CSE 501 Language Issues

Languages for High Performance Computing (HPC) and Parallelization

Brad Chamberlain, Chapel Team, Cray Inc.

UW CSE 501, Spring 2015

May 5th, 2015

Chapel:
The Language for HPC/Parallelization*

Brad Chamberlain, Chapel Team, Cray Inc.

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* NOTE: speaker may be somewhat biased

Safe Harbor Statement

This presentation may contain forward-looking statements that are based on our current expectations. Forward looking statements may include statements about our financial guidance and expected operating results, our opportunities and future potential, our product development and new product introduction plans, our ability to expand and penetrate our addressable markets and other statements that are not historical facts. These statements are only predictions and actual results may materially vary from those projected. Please refer to Cray's documents filed with the SEC from time to time concerning factors that could affect the Company and these forward-looking statements.

"Who is this guy Alvin dumped on us?"

2001: graduated from UW CSE with a PhD

- worked on the ZPL parallel programming language
- advisor: Larry Snyder (now Emeritus)

2001-2002: spent a lost/educational year at a startup

2002-present: have been working at Cray Inc.

- Hired to help with the HPCS program (see 2nd slide following)
- Convinced execs/customers that we should do a language

Also a UW CSE affiliate faculty member

Ground Rules

- **Please feel encouraged to ask questions as we go**
  - I'll throttle as necessary (my slides or the questions)
- **Optionally: Grab lunch afterwards**

Chapel's Origins: HPCS

DARPA HPCS: High Productivity Computing Systems

- **Goal:** improve productivity by a factor of 10x
- **Timeframe:** Summer 2002 – Fall 2012
- Cray developed a new system architecture, network, software stack…
  - this became the very successful Cray XC30™ Supercomputer Series

…and a new programming language: Chapel

What is Chapel?

- **An emerging parallel programming language**
  - Design and development led by Cray Inc.
    - in collaboration with academia, labs, industry; domestically & internationally

- **A work-in-progress**
  - Being developed as open source at GitHub
    - Uses Apache v2.0 license
  - Portable design and implementation, targeting:
    - multicore desktops and laptops
    - commodity clusters and the cloud
    - HPC systems from Cray and other vendors
    - *in-progress:* manycore processors, CPU+accelerator hybrids, …

Goal: Improve productivity of parallel programming

What does "Productivity" mean to you?

Recent Graduates:

"something similar to what I used in school: Python, Matlab, Java, …"

Seasoned HPC Programmers:

"that sugary stuff that I don't need because I ~~was born to suffer"~~
want full control
to ensure performance"

Computational Scientists:

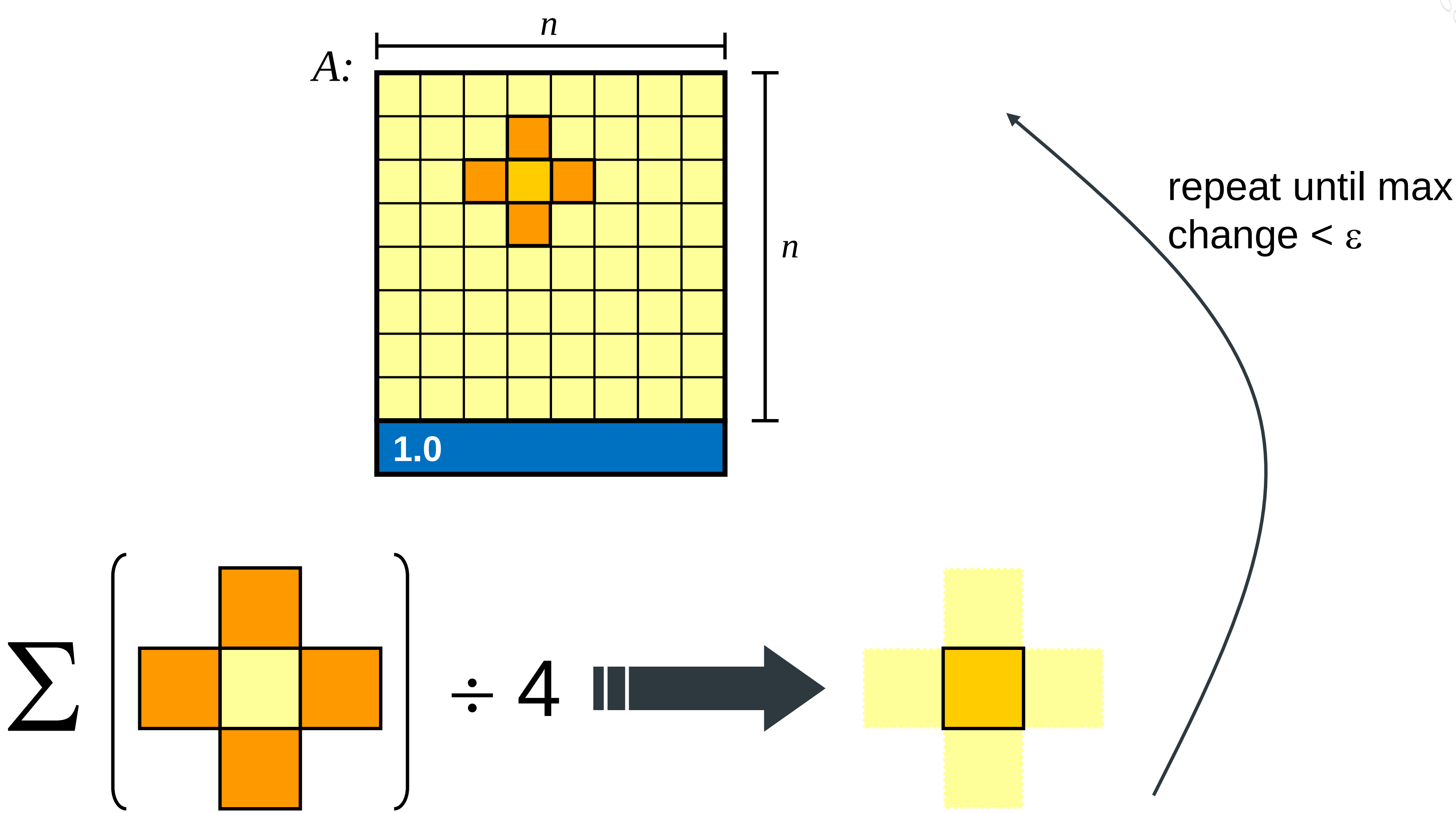
"something that lets me express my parallel computations
without having to wrestle with architecture-specific details"

Chapel Team:

"something that lets computational scientists express what they want,
without taking away the control that HPC programmers need,
implemented in a language as attractive as recent graduates want."

A Stencil Computation in Chapel

Chapel Stencil Example: Jacobi Iteration



Jacobi Iteration in Chapel

```
config const n = 6,
             epsilon = 1.0e-5;

const BigD = {0..n+1, 0..n+1},
         D = BigD[1..n, 1..n],
   LastRow = D.exterior(1,0);

var A, Temp : [BigD] real;

A[LastRow] = 1.0;

do {
  forall (i,j) in D do
    Temp[i,j] = (A[i-1,j] + A[i+1,j] + A[i,j-1] + A[i,j+1]) / 4;

  const delta = max reduce abs(A[D] - Temp[D]);
  A[D] = Temp[D];
} while (delta > epsilon);

writeln(A);
```

Jacobi Iteration in Chapel

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const BigD = {0..n+1, 0..n+1},
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var A, Temp : [BigD] real;

A[La

do {
  fo
                                                      ]) / 4;

  co
  A[
} wh

writ
```

Declare program parameters

const ⇒ can't change values after initialization

config ⇒ can be set on executable command-line

```
prompt> jacobi --n=10000 --epsilon=0.0001
```

note that no types are given; they're inferred from initializers

n ⇒ **default integer** (64 bits)

epsilon ⇒ **default real floating-point** (64 bits)

Jacobi Iteration in Chapel

```
config const n = 6,
             epsilon = 1.0e-5;

const BigD = {0..n+1, 0..n+1},
          D = BigD[1..n, 1..n],
    LastRow = D.exterior(1,0);

va

A[

do
                                                   j+1]) / 4;

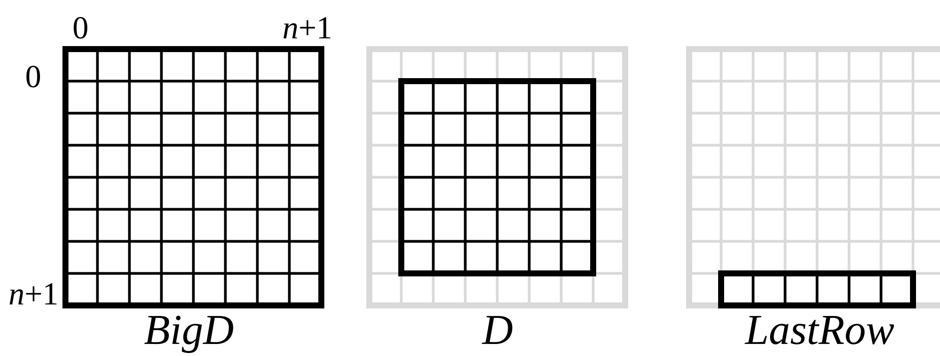
}

wr
```

Declare domains (first class index sets)

{lo..hi, lo2..hi2} ⇒ 2D rectangular domain, with 2-tuple indices

Dom1[Dom2] ⇒ computes the intersection of two domains



.exterior() ⇒ one of several built-in domain generators

Jacobi Iteration in Chapel

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const BigD = {0..n+1, 0..n+1},
         D = BigD[1..n, 1..n],
   LastRow = D.exterior(1,0);

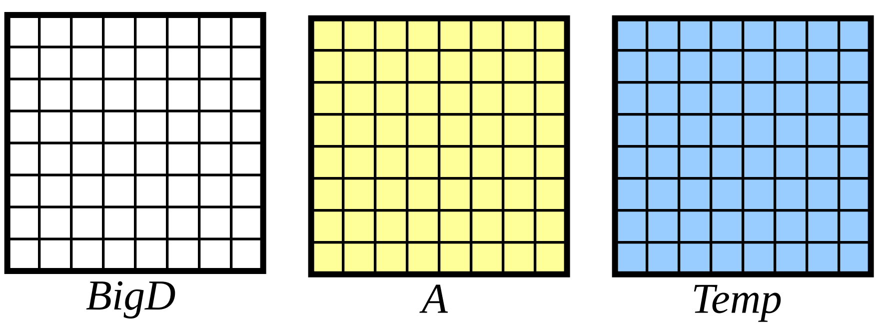
var A, Temp : [BigD] real;
```

Declare arrays

var ⇒ can be modified throughout its lifetime

: [*Dom*] T ⇒ array of size *Dom* with elements of type *T*

(no initializer) ⇒ values initialized to default value (0.0 for reals)




```
[i,j+1]) / 4;
```

Jacobi Iteration in Chapel

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config const n = 6,
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var A, Temp : [BigD] real;

A[LastRow] = 1.0;

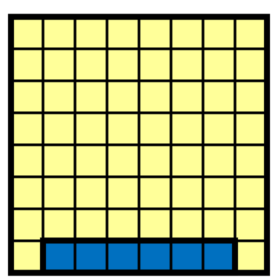
do
                                              j+1]) / 4;

}

wr
```

Set Explicit Boundary Condition

Arr[Dom] ⇒ refer to array slice (“forall i in Dom do …Arr[i]…”)



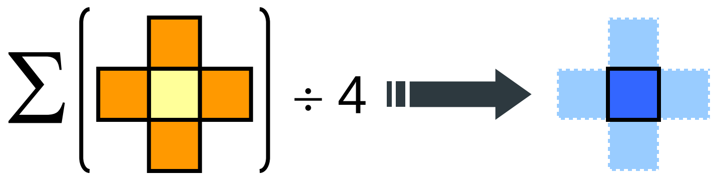
A

Jacobi Iteration in Chapel

```
config const n = 6,
```

Compute 5-point stencil

forall ***ind*** **in** ***Dom*** ⇒ parallel forall expression over *Dom*’s indices,
binding them to *ind*
(here, since *Dom* is 2D, we can de-tuple the indices)




```
do {
  forall (i,j) in D do
    Temp[i,j] = (A[i-1,j] + A[i+1,j] + A[i,j-1] + A[i,j+1]) / 4;

  const delta = max reduce abs(A[D] - Temp[D]);
  A[D] = Temp[D];
} while (delta > epsilon);

writeln(A);
```

Jacobi Iteration in Chapel

```
config const n = 6,
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```

Compute maximum change

***op* reduce** ⇒ collapse aggregate expression to scalar using *op*

Promotion: *abs()* and – are scalar operators; providing array operands results in *promotion*—parallel evaluation equivalent to:

```
forall (a,t) in zip(A,Temp) do abs(a – t)
```

```
do {
  forall (i,j) in D do
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config const n = 6,
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```

<u>Copy data back & Repeat until done</u>

uses slicing and whole-array assignment
standard *do…while* loop construct

```
do {
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  A[D] = Temp[D];
} while (delta > epsilon);

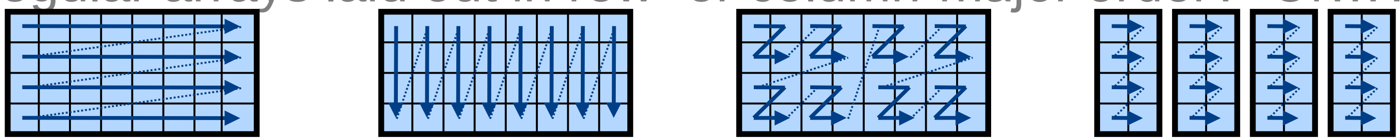
writeln(A);
```

Write array to console

Data Parallelism Implementation Qs

Q1: How are arrays laid out in memory?

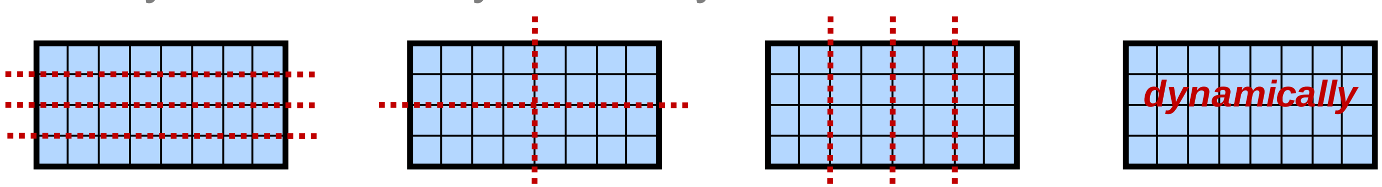
- Are regular arrays laid out in row- or column-major order? Or…?



- How are sparse arrays stored? (COO, CSR, CSC, block-structured, …?)

Q2: How are arrays stored by the locales (compute nodes)?

- Completely local to one locale? Or distributed?
- If distributed… In a blocked manner? cyclically? block-cyclically? recursively bisected? dynamically rebalanced? …?



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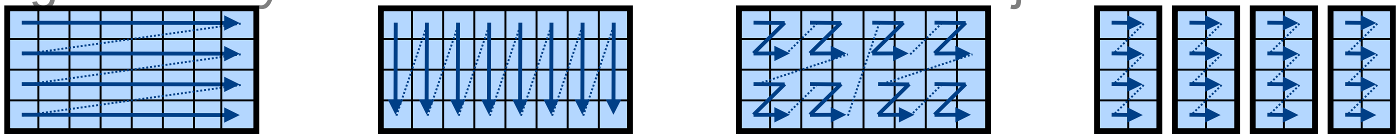

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Q2: How are arrays stored by the locales (compute nodes)?

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A: Chapel's *domain maps* are designed to give the user full control over such decisions

Jacobi Iteration in Chapel

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config const n = 6,
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const BigD = {0..n+1, 0..n+1},
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    LastRow = D.exterior(1,0);

var A, Temp : [BigD] real;
```

By default, domains and their arrays are mapped to a single locale.
Any data parallelism over such domains/ arrays will be executed by the cores on that locale.
Thus, this is a shared-memory/multi-core parallel program.

```
    Temp[i,j] = (A[i-1,j] + A[i+1,j] + A[i,j-1] + A[i,j+1]) / 4;

  const delta = max reduce abs(A[D] - Temp[D]);
  A[D] = Temp[D];
} while (delta > epsilon);

writeln(A);
```

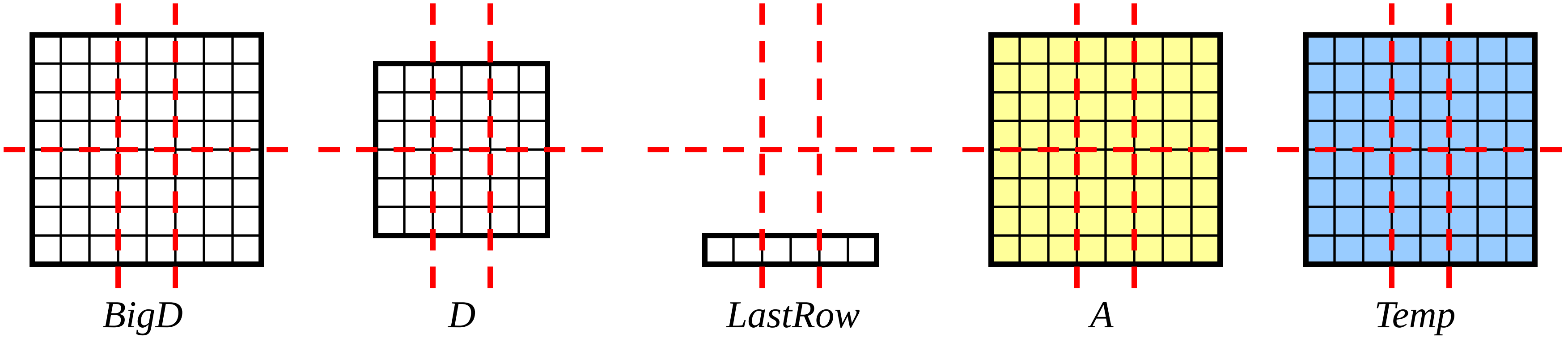
Jacobi Iteration in Chapel

```
config const n = 6,
             epsilon = 1.0e-5;

const BigD = {0..n+1, 0..n+1} dmapped Block({1..n, 1..n}),
         D = BigD[1..n, 1..n],
   LastRow = D.exterior(1,0);

var A, Temp : [BigD] real;
```

