GPU Font Rendering

Current State of the Art

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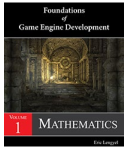
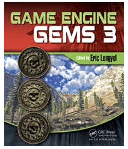
Terathon Software

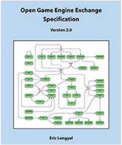
About the speaker

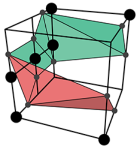
- Working in game/graphics dev since 1994
  - Previously at Sierra, Apple, Naughty Dog

- Current projects:
  - Slug Library, C4 Engine, The 31st, FGED









About this talk

- Unicode
- Glyphs
- TrueType
- Font Rendering
- Typography

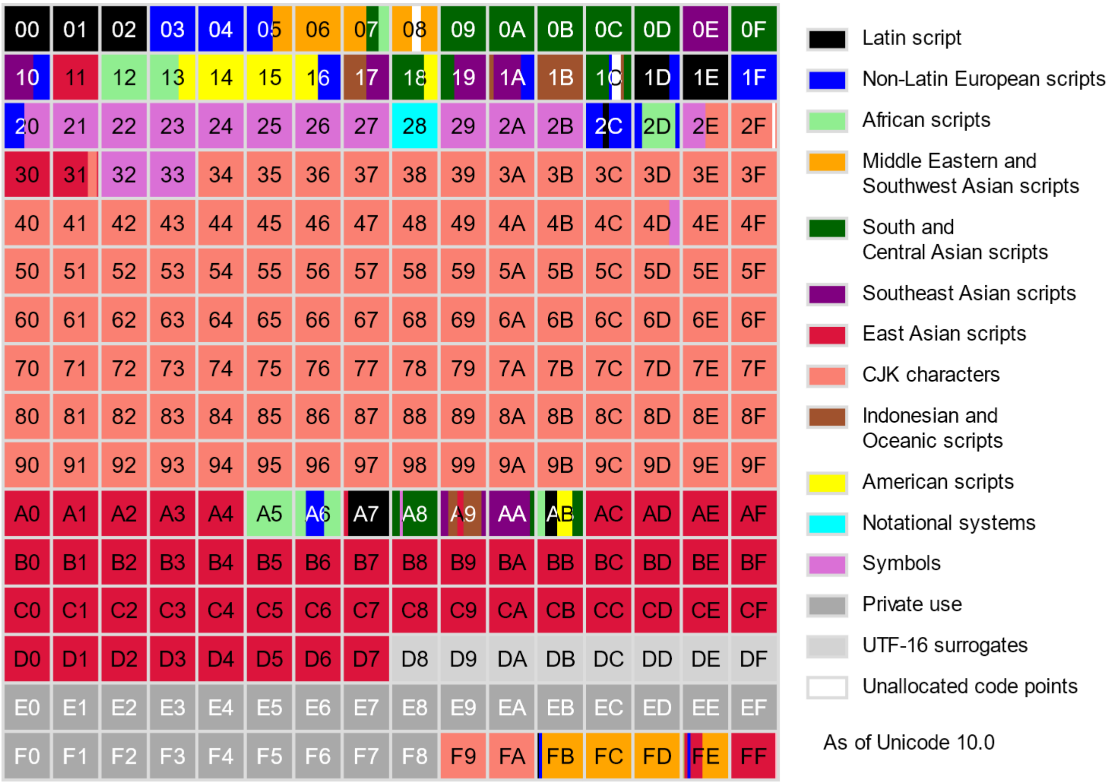
Unicode

- 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

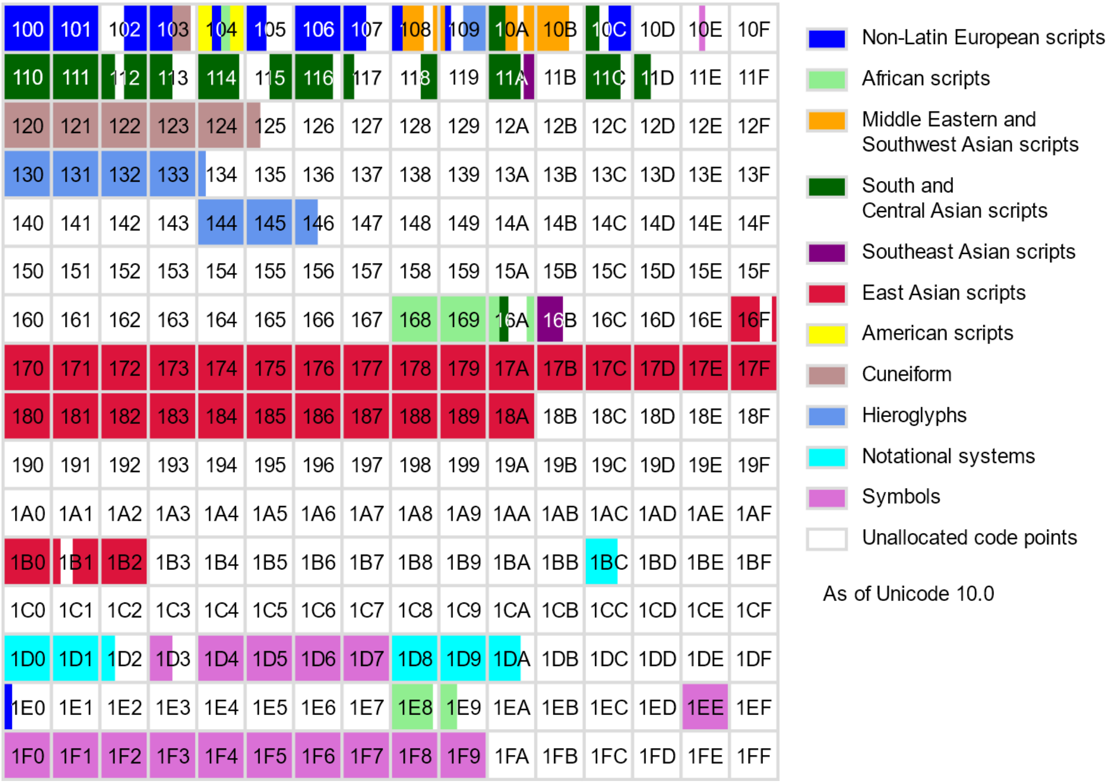


As of Unicode 10.0

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

As of Unicode 10.0

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

