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Locality Aware Scheduling For Scalable Heterogeneous Environments

ROSS 2020

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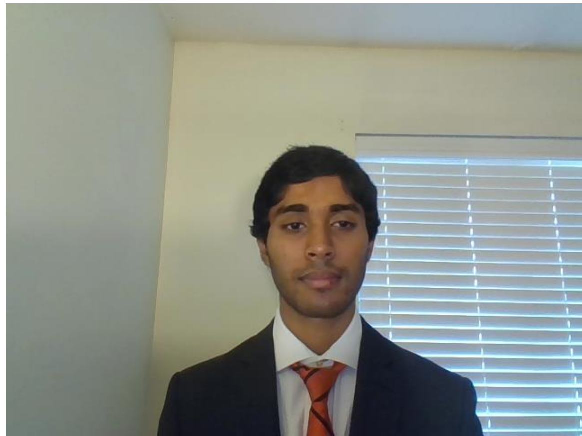
Outline

- Motivation
- The Minos Computing Library
- Architecture Details
  - Resident Memory
  - Scheduling Algorithm
- Experimental Results
  - SHOC Benchmarks
  - Hyper-parameter evaluation
- Conclusions and Future Work

Exploiting Scalable, Heterogeneous Systems

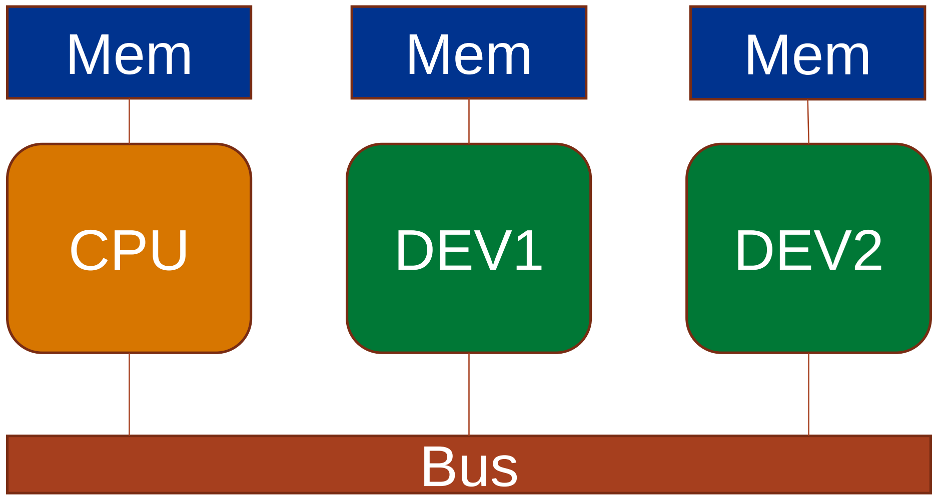
- Increasing levels of hardware specialization
  - i.e. GPUs, Deep Learning Accelerators, DSPs, etc.
- Higher complexity to program new applications
- Potential pitfalls when scaling to other architectures

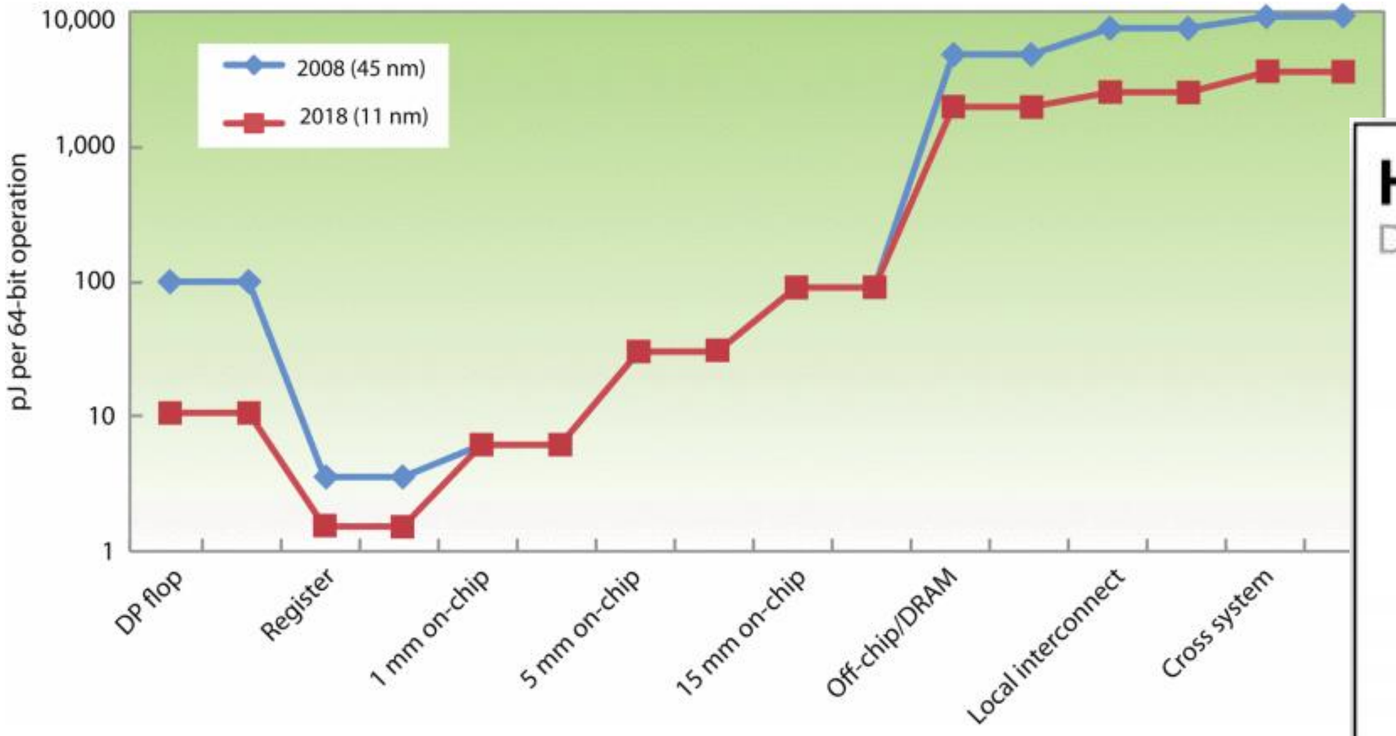


Motivation

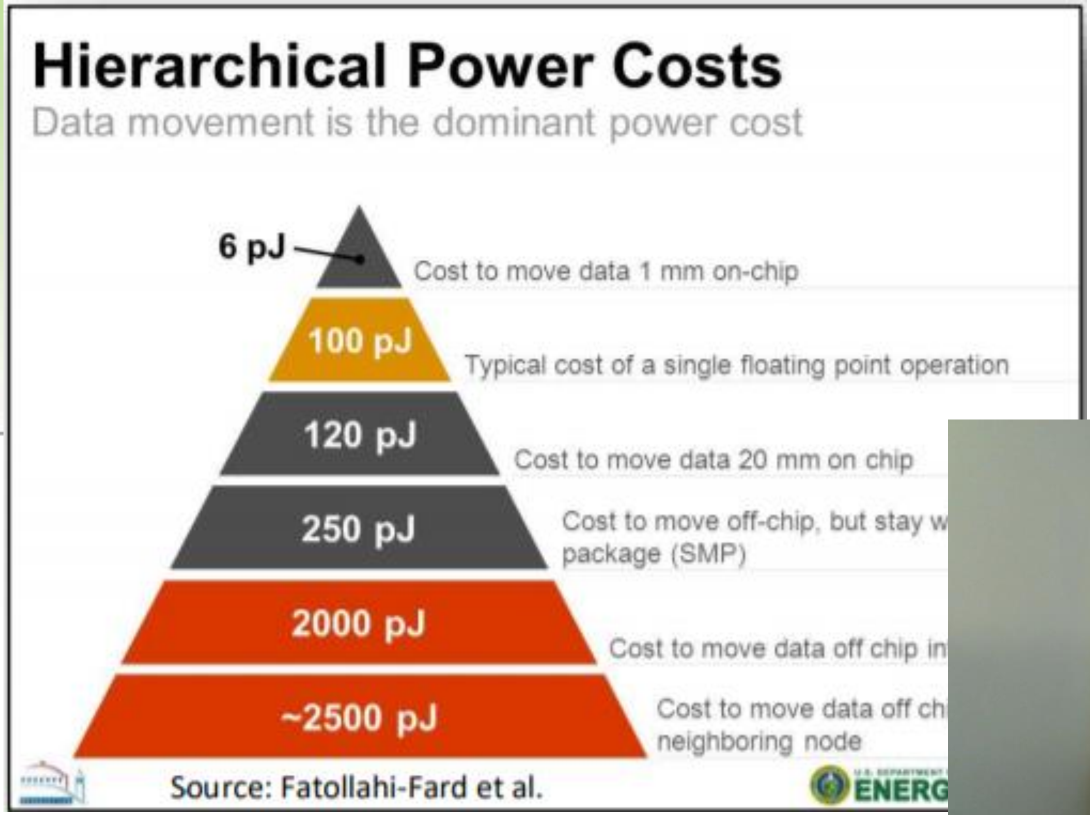
- Data movement is now the critical aspect of performance

