GENERATING GPU KERNELS FROM CHAPEL'S FEATURES FOR PARALLELISM AND LOCALITY

Engin Kayraklioglu, Andy Stone, David Iten, Sarah Nguyen,
Bradford L. Chamberlain, Michael Ferguson and Michelle Strout
Hewlett Packard Enterprise

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WHAT IS CHAPEL?

Chapel: A modern parallel programming language

- portable & scalable
- open-source & collaborative

Goals:

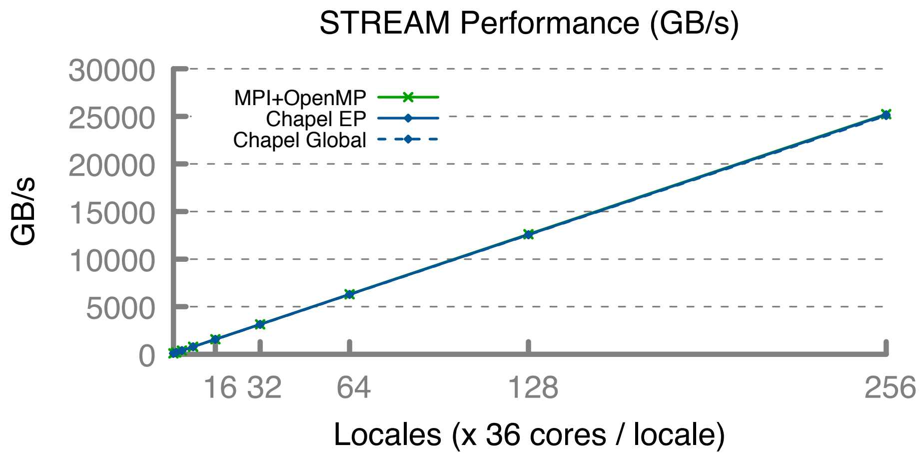
- Support general parallel programming
- Make parallel programming at scale far more productive

CHAPEL BENCHMARKS TEND TO BE CONCISE, CLEAR, AND COMPETITIVE

STREAM TRIAD: C + MPI + OPENMP

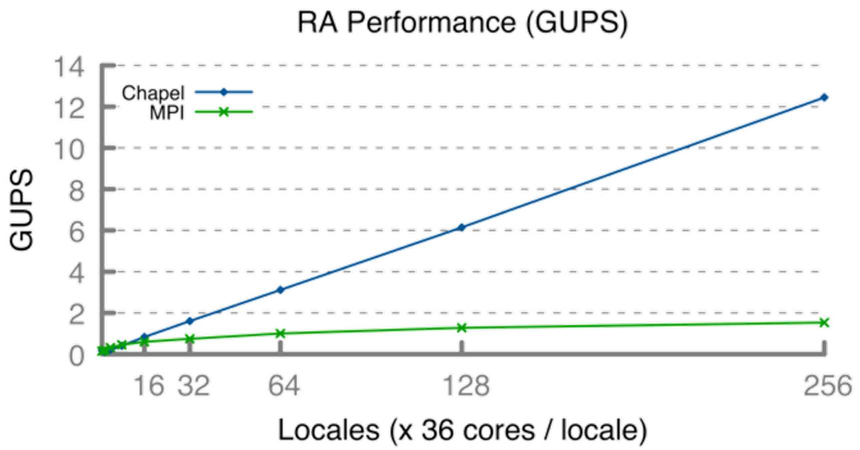
```c
#include <hpcc.h>
#ifdef _OPENMP
#include <omp.h>
#endif

static int VectorSize;
static double *a, *b, *c;

int HPCC_StarStream(HPCC_Params *params) {
  int myRank, commSize;
  int rv, errCount;
  MPI_Comm comm = MPI_COMM_WORLD;

  MPI_Comm_size( comm, &commSize );
  MPI_Comm_rank( comm, &myRank );

  rv = HPCC_Stream( params, 0 == myRank);
  MPI_Reduce( &rv, &errCount, 1, MPI_INT, MPI_SUM, 0, comm );

  return errCount;
}

int HPCC_Stream(HPCC_Params *params, int doIO) {
  register int j;
  double  scalar;

  VectorSize = HPCC_LocalVectorSize( params, 3, sizeof(double), 0 );

  a = HPCC_XMALLOC( double, VectorSize );
  b = HPCC_XMALLOC( double, VectorSize );
  c = HPCC_XMALLOC( double, VectorSize );

  if (!a || !b || !c) {
    if (c) HPCC_free(c);
    if (b) HPCC_free(b);
    if (a) HPCC_free(a);
    if (doIO) {
      fprintf( outFile, "Failed to allocate memory
      fclose( outFile );
    }
    return 1;
  }

#ifdef _OPENMP
#pragma omp parallel for
#endif
  for (j=0; j<VectorSize; j++) {
    b[j] = 2.0;
    c[j] = 1.0;
  }
  scalar = 3.0;

#ifdef _OPENMP
#pragma omp parallel for
#endif
  for (j=0; j<VectorSize; j++)
    a[j] = b[j]+scalar*c[j];

  HPCC_free(c);
  HPCC_free(b);
  HPCC_free(a);

  return 0;
}
```

```chapel
use BlockDist;

config const m = 1000,
             alpha = 3.0;

const Dom = {1..m} dmapped …;
var A, B, C: [Dom] real;

B = 2.0;
C = 1.0;

A = B + alpha * C;
```

