Interactive Volume Exploration of Petascale Microscopy Data Streams Using a Visualization-Driven Virtual Memory Approach

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The Connectome
Discovering the Wiring Diagram of the Brain

Harvard Center for Brain Science
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Ramón y Cajal, 1905

Harvard Center for Brain Science
Electron Microscopy (EM) Volumes

- Required for tiny structures (synapses, vesicles, …)
  - Pixel resolution: 3 to 5 nm
  - Slice thickness: 30 to 50 nm

- $1 \text{ mm}^3$
  - 200k x 200k images x 20k slices
  - 40 Gpixels x 20k = 800 Tvoxels
  - 800 TB

- 40 Mpixels / second
  - ~8 months
Our System

• Interactive EM volume exploration
  • Visualization-driven system design
  • Scales to petascale volumes

• Major design properties
  • Ray-cast in virtual volume space
  • Avoid pre-computation of 3D multi-resolution structure
  • Accept a continuous stream of microscope image data
System Overview

Electron Microscope → 2D Mipmap Generation and Tiling

EM driven

Visualization driven

Acquisition Archive

2D Mipmap Generation and Tiling → Visualization Archive

Visualization Archive

3D Block Stitching & Resampling

Virtual Memory Architecture

Ray-Casting

Cache Miss Detection
System Overview

Raw Tile Processing
Each EM tile is processed independently of all other tiles

- EM tile: 12,000 x 12,000; sub-tiles: 128 x 128
- 2D mipmap construction, sub-tiling, compression have to keep up
- EM rate: 40 Mpixels / second: new tile every 3.6 seconds
Octree Traversal vs. Virtual Memory Access

Viewport

Zoomed-in view
Octree Traversal vs. Virtual Memory Access

octree traversal

virtual memory access

zoomed-in view
Virtual Memory Architecture

Page Directory

Virtual Page Table

Virtual Voxel Volume

32^3 voxel block

resolution hierarchy

l=0 l=1 l=2

page table hierarchy

multi-resolution page directory
## Scalability of Virtual Memory Architecture

<table>
<thead>
<tr>
<th>resolution</th>
<th>size</th>
<th>resolution hierarchy</th>
<th>page table hierarchy</th>
<th>page directory</th>
</tr>
</thead>
<tbody>
<tr>
<td>32,000 x 32,000 x 4,000</td>
<td>4 TB</td>
<td>11 levels</td>
<td>2 levels</td>
<td>32 x 32 x 4</td>
</tr>
<tr>
<td>128,000 x 128,000 x 16,000</td>
<td>196 TB</td>
<td>13 levels</td>
<td>2 levels</td>
<td>128 x 128 x 16</td>
</tr>
<tr>
<td>512,000 x 512,000 x 64,000</td>
<td>15 PB</td>
<td>15 levels</td>
<td>3 levels</td>
<td>16 x 16 x 2</td>
</tr>
<tr>
<td>2,000,000 x 2,000,000 x 250,000</td>
<td>888 PB</td>
<td>17 levels</td>
<td>3 levels</td>
<td>64 x 64 x 8</td>
</tr>
</tbody>
</table>

- voxel blocks: $32^3$ voxels
- page table blocks: $32^3$ page table entries
visualization-driven architecture

spatial coherence:
look-up overhead very small
System Overview

Electron Microscope → EM driven

2D Mipmap Generation and Tiling

Visualization Archive

3D Block Stitching & Resampling

Virtual Memory Architecture

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Visualization driven

Cache Miss Detection
Visualization-Driven Architecture
Visualization-Driven Stitching

3D Block Stitching and Resampling

Virtual Volume
Requested Tiles

2D Subtile Fetching

Visualization Archive
## Rendering Performance

<table>
<thead>
<tr>
<th>volume</th>
<th>size</th>
<th>transfer function</th>
<th>page table hierarchy [fps]</th>
<th>octree hierarchy [fps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>mouse cortex</td>
<td>955 GB</td>
<td>#1</td>
<td>75</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td></td>
<td>#2</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>hippocampus 1</td>
<td>92 GB</td>
<td>#1</td>
<td>77</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td></td>
<td>#2</td>
<td>19</td>
<td>15</td>
</tr>
<tr>
<td>hippocampus 1</td>
<td>43 GB</td>
<td>#1</td>
<td>72</td>
<td>58</td>
</tr>
<tr>
<td></td>
<td></td>
<td>#2</td>
<td>22</td>
<td>13</td>
</tr>
</tbody>
</table>

- NVIDIA Quadro 6000; 1024 x 768 viewport; everything resident in cache
Hierarchy Traversal Complexity

- **avg**: 2~3
- **octree traversal**
- **page table hierarchy traversal**

Graph:
- **our system:**
  - avg
- **octree:**
  - avg

# hierarchy look-ups
Block Construction Complexity

- **Our System:**
  - 3D block construction requests

- **Octree:**
  - 3D block construction requests

- 36 block requests
- 18 block requests
- 512 x 512 x 32 blocks
Node / Page Table Update Complexity

- **5000 node pool updates**
- **4 page table block updates**

Graph showing the update complexity and cache usage for different resolution levels. The graph compares our system and an octree, with specific points marked for 5000 node pool updates and 4 page table block updates.
Conclusions

• Visualization-driven 3D data construction
  • **Decouples** visualization from data acquisition
  • Incomplete, continuously streaming data

• Virtual memory architecture
  • **Decouples** resolution hierarchy from hierarchy traversal in ray-caster
  • Better scalability than octree traversal

• Limitations
  • Latency of 3D data construction
  • All visible data must fit into the cache (can be circumvented with several strategies)
Thank You for Your Attention!

http://gmsv.kaust.edu.sa

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