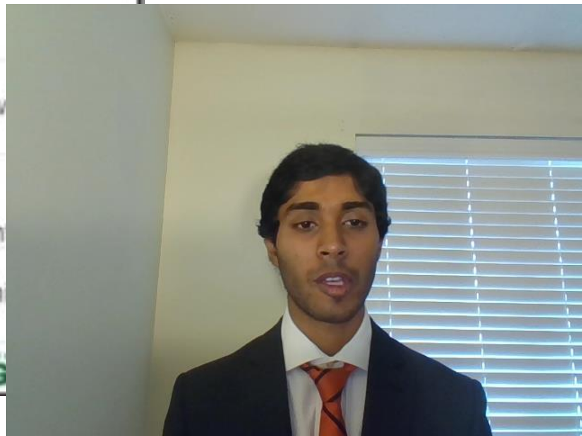
Multiple Memory Nodes





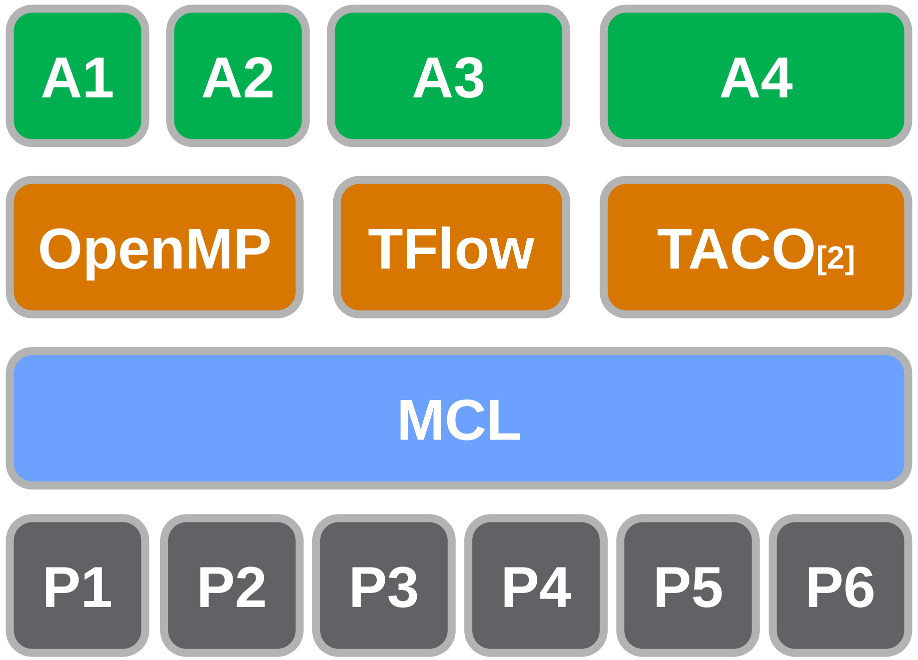
Source: Kogge, Shalf 2013



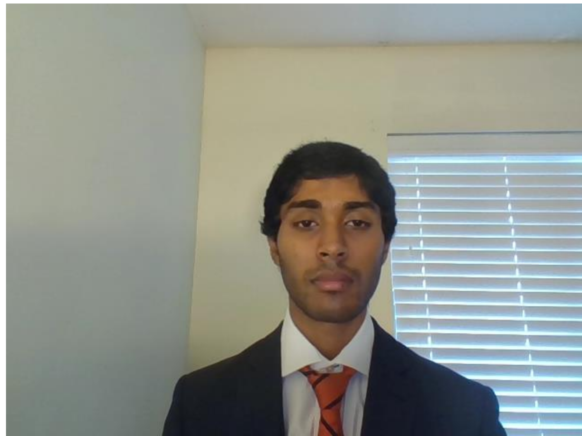


The Minos Computing Library (MCL) [1]

- Framework for programming heterogeneous systems
- Features
  - Dynamic task scheduling onto available resources
  - Co-schedule independent applications
  - Internal profiling and tracing capabilities
- Flexibility
  - Automatic scaling to available resources
  - Works/can be integrated with commonly used technologies
  - Independent scheduler framework



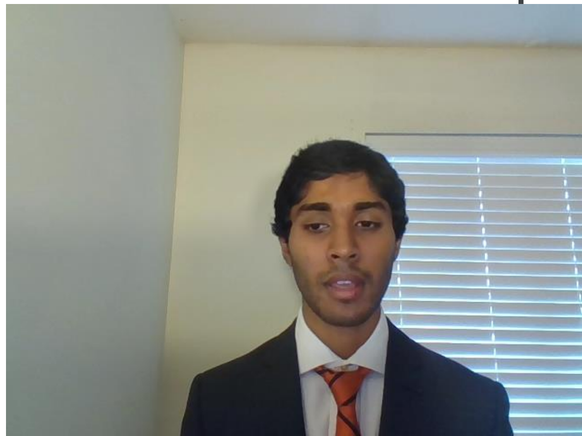
[1] R. Gioiosa, B. Mutlu, S. Lee, J. Vetter, G. Picierro, M. Cesati. 2020. The Minos Computing Library: Efficient Parallel Programming for Extremely Heterogeneous Systems. In General Purpose Processing Using GPU (GPGPU '20), February 23, 2020, San Diego, CA, USA
[2] G. Kestor, R. Gioiosa, M. Raugas. Towards Performance Portability through an Integrated Programming Eco-System for Tensor Algebra. In Performance, Portability, and Productivity in HPC Forum, to be held online, September 2020



MCL Program Example

- Same piece of code will exploit all available resources
- OpenCL kernels are directly usable by MCL

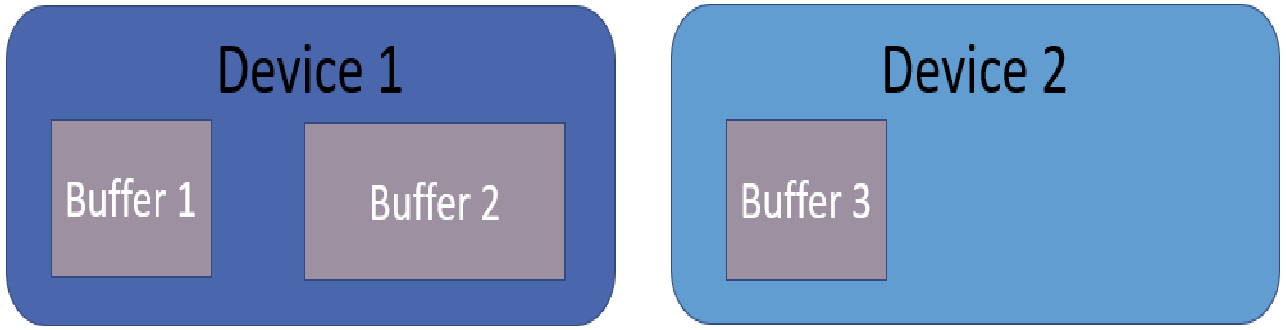
```c
#include <minos.h>

int main(void){
    mcl_init(NWorkers, <flags>);
....

    for(i=0; i< NIter; i++){
        hdl[i] = mcl_task_create(<filename>, <kernel>, <flags>);
        mcl_task_set_arg(hdl[i], 0, <addr>, <size>, <flags>);
        ...
        mcl_task_set_art(hdl[i], k, <addr>, <size>, <flags>);
        mcl_exec(hdl[i], <pes>, NULL, MCL_TASK_GPU);
    }
...
    mcl_wait_all();
...
    mcl_finit();

    return 0;
}
```



MCL Resident Memory Module

- Allows persistent data to remain in device memory across tasks
- Coordinates data movement so correct data is transferred to the correct device
- Supports read-only (i.e. multiple copies) and read-write data (exclusive copies)