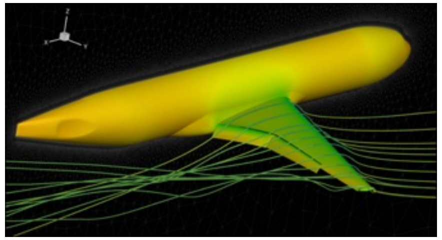


HPCC RA: MPI KERNEL

```chapel
forall (_, r) in zip(Updates, RAStream()) do
  T[r & indexMask].xor(r);
```



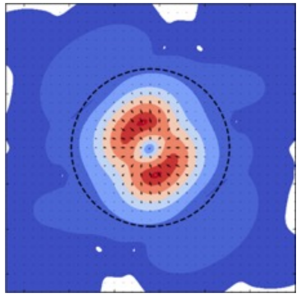
CURRENT FLAGSHIP CHAPEL APPLICATIONS



CHAMPS: 3D Unstructured CFD

Éric Laurendeau, Simon Bourgault-Côté, Matthieu Parenteau, et al.

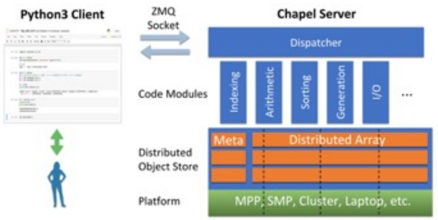
École Polytechnique Montréal



ChplUltra: Simulating Ultralight Dark Matter

Nikhil Padmanabhan, J. Luna Zagorac, *et al.*

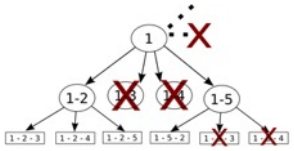
Yale University / University of Auckland



Arkouda: NumPy at Massive Scale

Mike Merrill, Bill Reus, et al.

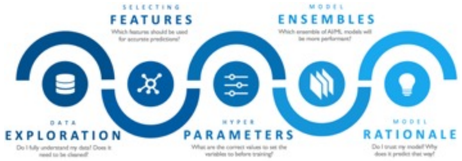
US DoD



ChOp: Chapel-based Optimization

Tiago Carneiro, Nouredine Melab, *et al.*

INRIA Lille, France



CrayAI: Distributed Machine Learning

Hewlett Packard Enterprise

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Your application here?

GPU PROGRAMMING IN CHAPEL
Overview

- We are developing support for GPU programming in Chapel
  - GPUs are very common, yet challenging to program
  - GPU support is frequently asked about by users
  - it would improve upon Chapel's "any parallel algorithm on any parallel hardware" theme

Collaborations / External Studies

- early work at UIUC [1] [2]
- partnership with AMD [3] [4] [5]
- recent work from Georgia Tech and ANU, featured at CHIUW 2019 [6], CHIUW 2020 [7] and CHIUW 2021 [8]
- meanwhile, user applications have run on GPUs via Chapel interoperability features (e.g., ChOp and CHAMPS)

Rough Timeline

- **August 2020:** Design effort and discussions start
- **1.24 (March 2021):** Can use non-user-facing features to generate GPU binaries for Chapel functions and launch them
- **1.25 (September 2021):** Can natively translate order-independent loops into GPU kernels that are automatically launched

