Exploring Page Fault Servicing in Nvidia's UVM Driver

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Undergraduate Project - III

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Nvidia Unified Virtual Memory

- Pointers can be used from CPU and GPU
- Explicit memory transfers are not needed

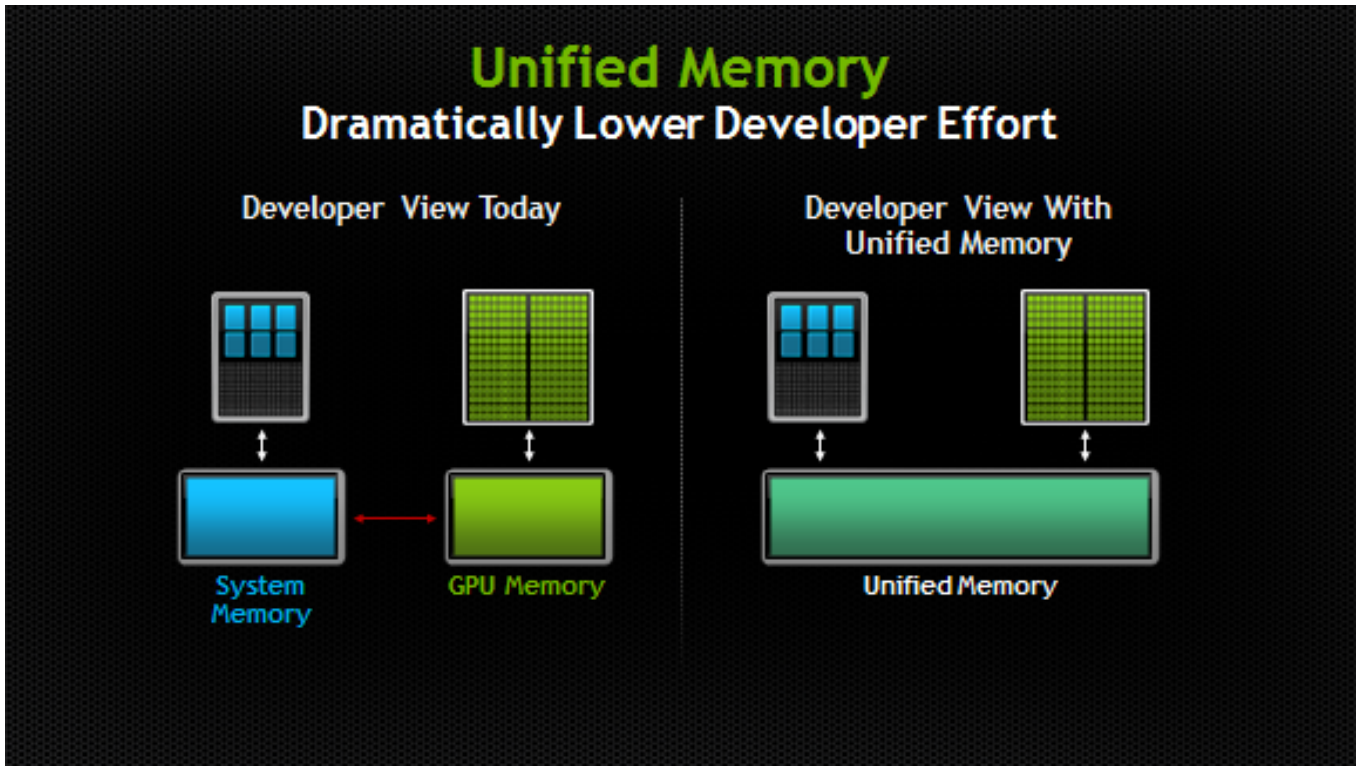


Image Source: https://developer.nvidia.com/blog/powerful-new-features-cuda-6/

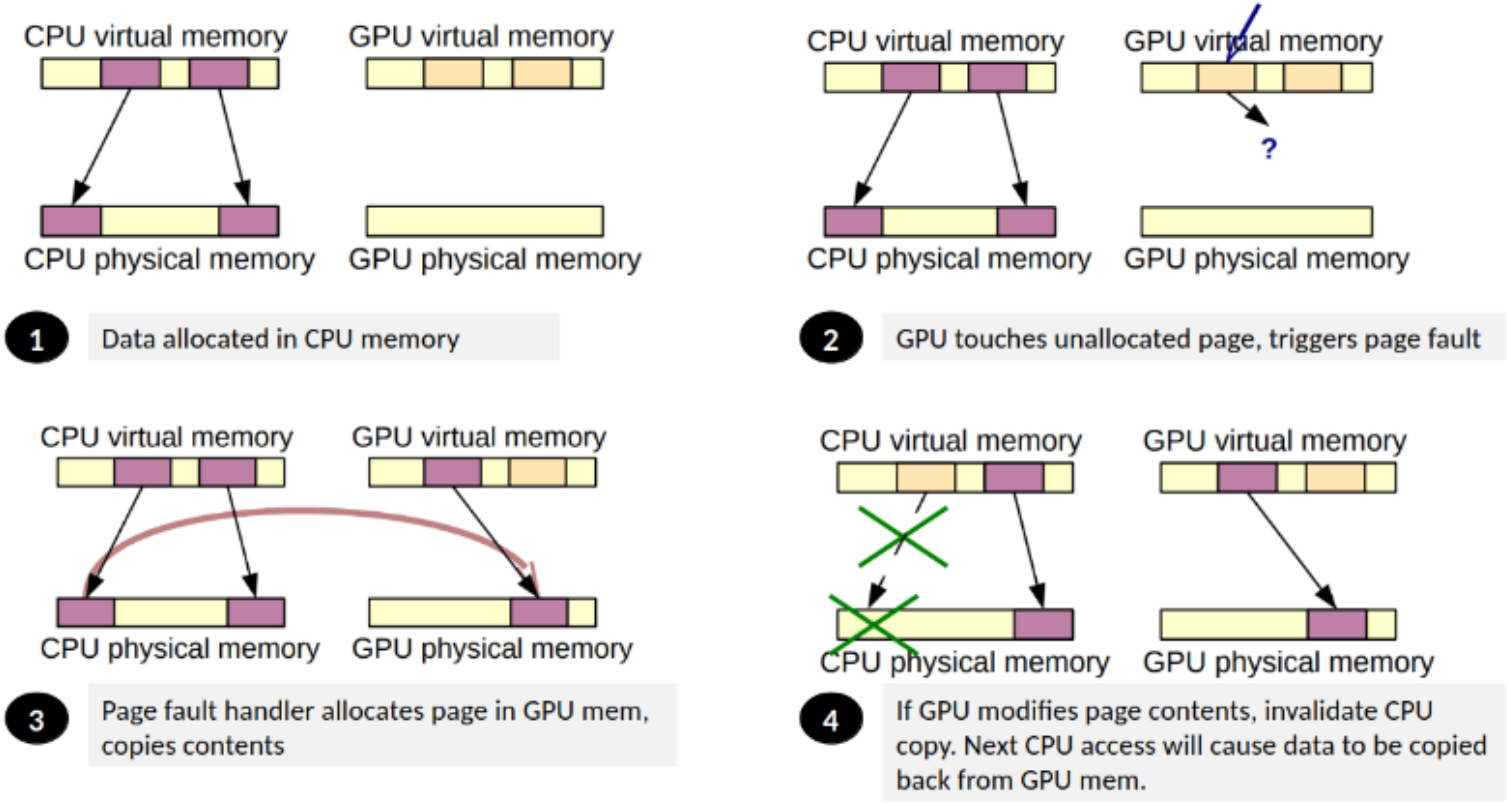
Nvidia Unified Virtual Memory

```
/*
 * Copy-then-execute
 *
 * hA resides on CPU
 * dA resides on GPU
 */

hA = malloc(N);
fread("input.txt", hA, N);

dA = cudaMalloc(N);

cudaMemcpy(dA, hA, N);
compute<<<512, 32>>>(dA, N);
cudaMemcpy(hA, dA, N);

fwrite("output.txt", hA, N);
```

```
/*
 * UVM
 *
 * uA resides in Unified
 * Virtual Memory
 */

uA = cudaMallocManaged(N);
fread("input.txt", uA, N);

// no-op

// no-op
compute<<<512, 32>>>(uA, N);
// no-op

fwrite("output.txt", uA, N);
```

Sample copy-then-execute and UVM programs

Demand-based Page Migration



- A page can reside in CPU or GPU memory
- Page faults are raised when the page is on the other device

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https://www.irisa.fr/alf/downloads/collange/cours/hpca2020_gpu_2.pdf

