Efficient antialiasing on Intel HD graphics

Alexander Reshetov
Talk Outline

• Goal
  – To present efficient post-processing antialiasing on Intel HD Graphics

• Level
  – Introductory

• Intended Audience
Intended Audience

• Practitioners (game developers)
  – Provide pluggable image-based anti-aliasing module which improves performance by 2.5X on Intel hardware (src code)

• Researchers
  – State-of-the-art in post-processing AA

• Practitioners & Researchers
  – What works on Intel hardware
What We’re Talking About

this one is antialiased ⇝

⇐ this one is not

(if you can read it, you can see it)
Substantive Outcome

• Sample code (C++ plus HLSL) of SAA
  – Or google for “Intel MLAA”
  – Both CPU (MLAA) and HD Graphics (SAA) code

• Separable antialiasing (SAA): the same advantages (and disadvantages) as state-of-the-art GPU MLAA
  – image-based ➔ can be used anywhere
  – “good enough” quality

• Runs at ~ 1 ms
Why It is Important

• Previous best MLAA result on Intel HD ~ 2.5 ms
  – But it is only for the top-of-the-line desktop machine
  – 5 ms on this notebook ➔ barely acceptable for games

• Can the new version be used on other hardware?
  – Sure. But we wouldn't advise it...
  – Dual support via DirectX techniques
Why Releasing the Source Code

• Helps with application customization
• Avoids some artifacts (small text)
• Could be deeply integrated into post-processing pipeline
• Makes the app independent from the driver
• Could be reused for other problems
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Notice revision #20110804
Research Agenda

• What is antialiasing (and aliasing)
• Review of existing AA techniques
• In the context of direct and deferred shading
• Deep dive into morphological methods
  – Existing GPU implementations
  – Modification for Intel HD graphics
Graphics Pipeline

- scene description
- graphics pipeline
- 2D image
Computer Vision Pipeline

scene description

data processing

2D image
What is Important

• https://www.google.com/search?q=computer+vision+silhouettes
  ~ 1 230 000 hits

• https://www.google.com/search?q=human+vision+silhouettes
  ~ 1 090 000 hits
Why It is Important
Aliasing Does Not Exist in Nature
## A Case Study

<table>
<thead>
<tr>
<th>Device</th>
<th>Intrinsic antialiasing</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Eye" /></td>
<td>✔️</td>
</tr>
<tr>
<td><img src="image" alt="Camera" /></td>
<td>✔️</td>
</tr>
<tr>
<td><img src="image" alt="Computer" /></td>
<td>✗</td>
</tr>
</tbody>
</table>
Resolution is Important

Scene from Call of Duty: Word at War® courtesy of Activision
Resolution is Important
Artistic Value of Coarsenessess

Georges-Pierre Seurat’s *La Parade* (from WIKIPEDIA): “The tiny juxtaposed dots of multi-colored paint allow the viewer's eye to blend colors optically, rather than having the colors blended on the canvas or pre-blended as a material pigment.”
A Single Pixel
Kazimir Malevich’s *Black Square*, 1915, Oil on Canvas
At What Resolution We Could Forget about AA?

• 300 dpi helps but aliasing is still noticeable...due to hyperacuity
  – John Hable’s blog
  – David Luebke’s The Ultimate Display
• It is possible to process at lower resolution and upscale latter
  – Saves energy
  – Scalable Smart Displays by Turner Whitted
• Morphological methods naturally reconstruct continuous images ➔ possibilities
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No Antialiasing ➔ Aliasing

This is a pixel ➔

all values are sampled @ the center
(depth, geometry, textures, etc)
Supersampling = Numerical Integration

values are sampled at multiple locations
(and resulting colors are averaged)
MultiSampling

It works because:

1. Geometry & shading values are correlated
2. ∃ hardware for bilinear interpolation of shading values

- Depth is sampled @ subsamples
- Everything else @ the center
MultiSampling Resolve
What is Deferred Shading?