WHAT'S TO COME IN THIS TALK

GPU Codegen from Chapel

User's loop

```
forall i in 1..n do arr[i] = i*mul;
```

The loop is replaced with:

```
if executingOnGPUSublocale()
  launch_kernel('kernel', n-1, 512, 1, 0,
                n, 0, &arr, 32, mul, 0);
else
  for (i=1 ; i<=n ; i++) {
    int *arrData = arr->data;
    int *addrToChange = &arrData[i];
    int newVal = i*mul;
    *addrToChange = newVal;
  }
```

Generated GPU kernel looks like:

```
__global__
void kernel(int startIdx, int endIdx,
            int *arrArg, int mulArg) {
  int blockIdxX  = __primitive('gpu blockIdx x');
  int blockDimX  = __primitive('gpu blockDim x');
  int threadIdxX = __primitive('gpu threadIdx x');

  int t0 = blockIdxX * blockDimX;
  int t1 = t0 + threadIdxX;
  int index = t1 + startIdx;

  bool chpl_is_oob = index > endIdx;
  if (chpl_is_oob) { return; }

  int arrData = arrArg->data;
  int *addrToChange = &arrData[index];
  int newVal = myIdx*mulArg;
  *addrToChange = newVal;
}
```

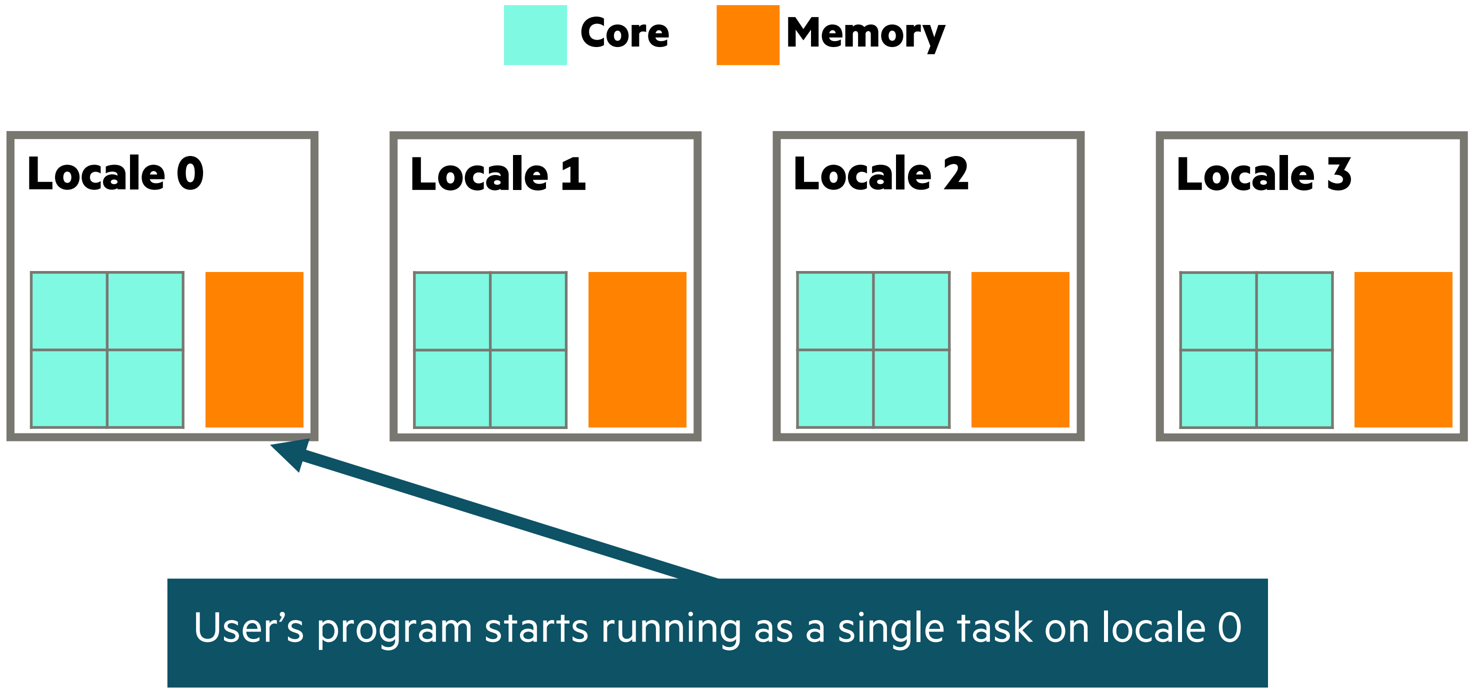
PARALLELISM AND LOCALITY AS FIRST-CLASS CONCEPTS

