OpenMP®

SC24 Booth Talk Series

Enabling Graph Execution with OpenMP Taskgraph

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ascender

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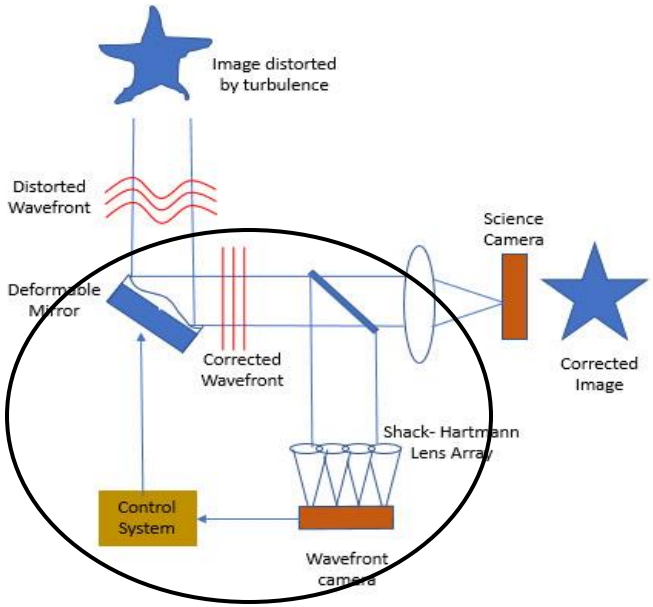
HiPART

Motivation – Modern CPS

- ➔ Real-time CPS (Cyber-Physical Systems) requiring tight time constraints: autonomous cars, astronomical telescopes (e.g., Adaptive Optics), etc.
- ➔ High performance requirement
- ➔ Constantly executing the same workflow

Adaptive Optics in Astronomy



credit: andor.oxinst.com

Illustrative Code of AO

```
int operationLoop(…) {
  #pragma omp parallel
  #pragma omp single
  {
    #pragma omp task depend(out:op1)
    calibration(…)

    #pragma omp task depend(in:op1)
    fillIntensities(…)

    // other computations

    #pragma omp task depend(in:op_x)
    commandActuators(…)
  }
}
```

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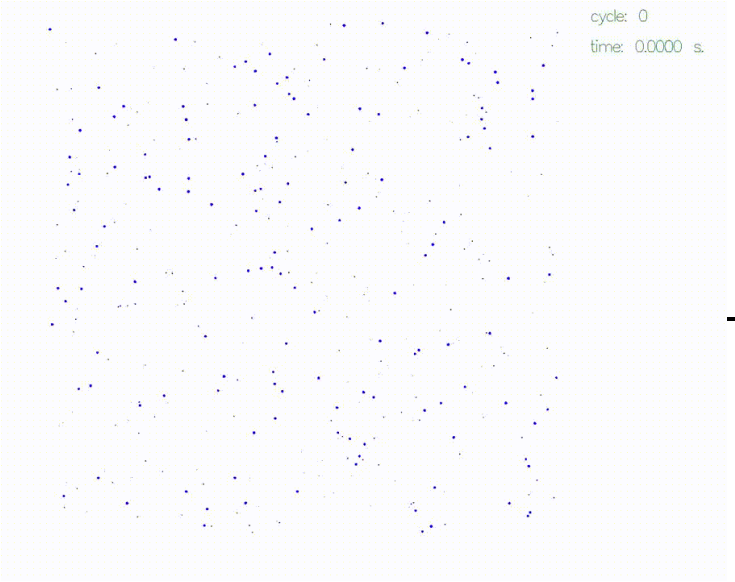
Motivation – Iterative Applications

- ➔ Simulations (Gauss-Seidel, N-body, etc) and linear system solvers such as Cholesky decomposition
- ➔ Performance requirement
- ➔ Same execution is replayed multiple times

Illustration of Nbody Simulation



credit: en.wikipedia.org

Example Code of Nbody

```
#pragma omp single
for (timestep < IterNumber):
  for (each particle):
    #pragma omp task depend(in:op_x)
    {
      calculate_force(…)
    }
  }
}
```

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Objective – Performance Enhancement

Taskgraph – a graph-based execution that allows us to

- **Reduce Overhead**
- **Lower the Contention on Shared Resource**
- **Easily Map to Other Programming Models**

Example Code of AO with Taskgraph

```
int operationLoop(…) {
  #pragma omp parallel
  #pragma omp single
  {
    #pragma omp taskgraph
    {
        #pragma omp task depend(out:op1)
        calibration(…)

        #pragma omp task depend(in:op1)
        fillIntensities(…)

        // other computations

        #pragma omp task depend(in:op_x)
        commandActuators(…)
    }
}
```

- The *single* thread records the tasks (computational functions) as nodes of the taskgraph
- When calling *operationLoop,* if a taskgraph is recorded, replay the taskgraph without to create the tasks
- Fewer accesses to task queues and no task dependency resolution overhead
- Potentially map the taskgraph to accelerators with OpenMP offloading and other PMs, e.g., CUDA

Outline

- How to use *taskgraph* construct, the expected syntax in OpenMP 6.0
- How are the graphs generated?
- Performance Evaluation with Host Tasks
- Interaction with other programming model (e.g., HIP and CUDA)
- Evaluating GPU graph created with *taskgraph*
- Conclusions

Taskgraph – Current Syntax[1]

#pragma omp taskgraph […]