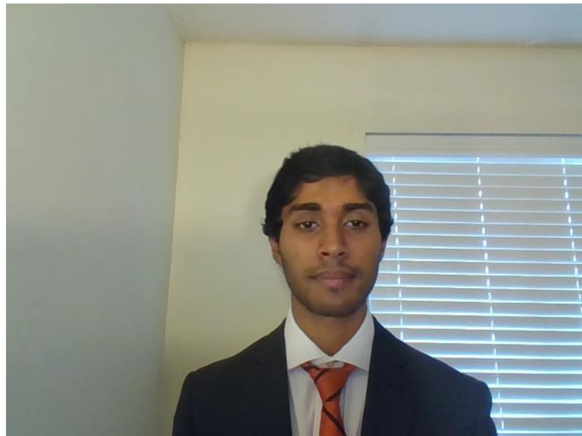
Pid	Memory	Concurrent Uses	Size	Device 1	Device 2
1	1	1	10 MB	1	0
1	2	1	20 MB	1	0
1	3	1	10MB	0	1
…	…	…	…	…	…



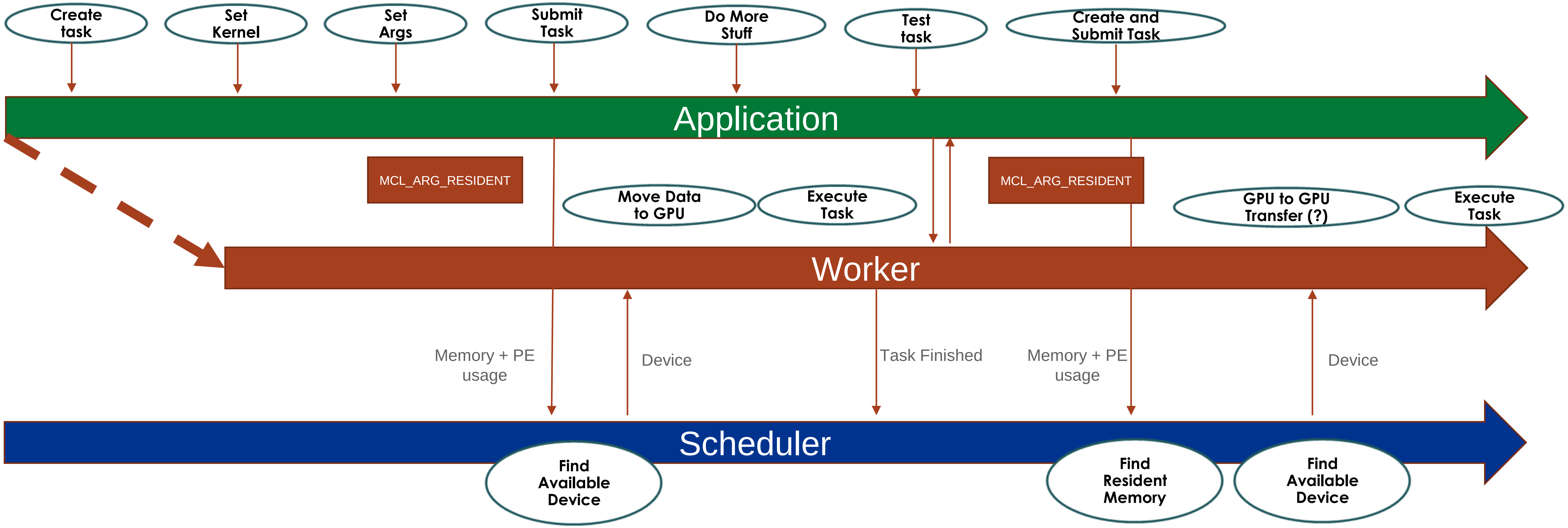
MCL_ARG_RESIDENT

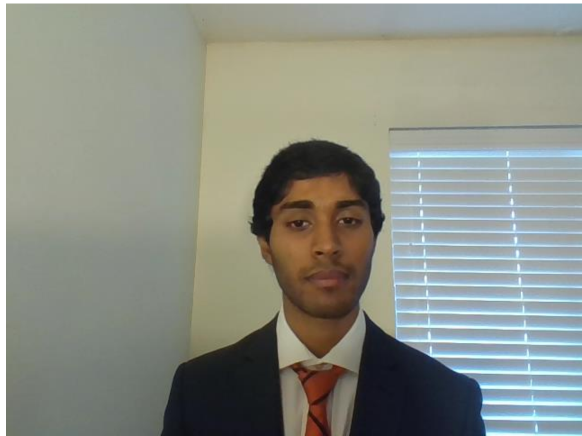
MCL_ARG_INVALID

MCL_ARG_DONE



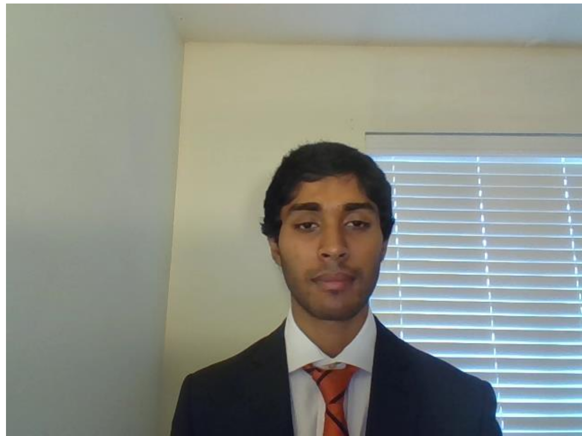
MCL Trace with Resident Memory





MCL Schedulers: Round-Robin Scheduler

- Schedules tasks in a first-in first out manner to the next available device
- Typically achieves high resource utilization
- Problems
  - Suffers from head-of-line blocking
  - Makes poor scheduling decisions when there is data reuse between kernels
  - **Unnecessary data transfers**



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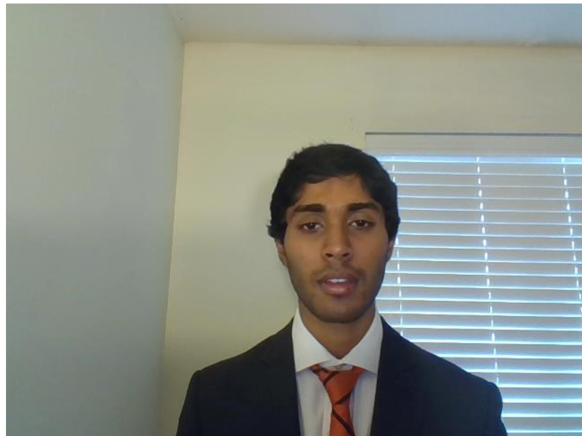
MCL Schedulers: Delay Scheduler

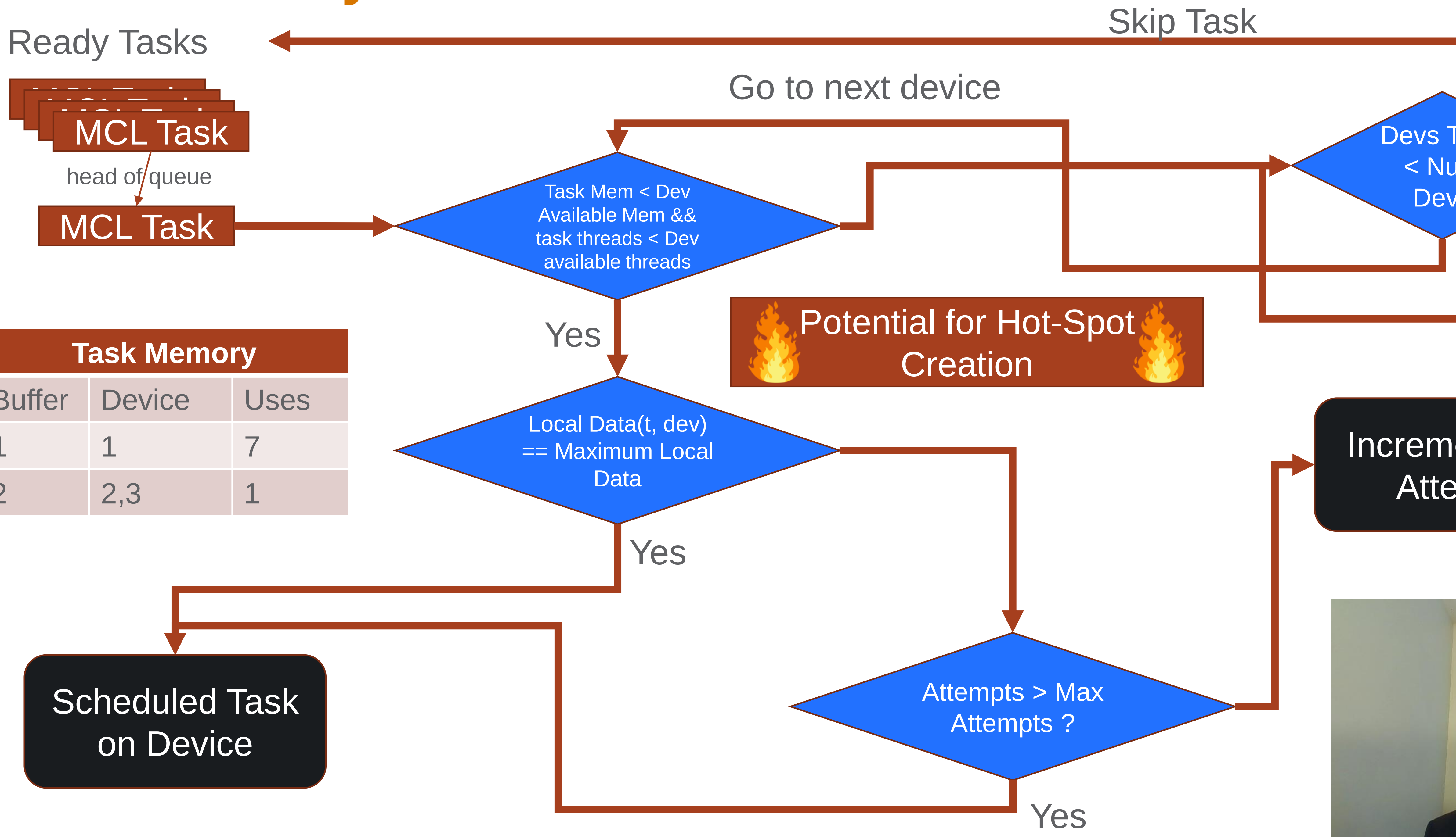
- Delays kernels from running on devices without device local data to minimize data transfers
- Skips devices that do not have device local data
- Skips tasks when waiting for busy devices
- Limits the number of times a task can be delayed to prevent a task from blocking too long

