SIGGRAPH 2012

The 39th International Conference and Exhibition on Computer Graphics and Interactive Techniques

Graphics Gems for Games

Findings from Avalanche Studios

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AVALANCHE STUDIOS

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Graphics Gems for Games

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- Particle trimming
- Merge-instancing
- Phone-wire Anti-Aliasing
- Second-Depth Anti-Aliasing

Particle trimming

Particle trimming

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- GPUs increasingly more powerful
  - ALU – Through the roof
  - TEX – Pretty decent increase
  - BW – Kind of sluggish
  - ROP – Glacial speed

	9700 Pro (2002)	HD 2900XT (2007)	HD 7970 (2012)	10 year speedup
ALU	33.8 GF/s	475 GF/s	3789 GF/s	112x
TEX	2.6 GT/s	11.9 GT/s	118.4 GT/s	46x
BW	19.84 GB/s	105.6 GB/s	288 GB/s	15x
ROP	2.6 GP/s	11.9 GP/s	29.6 GP/s	11x

Source: Wikipedia [1]

- ROP bound?
  1. Draw fewer pixels
  2. ???
  3. Goto 1

ALU and TEX has increased way more than Bandwidth and ROP over the last decade. Modern GPUs have an ALU / ROP ratio 10x larger than a decade ago.

There are very few possible optimization opportunities when you are ROP bound. Simply drawing fewer pixels is generally the only way to go. Another strategy is to make fancier shaders to shift the balance towards the ALU/TEX. However, that might make it prettier more or less for free, but it won’t make it go faster.

Particle trimming

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- Typical ROP bound cases
  - Particles
  - Clouds
  - Billboards
  - GUI elements
- Solutions
  - Render to low-res render target
  - Abuse MSAA
- Our solution
  - Trim particle polygon to reduce waste

There are a number of typically ROP bound cases in real games today. They generally consist of a simple shader, usually little more than just a texture.

There are some tricks that have been employed to various success before, such as rendering to a low-res render target and upscale, which essentially reduces the number of pixels. This may work for low-frequency data, such as a typical particle system. Another approach is to abuse MSAA to improve rasterize throughput. This may not work out if you are already using MSAA for antialiasing.

The solution presented here is to reduce the number of pixels by eliminating waste. This technique can generally be combined with the other two approaches.

Particle trimming

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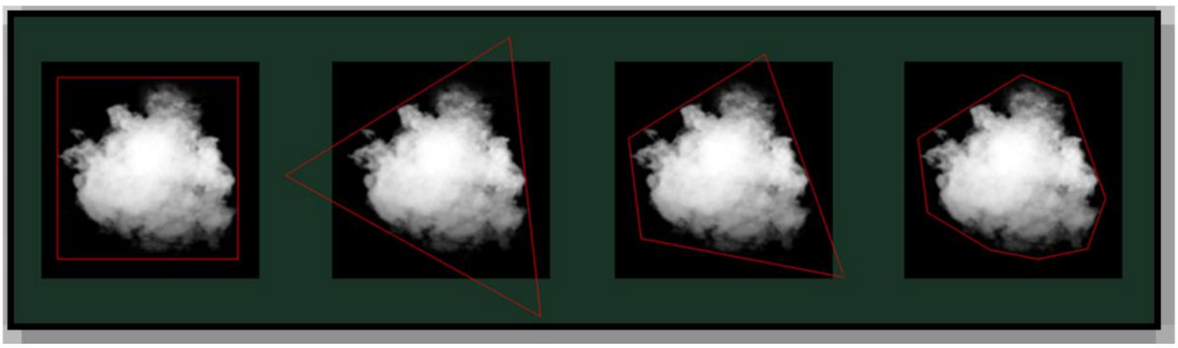
- Common with large alpha=0 areas
  - Wasted fillrate
  - Adjust particle geometry to minimize waste
  - Automated tool [2]



A typical particle texture has plenty of area where alpha is zero. Rendering those pixels will be a waste of fillrate as it contributes nothing to the final frame.

Instead of simply drawing a plain quad, a better approach is to use irregular polygons that tightly encloses the ”meat” of the particle. We made a tool that automatically finds an optimal enclosing polygon for a given texture.

Particle trimming

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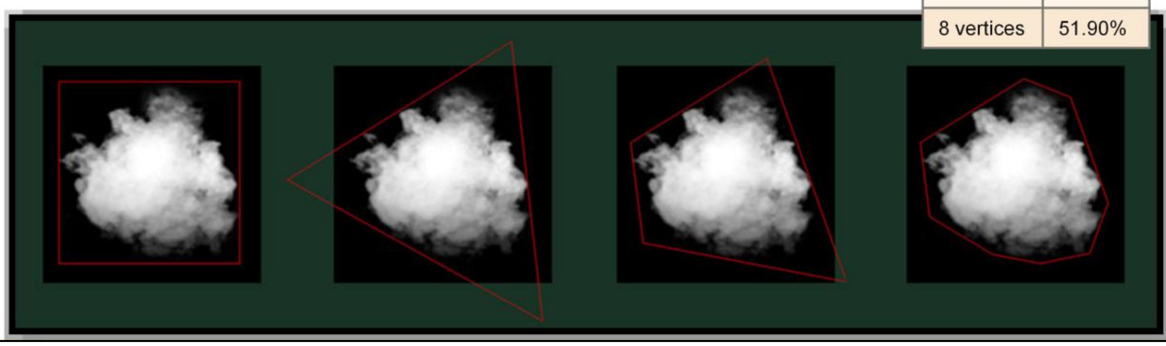
- Huge fillrate savings
  - More vertices ⇒ Bigger saving
  - Diminishing returns
  - Just Cause 2 used 4 for clouds, 8 for particle effects

Original	100%
Tight rect	69.23%
3 vertices	70.66%
4 vertices	60.16%
5 vertices	55.60%
6 vertices	53.94%
7 vertices	52.31%
8 vertices	51.90%



The more vertices you use, the bigger the fillrate saving will be, but there is a diminishing return. Going further than about 8 vertices is usually not really worth it. Even staying with four vertices can provide a substantial performance improvement.

