Chapel:
A Domain-Specific Language for Productive Parallel Programming at Scale

Brad Chamberlain, Chapel Team, Cray Inc.

University of Washington, CSEP 590c

May 9th, 2016

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A ~~Domain-Specific~~ Language for Productive Parallel Programming at Scale

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Chapel:
An Extremely General Language for Productive Programming on Modern Systems

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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.

My Background

Affiliations:

- Graduated from UW in 2001
  (and remain associated with UW as an affiliate professor)
- Spent a lost but educational year at a start-up
- Have worked at Cray Inc. since Fall 2002

R&D topics:

- Focus primarily on parallel language design & implementation
  - **at UW:** on the ZPL data-parallel language
  - **at start-up:** on a language for reconfigurable embedded computing
  - **at Cray:** on Chapel
- Most of my work has been in High-Performance Computing (HPC)
  (but, mainstream computing is becoming more and more like HPC)
  - parallel processors, GPU computing, cloud computing, data analytics, …
  - HPC challenges are becoming everyone's challenges: parallelism & locality

The Chapel Team at Cray (Spring 2015)

(Our team currently has an open language/compiler developer position)

Motivation for Chapel

Q: Why doesn't HPC programming have an equivalent to Python / Matlab / Java / C++ / __(your favorite programming language here)__?

- one that makes it easy to get programs up and running quickly
- one that is portable across system architectures and scales
- one that bridges the HPC, data analysis, and mainstream communities

A: We believe this is due not to any particular technical challenge, but rather a lack of sufficient…

…long-term efforts

…resources

…community will

…co-design between developers and users

…patience

Chapel is our attempt to reverse this trend!

HPC's Status Quo: SPMD Programming

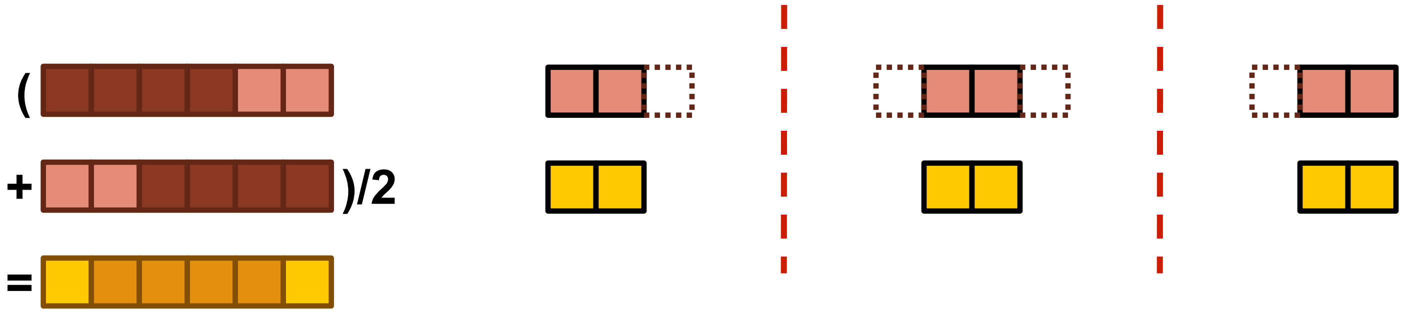
SPMD = Single Program, Multiple Data

- concept: write one program, run multiple copies of it in parallel
- arguably a "bottom-up" programming model design
  - "HPC systems can run lots of programs, so let's get parallelism that way"
- often clumsy in practice

SPMD by Example

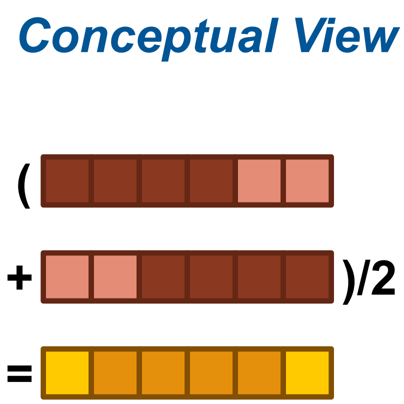
In pictures: "Apply a 3-Point Stencil to a vector"

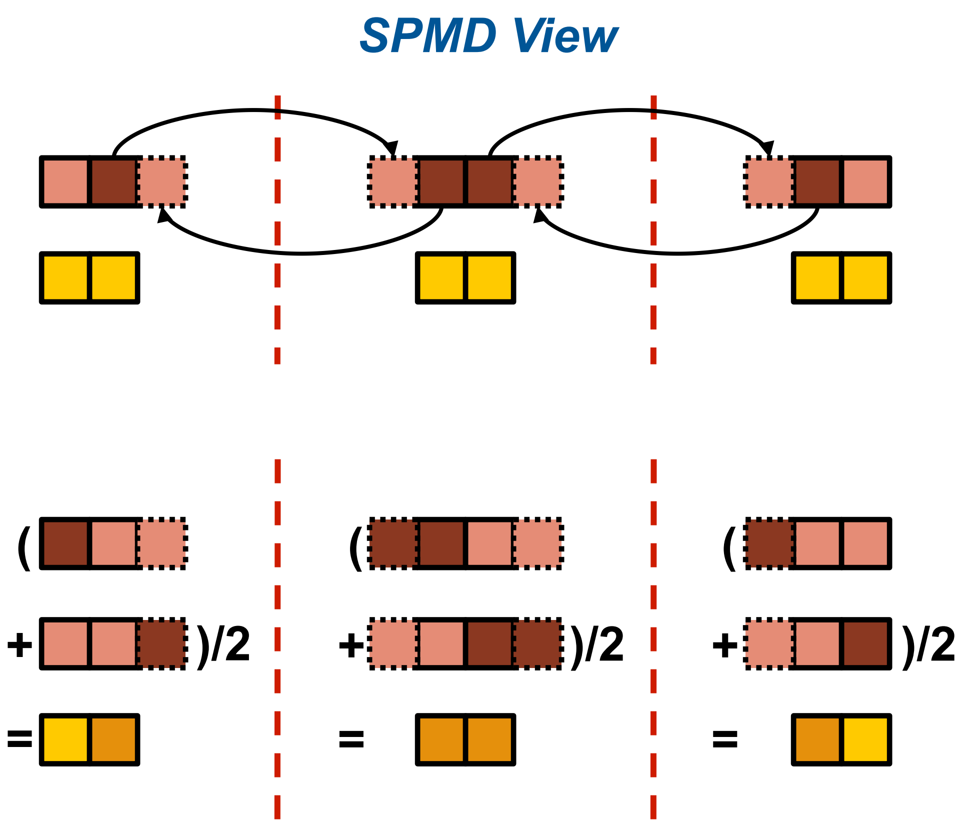
Conceptual View *SPMD View*



SPMD by Example

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

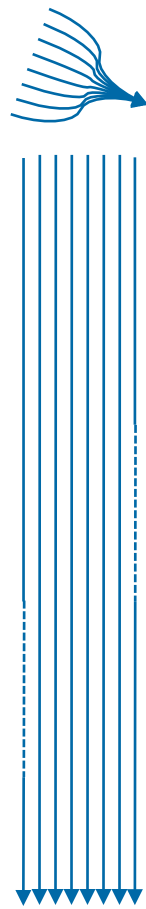




4) Global-View Abstractions

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

SPMD pseudo-code



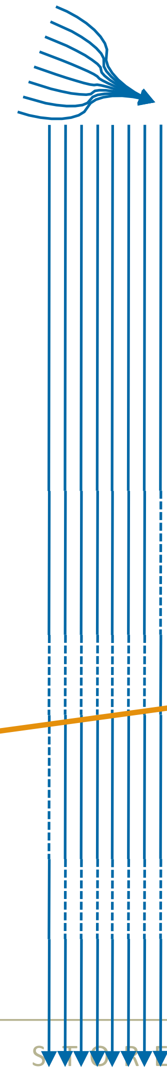
```
proc main() {
  var n = 1000;
  var p = numProcs(),
      me = myProc(),
      myN = n/p,
  var A, B: [0..myN+1] real;

  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

4) Global-View Abstractions

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

SPMD pseudo-code



```
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;
}
```

Assumes p divides n

Communication becomes geometrically more complex for higher-dimensional arrays

What is Chapel?

Chapel: An emerging parallel programming language

- extensible
- portable
- open-source
- a collaborative effort
- a work-in-progress
- a top-down language design

Goals:

- Support general parallel programming
  - "any parallel algorithm on any parallel hardware"
- Make parallel programming far more productive

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:

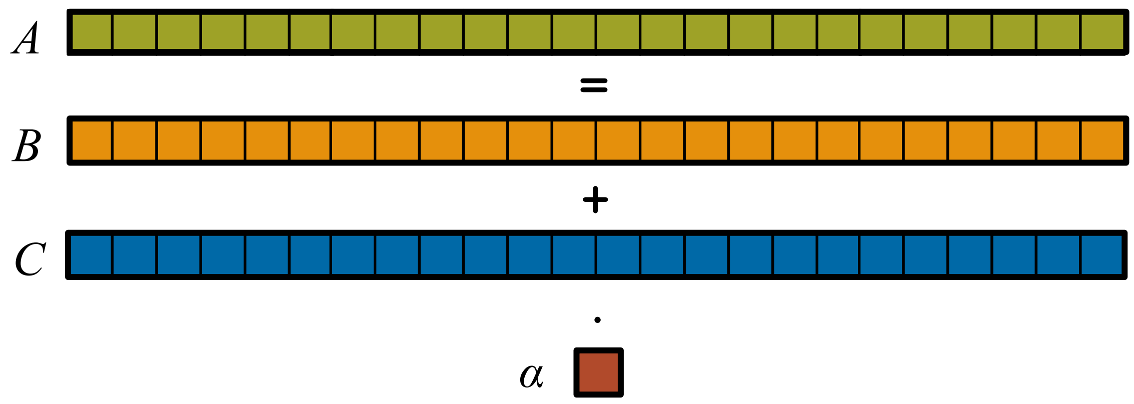
"something that lets computational scientists express what they want,
without taking away the control that HPC programmers want,
implemented in a language as attractive as recent graduates want."

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:

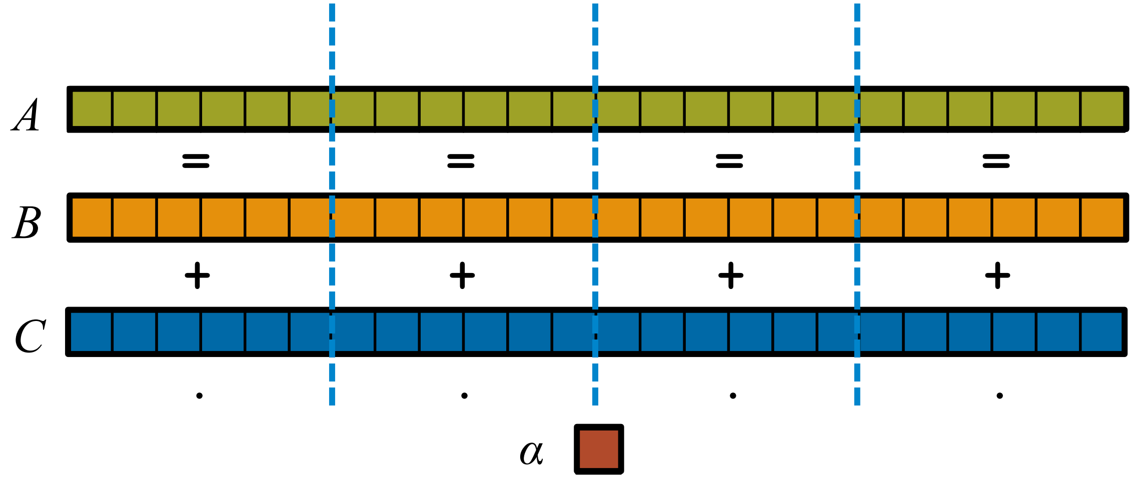


STREAM Triad: a trivial parallel computation

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:

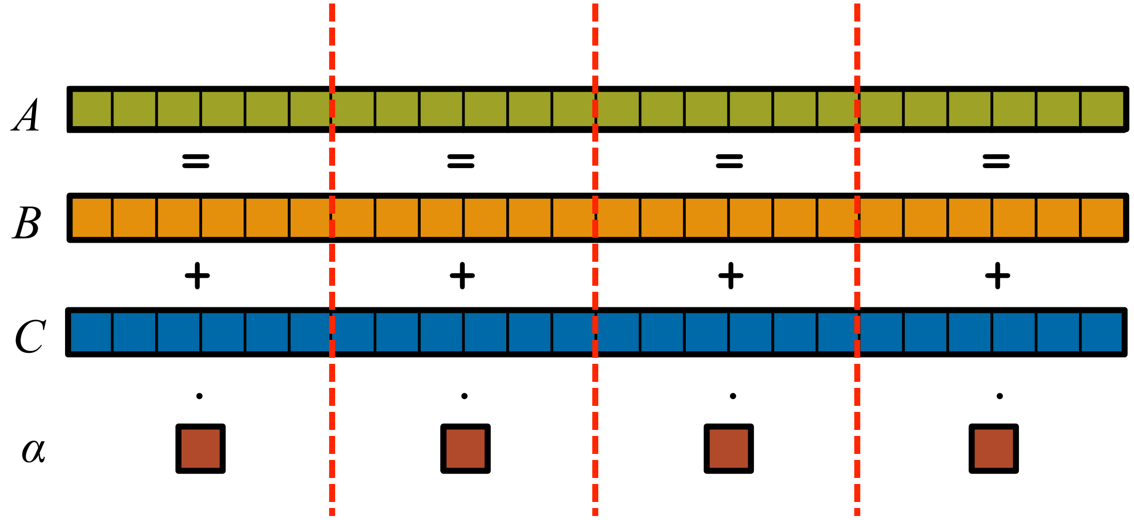


STREAM Triad: a trivial parallel computation

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):

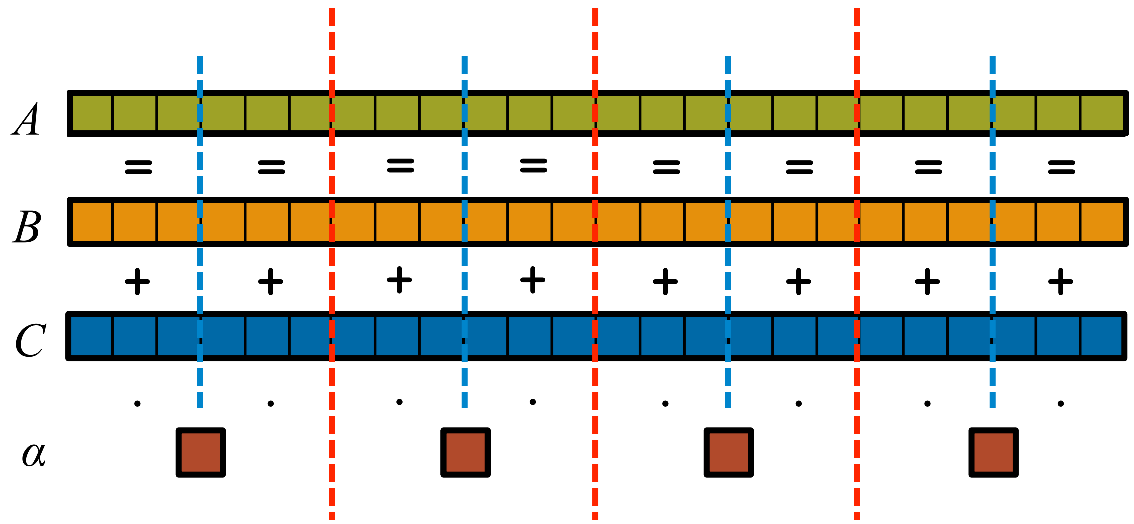


STREAM Triad: a trivial parallel computation

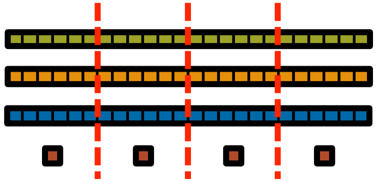
Given: m-element vectors A, B, C

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

In pictures, in parallel (distributed memory multicore):



STREAM Triad: MPI

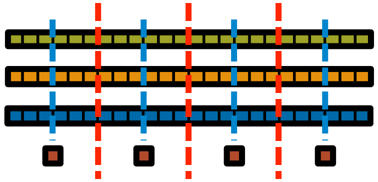


MPI

