Hewlett Packard
Enterprise

CHAPEL 1.29.0/1.30.0 RELEASE NOTES: GPU SUPPORT

Chapel Team

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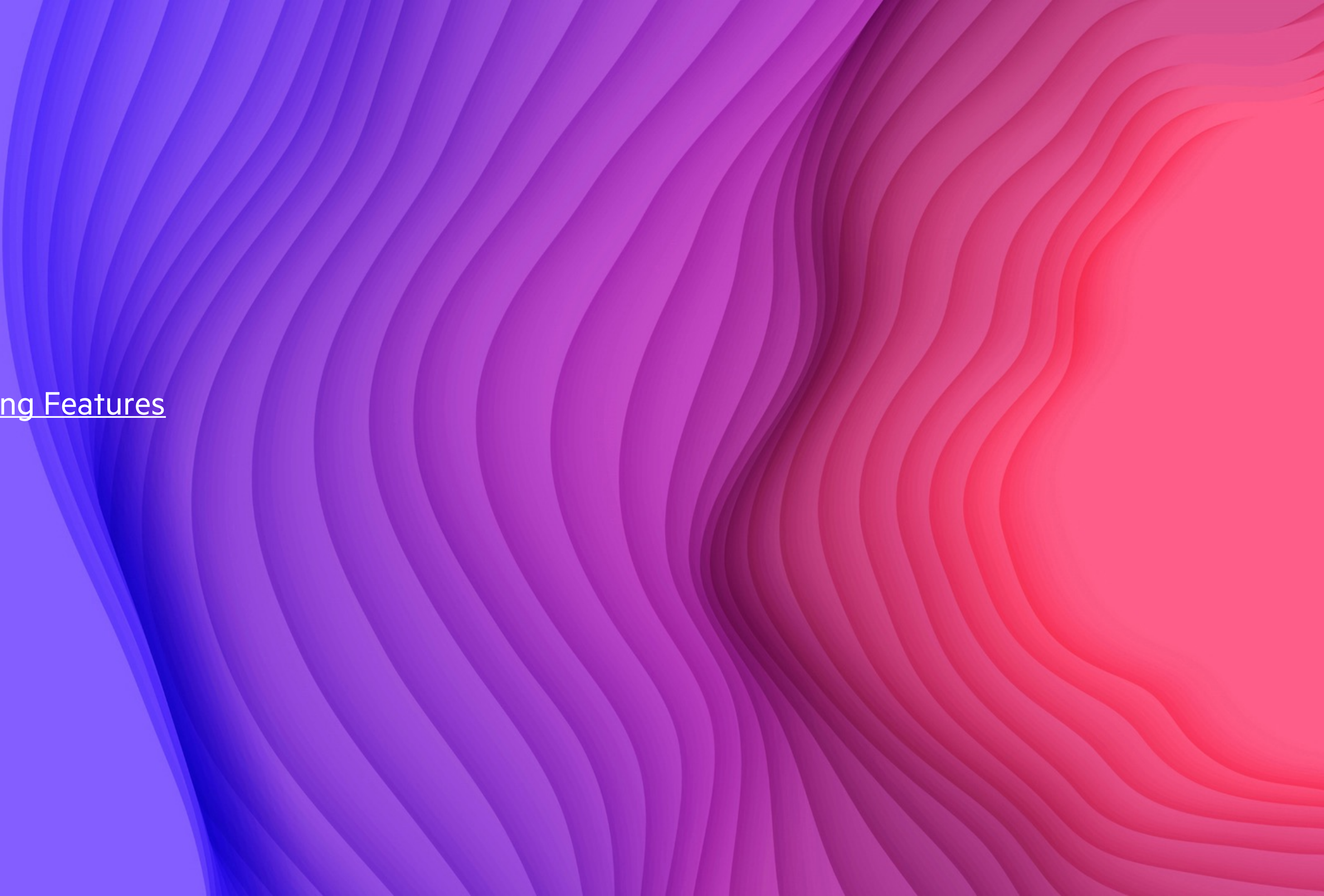
OUTLINE

