Hewlett Packard
Enterprise

Parallel Programming from Desktops to Supercomputers with Chapel

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Galois Tech Talk

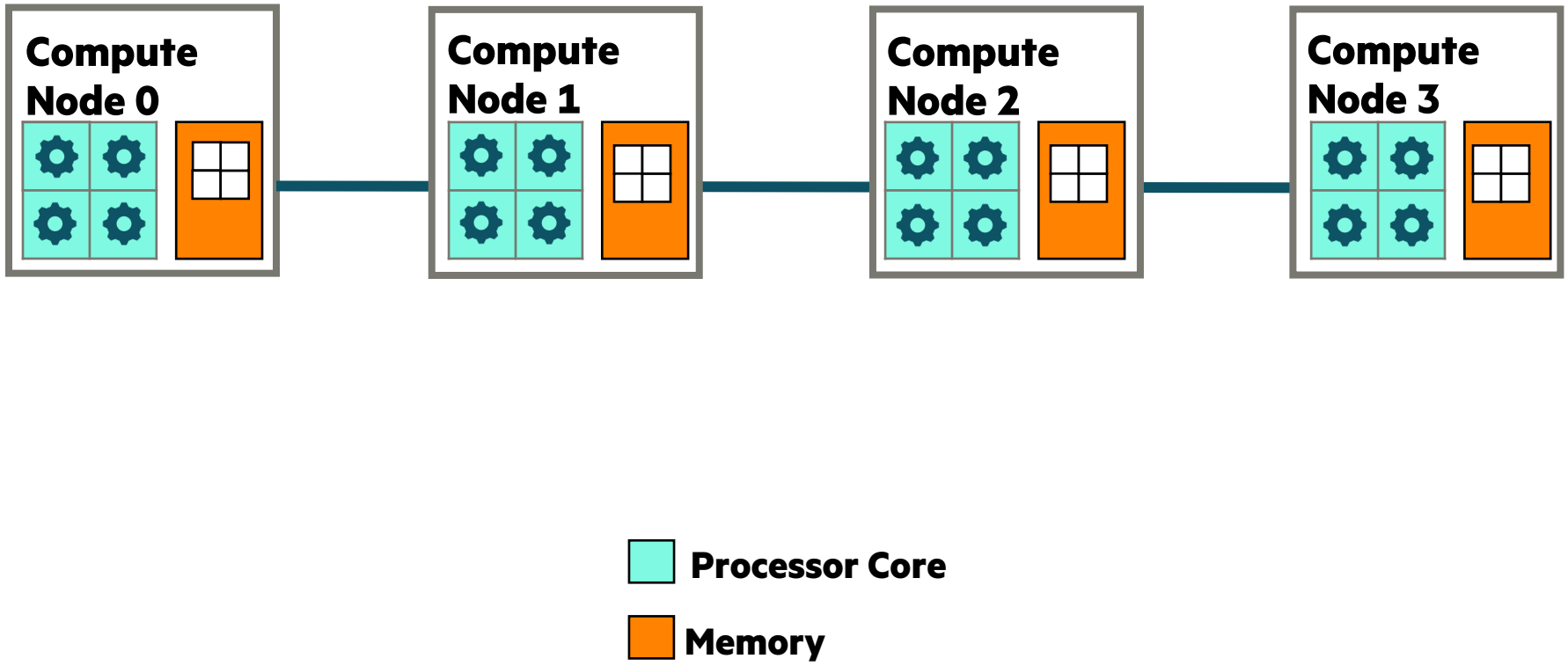
July 24, 2025


A Bit About Me

Motivation for Parallel Computing

Parallel Computing: Using the processors and memories of multiple compute resources

- in order to run a program…
  - faster than we could otherwise
  - and/or using larger problem sizes



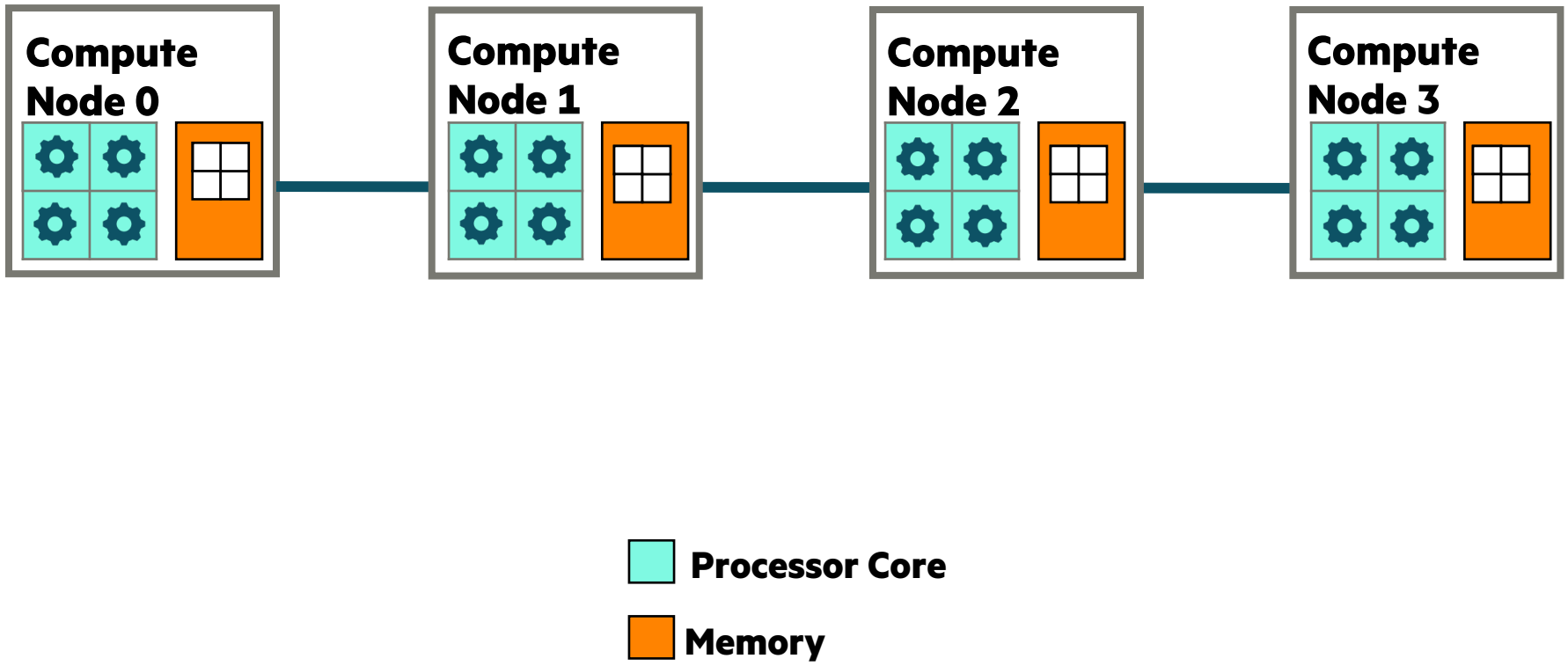
Parallel Computing has become Ubiquitous

Historical parallel computing:

- supercomputers
- commodity clusters

Today, we also have:

- multicore processors
- GPUs
- cloud computing



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

Productive Parallel Programming: One Definition

Imagine a programming language for parallel computing that is as…

…**readable and writeable** as Python

…yet also as…

…**fast** as Fortran / C / C++

…**scalable** as MPI / SHMEM

…**GPU-ready** as CUDA / HIP / OpenMP / Kokkos / OpenCL / OpenACC / …

…**portable** as C

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

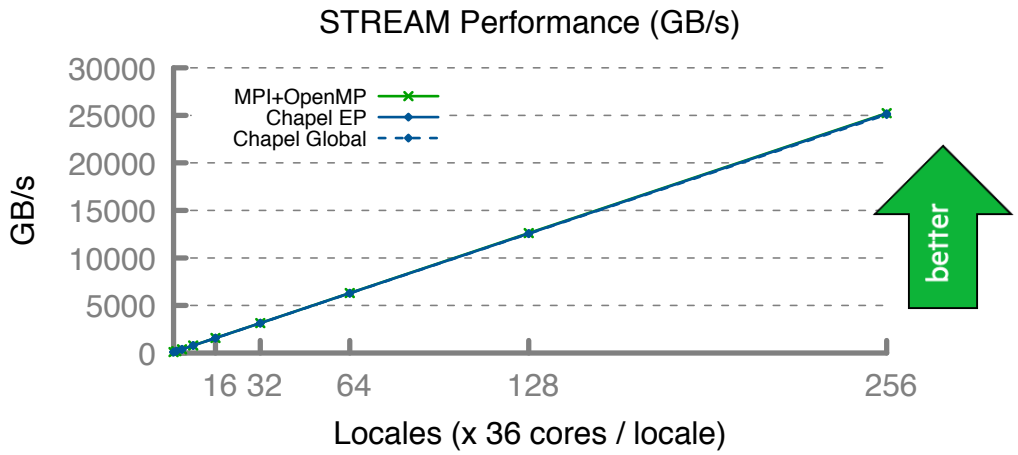
This is our motivation for Chapel

HPCC Stream Triad and RA in C + MPI + OpenMP vs. Chapel

STREAM TRIAD: C + MPI + OPENMP

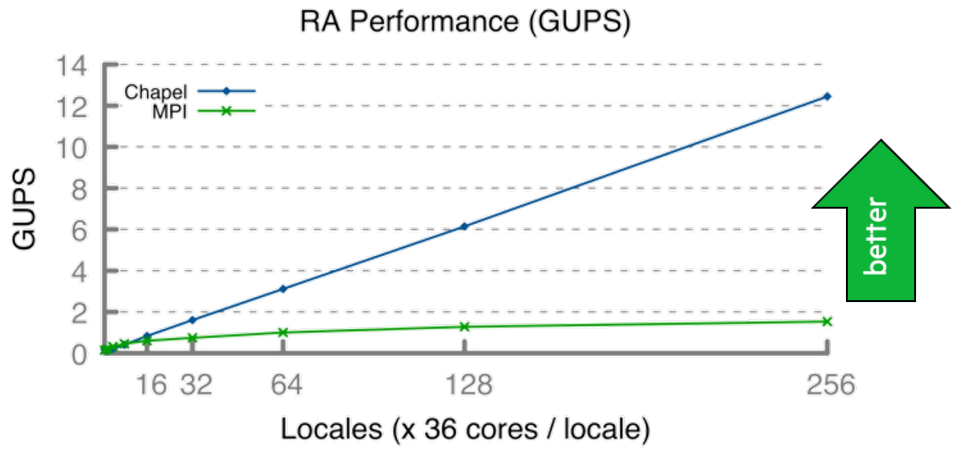
```
#include <hpcc.h>
#ifdef _OPENMP
#include <omp.h>
#endif

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 );
```

```
use BlockDist;

config const n = 1_000_000,
             alpha = 0.01;
const Dom = blockDist.createDomain({1..n});
var A, B, C: [Dom] real;

B = 2.0;
C = 1.0;

A = B + alpha * C;
```



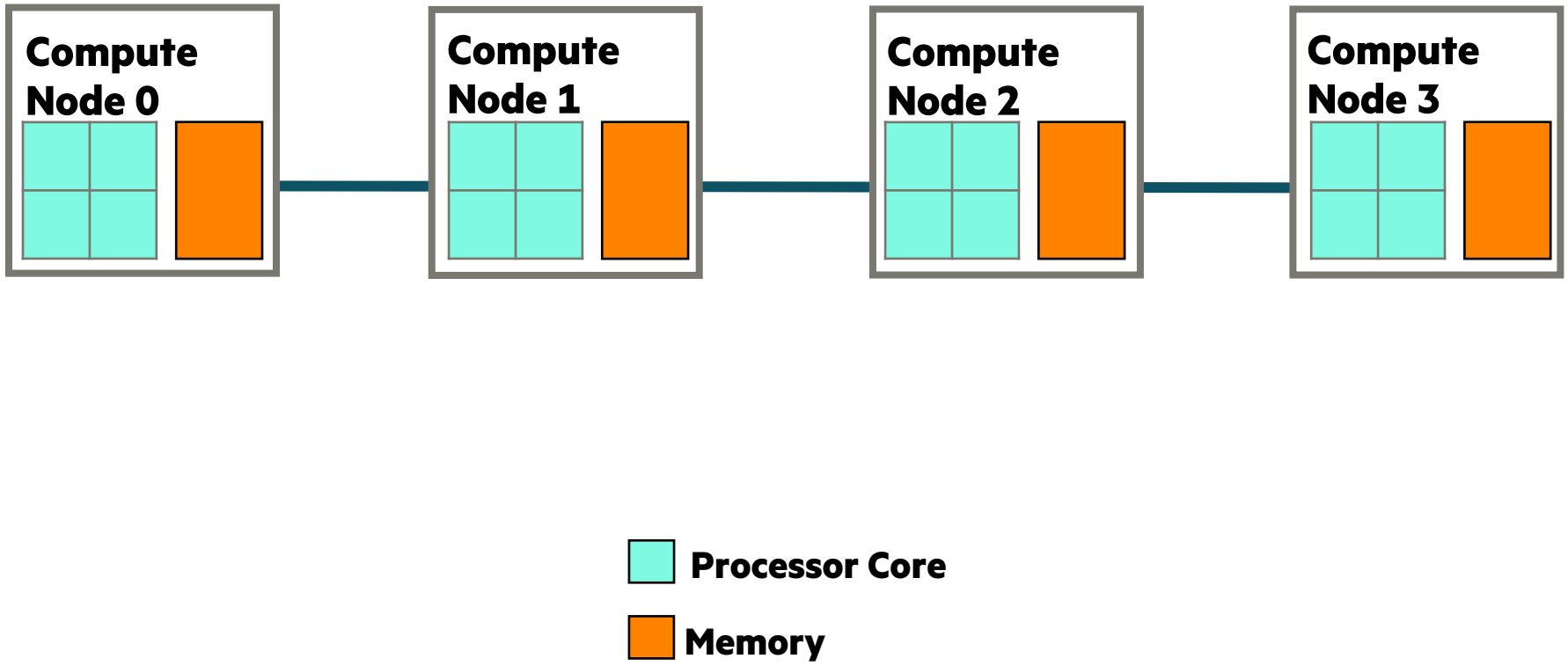
HPCC RA: MPI KERNEL

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



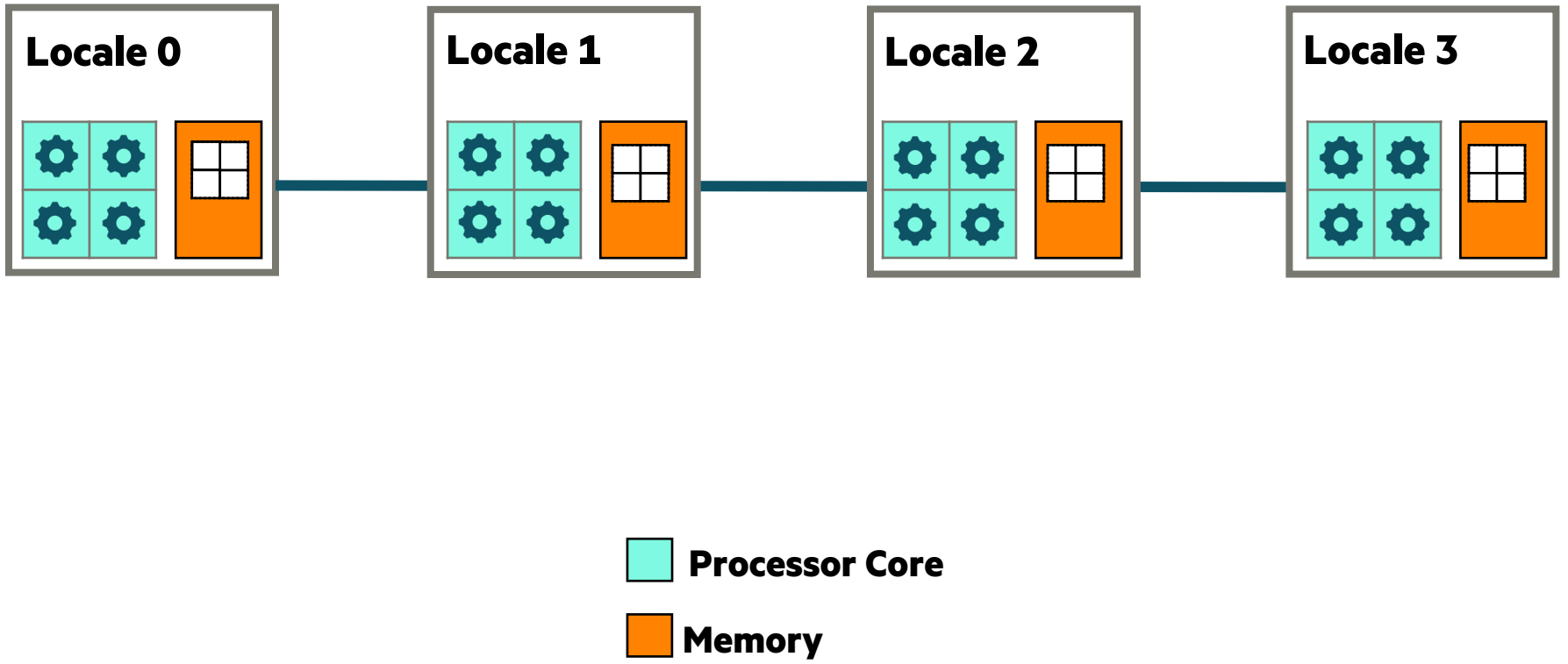
Locales in Chapel

- In Chapel, a *locale* refers to a compute resource with…
  - processors, so it can run tasks
  - memory, so it can store variables
- For now, think of each compute node as being a locale



Key Concerns for Scalable Parallel Computing

1. **parallelism:** What computational tasks should run simultaneously?
2. **locality:** Where should tasks run? Where should data be allocated?