- *graph_id(int)*
- *graph_reset(boolean)*
- *nogroup*
- *If (boolean)*

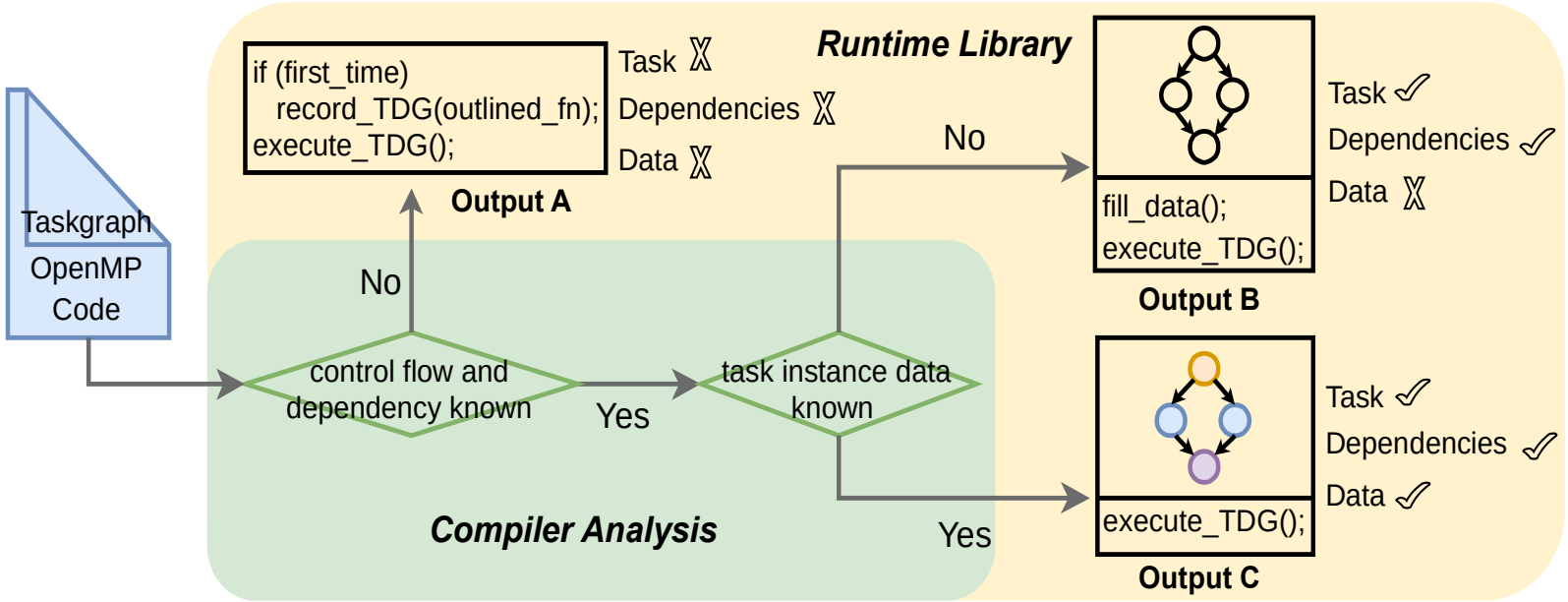
```
int operationLoop(num) {
  #pragma omp parallel
  #pragma omp single
  {
    #pragma omp taskgraph graph_id(num)
    {
        #pragma omp task depend(out:op1)
        calibration(…)

        #pragma omp task depend(in:op1)
        fillIntensities(…)

        // other computations

        #pragma omp task depend(in:op_x)
        commandActuators(…)
    }
}
```

- *graph_id(int)*: allows to instantiate different graphs with the same pragma, each associated with an ID. If implemented with a cache mechanism, could alternate the executions of different graphs.

- *graph_reset(boolean):* reset an existing graph. This allows users to overwrite an existing graph with a new set of tasks + data environment.

[1]: Refer to the technical report for more details: https://www.openmp.org/wp-content/uploads/openmp-TR13.pdf

Taskgraph – Graph Generation[2]



With compile-time analysis, depending on the available information, we either:

- Fully generate a graph with its task, data and dependencies
- Partially generate a graph, e.g., edges (dependencies) but not the tasks, as the task data is unknown
- Leave the generation of the graph to the runtime library, which incurs overhead at the first iteration

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[2]: Implementation details can be found at https://doi.org/10.1109/TPDS.2023.3284219

Evaluation – Set up[3]

	CPU (#cores)	RAM	OS	LLVM Version
Marenostrum 4	2 x Intel Xeon 8160 (48)	96GB	SuSE Linux	LLVM 15.0

- Synthetic kernel
- Heat diffusion (Gauss-Seidel)
- Nbody simulation
- Axpy kernel
- Dot product
- Cholesky decomposition
- HOG object detection
- NAS Parallel Benchmark

- OMP_NUM_THREADS=#Cores
- KMP_AFFINITY for core affinity
- Fix problem size, varying # tasks
- Optimization flag: -O3

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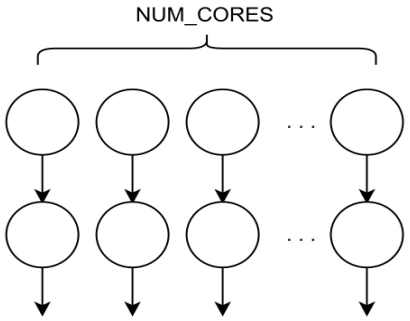
[3] : Applications available at https://github.com/yuchenle/tdg-benchs

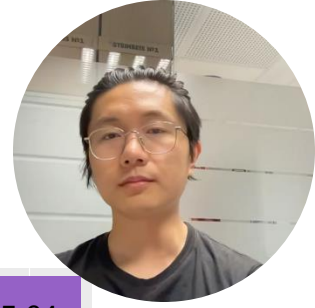
Evaluation – Overhead Reduction

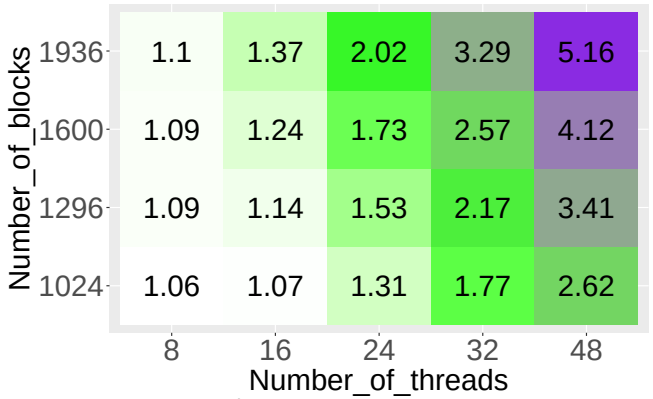
```
int deps[NUM_PROCS];
#pragma omp parallel
#pragma omp single
{
  START_TIMER;
  #pragma omp taskgraph
  {
    for (int i = 0; i < NUM_TASKS; i++) {
      index_depend = i % MAX_PAR;
      #pragma omp task depend(out:deps[index_depend])
      fn();
    }
  }
  END_TIMER;
}
```