- Background
- New User-facing Features
- AMD Support
- Performance
- Next Steps



BACKGROUND

GPU SUPPORT

Background

- We are adding native GPU support to Chapel
  - A highly desired feature, given the potential to be a clean and portable way of programming GPUs
  - GPUs are more and more common in supercomputers
    - Over 95% of the compute capability on Frontier (currently #1 on the top-500) comes from its GPUs
- In earlier releases, we've…

  …moved from an idea (**1.23**), to a demo (**1.24**), …

  …to a user-accessible feature on NVIDIA GPUs (**1.25**), …

  …to being able to drive multiple GPUs on one locale (**1.26**), and then multiple locales (**1.27**).

- **1.29** and **1.30** have primarily focused on performance and portability
  - **performance:** significantly improved the time to launch and execute kernels
  - **portability:** added support for AMD GPUs
    - **1.29:** could generate binaries for AMD GPUs using low-level features
    - **1.30:** raised level of abstraction to target a single locale's AMD GPUs using Chapel, similar to NVIDIA GPUs
  - also new features for users and capabilities for developers

GPU SUPPORT

Vector Increment Example: Basics

```
on here.gpus[0] {

  var GpuVec: [1..n] int;
  GpuVec += 1;
  writeln(GpuVec);

}
```

'on' statement targets a GPU

array data will be allocated on the targeted GPU

data-parallel operations will launch as a GPU kernel

GPU SUPPORT

Vector Increment Example: Data Offload via Bulk Array Assignment

```
var CpuVec: [1..n] int;

  on here.gpus[0] {


    var GpuVec = CpuVec;
    GpuVec += 1;
    CpuVec = GpuVec;

  }

writeln(CpuVec);
```

host-to-device copy

device-to-host copy

GPU SUPPORT

Vector Increment Example: Multiple GPUs via 'coforall'

```
var CpuVec: [1..n] int;

  coforall gpu in here.gpus do on gpu {
    const myChunk = ...;

    var GpuVec = CpuVec[myChunk];
    GpuVec += 1;
    CpuVec[myChunk] = GpuVec;

  }

writeln(CpuVec);
```

'coforall' creates a task per each local GPU

a slice of the data is copied between host and device

GPU SUPPORT

Vector Increment Example: Multiple GPUs on Multiple Locales

```
var CpuVec: [1..n] int;
coforall loc in Locales do on loc {
  coforall gpu in here.gpus do on gpu {
    const myChunk = ...;

    var GpuVec = CpuVec[myChunk];
    GpuVec += 1;
    CpuVec[myChunk] = GpuVec;

  }
}
writeln(CpuVec);
```

'coforall' over all locales

GPU SUPPORT

This Effort: Overview of Changes in 1.29 and 1.30

Performance:

- Much faster kernel launch
- Faster execution across many benchmarks

Portability:

- AMD GPUs can now be used in a single locale

Bug fixes:

- Fixed segmentation faults in “array on device” mode
- Fixed error handling while generating the GPU binary
- Fixed a bug that prevented using ‘nil’
- Worked around a thread synchronization bug in ‘clang’

New Features and Capabilities:

- Early support for NVIDIA profiler and debuggers
- New functions to…
  - create block-shared arrays
  - synchronize threads in the same block
  - set the block size of a kernel
  - measure time in a kernel
  - write to the console from a kernel

Studies and Explorations:

- Application-level improvements in ChOp
- Application-level improvements in SHOC Sort
- Implemented SHOC Transpose
- Coral image analysis

NEW USER-FACING FEATURES

GPU SUPPORT

New Utility Functions: Optimization and Advanced Features

Background: Optimized GPU codes tend to require advanced features

- e.g., synchronization, block-shared memory

This Effort: Added new user-facing procedures to the 'GPU' module:

```
foreach i in 1..n {
  setBlockSize(128);                           // set the block size to 128; the argument must be a 'param'
  var sharedArr = createSharedArray(int, 10);  // create a block-shared array of 10 ints; size must be a 'param'
  // ...
  syncThreads();                               // synchronize the threads within the block
  // ...
}
```

