Hewlett Packard Enterprise

PRODUCTIVE PARALLEL PROGRAMMING USING CHAPEL

Nordic-RSE Seminar Series

November 30, 2022

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

SCALABLE PARALLEL COMPUTING THAT'S AS EASY AS PYTHON?

Imagine having a programming language for parallel computing that was as…

…**programmable** as Python

…yet also as…

…**fast** as Fortran

…**scalable** as MPI

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

…**portable** as C

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

This is our motivation for Chapel

OUTLINE

- What is Chapel, and Why?
- Chapel Characteristics
- Chapel Benchmarks & Apps
- Chapel Features
- Wrap-up

CHAPEL CHARACTERISTICS

WHAT DO CHAPEL PROGRAMS LOOK LIKE?

helloTaskPar.chpl: print a message from each core in the system

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

```
> chpl helloTaskPar.chpl
> ./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
…
```

fillArray.chpl: declare and parallel-initialize a distributed array

```
use CyclicDist;

config const n = 1000;

const D = {1..n, 1..n}
        dmapped Cyclic(startIdx = (1,1));
var A: [D] real;

forall (i,j) in D do
  A[i,j] = i + (j - 0.5)/n;

writeln(A);
```

```
> chpl fillArray.chpl
> ./fillArray --n=5 --numLocales=4
1.1 1.3 1.5 1.7 1.9
2.1 2.3 2.5 2.7 2.9
3.1 3.3 3.5 3.7 3.9
4.1 4.3 4.5 4.7 4.9
5.1 5.3 5.5 5.7 5.9
```

FIVE KEY CHARACTERISTICS OF CHAPEL

1. **compiled:** to generate the best performance possible
2. **statically typed:** to avoid simple errors after hours of execution
3. **interoperable:** with C, Fortran, Python, …
4. **portable:** runs on laptops, clusters, the cloud, supercomputers
5. **open-source:** to reduce barriers to adoption and leverage community contributions

CHAPEL RELEASES

Q: What is provided in a Chapel release?

A: Chapel releases contain…

…**the Chapel compiler** (‘chpl’)**:** translates Chapel source code into optimized executables

…**runtime libraries:** maps Chapel programs to a system’s capabilities (e.g., processors, network, memory, …)

…**library modules:** provide standard algorithms, data types, capabilities, …

…**documentation** (also available online at: https://chapel-lang.org/docs/)

…**sample programs:** primers, benchmarks, etc.

Q: How often is Chapel released? And in what formats?

A: Chapel is released quarterly (March, June, Sept, Dec) in a variety formats:

- open-source tarballs on GitHub
- as a homebrew formula and bottle for Mac and Linux
- as a Docker image
- as a module on HPE Cray systems

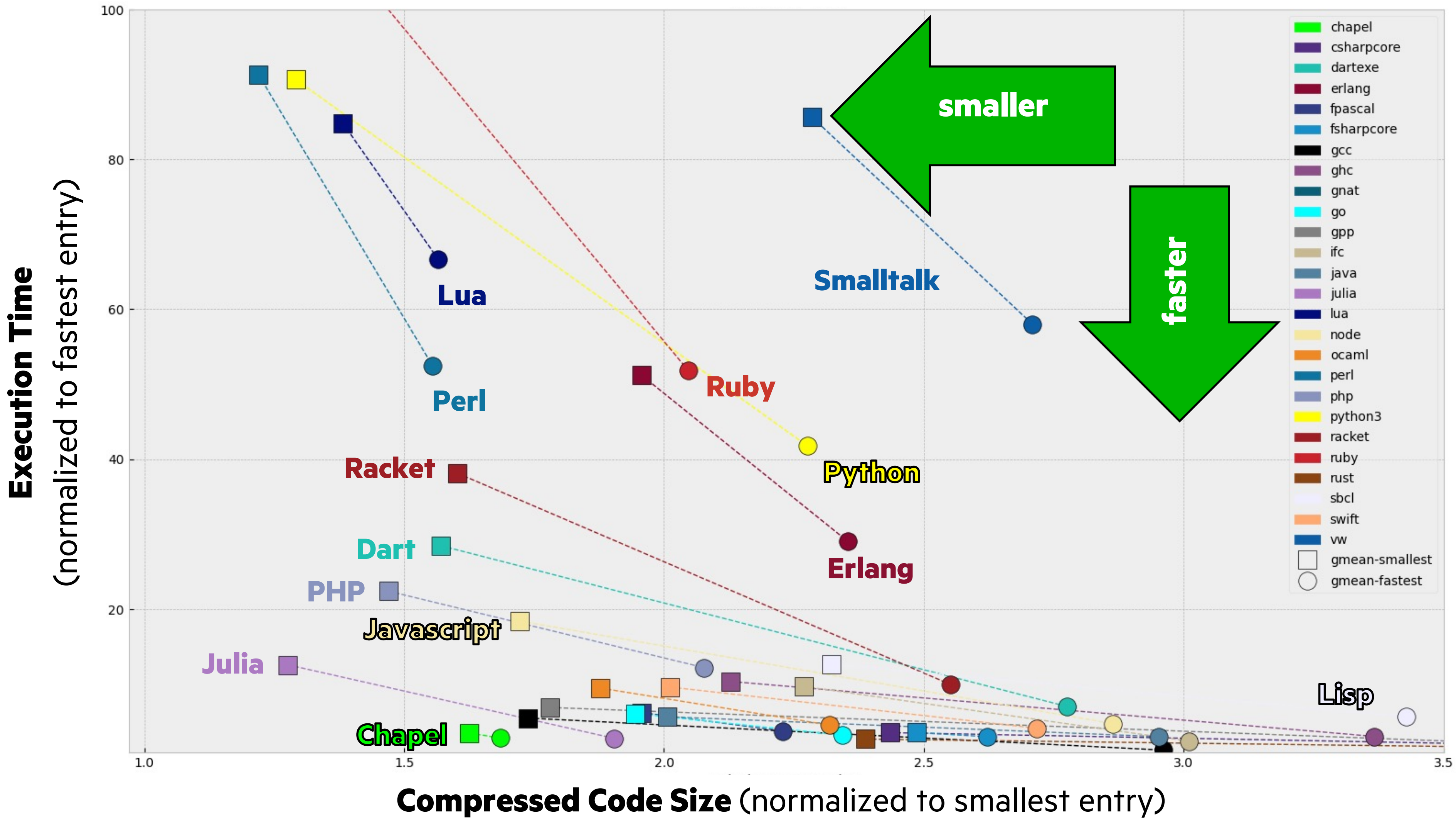
THE CHAPEL TEAM AT HPE

- Our core team consists of:
  - 16 developers + 1 starting early 2023
  - 1 visiting scholar
  - 1 manager
  - 1 tech lead
  - 1 project lead (technical manager)
  - 1/n director

