Z² Traversal Order for VR Stereo Rendering on Tile-based Mobile GPUs

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INTRODUCTION
• Explosion in VR market
  • Thanks to technical advances of HMDs and GPUs
  • A wide range of applications

• High computational costs for VR rendering
  • High screen resolution (e.g., FHD to UHD)
  • High frame/refresh rates (e.g., 60-120Hz)
  • Stereo rendering for the left and right eyes

• Thus, efficient VR rendering techniques are required for realistic VR experiences!
**MAIN CONTRIBUTIONS OF OUR WORK**

- Focus on efficient **GPU H/W architectures** for mobile VR applications

- Novel cache-efficient tile traversal orders for VR rendering
  - Interleaved version of the traditional Z-order curve [Morton 1966]
  - Two variants:
    - $Z^2$ LRTA (left-right tile assignment) & $Z^2$ STA (simultaneous tile access)

- Implementation of a simulation environment
  - Mesa OpenGL renderer + Oculus VR library + in-house H/W simulator
BACKGROUND AND RELATED WORK
• Brute-force approach

- 2X draw calls are required

* This classification refers to Reed and Sancho [2015]

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Shader multiview [Reed and Sancho, GDC 2015]

- API overhead reduction
- OpenGL extensions (e.g., GL_OVR_multiview2)

* This classification refers to Reed and Sancho [2015]
Shading reuse [Hasselgren and Akenine-Möller, EGSR 2006]

- Instead of exact PS evaluation, approximate PS evaluation is performed on the texture space for the right view (or multiple views)
- Aggressive & efficient for reducing PS costs
- Possibility of image quality degradation: problematic on view-dependent shading (e.g., specular highlights)

* This classification refers to Reed and Sancho [2015]

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VR STEREO RENDERING

- VR SLI/CrossFire

  - Left and right screens are distributed into two or more GPU cards connected by the SLI or CrossFire interface

* This classification refers to Reed and Sancho [2015]

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TECHNIQUES FOR REDUCING SHADED FRAGMENTS OF EACH VIEW

- Foveated rendering [Guenter et al., TVCG 2012]
  - High res. image in the fovea
  - Low res. image in the periphery

- Stencil mesh [Vlachos, GDC 2015]
  - Cull area hidden by warping in advance

- Multi-resolution shading [NVIDIA 2016]
  - Low res. image in the edges of the screen distorted by warping and lens distortion
• Tile-based GPU architectures

<table>
<thead>
<tr>
<th>GPU core 1</th>
<th>GPU core 2</th>
<th>...</th>
<th>GPU core n</th>
</tr>
</thead>
</table>

Local tile buffer

Frame Buffer

• The choice of most mobile GPUs: Adreno, Mali, and PowerVR
• Aiming at minimizing external memory accesses by using a local tile buffer
• # of tiles > # of GPU cores → various traversal orders can exist

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• Tile traversal orders
  • Cache-friendly traversal order can increase GPU performance
  • Representative examples

Scanline order
Z-order curve
Zig-zag pattern

[Scanline order] [Z-order curve] [Zig-zag pattern]

[Morton 1966] [Ellis et al. 2015]
$Z^2$ TILE TRAVERSAL ORDER
The left and right views are usually similar to each other; binocular disparity is not very high.

Interleaved tile traversal between the left and right views can increase texture cache efficiency.

This idea was inspired by Hasselgren and Akenine-Möller [2006].

Our main idea: Z-order curve + left-right interleaving.
Not effectively exploit locality between the left and right views
Z² LRTA
(LEFT-RIGHT TILE ASSIGNMENT)

- Render the tiles in the left and right screens by turns
- Exploit locality between the left and right views
- Simple implementation

Shader core #1
L2 cache
Shader core #2

Left view
Right view

1 3 9 11
2 4 10 12
5 7 13 15
6 8 14 16
17 19 25 27
18 20 26 28
21 23 29 31
22 24 30 32

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## Z² STA (SIMULTANEOUS TILE ACCESS)

<table>
<thead>
<tr>
<th>Left view</th>
<th>Right view</th>
</tr>
</thead>
<tbody>
<tr>
<td>1L 2L 5L 6L</td>
<td>1R 2R 5R 6R</td>
</tr>
<tr>
<td>3L 4L 7L 8L</td>
<td>3R 4R 7R 8R</td>
</tr>
<tr>
<td>9L 10L 13L 14L</td>
<td>9R 10R 13R 14R</td>
</tr>
<tr>
<td>11L 12L 15L 16L</td>
<td>11R 12R 15R 16R</td>
</tr>
</tbody>
</table>

- Fetch two tiles in the left and right screens simultaneously
- Triangles in the left and right triangle lists are rendered by turns
- Best for two screen tiles consisting the same or similar triangle lists
- Require double-sized tile memory

Diagram:

- Shader core #1
- L2 cache
- Shader core #2
- Time

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• Use of shader multiview extensions is required
  • Brute-force case: no clue how to obtain the geometry lists of the left and right views simultaneously
  • Our traversal order can be enabled only if the tiling stage can sort all geometry of the left and right views together in a single render pass
EXPERIMENTS AND RESULTS
SIMULATION ENVIRONMENT

OpenGL app

VR library

Texturing Pipeline

Virtual grid construction (for emulating tile-based arch.)

Output trace to a file

The Mesa 3D Graphics Library

H/W Simulator

• Cache statistics
• Memory traffic
• Texture mapping unit (TMU) utilization

Our implementation

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H/W assumptions in our experiment

- MP2 GPU configuration:
  - two L1 caches (8-16KB) and an L2 cache (128-256KB)
- L1 and L2 miss penalties: 20 and 200 cycles, respectively
- The texture pipeline is stalled when a cache miss occurs
- 16×16 tile size

Test scene

- GFXBench T-Rex rendered with Oculus VR library
- Resolution: 960×1080×2
- DXT1 compressed textures
Both $Z^2$ LRTA and $Z^2$ STA show slightly lower L1 cache miss rates than Z-order curve.
• Z² LRTA considerably reduces L2 cache miss rates
• Z² STA reduces the miss rates further in most cases
• $Z^2$ LRTA and $Z^2$ STA reduce memory traffic by 21-30%  
• $Z^2$ STA shows slightly better results than $Z^2$ LRTA  

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Z\textsuperscript{2} LRTA and Z\textsuperscript{2} STA can achieve 5-8% performance gain over Z-order curve in texture-heavy scenes.

Higher is better

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WRAP UP
CONCLUSIONS AND FUTURE WORK

- Two variations of the Z-order curve for tile-based GPUs
  - Specially designed for VR stereo rendering
  - $Z^2$ LRTA – simpler implementation and no area overhead
  - $Z^2$ STA – higher efficiency
  - Orthogonal to other VR acceleration techniques

- Future work
  - Experiments in more scenes
  - Investigation on the effects of disparity manipulation techniques (e.g., gloss depiction [Templin et al., TOG 2012])
  - Extension to ray tracers using Z-order curve (e.g., RayCore [Nah et al., TOG 2014])
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