Hewlett Packard Enterprise

WHAT'S NEW WITH CHAPEL:
APPLICATIONS, AGGREGATORS, AND ACCELERATORS

Brad Chamberlain

Charm++ 2021 workshop
October 18, 2021

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, RELATIVE TO OTHER LANGUAGES

Chapel strives to be as...

...**programmable** as Python

...**fast** as Fortran

...**scalable** as MPI, SHMEM, or UPC

...**portable** as C

...**flexible** as C++

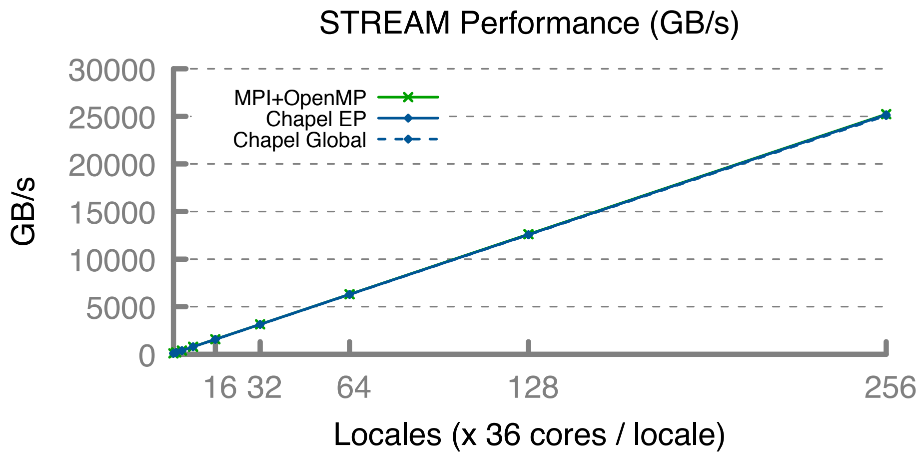
...**fun** as [your favorite programming language]

CHAPEL BENCHMARKS TEND TO BE CONCISE, CLEAR, AND COMPETITIVE

STREAM TRIAD: C + MPI + OPENMP

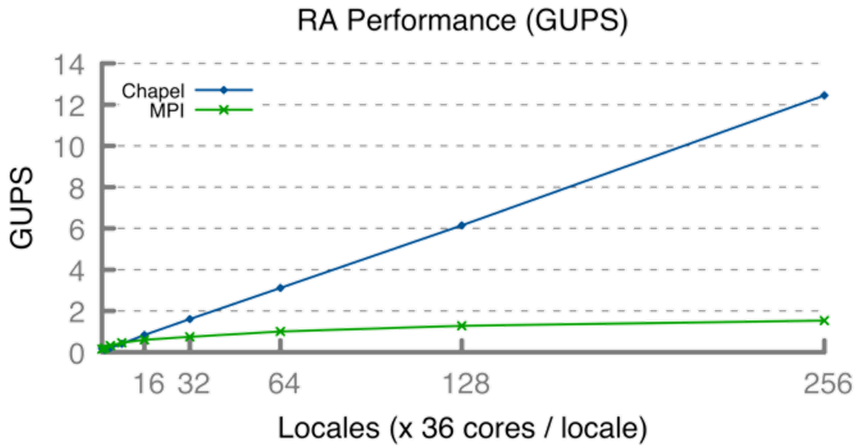
```c
#include <hpcc.h>
#ifdef _OPENMP
#include <omp.h>
#endif

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;
```

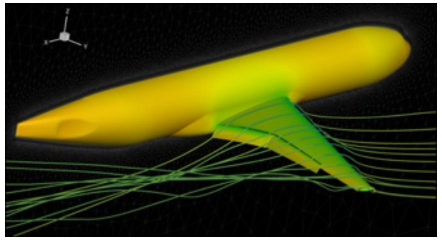


HPCC RA: MPI KERNEL

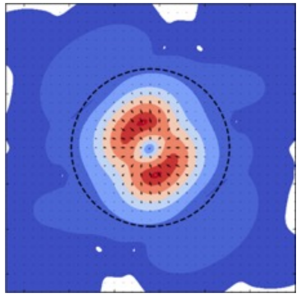
```chapel
…
forall (_, r) in zip(Updates, RAStream()) do
  T[r & indexMask].xor(r);
…
```



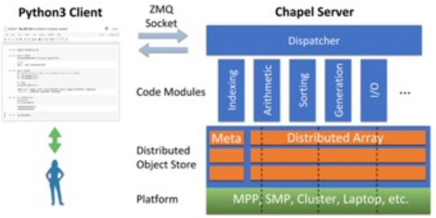
NOTABLE CURRENT APPLICATIONS OF CHAPEL



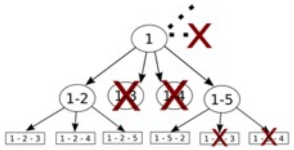
CHAMPS: 3D Unstructured CFD
Éric Laurendeau, Simon Bourgault-Côté, Matthieu Parenteau, et al.
École Polytechnique Montréal
~48k lines of Chapel



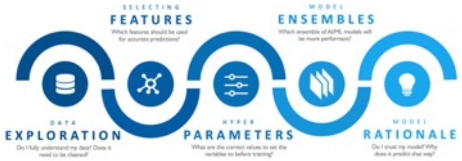
ChplUltra: Simulating Ultralight Dark Matter
Nikhil Padmanabhan, J. Luna Zagorac, Richard Easther, *et al.*
Yale University / University of Auckland



Arkouda: NumPy at Massive Scale
Mike Merrill, Bill Reus, et al.
US DoD
~16k lines of Chapel



ChOp: Chapel-based Optimization
Tiago Carneiro, Nouredine Melab, *et al.*
INRIA Lille, France



CrayAI: Distributed Machine Learning
Hewlett Packard Enterprise

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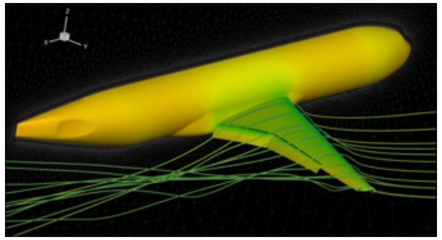
Your Project Here?

OUTLINE

NOTABLE CURRENT APPLICATIONS OF CHAPEL



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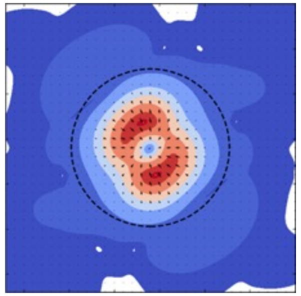

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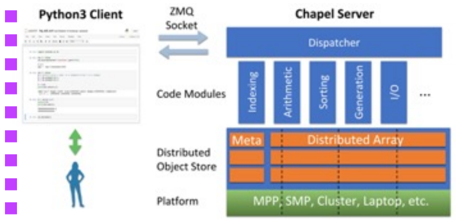

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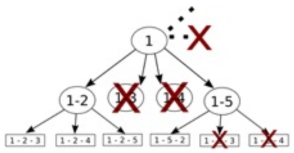

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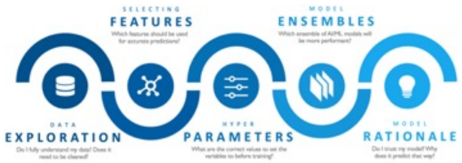

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ARKOUDA IN ONE SLIDE

What is it?

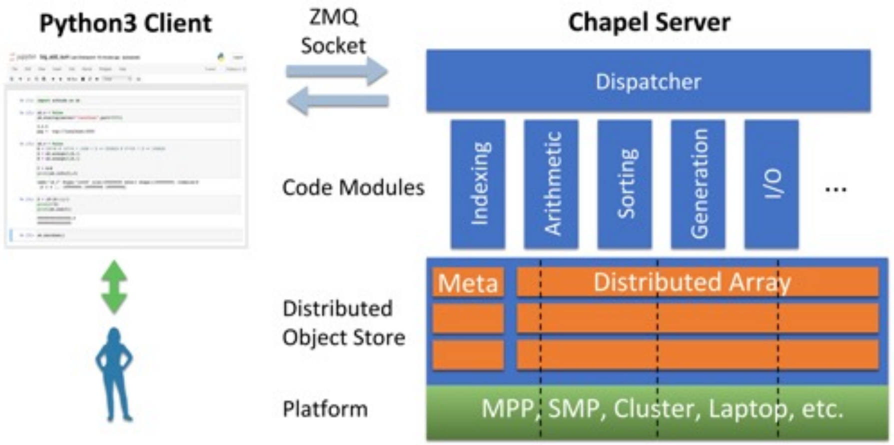
- A Python library supporting a key subset of NumPy and Pandas for Data Science
  - Computes massive-scale results within the human thought loop (seconds to minutes on multi-TB-scale arrays)
  - Uses a Python-client/Chapel-server model to get scalability and performance
- ~16k lines of Chapel, largely written in 2019, continually improved since then

Who wrote it?

