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MCL Multi-GPU Support + Schedulers

PPoPP '21

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Use Cases

- Translating OpenCL code from one device to multiple:

```
For dev in devs:
    clCreateContext ...
    clCreateProgramWithSrc ...
    clCreateCommandQueueWithProps ..
    clCreateKernel ...
    //Create a buffer for each array
    //etc.
```

- Lots of complexity overhead for each device
- Coordinate which devices are busy and idle
- Coordinate memory between devices

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Use Cases

- Translating MCL Code from single device to multiple devices

```
mcl_exec(task, pes, block_size, MCL_TASK_GPU);
```

```
mcl_exec(task, pes, block_size, MCL_TASK_GPU);
```

- Same code runs on all available resources
- MCL takes care of and hides complexity overhead

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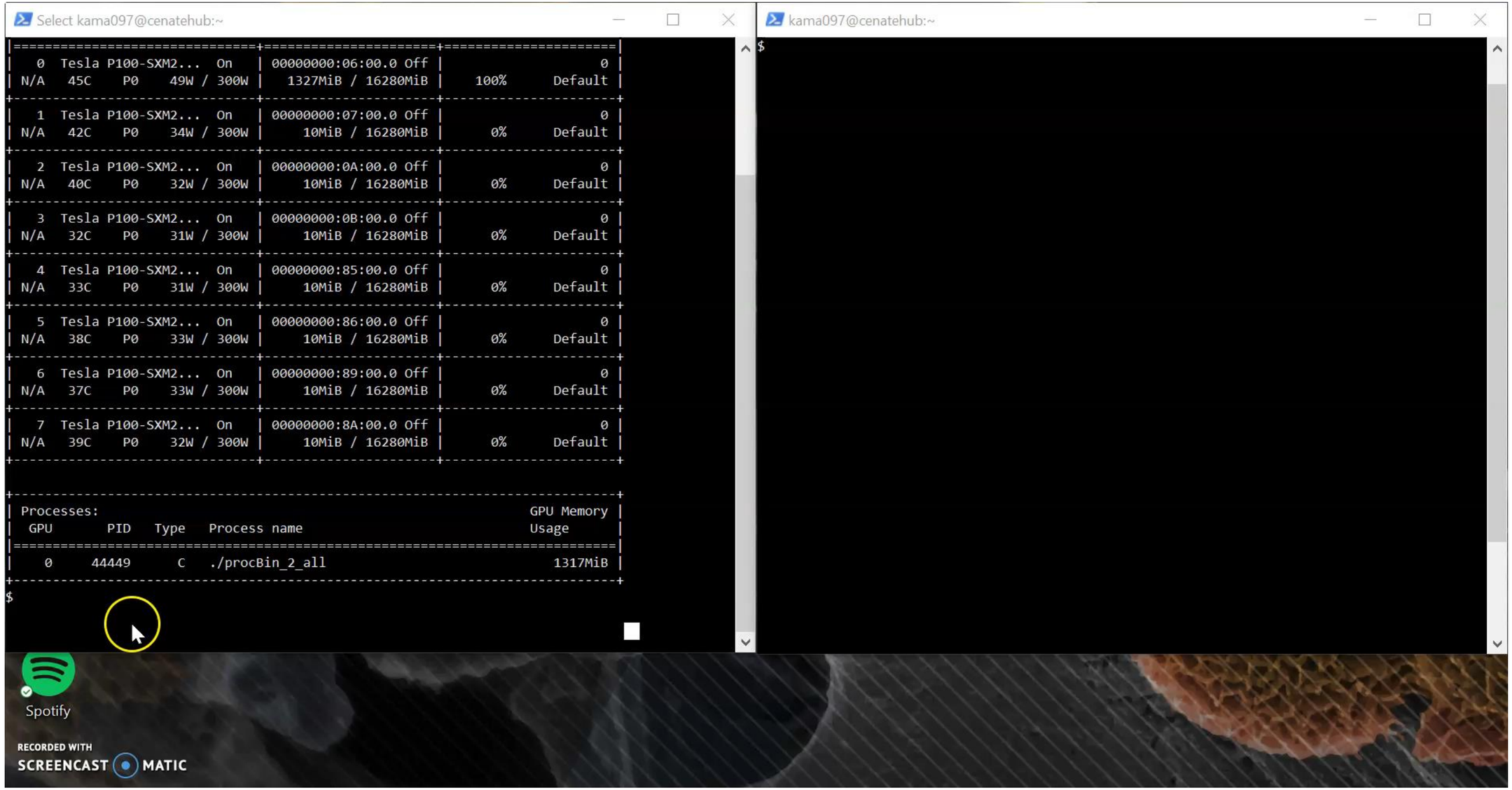
Example – Easy Scaling



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Running Commands

- To replicate the results in the video, you can run these commands on your own GPU enabled system

```
>>> mcl_sched -s fffs -p rr &
>>> cd mcl/test
>>> make mcl_gemm
>>> ./mcl_gemm -r 8092 -w 16
-----------------------------------------
>>> export CUDA_VISIBLE_DEVICES=1,2,3,4,5,6,7
>>> mcl_sched -s fffs -p rr &
>>> cd mcl/test
>>> make mcl_gemm
>>> ./mcl_gemm -r 8092 -w 16
```

Commands used for DGX-1 demo 1

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MCL Schedulers

- MCL scheduler is a separate process that determines where and when tasks are run
- Flexible – i.e. different scheduler policies divided into too classes
  - First In First Out – The first task in the queue must be scheduled first,
  - FFFS scheduler – Allows the resource scheduler to select and of the currently enqueued tasks
- Different Policies
  - First Fit
  - Round Robbin
  - Delay Scheduler
  - Hybrid Scheduler

```
$ ~/local/bin/mcl_sched -h
Usage: /home/kama097/local/bin/mcl_sched [options]
        -s, --sched-class {fifo|fffs}  Select scheduler class (def = 'fifo')
        -p, --res-policy {ff|rr|delay|hybrid}  Select resource policy (def = class dependant)
        -h, --help                     Show this help
$
```

First Fit Scheduler

- Schedules the next available task onto the current device if there is space
- Only moves onto the next device if the current device is full
- Space is determined by both memory and available processing threads
- Low Overhead

```
>>> mcl_sched -s fffs -p ff &
```

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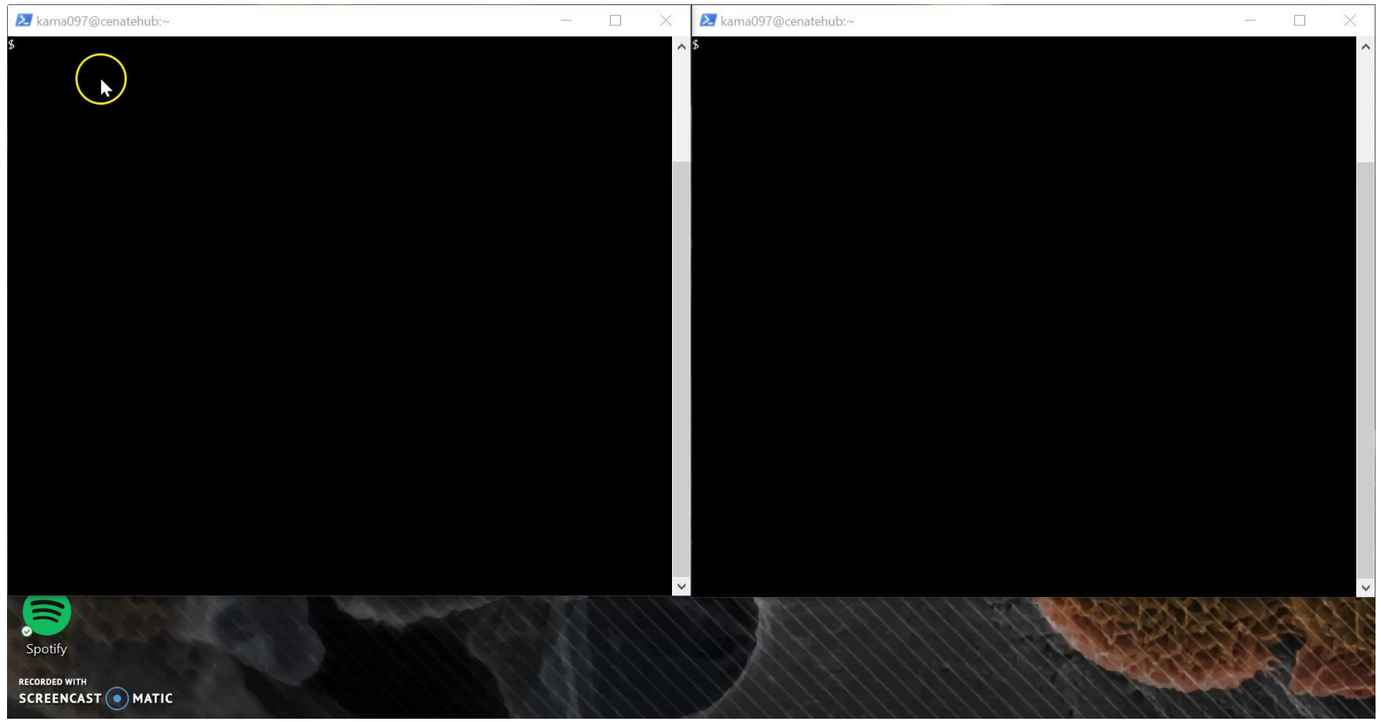
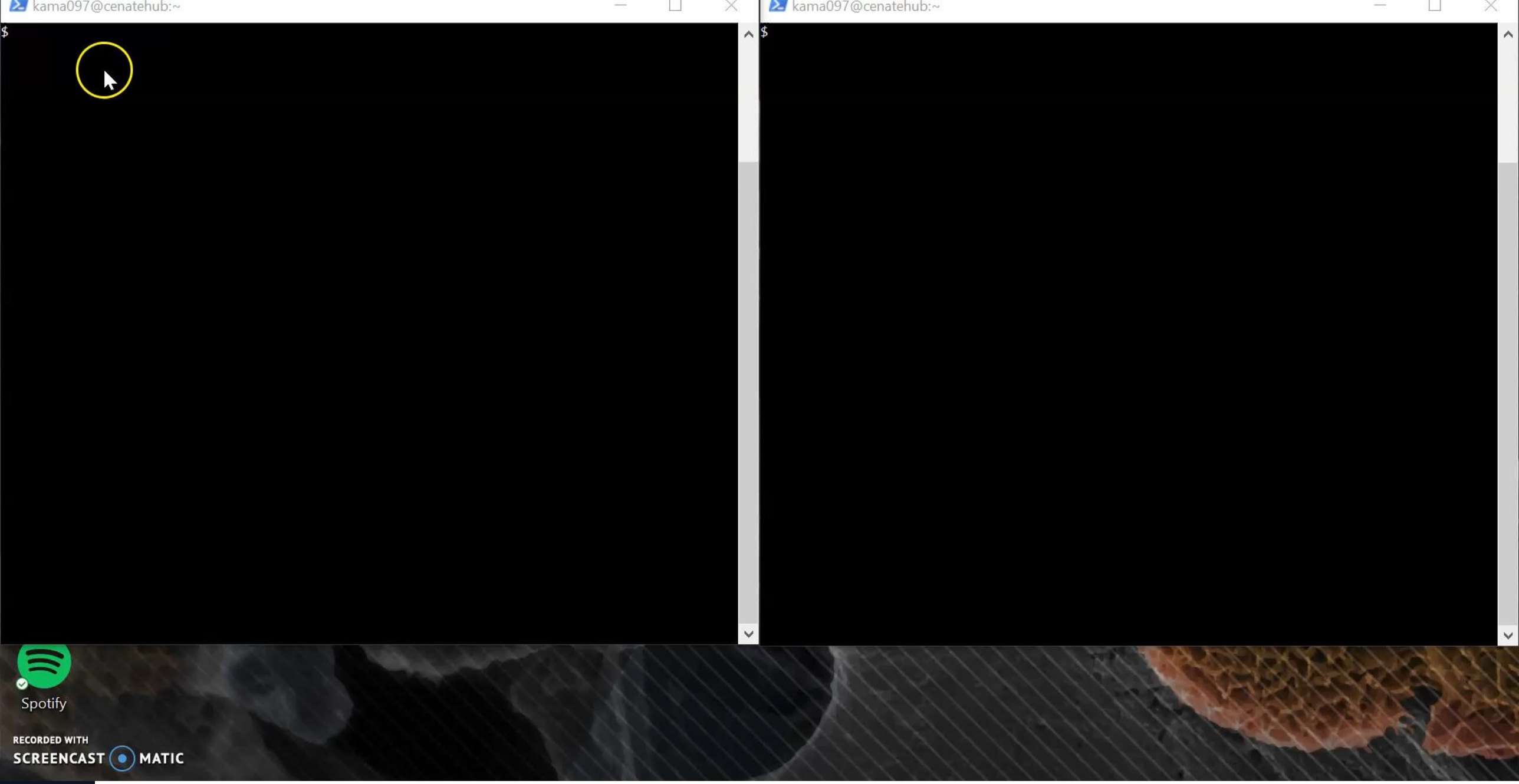
To Run First Fit Scheduler with Trace

```
>>> make clean
>>> ./configure --enable-trace
>>> make && make install
>>> mcl_sched -s fffs -p ff &
>>> cd test
>>> make mcl_gemm
>>> ./mcl_gemm -r 8092 -w 16
```

