GPU-Centered Font Rendering
Directly from Glyph Outlines

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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

- Technical details about the “Slug” font rendering algorithm
- Paper published in JCGT in June 2017
- New developments in past year
Font Rendering Ubiquity

- Text rendered everywhere in 3D applications
  - GUI: Buttons, checkboxes, lists, menus, ...
  - Games: Score, health, ammo, ...
  - In scene: Signs, labels, computer screens, ...
  - Debug info: Console, stats, timings, ...
GPU-Centered Font Rendering Directly from Glyph Outlines
Font Rendering Design Goals

- **Unified approach**
  - Same technique used to render all text in all situations

- Runs in shader on GPU
  - Fully dynamic, but also allows caching
  - Can be combined with other materials
Font Rendering Design Goals

- Total resolution independence
  - No precomputed images or distance fields
- Ability to render with any transform
  - Arbitrary scale, rotation, perspective
- Must look good at large and small font sizes
Font Rendering Design Goals

- Minimal triangulation
  - Don’t want lots of small triangles
  - GPUs perform best with large triangles
  - A fixed per-glyph vertex count is desirable
  - Would like to be able to easily clip text
  - Would like to apply text to curved surfaces
Rendering Algorithm Priorities

1. Works correctly
2. Looks good
3. Runs fast
Glyphs in TrueType

- Glyph defined by one or more closed contours
- Each contour composed of continuous sequence of quadratic Bézier curves
- Each Bézier curve has three control points
GPU-Centered Font Rendering Directly from Glyph Outlines
Glyph Space

- Glyphs are defined on em square
- Coordinates in range $[0,1]$ inside em square
- Curves can extend outside em square
GPU-Centered Font Rendering Directly from Glyph Outlines

Glyph Space

em square

bounding box

y

(0,0)

advance width

x

(1,1)
Winding Number

- To determine whether point inside glyph, calculate *winding number* with respect to each contour and sum

- Point inside glyph outline if sum of winding numbers is nonzero
Winding Number

- The winding number is the count of complete loops a contour makes around a point.

- One direction (arbitrary, either CW or CCW) is considered positive, and opposite direction is then considered negative.
Winding Number

- To calculate winding number, fire a ray from point being rendered to infinity
- Direction doesn’t matter, so use +x direction for convenience
- Look for contour intersections along the ray
Winding Number

- When contour crosses ray from left to right, increment winding number
- When contour crosses ray from right to left, decrement winding number
- Or other way around, as long as consistent
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Quadratic Bézier Curve

- Three control points $p_1, p_2, p_3$

- Parametric curve with $0 \leq t \leq 1$:

$$C(t) = (1-t)^2 p_1 + 2t (1-t) p_2 + t^2 p_3$$
Ray-Curve Intersection

- Translate control points so ray origin is (0,0)
- Assume ray direction is +x axis
- Solve for values of $t$ where $y$ coordinate of Bézier curve is zero
Ray-Curve Intersection

- Let \( p_i = (x_i, y_i) \)

- Ray intersects curve at roots of polynomial

\[
(y_1 - 2y_2 + y_3)t^2 - 2(y_1 - y_2)t + y_1 = 0
\]

\[
a = y_1 - 2y_2 + y_3 \quad b = y_1 - y_2 \quad c = y_1
\]
Ray-Curve Intersection

- Roots $t_1$ and $t_2$ given by

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

- If $a$ near zero, use root of linear polynomial:

$$
t_1 = t_2 = \frac{c}{2b}
$$
Ray-Curve Intersection

- Valid intersection at $t_i$ when:
  - $0 \leq t_i \leq 1$ (between curve endpoints)
  - $C_x(t_i) \geq 0$ (at positive distance along ray)

- $t_i = 1$ specifically disallowed
  - Corresponds to intersection at $t_i = 0$ on next Bézier curve, and don’t want to count twice
Ray-Curve Intersection

\[(0, 0)\]

- \(p_1\) at \(t = 0\)
- \(p_2\)
- \(p_3\) at \(t = 1\)
Ray-Curve Intersection

- Increment or decrement winding number?
- Look at y values in range $0 \leq t_i \leq 1$
  - Positive before $t_i$ or negative after $t_i$: increment
  - Negative before $t_i$ or positive after $t_i$: decrement
- Can’t rely on derivative
  - Zero if ray tangent to curve
Robustness

- Sound from purely mathematical standpoint
- But plagued by numerical precision errors!
- Floating-point limits cause huge problems for roots near endpoints where $t_i = 0$ or $t_i = 1$
Numerical Precision Errors