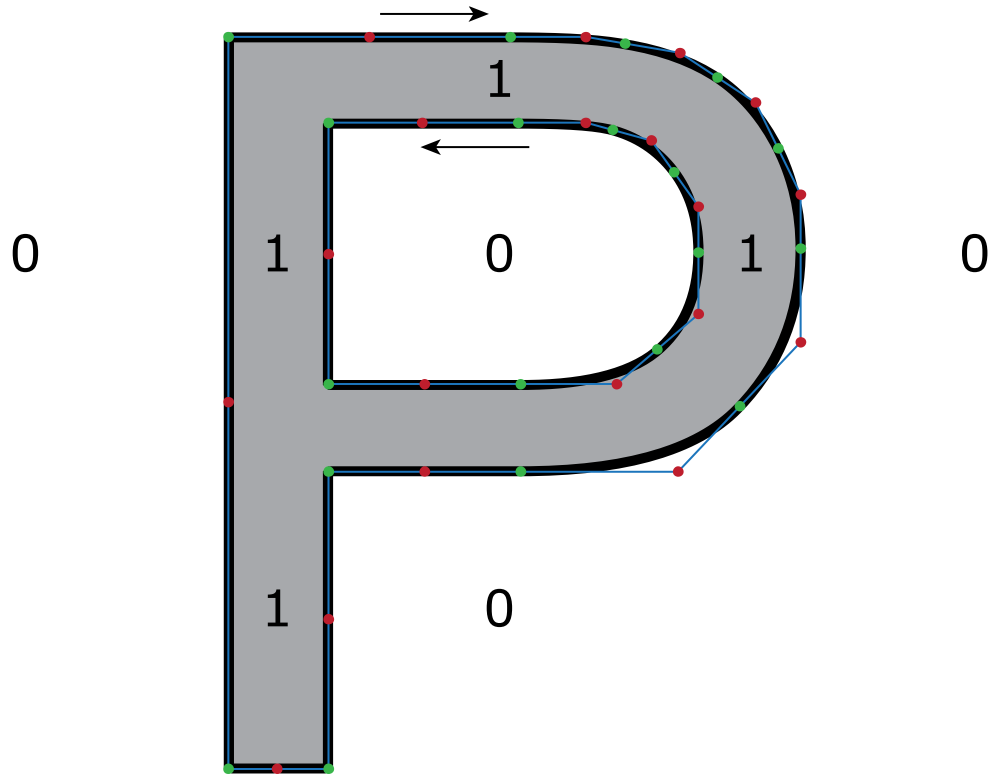
- Contours defining outer edge of glyph wound in one direction (either CW or CCW is okay)

- 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

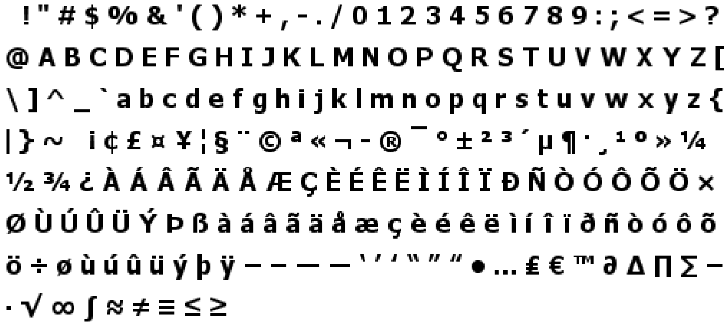
- Text rendered in lots of places
  - GUI: Buttons, menus, …
  - HUD: Score, health, ammo, …
  - In scene: Signs, labels, computer screens, …
  - Debug info: Console, stats, timings, …


77
Score
0
90
Axe 1
Pistol 1
Shotgun 2
Crossbow 3
Spike Shooter 4
Grenade Launcher 5
Quantum Charger 6
Rocket Launcher 7
Plasma Gun 8
Proton Cannon 9
TUNNEL
4-A
Time
213 fps 4.6 ms
CPU
Premove task 0.0 ms
World move 0.7 ms
Postmove task 0.0 ms
World render 2.7 ms
Interface render 0.4 ms
Present 0.2 ms
GPU
Structure 0.1 ms
Occlusion 0.9 ms
Render 1.7 ms
Shadow 0.1 ms
Postprocess 0.2 ms
Interface 0.1 ms