see: https://chapel-lang.org/contributors.html

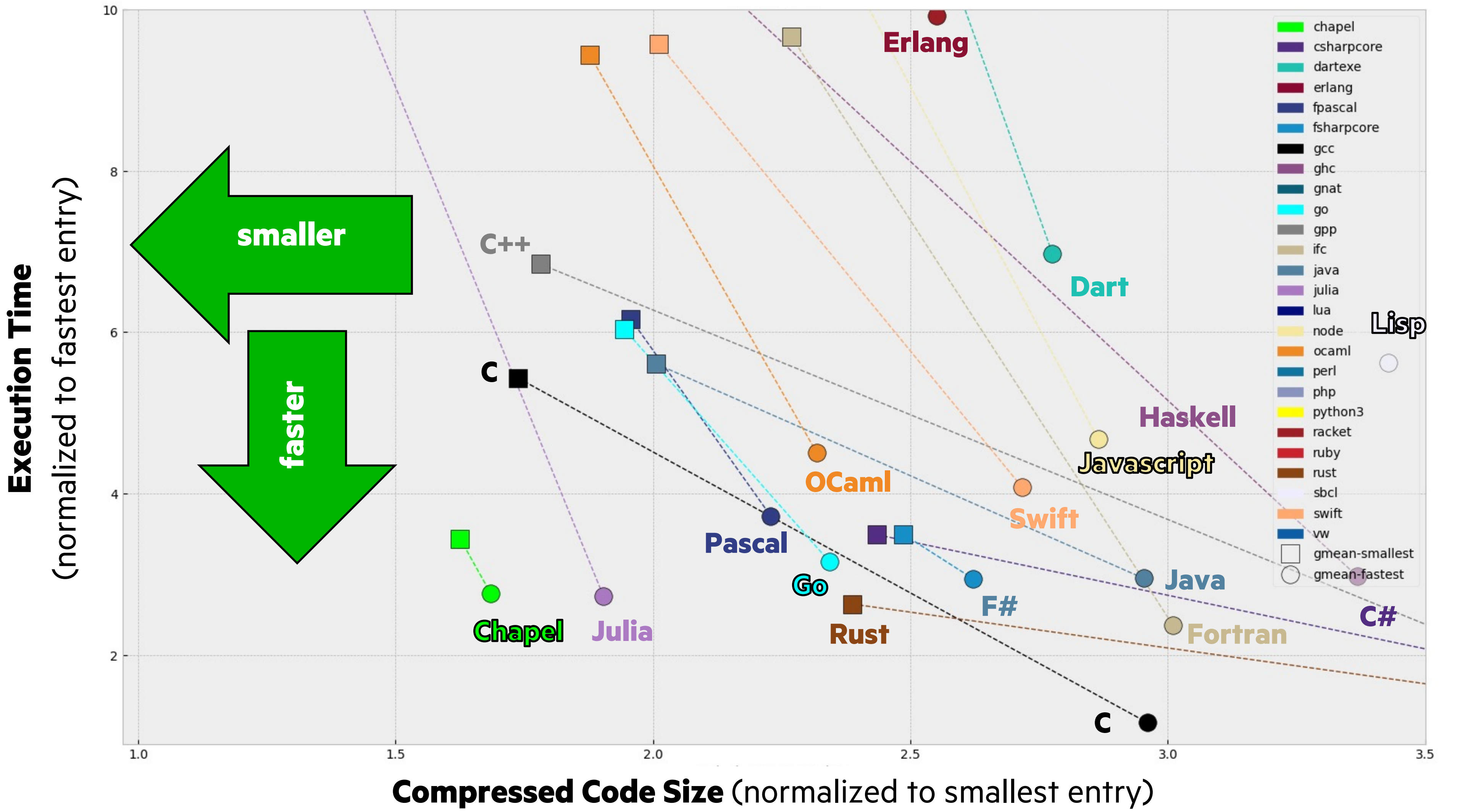
CHAPEL BENCHMARKS AND APPLICATIONS

FOR DESKTOP BENCHMARKS, CHAPEL IS COMPACT AND FAST



[plot generated by summarizing data from https://benchmarksgame-team.pages.debian.net/benchmarksgame/index.html as of May 10, 2022]

FOR DESKTOP BENCHMARKS, CHAPEL IS COMPACT AND FAST (ZOOMED)



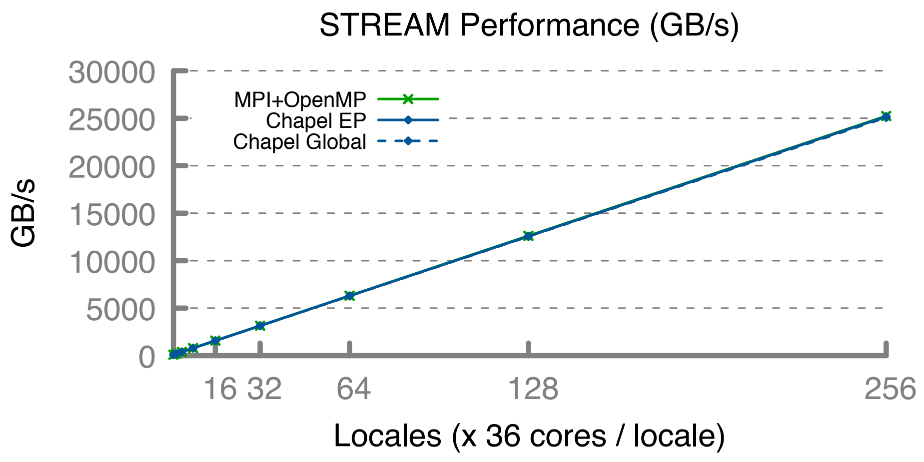
[plot generated by summarizing data from https://benchmarksgame-team.pages.debian.net/benchmarksgame/index.html as of May 10, 2022]

FOR HPC BENCHMARKS, CHAPEL TENDS TO BE CONCISE, CLEAR, AND COMPETITIVE

STREAM TRIAD: C + MPI + OPENMP

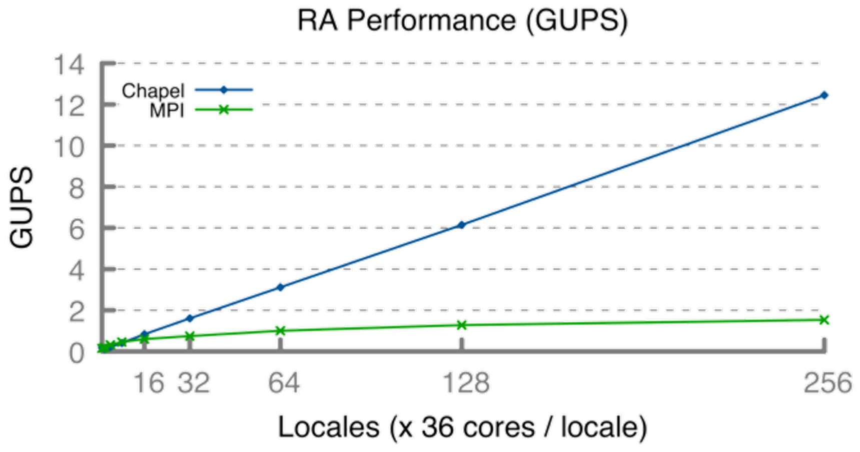
```c
#include <hpcc.h>
#ifdef _OPENMP
#include <omp.h>
#endif

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;
```

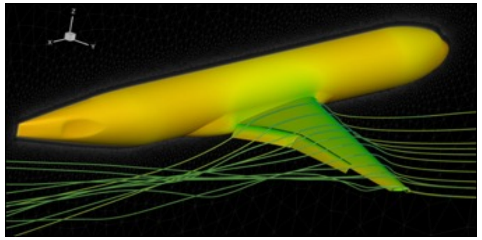


HPCC RA: MPI KERNEL

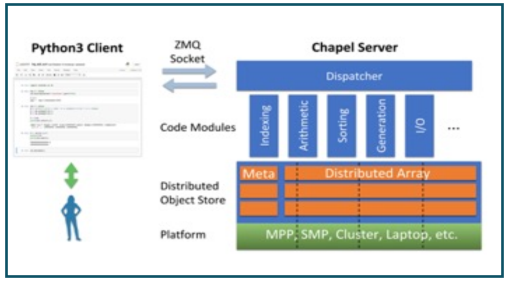
```chapel
…
forall (_, r) in zip(Updates, RAStream()) do
  T[r & indexMask].xor(r);
…
```



TWO FLAGSHIP CHAPEL APPLICATIONS



CHAMPS: 3D Unstructured Computational Fluid Dynamics (CFD)

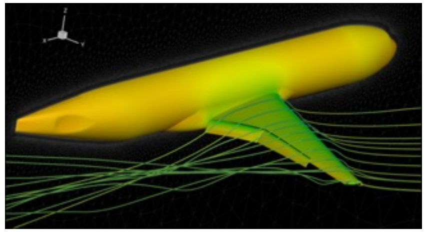


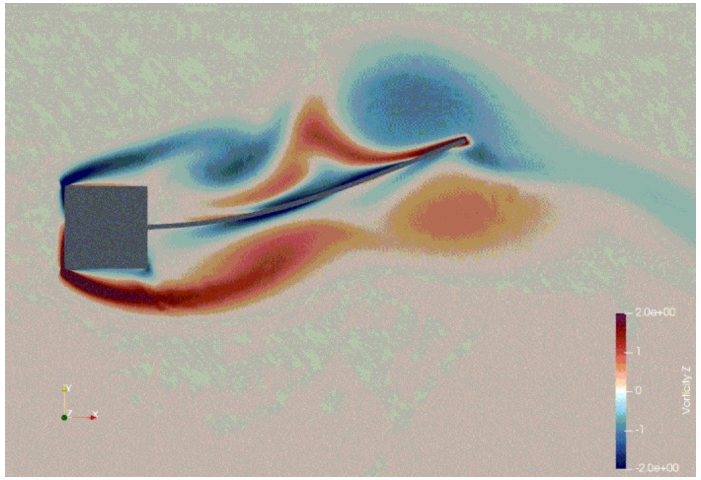
Arkouda: Interactive Data Analytics at Supercomputing Scale

CHAMPS SUMMARY

What is it?

- 3D unstructured CFD framework for airplane simulation
- ~85k lines of Chapel written from scratch in ~3 years

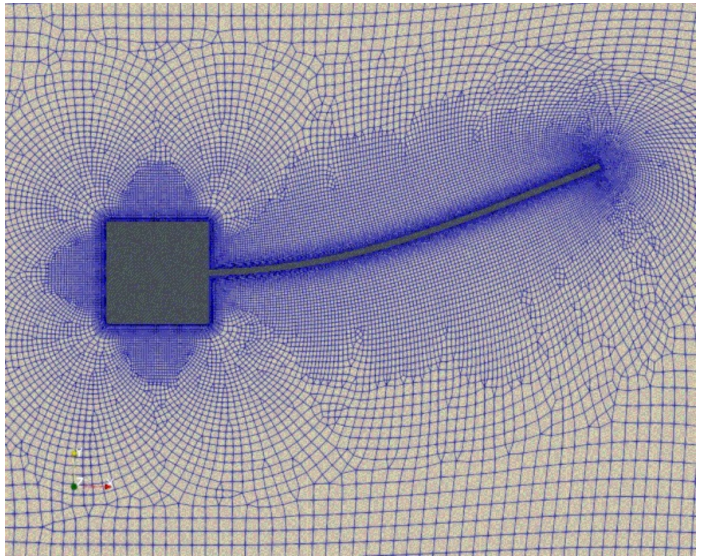




Who wrote it?