```
#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



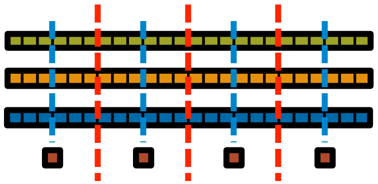
MPI + OpenMP

```
#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);
```

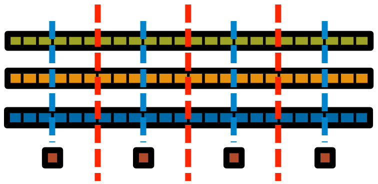
STREAM Triad: MPI+OpenMP vs. CUDA

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 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

Why so many programming models?

HPC tends to approach programming models bottom-up:

Given a system and its core capabilities…

…provide features that can access the available performance.

- portability, generality, programmability: not strictly necessary.

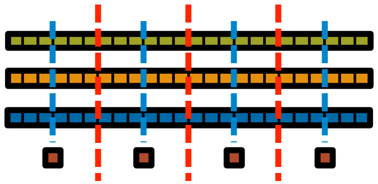
Type of HW Parallelism	Programming Model	Unit of Parallelism
Inter-node	MPI	executable
Intra-node/multicore	OpenMP / pthreads	iteration/task
Instruction-level vectors/threads	pragmas	iteration
GPU/accelerator	CUDA / Open[CL|MP|ACC]	SIMD function/task

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

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

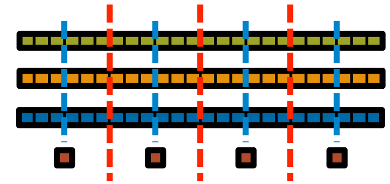
Rewinding a few slides…

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;
}

  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);

  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];
}
```

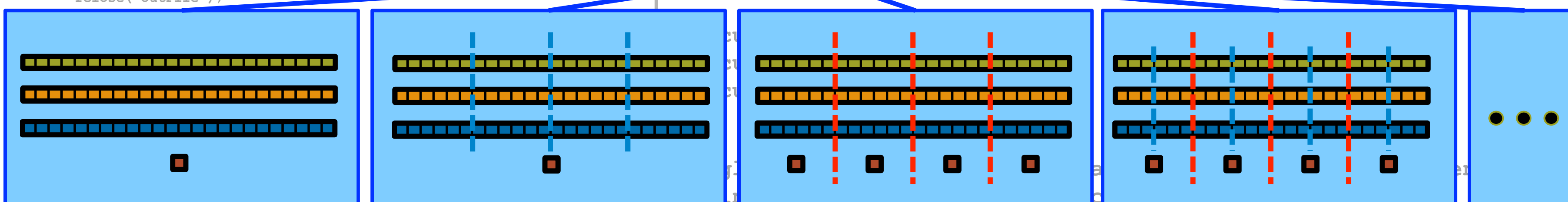
HPC suffers from too many distinct notations for expressing parallelism and locality

STREAM Triad: Chapel

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, *top-down* language design can tease system-specific implementation details away from an algorithm, permitting the compiler, runtime, applied scientist, and HPC expert to each focus on their strengths.

Outline

- ✓ Motivation
- ➢ Chapel's Design Themes
- Survey of Chapel Concepts
- Project Status and Next Steps

Design Themes for Chapel

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

Design Themes for Chapel

1) General Parallel Programming
2) Reduce HPC ↔ Mainstream Language Gap
3) Global-View Abstractions
4) Multiresolution Design
5) Control over Locality/Affinity } We'll cover this one as we go

1) General Parallel Programming

With a unified set of concepts...

...target any hardware parallelism available in the system

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

...express any software parallelism desired by the user

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

Type of HW Parallelism	Programming Model	Unit of Parallelism
Inter-node	Chapel	task (or executable)
Intra-node/multicore	Chapel	iteration/task
Instruction-level vectors/threads	Chapel	iteration
GPU/accelerator	Chapel	SIMD function/task

2) Reduce HPC ↔ Mainstream Language Gap

Consider:

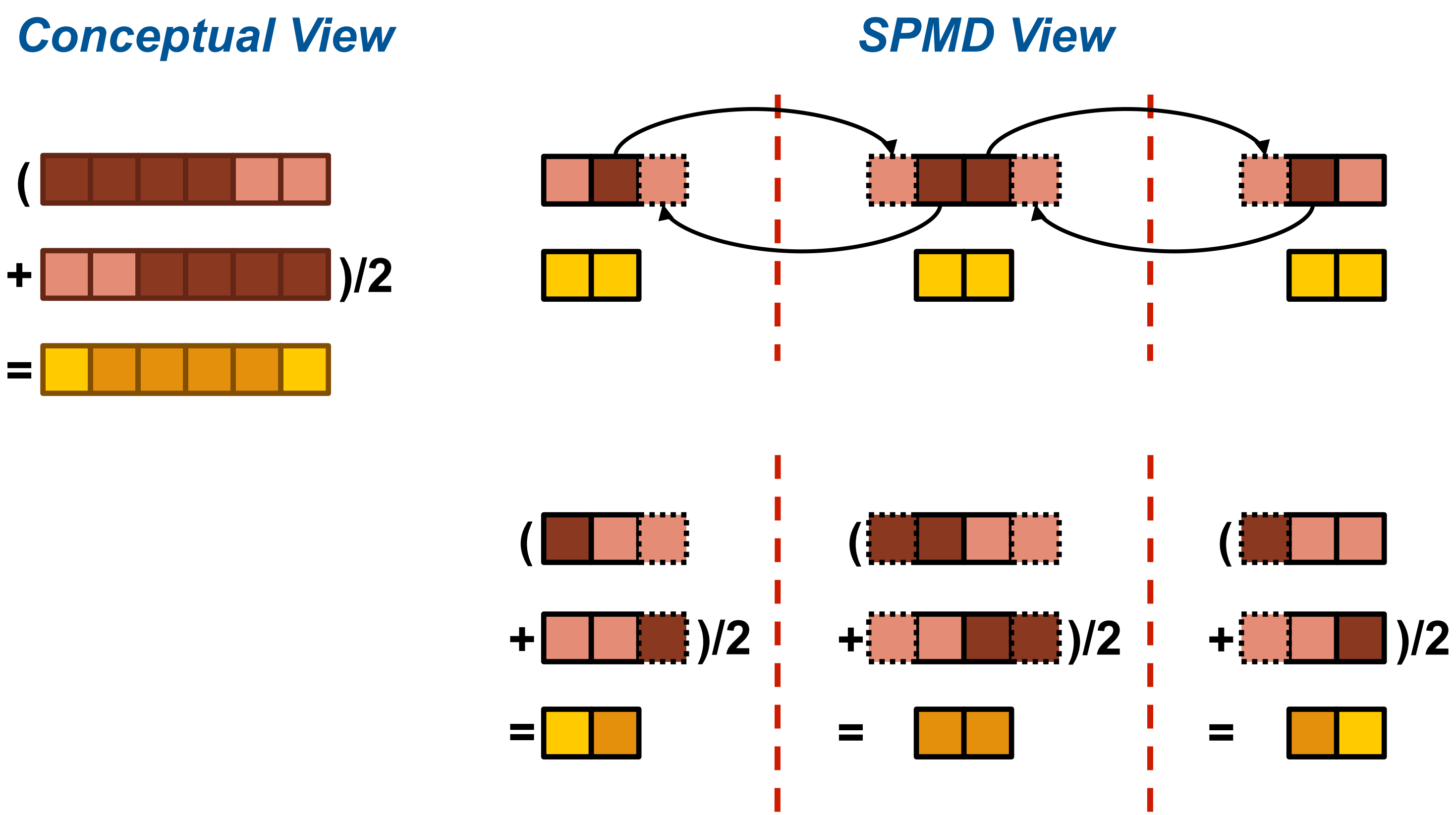
- Students graduate with training in Java, Matlab, Python, etc.
- Yet HPC programming is dominated by Fortran, C/C++, MPI, …

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

3) Global-View Abstractions

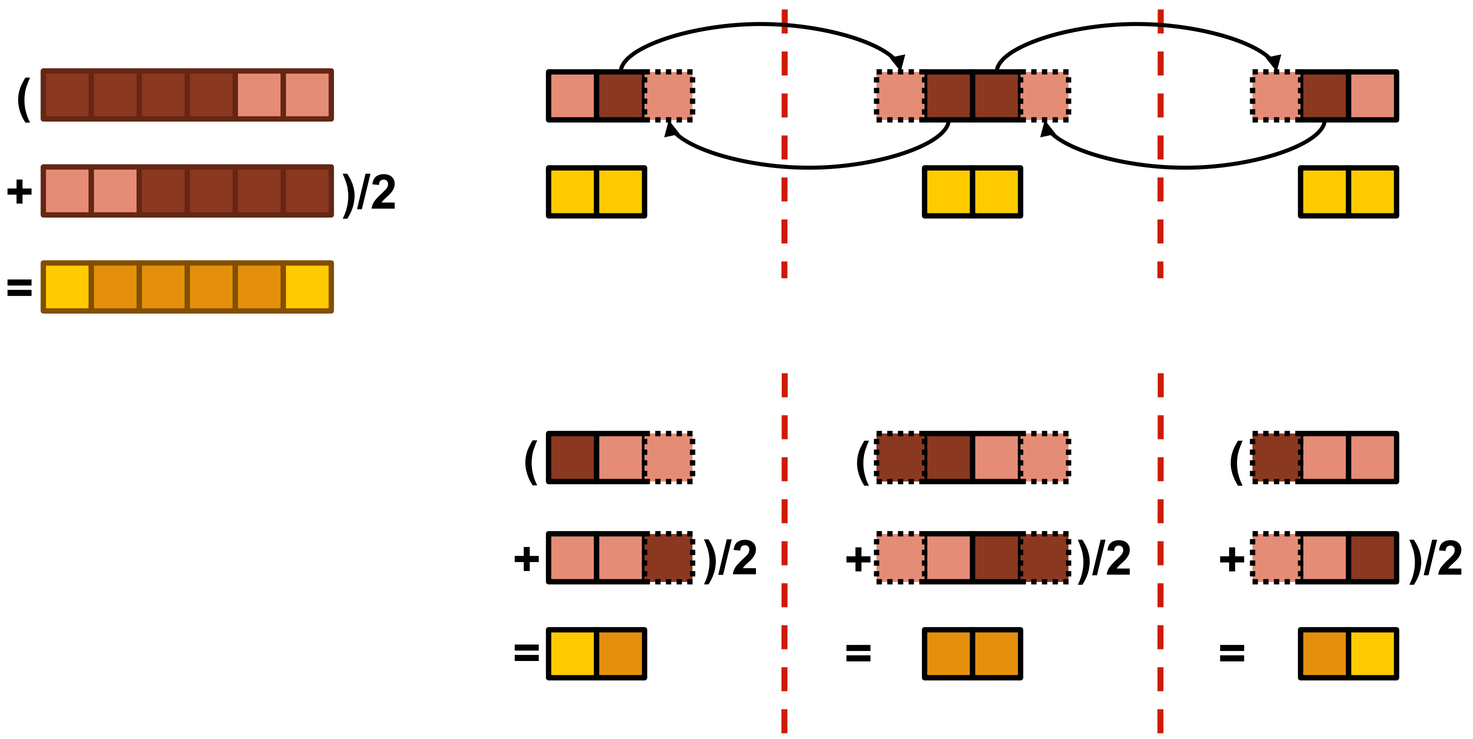
In pictures: “Apply a 3-Point Stencil to a vector”



3) Global-View Abstractions

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

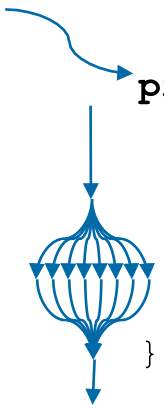
Global-View *Local-View*



3) Global-View Abstractions

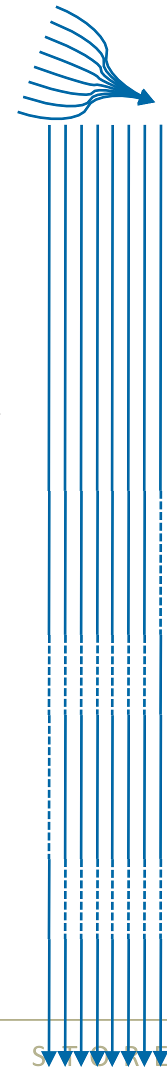
In code: "Apply a 3-Point Stencil to a vector"

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;
}
```