- Mike Merrill, Bill Reus, et al., US DoD
- Open-source: https://github.com/Bears-R-Us/arkouda

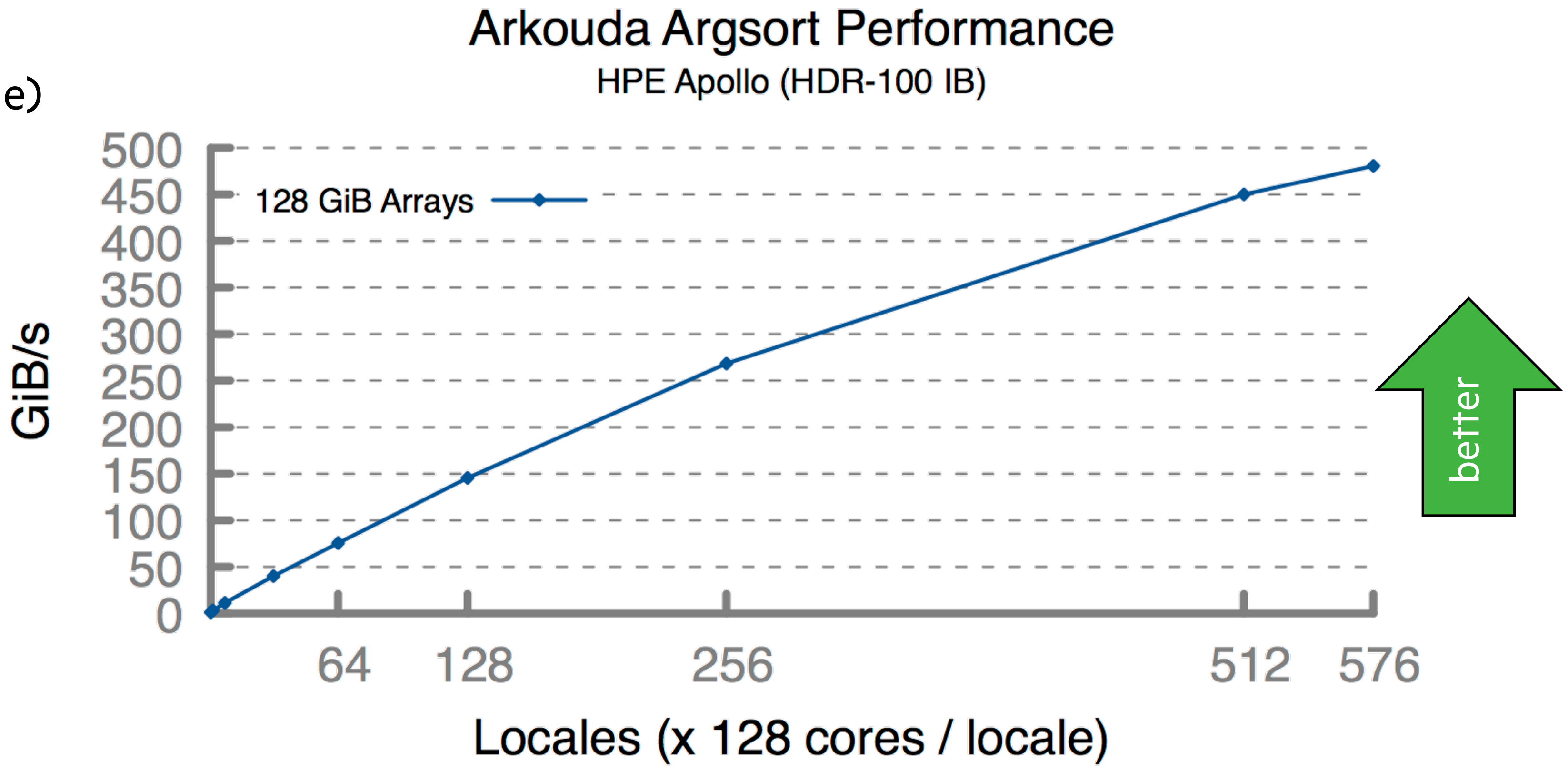
Why Chapel?

- high-level language with performance and scalability
  - close to Pythonic—doesn't repel Python users who look under the hood
- great distributed array support
- ports from laptop to supercomputer



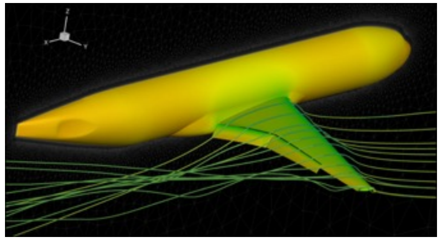
ARKOUDA ARGSORT: HERO RUN

- Recent run performed on a large Apollo system
  - 72 TiB of 8-byte values
  - 480 GiB/s (2.5 minutes elapsed time)
  - used 73,728 cores of AMD Rome
  - ~100 lines of Chapel code



Close to world-record performance—Quite likely a record for performance::lines of code

NOTABLE CURRENT APPLICATIONS OF CHAPEL



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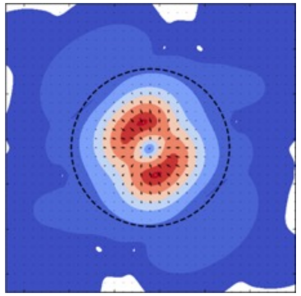

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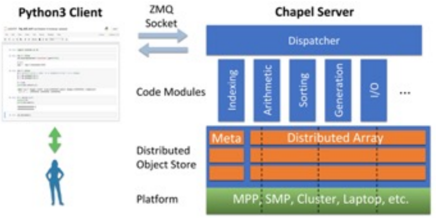

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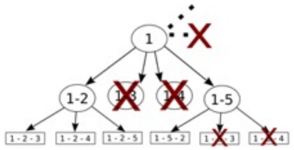

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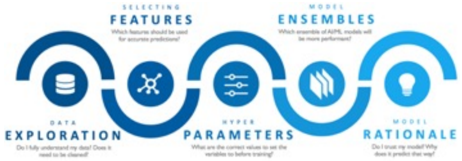

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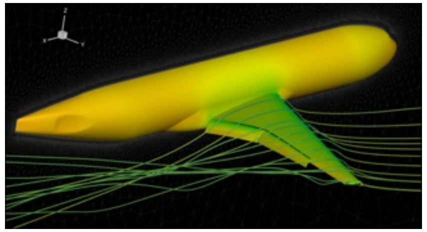
CHAMPS SUMMARY

What is it?

- 3D unstructured CFD framework for airplane simulation
- ~48k lines of Chapel written from scratch in ~2 years



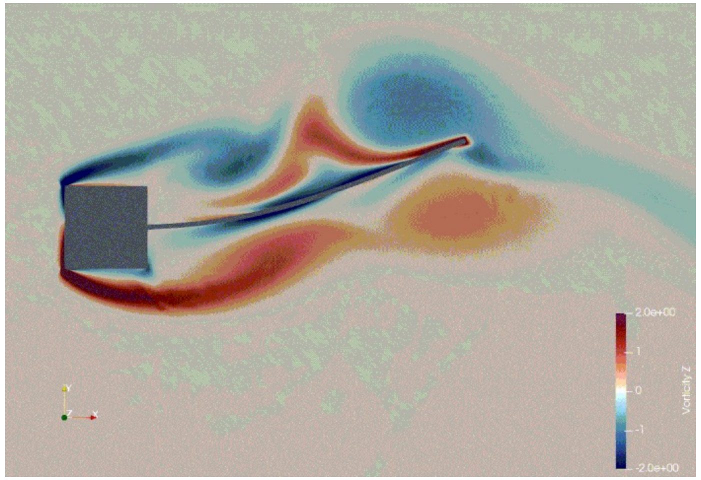
Who wrote it?

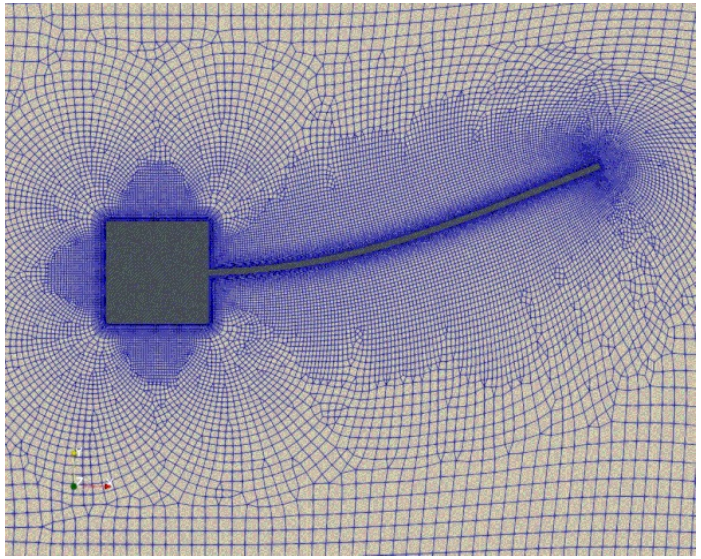
- Professor Éric Laurendeau's team at Polytechnique Montreal

POLYTECHNIQUE
MONTRÉAL

Why Chapel?