https://cse.iitk.ac.in/users/swarnendu/courses/autumn2024-cs610/gpu-cuda.pdf

Demand-based Page Migration

- Permits oversubscribing GPU memory
- Pages are *evicted* if GPU memory is full

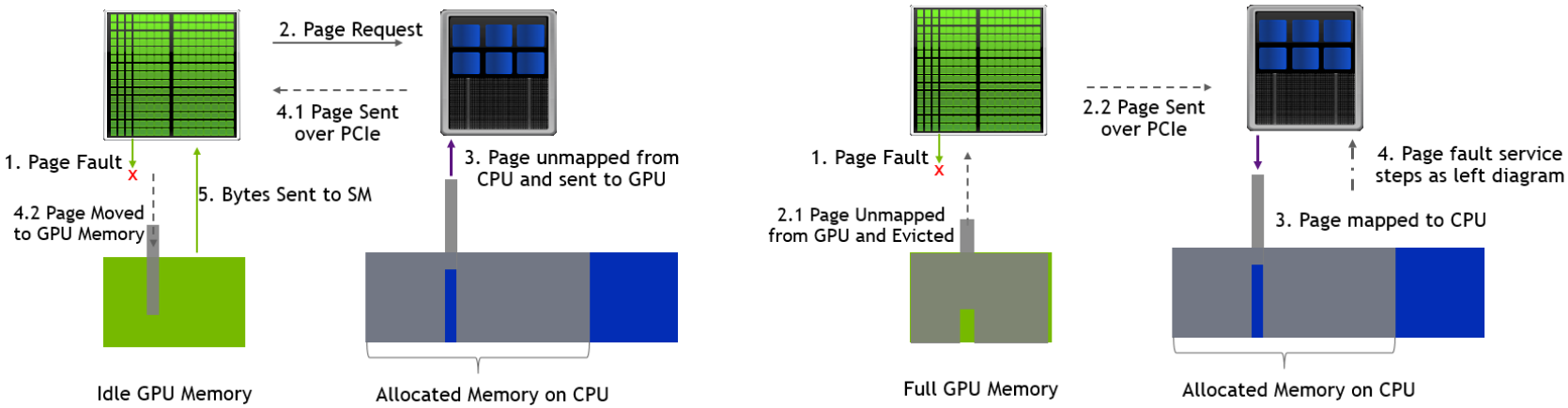

Figure: GPU far faults (left) and GPU oversubscription (right)

https://developer.nvidia.com/blog/improving-gpu-memory-oversubscription-performance/

Nvidia Unified Virtual Memory - Virtualization Overhead

- Page faults incur higher latency and CPU usage
- UVM is costlier despite overlapping computation and page migration
- Fault servicing latency: 30-45 μs

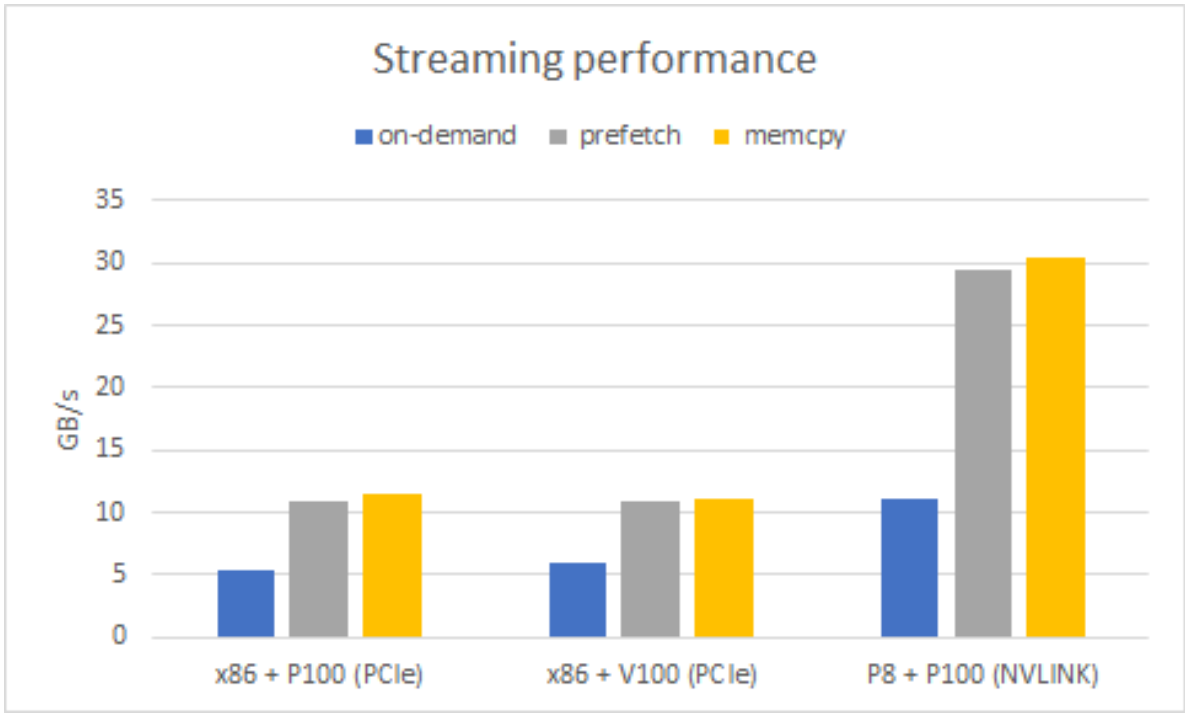

Image source: https://developer.nvidia.com/blog/maximizing-unified-memory-performance-cuda/

CUDA Software Stack

- Compiler: `nvcc`
- Userspace library/runtime: `libcudart.so`
- OS driver (loadable module): `nvidia-uvm.ko`, ...
- Profiling and debugging tools
- ...