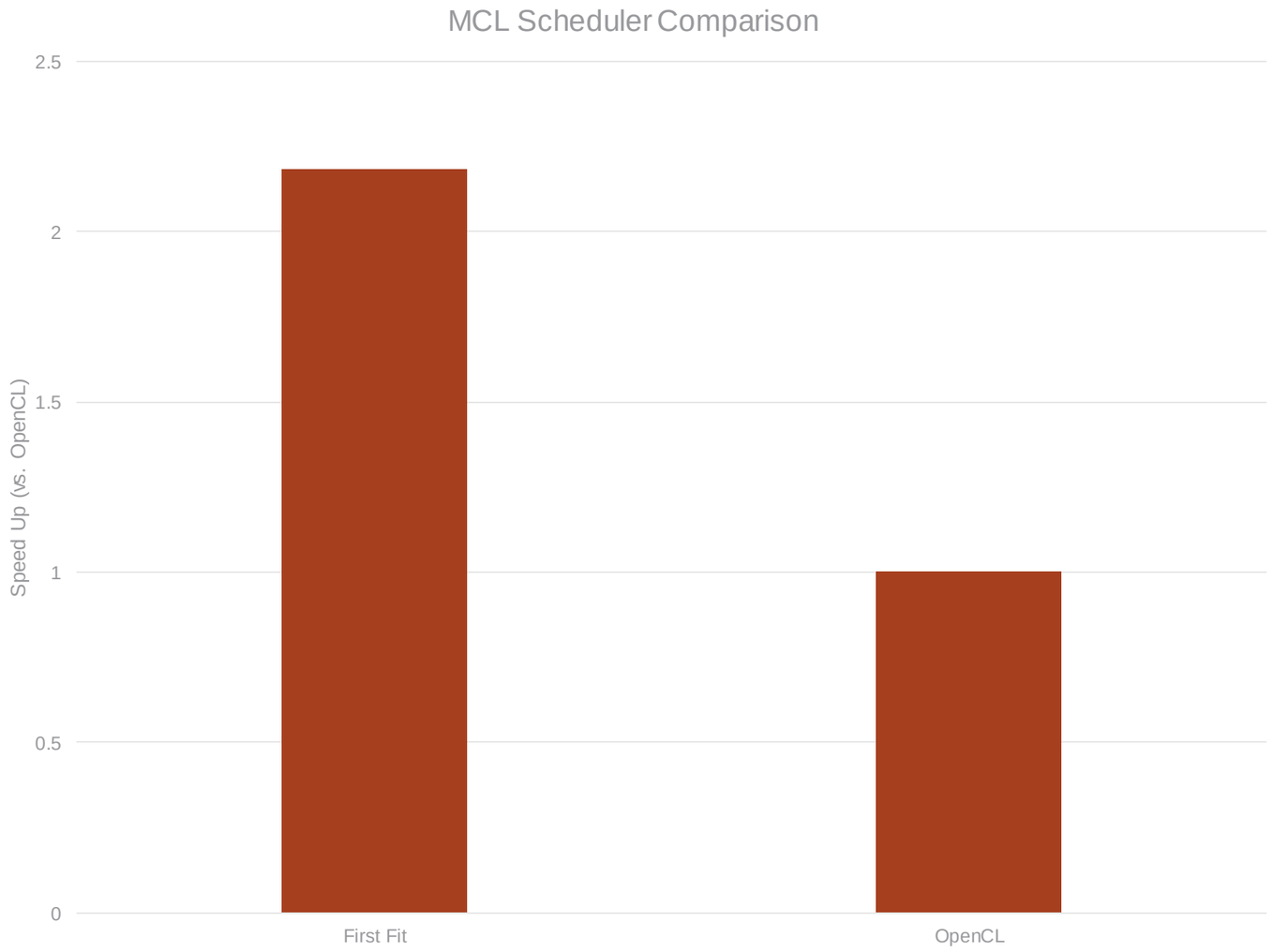



kama097@cenatehub:~
$
kama097@cenatehub:~
$
Spotify
RECORDED WITH
SCREENCAST MATIC

First Fit Scheduler Results

DGEMM Benchmark:
- 64 X 64 matrices
- 1024 tasks

Nvidia DGX-1 System:
- 2 Intel Xeon CPUs
- 8 Nvidia Pascal GPUS
- 256 GB memory + 16 GB per GPU memory



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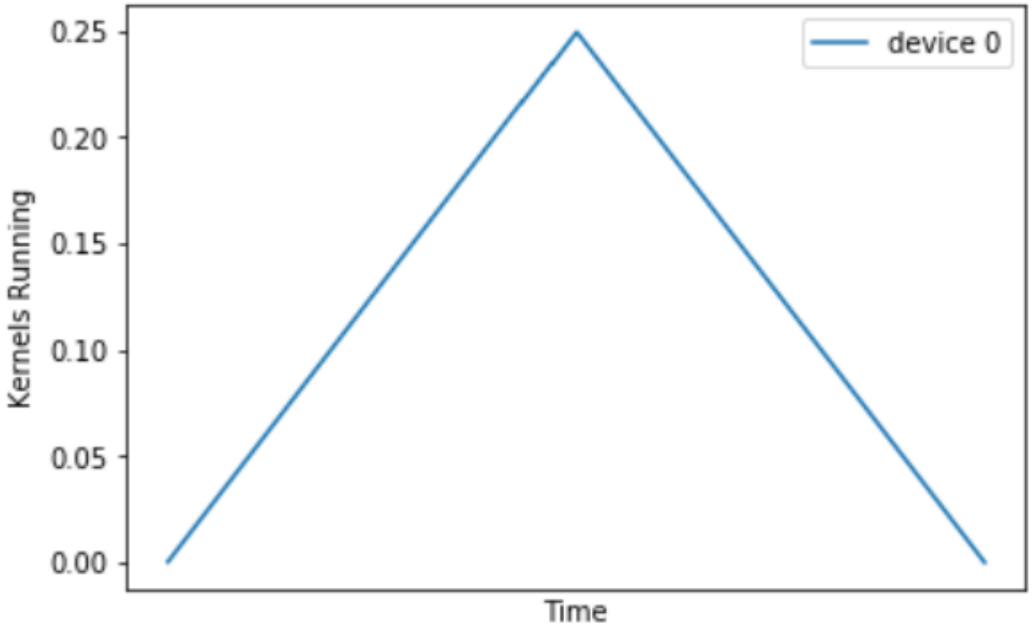
Scheduler Trace



