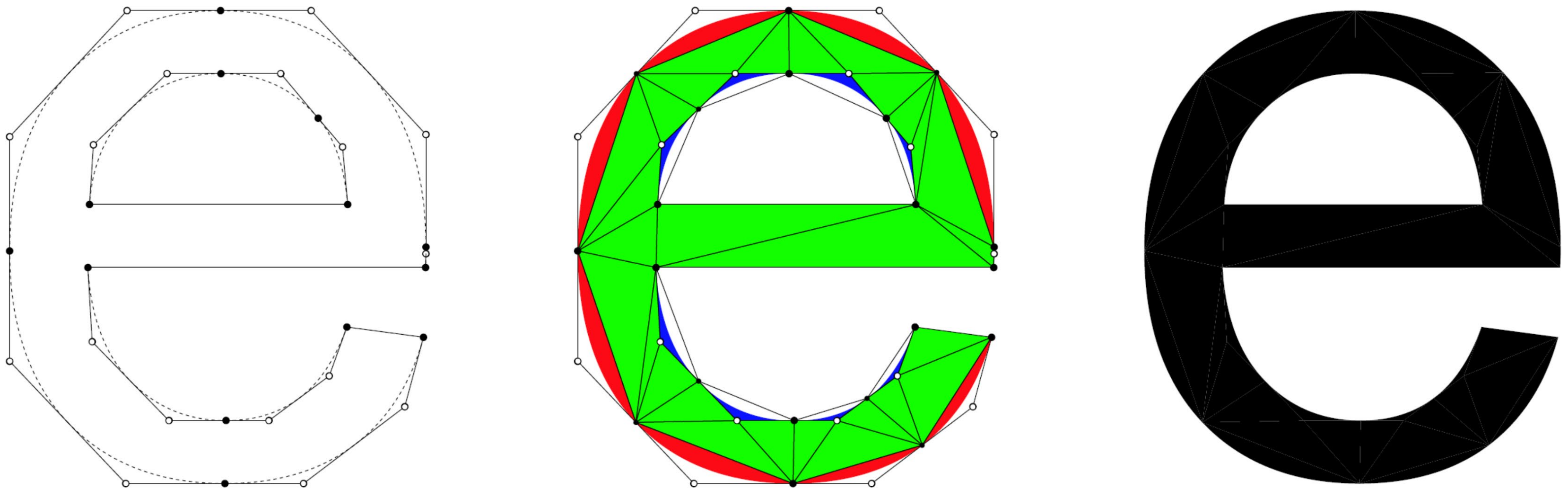


Image credit: Charles Loop and Jim Blinn, “Resolution Independent Curve Rendering using Programmable Graphics Hardware”, 2005.

Loop-Blinn Method

- Needs further subdivision for interior triangles so they never border more than one curve
- Correct antialiasing also requires more triangles in the exterior
  - Consider a pixel intersecting the outline but without its center covered by a triangle

Loop-Blinn Method

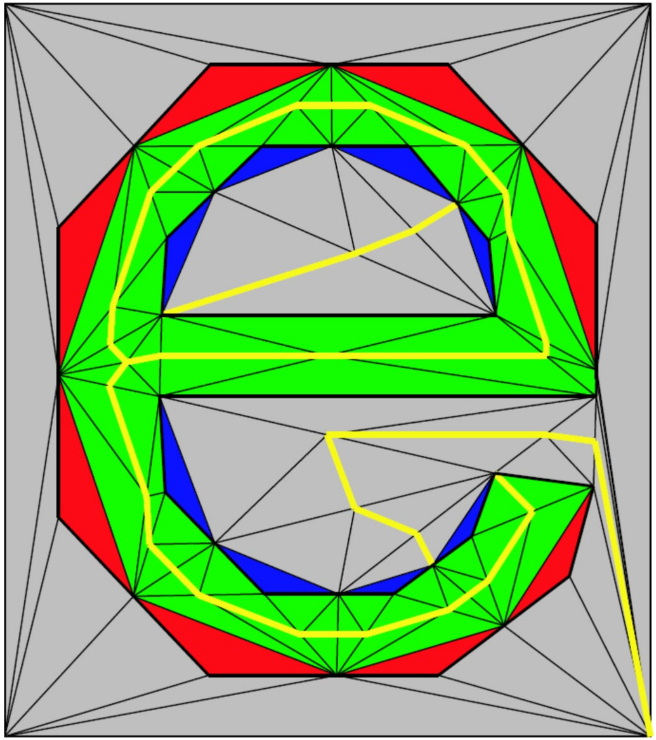


Image credit: Charles Loop and Jim Blinn, “Resolution Independent Curve Rendering using Programmable Graphics Hardware”, 2005.