- Scene description
- Deferred shading pipeline
- 2D image
Advantages of Deferred Shading/Lighting

• Shading only visible pixels
• more lights (each light is processed only for affected pixels)
• Pipeline simplification
• Post effects
MSAA + Deferred Shading
MSAA + Deferred Shading
Alternative Techniques

• Goal: a reasonable quality while reducing
  – Bandwidth and/or
  – Memory footprint
  – # of computations

Achieved by MLAA + orthogonal to the pipeline + universal

• ~30 entries on AA Naming Guide on AnandTech
## Filtering Approaches for Real-Time Anti-Aliasing

<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
<th>Speaker</th>
</tr>
</thead>
<tbody>
<tr>
<td>2:00</td>
<td>Introduction</td>
<td>Diego Gutierrez</td>
</tr>
<tr>
<td>2:05</td>
<td>A Directionally Adaptive Edge Anti-Aliasing Filter</td>
<td>Jason Yang</td>
</tr>
<tr>
<td>2:20</td>
<td>Morphological Anti-Aliasing (MLAA)</td>
<td>Alexander Reshetov</td>
</tr>
<tr>
<td>2:35</td>
<td>Jimenez’s MLAA &amp; SMAA (Subpixel Morphological Anti-Aliasing)</td>
<td>Jorge Jimenez</td>
</tr>
<tr>
<td>2:50</td>
<td>Hybrid CPU/GPU MLAA on the Xbox-360</td>
<td>Pete Demoreuille</td>
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<tr>
<td>3:05</td>
<td>MLAA on the PS3</td>
<td>Cedric Perthuis, Tobias Berghoff</td>
</tr>
<tr>
<td>3:35</td>
<td>The Saboteur Anti-Aliasing (SPUAA)</td>
<td>Henry Yu</td>
</tr>
<tr>
<td>4:00</td>
<td>Subpixel Reconstruction Anti-Aliasing (SRAA)</td>
<td>Morgan McGuire</td>
</tr>
<tr>
<td>4:15</td>
<td>FXAA 3.11 in 15 Slides</td>
<td>Timothy Lottes</td>
</tr>
<tr>
<td>4:30</td>
<td>Distance-to-edge Anti-Aliasing (DEAA)</td>
<td>Hugh Malan</td>
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<tr>
<td>4:45</td>
<td>Geometry Buffer Anti-Aliasing (GBAA)</td>
<td>Emil Persson</td>
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<tr>
<td>4:55</td>
<td>Directionally Localized Anti-Aliasing (DLAA)</td>
<td>Dmitry Andreev</td>
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<tr>
<td>5:10</td>
<td>Anti-Aliasing Methods in CryENGINE 3</td>
<td>Tiago Sousa</td>
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</table>
# AA Taxonomy

<table>
<thead>
<tr>
<th>antialiasing method</th>
<th>quantity</th>
<th>depth</th>
<th>coverage</th>
<th>geometry</th>
<th>shading</th>
<th>values</th>
<th>storage</th>
<th>BW</th>
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<tbody>
<tr>
<td>no antialiasing</td>
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<tr>
<td>multisampling antialiasing MSAA [Ake93]</td>
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<td>coverage sampling antialiasing CSAA [You06]</td>
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<td>supersampling antialiasing SSAA [Lee80]</td>
<td>x</td>
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<td>MLAA [Res09, BHD10, Per10, Bir11, JME’11], FXAA [Lot11], SMAA 1x [JES’12]</td>
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<td>a directionally adaptive edge antialiasing [YP09, Joh12]</td>
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<td>geometric methods [BWG03, CD05, Mal10, GG12, Per12]</td>
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<td>edge blurring: directionally localized DLAA [And11], normal filter NFAA, screen-space SSAA [Uen11]</td>
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<td>temporal reprojection [NSL’07, YNS’09, Kap10]</td>
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<tr>
<td>spatial/temporal supersampling + morphological antialiasing SMAA 4x [JES’12]</td>
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<td>deferred MSAA [Pet10]</td>
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<td>subpixel reconstruction antialiasing SRAA [CML11]</td>
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<td>surface based antialiasing SBA [SV12]</td>
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<td>resampling antialiasing RSAA [Res12]</td>
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</tbody>
</table>