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



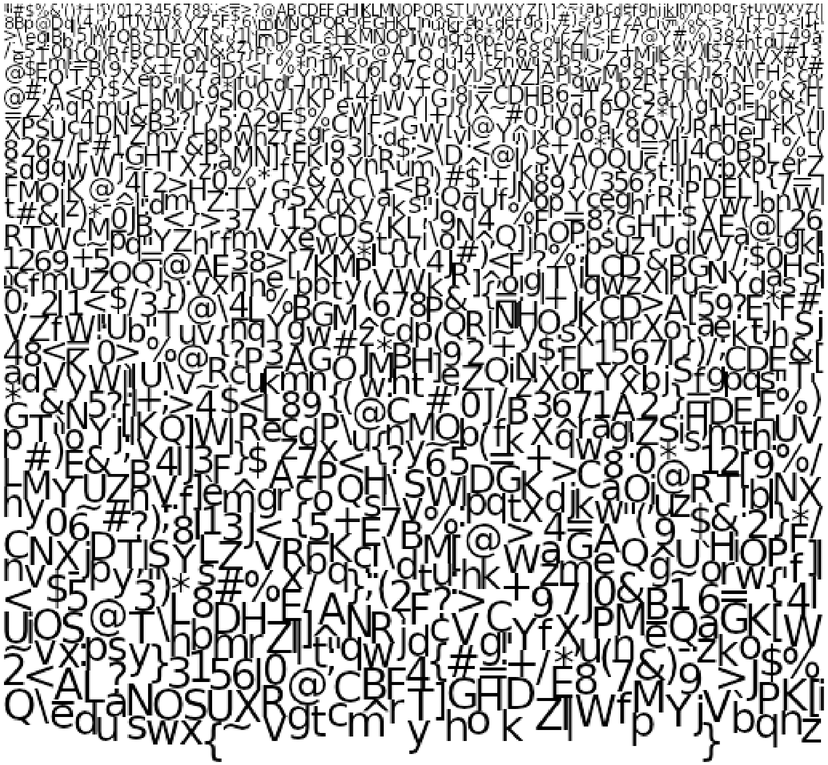


Image credit: freetype-gl

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

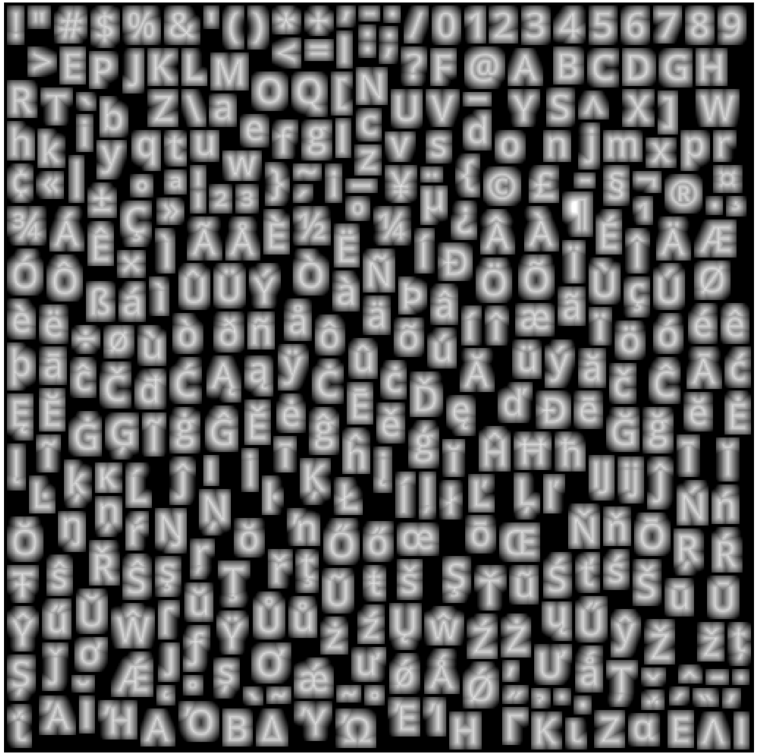


Image credit: Konstantin Käfer, "Drawing Text with Signed Distance Fields in Mapbox GL", 2014.

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

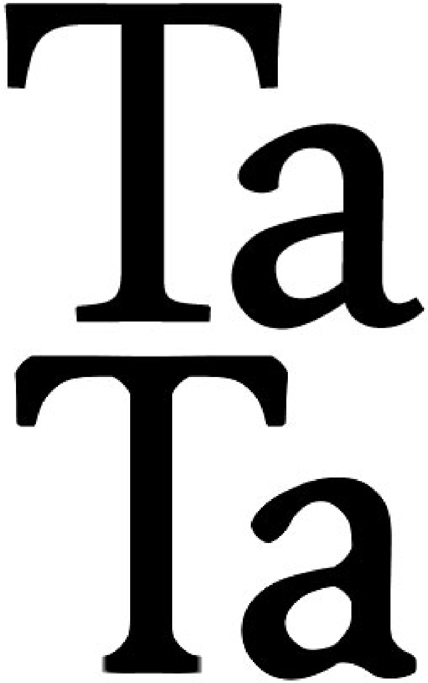


Image credit: David Rosen, "High-quality text rendering", 2013.

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

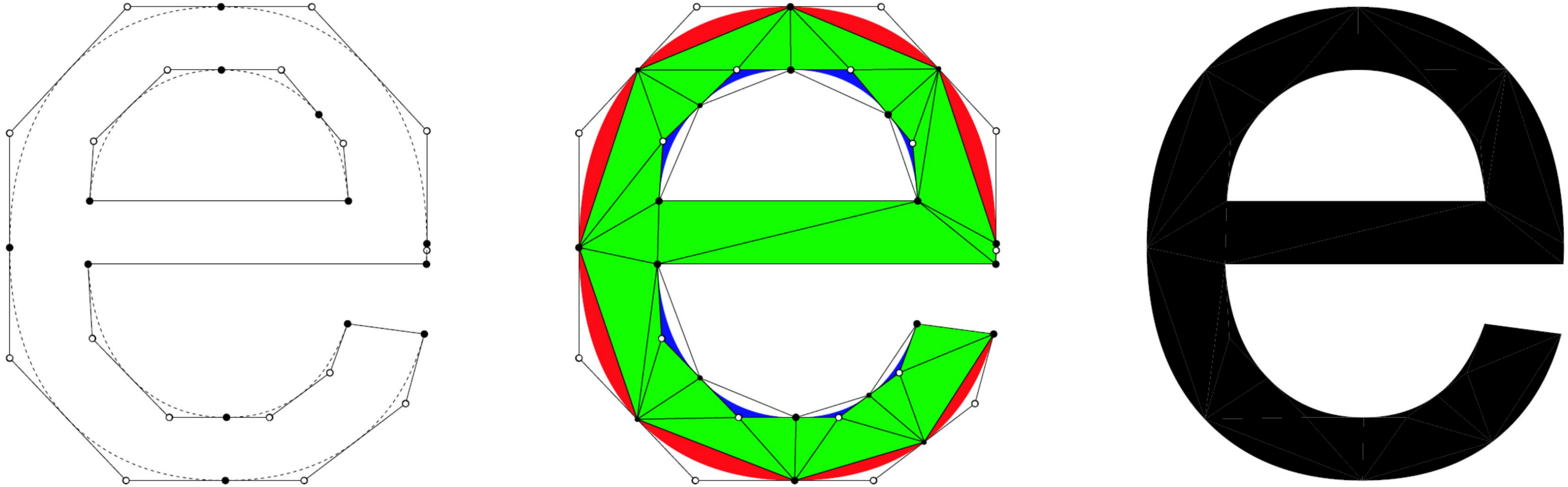


Image credit: Charles Loop and Jim Blinn, “Resolution Independent Curve Rendering using Programmable Graphics Hardware”, 2005.