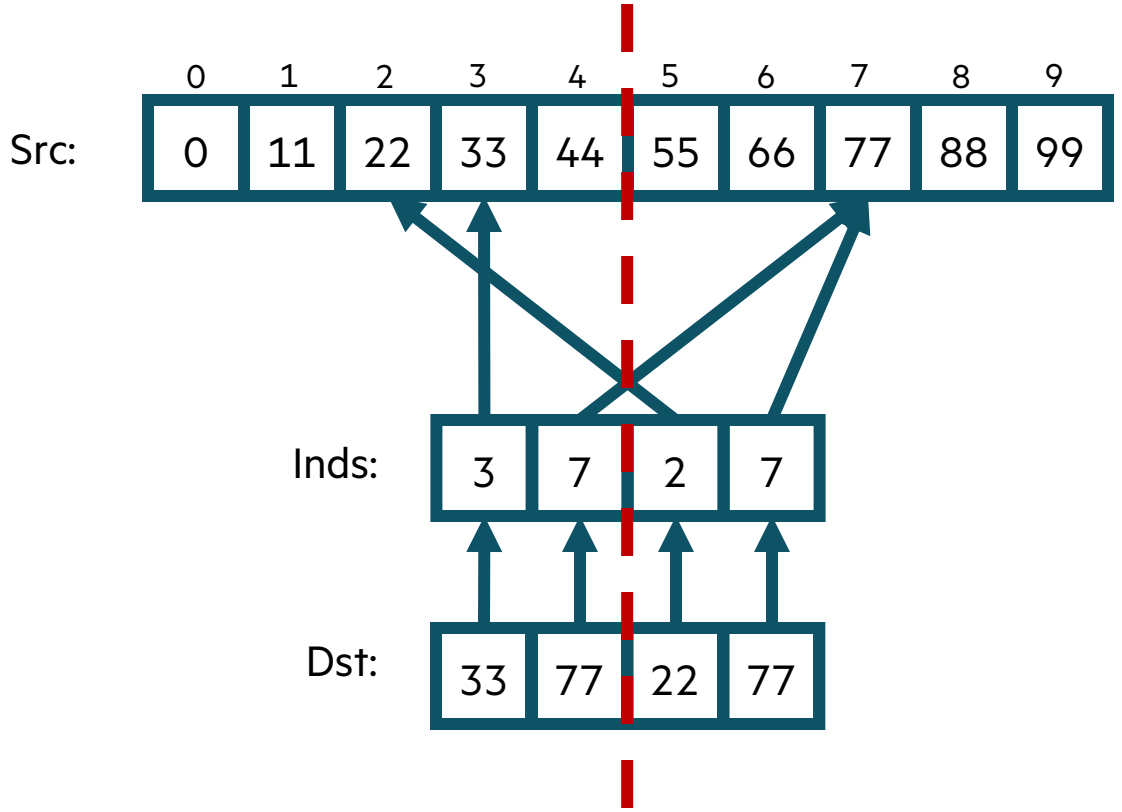


Outline

- Motivation and Context
- **Chapel by Example**
- **Applications of Chapel**
- **Chapel on GPUs**
- **Wrap-up**

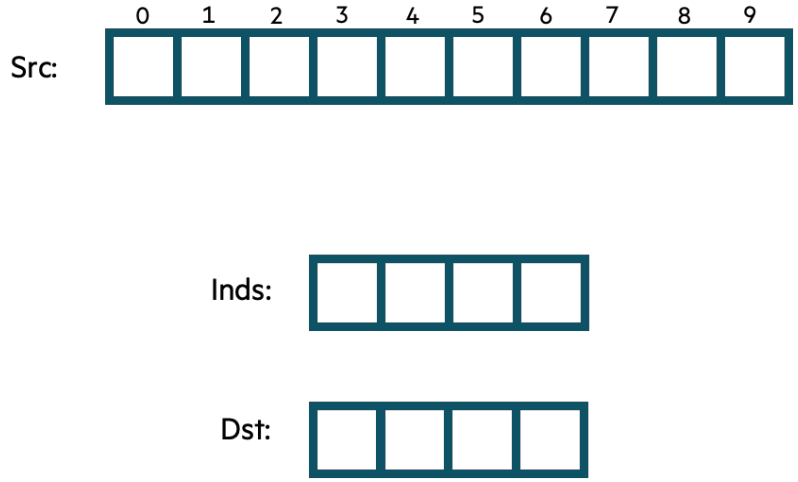
Chapel by Example:
Bale Index Gather (IG)

Bale Index Gather (IG): In Pictures



Bale IG in Chapel: Array Declarations

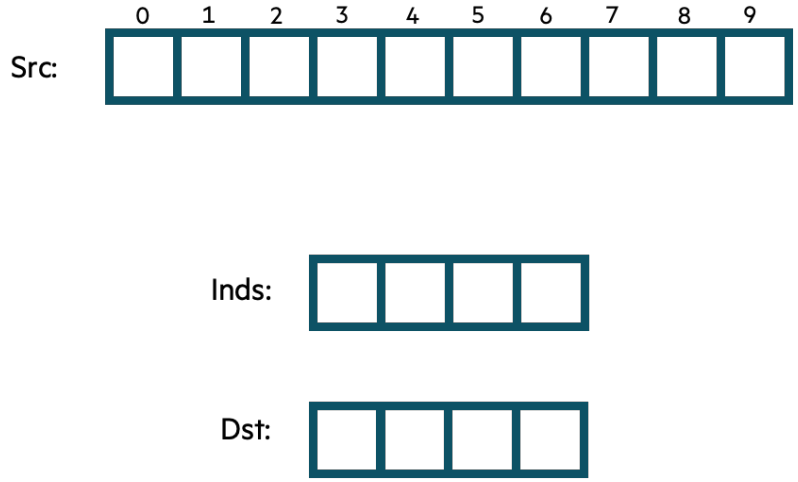
```
config const n = 10,
             m = 4;



var Src: [0..<n] int,
    Inds, Dst: [0..<m] int;
```




```
$
```

Bale IG in Chapel: Compiling

```
config const n = 10,
             m = 4;



var Src: [0..<n] int,
    Inds, Dst: [0..<m] int;
```

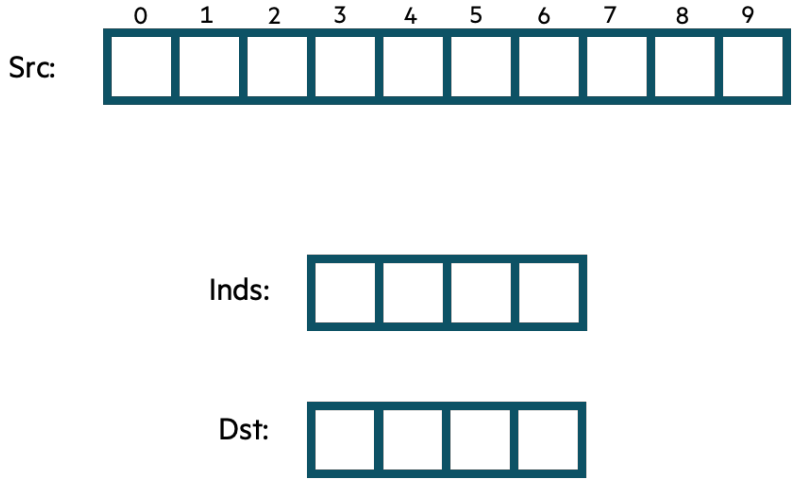


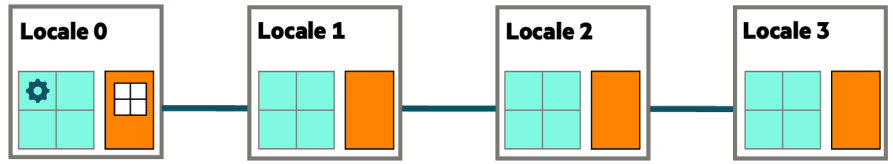

```
$ chpl bale-ig.chpl
$
```

Bale IG in Chapel: Executing

```
config const n = 10,
             m = 4;



var Src: [0..<n] int,
    Inds, Dst: [0..<m] int;
```

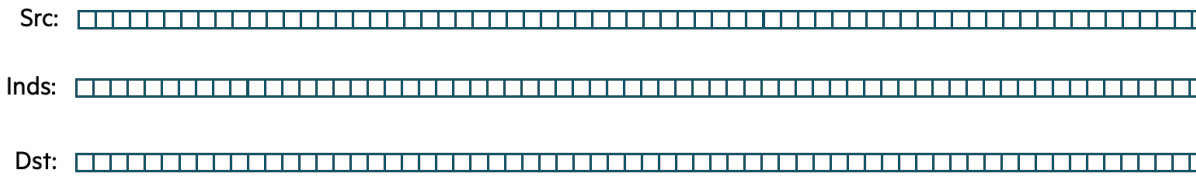
```
$ chpl bale-ig.chpl
$ ./bale-ig
$
```



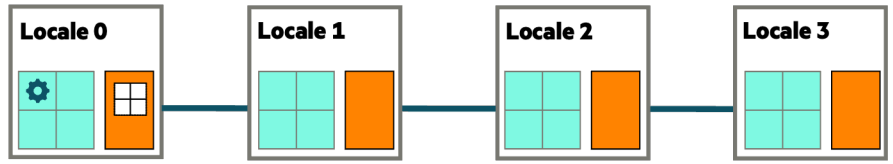


Bale IG in Chapel: Executing, Overriding Configs

```
config const n = 10,
             m = 4;



var Src: [0..<n] int,
    Inds, Dst: [0..<m] int;
```



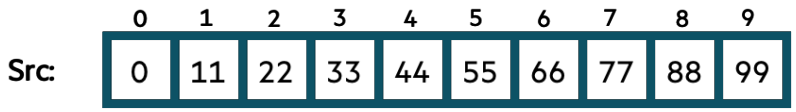

```
$ chpl bale-ig.chpl
$ ./bale-ig --n=1_000_000 --m=1_000_000
$
```

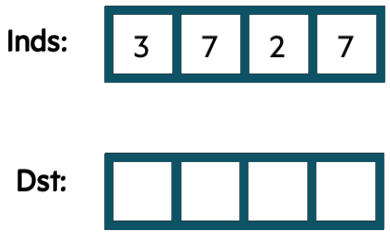


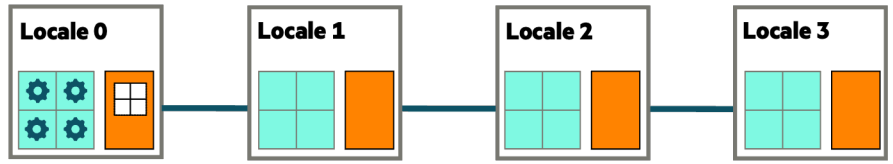
Bale IG in Chapel: Array Initialization

```
use Random;

config const n = 10,
             m = 4;




var Src: [0..<n] int,
    Inds, Dst: [0..<m] int;

Src = [i in 0..<n] i*11;
fillRandom(Inds, min=0, max=n-1);
```

```
$ chpl bale-ig.chpl
$ ./bale-ig
$
```



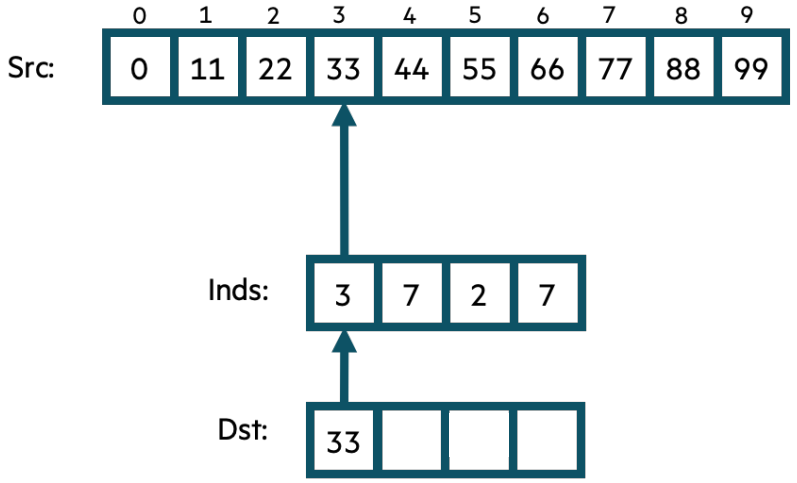


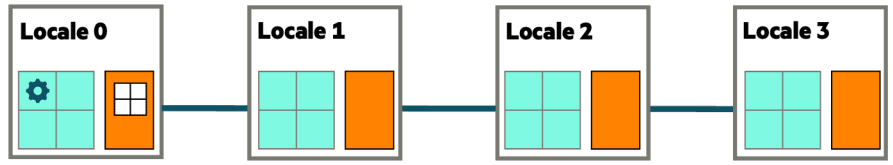


Bale IG in Chapel: Serial Version

```
config const n = 10,
             m = 4;




var Src: [0..<n] int,
    Inds, Dst: [0..<m] int;
…
for i in 0..<m do
  Dst[i] = Src[Inds[i]];
```

```
$ chpl bale-ig.chpl
$ ./bale-ig
$
```

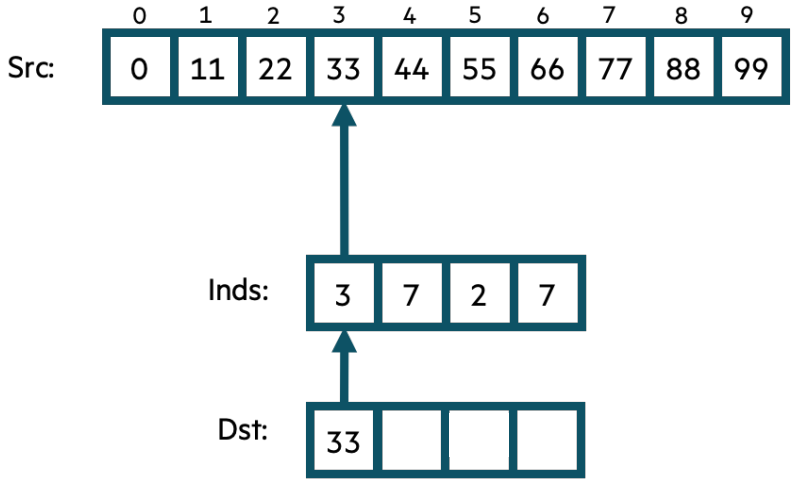


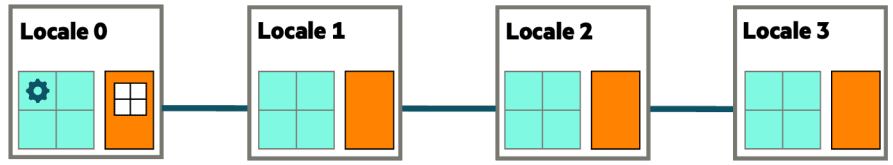


Bale IG in Chapel: Serial, Zippered Version

```
config const n = 10,
             m = 4;




var Src: [0..<n] int,
    Inds, Dst: [0..<m] int;
…
for (d, i) in zip(Dst, Inds) do
  d = Src[i];
```

```
$ chpl bale-ig.chpl
$ ./bale-ig
$
```