Algorithm 1 Device Local Data

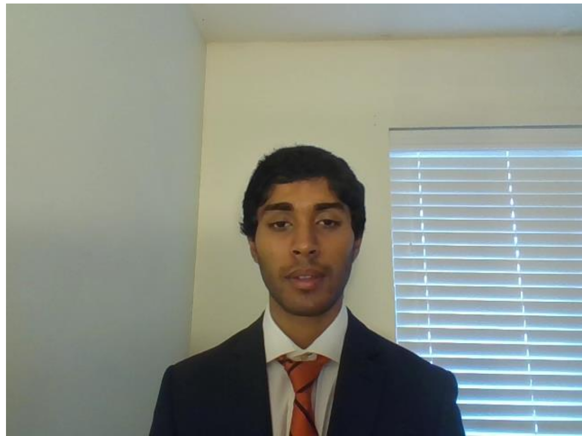
LocalData(Device δ**, Task** t**):**
$bytes \leftarrow 0$
for all β in $t.buffers$ **do**
    if β in $\delta.data$ **then**
        $bytes \leftarrow bytes + \beta.size$
    end if
end for
return($bytes$)
end LocalData



Delay Scheduler Illustration



Task Memory		
Buffer	Device	Uses
1	1	7
2	2,3	1

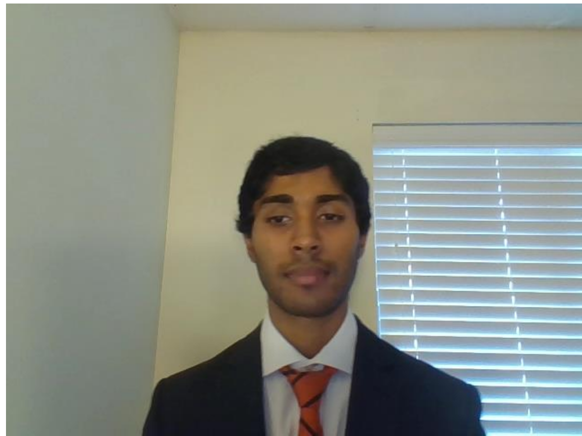


MCL Schedulers: Mixed Scheduler

- Attempts to balance system utilization with data locality concerns
- Detects popular pieces of data to create replicas
- The best predictor of how popular data will be is how popular it was in the past

Algorithm 3 Device Local Data With Copy Factor

LocalDataCopyFactor(Device δ**, Task** t**, CopyFactor** γ**):**
$bytes \leftarrow 0$
for all β in $t.buffers$ **do**
  if β in $\delta.data$ and DEVICES(β)$\geq$ $\log_\gamma$ TASKS(β) **then**
    $bytes \leftarrow bytes + \beta.size$
  end if
end for
return($bytes$)
end LocalDataCopyFactor

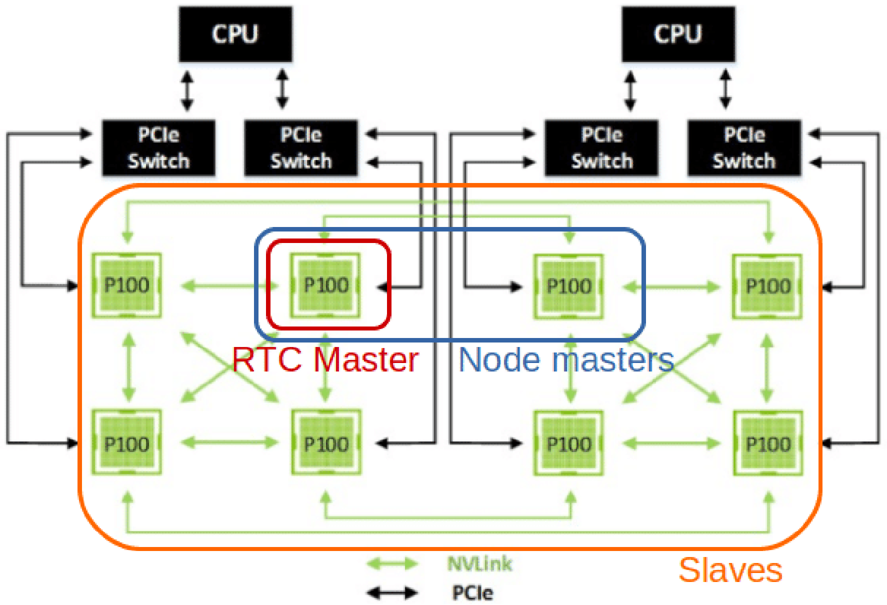


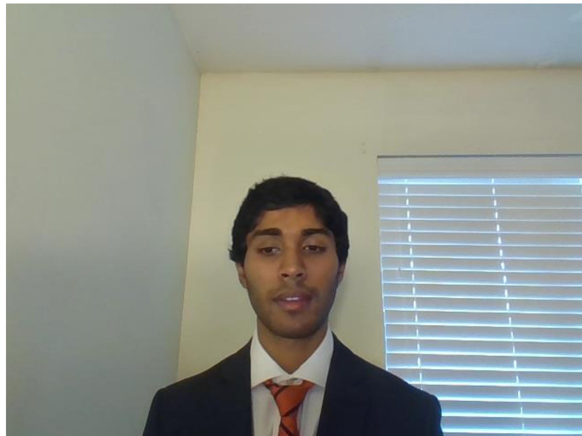
Experimental Setup

- Benchmarks (from SHOC)
  - BFS*
  - Sort*
  - FFT*
  - DGEMM
  - SPMV
  - MD5Hash

