Hewlett Packard Enterprise

CHAPEL TUTORIAL FOR PYTHON PROGRAMMERS: PRODUCTIVITY AND PERFORMANCE IN ONE LANGUAGE

Michelle Strout and Chapel team members

RMACC Rocky Mountain Advanced Computing Consortium

May 18, 2023

HOW TO PARTICIPATE IN THIS TUTORIAL

See https://github.com/mstrout/ChapelForPythonProgrammersMay2023 for more info and for example code.

- **Poll Everywhere link**: pollev.com/michellestrout402
  - There will be fun questions throughout the tutorial

- **Attempt this Online website for running Chapel code**
  - Go to main Chapel webpage at https://chapel-lang.org/
  - Click on the little ATO icon on the lower left that is above the YouTube icon

- **Using a container on your laptop**
  - First, install docker or podman for your machine and then start them up
  - Then, the below commands work with docker (see github README.md for podman)

```
docker pull docker.io/chapel/chapel     # takes about 5 minutes
cd ChapelForPythonProgrammersMay2023    # assuming git clone has happened
docker run --rm -v "$PWD":/myapp -w /myapp chapel/chapel chpl hello.chpl
docker run --rm -v "$PWD":/myapp -w /myapp chapel/chapel ./hello
```

CHAPEL PROGRAMMING LANGUAGE

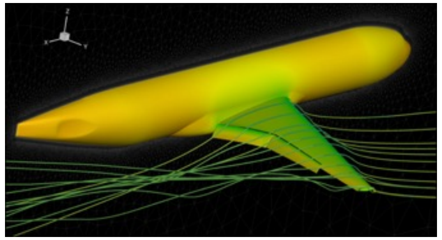
Chapel is a general-purpose programming language that provides

ease of parallel programming,
high performance, and
portability.

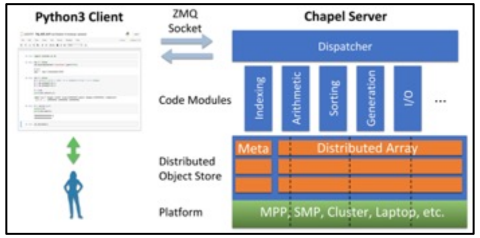
And is being used in applications in various ways:

refactoring existing codes,
developing new codes,
serving high performance to Python codes **(Chapel server with Python client),** and
providing distributed and shared memory parallelism for existing codes.

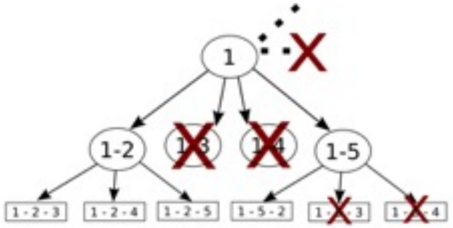
APPLICATIONS OF CHAPEL



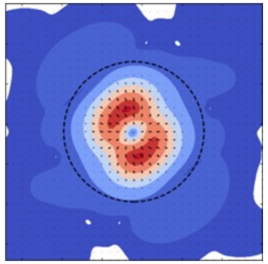
CHAMPS: 3D Unstructured CFD
Laurendeau, Bourgault-Côté, Parenteau, Plante, et al.
École Polytechnique Montréal



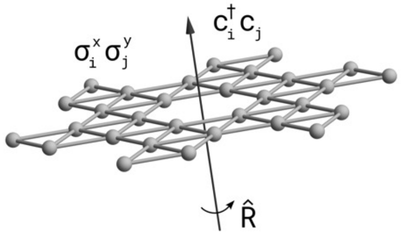
Arkouda: Interactive Data Science at Massive Scale
Mike Merrill, Bill Reus, et al.
U.S. DoD



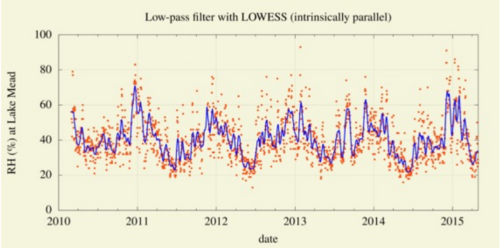
ChOp: Chapel-based Optimization
T. Carneiro, G. Helbecque, N. Melab, et al.
INRIA, IMEC, et al.