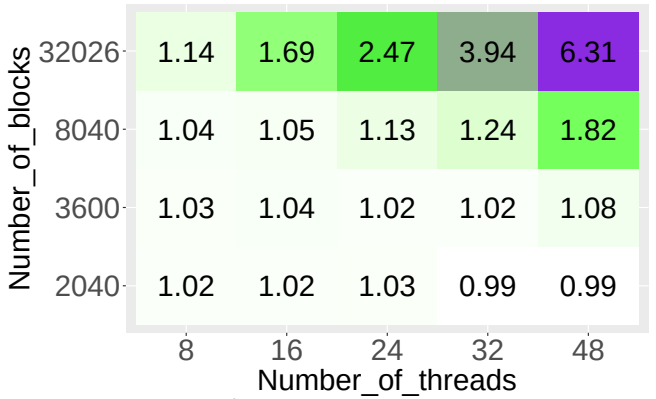
	1	10	10^2	10^3	10^4	10^5
GCC	0.2	0.2	0.25	11.8	345.4	**3582.6**
GCC + Taskgraph	0.2	0.1	0.2	0.2	29.4	**345.3**
LLVM	1.6	0.6	0.6	1.5	36.7	**466.2**
LLVM + Taskgraph	0.2	0.1	0.2	0.3	9.9	**132.2**

