Exploring a multi-resolution GPU programming model for Chapel

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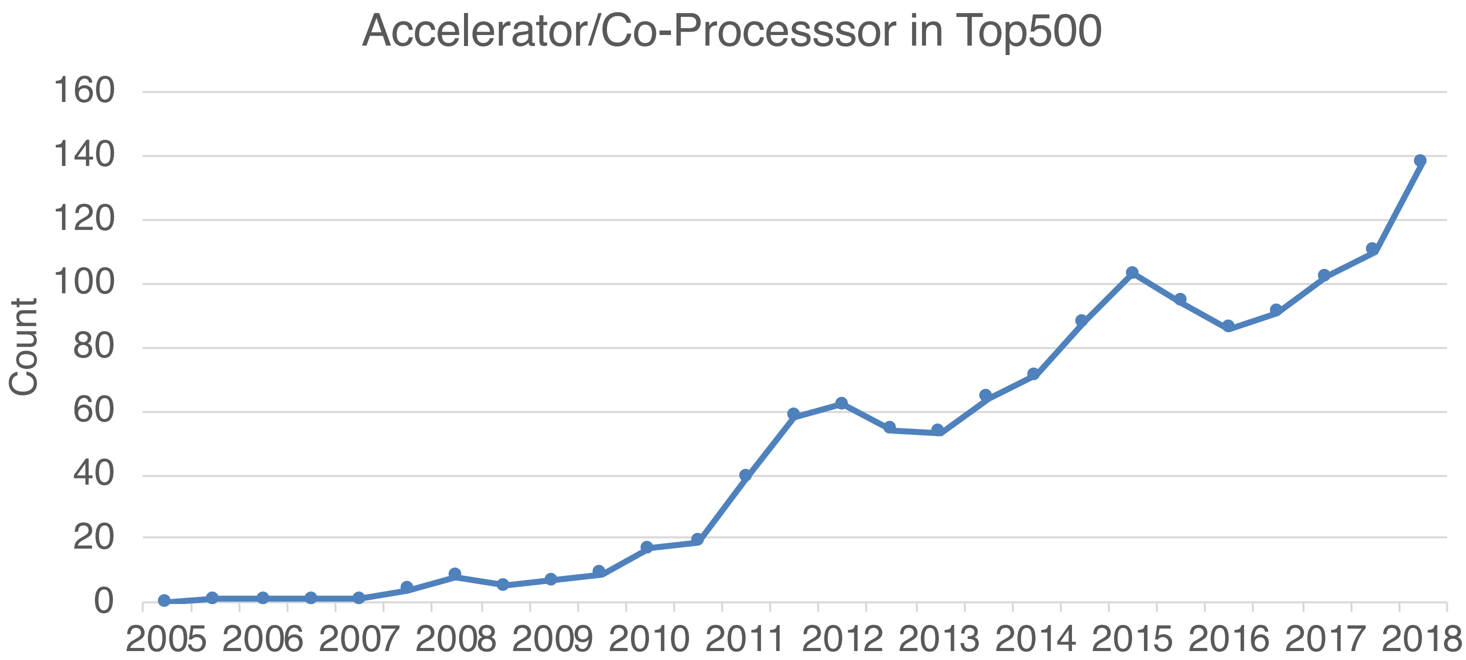
A multi-resolution GPU programming model for Chapel

MOTIVATION

GPUs are a common source of performance improvement in HPC



Aurora (ANL)
El Capitan(LLNL)
Frontier (ORNL)
all plan
to include GPUs!

2021

Source: https://www.top500.org/statistics/list/

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GPU Programming in Chapel

- Chapel's multi-resolution concept

High-level

  - Start with writing "forall" loops
    (on CPU, proof-of-concept)

```
forall i in 1..n {
  …
}
```

  - Apply automatic GPU code generators [1][2] when/where possible
  - Consider using the GPUIterator module [3] (Mason-registry)

Low-level

  - Consider writing GPU kernels using CUDA/HIP/OpenCL or other accelerator language, and invoke them from Chapel

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[1] Albert Sidelnik et al. Performance Portability with the Chapel Language (IPDPS '12).
[2] Michael L. Chu et al. GPGPU support in Chapel with the Radeon Open Compute Platform (CHIUW'17).
[3] Akihiro Hayashi et al. GPUIterator: Bridging the gap between Chapel and GPU Platforms (CHIUW'19).

Example:
STREAM (Original)

```
var A: [1..n] real(32);
var B: [1..n] real(32);
var C: [1..n] real(32);
// STREAM
forall i in 1..n {
  A(i) = B(i) + alpha * C(i);
}
```

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Example: STREAM (C interoperability)

- Invoking CUDA/HIP/OpenCL code using the C interoperability feature

```
extern proc GPUST(A: [] real(32),
                  B: [] real(32),
                  C: [] real(32),
                  al: real(32),
                  lo: int, hi: int);
var A: [1..n] real(32);
var B: [1..n] real(32);
var C: [1..n] real(32);
// Invoking CUDA/OpenCL program
GPUST(A, B, C, alpha, 1, n);
```

```
// separate C file
void GPUST(float *A,
           float *B,
           float *C,
           float al,
           int start,
           int end) {
  // CUDA/HIP/
     OpenCL Code
}
```

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Example: STREAM (GPUIterator)

- Connecting the GPU version with the forall loop using the GPUIterator module

```
// GPU Iterator (in-between)
var G = lambda (lo: int, hi: int,
                nElems: int) {
  GPUST(A, B, C, alpha, 1, n);
};
var CPUPercent = 50;
forall i in GPU(1..n, G, CPUPercent) {
  A(i) = B(i) + alpha * C(i);
}
```

```
// separate C file
void GPUST(float *A,
           float *B,
           float *C,
           float al,
           int start,
           int end) {
  // CUDA/HIP/
     OpenCL Code
}
```

Note: the GPUIterator is designed to facilitate 1) hybrid execution (CPUs+GPUs), and 2) distributed execution

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Example:
No appropriate GPU abstraction

Highest-level Chapel-GPU Programming

```
forall i in 1..n {
  A(i) = B(i) + alpha * C(i);
}
```

A huge gap!