- Produce sparkle and streak artifacts
- Hacks like epsilons and coordinate perturbation just shift problem cases around
- Need something that’s 100% robust
Slug Algorithm

- Calculates winding number
  - Input is arbitrary set of closed contours composed of quadratic Bézier curves

- Performs antialiasing
  - Determines fractional coverage at each pixel
Priority #1: Works Correctly

- Robust for all valid inputs
  - Meaning any floating-point coordinates that are not infinity or NaN

- No distortion of glyph outlines

- No sparkle artifacts
Equivalence Class Algorithm

● Infinite problem space reduced to a finite number of equivalence classes

● Same procedure followed for all cases in each equivalence class

● Same abstract idea as Marching Cubes
Bézier Curve Classification

- Look at $y$ coordinates of the three control points
- Each positive, negative, or zero
- 27 classes based on these states
Bézier Curve Classification

- It turns out we can do better than 27 classes
- Classify each control point based on whether the $y$ coordinate is nonnegative or negative
- Only 8 equivalence classes
Bézier Curve Classification

- Roots (ray intersections) always occur in the same way for all cases in each class
- We care about places where curve transitions between nonnegative and negative
- Only have to decide how to modify winding number for each root
Winding Number Modification

- Consider derivative of $y$ coordinate:

$$y'(t) = 2at - 2b$$

$$a = y_1 - 2y_2 + y_3 \quad b = y_1 - y_2$$
Winding Number Modification

- An observation about the roots for nonzero discriminant $D$:

  $t_1 = \frac{b - \sqrt{D}}{a}$  \hspace{1cm}  $t_2 = \frac{b + \sqrt{D}}{a}$

  $D = b^2 - ac$

  $y'(t_1) = -2\sqrt{D}$  \hspace{1cm}  $y'(t_2) = +2\sqrt{D}$
Winding Number Modification

- Root at $t_1$ always crosses ray from left to right
  - Going from nonnegative to negative
  - Always increment winding number

- Root at $t_2$ always crosses ray from right to left
  - Going from negative to nonnegative
  - Always decrement winding number
Winding Number Modification

- We can also incorporate cases where ray intersects an endpoint tangentially.

- Winding number modified only when transition between nonnegative and negative occurs.

- $x$ coordinate at transition must be positive.
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A

B

C

D

E

F

G

H
Class A: All Nonnegative

- Nothing happens to winding number
Class H: All Negative

- Nothing happens to winding number
Classes B and D: One Transition

- Winding number decremented if \( x(t_2) > 0 \)
Classes E and G: One Transition

- Winding number incremented if $x(t_1) > 0$
Class C: Two Transitions

- Winding number incremented if $x(t_1) > 0$
- Winding number decremented if $x(t_2) > 0$
Class F: Two Transitions

- Winding number incremented if \( x(t_1) > 0 \)
- Winding number decremented if \( x(t_2) > 0 \)
Discriminant Clamping

- In classes C and F, we could have a negative discriminant $D$

- To handle with uniformity, clamp $D$ to zero

- Always two transitions at same $x$ coordinate, so guaranteed to cancel each other out
float2 SolvePoly(float4 p12, float2 p3)
{
    float2 a = p12.xy - p12.zw * 2.0 + p3;  // Calculate coefficients.
    float2 b = p12.xy - p12.zw;
    float ra = 1.0 / a.y;
    float rb = 0.5 / b.y;

    float d = sqrt(max(b.y * b.y - a.y * p12.y, 0.0));  // Clamp discriminant to zero.
    float t1 = (b.y - d) * ra;
    float t2 = (b.y + d) * ra;

    if (abs(a.y) < epsilon) t1 = t2 = p12.y * rb;  // Handle linear case where |a| \approx 0.