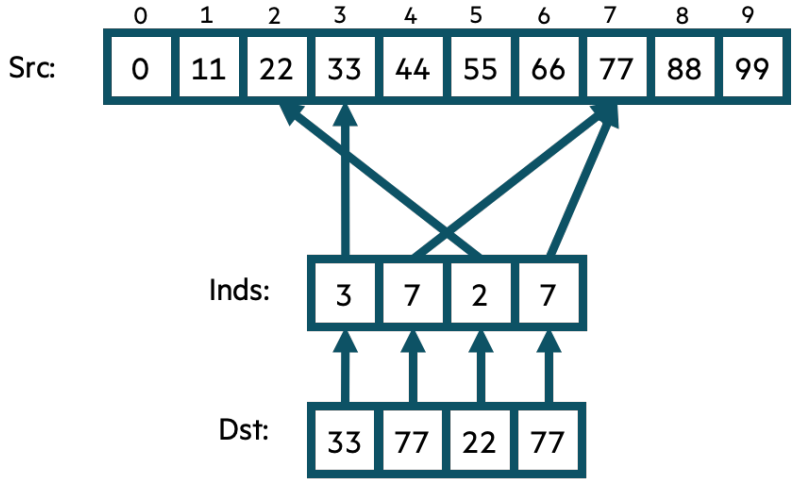


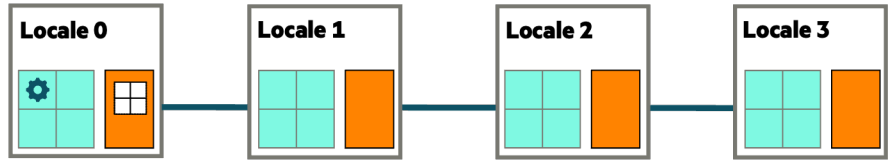


Bale IG in Chapel: Parallel, Zippered Version (Vectorized)

```
config const n = 10,
             m = 4;




var Src: [0..<n] int,
    Inds, Dst: [0..<m] int;
…
forall (d, i) in zip(Dst, Inds) do
  d = Src[i];
```

```
$ chpl bale-ig.chpl
$ ./bale-ig
$
```

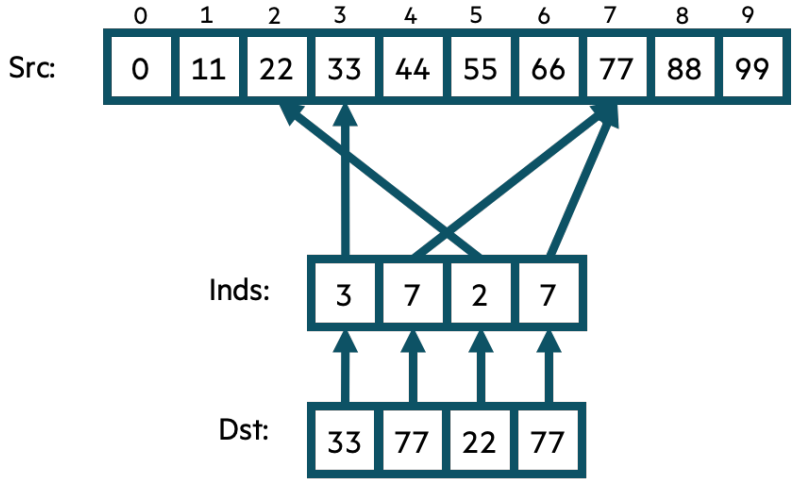


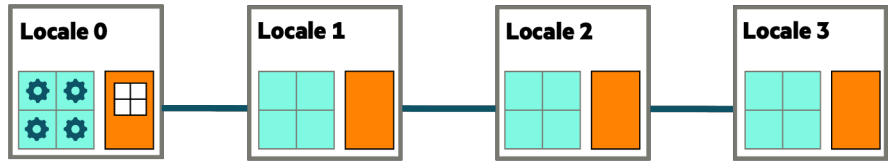


Bale IG in Chapel: Parallel, Zippered Version (Multicore)

```
config const n = 10,
             m = 4;




var Src: [0..<n] int,
    Inds, Dst: [0..<m] int;
…
forall (d, i) in zip(Dst, Inds) do
  d = Src[i];
```

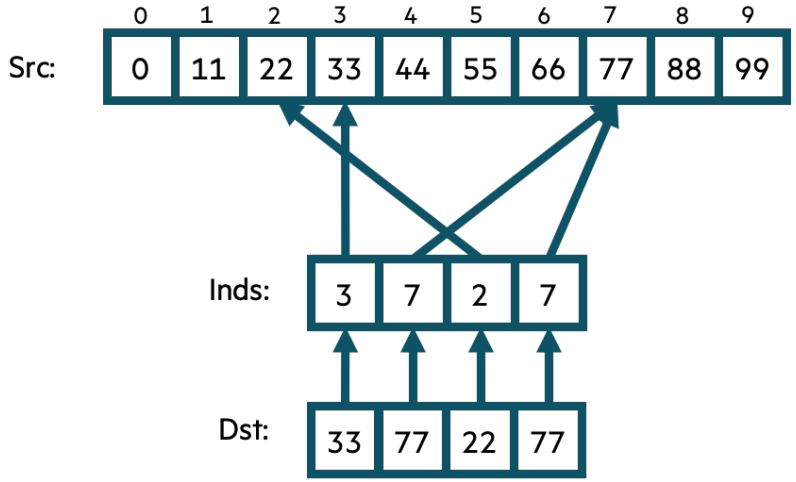
```
$ chpl bale-ig.chpl
$ ./bale-ig
$
```



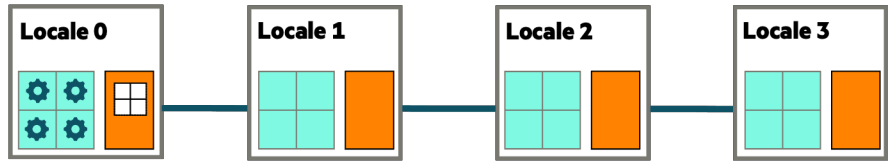


Bale IG in Chapel: Parallel Promoted Version (equivalent to previous version)

```
config const n = 10,
             m = 4;



var Src: [0..<n] int,
    Inds, Dst: [0..<m] int;
…
Dst = Src[Inds];
```



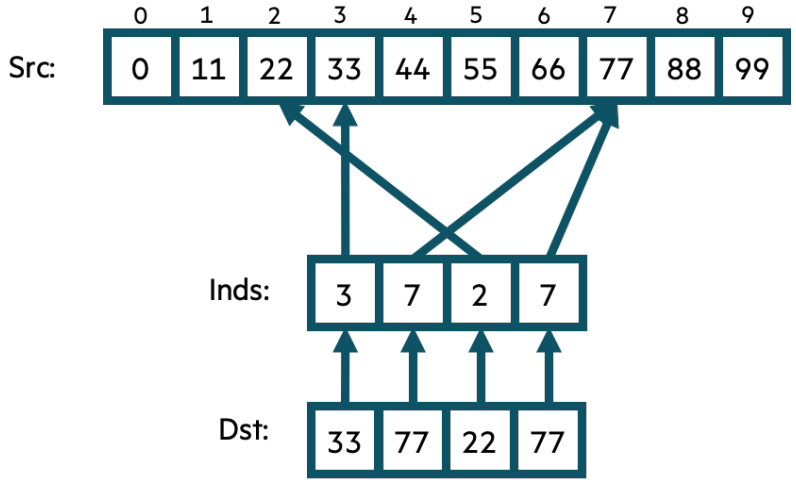

```
$ chpl bale-ig.chpl
$ ./bale-ig
$
```

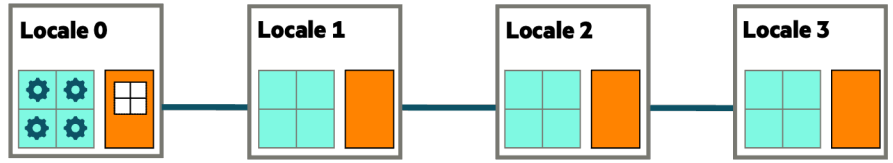


Bale IG in Chapel: Parallel, Zippered Version (Multicore)

```
config const n = 10,
             m = 4;




var Src: [0..<n] int,
    Inds, Dst: [0..<m] int;
…
forall (d, i) in zip(Dst, Inds) do
  d = Src[i];
```

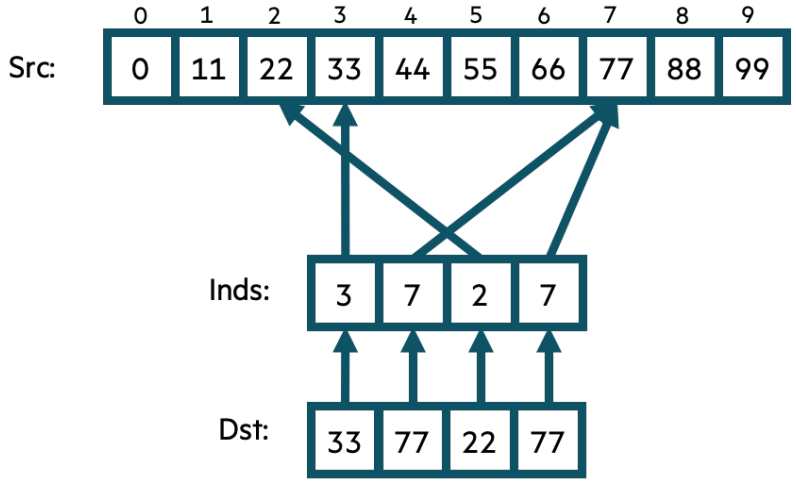
```
$ chpl bale-ig.chpl
$ ./bale-ig
$
```



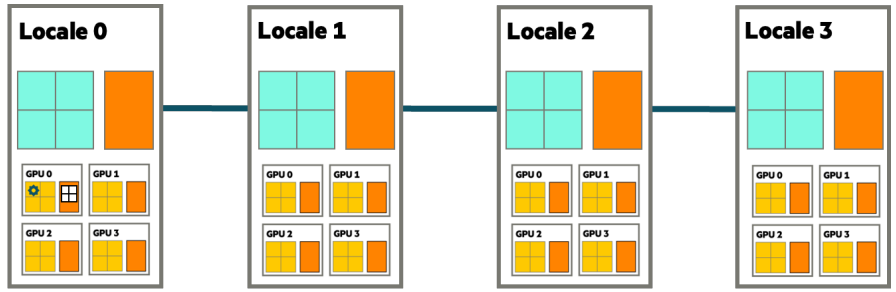


Bale IG in Chapel: Parallel, Zippered Version for a GPU

```
config const n = 10,
             m = 4;



on here.gpus[0] {
  var Src: [0..<n] int,
      Inds, Dst: [0..<m] int;
  …
  forall (d, i) in zip(Dst, Inds) do
    d = Src[i];
}
```



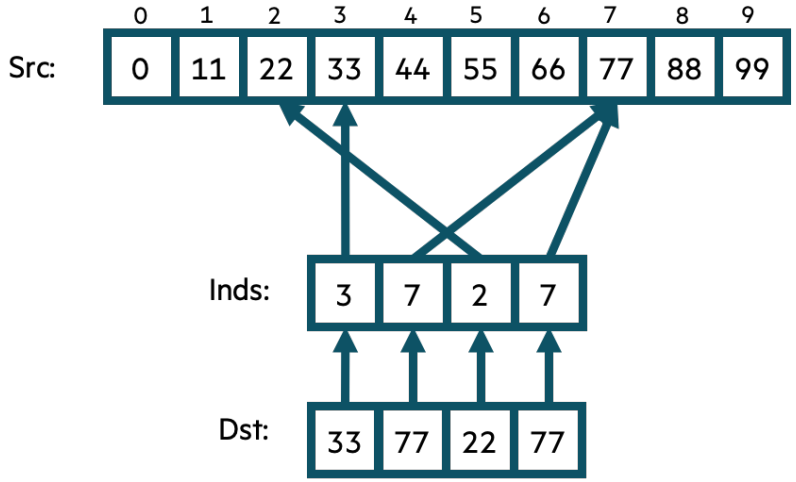

```
$ chpl bale-ig.chpl
$ ./bale-ig
$
```

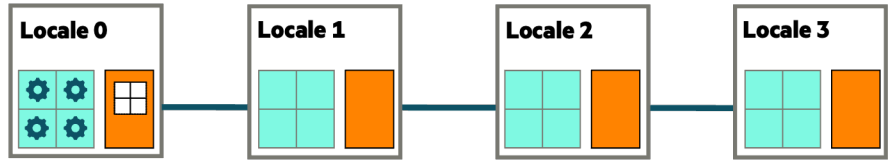


Bale IG in Chapel: Parallel, Zippered Version (Multicore)

```
config const n = 10,
             m = 4;




var Src: [0..<n] int,
    Inds, Dst: [0..<m] int;
…
forall (d, i) in zip(Dst, Inds) do
  d = Src[i];
```

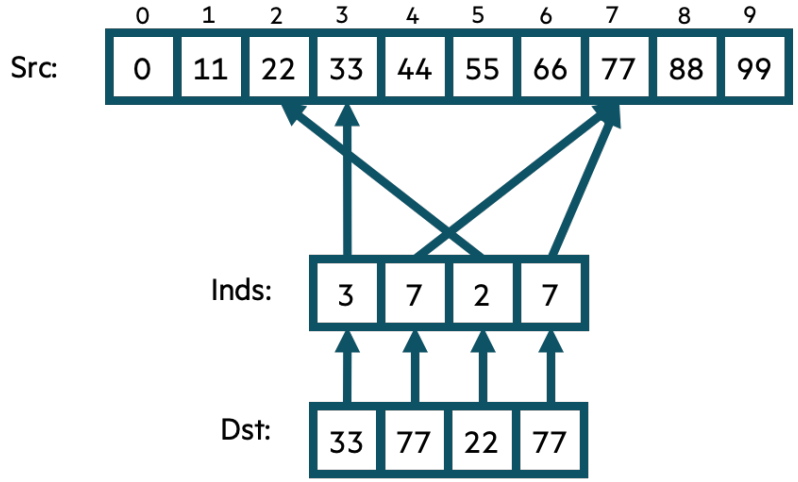
```
$ chpl bale-ig.chpl
$ ./bale-ig
$
```



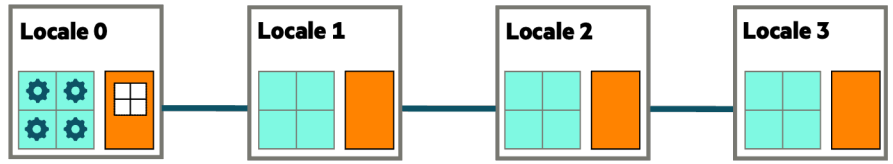


Bale IG in Chapel: Parallel , Zippered Version with Named Domains (Multicore)

```
config const n = 10,
             m = 4;

const SrcInds = {0..<n},
      DstInds = {0..<m};

var Src: [SrcInds] int,
    Inds, Dst: [DstInds] int;
…
forall (d, i) in zip(Dst, Inds) do
  d = Src[i];
```



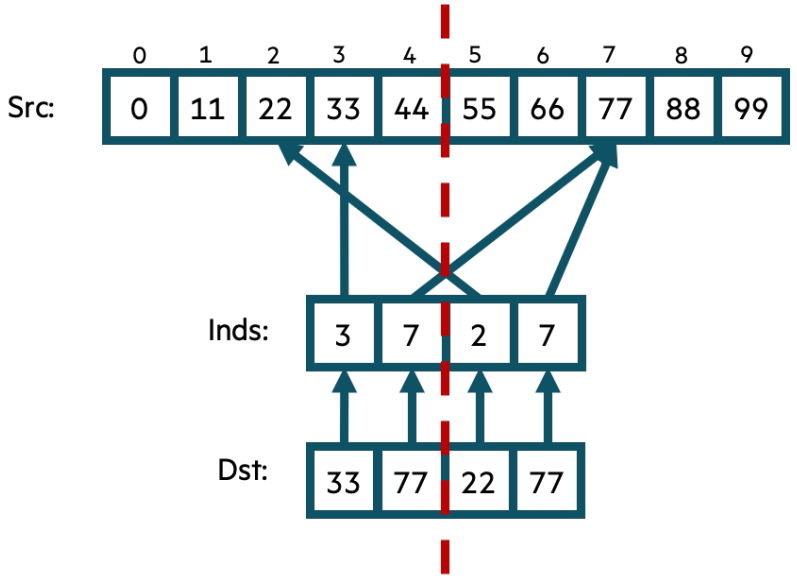

```
$ chpl bale-ig.chpl
$ ./bale-ig
$
```