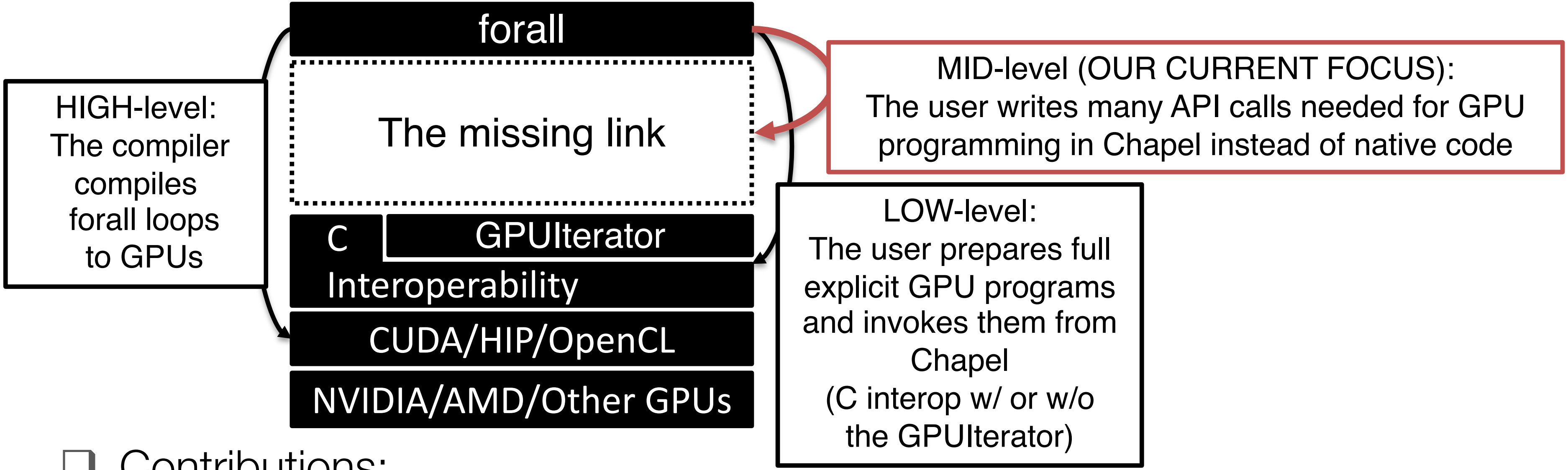
Lowest-level Chapel-GPU Programming (C Interoperability only or GPUIterator)

```
// separate C file
__global__ void stream(float *dA, float *dB, float *dC,
                       float alpha, int N) {
    int id = blockIdx.x * blockDim.x + threadIdx.x;
    if (id < N) {
        dA[id] = dB[id] + alpha * dC[id];
    }
}
void GPUST(float *A, float *B, float *C, float alpha,
           int start, int end, int GPUN) {
  float *dA, *dB, *dC;
  CudaSafeCall(cudaMalloc(&dA, sizeof(float) * GPUN));
  CudaSafeCall(cudaMalloc(&dB, sizeof(float) * GPUN));
  CudaSafeCall(cudaMalloc(&dC, sizeof(float) * GPUN));
  CudaSafeCall(cudaMemcpy(dB, B + start, sizeof(float) *
                          GPUN, cudaMemcpyHostToDevice));
  CudaSafeCall(cudaMemcpy(dC, C + start, sizeof(float) *
                          GPUN, cudaMemcpyHostToDevice));

  stream<<<ceil(((float)GPUN)/1024), 1024>>>
                                     (dA, dB, dC, alpha, GPUN);
  CudaSafeCall(cudaDeviceSynchronize());
  CudaSafeCall(cudaMemcpy(A + start, dA, sizeof(float) *
                          GPUN, cudaMemcpyDeviceToHost));
  CudaSafeCall(cudaFree(dA));
  CudaSafeCall(cudaFree(dB));
  CudaSafeCall(cudaFree(dC));
}
```

Research Question:
What is an appropriate and portable programming interface that bridges the "forall" and GPU versions?

Big Picture: A Multi-level Chapel GPU Programming Model



- Contributions:
  - Design and implementation of “MID”/” LOW-MID” levels Chapel GPU API
  - Performance evaluations on different distributed and single-node platforms (Summit, Cori, and a single-node AMD machine)

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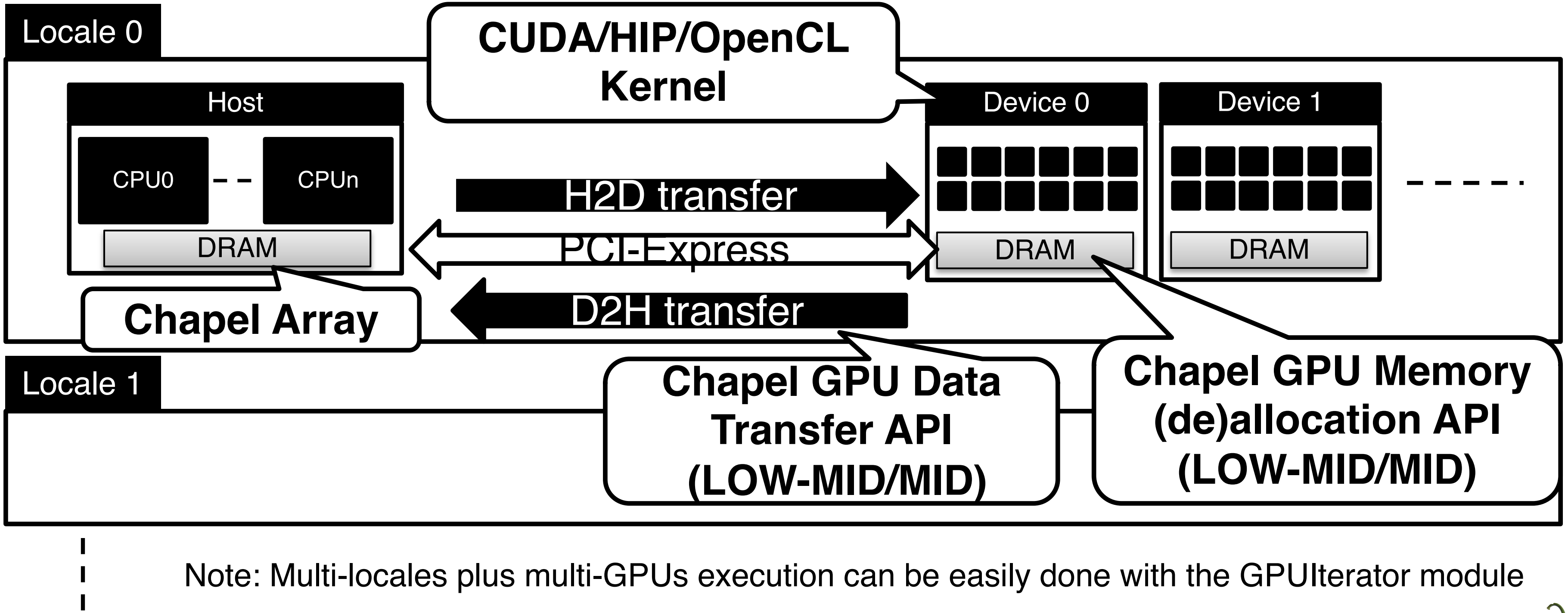
DESIGN

