PGAS Programming and Chapel

Brad Chamberlain, Chapel Team, Cray Inc.

UW CSEP 524, Spring 2015

April 28th, 2015

Safe Harbor Statement

"Who is this guy Mike 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/instructive year at a startup

2002-present: have been working at Cray Inc.

- Hired to help with the HPCS program
- Convinced execs/customers that we should do a language
- Have been working on Chapel ever since

Also a UW CSE affiliate faculty member

- taught this class last time around Winter 2013

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**

- **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, …"

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to ensure performance”

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Computational Scientists:

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

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Computational Scientists:

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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."

Chapel's Implementation

- **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, …

Game Plan for Tonight

- **Rough outline:**
  - a bit of context: PGAS programming languages
  - lots of Chapel
- **Please feel free to ask questions as we go**
  - I can throttle as necessary
- **optionally: “Happy Office Hour” afterwards**
  - or: go catch Lightning Bolt at Neumo’s

Terminology Check

+

Introduction to PGAS* Programming

(* Partitioned Global Address Space)

Shared vs. Distributed Memory

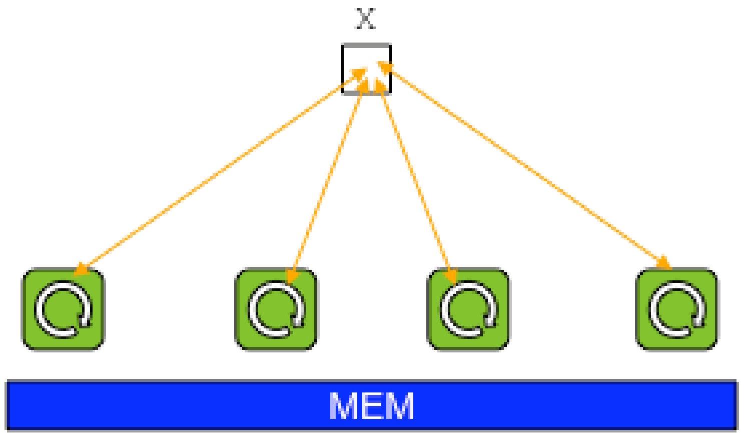
- **Shared Memory Architectures:**

- **Distributed Memory Architectures:**

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



SPMD Programming/Execution Models

SPMD =

SPMD Programming/Execution Models

***SPMD* = Single Program, Multiple Data**

- the dominant model for distributed memory programming
- Concept:
  - write one copy of a program
  - execute multiple copies of it simultaneously
    - various terms: *images*, *processes, PEs* (*Processing Elements*)*, ranks, …*
    - one per compute node? one per core?
  - in a pure SPMD model, this is the only source of parallelism
    - i.e., run *p* copies of my program in parallel
    - our parallel tasks are essentially the program images
  - in practice, each program can also contain parallelism
    - typically achieved by mixing two notations (e.g., MPI + OpenMP)

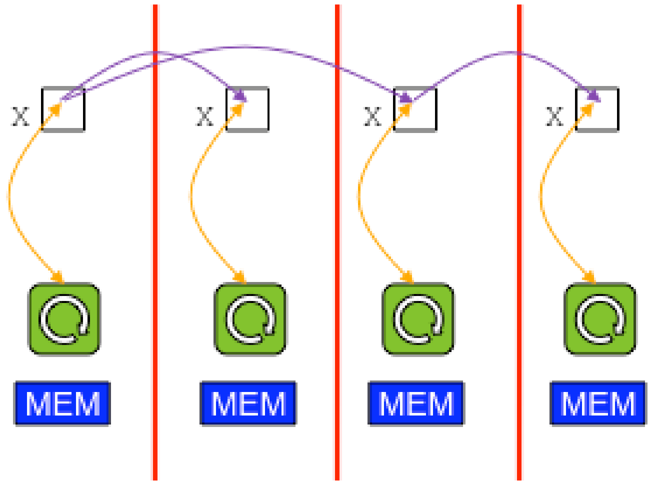
How Do SPMD Program Images Interact?

- **Message Passing (the most common HPC paradigm):**
  - “messages”: essentially buffers of data
  - primitive message passing operations: send/receive
  - primary example: MPI

Message Passing Programming Models (Distributed Memory)

e.g., MPI

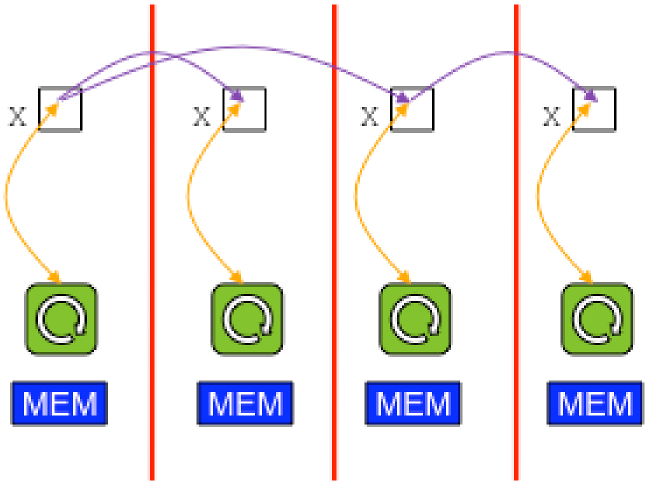
+ a more constrained model; can only access local data
+ runs on most large-scale parallel platforms
  - and for many of them, can achieve near-optimal performance
+ is *relatively* easy to implement
+ can serve as a strong foundation for higher-level models
+ users have been able to get real work done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



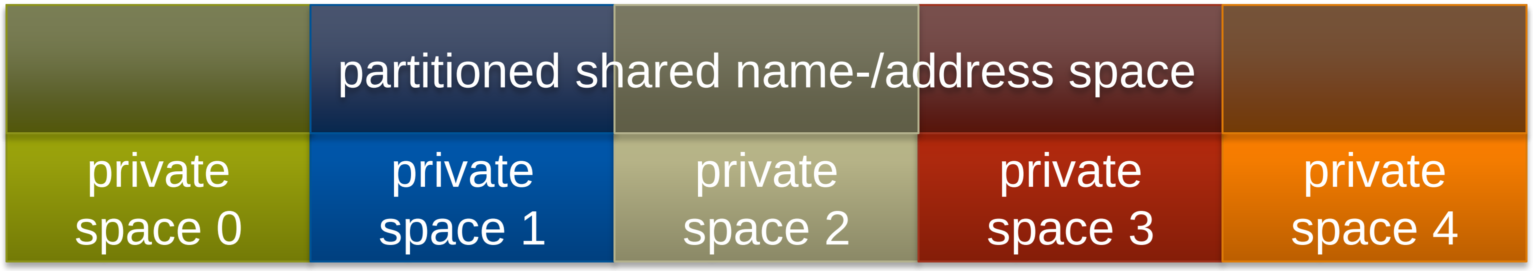
How Do SPMD Program Images Interact?

- **Message Passing (the most common HPC paradigm):**
  - "messages": essentially buffers of data
  - primitive message passing operations: send/receive
  - primary example: MPI
- **Other alternatives:**
  - Single-Sided Communication
  - Partitioned Global Address Spaces
  - Active Messages
  - …

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



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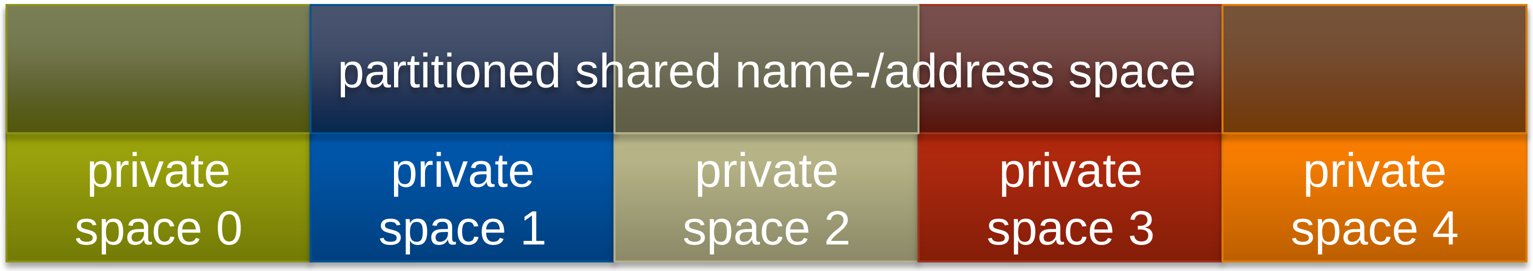
    - every variable has a well-defined location
    - local variables are cheaper to access than remote ones



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- **abstract concept:**
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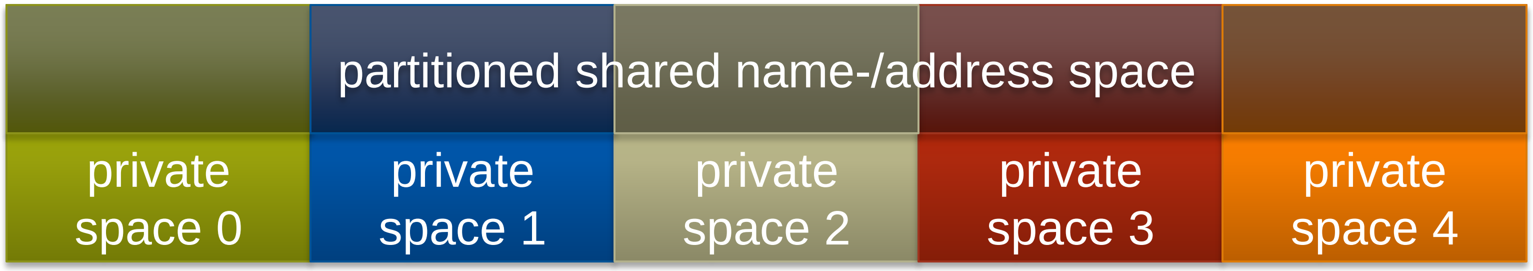
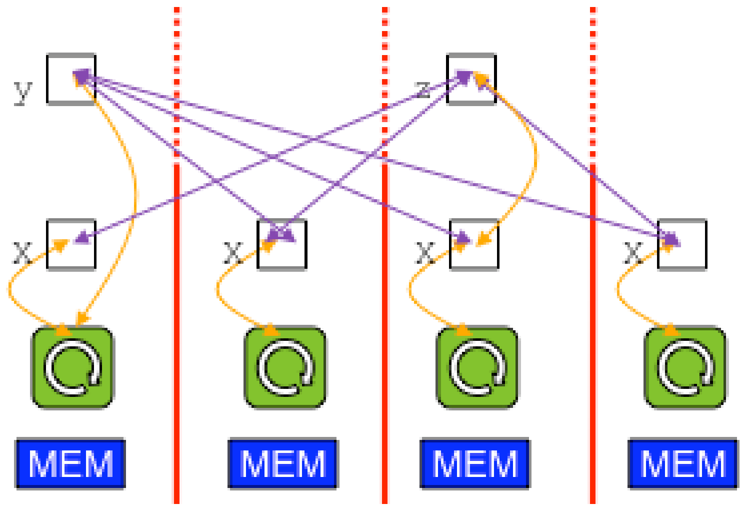
- **traditional PGAS languages have been SPMD in nature**
  - best-known examples: Co-Array Fortran, UPC



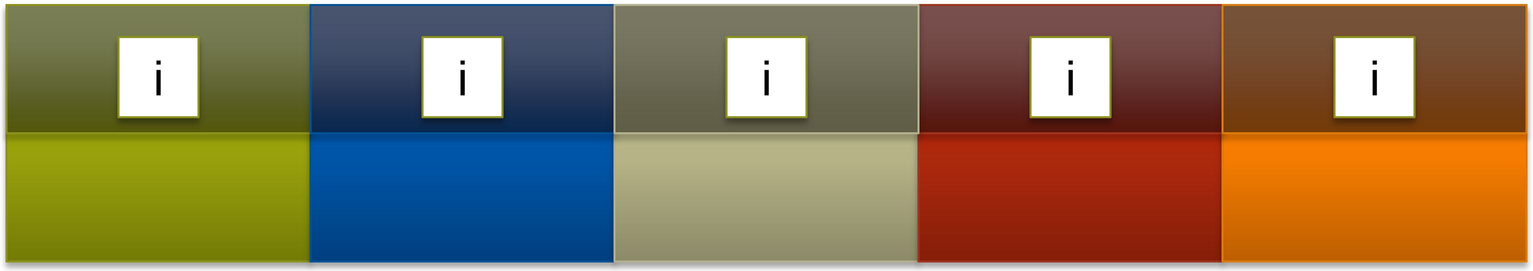
Traditional PGAS Languages

e.g., Co-Array Fortran, UPC



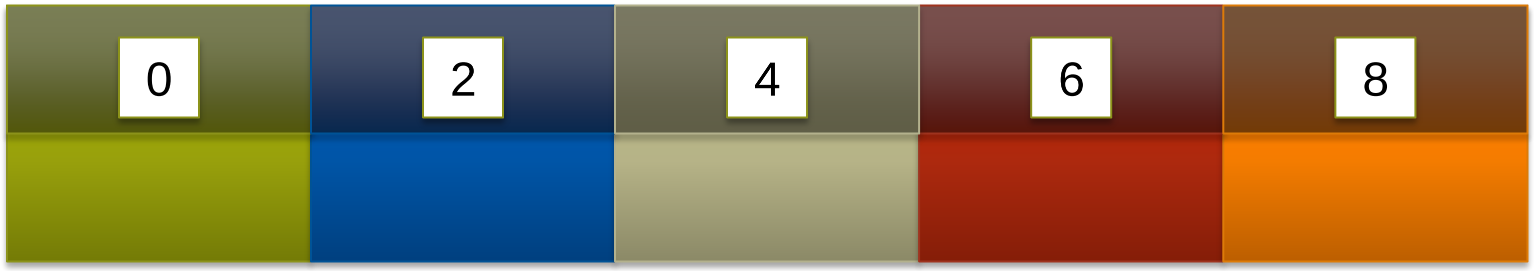
SPMD PGAS Languages (using a pseudo-language)