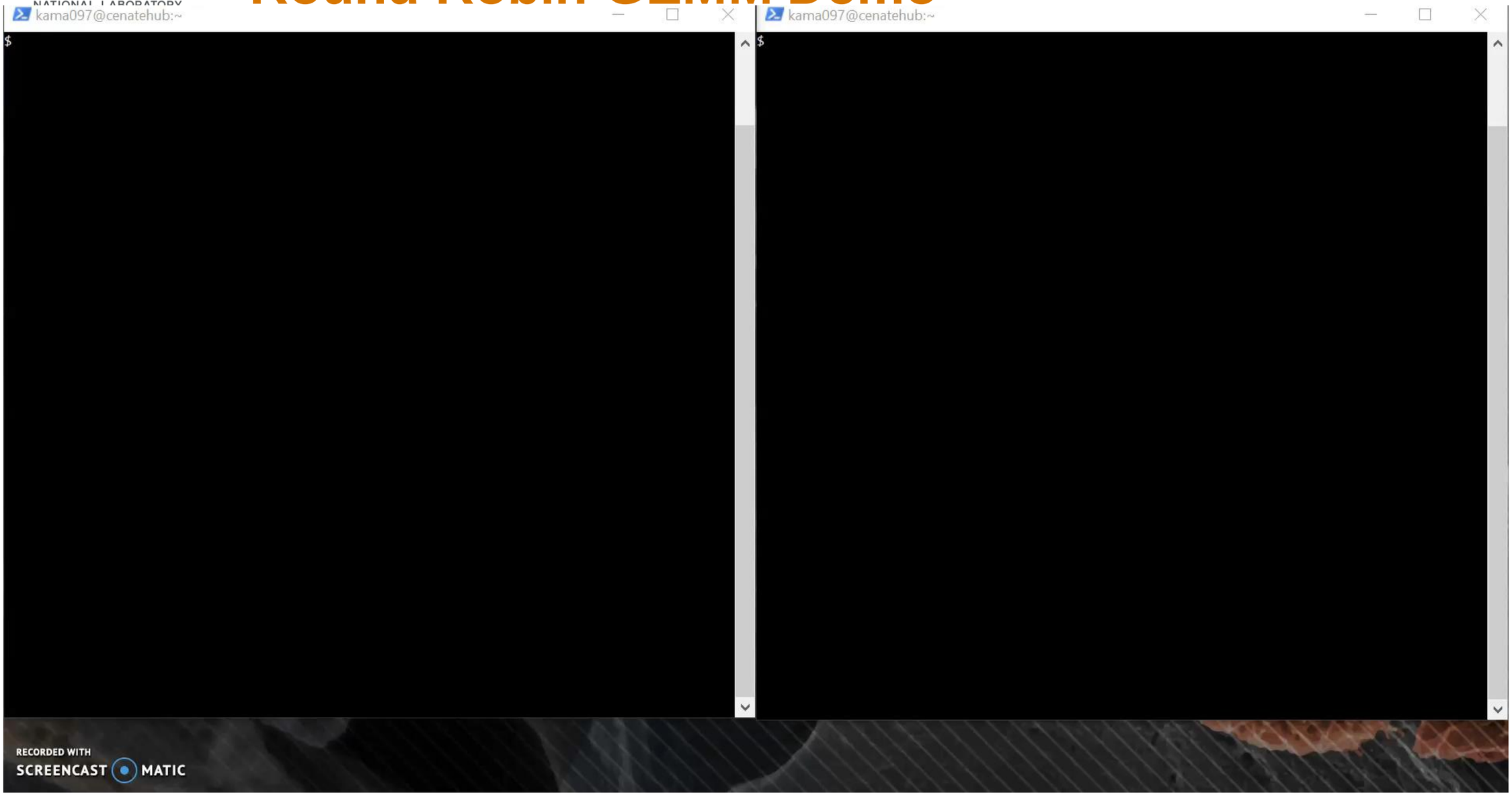
- MCL scheduler trace can be enable by compiling with `—enable-trace`
- Allows us to visualize memory use, processing element use, and number of busy tasks on each device
- Where are the rest of the GPUS?
  - Some GPUs are heavily utilized; rest of the GPUs are under utilized

Round Robin Scheduler

- Schedules tasks to devices in a circular manner
- Maintains a queue of devices.
  - Each incoming task gets assigned to the next device in the queue that is compatible
  - That device is moved to the back of the queue
- Typically achieves good full-system utilization

```
>>> mcl_sched -s fffs -p rr &
```

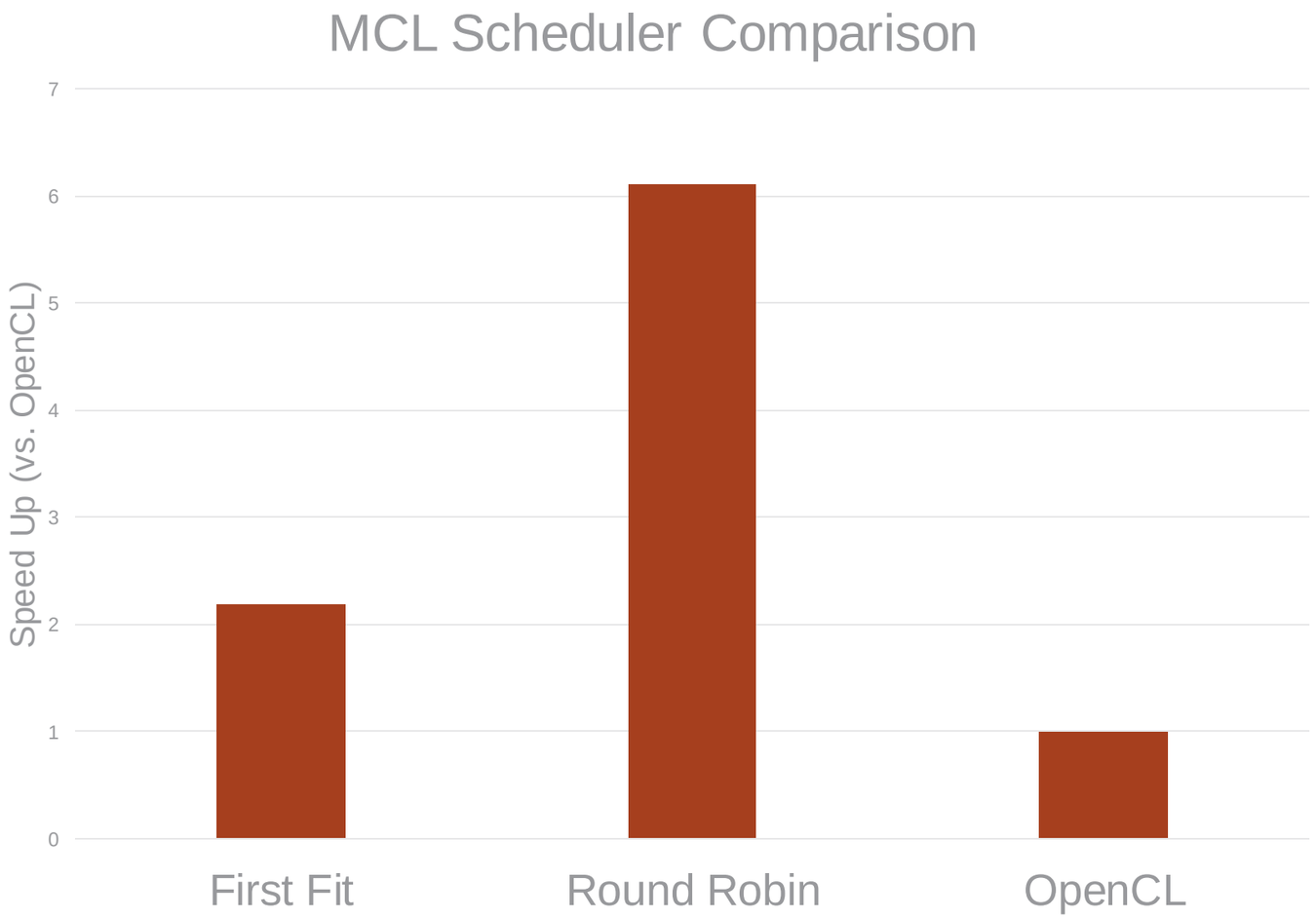
Round Robin GEMM Demo



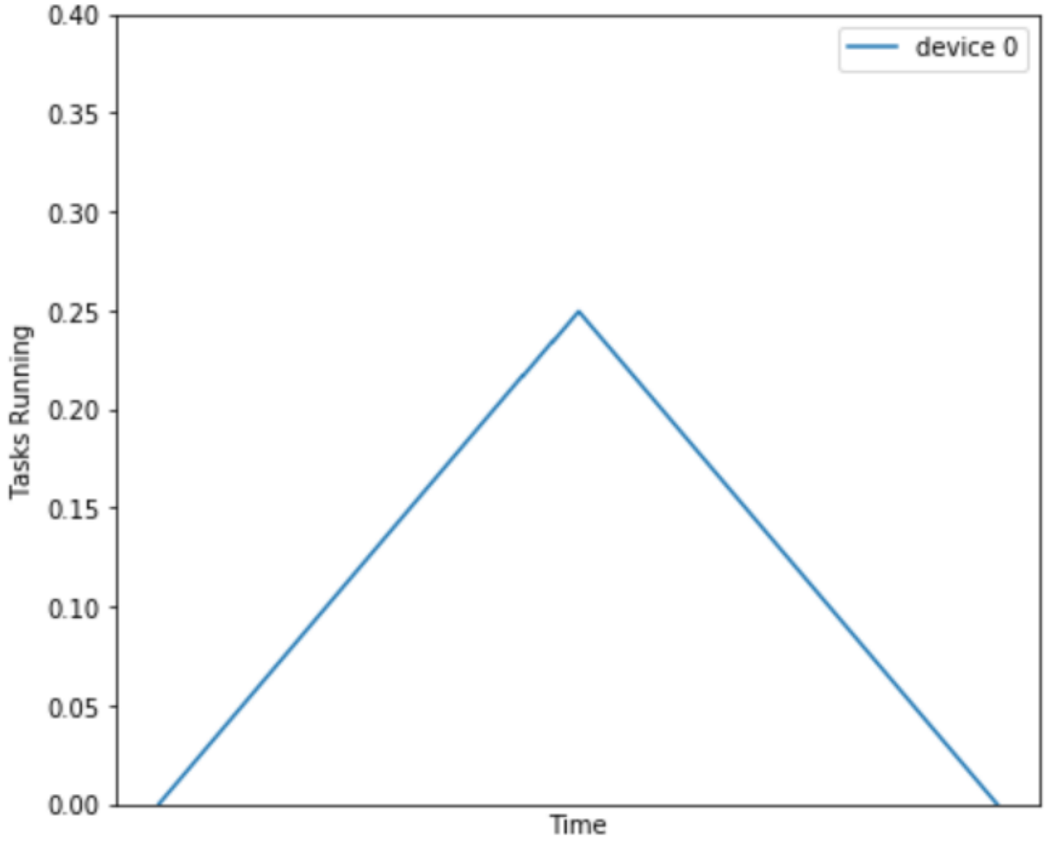
Round Robin Scheduler Results

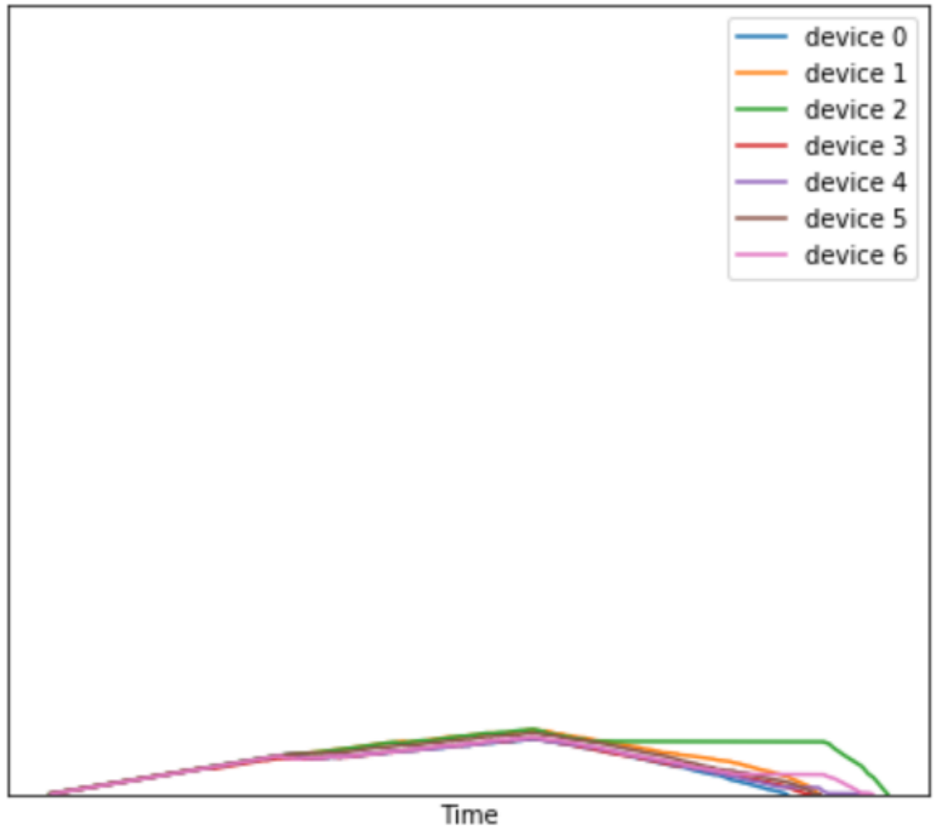
DGEMM Benchmark:
- 64 X 64 matrices
- 1024 tasks

