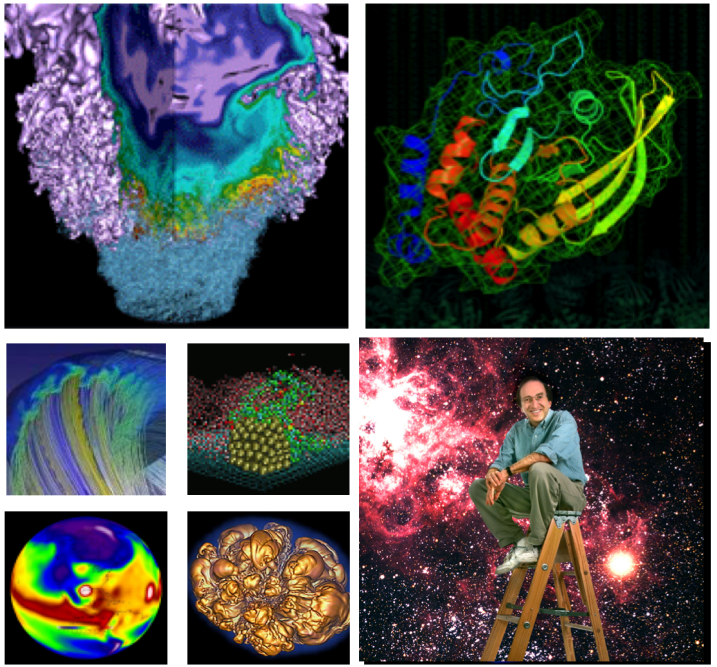
Evaluating the Performance of a Portable Version of the HPGMG Benchmark for Accelerators



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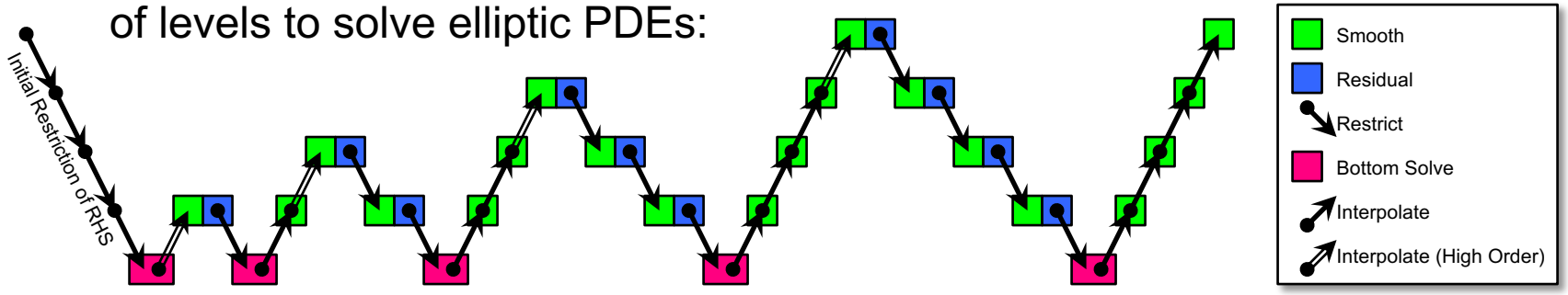
Overview

- **This presentation will evaluate OpenMP target offload and OpenACC Performance, Portability and Productivity (PPP) for the HPGMG benchmark**
- **HPGMG is a Finite Volume Geometric Multigrid benchmark**
- **OpenMP target offload/OpenACC PPP will be shown for**
  1. A base version of HPGMG ported from a CUDA Managed Memory version of HPGMG
  2. A new version of HPGMG using explicit data movement instead of Managed Memory

Multigrid methods and HPGMG overview

Multigrid method use a hierarchy of levels to solve elliptic PDEs:



- Levels consist of 2^3, 4^3, 8^3, … grid points (full Multigrid configuration)
- HPGMG divides the level data into blocks and distributes the blocks across MPI ranks
- HPGMG allocates large data buffers per level: block pointers are used to read/write at various offsets in these large data buffers