Loop-Blinn Method

- Requires a large number of triangles for each glyph
- More complex glyphs could require 1000s!
- Calculation of triangles is complex

Loop-Blinn Method

- Produces high-quality magnification
- However, minification is poor
  - Any pixel is covered by at most one triangle
  - Each triangle corresponds to only one curve
  - Thus, it’s impossible for one pixel to consider contribution from multiple nearby curves

Dobbie Method

- Covers each glyph with a single quad
- Pixel shader considers subset of all Bézier curves to determine winding number
- Basically ray tracing glyphs

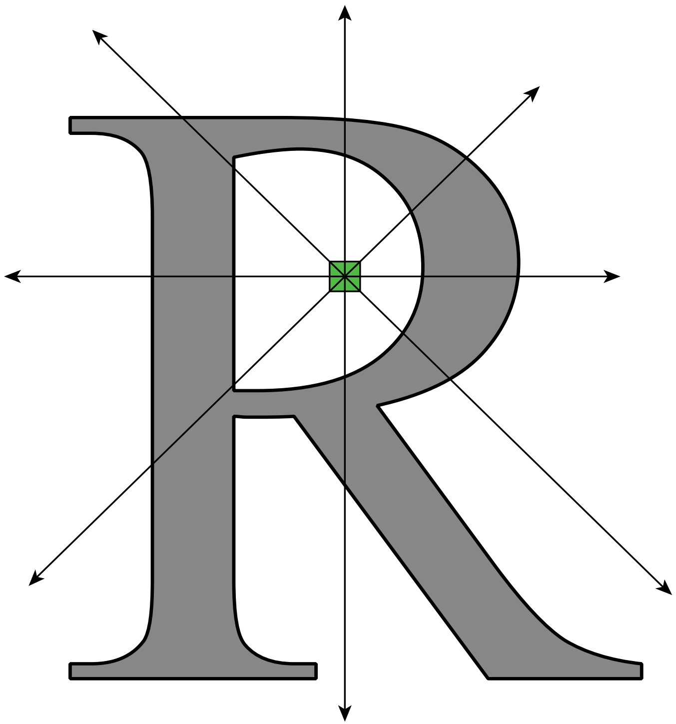
Dobbie Method

- For a given point, shoot a ray outward and count curve intersections
- An intersection makes a positive or negative contribution based on its winding direction
- Nonzero total means inside glyph boundary

Dobbie Method

- Antialiasing possible along ray direction
- If intersection occurs within pixel, it makes a fractional contribution
- Test rays in multiple directions and average to get isotropic antialiasing

Dobbie Method



Dobbie Method

- Very slow to test all Bézier curves defining the glyph for each ray
- Dobbie method divides glyph’s bounding box into cells
- Each cell has list of intersecting curves

Dobbie Method

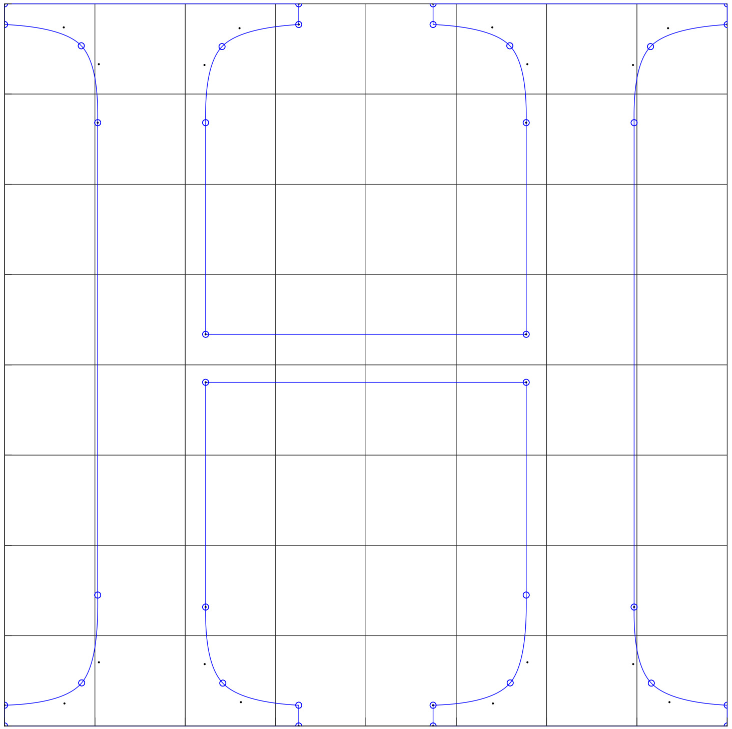


Image credit: Will Dobbie, "GPU text rendering with vector textures", 2016.

