OIT to Volumetric Shadow Mapping, 101 Uses for Raster Ordered Views using DirectX 12

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Introduction

Raster Ordered Views

Applications + R&D Topics

Performance Tips & Tricks

Summary

Q&A
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Why Raster Ordered Views?

- The DX API specifies “in order” processing rules for the raster pipeline.
- If two triangles sent to the GPU touch the same XY screen location, the GPU hardware guarantees that triangle “A” will blend its color result before “B” blends it.
- Hardware in the ROP is responsible for enforcing this ordering requirement.
- Pipeline back-end* still not programmable, color, z & stencil operations from a fixed menu..
- DX11 added Unordered Access Views, leverage power of shaders.
UAV Limitations

- UAV’s enable arbitrary R/W memory ops from a pixel shader but no ordering of data input...

Timeline

shade fragment from 1st triangle  r/m/w

e.g. programmable blending

shade fragment from 2nd triangle  r/m/w
UAV Limitations

- UAV’s enable arbitrary R/W memory ops from a pixel shader but no ordering of data input...
- Fragments mapping to same pixel can cause data races

Timeline

shade fragment from 1st triangle → r/m/w → data race → shade fragment from 2nd triangle → r/m/w

e.g. programmable blending
UAV Limitations

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UAV Limitations

- UAV’s enable arbitrary R/W memory ops from a pixel shader but no ordering of data input...
- Fragments mapping to same pixel can cause data races
- Fragments can be shaded out-of-order, can’t support order-dependent algorithms
Out-of-Order Artefacts

- The more parallel the GPU the greater race conditions
We need the hardware to detect dependencies among fragments writing to the same X,Y screen coordinate and:

- Avoid data races
- Guarantee primitive order for R/M/W operations
That's easy what happens if fragment 2 runs first?

Timeline

shade fragment from 1st triangle

r/m/w

shade fragment from 2nd triangle

r/m/w
That's easy what happens if fragment 2 runs first?
We just get a longer wait 😊
This isn't "just" a critical section
Little to no performance impact in most cases
- Fragment 1 completes before Fragment 2 hits barrier
- Fragments don’t touch same X,Y screen Coordinate
Haven’t we seen this before?

“We have a pretty long list of all the stuff we typically go through and then talk to them with, but **one very concrete thing we’d like to see, and actually Intel has already done this on their hardware, they call it PixelSync, which is their method of synchronizing the graphics pipeline in a very efficient way on a per-pixel basis.** You can do a lot of cool techniques with it such as order-independent transparency for hair rendering or for foliage rendering. And they can do programmable blending where you want to have full control over the blending instead of using the fixed-function units in the GPU. There’s a lot of cool components that can be enabled by such a programmability primitive there and **I would like to see AMD and NVidia implement something similar to that as well.** It’s also very power-efficient and efficient overall on Intel’s hardware, so I guess the challenge for NVidia and AMD would be if they were able to do that efficiently because they have a lot of the different architectures there. **So that's one thing.**”

Johan Andersson, DICE (2013)

Source: [http://www.tomshardware.com/reviews/johan-andersson-battlefield-4-interview,3688-2.html](http://www.tomshardware.com/reviews/johan-andersson-battlefield-4-interview,3688-2.html)
Almost perfect match for Intel Pixel Synchronization extension introduced on 4\textsuperscript{th} Gen Core processors in 2013.

Lots of existing samples and even games using it!
HLSL only construct, modifies access behavior to UAV’s

New (HLSL) objects, only available to the pixel shader:

- RasterizerOrderedBuffer
- RasterizerOrderedByteAddressBuffer
- RasterizerOrderedStructuredBuffer
- RasterizerOrderedTexture1D
- RasterizerOrderedTexture1DArray
- RasterizerOrderedTexture2D
- RasterizerOrderedTexture2DArray
- RasterizerOrderedTexture3D

Used in the same manner as other UAV objects
ROV’s vs Pixel Sync

Pixel Sync

```c
#include "IntelExtensions.hlsl"

RWTexture2D <t> gRGBEBuffer : register( u1 );

void PS_RGBE_Blend (...) {
    IntelExt_Init();
    // Code that doesn’t reference UAV’s
    IntelExt_BeginPixelOrderingOnUAV(1);
    // Access UAV
    uint rgbe = gRGBEBuffer[xy];
    // Manipulate UAV
}
```

Raster Ordered View

```c
RasterOrderedTexture2D<t> gRGBEBuffer;

void PS_RGBE_Blend (...) {
    // Code that doesn’t reference UAV’s
    // Access UAV
    uint rgbe = gRGBEBuffer[xy];
    // Manipulate UAV
}
```
Writing to a UAV disables both Early-Z and Hi-Z

Declaring [earlydepthstencil] in front of a pixel shader guarantees the depth test happens early even if the shader writes to a UAV

[earlydepthstencil] means Depth is updated even if you discard in the pixel shader, unless completely disabled
Applications
Programmable Blending Applications

- New blending operators, non-linear color spaces, exotic encodings, etc.
  - e.g. RGBE, LogLuv, etc.