THE LOCALE: CHAPEL'S KEY FEATURE FOR LOCALITY

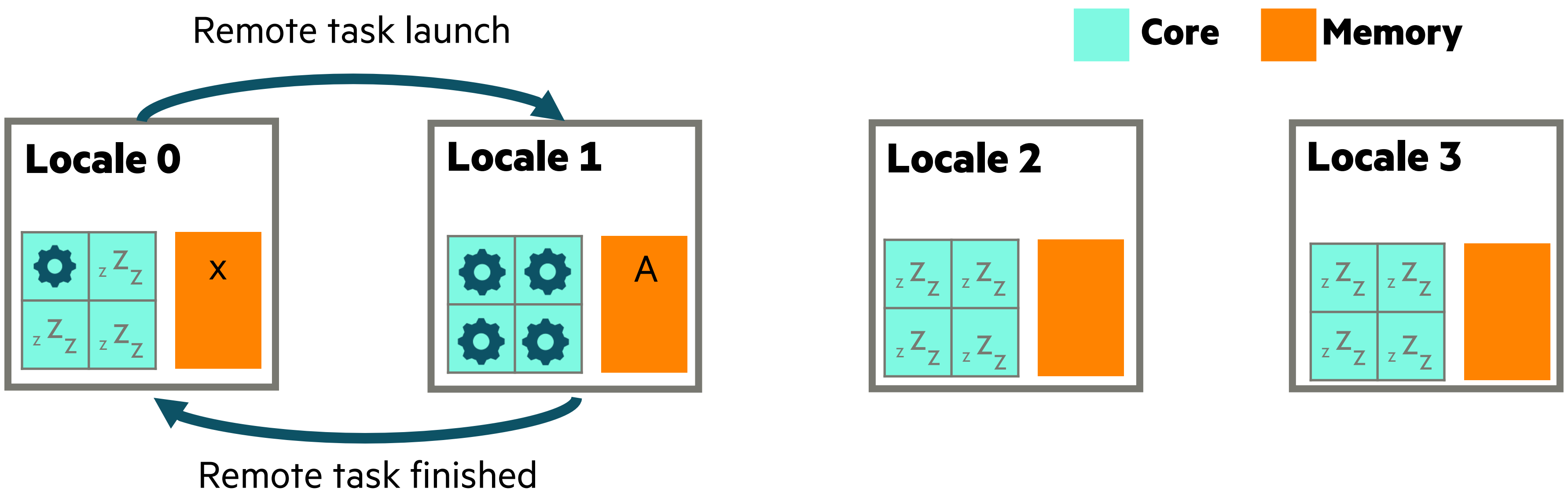
- *locale:* a unit of the target architecture that can run tasks and store variables
  - Think "compute node" on a typical HPC system

```
prompt> ./myChapelProgram --numLocales=4    # or '-nl 4'
```

`Locales` array:



PARALLELISM AND LOCALITY IN ONE SLIDE



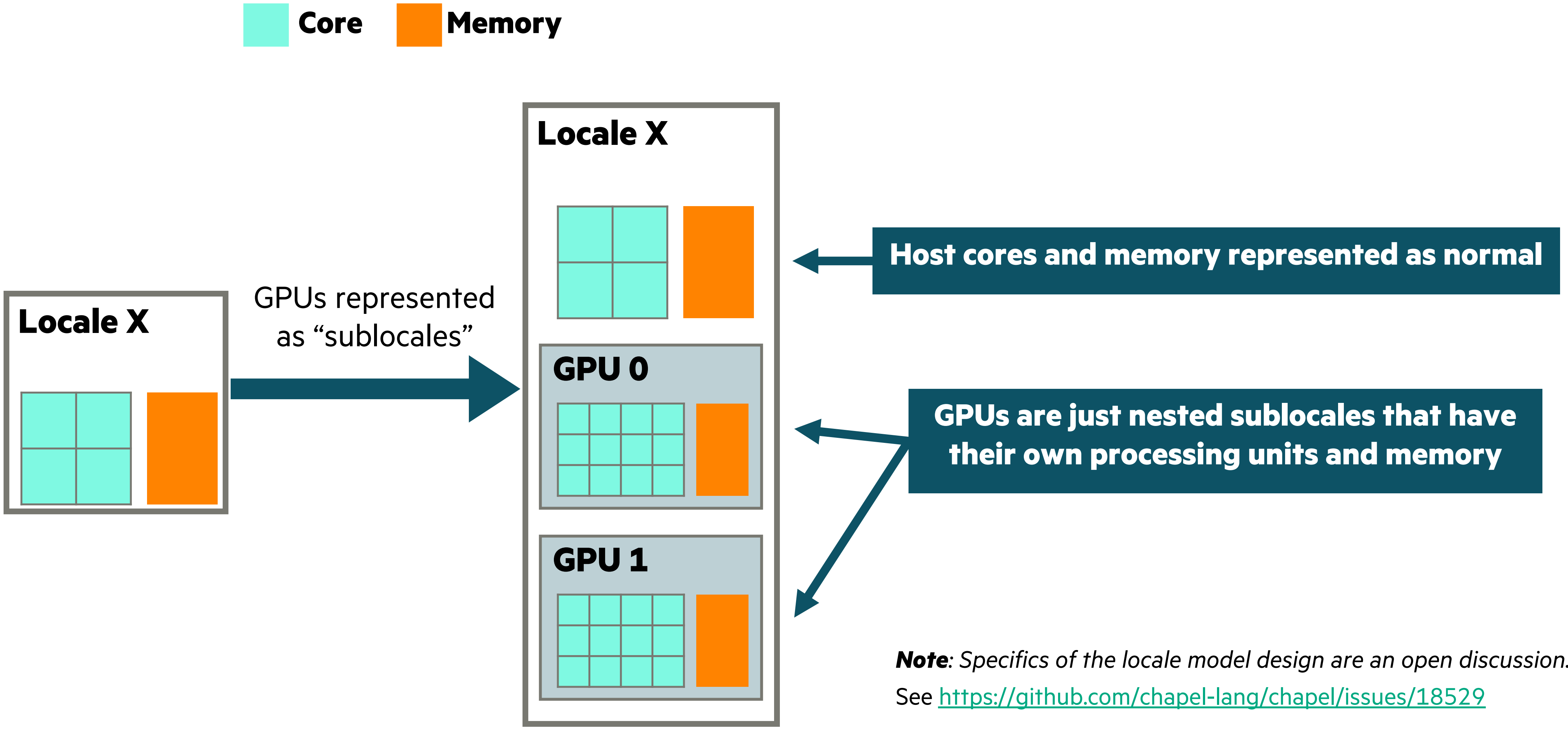

```
var x = 10;

on Locales[1] {
  var A = [1, 2, 3, 4, 5, ...];
  forall a in A do a += 1;
}

writeln(x);
```

Takeaway:
The 'on' statement and the 'forall' loop can be used to control locality and parallelism

Note: *The 'forall' loop can result in distributed computation by itself, but that's out of scope for this talk*