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

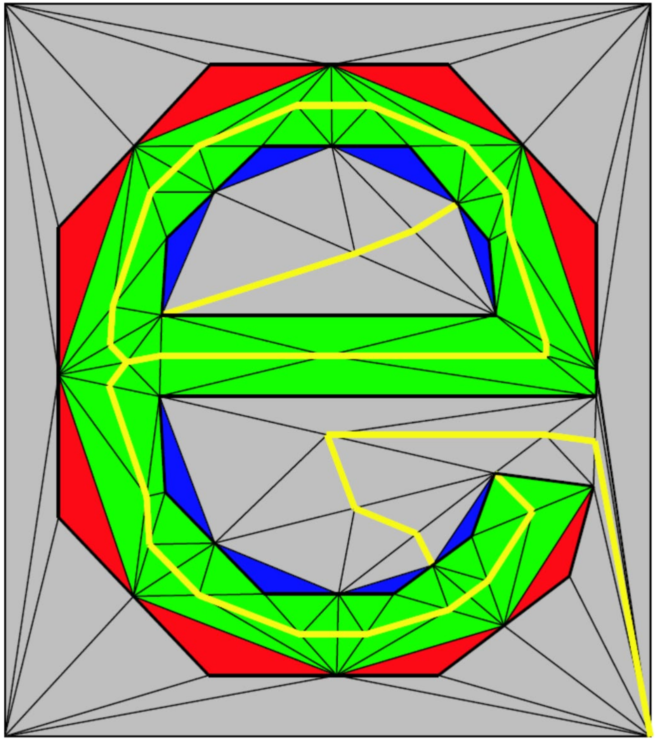


Image credit: Charles Loop and Jim Blinn, "Resolution Independent Curve Rendering using Programmable Graphics Hardware", 2005.

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

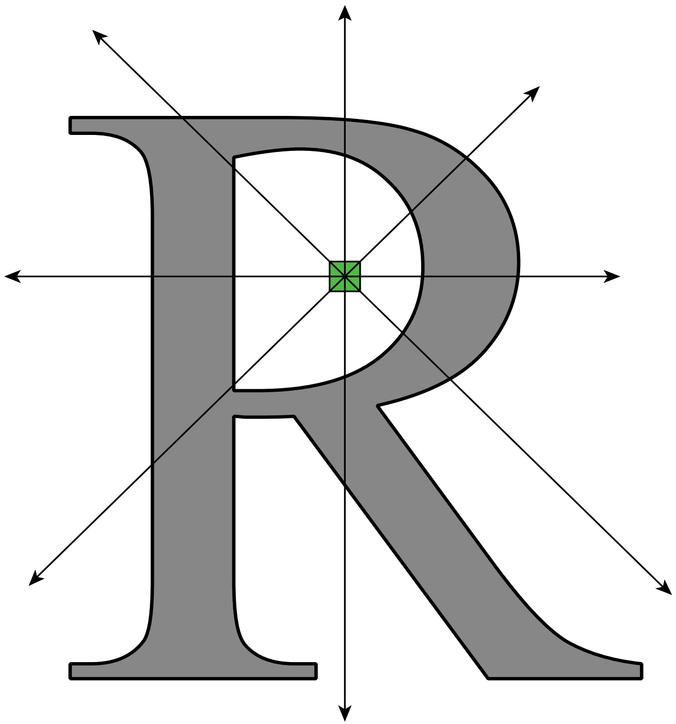
Dobbie Method

- 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

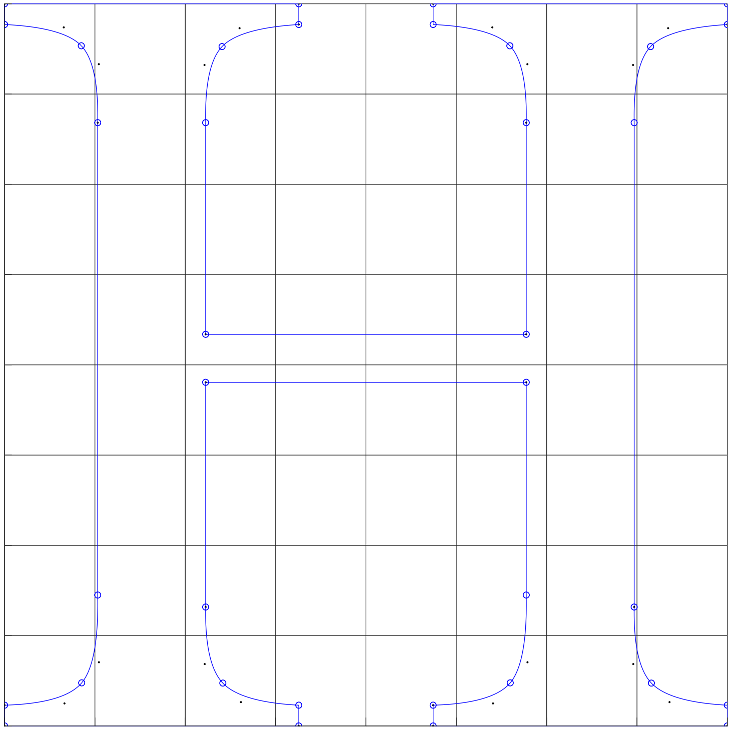


Image credit: Will Dobbie, "GPU text rendering with vector textures", 2016.