ChplUltra: Simulating Ultralight Dark Matter
Nikhil Padmanabhan, J. Luna Zagorac, et al.
Yale University et al.

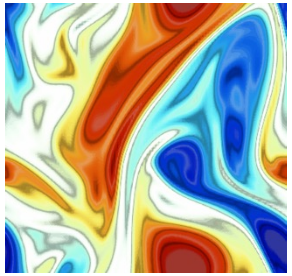


Lattice-Symmetries: a Quantum Many-Body Toolbox
Tom Westerhout
Radboud University

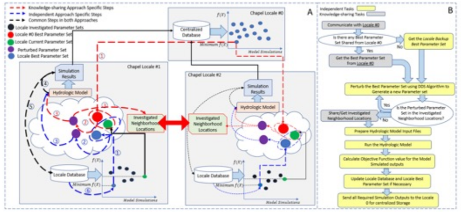


Desk dot chpl: Utilities for Environmental Eng.
Nelson Luis Dias
The Federal University of Paraná, Brazil

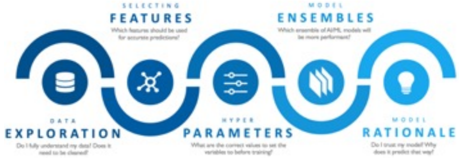
RapidQ: Mapping Coral Biodiversity
Rebecca Green, Helen Fox, Scott Bachman, et al.
The Coral Reef Alliance



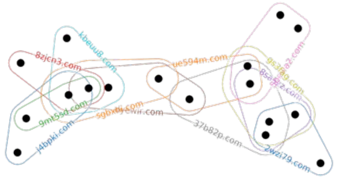
ChapQG: Layered Quasigeostrophic CFD
Ian Grooms and Scott Bachman
University of Colorado, Boulder et al.



Chapel-based Hydrological Model Calibration
Marjan Asgari et al.
University of Guelph



CrayAI HyperParameter Optimization (HPO)
Ben Albrecht et al.
Cray Inc. / HPE



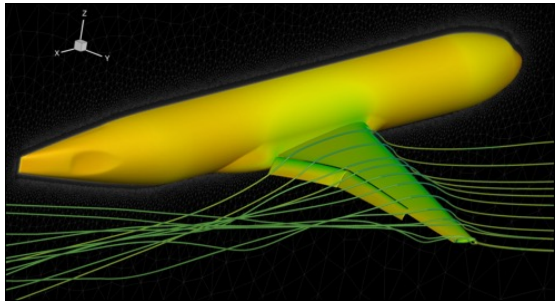
CHGL: Chapel Hypergraph Library
Louis Jenkins, Cliff Joslyn, Jesun Firoz, et al.
PNNL

?

Your Application Here?

(images provided by their respective teams and used with permission)

HIGHLIGHTS OF CHAPEL USAGE



CHAMPS: Computational Fluid Dynamics framework for airplane simulation

- Professor Eric Laurendeau's team at Polytechnique Montreal
- Performance: achieves competitive results w.r.t. established, world-class frameworks from Stanford, MIT, etc.
- Programmability: "*We ask students at the master's degree to do stuff that would take 2 years and they do it in 3 months.*"

Arkouda: data analytics framework (https://github.com/Bears-R-Us/arkouda)

- Mike Merrill, Bill Reus, et al., US DOD
- Python front end client, Chapel server that processes dozens of terabytes in seconds
- April 2023: 1200 GiB/s for argsort on an HPE EX system