Status: New procedures are unstable, along with the 'GPU' module as a whole

Next Steps: Develop a more Chapeltastic way of writing more advanced GPU code

GPU SUPPORT

New Feature: Enabling Efficient use of Nsight Compute Profiler

Background:

- Debugging and profiling GPU kernels are typically more difficult than CPU applications
  - I/O support is typically poor, execution model is less intuitive, esoteric challenges
- NVIDIA has numerous profilers, where NSight Compute is used for profiling kernel performance
  - While using profilers for Chapel in general is not very straightforward, focusing on kernels is easier
- Out-of-the-box: NSight Compute was able to show line-by-line hardware counters when '-g' was used
  - However, '--fast -g' thwarted assembler optimizations → reduced kernel performance → less valuable profiling

This Effort:

- Added the '--gpu-ptxas-enforce-optimizations' flag to ensure that assembler optimizations are enabled

Impact:

- Significant help while trying to understand performance of compiler-generated kernels
  - Kernel performance is virtually unaffected
  - Profiler shows line-by-line information accurately
- Can compare performance behavior of a reference version against the Chapel version

GPU SUPPORT

New Utility Functions: Debugging and Introspection

Background: Needed a way to trace code and measure performance when writing benchmarks

This Effort: Add 'gpuWrite( )', 'gpuClock( )', and 'gpuClocksPerSec( )' procedures

```
foreach i in 0..<N {
  gpuWrite(c"Start\n");          // gpuWrite() called on GPU; takes a c_string; output flushed on kernel termination
  const start = gpuClock();      // gpuClock() called on GPU; per-processor counter that increments every clock cycle
  A = bigComputation(B);
  const end = gpuClock();
  gpuWrite(c"Stop\n");
  t1[i] = start; t2[i] = end;
}
const div = gpuClocksPerSec(0);   // gpuClocksPerSec() must be called on the host; passed GPU device ID
writeln("Time took: ", (t2[0] - t1[0]):real / div:real));
```

Next Steps: Replace these routines with stabilized versions in a future release

- Remove 'gpuWrite( )' and get 'write( )'/'writeln( )'/'writef( )' working inside GPU kernels
- Remove 'gpuClock( )' and get Chapel's ‘stopwatch’ working inside GPU kernels

AMD SUPPORT

GPU SUPPORT

Targeting AMD GPUs

Background: In previous releases we only supported NVIDIA GPUs

- However, we intend for Chapel’s GPU support to run on devices from diverse vendors

This Effort: Add support for AMD GPUs

- Added 'CHPL_GPU_CODEGEN' to choose between working with an AMD or NVIDIA GPU
  - it will be set automatically if 'nvcc' or 'hipcc' are present
- Note that AMD GPU support requires the 'AMDGPU' LLVM target and the ROCM/HIP runtime libraries
  - the 'AMDGPU' LLVM is included in the bundled LLVM
  - the ROCM/HIP runtime is packaged as part of 'hipcc'

Impact:

- Now you can use Chapel to write code that runs on AMD GPUs
- Chapel code that was working on an NVIDIA GPU can be run on an AMD GPU without changing the code

GPU SUPPORT

Targeting AMD GPUs

Status:

- AMD GPU support has feature parity with NVIDIA GPU support except for:
  - certain 64-bit math functions
  - multilocale support: the AMD GPUs currently only work on a single locale ('CHPL_COMM=none')
- Applications are compiled to either run on NVIDIA GPUs or AMD GPUs, not both at once
- Performed first run on Frontier using HPCC Stream
  - Very close performance to baseline version at >10 TB/s bandwidth per node

Next Steps:

- Our aim is for Chapel to be completely portable between NVIDIA, AMD, and Intel GPUs
  - for AMD: support missing math functions and add multilocale support
  - for Intel: start adding support
- Consider using the 'hipify' tool to produce part (or all) of our AMD vendor-specific runtime
- Consider supporting a single binary that can run across GPUs from different vendors