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- Userspace library/runtime: `libcudart.so`
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- Profiling and debugging tools
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- Memory management and UVM are implemented in the driver
- Open-sourced in 2022

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- Service Routine:
  1. Unmap page from GPU
  2. Initiate page migration (asynchronous)
  3. Map page in CPU page table
  4. Wait for migration
  5. Return to userspace, repeat instruction

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- Fault service routine:
  1. Fetch fault(s) from fault buffer
  2. Preprocess faults (de-duplicate, group)
  3. Initiate page migration (asynchronous)
  4. Unmap page from CPU
  5. Map page in GPU memory
  6. Wait for migration
  7. "push replay" on GPU, repeat faulting instruction

Memory Prefetching

- Neighbouring Pages are selected for prefetching and transferred in advance
- Current prefetching policy: tree-based neighbourhood prefetcher

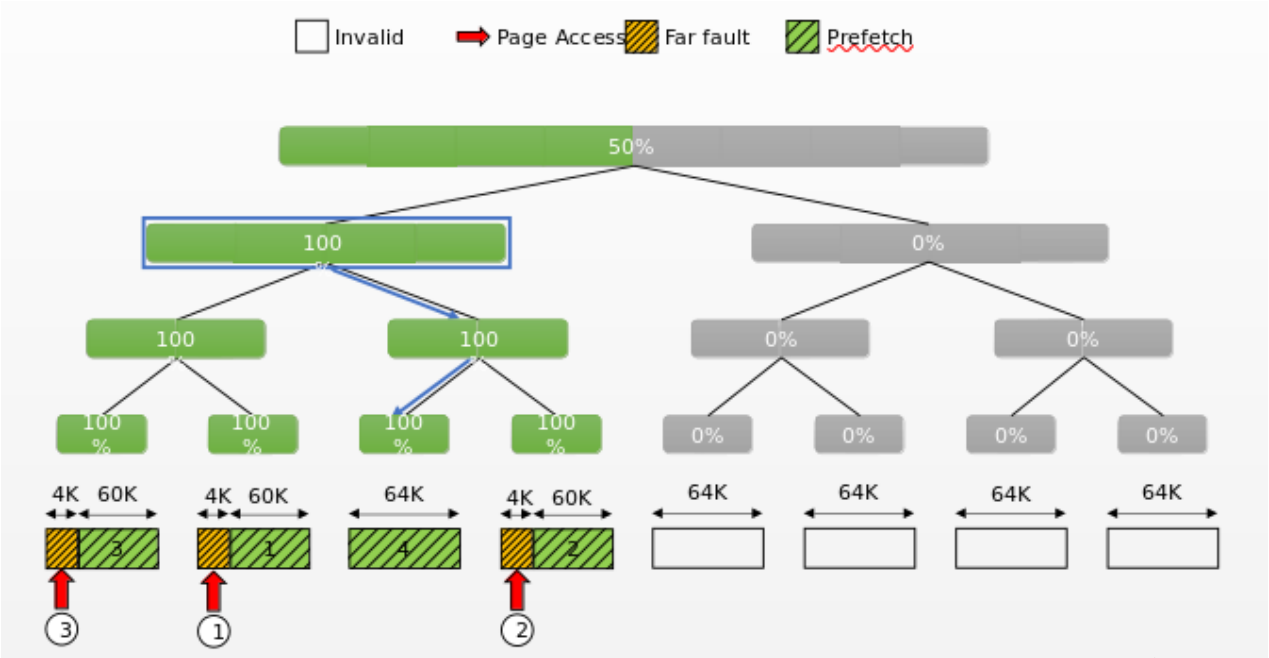

Figure: Tree-based Neighbourhood Prefetcher [1]

[1] Source: https://people.cs.pitt.edu/ debashis/presentations/ISCA2019.pptx

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- Prefetching policy
- Eviction policy
- VA translation and multiprocessing

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- Study prefetching policy and explain performance variation
- Find optimization possibilities