Dobbie Method

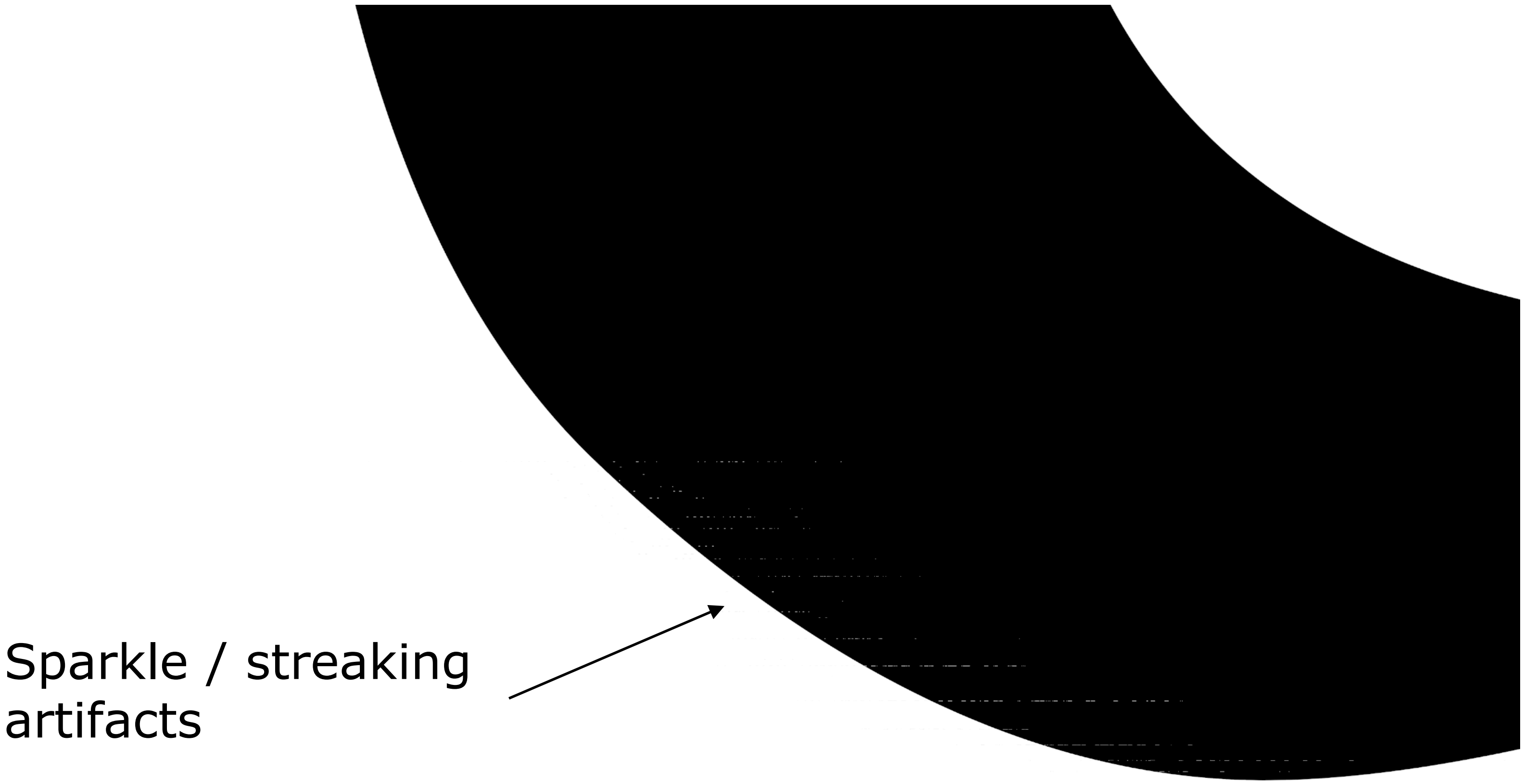
- Pixel footprint could overlap multiple cells
  - Have to sort that out in pixel shader

- Need to precompute whether cell center inside or outside glyph boundary
  - Then trace extra ray from pixel location to cell center to fix up winding number

Dobbie Method

- There’s a serious problem:
- Numerical robustness
- Floating-point round-off error causes rendering artifacts