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



SPMD PGAS Languages (using a pseudo-language)

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



SPMD PGAS Languages (using a pseudo-language)

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proc main() {
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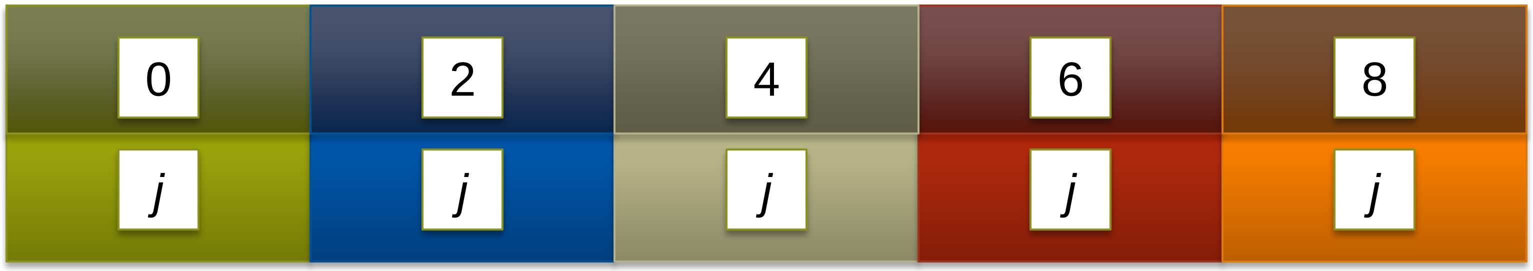
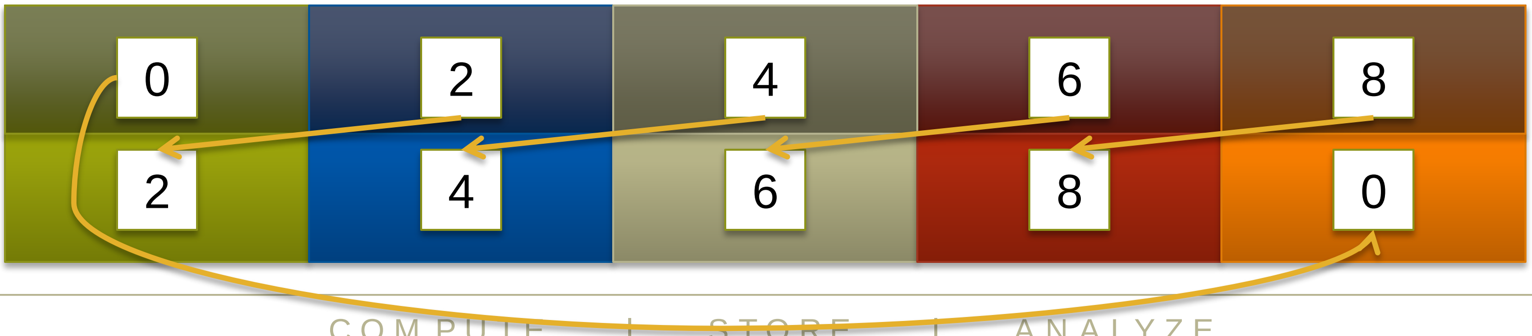


SPMD PGAS Languages (using a pseudo-language)

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

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



Traditional PGAS Languages

founding PGAS members: Co-Array Fortran, UPC, Titanium

- extensions to Fortran, C, and Java, respectively
- details vary, but potential for:
  - arrays that are decomposed across compute nodes
  - pointers that refer to remote objects
- note that earlier languages could also be considered PGAS, but the term hadn't been coined yet

UPC: Unified Parallel C

UPC: **A "traditional" PGAS language**

- developed ~1999
- "unified" in the sense that it combined 3 distinct parallel C's:
  - AC, Split-C, Parallel C Preprocessor
- though a sibling to CAF, philosophically quite different

Motivating Philosophy:

- extend C concepts logically to support SPMD execution
  - 1D arrays
  - for loops
  - pointers (and pointer/array equivalence)

UPC is also SPMD

- **SPMD programming/execution model**
  - program copies are referred to as ‘threads’
- **Built-in constants provide the basics:**

```
int p, me;
p = THREADS;      // returns number of processes
me = MYTHREAD;    // returns a value in 0..THREADS-1
```

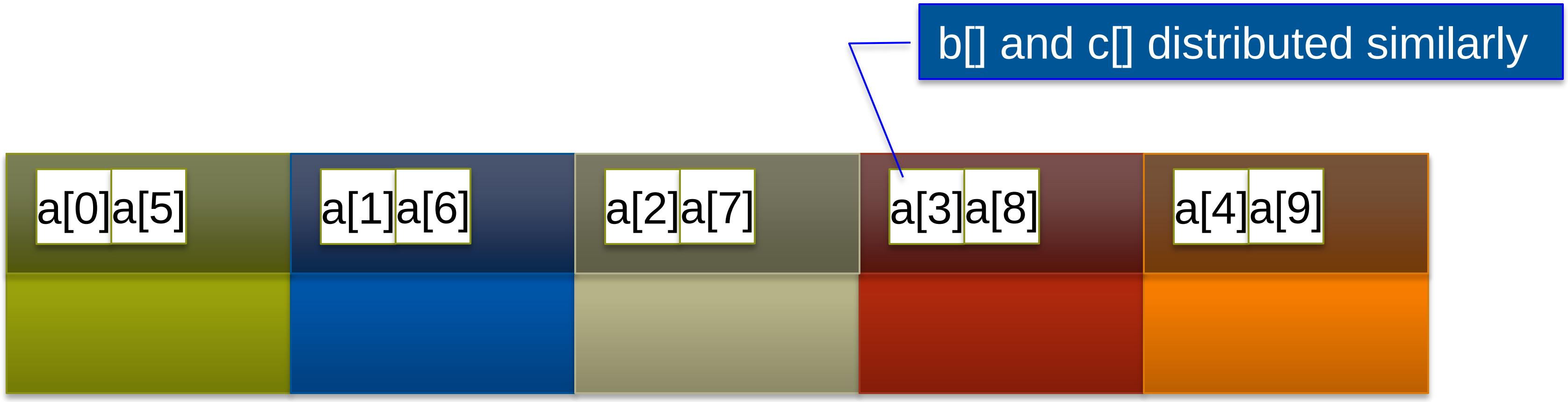
- **Barrier synch statement:**

```
upc_barrier;      // wait for all processes/threads
```

Distributed Arrays in UPC

- **Arrays declared with the ‘shared’ keyword are distributed within the shared space**
  - uses a cyclic distribution by default

```
#define N 10
shared float a[N], b[N], c[N];
```



Distributed Arrays in UPC

- **Arrays declared with the ‘shared’ keyword are distributed within the shared space**
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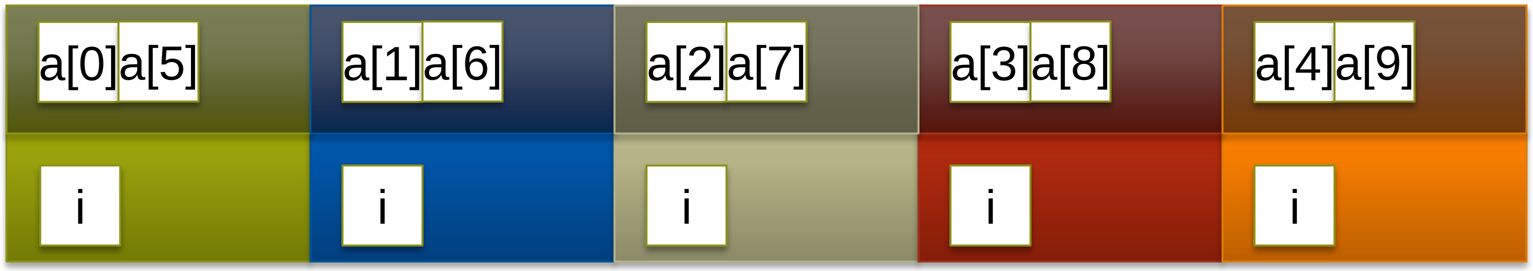
```
#define N 10
shared float a[N], b[N], c[N];
int i=0; // no "shared" keyword => stored privately
```



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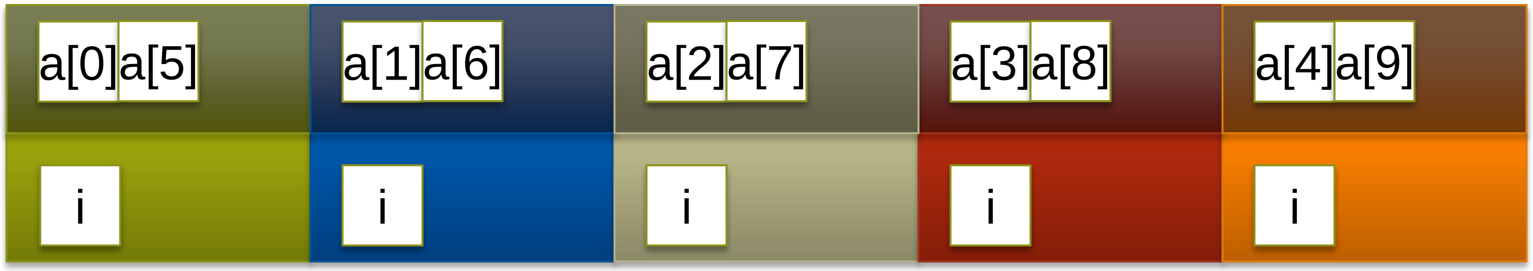
```
#define N 10
shared float a[N], b[N], c[N];
for (int i=0; i<N; i++) { // dumb loop: O(N)
  if (i%THREADS == MYTHREAD) {
    c[i] = a[i] + alpha * b[i];
  }
}
```



Distributed Arrays in UPC

- **Arrays declared with the ‘shared’ keyword are distributed within the shared space**
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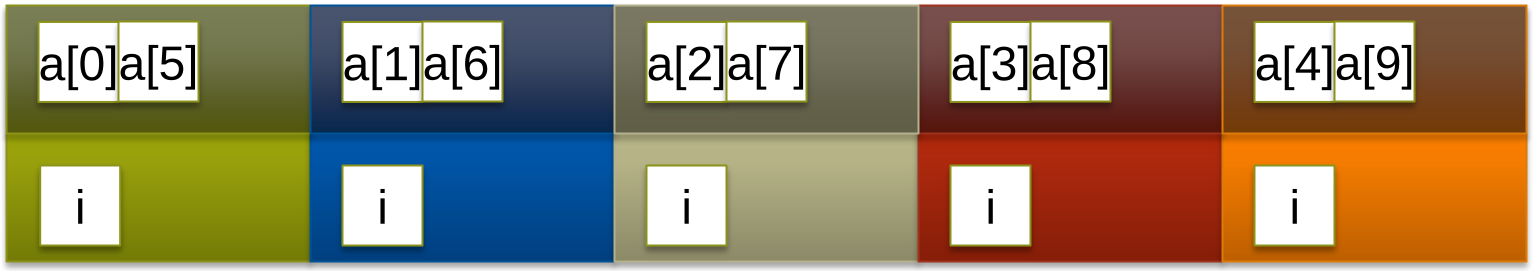
```
#define N 10
shared float a[N], b[N], c[N];
// smarter loop: O(N/THREADS)
for (int i=MYTHREAD; i<N; i+=THREADS) {
  c[i] = a[i] + alpha * b[i];
}
```



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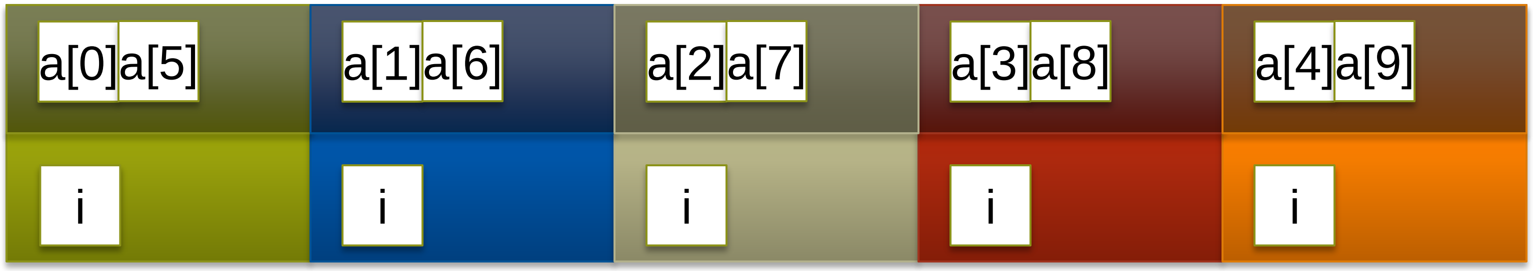
```
#define N 10
shared float a[N], b[N], c[N];
upc_forall (int i=0; i<N; i++; i) {
  c[i] = a[i] + alpha * b[i];
}
```

Affinity field: Which thread should execute this iteration? (if int, %THREADS to get ID)

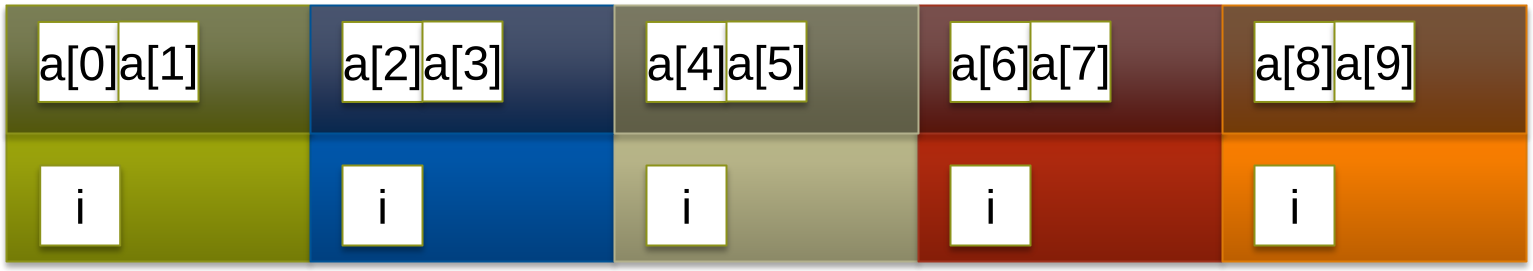


Distributed Arrays in UPC

- **Arrays declared with the ‘shared’ keyword are distributed within the shared space**
  - can specify a block-cyclic distribution as well

```
#define N 10
shared [2] float a[N], b[N], c[N];
upc_forall (int i=0; i<N; i++; &c[i]) {
  c[i] = a[i] + alpha * b[i];
}
```