Particles will have to be very small for a smaller vertex count to really pay off from a GPU performance point of view. You'll rarely be bound by the vertex shader. However, if the particles are generated on the CPU, computing more vertices may be costly. For this reason we stuck with 4 vertices for the clouds in Just Cause 2. However, the particle effects were drawn with GPU generated vertices, so we went all the way to 8 there.

Particle trimming

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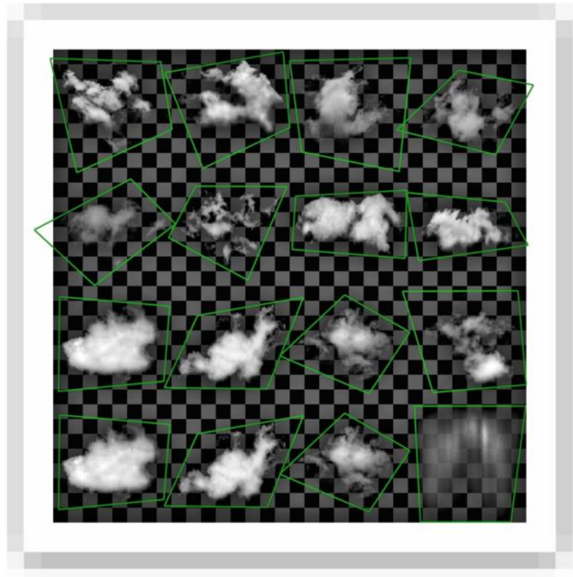
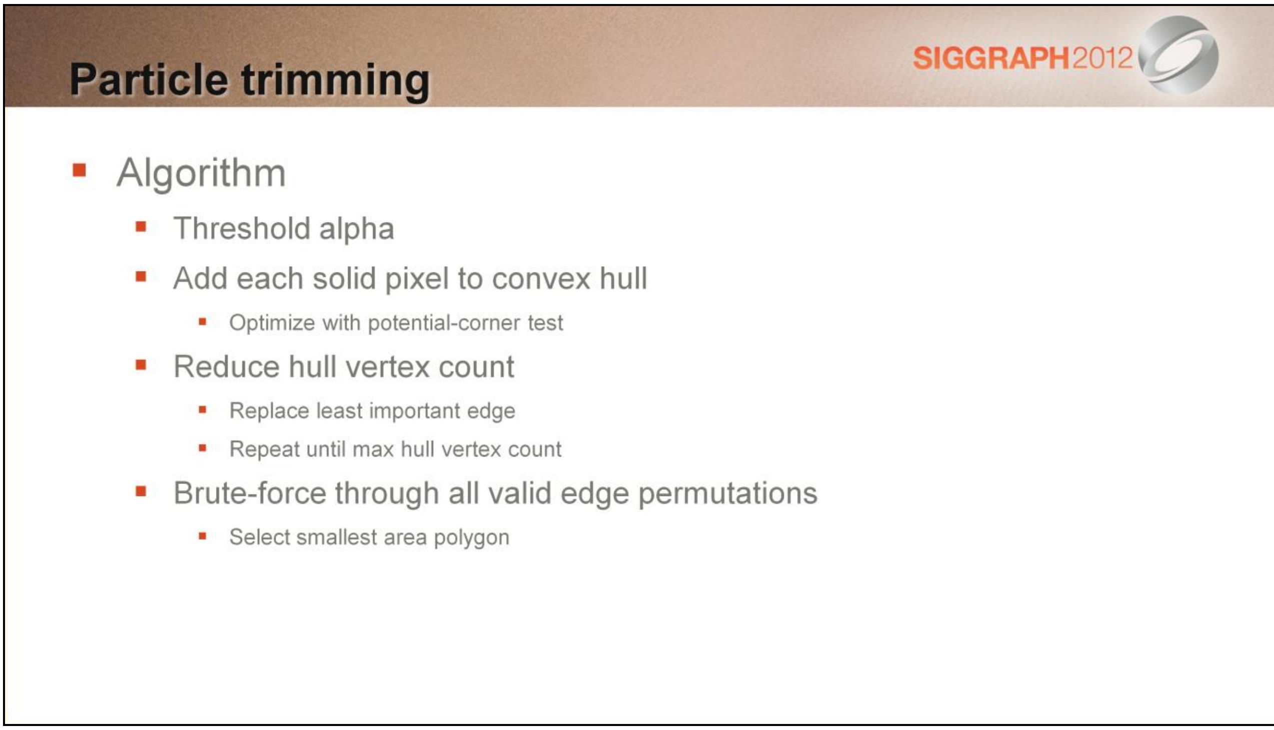
- First attempt: Manual trimming
  - Tedious, but proved the concept
  - OK for our cloud atlas
    - > 2x performance
  - Dozens of atlased particle textures
- Automatic tool [3]
  - Input:
    - Texture and Alpha threshold
    - Vertex count
  - Output:
    - Optimized enclosing polygon



Before making the tool we tried manual trimming with a rudimentary in-game tweaking system temporarily added to the debug-menu. This was done on the clouds texture atlas. It worked, but was tedious. The large performance benefit motivated expanding this to general particle effects. However, the manual approach did not scale. Instead of a single atlas with 16 tiles we had dozens of textures, some with 64 animation frames. It would be weeks or months of works to do them all manually.