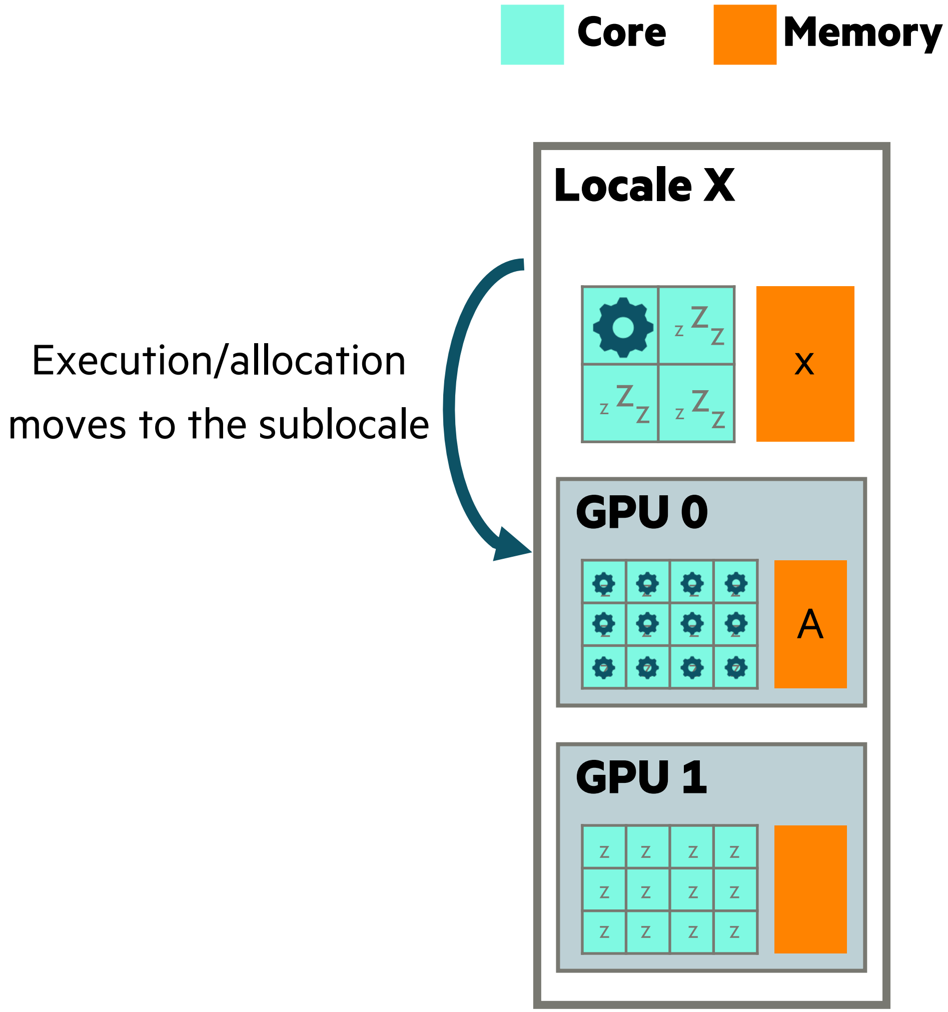
GPU PROGRAMMING
AS FIRST-CLASS CONCEPTS

HIERARCHICAL LOCALES TO REPRESENT GPUS



Note: *Specifics of the locale model design are an open discussion.*
See https://github.com/chapel-lang/chapel/issues/18529

PARALLELISM AND LOCALITY IN THE CONTEXT OF GPUS




```
var x = 10;

on here.getGPU(0) {
  var A = [1, 2, 3, 4, 5, ...];
  forall a in A do a += 1;
}

writeln(x);
```

OUR GOAL AND WHERE WE ARE

Sample Computation: Status in 1.25

The 'on' statement moves the execution to a GPU sublocale

Our Goal:

```
on here.getGPU(0) {
  var A = [1, 2, 3, 4, 5];
  forall a in A do a += 1;
}
```

What works today (1.25.x):

```
on here.getChild(1) {
  var A = [1, 2, 3, 4, 5];
  forall a in A do a += 1;
}
```

Dynamic memory is allocated on the device

The 'forall' loop turns into a GPU kernel

Locale interface design is an ongoing work

GPU CODEGEN: PART 1

Creating GPU Kernels from Loops

User's loop

```
forall i in 1..n do arr[i] = i*mul
```

Conceptual C loop

```
for (i=1 ; i<=n ; i++) {   // order-independent loop
  int *arrData = arr->data;
  int *addrToChange = &arrData[i];
  int newVal = i*mul;
  *addrToChange = newVal;
}
```

Generated GPU Kernel

```
__global__
void kernel(int startIdx, int endIdx, int *arrArg, int mulArg) {
  int index = ...; // calculate and return if >length

  int *arrData = arrArg->data;
  int *addrToChange = &arrData[index];
  int newVal = index*mulArg;
  *addrToChange = newVal;
}
```

The loop's start and end indices are passed by value

Outer variables are passed depending on their type

Loop body is copied

Variables declared inside remain untouched

Symbols are replaced appropriately

GPU CODEGEN: PART 2

Launching GPU Kernels

User's loop

```
forall i in 1..n do arr[i] = i*mul
```

Conceptual C loop

```
for (i=1 ; i<=n ; i++) {
  int *arrData = arr->data;
  int *addrToChange = &arrData[i];
  int newVal = i*mul;
  *addrToChange = newVal;
}
```

Generated Kernel Launch

```
if executingOnGPUSublocale()
  launch_kernel('kernel', n-1, 512, 1, 0, n, 0, &arr, 32, mul, 0);
else
  // loop with no change
```

Kernel signature

```
__global__
void kernel(int startIdx, int length,
            int *arrArg, int mulArg);
```

Function name

Loop length and block size are used for dimension calculation

Pass-by-value arguments have an accompanying 0

Pass-by-offload arguments have an accompanying copy size

A dynamic check for GPU execution is added

GPU CODEGEN: PART 3

Translating Loop Indices Into Kernel Indices

Kernel function

```
__global__
void kernel(int startIdx, int endIdx,
            int *arrArg, int mulArg) {
  int blockIdxX  = __primitive('gpu blockIdx x');
  int blockDimX  = __primitive('gpu blockDim x');
  int threadIdxX = __primitive('gpu threadIdx x');

  int t0 = blockIdxX * blockDimX;
  int t1 = t0 + threadIdxX;
  int index = t1 + startIdx;

  bool chpl_is_oob = index > endIdx;
  if (chpl_is_oob) { return; }

  // copied loop body
}
```