PERFORMANCE

GPU SUPPORT

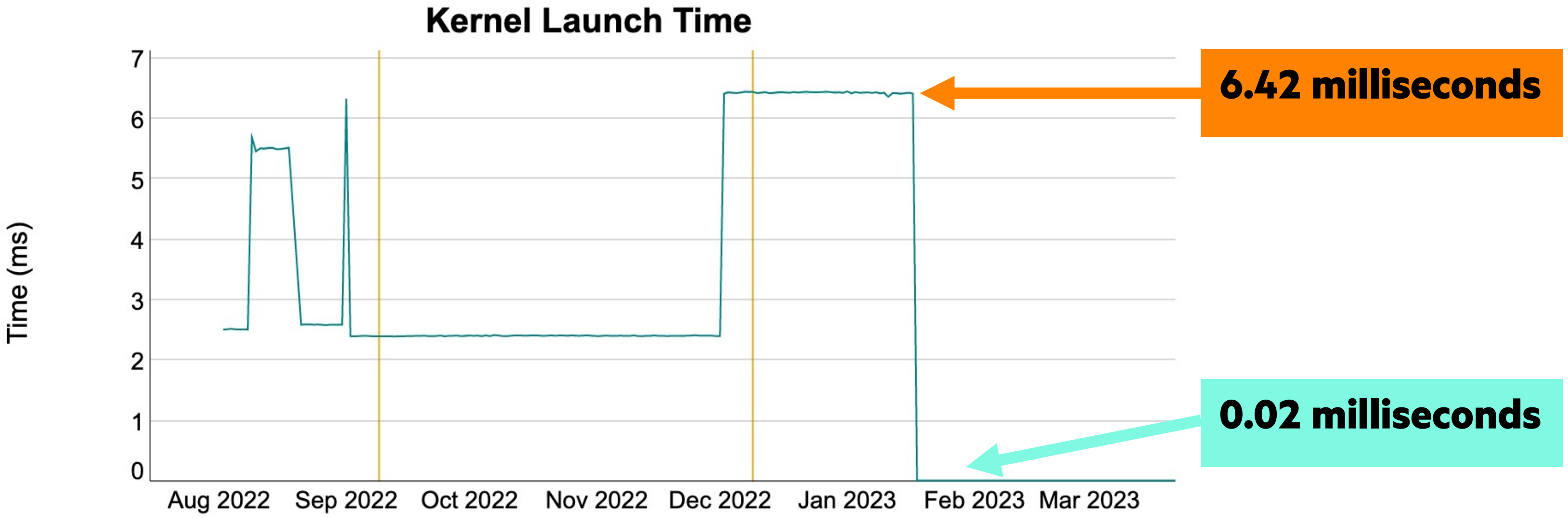
Eager Binary Loading

Background: Previously, the runtime would load the GPU binary whenever a kernel was launched

- This was mostly an artifact from earlier stages of development

This Effort & Impact: The GPU binary is loaded at application startup time

- Led to more than 300x faster kernel launch performance
- Significant improvements in HPCC Stream Triad with small vector sizes (see next slide)



6.42 milliseconds

0.02 milliseconds

GPU SUPPORT

Benefits from Loop-Invariant Code Motion (LICM)

Background:

- LICM is a compiler optimization to avoid redundantly performing a computation in a loop
- Chapel moves the body of GPU-eligible loops into separate kernel functions
- Some instances where LICM could improve performance were missed because we convert loops into kernels

This Effort:

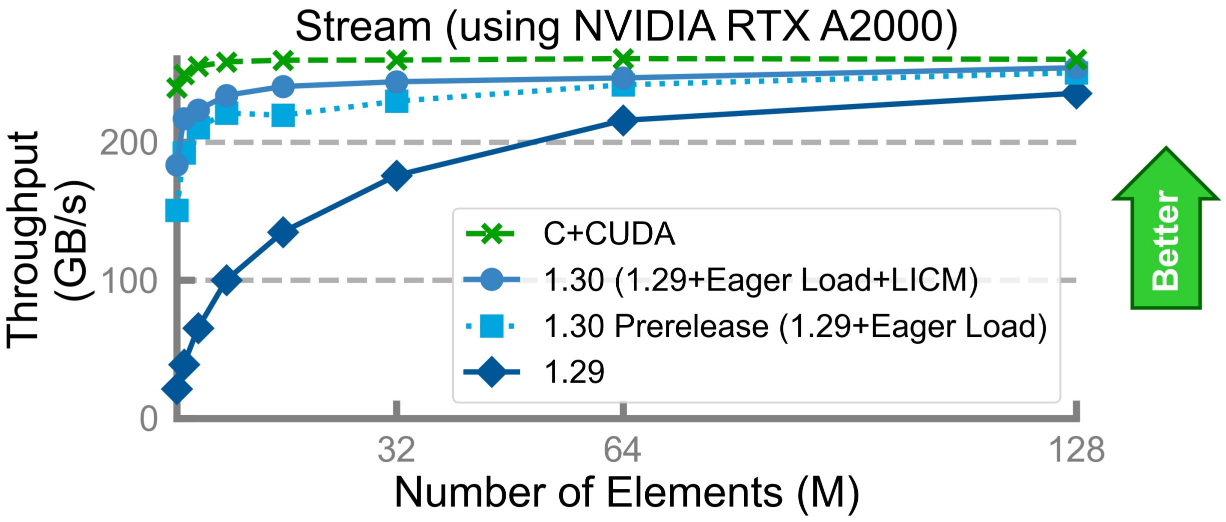
- Solution: reorder how we do things to do LICM first

Impact:

- Can introduce extra arguments to kernel functions
- Improved performance of Stream and ChOp

Next Steps:

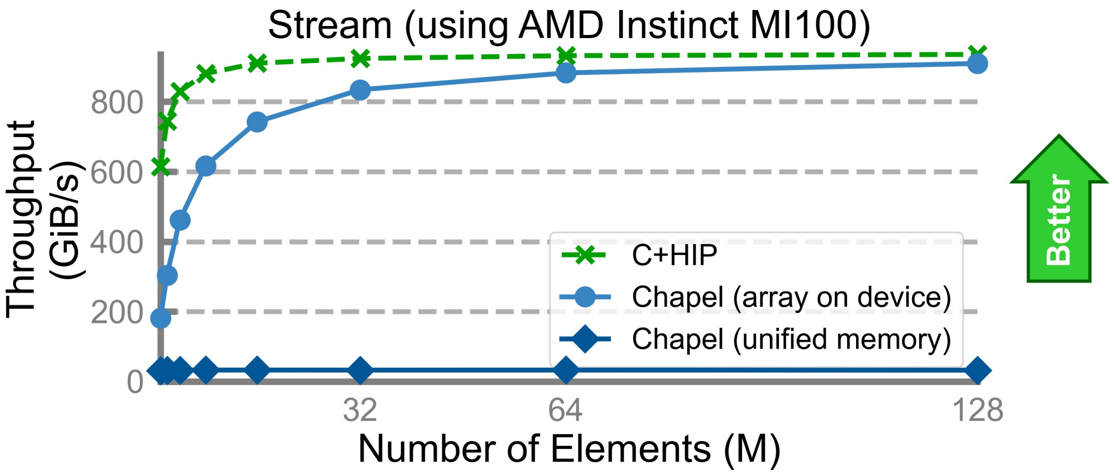
- Find and mitigate remaining overhead(s) in Stream
- Improve LICM for better GPU performance