Code version #1: A Managed Memory implementation of HPGMG

- **HPGMG-CUDA is an NVIDIA fork of HPGMG (https://bitbucket.org/nsakharnykh/hpgmg-cuda)**
  - Depends on Managed Memory
  - Shallow copies a level data structure to the GPU
- **We ported HPGMG-CUDA to OpenMP target offload and OpenACC using the following approach**
  - Copy the body of the CUDA kernels into new functions
  - Replace CUDA thread indexing (blockIdx, threadIdx) with work-shared OpenMP target offload / OpenACC loops
  - Retain cudaMallocManaged CUDA runtime API calls

Platforms used

	Cori-GPU	Summit
Node architecture	Cray CS-Storm 500NX	IBM AC922
Node CPUs	2 x Intel Skylake	2 x IBM Power 9
Available cores per CPU	20 @ 2.40 GHz	21 @ 3.07 GHz
Node GPUs	8 x 16 GB NVIDIA V100	6 x 16 GB NVIDIA V100
CPU-GPU interconnect	PCIe 3.0 switch	NVLink 2.0

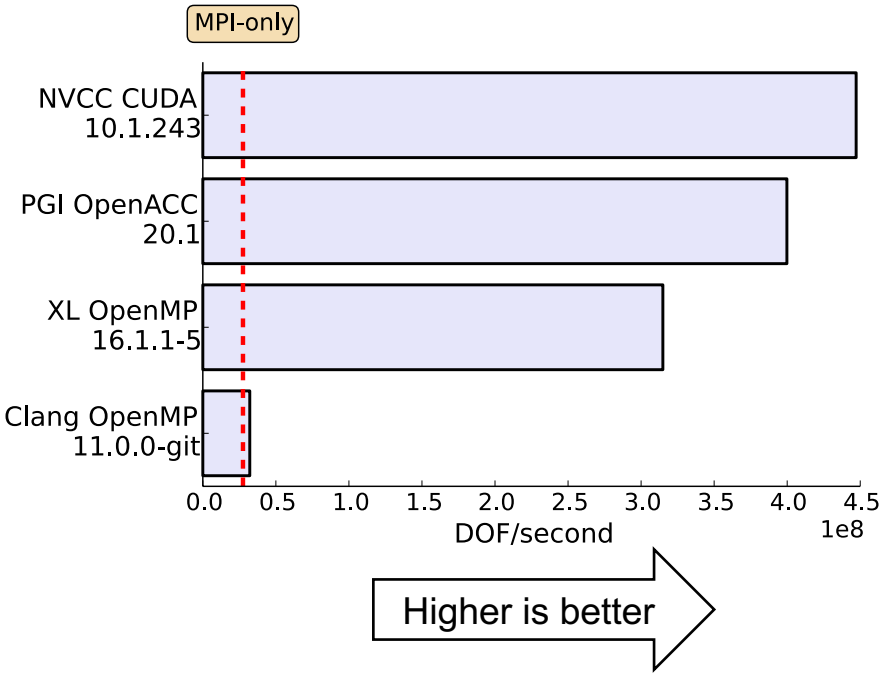
Compilers used

Compiler	GPU offload	Cori-GPU version	Summit version
GCC + NVCC	CUDA	7.3.0 + 10.1.244	7.4.0 + 10.1.243
NVIDIA/PGI	OpenACC	20.4	20.1
Cray CCE	OpenMP	9.1.0 (LLVM version)	-
IBM XL	OpenMP	-	16.1.1-5
LLVM/Clang	OpenMP	11.0.0-git (#17d8334)	11.0.0-git (#17d8334)

HPGMG configuration used

- We used the Top-500 HPGMG configuration: 4th order accurate, GSRB smoother, and BiCGStab bottom solver
- Grid spacing = 1/512: creates 9 levels from 2^3 to 512^3 grid points
  - Maximum box size = 32^3
- Memory footprint ~38 GiB
- CPU-only configuration run on 1 CPU socket: 1 MPI rank per core
- GPU configuration run on 1 CPU socket and 3 GPUs: 1 MPI rank per GPU