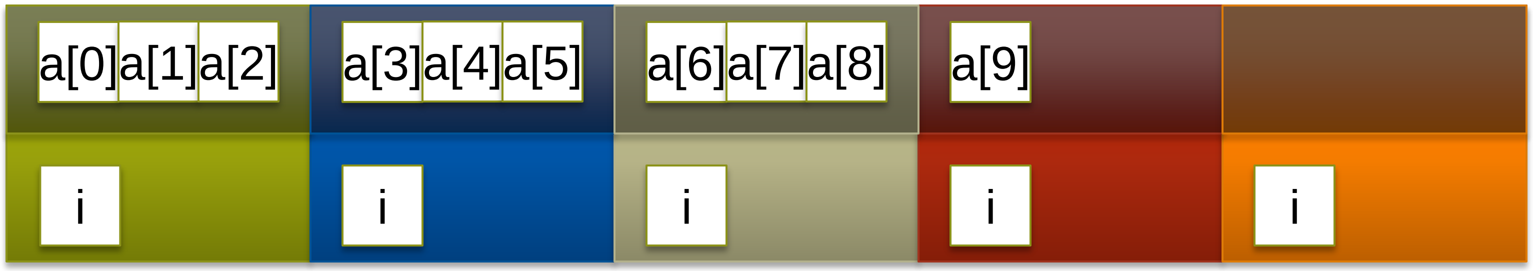
Affinity field: Which thread should execute this iteration? (if ptr-to-shared, owner does)



Distributed Arrays in UPC

- **Arrays declared with the ‘shared’ keyword are distributed within the shared space**
  - can specify a block-cyclic distribution as well

```
#define N 10
shared [3] float a[N], b[N], c[N];
upc_forall (int i=0; i<N; i++; &c[i]) {
  c[i] = a[i] + alpha * b[i];
}
```



Distributed Arrays in UPC

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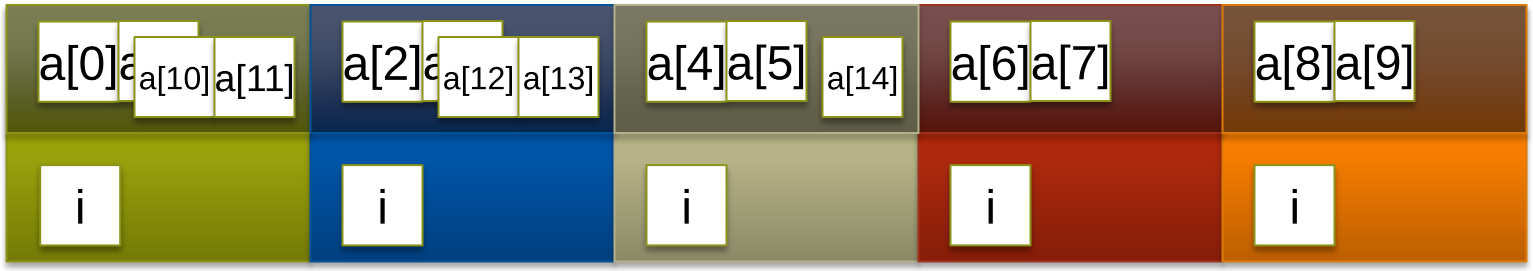
```
#define N 15
shared [2] float a[N], b[N], c[N];
upc_forall (int i=0; i<N; i++; &c[i]) {
  c[i] = a[i] + alpha * b[i];
}
```

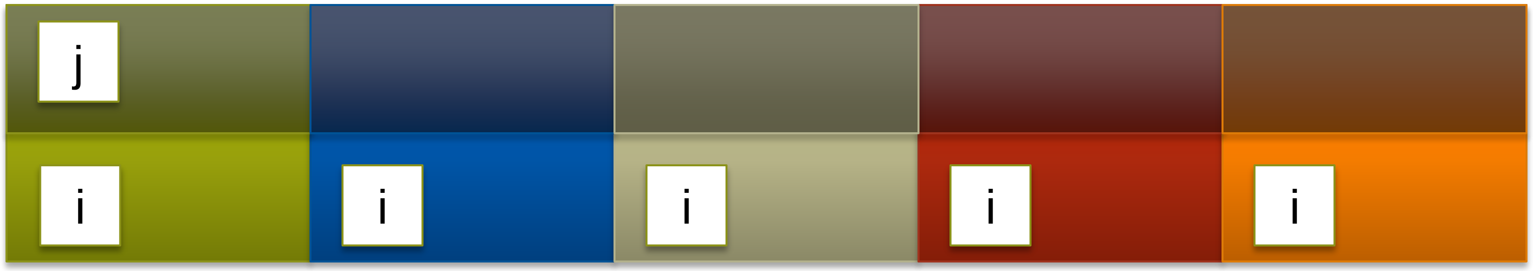


Scalars in UPC

- Somewhat confusingly (to me anyway*), shared scalars in UPC result in a single copy on thread 0

```
int i;
shared int j;
```

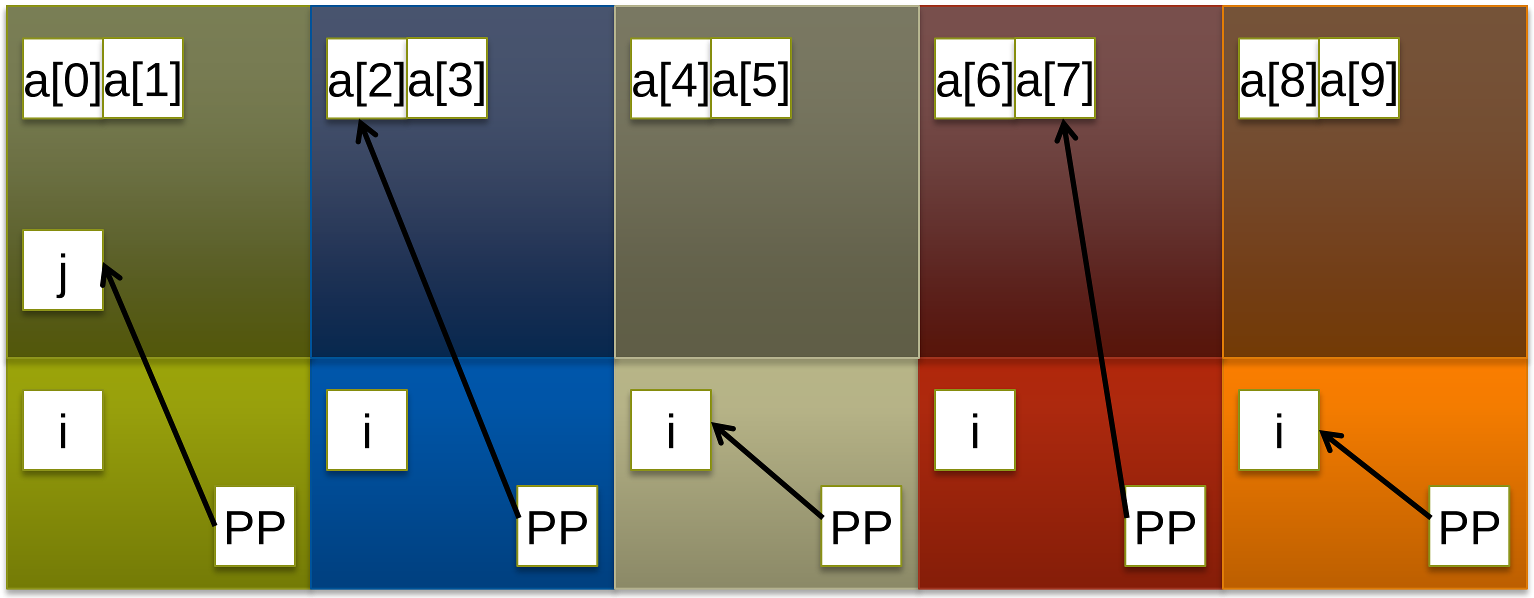
* = because it seems contrary to SPMD programming



Pointers in UPC

- UPC Pointers may be private/shared and may point to private/shared

```
int* PP; // private pointer to local data
```



Pointers in UPC

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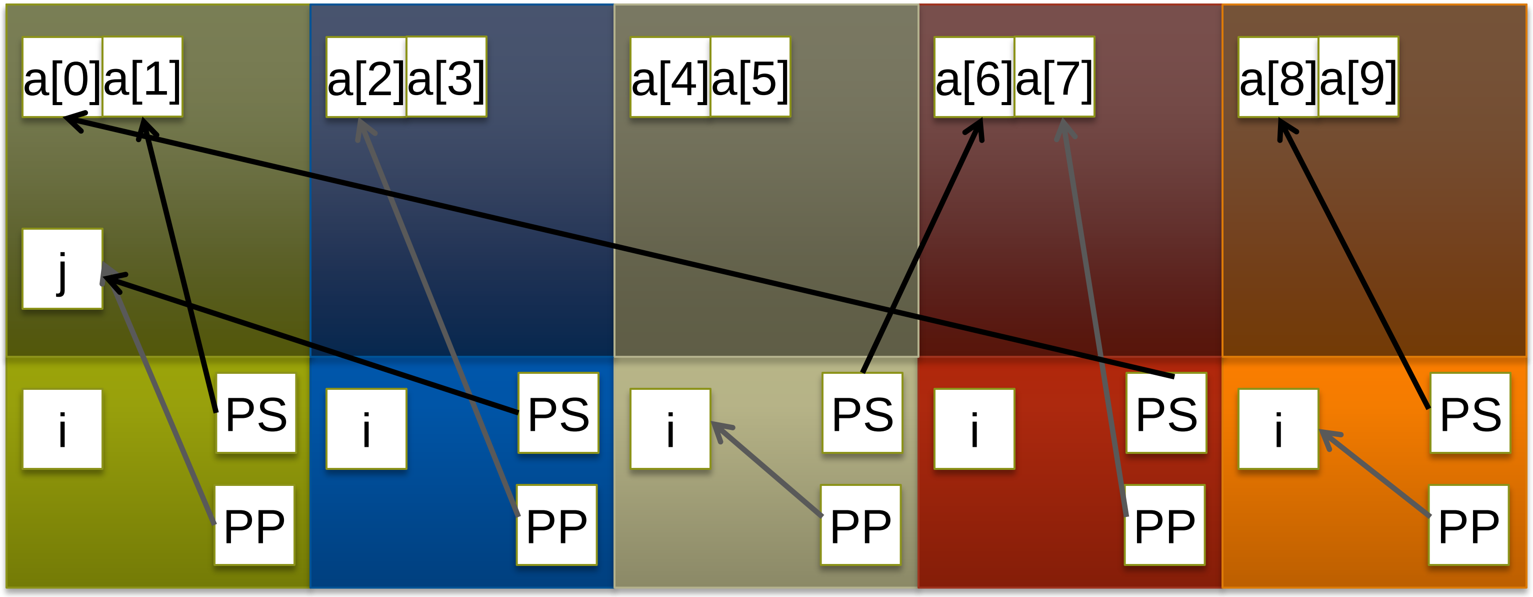
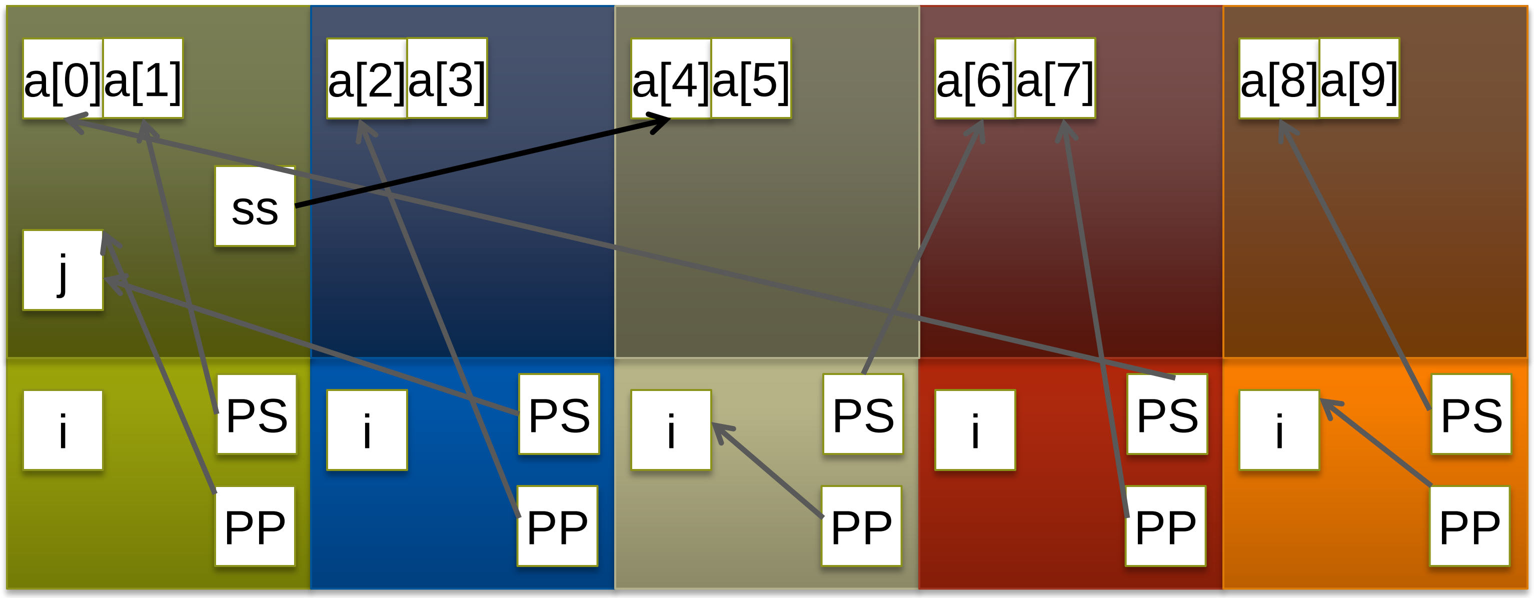
```
int* PP;  // private pointer to local data
shared int* PS;  // private pointer to shared data
```