Nvidia DGX-1 System:
- 2 Intel Xeon CPUs
- 8 Nvidia Pascal GPUS
- 256 GB memory + 16 GB per GPU memory



Round Robin vs. First Fit





The load that is just on GPU 0 in the First Fit scheduler is now balanced

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Another Problem

- Breadth First Search
  - Graph is represented in two arrays: one storing an adjacency list, one storing the offsets of each vertex – read only data structure
  - On each iteration i:
    - ✓ The frontier has an array of vertices that distance I from the source
    - ✓ The cost array has best known cost for each vertex
    - ✓ "Explore" indices that are i+1 away from the source using the frontier array
- Each iteration is a new task reusing the same data from the previous tasks
- Memory transfers dominate compared to computation

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Breadth First Search

- Breadth First Search Code per iterations:

```
mcl_handle* hdl = mcl_task_create();
mcl_task_set_kernel(hdl, kernel_path, "BFS", 8, "", 0x0);
mcl_task_set_arg( hdl, 0, (void*)frontier, ..., flags);
mcl_task_set_arg(hdl, 1, (void*)edge_offsets, ..., flags);
mcl_task_set_arg(hdl, 2, (void*)edge_list, ..., flags);
...
mcl_task_set_arg(hdl, 6, (void*)&iters, sizeof(uint32_t), MCL_ARG_SCALAR);
mcl_exec(hdl, pes, lsize, MCL_TASK_ANY);
```

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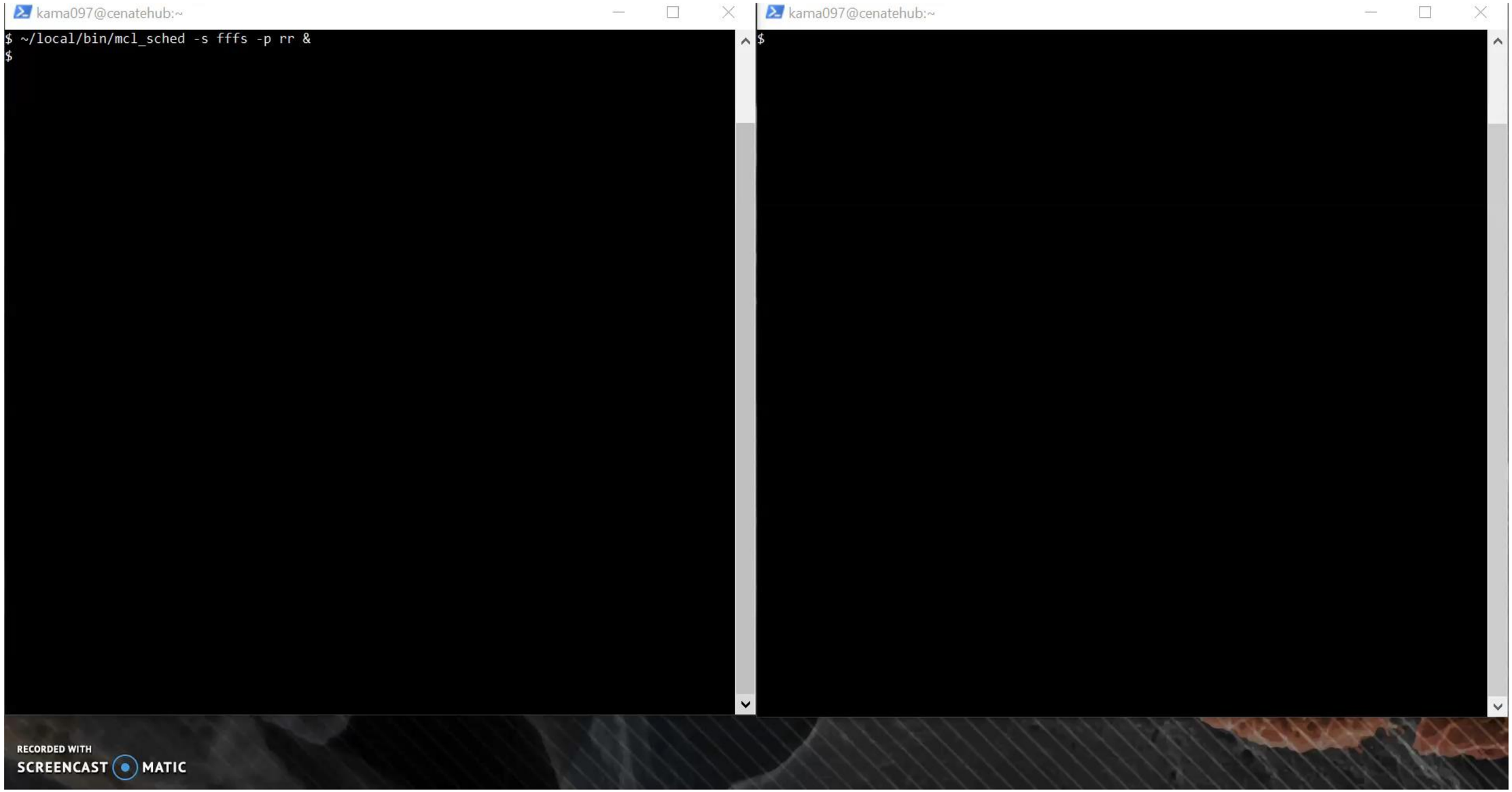
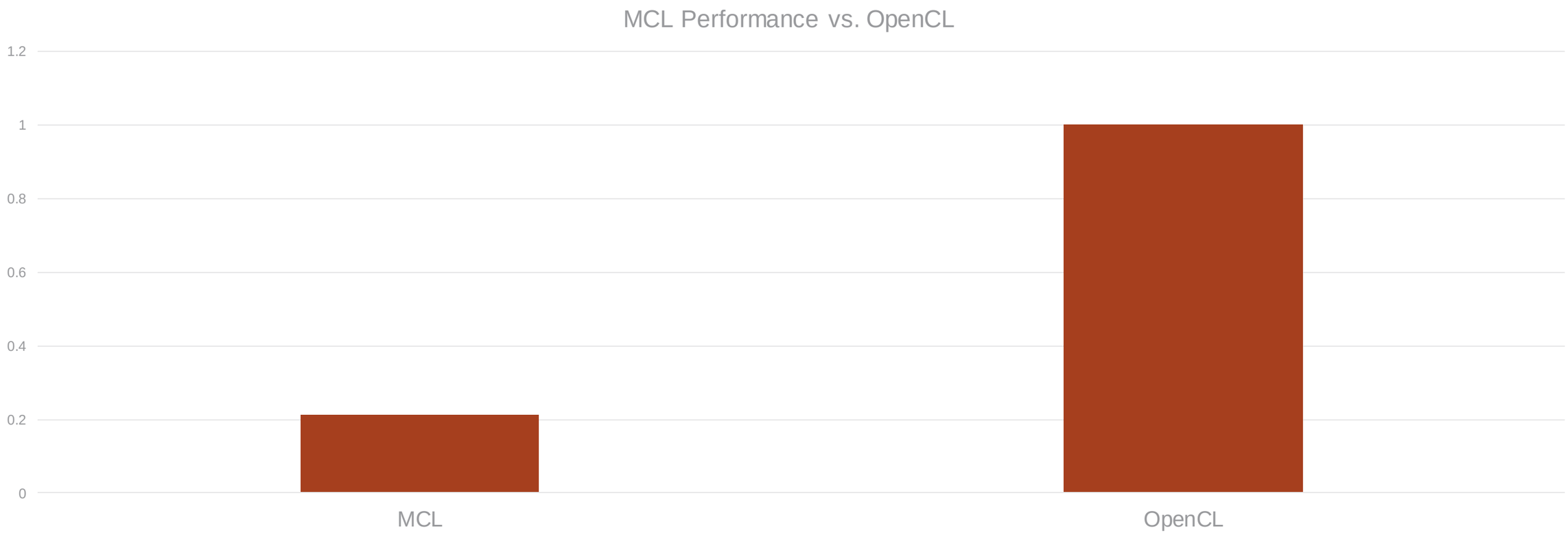
Running Breadth First Search



Breadth Fist Scheduler v1



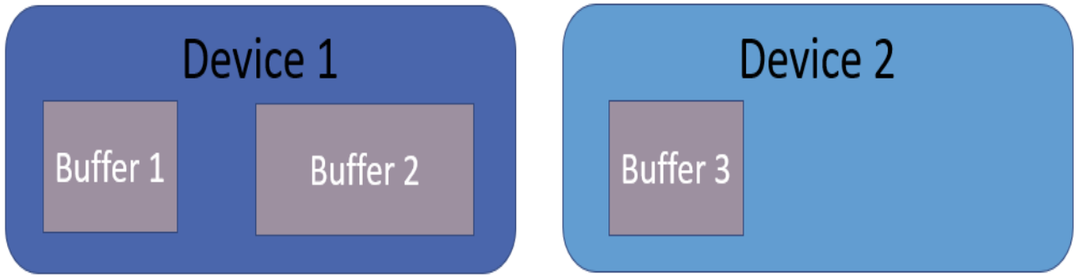
Why so slow?