Recent Journal Paper on using Chapel for calibrating hydrologic models

- Marjan Asgari et al, "Development of a knowledge-sharing parallel computing approach for calibrating distributed watershed hydrologic models", Environmental Modeling and Software.
- They report super-linear speedup

INTRODUCTIONS

- Let's take some time to introduce ourselves
  - Michelle Strout
    - Chapel team leader
    - Affiliate faculty in the Department of Computer Science at UArizona
  - Current Chapel team →
    - Tech Lead: Brad Chamberlain
    - Visiting Scholar from NCAR: Scott Bachman

  - **Participants, tell us some about yourself**
    - Your institution
    - Proudest HPC accomplishment
    - Biggest HPC challenge

LEARNING OBJECTIVES FOR TODAY'S TUTORIAL

- Compile and run Chapel programs in a web browser and/or on your laptop

- Familiarity with the Chapel execution model including how to run codes in parallel on a single node, across nodes, and both

- Experiment compiling and running provided Chapel code examples
  - k-mer counting (bioinformatics application)
  - Processing files in parallel using parallelism over multiple nodes and threads
  - Solving a diffusion PDE (partial differential equation)
  - Image processing (coral reef diversity example)
  - Same code can be compiled to run on a multi-core CPU AND a GPU

- Where to get help and how you can participate in the Chapel community

HOW TO PARTICIPATE IN THIS TUTORIAL

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```

Try one of these options for using Chapel

Which option did you choose to try out Chapel during this tutorial?

Attempt This Online

Container on your laptop

Doing the polls and watching a neighbor

Learning from the examples in the slides

PARALLELISM ACROSS NODES AND WITHIN NODES

- **Parallel hello world**
  - ExamplesInSlides/hellopar.chpl
- **Key concepts**
  - 'coforall'
  - configuration constants, 'config const'
  - range values, '0..#tasksPerLocale'
  - 'writeln'
  - inline comments start with '//'

```
// can be set on the command line with --tasksPerLocale=2
config const tasksPerLocale = 1;

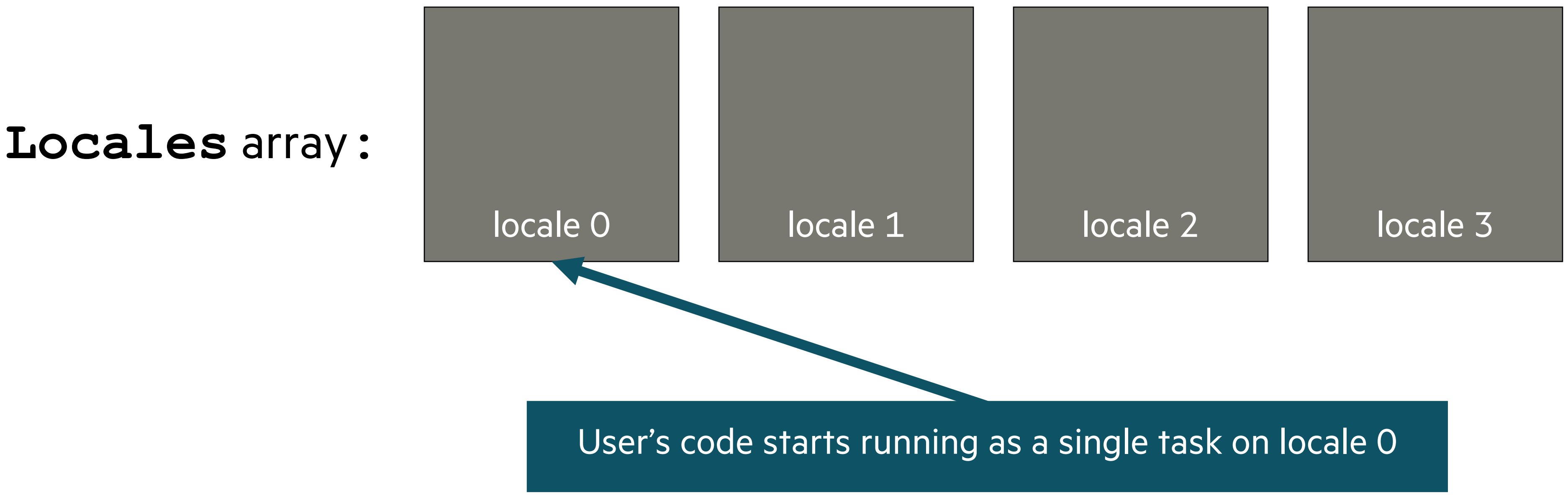
// parallel loops over nodes and then over threads
coforall loc in Locales do on loc {
  coforall tid in 0..#tasksPerLocale {

    writeln("Hello world! ",
            "(from task ", tid,
            " of ", tasksPerLocale,
            " on locale ", here.id,
            " of ", numLocales, ")" );
  }
}
```