    // Return x coordinates at t1 and t2.
    return (float2((a.x * t1 - b.x * 2.0) * t1 + p12.x,
                    (a.x * t2 - b.x * 2.0) * t2 + p12.x));
}
Root Eligibility

- We know what to do for each root
- Just need to decide whether to actually do it!
- Use a lookup table for root eligibility
Root Eligibility

- Nonnegative/negative gives us 3-bit state
  - Just use sign bits of $y$ coordinates

- Look up 2-bit root eligibilities for $t_1$ and $t_2$

- Total LUT size is a tiny 16 bits
### Root Eligibility Lookup Table

<table>
<thead>
<tr>
<th>Class</th>
<th>$y_3 \geq 0$</th>
<th>$y_2 \geq 0$</th>
<th>$y_1 \geq 0$</th>
<th>Root 2</th>
<th>Root 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>D</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>E</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>F</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>G</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>H</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>0x2E</th>
<th>0x74</th>
</tr>
</thead>
</table>

References:
Calculating Root Codes

```c
uint CalcRootCode(float y1, float y2, float y3)
{
    uint i1 = asuint(y1) >> 31U;
    uint i2 = asuint(y2) >> 30U;
    uint i3 = asuint(y3) >> 29U;

    uint shift = (i2 & 2U) | (i1 & ~2U);
    shift = (i3 & 4U) | (shift & ~4U);

    return ((0x2E74U >> shift) & 0x0101U);
}

bool TestCurve(uint code)
{
    return (code != 0U);
}

bool TestRoot1(uint code)
{
    return ((code & 1U) != 0U);
}

bool TestRoot2(uint code)
{
    return (code > 1U);
}
```
Ternary Logic Instruction

- Recent Nvidia GPUs have a ternary logic instruction (LOP3)
- Maps arbitrary 3-bit input to 1-bit output with 8-bit lookup table encoded in the instruction
- Perfect fit for our algorithm!
Ternary Logic Instruction

- Instruction not directly accessible from pixel shader code
- Compiler can recognize arbitrary sequence of AND, OR, XOR, NOT operations and generate single ternary instruction
Ternary Logic Instruction

- With LOP3, root code calculation requires only 2 instructions where otherwise need at least 7
- Shader gets about 4% faster in all cases
Root Codes with Ternary Logic

```c
int2 CalcRootCode(float y1, float y2, float y3) {
    int a = asint(y1);
    int b = asint(y2);
    int c = asint(y3);

    return (int2(~a & (b | c) | (~b & c),
                 a & (~b | ~c) | (b & ~c)));
}

bool TestCurve(int2 code) {
    return ((code.x | code.y) < 0);
}

bool TestRoot1(int2 code) {
    return (code.x < 0);
}

bool TestRoot2(int2 code) {
    return (code.y < 0);
}
```
Total Winding Number

```c
int winding = 0;
for (all Bézier curves)
{
    float4 p12 = first (.xy) and second (.zw) control points
    float2 p3 = third (.xy) control point

code = CalcRootCode(p12.y, p12.w, p3.y);
if (TestCurve(code))
{
    float2 r = SolvePoly(p12, p3);

    if ((TestRoot1(code)) && (r.x > 0.0)) winding += 1;
    if ((TestRoot2(code)) && (r.y > 0.0)) winding -= 1;
}
}

if (winding != 0) then pixel is inside glyph outline
```
Priority #2: Looks Good

- Performs accurate antialiasing
- Handles arbitrary transforms well
- Handles minification well
Fractional Coverage

- Integer winding number produces simple in/out state for each pixel

- Correct, but has jagged edges everywhere

- We need fractional pixel coverage values
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Fractional Coverage

- Ray origin is at pixel center
- Previously, we incremented or decremented winding number when $x(t_i) > 0$
- Now, we add or subtract the fractional distance ray makes it through pixel before intersection
Fractional Coverage

- Let $u$ be number of pixels per em
  - Scales coordinates so that width of pixel = 1 unit

- Always change winding number (WN) by

$$\text{saturate} \left( u \cdot x(t_i) + \frac{1}{2} \right)$$
Fractional Coverage

- If $u \cdot x(t_i) \leq -0.5$, then no change to WN
- If $u \cdot x(t_i) \geq 0.5$, then WN always changed by 1
- In between, WN changed by fractional value
- Accounts for multiple curves per pixel
GPU-Centered Font Rendering Directly from Glyph Outlines
Fractional Winding Number

```c
float coverage = 0.0;
for (all Bézier curves)
{
    float4 p12 = first (.xy) and second (.zw) control points
    float2 p3 = third (.xy) control point

    code = CalcRootCode(p12.y, p12.w, p3.y);
    if (TestCurve(code))
    {
        float2 r = SolvePoly(p12, p3) * pixelsPerEm;
        if (TestRoot1(code)) coverage += saturate(r.x + 0.5);
        if (TestRoot2(code)) coverage -= saturate(r.y + 0.5);
    }
}
```
Antialiasing

- This gives us excellent 1D antialiasing
  - Looks great when curves are mostly vertical