- Graph is naively transferred for each iteration

MCL Resident Memory Module

- Allows persistent data to remain in device memory across tasks
- Orchestrates 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
…	…	…	…	…	…



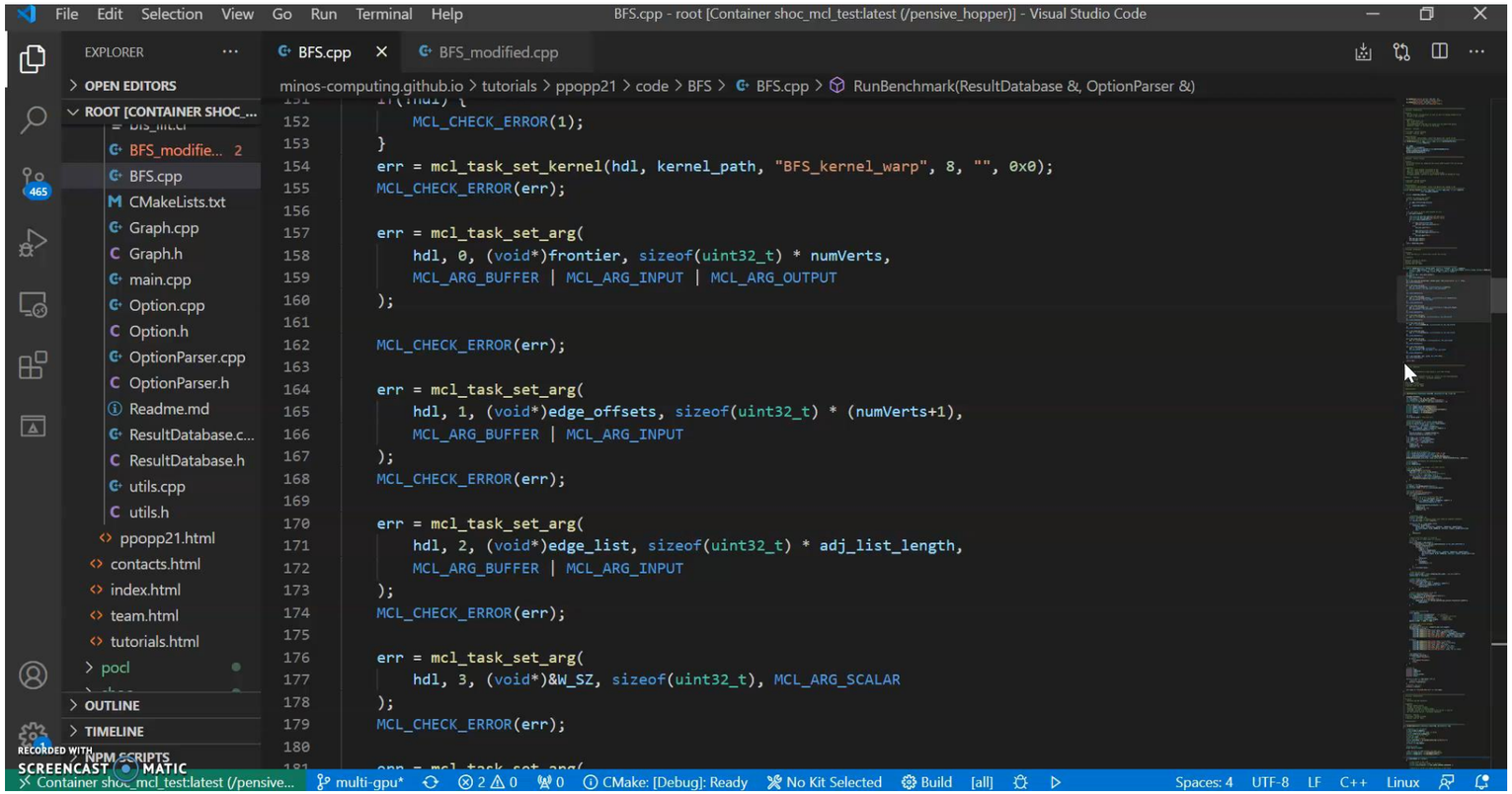
MCL_ARG_RESIDENT

MCL_ARG_INVALID

MCL_ARG_DONE

Code Modification Demo

- Show (live?) modifications from non-resident memory to resident memory.
- If you are following along in the code, this is the difference between BFS.cpp and BFS-modified.cpp



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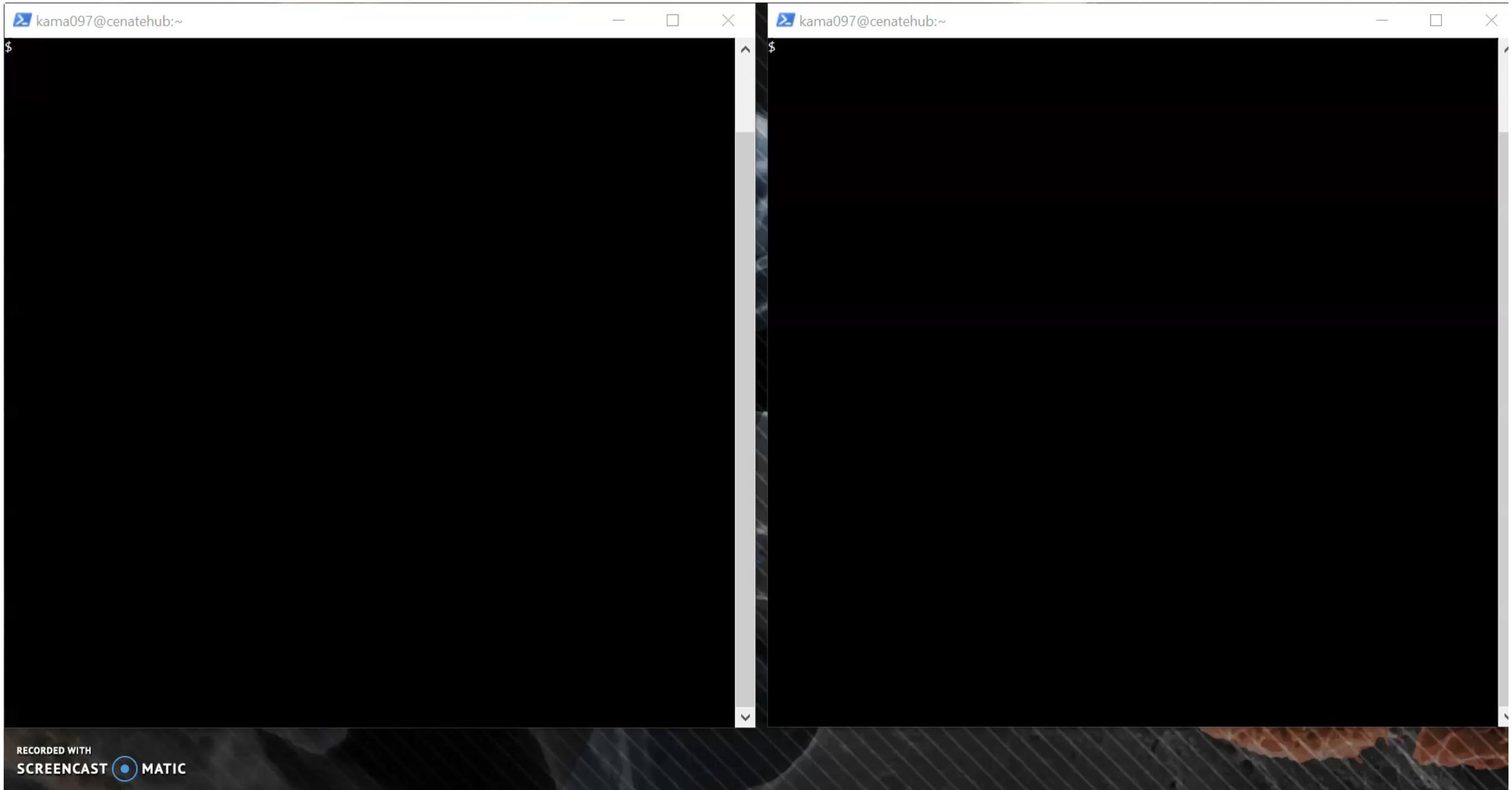
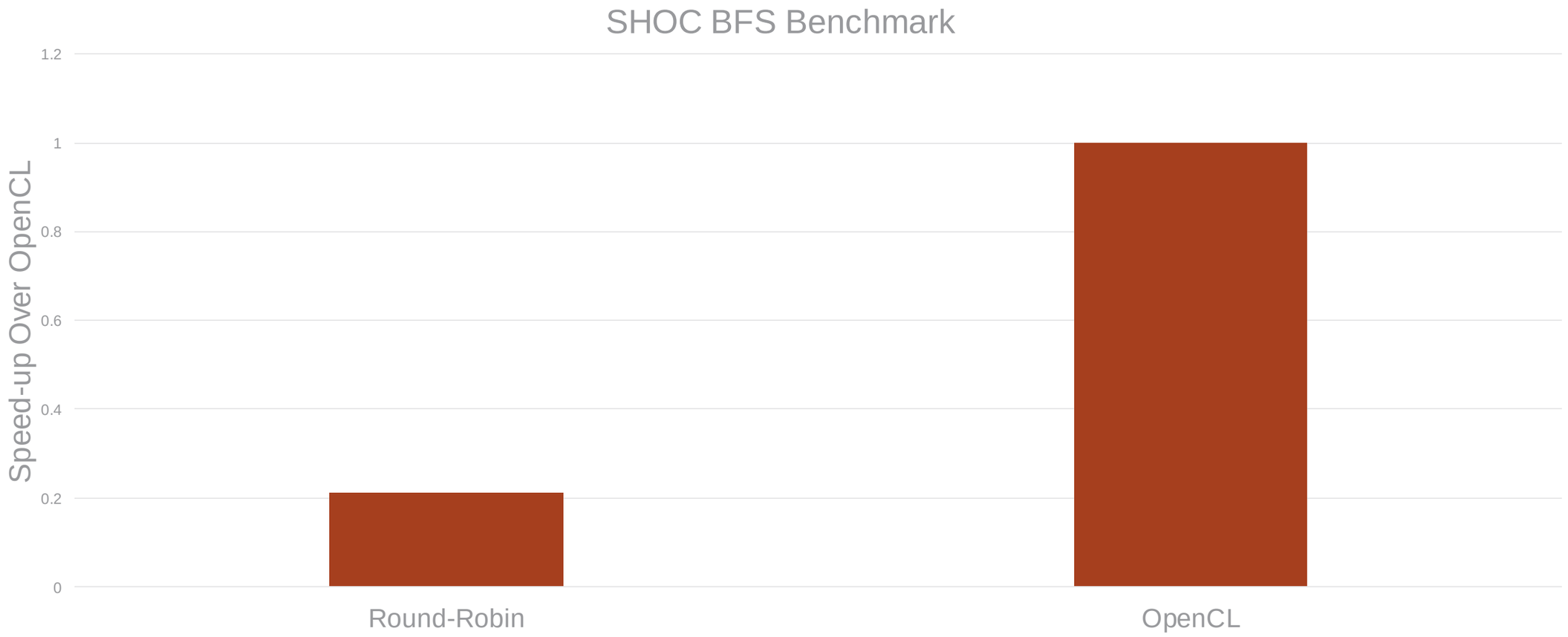
Running The New Code



Breadth First Search v2



Still so slow?