Evaluation – Speedup vs *task*

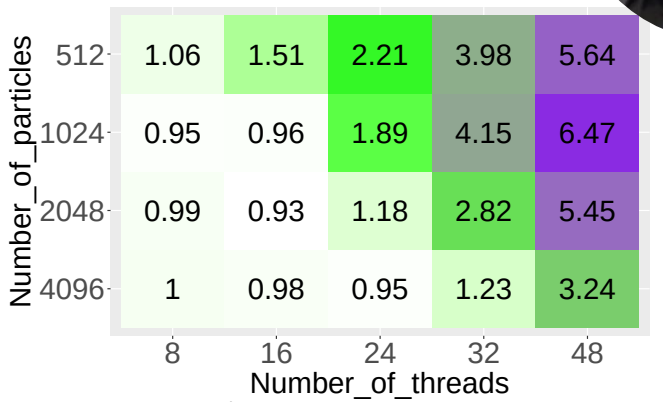




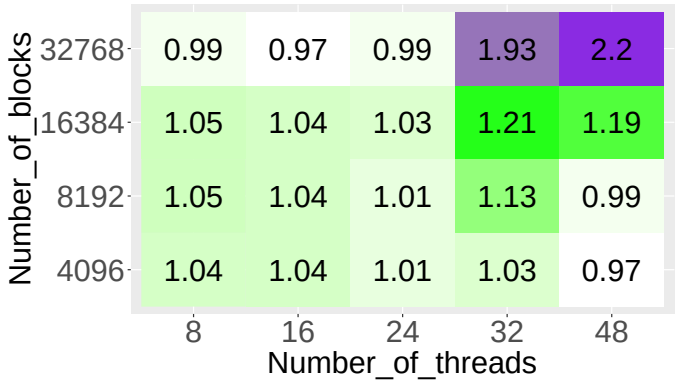
a) Heat dissipation



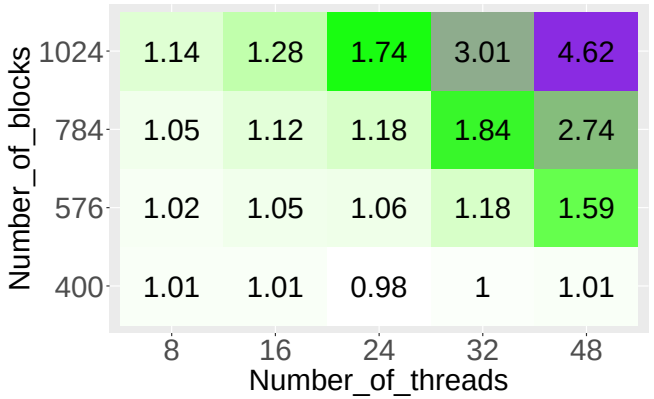
b) Hog object detector



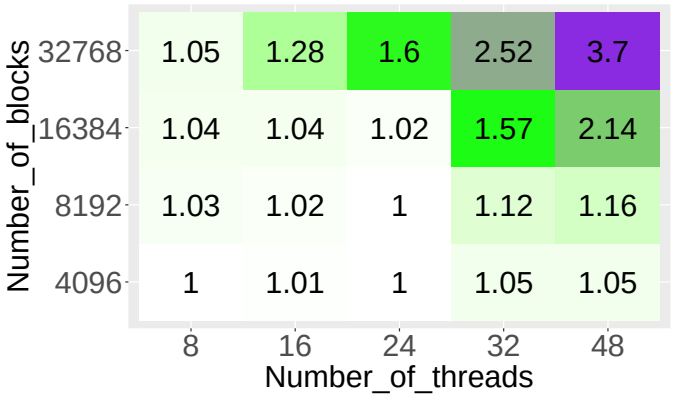
c) N-body simulation



d) SAXPY



e) Cholesky decomposition



f) Dot product

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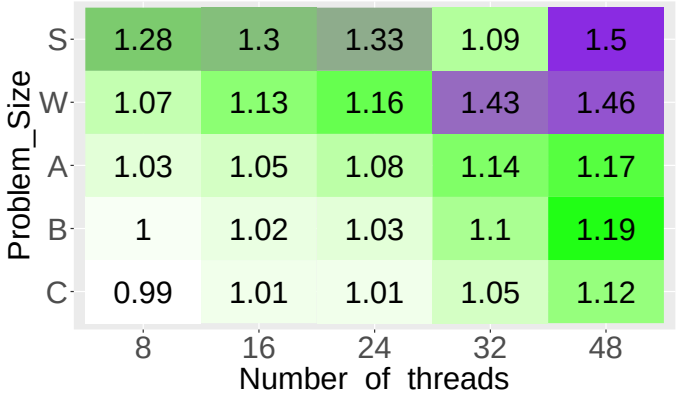
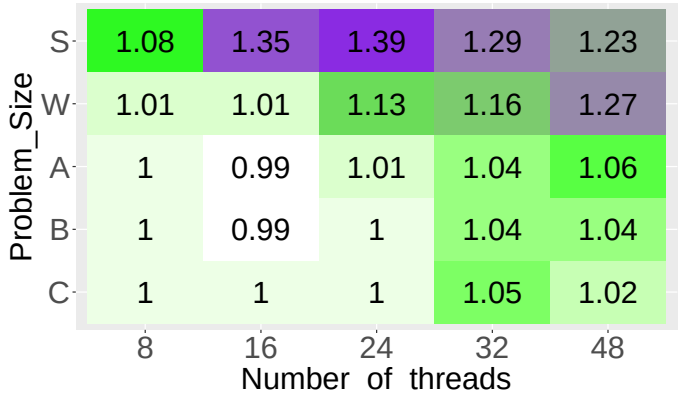
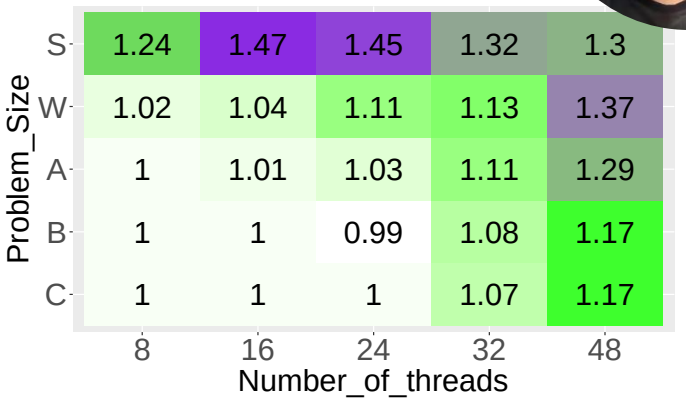
Evaluation – Speedup vs *taskloop*