Profiling GPU Fault Servicing: Batch Characteristics

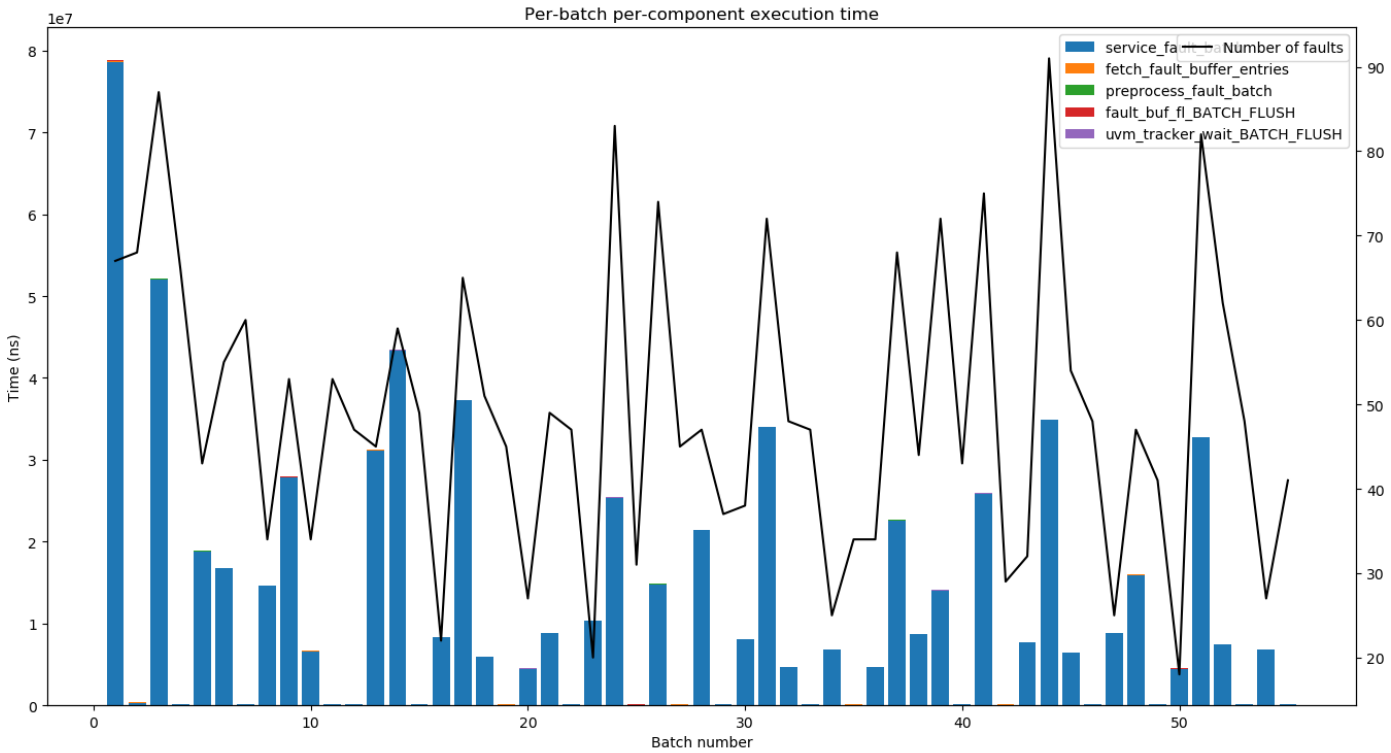
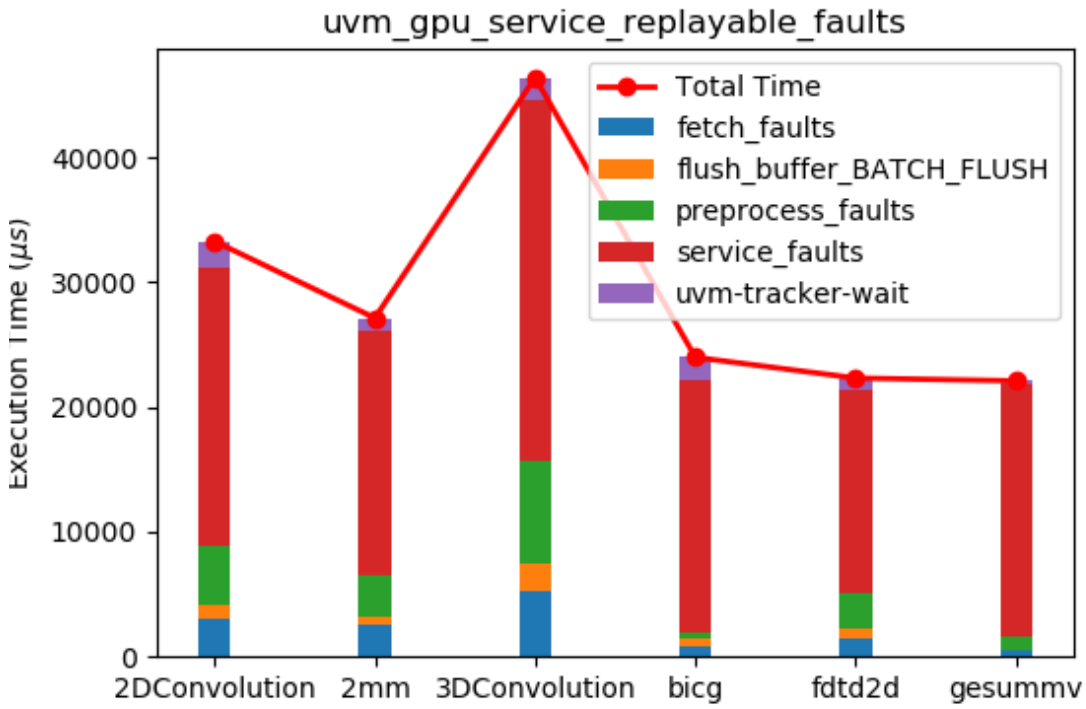


Figure: Fault batch size and service time

- Fault batches have varying sizes because of non-deterministic GPU scheduling
- Usually, a fault batch has faults from a single process