- performance and scalability competitive with MPI + C++
- students found it far more productive to use

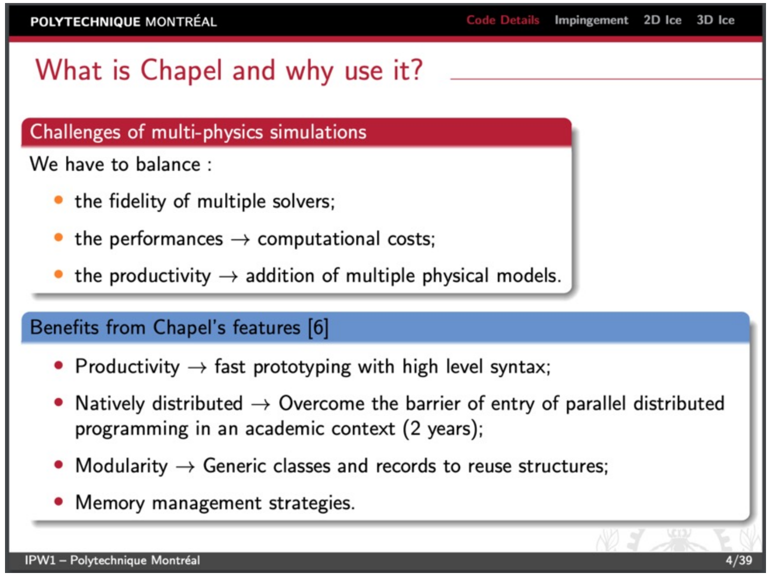




CHAMPS 2021 HIGHLIGHTS

- Presented at CASI/IASC Aero 21 Conference
- Participated in 1st AIAA Ice Prediction Workshop
- Participating in 4th AIAA CFD High-lift Prediction Workshop
- Student presentation to CFD Society of Canada (CFDSC)

- **Achieving large-scale, high-quality results comparable to other major players in industry, government, academia:**
  - e.g., Boeing, Lockheed Martin, NASA, JAXA, Georgia Tech, …



CHAMPS: EXCERPT FROM ERIC'S CHIUW 2021 KEYNOTE

HPC Lessons From 30 Years of Practice in CFD Towards Aircraft Design and Analysis

"To show you what Chapel did in our lab… [NSCODE, our previous framework] ended up 120k lines. And my students said, 'We can't handle it anymore. It's too complex, we lost track of everything.' And today, they went ***from 120k lines to 48k lines, so 3x less****.*

But the code is not 2D, it's 3D. And it's not structured, it's unstructured, which is way more complex. And it's multi-physics: aeroelastic, aero-icing. ***So, I've got industrial-type code in 48k lines.***

So, for me, this is like the proof of the benefit of Chapel, ***plus the smiles I have on my students everyday in the lab because they love Chapel as well.*** *So that's the key, that's the takeaway.*

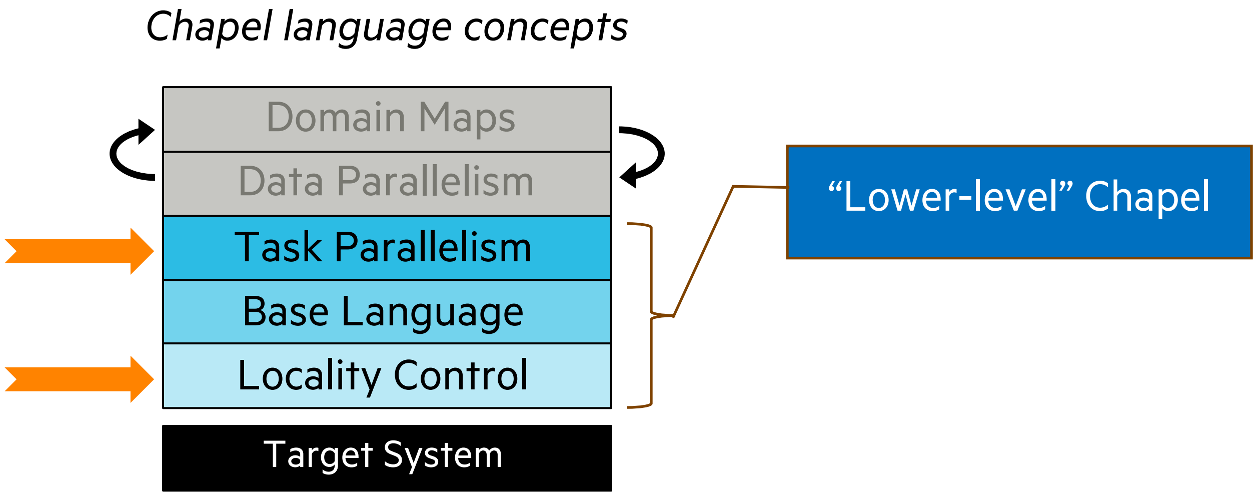
POLYTECHNIQUE MONTRÉAL

[Chapel] promotes the programming efficiency … ***We ask students at the master's degree to do stuff that would take 2 years and they do it in 3 months.*** *So, if you want to take a summer internship and you say, 'program a new turbulence model,' well they manage. And before, it was impossible to do."*

- Talk available online: https://youtu.be/wD-a_KyB8aI?t=1904 (hyperlink jumps to the section quoted here)

BASIC CHAPEL FEATURES

CHAPEL'S "LOWER-LEVEL" FEATURES

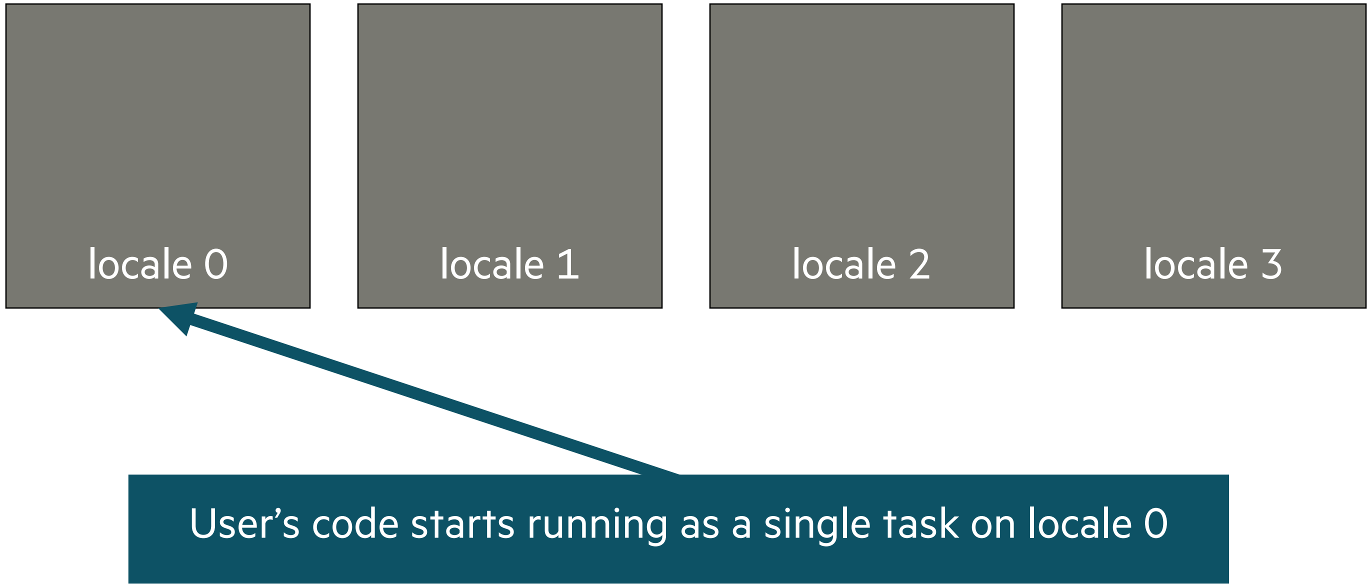


CHAPEL TERMINOLOGY: LOCALES

- *Locales:* a unit of the target architecture that 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’
```

`Locales` array:



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”

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" (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 -numLocales=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
…
```


CHAPEL AGGREGATORS

BALE INDEX GATHER KERNEL IN CHAPEL: NAÏVE VERSION

```
// Naive index gather
forall (d, i) in zip(Dst, Inds) do
  d = Src[i];
```