With this simple change, we specify a mapping from the domains and arrays to locales
Domain maps describe the mapping of domain indices and array elements to *locales*
- specifies how array data is distributed across locales
- specifies how iterations over domains/arrays are mapped to locales



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var A, Temp : [BigD] real;
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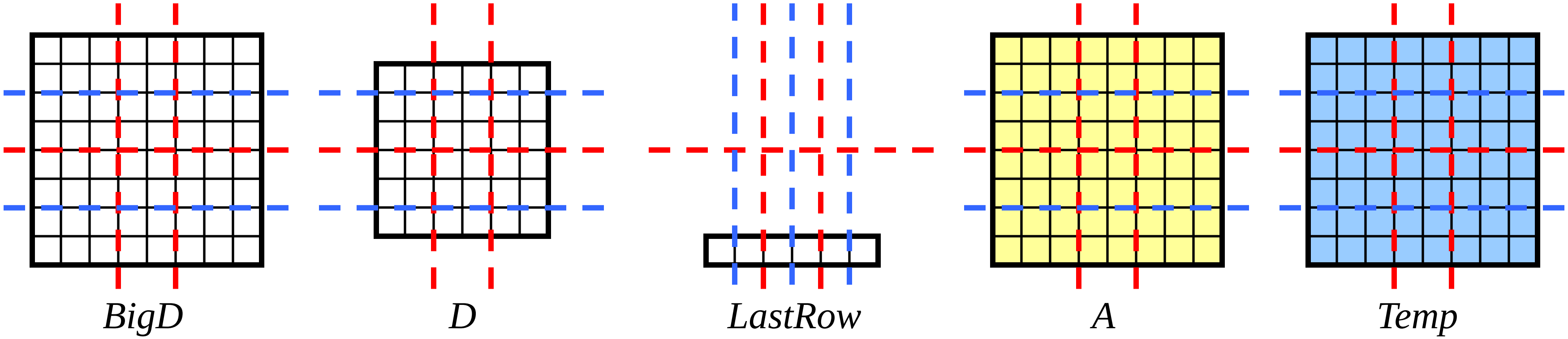
Domain maps describe the mapping of domain indices and array elements to *locales*

- specifies how array data is distributed across locales
- specifies how iterations over domains/arrays are mapped to locales

…including multicore parallelism



Jacobi Iteration in Chapel

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var A, Temp : [BigD] real;

A[LastRow] = 1.0;

do {
  forall (i,j) in D do
    Temp[i,j] = (A[i-1,j] + A[i+1,j] + A[i,j-1] + A[i,j+1]) / 4;

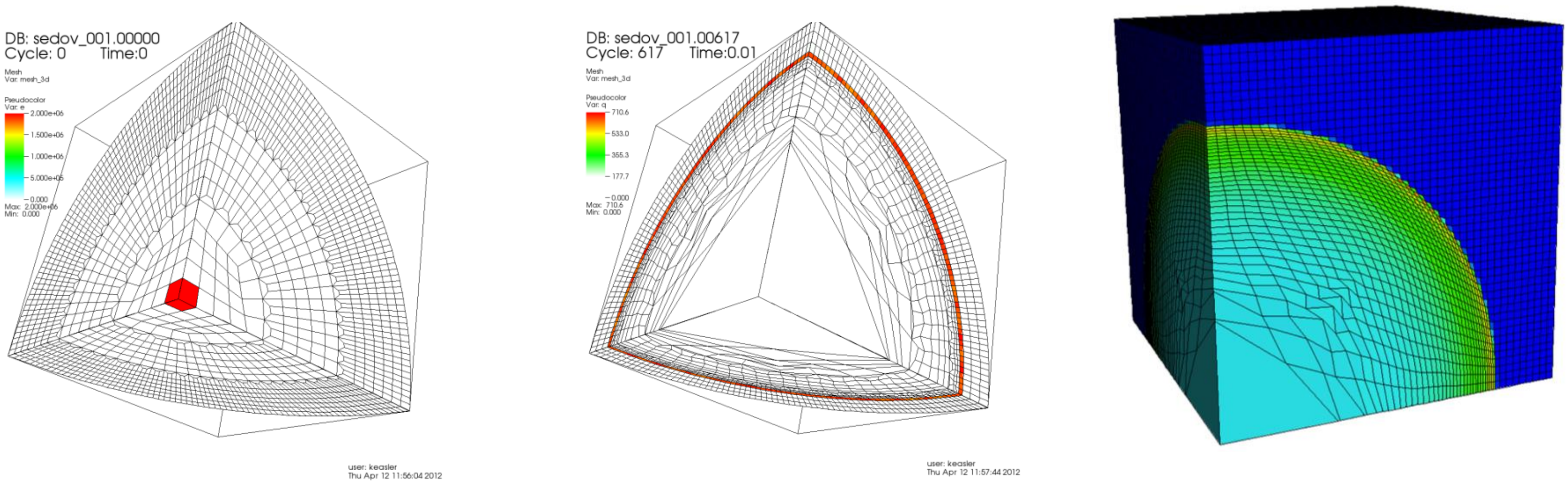
  const delta = max reduce abs(A[D] - Temp[D]);
  A[D] = Temp[D];
} while (delta > epsilon);

writeln(A);

use BlockDist;
```

LULESH: a DOE Proxy Application

Goal: Solve one octant of the spherical Sedov problem (blast wave) using Lagrangian hydrodynamics for a single material



pictures courtesy of Rob Neely, Bert Still, Jeff Keasler, LLNL

LULESH in Chapel

LULESH in Chapel

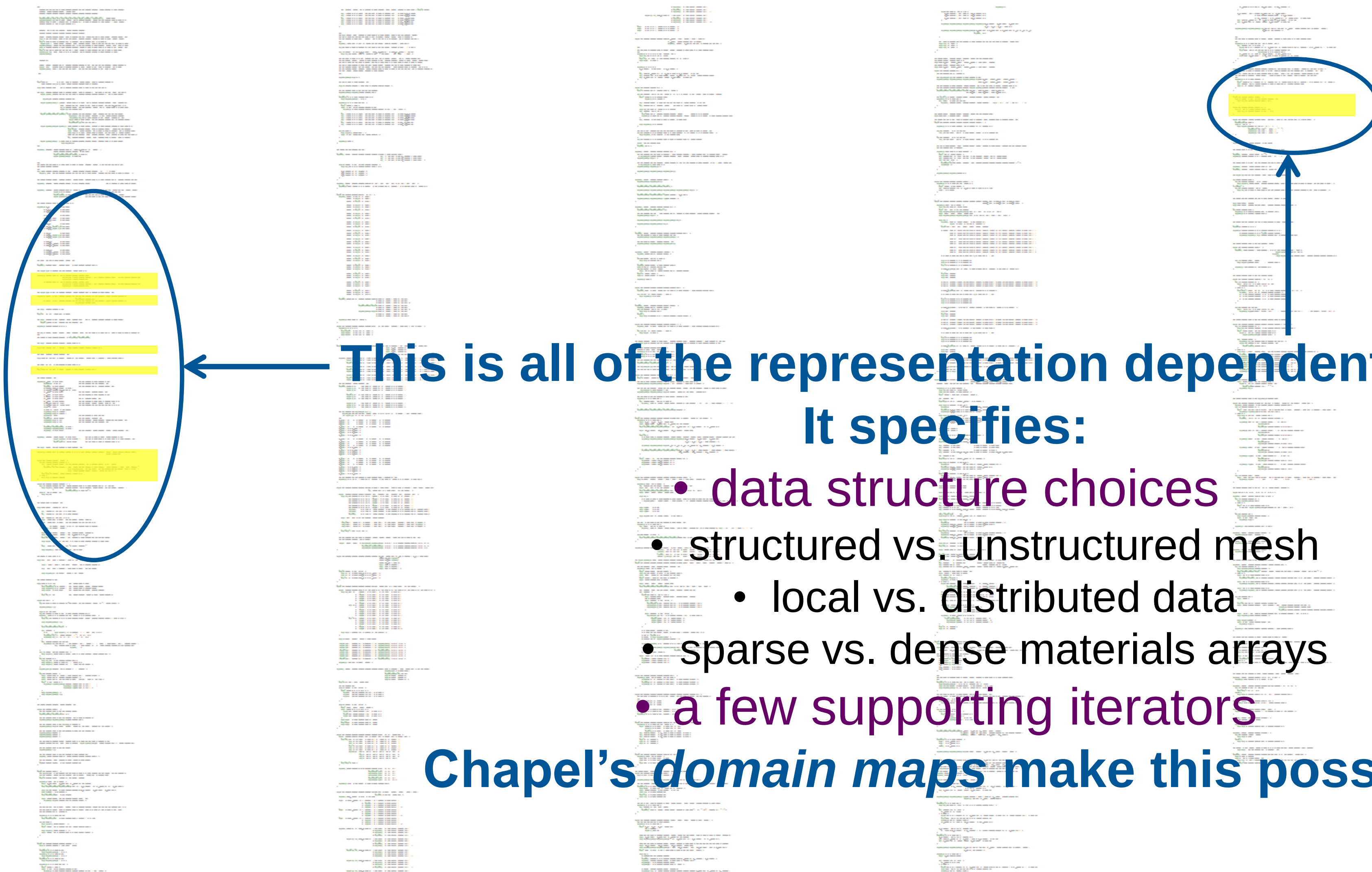
1288 lines of source code

plus 266 lines of comments
487 blank lines

(the corresponding C+MPI+OpenMP version is nearly 4x bigger)

This can be found in Chapel v1.9 in examples/benchmarks/lulesh/*.chpl

LULESH in Chapel



This is all of the representation dependent code.

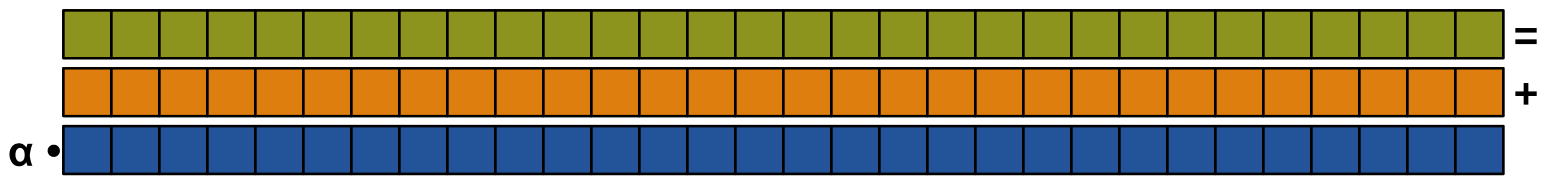
It specifies:

- data structure choices
    - structured vs. unstructured mesh
    - local vs. distributed data
    - sparse vs. dense materials arrays
- a few supporting iterators

Chapel's *domain maps* make this possible

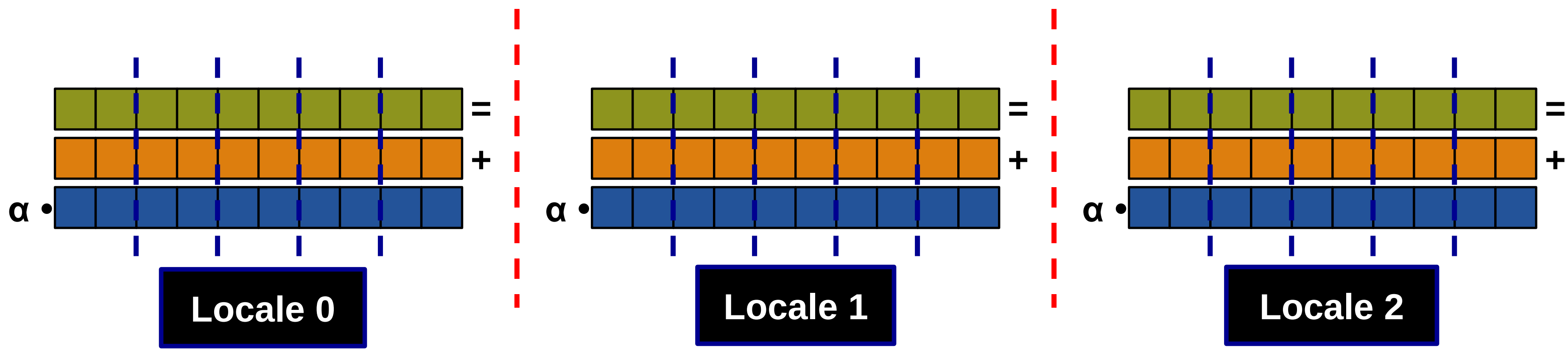
Domain Maps

Domain maps are “recipes” that instruct the compiler how to map the global view of a computation…

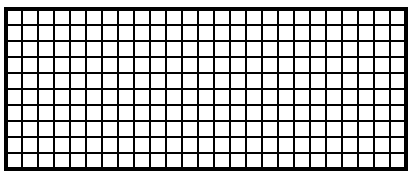



