In-Depth Analyses of Unified Virtual Memory System for GPU Accelerated Computing

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Accelerated Computing

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  - System Model: CPU host offloading “hard” tasks to accelerator.
  - Accelerators are frequently GPUs; other devices are interesting.
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  - Accelerators are frequently GPUs; other devices are interesting.

- Increasingly complex system $\rightarrow$ complex programming; difficulties:
  - Programming against independent architectures.
  - Different programming paradigms.
  - Low level hardware management and coordination.
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![Summit Node Diagram](image credit: ORNL/OLCF)
Programmability of Accelerated Computing

- High programmability is required for heterogeneous systems.
  - Hardware control code, e.g. memory management, is notoriously difficult.
  - Heterogeneous systems require far more low-level control.
  - HPC systems are frequently used by domain scientists - not software engineers.
Programmability of Accelerated Computing

- High programmability is required for heterogeneous systems.
- Memory management is increasingly hard for heterogeneous memory systems.
  - Data must be explicitly transferred between host, accelerator.
  - This is hard for deep data structures, e.g. sparse matrix representations.
  - Code is now increasingly about memory management, not domain science.
Programmability of Accelerated Computing

- High programmability is required for heterogeneous systems.
- Memory management is increasingly hard for heterogeneous memory systems.
- Systems should carry more of the programming burden - particularly memory:
  - Shared memory semantics have been applied to heterogeneous systems.
  - This provides a **unified memory** address space.
  - This can effectively eliminate memory programming - with a catch.
  - Should support a common interface, mechanism for arbitrary accelerators.

The Performance Problem

- Unified Memories for Heterogeneous Computing are slow.
  - Figure: performance (hexagon, diamond) is *bad* compared to direct transfer.
  - Special optimizations can narrow the gap (square, star).
  - Still significant gap between direct management and systems software.
The Performance Problem

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- Research Questions:
  - What causes the gap between management and systems software?
  - Are there specific costs that can be optimized?
Our Work

- Our work investigates system-level performance issues for unified memory.
  - We look at system-level root causes of performance loss.
  - We examine software and hardware costs at host, accelerator.

- Three key sections:
  - Accelerator system-workload creation
  - Top-down driver/runtime performance analysis
  - Performance analysis with advanced features
State of the Art

- Two main categories: Application Analysis and Redesign/Optimization.
- Application Analysis:
  - Most study overall application performance vs. direct transfer.
  - **Our work** takes system-level perspective, identifies root causes.
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- **Application Analysis:**
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  - *Our work* takes system-level perspective, identifies root causes.
- **Redesign/Optimization:**
  - Primarily GPU, interconnect, and/or memory hierarchy alterations
  - Requires full-system hardware design changes - mid-to-far future.
  - *Our work* focuses on existing, near-future software, hardware.
Environment: Unified Virtual Memory

- UM defines a generic hardware/software interface and behavior.
- Standard Characteristics of Unified Memory:
  - Extend host virtual memory to support accelerator.
  - This includes data migration systems, specifically **paging**.
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  - NVIDIA’s unified memory implementation
- Heterogeneous Memory Management (HMM) as an alternative?
  - HMM is Linux-integrated support for unified memory.
  - HMM only resolves host-side management; requires companion device driver (UVM).

- We use UVM as an example implementation and testbed.
Background: UVM System Architecture

- UVM is managed by the UVM driver on the host.
  - Interactions triggered by interrupt to wake up driver.
  - Faults are written to fault buffer by GPU, read by host.
  - Optimization: Faults read, serviced in batches.
    ▶ Many faults handled at the same time.
This is a simple parallelized vector addition.

UM causes GPU computation, fault handling to be largely serialized.
  - Page faults are generated much faster than they are serviced.

At scale, fault batches contain similar number of faults from all SMs.
  - Several rate-limiting mechanisms enforce this.
Batched Data Movement Across Applications

- Data migration cost varies between applications due to batch composition.
- Data migration itself is **not** the majority of the time cost.
Batch-Level Access Pattern

- VABlock: Memory abstraction, 2MB contiguous chunks.
  - This is a rough metric for page-level locality.
- Each VABlock is processed independently.
  - This creates a source of performance variance in batch processing.
Case: Host Page Unmapping Cost

*Pages are unmapped from the host during a fault before migration.*
*We find this cost takes a significant amount of batch time.*
*We also find application parallelism can exacerbate this.*
*Ongoing work identifies this cost to be primarily **TLB Shootdowns**.*

This is an example of host compute architecture impacting UVM performance.

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(a) OMP - 1 Thread

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Batch Analysis with Prefetching Enabled

- Overall, prefetching reduces the number of batches.
- High-cost batches are still present (unmapping).
- Outliers are attributed to DMA tracking and management data structures (Right).
  - Example of software and host OS impacting latency.
Oversubscription: Feature enabling page swapping for out-of-core GPU workloads.

Due to problem size, naturally there are more batches.

Evictions distinguish themselves as a flat cost per eviction.
Prefetching and eviction are indirectly related performance-wise.
Key Insights, Contribution, and Future Work

- Contributions
  - Characterization of GPU hardware fault creation.
  - Comprehensive batch-level performance analysis.
  - Reproducable data collection methodology for future work.
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  - Interconnect bandwidth is not the key bottleneck.
  - Host architectural issues are also a major component, e.g. TLB coherency.
  - Advanced features alter fault generation rate, but fundamentals stay the same.
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- **Future Work**
  - Investigate GPU-to-GPU UM behaviors.
  - Optimize page unmapping, tlb coherency for improved generic UM performance.
  - New algorithms for eviction to eliminate flat cost.
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