Pointers in UPC

- UPC Pointers may be private/shared and may point to private/shared

```
int* PP;                 // private pointer to local data
shared int* PS;          // private pointer to shared data
shared int* shared SS;   // shared pointer to shared data
```

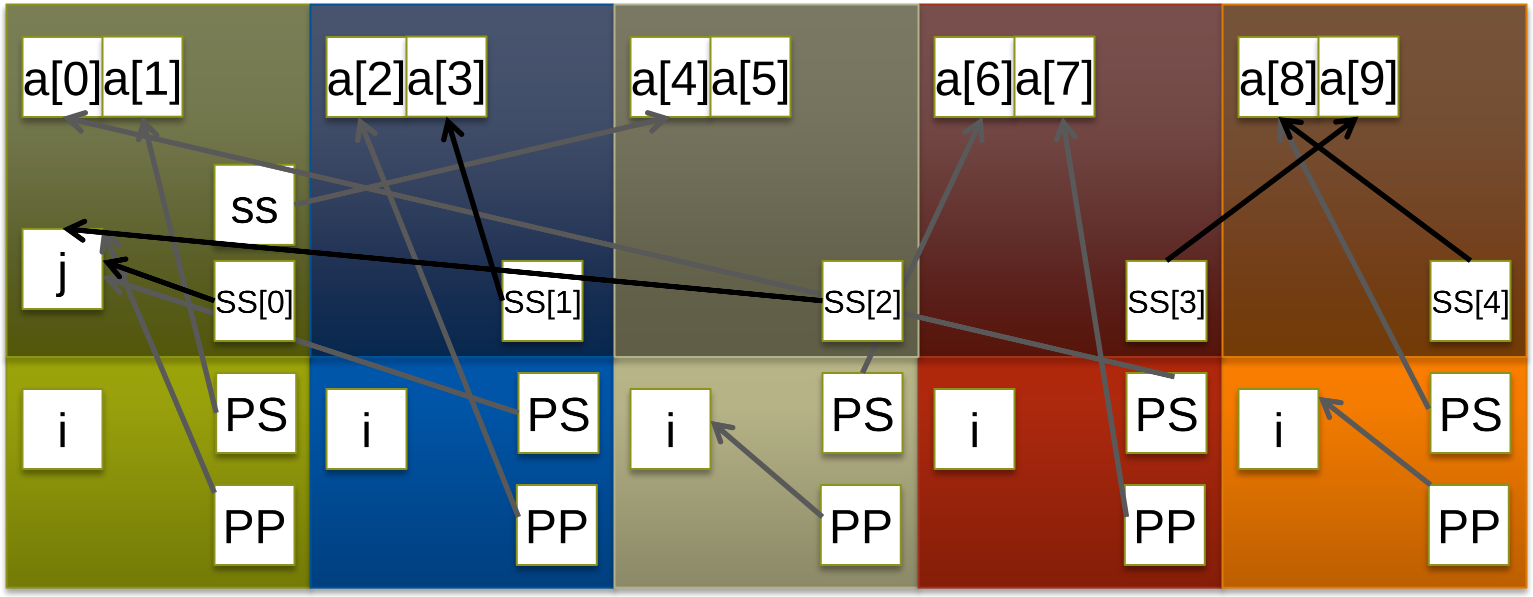


Arrays of Pointers in UPC

- Of course, one can also create arrays of pointers

```
// array of shared pointer to shared data
shared int* shared SS[THREADS];
```

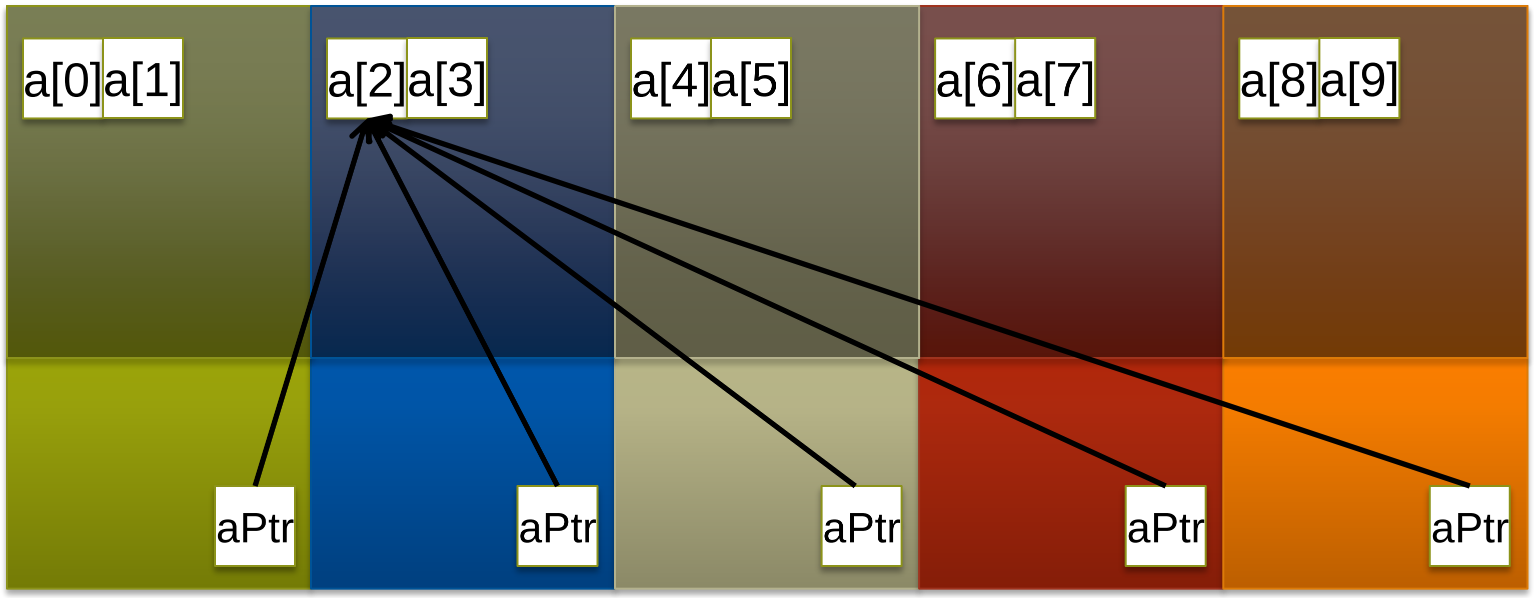
- As you can imagine, one UPC's strengths is its ability to create fairly arbitrary distributed data structures



Array/Pointer Equivalence in UPC

- As in C, pointers can be walked through memory

```
shared [2] float a[N];
shared float* aPtr[THREADS] = &(a[2]);
```



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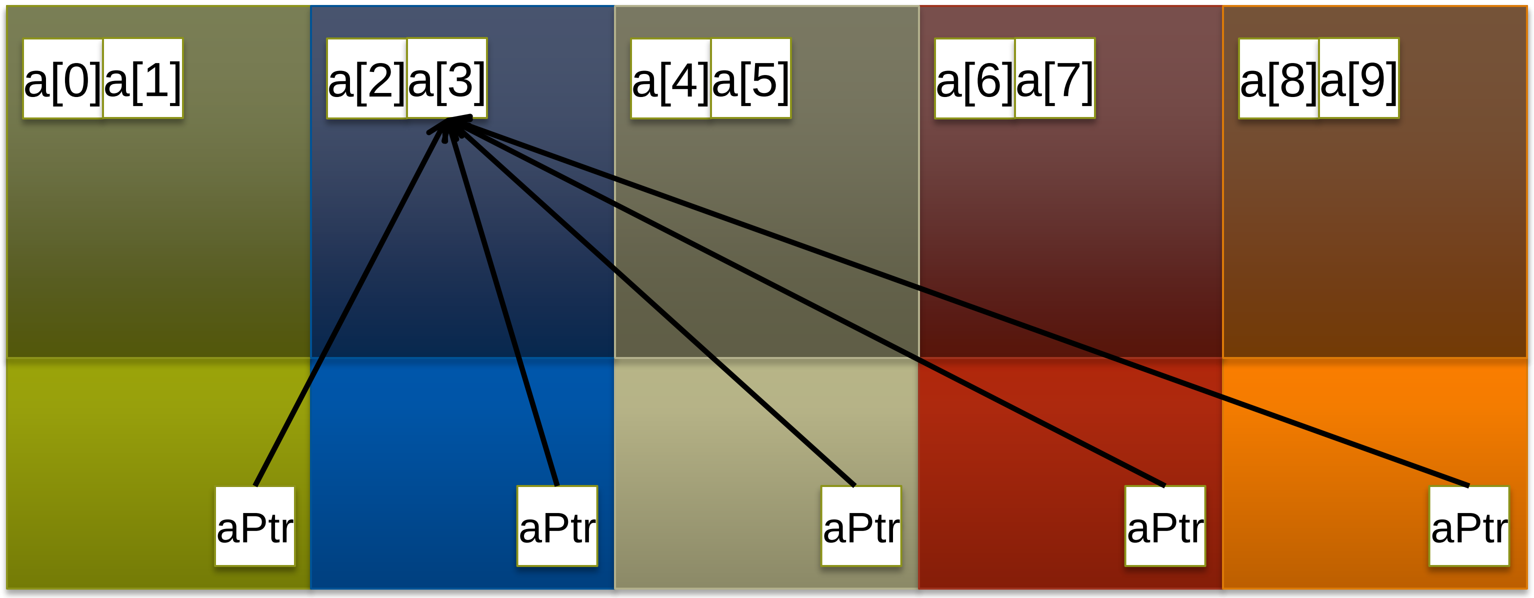

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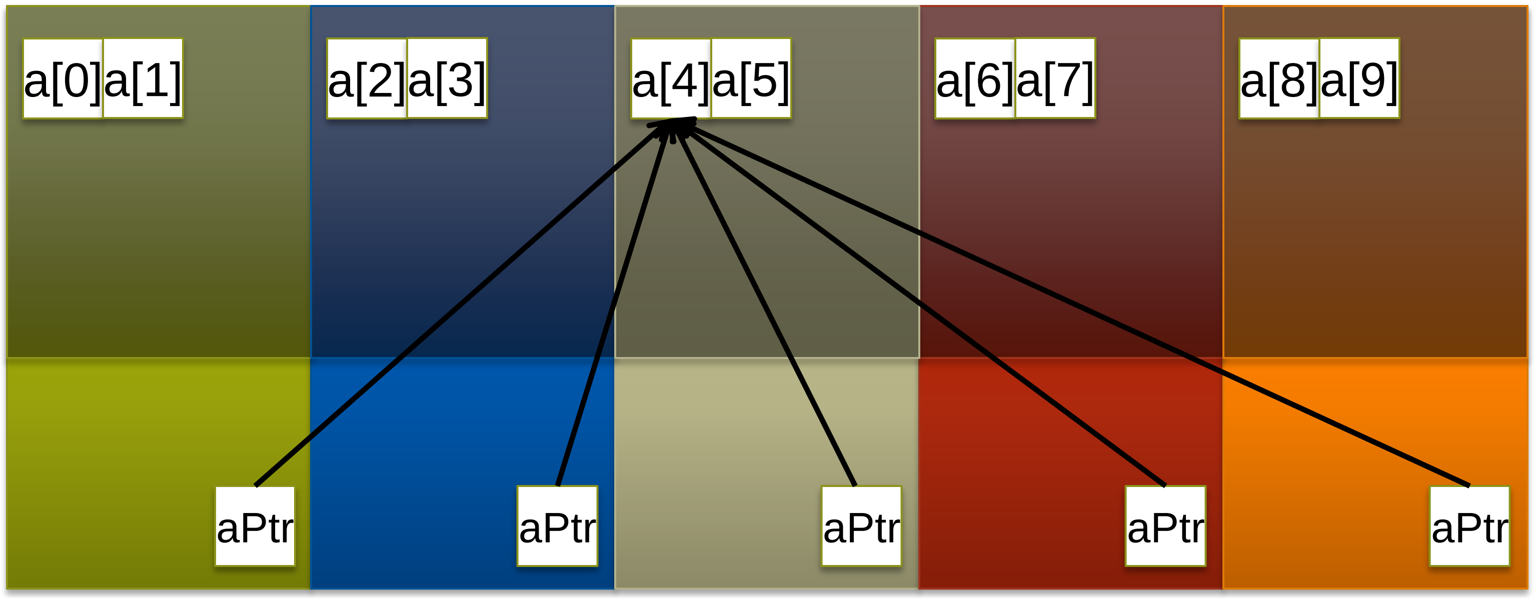


How are UPC Pointers Implemented?