Dobbie Method



Glyphy

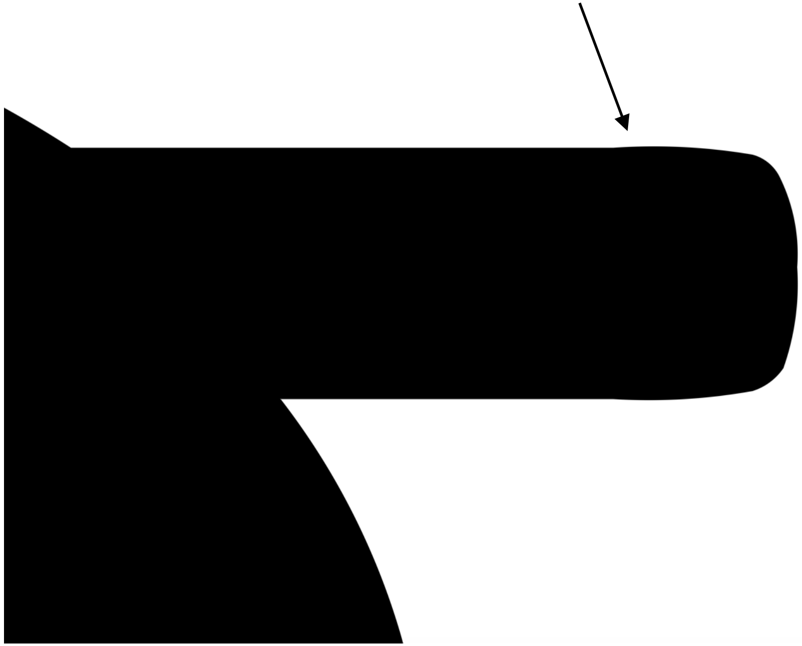
- Similar to Dobbie method in that a glyph is covered by a single quad

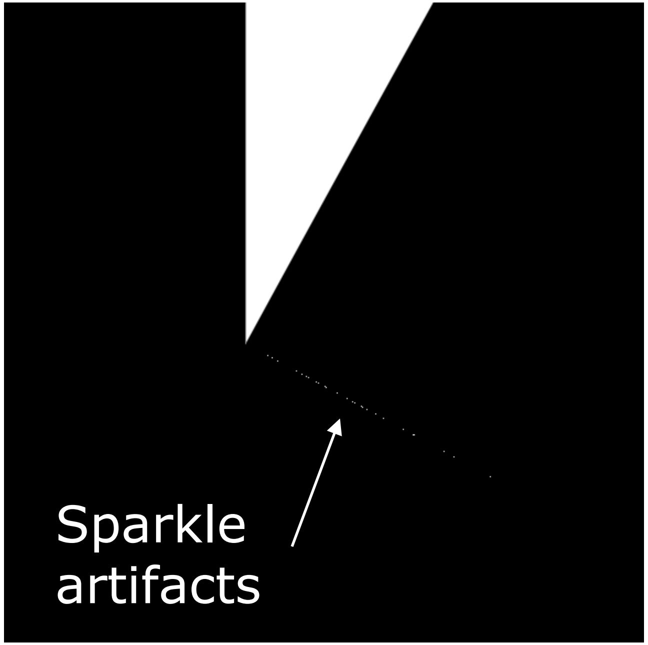
- Pixel shader determines distance to nearest Bézier curve

Glyphy

- Original outlines not preserved
- Also has numerical robustness problems

Glyphy





SLUG

Slug Library

- The result of my own research begun in 2016
- Uses one quad per glyph
- Calculates winding number in pixel shader
- Has *perfect* numerical robustness

Numerical Robustness

- Round-off errors in previous methods:
  - Generally come from determining whether roots of ray-curve intersections fall in [0,1] range
  - Problems typically occur at the endpoints
  - Especially bad when ray nearly tangent to curve
  - Hacks like using epsilons or perturbing coordinates just shift the problem cases around