- Doesn’t work well for mostly horizontal curves

- So fire a ray in the $y$ direction, too
  - Looks great when curves are mostly horizontal
Antialiasing

- Calculate coverage for two rays at each pixel
  - One in \( x \) direction, and one in \( y \) direction
  - Note pixels per em could be different in \( x \) and \( y \)

- Combine two coverage values for good 2D antialiasing
  - Lots of ways to calculate weighted average
Antialiasing

- Output is linear coverage value
- Works best when blended into sRGB framebuffer
Bounding Box Dilation

- Draw one quad per glyph coinciding with glyph’s bounding box
- GPU fills pixels with centers covered by quad
- Could miss pixels on boundary with up to 50% fractional coverage value
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i3D 2018
Montréal
Bounding Box Dilation

- Must dilate bounding box by half pixel width

- In em space, dilate by $0.5 / \text{font size}$

- If size dynamically change, need to estimate smallest on-screen pixels per em
Minification

- At very small font sizes, lots of detail can occur inside each pixel
- Can’t be captured by single sample position at pixel center
Adaptive Supersampling

- As pixels get larger in em space, increase number of samples
- Use screen space derivatives to dynamically calculate sample counts for horizontal and vertical rays
GPU-Centered Font Rendering Directly from Glyph Outlines
Adaptive Supersampling

- Example sample count calculation
  - 1–4 samples per pixel in each direction

```c
float2 emsPerPixel = fwidth(renderCoord);
int2 sampleCount = clamp(int2(emsPerPixel * 32.0 + 1.0), int2(1, 1), int2(4, 4));
```
GPU-Centered Font Rendering Directly from Glyph Outlines

Adaptive Supersampling

Single sample

Supersampling
Priority #3: Runs Fast

- Minimize raw computation
  - We want to examine as few Bézier curves as possible in the pixel shader

- Promote high GPU resource utilization
  - We want low thread divergence in the pixel shader
Computation

- Looking for ray intersections with all Bézier curves would be very slow

- Many curves far away from ray and never contribute to coverage (classes A and H)

- Need to reduce active set of curves
Banding

- Divide glyph’s bounding box into many horizontal and vertical bands
Bandung

- 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 footprint gets
  - Pixel size only matters in ray direction
  - Band parallel to ray extends forever
Banding

- Perfectly horizontal lines are never added to horizontal bands
- Perfectly vertical lines are never added to vertical bands
- Ray intersections with these can’t happen
Banding

- Further dividing into cells causes problems
  - Pixel could cover multiple cells along ray direction
  - Those cells often won’t have disjoint curve sets
  - Can’t calculate final winding number without additional per-cell fix-ups that aren’t robust

- Bands are a much cleaner and faster solution
Banding

- Using large numbers of bands is faster
  - Allows fewer curves per band

- Minimize number of curves in worst band
  - GPU thread coherence makes shader wait for highest number of loop iterations in a group of pixels (32 or 64, hardware dependent)
Banding

- Can merge data for bands containing identical sets of Bézier curves
Curve Sorting

- Curves in each horizontal band are sorted in descending order by the maximum \( x \) coordinate of the three control points.

- This is an early-exit optimization that makes the shader about twice as fast compared to not sorting curves at all.
Curve Sorting

- Translate control points so that pixel center is at (0,0), and perform test:

  \[
  \text{if } (\max(\max(p12.x, p12.z), p3.x) \times \text{pixelsPerEm.x } < -0.5) \text{ break;}
  \]

- If true, then it’s not possible to hit this curve or any that follow

  - Sorted in descending order, so must also be true for all later curves in the band
Symmetric Band Optimization

- Can do even better at large font sizes
- Also sort in ascending order by minimum $x$ coordinate of the three control points
- Use a left-pointing ray when pixel $x$ coordinate is less than a band split value
Symmetric Band Optimization
Symmetric Band Optimization

- Sorting and split values also apply to vertical bands
- Splits values introduce divergence in shader
  - Faster for large font sizes where lots of pixels will choose same execution path
  - Slower for small font sizes due to decoherence
Bounding Polygons

- Glyphs tend to have empty space near the corners of their bounding boxes
- Clip these corners off to reduce pixels filled
- Adds more triangles, but roughly 10% faster with larger font sizes
Bounding Polygons

ABCDEF

OPQRST

abcdefghijklmnopqrstuvwxyz

0123456789\?!@#$&\'\(\)
Bounding Polygons

- As with symmetric band splits, bounding polygons increase performance for large font sizes, but can hurt at small font sizes.