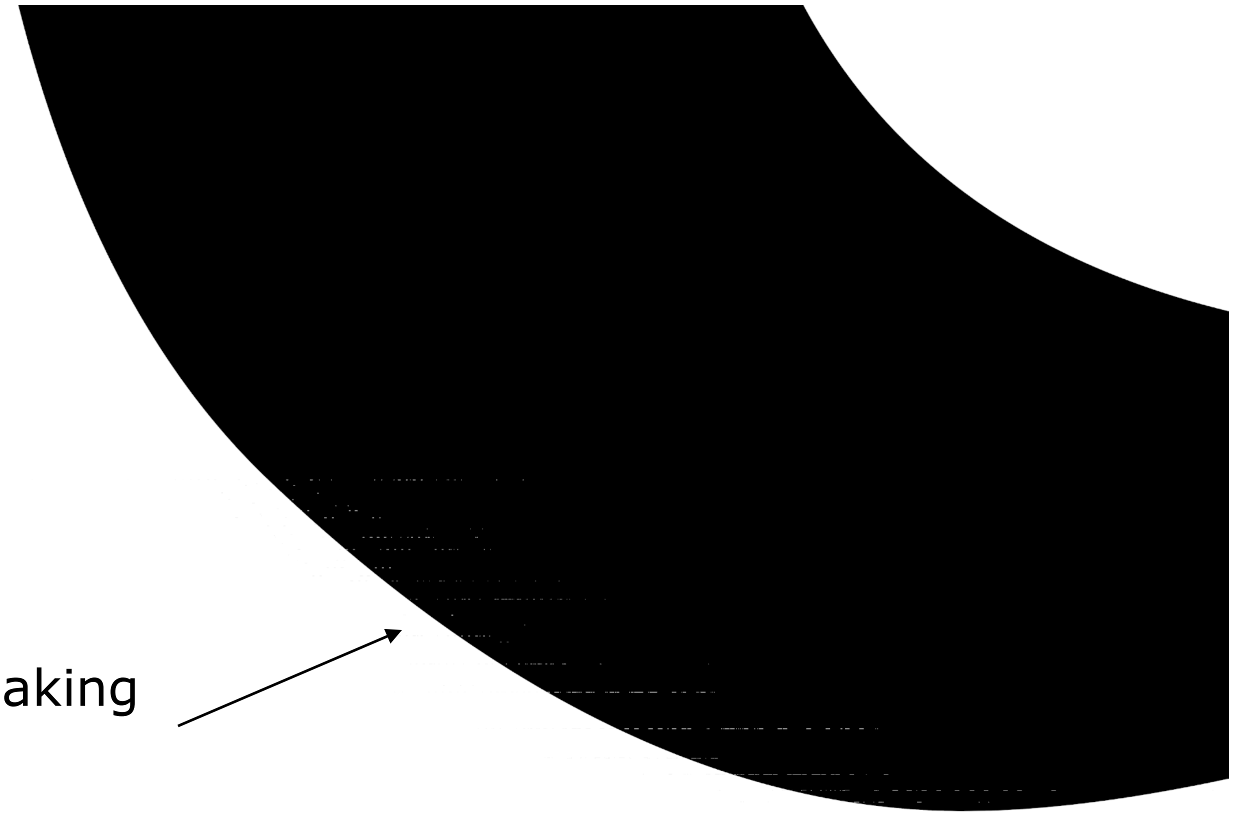
Dobbie Method

- 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



Sparkle / streaking artifacts

Glyphy

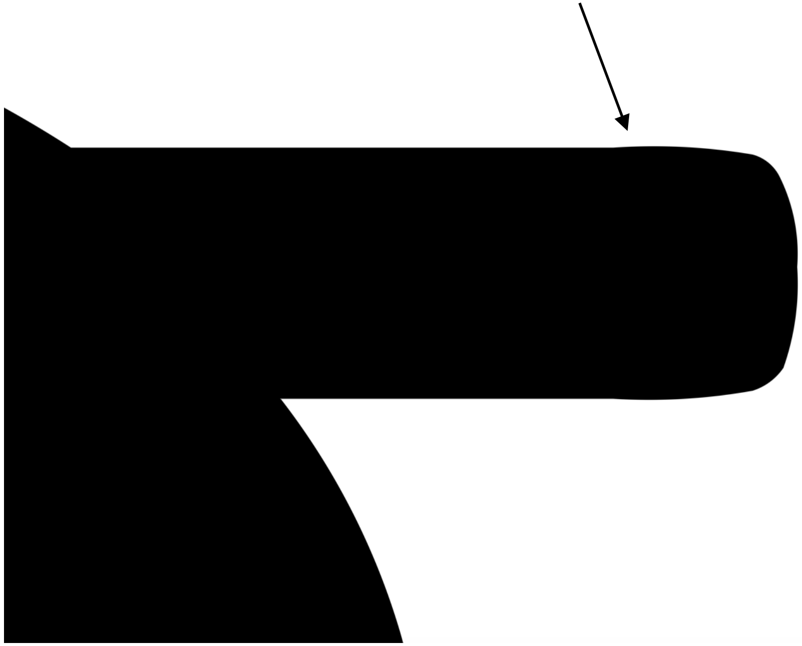
- Similar to Dobbie method in that a glyph is covered by a single quad
- Pixel shader determines distance to nearest Bézier curve