CHAPEL EXECUTION MODEL AND TERMINOLOGY: LOCALES

- Locales can run tasks and store variables
  - Think “compute node” on a parallel system
  - User specifies number of locales on executable’s command-line

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



TASK-PARALLEL "HELLO WORLD"

helloTaskPar.chpl

```
const numTasks = here.numPUs();
coforall tid in 1..numTasks do
  writef("Hello from task %n of %n on %s\n",
         tid, numTasks, here.name);
```

TASK-PARALLEL "HELLO WORLD"

helloTaskPar.chpl

```
const numTasks = here.numPUs();
coforall tid in 1..numTasks do
  writef("Hello from task %n of %n on %s\n",
         tid, numTasks, here.name);
```

'here' refers to the locale on which we're currently running

how many processing units (think "cores") does my locale have?

what's my locale's name?

TASK-PARALLEL "HELLO WORLD"

helloTaskPar.chpl

```
const numTasks = here.numPUs();
coforall tid in 1..numTasks do
  writef("Hello from task %n of %n on %s\n",
         tid, numTasks, here.name);
```

a 'coforall' loop executes each iteration as an independent task

```
prompt> chpl helloTaskPar.chpl
prompt> ./helloTaskPar
Hello from task 1 of 4 on n1032
Hello from task 4 of 4 on n1032
Hello from task 3 of 4 on n1032
Hello from task 2 of 4 on n1032
```

TASK-PARALLEL "HELLO WORLD"

helloTaskPar.chpl

```
const numTasks = here.numPUs();
coforall tid in 1..numTasks do
  writef("Hello from task %n of %n on %s\n",
         tid, numTasks, here.name);
```

```
prompt> chpl helloTaskPar.chpl
prompt> ./helloTaskPar
Hello from task 1 of 4 on n1032
Hello from task 4 of 4 on n1032
Hello from task 3 of 4 on n1032
Hello from task 2 of 4 on n1032
```

So far, this is a shared-memory program

Nothing refers to remote locales, explicitly or implicitly

TASK-PARALLEL "HELLO WORLD" (DISTRIBUTED VERSION)

helloTaskPar.chpl

```
coforall loc in Locales {
  on loc {
    const numTasks = here.numPUs();
    coforall tid in 1..numTasks do
      writef("Hello from task %n of %n on %s\n",
             tid, numTasks, here.name);
  }
}
```

TASK-PARALLEL “HELLO WORLD” (DISTRIBUTED VERSION)

helloTaskPar.chpl

```
coforall loc in Locales {
  on loc {
    const numTasks = here.numPUs();
    coforall tid in 1..numTasks do
      writef("Hello from task %n of %n on %s\n",
             tid, numTasks, here.name);
  }
}
```

create a task per locale on which the program is running

have each task run ‘on’ its locale

then print a message per core, as before

```
prompt> chpl helloTaskPar.chpl
prompt> ./helloTaskPar -nl=4
Hello from task 1 of 4 on n1032
Hello from task 4 of 4 on n1032
Hello from task 1 of 4 on n1034
Hello from task 2 of 4 on n1032
Hello from task 1 of 4 on n1033
Hello from task 3 of 4 on n1034
Hello from task 1 of 4 on n1035
…
```