Local-View (SPMD)



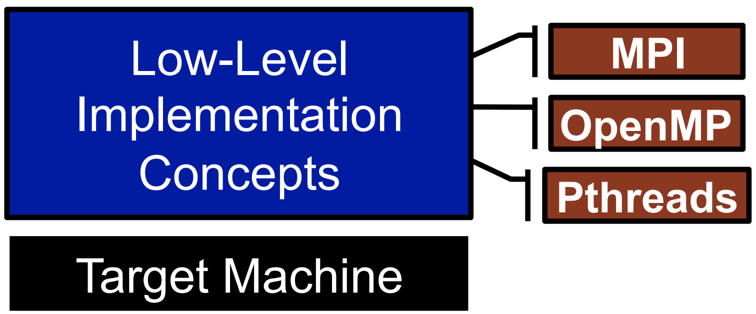
```
proc main() {
  var n = 1000;
  var p = numProcs(),
      me = myProc(),
      myN = n/p,
      myLo = 1,
      myHi = myN;
  var A, B: [0..myN+1] real;

  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;
}
```

3) Global-View Abstractions: A Final Note

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

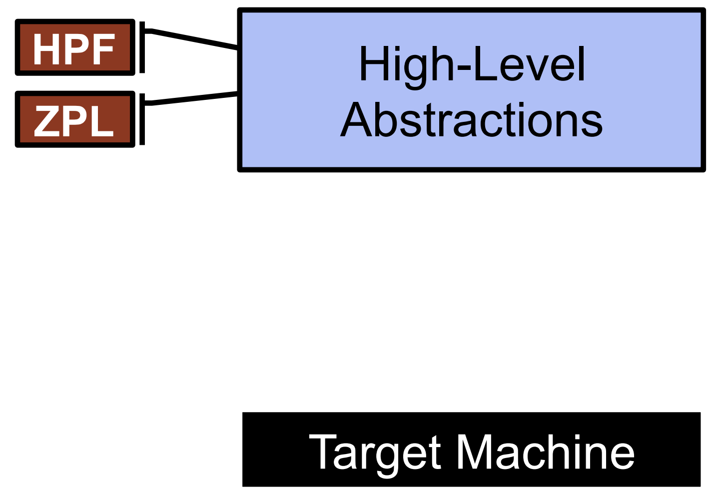
```
proc main() {
  coforall loc in Locales do
    on loc do
      MySPMDProgram(loc.id, Locales.numElements);

}

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

4) Multiresolution Design: Motivation



"Why is everything so tedious/difficult?"

"Why don't my programs trivially port to new systems?"



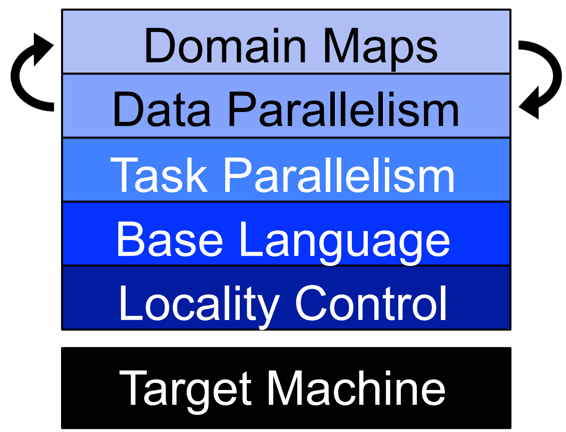
"Why don't I have more control?"

4) Multiresolution Design

Multiresolution Design: Support multiple tiers of features

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

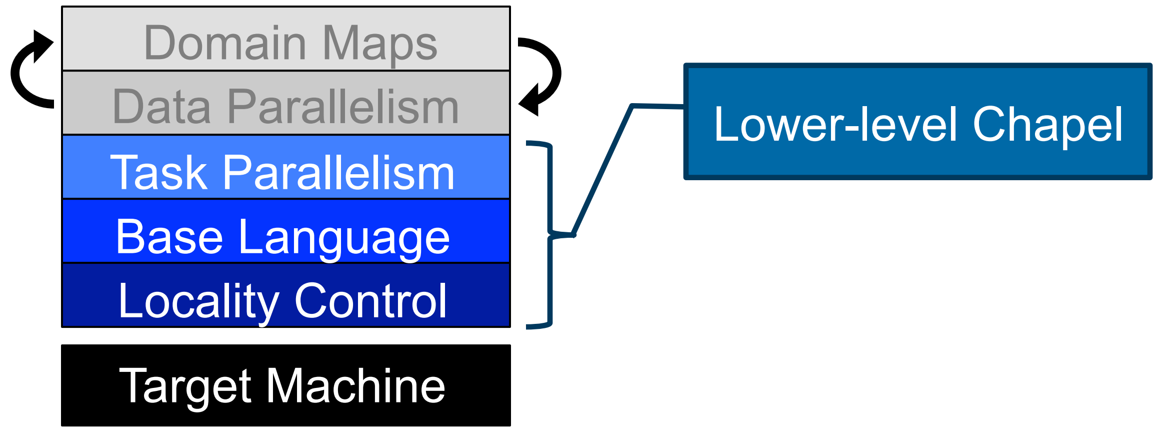
Chapel language concepts



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

Outline

- ✓ Motivation
- ✓ Chapel's Design Themes
- ➢ Survey of Chapel Concepts



- Project Status and Next Steps

Outline

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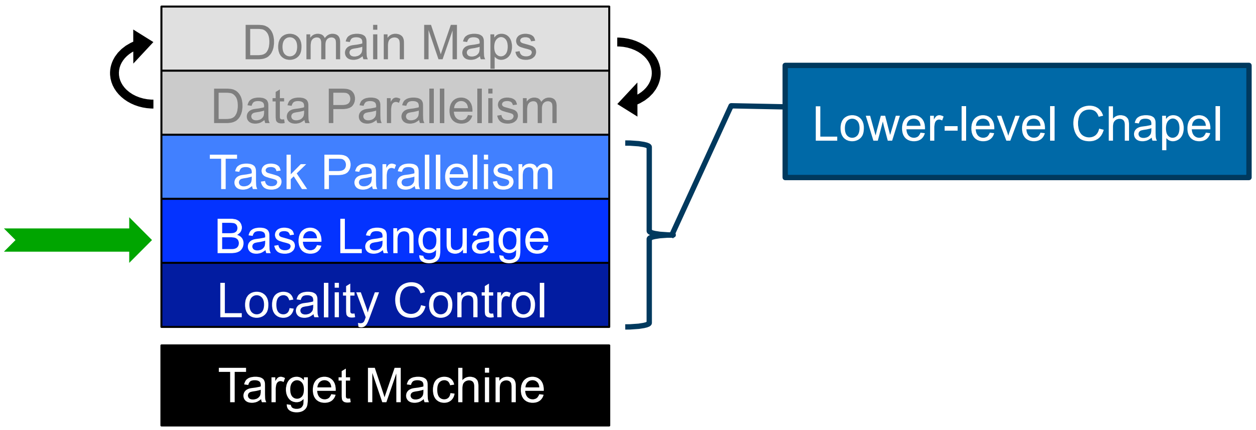

- Project Status and Next Steps

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, Values, and Operators

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

Outline

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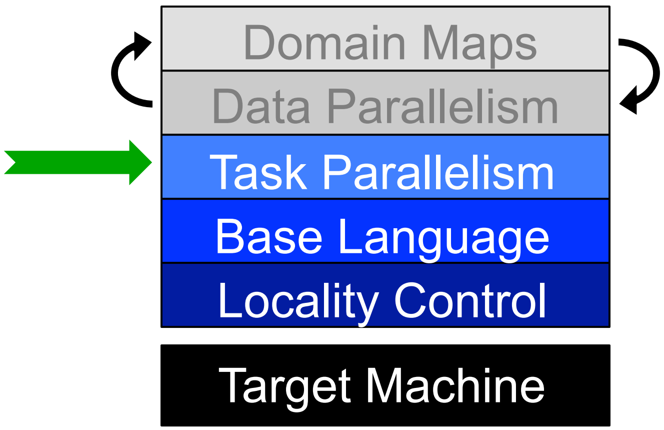

- Project Status and Next Steps

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
```

Other Task Parallel Concepts

- **cobegins:** create tasks using compound statements

- **atomic variables:** support atomics ops, similar to modern C++
- **sync/single variables:** support producer/consumer patterns

- **sync statements:** join unstructured tasks
- **serial statements:** conditionally squash parallelism

Outline

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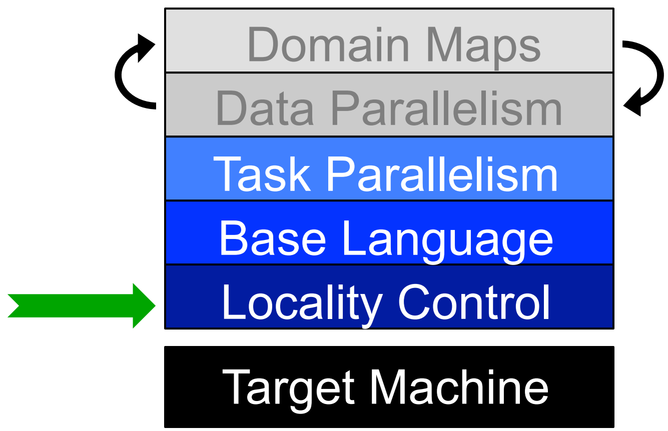


Theme 5: Control over Locality/Affinity

- Project Status and Next Steps

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");
```

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

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 and 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!");
```

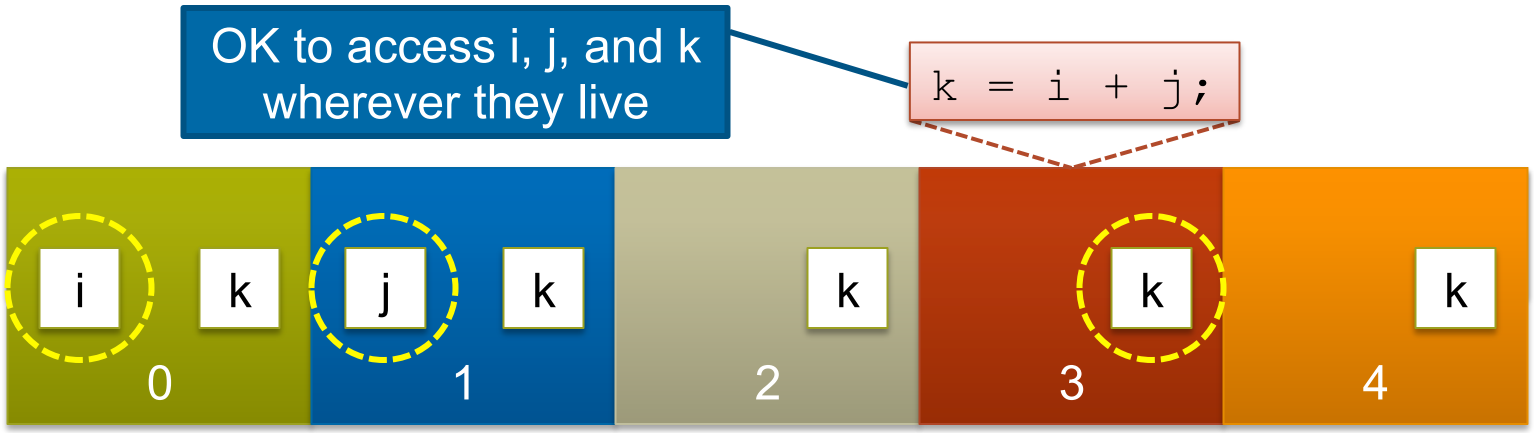
Time Check!
Do we have time for a sidebar on PGAS?