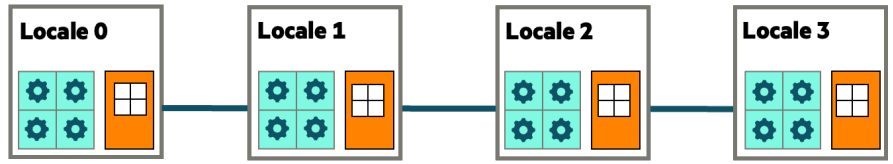


Bale IG in Chapel: Distributed Parallel Version

```
use BlockDist;

config const n = 10,
             m = 4;

const SrcInds = blockDist.createDomain(0..<n),
      DstInds = blockDist.createDomain(0..<m);

var Src: [SrcInds] int,
    Inds, Dst: [DstInds] int;
…
forall (d, i) in zip(Dst, Inds) do
  d = Src[i];
```

```
$ chpl bale-ig.chpl
$ ./bale-ig --n=… --m=… -nl 4
$
```

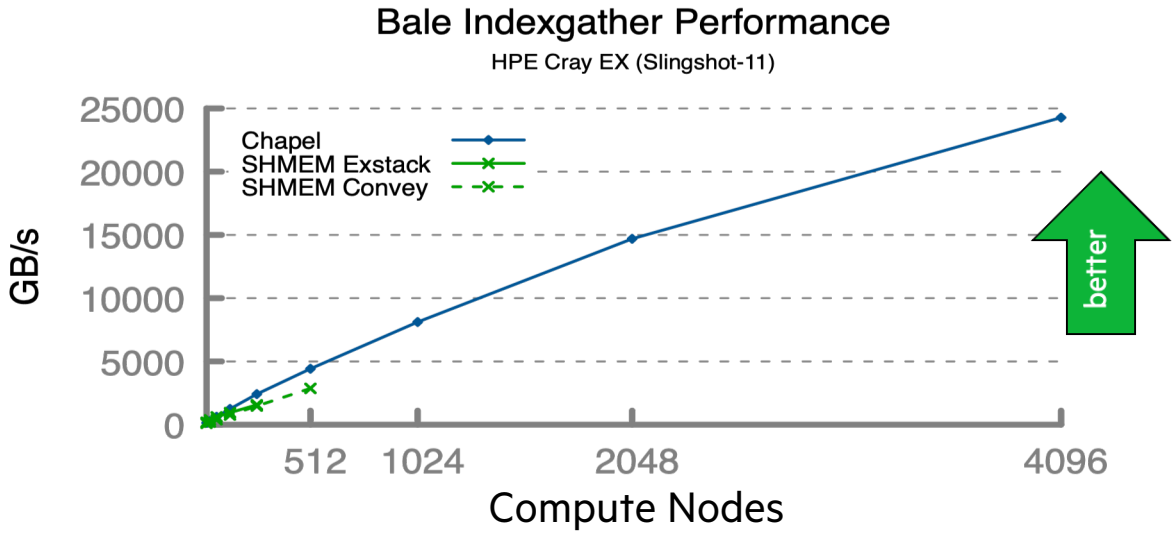


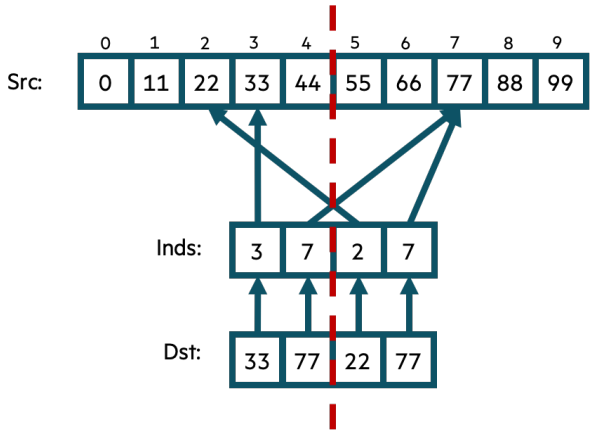


Bale IG in Chapel: Distributed Parallel Version

```
use BlockDist;

config const n = 10,
             m = 4;

const SrcInds = blockDist.createDomain(0..<n),
      DstInds = blockDist.createDomain(0..<m);

var Src: [SrcInds] int,
    Inds, Dst: [DstInds] int;
…
forall (d, i) in zip(Dst, Inds) do
  d = Src[i];
```

```
$ chpl bale-ig.chpl --fast --auto-aggregation
$ ./bale-ig --n=… --m=… -nl 4096
$
```





Bale IG in Chapel vs. SHMEM on HPE Cray EX (Slingshot-11)

Chapel (Simple / Auto-Aggregated version)

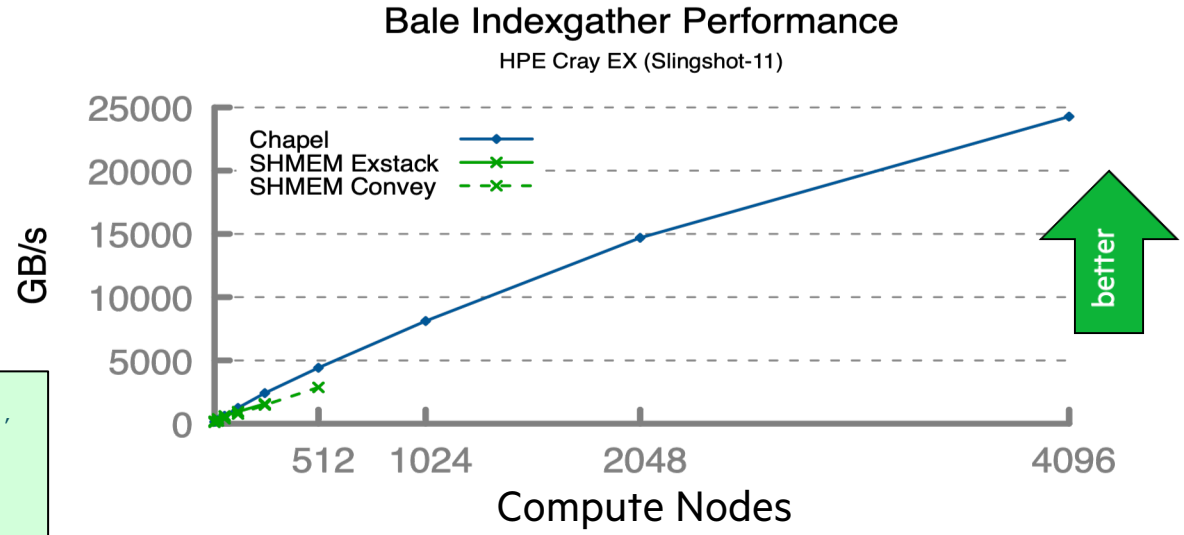
```
forall (d, i) in zip(Dst, Inds) do
  d = Src[i];
```

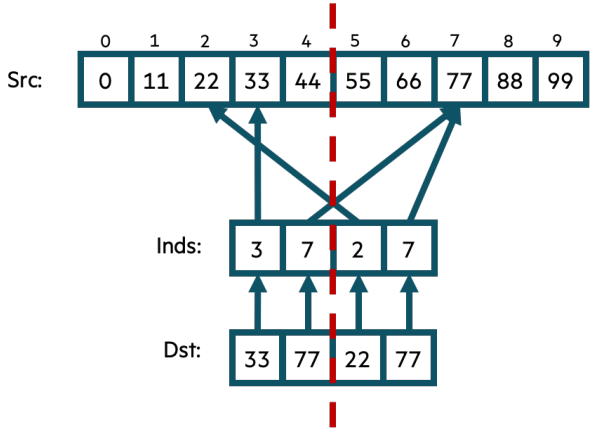
SHMEM (Exstack version)

```
i=0;
while( exstack_proceed(ex, (i==l_num_req)) ) {
  i0 = i;
  while(i < l_num_req) {
    l_indx = pckindx[i] >> 16;
    pe  = pckindx[i] & 0xffff;
    if(!exstack_push(ex, &l_indx, pe))
      break;
    i++;
  }

  exstack_exchange(ex);

  while(exstack_pop(ex, &idx , &fromth)) {
    idx  = ltable[idx];
    exstack_push(ex, &idx, fromth);
  }
  lgp_barrier();
  exstack_exchange(ex);

  for(j=i0; j<i; j++) {
    fromth = pckindx[j] & 0xffff;
    exstack_pop_thread(ex, &idx, (uint64_t)fromth);
    tgt[j] = idx;
  }
  lgp_barrier();
}
```

SHMEM (Conveyors version)

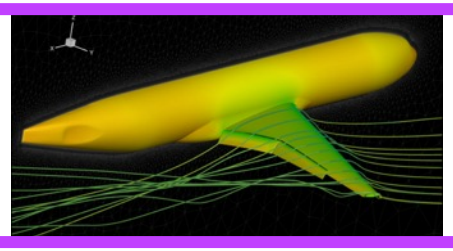
```
i = 0;
while (more = convey_advance(requests, (i == l_num_req)),
       more | convey_advance(replies, !more)) {

  for (; i < l_num_req; i++) {
    pkg.idx = i;
    pkg.val = pckindx[i] >> 16;
    pe = pckindx[i] & 0xffff;
    if (! convey_push(requests, &pkg, pe))
      break;
  }

  while (convey_pull(requests, ptr, &from) == convey_OK) {
    pkg.idx = ptr->idx;
    pkg.val = ltable[ptr->val];
    if (! convey_push(replies, &pkg, from)) {
      convey_unpull(requests);
      break;
    }
  }

  while (convey_pull(replies, ptr, NULL) == convey_OK)
    tgt[ptr->idx] = ptr->val;
}
```





Applications of Chapel

Applications of Chapel



CHAMPS: 3D Unstructured CFD
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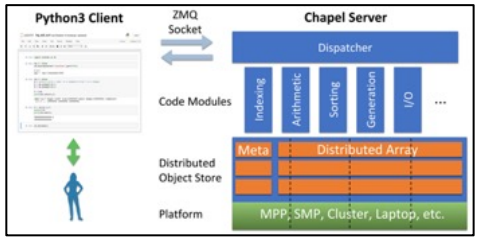
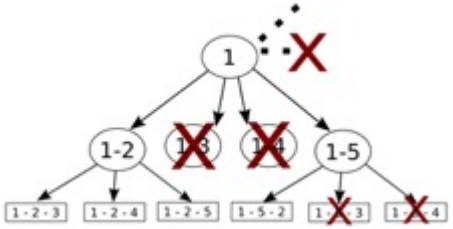
École Polytechnique Montréal



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



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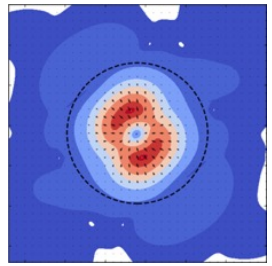
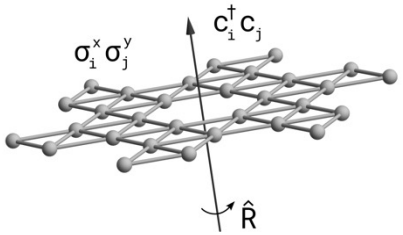


ChplUltra: Simulating Ultralight Dark Matter
Nikhil Padmanabhan, J. Luna Zagorac, et al.
Yale University et al.



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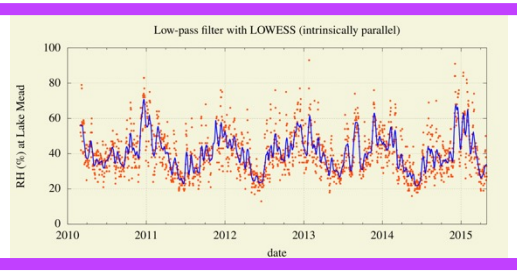

Desk dot chpl: Utilities for Environmental Eng.
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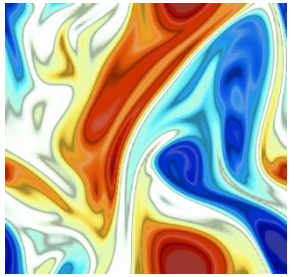

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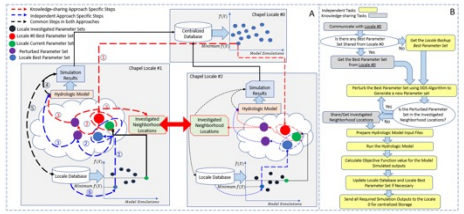

Chapel-based Hydrological Model Calibration
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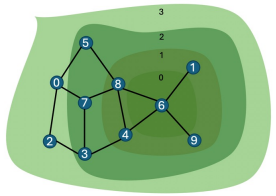

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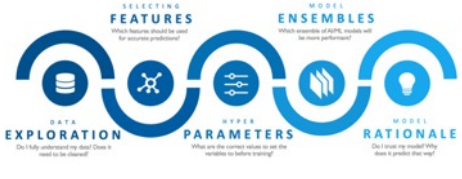
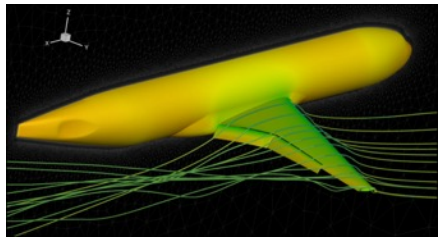


CrayAI HyperParameter Optimization (HPO)
Ben Albrecht et al.
Cray Inc. / HPE

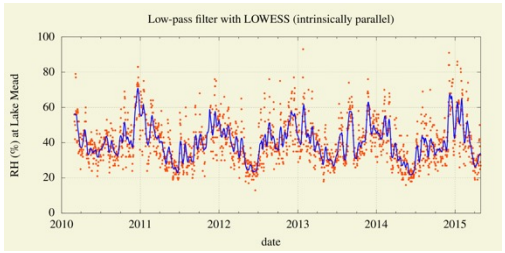
[images provided by their respective teams and used with permission]

Productivity Across Diverse Application Scales (code and system size)

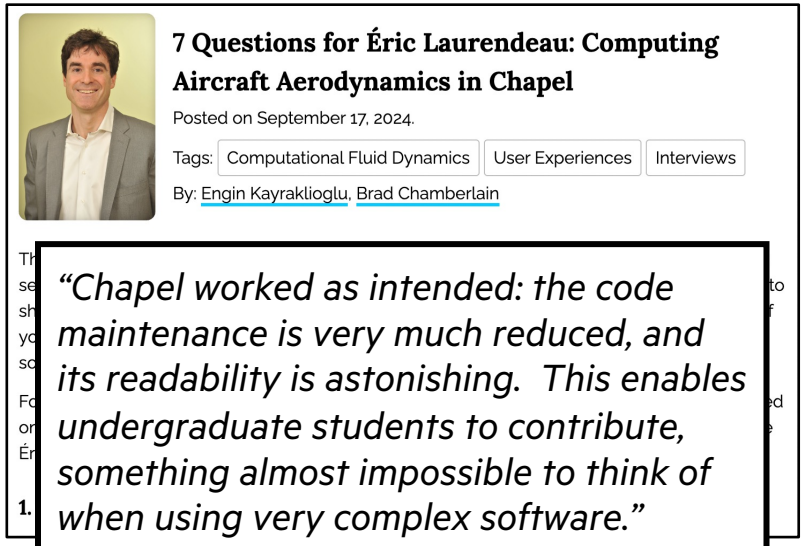


Computation: Aircraft simulation / CFD
Code size: 100,000+ lines
Systems: Desktops, HPC systems

Computation: Coral reef image analysis
Code size: ~300 lines
Systems: Desktops, HPC systems w/ GPUs



Computation: Atmospheric data analysis
Code size: 5000+ lines
Systems: Desktops, sometimes w/ GPUs



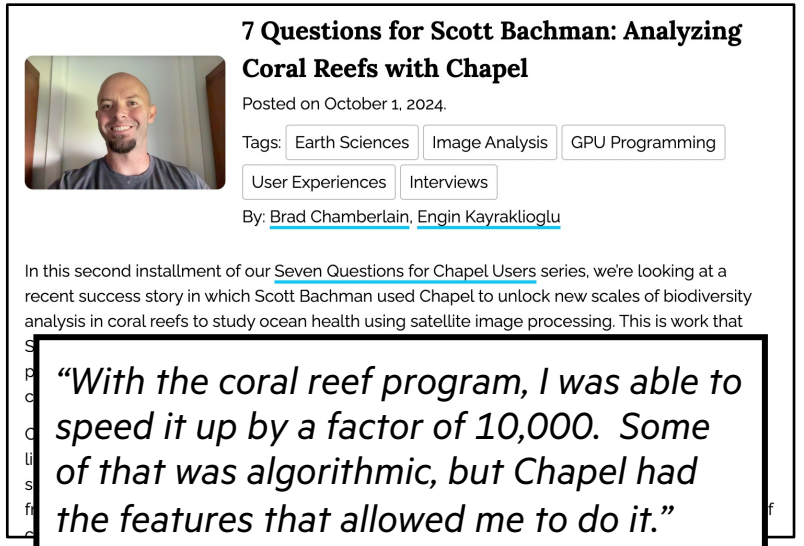
7 Questions for Éric Laurendeau: Computing Aircraft Aerodynamics in Chapel

Posted on September 17, 2024.