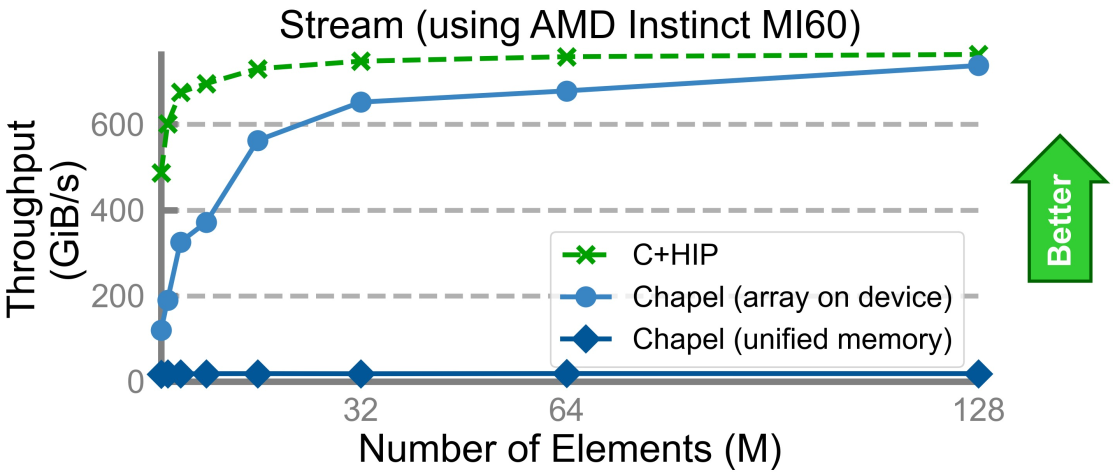


GPU SUPPORT

Sidebar: Stream Performance with AMD

- Baseline was made by taking a CUDA implementation of Stream and running it through 'hipify'
- With array-on-device mode we see worse performance on small data sizes; more competitive on larger
- In unified memory mode, performance suffers; we have not yet investigated why this is





GPU SUPPORT

Communication Overlap

Background:

- GPUs can communicate and compute at the same time, and making use of that may improve performance
- In array-on-device mode, assignment statements perform synchronous (blocking) communication

This Effort:

- Explored how overlapped communication can be expressed in Chapel when in array-on-device mode
- Specifically, we created two Chapel versions of the SHOC Triad benchmark:
  - version 1: uses 'begin' statements and synchronization variables
  - version 2: adds explicit asynchronous communication routines to Chapel and uses them in the benchmark

Status:

- New API for asynchronous communication is implemented in the 'GPU' module but is undocumented
- Our Chapel versions do not yet show a benefit from using an overlap
- We have open questions about why the CUDA version does show a benefit

GPU SUPPORT

Communication Overlap

Next Steps:

- Consider adding asynchronous PUT and GET functions in the 'Communication' module
  - these could be generalized for both CPU-to-CPU and CPU-to-GPU communication
- Consider whether new language features would make such patterns easier to express
- Better understand why the CUDA version of SHOC Triad sees a benefit from asynchronous communication
  - or, find a better benchmark to demonstrate the value of computation/communication overlap
- Consider if using CUDA/HIP streams for regular allocations and launches can improve overall performance

GPU SUPPORT

Memory Strategies

Background: We have two memory strategies controlled by 'CHPL_GPU_MEM_STRATEGY'