Profiling GPU Fault Servicing: Cost Breakdown



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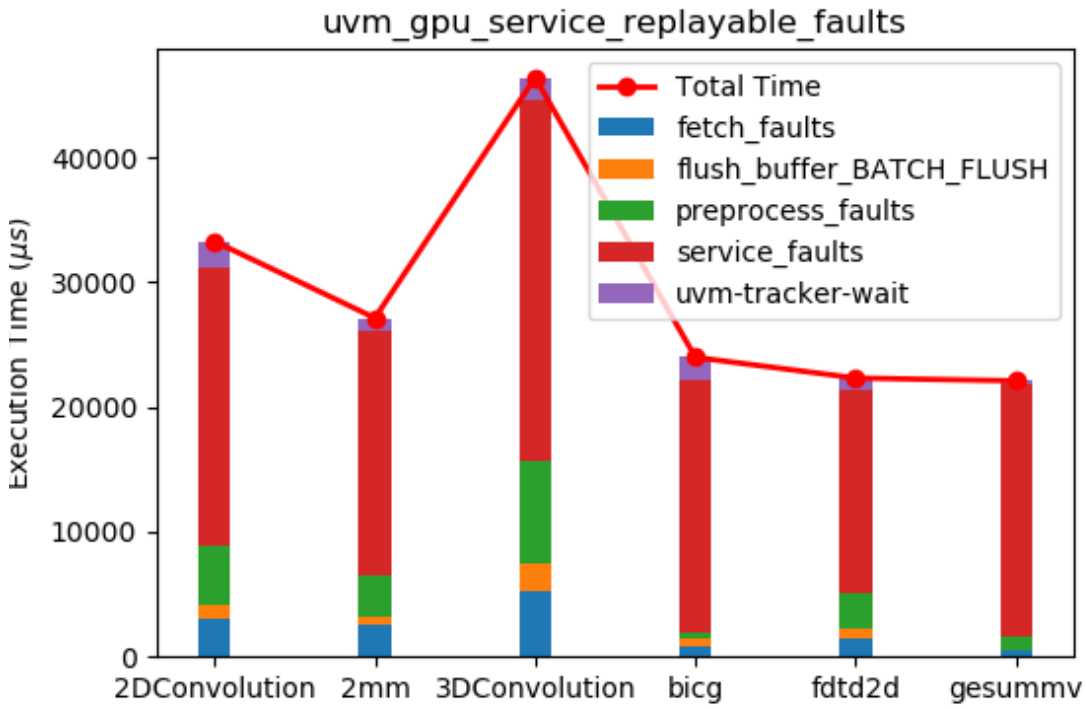

Figure: GPU fault servicing cost breakdown

- Fault servicing is the costliest step
- Page transfers are deferred: hence the `uvm_tracker_wait`
- Breakdown varies with program behaviour

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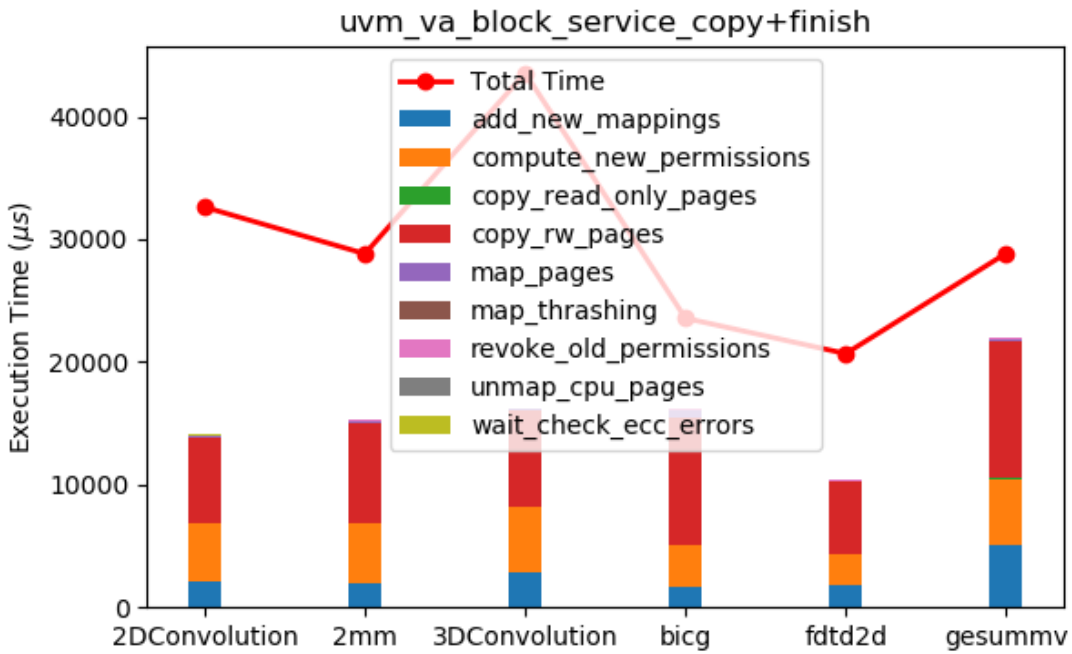