Tags: Computational Fluid Dynamics | User Experiences | Interviews

By: Engin Kayraklioglu, Brad Chamberlain

"Chapel worked as intended: the code maintenance is very much reduced, and its readability is astonishing. This enables undergraduate students to contribute, something almost impossible to think of when using very complex software."



7 Questions for Scott Bachman: Analyzing Coral Reefs with Chapel

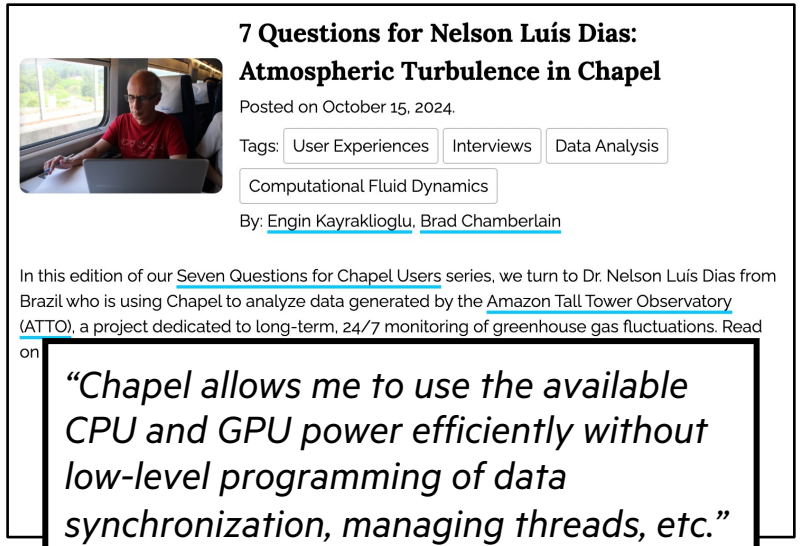
Posted on October 1, 2024.

Tags: Earth Sciences | Image Analysis | GPU Programming | User Experiences | Interviews

By: Brad Chamberlain, Engin Kayraklioglu

In this second installment of our Seven Questions for Chapel Users series, we're looking at a recent success story in which Scott Bachman used Chapel to unlock new scales of biodiversity analysis in coral reefs to study ocean health using satellite image processing. This is work that

"With the coral reef program, I was able to speed it up by a factor of 10,000. Some of that was algorithmic, but Chapel had the features that allowed me to do it."



7 Questions for Nelson Luís Dias: Atmospheric Turbulence in Chapel

Posted on October 15, 2024.

Tags: User Experiences | Interviews | Data Analysis | Computational Fluid Dynamics

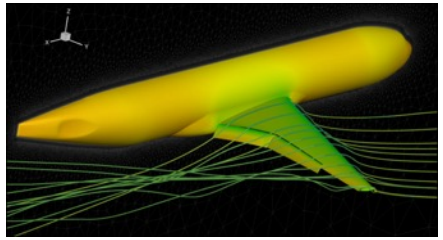
By: Engin Kayraklioglu, Brad Chamberlain

In this edition of our Seven Questions for Chapel Users series, we turn to Dr. Nelson Luís Dias from Brazil who is using Chapel to analyze data generated by the Amazon Tall Tower Observatory (ATTO), a project dedicated to long-term, 24/7 monitoring of greenhouse gas fluctuations. Read on

"Chapel allows me to use the available CPU and GPU power efficiently without low-level programming of data synchronization, managing threads, etc."

[read this interview series at: https://chapel-lang.org/blog/series/7-questions-for-chapel-users/]

Applications of Chapel



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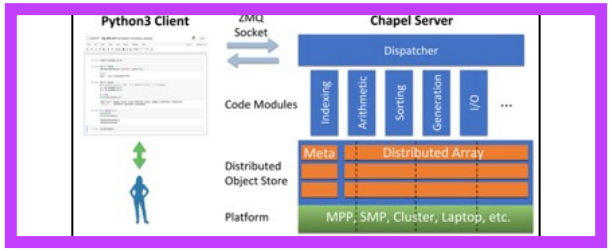

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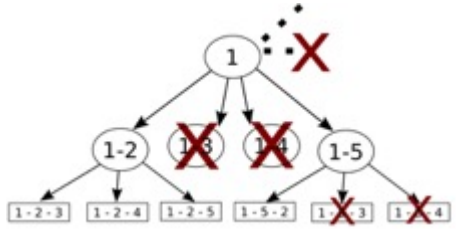

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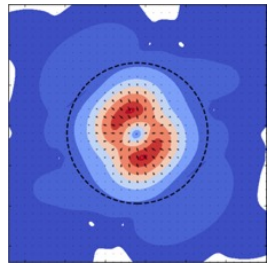

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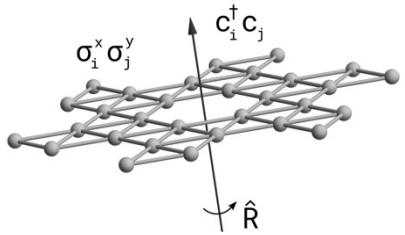

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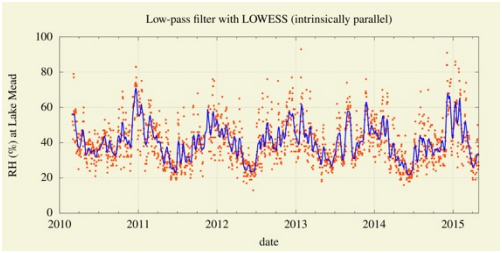

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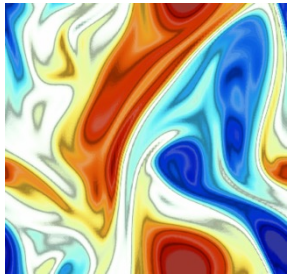

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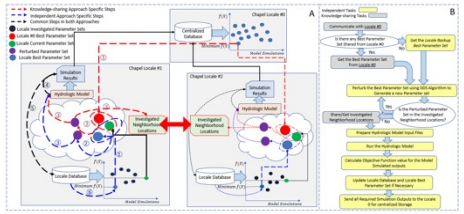

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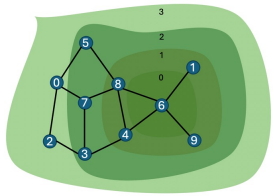

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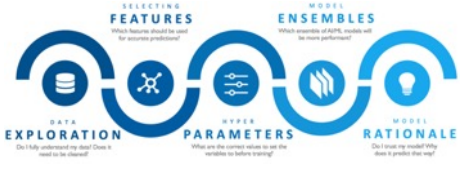


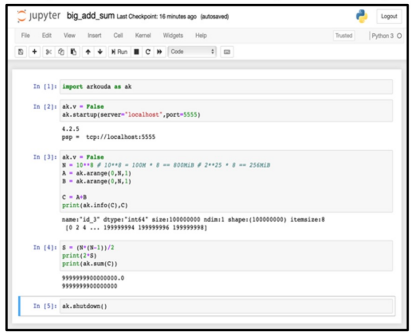
CrayAI HyperParameter Optimization (HPO)
Ben Albrecht et al.
Cray Inc. / HPE

[images provided by their respective teams and used with permission]

What is Arkouda?

Q: “What is Arkouda?”

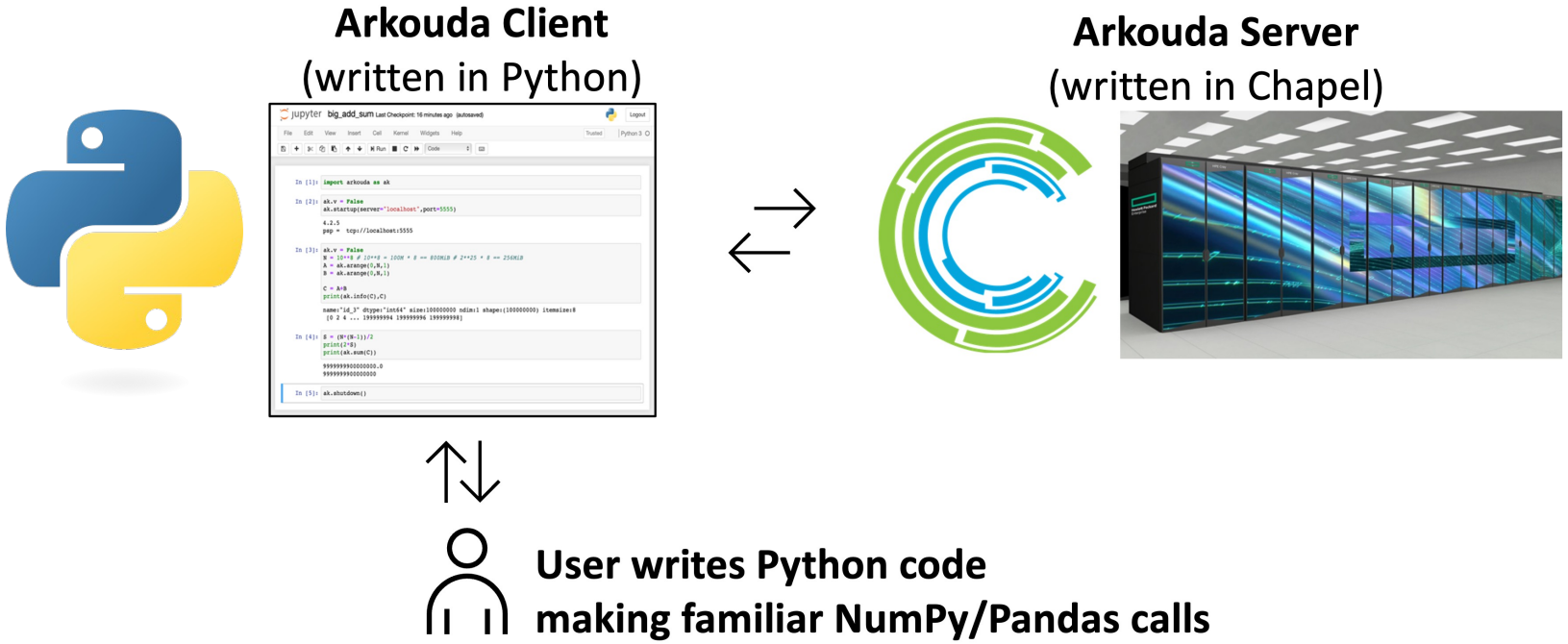
Arkouda Client
(written in Python)



User writes Python code
making familiar NumPy/Pandas calls

What is Arkouda?

Q: “What is Arkouda?”



A: “A scalable version of NumPy / Pandas for data scientists”

Performance and Productivity: Arkouda Argsort

HPE Cray EX

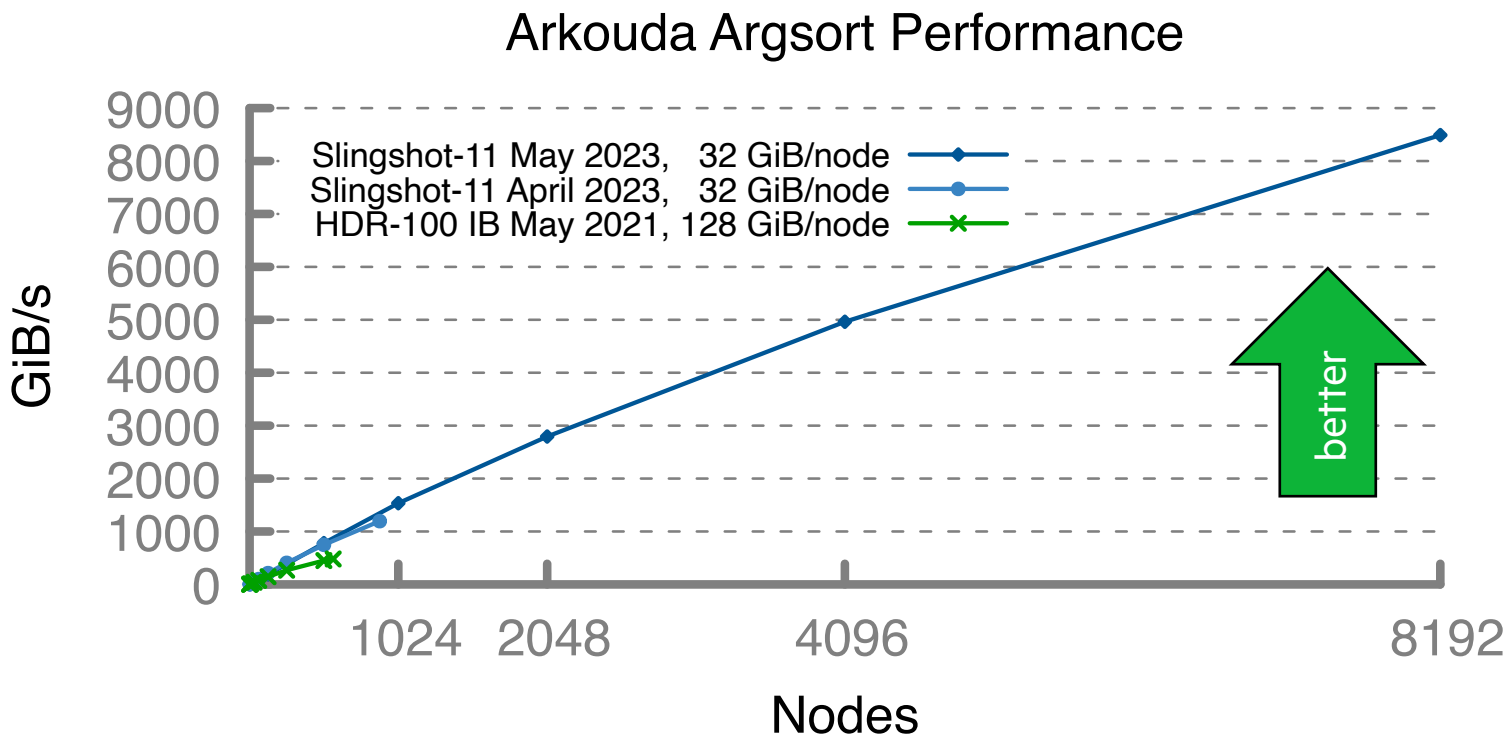
- Slingshot-11 network (200 Gb/s)
- 8192 compute nodes
- 256 TiB of 8-byte values
- ~8500 GiB/s (~31 seconds)

HPE Cray EX

- Slingshot-11 network (200 Gb/s)
- 896 compute nodes
- 28 TiB of 8-byte values
- ~1200 GiB/s (~24 seconds)