Intel RGBE blending sample

HDR in to custom R10G10B10A2 in GRID Autosport
Blending on a R G B E c o l o r b u f f e r

```c
RasterOrderedTexture2D<t> gRGBEBuffer;

void PS_RGBE_Blend (...) {
    float3 rgb = ...
    float alpha = ...

    uint rgbe = gRGBEBuffer[xy];
    float3 dstRGB = R G B E_ t o _ R G B(rgbe);
    dstRGB = alpha * rgb + (1 - alpha) * dstRGB;
    gRGBEBuffer[xy] = R G B_ t o _ R G B E(dstRGB);
}
```
Blending for deferred shaders

To apply a bullet hole or an axe mark...

simply

- Render your G-Buffer
- Take a normal map of a decal
- Blend it with the G-Buffer
- Result will be a correctly mapped bullet hole
K-Buffer

- Generalization of the Z-Buffer*
- Render N-layers of the image in a single pass
- Under DX11 requires Per pixel linked lists and append buffers
  - Unbounded memory requirement
  - Memory bandwidth heavy
- Countless applications:
  - Depth-peeling
  - Constructive solid geometry
  - Depth-of-field & motion blur
  - Volume rendering
  - <insert your idea here 😊>
K-Buffer: Single-Pass Depth Peeling

```c
RasterizerOrderedBuffer gBuffer;
void PSMain(...) {
    Fragment frag = {...};

    Fragment fragArray[N] = gBuffer[xy];
    for (int i = 0; i < N; i++) {
        if (frag.Z < fragArray[i].Z) {
            Fragment temp = frag;
            frag = fragArray[i];
            fragArray[i] = temp;
        }
    }
    gBuffer[xy] = fragArray;
}
```

- Compute fragment color, z, etc..
- Read N fragments from K-buffer
- Write N fragments to K-buffer
- Enable pixel synchronization
- Bubble sort (1 pass)
Correct compositing, rendering foliage & fences with zero aliasing, etc..

DX11-style order-independent transparency has significant drawbacks

– Requires unbounded memory (per-pixel lists)
– Not so great performance due to global atomics, fragments sorting, etc.
Order-Independent Transparency

- Raster Ordered View enable a new approach
  - Single geometry pass and fixed memory requirements
  - Stable and predictable performance
  - Scalable: easily trade-off image quality for performance/memory

GRID Autosport 2014
OIT on 15watt 4th Gen Core™ Processor
Multi-Layer Alpha Blending

✧ Step 1: Improve alpha-blending
  – Use depth to decide whether to composite incoming fragment over or under
  – Much better than vanilla alpha-blending but in some cases not quite correct

✧ Step 3: Use more layers to trade-off image quality for perf/memory
  – Sort N Layers, blend furthest fragments

✧ Step 3: Or use an Adaptive Transparency Function
Adaptive Visibility Function

- Store Visibility Function as a sorted fixed-size array of nodes, in UAV surface
- Each red node corresponds to a pair of values for depth and transmittance: $(d, t)$
- To compress visibility we remove the node that generates the smallest area variation

```c
struct TransparencyData {
    float depth[MAX_LAYERS];
    float4 colour[MAX_LAYERS];
};
```
Adaptive Visibility Function

- Store Visibility Function as a sorted fixed-size array of nodes, in UAV surface.
- Each red node corresponds to a pair of values for depth and transmittance: \((d, t)\).
- To compress visibility we remove the node that generates the smallest area variation.
- Used for early Order Independent Transparency samples.

```
struct TransparencyData {
    float depth[MAX_LAYERS];
    float4 colour[MAX_LAYERS];
};
```
Combining OIT with sorted Transparency

- Only add transparent pixels into the OIT structure if there is already OIT data in the buffer
  - Store mask of pixels in R32 target to flag pixels that contain OIT data
  - Use the mask to identify pixels where traditional transparency needs to be merged with OIT
  - All other pixels are rendered with normal alpha blending, because there is no overlap
Hair Rendering

Model courtesy of Cem Yuksel.

Alpha Blending

Adaptive Transparency
Adaptive Volumetric Shadow Maps

- Like Deep Shadow Maps but designed for real-time rendering
- Encode per-pixel visibility function from light point-of-view
- Lossy compression of the visibility data
- Raster Ordered Views enables first fixed memory implementation of AVSM
AVSM Quality Comparison

- AVSM with 8 to 12 nodes closely matches ground truth results
- 4 Nodes suitable for many situations, used in GRID 2.
- Fourier Opacity Maps suffer from artefacts generated by high-frequency light blockers like hair and sub-optimal depth bounds
- Hair model courtesy of Cem Yuksel.
Accelerating AVSM

- Overdraw of particles means even small increases in per-pixel costs are noticeable

- Shadow map generation can use simplified particles
  - Less particles, larger area, higher opacity

- Per Pixel lighting of particles took >=10ms...
  - Tessellated vertex lighting actually looked better!
  - Tessellation is 2-3x faster than per-pixel
Volume-Aware Blending

- Billboard sprites representing clouds volumes
- Composited using Alpha blending
- Popping Artefacts as billboard sprites change order
Volume-Aware Blending

- Billboard clouds using volume aware blending
- No popping
- Smooth blending of intersecting volumes
Blending volumetric particles

- If particles do not overlap, blending is trivial
- How can we correctly blend overlapping particles?