Managed Memory performance on Summit: 1 Power 9 CPU and 3 Volta GPUs

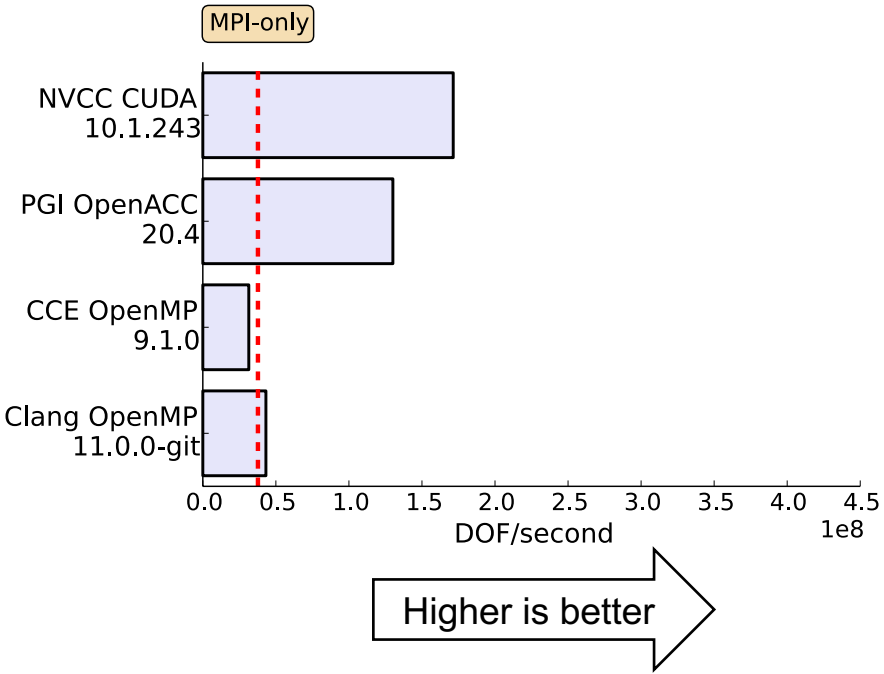


NVCC CUDA: 16x faster than the MPI-only configuration on a single CPU (21c)

GPU offload using directives can be competitive with CUDA:
PGI OpenACC: 0.89x
XL OpenMP: 0.70x

Clang performed poorly because of OpenMP runtime overheads (~80% of total runtime spent in cuMemAlloc and cuMemFree)

Managed Memory performance on Cori-GPU: 1 Skylake CPU and 3 Volta GPUs



NVCC CUDA and PGI OpenACC are 2.6x and 3.1x slower on Cori-GPU than Summit!

3 reasons for the slowdown:

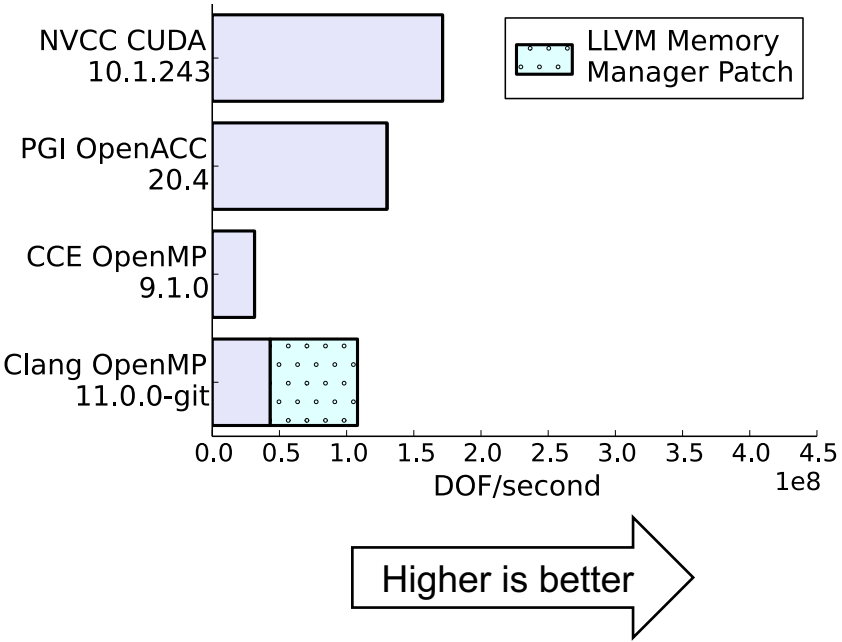
- More page faults
- More data movement between CPU and GPU
- Lower bandwidth transfers between CPU and GPU