- Different frontiers must be transferred from other devices

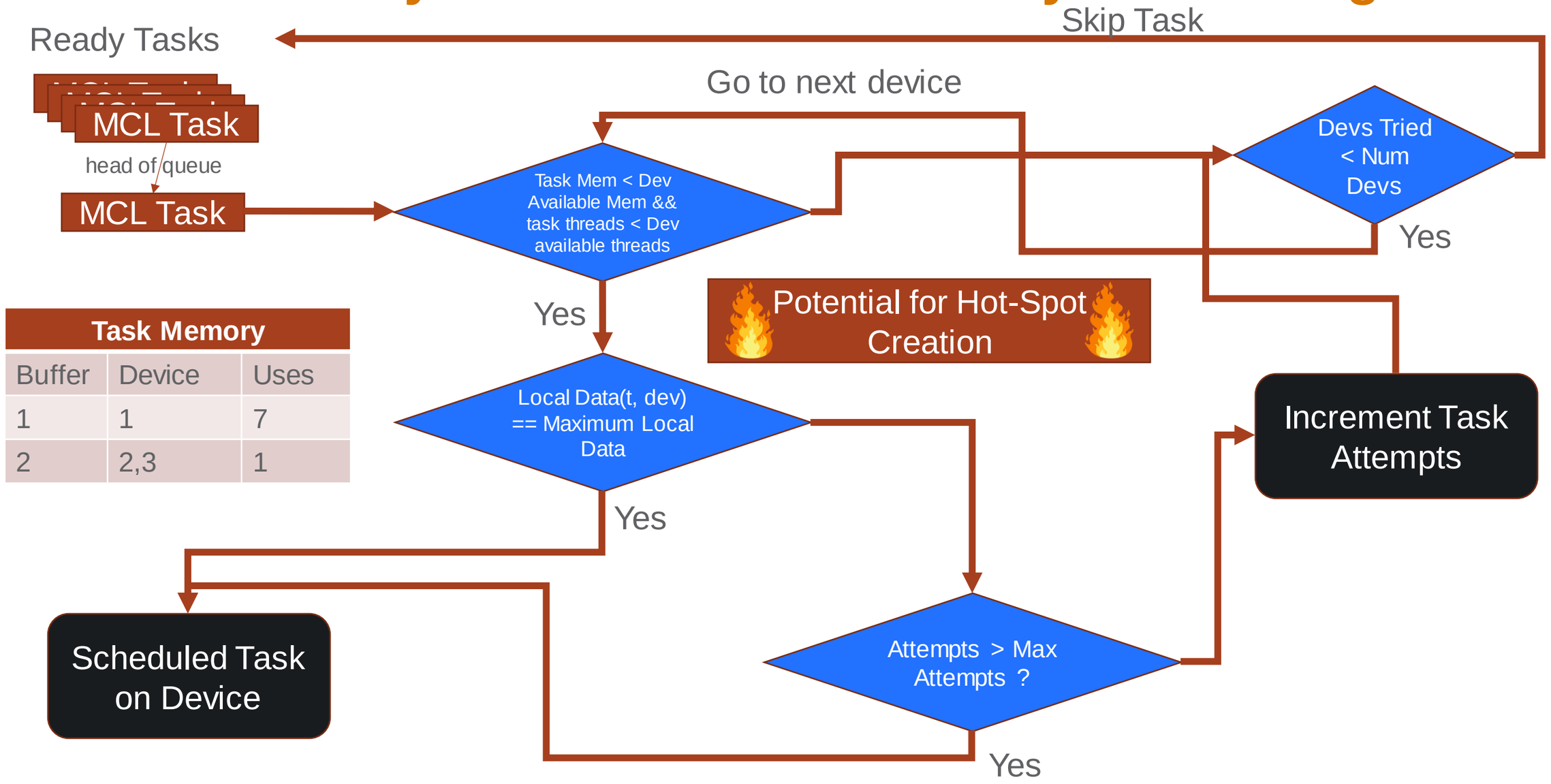
Locality Aware Scheduler: Delay Scheduling

- Scheduler needs to choose the optimal device based off where resident memory is located
- Delay Scheduling:
  - 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
  - "Local data" is required data that is currently on a device

Algorithm 1 Device Local Data

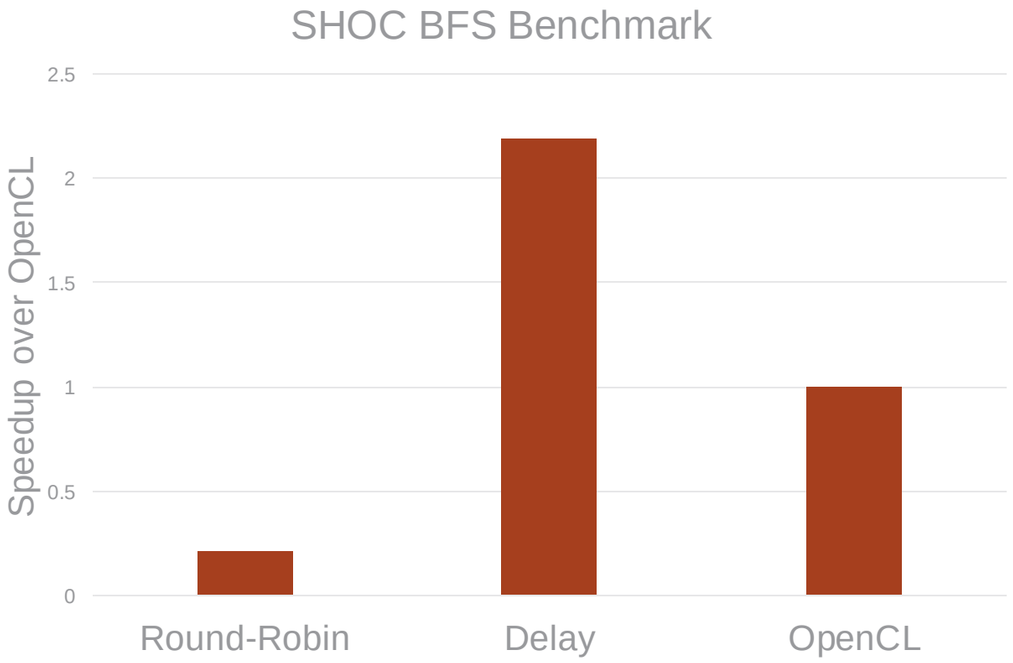
```
1: LocalData(Device δ, Task t):
2: bytes ← 0
3: for all β in t.buffers do
4:     if β in δ.data then
5:         bytes ← bytes + β.size
6:     end if
7: end for
8: return(bytes)
9: end LocalData
```

Locality Aware Scheduler: Delay Scheduling

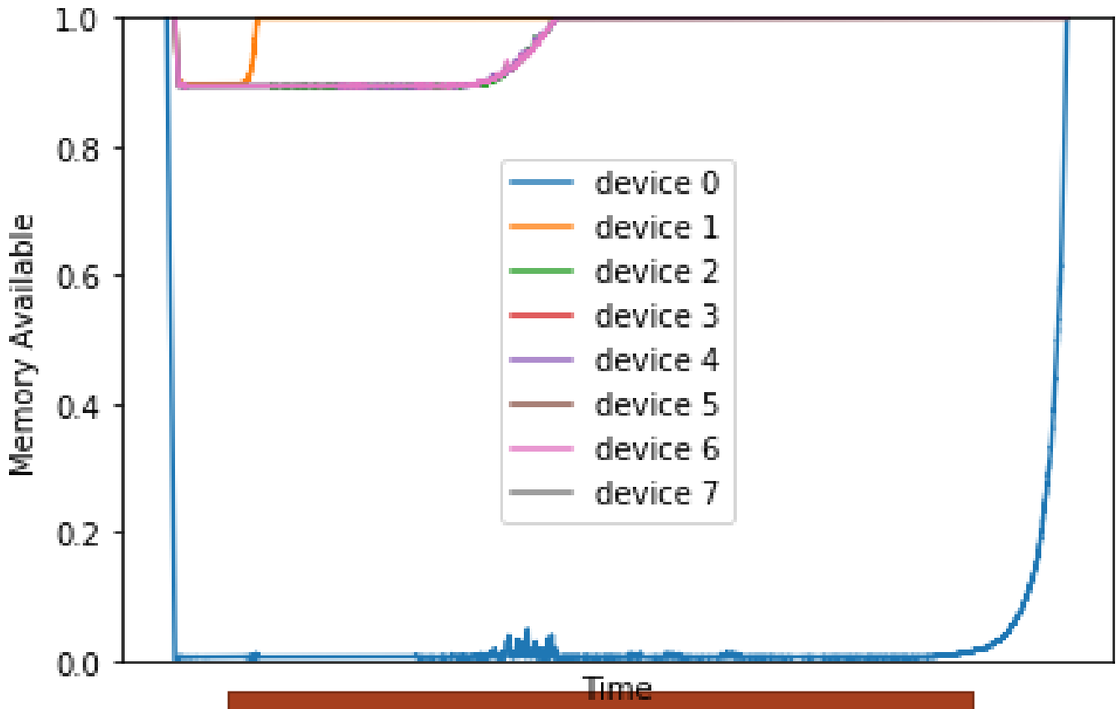


Task Memory		
Buffer	Device	Uses
1	1	7
2	2,3	1

Delay Scheduler Results



Performance Improves! But can we do better...?