Numerical Robustness

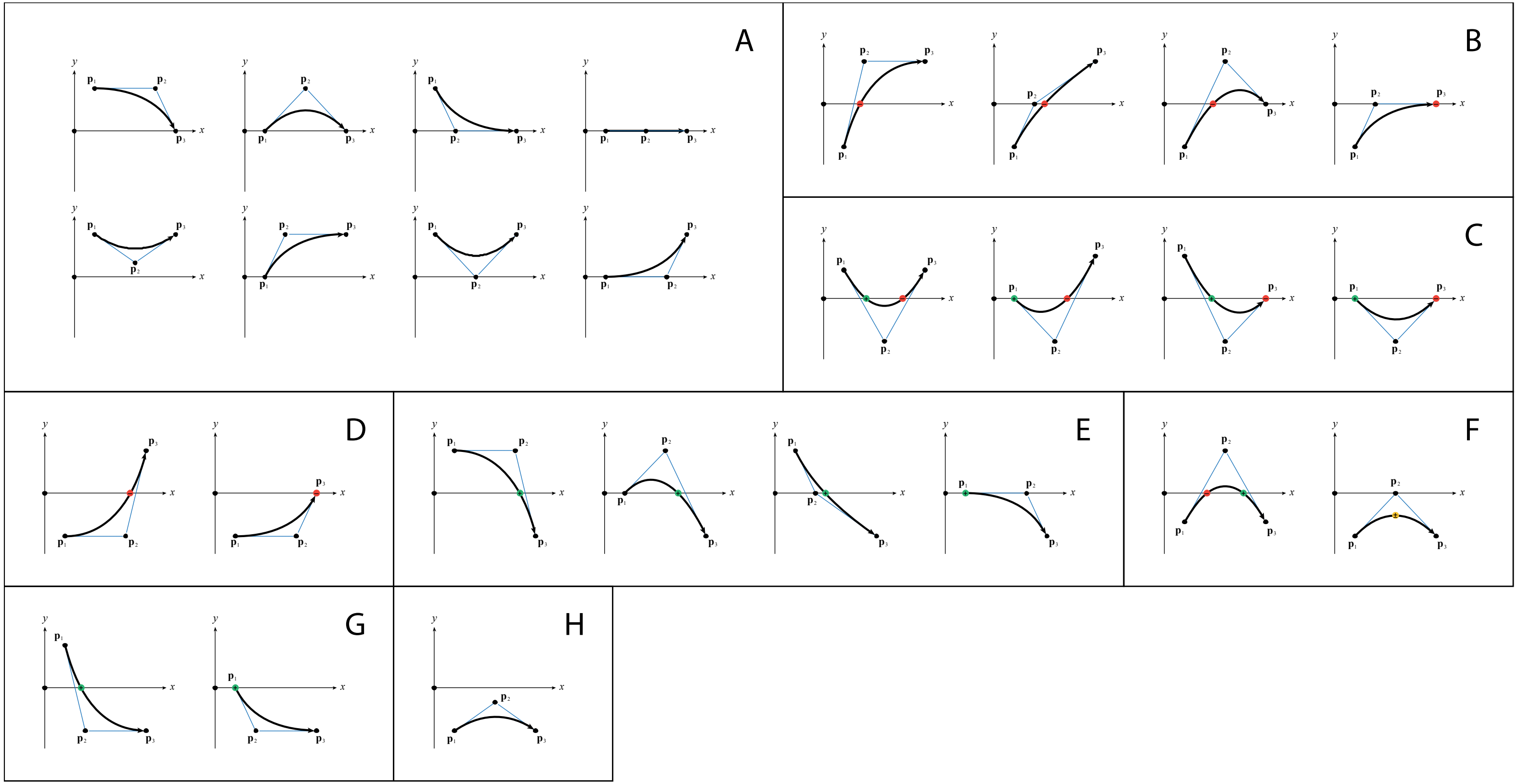
- Only way to solve is to completely eliminate the [0,1] range test

- Slug introduces an equivalence class algorithm
  - Equivalence class represents control point state
  - Same actions taken for all cases in same class

Equivalence Classes

- With respect to a given ray, a particular quadratic Bézier curve is classified into one of 8 possible equivalence classes
- Based on which side of ray each of three control points falls, positive or negative
  - Exactly on ray is considered positive

Equivalence Classes



Equivalence Classes

- For each Bézier curve, always calculate roots

$$(y_1 - 2y_2 + y_3)t^2 - 2(y_1 - y_2)t + y_1$$

$$t_1 = \frac{b - \sqrt{b^2 - ac}}{a} \quad \text{and} \quad t_2 = \frac{b + \sqrt{b^2 - ac}}{a}$$

$$a = y_1 - 2y_2 + y_3 \qquad b = y_1 - y_2 \qquad c = y_1$$

Equivalence Classes

- A 16-bit LUT tells us what to do with roots for each equivalence class (8 classes x 2 roots)
- Action taken only when x coordinate positive at a root, meaning intersection was on ray

Winding Number

- 1 in LUT for first root means add one
- 1 in LUT for second root means subtract one

- Total after considering all curves is winding number at pixel location
- Fractional values used when roots within pixel distance of ray origin

Antialiasing

- Result is coverage value with perfect one-dimensional antialiasing
- Evaluate horizontal and vertical rays
- Combine to produce 2D antialiasing