Which Chapel code does the same thing as this python code?

```
x = 42
str = "answer"
print(str, " = ", x)
```

A

B

C

Start the presentation to see live content. For screen share software, share the entire screen. Get help at **pollev.com/app**

A

```
var x = 42;
var str = "answer";
writeln(str, " = ", x);
```

B

```
config const tasksPerLocale = 2;
coforall tid in 0..#tasksPerLocale {
  var message = "answer = ";
  message += 42:string;
  writeln(message);
}
```

C

```
var x = 42;
var str = "answer";
coforall loc in Locales {
  on loc {
    writeln(x, " = ", str);
  }
}
```

K-MER COUNTING FROM BIOINFORMATICS

kmer.chpl

```
use Map, IO;

config const infilename = ("kmer_large_input.txt");
config const k = 4;

var sequence, line : string;
var f = open(infilename, ioMode.r);
var infile = f.reader();
while infile.readLine(line) {
 sequence += line.strip();
}
infile.close();

var nkmerCounts : map(string, int);

for ind in 0..<(sequence.size-k) {
 nkmerCounts[sequence[ind..#k]] += 1;
}
```

'Map' and 'IO' are two of the standard libraries provided in Chapel. A 'map' is like a dictionary in python.

'config const' indicates a configuration constant, which result in built-in command-line parsing

Reading all of the lines from the input file into the string 'sequence'.

The variable 'nkmerCounts' is being declared as a dictionary mapping strings to ints

Counting up each kmer in the sequence

EXPERIMENTING WITH THE K-MER EXAMPLE

See https://github.com/mstrout/ChapelForPythonProgrammersMay2023 for more info and for example code.

- **Some things to try out with 'ExamplesInSlides/kmer.chpl'**

```
chpl kmer.chpl
./kmer

./kmer --k=10                                  # can change k
./kmer --infilename="kmer.chpl"                # can change the infilename
./kmer --k=10 --infilename="kmer.chpl"         # can change both
```

What Chapel code does the same thing as this python code?

```python
# read in a file into a list of strings
# where each string has a line with the newline at the end removed
with open("filename.txt") as file:
  lines = [line.strip() for line in file]

print(lines)
```

A

B

C

A

```
// declare a dictionary/map to store the count per kmer
var nkmerCounts : map(string, int);

// count up the number of times each kmer occurs
for ind in 0..<(sequence.size-k) {
  nkmerCounts[sequence[ind..#k]] += 1;
}
```

B

```
var sequence, line : string;
var f = open(infilename, ioMode.r);
var infile =  f.reader();
while infile.readLine(line) {
  sequence += line.strip();
}
```

C

```
use List, IO;

var line : string;
var lines : list(string);
var infile = open("filename.txt",ioMode.r).reader();
while infile.readLine(line) {
  lines.append(line.strip());
}

writeln(lines);
```

2D DIFFUSION PARTIAL DIFFERENTIAL EQUATION EXAMPLE

See https://github.com/mstrout/ChapelForPythonProgrammersMay2023 for more info and for example code.

- **See 'ExamplesInSlides/diffusion.chpl' in the repository**
- **Some things to try out with 'diffusion.chpl'**

```
chpl diffusion.chpl
./diffusion

--xLen=4 --yLen=4 --nx=61 --ny=61  # doubles the size of the domain
                                   # along each dimension, keeping the
                                   # density of points the same

--nu=0.025                         # reduces the fluid viscosity

--nt=100                           # twice as many timesteps
```