MCL scheduler trace reveals that one device is heavily used

Hybrid Scheduler

- Needed to balance locality concerns against system utilization=
- Detects popular pieces of data to create replicas – done by changing how we calculate local data
- Hyperparameters are controlled with environment variables: MCL_SCHED_MAX_ATTEMPTS and MCL_SCHED_COPY_FACTOR

Algorithm 3 Device Local Data With Copy Factor

```
1: LocalDataCopyFactor(Device δ, Task t, CopyFactor γ):
2: bytes ← 0
3: for all β in t.buffers do
4:     if β in δ.data and DEVICES(β) ≥ log_γ TASKS(β) then
5:         bytes ← bytes + β.size
6:     end if
7: end for
8: return(bytes)
9: end LocalDataCopyFactor
```

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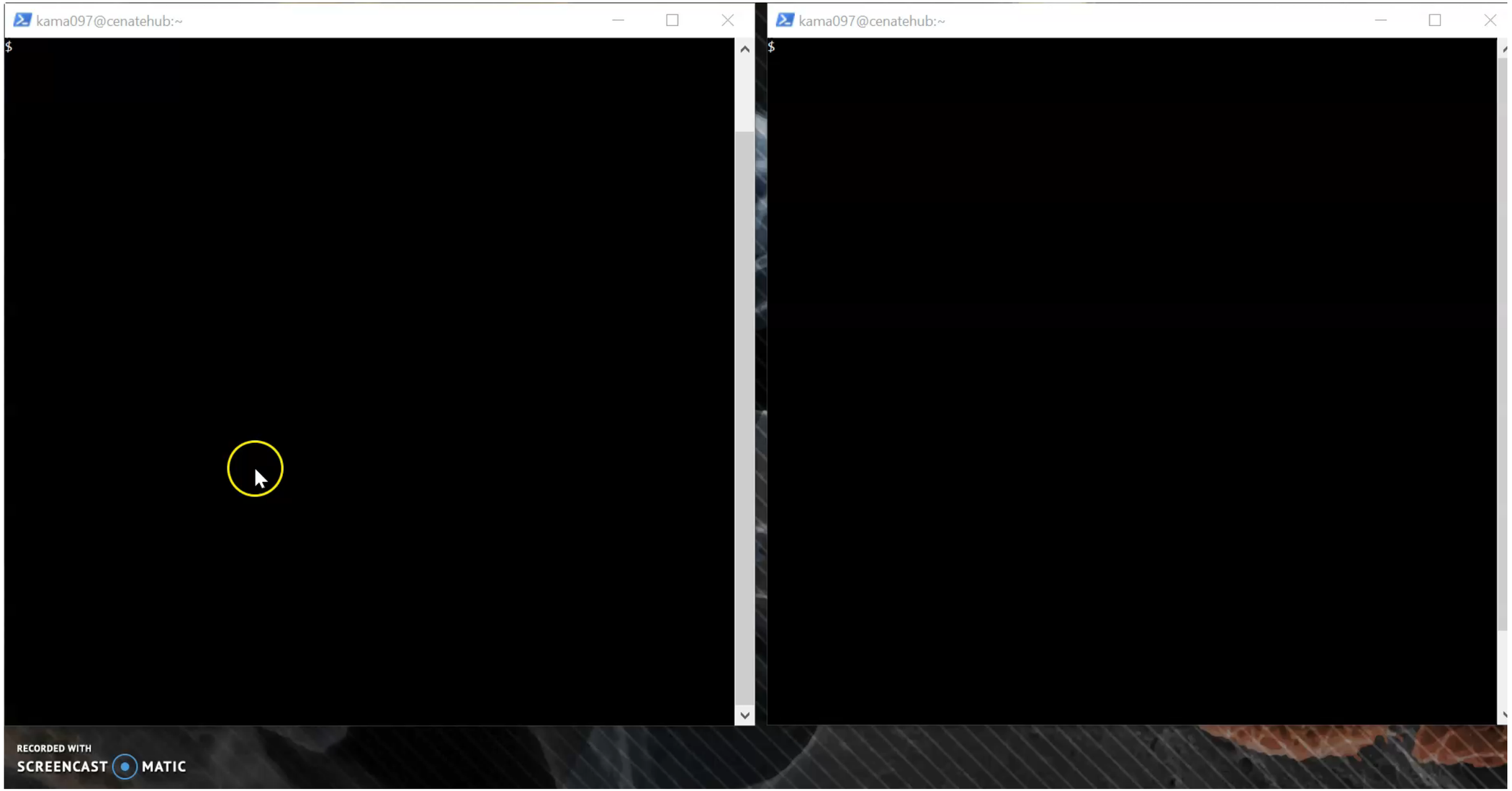
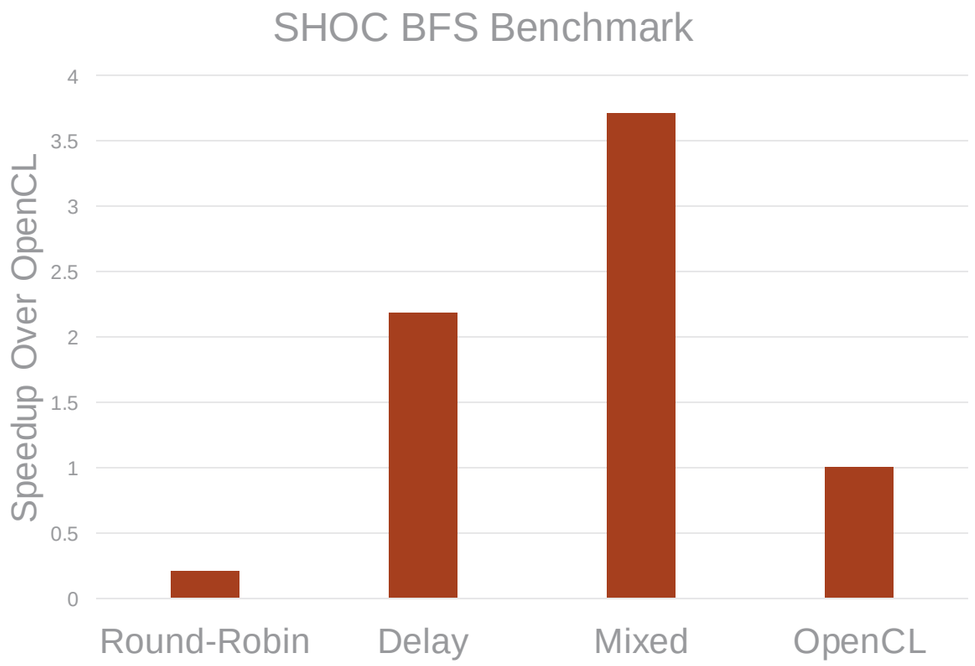
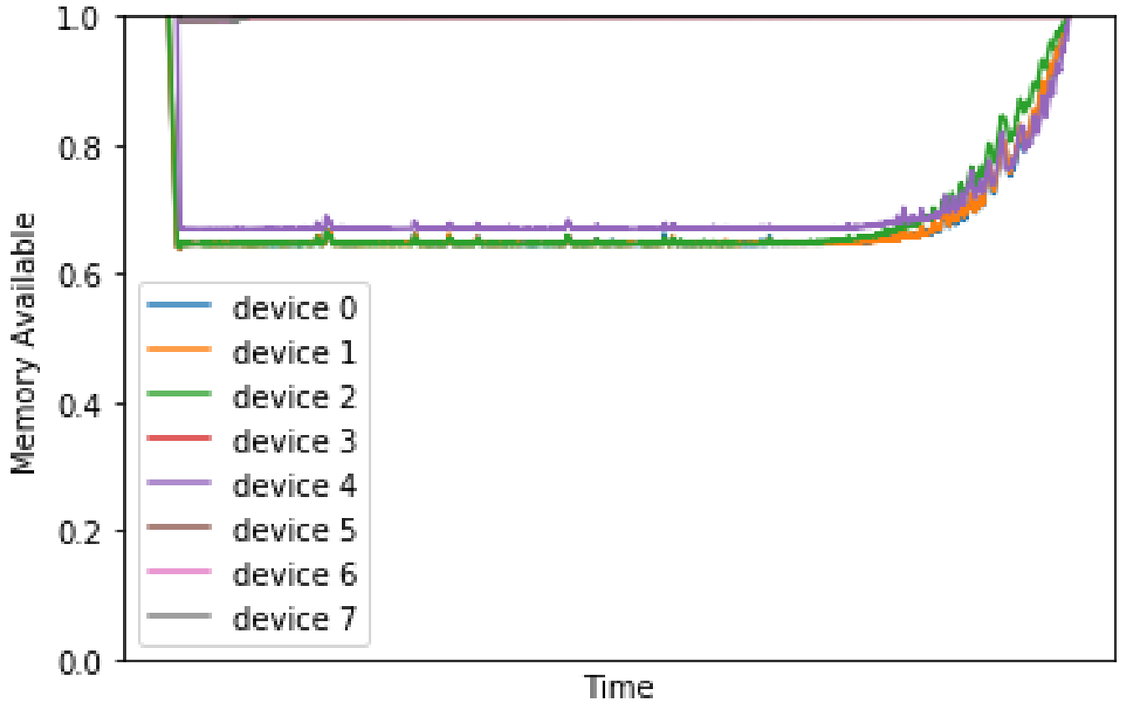
BFS – Final Version Demo



Breadth First Search Results

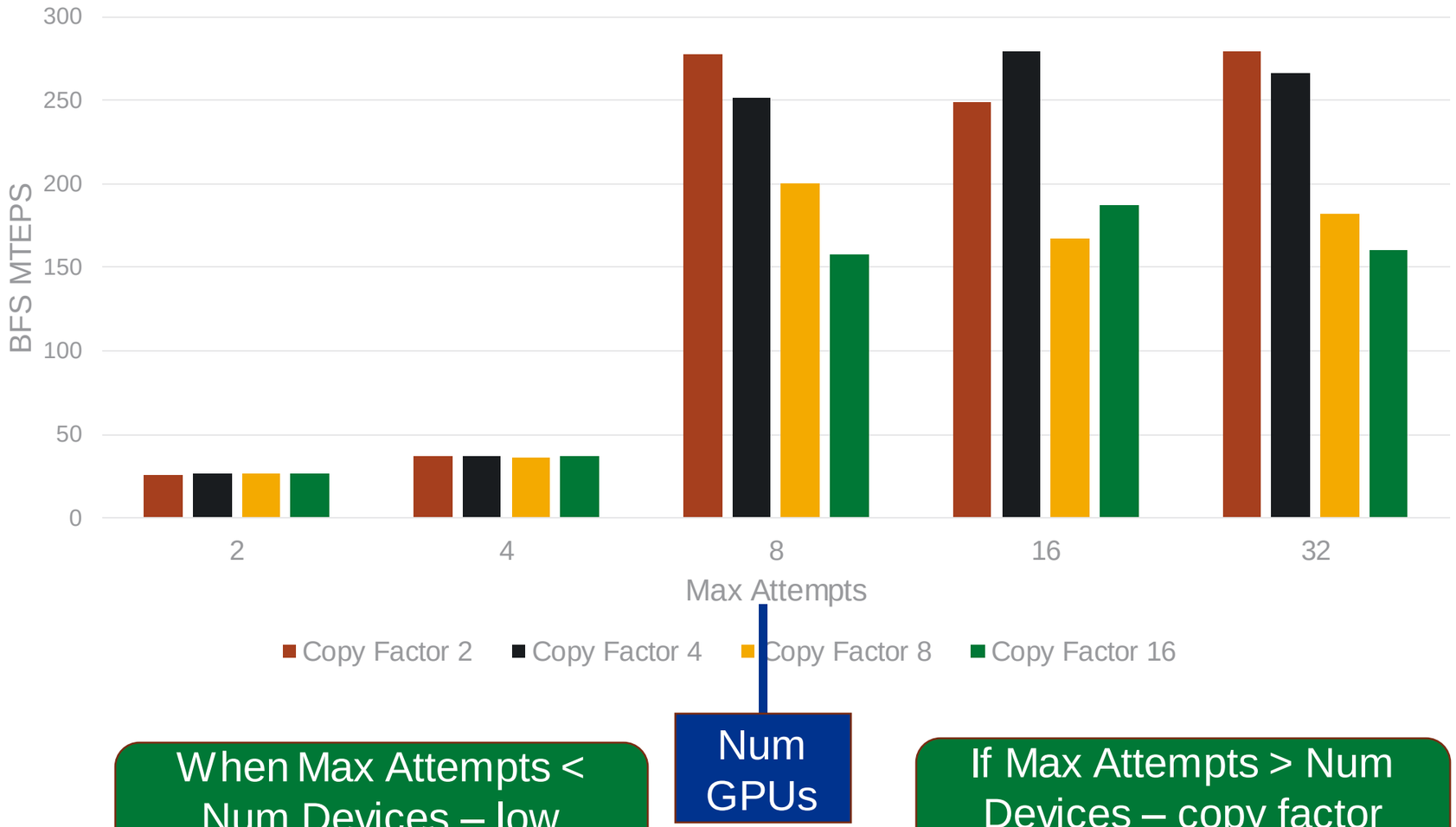




Best performance!