We came up with a tool that given a texture, an alpha threshold, and a target vertex count computed an optimized enclosing polygon. This tool is open-source and available online [3]. We have continued to develop it internally though and integrated it into our pipeline. However, the open-source version is a good start for integrating this technique into your tool chain.



Adding pixels to the convex hull can be quite slow if we are adding every solid pixel. So whenever a pixel is deemed to not be a potential corner pixel, e.g. it is surrounded by other solid pixel and thus completely within solid space, then we simply skip it. This made the construction of the convex hull substantially faster.

The convex hull is typically a fair bit larger than the target vertex count, anything from a few dozen up to hundreds of vertices. To find the most optimal polygon we loop through all permutation of edges in the hull and select the one that results in the smallest area. This is a brute-force approach, so it is important to reduce the search space prior to this selection phase. So we remove vertices from the convex hull, one-by-one, by finding the edge that grows the convex hull the least when removed.

Particle trimming

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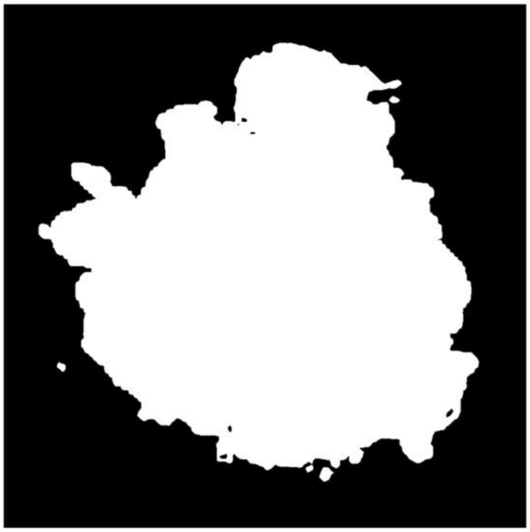
Original texture

Particle trimming



Thresholded texture

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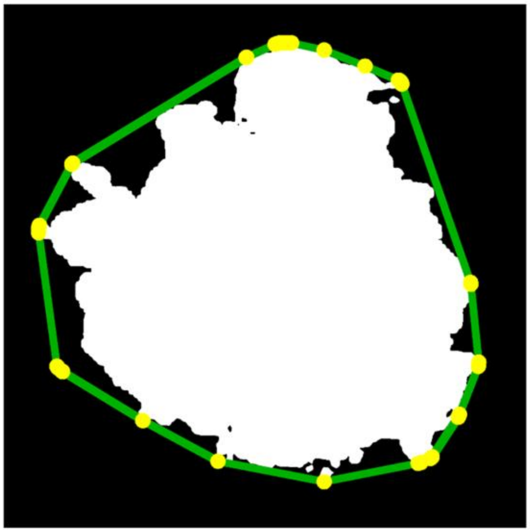

Convex hull

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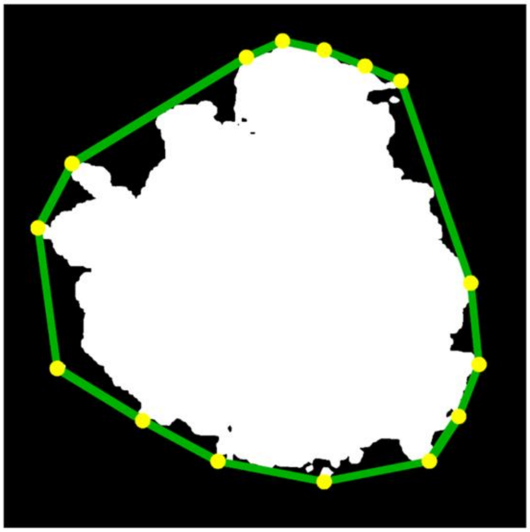
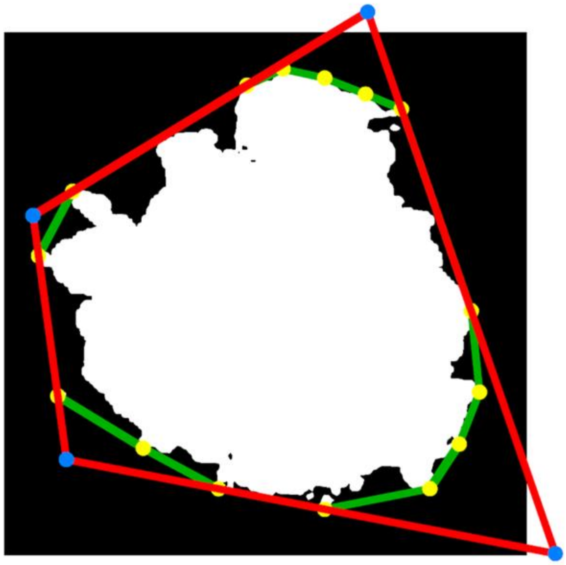


Reduced convex hull

Particle trimming



Final 4 vertex polygon (60.16%)

Particle trimming

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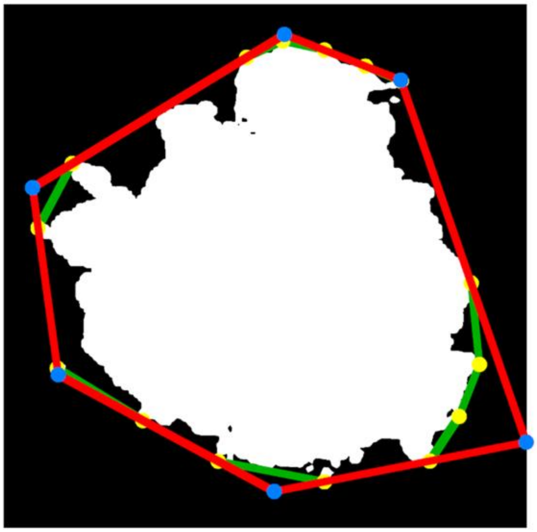