Yes? No!

PGAS Programming in a Nutshell

Global Address Space:

- permit parallel tasks to access variables by naming them
  - regardless of whether they are local or remote
  - compiler / library / runtime will take care of communication



Images / Threads / Locales / Places / etc. (think: “compute nodes”)

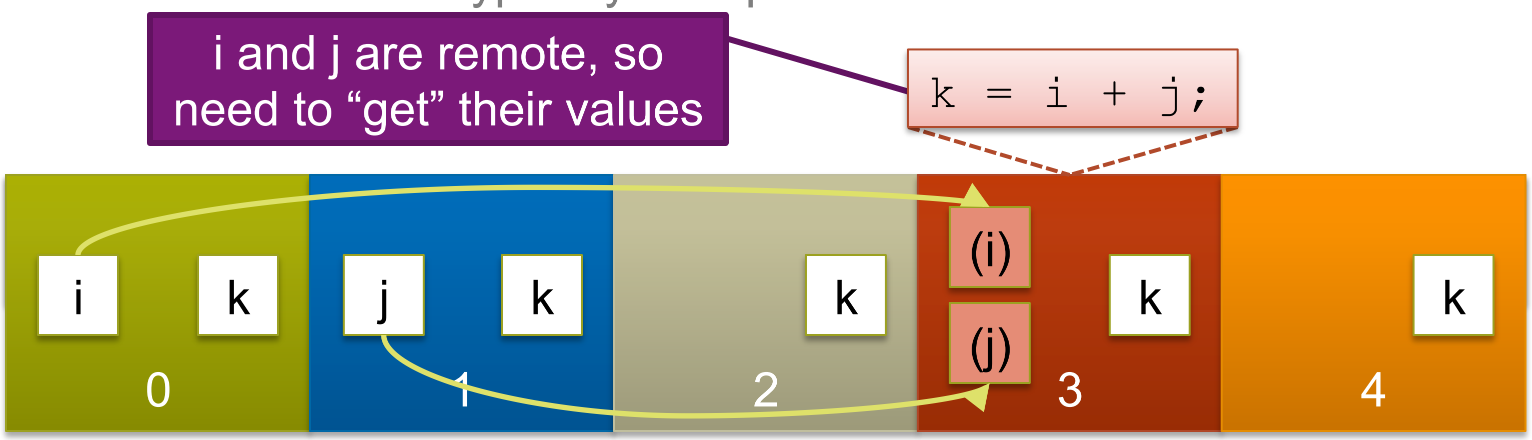
PGAS Programming in a Nutshell

Global Address Space:

- permit parallel tasks to access variables by naming them
  - regardless of whether they are local or remote
  - compiler / library / runtime will take care of communication

Partitioned:

- establish a strong model for reasoning about locality
  - every variable has a well-defined location in the system
  - local variables are typically cheaper to access than remote ones



Images / Threads / Locales / Places / etc. (think: “compute nodes”)

PGAS Programming in a Nutshell

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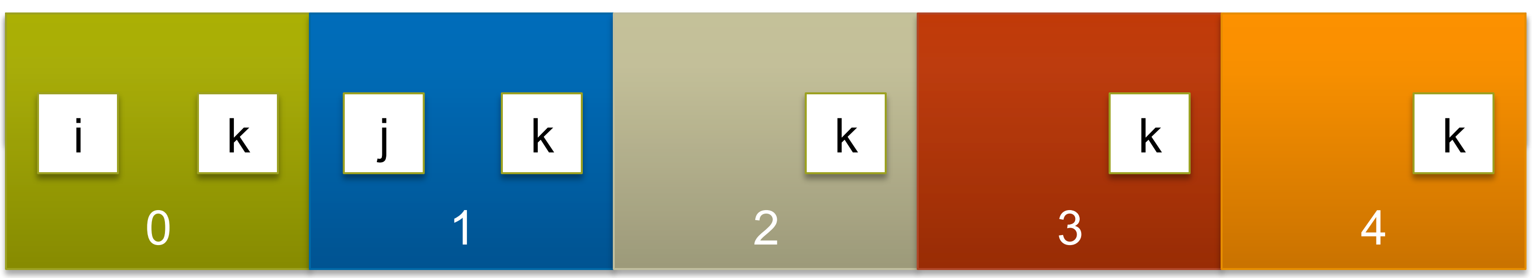
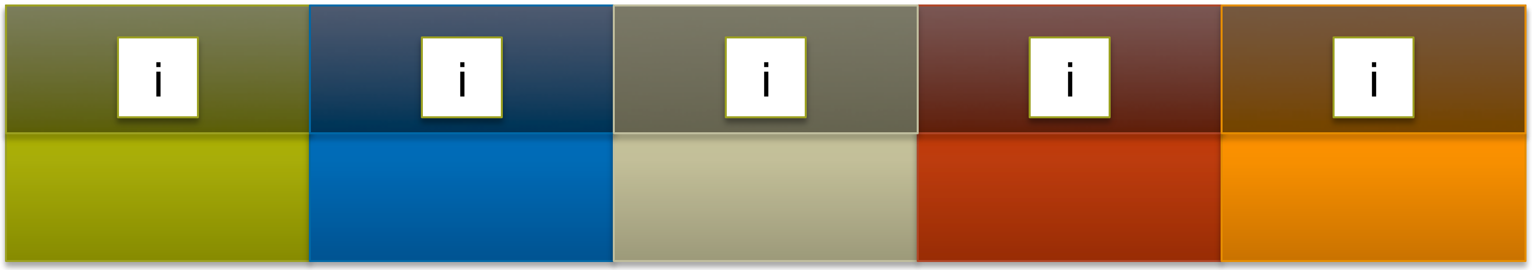


Images / Threads / Locales / Places / etc. (think: “compute nodes”)

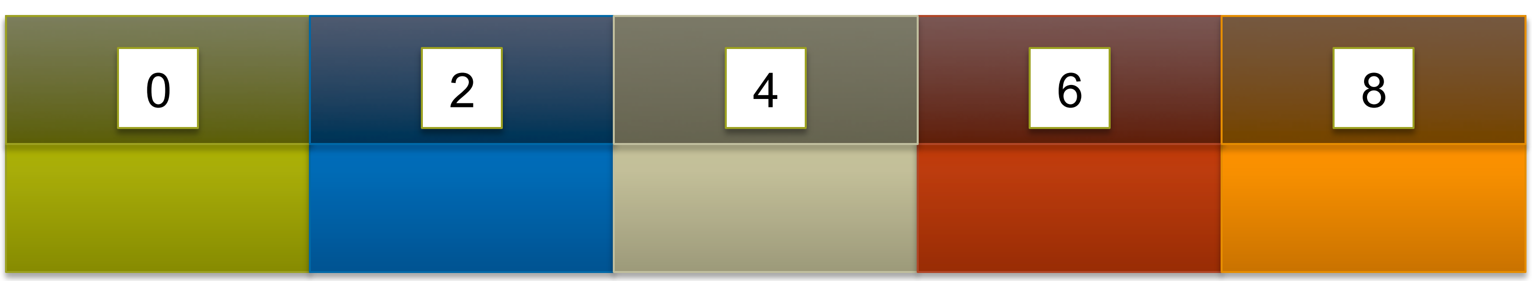
SPMD PGAS Languages (using a pseudo-language, not Chapel)

```
proc main() {
  var i(*): int;          // declare a shared variable i
```



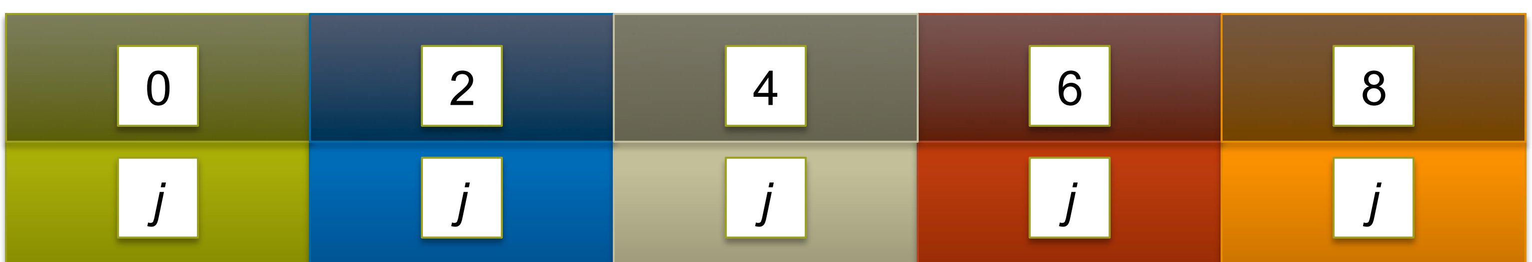
SPMD PGAS Languages (using a pseudo-language, not Chapel)

```
proc main() {
  var i(*): int;          // declare a shared variable i
  i = 2*this_image();     // each image initializes its copy
```



SPMD PGAS Languages (using a pseudo-language, not Chapel)

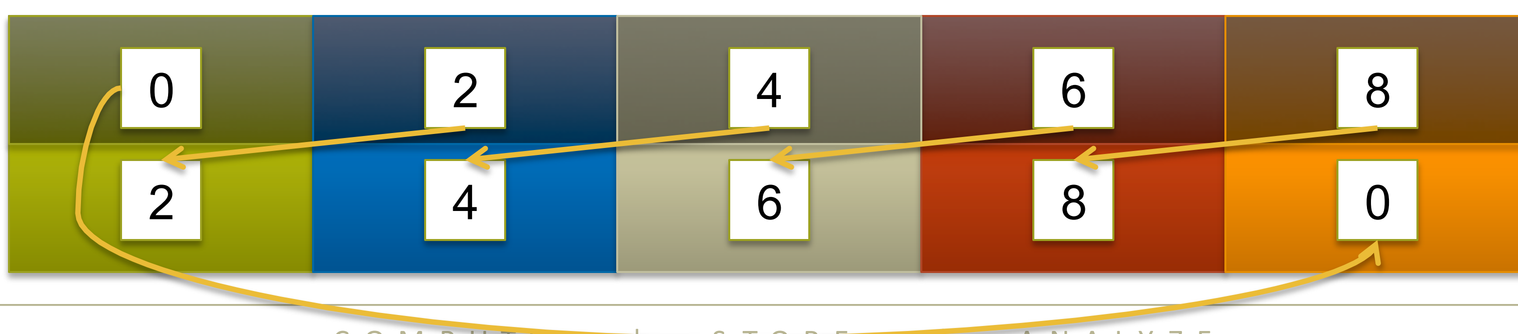
```
proc main() {
  var i(*): int;          // declare a shared variable i
  i = 2*this_image();     // each image initializes its copy
  var j: int;             // declare a private variable j
```



SPMD PGAS Languages (using a pseudo-language, not Chapel)

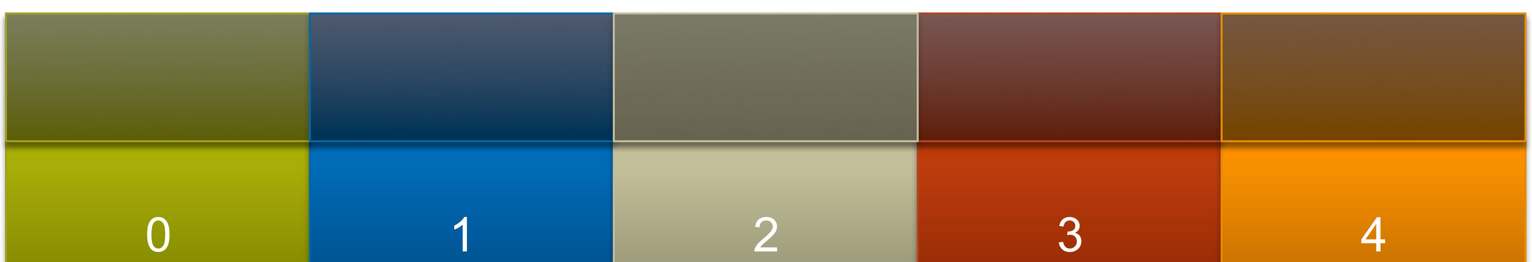
```
proc main() {
  var i(*): int;              // declare a shared variable i
  i = 2*this_image();         // each image initializes its copy
  var j: int;                 // declare a private variable j
  j = i( (this_image()+1) % num_images() );
    // ^^ access our neighbor's copy of i
    // communication is implemented by the compiler + runtime

    // How did we know our neighbor had an i?
   // Because it's SPMD – we're all running the same program.
```