- Professor Éric Laurendeau’s students + postdocs at Polytechnique Montreal
- Not open-source, but available on request

POLYTECHNIQUE MONTRÉAL



Why Chapel?

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

(images provided by the CHAMPS team and used with permission)

CHAMPS: EXCERPT FROM ÉRIC'S CHIUW 2021 KEYNOTE (TRANSCRIPT)

HPC Lessons From 30 Years of Practice in CFD Towards Aircraft Design and Analysis (June 4, 2021)

> *"To show you what Chapel did in our lab… [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… **So, I've got industrial-type code in 48k lines.**"*
>
> *"[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."*
>
> *"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

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

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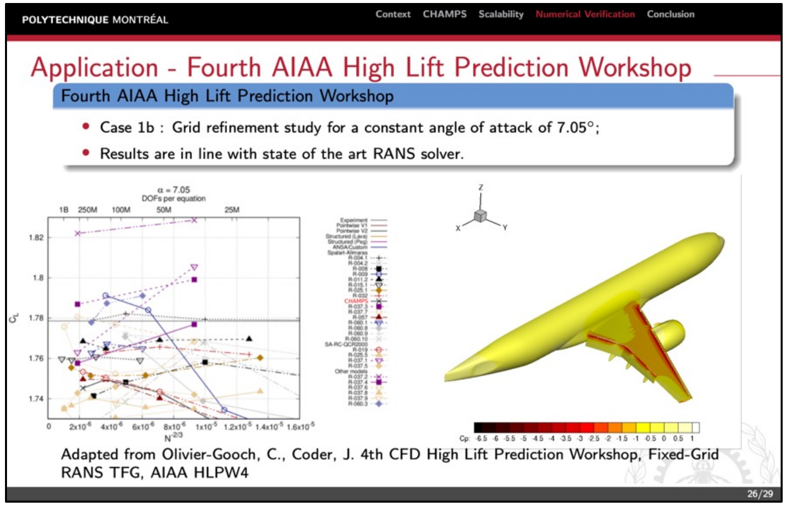
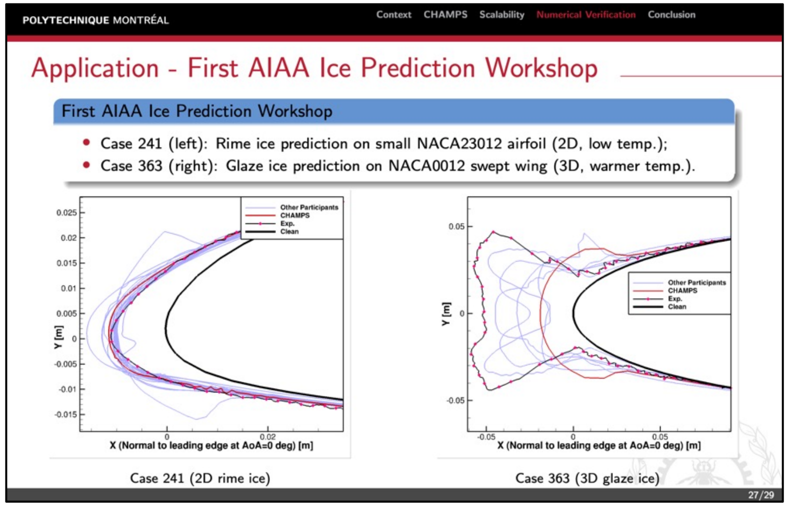
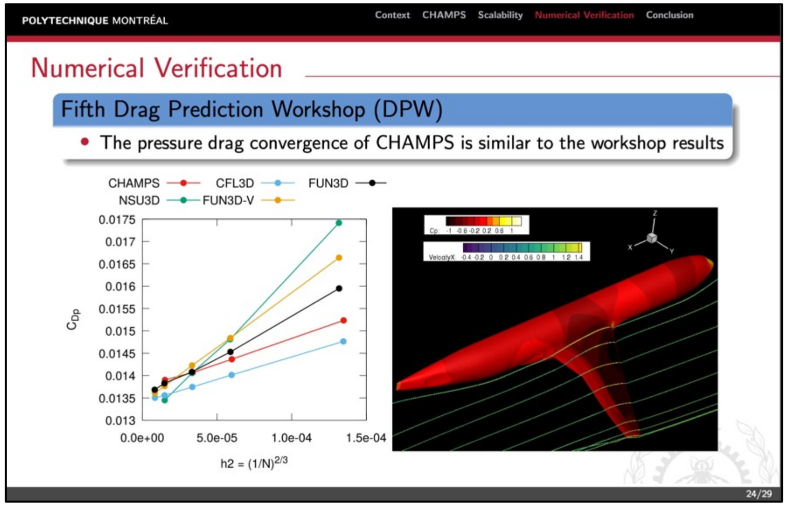
CHAMPS HIGHLIGHTS

Community Activities:

- Team participated in the **7^{th} AIAA High-lift Prediction Workshop** and **1^{st} AIAA Ice Prediction Workshop**
  - Generating comparable results to high-profile sites: Boeing, Lockheed Martin, NASA, JAXA, Georgia Tech, …
- Five papers published this past summer at **2022 AIAA Aviation**
- While on sabbatical, Éric has presented CHAMPS and Chapel at **ONERA**, **DLR**, **Université de Strasbourg**, …
- Student presentations at **CASI/IASC Aero 21 Conference** and to **CFD Society of Canada (CFDSC)**

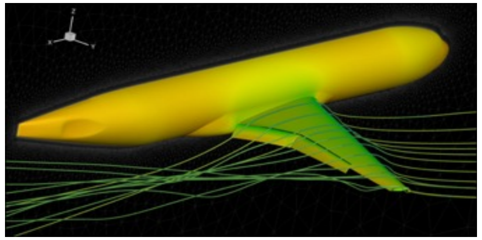




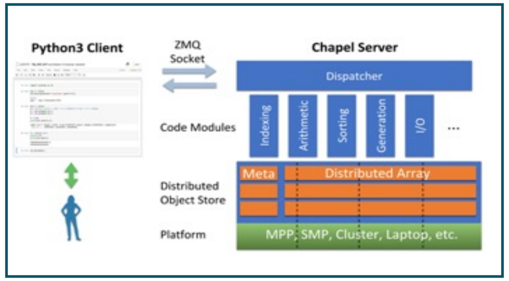


(slide images taken from Éric Laurendeau's SIAM PP22 talk, A Case Study on the Impact of Chapel within an Academic Computational Aerodynamic Laboratory, with permission)

TWO FLAGSHIP CHAPEL APPLICATIONS



CHAMPS: 3D Unstructured Computational Fluid Dynamics (CFD)



Arkouda: Interactive Data Analytics at Supercomputing Scale

DATA SCIENCE IN PYTHON AT SCALE?

Motivation: Say you've got…

…HPC-scale data science problems to solve

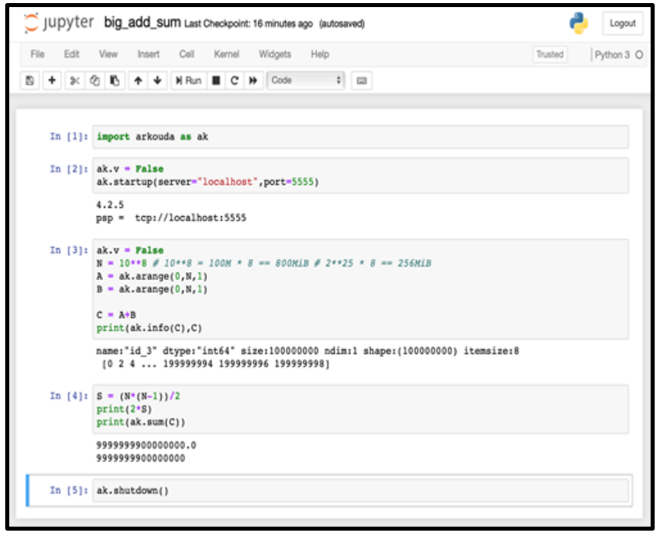
…a bunch of Python programmers

…access to HPC systems

How will you leverage your Python programmers to get your work done?

ARKOUDA'S HIGH-LEVEL APPROACH

Arkouda Client
(written in Python)



Arkouda Server
(written in Chapel)

User writes Python code in Jupyter, making familiar NumPy/Pandas calls

ARKOUDA SUMMARY

What is it?