An overview of the LOW-MID/MID GPU API for Chapel



Note: Multi-locales plus multi-GPUs execution can be easily done with the GPUIterator module

Chapel GPU API Design: Summary

- Use case:
  - The user would like to 1) write GPU kernels, or 2) utilize highly-tuned GPU libraries, and would like to stick with Chapel for the other parts (allocation, data transfers)
- Provides two levels of GPU API
  - LOW-MID: Provides wrapper functions for raw GPU APIs

    Example: `var ga: c_void_ptr = GPUAPI.Malloc(sizeInBytes);`
  - MID: Provides more user-friendly APIs

    Example: `var ga = new GPUArray(A);`
- Important design decisions
  - The user is still supposed to write kernels in CUDA/HIP/OpenCL
  - The APIs significantly facilitates the orchestration of:
    - ✓ Device memory (de)allocation, and host-to-device/device-to-host data transfers,
  - The use of the APIs does not involve any modifications to the Chapel compiler

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Chapel GPU API Design: LOW-MID GPU API

- Summary
  - Provides the same functionality as CUDA/HIP/OpenCL
  - The user is still supposed to write CUDA/HIP/OpenCL kernels
  - The user is supposed to handle both C types and Chapel types
- Key APIs
  - Device Memory Allocation
    - ✓ `Malloc(ref devPtr: c_void_ptr, size: size_t);`
  - Host-to-device, and device-to-host data transfers
    - ✓ `Memcpy(dst: c_void_ptr, src: c_void_ptr, count: size_t, direction: int);`
  - Ensuring the completion of GPU computations
    - ✓ `DeviceSynchronize(void);`
  - Device Memory deallocation
    - ✓ `Free(c_void_ptr);`

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Chapel GPU API Design: MID GPU API

- Summary
  - More natural to Chapel programmers
  - The user is still supposed to write CUDA/HIP/OpenCL kernels
- Key APIs
  - Device Memory Allocation
    - ✓ `var dA = new GPUArray(A);`
  - Host-to-device, and device-to-host data transfers
    - ✓ `ToDevice(dA:GPUArray, …); FromDevice(dA: GPUArray, …);`
    - ✓ `dA.ToDevice(); dA.fromDevice();`
  - Device Memory deallocation
    - ✓ `Free(dA:GPUArray, …);`
    - ✓ `dA.Free();`

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Chapel GPU API Design: LOW-MID/MID GPU API Example

LOW-MID Level

```
use GPUAPI;
var A: [1..n] real(32);
var B: [1..n] real(32);
var C: [1..n] real(32);
var dA, dB, dC: c_void_ptr;
var size: size_t =
   (A.size:size_t * c_sizeof(A.eltType));
Malloc(dA, size);
Malloc(dB, size);
Malloc(dC, size);
Memcpy(dB, c_ptrTo(B), size, TODEVICE);
Memcpy(dC, c_ptrTo(C), size, TODEVICE);
LaunchST(dA, dB, dC, alpha, N: size_t);
DeviceSynchronize();
Memcpy(c_ptrTo(A), dA, size, FROMDEVICE);
Free(dA); Free(dB); Free(dC);
```

MID-level

```
use GPUAPI;
var A: [1..n] real(32);
var B: [1..n] real(32);
var C: [1..n] real(32);
var dA = new GPUArray(A);
var dB = new GPUArray(B);
var dC = new GPUArray(C);
toDevice(dB, dC);
LaunchST(dA.dPtr(), dB.dPtr(),
         dC.dPtr(), alpha,
         dN: size_t);
DeviceSynchronize();
FromDevice(dA);
Free(dA, dB, dC);
```

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Example: Single-node execution of STREAM (MID-level w/ GPUIterator)

```
var A: [1..n] real(32);
var B: [1..n] real(32);
var C: [1..n] real(32);
var GPUCallBack = lambda (lo: int, hi: int, nElems: int) {
  var dA = new GPUArray(A);
  var dB = new GPUArray(B);
  var dC = new GPUArray(C);
  toDevice(dB, dC);
  LaunchST(dA.dPtr(), dB.dPtr(),
           dC.dPtr(), alpha,
           dN: size_t);
  DeviceSynchronize();
  FromDevice(dA);
  Free(dA, dB, dC);
};
forall i in GPU(1..n, GPUCallBack,
                      CPUPercent) {
  A(i) = B(i) + alpha * C(i);
}
```

The user has the option of writing a device function(s), a device lambda(s), or a library call(s)

```
// separate C file (CUDA w/ device lambda)
void LaunchST(float *dA, float *dB,
              float *dC, float alpha, int N) {
  GPU_FUNCTOR(N, 1024, NULL,
    [=] __device__ (int i) {
      dA[i] = dB[i] + alpha * dC[i];
    });
}
```

Example: Distributed execution of STREAM (MID-level w/ GPUIterator)

```
var D: domain(1) dmapped Block(boundingBox={1..n}) = {1..n};
var A: [D] real(32);
var B: [D] real(32);
var C: [D] real(32);
var GPUCallBack = lambda (lo: int, hi: int, nElems: int) {
  var dA = new GPUArray(A.localSlice(lo..hi));
  var dB = new GPUArray(B.localSlice(lo..hi));
  var dC = new GPUArray(C.localSlice(lo..hi));
  toDevice(dB, dC);
  LaunchST(dA.dPtr(), dB.dPtr(),
           dC.dPtr(), alpha,
           dN: size_t);
  DeviceSynchronize();
  FromDevice(dA);
  Free(dA, dB, dC);
};
forall i in GPU(D, GPUCallBack,
                   CPUPercent) {
  A(i) = B(i) + alpha * C(i);
}
```

The user has the option of writing a device function(s), a device lambda(s), or a library call(s)

```
// separate C file (CUDA w/ device lambda)
void LaunchST(float *dA, float *dB,
              float *dC, float alpha, int N) {
  GPU_FUNCTOR(N, 1024, NULL,
    [=] __device__ (int i) {
      dA[i] = dB[i] + alpha * dC[i];
    });
}
```