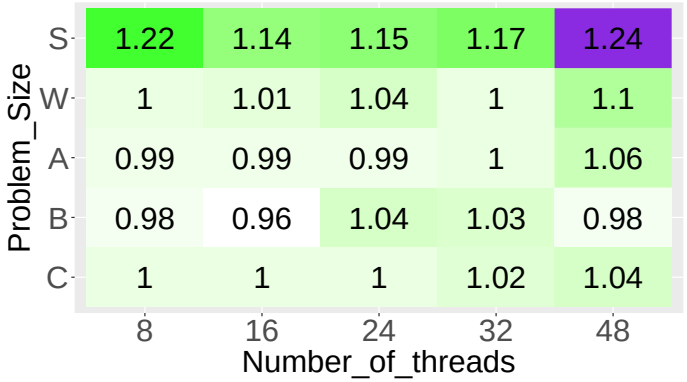
a) NAS CG



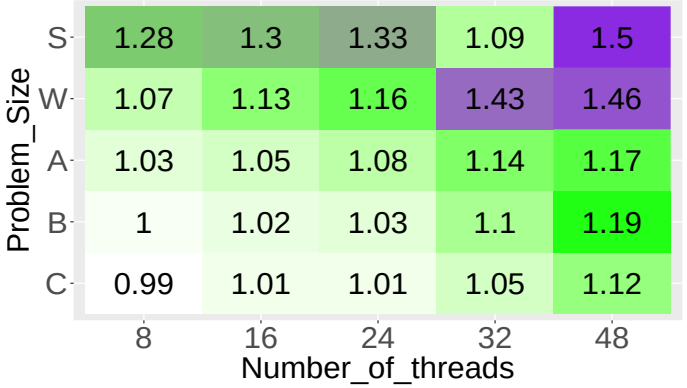
b) NAS BT



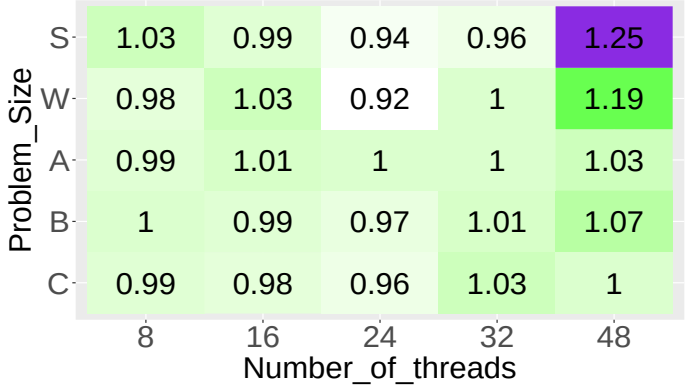
c) NAS SP



d) NAS FT

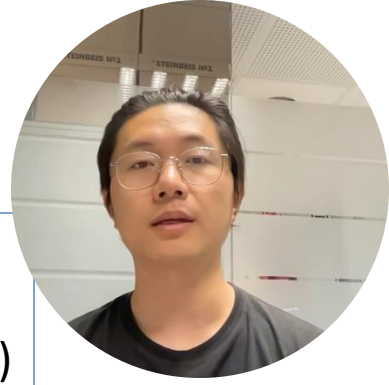


e) NAS LU



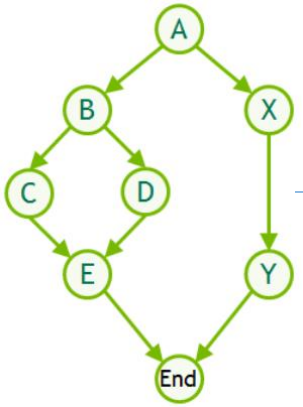
f) NAS EP

Taskgraph – Device Graph

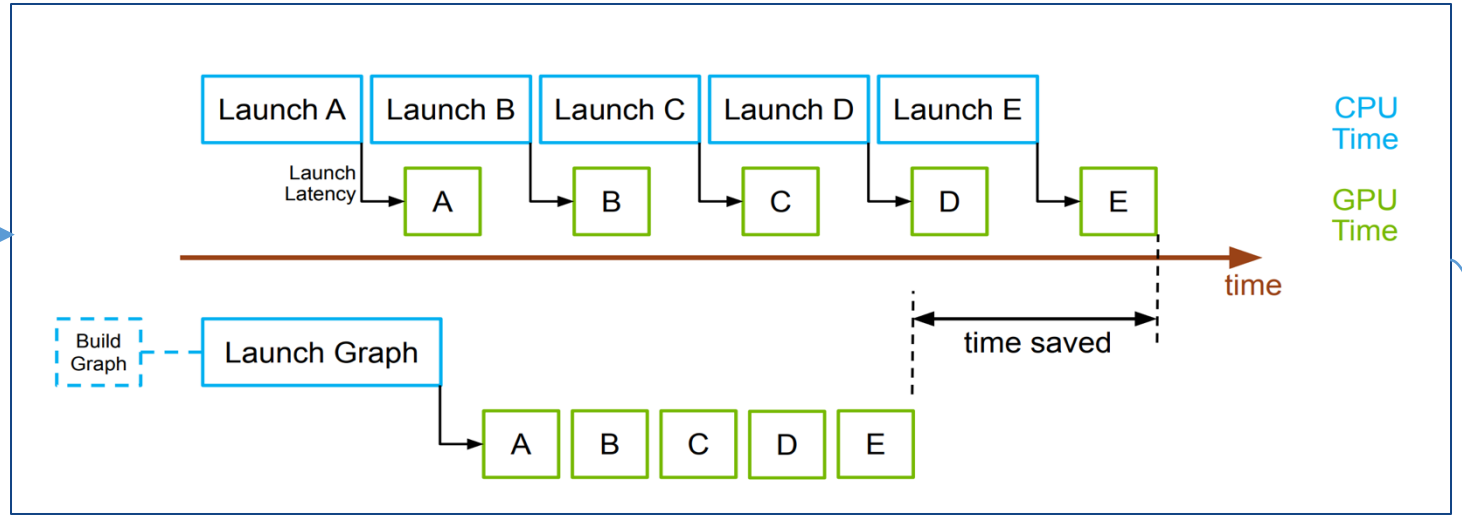


- 9 out of 10 of TOP 10 supercomputers integrate scientific GPU
- GPU kernels are short and launched repetitively (image processing, AI workload, etc)

credit: olcf.ornl.gov



credit:nvidia.com



- Stream record API, unsuitable for complex dependency
- Graph API, fine-grained control but verbose:
  - `hipGraphAddKernelNode ( hipGraphNode_t* pGraphNode, … )`
  - `hipGraphAddHostNode ( hipGraphNode_t* pGraphNode, … )`
  - `hipGraphAddMemcpyNode ( hipGraphNode_t* pGraphNode, … )`

How to define a graph, taking HIP as example

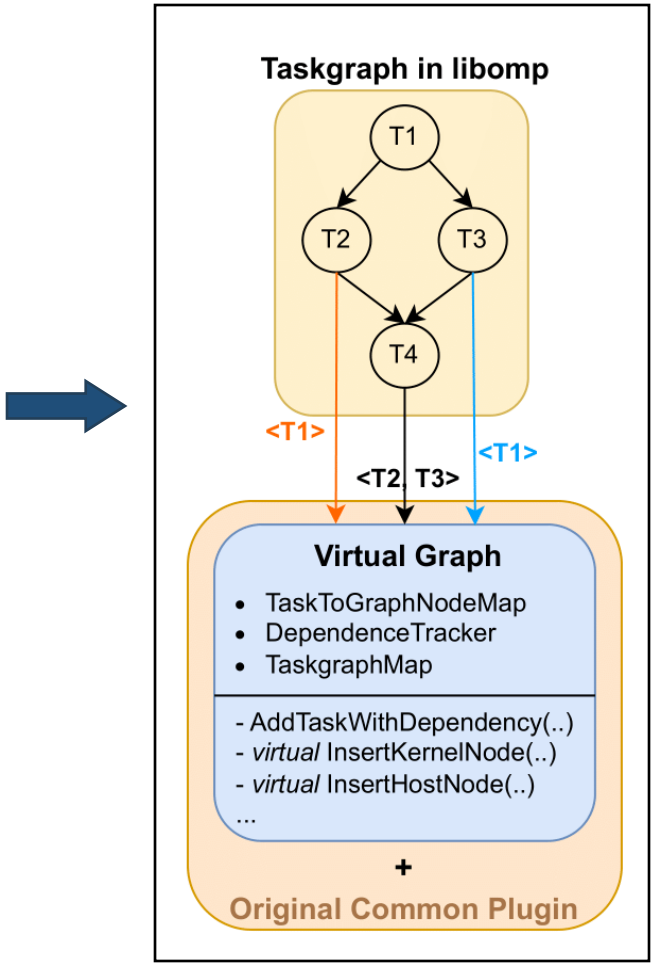
Implementation – Device Graph in LLVM

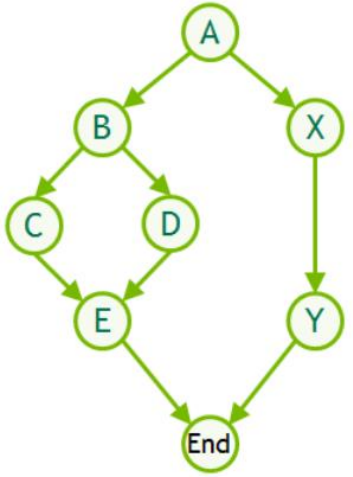
```
int operationLoop(…) {
  #pragma omp parallel
  #pragma omp single
  {
    #pragma omp taskgraph
    {
        #pragma omp task depend(out:op1)
        calibration(…)

        #pragma omp task depend(in:op1)
        fillIntensities(…)

        // other computations

        #pragma omp task depend(in:op_x)
        commandActuators(…)
    }
}
```





credit:nvidia.com

Evaluation – Set up[4]