Final 6 vertex polygon
(53.94%)

Particle trimming

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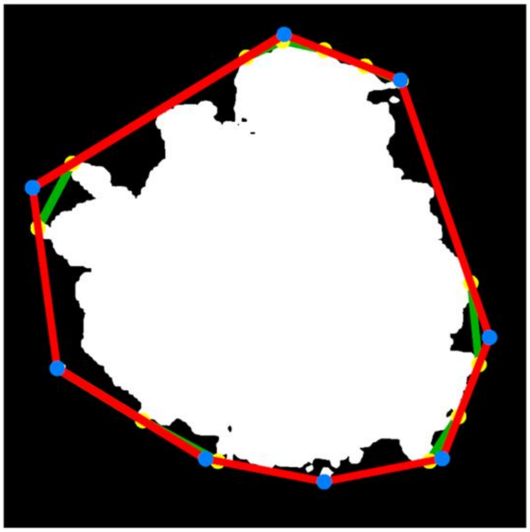

Final 8 vertex polygon (51.90%)

Particle trimming

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- Issues
  - Polygon extending outside original quad
    - No problem for regular textures. Use CLAMP.
    - May cut into neighboring atlas tiles …
    - Compute all hulls first, reject solutions that intersect another hull.
    - Revert to aligned rect if no valid solution remains
  - Performance
    - Brute-force
    - Keep convex hull vertex count reasonably low
  - Filtering
    - Add all four corners of a pixel (faster), or interpolate subpixel alpha values (accurate)
  - Handling ”weird” textures
    - I.e. alpha != 0 at texture edge

The optimized polygons can sometimes include long sharp wedges that extend outside of the original quad. For a regular texture this is fine, just use CLAMP mode. For texture atlases this could mean that part of the ”meat” from another particle gets included, which produces ugly artifacts. This is generally only a problem in practice for small vertex counts, like 3-5 vertices. In Just Cause 2 we used 8 vertices, so this was not a problem. For the clouds texture that used 4 vertices this was avoided manually as part of the tweaking, which occasionally led to somewhat larger polygons than otherwise necessary. Post-JC2 we have added a proper solution that simply rejects solutions where the resulting polygon would intersect the convex hull of another atlas tile. This typically allows a fair amount of cutting into neighboring quads, but never into the actual particle.

Merge-Instancing

Merge-Instancing

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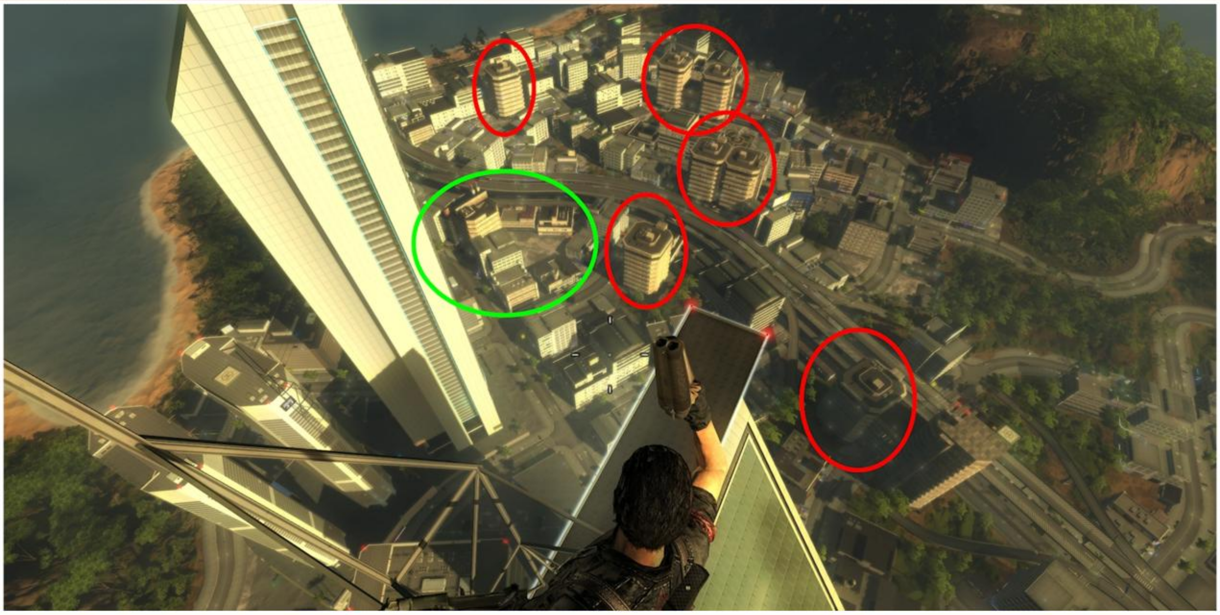
- Instancing
  - One mesh, multiple instances
- Merging
  - Multiple meshes, one instance of each
- What about: Multiple meshes, multiple instances of each?
  - Instancing: Multiple draw-calls
  - Merging: Duplication of vertex data
  - Merge-Instancing: One draw-call, no vertex duplication

When reducing the number of draw calls there are two standard approaches. Multiple instances of a single mesh is typically done with regular instancing. If there are multiple meshes, but a single instance of each, they can be merged into a single vertex and index buffer and drawn with a single draw call. However, sometimes you want to draw multiple meshes, with multiple instances of each, and each with their own transforms or other instance data. With instancing this results in multiple draw calls. With the standard merging approach you need to duplicate the vertex data.