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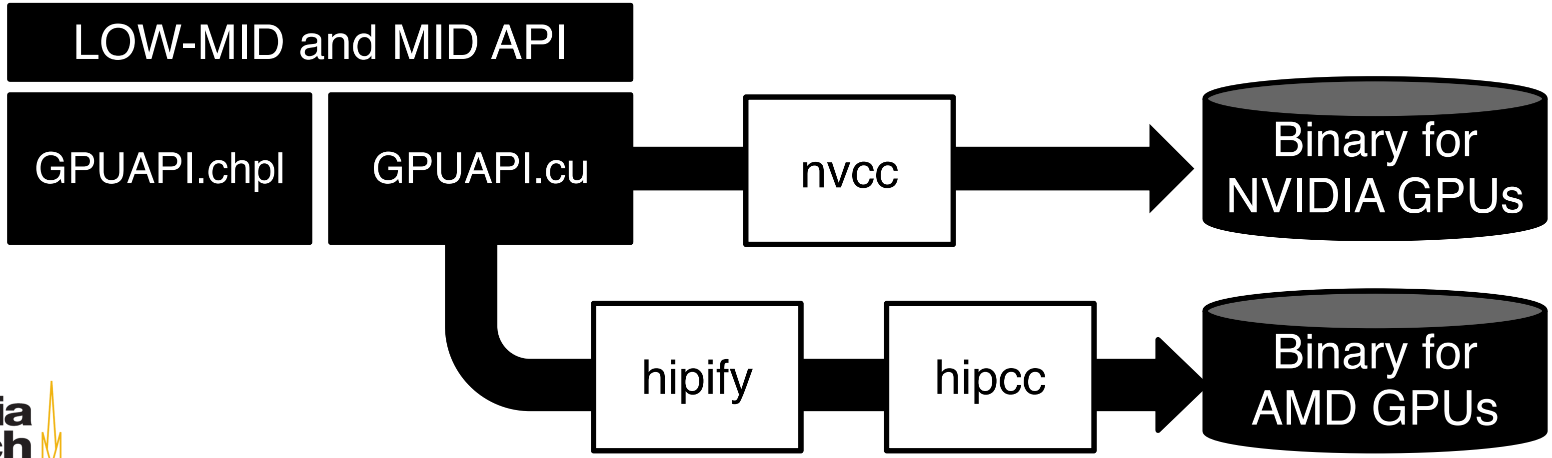
IMPLEMENTATION

Implementation of GPU API

- Provides an external module (GPUAPI)
  - Can be used either stand-alone or with the GPUIterator module
  - https://github.com/ahayashi/chapel-gpu
    - ✓ The “feature/explicit” branch
- Currently supports NVIDIA and ROCM-ready AMD GPUs



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PERFORMANCE EVALUATIONS

Performance Evaluations

- ❑ Platforms
  - Cori GPU@NERSC: Intel Xeon (Skylake) + NVIDIA V100 GPU
  - Summit@ORNL: IBM POWER9 + NVIDIA Tesla V100 GPU
  - A single-node AMD machine: Ryzen9 3900 + Radeon RX570
- ❑ Chapel Compilers & Options
  - Chapel Compiler 1.20.0 with the --fast option
- ❑ GPU Compilers
  - CUDA: NVCC 10.2 (Cori), 10.1 (Summit) with the -O3 option
  - AMD: ROCM 2.9.6, HIPCC 2.8 with the -O3 option

Performance Evaluations (Cont'd)

- Tasking & Multi-locale execution
  - CHPL_TASK=qthreads
  - CHPL_COMM=gasnet
  - CHPL_COMM_SUBSTRATE=ibv
- GPUIterator (For distributed GPU execution)
  - https://github.com/ahayashi/chapel-gpu/tree/feature/explicit
- Applications
  - Stream
  - BlackScholes
  - Matrix Multiplicaiton
  - Logistic Regression
  - Source code can be found at: https://github.com/ahayashi/chapel-gpu/tree/feature/explicit/apps

How many lines are added/modified?

	LOC Baseline (Chapel LOW + CUDA)	LOC LOW-MID (Chapel LOW-MID + CUDA)	LOC MID (Chapel MID + CUDA)
Stream	4 + 24 = 28	16 + 9 = 25	11 + 9 = 20
BlackScholes	4 + 99 = 103	16 + 83 = 99	11 + 83 = 94
Logistic Regression	2 + 36 = 38	16 + 18 = 34	10 + 18 = 28
Matrix Multiplication	3 + 30 = 33	14 + 15 = 29	10 + 16 = 26