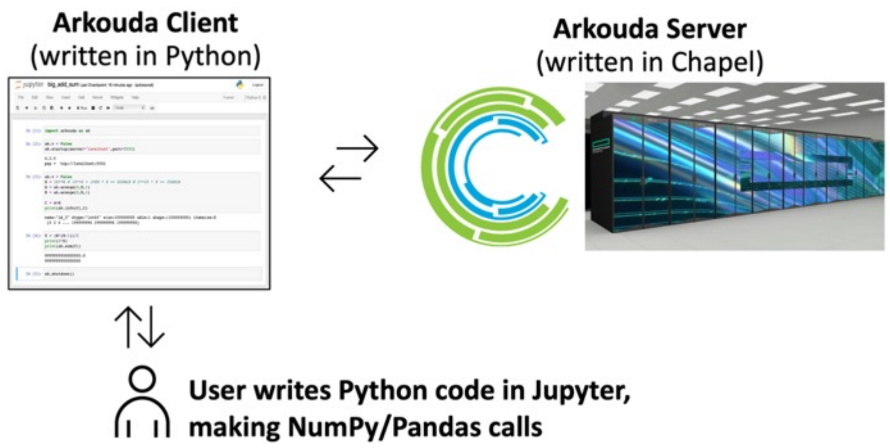
- A Python library supporting a key subset of NumPy and Pandas for Data Science
  – Uses a Python-client/Chapel-server model to get scalability and performance
  – Computes massive-scale results (multi-TB-scale arrays) within the human thought loop (seconds to a few minutes)
- ~25k lines of Chapel, written since 2019

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
  – enabled writing Arkouda rapidly
  – doesn't repel Python users who look under the hood
- ports from laptop to supercomputer

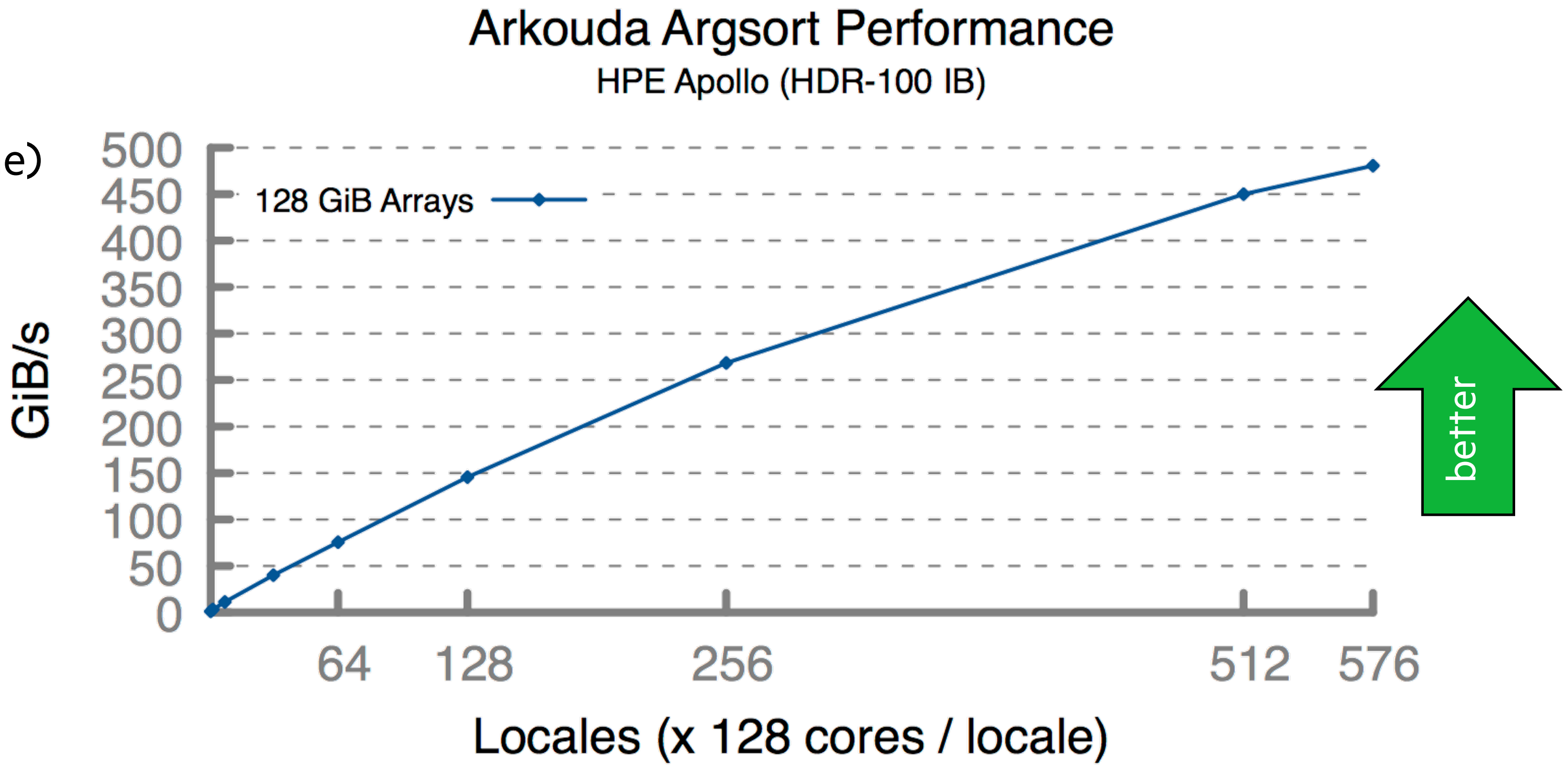


ARKOUDA PERFORMANCE COMPARED TO NUMPY

benchmark	NumPy 0.75 GB	Arkouda (serial) 0.75 GB 1 core, 1 node	Arkouda (parallel) 0.75 GB 36 cores x 1 node	Arkouda (distributed) 384 GB 36 cores x 512 nodes
argsort	0.03 GiB/s --	0.05 GiB/s **1.66x**	0.50 GiB/s **16.7x**	55.12 GiB/s **1837.3x**
coargsort	0.03 GiB/s --	0.07 GiB/s **2.3x**	0.50 GiB/s **16.7x**	29.54 GiB/s **984.7x**
gather	1.15 GiB/s --	0.45 GiB/s 0.4x	13.45 GiB/s **11.7x**	539.52 GiB/s **469.1x**
reduce	9.90 GiB/s --	11.66 GiB/s **1.2x**	118.57 GiB/s **12.0x**	43683.00 GiB/s **4412.4x**
scan	2.78 GiB/s --	2.12 GiB/s 0.8x	8.90 GiB/s **3.2x**	741.14 GiB/s **266.6x**
scatter	1.17 GiB/s --	1.12 GiB/s **1.0x**	13.77 GiB/s **11.8x**	914.67 GiB/s **781.8x**
stream	3.94 GiB/s --	2.92 GiB/s 0.7x	24.58 GiB/s **6.2x**	6266.22 GiB/s **1590.4x**

ARKOUDA ARGSORT AT MASSIVE SCALE

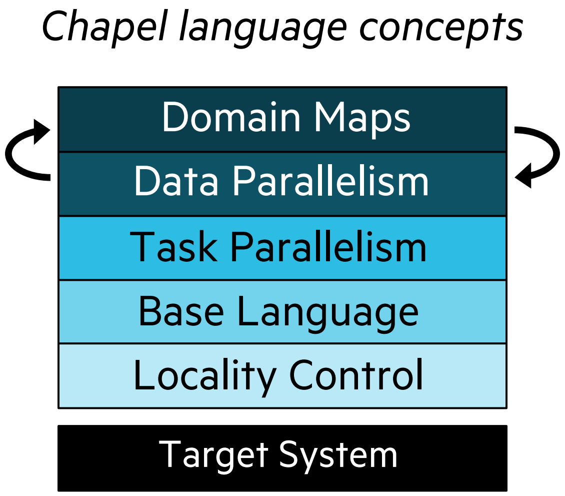
- Ran on a large Apollo system, summer 2021
  - 73,728 cores of AMD Rome
  - 72 TiB of 8-byte values
  - 480 GiB/s (2.5 minutes elapsed time)
  - ~100 lines of Chapel code



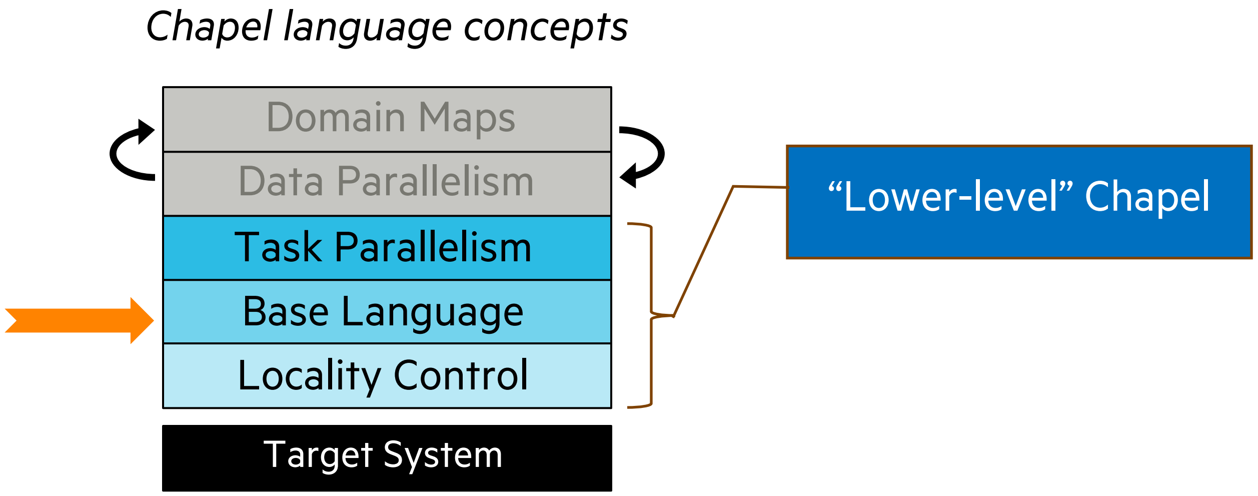
Close to world-record performance—quite likely a record for performance/SLOC