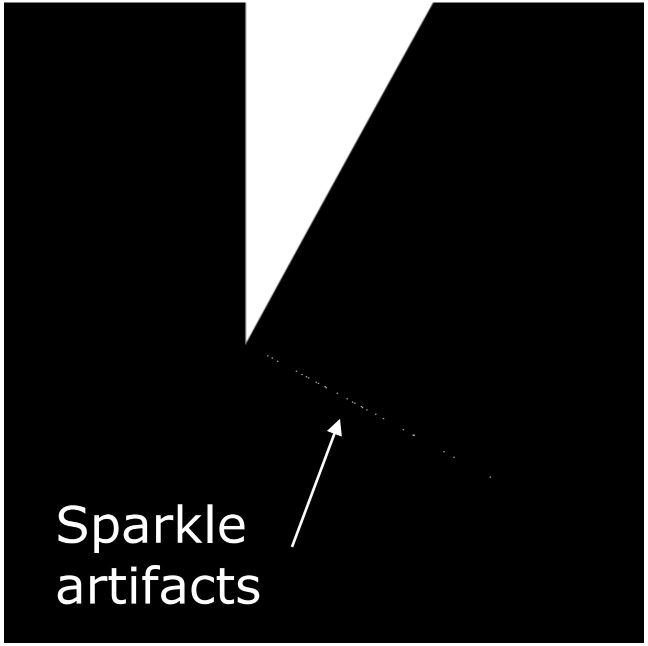
Glyphy

- Original outlines not preserved
- Also has numerical robustness problems

Glyphy

Straight lines rounded





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

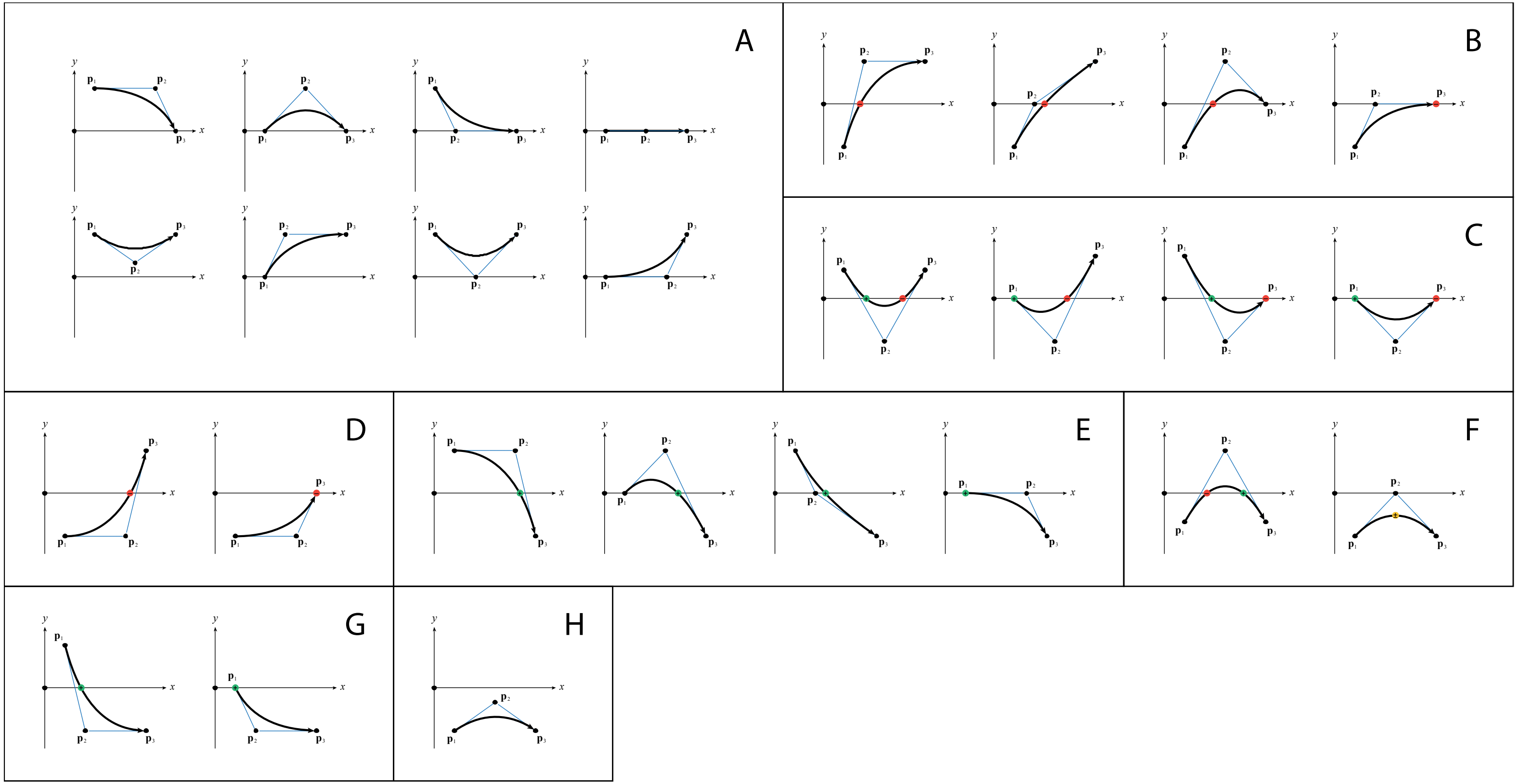
Numerical Robustness

- 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

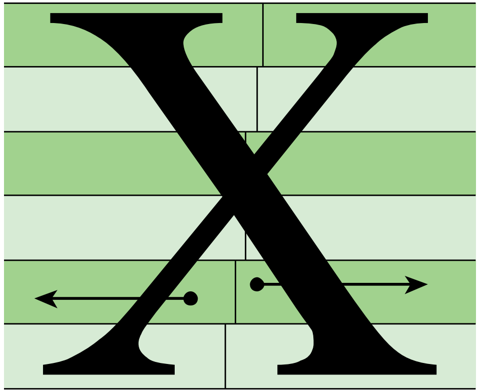
- Result is coverage value with perfect one-dimensional antialiasing
- Evaluate horizontal and vertical rays
- Combine to produce 2D antialiasing