Chapel and PGAS

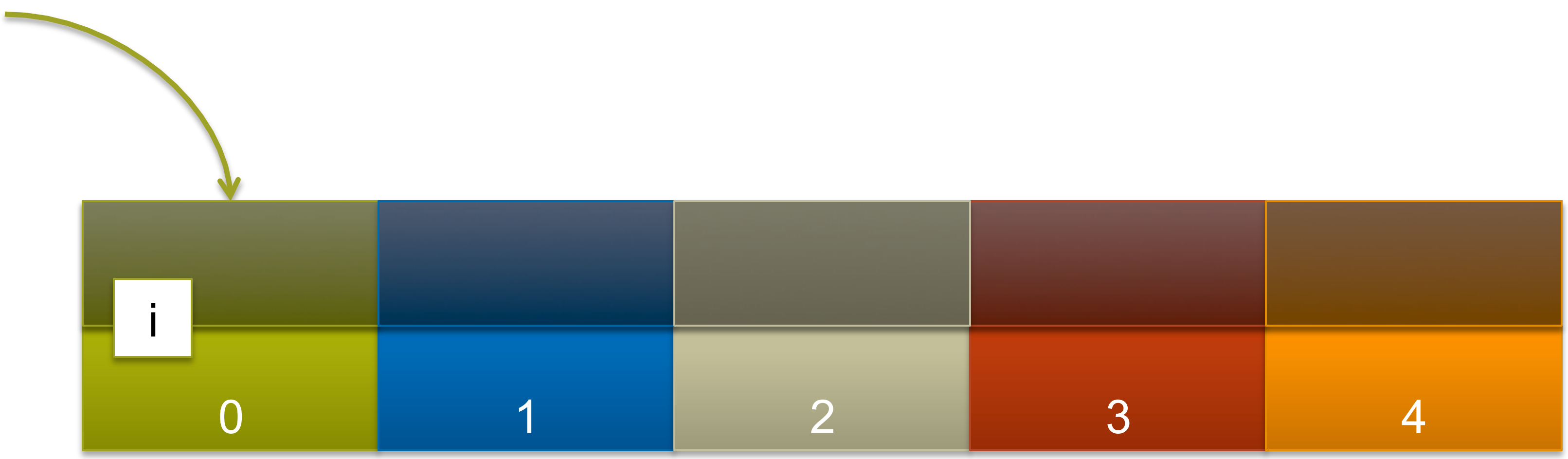
- **Chapel is PGAS, but unlike most, it's not inherently SPMD**
  - ⇒ never think about "the other copies of the program"
  - ⇒ "global name/address space" comes from lexical scoping
    - as in traditional languages, each declaration yields one variable
    - variables are stored on the locale where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



Locales (think: "compute nodes")

Chapel: Scoping and Locality

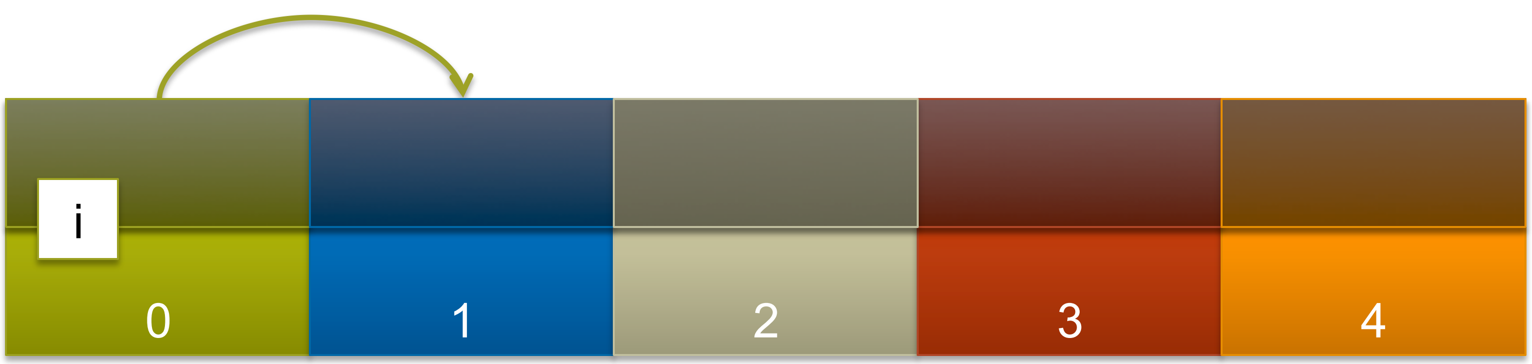
```
var i: int;
```



Locales (think: “compute nodes”)

Chapel: Scoping and Locality

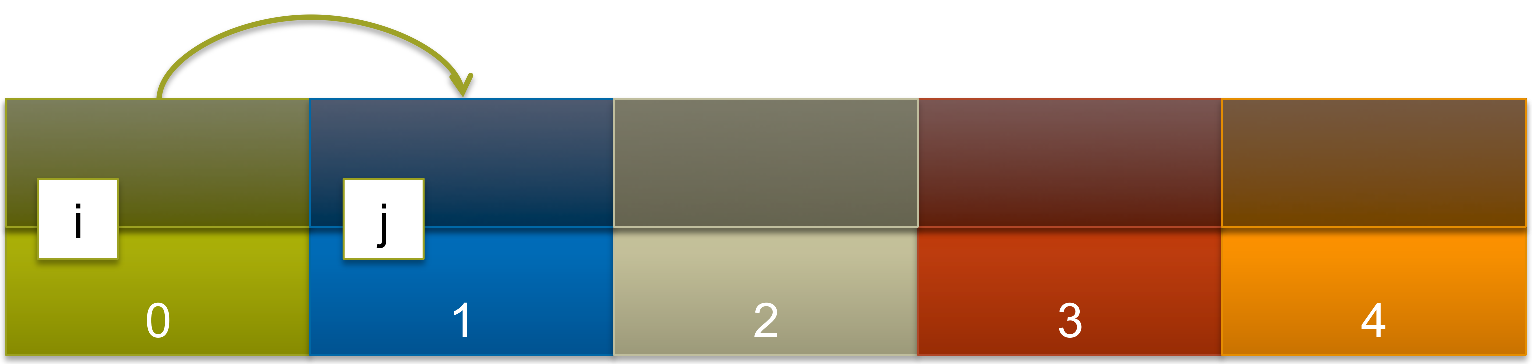
```
var i: int;
on Locales[1] {
```



Locales (think: "compute nodes")

Chapel: Scoping and Locality

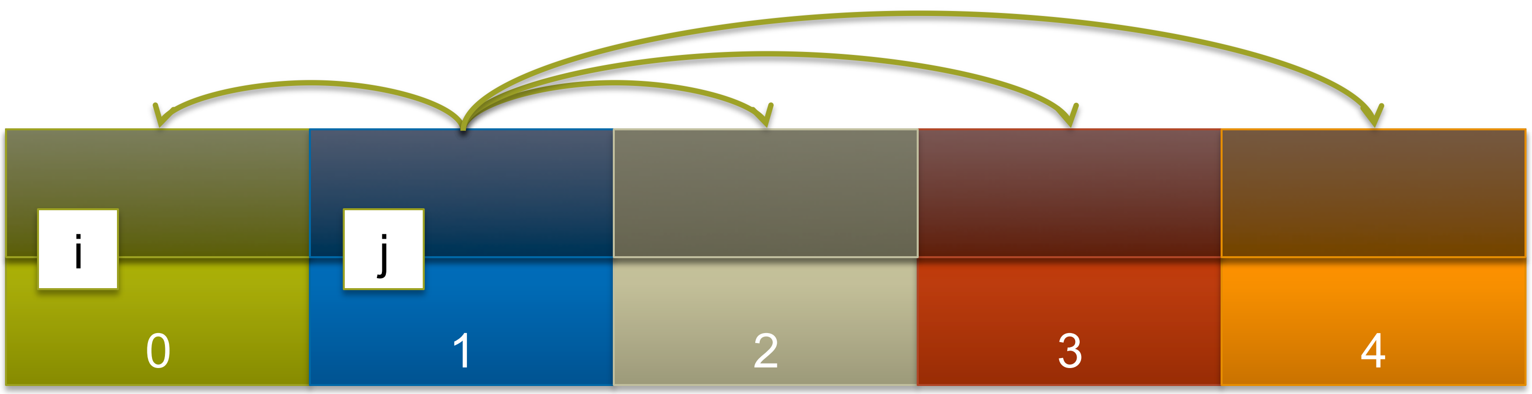
```
var i: int;
on Locales[1] {
  var j: int;
```



Locales (think: "compute nodes")

Chapel: Scoping and Locality

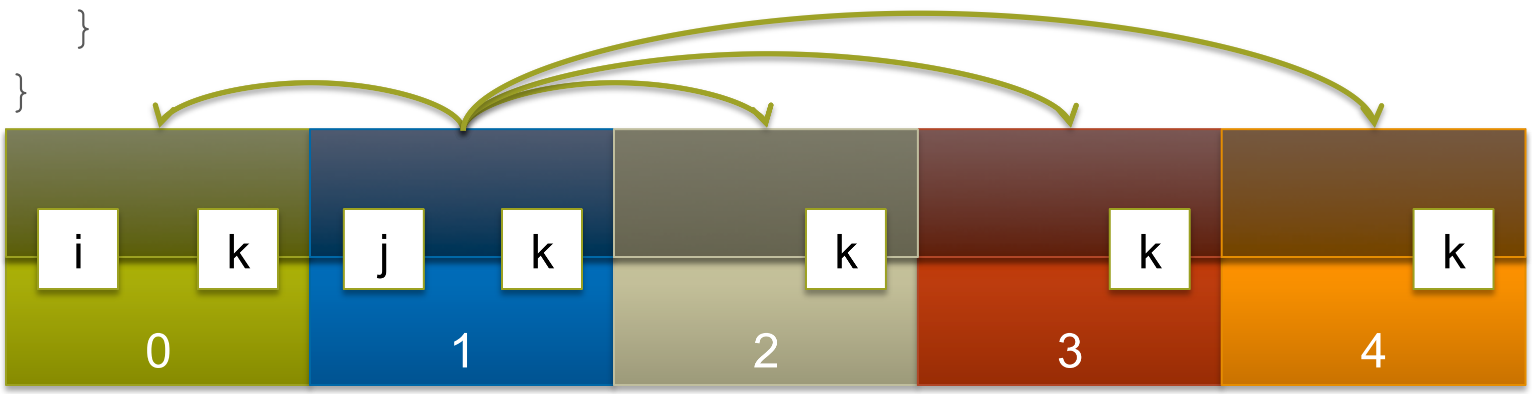
```
var i: int;
on Locales[1] {
  var j: int;
  coforall loc in Locales {
    on loc {
```



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. For example:
      k = 2*i + j;
      // The implementation manages any communication.
    }
  }
}
```

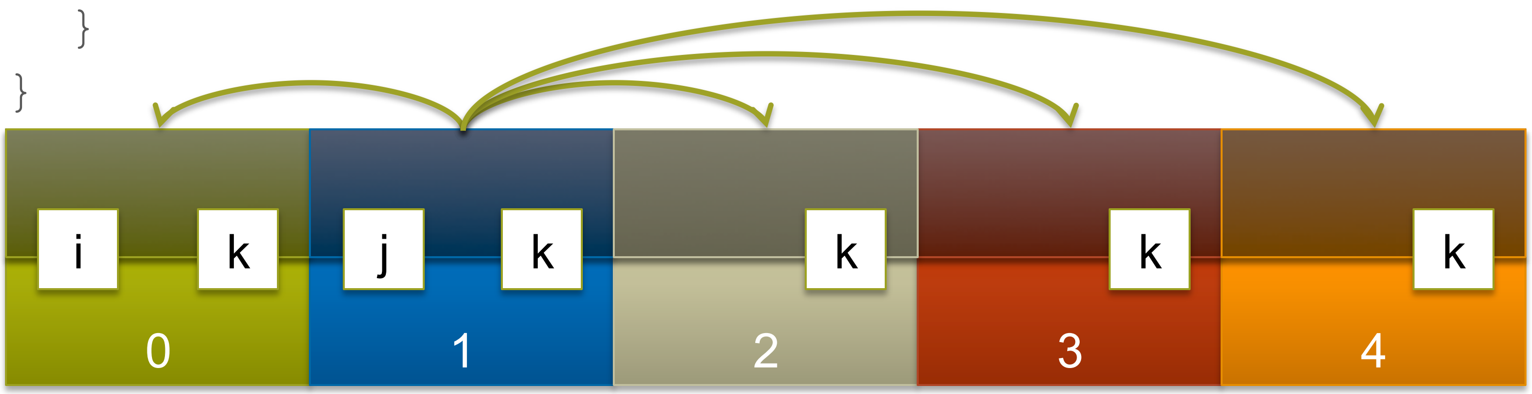


Locales (think: "compute nodes")

Chapel: Locality queries

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

      …here…       // query the locale on which this task is running
      …j.locale…   // query the locale on which j is stored
    }
  }
}
```