- **Local pointers to local: just an address, as always**
- **Pointers to shared: 3 parts**
  - thread ID
  - base address of block within the thread
  - phase/offset within the block (0..blocksize-1)
- **UPC supports a number of utility functions that permit you to query this information from pointers**
- **Casting between pointer types is permitted**
  - but can be dangerous (as in C) and/or lossy

Other Features in UPC

- **Collectives Library**
- **Memory Consistency Model**
  - among the first/foremost memory models in HPC
  - ability to move between strict and relaxed models
  - fence operations
- **Dynamic Memory Management**
- **Locks**
- **Parallel I/O**
- **…**

UPC Summary

- **Program in SPMD style**
- **Communicate via shared arrays/pointers**
  - cyclic and block-cyclic arrays
  - pointers to shared and private data
  - array-pointer equivalence
- **Other stuff too, but this gives you the main idea**
- **For more information, see https://upc-lang.org/upc/**

Other Notable SPMD PGAS Languages

Founding Fathers:

- **Co-Array Fortran (CAF):** A Fortran-based PGAS language
  - Remote accesses are much more explicit than in UPC
  - Distributed arrays are better (multidimensional, like Fortran's)
    - …but also worse (must declare in terms of per-image chunks)
  - Adopted into the Fortran 2008 standard
- **Titanium: A Java-based PGAS language**
  - my favorite of the three

New Kids on the Block:

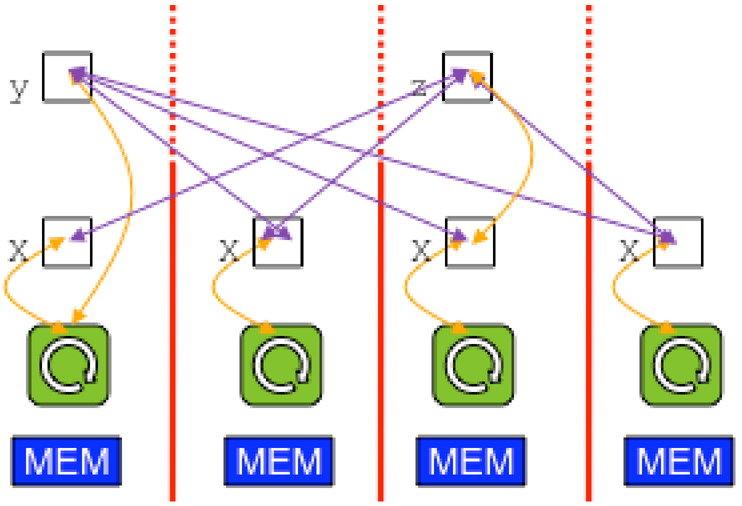
- **UPC++**
- **Co-Array C++**

} C++ PGAS languages designed using template meta-programming (so, no compiler required)

Traditional PGAS Languages

e.g., Co-Array Fortran, UPC

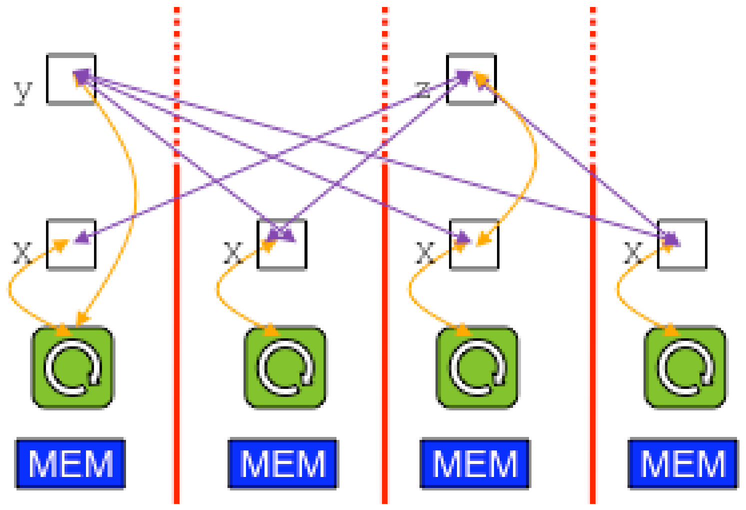
+ support a shared namespace, like shared-memory
+ support a strong sense of ownership and locality
  - each variable is stored in a particular memory segment
  - tasks can access any visible variable, local or remote
  - local variables are cheaper to access than remote ones
+ implicit communication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



Traditional PGAS Languages

***e.g.*, Co-Array Fortran, UPC**

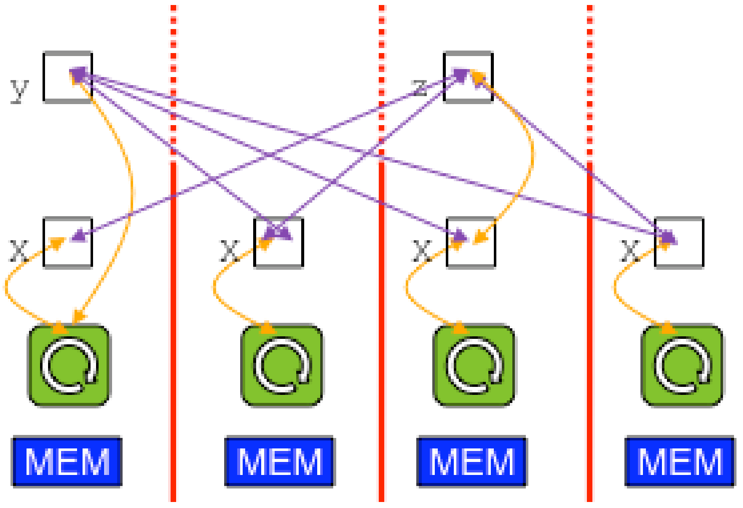
- restricted to SPMD programming and execution models
- data structures not as flexible/rich as one might like
- retain many of the downsides of shared-memory
  - error cases, memory consistency models



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



Chapel Motivation

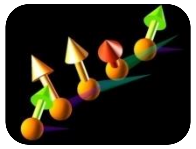
Sustained Performance Milestones

1 GF – 1988: Cray Y-MP; 8 Processors

- Static finite element analysis

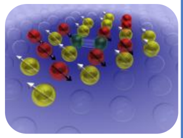
1 TF – 1998: Cray T3E; 1,024 Processors

- 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

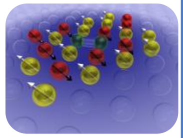
- Static finite element analysis
- Fortran77 + Cray autotasking + vectorization

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?

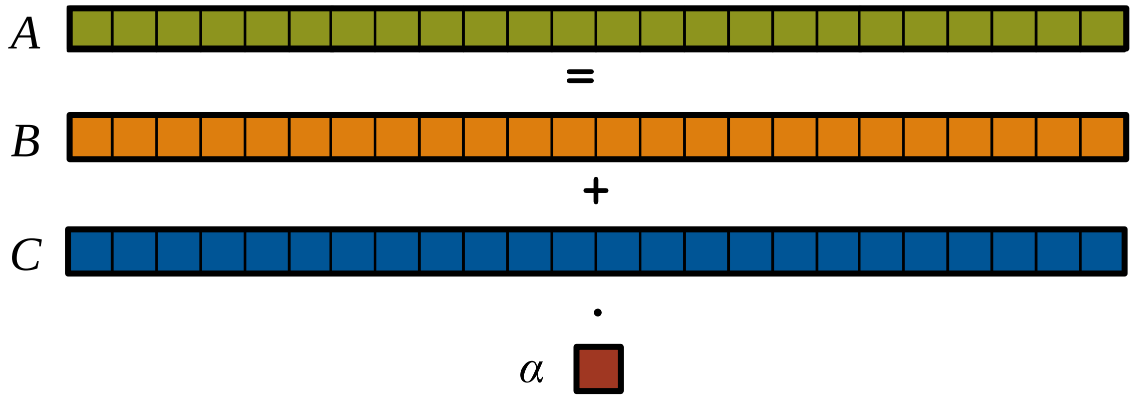
Or, perhaps something completely different?

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

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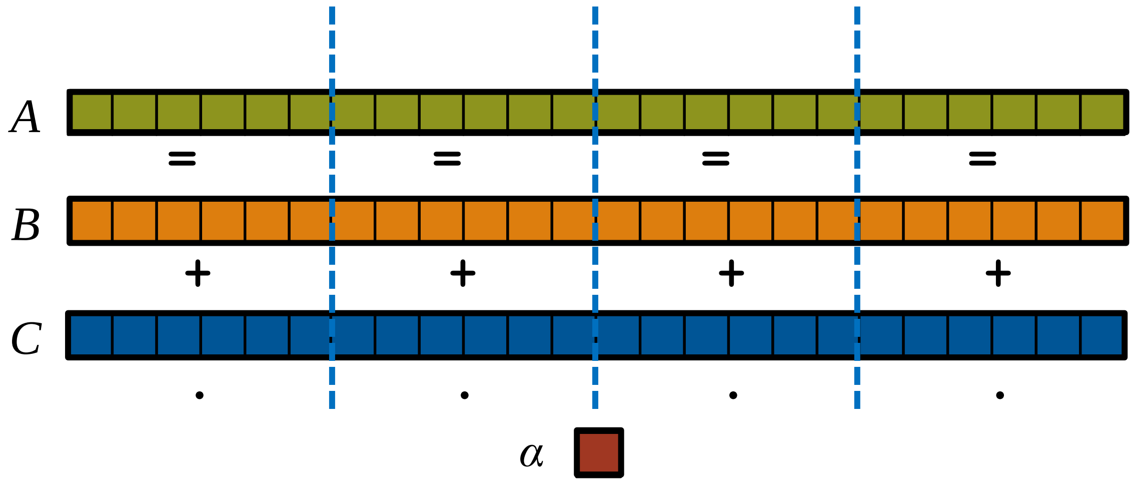
In pictures, in parallel:

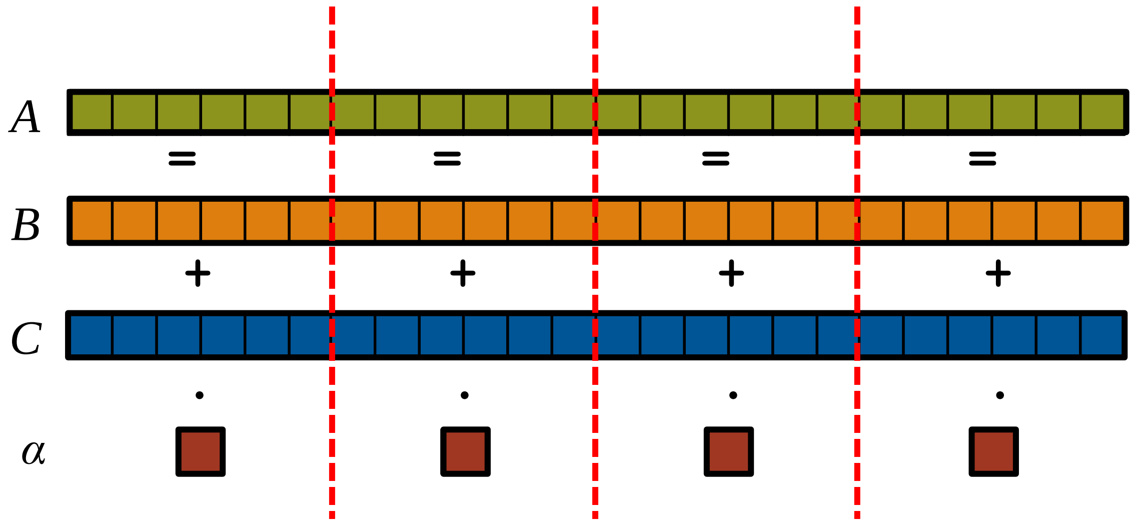


STREAM Triad: a trivial parallel computation

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):

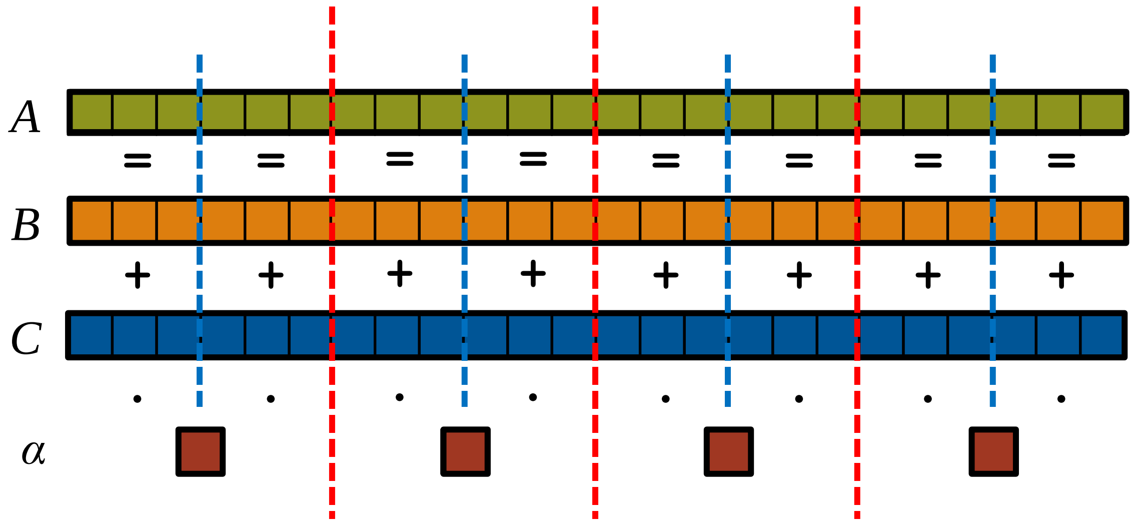


STREAM Triad: a trivial parallel computation

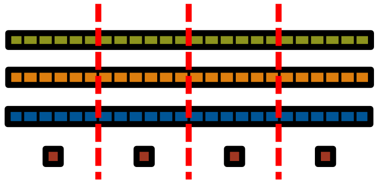
Given: m-element vectors A, B, C

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

In pictures, in parallel (distributed memory multicore):



STREAM Triad: MPI

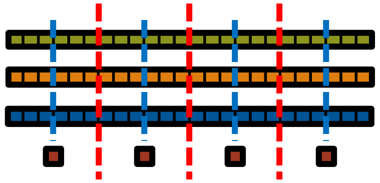


MPI

```
#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



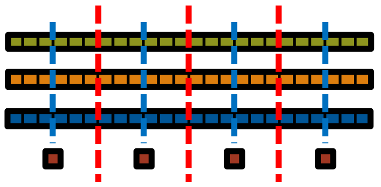
MPI + OpenMP