We came up with an approach that combine the benefits of merging and instancing such that you can draw it all with a single draw call without duplicating vertex data. Thus, for the lack of a better name, it can be referred to as Merge-Instancing.

Merge-Instancing



In this screenshot from Just Cause 2 you may think that those building in the red circles would be prime candidates for drawing with instancing, considering that they are the same model, just different transforms. However, this means that either they all have to be merged into the same bounding box for culling, which will greatly reduce the effectiveness of culling due to the enormous bounding box required to enclose them all. Alternatively you cull them all individually, which means that you are paying a much higher price in the culling stage, likely to far exceed the benefit of reduced draw call count, besides the complexity of managing multiple instances as a single entity and dynamically generating the instance buffer every frame.

Ideally you want to merge the models in the green circle, because they are close to each other and can easily share a common bounding box and be dealt with as a single instance. Unfortunately, neighboring houses are rarely all of the same mesh, but typically contain a mix of different meshes. Hence the need for this technique.

Merge-Instancing

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Instancing

```
for (int instance = 0; instance < instance_count; instance++)
  for (int index = 0; index < index_count; index++)
    VertexShader( VertexBuffer[IndexBuffer[index]], InstanceBuffer[instance] );
```

Merge-Instancing

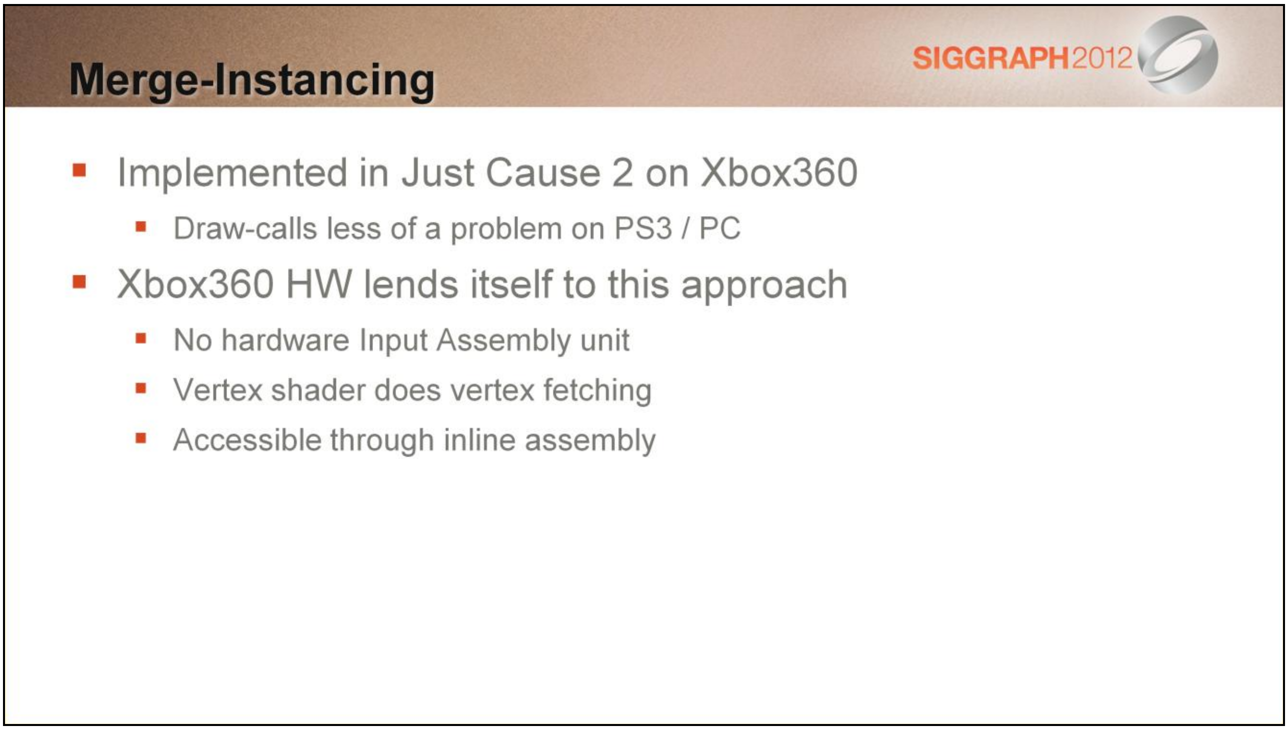
```
for (int vertex = 0; vertex < vertex_count; vertex++)
{
    int instance = vertex / freq;
    int instance_subindex = vertex % freq;

    int indexbuffer_offset = InstanceBuffer[instance].IndexOffset;
    int index = IndexBuffer[indexbuffer_offset + instance_subindex];

    VertexShader( VertexBuffer[index], InstanceBuffer[instance] );
}
```

This is how instancing and merge-instancing compare on a higher level. Instancing just loops over the instances, and for each instance it loops over the mesh indexes and passes the corresponding vertex and instance data to the vertex shader. Here the Input Assembly unit takes care of feeding the vertex shader a nicely packaged set of data in its input attributes.

Merge-Instancing requires that the vertex shader does all the work itself. The only input is the vertex id. So it loops over the total number of vertices for the entire batch, computes which instance it belongs to and where within the instance we are. This is used to fetch the index from the index buffer, the corresponding vertex and of course the instance data. Once the final vertex has been fetched the same vertex shader logic proceeds as normal.



For Just Cause 2 we only implemented this on Xbox360. One reason is that it was the only platform that really had much of a problem with draw-calls. The PS3 has a more lightweight API and did not suffer as much when the draw-call count increased. We were also running our rendering code on the SPUs, which further made rendering code run fast. For the PC the sheer amount of raw power compared to the consoles, together with a much more efficient DX10 API, made draw-calls not much a problem.