Locales (think: "compute nodes")

Outline

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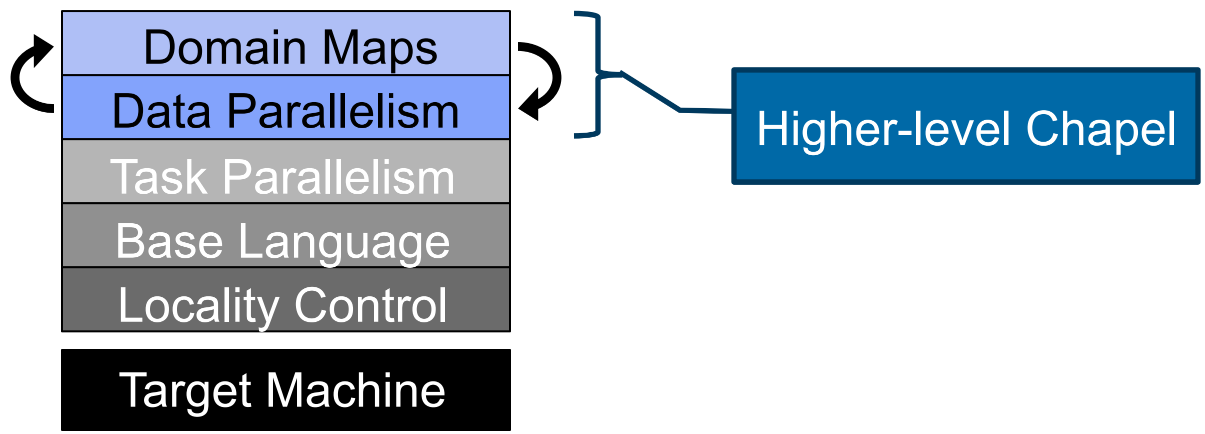
- ✓ Chapel's Design Themes
- ➢ Survey of Chapel Concepts



- Project Status and Next Steps

Outline

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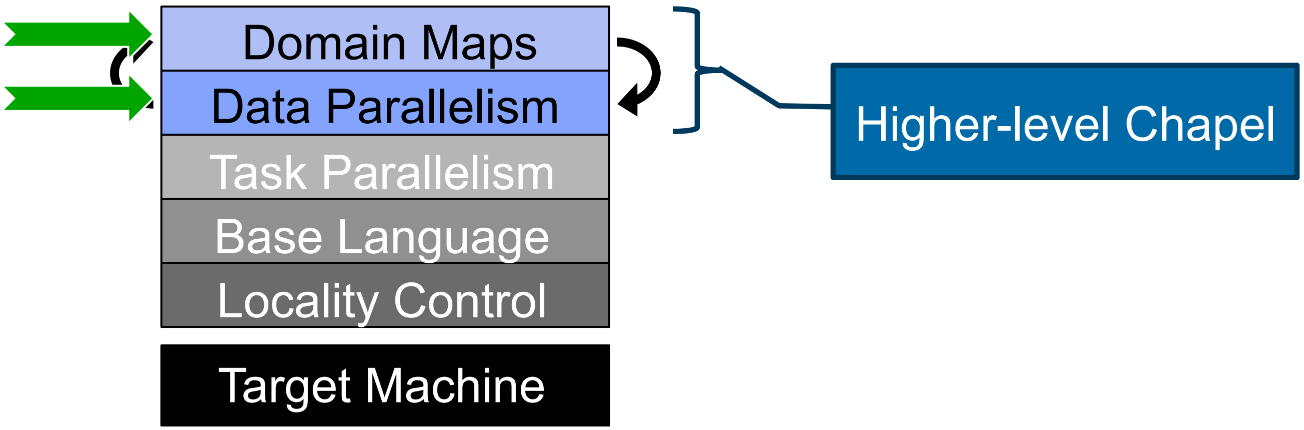
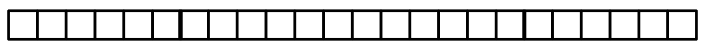


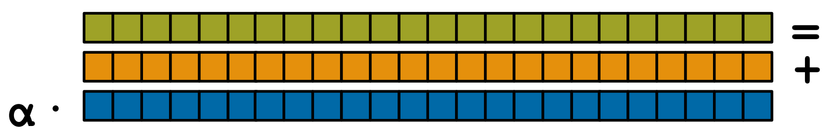
- Project Status and Next Steps

Data Parallelism By Example: STREAM Triad

```
const ProblemSpace = {1..m};
```



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

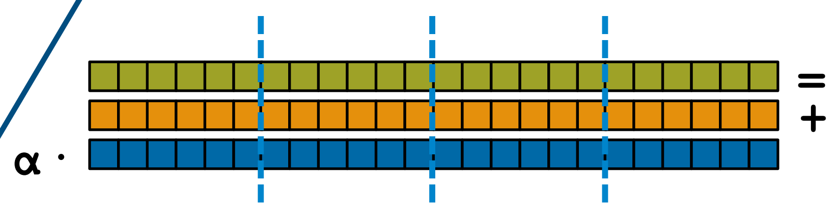



```
A = B + alpha * C;
```

STREAM Triad: Chapel (multicore)

```
const ProblemSpace = {1..m};
```

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

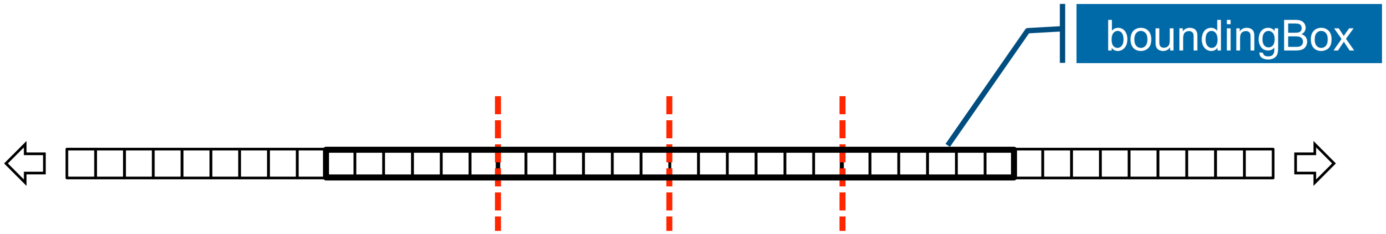



```
A = B + alpha * C;
```

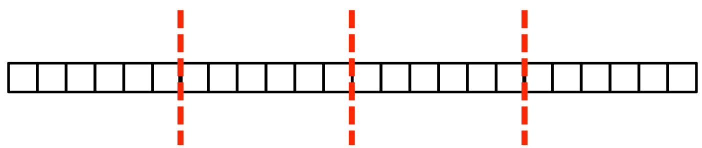
No domain map specified ⇒ use default layout

- current locale owns all domain indices and array values
- computation will execute using local processors only

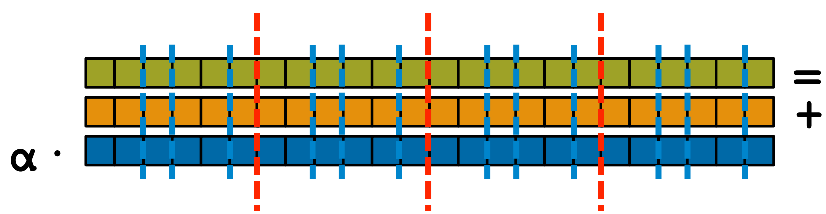
STREAM Triad: Chapel (multilocale, blocked)




```
const ProblemSpace = {1..m}
                         dmapped Block(boundingBox={1..m});
```

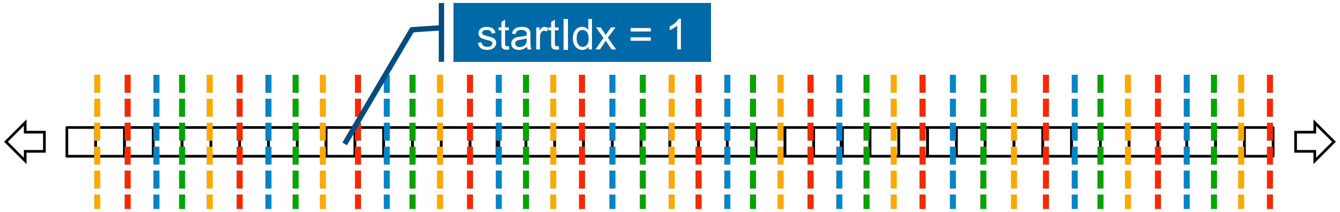


```
var A, B, C: [ProblemSpace] real;
```

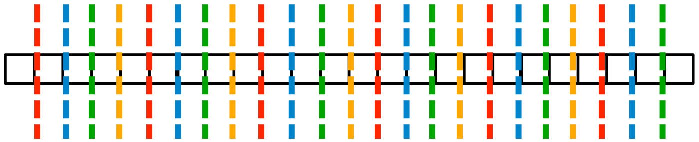



```
A = B + alpha * C;
```

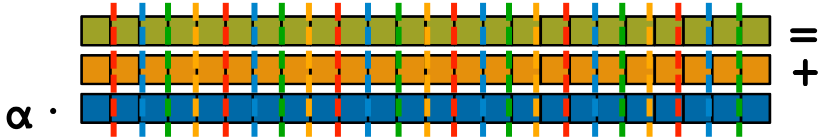
STREAM Triad: Chapel (multilocale, cyclic)




```
const ProblemSpace = {1..m}
                          dmapped Cyclic(startIdx=1);
```



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




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

STREAM Triad: Chapel

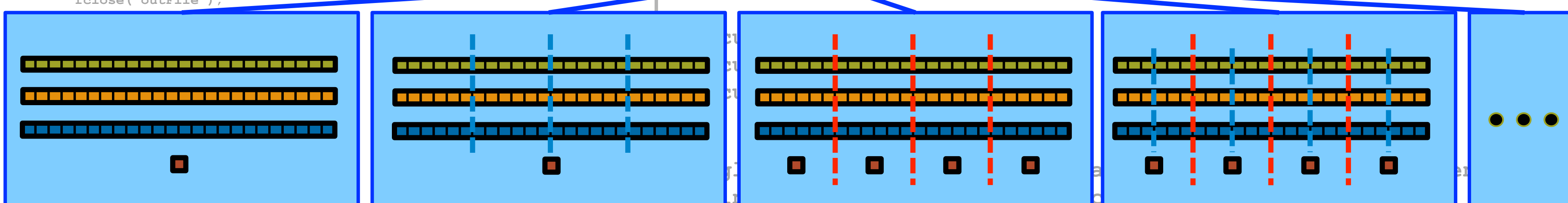
MPI + OpenMP

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

static int VectorSize;
static double *a, *b, *c;

int HPCC_StarStream(HPCC_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 == myR
  MPI_Reduce( &rv, &errCount, 1, MPI

  return errCount;
}

int HPCC_Stream(HPCC_Params *params,
  register int j;
  double  scalar;

  VectorSize = HPCC_LocalVectorSize(

  a = HPCC_XMALLOC( double, VectorSi
  b = HPCC_XMALLOC( double, VectorSi
  c = HPCC_XMALLOC( double, VectorSi