	CPU (#cores)	GPU	OS	CUDA
Data Center	2 x Intel Xeon 8460 (80)	Nvidia H100	Ubuntu 22.04	V. 12.2
Customer	Intel i7-12700 (20)	Nvidia RTX 4080	Ubuntu 22.04	V. 12.2
Embedded	ARMv8 (12)	Integrated Nvidia GPU	Tegra Linux	V. 11.4

- Gridmini
- TestSNAP
- Neutral
- Points2Image

Proxy applications

- Heat propagation
- Nbody

Simulations

- OMP_NUM_THREADS=#Cores
- KMP_AFFINITY for core affinity
- 32 graph nodes (tasks) for all applications
- Optimization flag: -O3

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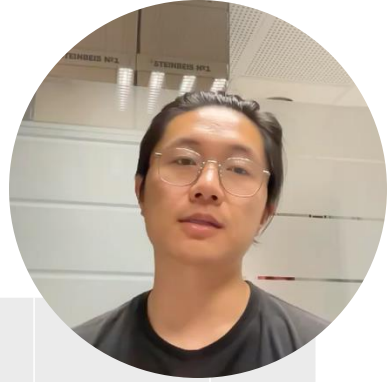
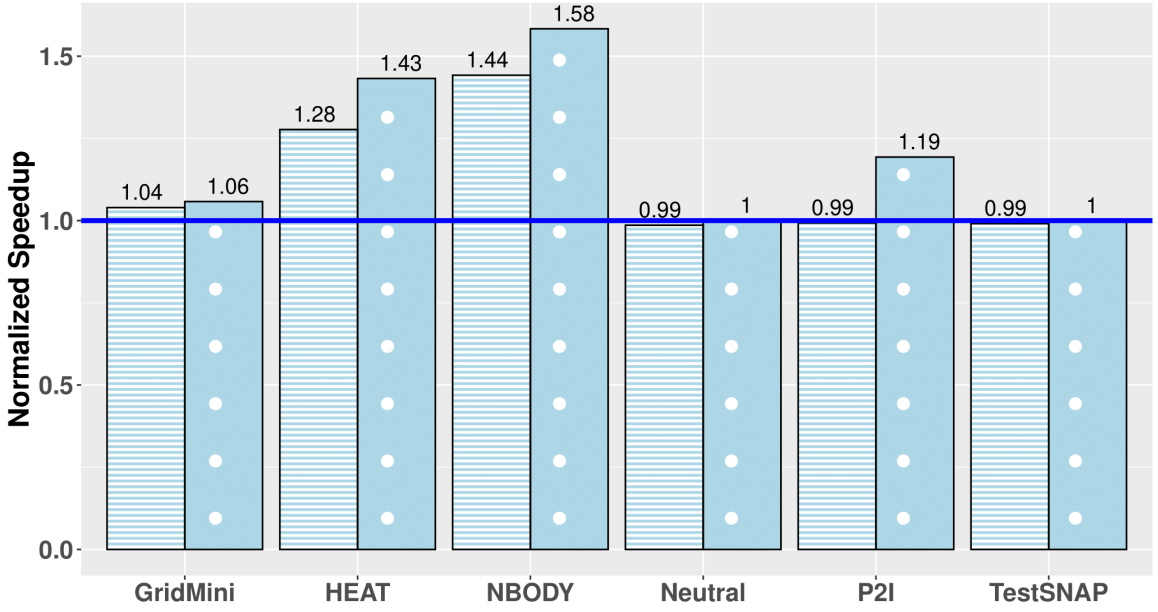
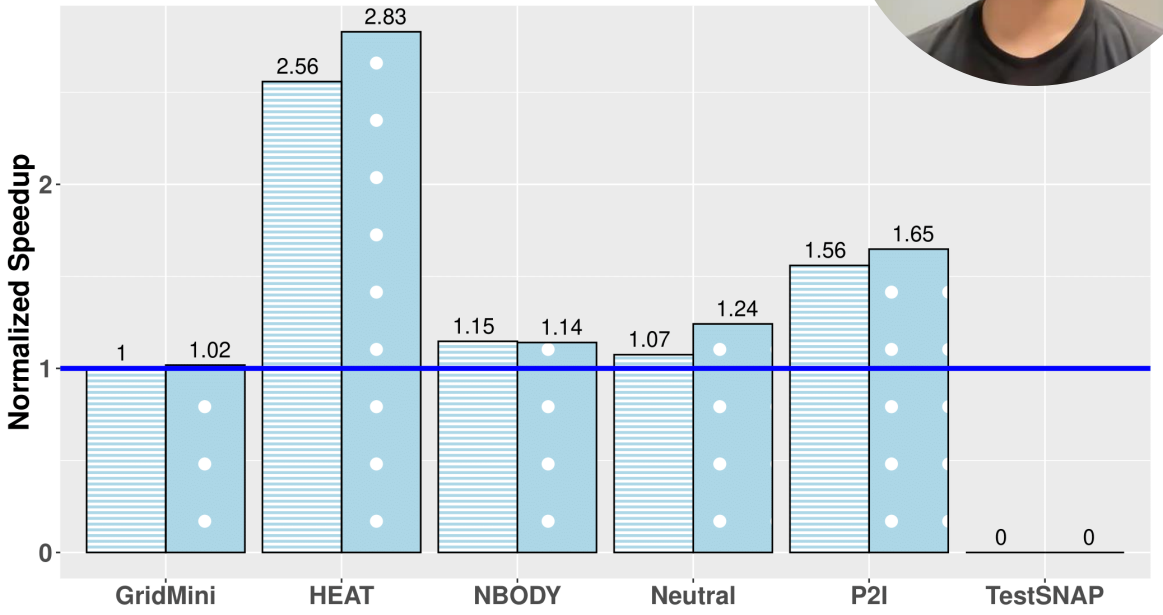
[4] : Refer to https://zenodo.org/records/11634155 for files to replicate the experiments

Evaluation – Mean Time





I7 + RTX 4080



Xeon + H100

The framework is:

