Pixel Synchronization:
Solving Old Graphics Problems with New Data Structures

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My Background

• 7 yrs as Gfx Enginee on PC and two generations of Sony & MS consoles
  • High performance 3D engines
  • Exponential shadow maps & deferred shadowing
  • HDR rendering & MSAA with LogLuv buffers (aka nao32 😊)
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- Intel R&D – Tech Lead in Advanced Rendering Technology team (2008 – present)
  - Shadow map filtering & partitioning schemes
  - OIT, anti-aliasing, volumetric shadows
  - Stochastic rasterization & shader caches
  - New graphics architectures
Talk Outline

• Introduction and Problem Statement
• Pixel Synchronization
• Applications & Demos
• Performance Tips & Tricks
• Summary
• Q&A
Problem Statement

- Programmable shaders had (and continue to have) huge impact
  - Spurred the development of countless new rendering techniques
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  - Can only order color, z & stencil operations from a fixed menu..
  - ..but very fast and power efficient
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  • ...but very fast and power efficient

• Add new programmable back-end?
  • Let it coexist side by side with fixed function HW to leverage respective strengths
Programmable Back-End

• DX11/0GL 4.2 enable arbitrary R/W memory ops from a pixel shader but..
Programmable Back-End

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Shade fragment from 1st triangle → r/m/w

E.g. programmable blending
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  - Fragments mapping to same pixel can cause data races

  e.g. programmable blending

  data race

  shade fragment from 1st triangle

  r/m/w

  shade fragment from 2nd triangle

  r/m/w

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Programmable Back-End

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shade fragment from 2nd triangle  r/m/w
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Programmable Back-End

- DX11/OGL 4.2 enable arbitrary R/W memory ops from a pixel shader but...
  - Fragments mapping to same pixel can cause data races
  - Fragments can be shaded out-of-order, can’t support order-dependent algorithms
Programmable Back-End

shade fragment from 1st triangle  r/m/w
Programmable Back-End

- Shade fragment from 1st triangle
- Shade fragment from 2nd triangle
- r/m/w
Programmable Back-End

shaded fragment from 1st triangle

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Programmable Back-End

• Haswell can detect dependencies among fragments and..

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Programmable Back-End

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Programmable Back-End

- Haswell can detect dependencies among fragments and..
  - Avoid data races
Programmable Back-End

- Haswell can detect dependencies among fragments and...
  - Avoid data races
  - Guarantee primitive submission order for R/M/W memory operations

well-defined order

shade fragment from 1st triangle 

r/m/w

data is safe

shade fragment from 2nd triangle 

wait 

r/m/w
Pixel Synchronization

- **Simple extension for pixel/fragment shaders**
  - Enable ordering for R/W memory accesses (i.e. same order as alpha-blending)
  - Just a function call in your shader: `IntelExt_BeginPixelOrdering()`
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- Very good performance
  - Little to no performance impact in most cases
  - R/W memory accesses are backed by the full SoC cache hierarchy
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- **More powerful than reading back the frame buffer from a pixel shader**
  - Build and access data structures of arbitrary size/type/dimensionality (including voxels 😊)
  - Decoupled from MSAA, can work with per-pixel and/or per-sample data structures
Example: Blending on a RGBE color buffer
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}
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- **Compute fragment color & alpha**
- **Initialize shader extensions**
- **Enable pixel synchronization**
Example: Blending on a RGbE color buffer

```c
void PS_RGBE_Blend (...)
{
    IntelExt_Init();
    float3 rgb = ...
    float alpha = ...

    IntelExt_BeginPixelOrdering();

    uint rgbe = gRGBEBuffer[xy];
    float3 dstRGB = RGBE_to_RGB(rgbe);
}```
Example: Blending on a RGENE color buffer

```c
void PS_RGENE_Blend (...) {
    IntelExt_Init();

    float3 rgb = ...
    float alpha = ...

    IntelExt_BeginPixelOrdering();

    uint rgbe = gRGBEBuffer[xy];
    float3 dstRGB = RGENE_to_RGB(rgbe);

    dstRGB = alpha * rgb + (1 - alpha) * dstRGB;
}
```
Example: Blending on a Rgbe color buffer

```c
void PS_RGBE_Blend (...) {
    IntelExt_Init();

    float3 rgb = ...
    float alpha = ...

    IntelExt_BeginPixelOrdering();

    uint rgbe = gRGBEBuffer[xy];
    float3 dstRGB = RGBE_to_RGB(rgbe);

    dstRGB = alpha * rgb + (1 - alpha) * dstRGB;

    gRGBEBuffer[xy] = RGB_to_RGBE(dstRGB);
}
```

- **Compute fragment color & alpha**
- **Read Rgbe buffer & convert to Rgb**
- **Conversion to Rgbe & buffer write**
- **Initialize shader extensions**
- **Enable pixel synchronization**
- **Alpha-blending in RGB space**

Advances in Real-Time Rendering in Games course
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A Few Programmable Blending Applications

• New blending operators, non-linear color spaces, exotic encodings, etc.
  • e.g. RGBE, LogLuv, etc.
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- Blending for deferred shaders
  - e.g. Apply decals by blending normals and other material attributes
K-Buffer

• Generalization of the Z-Buffer*
  • Render N-layers of the image in a single pass

*Bavoil et al. “Multi-fragment effects on the GPU using the $k$-buffer”. Proceedings of the 2007 symposium on Interactive 3D graphics and games
K-Buffer

• Generalization of the Z-Buffer*
  • Render N-layers of the image in a single pass

• Countless applications:
  • Depth-peeling
  • Constructive solid geometry
  • Depth-of-field & motion blur
  • Volume rendering
  • ...
  • <insert your idea here 😊>
K-Buffer: Single-Pass Depth Peeling

void PSMain(...) {
  IntelExt_Init();
  Fragment frag = {...};
}

Compute fragment color, z, etc..
K-Buffer: Single-Pass Depth Peeling

void PSMain(...) {
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    Enable pixel synchronization
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```c
void PSMain(...) {
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    Fragment frag = {...};
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    Fragment fragArray[N] = gBuffer[xy];
}```
K-Buffer: Single-Pass Depth Peeling