The other reason is that the Xbox360 API lends itself very well to this technique. It is possible to implement similarly on other platforms, but you may need to jump through some hoops to make it happen and may pay a higher price in performance. However, the Xbox360 GPU does not have a traditional Input Assembly unit. Instead it is the vertex shader itself that does all vertex fetching. Every time you set a new vertex declaration the runtime may have to patch your shader to insert new vertex fetch instructions. The vertex fetch instructions are accessible for general shader development through inline assembly. Consequently there is plenty of flexibility in how to fetch vertices, i.e. it does not have to be done in the typical Input Assembly kind of way. Since we're not really replacing a fixed function unit with shader logic there is no particular overhead in doing it manually rather than relying on patched shader instructions.

Merge-Instancing

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- Merging odd sized meshes
  - Choose common frequency
  - Duplicate instance data as needed
  - Pad with degenerate triangles as needed
- Example
  - Mesh0: 39 vertices,   Mesh1: 90 vertices
    - Choose frequency = 45
    - Pad Mesh0 with 2 degenerate triangles (6 vertices)
    - Instances[] = {

      (Mesh0, InstanceData[0]),

      (Mesh1, InstanceData[1]),

      (Mesh1 + 45, InstanceData[1]) }

To make this work we have to align meshes on a common frequency. This may also mean we have to insert a few degenerate triangles, depending on the sizes of the meshes involved. For larger meshes we may need to use more than one instance data slot. This is a small amount of data though compared to duplicating vertices. In the example here the second mesh is more than twice as big, so we represent this as two instances, where the first instance points to the first half of the mesh, and the other to the second half of the mesh.

Phone-wire Anti-Aliasing

Phone-wire AA

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- Sources of aliasing
  - Geometric edges
    - Mostly solved by MSAA
    - Post-AA usually works too
    - Breaks down with thin geometry
  - Shading
    - Sort of solved by mipmapping
    - Poorly researched / understood
    - Few practical techniques for games
    - LEAN mapping [4]

At one point aliasing was sort of a solved problem, first through mipmapping for the shading and later through MSAA for geometric edges. However, aliasing in games is on the rise again. As shaders get more advanced mipmapping alone does not fully solve the shader aliasing problem. More complex lighting introduces aliasing where the mipmapped textures alone exhibit none. In particular the specular component tends to cause lots of aliasing. This field is poorly researched and only quite few approaches exist to properly deal with the problem. The most notable work here is LEAN mapping. On the geometry side we are getting increasingly denser geometry, and as geometry gets down to the sub-pixel level, MSAA is not always sufficient.

Phone-wire AA

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- Sources of aliasing
  - Geometric edges
    - Mostly solved by MSAA
    - Post-AA usually works too
    - **Breaks down with thin geometry**
  - Shading
    - Poorly researched / understood
    - Few practical techniques for games
    - LEAN mapping

This technique takes a stab at solving the thin geometry case, at least for a subset of common content in games exhibiting an aliasing problem, in particular phone-wires.

Phone-wire AA

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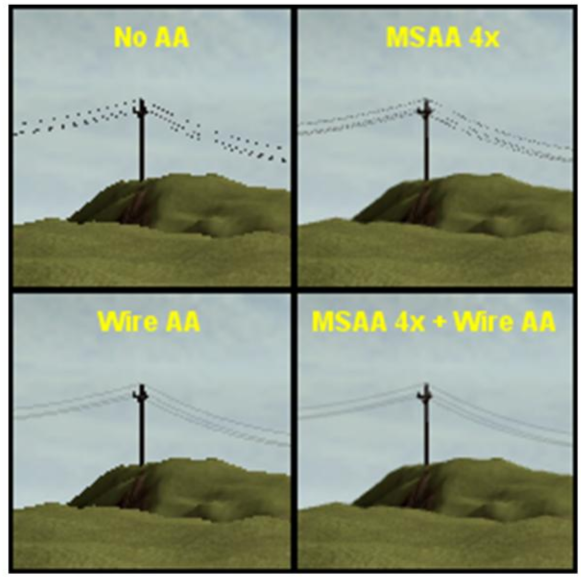
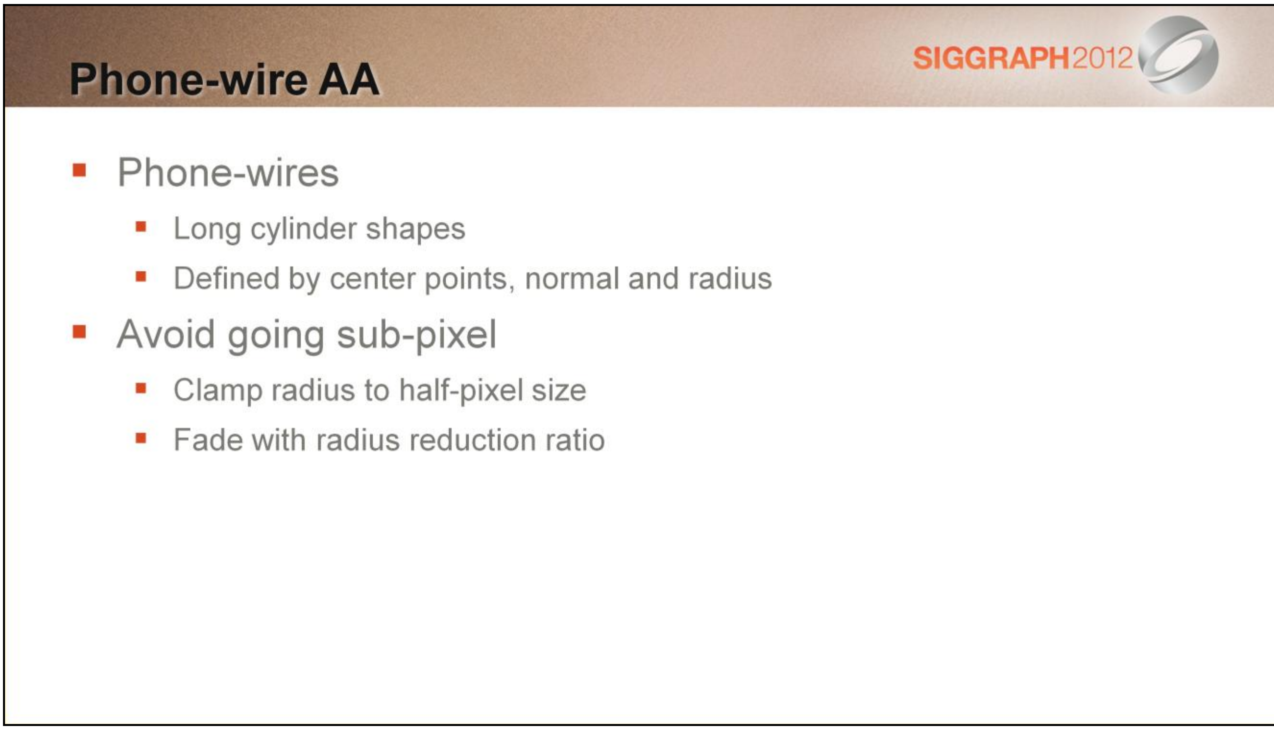
- Phone-wires
  - Common game content
  - Often sub-pixel sized
- MSAA helps
  - … but not that much
  - Breaks at sub-sample size
- Idea
  - Let’s not be sub-pixel sized!