HPE Apollo

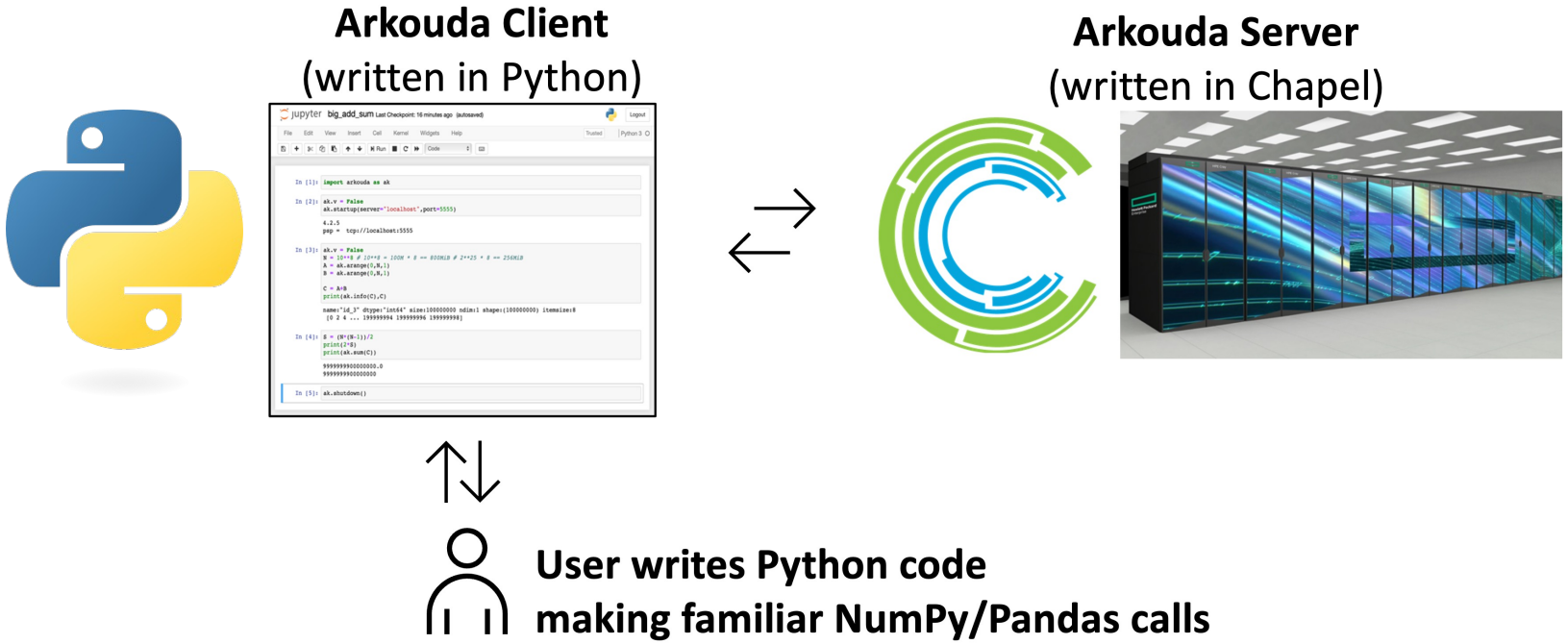
- HDR-100 InfiniBand network (100 Gb/s)
- 576 compute nodes
- 72 TiB of 8-byte values
- ~480 GiB/s (~150 seconds)



Implemented using ~100 lines of Chapel

What is Arkouda?

Q: “What is Arkouda?”



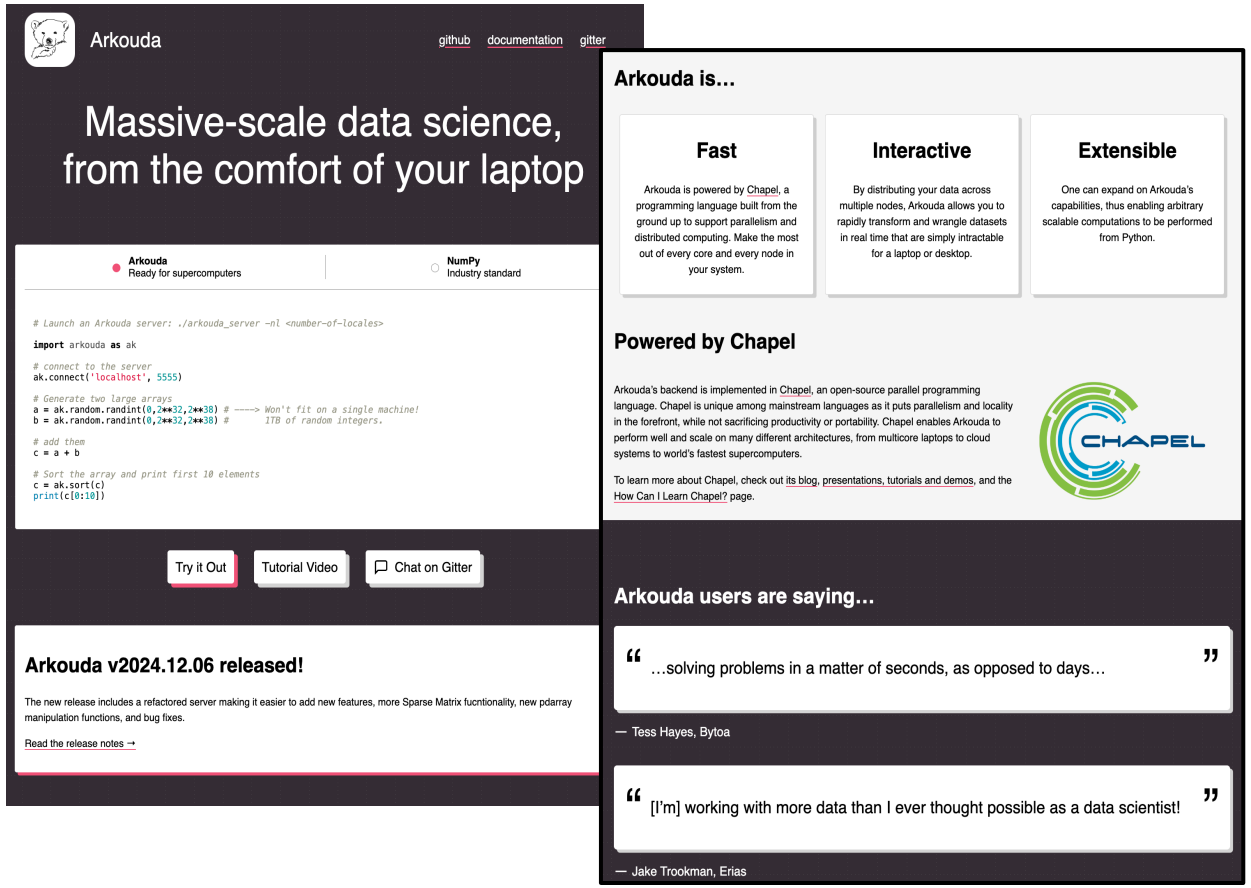
Classic Arkouda: “A scalable version of NumPy / Pandas for data scientists”

Current Arkouda: “An extensible framework for arbitrary HPC computations”

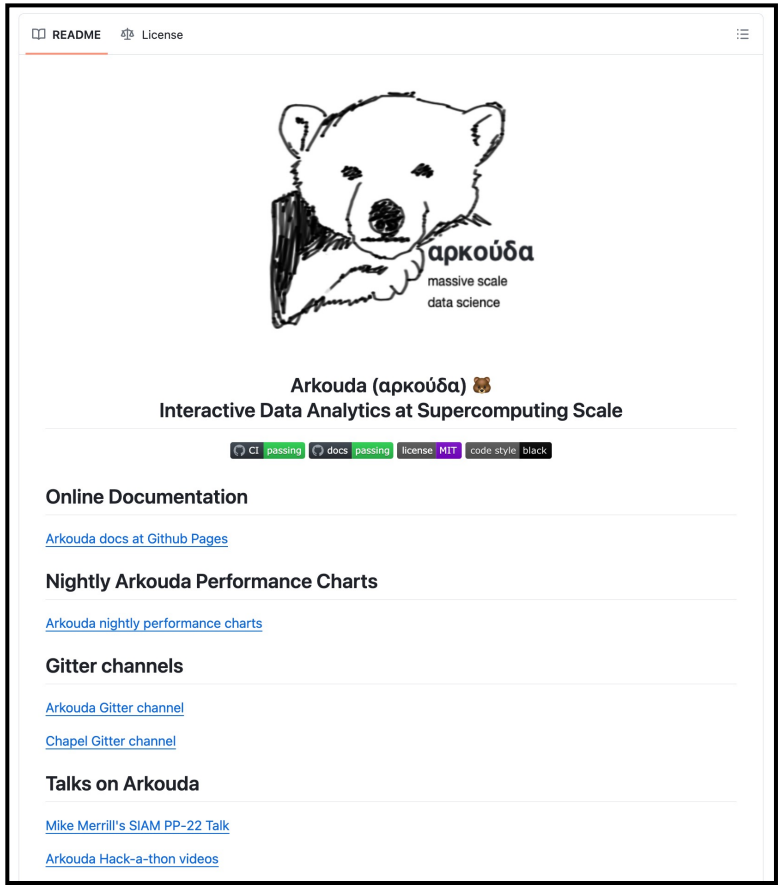
Both: “A way to drive HPC systems interactively from Python on a laptop”

Arkouda Resources

Website: https://arkouda-www.github.io/

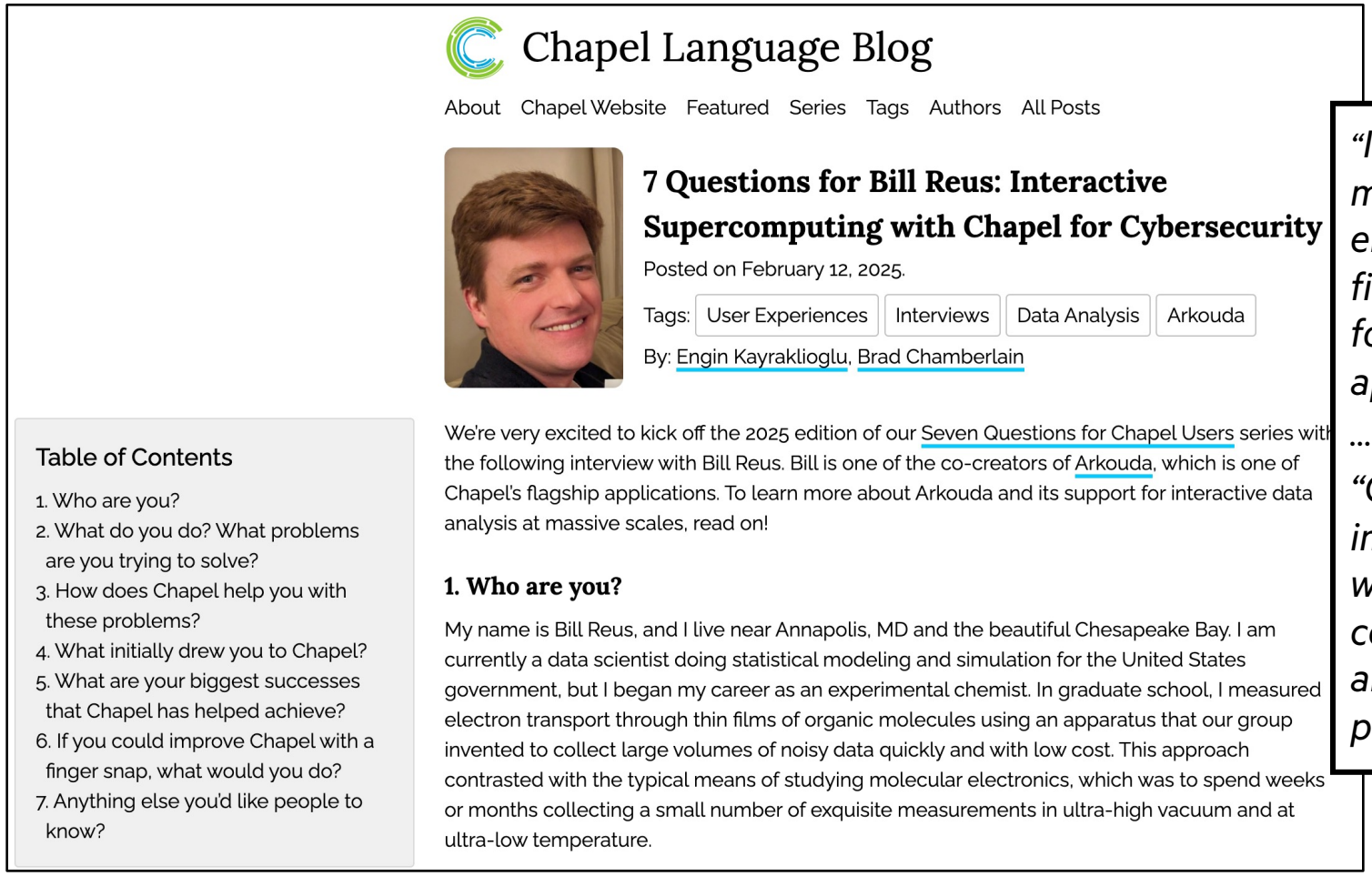


GitHub: https://github.com/Bears-R-Us/arkouda



Arkouda Interview

Blog: Interview with co-founding developer, Bill Reus: https://chapel-lang.org/blog/posts/7qs-reus/



Chapel Language Blog

About Chapel Website Featured Series Tags Authors All Posts

7 Questions for Bill Reus: Interactive Supercomputing with Chapel for Cybersecurity

Posted on February 12, 2025.

Tags: User Experiences | Interviews | Data Analysis | Arkouda

By: Engin Kayraklioglu, Brad Chamberlain

Table of Contents

1. Who are you?
2. What do you do? What problems are you trying to solve?
3. How does Chapel help you with these problems?
4. What initially drew you to Chapel?
5. What are your biggest successes that Chapel has helped achieve?
6. If you could improve Chapel with a finger snap, what would you do?
7. Anything else you'd like people to know?

We're very excited to kick off the 2025 edition of our Seven Questions for Chapel Users series with the following interview with Bill Reus. Bill is one of the co-creators of Arkouda, which is one of Chapel's flagship applications. To learn more about Arkouda and its support for interactive data analysis at massive scales, read on!

1. Who are you?

My name is Bill Reus, and I live near Annapolis, MD and the beautiful Chesapeake Bay. I am currently a data scientist doing statistical modeling and simulation for the United States government, but I began my career as an experimental chemist. In graduate school, I measured electron transport through thin films of organic molecules using an apparatus that our group invented to collect large volumes of noisy data quickly and with low cost. This approach contrasted with the typical means of studying molecular electronics, which was to spend weeks or months collecting a small number of exquisite measurements in ultra-high vacuum and at ultra-low temperature.

"I was on the verge of resigning myself to learning MPI when I first encountered Chapel. After writing my first Chapel program, I knew I had found something much more appealing."