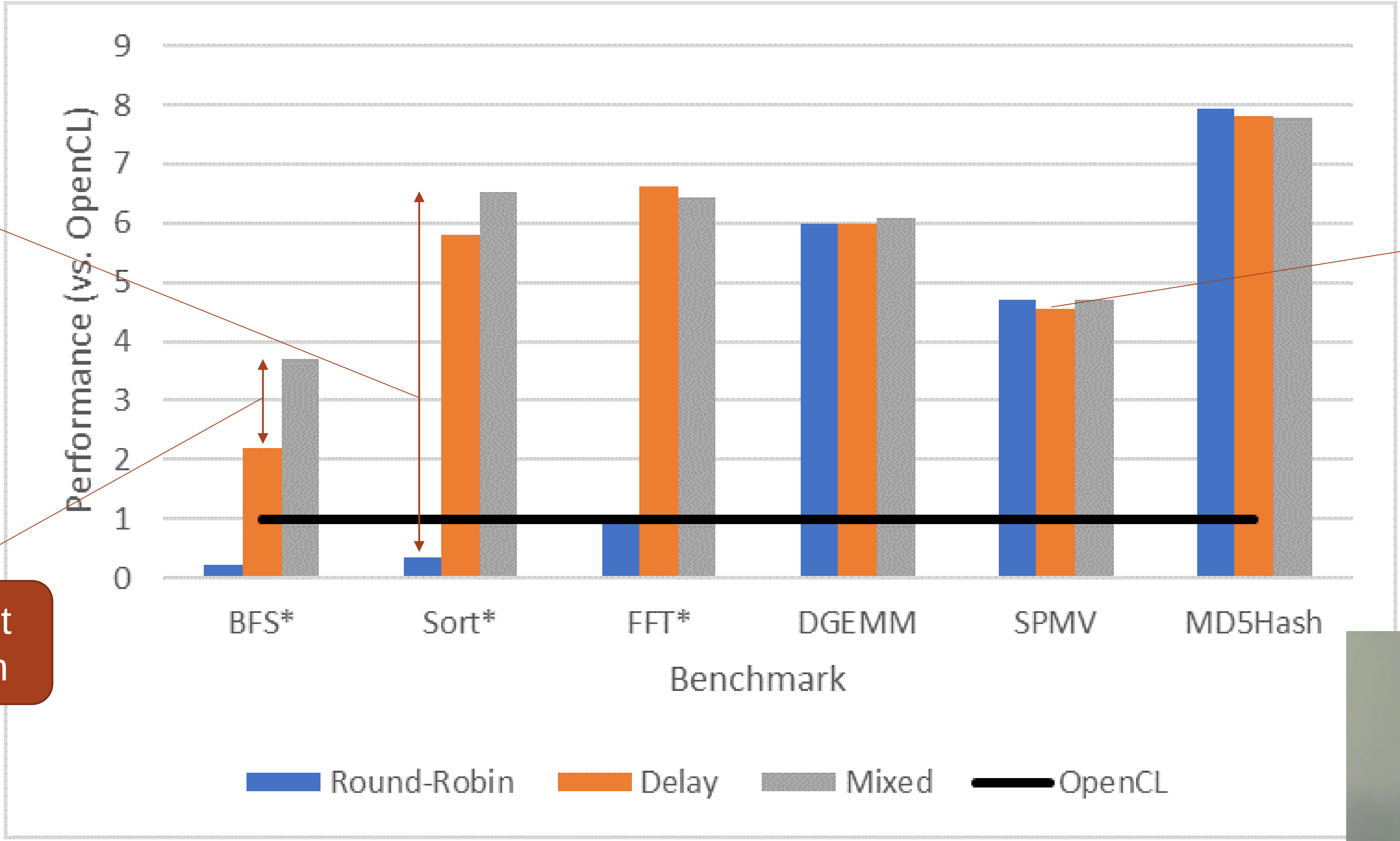
* = Exploits Data Locality

DGX-1 P100
- 2x 20 Core Intel Xeon CPU
- 8x Nvidia P100 GPU, NVLINK
- 256 GB RAM + 16 GPU





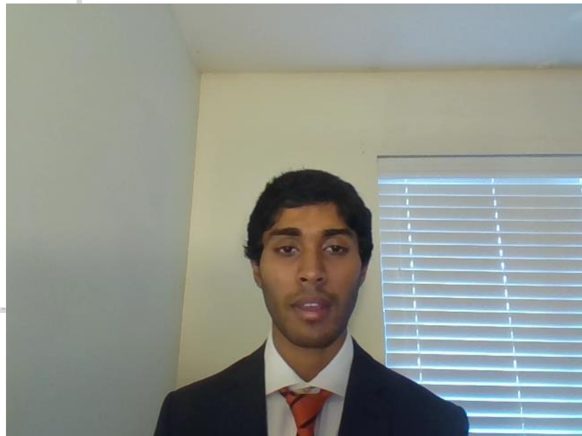
Scheduling Evaluation