'*Dst*' and '*Inds*' are distributed arrays with *numUpdates* elements

'*Src*' is a distributed array with *numEntries* elements

BALE INDEX GATHER KERNEL IN CHAPEL: NAÏVE VERSION

```
// Naive index gather
forall (d, i) in zip(Dst, Inds) do
  d = Src[i];
```

Gets lowered roughly to…

```
coforall loc in Dst.targetLocales do
  on loc do
    coforall tid in 0..<here.numPUs() do
      for idx in myInds(loc, tid, …) do
        D[idx] = Src[Inds[idx]];
```

- `coforall loc in Dst.targetLocales do` — A concurrent loop over the compute nodes
- `coforall tid in 0..<here.numPUs() do` — A nested concurrent loop over each node's cores
- `for idx in myInds(loc, tid, …) do` — A serial loop to compute each task's chunk of gathers

BALE INDEX GATHER KERNEL IN CHAPEL: NAÏVE VERSION

```
// Naive index gather
forall (d, i) in zip(Dst, Inds) do
  d = Src[i];
```

Gets lowered roughly to...

```
coforall loc in Dst.targetLocales do
  on loc do
    coforall tid in 0..<here.numPUs() do
      for idx in myInds(loc, tid, …) do
        D[idx] = Src[Inds[idx]];
```

But, for a parallel loop with no data dependencies, why perform these high-latency operations serially?

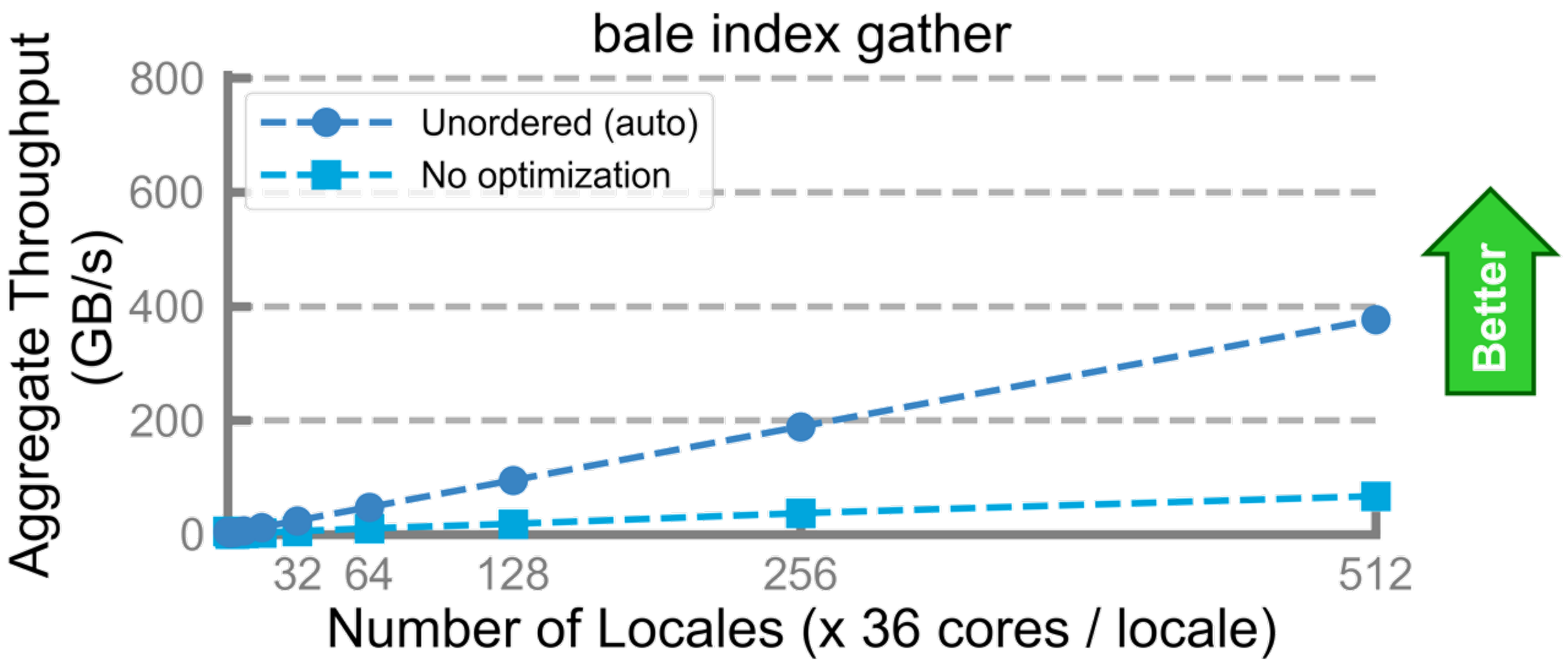
So, our compiler rewrites the inner loop to perform the ops asynchronously

```
for idx in myInds(loc, tid, …) do
  unorderedCopy(D[idx], Src[Inds[idx]]);
unorderedCopyTaskFence();
```

- Implemented by Michael Ferguson and Elliot Ronaghan, 2019

BALE INDEX GATHER KERNEL IN CHAPEL: NAÏVE VERSION

```
// Naive index gather
forall (d, i) in zip(Dst, Inds) do
  d = Src[i];
```



BALE INDEX GATHER KERNEL IN CHAPEL: AGGREGATOR VERSION

```
use CopyAggregation;

// Aggregated index gather
forall (d, i) in zip(Dst, Inds) with (var agg = new SrcAggregator(int)) do
  agg.copy(d, Src[i]);
```

‘use’ the module providing the aggregators

‘with (var …)’ creates a variable per task that’s executing the ‘forall’ loop

Here, we’re giving each task a “source aggregator”, *agg*, which aggregates remote ‘gets’ locally, then performs them

To use it, we simply replace the assignment with ‘agg.copy’

As the aggregator’s buffers fill up, it communicates the operations to the remote locale, automatically and asynchronously