OVERVIEW OF CHAPEL FEATURES

CHAPEL FEATURE AREAS



BASE LANGUAGE



A TOY COMPUTATION: THE FIBONACCI SEQUENCE

- Our first program shows a stylized way of computing *n* values of the Fibonacci sequence in Chapel…
  - This is admittedly a very artificial example, but it's short and illustrative
- The Fibonacci Sequence:
  - Starts with: 0, 1
  - Successive terms obtained by adding the previous two terms: 1, 2, 3, 5, 8, …

FIBONACCI ITERATION

fib.chpl

```
config const n = 10;

for f in fib(n) do
  writeln(f);

iter fib(x) {
  var current = 0,
      next = 1;

  for i in 1..x {
    yield current;
    current += next;
    current <=> next;
  }
}
```

```
prompt> chpl fib.chpl
prompt>
```

FIBONACCI ITERATION

fib.chpl

```
config const n = 10;

for f in fib(n) do
  writeln(f);

iter fib(x) {
  var current = 0,
      next = 1;

  for i in 1..x {
    yield current;
    current += next;
    current <=> next;
  }
}
```

Drive this loop by invoking fib(n)

```
prompt> chpl fib.chpl
prompt> ./fib
```

FIBONACCI ITERATION

fib.chpl

```
config const n = 10;

for f in fib(n) do
  writeln(f);

iter fib(x) {
  var current = 0,
      next = 1;

  for i in 1..x {
    yield current;
    current += next;
    current <=> next;
  }
}
```

Execute the loop's body for that value

'yield' this expression back to the loop's index variable

```
prompt> chpl fib.chpl
prompt> ./fib
0
```

FIBONACCI ITERATION

fib.chpl

```
config const n = 10;

for f in fib(n) do
  writeln(f);

iter fib(x) {
  var current = 0,
      next = 1;

  for i in 1..x {
    yield current;
    current += next;
    current <=> next;
  }
}
```

Execute the loop's body for that value

Then continue the iterator from where it left off

Repeating until we fall out of it (or return)

```
prompt> chpl fib.chpl
prompt> ./fib
0
1
1
2
3
5
8
13
21
34
```

FIBONACCI ITERATION

fib.chpl

```
config const n = 10;

for f in fib(n) do
  writeln(f);

iter fib(x) {
  var current = 0,
      next = 1;

  for i in 1..x {
    yield current;
    current += next;
    current <=> next;
  }
}
```

Config[urable] declarations support command-line overrides

```
prompt> chpl fib.chpl
prompt> ./fib --n=1000
0
1
1
2
3
5
8
13
21
34
55
89
144
233
377
…
```

FIBONACCI ITERATION

fib.chpl

```
config const n = 10;

for f in fib(n) do
  writeln(f);

iter fib(x) {
  var current = 0,
      next = 1;

  for i in 1..x {
    yield current;
    current += next;
    current <=> next;
  }
}
```

Static type inference for:

- constants / variables
- arguments
- return types

Explicit typing also supported

```
prompt> chpl fib.chpl
prompt> ./fib --n=1000
0
1
1
2
3
5
8
13
21
34
55
89
144
233
377
…
```

FIBONACCI ITERATION

fib.chpl

```
config const n: int = 10;

for f in fib(n) do
  writeln(f);

iter fib(x: int): int {
  var current: int = 0,
      next: int = 1;

  for i in 1..x {
    yield current;
    current += next;
    current <=> next;
  }
}
```

Explicit typing also supported

```
prompt> chpl fib.chpl
prompt> ./fib --n=1000
0
1
1
2
3
5
8
13
21
34
55
89
144
233
377
…
```

FIBONACCI ITERATION

fib.chpl

```
config const n = 10;

for (i,f) in zip(0..<n, fib(n)) do
  writeln("fib #", i, " is ", f);

iter fib(x) {
  var current = 0,
      next = 1;

  for i in 1..x {
    yield current;
    current += next;
    current <=> next;
  }
}
```

Zippered iteration

```
prompt> chpl fib.chpl
prompt> ./fib --n=1000
fib #0 is 0
fib #1 is 1
fib #2 is 1
fib #3 is 2
fib #4 is 3
fib #5 is 5
fib #6 is 8
fib #7 is 13
fib #8 is 21
fib #9 is 34
fib #10 is 55
fib #11 is 89
fib #12 is 144
fib #13 is 233
fib #14 is 377
…
```

FIBONACCI ITERATION

fib.chpl

```
config const n = 10;

for (i,f) in zip(0..<n, fib(n)) do
  writeln("fib #", i, " is ", f);

iter fib(x) {
  var current = 0,
      next = 1;

  for i in 1..x {
    yield current;
    current += next;
    current <=> next;
  }
}
```

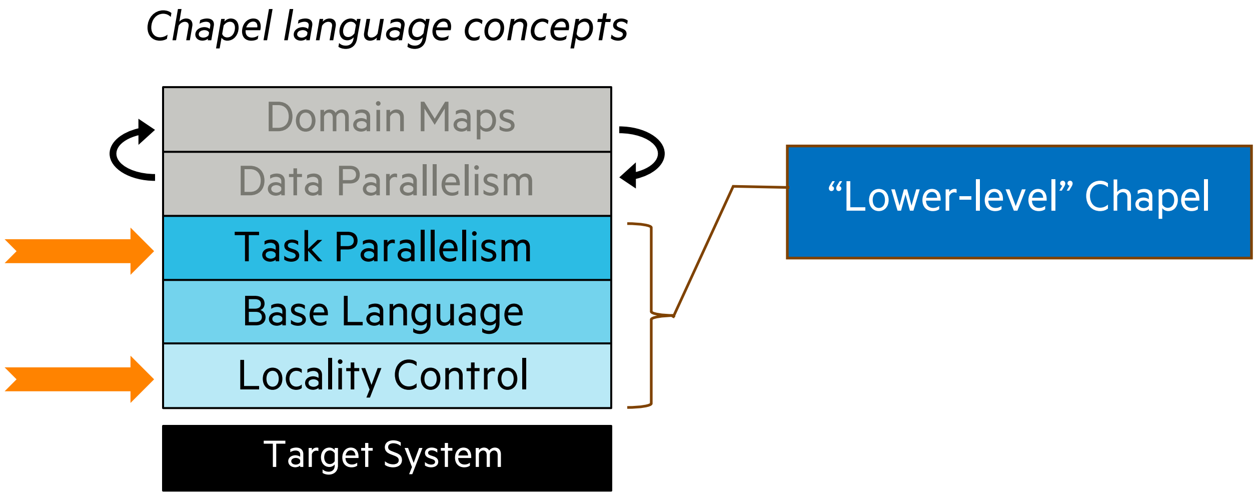
Range types and operators

```
prompt> chpl fib.chpl
prompt> ./fib --n=1000
fib #0 is 0
fib #1 is 1
fib #2 is 1
fib #3 is 2
fib #4 is 3
fib #5 is 5
fib #6 is 8
fib #7 is 13
fib #8 is 21
fib #9 is 34
fib #10 is 55
fib #11 is 89
fib #12 is 144
fib #13 is 233
fib #14 is 377
…
```

OTHER BASE LANGUAGE FEATURES

- **Various basic types:** bool, int(w), uint(w), real(w), imag(w), complex(w), enums, tuples
- **Error-handling**
- **Compile-time meta-programming**
- **Object-oriented programming**
  - Value-based records (like C structs supporting methods, generic fields, etc.)
  - Reference-based classes (somewhat like Java classes or C++ pointers-to-classes)
    - Nilable vs. non-nilable variants
    - Memory-management strategies (shared, owned, borrowed, unmanaged)
    - Lifetime checking
- **Generic programming / polymorphism**
- **Procedure overloading / filtering**
- **Arguments:** default values, intents, name-based matching, type queries
- **Modules** (supporting namespaces)
- and more…