  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 );
```

Chapel

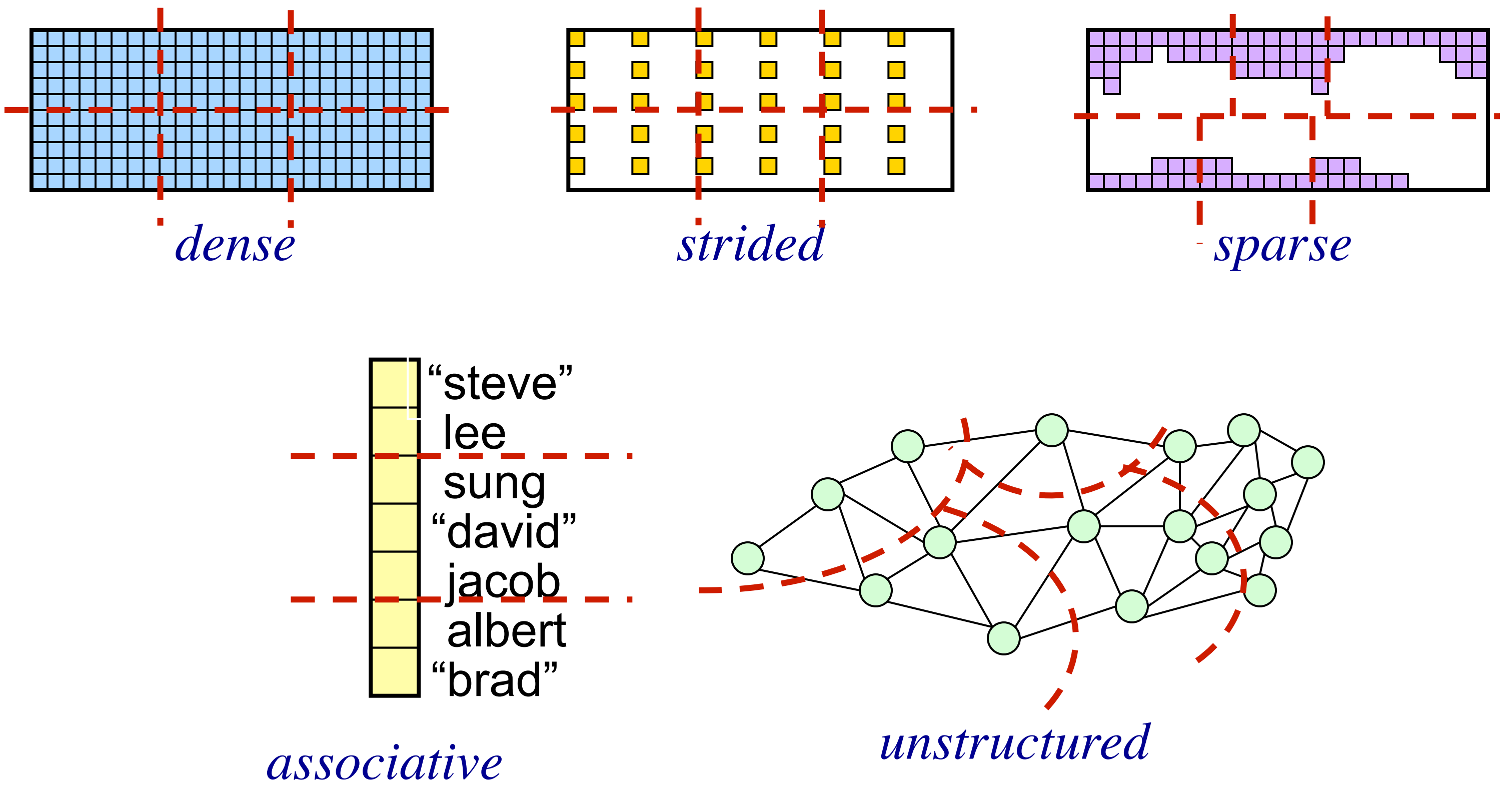
```
config const m = 1000,
             alpha = 3.0;

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

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

B = 2.0;
C = 3.0;