BALE INDEX GATHER KERNEL IN CHAPEL: AGGREGATOR VERSION

```
use CopyAggregation;

// Aggregated index gather
forall (d, i) in zip(Dst, Inds) with (var agg = new SrcAggregator(int)) do
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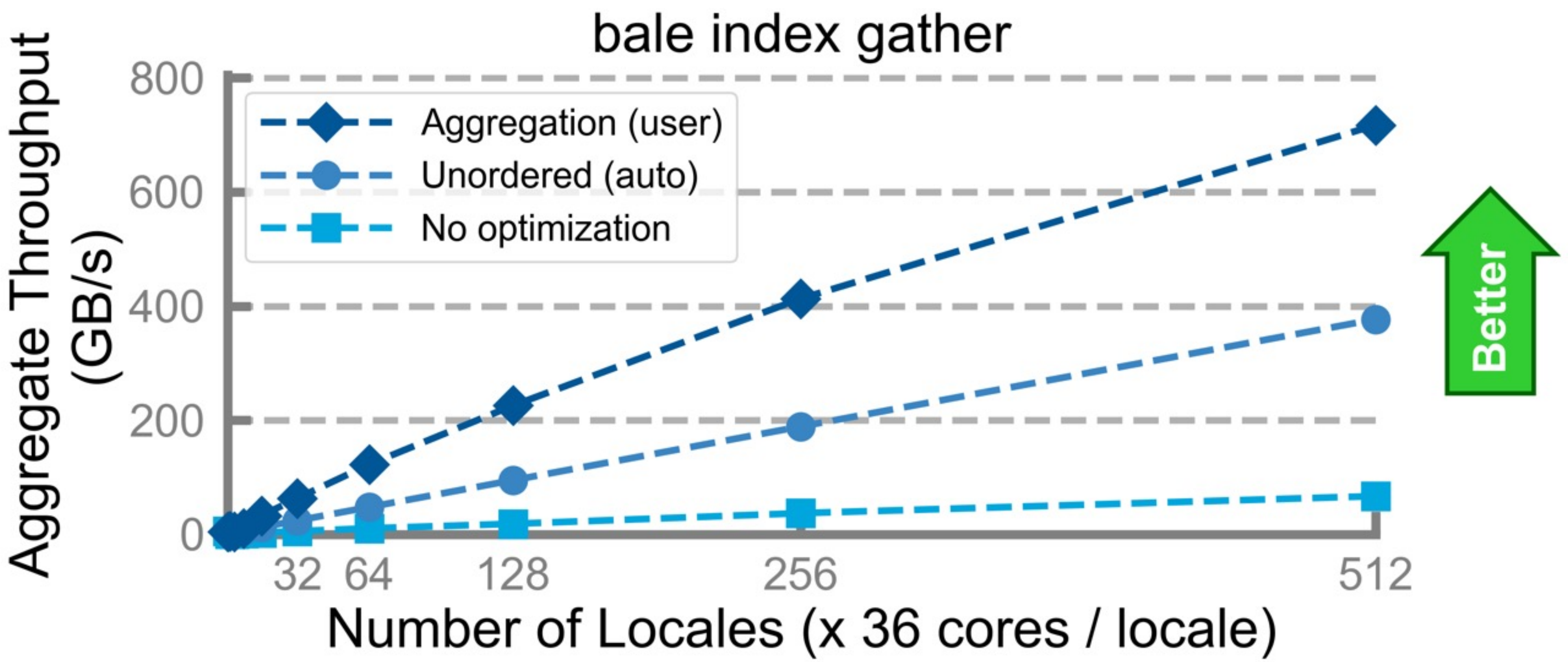


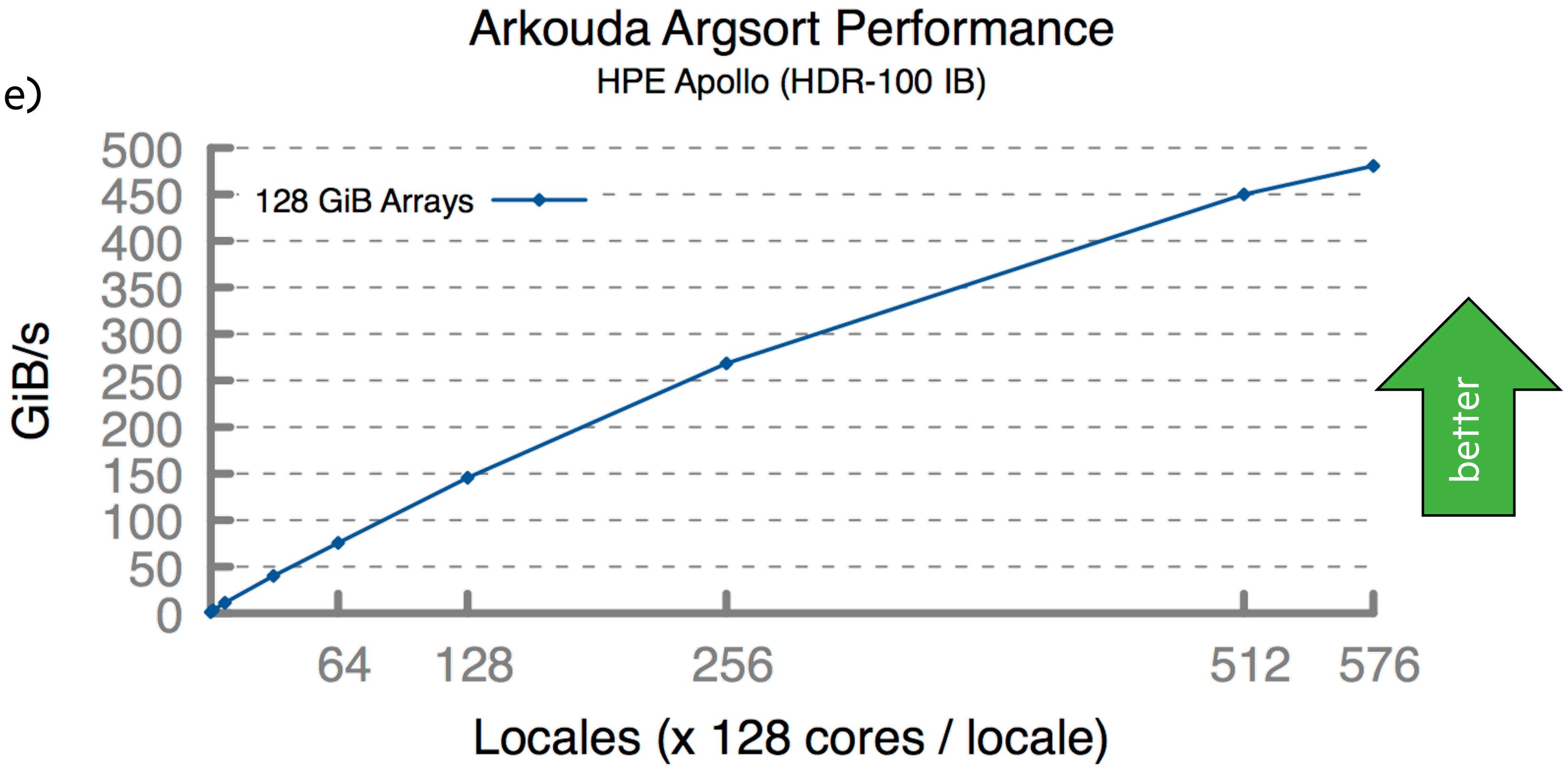
IMPLEMENTING CHAPEL'S AGGREGATORS

- Chapel's aggregators are implemented as Chapel source code
  - no language or compiler changes were required
  - ~100 lines of reasonably straightforward code to implement 'SrcAggregator' used here
    - (~420 lines for the entire 'CopyAggregation' module)

- Developed by Elliot Ronaghan, 2020–present

ARKOUDA ARGSORT: HERO RUN

- Recent hero run performed on a large Apollo system
  - 72 TiB of 8-byte values
  - 480 GiB/s (2.5 minutes elapsed time)
  - used 73,728 cores of AMD Rome
  - ~100 lines of Chapel code



Aggregators have been key to getting results like these

CAN WE AUTOMATE AGGREGATION?

Q: Is there an opportunity for the compiler to introduce aggregators automatically?

```
// Naive index gather
forall (d, i) in zip(Dst, Inds) do
  d = Src[i];
```

user writes straightforward code
compiler optimizes as:

```
use CopyAggregation;

// Aggregated index gather
forall (d, i) in zip(Dst, Inds) with (var agg = new SrcAggregator(int)) do
  agg.copy(d, Src[i]);
```

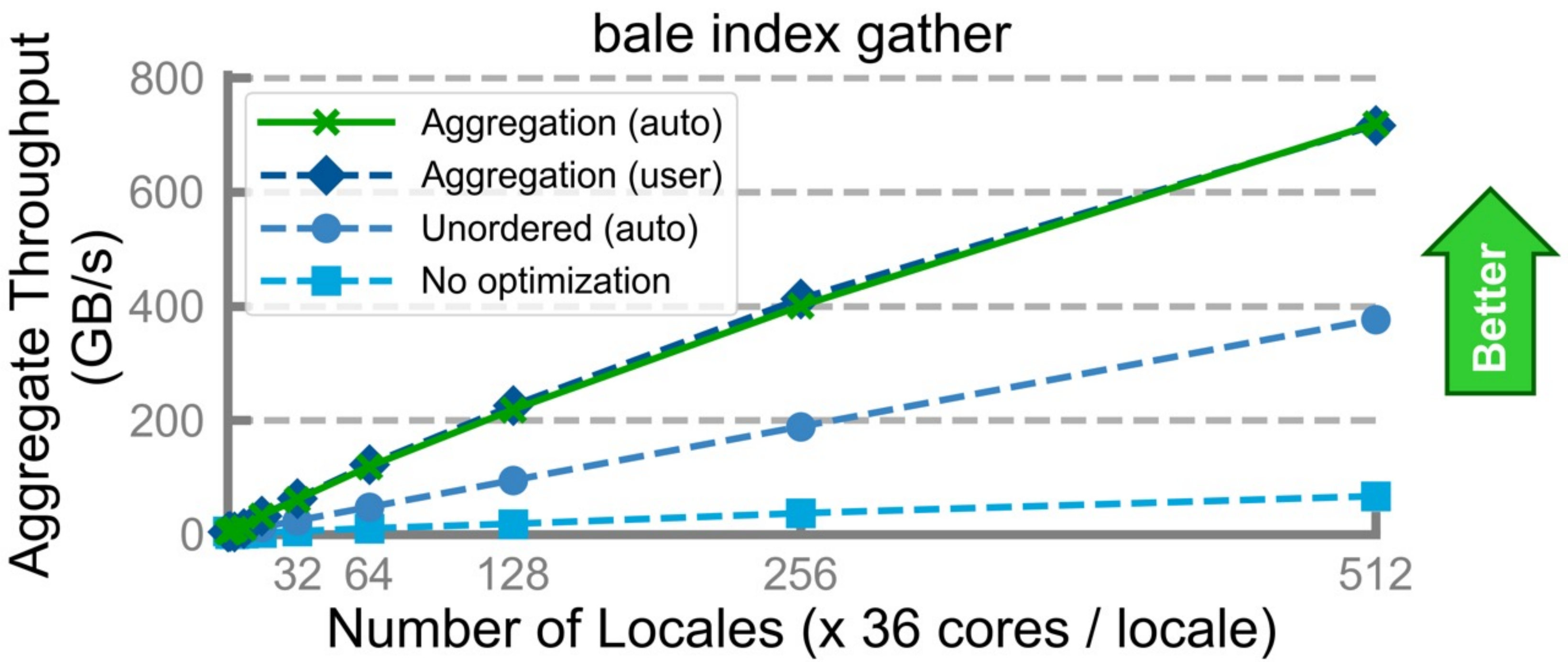
A: In many cases, yes

- developed by Engin Kayraklioglu, 2021
- combines previous 'unordered' analysis with a new locality analysis of RHS/LHS expressions
- for details, see Engin's LCPC 2021 paper: https://lcpc2021.github.io/

AUTO-AGGREGATION: IMPACT

- As a result, the naïve version can now compete with the user-written aggregators