Phone-wires are common in games and highly aliasing prone. They tend to go sub-pixel sized and end up as a set of random disconnected dots flickering in motion. MSAA helps somewhat, but does not fix the problem. It’s just somewhat less objectionable. Essentially it pushes the problem further into the distance, much like a higher resolution would do, but stil completely breaks once you’re down to sub-sample size. The solution is simply to avoid going sub-pixel.



Phone-wires are essentially long cylinder shapes, and for the purpose of this technique they will be represented in the vertex buffer as a center point, a normal and a radius. This is so that we can dynamically adjust the radius of the wire. Note also that this technique works for any cylinder shape, not necessarily only phone-wires. There are other fairly common game content that it also applies to, such as antenna towers, railings, bars etc.

The idea is simple. We avoid going sub-pixel by simply clamping the radius to the width that represents a pixel wide wire at that distance. To simulate the sub-pixel coverage we simply fade it away, for instance, if the actual wire would be half a pixel wide, but we clamp it to a full pixel, then we simply output 0.5 to the alpha and blend.

Phone-wire AA

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```
// Compute view-space w
float w = dot(ViewProj[3], float4(In.Position.xyz, 1.0f));

// Compute what radius a pixel wide wire would have
float pixel_radius = w * PixelScale;

// Clamp radius to pixel size. Fade with reduction in radius vs original.
float radius = max(actual_radius, pixel_radius);
float fade = actual_radius / radius;