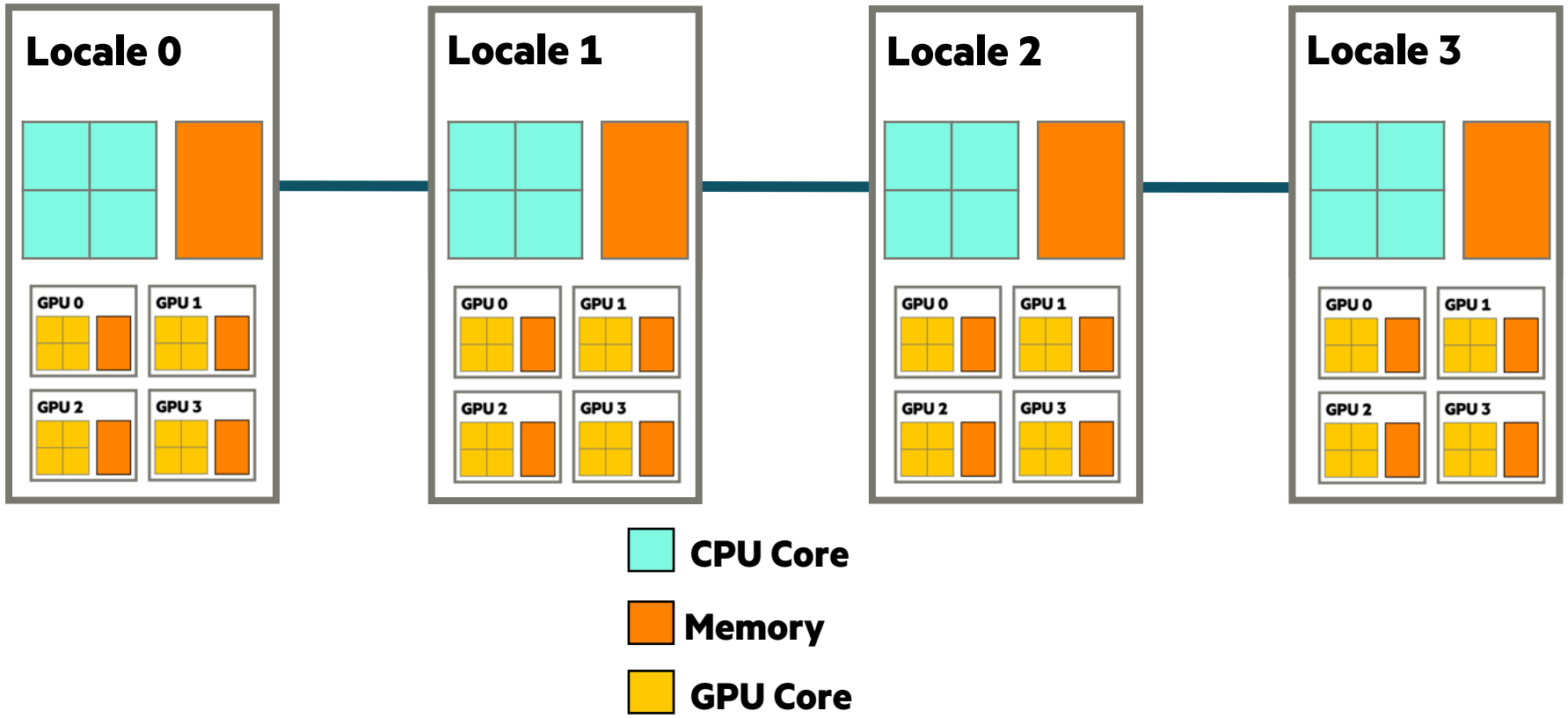
...

"Chapel's separation of concerns immediately felt like the most natural way to think about large-scale computing. I would highly encourage anyone wanting to get into HPC programming to start with Chapel."

Chapel on GPUs

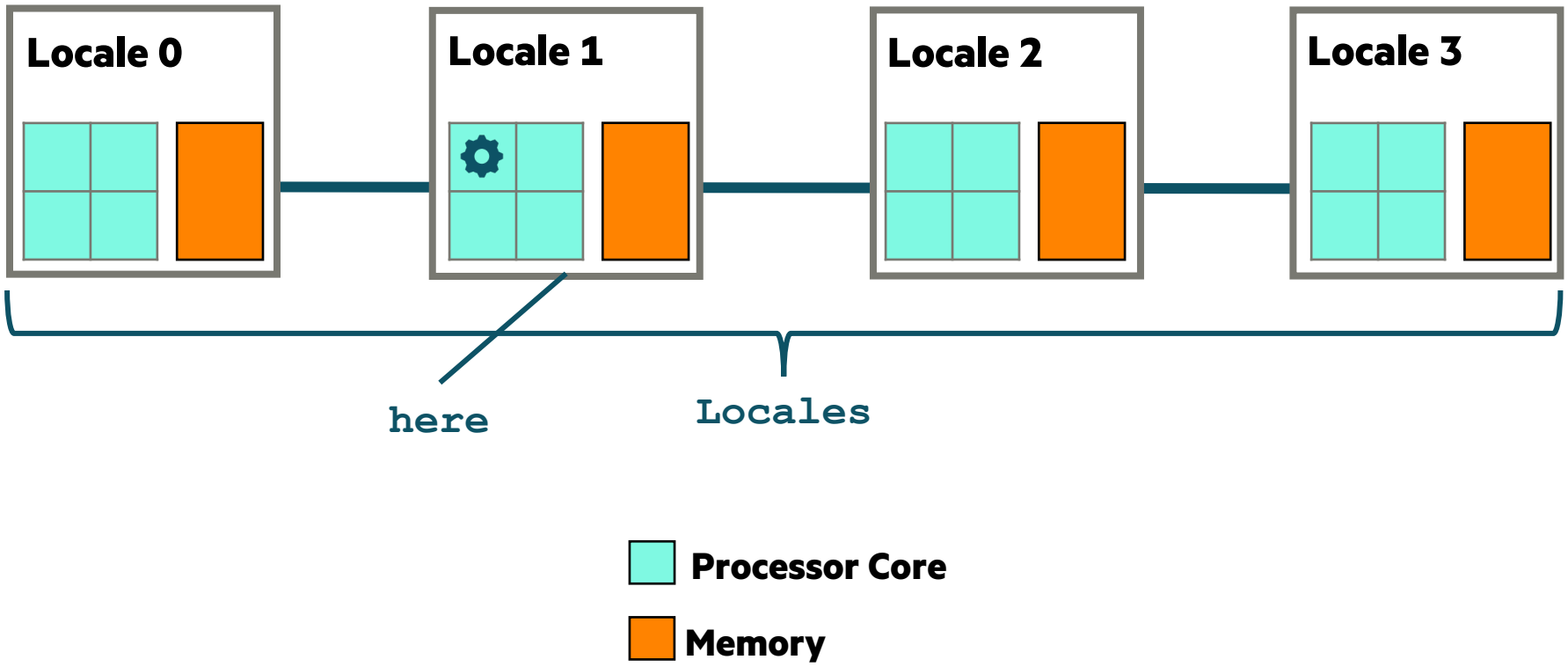
Compute Nodes with GPUs

- Many modern HPC systems have GPUs in addition to CPUs
  - These GPUs have their own distinct cores and memory



Built-In Locale Variables in Chapel

- Two key built-in variables for referring to Chapel programs:
  - **`Locales`**: An array of locale values representing the system resources on which the program is running
  - **`here`**: The locale on which the current task is executing



Basic Features for Locality

basics-on.chpl

```
writeln("Hello from locale ", here.id);

var A: [1..2, 1..2] real;

for loc in Locales {
  on loc {
    var B = A;
  }
}
```

All Chapel programs begin running as a single task on locale 0

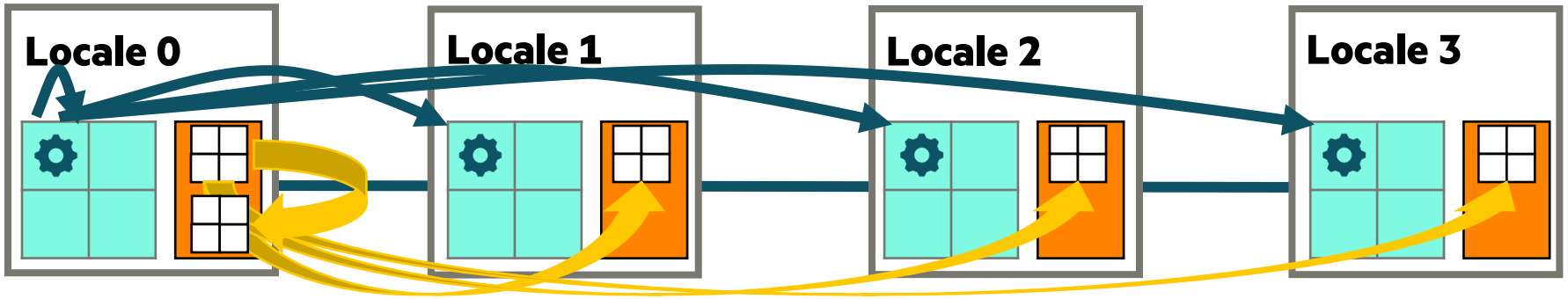
Variables are stored using the memory local to the current task

This loop will serially iterate over the program's locales

on-clauses move tasks to target locales

remote variables can be accessed directly

This is a distributed, yet serial, computation



Mixing Locality with Task Parallelism

basics-coforall.chpl

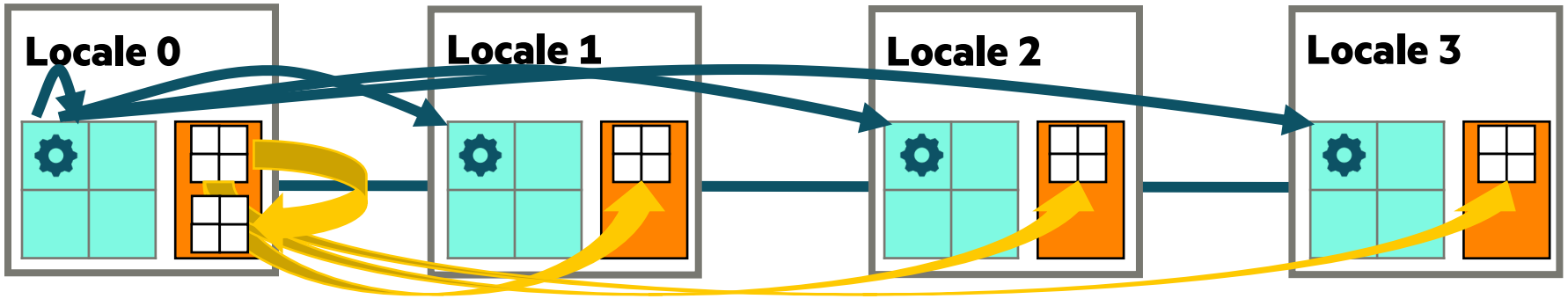
```
writeln("Hello from locale ", here.id);

var A: [1..2, 1..2] real;

coforall loc in Locales {
  on loc {
    var B = A;
  }
}
```

The coforall loop creates
a parallel task per iteration
(in this case, a task per locale)

This results in a distributed parallel computation

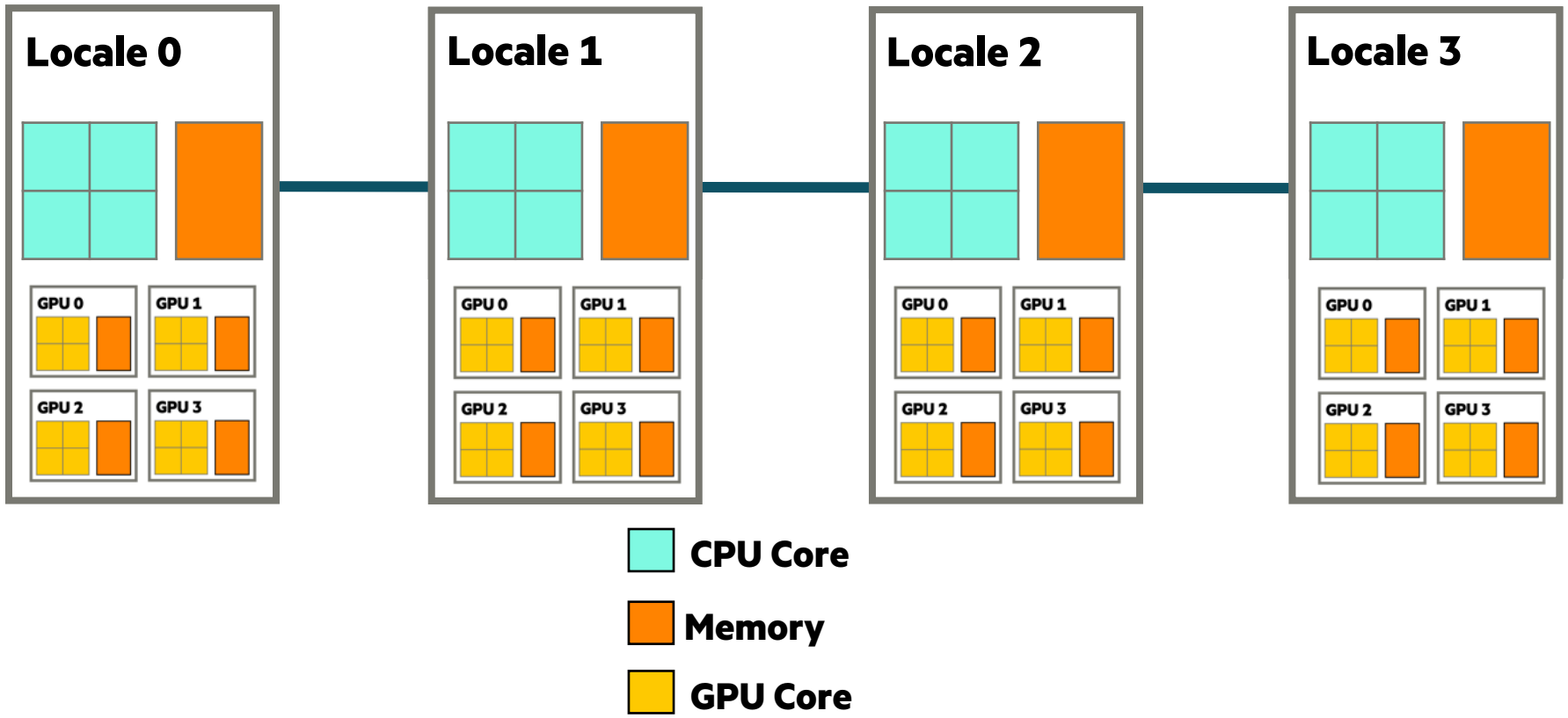


Representing GPUs in Chapel

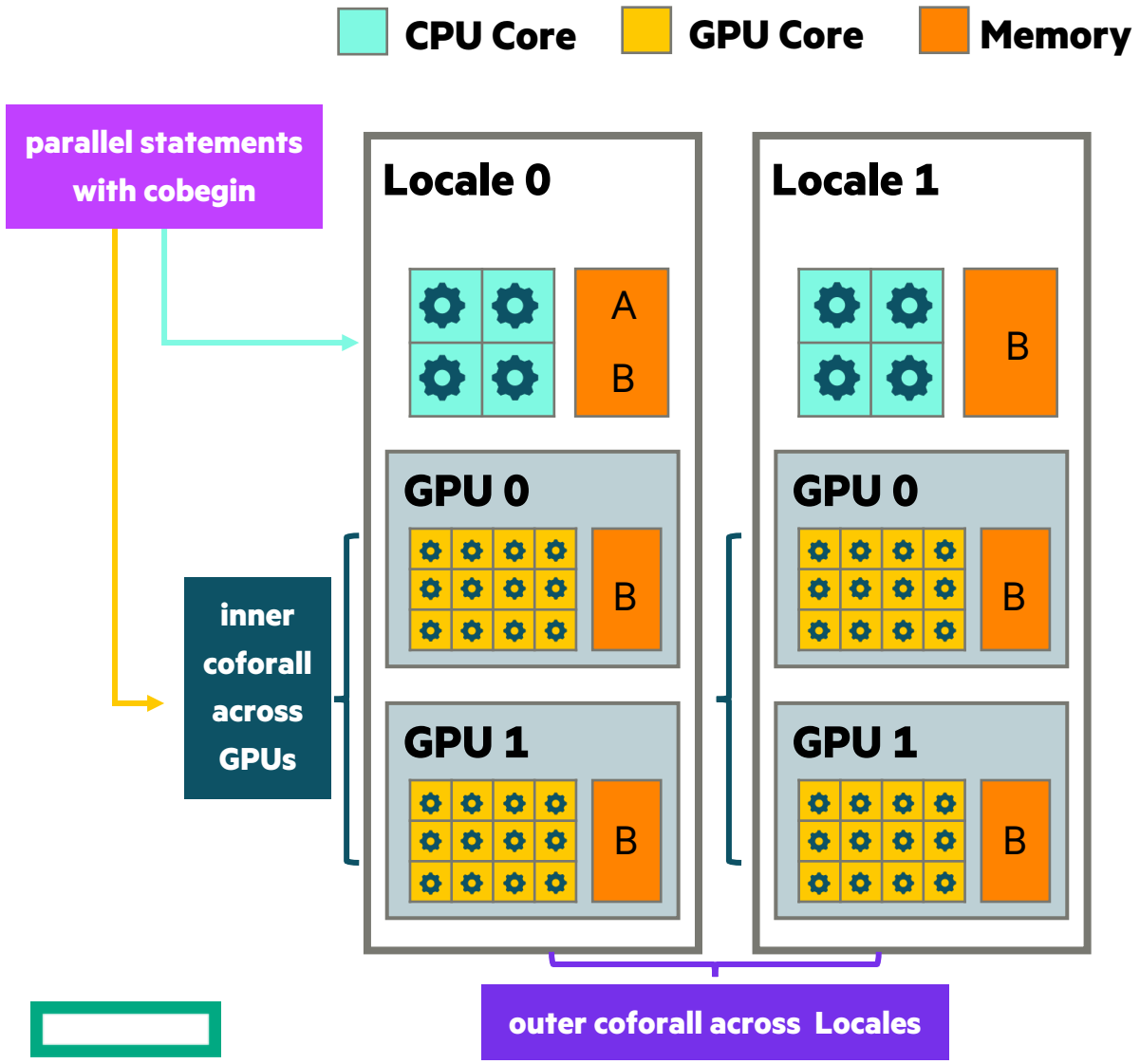
- In Chapel, we represent GPUs as *sub-locales*
  - Each top-level locale may have an array of locales called 'gpus'
  - We can then target them using Chapel's traditional features for parallelism + locality

```
on here.gpus[0] { … }
```

```
coforall gpu in here.gpus do on gpu { … }
```