```
A = B + alpha * C;
```

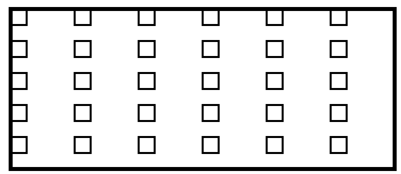
…to the target locales’ memory and processors:



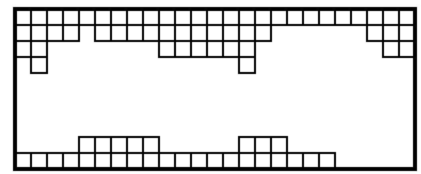
Chapel Domain Types



dense

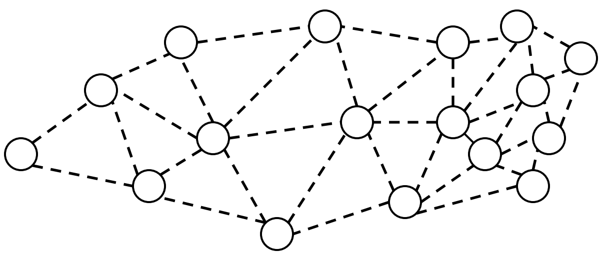


strided



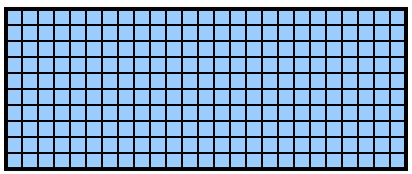
sparse

associative

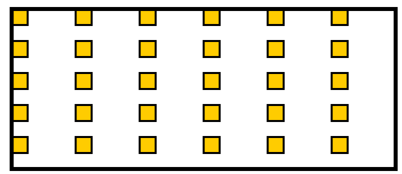


unstructured

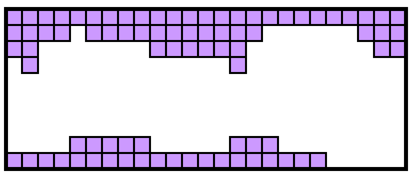
Chapel Array Types



dense



strided



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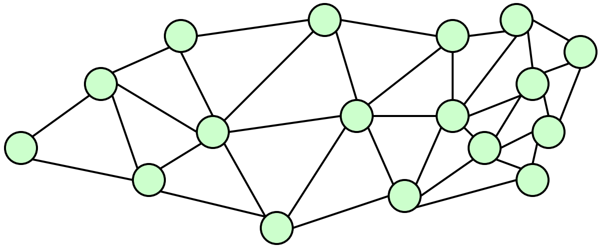
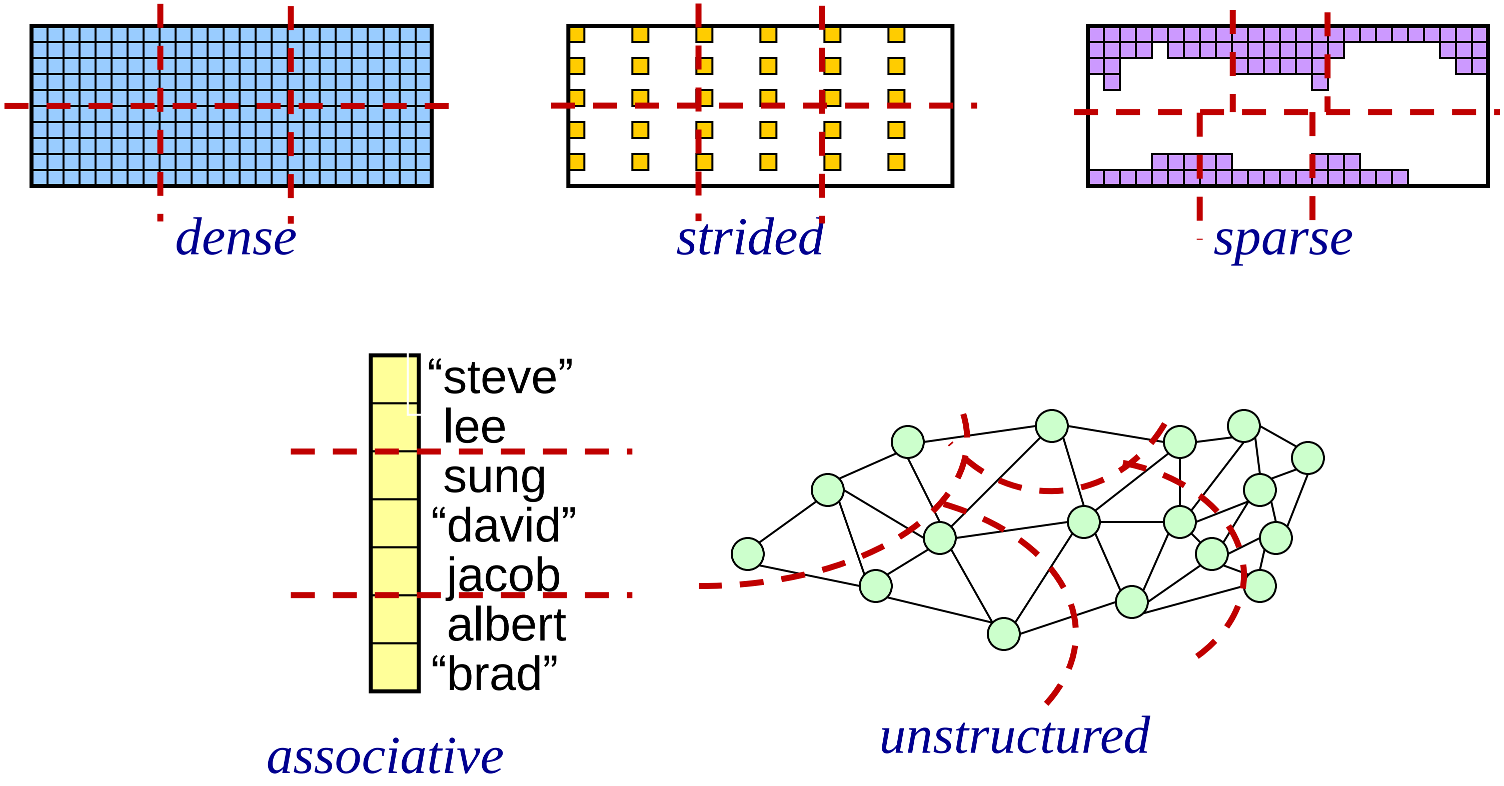


unstructured

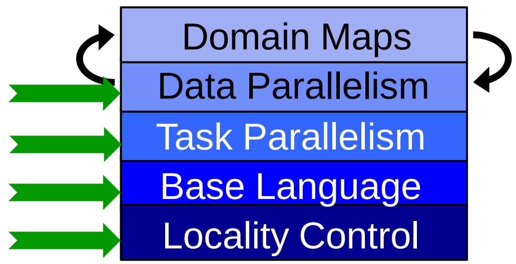
All Domain Types Support Domain Maps



Chapel's Domain Map Philosophy

1. **Chapel provides a library of standard domain maps**
   - to support common array implementations effortlessly

2. **Expert users can write their own domain maps in Chapel**
   - to cope with any shortcomings in our standard library



3. **Chapel's standard domain maps are written using the same end-user framework**
   - to avoid a performance cliff between "built-in" and user-defined cases

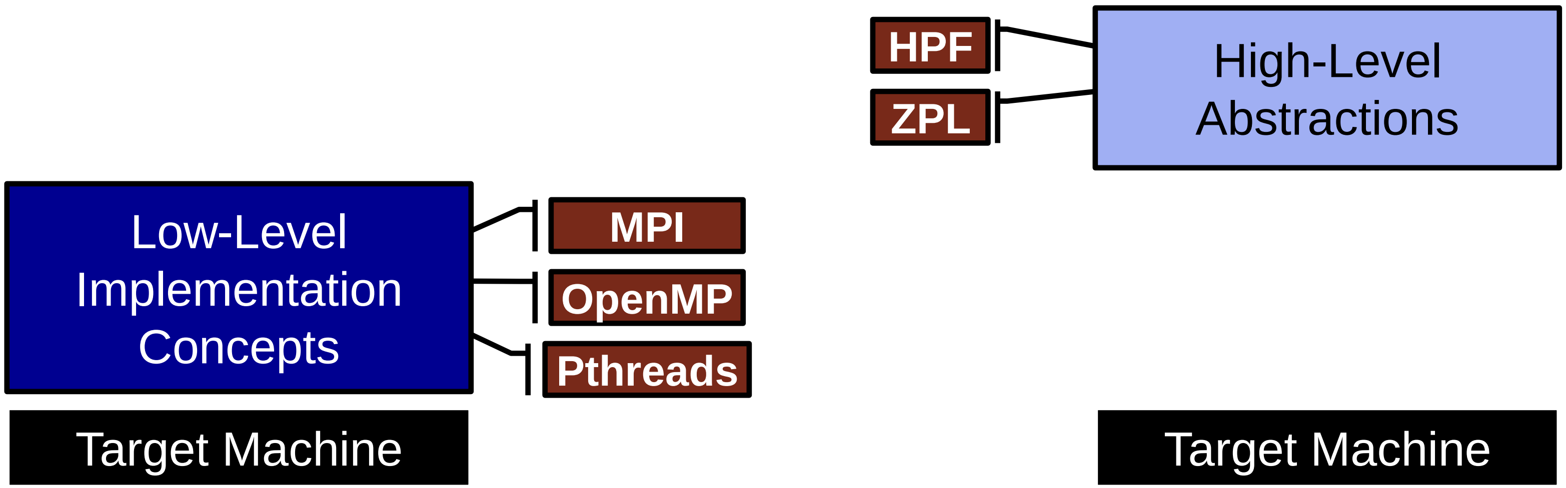
Motivating Chapel Themes

1) General Parallel Programming
2) Global-View Abstractions
3) Multiresolution Design
4) Control over Locality/Affinity
5) Reduce HPC ↔ Mainstream Language Gap

Motivating Chapel Themes

1) General Parallel Programming
2) Global-View Abstractions
3) **Multiresolution Design** ←
4) Control over Locality/Affinity
5) Reduce HPC ↔ Mainstream Language Gap

3) Multiresolution Design: Motivation



"Why is everything so tedious/difficult?"
"Why don't my programs port trivially?"

"Why don't I have more control?"

3) Multiresolution Design

Multiresolution Design: **Support multiple tiers of features**

- higher levels for programmability, productivity
- lower levels for greater degrees of control

Chapel language concepts

Domain Maps
Data Parallelism
Task Parallelism
Base Language
Locality Control

Target Machine

- build the higher-level concepts in terms of the lower
- permit the user to intermix layers arbitrarily

Domain Maps Summary

- **Data locality requires mapping arrays to memory well**
  - distributions between distinct memories
  - layouts within a single memory
- **Most languages define a single data layout & distribution**
  - where the distribution is often the degenerate "everything's local"
- **Domain maps…**

  …move such policies into user-space…

  …exposing them to the end-user through high-level declarations

```
const Elems = {0..#numElems} dmapped Block(…)
```

Two Other Thematically Similar Features

1) **parallel iterators:** Define parallel loop policies

2) **locale models:** Define target architectures

Like domain maps, these are…

…written in Chapel by expert users using lower-level features

- e.g., task parallelism, on-clauses, base language features, …

…available to the end-user via higher-level abstractions

- e.g., forall loops, on-clauses, lexically scoped PGAS memory, …

Multiresolution Summary

Chapel's multiresolution philosophy allows users to write…

- **…custom array implementations** via domain maps
- **…custom parallel iterators** via parallel iterators
- **…custom architectural models** via hierarchical locales

The result is a language that decouples crucial policies for managing data locality out of the language's definition and into an expert user's hand…

…while making them available to end-users through high-level abstractions

For More Information on…

…domain maps

User-Defined Distributions and Layouts in Chapel: Philosophy and Framework [slides], Chamberlain, Deitz, Iten, Choi; HotPar'10, June 2010.

Authoring User-Defined Domain Maps in Chapel [slides], Chamberlain, Choi, Deitz, Iten, Litvinov; Cug 2011, May 2011.

…parallel iterators

User-Defined Parallel Zippered Iterators in Chapel [slides], Chamberlain, Choi, Deitz, Navarro; PGAS 2011, October 2011.

…hierarchical locales

Hierarchical Locales: Exposing Node-Level Locality in Chapel, Choi; 2nd KIISE-KOCSEA SIG HPC Workshop talk, November 2013.

Status: all of these concepts are in-use in every Chapel program today (pointers to code/docs in the release available by request)

Outline

- ✓ Setting
- ✓ Chapel By Example: Jacobi Stencil
- ✓ Multiresolution Philosophy: Domain Maps and such
- ➢ Chapel Motivation
- Parallel Programming Model Taxonomy, Pluses/Minuses
- Chapel Motivating Themes
- Survey of Chapel Concepts
- Compiling Chapel
- Project Status and Next Steps

Sustained Performance Milestones

1 GF – 1988: Cray Y-MP; 8 Processors

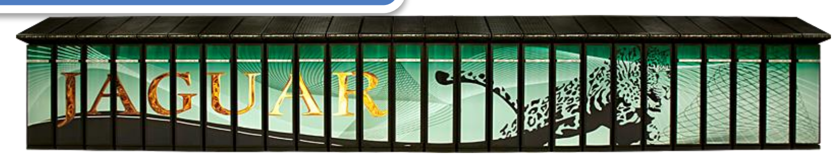
- Static finite element analysis

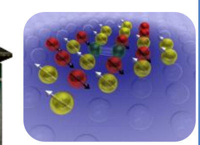
1 TF – 1998: Cray T3E; 1,024 Processors

- Modeling of metallic magnet atoms

1 PF – 2008: Cray XT5; 150,000 Processors

- Superconductive materials





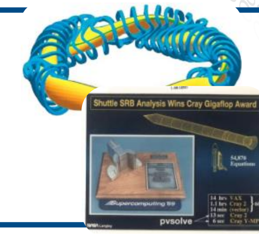
1 EF – ~2018: Cray ____; ~10,000,000 Processors

- TBD

Sustained Performance Milestones

1 GF – 1988: Cray Y-MP; 8 Processors

- Static finite element analysis
- Fortran77 + Cray autotasking + vectorization

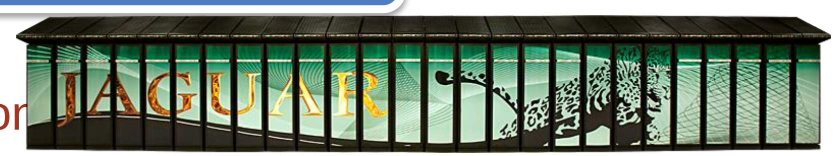


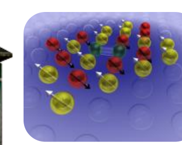
1 TF – 1998: Cray T3E; 1,024 Processors

- Modeling of metallic magnet atoms
- Fortran + MPI (Message Passing Interface)

1 PF – 2008: Cray XT5; 150,000 Processors

- Superconductive materials
- C++/Fortran + MPI + vectorization





1 EF – ~2018: Cray ____; ~10,000,000 Processors

- TBD
- TBD: C/C++/Fortran + MPI + OpenMP/OpenACC/CUDA/OpenCL?

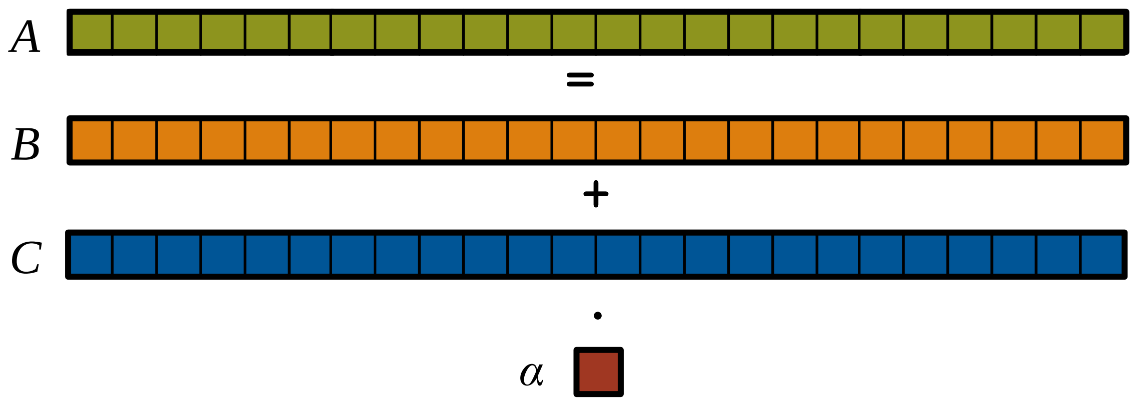
Or, perhaps something completely different?

STREAM Triad: a trivial parallel computation

Given: m-element vectors A, B, C

Compute: $\forall i \in 1..m, A_i = B_i + \alpha \cdot C_i$

In pictures:

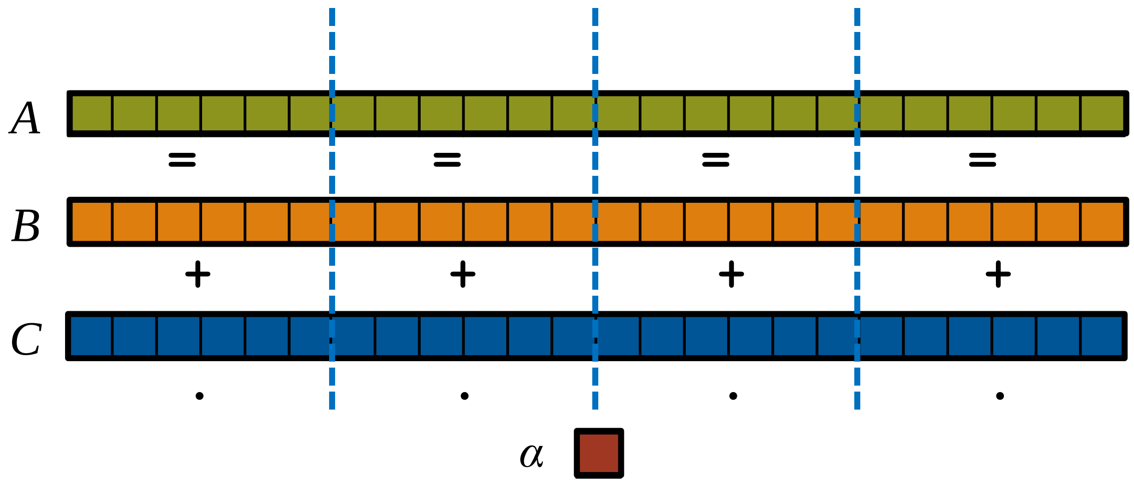


STREAM Triad: a trivial parallel computation

Given: m-element vectors A, B, C

Compute: $\forall i \in 1..m, A_i = B_i + \alpha \cdot C_i$

In pictures, in parallel:

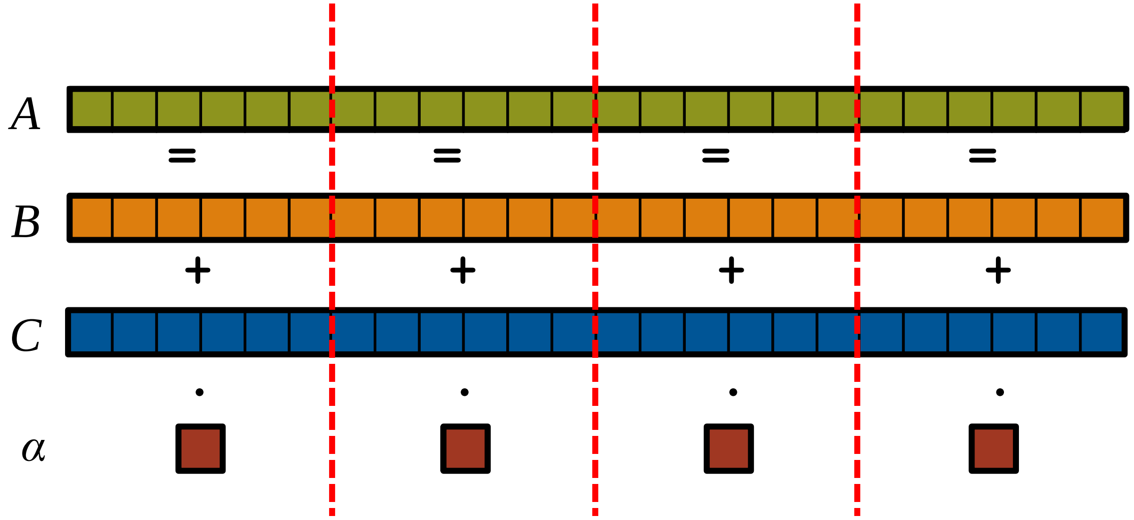


STREAM Triad: a trivial parallel computation

Given: m-element vectors A, B, C

Compute: $\forall i \in 1..m, A_i = B_i + \alpha{\cdot}C_i$

In pictures, in parallel (distributed memory):

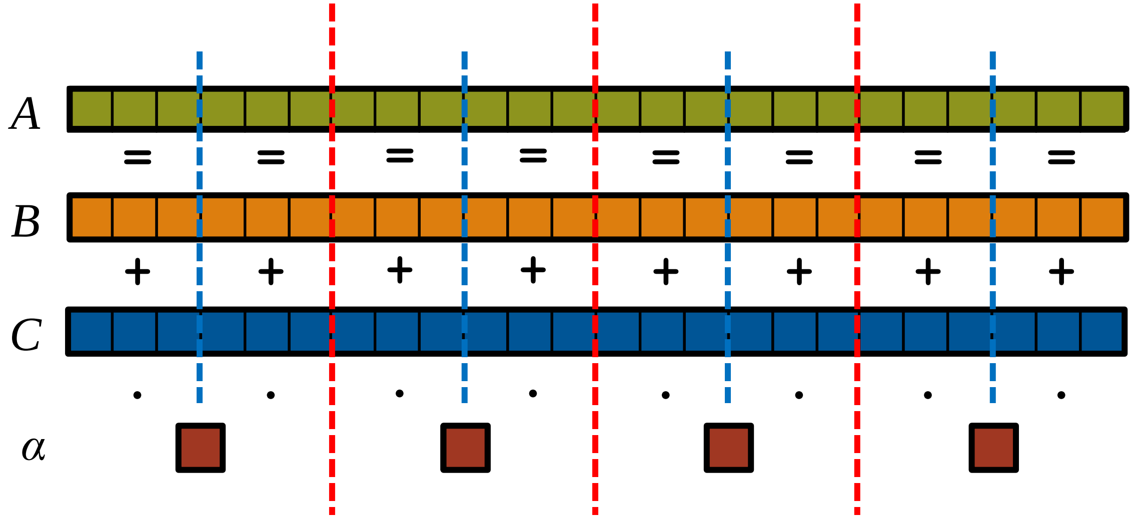


STREAM Triad: a trivial parallel computation

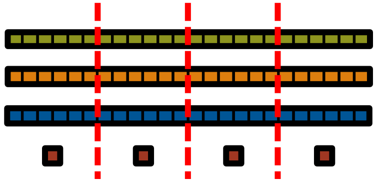
Given: m-element vectors A, B, C

Compute: $\forall i \in 1..m, A_i = B_i + \alpha \cdot C_i$

In pictures, in parallel (distributed memory multicore):



STREAM Triad: MPI



MPI