```
// Naive index gather
forall (d, i) in zip(Dst, Inds) do
  d = Src[i];
```



CHAPEL ON GPUS

THE CASE FOR CHAPEL ON GPUS

- “any parallel algorithm on any parallel architecture”
  - yet, Chapel has not supported compilation to GPUs—an obvious important case for many HPC systems

- Related efforts:
  - Albert Sidelnik et al. (UIUC), **Performance portability with the Chapel language**, *IPDPS 2012*
  - Brad Chamberlain, **Chapel Support for Heterogeneous Architectures via Hierarchical Locales**, PGAS-X 2012
  - Mike Chu et al. (AMD), **various works**, *CHIUW 2015–2018*
  - Akihiro Hayasi et al. (Georgia Tech), **various works**, *CHIUW 2019–present*

- Users *have* used Chapel with GPUs through interoperating with kernels written in CUDA, OpenCL, …
  - e.g., the CHAMPS and ChOp applications do this

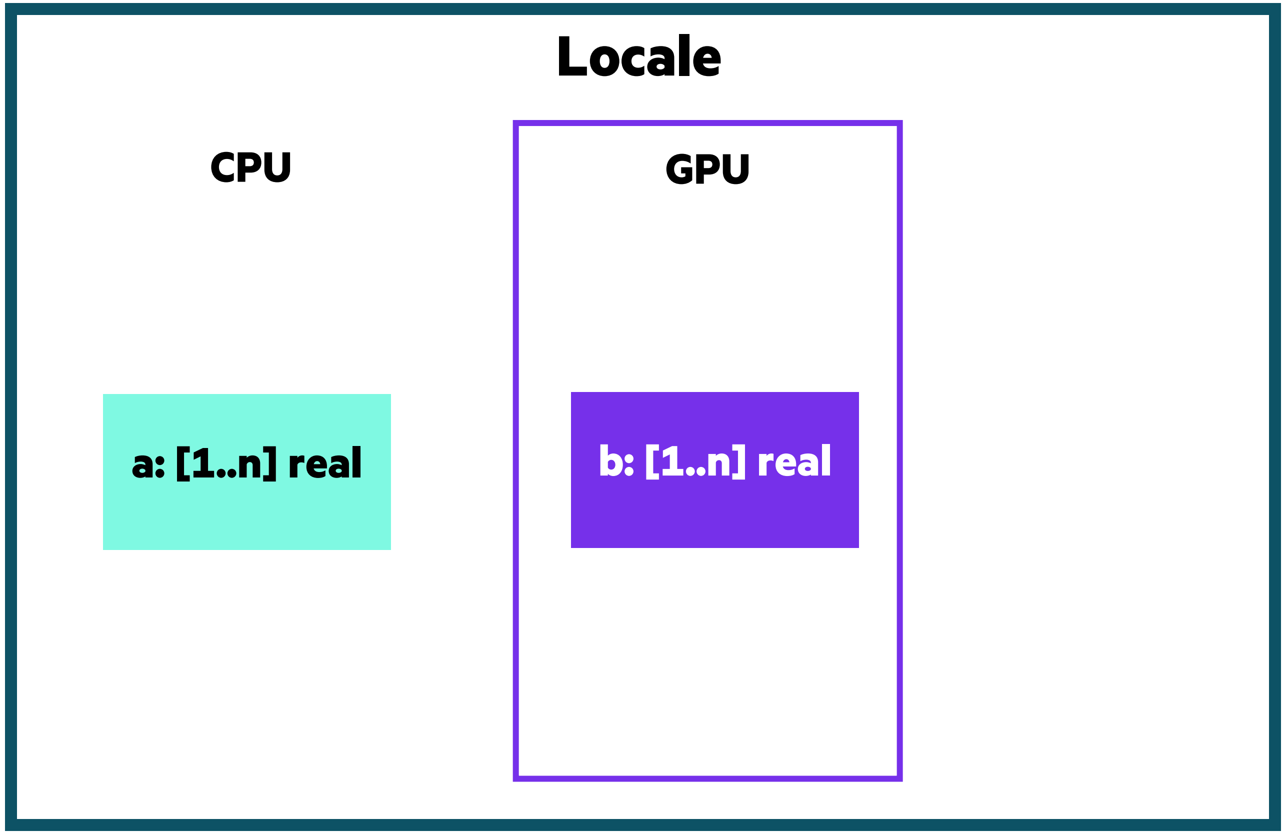
- Yet, Chapel’s features for parallelism and locality are a good match for GPUs
  - code generation has been the major sticking point
  - we’re currently leveraging our LLVM-based back-end to address this

HIERARCHICAL LOCALES: A NOTIONAL CPU+GPU LOCALE MODEL

- A simple 'gpu' locale model might have a sub-locale for the GPU

```
var a: [1..n] real;

on here.GPU {
  var b: [1..n] real;
  ...
}
```



GPUS: NOTIONAL GOAL

A Sample GPU Computation, notionally:

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

GPUS: SIX MONTHS AGO

A Sample GPU Computation, as of Chapel 1.24:

```
pragma "codegen for GPU"
export proc add_nums(A: c_ptr(real(64))){
  A[0] = A[0]+5;
}

var funcPtr = createFunction();
var A = [1, 2, 3, 4, 5];
__primitive("gpu kernel launch", funcPtr,
            <grid and block size>,…,
            c_ptrTo(A), …);
writeln(A);
```

```
extern {
  #define FATBIN_FILE "chpl__gpu.fatbin"
  double createFunction(){
    fatbinBuffer = <read FATBIN_FILE into buffer>
    cuModuleLoadData(&cudaModule, fatbinBuffer);
    cuModuleGetFunction(&function, cudaModule,
                        "add_nums");}