CCE OpenMP performed poorly because –O0 compilation used for correctness

Addressing Managed Memory Performance Gaps

- **We don't understand why there were more page faults and data moved on x86**
  - The inefficient data transfer could potentially be addressed by prefetching the data using cudaMemPrefetchAsync() [Future work]
- **We do understand that LLVM/Clang performed poorly on x86 and Power because of significant OpenMP runtime memory management**
  - There is a repeated transfer of ~1 KB to shallow copy the level data structure for each OpenMP target region
  - Shilei Tian (Stony Brook University) has enhanced the LLVM OpenMP runtime to buffer target memory instead of returning it to the device: commit #0289696 (08/19/2020)

LLVM Memory Manager significantly improved Clang performance on Cori-GPU

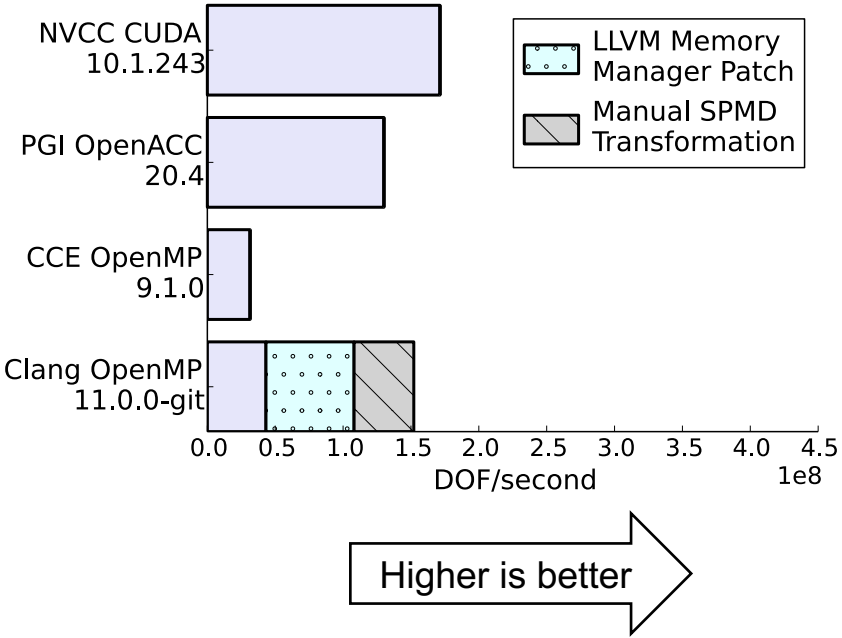


Nvprof shows significantly less time spent in memory management API calls

Original:
34,139 calls to cuMemFree (38.4% time)
34,139 calls to cuMemAlloc (35.5% time)

LLVM Memory Manager Patch:
0 calls to cuMemFree (0.0% time)
5 calls to cuMemAlloc (0.0% time)

Modifying the directives further improved Clang performance on Cori-GPU



Achieved 0.89x of CUDA performance!