TASK PARALLELISM AND LOCALITY CONTROL

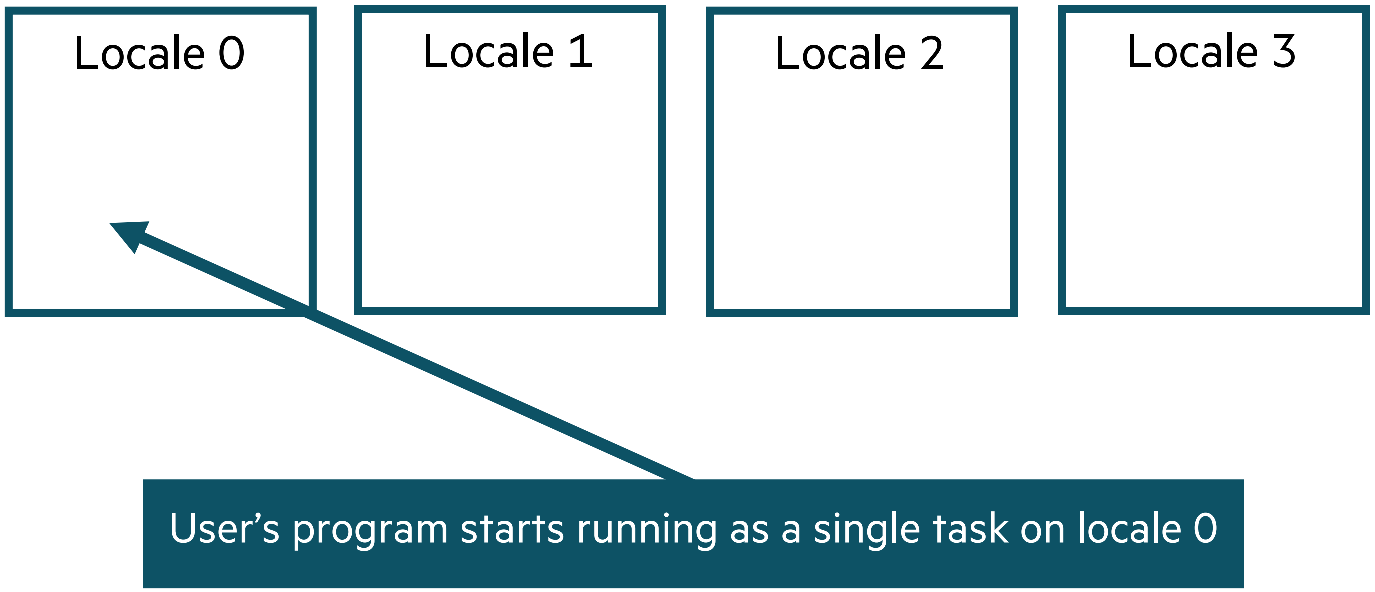


THE LOCALE: CHAPEL'S KEY FEATURE FOR LOCALITY

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

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

`Locales` array:



TASK-PARALLEL "HELLO WORLD"

helloTaskPar.chpl

```
const numTasks = here.maxTaskPar;
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.maxTaskPar;
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 this code is currently running

how many parallel tasks can my locale run at once?

what's my locale's name?

TASK-PARALLEL "HELLO WORLD"

helloTaskPar.chpl

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

the array of locales we're running on (introduced a few slides back)

Locales array:

Locale 0	Locale 1	Locale 2	Locale 3

TASK-PARALLEL "HELLO WORLD" (DISTRIBUTED VERSION)

helloTaskPar.chpl

```
coforall loc in Locales {
  on loc {
    const numTasks = here.maxTaskPar;
    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
…
```

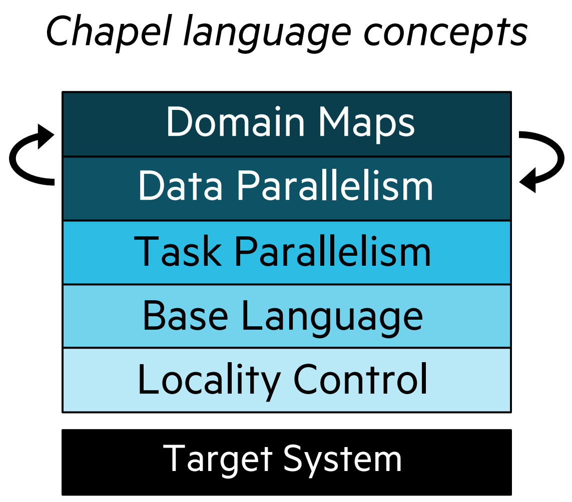
TASK-PARALLEL "HELLO WORLD" (DISTRIBUTED VERSION)

helloTaskPar.chpl

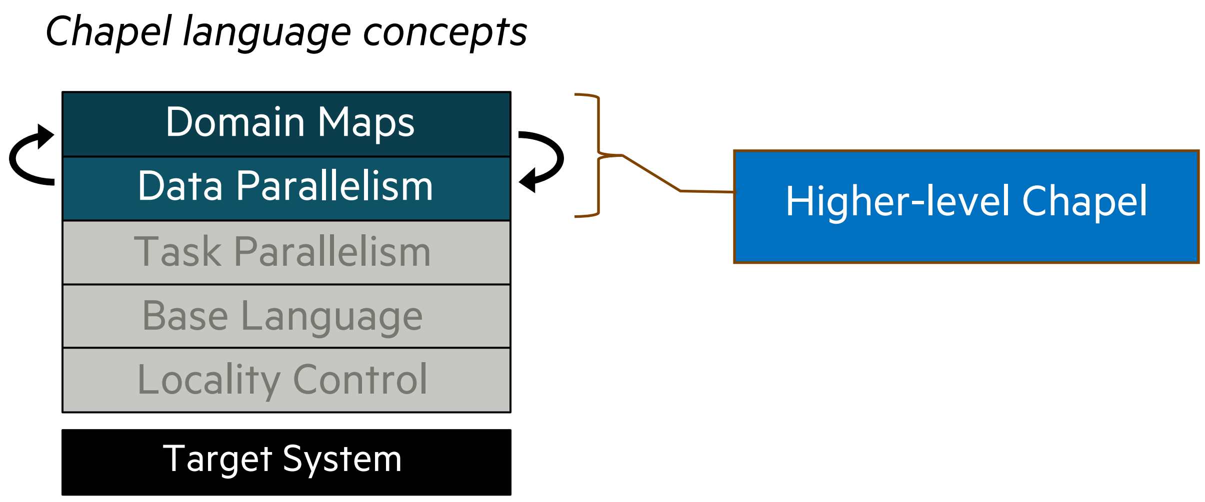
```
coforall loc in Locales {
  on loc {
    const numTasks = here.maxTaskPar;
    coforall tid in 1..numTasks do
      writef("Hello from task %n of %n on %s\n",
                 tid, numTasks, here.name);
  }
}
```

```
prompt> chpl helloTaskPar.chpl
prompt> ./helloTaskPar -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 FEATURE AREAS



DATA PARALLELISM AND DOMAIN MAPS



DATA-PARALLEL ARRAY FILL

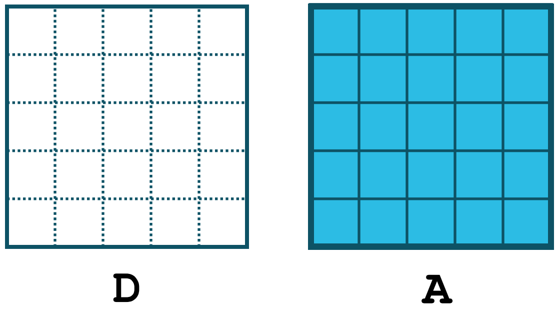
fillArray.chpl

```
config const n = 1000;

const D = {1..n, 1..n};

var A: [D] real;

forall (i,j) in D do
  A[i,j] = i + (j - 0.5)/n;

writeln(A);
```

DATA-PARALLEL ARRAY FILL

fillArray.chpl

```
config const n = 1000;

const D = {1..n, 1..n};

var A: [D] real;

forall (i,j) in D do
  A[i,j] = i + (j - 0.5)/n;

writeln(A);
```



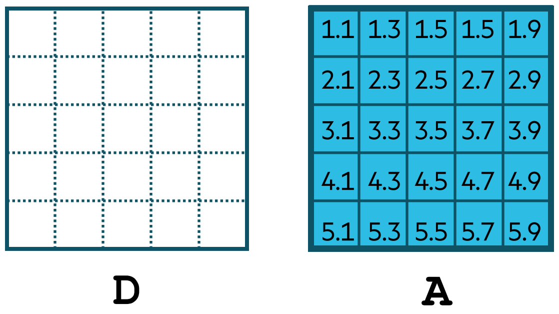
declare a domain, a first-class index set

declare an array over that domain

DATA-PARALLEL ARRAY FILL

fillArray.chpl

```
config const n = 1000;

const D = {1..n, 1..n};

var A: [D] real;

forall (i,j) in D do
  A[i,j] = i + (j - 0.5)/n;

writeln(A);
```



declare a domain, a first-class index set

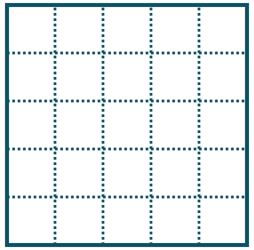
declare an array over that domain

iterate over the domain's indices in parallel, assigning to the corresponding array elements

DATA-PARALLEL ARRAY FILL

fillArray.chpl

```
config const n = 1000;

const D = {1..n, 1..n};

var A: [D] real;

forall (i,j) in D do
  A[i,j] = i + (j - 0.5)/n;

writeln(A);
```