```
#include <hpcc.h>


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
  (%d).\n", VectorSize );
    fclose( outFile );
  }
  return 1;
}

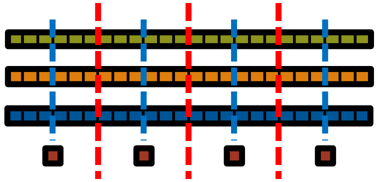

for (j=0; j<VectorSize; j++) {
  b[j] = 2.0;
  c[j] = 0.0;
}

scalar = 3.0;


for (j=0; j<VectorSize; j++)
  a[j] = b[j]+scalar*c[j];

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

STREAM Triad: MPI+OpenMP



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 );
```

```
  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
    (%d).\n", VectorSize );
      fclose( outFile );
    }
    return 1;
  }

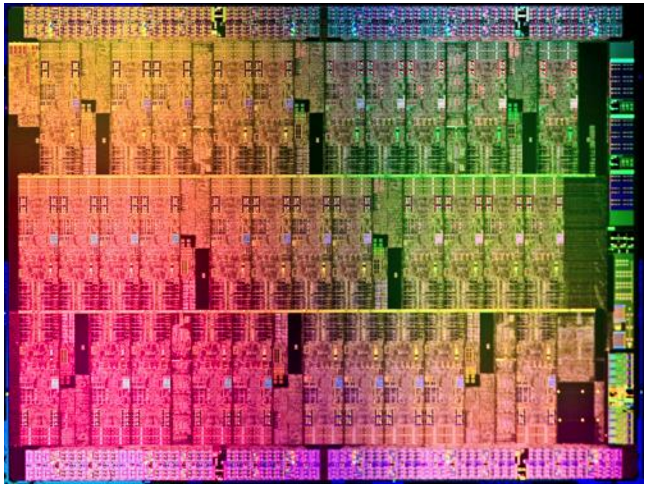
#ifdef _OPENMP
#pragma omp parallel for
#endif
  for (j=0; j<VectorSize; j++) {
    b[j] = 2.0;
    c[j] = 0.0;
  }

  scalar = 3.0;

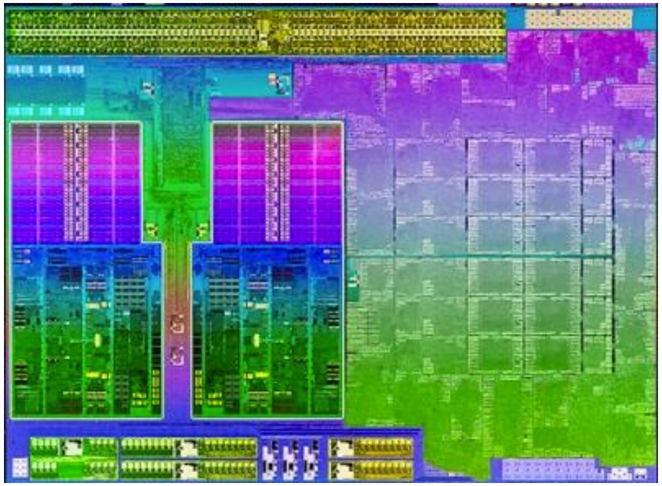
#ifdef _OPENMP
#pragma omp parallel for
#endif
  for (j=0; j<VectorSize; j++)
    a[j] = b[j]+scalar*c[j];

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

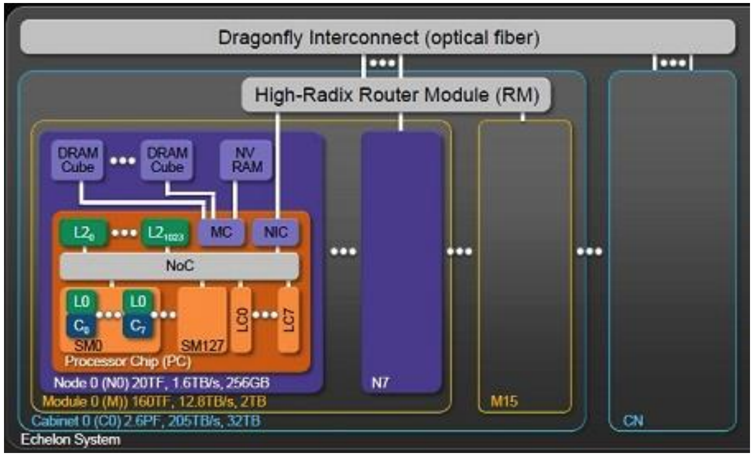
Prototypical Next-Gen Processor Technologies



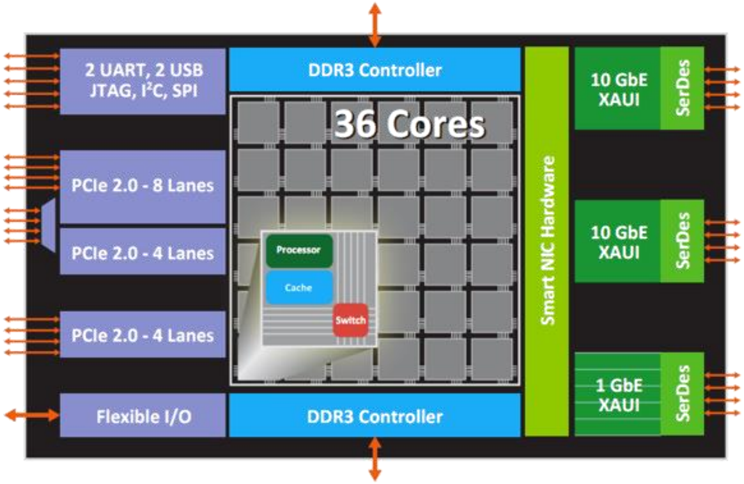
Intel Phi



AMD APU



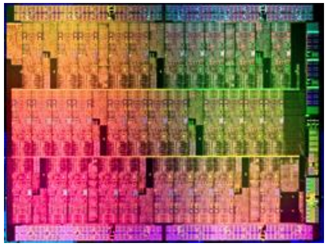
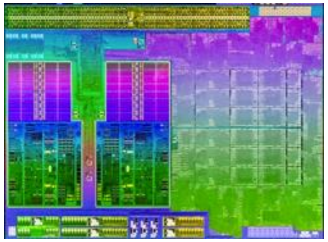
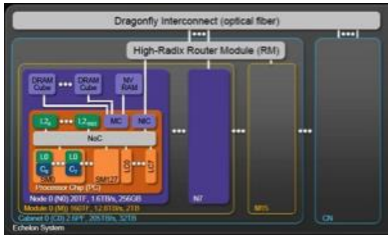
Nvidia Echelon

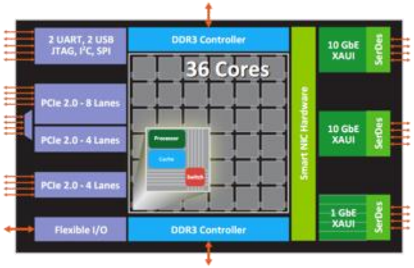


Tilera Tile-Gx

http://download.intel.com/pressroom/images/Aubrey_Isle_die.jpg http://www.zdnet.com/amds-trinity-processors-take-on-intels-ivy-bridge-3040155225/
http://insidehpc.com/2010/11/26/nvidia-reveals-details-of-echelon-gpu-designs-for-exascale/ http://tilera.com/sites/default/files/productbriefs/Tile-Gx%203036%20SB012-01.pdf

General Characteristics of These Architectures



- Increased hierarchy and/or sensitivity to locality
- Potentially heterogeneous processor/memory types

⇒ Next-gen programmers will have a lot more to think about at the node level than in the past

(“Glad I’m not an HPC Programmer!”)

A Possible Reaction:

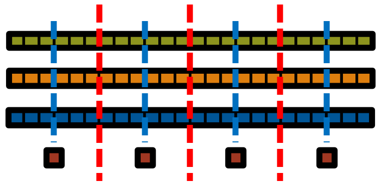
“This is all well and good for HPC users, but I’m a mainstream desktop programmer, so this is all academic for me.”

The Unfortunate Reality:

- Performance-minded mainstream programmers will increasingly need to deal with parallelism and locality too

STREAM Triad: MPI+OpenMP vs. CUDA

MPI + OpenMP



```
#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 (%d).\n", VectorSize );
      fclose( outFile );
    }
    return 1;
  }

#ifdef _OPENMP
#pragma omp paralle
#endif
  for (j=0; j<Vecto
    b[j] = 2.0;
    c[j] = 0.0;
  }

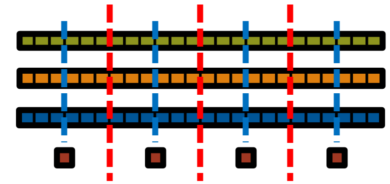
  scalar = 3.0;

#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;
}
```

CUDA



```
#define N       2000000

int main() {
  float *d_a, *d_b, *d_c;
  float scalar;

  cudaMalloc((void**)&d_a, sizeof(float)*N);
  cudaMalloc((void**)&d_b, sizeof(float)*N);
  cudaMalloc((void**)&d_c, sizeof(float)*N);

  dim3 dimBlock(128);
  dim3 dimGrid(N/dimBlock.x );
  if( N % dimBlock.x != 0 ) dimGrid

  set_array<<<dimGrid,dimBlock>>>(d_b, .5f, N);
  set_array<<<dimGrid,dimBlock>>>(d_c, .5f, N);

  scalar=3.0f;
  STREAM_Triad<<<dimGrid,dimBlock>>>(d_b, d_c, d_a, scalar,  N);
  cudaThreadSynchronize();

  cudaFree(d_a);
  cudaFree(d_b);

                                                  int len) {
  int idx = threadIdx.x + blockIdx.x * blockDim.x;
  if (idx < len) a[idx] = value;
}

__global__ void STREAM_Triad( float *a, float *b, float *c,
                              float scalar, int len) {
  int idx = threadIdx.x + blockIdx.x * blockDim.x;
  if (idx < len) c[idx] = a[idx]+scalar*b[idx];
}
```

HPC suffers from too many distinct notations for expressing parallelism and locality

(Consider how much more different these would be if we were actually doing something interesting, like a stencil!)

Why so many programming models?

HPC has traditionally given users…

…low-level, *control-centric* programming models

…ones that are closely tied to the underlying hardware

…ones that support only a single type of parallelism

Type of HW Parallelism	Programming Model	Unit of Parallelism
Inter-node	MPI	executable
Intra-node/multicore	OpenMP/pthreads	iteration/task
Instruction-level vectors/threads	pragmas	iteration
GPU/accelerator	CUDA/OpenCL/OpenACC	SIMD function/task

benefits: lots of control; decent generality; easy to implement

downsides: lots of user-managed detail; brittle to changes

By Analogy: Let's Cross the United States!

OK, got my walking shoes on!

OK, let's upgrade to hiking boots

Oops, need my ice axe

I guess we need a canoe?!

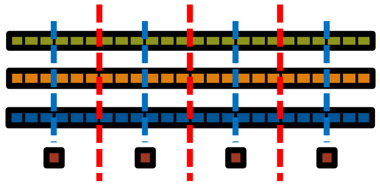
What a bunch of gear we have to carry around! This is getting old…

By Analogy: Let's Cross the United States!

…Hey, what's that sound?

Rewinding a few slides…

MPI + OpenMP



```
#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 (%d).\n", VectorSize );
      fclose( outFile );
    }
    return 1;
  }

#ifdef _OPENMP
#pragma omp parallel for
#endif
  for (j=0; j<VectorSize; j++) {
    b[j] = 2.0;
    c[j] = 0.0;
  }

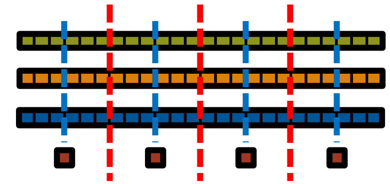
  scalar = 3.0;

#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;
}
```

CUDA



```
#define N       2000000

int main() {
  float *d_a, *d_b, *d_c;
  float scalar;

  cudaMalloc((void**)&d_a, sizeof(float)*N);
  cudaMalloc((void**)&d_b, sizeof(float)*N);
  cudaMalloc((void**)&d_c, sizeof(float)*N);

  dim3 dimBlock(128);
  dim3 dimGrid(N/dimBlock.x );
  if( N % dimBlock.x != 0 ) dimGrid

  set_array<<<dimGrid,dimBlock>>>(d_b, .5f, N);
  set_array<<<dimGrid,dimBlock>>>(d_c, .5f, N);

  scalar=3.0f;
  STREAM_Triad<<<dimGrid,dimBlock>>>(d_b, d_c, d_a, scalar,  N);
  cudaThreadSynchronize();

  cudaFree(d_a);
  cudaFree(d_b);
  cudaFree(d_c);


__global__ void set_array(float *a,  float value, int len) {
  int idx = threadIdx.x + blockIdx.x * blockDim.x;
  if (idx < len) a[idx] = value;
}

__global__ void STREAM_Triad( float *a, float *b, float *c,
                              float scalar, int len) {
  int idx = threadIdx.x + blockIdx.x * blockDim.x;
  if (idx < len) c[idx] = a[idx]+scalar*b[idx];
}
```

HPC suffers from too many distinct notations for expressing parallelism and locality

STREAM Triad: Chapel

MPI + OpenMP

Chapel

```
config const m = 1000,
             alpha = 3.0;

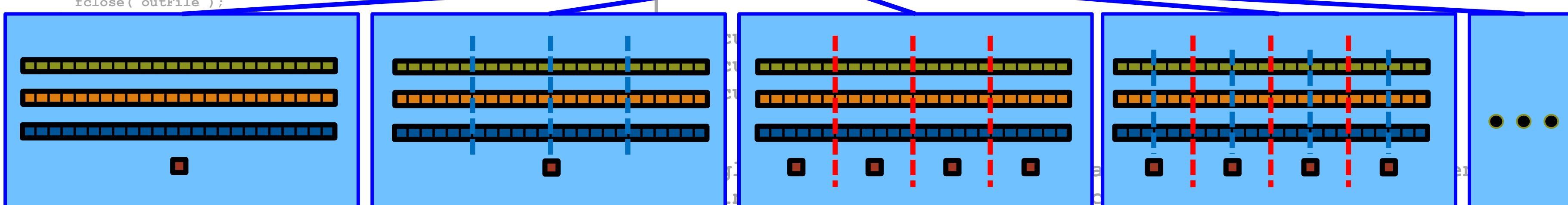
const ProblemSpace = {1..m} dmapped …;

var A, B, C: [ProblemSpace] real;

B = 2.0;
C = 3.0;

A = B + alpha * C;
```

the special sauce



<u>Philosophy:</u> Good language design can tease details of locality and parallelism away from an algorithm, permitting the compiler, runtime, applied scientist, and HPC expert to each focus on their strengths.