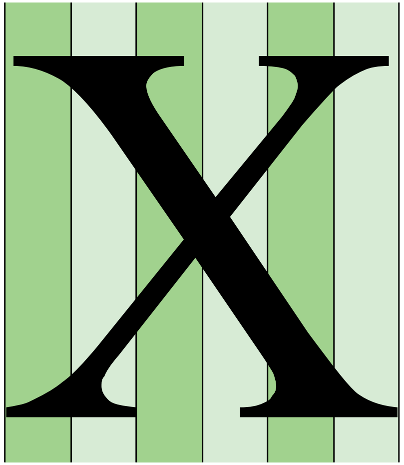
Banding

- 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

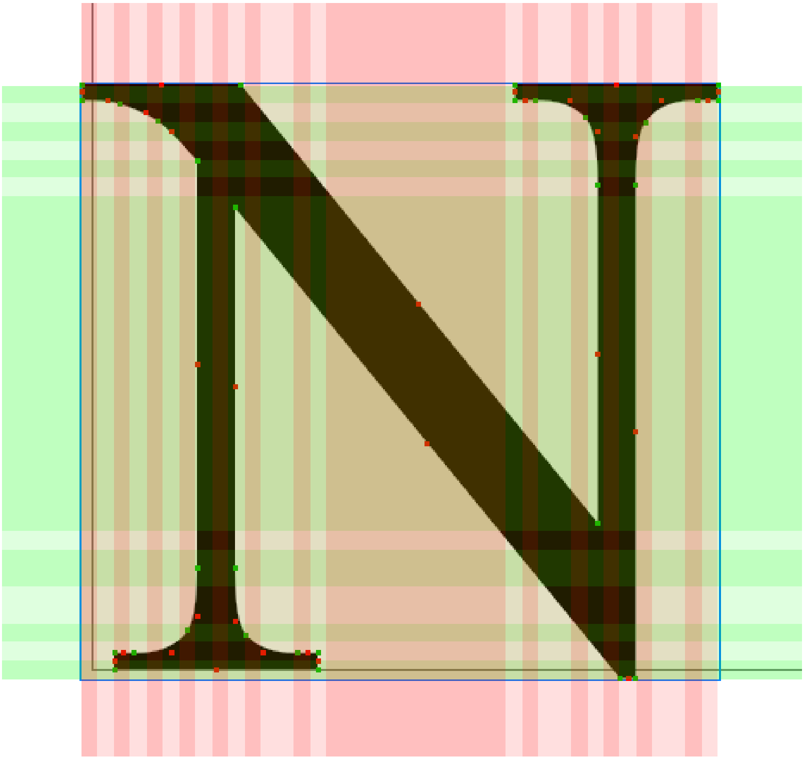
Banding

- 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

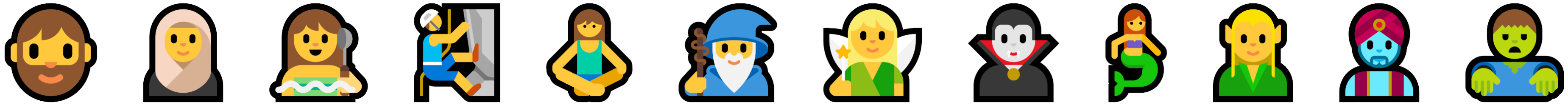
Minification

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

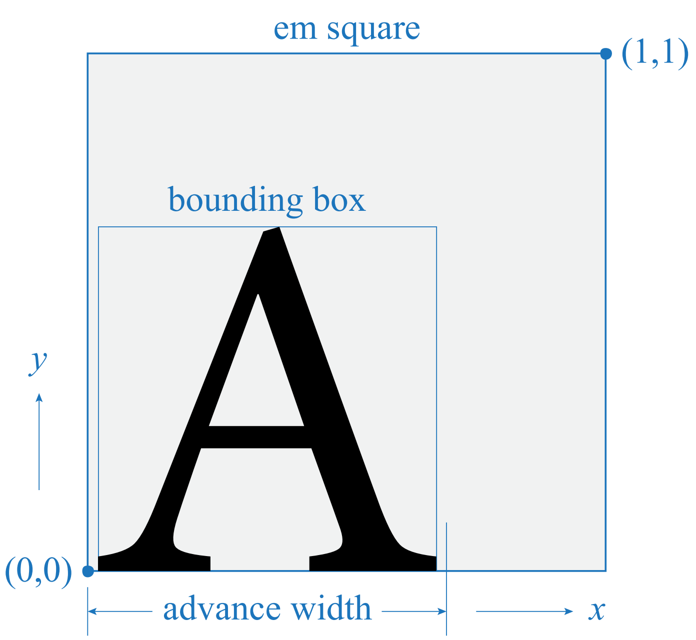


Typography

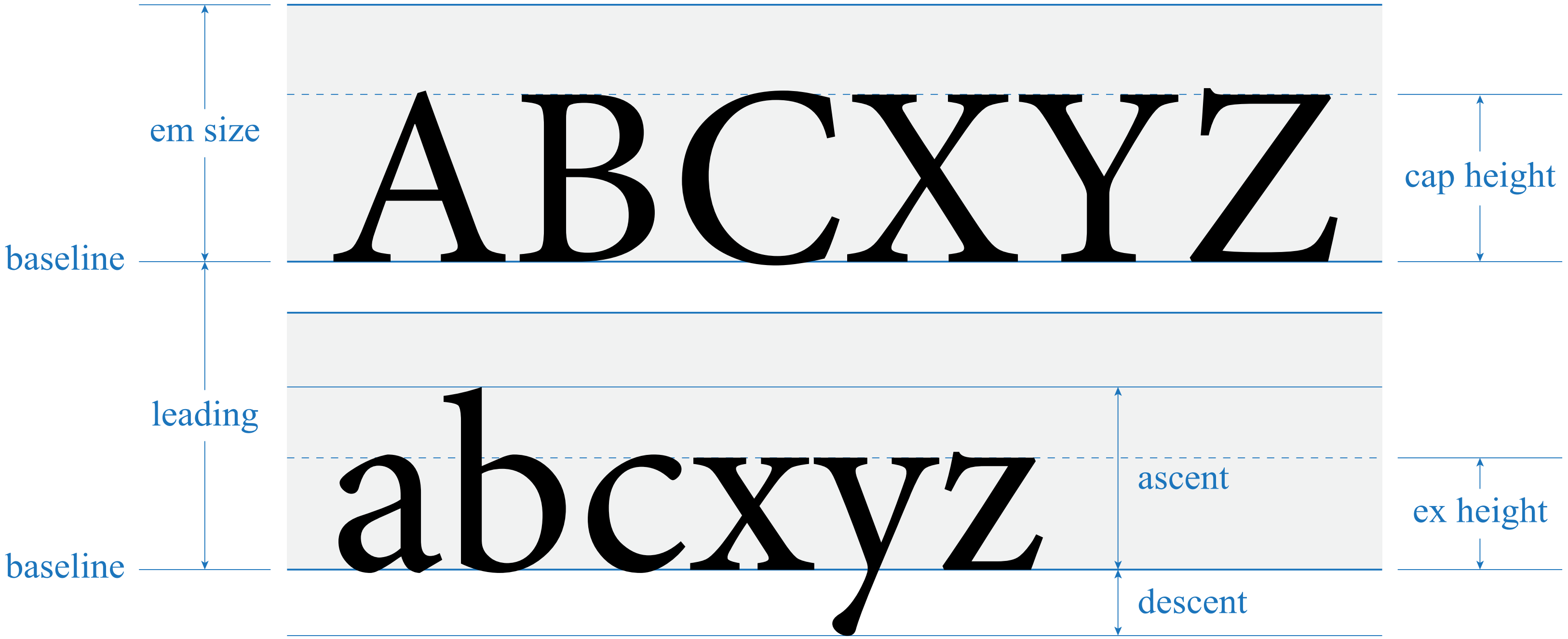
- Slug algorithm can make individual glyphs look great at any scale or from any perspective

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

Metrics



Metrics


em size
baseline
leading
baseline
ABCXYZ
abcxyz
cap height
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

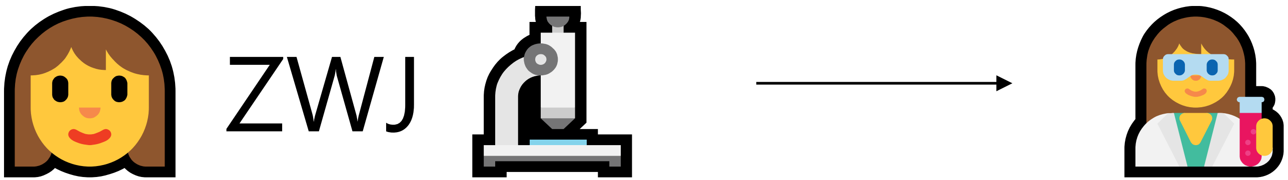
The ﬁreﬂy craft. With ligatures

ZWJ Sequences

- Unicode has control character “zero-width joiner” (ZWJ)