**Legend:**
- **X:** not used
- **once:** used once
- **some:** used in some cases
- **many:** used in many cases
- **all:** used in all cases
- **∞:** used indefinitely

**Sampling Rate per Pixel:**
- **X:** not used
It is All About Sampling Frequency

- No antialiasing: everything done once per pixel
- Supersampling: everything many times per pixel
- Multisampling: decoupling geometry and shading
  - Also in SRAA, deferred MSAA, and RSAA (all targeting deferred shading applications)
- Coverage sampling: decoupling area estimation
- Surface-based AA: decoupling storage
Geometric Antialiasing
Geometric Antialiasing

complexity will increase as $n^2$
Geometric Antialiasing

complexity will increase as n
Pro et Contra of Geometric Methods

+ Infinite resolution... when it works
- Difficult to find silhouettes (needs topology)
- There could be too many of them
- Some cases are not handled (or difficult): shadows, overlaps, textured objects...
- Requires pipeline modifications
- It is application specific
Existing Geometric Antialiasing Techniques

- Distance-to-edge Anti-Aliasing, Hugh Malan
  - Output all edges → use colors to decide what to use
- Geometry Buffer **Anti-Aliasing**, Emil Persson
  - Resolve fg/bg pixels by searching the neighborhood
- Smoothed Lines **Anti-Aliasing**, Gjol Mikkel and Mark
  - Targeting mobile devices
Infinite resolution... when it works

- Difficult to find silhouettes (needs topology)
- There could be too many of them
- Some cases are not handled (or difficult): shadows, overlaps, textured objects...
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- It is application specific

Raison d’être for Morphological Methods
Research Agenda

• What is antialiasing (*and* aliasing)
• Review of existing AA techniques
• In the context of direct and deferred shading
• **Deep dive into morphological methods**
  – Existing GPU implementations
  – Modification for Intel HD graphics
1. Somehow find silhouettes in images (and hope that it will correspond to real objects)
2. Blend (aka filter) colors around the silhouettes
MLAA in 3 Steps
1. Discontinuities
2. Silhouettes
3. Color Blending
How to Blend Colors

pixel color = \[ \text{left pixel color} \times \text{red} + \text{current pixel color} \times \text{blue} \]

( \text{red} \text{ comes from the left pixel, blue} \text{ — from the current one} )
# How to decide if pixels are different

<table>
<thead>
<tr>
<th>Method</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>threshold for each color channel</td>
<td>• ≠ human vision</td>
</tr>
<tr>
<td></td>
<td>• issues with illumination changes near silhouettes</td>
</tr>
<tr>
<td>luminosity [ITU-R BT. 709]</td>
<td>• false negatives</td>
</tr>
<tr>
<td>Non-linear thresholding (in God of War 3 and SMAA)</td>
<td>• good detection over the whole range</td>
</tr>
<tr>
<td></td>
<td>• requires artist’s adjustment</td>
</tr>
<tr>
<td>depth only</td>
<td>• choosing a scale is difficult</td>
</tr>
<tr>
<td></td>
<td>• problems with corners</td>
</tr>
<tr>
<td>Local filter (3x3 Sobol in FXAA)</td>
<td>• avoids spurious edges</td>
</tr>
<tr>
<td></td>
<td>• requires more computations</td>
</tr>
</tbody>
</table>
MLAA Steps

1. Find discontinuities between pixels
2. Extract silhouettes
3. Blend colors
Pixel Discontinuities $\Rightarrow$ Silhouettes

silhouette segments start/end at edges of pixels at which horizontal and vertical separation lines intersect
Silhouette Disambiguation