- ☐ The use of GPU API decreases LOC

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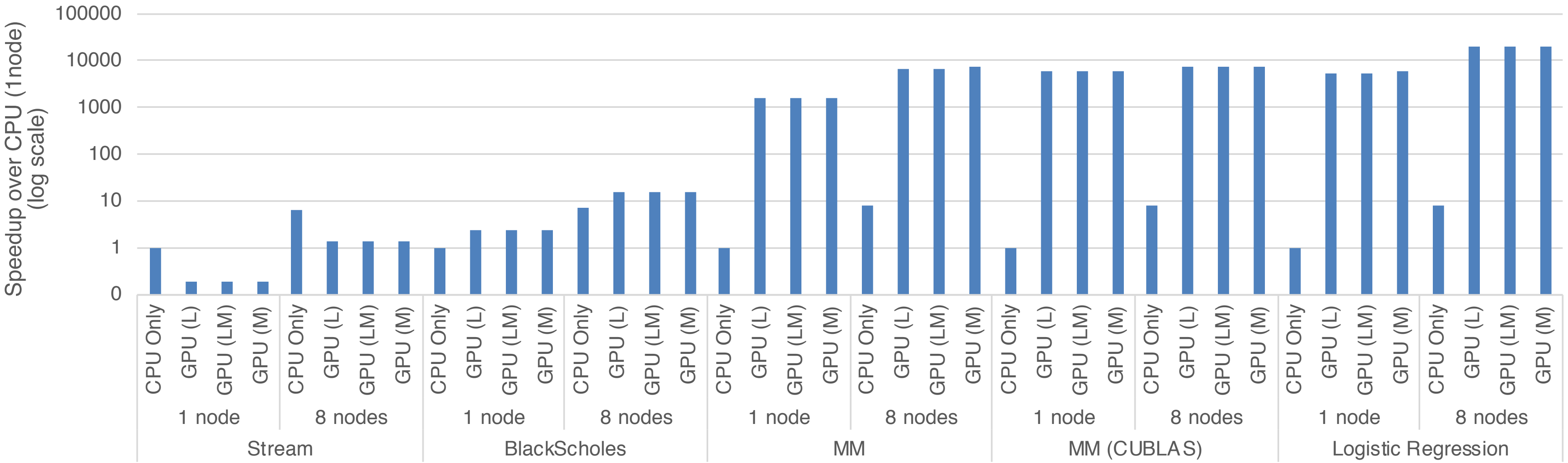
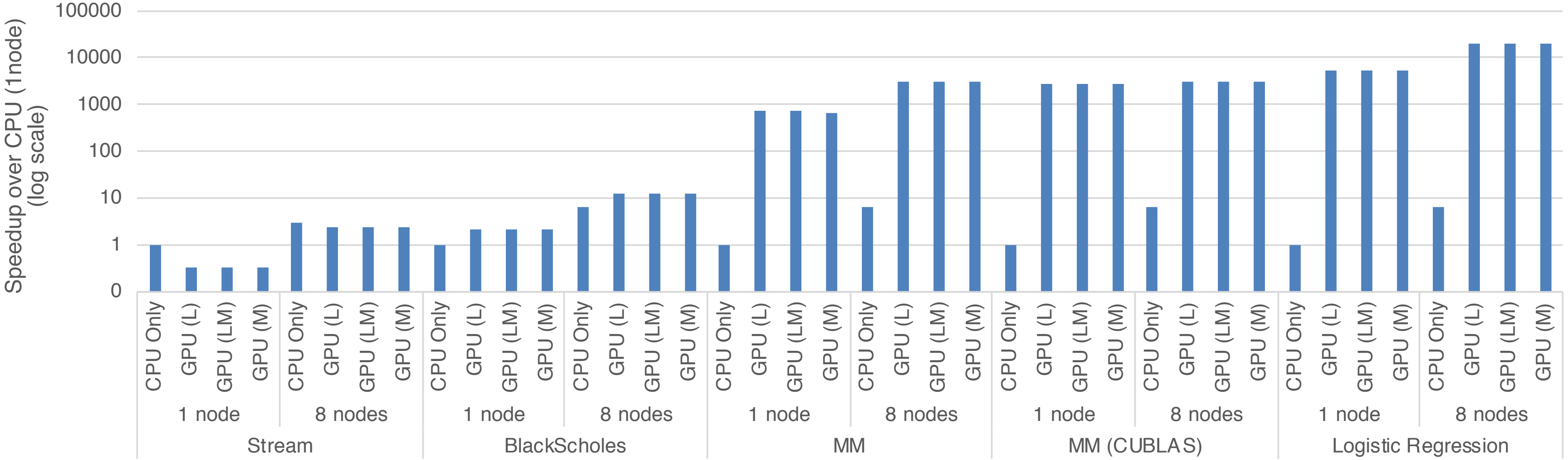
How fast are GPUs? (Multi-nodes, 1GPU/node, Cori)



- Each app shows good strong scalability
- No significant performance difference between L (LOW), LM (LOW-MID), and M (MID)

Data Size: n = 2^30 (Stream, BlackScholes)
4096x4096 (MM) nFeatures = 2^18, nSamples = 2^4

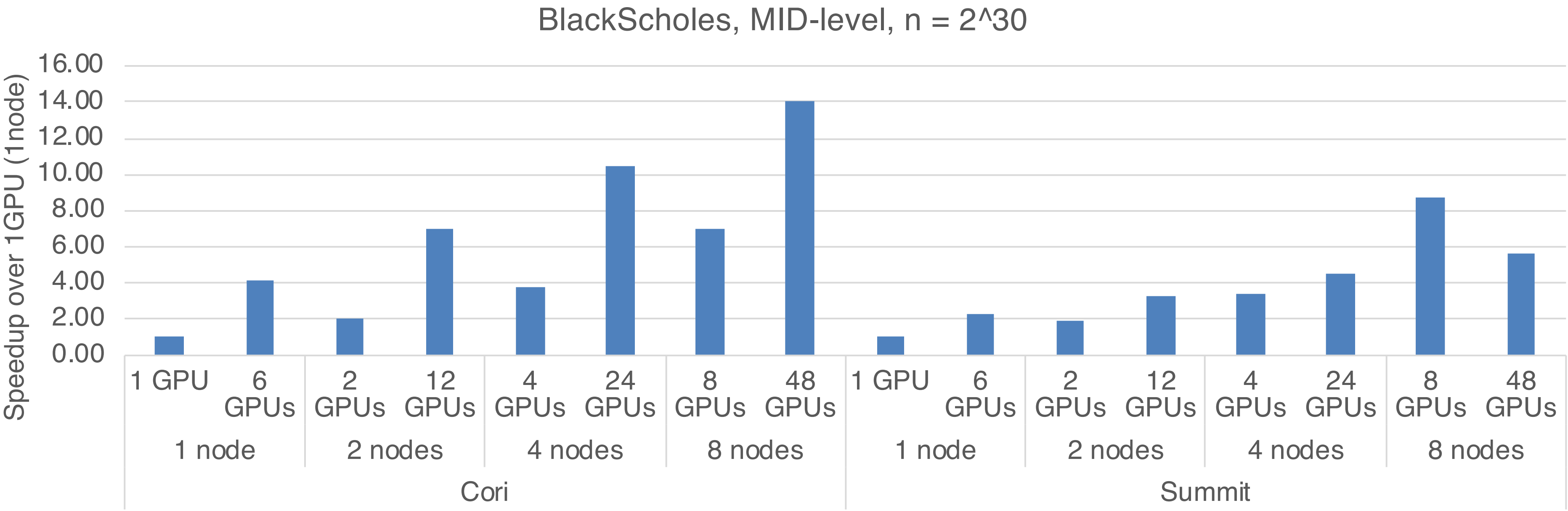
How fast are GPUs? (Multi-nodes, 1GPU/node, Summit)