// Compute final position
float3 position = In.Position + radius * normalize(In.Normal);
```

- Demo + source available! [5]

First we compute the w value, or the view distance. Then the radius corresponding to pixel wide wire is computed. This is just the view distance multiplied with a constant scale factor which can be derived from your projection. Then we do the clamping of the radius and the resulting fade required, and finally compute the vertex position given the center point, normal and final radius. Full source is available online. [5]

This is with only MSAA enabled. As you can see, the quality is far from perfect. The close wires on the right look sort of OK, but in the distance it’s just a mess of random dots.

Phone-wire AA on, MSAA 4x

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If we enable this technique the wires the clean and smooth, just like we want them. Note though that this technique does nothing for “jaggies”. This technique alone would produce a smooth and fully connected wire, but with your typical stair-stepped pixel edges. Thus we still need a regular antialiasing scheme for dealing with the jaggies, for instance MSAA. It may also work with post-AA techniques, such as MLAA and FXAA, but your mileage may vary. With Phone-wire AA and MSAA used together, we get perfectly aliasing free wires. It should be noted though that it is important that other aspects of the wires are also aliasing free, such as the lighting, otherwise there may still be lighting. In the demo a simple lighting model is used, which is not particularly aliasing prone. For more advanced shading, an approach can be to simply fade away lighting towards a constant color before the wire gets too thin, or from whatever distance aliasing typically becomes visible.

Second-Depth Anti-Aliasing

At Siggraph 2011 there was a course on Filtering Approaches for Real-Time Anti-Aliasing where numerous different techniques and implementations were presented. The techniques can be roughly categorized in two classes: Post-AA techniques and Analytical approaches. Post-AA techniques operate entirely on final pixel buffers that are already available and does not care how the buffer was generated. They are decoupled from the rest of the rendering pipeline, which is a great property. The analytical approaches note that aat least for games the game engine generally has information available that could help the process and provide much more accurate results. Instead of reverse-engineering a pixel-buffer through a bunch of heuristics, they use engine provided data to find the edges through direct computation. The technique here, SDAA, belongs to that latter class of techniques. It should generally be less intrusive on the game engine design than the previous methods.

Second-Depth Anti-Aliasing

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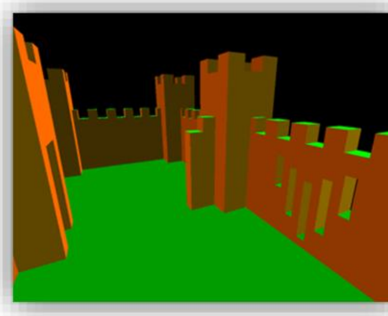
- Depth buffer and second-depth buffer
- Depth is linear in screen-space
  - Simplifies edge detection
  - Enables prediction of original geometry
- Two types of edges
  - Creases
  - Silhouettes
- Silhouettes require second-depth buffer
  - Do pre-z pass with front-face culling
  - Alternatively, output depth to render target for back-facing geometry



The key enabler of this technique is that depth values as interpolated by the rasterizer and stored in a depth buffer is linear in screen-space. This property is illustrated with the picture here where ddx(z) and ddy(z) has been outputted directly to the screen. This results in completely flat-shaded surfaces. In other words, the delta from pixel to pixel will be constant within a surface. So edge detection on a depth buffer is merely about finding a discontinuity in the slope. The slopes can also be used to find where the original geometric edge is located.

There are two types of edges, creases and silhouettes. The former only needs the regular depth buffer, but the latter requires the second-depth buffer as well. The easiest way to generate a second-depth buffer is just to use a pre-z pass, but using front-face culling, then copying the results to a texture before proceeding with general scene rendering. If you don't want a pre-z pass, there are other single-pass options that could work.

Second-Depth Anti-Aliasing

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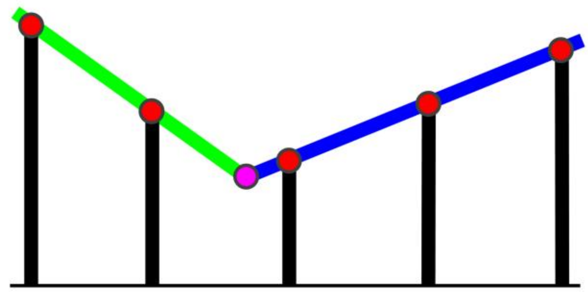
- Attempt crease case first
- Look at depth slopes
- Compute intersection point
  - Valid if distance < one pixel
  - Used if distance < half pixel
- If invalid, try silhouette



When resolving for AA in the end, for each edge pixel we first attempt to resolve it as a crease. This is done by computing the intersection point between the two slopes. If the intersection point lands within a pixel, we have a crease. But we only use it if it’s within half a pixel. The reason for that is that if the edge is further away than that, it is actually not touching this pixel’s area, but belongs to the neighboring pixel in that direction. If the edge cannot be resolved as a crease, we proceed to the silhouette case.

Second-Depth Anti-Aliasing

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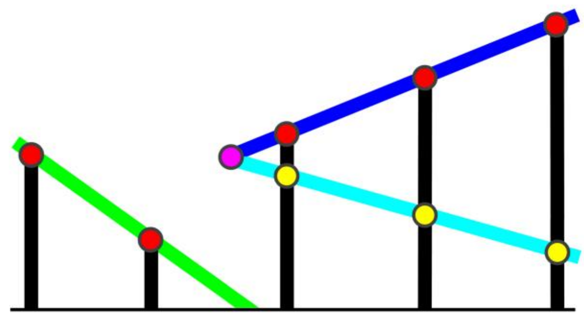
- Try as silhouette
- Neighbor depths useless
  - Look at second-depths
- Compute intersection point
  - Used if distance < half pixel



For the silhouette case we cannot know where the original geometric edge was by looking at the regular depth buffer alone. In the picture, from the red dots we can only know that the blue surface ends somewhere between the second and third sample, but we cannot know how far it extends over the gap. However, by looking at the depths of the back-facing geometry we can compute the intersection point in the same way as with a crease. Again, if it's within half a pixel we will use the result.

Second-Depth Anti-Aliasing

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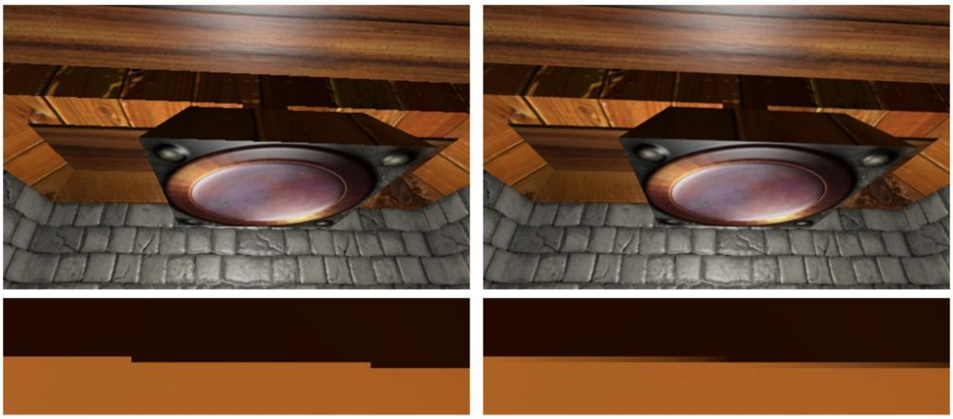
- Results



- Demo + source available! [7]

This technique can compute the original edge’s position very accurately. As a result, the gradients are very smooth, limited only in the resolution of the underlying color format in the buffer.

This technique is quite sensitive to depth buffer precision. At least a 24bit buffer is required, even for the simple test scene in the demo.

References

[1] http://en.wikipedia.org/wiki/Comparison_of_AMD_graphics_processing_units
[2] http://www.humus.name/index.php?page=News&ID=266
[3] http://www.humus.name/index.php?page=Cool&ID=8
[4] http://www.csee.umbc.edu/~olano/papers/lean/
[5] http://www.humus.name/index.php?page=3D&ID=89
[6] http://iryoku.com/aacourse/
[7] http://www.humus.name/index.php?page=3D&ID=88

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Thank you!

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