Based on this code, we can conclude that Chapel can do summation, min, and max reductions over lists and arrays.

```
var oneDimArray : [1..4] int = [20, 30, 40, 50];
writeln("oneDimArray = ", oneDimArray);
writeln("+ reduce oneDimArray = ", + reduce oneDimArray);

use List;
var aList : list(real) = new list([50, 20, 30, 40]);

writeln("aList = ", aList);
writeln("min reduce aList = ", min reduce aList);
```

True

False

WRITING OUT EVERYTHING EXAMPLE

- **See 'ExamplesInSlides/writelnExamples.chpl' in the repository**
- **Key points**
  - The Chapel compiler provides default 'writeThis' routines for every standard library and user-defined datatype
  - This helps enable "printf" debugging through the use of 'writeln' calls

See https://github.com/mstrout/ChapelForPythonProgrammersMay2023 for more info and for example code.

ANALYZING MULTIPLE FILES USING PARALLELISM

parfilekmer.chpl

```
use FileSystem;
config const dir = "DataDir";
var fList = findFiles(dir);
var filenames =
  Block.createArray(0..#fList.size,string);
filenames = fList;

// per file word count
forall f in filenames {
   ...
   // code from kmer.chpl
   ...
}
```

```
prompt> chpl --fast parfilekmer.chpl
prompt> ./parfilekmer
prompt> ./parfilekmer –nl 4
```

Shared and Distributed-Memory Parallelism using forall, a distributed array, and command line options to indicate number of locales

PROCESSING FILES IN PARALLEL

See https://github.com/mstrout/ChapelForPythonProgrammersMay2023 for more info and for example code.

- **See 'ExamplesInSlides/parfilekmer.chpl' in the repository**

- **Some things to try out with 'parfilekmer.chpl'**

```
# put more and bigger files into DataDir/
# or set the config const dir to something else
chpl parfilekmer.chpl
./parfilekmer --dir="SomethingElse/"

./parfilekmer --k=10                              # can also change k
```

What does the following Chapel code do?

```
var array = [1,2,3,4];
var result = "";
for num in array {
  result += num:string + ":";
}
result = result[0..#result.size-1];
var sum : int;
for substr in result.split(":") {
  sum += substr : int;
}
writeln("sum = ", sum);
```

Converts an array of strings to integers and then prints their sum.

Converts an array of integers to strings, concatenates them with a colon in-between, then splits that string and sums up resulting integers.

Sums an array of integers and then concatenates them into a string.

IMAGE PROCESSING EXAMPLE

See https://github.com/mstrout/ChapelForPythonProgrammersMay2023 for more info and for example code.

- **See 'image_analysis_example/' subdirectory in the repository**
  - Coral reef diversity analysis written by Scott Bachman
  - Calls out to libpng to read and write PNG files
  - Uses distributed and shared memory parallelism

- **'image_analysis_example/README.md' explains how to compile and run it**

- **Some things to try out when running 'main'**

```
./main -nl 4 --inname=Roatan_benthic_r3_gray.png --outname=out1.png --radius=10

./main -nl 4 --inname=Roatan_benthic_r3_gray.png --outname=out2.png --radius=100

# Can also change the number of locales, but only up to the -N number given to salloc
```

GPU SUPPORT IN CHAPEL

- **Generate code for GPUs**
  - Support for NVIDIA and AMD GPUs
  - Exploring Intel support
- **Chapel code calling CUDA examples**
  - https://github.com/chapel-lang/chapel/blob/main/test/gpu/interop/stream/streamChpl.chpl
  - https://github.com/chapel-lang/chapel/blob/main/test/gpu/interop/cuBLAS/cuBLAS.chpl
- **Key concepts**
  - Using the 'locale' concept to indicate execution and data allocation on GPUs
  - 'forall' and 'foreach' loops will be converted to kernels
  - Arrays declared in 'on here.gpus[i]' blocks are allocated on the GPU
- **For more info…**
  - https://chapel-lang.org/docs/technotes/gpu.html

```
use GpuDiagnostics;
startGpuDiagnostics();

var operateOn =
  if here.gpus.size>0 then here.gpus
                      else [here,];

// Same code can run on GPU or CPU
coforall loc in operateOn do on loc {
 var A : [1..10] int;
 foreach a in A do a+=1;
 writeln(A);
}

stopGpuDiagnostics();
writeln(getGpuDiagnostics());
```