- Generally more efficient than the original accelerator task (*omp target nowait*)
- As efficient as SPMD mode (*omp target teams distribute*) or faster

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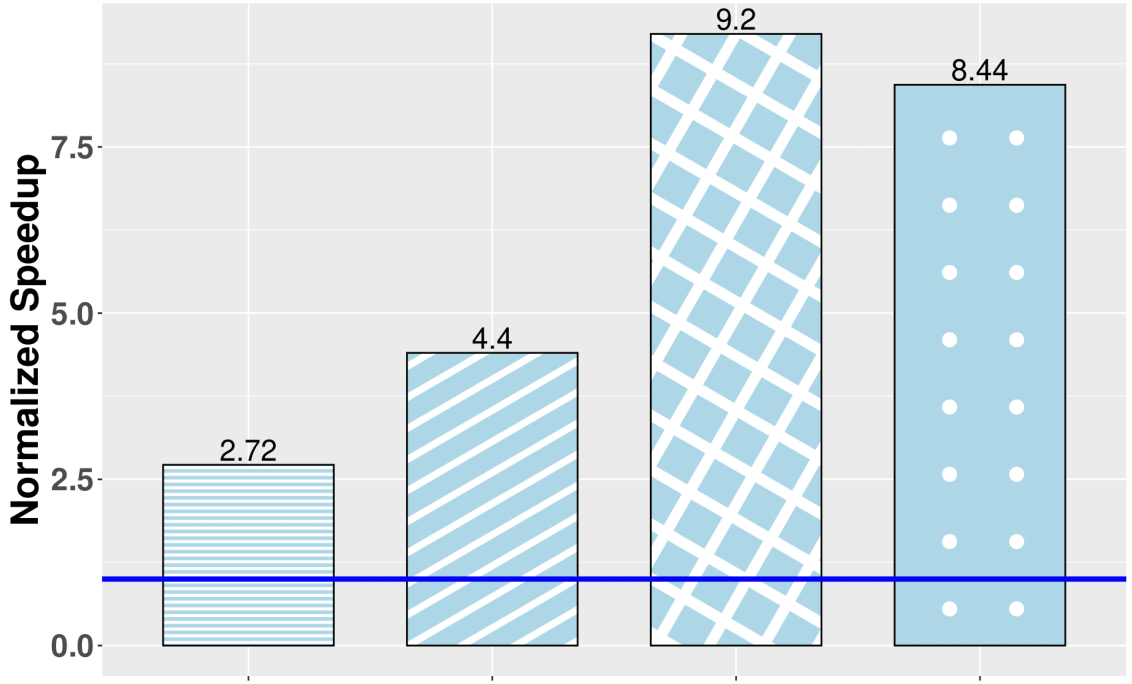
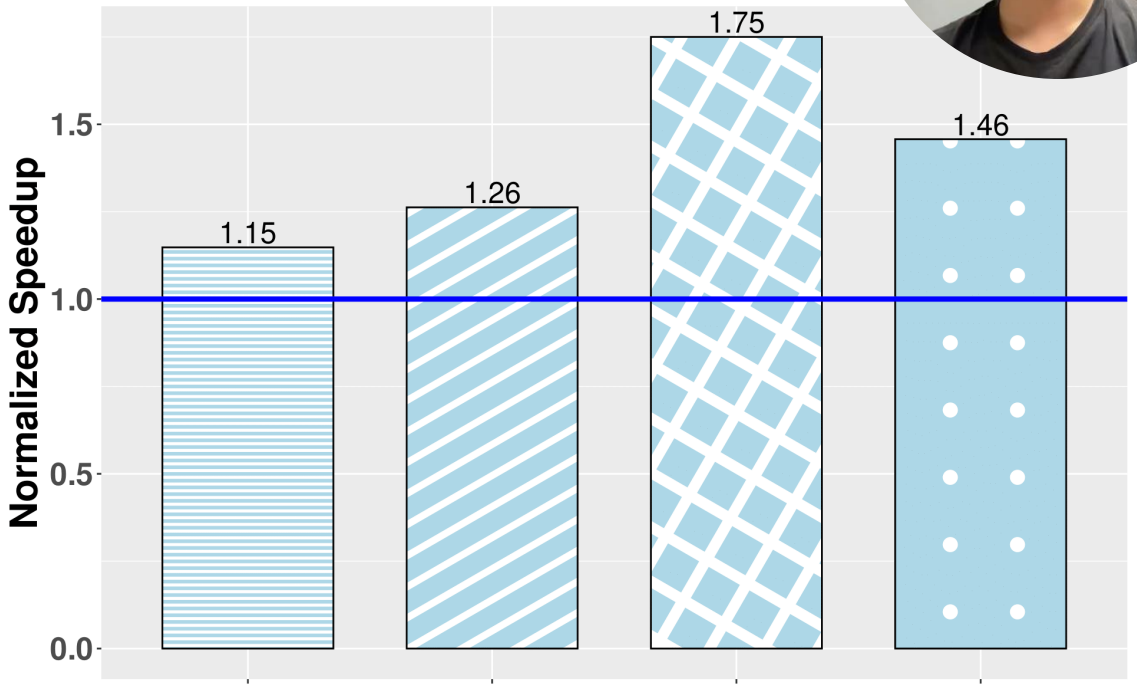
Evaluation – Scalability



Heat Propagation on Intel Xeon and H100



Nbody on Intel Xeon and H100

By varying the number of graph nodes, the framework is demonstrated to be more consistent