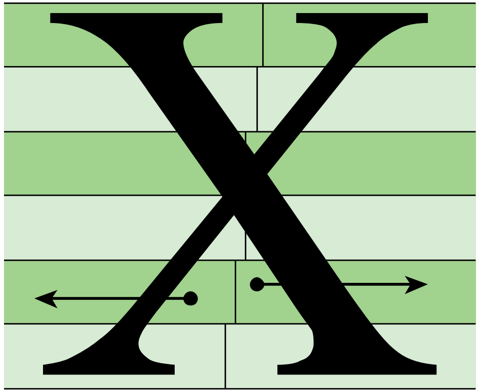
Banding

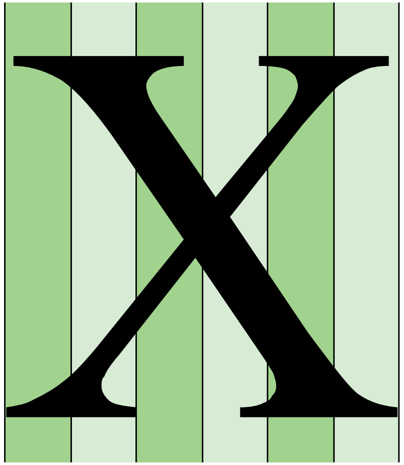
- For best performance, we want to minimize number of curves tested

- Cells don’t work well
  - Pixel footprint can cover multiple cells
  - Pixels get larger as font size decreases

Banding

- Instead of cells, use horizontal and vertical bands that extend to infinity





Banding

- Bézier curves are sorted into the bands
  - A curve can belong to multiple bands
  - When rendering, band selected based on ray origin
- Doesn’t matter how large pixel footprints get
  - Only matters in ray direction
  - Band parallel to ray extends forever

Banding

- Curves in each band are sorted to allow early exit in pixel shader

- Once right-pointing ray’s origin is beyond maximum curve x coordinate, we’re done

Banding

- Curves sorted in both directions
- Ray points left or right depending on pixel position within a band
- Reduces number of curves tested

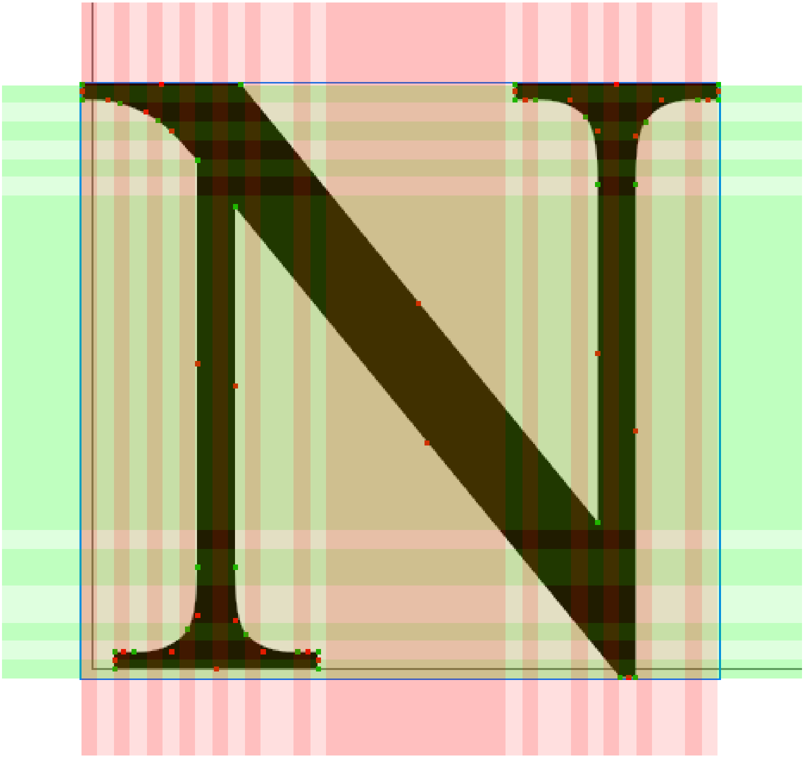
Banding

- We want worst-case band to contain fewest curves possible

- GPU thread coherence will make shader wait for longest number of loop iterations in a group of pixels (32 or 64)

Banding

- Use large number of bands
- Merge those with equal subsets of Bézier curves



Minification

- High-quality minification achieved with adaptive supersampling
    - Based on screen-space derivatives

- Already have perfect 1D antialiasing
    - Take *n* samples in *x* and *y* directions
    - Produces better than *n* x *n* supersampling

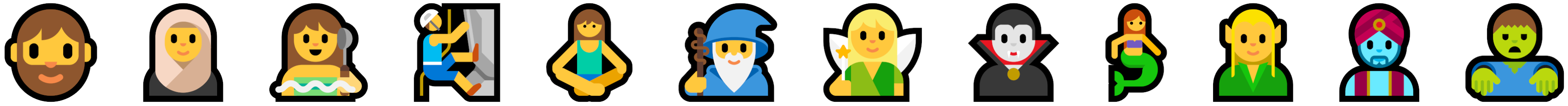
Minification

Font Data

- Two texture maps, data only (no images)
- Curve texture, 4 x 16-bit float
  - Contains all Bézier curves
- Band texture, 4 x 16-bit integer
  - Contains curve subsets for all bands