D

1.1	1.3	1.5	1.5	1.9
2.1	2.3	2.5	2.7	2.9
3.1	3.3	3.5	3.7	3.9
4.1	4.3	4.5	4.7	4.9
5.1	5.3	5.5	5.7	5.9

A

```
prompt> chpl dataParallel.chpl
prompt> ./dataParallel --n=5
1.1 1.3 1.5 1.7 1.9
2.1 2.3 2.5 2.7 2.9
3.1 3.3 3.5 3.7 3.9
4.1 4.3 4.5 4.7 4.9
5.1 5.3 5.5 5.7 5.9
```

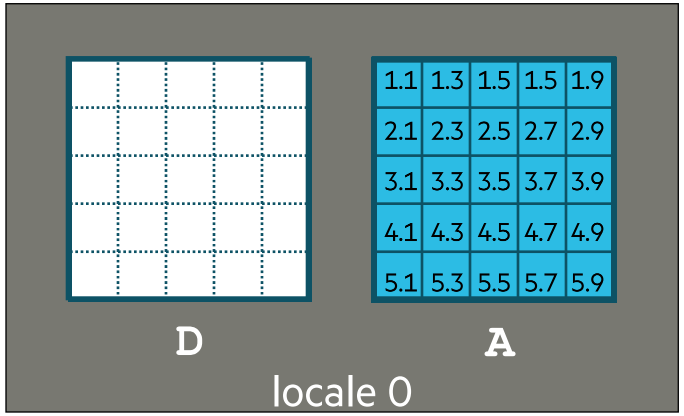
So far, this is a shared-memory program

Nothing refers to remote locales, explicitly or implicitly

DATA-PARALLEL ARRAY FILL

fillArray.chpl

```
config const n = 1000;

const D = {1..n, 1..n};

var A: [D] real;

forall (i,j) in D do
  A[i,j] = i + (j - 0.5)/n;

writeln(A);
```




```
prompt> chpl dataParallel.chpl
prompt> ./dataParallel --n=5
1.1 1.3 1.5 1.7 1.9
2.1 2.3 2.5 2.7 2.9
3.1 3.3 3.5 3.7 3.9
4.1 4.3 4.5 4.7 4.9
5.1 5.3 5.5 5.7 5.9
```

So far, this is a shared-memory program

Nothing refers to remote locales, explicitly or implicitly

DATA-PARALLEL ARRAY FILL

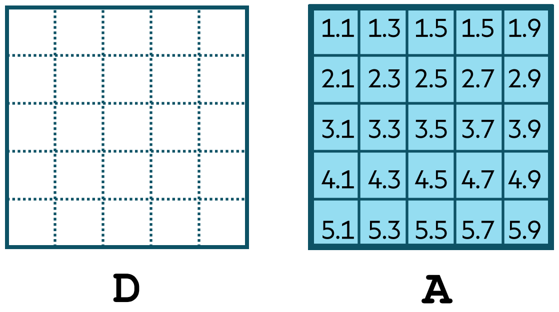
fillArray.chpl

```
config const n = 1000;

const D = {1..n, 1..n};

var A: [D] real;

forall (i,j) in D do
  A[i,j] = i + (j - 0.5)/n;

writeln(A);
```

DATA-PARALLEL ARRAY FILL (DISTRIBUTED VERSION)

fillArray.chpl

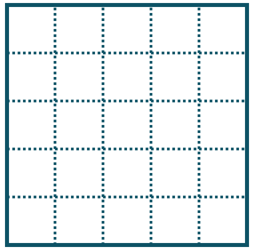
```
use CyclicDist;

config const n = 1000;

const D = {1..n, 1..n}
          dmapped Cyclic(startIdx = (1,1));
var A: [D] real;

forall (i,j) in D do
  A[i,j] = i + (j - 0.5)/n;

writeln(A);
```



DATA-PARALLEL ARRAY FILL (DISTRIBUTED VERSION)

fillArray.chpl

```
use CyclicDist;

config const n = 1000;

const D = {1..n, 1..n}
          dmapped Cyclic(startIdx = (1,1));
var A: [D] real;

forall (i,j) in D do
  A[i,j] = i + (j - 0.5)/n;

writeln(A);
```



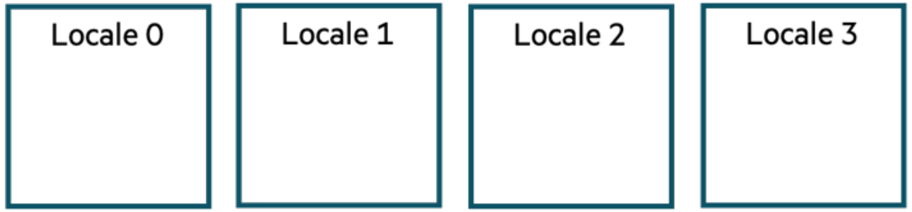
D

1.1	1.3	1.5	1.5	1.9
2.1	2.3	2.5	2.7	2.9
3.1	3.3	3.5	3.7	3.9
4.1	4.3	4.5	4.7	4.9
5.1	5.3	5.5	5.7	5.9

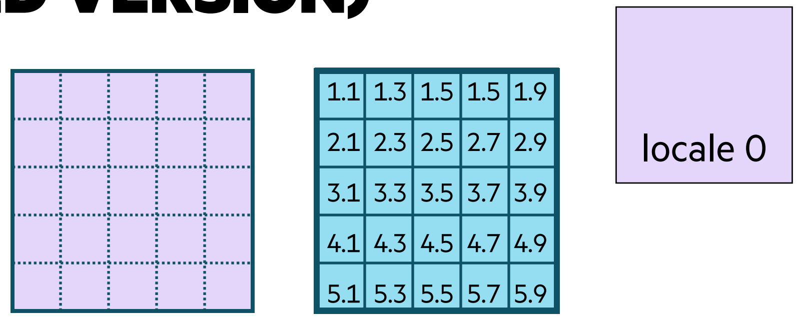
A

apply a domain map, specifying how to implement…
…the domain's indices,
…the array's elements,
…the loop's iterations,
…on the program's locales

Locales array:



DATA-PARALLEL ARRAY FILL (DISTRIBUTED VERSION)



fillArray.chpl

```
use CyclicDist;

config const n = 1000;

const D = {1..n, 1..n}
          dmapped Cyclic(startIdx = (1,1));
var A: [D] real;

forall (i,j) in D do
  A[i,j] = i + (j - 0.5)/n;

writeln(A);
```

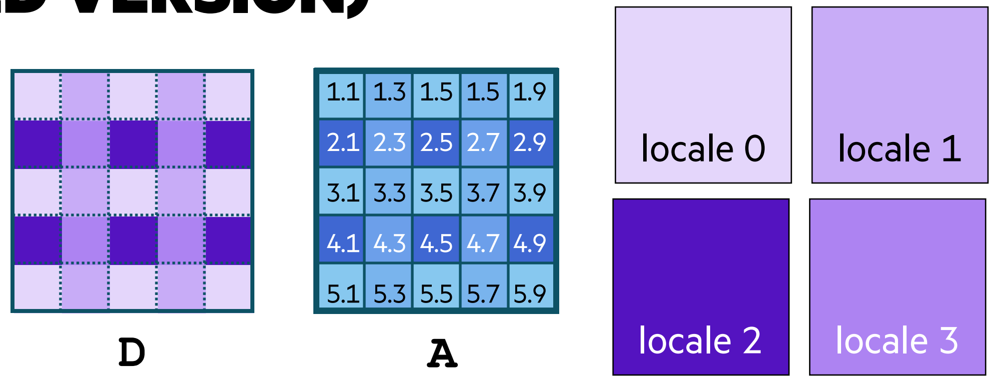
```
prompt> chpl dataParallel.chpl
prompt> ./dataParallel --n=5 --numLocales=1
1.1 1.3 1.5 1.7 1.9
2.1 2.3 2.5 2.7 2.9
3.1 3.3 3.5 3.7 3.9
4.1 4.3 4.5 4.7 4.9
5.1 5.3 5.5 5.7 5.9
```

Because this computation is independent of the locales,
changing the number of locales or distribution doesn't affect the output

DATA-PARALLEL ARRAY FILL (DISTRIBUTED VERSION)

fillArray.chpl

```
use CyclicDist;

config const n = 1000;

const D = {1..n, 1..n}
          dmapped Cyclic(startIdx = (1,1));
var A: [D] real;

forall (i,j) in D do
  A[i,j] = i + (j - 0.5)/n;

writeln(A);
```