Required convoluted code changes to remove user code between “target” and “parallel” directives to use a faster code generation scheme (SPMD): https://clang.llvm.org/docs/OpenMPSupport.html#directives-execution-modes

Johannes Doerfert (ANL) has started compiler development work to save users from manually doing this transformation: https://reviews.llvm.org/D59319

Code Version #2: Explicit data management using data directives

```
void smooth(level_type level, ...)
{
#pragma omp target teams distribute map(to:level)
  for (int blk=0; blk < level.num_my_blocks; blk++) {
```

```
void smooth(level_type *level, ...)
{
#pragma omp target teams distribute map(to:level[:0])
  for (int blk=0; blk < level->num_my_blocks; blk++) {
```

The Managed Memory version does a shallow copy of “level” to the device for each target region

The explicit data management version creates “level” on the device at program start and then passes a pointer to “level” for each target region

Thanks to Mat Colgrove for the initial OpenACC implementation

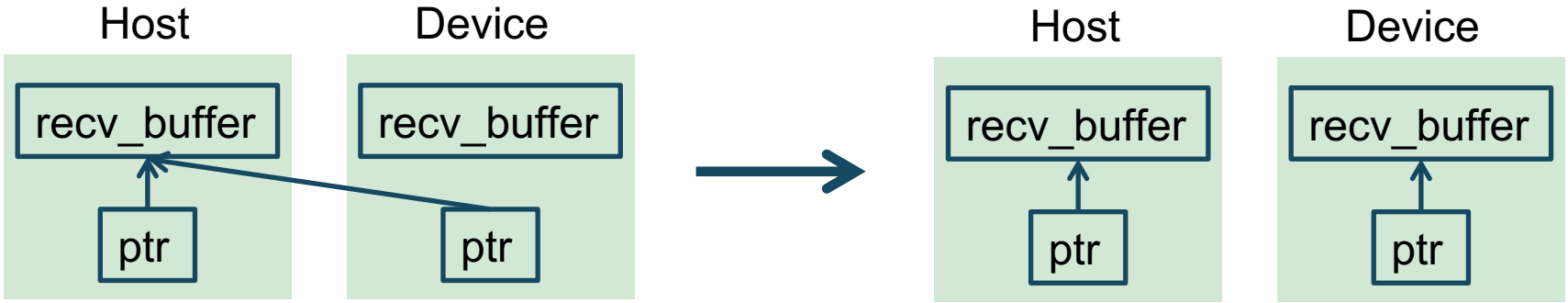
The “level” data structure is complicated – ~250 lines of code to create it on the device

```
typedef struct {
  struct {
    double * ptr;
    // + other variables
  } read, write;
} blockCopy_type;

typedef struct {
  double ** send_buffers;
  double ** recv_buffers;
  blockCopy_type * blocks[3];
  // + other variables
} communicator_type;

typedef struct {
  double ** vectors;
  communicator_type exchange_ghosts[STENCIL_MAX_SHAPES];
  communicator_type restriction[4];
  communicator_type interpolation; // + other variables
} level_type;
```

level_type is a nested data structure containing many pointers and double pointers

Block pointers (see blockCopy_type “ptr”) may be NULL or may point to communicator_type “send_buffers” or “recv_buffers”

Use “target enter data” to point the block pointers to device data buffers




```
for (shape=0; shape<STENCIL_MAX_SHAPES; shape++) {
  for (block=0; block<3; ++block) {
    for (b=0; b<level->exchange_ghosts[shape].num_blocks[block]; ++b) {
#pragma omp target enter data \
   map(alloc:level->exchange_ghosts[shape].blocks[block][b].read.ptr[:0])
```