Multicolor Glyphs

- Microsoft fonts use vector data for color emoji
- Layered glyphs with color palette
- Easy to handle with loop in pixel shader

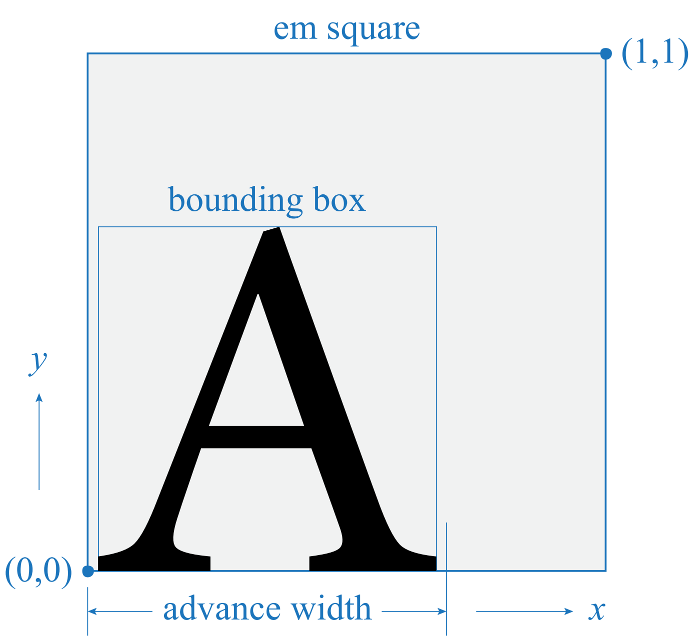


Typography

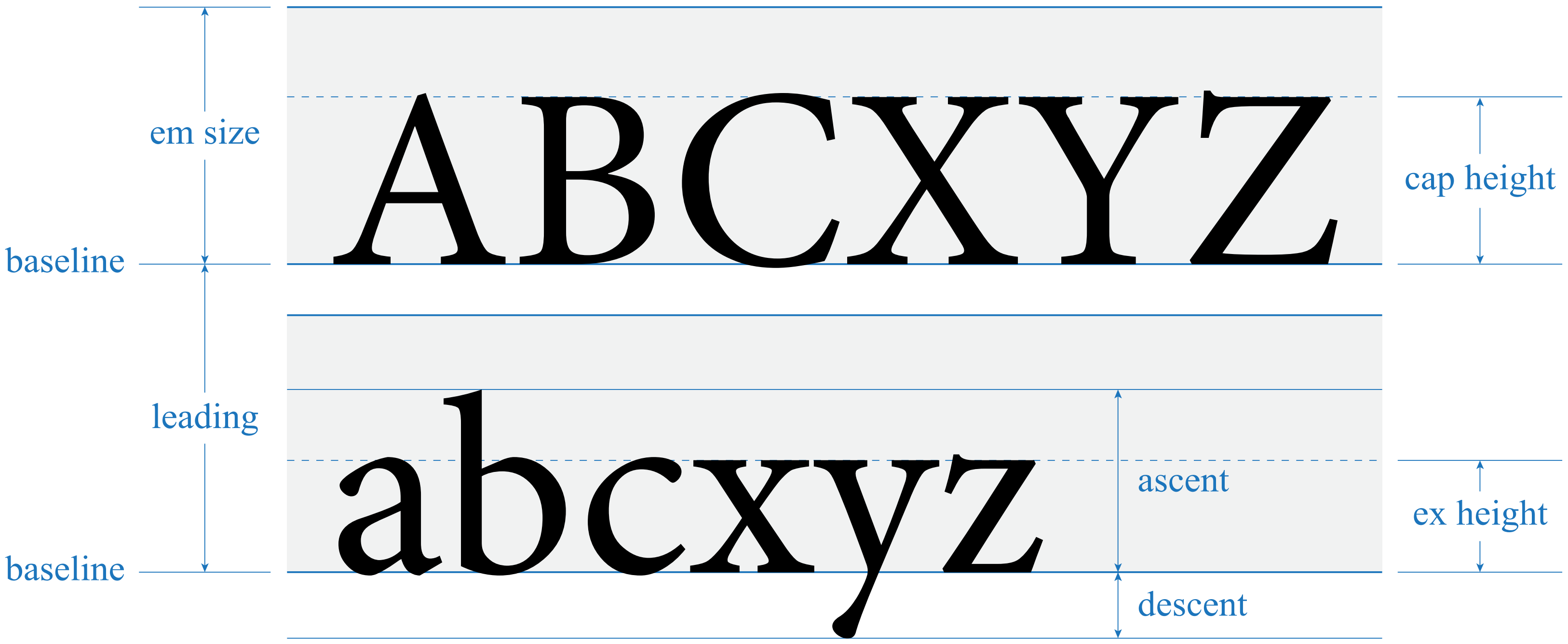
- Slug algorithm can make individual glyphs look great at any scale or from any perspective