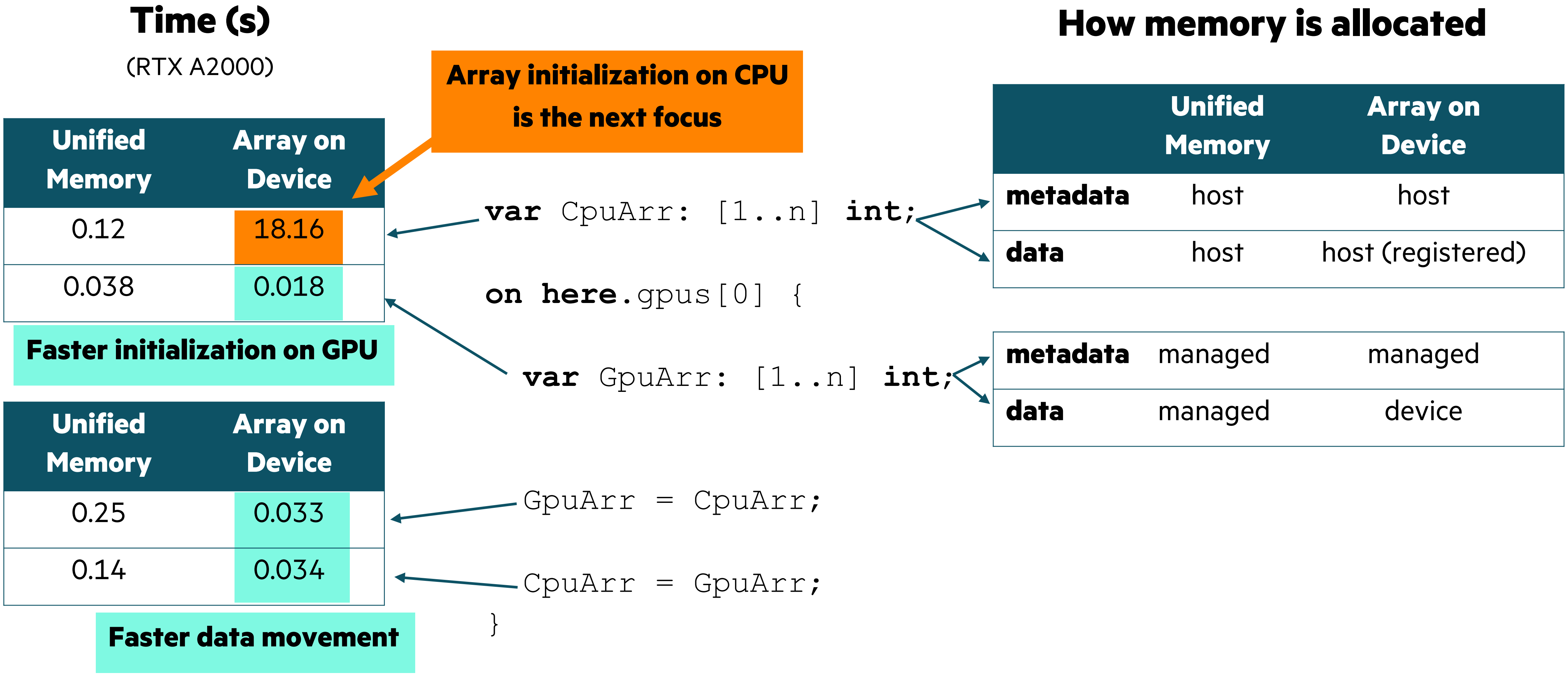
- 'unified_memory' is the default strategy, relies on managed memory
  - Allows both host and device to access memory, where the underlying layer migrates pages between device and host
  - Easy to program, not ideal for performance
  - Some GPU features can't be used with this mode
- 'array_on_device': Closer to conventional GPU programming
  - Array data is allocated on device memory, where metadata is still on managed memory for easy initialization
  - Probably the only way to support GPU-driven communication in an efficient way
  - Our implementation showed promising performance in some cases, but also had segfaults

This Effort: Made progress towards making 'array_on_device' the default strategy

- Segfaults are fixed
- Investigated its performance and discovered some issues

GPU SUPPORT

'array_on_device' Performance



Time (s)

(RTX A2000)

Unified Memory	Array on Device
0.12	18.16
0.038	0.018

Array initialization on CPU is the next focus

Faster initialization on GPU

Unified Memory	Array on Device
0.25	0.033
0.14	0.034

Faster data movement

```
var CpuArr: [1..n] int;

on here.gpus[0] {

  var GpuArr: [1..n] int;


  GpuArr = CpuArr;

  CpuArr = GpuArr;
}
```

How memory is allocated

	Unified Memory	Array on Device
metadata	host	host
data	host	host (registered)

metadata	managed	managed
data	managed	device

GPU SUPPORT

Study: ChOp

Background:

- **Ch**apel-based **Op**timization*
  - a user application that's part of our nightly performance tracking
  - branch-and-bound algorithms for combinatorial optimizations

This Effort:

- Initially Chapel was off by 10x from the reference version
  - with an application-level performance bug fixed, we were 2x off
- With the new profiler support, we profiled the Chapel version
  - application-level optimizations → ~1.8x improvement in Chapel
  - back-ported same optimizations to interop version → ~1.2x improvement
- We are about 15–20% off on NVIDIA

Next Steps:

- Investigate the source(s) of the remaining overhead
- Understand AMD performance better (in general and for ChOp)

N-Queens Performance with ChOp

(1x NVIDIA P100)

N	Interop (s)	Native (s)	Off by
15	0.30	0.36	*19%*
16	1.79	2.06	*15%*
17	12.47	14.76	*18%*
18	94.94	110.98	*17%*

(1x AMD MI100)

N	Interop (s)	Native (s)	Off by
15	0.40	0.55	*36%*
16	1.14	2.18	*91%*
17	6.36	13.28	*209%*
18	47.04	115.51	*246%*

*Tiago Carneiro , Nouredine Melab, Jan Gmys, Guillaume Helbecque. et al. — INRIA Lille, France; Imec, Belgium; University of Mons, Belgium; et al.