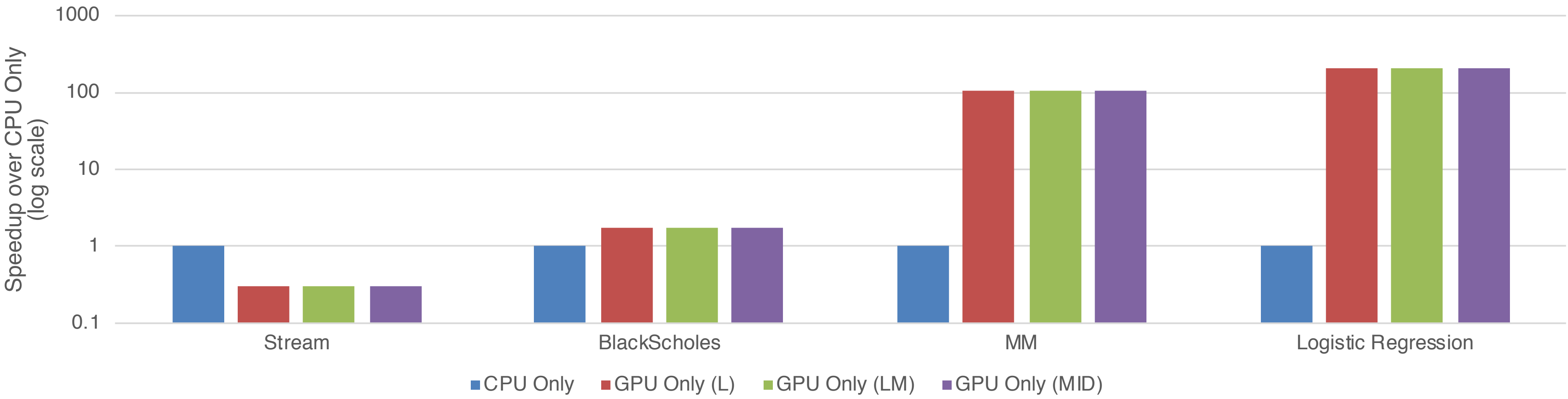
- ❑ Each app shows good strong scalability
- ❑ No significant performance difference between L (LOW), LM (LOW-MID), and M (MID)

Data Size: n = 2^30 (Stream, BlackScholes)
4096x4096 (MM) nFeatures = 2^18, nSamples = 2^4

How fast are GPUs? (Multi-nodes, 6GPUs/node, Cori, Summit)



How fast are GPUs? (A single-node, Ryzen9 + Radeon RX570)



- ❑ The GPUAPI works on an AMD GPU machine

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CONCLUSIONS & FUTURE WORK

Conclusions

- Summary
  - The GPUAPI provides an appropriate interface between Chapel and accelerator programs
    - ✓ Souce code is available (the feature/explicit branch):
      - https://github.com/ahayashi/chapel-gpu
  - The LOW-MID and MID level GPU API enable a higher-level GPU programming interface w/ minimal performance overhead
    - ✓ Verified on NVIDIA and AMD GPUs
  - The GPUAPI + the GPUIterator module facilitate distributed GPU programming using Chapel
    - ✓ Verified on Summit and Cori
    - ✓ The use of GPUs can significantly improve the performance of Chapel programs

Future Work

- Building a higher-level programming model
  - Built on top of the MID-level API
  - forall + “intents”

```
forall i in D with (in: B, out: A) {…}
=>
var dA = GPUArray(A); var dB = GPUArray(B); toDevice(B);
kernel(); fromDevice(A);
```

  - For the kernel code generation, will explore the possibility of avoiding/minimizing compiler modifications
    - ✓ e.g., generate a C/C++ loop + OpenMP/OpenACC/Other pragma
      - Chapel’s Vectorizing Iterator does a similar thing (vectorizeOnly())
- Asynchronous GPU API + Futures

Future work (Cont'd)

- Wish List: lambda + capture by reference

Current MID-level

```
use GPUAPI;
var A: [1..n] real(32);
var B: [1..n] real(32);
var dA = new GPUArray(A);
var dB = new GPUArray(B);
toDevice(dB);
LaunchVC(dA.dPtr(),
         dB.dPtr(), N: size_t);
DeviceSynchronize();
FromDevice(dA);
Free(dA, dB);
```

If dA, dB, N can be captured…

```
use GPUAPI;
var A: [1..n] real(32);
var B: [1..n] real(32);
var dA = new GPUArray(A);
var dB = new GPUArray(B);
var in = (dB); // tuple
var out = (dA); // tuple
Launch (in, out, lambda () {
 LaunchVC(dA.dPtr(),
          dB.dPtr(), N: size_t);
});
```

Thank you for your attention!

Any questions?

Backup Slides

Chapel’s iterator

- Chapel’s iterator allows us to control over the scheduling of the loops in a productive manner

```
// Iterator over fibonacci numbers
forall i in fib(10) {
  A(i) = B(i);
}
```

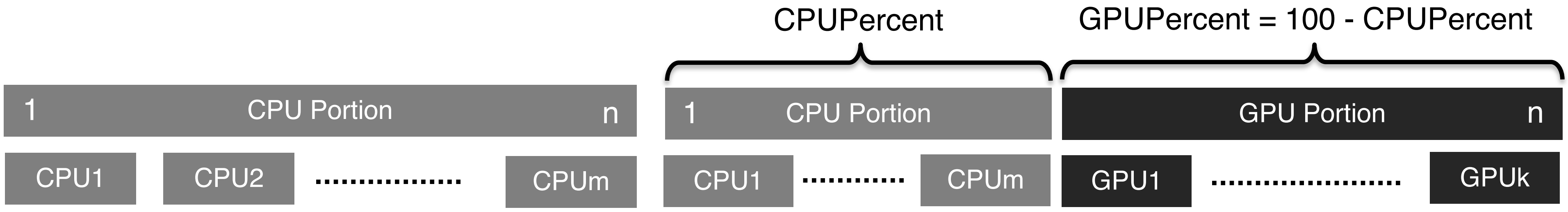
CPU1					CPU2				
0	1	1	2	3	5	8	13	21	34

https://chapel-lang.org/docs/master/primers/parIters.html

The GPUIterator automates work distribution across CPUs+GPUs

```
forall i in 1..n {
  A(i) = B(i);
}
```

```
forall i in GPU(1..n, GPUWrapper,
                CPUPercent) {
  A(i) = B(i);
}
```



How to use the GPUIterator?

```
var GPUCallBack = lambda (lo: int,
                          hi: int,
                      nElems: int){
  assert(hi-lo+1 == nElems);
  GPUVC(A, B, lo, hi);
};
forall i in GPU(1..n, GPUCallBack,
                      CPUPercent) {
  A(i) = B(i);
}
```

This callback function is called after the GPUIterator has computed the subspace (lo/hi: lower/upper bound, n: # of elements)

GPU() internally divides the original iteration space for CPUs and GPUs

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Tip: declaring CPUPercent as a command-line override ("config const") helps us to explore different CPU+GPU executions