```
void PSMain(...)
{
    IntelExt_Init();
    Fragment frag = {...};

    IntelExt_BeginPixelOrdering();

    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;
        }
    }
}
```

- Compute fragment color, z, etc..
- Read N fragments from K-buffer
- Enable pixel synchronization
- Bubble sort (1 pass)
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    }

    gBuffer[xy] = fragArray;
}

Enable pixel synchronization

Compute fragment color, z, etc..

Read N fragments from K-buffer

Write N fragments to K-buffer

Bubble sort (1 pass)

Advances in Real-Time Rendering in Games course
Order-Independent Transparency

• Why order-independent transparency?
  • Correct compositing, rendering foliage & fences with zero aliasing 😊, etc.
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  • Requires unbounded memory (per-pixel lists)
  • Not so great performance due to global atomics, fragments sorting, etc.
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- **Pixel Synchronization enables new methods**
  - Single geometry pass and fixed memory requirements
  - Stable and predictable performance
  - Scalable: easily trade-off image quality for performance/memory
A Recipe for Order-Independent Transparency
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• **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
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  - Store N layers per pixel & pick the “best” one when compositing incoming fragment
  - Use full screen pass to resolve data and blend resulting color over opaque color buffer
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• **Step 3: Use more layers to trade-off image quality for perf/memory**
Deep Shadow Maps

• DSMs encode per-pixel visibility function from light point-of-view
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- Adaptive Volumetric Shadow Maps*
  - Like DSMs but designed for real-time rendering
  - Lossy compression of the visibility data

- Pixel synchronization enables first fixed memory implementation of AVSM
  - Demo 😊

Voxelization

• Build complex per-voxel data structures on the GPU at voxelization time
  • e.g. direction-dependent representations (anisotropic voxels, etc.)
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  • But global atomic ops are slow and pose significant restrictions on struct size, type, etc.
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• **Use pixel synchronization to build 3D data structures at voxelization time**
  • Problem: fragment dependencies cannot be tracked over multiple 2D planes
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- Use pixel synchronization to build 3D data structures at voxelization time
  - Problem: fragment dependencies cannot be tracked over multiple 2D planes

- 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
Advanced Anti-Aliasing

• Use pixel synchronization to improve or replace multi-sampling anti-aliasing
  • Higher image quality vs. lower memory requirements vs. better performance
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- \( Z^3 \) anti-aliasing* (1999)
  - Originally developed as HW based high-quality anti-aliasing algorithm
    - Store N fragment per pixel \((z, \partial z/\partial x, \partial z/\partial y, \text{color, coverage})\)
    - Merge fragments (lossy)

*Jouppi et al. “\( Z^3 \): an economical hardware technique for high-quality antialiasing and transparency”. Proceedings of the ACM SIGGRAPH/EUROGRAPHICS workshop on Graphics hardware
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• Analytic methods
  • Render scene using conservative rasterization
  • Build per-pixel spatial subdivision structure using primitive edges (per-pixel BSP? 😊)
  • Compute fragment weights from fraction of pixel area covered by leaf cells and resolve

Performance Tips & Tricks

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Read clear mask

Clear this!

Mark pixel as “used” and initialize large struct

If pixel is not in clear state load large struct and update it

Not this!

Write large struct data back to memory
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  • Use more instructions to pack/unpack data
  • Balance data structure size and amount of packing/unpacking code
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  - e.g. 1x2 or 2x2 (2D textures), 2x2x2 (voxels), etc..
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• Prefer inserting the synchronization point in the second half of the shader
  • Increase likelihood of concurrently shading fragments that map to the same pixel
  • Corollary: use HW z-test when possible for better performance (Hi-Z is fast!)
Summary

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  2. Draw geometry to build your data in a streaming fashion
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  3. Use the data & enjoy your results (sip tea or coffee 😊)
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• DX11+ extension available now (download demos), OpenGL extension in development.
Q&A

• **Acknowledgements**
  • The ART team
  • Tom Piazza, Chuck Lingle, Tomasz Janczak, Prasoon Surti, Mike Dwyer, Andy Dayton, Mike Apodaca, Aaron Lefohn, Larry Seiler, Leigh Davies, Filip Strugar, Matthew Fife, Steve Hughes, Axel Mamode, Richard Huddy and many others

• **Source code**
  • Programmable Blending: bit.ly/pixelsync_pb
  • Order-Independent Transparency: bit.ly/pixelsync_oit
  • Adaptive Volumetric Shadow Maps: bit.ly/pixelsync_avsm

• **Contacts**
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  • twitter: @marcosalvi