Primitives correspond to CUDA threadIdx, blockIdx, blockDim, and gridDim variables

They lower to calls to corresponding llvm intrinsics (e.g., `llvm.nvvm.read.ptx.sreg.ctaid.x`)

Index computation

Currently we are only targeting 1-dimensional kernels

Check that index is in bounds

Can occur if length is not evenly divisible by block size

Loop body is copied

GPU CODEGEN

Putting the Pieces Together

User's loop

```
forall i in 1..n do arr[i] = i*mul;
```

The loop is replaced with:

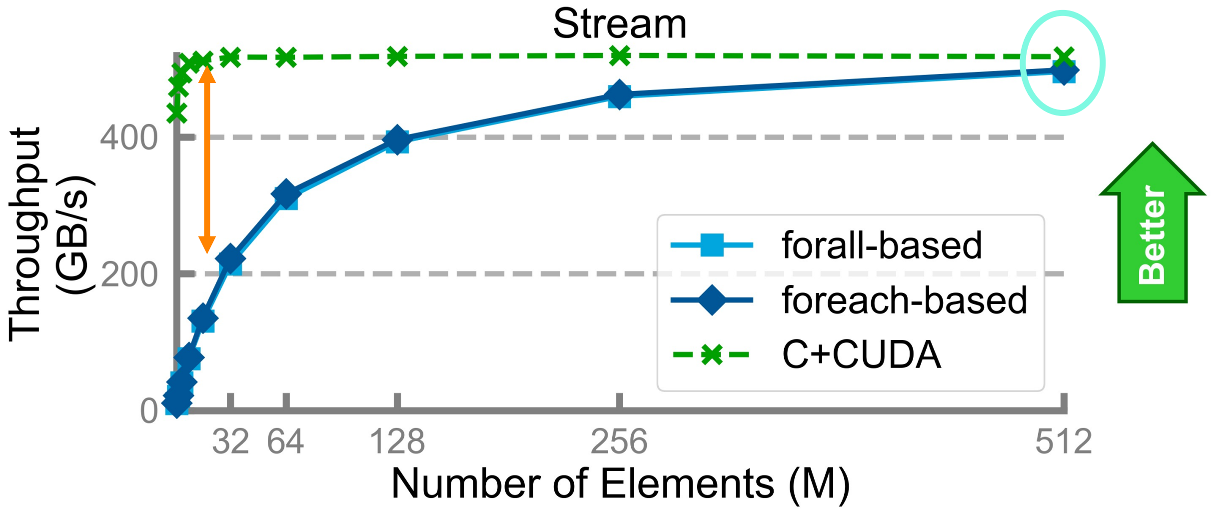
```
if executingOnGPUSublocale()
  launch_kernel("kernel", n-1, 512, 1, 0,
                n, 0, &arr, 32, mul, 0);
else
  for (i=1 ; i<=n ; i++) {
    int *arrData = arr->data;
    int *addrToChange = &arrData[i];
    int newVal = i*mul;
    *addrToChange = newVal;
  }
```

Generated GPU kernel looks like:

```
__global__
void kernel(int startIdx, int endIdx,
            int *arrArg, int mulArg) {
  int blockIdxX  = __primitive('gpu blockIdx x');
  int blockDimX  = __primitive('gpu blockDim x');
  int threadIdxX = __primitive('gpu threadIdx x');

  int t0 = blockIdxX * blockDimX;
  int t1 = t0 + threadIdxX;
  int index = t1 + startIdx;

  bool chpl_is_oob = index > endIdx;
  if (chpl_is_oob) { return; }

  int arrData = arrArg->data;
  int *addrToChange = &arrData[index];
  int newVal = myIdx*mulArg;
  *addrToChange = newVal;
}
```

GPU PROGRAMMING IN CHAPEL

A **Very** Early Performance Study



At smaller vector sizes throughput is low

At larger vector sizes efficiency reaches 96%

Observations

- Can perform comparably to hand-written code
- Gets close to 100% efficiency with large datasets
- 'foreach' is slightly faster than 'forall'