Targeting CPUs and GPUs using Parallelism and Locality




```
var A: [1..n, 1..n] real;
coforall l in Locales do on l {
  cobegin {
    {
      var B: [1..n, 1..n] real;
      B = 2;
      A = B;
    }
    coforall g in here.gpus do on g {
      var B: [1..n, 1..n] real;
      B = 2;
      A = B;
    }
  }
}
writeln(A);
```

Parallel Programming and Chapel: Then and Now

20 Years Ago vs. Today

2005:

- **Popular Languages:** C++, Java, Perl, Python
- **HPC Hardware:**
  - processors: single- or dual-core
  - nodes: single-socket, UMA, single-NIC, no GPUs
  - Top 5 systems from the Top-500:
    - core counts: 4,800–65,536
    - RMax perf: 27.91–136.80 TFlop/s
- **HPC Programming:**
  - languages: Fortran, C, C++, UPC
  - libraries: MPI, SHMEM
  - directives: OpenMP
  - GPUs: N/A
- **Chapel:** no public releases; only serial programs
  - draft language spec defines locality + parallel features

2025:

- **Popular Languages:** Python, Rust, Go, Julia, Swift
- **HPC Hardware:**
  - processors: multicore
  - nodes: multi-socket, NUMA, multi-NIC, multi-GPU
  - Top-5 systems from the Top-500:
    - core counts: 2,073,600–11,039,616 **(31x–2,300x)**
    - RMax perf: 477.9–1,742.0 PFlop/s **(3,493x–62,415x)**
- **HPC Programming:**
  - languages: Fortran, C, C++, Python (as glue code)
  - libraries: MPI, SHMEM
  - directives: OpenMP
  - GPUs: CUDA, HIP, SYCL, Kokkos, OpenACC, OpenCL, …
- **Chapel:** 42 public releases; production apps
  - locality + parallel features essentially the same

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HPC hardware has become far more complex

HPC programming has not gotten any easier

Chapel has adapted well, due to its focus on parallelism and locality

2025:

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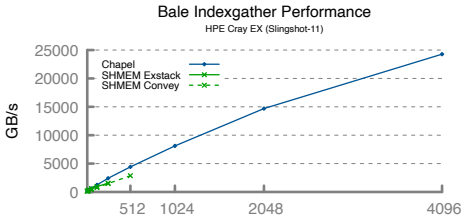
Wrap-up

Summary

Chapel is unique among programming languages

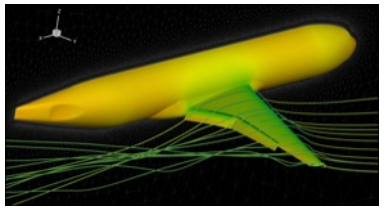
- features first-class concepts for parallelism and locality
- ports and scales from laptops to supercomputers
- supports clean, concise code relative to conventional approaches
- supports GPUs in a vendor-neutral manner

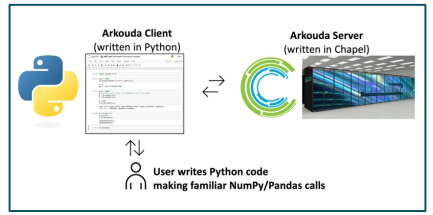
```
use BlockDist;

config const n = 10,
             m = 4;

const SrcInds = blockDist.createDomain(0..<n),
      DstInds = blockDist.createDomain(0..<m);

var Src: [SrcInds] int,
    Inds, Dst: [DstInds] int;
…
forall (d, i) in zip(Dst, Inds) do
  d = Src[i];
```

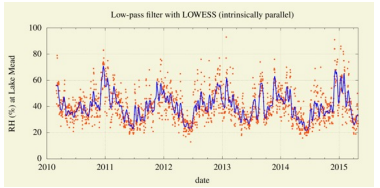


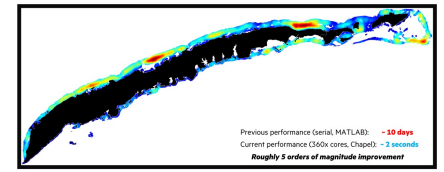
Chapel is being used for productive parallel computing at all scales

- users are reaping its benefits in practical, cutting-edge applications
- applicable to domains as diverse as physical simulations and data science
- Arkouda is a notable case, supporting extensible, interactive HPC

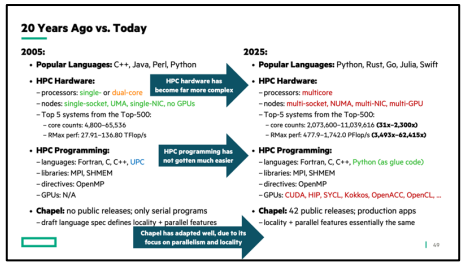








Chapel's general features for parallelism and locality have permitted it to adapt to the evolving parallel hardware landscape



The Advanced Programming Team at HPE

Ways to Engage with the Chapel Community

"Live" (Virtual) Community Events

- ChapelCon (formerly CHIUW), annually
- Project Meetings, weekly
- Deep Dive / Demo Sessions, weekly timeslot

Electronic Broadcasts

- Chapel Blog, 1–4 articles per month
- Community Newsletter, quarterly
- Announcement Emails, around big events

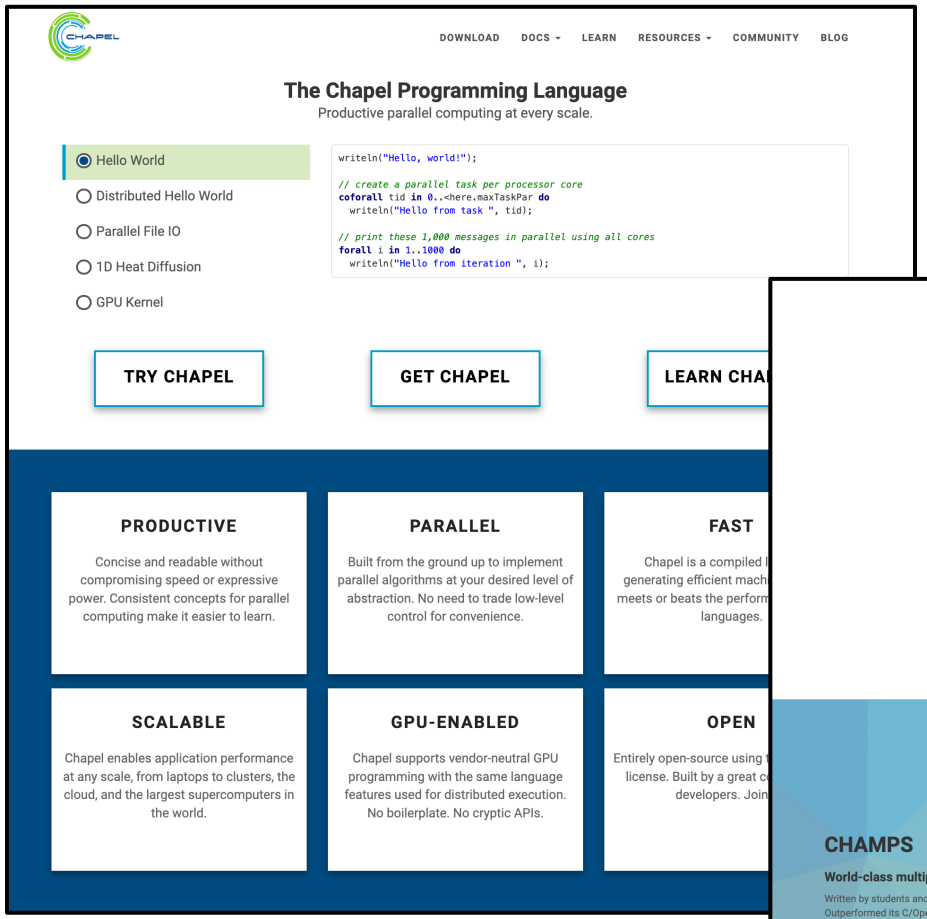
Community / User Forums

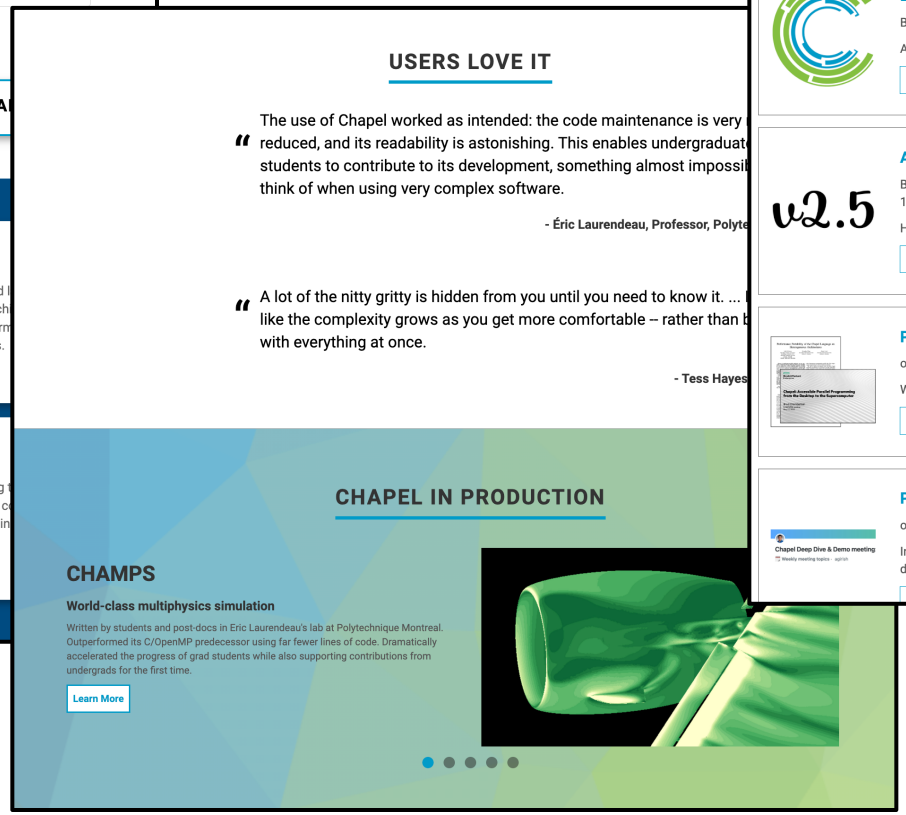
- Discord
- Discourse
- Email Contact Alias `chapel+qs@discoursemail.com`
- GitHub Issues
- Gitter
- Reddit
- Stack Overflow

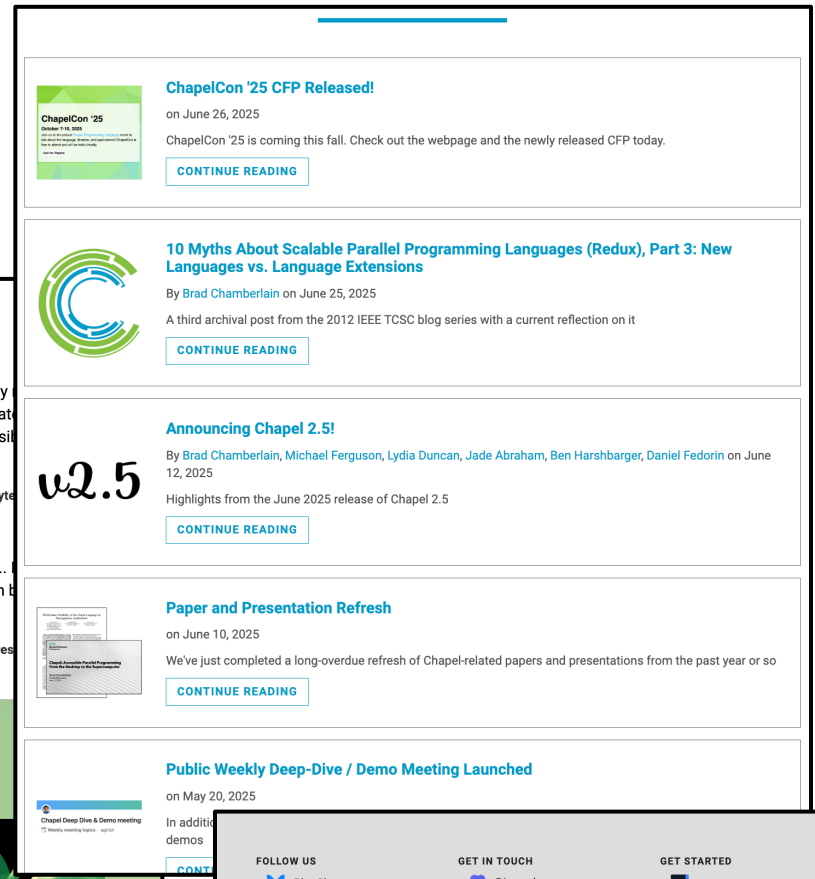
Social Media

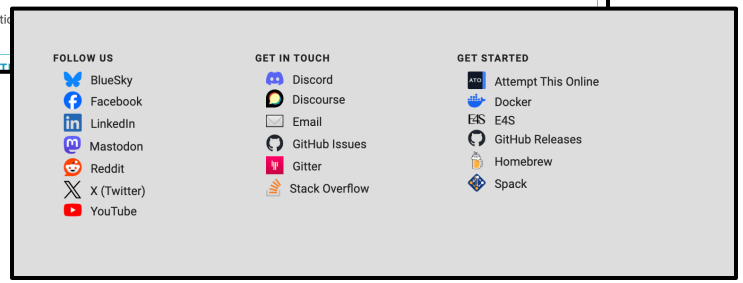
- Bluesky
- Facebook
- LinkedIn
- Mastodon
- X / Twitter
- YouTube

Chapel Website









chapel-lang.org

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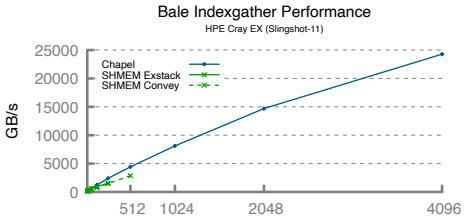

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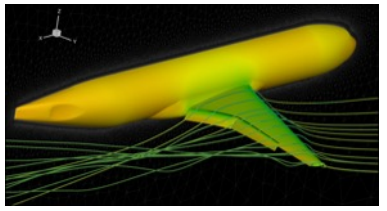

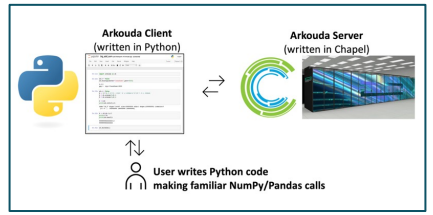

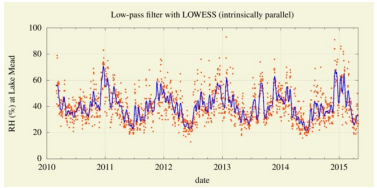

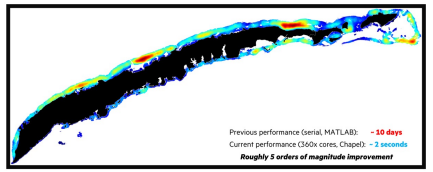

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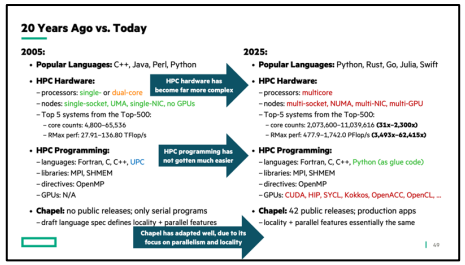

Thank you

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