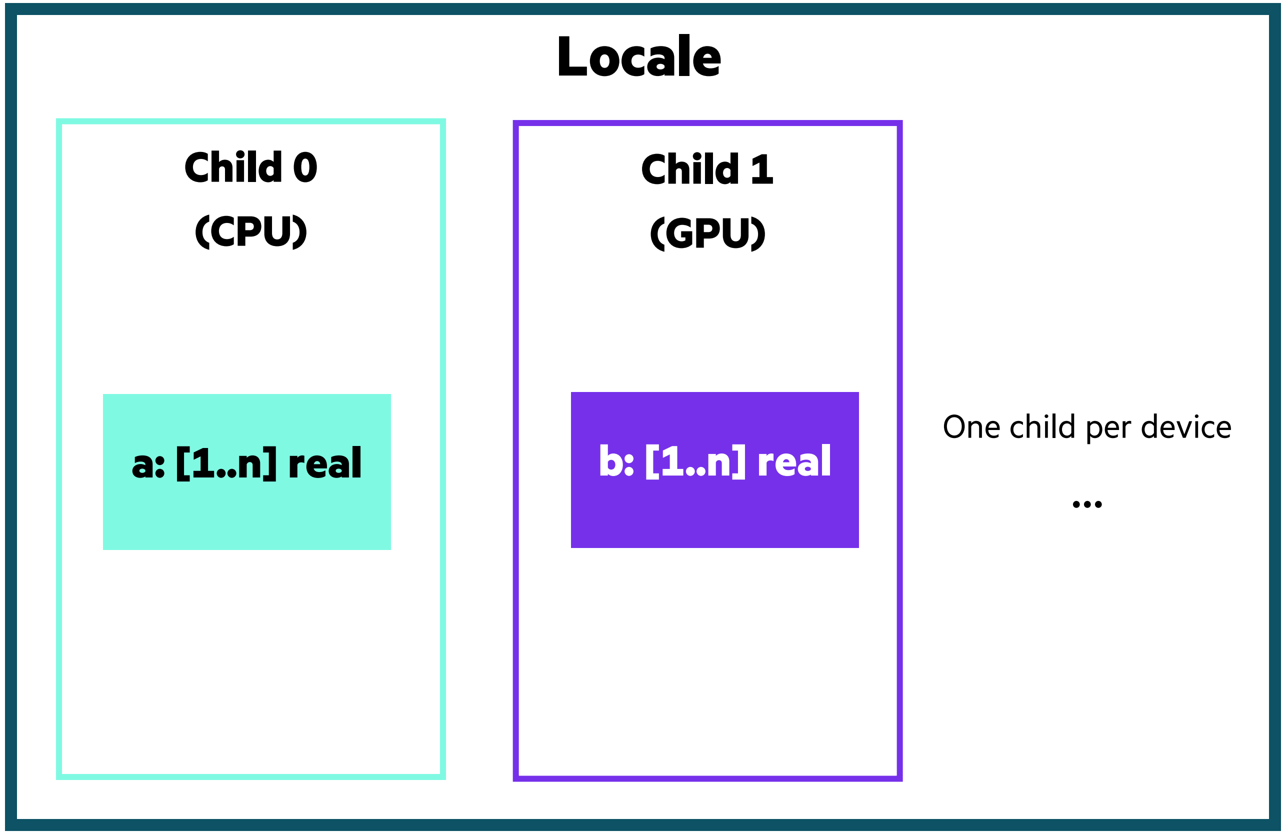
}
```

Read fat binary and create a CUDA function

GPUS: TODAY

A Sample GPU Computation, in Chapel 1.25:

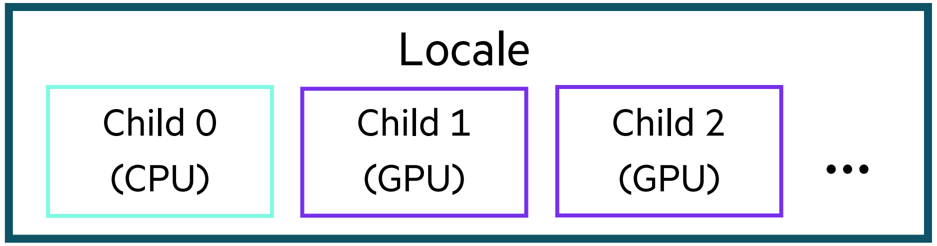
```
on here.getChild(1) {
  var A = [1, 2, 3, 4, 5];
  forall a in A do
    a += 5;
}
```



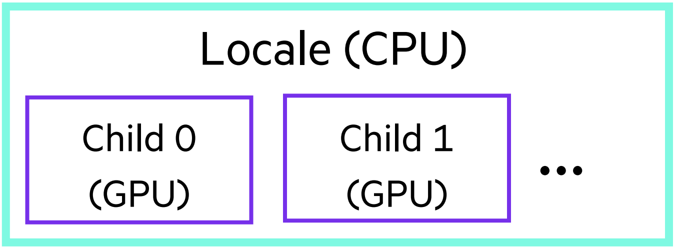
- developed by Engin Kayraklioglu, Andy Stone, and David Iten

ALTERNATIVE GPU LOCALE MODELS

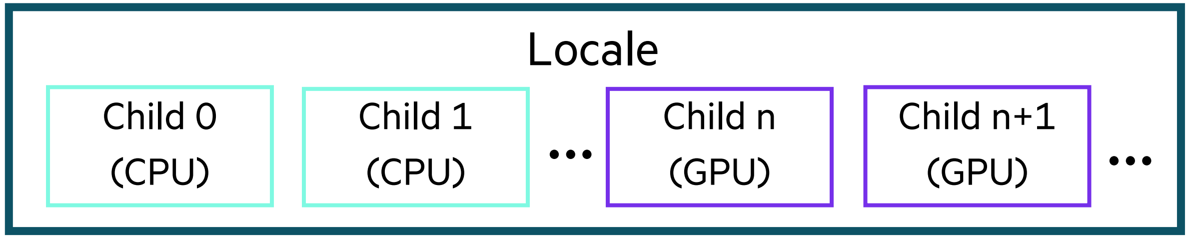
What we have now (sub-locale 0 = CPU)



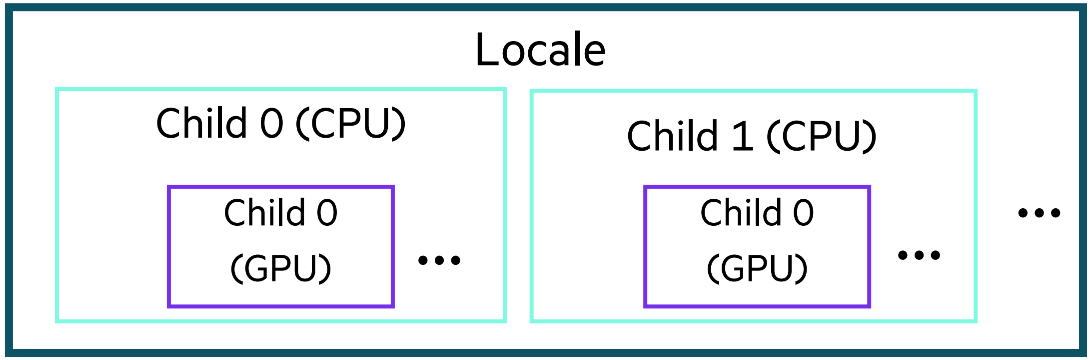
Locale for CPU; sub-locales for GPUs



NUMA-aware (flat)



NUMA-aware (hierarchical)



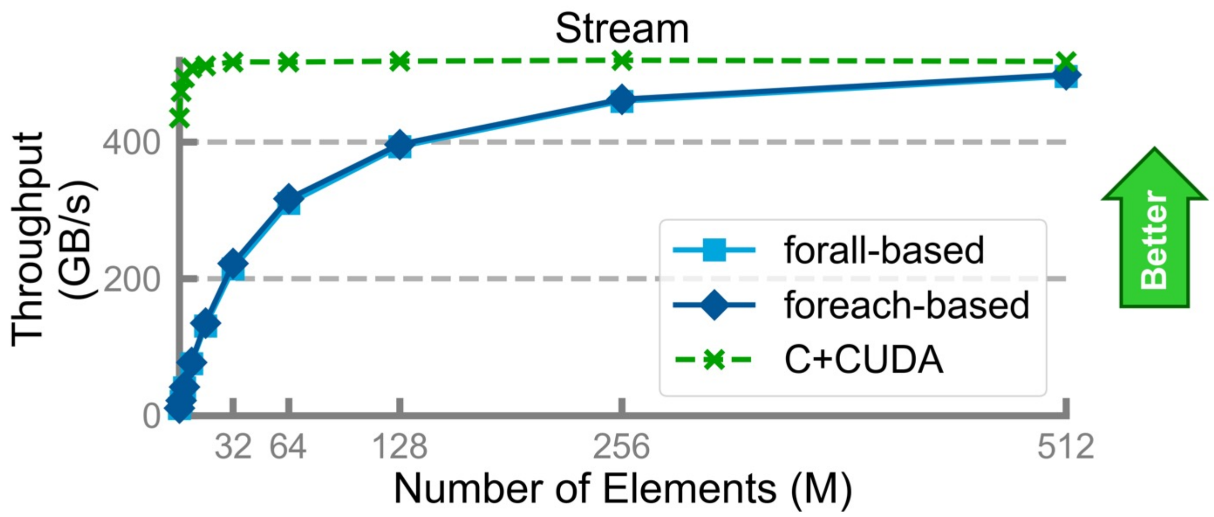
GPUS: INITIAL PERFORMANCE STUDY

HPCC Stream: very few changes needed to our typical Stream code to target GPUs

```
on here.getChild(1) {
  var A, B, C: [1..n] real;
  const alpha = 2.0;

  forall b in B do b = 1.0;
  forall c in C do c = 2.0;