STREAM TRIAD: SHARED MEMORY

stream-ep.chpl

```
config var n = 1_000_000,
           alpha = 0.01;




    var A, B, C: [1..n] real;
    A = B + alpha * C;
```

Declare three arrays of size ‘n’

Whole-array operations compute Stream Triad in parallel

So far, this is simply a multi-core program

Nothing refers to remote locales (nodes), explicitly or implicitly

STREAM TRIAD: DISTRIBUTED MEMORY

stream-ep.chpl

```
config var n = 1_000_000,
           alpha = 0.01;

coforall loc in Locales {
  on loc {
    var A, B, C: [1..n] real;
    A = B + alpha * C;
  }
}
```

'coforall' loops execute each iteration as an independent task

the array of locales (nodes) on which this program is running

have each task run 'on' its locale

then run multi-core Stream, as before

This is a CPU-only program

Nothing refers to GPUs, explicitly or implicitly

STREAM TRIAD: DISTRIBUTED MEMORY, GPUS ONLY

stream-ep.chpl

```
config var n = 1_000_000,
           alpha = 0.01;

coforall loc in Locales {
  on loc {

      coforall gpu in here.gpus do on gpu {
        var A, B, C: [1..n] real;
        A = B + alpha * C;
      }
  }
}
```

Use a similar ‘coforall’ + ‘on’ idiom to run a Triad concurrently on each of this locale’s GPUs

This is a GPU-only program

Nothing other than coordination code runs on the CPUs

STREAM TRIAD: DISTRIBUTED MEMORY, GPUS AND CPUS

stream-ep.chpl

```
config var n = 1_000_000,
           alpha = 0.01;

coforall loc in Locales {
  on loc {
    cobegin {
      coforall gpu in here.gpus do on gpu {
        var A, B, C: [1..n] real;
        A = B + alpha * C;
      }
      {
        var A, B, C: [1..n] real;
        A = B + alpha * C;
      }
    }
  }
}
```

'cobegin { … }' creates a task per child statement

one task runs our multi-GPU triad

the other runs the multi-CPU triad

This program uses all CPUs and GPUs across all of your compute nodes

STREAM TRIAD: DISTRIBUTED MEMORY, GPUS AND CPUS (REFACTOR)

stream-ep.chpl

```
config var n = 1_000_000,
           alpha = 0.01;

coforall loc in Locales {
  on loc {
    cobegin {
      coforall gpu in here.gpus do on gpu {
        runTriad();
      }
      runTriad();
    }
  }
}
proc runTriad() {
   var A, B, C: [1..n] real;
   A = B + alpha * C;
}
```

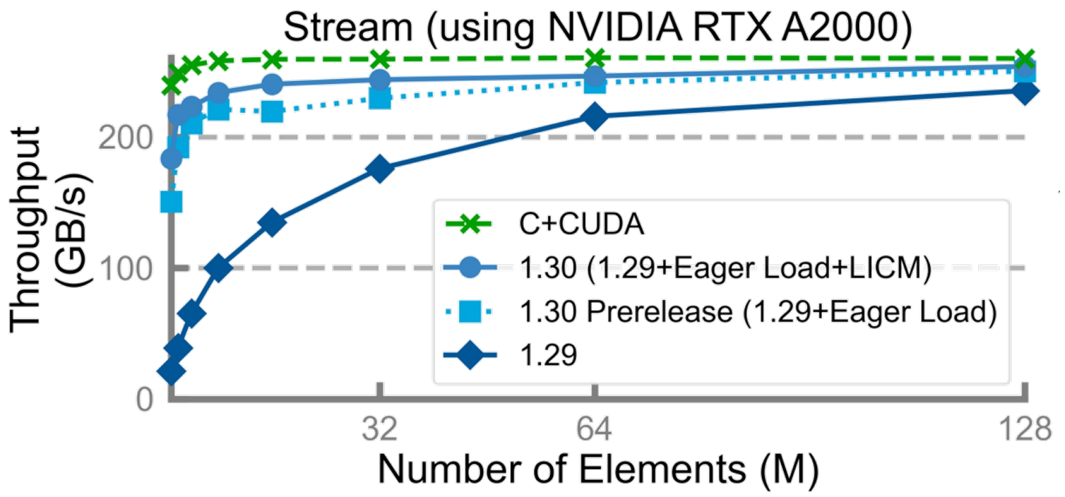
'cobegin { … }' creates a task per child statement