```
#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);
```

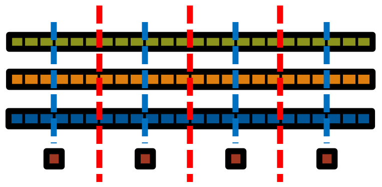
STREAM Triad: MPI+OpenMP vs. CUDA

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 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!

By Analogy: Let's Cross the United States!

OK, got my walking shoes on!

By Analogy: Let's Cross the United States!

OK, let's upgrade to hiking boots

By Analogy: Let's Cross the United States!

Washington
Oregon
Idaho
Montana
North Dakota
Minnesota
Wisconsin
Michigan
Maine
Vermont
New York
New Hampshire
Massachusetts
Connecticut
Rhode Island
South Dakota
Wyoming
United States
Nebraska
Iowa
Pennsylvania
New Jersey
Nevada
Utah
Colorado
Illinois
Indiana
Ohio
Delaware
Maryland
West Virginia
Virginia
Kansas
Missouri
Kentucky
California
Arizona
New Mexico
Oklahoma
Arkansas
Tennessee
North Carolina
South Carolina
Mississippi
Georgia
Alabama
Texas
Louisiana
Florida
Oops, need my ice axe

By Analogy: Let's Cross the United States!

I guess we need a canoe?!

By Analogy: Let's Cross the United States!

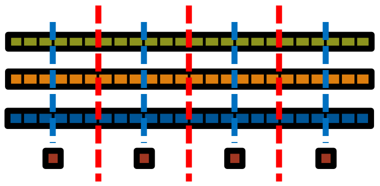
What a bunch of gear we have to carry around! This is getting old…

By Analogy: Let's Cross the United States!

…Hey, what's that sound?

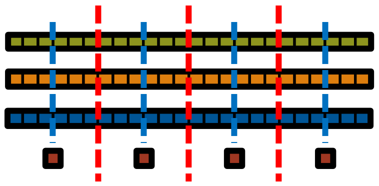
Rewinding a few slides…

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

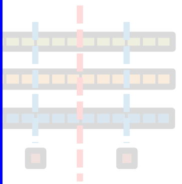
```
#include <hpcc.h>
#ifdef _OPENMP
#include <omp.h>
#endif

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

int HPCC_StarStream(HPCC_Params *par
  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 );
```

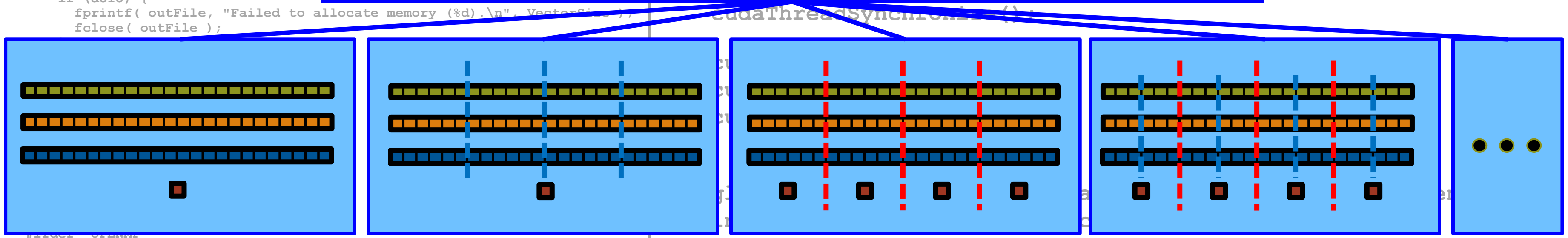
Chapel

```
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

```
;
;
;
N);
N);
_c, d_a, scalar,   N);
cudaThreadSynchronize();
```





```
#pragma omp parallel for
#endif
  for
    a[

  HPCC
  HPCC
  HPCC

  retu
}
```

```
if (idx < len) a[idx] = value;
```

<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

- ✓ Motivation
- ➢ Chapel Background and Themes
- ● Survey of Chapel Concepts
- ● Project Status and Next Steps

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

1) General Parallel Programming

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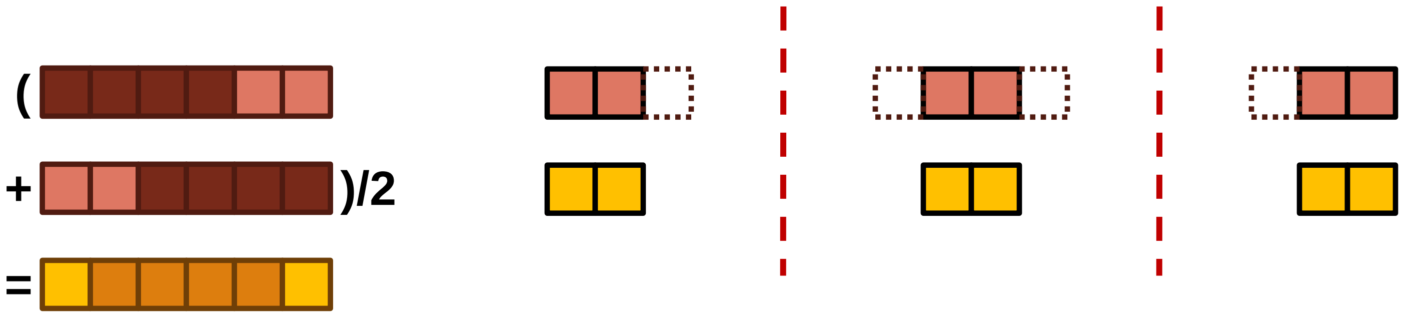
Instruction-level vectors/threads	Chapel	iteration
GPU/accelerator	Chapel	SIMD function/task

2) Global-View Abstractions

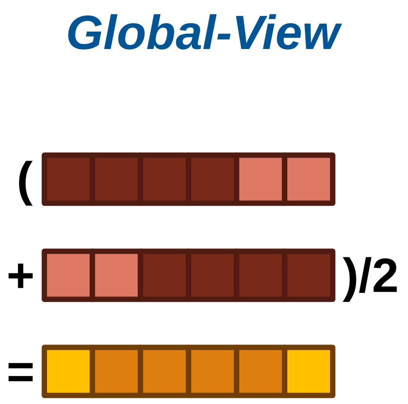
In pictures: “Apply a 3-Point Stencil to a vector”

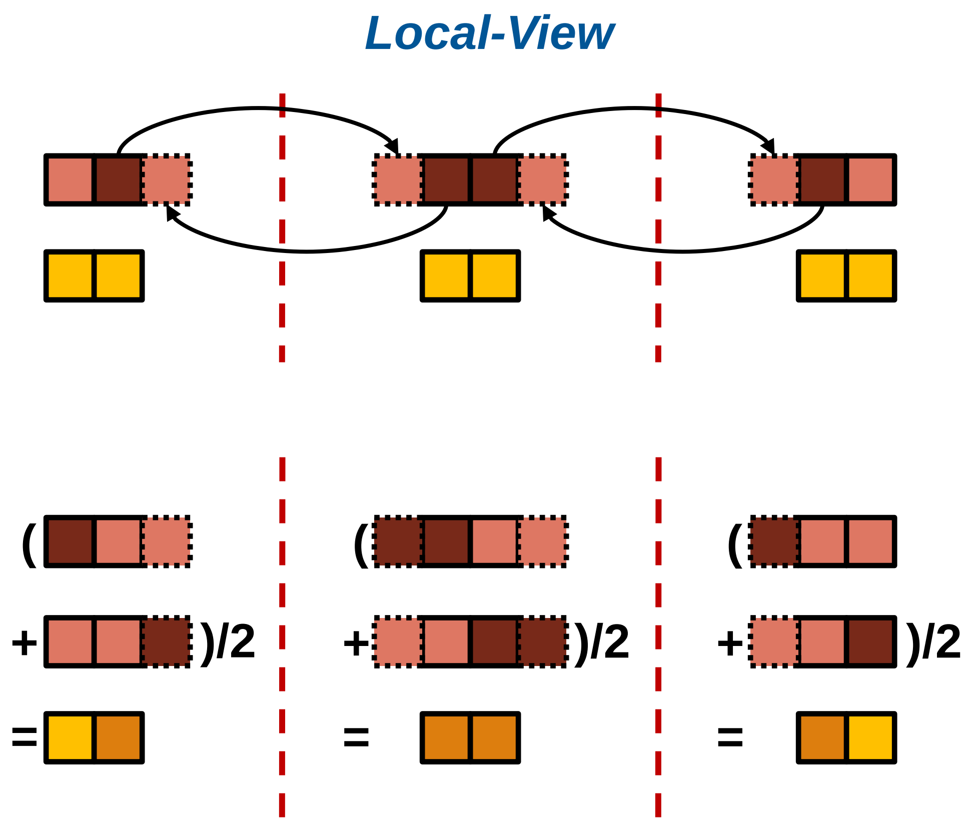
Global-View | *Local-View*



2) Global-View Abstractions

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

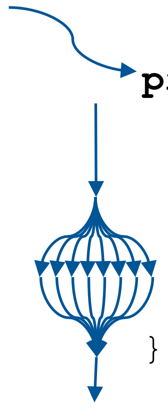




2) Global-View Abstractions

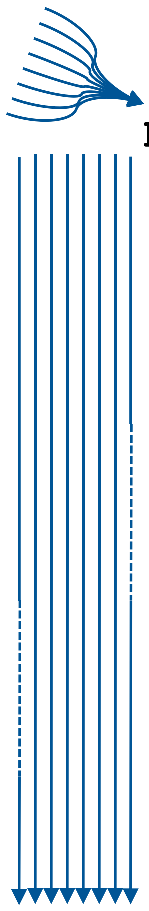
In code: “Apply a 3-Point Stencil to a vector”

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;
}
```

Local-View (SPMD)



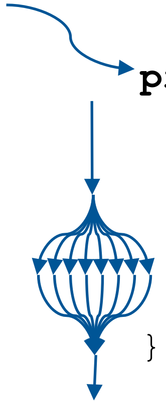
```
proc main() {
  var n = 1000;
  var p = numProcs(),
      me = myProc(),
      myN = n/p,
  var A, B: [0..myN+1] real;

  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"

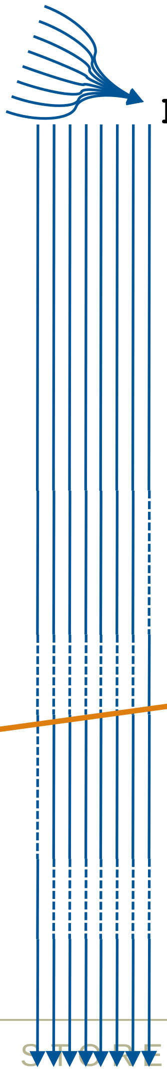
Global-View



```
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)



```
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;
}
```

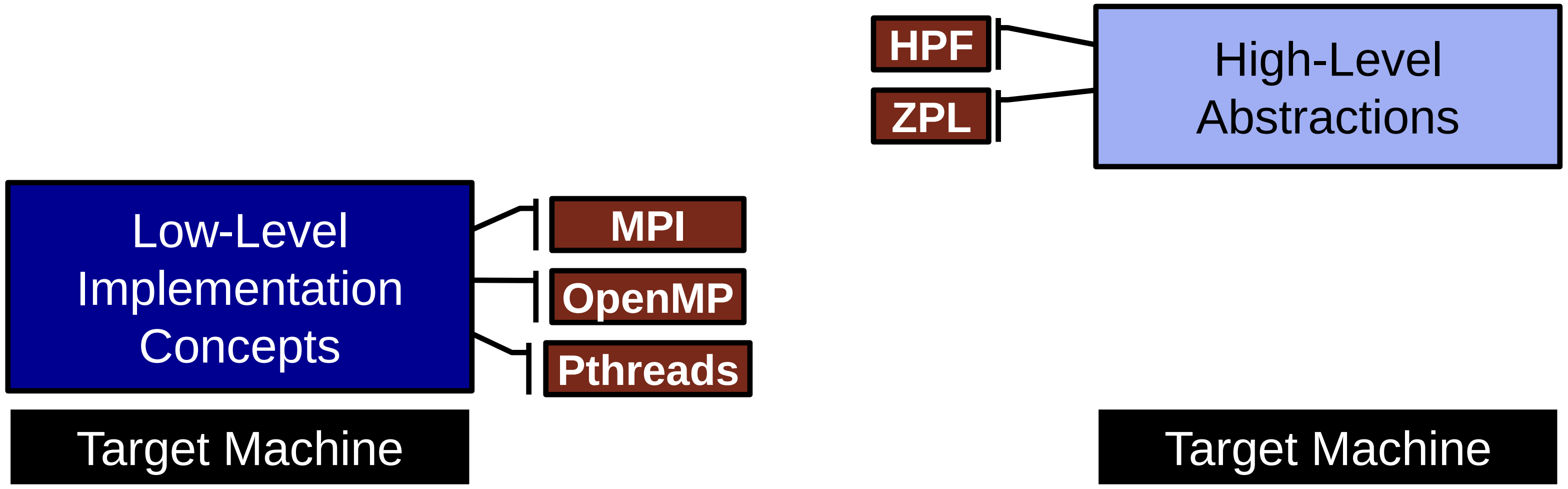
Assumes p divides n

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) {
  ...
}
```

3) Multiresolution Design: Motivation



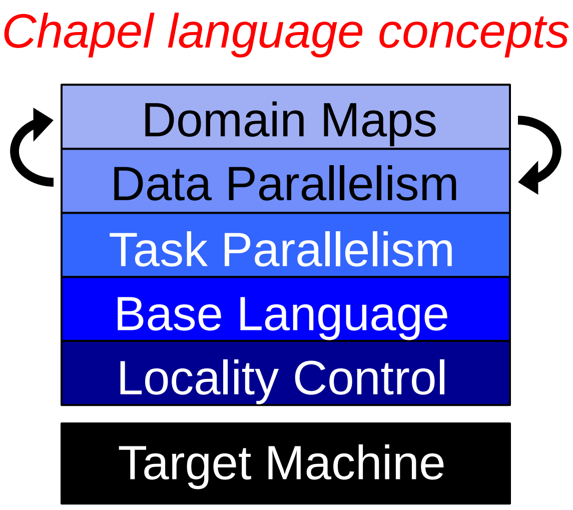
"Why is everything so tedious/difficult?"
"Why don't my programs port trivially?"