- Higher-level:
  Make entire lines of text look good

Metrics



Metrics


em size
baseline
leading
baseline
ABCXYZ
cap height
abcxyz
ascent
descent
ex height

Kerning

- Some pairs of glyphs appear to the eye to have too much space in between
- Fonts usually contain kerning tables to improve overall appearance

Kerning

“Too Wavy.” Kerning off

“Too Wavy.” Kerning on

Ligatures

- Replaces a sequence of glyphs with one new glyph that looks better
- In some languages, ligatures that change appearance are required for correctness

Ligatures

The firefly craft. Normal text

The ﬁreﬂy craft. With ligatures

ZWJ Sequences

- Unicode has control character “zero-width joiner” (ZWJ)
- Often used by fonts for combining several glyphs into single ligature

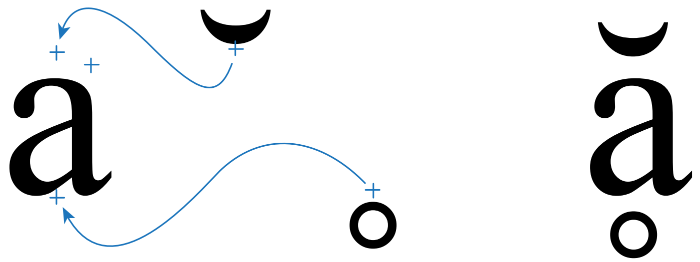
ZWJ Sequences

Combining Marks

- Unicode defines many accents and other symbols that are designed to combine with a preceding base character

- Fonts determine how this combination works by defining attachment points

Combining Marks



Alternate Substitution

- OpenType fonts define a large array of substitution features
- Independent of Unicode
- Not directly accessible through characters

Alternate Substitution

- Small caps
- Subscripts and superscripts
- Case-sensitive forms
- Stylistic alternates
- Tabular and proportional figures
- Lining and old-style figures

Small Caps

TEXT — Small caps alternates

TEXT — Scaled glyphs

Lining and Old-style Figures

0123456789

0123456789

Cursive Joining

- In languages like Arabic, letters have multiple forms depending on position in word
- Isolated, initial, medial, final forms
- Do not have separate character codes

Cursive Joining

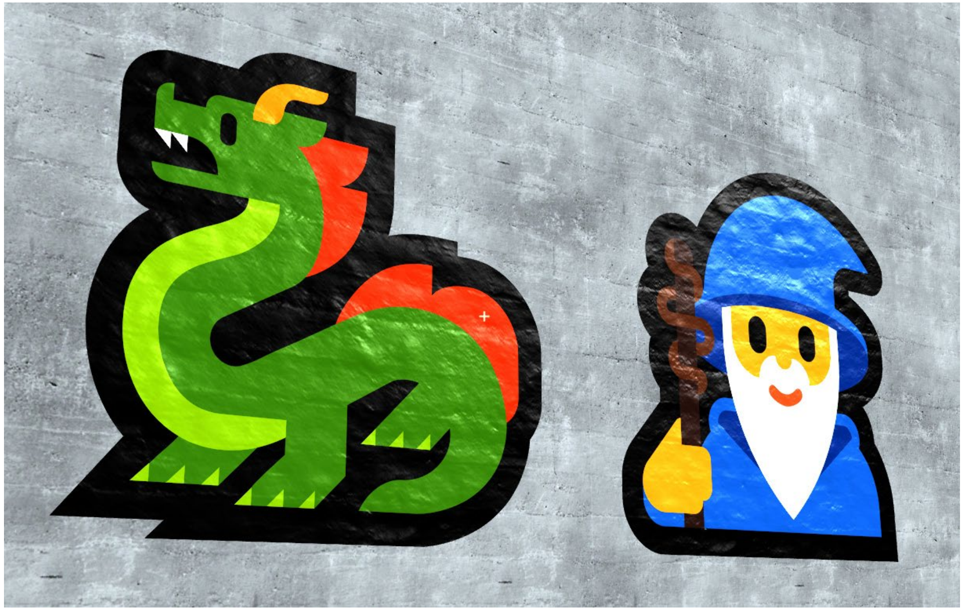
متقدمة تقديم الخط وتخطيط النص

متقدمة تقديم الخط وتخطيط النص

Materials

- Rendering glyphs outputs coverage value
  - (Plus color for multi-color emoji)
- Can be combined with other materials in game

Materials



Contact / More Info

- lengyel@terathon.com
- Twitter: @EricLengyel
- sluglibrary.com