MCL scheduler trace reveals balance among first 4 devices

Effect of Hyperparameters on Performance



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

When Max Attempts < Num Devices – low performance

If Max Attempts > Num Devices – copy factor dominates performance

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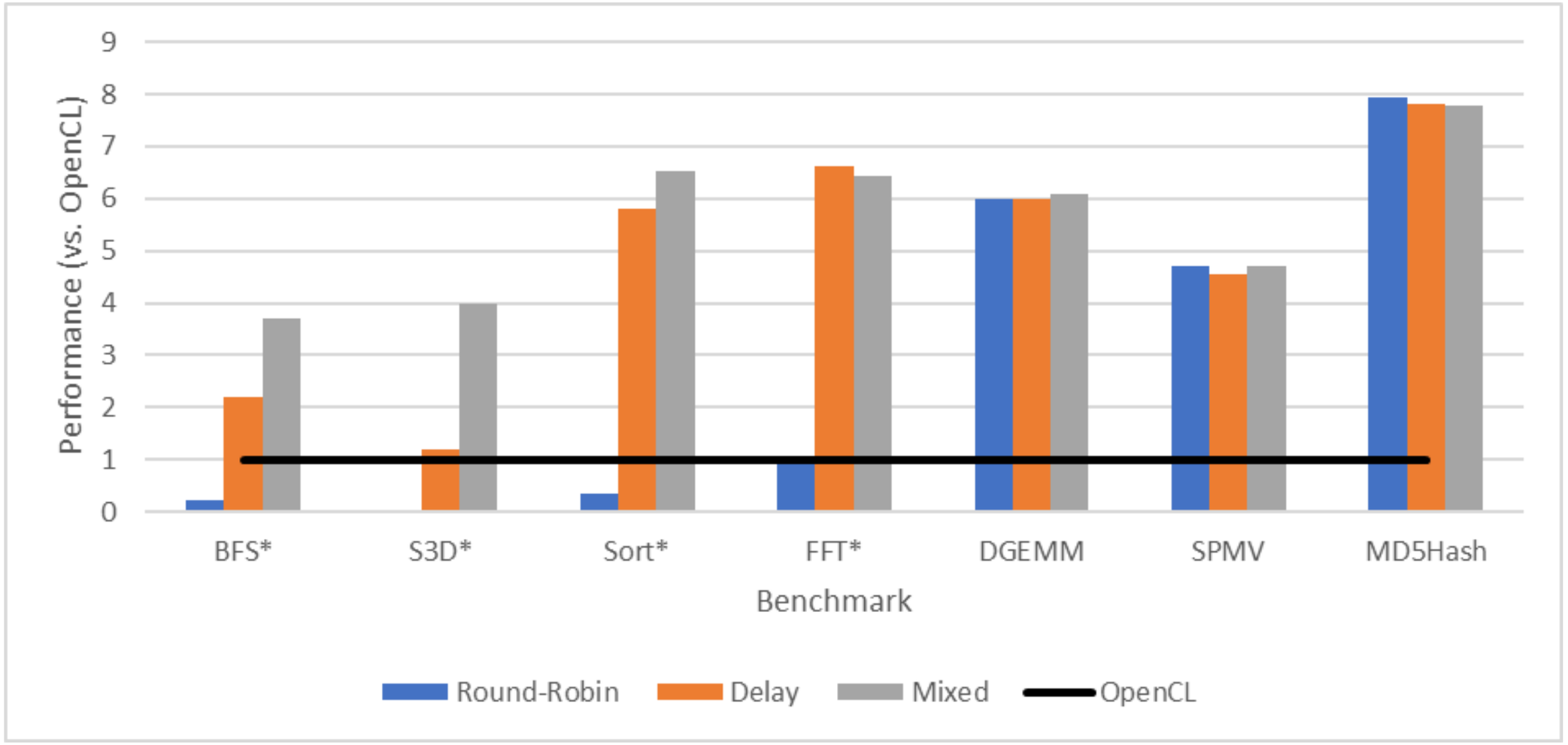
Full Scheduler Comparison



Writing Your Own Scheduler

- Certain applications require specific requirements from the scheduler
- `init(mcl_resource_t* r, int ndevs)` – initialize representation of resource and any other representation needed
- `find_resource(sched_req_t r)` – Find the device r should run on. Also, set `r->dev` to the assigned device
- `assign_resource (sched_req_t r)` – Allocate resources in resource to the scheduled device
- `assign_resource (sched_req_t r)` – Release resources in resource model from scheduled device

Eviction Policy

- 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

Upcoming Work – Multi-Application Scheduling

- Different applications needs to be run in a pipeline
  - A physics simulation -> a data analysis application to detect events
  - A MD-simulation guided by reinforcement learning
  - Combustion Simulation + Machine Learning
  - Etc.
- Currently in 2 ways:
  - Modify exiting application -> specific to each application, lots of extra work,
  - Leverage Files

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Shared Memory Design

- Leverage POCL to create an additional OpenCL interface that allows buffers to be shared
- Scheduler is aware of where necessary data is even across applications
- The same data does not have to transferred again in different applications
- Patterns Supported:
  - Scratch Pad
  - Producer-Consumer
  - Circular Buffer

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Pipelining Applications Code

- Experimental Application
  - Producer performs an arbitrary number of floating-point operations on a buffer
  - Consumer reads producers buffer and performs its own operations
- Comparisons:
  - MCL Shared memory
  - OpenCL – File
  - OpenCL – POSIX Shared Mem + Pipe (Statically Partitioned GPUs)

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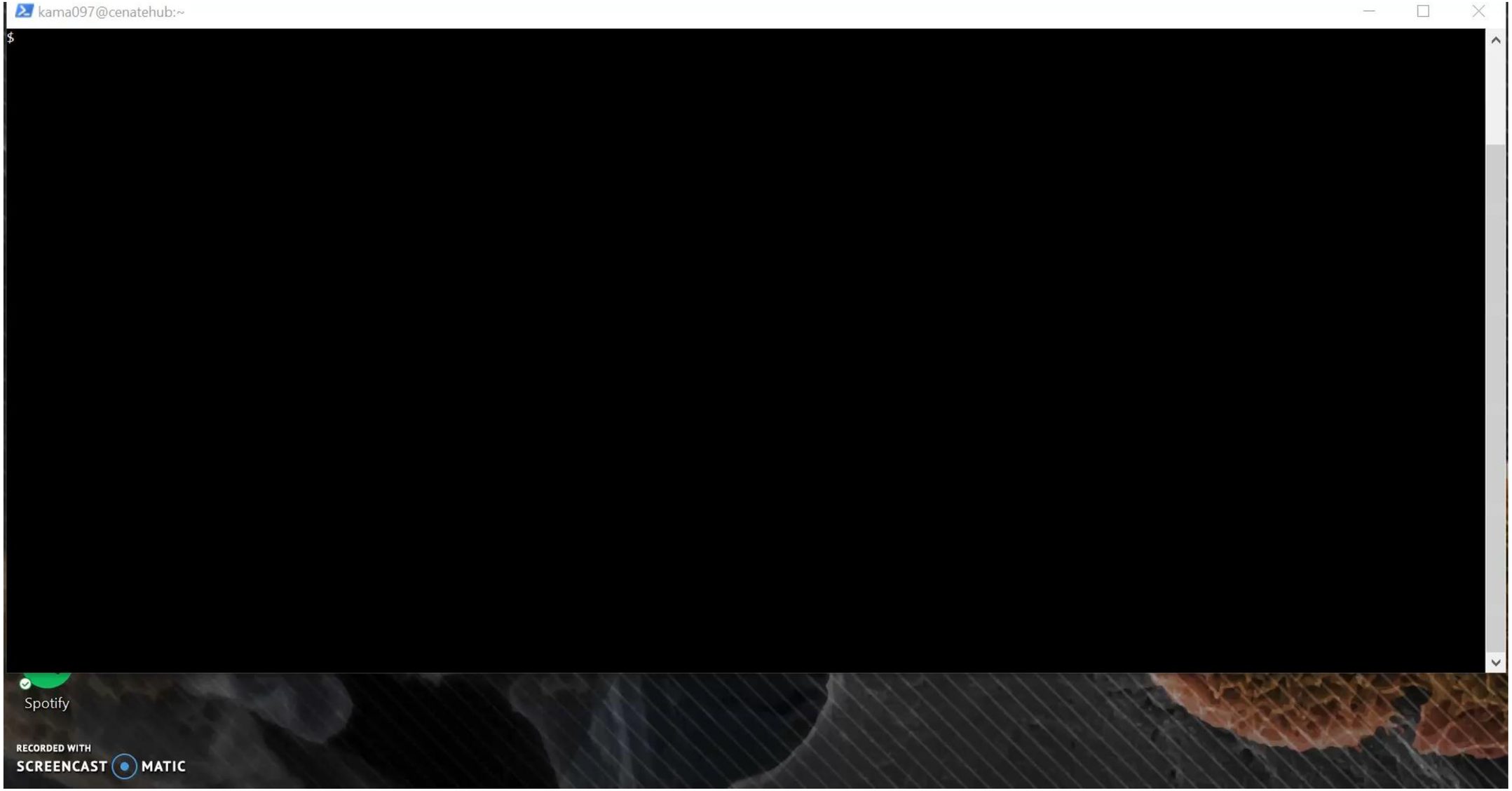
Pipelined Applications (Example)



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Thank you