Update device pointer using zero length array section

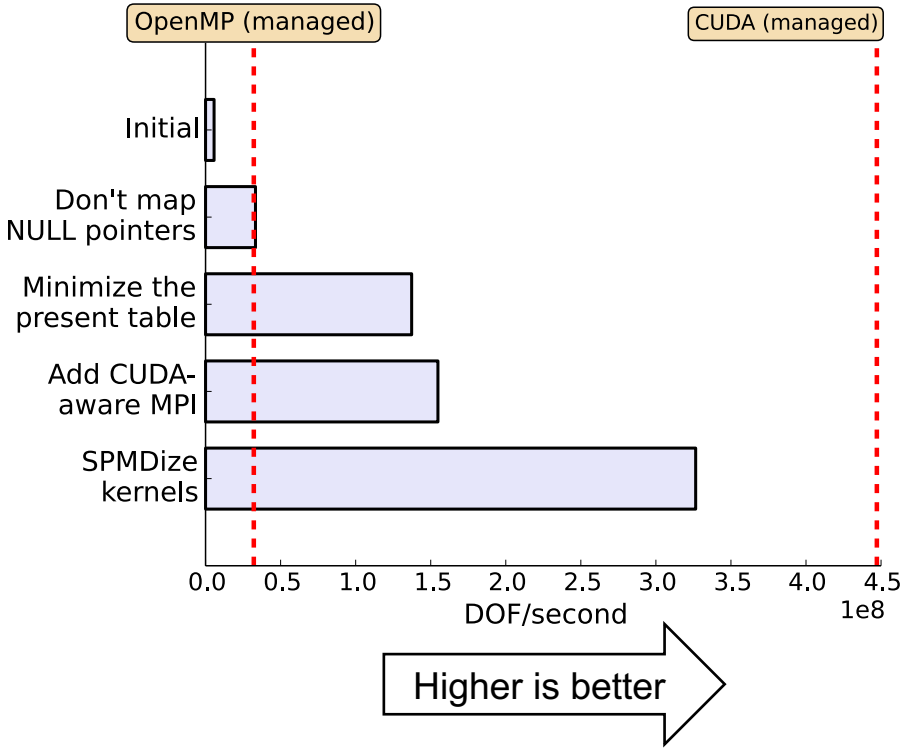
It worked but exposed issues in multiple compilers

- **The PGI compiler successfully executed the OpenACC version**
- **Only LLVM/Clang successfully executed the OpenMP version of the application**
  - Runtime errors in XL and CCE compilers
- **LLVM/Clang performance was worse than the unoptimized Managed Memory version of the code**
  - A profile showed that a huge amount of time was spent in a “target update from” directive used to copy data from GPU to CPU
  - Most of the time was spent in the OpenMP runtime rather than moving data!

Addressing LLVM OpenMP runtime overhead

- **OpenMP runtimes use a present table to maintain the association between host and device pointers**
- **We added ~100K entries to the present table when updating HPGMG block pointers (using "target enter data" directive)**
  - This caused high lookup time in "target update from" directive (https://bugs.llvm.org/show_bug.cgi?id=46107)
- **We tested 2 ways to minimize the present table:**
  1. Don't update a device pointer if the host block pointer is NULL
  2. Update the block pointers on the device in a OpenMP target region: avoids adding an entry to the present table

Incremental optimizations to improve LLVM/Clang performance on Summit



Present table optimizations improved performance by 24.2x

CUDA-aware MPI and SPMD code transformations improved performance by another 2.4x

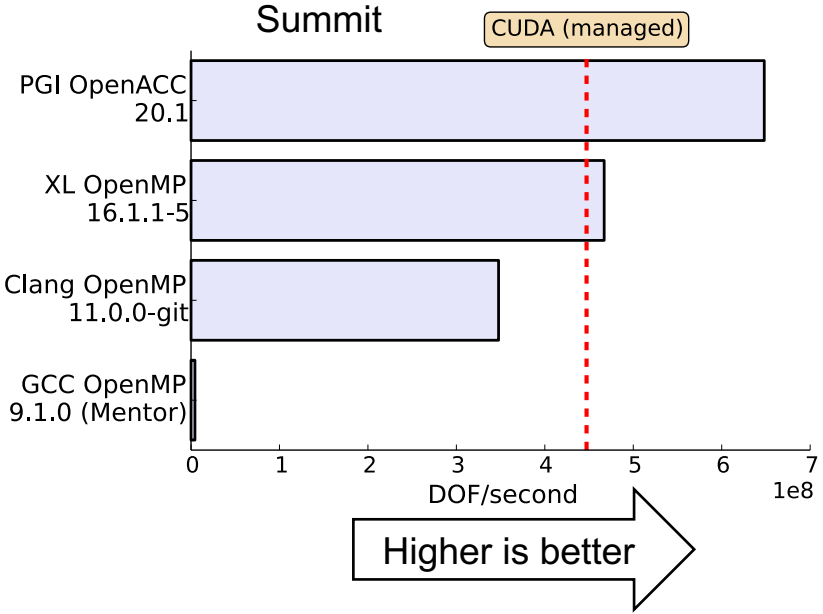
Code version #3: Explicit data management using OpenMP runtime API