Figure: Subroutines of GPU fault servicing

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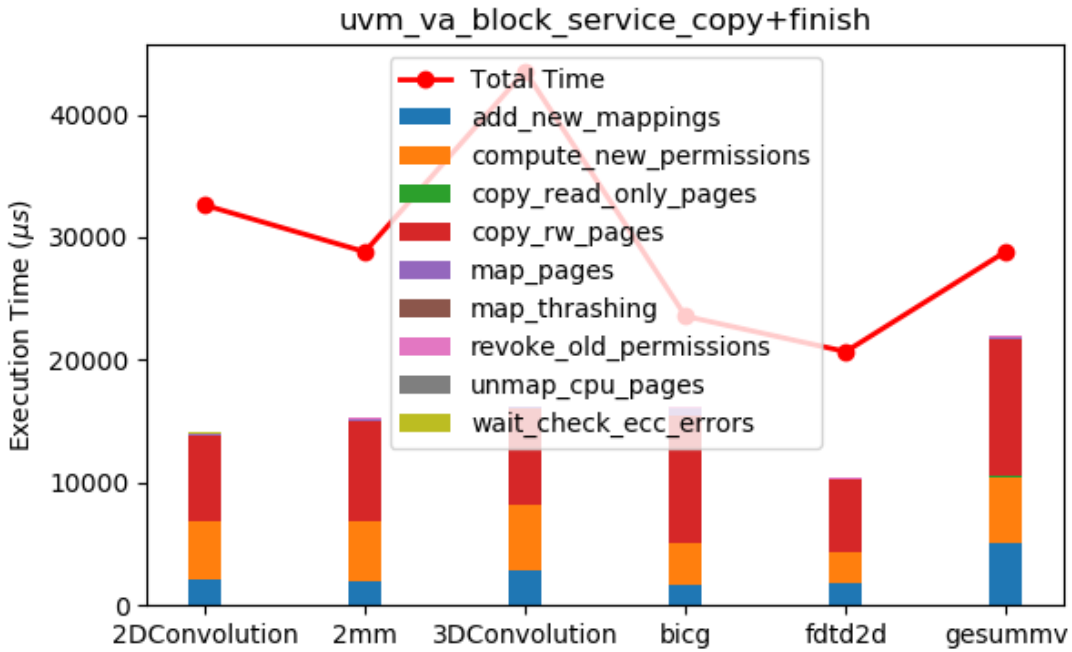

Figure: Subroutines of GPU fault servicing

- For this suite, variation is in fetching and preprocessing faults
- Metadata management cost is comparable to copying pages (at this level)

Profiling GPU Fault Servicing: Copying Pages

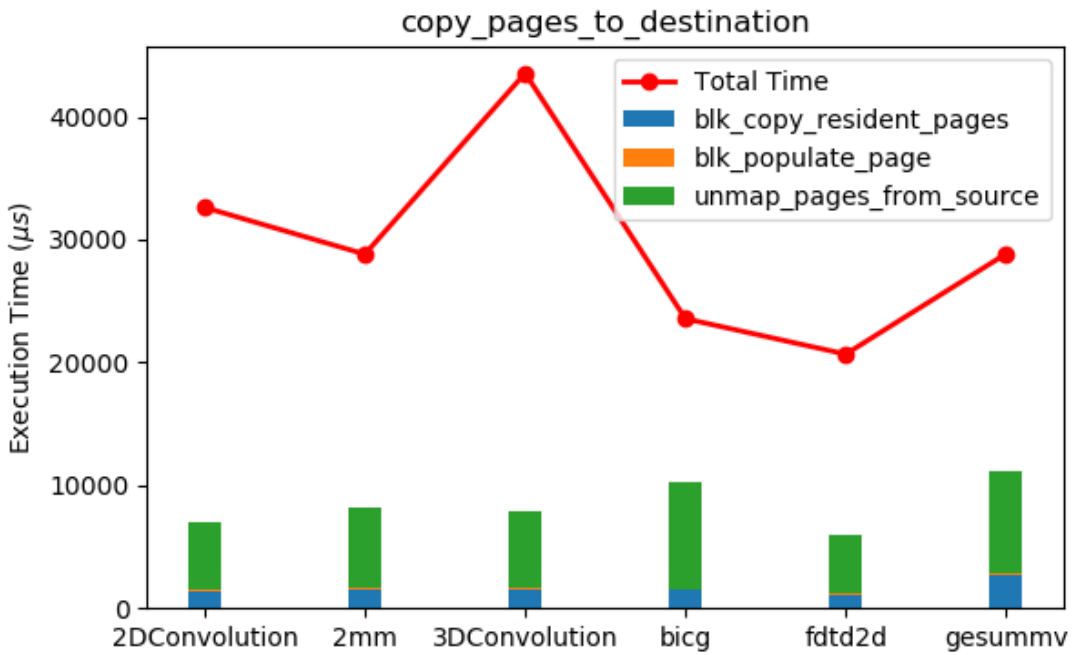

Figure: Steps in copying pages: unmap from source, allocate memory at destination and copy