The GPUIterator supports Zippered-forall

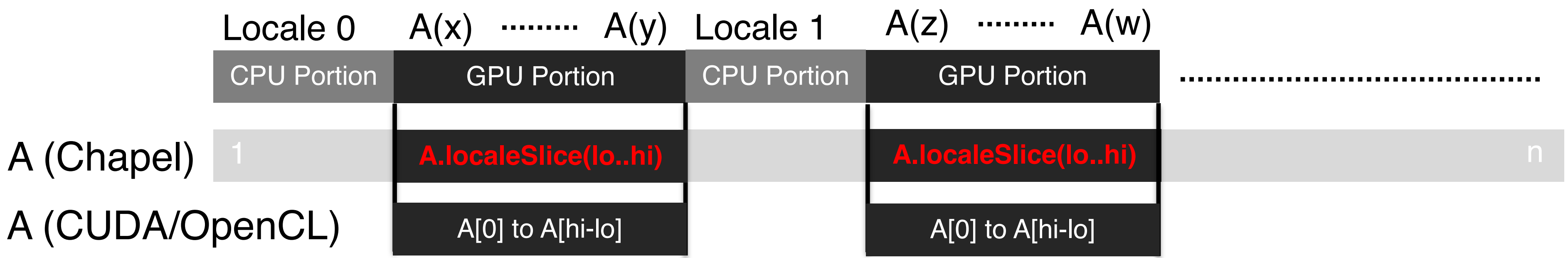
```
forall (_, a, b) in zip(GPU(1..n, ...), A, B) {
  a = b;
}
```

- Restriction
  - The GPUIterator must be the leader iterator

Bradford L. Chamberlain et al. “User-Defined Parallel Zippered Iterators in Chapel.” (PGAS2011)

The GPUIterator supports Distributed Arrays (Cont'd)

- No additional modifications for supporting multi-locales executions

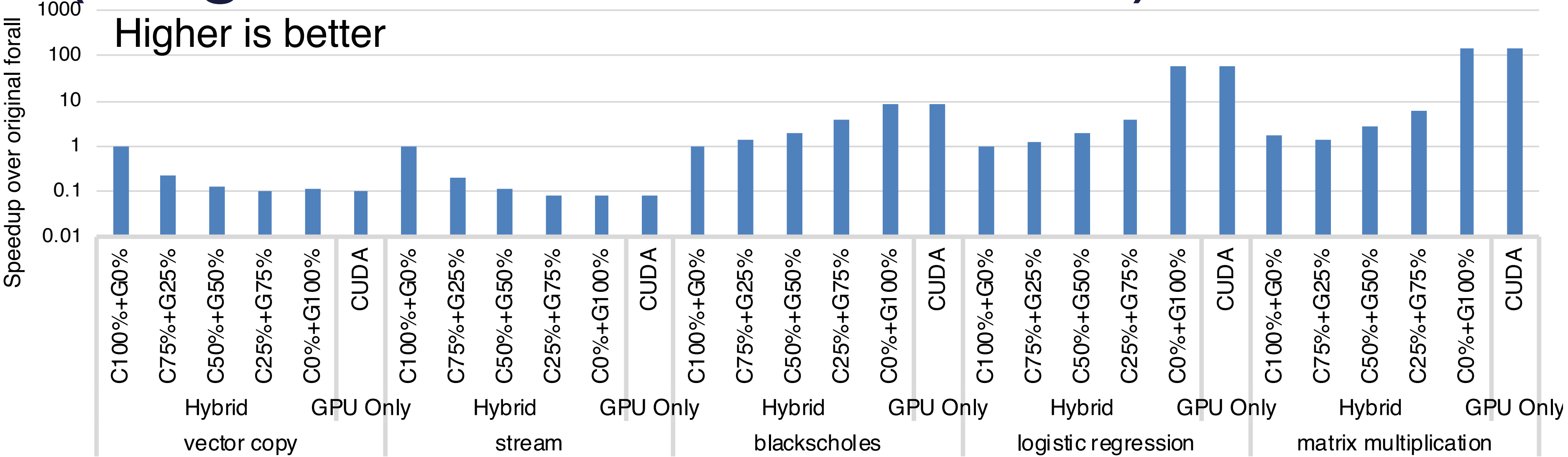


Note: localeSlice is Chapel's array API

Implementation of the GPUIterator

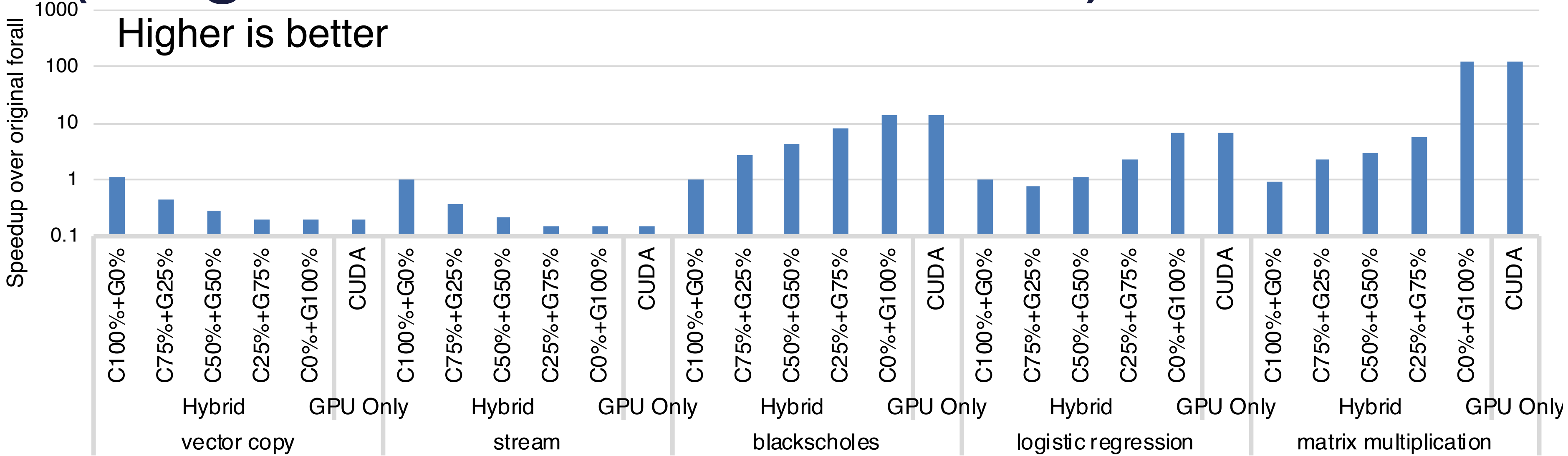
```
coforall subloc in 0..1 {
  if (subloc == 0) {
     const numTasks = here.getChild(0).maxTaskPar;
     coforall tid in 0..#numTasks {
       const myIters = computeChunk(…);
       for i in myIters do
         yield i;
     }
  } else if (subloc == 1) {
     GPUCallBack(…);
  }
}
```