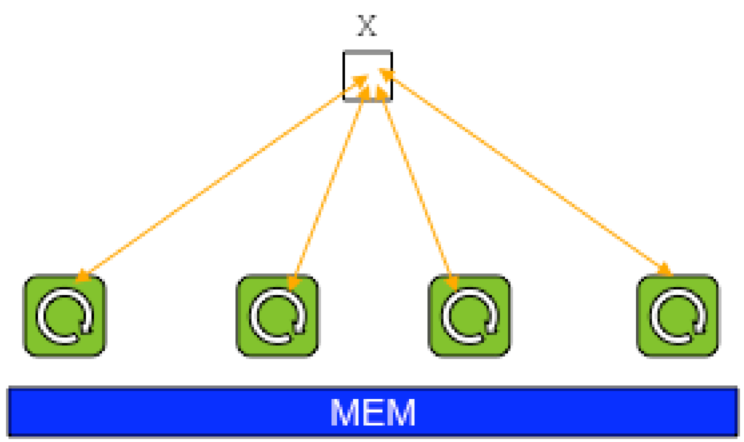
Outline

- ✓ Setting
- ✓ Chapel By Example: Jacobi Stencil
- ✓ Multiresolution Philosophy: Domain Maps and such
- ✓ Chapel Motivation
- ➢ Parallel Programming Model Taxonomy, Pluses/Minuses
- Chapel Motivating Themes
- Survey of Chapel Concepts
- Compiling Chapel
- Project Status and Next Steps

Global Address Space Programming Models (Shared Memory)

e.g., OpenMP, Pthreads

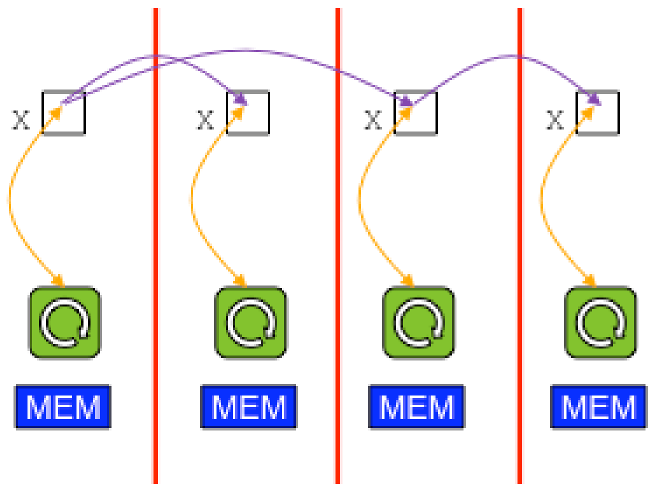
+ support dynamic, fine-grain parallelism
+ considered simpler, more like traditional programming
  - "if you want to access something, simply name it"
– no support for expressing locality/affinity; limits scalability
– bugs can be subtle, difficult to track down (race conditions)
– tend to require complex memory consistency models



Message Passing Programming Models (Distributed Memory)

e.g., MPI

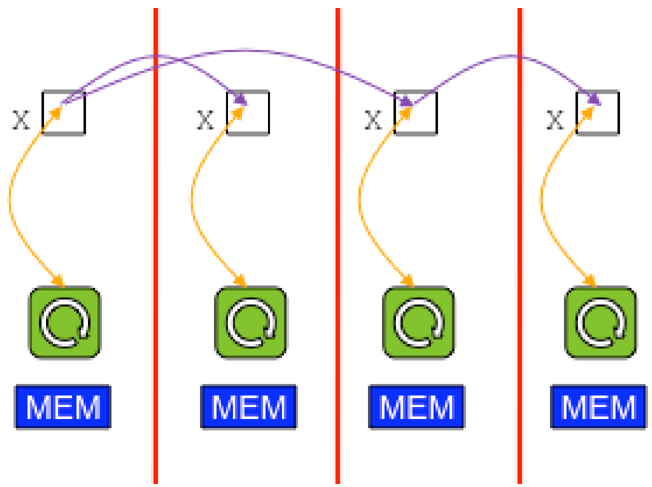
+ a more constrained model; can only access local data
+ runs on most large-scale parallel platforms
  - and for many of them, can achieve near-optimal performance
+ is *relatively* easy to implement
+ can serve as a strong foundation for higher-level models
+ users have been able to get real work done with it



Message Passing Programming Models (Distributed Memory)

e.g., MPI

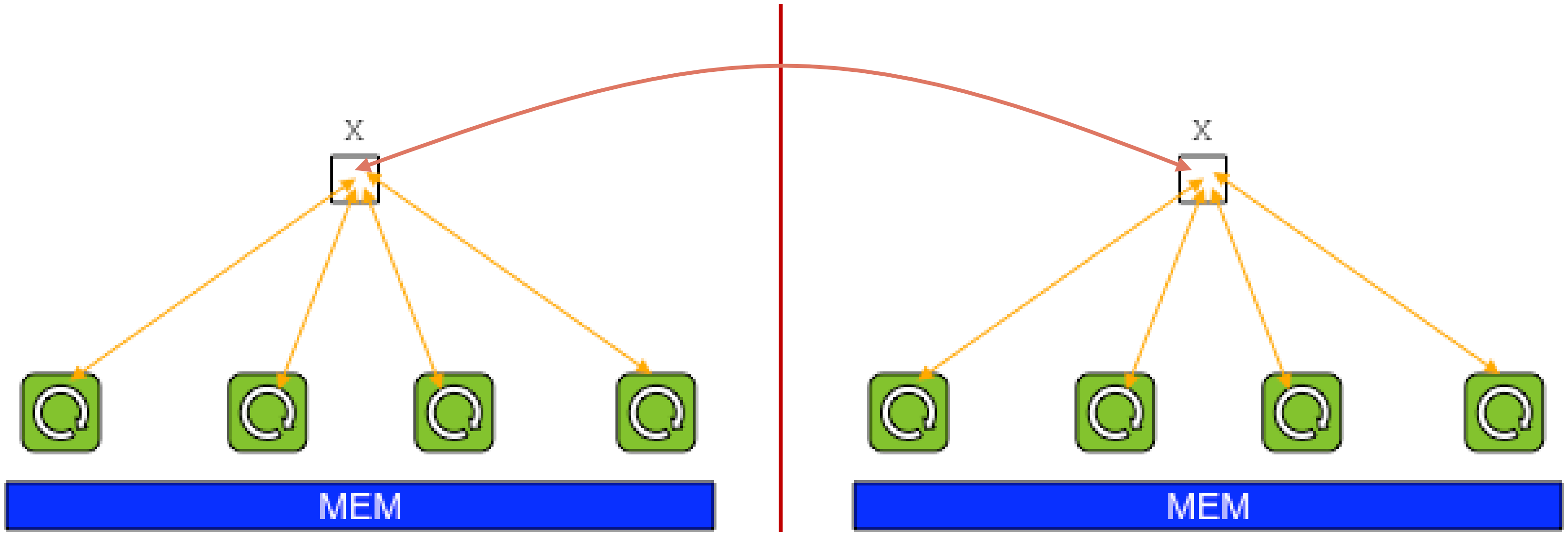
- communication must be used to get copies of remote data
  - tends to reveal too much about *how* to transfer data, not simply *what*
- only supports "cooperating executable"-level parallelism
- couples data transfer and synchronization
- has frustrating classes of bugs of its own
  - e.g., mismatches between sends/recvs, buffer overflows, etc.



Hybrid Programming Models

_e.g._, MPI+OpenMP/Pthreads/CUDA, UPC+OpenMP, …

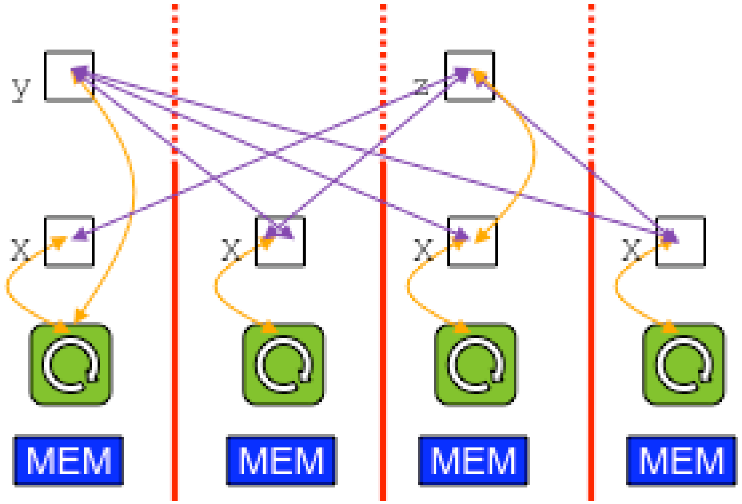
+ supports a division of labor: each handles what it does best
+ permits overheads to be amortized across processor cores, as compared to using MPI alone
– requires multiple notations to express a single logical parallel algorithm, each with its own distinct semantics



Traditional PGAS Languages

e.g., Co-Array Fortran, UPC

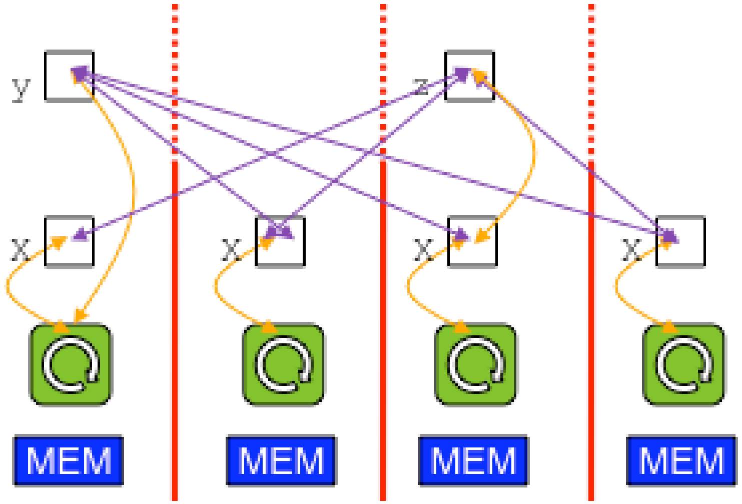
- support a shared namespace, like shared-memory
- support a strong sense of ownership and locality
  - each variable is stored in a particular memory segment
  - tasks can access any visible variable, local or remote
  - local variables are cheaper to access than remote ones
- implicit communication eases user burden; permits compiler to use best mechanisms available



Traditional PGAS Languages

e.g., Co-Array Fortran, UPC

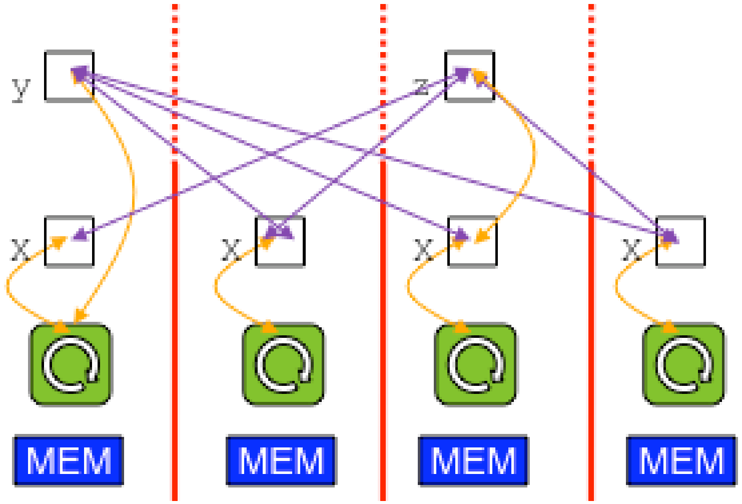
- restricted to SPMD programming and execution models
- data structures not as flexible/rich as one might like
- retain many of the downsides of shared-memory
  - error cases, memory consistency models



Next-Generation PGAS Languages

e.g., Chapel (also Charm++, X10, Fortress, …)

+ breaks out of SPMD mold via global multithreading
+ richer set of distributed data structures
– retains many of the downsides of shared-memory
  - error cases, memory consistency models



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Motivating Chapel Themes

1) General Parallel Programming
2) Global-View Abstractions
3) Multiresolution Design
4) Control over Locality/Affinity
5) Reduce HPC ↔ Mainstream Language Gap

1) General Parallel Programming

With a unified set of concepts...

...express any parallelism desired in a user's program

- **Styles:** data-parallel, task-parallel, concurrency, nested, …
- **Levels:** model, function, loop, statement, expression

...target any parallelism available in the hardware

- **Types:** machines, nodes, cores, instructions

Type of HW Parallelism	Programming Model	Unit of Parallelism
Inter-node	MPI	executable
Intra-node/multicore	OpenMP/pthreads	iteration/task
Instruction-level vectors/threads	pragmas	iteration
GPU/accelerator	CUDA/OpenCL/OpenACC	SIMD function/task

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Inter-node	Chapel	executable/task
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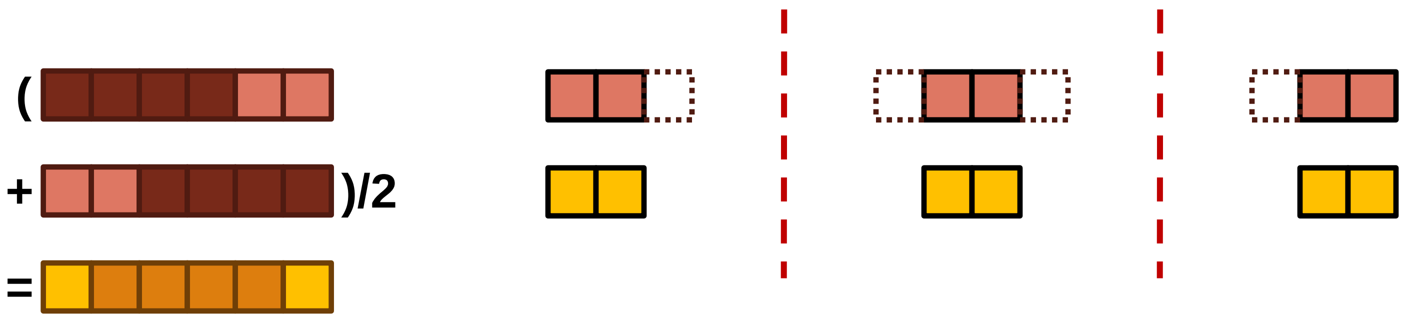
2) Global-View Abstractions

In pictures: "Apply a 3-Point Stencil to a vector"

Global-View *Local-View*



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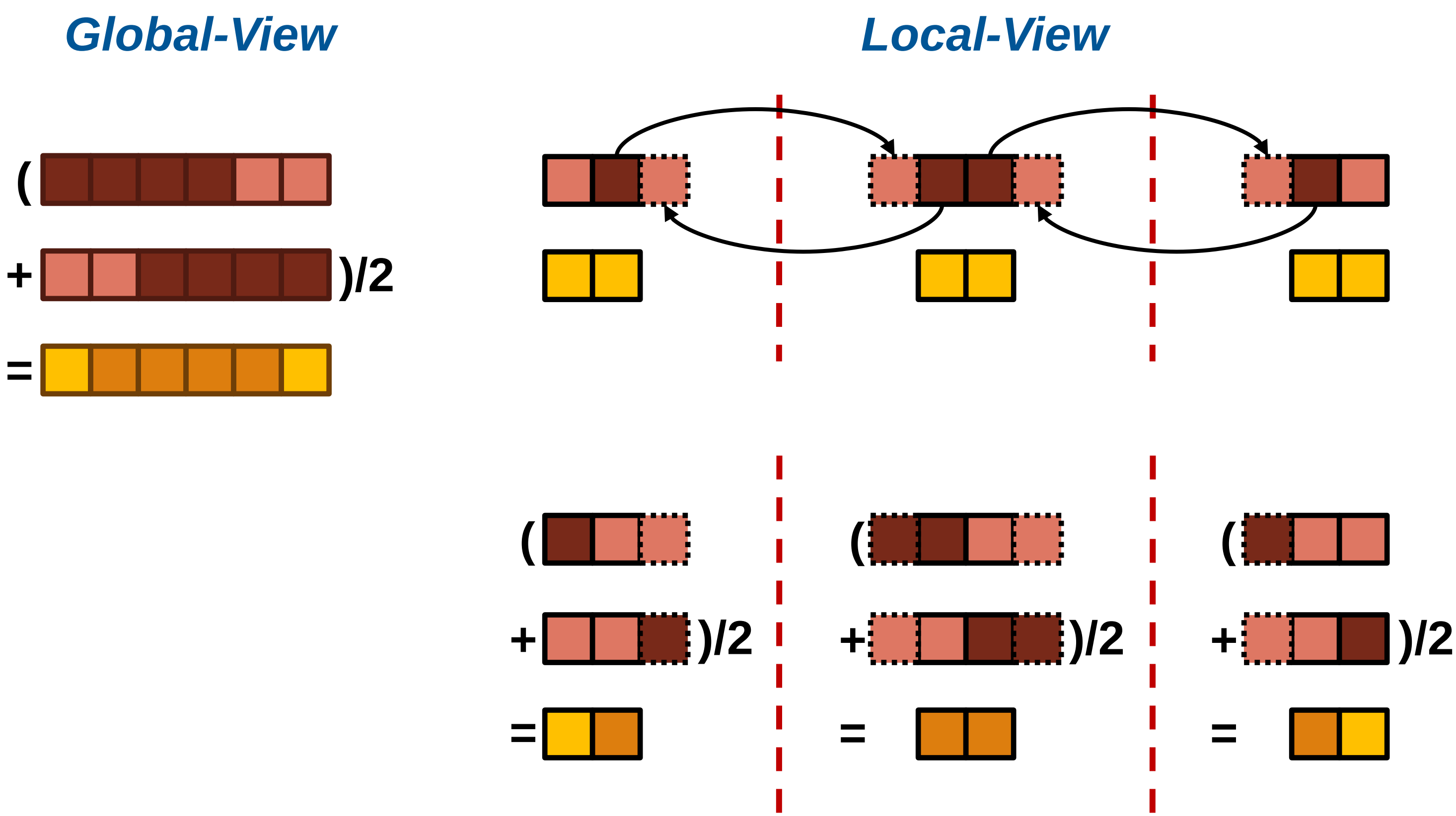