GPU SUPPORT

Study: SHOC-Sort and SHOC-Transpose

SHOC-Sort:

- A radix-sort implementation on the GPU
- Initial port was about 6–7x off from the base version
  - Dynamically creating and destroying lists on the host was a big source of overhead
- Fixing that, our implementation is closer to the base version in terms of behavior
  - currently, still 2x off

SHOC-Transpose:

- Tiled matrix transposition using shared memory
- We’ve implemented:
  - a naïve version, i.e.,

```
foreach (i,j) in Dom do A[i,j] = B[j,i];
```

  - an optimized implementation using tiling within the 'foreach' loop
  - a low-level version that uses non-user-facing ways to launch kernels
- The low-level version is within percentages of reference, others are 4x off
  - Naïve is expected to perform poorly over tiled one, the optimized version requires more investigation

GPU SUPPORT

Next Steps: Performance

- Fix expensive CPU array initialization on 'array_on_device' mode
  - This is expected to be resolved via a more general effort to improve CPU performance of the GPU locale model

- Investigate specializing AST for GPU code paths
  - This would involve code cloning/versioning during compilation to specialize code being executed on the GPU
  - Today, only the loop body is specialized by virtue of creating a kernel from it
    - 'on' statements or other functions called from the GPU aren’t specialized by the Chapel compiler

- Investigate loop-invariant code motion (LICM) improvements
  - Moving GPU transformation after LICM improved performance in many cases
    - However, LICM can be more aggressive, as we see invariants in GPU kernels in some cases
    - It can also help if LICM can reduce redundancy in cases where an array is accessed multiple times in a kernel

- Continue working on the benchmarks where performance is behind reference

NEXT STEPS

GPU SUPPORT

Summary: Highlights from 1.29 and 1.30

- AMD GPUs can be used in single-locale settings
  - Feature/correctness parity with NVIDIA except for missing support for some 64-bit math
  - Initial performance tests didn't point to any major issue, though it is behind NVIDIA in some cases
  - First run on Frontier using HPCC Stream
    - Very close performance to base at >10 TB/s bandwidth per node
- Significant performance improvements
  - 300x faster kernel launch
  - Performance optimizations that led to improvements in HPCC Stream, SHOC Triad, SHOC Sort, and ChOp
  - Application-level improvements in ChOP and SHOC Sort
- Usability improvements
  - Several new functions
    - gpuClock( ), gpuWriteln( ), setBlockSize( ), createSharedArray( ), syncThreads( )
  - Initial support for debugger and profilers

GPU SUPPORT

Proposed Next Steps for 1.31 and 1.32

Performance:

- Continue investigating low-performance cases
- Fix 'array_on_device' performance issues
  - make it the default memory strategy
- Improve non-GPU execution performance
- Investigate streams for better CPU/GPU overlap
- Gain experience with NVLink and ensure its utilization

Portability:

- Start working towards Intel GPU support
- Gain experience with EX

Features:

- Make progress on distributed array support
- Make progress on design of new features
  - querying task/thread/vector lane ids
  - block-synchronization
  - shared memory allocation
- Outer-loop vectorization for CPU

Explorations:

- Shadow variables in GPU kernels
- User applications
  - CHAMPS, Coral Image Analysis

OTHER GPU IMPROVEMENTS

OTHER GPU IMPROVEMENTS

For a more complete list of GPU support changes and improvements in the 1.29.0 and 1.30.0 releases, refer to the following sections in the CHANGES.md file:

- ‘GPU Computing’
- ‘Bug Fixes for GPU Computing’

THANK YOU

https://chapel-lang.org
@ChapelLanguage