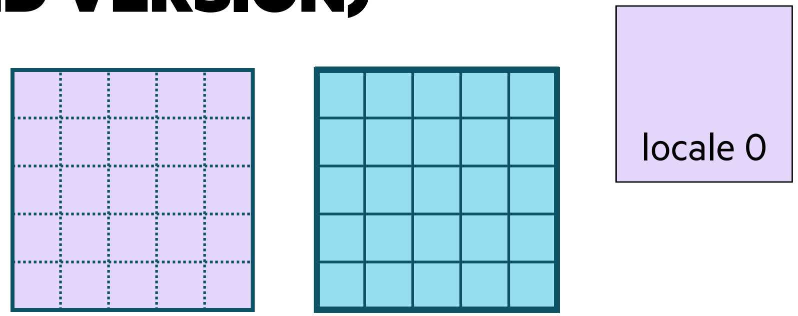

```
prompt> chpl dataParallel.chpl
prompt> ./dataParallel --n=5 --numLocales=4
1.1 1.3 1.5 1.7 1.9
2.1 2.3 2.5 2.7 2.9
3.1 3.3 3.5 3.7 3.9
4.1 4.3 4.5 4.7 4.9
5.1 5.3 5.5 5.7 5.9
```

Because this computation is independent of the locales,
changing the number of locales or distribution doesn't affect the output

DATA-PARALLEL ARRAY FILL (DISTRIBUTED VERSION)

fillArray.chpl

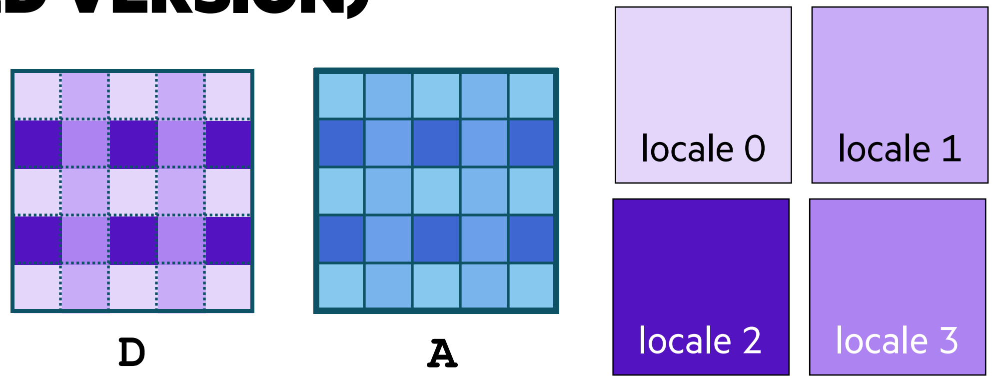
```
use CyclicDist;

config const n = 1000;

const D = {1..n, 1..n}
        dmapped Cyclic(startIdx = (1,1));
var A: [D] real;

forall (i,j) in D do
  A[i,j] = i*10 + j + (here.id+1)/10.0;

writeln(A);
```




```
prompt> chpl dataParallel.chpl
prompt> ./dataParallel --n=5 --numLocales=1
11.1 12.1 13.1 14.1 15.1
21.1 22.1 23.1 24.1 25.1
31.1 32.1 33.1 34.1 35.1
41.1 42.1 43.1 44.1 45.1
51.1 52.1 53.1 54.1 55.1
```

If we make it sensitive to the locales,
the output varies with the distribution details

DATA-PARALLEL ARRAY FILL (DISTRIBUTED VERSION)



fillArray.chpl

```
use CyclicDist;

config const n = 1000;

const D = {1..n, 1..n}
          dmapped Cyclic(startIdx = (1,1));
var A: [D] real;

forall (i,j) in D do
  A[i,j] = i*10 + j + (here.id+1)/10.0;

writeln(A);
```

```
prompt> chpl dataParallel.chpl
prompt> ./dataParallel --n=5 --numLocales=4
11.1 12.2 13.1 14.2 15.1
21.3 22.4 23.3 24.4 25.3
31.1 32.2 33.1 34.2 35.1
41.3 42.4 43.3 44.4 45.3
51.1 52.2 53.1 54.2 55.1
```

If we make it sensitive to the locales,
the output varies with the distribution details

DATA-PARALLEL ARRAY FILL (DISTRIBUTED VERSION)

fillArray.chpl

```
use CyclicDist;

config const n = 1000;

const D = {1..n, 1..n}
          dmapped Cyclic(startIdx = (1,1));
var A: [D] real;

forall (i,j) in D do
  A[i,j] = i*10 + j + (here.id+1)/10.0;

writeln(A);
```

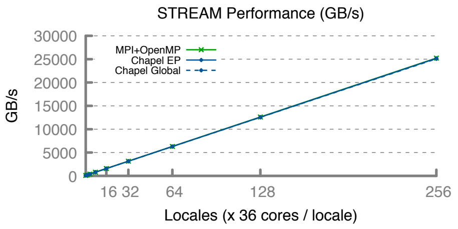
WRAP-UP

SUMMARY

Chapel is unique among programming languages

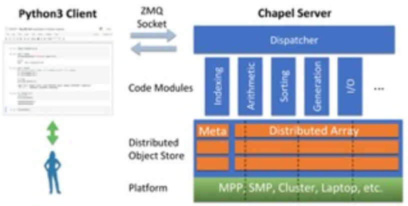
- built-in features for scalable parallel computing make it HPC-ready
- supports clean, concise code relative to conventional approaches
- ports and scales from laptops to supercomputers

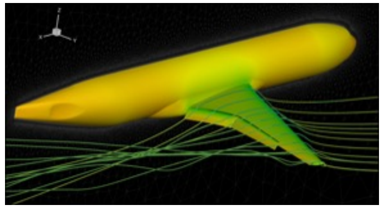
```
use BlockDist;

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;
```



Chapel is being used for productive parallel computing at scale

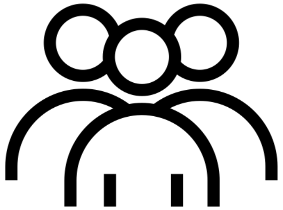
- users are reaping its benefits in practical, cutting-edge applications
- applicable to domains as diverse as physical simulations and data science





If you or your users are interested in taking Chapel for a spin, let us know!

- we're happy to work with users and user groups to help ease the learning curve



CHAPEL RESOURCES

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

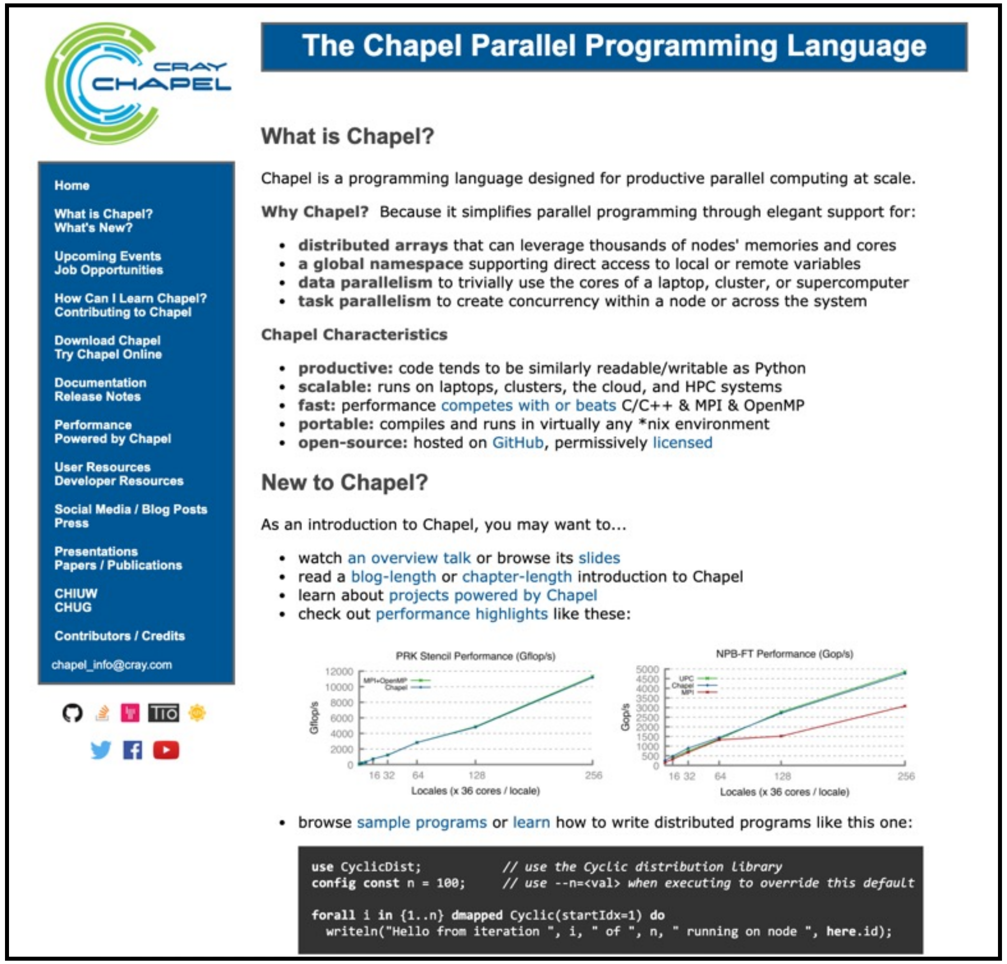
- (points to all other resources)

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



THANK YOU

https://chapel-lang.org
@ChapelLanguage