"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



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

4) Control over Locality/Affinity

Consider:

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

Therefore:

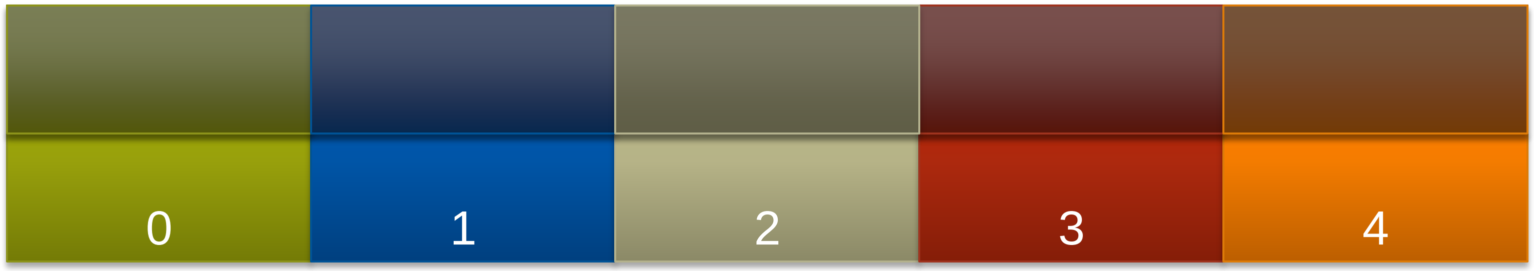
- Placement of data relative to tasks affects scalability
- Give programmers control of data and task placement

Note:

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

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:

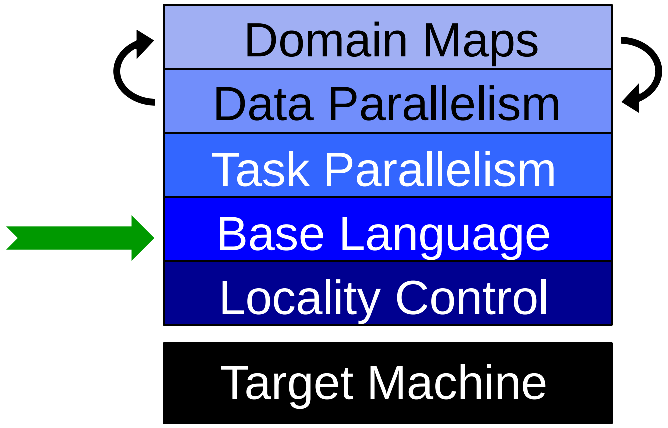
- Students graduate with training in Java, Matlab, Python, etc.
- Yet HPC programming is dominated by Fortran, C/C++, MPI

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

- ✓ Motivation
- ✓ Chapel Background and Themes
- ➢ Survey of Chapel Concepts



- 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 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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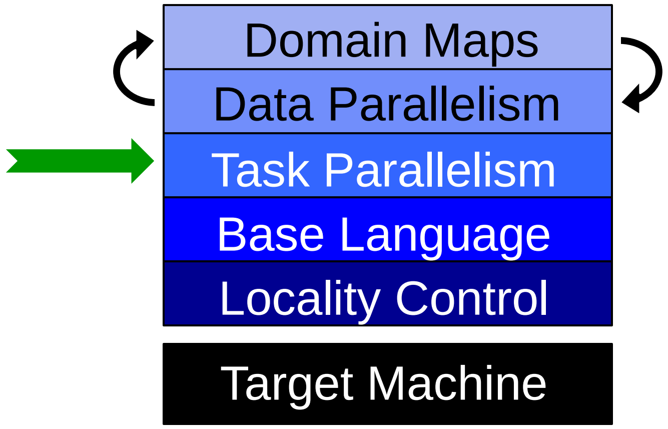

- Project Status and Next Steps

Defining our Terms

Task:

Defining our Terms

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

Task Parallelism:

(in contrast with):

Data Parallelism:

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: Cobegin Statements

```
// create a task per child statement
cobegin {
  producer(1);
  producer(2);
  consumer(1);
}  // implicit join of the three tasks here
```

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

Bounded Buffer Producer/Consumer Example

```
begin producer();
consumer();

// 'sync' types store full/empty state along with value
var buff$: [0..#buffersize] sync real;

proc producer() {
  var i = 0;
  for … {
    i = (i+1) % buffersize;
    buff$[i] = …;   // writes block until empty, leave full
} }

proc consumer() {
  var i = 0;
  while … {
    i= (i+1) % buffersize;
    …buff$[i]…;    // reads block until full, leave empty
} }
```

Outline

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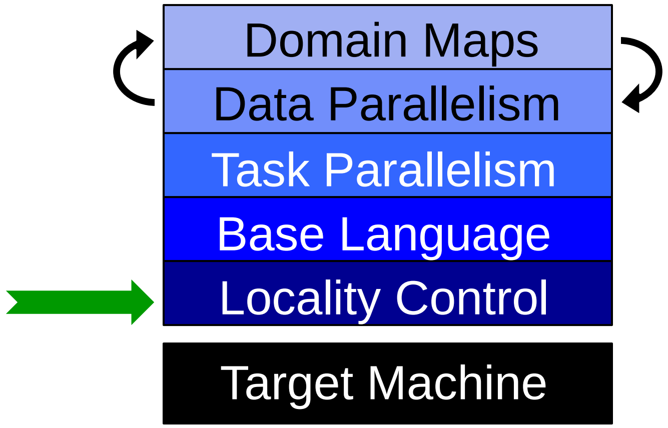

- Project Status and Next Steps

Chapel and PGAS

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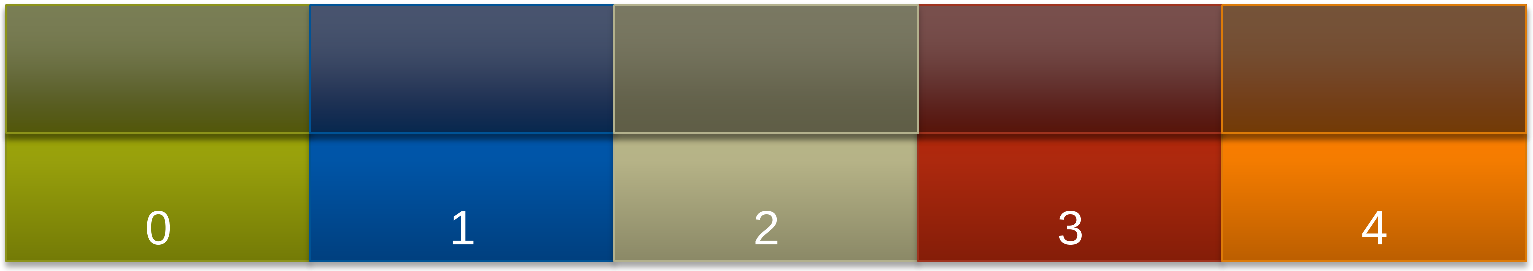
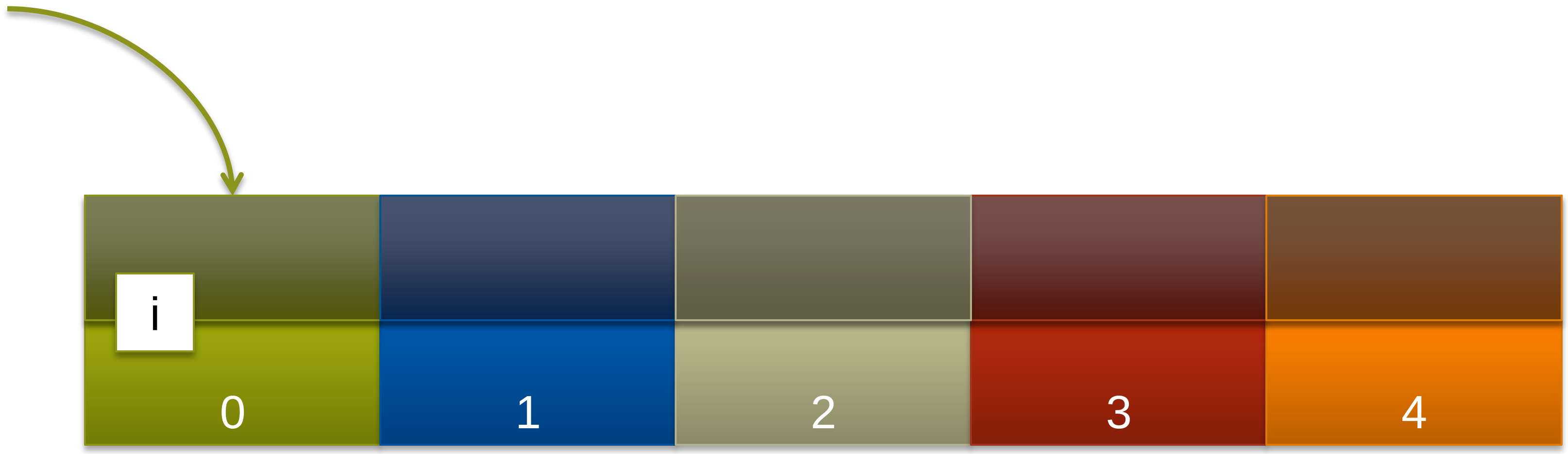
    - variables are stored on the locale where the task declaring it is executing



Locales (think: "compute nodes")

Chapel: Scoping and Locality

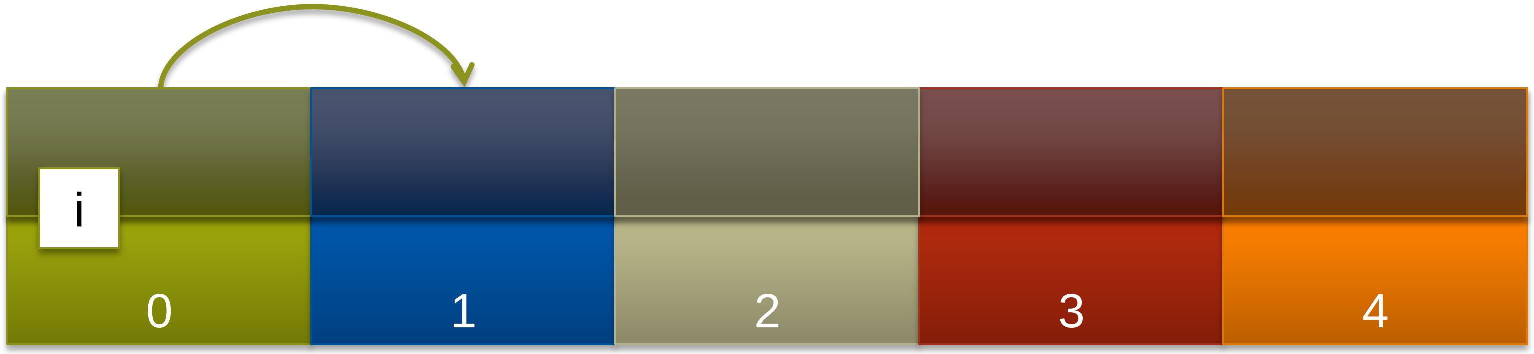
```
var i: int;
```



Locales (think: “compute nodes”)

Chapel: Scoping and Locality

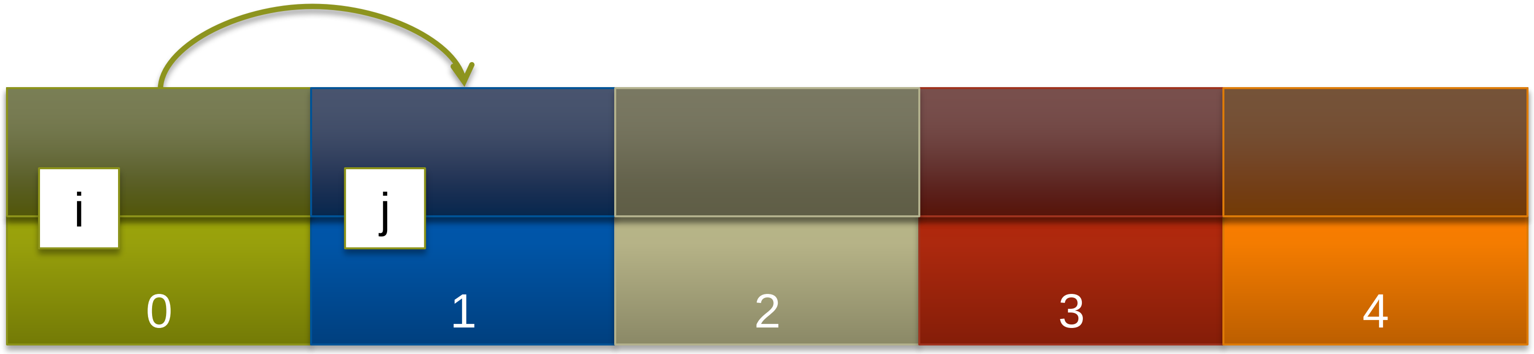
```
var i: int;
on Locales[1] {
```



Locales (think: “compute nodes”)

Chapel: Scoping and Locality

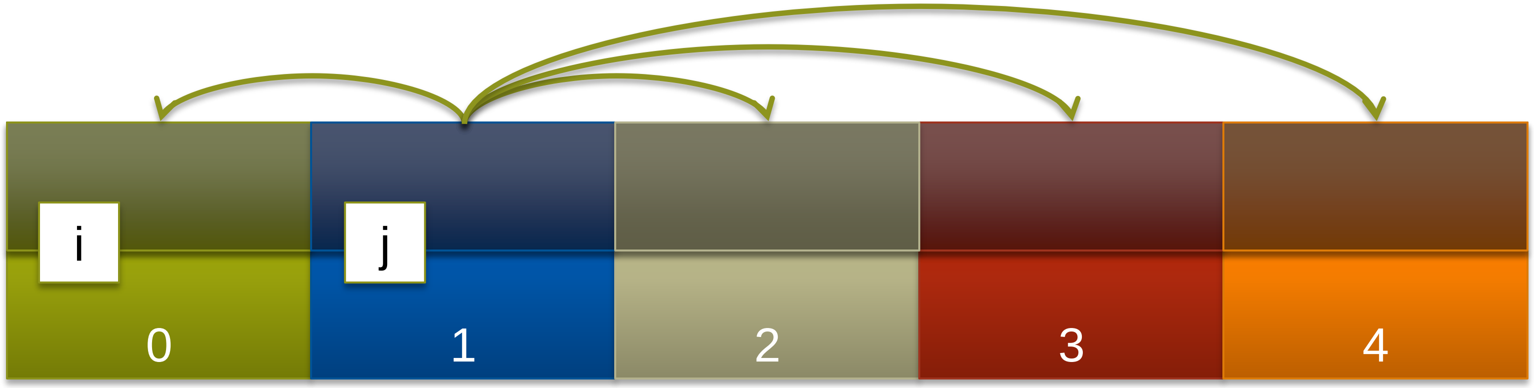
```
var i: int;
on Locales[1] {
  var j: int;
```