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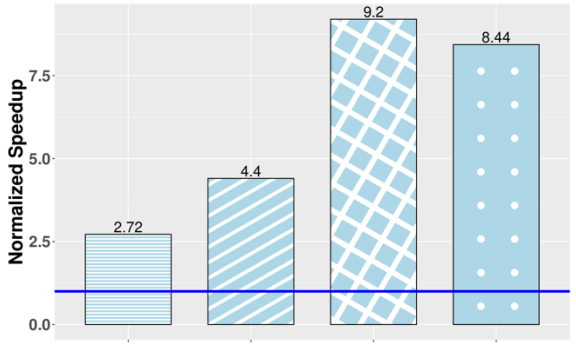
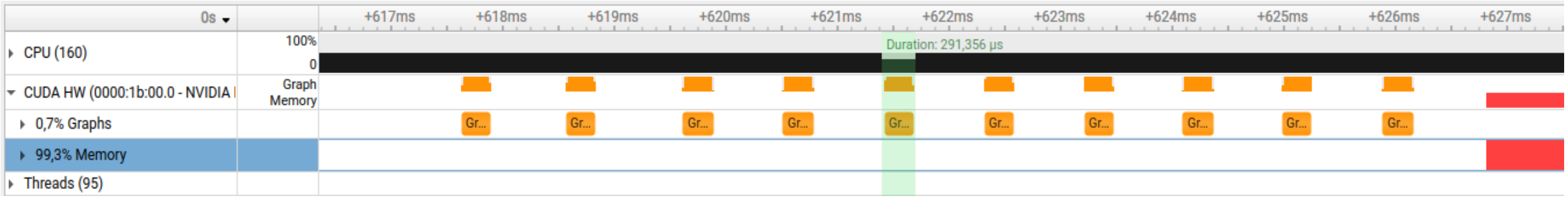
Evaluation – Scalability

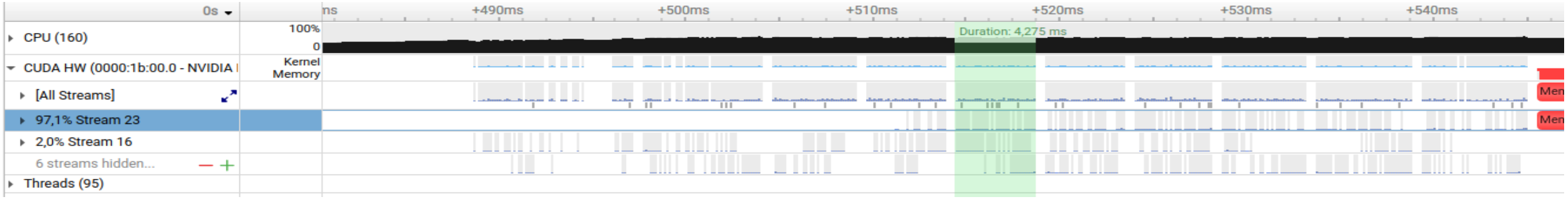
The graph execution is substantially faster but takes longer to instantiate



Heat Propagation on Intel Xeon and H100



Nsight trace for device graph on Marenostrum 5



Nsight trace for target task on Marenostrum 5

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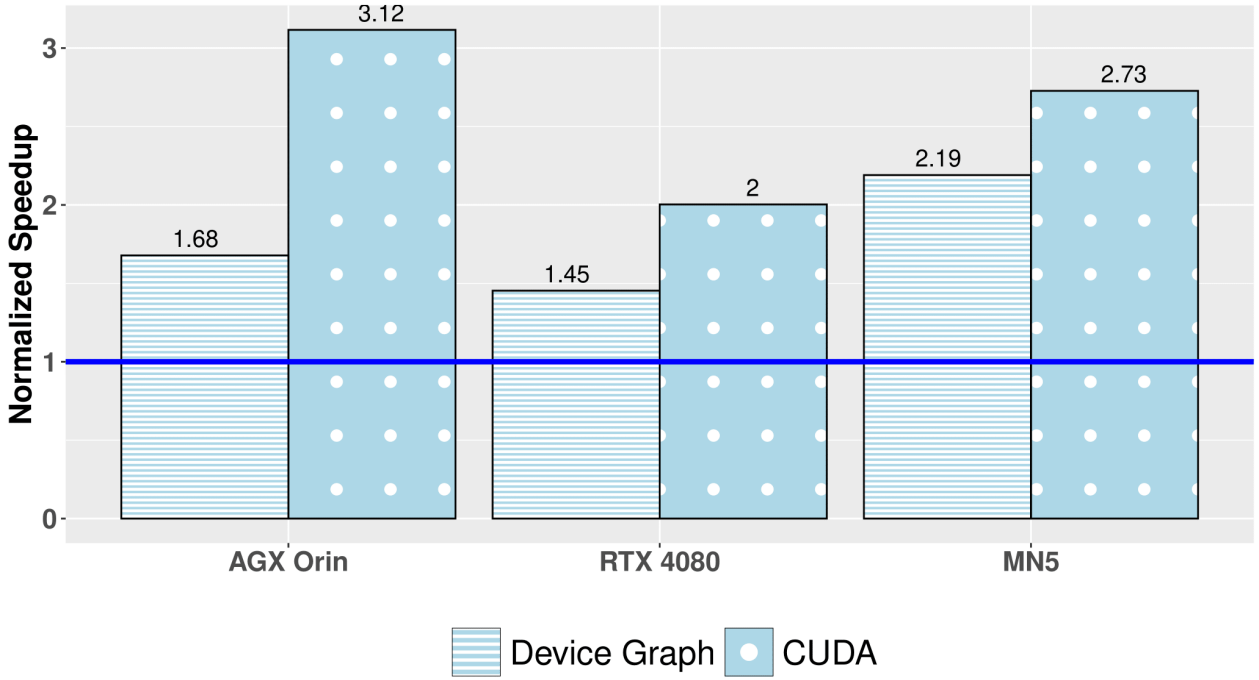
Evaluation – Versus CUDA



Points2Image benchmark from DAPHNE suite

Competitive in some cases, but mostly falling behind.

However, LLVM OpenMP implementation continuously improves[5], closing the performance gap.

[5] Co-Designing an OpenMP GPU Runtime and Optimizations for Near-Zero Overhead Execution (10.1109/IPDPS53621.2022.00055)

Conclusion

- *taskgraph* directive to be introduced in OpenMP 6.0
- Current results show clear performance gain with fine-grained tasks
- Ready to be mapped to accelerators as device graph
  (e.g., HIP and CUDA graphs)

Future step:

- LLVM upstream implementation
- Tackle current restrictions in OpenMP 6.0

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