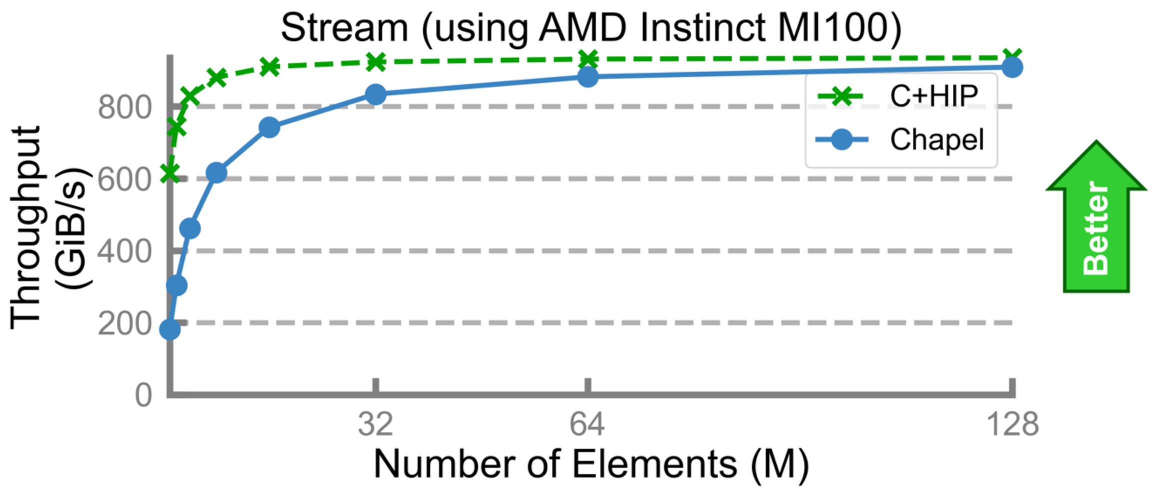
one task runs our multi-GPU triad

the other runs the multi-CPU triad

the compiler creates CPU and GPU versions of this procedure

STREAM TRIAD: PERFORMANCE VS. REFERENCE VERSIONS





Performance vs. reference versions has become increasingly competitive over the past 4 months

OTHER CHAPEL EXAMPLES

- **Primers**
  - https://chapel-lang.org/docs/primers/index.html

- **Blog posts for Advent of Code**
  - https://chapel-lang.org/blog/index.html

- **Test directory in main repository**
  - https://github.com/chapel-lang/chapel/tree/main/test

TUTORIAL SUMMARY

- **Takeaways**
  - Chapel is a general-purpose programming language designed to leverage parallelism
  - It is being used in some large production codes
  - Our team is responsive to user questions and would enjoy having you participate in our community
- **How to get more help**
  - Ask us questions on discourse, gitter, or stack overflow
  - Also feel free to email me at michelle.strout@hpe.com
- **Engaging with the community**
  - Share your sample codes with us and your research community!
  - Join us at our free, virtual workshop in June, https://chapel-lang.org/CHIUW.html

CHAPEL RESOURCES

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

- (points to all other resources)

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