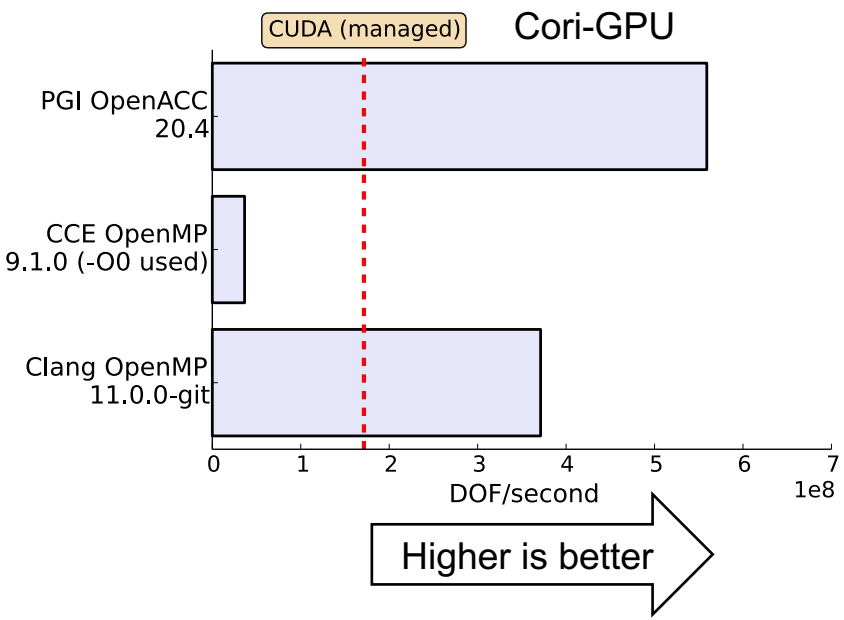
- Used separate host and device “level” variables
- Data directives replaced by omp_target_alloc and omp_target_memcpy (~2x increase in data management code)

Compiler	Managed Memory (#1)	Explicit Mgmt - directives (#2)	Explicit Mgmt - runtime API (#3)
XLC 16.1.1-5	✓	✗ (RE)	✓
CCE 10.0.2	✓	✗ (RE)	✓
LLVM 11.0.0-git (#17d8334)	✓	✓	✓
GCC 9.1.0 (Mentor)	✓	✗ (CE)	✓

CE = Compile Error
RE = Runtime Error

Explicit data management performance on Summit and Cori-GPU





Explicit data management significantly improves upon Managed Memory performance on Cori-GPU (x86)

Conclusions

- **3 OpenMP / OpenACC compilers achieved 70-90% of CUDA performance (LLVM/Clang, XL, PGI)**
- **OpenMP / OpenACC data directives enabled us to add explicit data management to HPGMG in a much simpler way than runtime APIs**
  - Hard to imagine porting HPGMG to runtime API data management without first starting from a data directive version
  - Non-trivial usage of data directives caused issues in 3 OpenMP compilers (XL, CCE, GCC) [compiler maturity issues]
- **Managed Memory performance was relatively poor on x86 whether using CUDA, OpenACC or OpenMP**
  - Explicit data management performed well on x86 and Power

Thanks for listening

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