Benefit of Locality

Hot-Spot Creation

Low Additional Overhead



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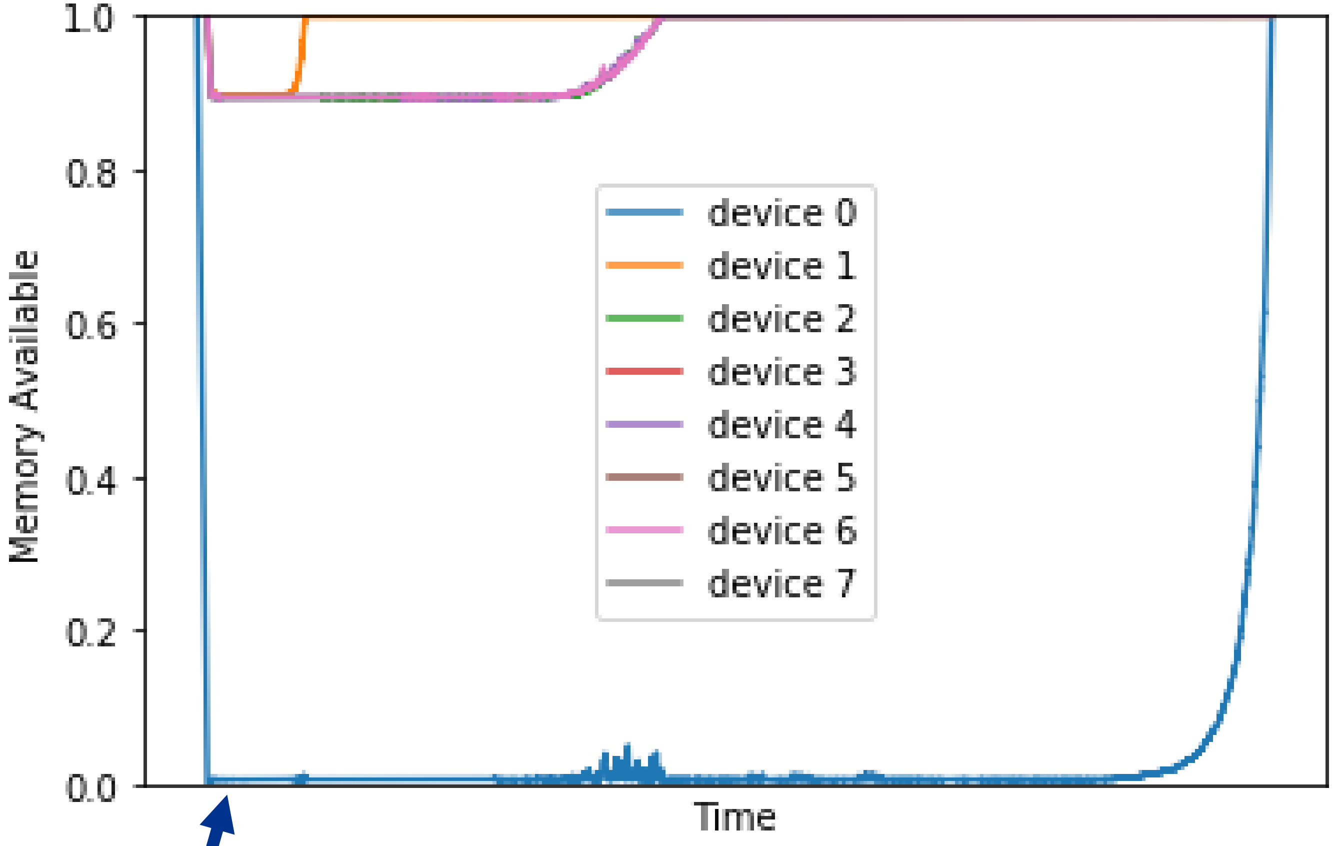
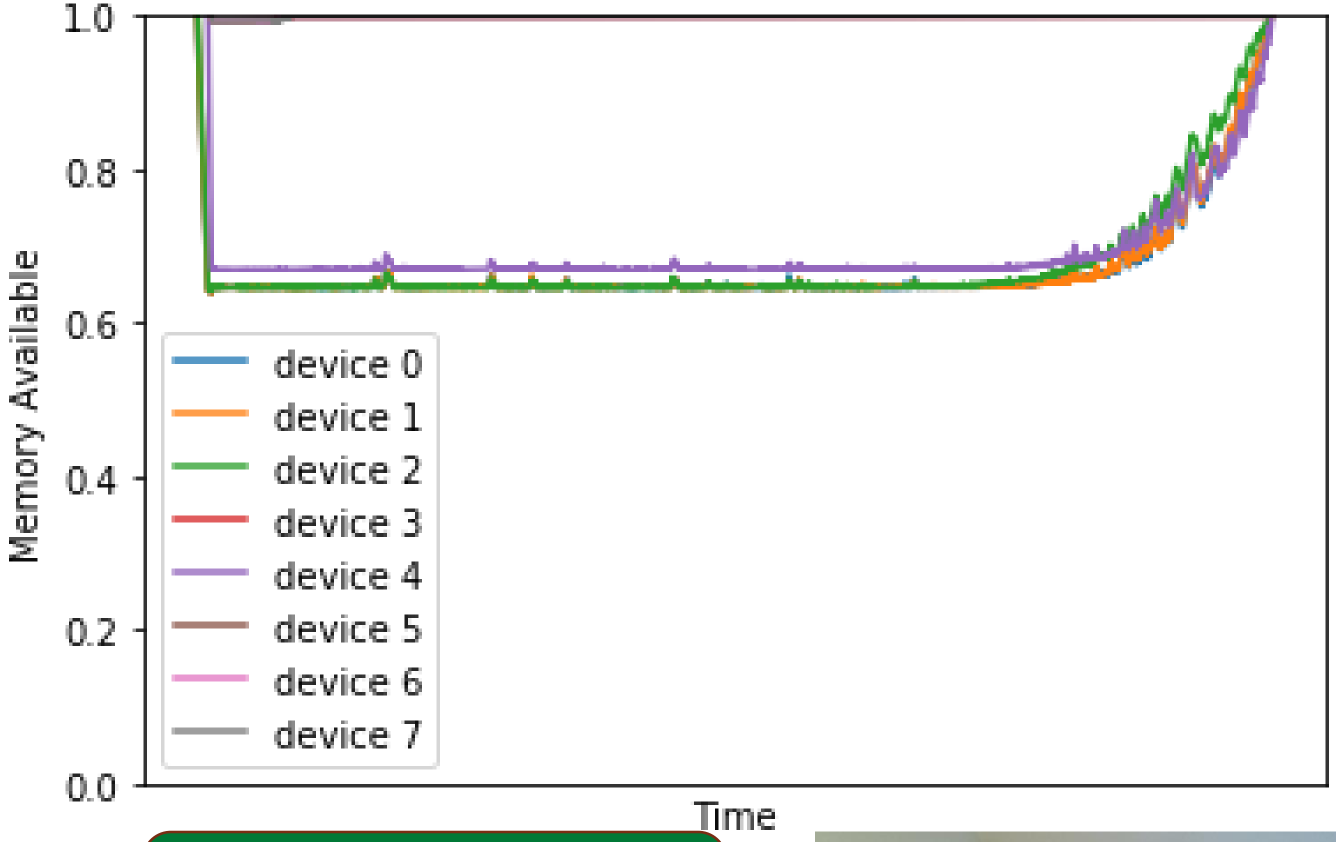
BFS Memory Usage Comparison