- Final color and transparency:

\[ T_{\text{Final}} = T_{\text{Front}} \cdot T_{\text{Isec}} \cdot T_{\text{Back}} \]

\[ C_{\text{Final}} = \frac{C_{\text{Front}} + C_{\text{Isec}} \cdot T_{\text{Front}} + C_{\text{Back}} \cdot T_{\text{Front}} \cdot T_{\text{Isec}}}{1 - T_{\text{Final}}} \]

- Division by \( 1 - T_{\text{Final}} \) because we do not want alpha pre-multiplied color
Blending volumetric particles - Implementation

- Color, density and min/max extent of the current particle are stored in the UAV buffer
- Each new particle is tested against the currently stored
  - If new particle is in front of the current, the current is blended into the back buffer and replaced with the new one
  - If new particle overlaps with the current, they are blended and stored
  - Particles need to be sorted

Volume-Aware Blending

Alpha Blended

Volume Blended
R&D Topics
Advanced Anti-Aliasing

- Use Raster Ordered Views to improve or replace multi-sampling anti-aliasing
  - Higher image quality vs. lower memory requirements vs. better performance

- \( Z^3 \) anti-aliasing* (1999)
  - Originally developed as HW based high-quality anti-aliasing algorithm
    - Store \( N \) fragment per pixel \((z, \partial z/\partial x, \partial z/\partial y, \text{color}, \text{coverage})\)
    - Merge fragments (lossy)
Advanced Anti-Aliasing

- **Analytic methods**
  - Render scene using conservative rasterization
  - Build per-pixel spatial subdivision structure using primitive edges
  - Compute fragment weights from fraction of pixel area covered and resolve
  - Think targeted OIT

Conservative rasterization renders any pixels that are even partially covered are rasterized.
Voxelization

- Build complex per-voxel data structures on the GPU at voxelization time
  - e.g. direction-dependent representations (anisotropic voxels, etc.)
- Voxelization via 2D rasterization projects triangles to XY, YZ or XZ plane
Use Raster Ordered Views to build 3D data structures at voxelization time, think Depth Peeling
- Problem: fragment dependencies cannot be tracked over multiple 2D planes in a single render call.

Easy fix: voxelize onto one 2D plane at time
- 3 draw calls per mesh, one per 2D plane (i.e. reject triangles that map to other planes)

Number of generated voxels doesn’t change & more flexible than using global atomics

Can be further optimized by Conservative Rasterization
Don't clear large buffers. Clear a small buffer and use it as a clear mask.

```cpp
bool clear = gClearMask[xy];
if (clear) {
    gClearMask[xy] = false;
    myLargeStruct = ...;
} else {
    myLargeStruct = gLargeDataStruct[xy];
    ...;
}
gLargeDataStruct[xy] = myStruct;
```
Balance data size vs Packing

Small(er) data structures can improve performance

Use more instructions to pack/unpack data
Address 1D structured buffers as tiled to better data exploit locality
- e.g. 1x2 or 2x2 (2D textures), 2x2x2 (voxels), etc..
- Saved 1ms in Grid 2 by Codemasters in OIT.

```c
uint AOITAddrGen(uint2 addr2D, uint surfaceWidth)
{
    #ifdef AOIT_TILED_ADDRESSING
        surfaceWidth    = surfaceWidth >> 1U;
        uint2 tileAddr2D = addr2D >> 1U;
        uint  tileAddr1D =
            (tileAddr2D[0] + surfaceWidth * tileAddr2D[1]) << 2U;
        uint  pixelAddr2D = addr2D & 0x1U;
        uint  pixelAddr1D = (pixelAddr2D[1] << 1U) + pixelAddr2D[0];
        return tileAddr1D | pixelAddr1D;
    #else
        return addr2D[0] + surfaceWidth * addr2D[1];
    #endif
}
```
Synch Late

- Prefer inserting the synchronized UAV read in the second half of the shader
- Increase likelihood of concurrently shading fragments that map to the same pixel

```c
RasterOrderedTexture2D<gRGBEBuffer

void PS_RGBE_Blend (...) {
    uint rgbe = gRGBEBuffer[xy];
    float3 rgb = ... Complex stuff....
    float alpha = ... Potentially can run concurrent with other shaders
    uint rgbe = gRGBEBuffer[xy];
}
```
Avoid Synch Altogether!

- Ok not 100% possible but clever organisation of the triangles in can limit sync points
  - Randomize instancing data to avoid consecutive overlapping models.
- Small render targets aren’t always your friend, can increase hits to the same pixel.
Summary

- Raster Ordered Views are a new tool that injects new life in the 3D pipeline
- Very simple to use, high performance
- Build complex 3D data structures in bounded memory
- Solve many long standing problems
  - OIT
  - Depth Peeling
  - Volume Rendering and Blending
Questions?
References

- http://www.gdcvault.com/play/1020221/Rendering-in-Codemasters-GRID2-and