- Greater number of triangles increase number of pixels double-shaded in 2x2 quads along triangle edges.
Rectangle Primitives

- Even when rendering quads, double-shading along the interior edge can be a significant expense at small font sizes
- Expense can be eliminated for text that’s aligned to screen axes
Rectangle Primitives

- Most GPUs support rectangle primitives
  - Exposed through GL_NV_fill_rectangle extension

- Specify three vertices, and screen-aligned enclosing rect is drawn without internal edge

- Up to 15% faster for typical font sizes
Rectangle Primitives

- Can be combined with conservative rasterization to handle glyph dilation
- Automatically shades pixels with any amount of coverage
Multicolor Glyphs

- Microsoft emoji font uses vector artwork
  - Based on same TrueType quadratic Bézier curves
- Multiple layers composited back to front
  - Adds an outer loop to the pixel shader
Data Stored in Two Texture Maps

- **Curve texture**
  - 4-channel 16-bit floating-point
  - Stores all Bézier curve control points

- **Band texture**
  - 4-channel 16-bit integer
  - Stores lists of curves for all bands
Curve Texture

- Third control point of one curve is always same as first control point of next curve in contour

<table>
<thead>
<tr>
<th>Red (16 bits)</th>
<th>Green (16 bits)</th>
<th>Blue (16 bits)</th>
<th>Alpha (16 bits)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p1.x (curve 1)</td>
<td>p1.y (curve 1)</td>
<td>p2.x (curve 1)</td>
<td>p2.y (curve 1)</td>
</tr>
<tr>
<td>p3.x (curve 1)</td>
<td>p3.y (curve 1)</td>
<td>p2.x (curve 2)</td>
<td>p2.y (curve 2)</td>
</tr>
<tr>
<td>p1.x (curve 2)</td>
<td>p1.y (curve 2)</td>
<td>p2.x (curve 2)</td>
<td></td>
</tr>
<tr>
<td>p3.x (curve 2)</td>
<td>p3.y (curve 2)</td>
<td>p2.x (curve 3)</td>
<td></td>
</tr>
<tr>
<td>p1.x (curve 3)</td>
<td>p1.y (curve 3)</td>
<td>p2.x (curve 3)</td>
<td></td>
</tr>
</tbody>
</table>

...
Band Texture

- Each glyph has a list of H bands and V bands.
- Each band contains a list of curves, sorted in both directions.

<table>
<thead>
<tr>
<th></th>
<th>Red (16 bits)</th>
<th>Green (16 bits)</th>
<th>Blue (16 bits)</th>
<th>Alpha (16 bits)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H band curve count</td>
<td>H band data offset</td>
<td>H band split value</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H band curve count</td>
<td>H band data offset</td>
<td>H band split value</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V band curve count</td>
<td>V band data offset</td>
<td>V band split value</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V band curve count</td>
<td>V band data offset</td>
<td>V band split value</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Curve location, descending max sort</td>
<td>Curve location, ascending min sort</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Curve location, descending max sort</td>
<td>Curve location, ascending min sort</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- One texel for each horizontal band.
- One texel for each vertical band.
- One texel for each curve in each band.
GPU-Centered Font Rendering Directly from Glyph Outlines

Results

- 4K display filled with text, timed on NV GeForce 1060

<table>
<thead>
<tr>
<th>Font</th>
<th>Sample</th>
<th>Complexity</th>
<th>Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arial</td>
<td>ABCDEFG</td>
<td>28</td>
<td>0.70</td>
</tr>
<tr>
<td>Minion</td>
<td>ABCDEFG</td>
<td>35</td>
<td>0.71</td>
</tr>
<tr>
<td>Times</td>
<td>ABCDEFG</td>
<td>35</td>
<td>0.73</td>
</tr>
<tr>
<td>Jokerman</td>
<td>ABCDEFG</td>
<td>60</td>
<td>1.1</td>
</tr>
<tr>
<td>Spider</td>
<td>#BDEFG</td>
<td>500</td>
<td>2.8</td>
</tr>
</tbody>
</table>
Results

ABCDEFGHIJKLMNOPQRSTUVWXYZ
ABCDFGHIJKLMNOPQRSTUVWXYZ
ABCDEFGHIJKLMNOPQRSTUVWXYZ
ABCDEFGHIJKLMNOPQRSTUVWXYZ
ABCDEFGHIJKLMNOPQRSTUVWXYZ
Results
Results
Questions?

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