for each separation line

• look at all start/end points on adjacent orthogonal lines

• choose the longest segment
<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>original CPU implementation</td>
<td>proof of concept</td>
</tr>
<tr>
<td></td>
<td>Metro 2033, Saboteur</td>
<td>unpublished</td>
</tr>
<tr>
<td>2010</td>
<td>Practical Morphological Antialiasing on the GPU</td>
<td>recursive doubling</td>
</tr>
<tr>
<td></td>
<td>God of War 3 by Sony (reference implementation)</td>
<td>inside current frame</td>
</tr>
<tr>
<td></td>
<td>AMD driver (now MLAA 2.0)</td>
<td>allowing older games</td>
</tr>
<tr>
<td></td>
<td>Nvidia FXAA (Sobol; fractional supersampling)</td>
<td>many modes</td>
</tr>
<tr>
<td></td>
<td>Jimenez’ MLAA @ GPU Pro 2</td>
<td>leveraging TS, src available</td>
</tr>
<tr>
<td>2011</td>
<td>Hybrid CPU/GPU MLAA</td>
<td>Xbox 360</td>
</tr>
<tr>
<td></td>
<td>Siggraph course</td>
<td>CPU/GPU/consoles</td>
</tr>
<tr>
<td>2012</td>
<td>SMAAA (from 1x to 4x supersampling)</td>
<td>many modes; improved</td>
</tr>
<tr>
<td></td>
<td>Nvidia TXAA</td>
<td>Kepler+</td>
</tr>
</tbody>
</table>
MLAA \hspace{2cm} GPU

- Restrict neighborhood search $\Rightarrow$ precompute everything and use textures
- Use texture sampler creatively
- Mask operations by using the stencil buffer

**Bottom line:**
- Avoid branches
- Trade memory BW for computations

As implemented in Jorge Jimenez’ MLAA and SMAA
How to Train Your Texture Unit

• Texture stores 0.0 (no edge) and 1.0 (edge)
  – Sample at (0,0) – get back 0.0 or 1.0
  – Sample at offset position – learn 4 values at once

\[
f_{xy}(b, x, y) = f_x(b_1, b_2, x) \cdot y + f_x(b_3, b_4, x) \cdot (1 - y)
\]
SMAA performance

• GTX 580, 1280x720 resolution
  – 0.35 ms for 1 color sample per pixel
  – 1 ms for 2 color samples

• Intel® HD 4000 Graphics
  – 2.5 ms (1 sample)
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What We Know about Intel HD 4000

- Well-balanced machine
- With flexible instruction set
- Does not have a specialized memory
- Texture unit is small
- Good integer performance (for GPU)
- SMAAA characteristics are not particularly enticing
  - Avoid branches
  - Trade memory BW for computations
Reducing BW

• Use bits instead of floats
  – Addressable as bytes
  – Extracting bits with firstbitlow/firstbithigh (SL 5)

• One caveat: no support for 2D arrays of bits

• Solution: never mix horizontal and vertical operations

→ Let’s call the new algorithm Separable Anitaliasing
Separating Horizontal and Vertical Operations

don’t need blue vertical lines to deduce the end points for horizontal separation lines.
HLSL Edge-Detection Kernel

- 32 threads in a thread group
- Each thread handles a column of 32 pixels
- Horizontal: InterlockedAdd to avoid conflicts between different threads
- Vertical: Accumulate bits and write them at once
Blending Pass

• Detect silhouettes ➔ blend colors (no reason to store the silhouettes)
• One horizontal and one vertical pass
• Also want to do it with tiles
• Problem: pixels @ borders could be blended twice
Solution: Consider Only Edges with Padding
Side Effect: Helps with Small Text

<table>
<thead>
<tr>
<th></th>
<th>separable antialiasing algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>No AA</td>
<td></td>
</tr>
<tr>
<td>SAA</td>
<td></td>
</tr>
<tr>
<td>MLAA</td>
<td></td>
</tr>
</tbody>
</table>
Performance @ 1280x720

- 0.5 ms for edge detection
- 0.25 ms for each of (H/V) blending passes
- The same performance for OpenCL
- 20% faster with hand-coded optimization
  - Slicing register file
  - Using media reads/writes
Wrap-up: SAA characteristics (and how it is optimized for Intel HD Graphics)

• Lots of integer ops
• Branchy code benefits from short SIMD size (16)
• Cache-optimized layout
  – Processing of vertical edges allows efficient cache-friendly memory ops
  – InterlockedAdds for horizontal edges have small impact
Thank You!

The Team

Alexei Soupikov
OpenCL implementation
low-level optimization

Thomas F Raoux
HLSL implementation

Alexandre De Pereyra
CPU optimization
code samples