- Often used by fonts for combining several glyphs into single ligature

ZWJ Sequences

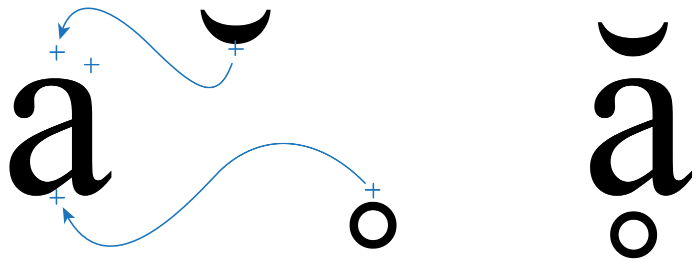


Combining Marks

- 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

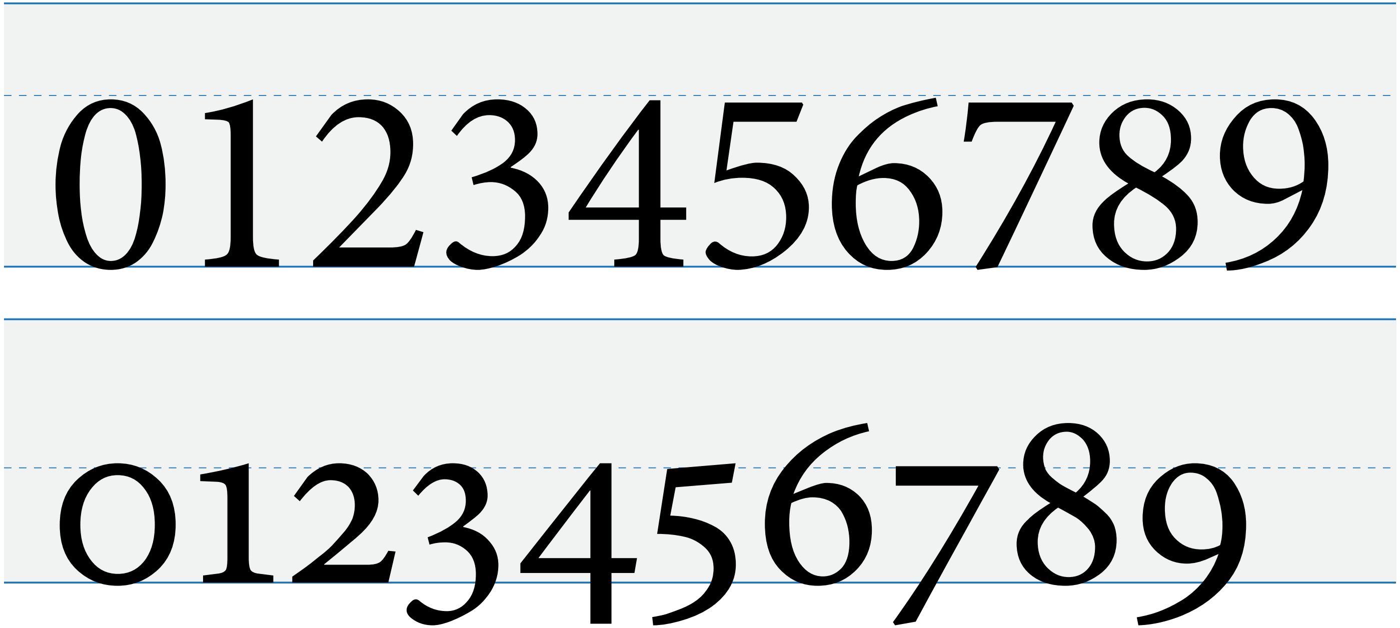
- Small caps
- Subscripts and superscripts
- Case-sensitive forms
- Stylistic alternates
- Tabular and proportional figures
- Lining and old-style figures

Small Caps

TEXT — Small caps alternates

TEXT — Scaled glyphs

Lining and Old-style Figures



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

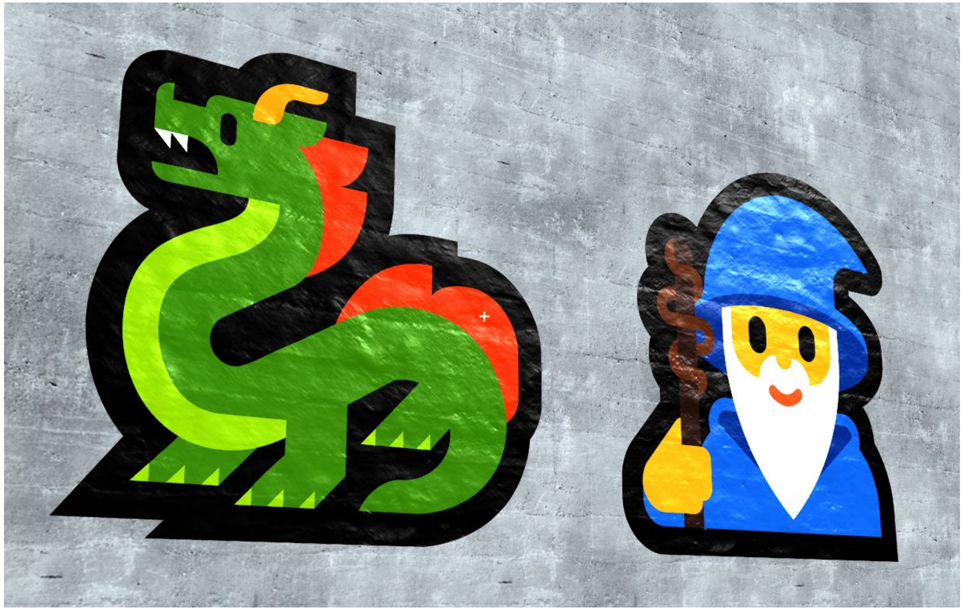
متقدمة تقديم الخط وتخطيط النص

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



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