A = B + alpha * C;
```

the special sauce



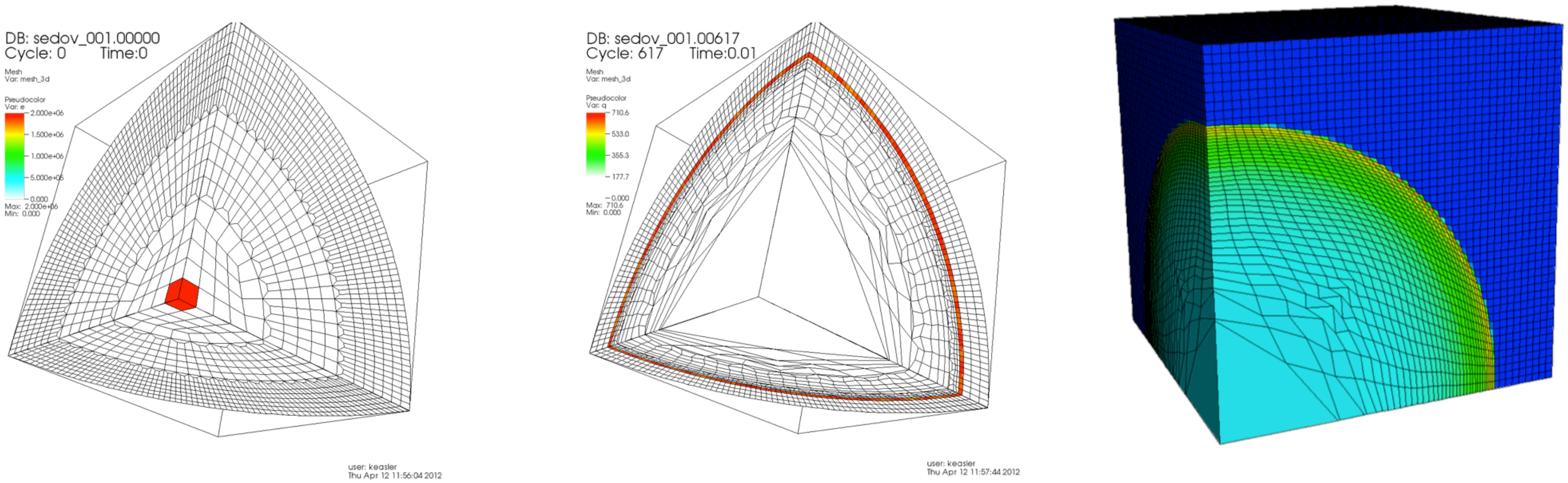
Philosophy: Good, *top-down* language design can tease system-specific implementation details away from an algorithm, permitting the compiler, runtime, applied scientist, and HPC expert to each focus on their strengths.

Chapel has Many Types of Domains/Arrays



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

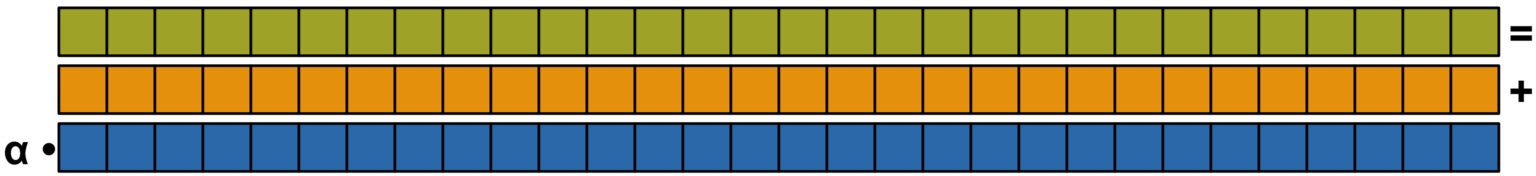
This is the only representation-dependent code.
It specifies:

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

Domain maps insulate the rest of the application from these choices

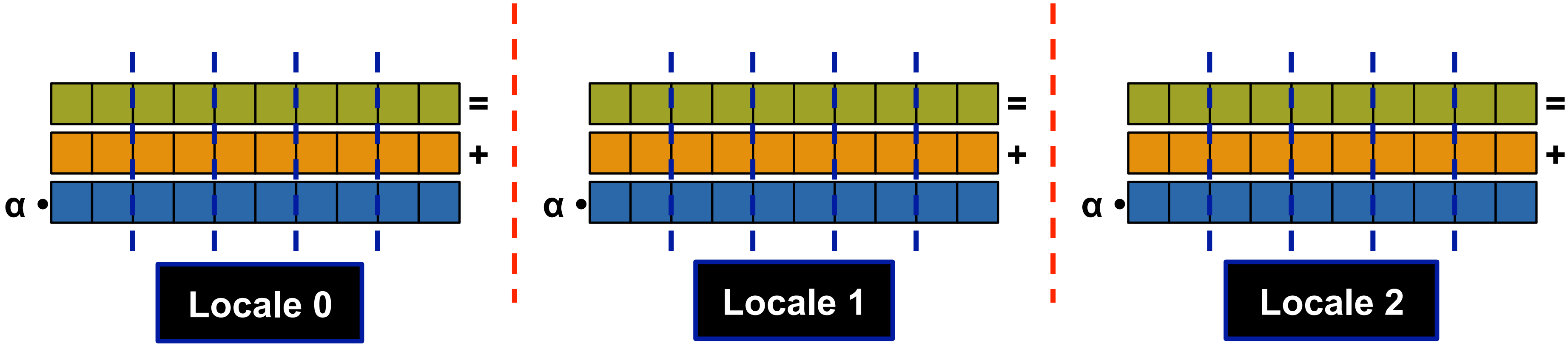
Domain Maps

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




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

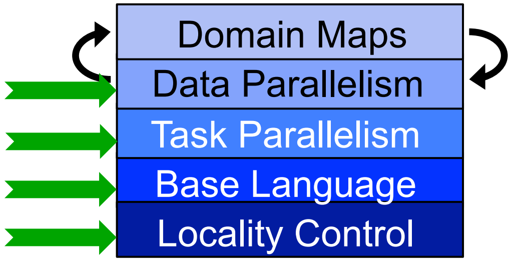
…to the target locales’ memory and processors:



Chapel'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

For More Information on Domain Maps

HotPAR'10: *User-Defined Distributions and Layouts in Chapel: Philosophy and Framework*
Chamberlain, Deitz, Iten, Choi; June 2010

CUG 2011: *Authoring User-Defined Domain Maps in Chapel*
Chamberlain, Choi, Deitz, Iten, Litvinov; May 2011

Chapel release:

- Technical notes detailing the domain map interface for implementers:
  http://chapel.cray.com/docs/latest/technotes/dsi.html
- Current domain maps:
  $CHPL_HOME/modules/dists/*.chpl
  layouts/*.chpl
  internal/Default*.chpl

Two Other Thematically Similar Features

1) **parallel iterators:** Permit users to specify the parallelism and work decomposition used by forall loops
   - including zippered forall loops

2) **locale models:** Permit users to model the target architecture and how Chapel should be implemented on it
   - e.g., how to manage memory, create tasks, communicate, …

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, …

Language Summary

HPC programmers deserve better programming models

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

- yet, without necessarily abdicating control
- Chapel does this via its multiresolution design
  - domain maps, parallel iterators, and locale models are all examples
  - avoids locking crucial policy decisions into the language definition

We believe Chapel can greatly improve productivity

…for current and emerging HPC architectures

…for HPC users and mainstream uses of parallelism at scale

Outline

- ✓ Motivation
- ✓ Chapel's Design Themes
- ✓ Survey of Chapel Concepts
- ➢ **Project Status and Next Steps**

Chapel is Portable

- **Chapel's design is intended to be hardware-independent**

- **The current release requires:**
  - a C/C++ compiler
  - a *NIX environment (Linux, OS X, BSD, Cygwin, …)
  - POSIX threads
  - (for distributed execution): support for RDMA, MPI, or UDP

- **Chapel can run on…**

  …laptops and workstations
  …commodity clusters
  …the cloud
  …HPC systems from Cray and other vendors
  …modern processors like Intel Xeon Phi, GPUs*, etc.

* = academic work only; not yet supported in the official release

Chapel is Open-Source

- **Chapel's development is hosted at GitHub**
  - https://github.com/chapel-lang
- **Chapel is licensed as Apache v2.0 software**
- **Instructions for download + install are online**
  - see http://chapel.cray.com/download.html to get started

A Year in the Life of Chapel

- **Two major releases per year** (April / October)
  - **~a month later:** detailed release notes
- **CHIUW:** Chapel Implementers and Users Workshop (May/June)
  - (3rd annual) CHIUW 2016 will be held at IPDPS (Chicago, IL)
- **SC** (Nov)
  - tutorials, panels, BoFs, posters, educator sessions, exhibits, …
  - annual **CHUG (Chapel Users Group) happy hour**
- **Talks, tutorials, research visits, blog posts, …** (year-round)

Chapel is a Collaborative Effort

Colorado State University

RICE

LTS Laboratory for Telecommunications Sciences

ETH Zürich

Lawrence Livermore National Laboratory

Sandia National Laboratories

BERKELEY LAB
Lawrence Berkeley National Laboratory

Argonne NATIONAL LABORATORY

OAK RIDGE National Laboratory

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

東京大学 THE UNIVERSITY OF TOKYO

UNIVERSIDAD DE MÁLAGA

UNIVERSITY OF MARYLAND

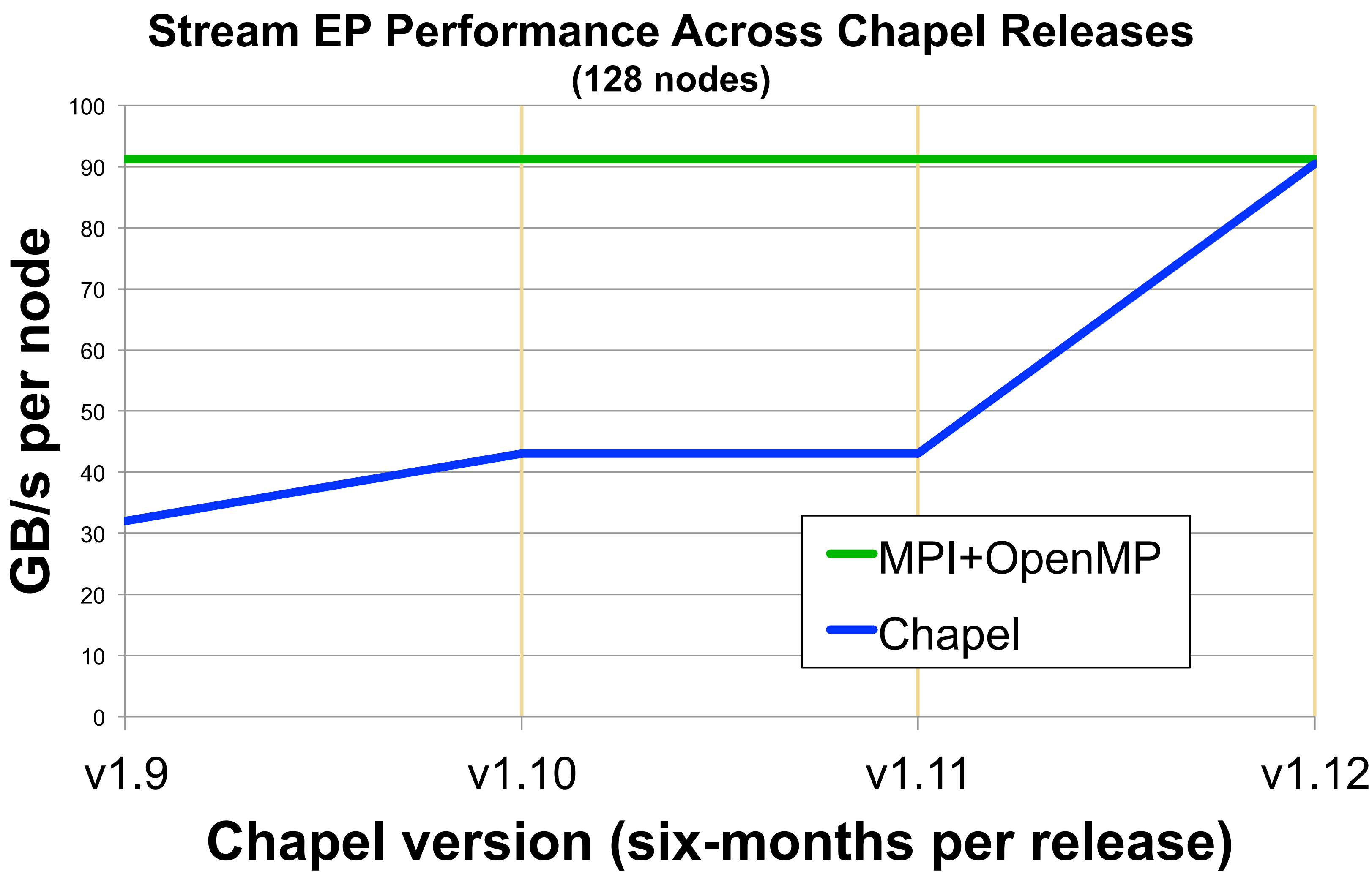
(and many others as well…)

http://chapel.cray.com/collaborations.html

Chapel is a Work-in-Progress

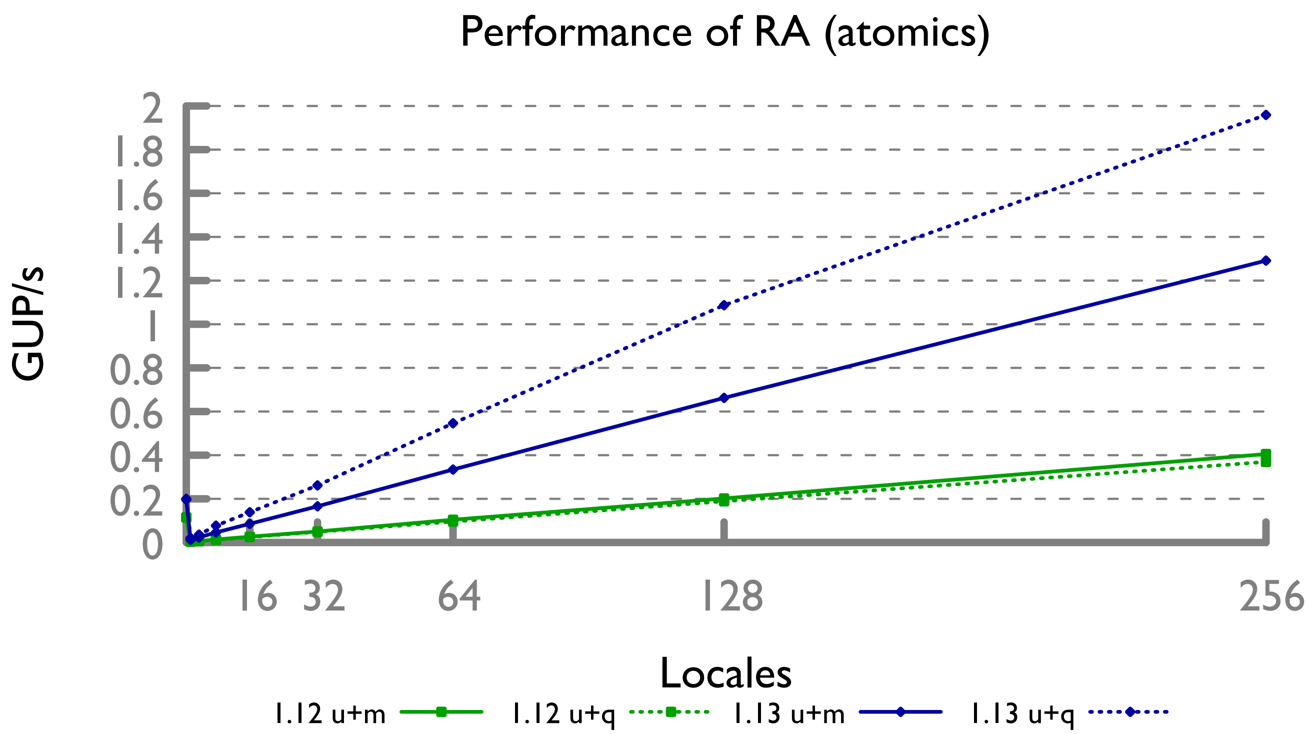
- **Currently being picked up by early adopters**
  - Users who try it generally like what they see
  - Last release got 1400+ downloads over six months
- **Most features are functional and working well**
  - some areas need improvements: strings, object-oriented features, …
- **Performance can be hit-or-miss**
  - shared memory performance is often competitive with C+OpenMP
  - distributed memory performance needs more work
- **We are actively working to address these lacks**

Stream-EP Performance Over Time



Scalability: RA (atomics) Performance

- **RA (atomics) summary**
  - 5x better performance for ugni-qthreads
  - 3x better performance for ugni-muxed



Chapel Resources: For More Information

Chapel Websites

Project page: http://chapel.cray.com

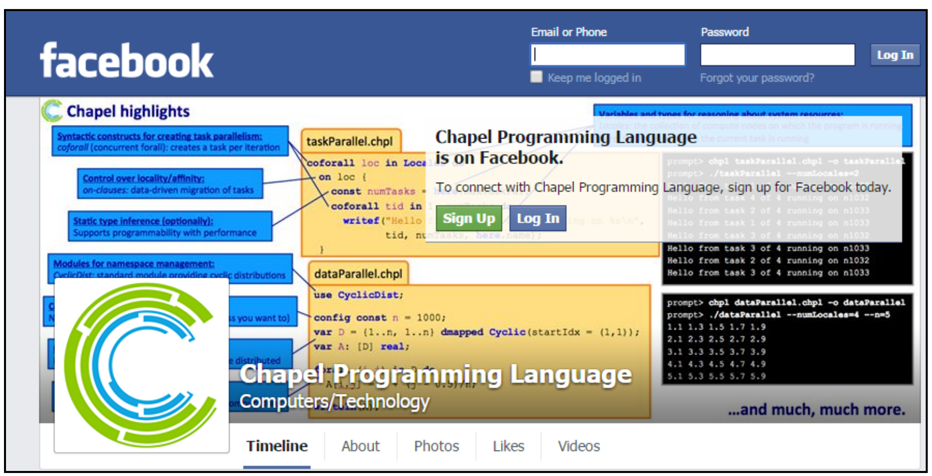
- overview, papers, presentations, language spec, …

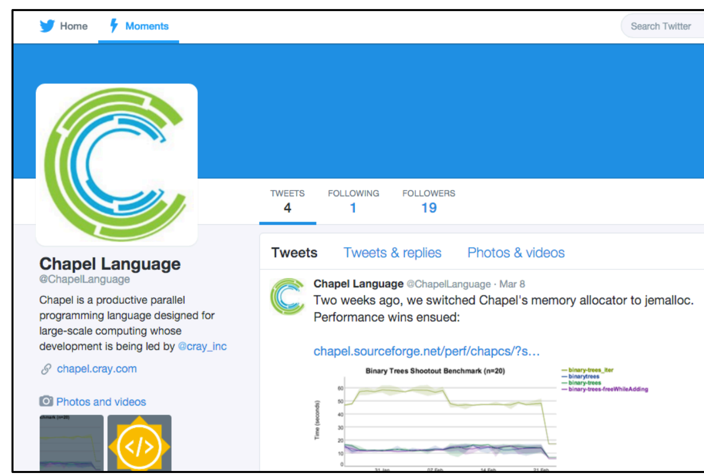
GitHub: https://github.com/chapel-lang

- download Chapel; browse source repository; contribute code

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

Twitter: https://twitter.com/ChapelLanguage

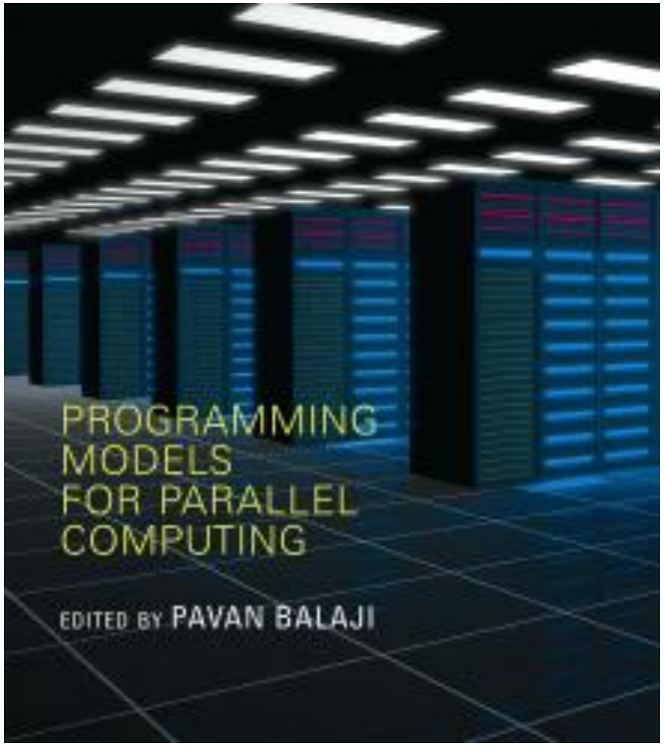




Suggested Reading

Chapel chapter from ***Programming Models for Parallel Computing***

- *a detailed overview of Chapel's history, motivating themes, features*
- *edited by Pavan Balaji, published by MIT Press*
- *an early draft is available online, entitled A Brief Overview of Chapel*



Other Chapel papers/publications available at **http://chapel.cray.com/papers.html**

Chapel Blog Articles

Chapel: Productive Parallel Programming, Cray Blog, May 2013.

- *a short-and-sweet introduction to Chapel*

Chapel Springs into a Summer of Code, Cray Blog, April 2016.

- *a run-down of some current events*

Six Ways to Say "Hello" in Chapel **(parts 1, 2, 3)**, Cray Blog, Sep-Oct 2015.

- *a series of articles illustrating the basics of parallelism and locality in Chapel*

Why Chapel? **(parts 1, 2, 3)**, Cray Blog, Jun-Oct 2014.

- *a series of articles answering common questions about why we are pursuing Chapel in spite of the inherent challenges*

[Ten] Myths About Scalable Programming Languages, IEEE TCSC Blog (index available on chapel.cray.com "blog articles" page), Apr-Nov 2012.

- *a series of technical opinion pieces designed to argue against standard reasons given for not developing high-level parallel languages*

Chapel Mailing Lists

low-traffic (read-only):

- chapel-announce@lists.sourceforge.net: announcements about Chapel

community lists:

- chapel-users@lists.sourceforge.net: user-oriented discussion list
- chapel-developers@lists.sourceforge.net: developer discussions
- chapel-education@lists.sourceforge.net: educator discussions
- chapel-bugs@lists.sourceforge.net: public bug forum

(subscribe at SourceForge: http://sourceforge.net/p/chapel/mailman/**)**

To contact the Cray team:

- chapel_info@cray.com: contact the team at Cray
- chapel_bugs@cray.com: for reporting non-public bugs

Questions?

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