Delay Scheduler Memory Trace



Mixed Scheduler Memory Trace

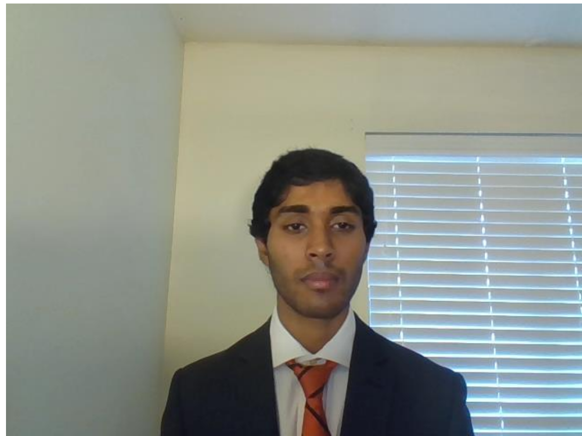


GPU 1

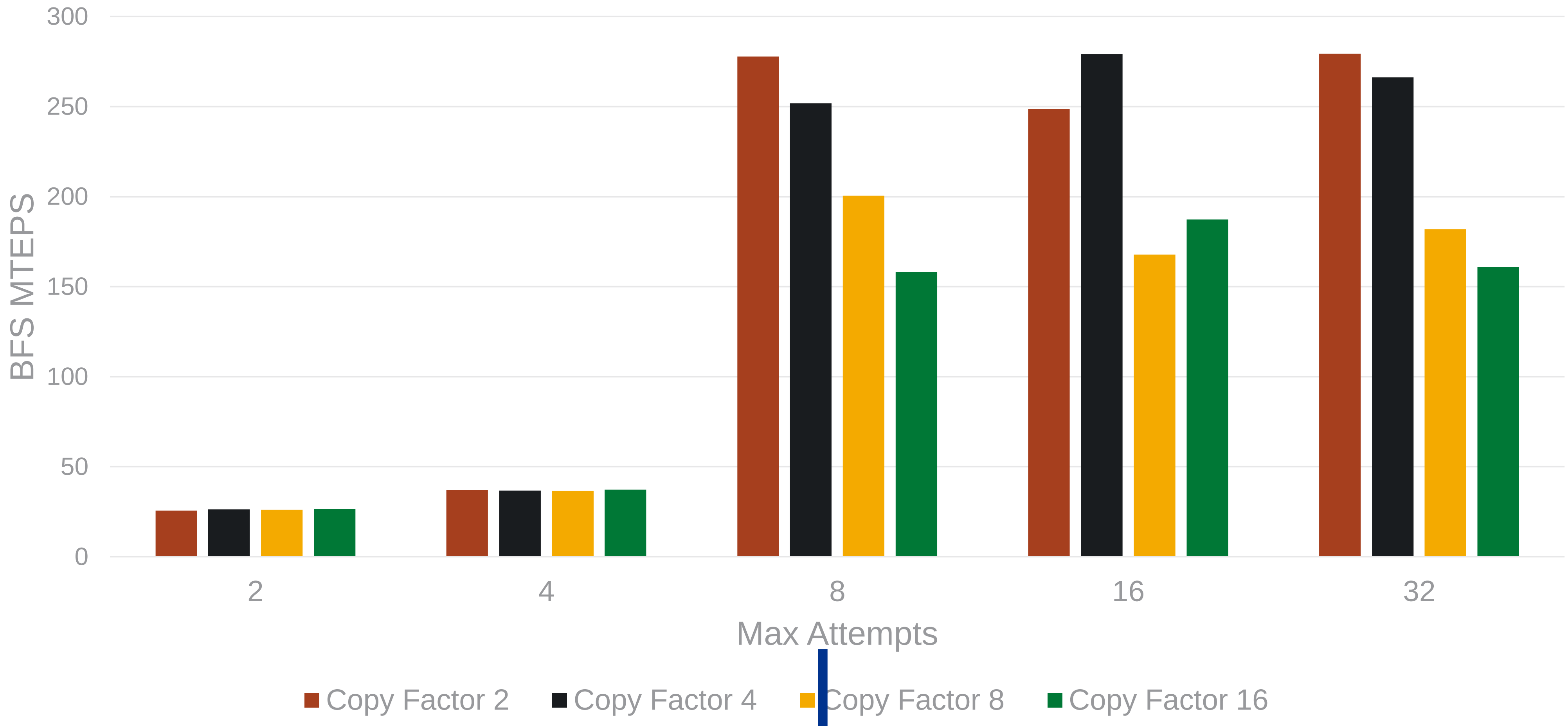
Hot Spot creation on device 1

Adaptive replication of popular data

Memory use from MCL internal trace capabilities



Effect of Hyperparameters on Performance

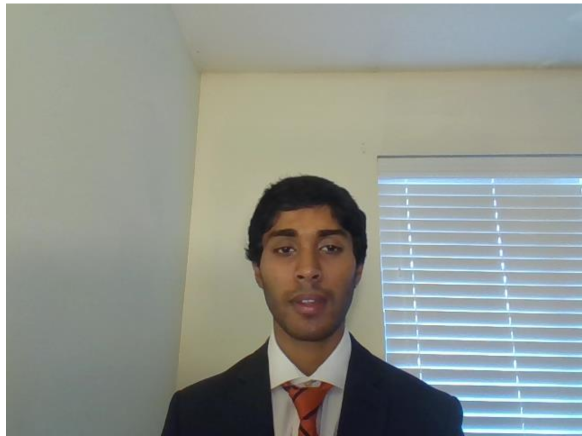


BFS Benchmark
- 1,000,000 vertices
- 4096 Tasks

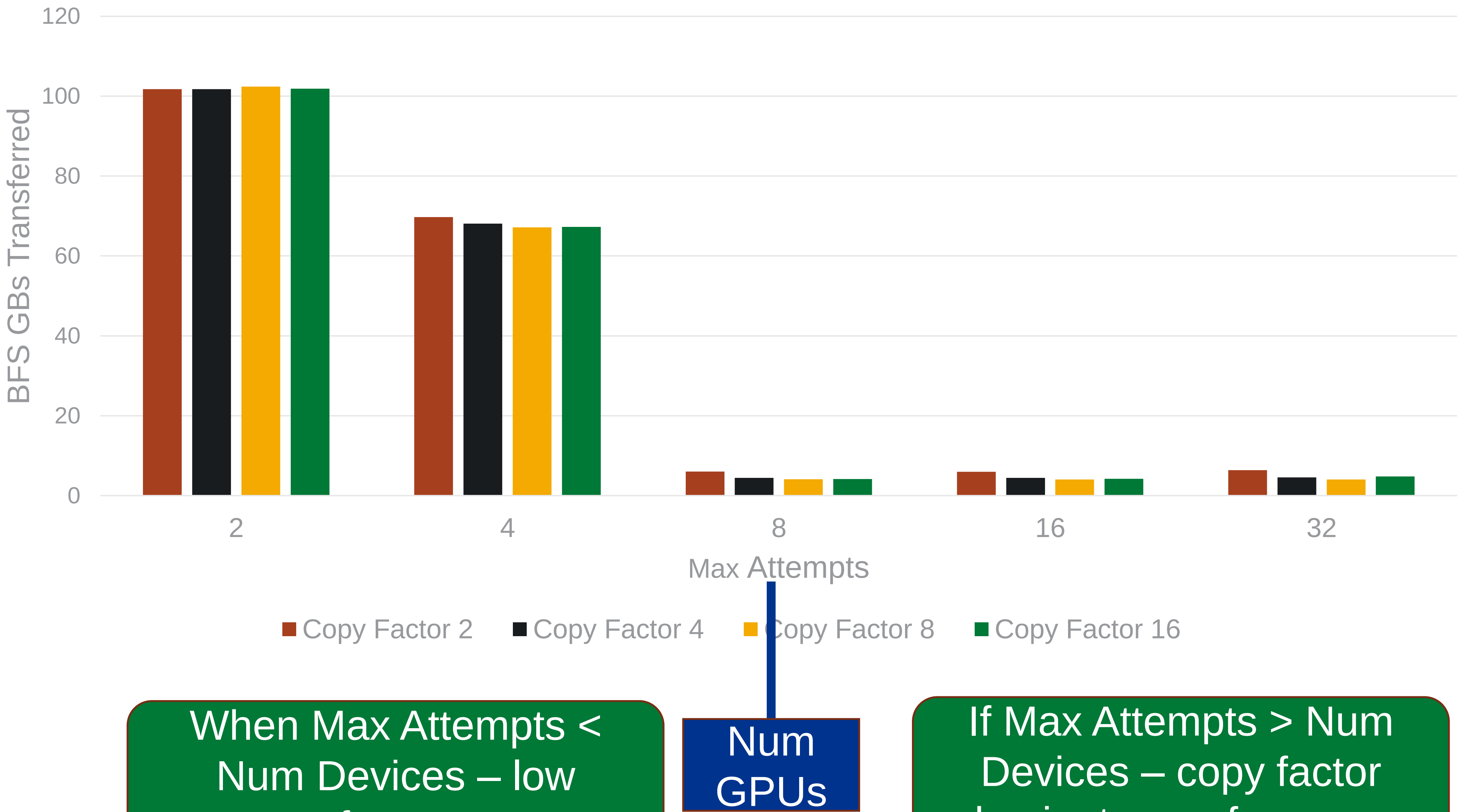
Num GPUs

When Max Attempts < Num Devices – low performance

If Max Attempts > Num Devices – copy factor dominates performance



Effect of Hyperparameters on GBs Transferred



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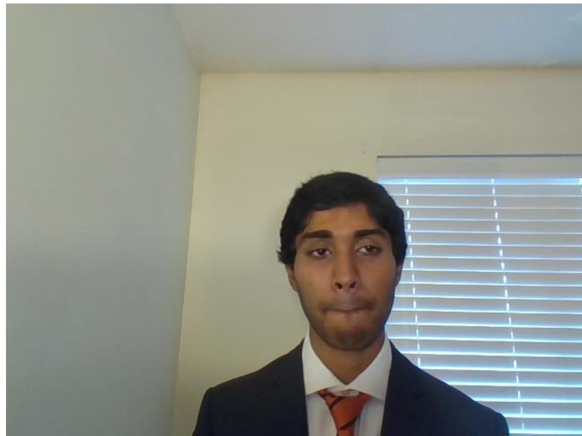

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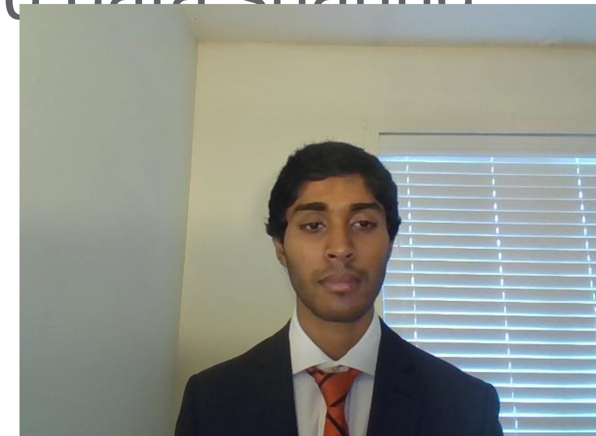
Conclusions + Future Work

- One of the primary challenges of using multiple devices is managing memory and coordinating data movements
- We introduce MCL Resident Memory to seamlessly manage device memory and coordinate data transfers
- Results demonstrate the importance of locality in achieving performance speedups
- Improves performance against other baselines
- Improve scheduler by dynamically determining hyperparameters
- In the future we want to expand this work to allow scheduling and data sharing among multiple applications