How fast are GPUs? (Single-node, POWER8 + K80)



- The iterator enables exploring different CPU+GPU strategies with very low overheads
- The GPU is up to 145x faster than the CPU, but is slower than the GPU due to data transfer costs in some cases

How fast are GPUs? (Single-node, Xeon + M2050)



- The iterator enables exploring different CPU+GPU strategies with very low overheads
- The GPU is up to 126x faster than the CPU, but is slower than the GPU due to data transfer costs in some cases

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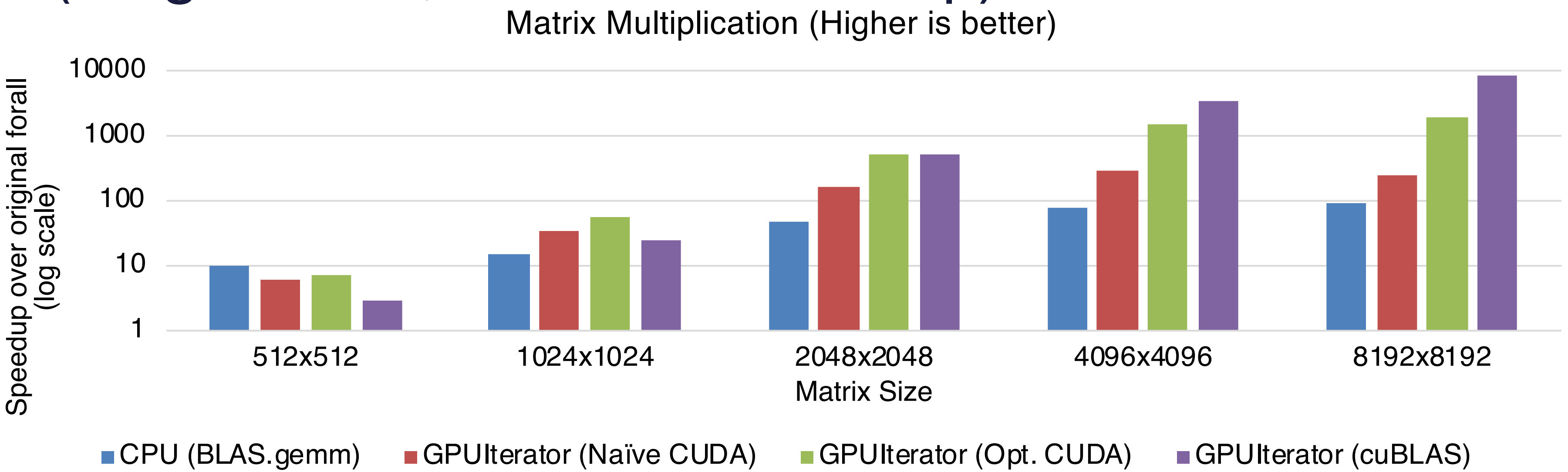
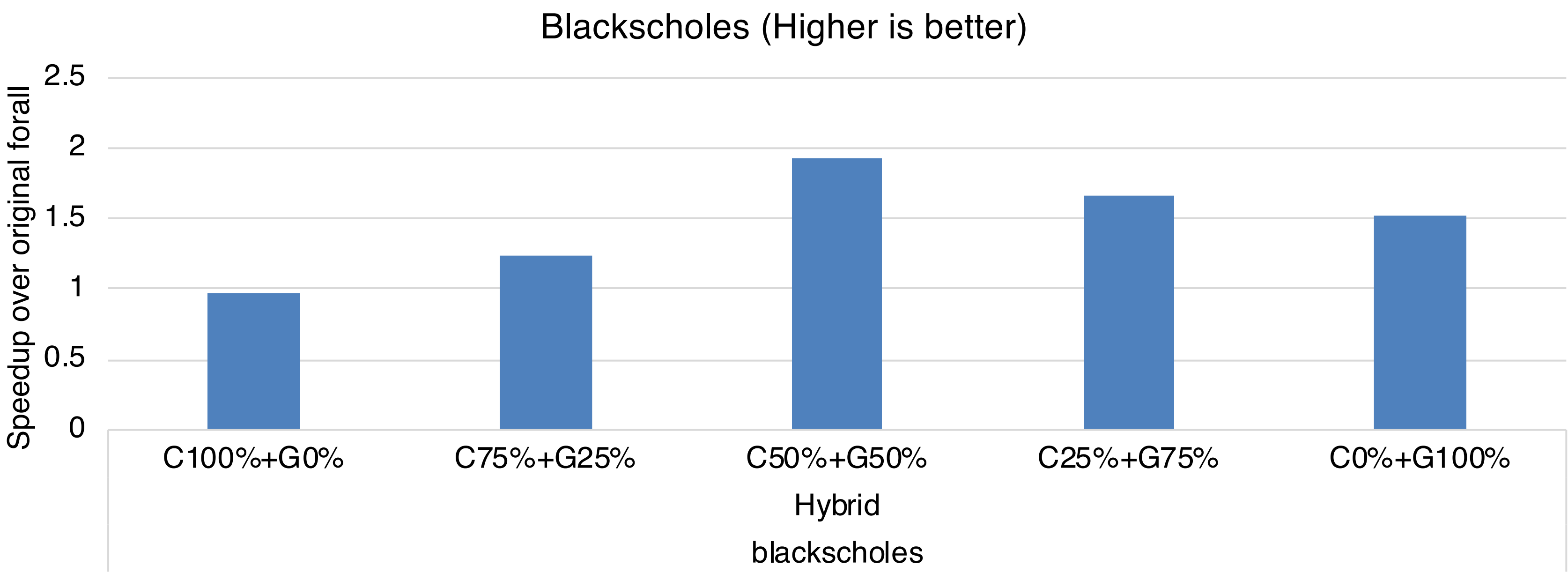
How fast are GPUs compared to Chapel's BLAS module on CPUs? (Single-node, Core i5 + Titan Xp)



- Motivation: to verify how fast the GPU variants are compared to a highly-tuned Chapel-CPU variant
- Result: the GPU variants are mostly faster than OpenBLAS's gemm (4 core CPUs)

When is hybrid execution beneficial? (Single node, Core i7+UHD)



- ❑ With tightly-coupled GPUs, hybrid execution is more beneficial

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