Potential Sources of Overhead

- Unified memory vs. device memory
- Dynamic allocations per kernel launch

Future Work for Performance

- Understand the performance with small vectors
- Profile the remaining costs
- Study other benchmarks

GPU PROGRAMMING IN CHAPEL

Summary

- Chapel's language constructs for parallelism and locality suit GPU programming well
- The most recent Chapel release has a prototype feature for native GPU programming
- We:
  - have taken big steps in the recent releases
  - obtained very promising results both in terms of productivity and performance

Future Work

- A new locale model design
- Portability improvements
- Ability to create distributed arrays on GPUs
- Support more of the language features for GPU operations

CHAPEL RESOURCES

Chapel homepage: https://chapel-lang.org

Social Media:

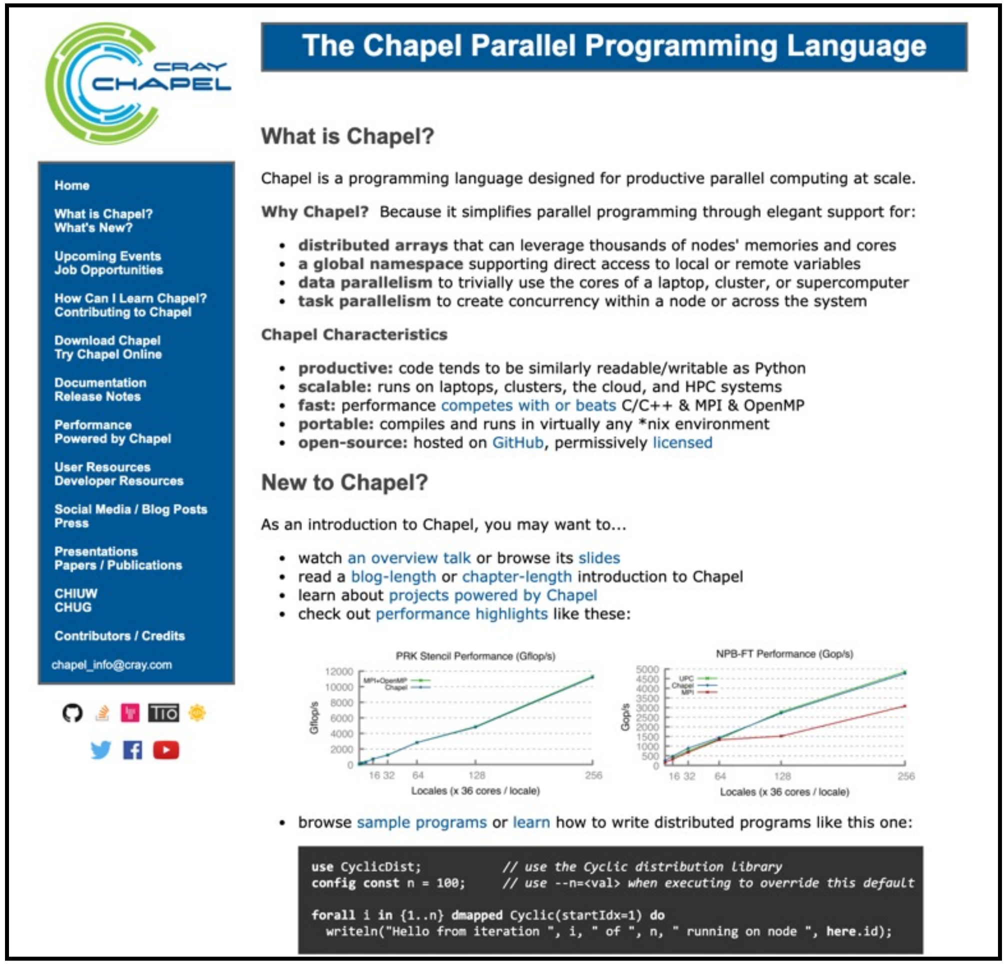
- Twitter: @ChapelLanguage
- Facebook: @ChapelLanguage
- YouTube: http://www.youtube.com/c/ChapelParallelProgrammingLanguage

Community Discussion / Support:

- Discourse: https://chapel.discourse.group/
- Gitter: https://gitter.im/chapel-lang/chapel
- Stack Overflow: https://stackoverflow.com/questions/tagged/chapel
- GitHub Issues: https://github.com/chapel-lang/chapel/issues

GPU Technote:

- See https://chapel-lang.org/docs/master/technotes/gpu.html



THANK YOU

engin@hpe.com
linkedin.com/in/engink

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