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Thank you

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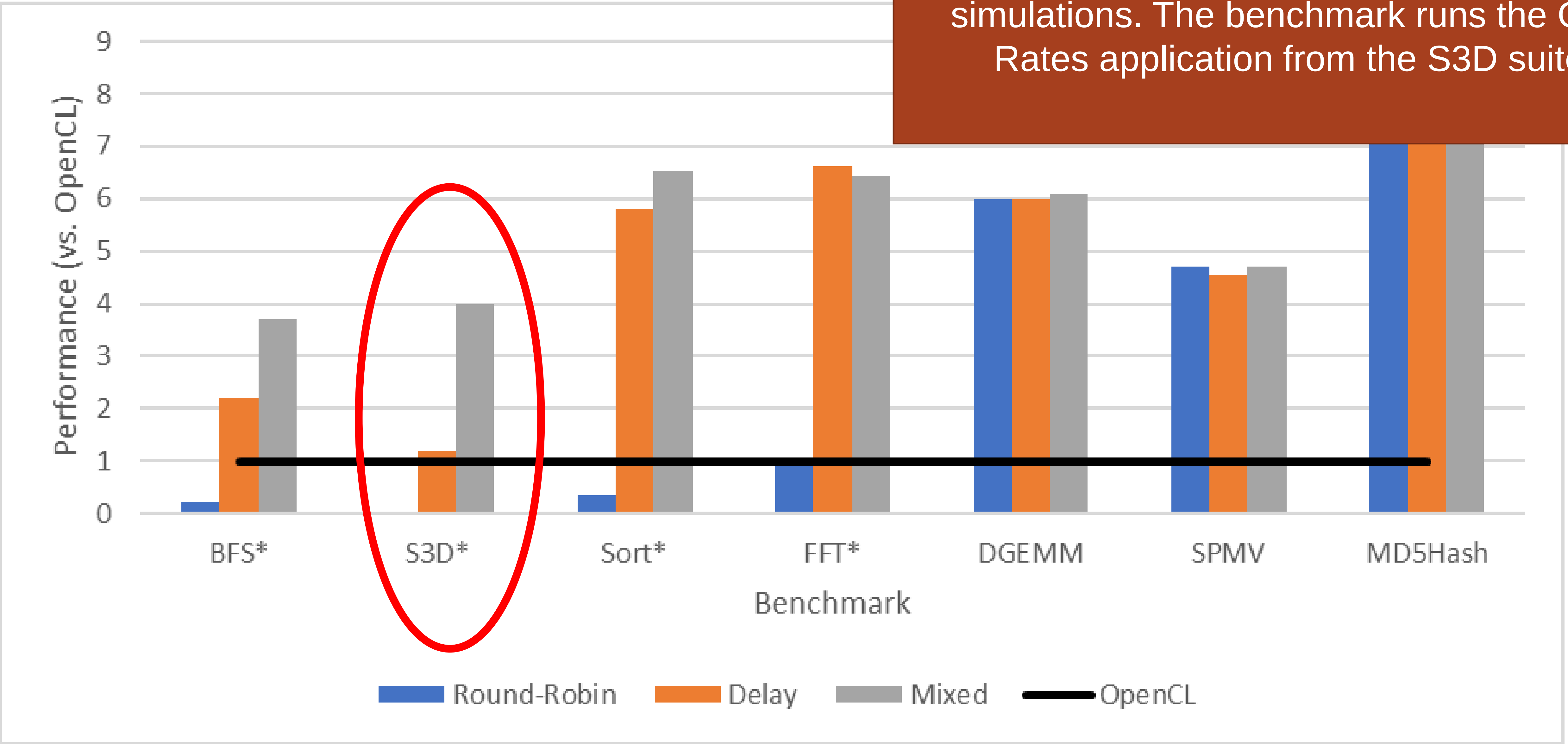
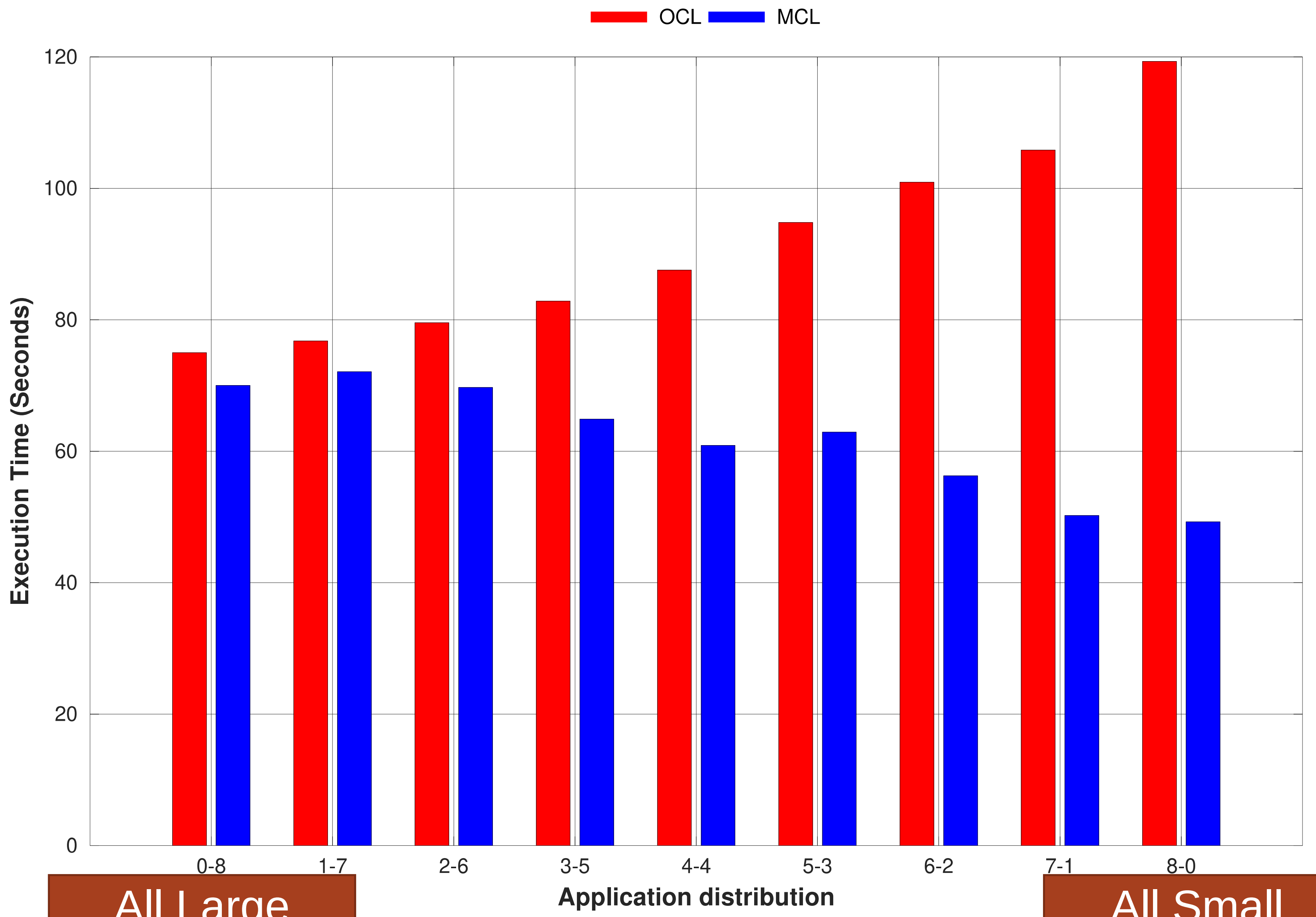
Additional Slides

Results With S3D

S3D is a standard direct numerical solver (DNS) used for combustion and other chemical simulations. The benchmark runs the Get-Rates application from the S3D suite



Application Composition



All Large Tasks

All Small Tasks

Experiment Details:

- OpenCL application partitioned among 8 devices
- A variable mix of small (64x64) and large (1024x1024) GEMMS

Eviction/Checkpointing

- Memory Usage is a limited resource that is under demand in a HPC system
- MCL supports flexible eviction policies that can be combined with scheduler policies
- When applications are unable to be run because no device has enough available memory, resident data can be evicted back to main memory
- To the user, MCL still behaves the same
- Currently supports a LRU policy

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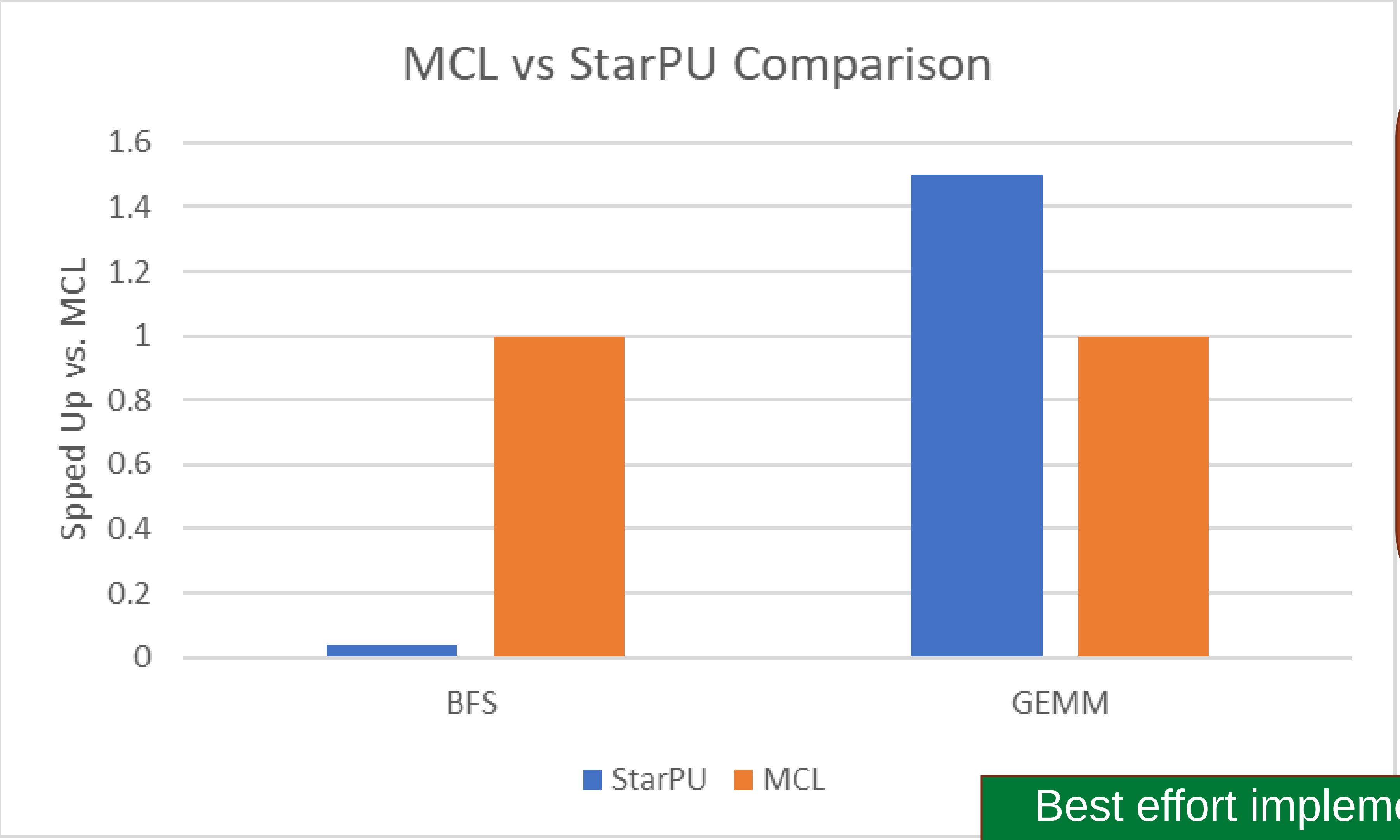
Comparison Against StarPU



StarPU Scheduling LWS:

- Task is automatically scheduled on worker that released it
- Idle workers use data transfer performance estimates to determine weather to move data and “steal” work

Best effort implementation of StarPU – still investigating performance discrepancy