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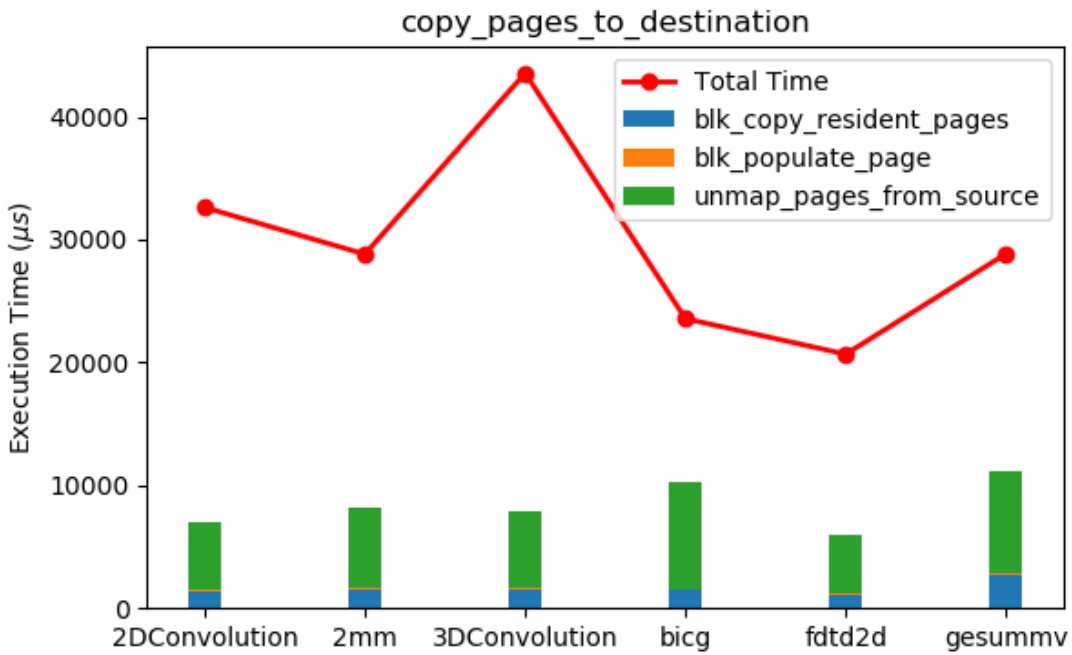

Figure: Steps in copying pages: unmap from source, allocate memory at destination and copy

- Delving deeper, we see that unmapping pages from source is a part of "copying"
- Populating and copying pages are deferred
- Unmapping from CPU cannot be deferred

Profiling GPU Fault Servicing: Unmapping CPU pages

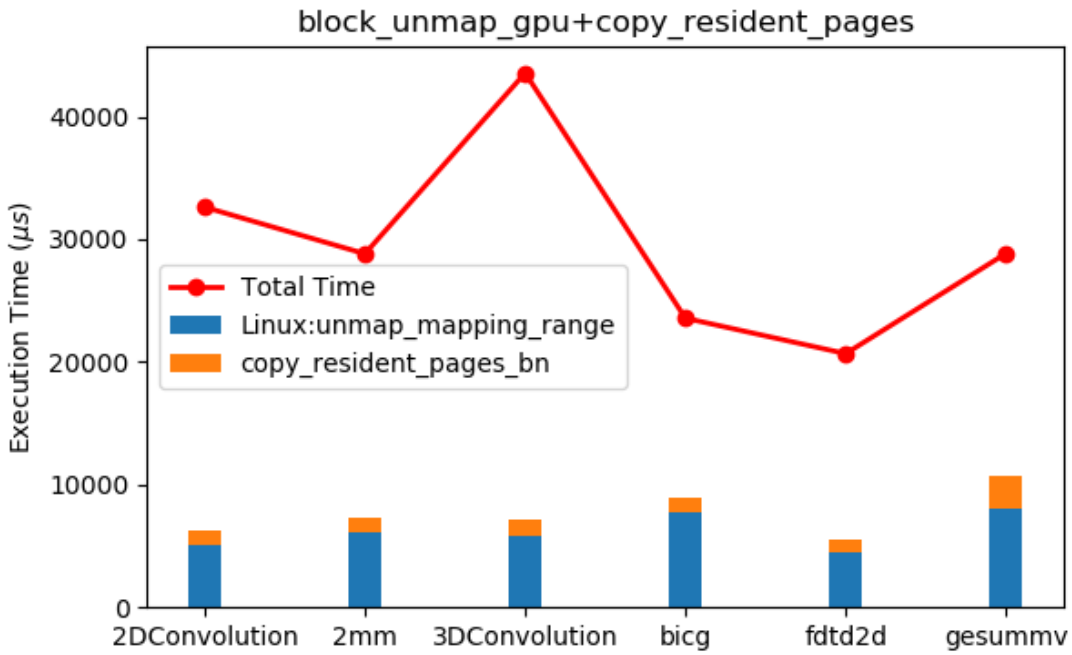

Figure: Further breakdown of previous plot (Page migration cost)

- Upon further analyzing the previous function, we confirm that there are no "hidden" steps in unmapping pages.
- `unmap_mapping_range` (single-threaded) takes about as much time as its caller.

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- Multiple CUDA contexts (or user processes) cannot run concurrently in the GPU. Kernels from the same thread group can run concurrently, as page tables are shared.

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- Improve current prefetching and eviction policies

Conclusion and Acknowledgements

Work done with Binong Kiri Bey.

Work done under the supervision of Prof Swarnendu Biswas and Prof Debadatta Mishra.

Thank You!