  forall a, b, c in zip(A, B, C) do
    a = b + alpha * c;
}
```



GPUS: NEXT STEPS

- Plenty of housecleaning, refactoring, streamlining, etc.
- Language design issues
- Further performance analysis and optimization
- Support richer and more flexible styles of programming
- Support a richer model of memory and inter-device data transfers (today: unified memory only)
- Support a wider variety of vendors (today: Nvidia only)

WRAP-UP

CHAPEL RESOURCES

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

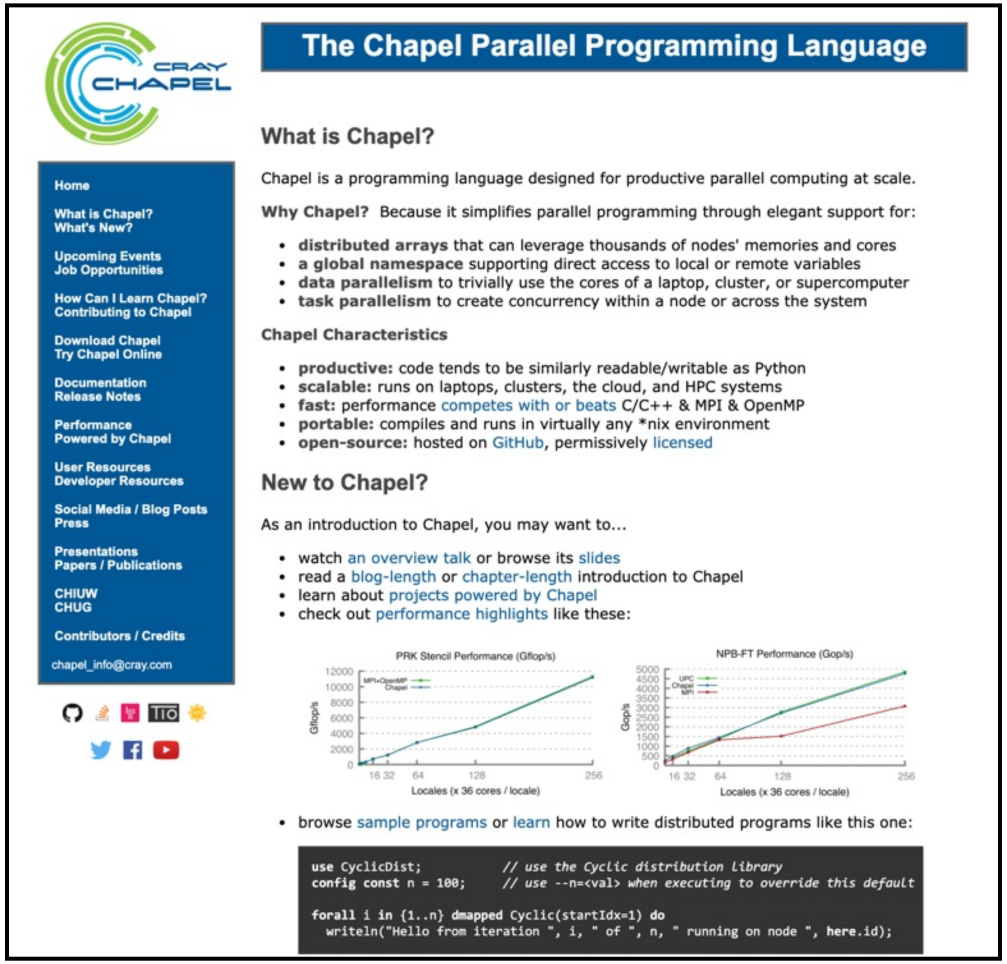
- (points to all other resources)

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



SUGGESTED READING / VIEWING

Chapel Overviews / History (in chronological order):

- *Chapel* chapter from *Programming Models for Parallel Computing*, MIT Press, edited by Pavan Balaji, November 2015
- *Chapel Comes of Age: Making Scalable Programming Productive*, Chamberlain et al., *CUG 2018*, May 2018
- Proceedings of the *8th Annual Chapel Implementers and Users Workshop* (CHIUW 2021), June 2021
- Chapel Release Notes — current version 1.25, October 2021

Arkouda:

- Bill Reus's CHIUW 2020 keynote talk: https://chapel-lang.org/CHIUW2020.html#keynote
- Arkouda GitHub repo and pointers to other resources: https://github.com/Bears-R-Us/arkouda

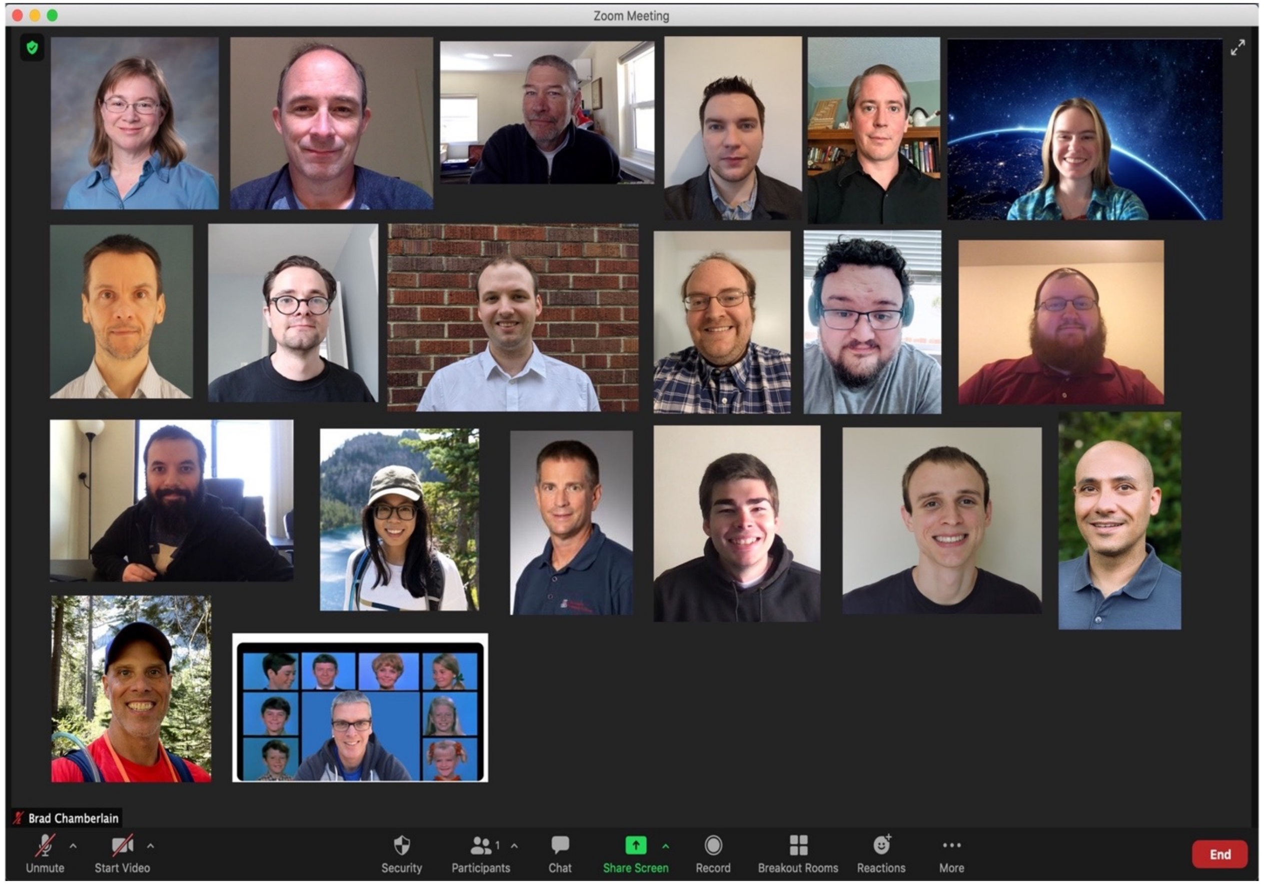
CHAMPS:

- Eric Laurendeau's CHIUW 2021 keynote talk: https://chapel-lang.org/CHIUW2021.html#keynote
  - two of his students also gave presentations at CHIUW 2021, also available from the URL above
- Another paper/presentation by his students at https://chapel-lang.org/papers.html (search "Laurendeau")

CHAPEL IS HIRING

- Chapel team at HPE is currently 18.5 full-time employees
  - planning to add 1–2 more during 2021–2022
  - see: https://chapel-lang.org/jobs.html

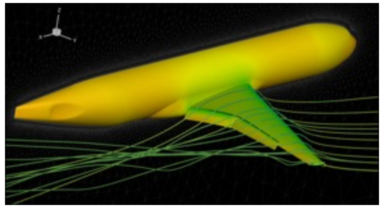
- During summers, we also host interns and mentor Google Summer of Code students



SUMMARY

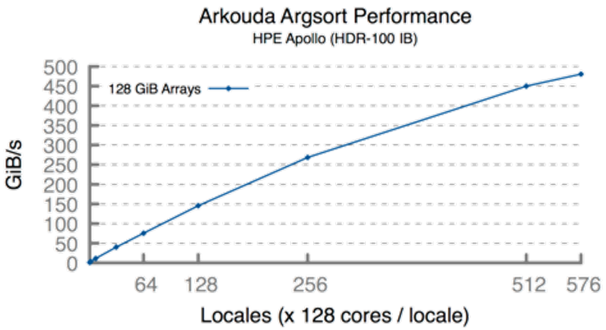
Chapel is being used for productive parallel programming at scale

- recent users have reaped its benefits in 16k–48k-line applications



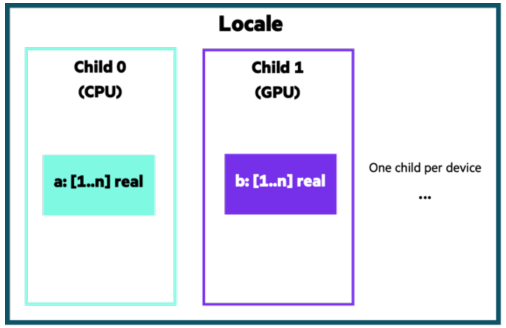
For gather/scatter/sort patterns, copy aggregation is key

- particularly important for key operations in Arkouda



Though Chapel support for GPUs is still in its early days, it's improving by leaps and bounds

- should enable users like the CHAMPS team to leverage GPUs more productively



THANK YOU

https://chapel-lang.org
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