2) Global-View Abstractions

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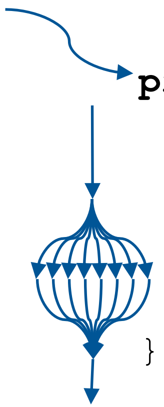
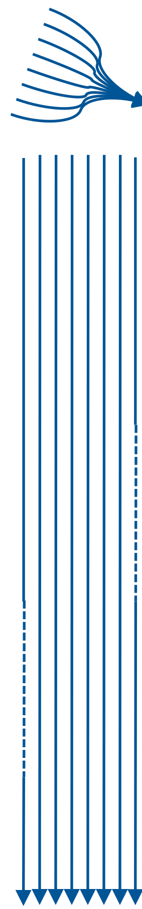
Global-View



```
proc main() {
  var n = 1000;
  var A, B: [1..n] real;

  forall i in 2..n-1 do
    B[i] = (A[i-1] + A[i+1])/2;
}
```

Local-View (SPMD)



```
proc main() {
  var n = 1000;
  var p = numProcs(),
      me = myProc(),
      myN = n/p,
  var A, B: [0..myN+1] real;

  if (me < p-1) {
    send(me+1, A[myN]);
    recv(me+1, A[myN+1]);
  }
  if (me > 0) {
    send(me-1, A[1]);
    recv(me-1, A[0]);
  }
  forall i in 1..myN do
    B[i] = (A[i-1] + A[i+1])/2;
}
```

Bug: Refers to uninitialized values at ends of A

2) Global-View Abstractions

In code: “Apply a 3-Point Stencil to a vector”

Global-View

```
proc main() {
  var n = 1000;
  var A, B: [1..n] real;

  forall i in 2..n-1 do
    B[i] = (A[i-1] + A[i+1])/2;
}
```

Communication becomes geometrically more complex for higher-dimensional arrays

Local-View (SPMD)

Assumes p divides n

```
proc main() {
  var n = 1000;
  var p = numProcs(),
      me = myProc(),
      myN = n/p,
      myLo = 1,
      myHi = myN;
  var A, B: [0..myN+1] real;

  if (me < p-1) {
    send(me+1, A[myN]);
    recv(me+1, A[myN+1]);
  } else
    myHi = myN-1;
  if (me > 0) {
    send(me-1, A[1]);
    recv(me-1, A[0]);
  } else
    myLo = 2;
  forall i in myLo..myHi do
    B[i] = (A[i-1] + A[i+1])/2;
}
```

2) Global-View Programming: A Final Note

- A language may support both global- and local-view programming — in particular, Chapel does

```
proc main() {
  coforall loc in Locales do
    on loc do
      MySPMDProgram(loc.id, Locales.numElements);

}

proc MySPMDProgram(myImageID, numImages) {
  ...
}
```

4) Control over Locality/Affinity

Consider:

- Scalable architectures package memory near processors
- Remote accesses take longer than local accesses

Therefore:

- Placement of data relative to tasks affects scalability
- Give programmers control of data and task placement

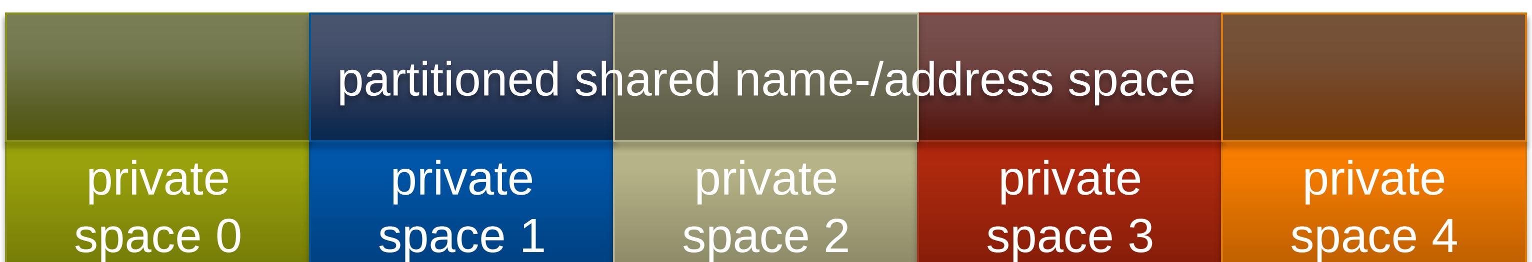
Note:

- Over time, we expect locality to matter more and more within the compute node as well

Partitioned Global Address Space (PGAS) Languages

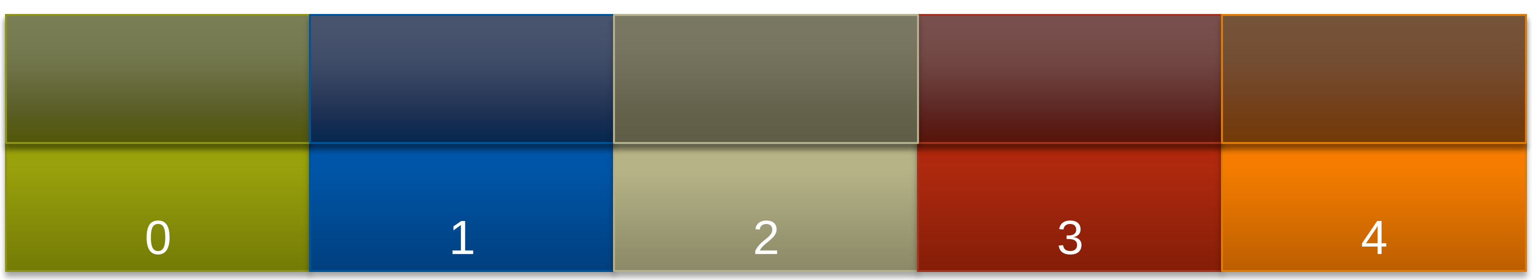
(Or perhaps: partitioned global namespace languages)

- **abstract concept:**
  - support a shared namespace on distributed memory
    - permit parallel tasks to access remote variables by naming them
  - establish a strong sense of ownership
    - every variable has a well-defined location
    - local variables are cheaper to access than remote ones
- **traditional PGAS languages have been SPMD in nature**
  - best-known examples: Co-Array Fortran, UPC



Chapel and PGAS

- **Chapel is PGAS, but unlike most, it's not restricted to SPMD**
  ⇒ never think about "the other copies of the program"
  ⇒ "global name/address space" comes from lexical scoping
    - as in traditional languages, each declaration yields one variable
    - variables are stored on the locale where the task declaring it is executing



Locales (think: "compute nodes")

5) Reduce HPC ↔ Mainstream Language Gap

Consider:

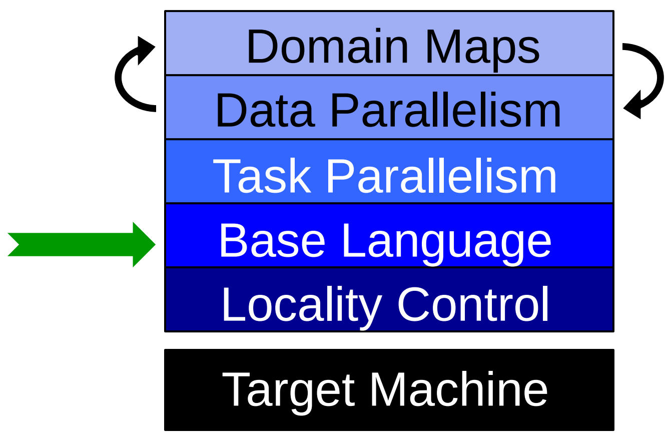
- Students graduate with training in Java, Matlab, Python, etc.
- Yet HPC programming is dominated by Fortran, C/C++, MPI

We'd like to narrow this gulf with Chapel:

- to leverage advances in modern language design
- to better utilize the skills of the entry-level workforce...
- ...while not alienating the traditional HPC programmer
  - e.g., support object-oriented programming, but make it optional

Outline

- ✓ Blah blah blah
- ✓ Blah blah blah
- ➢ Survey of Chapel Concepts



- Blah blah blah

Static Type Inference

```
const pi = 3.14,               // pi is a real
      coord = 1.2 + 3.4i,      // coord is a complex…
      coord2 = pi*coord,       // …as is coord2
      name = “brad”,           // name is a string
      verbose = false;         // verbose is boolean

proc addem(x, y) {             // addem() has generic arguments
  return x + y;                //   and an inferred return type
}

var sum = addem(1, pi),                  // sum is a real
    fullname = addem(name, “ford”);      // fullname is a string

writeln((sum, fullname));
```

```
(4.14, bradford)
```

Range Types and Algebra

```
const r = 1..10;

printVals(r);
printVals(r # 3);
printVals(r by 2);
printVals(r by -2);
printVals(r by 2 # 3);
printVals(r # 3 by 2);
printVals(0.. #n);

proc printVals(r) {
  for i in r do
    write(r, " ");
  writeln();
}
```

```
1 2 3 4 5 6 7 8 9 10
1 2 3
1 3 5 7 9
10 8 6 4 2
1 3 5
1 3
0 1 2 3 4 … n-1
```

Iterators

```
iter fibonacci(n) {
  var current = 0,
      next = 1;
  for 1..n {
    yield current;
    current += next;
    current <=> next;
  }
}
```

```
for f in fibonacci(7) do
  writeln(f);
```

```
0
1
1
2
3
5
8
```

```
iter tiledRMO(D, tilesize) {
  const tile = {0..#tilesize,
                0..#tilesize};
  for base in D by tilesize do
    for ij in D[tile + base] do
      yield ij;
}
```

```
for ij in tiledRMO({1..m, 1..n}, 2) do
  write(ij);
```

```
(1,1)(1,2)(2,1)(2,2)
(1,3)(1,4)(2,3)(2,4)
(1,5)(1,6)(2,5)(2,6)
…
(3,1)(3,2)(4,1)(4,2)
```

Zippered Iteration

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

```
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
…
```

Other Base Language Features

- tuple types and values
- rank-independent programming features
- interoperability features
- compile-time features for meta-programming
  - e.g., compile-time functions to compute types, parameters
- OOP (value- and reference-based)
- argument intents, default values, match-by-name
- overloading, where clauses
- modules (for namespace management)
- …

Outline

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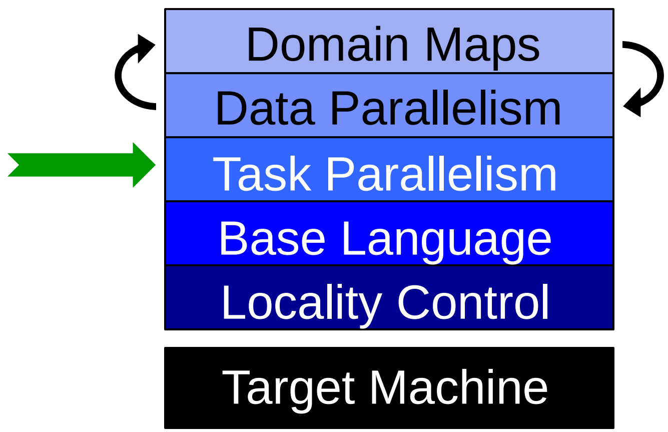

- Blah blah blah

Defining our Terms

Task: a unit of computation that can/should execute in parallel with other tasks

Task Parallelism: a style of parallel programming in which parallelism is driven by programmer-specified tasks

(in contrast with):

Data Parallelism: a style of parallel programming in which parallelism is driven by computations over collections of data elements or their indices

Task Parallelism: Begin Statements

```
// create a fire-and-forget task for a statement
begin writeln("hello world");
writeln("goodbye");
```

Possible outputs:

```
hello world
goodbye
```

```
goodbye
hello world
```

Task Parallelism: Coforall Loops

```
// create a task per iteration
coforall t in 0..#numTasks {
  writeln("Hello from task ", t, " of ", numTasks);
} // implicit join of the numTasks tasks here

writeln("All tasks done");
```

Sample output:

```
Hello from task 2 of 4
Hello from task 0 of 4
Hello from task 3 of 4
Hello from task 1 of 4
All tasks done
```

Task Parallelism: Data-Driven Synchronization

1) ***atomic variables:*** support atomic operations (as in C++)
- e.g., compare-and-swap; atomic sum, mult, etc.

2) ***single-assignment variables:*** reads block until assigned

3) ***synchronization variables:*** store full/empty state
- by default, reads/writes block until the state is full/empty

Outline

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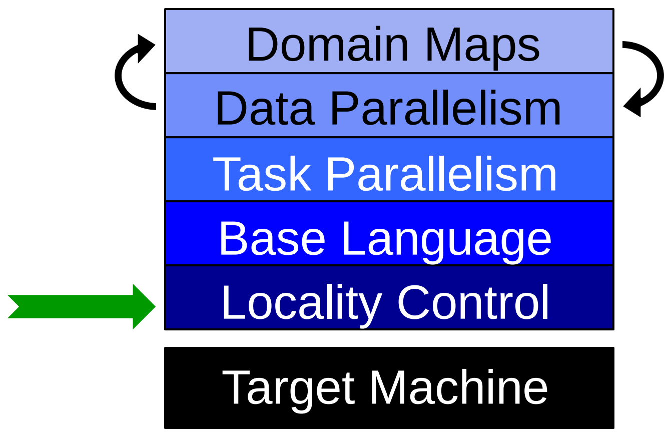

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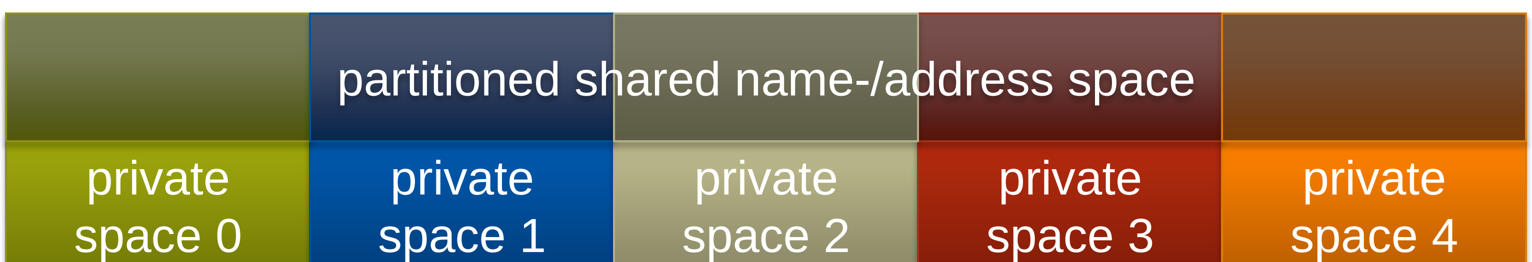

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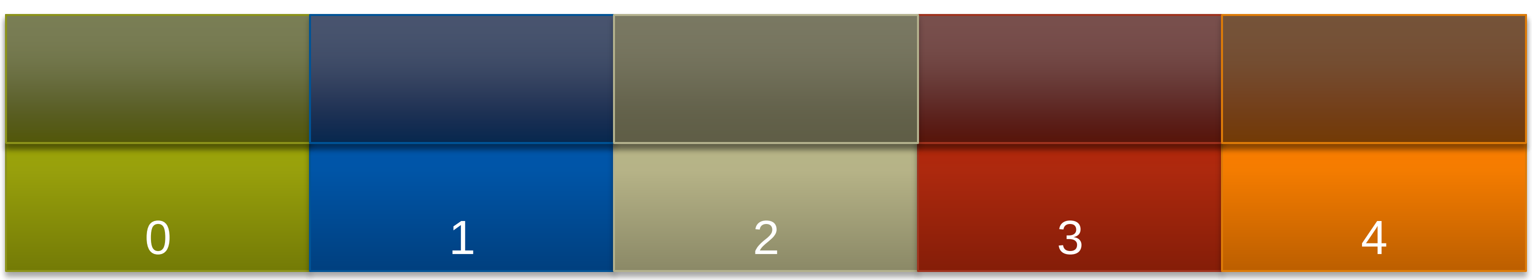
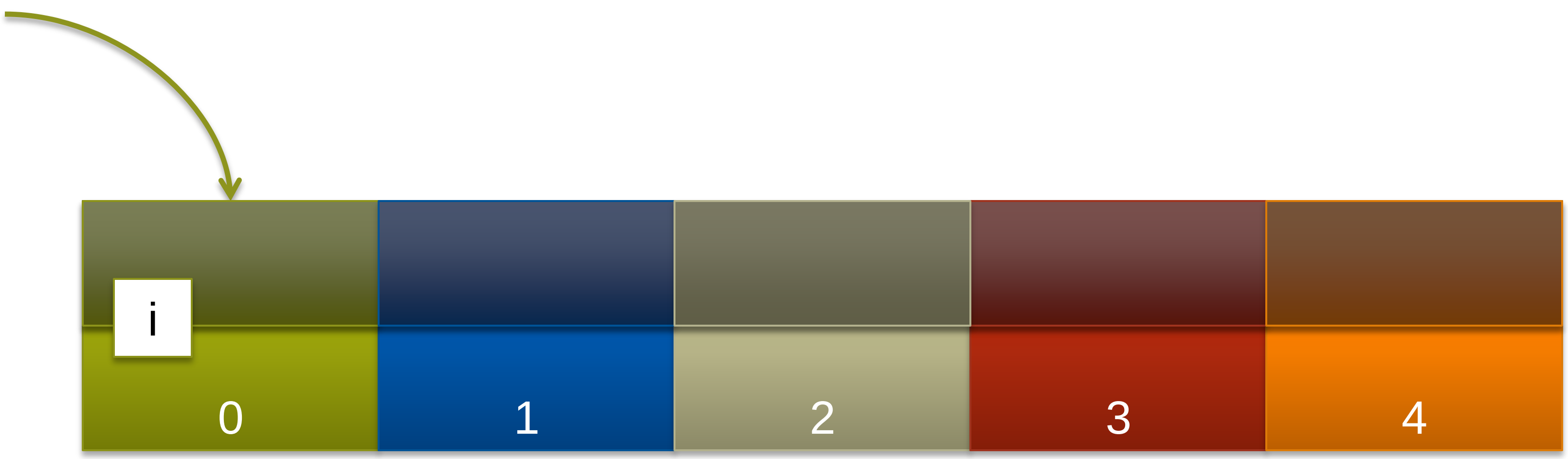


Locales (think: "compute nodes")

Chapel: Scoping and Locality

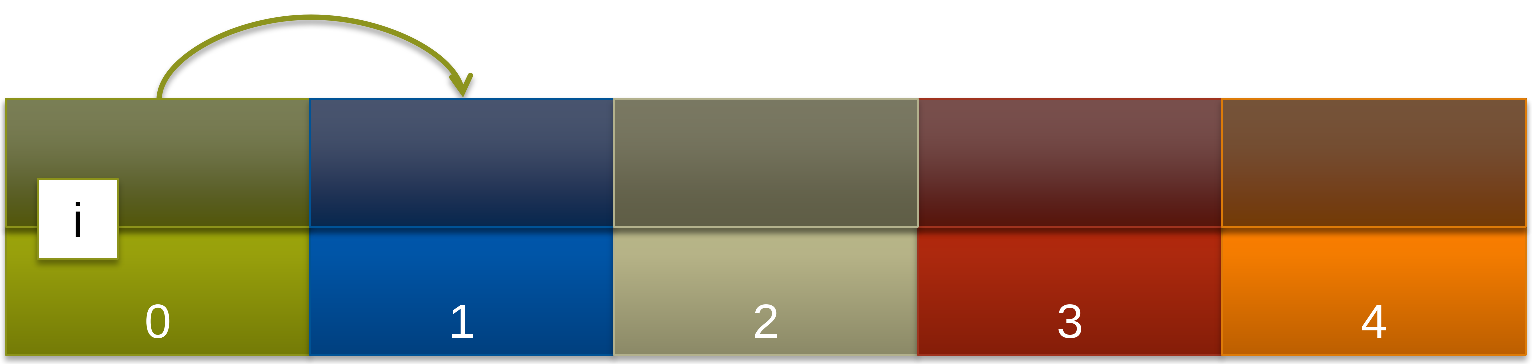
```
var i: int;
```



Locales (think: “compute nodes”)

Chapel: Scoping and Locality

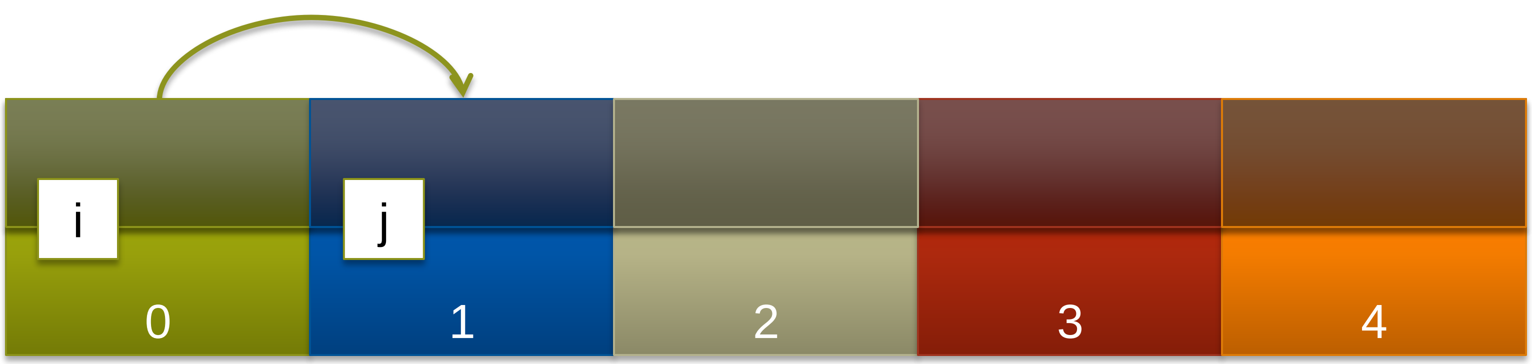
```
var i: int;
on Locales[1] {
```



Locales (think: "compute nodes")

Chapel: Scoping and Locality

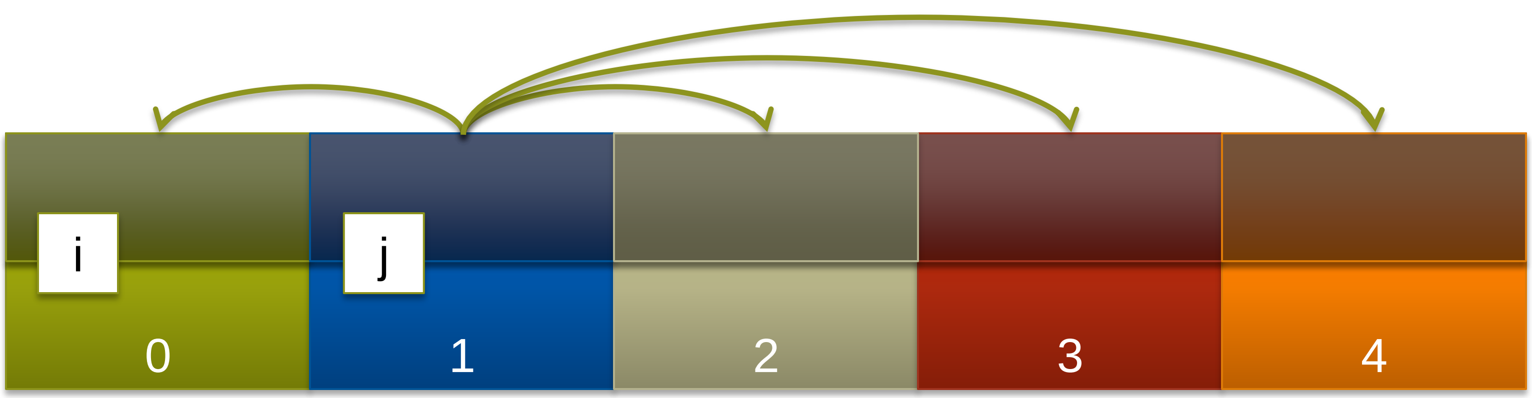
```
var i: int;
on Locales[1] {
  var j: int;
```



Locales (think: "compute nodes")

Chapel: Scoping and Locality

```
var i: int;
on Locales[1] {
  var j: int;
  coforall loc in Locales {
    on loc {
```

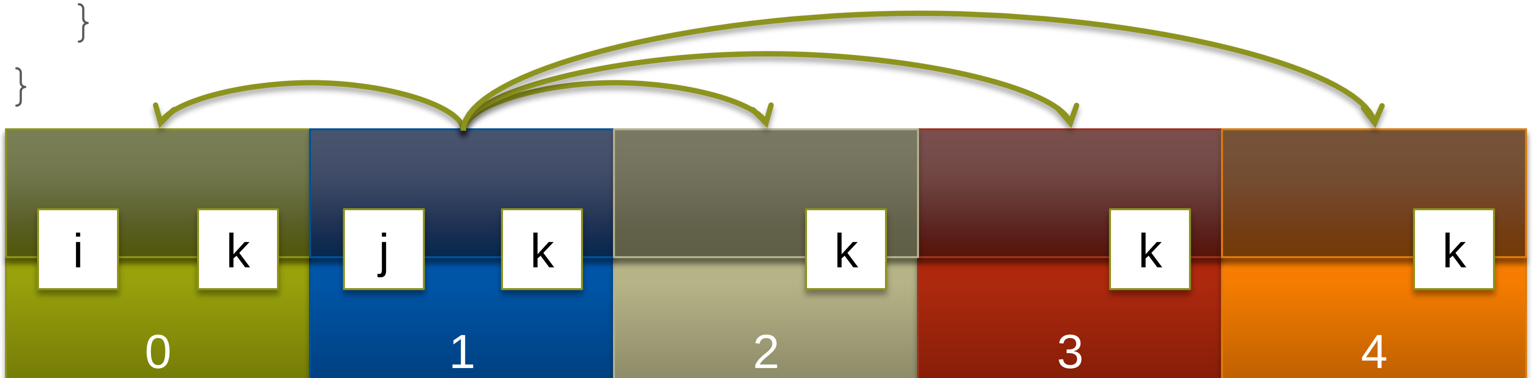


Locales (think: "compute nodes")

Chapel: Scoping and Locality

```
var i: int;
on Locales[1] {
  var j: int;
  coforall loc in Locales {
    on loc {
      var k: int;

      // within this scope, i, j, and k can be referenced;
      // the implementation manages the communication for i and j
    }
  }
}
```



Locales (think: “compute nodes”)

The Locale Type

Definition:

- Abstract unit of target architecture
- Supports reasoning about locality
  - defines “here vs. there” / “local vs. remote”
- Capable of running tasks and storing variables
  - i.e., has processors and memory

Typically: A compute node (multicore processor or SMP)

Getting started with locales

- **Specify # of locales when running Chapel programs**

```
% a.out --numLocales=8
```

```
% a.out -nl 8
```

- **Chapel provides built-in locale variables**

```
config const numLocales: int = …;
const Locales: [0..#numLocales] locale = …;
```

Locales

L0	L1	L2	L3	L4	L5	L6	L7

- **User's `main()` begins executing on locale #0**

Locale Operations

- Locale methods support queries about the target system:

```
proc locale.physicalMemory(…) { … }
proc locale.numCores { … }
proc locale.id { … }
proc locale.name { … }
```

- *On-clauses* support placement of computations:

```
writeln("on locale 0");

on Locales[1] do
  writeln("now on locale 1");

writeln("on locale 0 again");
```

```
begin on A[i,j] do
    bigComputation(A);

begin on node.left do
    search(node.left);
```

Parallelism and Locality: Orthogonal in Chapel

- **This is a parallel, but local program:**

```
begin writeln("Hello world!");
writeln("Goodbye!");
```

- **This is a distributed, but serial program:**

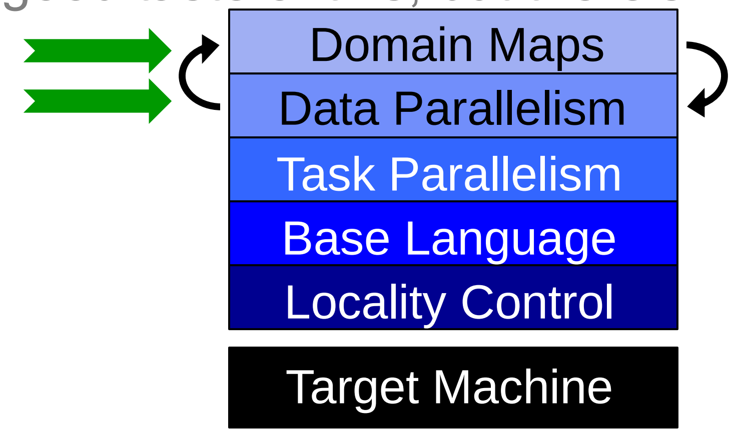
```
writeln("Hello from locale 0!");
on Locales[1] do writeln("Hello from locale 1!");
writeln("Goodbye from locale 0!");
```

- **This is a distributed, parallel program:**

```
begin on Locales[1] do writeln("Hello from locale 1!");
on Locales[2] do begin writeln("Hello from locale 2!");
writeln("Goodbye from locale 0!");
```

Outline

- ✓ Blah blah blah
- ✓ Blah blah blah
- **Survey of Chapel Concepts**
  - You've had a good taste of this, but there's more as well…



- [Compiling Chapel]

Notes on Forall Loops

```
forall a in A do
  writeln("Here is an element of A: ", a);
```

Typically:
- 1 ≤ #Tasks << #Iterations
- #Tasks ≈ amount of HW parallelism

```
forall (a, i) in zip(A, 1..n) do
  a = i / 10.0;
```

Like for loops, forall-loops may be zippered, and corresponding iterations will match up

Promotion Semantics

Promoted functions/operators are defined in terms of zippered forall loops in Chapel. For example…

```
A = B;
```

…is equivalent to:

```
forall (a,b) in zip(A,B) do
  a = b;
```

Impact of Zippered Promotion Semantics

Whole-array operations are implemented element-wise…

```
A = B + alpha * C;
```

⇒

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

…rather than operator-wise.

```
A = B + alpha * C;
```

~~⇒~~

```
T1 = alpha * C;
A = B + T1;
```

⇒ No temporary arrays required by semantics

- ⇒ No surprises in memory requirements
- ⇒ Friendlier to cache utilization

⇒ Differs from traditional array language semantics

```
A[D] = A[D-one] + A[D+one];
```

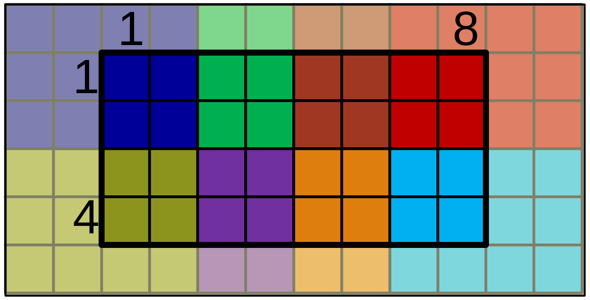
⇒

```
forall (a1, a2, a3)
  in (A[D], A[D-one], A[D+one]) do
    a1 = a2 + a3;
```

Read/write race!

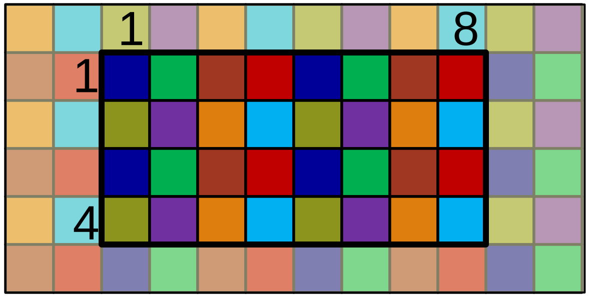
Sample Distributions: Block and Cyclic

```
var Dom = {1..4, 1..8} dmapped Block( {1..4, 1..8} );
```



distributed to


```
var Dom = {1..4, 1..8} dmapped Cyclic( startIdx=(1,1) );
```



distributed to

Domain Map Descriptors

Domain Map

Represents: a domain map value

Generic w.r.t.: index type

State: the domain map's representation

Typical Size: Θ(1)

Required Interface:
- create new domains

Domain

Represents: a domain

Generic w.r.t.: index type

State: representation of index set

Typical Size: Θ(1) → Θ(*numIndices*)

Required Interface:
- create new arrays
- queries: size, members
- iterators: serial, parallel
- domain assignment
- index set operations

Array

Represents: an array

Generic w.r.t.: index type, element type

State: array elements

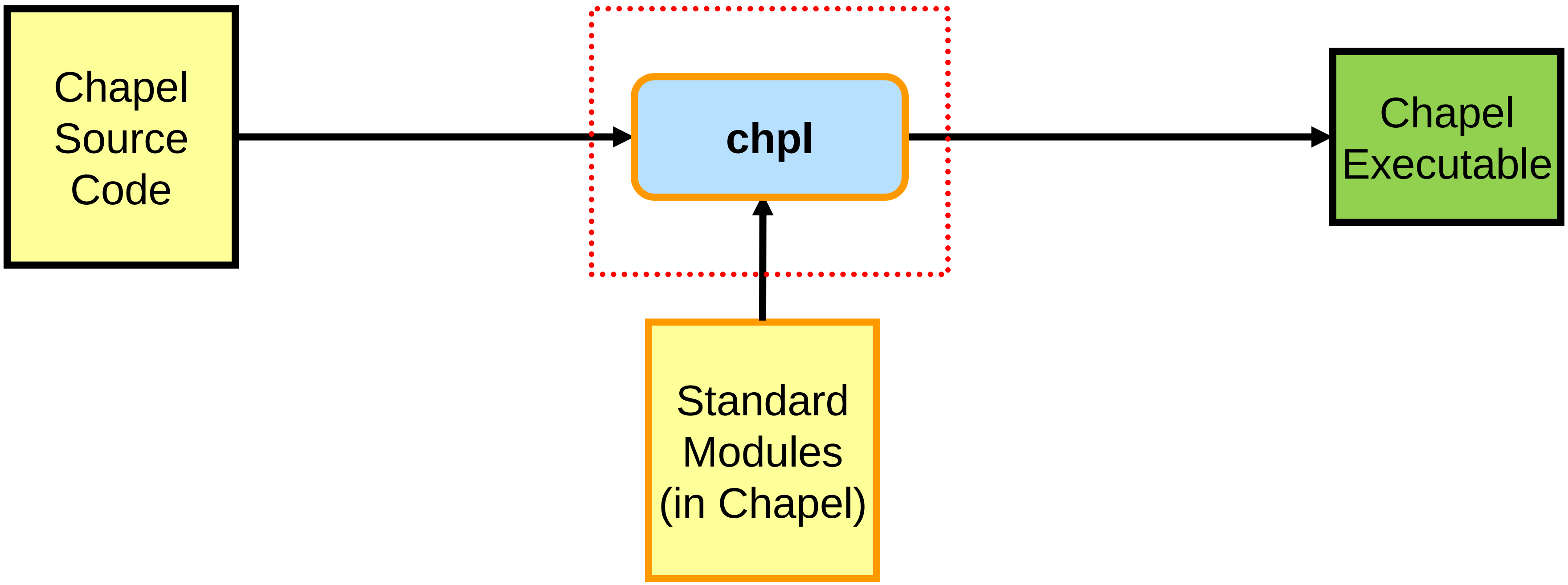
Typical Size: Θ(*numIndices*)

Required Interface:
- (re-)allocation of elements
- random access
- iterators: serial, parallel
- slicing, reindexing, aliases
- get/set of sparse "zero" values

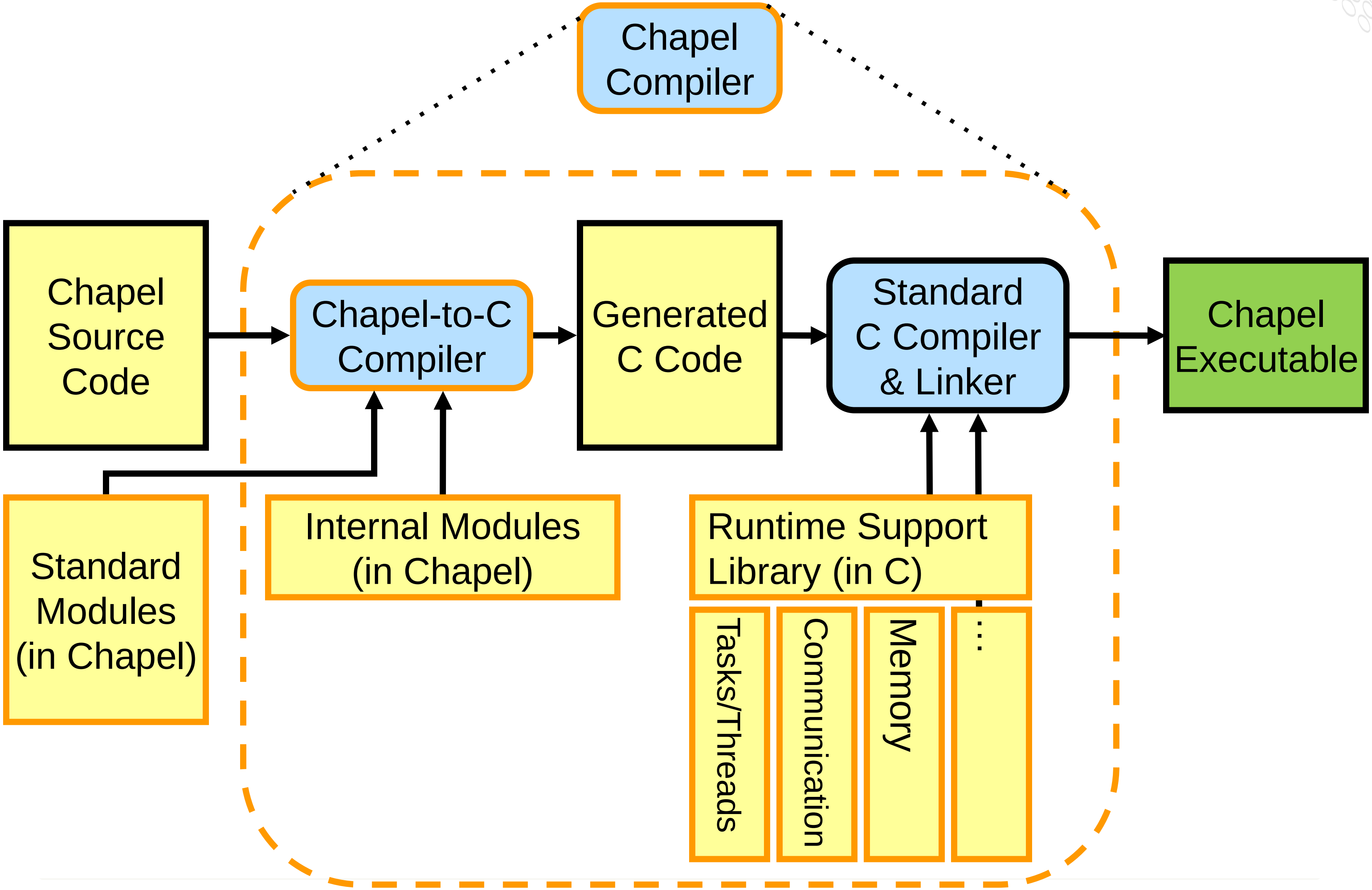
Outline

- ✓ Setting
- ✓ Chapel By Example: Jacobi Stencil
- ✓ Multiresolution Philosophy: Domain Maps and such
- ✓ Chapel Motivation
- ✓ Parallel Programming Model Taxonomy, Pluses/Minuses
- ✓ Chapel Motivating Themes
- ✓ Survey of Chapel Concepts
- ➢ Compiling Chapel
- Project Status and Next Steps

Compiling Chapel



Chapel Compiler Architecture



Key Compiler Passes Required by Chapel

- **Transform higher-level Chapel constructs to C**
  - iterators
  - overloading, classes, generics, where clauses, tuples, …
- **Transform parallel constructs to C routines**
- **Transform on-clauses to C routines**

Key Compiler Analyses Required by Chapel

- **Static type inference + Function Resolution**
- **Multiresolution Optimizations**
  - Given plug-in nature of…
    - domain maps
    - parallel iterators
    - locale models

    …how to get performance competitive with C/Fortran?
- **Locality Analysis (in the "locale" sense)**
  - What might be referred to remotely? What is known to be local?
- **Communication Optimizations**
  - Overlap of communication and computation to hide latency
  - Combining similar/Eliminating redundant communications
  - (still haven't caught up to ZPL work, in this regard)
- **Plus, traditional optimizations (LICM, DCE, scalar repl., …)**

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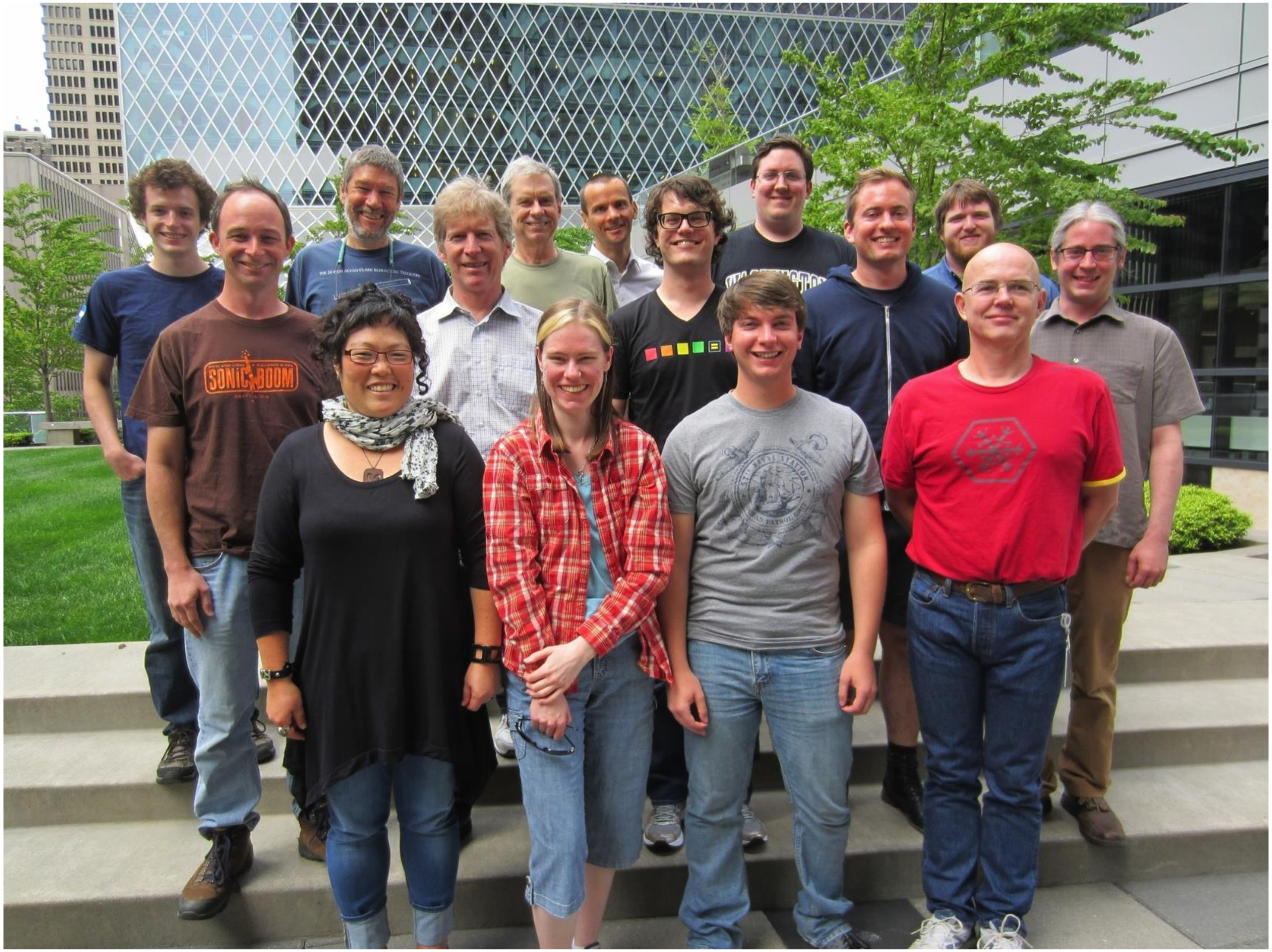
The Cray Chapel Team (Summer 2014)



Chapel…

…is a collaborative effort — join us!

A Year in the Life of Chapel

- **Two major releases per year** (April / October)
  - **latest release:** version 1.11, April 2nd, 2015
  - **~a month later:** detailed release notes
    - version 1.11 release notes: http://chapel.cray.com/download.html#releaseNotes

- **CHIUW:** Chapel Implementers and Users Workshop (May-June)
  - workshop focusing on community efforts, code camps
  - this year will be held in Portland, June 13-14

- **SC** (Nov)
  - the primary conference for the HPC industry
  - we give tutorials, BoFs, talks, etc. to show off year's work

- **Talks, tutorials, research visits, blogs, …** (year-round)

Implementation Status -- Version 1.11 (Apr 2015)

Overall Status:

- **User-facing Features:** generally in good shape
  - some require additional attention (e.g., strings, memory mgmt)
- **Multiresolution Features:** in use today
  - their interfaces are likely to continue evolving over time
- **Error Messages:** not always as helpful as one would like
  - correct code works well, incorrect code can be puzzling
- **Performance:** hit-or-miss depending on the idioms used
  - Chapel designed to ultimately support competitive performance
  - to-date, we've focused primarily on correctness and local perf.

This is a great time to:

- Try out the language and compiler
- Use Chapel for non-performance-critical projects
- Give us feedback to improve Chapel
- Use Chapel for parallel programming education

Chapel and Education

- **When teaching parallel programming, I like to cover:**
  - data parallelism
  - task parallelism
  - concurrency
  - synchronization
  - locality/affinity
  - deadlock, livelock, and other pitfalls
  - performance tuning
  - …

- **I don't think there's been a good language out there…**
  - for teaching *all* of these things
  - for teaching *some* of these things well at all
  - ***until now:*** We believe Chapel can play a crucial role here

(see http://chapel.cray.com/education.html for more information and http://cs.washington.edu/education/courses/csep524/13wi/ for my use of Chapel in class)

Chapel: the five-year push

- **Harden prototype to production-grade**
  - add/improve lacking features
  - optimize performance
  - improve interoperability

- **Target more complex/modern compute node types**
  - e.g., Intel Phi, CPU+GPU, AMD APU, …

- **Continue to grow the user and developer communities**
  - including nontraditional circles: desktop parallelism, “big data”
  - transition Chapel from Cray-managed to community-governed

Summary

Higher-level programming models can help insulate algorithms from parallel implementation details

- yet, without necessarily abdicating control
- Chapel does this via its multiresolution design
  - here, we saw it principally in domain maps
    - parallel iterators and locale models are other examples
  - these avoid locking crucial policy decisions into the language

We believe Chapel can greatly improve productivity

…for current and emerging HPC architectures

…for emerging mainstream needs for parallelism and locality

For More Information: Online Resources

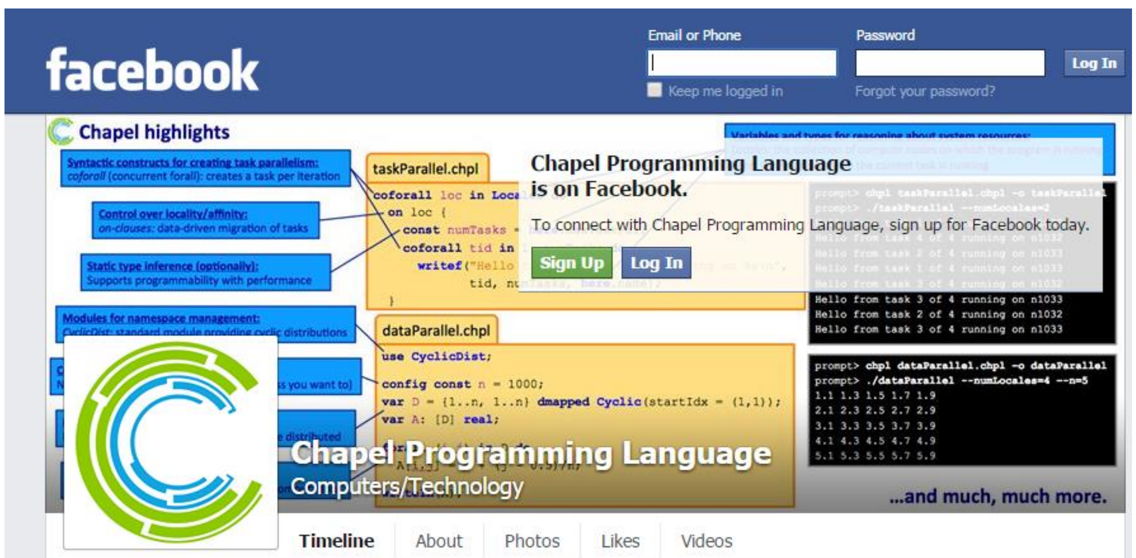
Chapel project page: http://chapel.cray.com

- overview, papers, presentations, language spec, …

Chapel GitHub page: https://github.com/chapel-lang

- download 1.11.0 release, browse source repository

Chapel Facebook page: https://www.facebook.com/ChapelLanguage



For More Information: Community Resources

Chapel SourceForge page: https://sourceforge.net/projects/chapel/

- join community mailing lists; alternative release download site

Mailing Aliases:

- chapel_info@cray.com: contact the team at Cray
- chapel-announce@lists.sourceforge.net: list for announcements only
- chapel-users@lists.sourceforge.net: user-oriented discussion list
- chapel-developers@lists.sourceforge.net: developer discussion
- chapel-education@lists.sourceforge.net: educator discussion
- chapel-bugs@lists.sourceforge.net: public bug forum

For More Information: Suggested Reading

Overview Papers:

- *A Brief Overview of Chapel*, Chamberlain (pre-print of a chapter for *A Brief Overview of Parallel Programming Models*, edited by Pavan Balaji, to be published by MIT Press in 2014).
  - *a detailed overview of Chapel's history, motivating themes, features*

- *The State of the Chapel Union* [slides], Chamberlain, Choi, Dumler, Hildebrandt, Iten, Litvinov, Titus. CUG 2013, May 2013.
  - *a higher-level overview of the project, summarizing the HPCS period*

For More Information: Lighter Reading

Blog Articles:

- *Chapel: Productive Parallel Programming*, Chamberlain, Cray Blog, May 2013.
  - *a short-and-sweet introduction to Chapel*

- *Why Chapel?* (part 1, part 2, part 3*)*, Chamberlain, Cray Blog, June-August 2014.
  - *a current series of articles answering common questions about why we are pursuing Chapel in spite of the inherent challenges*

- *[Ten] Myths About Scalable Programming Languages* (index available here), Chamberlain, IEEE TCSC Blog, April-November 2012.
  - *a series of technical opinion pieces designed to combat standard arguments against the development of high-level parallel languages*

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