Locales (think: “compute nodes”)

Chapel: Scoping and Locality

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

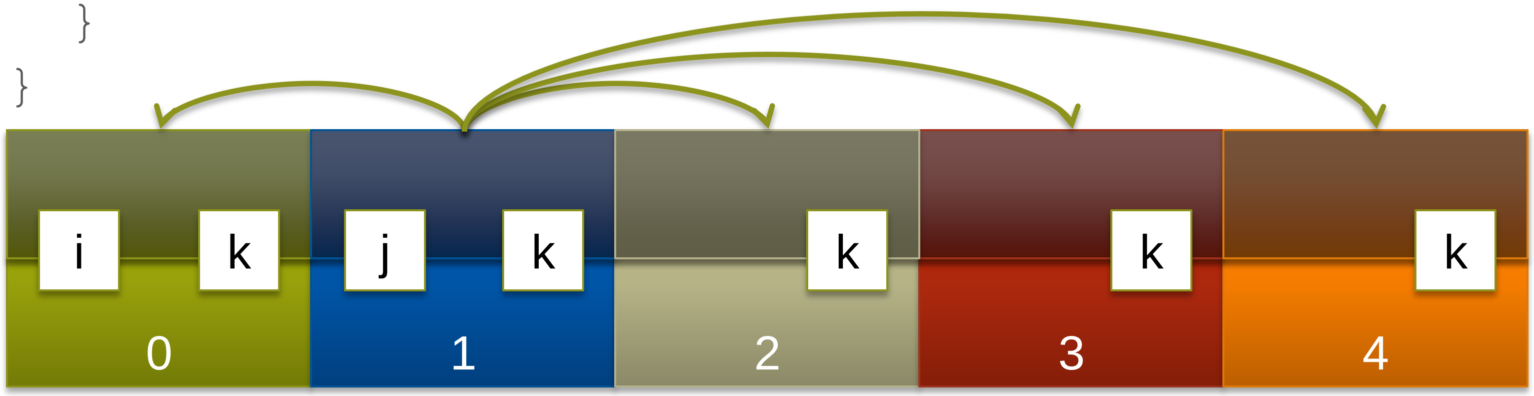


Locales (think: "compute nodes")

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;
      // the implementation manages the communication for i and j
    }
  }
}
```



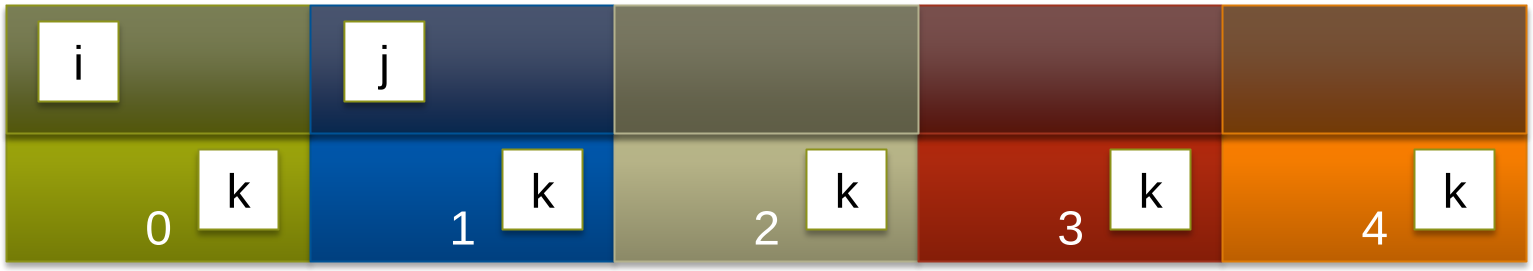
Locales (think: "compute nodes")

Chapel and PGAS: Public vs. Private

How public a variable is depends only on scoping

- who can see it?
- who actually bothers to refer to it non-locally?

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

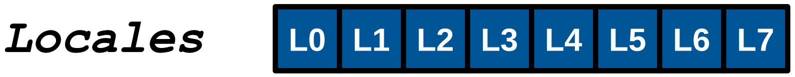
- Specify # of locales when running Chapel programs

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

```
% a.out –nl 8
```

- Chapel provides built-in locale variables

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



- 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);
```

Outline

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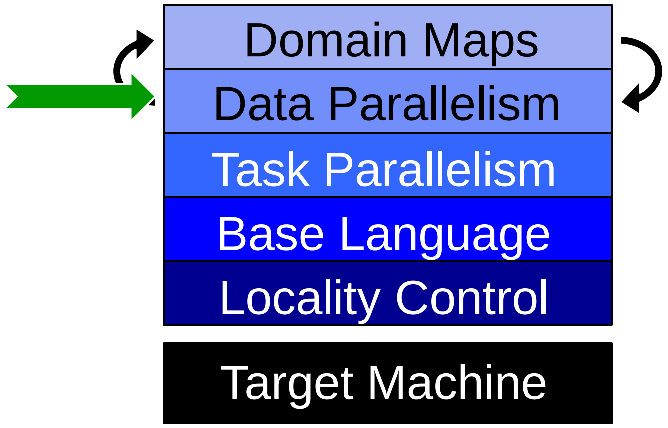


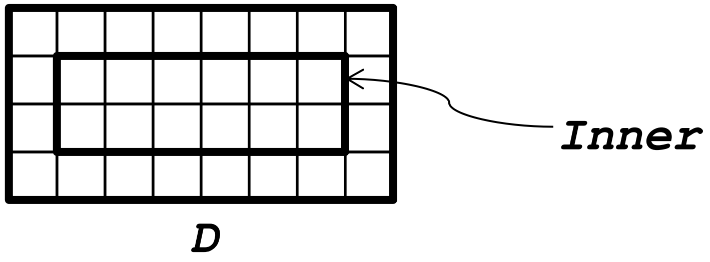
- Project Status and Next Steps

Domains

Domain:

- A first-class index set
- The fundamental Chapel concept for data parallelism

```
config const m = 4, n = 8;

const D = {1..m, 1..n};
const Inner = {2..m-1, 2..n-1};
```

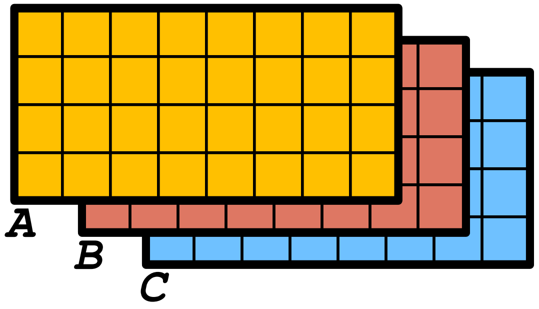


Domains

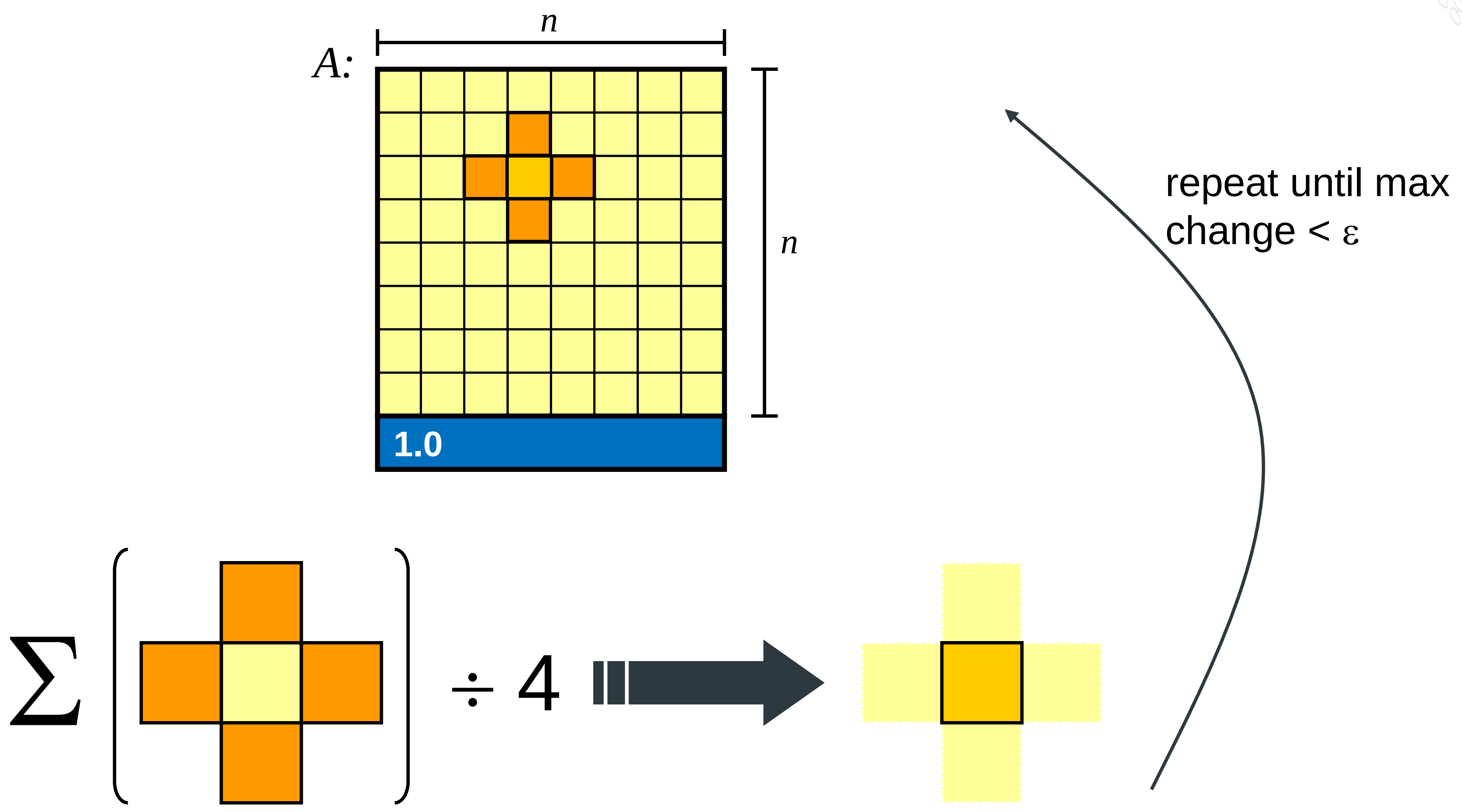
Domain:

- A first-class index set
- The fundamental Chapel concept for data parallelism
- Useful for declaring arrays and computing with them

```
config const m = 4, n = 8;

const D = {1..m, 1..n};
const Inner = {2..m-1, 2..n-1};

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



Data Parallelism by 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

```
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[La

do {
  fo
                                                  ]) / 4;

  co
  A[
} wh

writ
```

<u>Declare program parameters</u>

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)

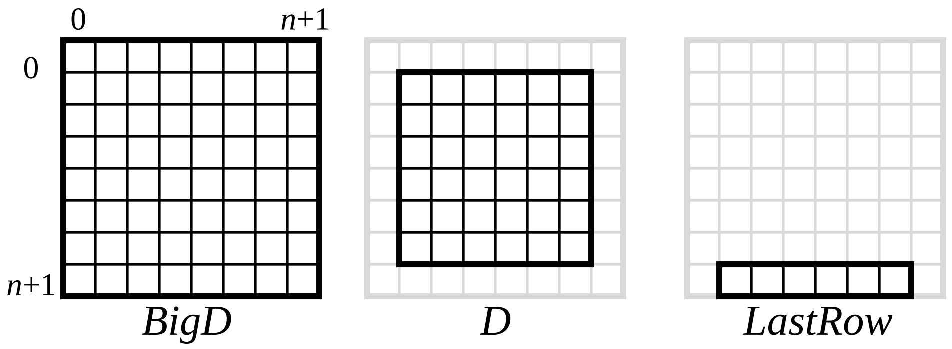
Jacobi Iteration in Chapel

```
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
```

<u>Declare domains (first class index sets)</u>

{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

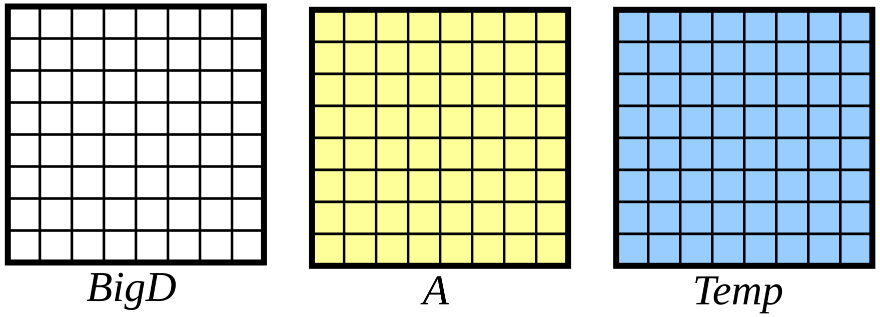
Jacobi Iteration in Chapel

```
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;
```

[i,j+1]) / 4;

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)

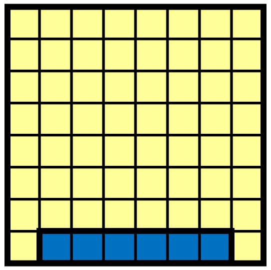


Jacobi Iteration in Chapel

```
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
                                                j+1]) / 4;



}

wr
```

Set Explicit Boundary Condition

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



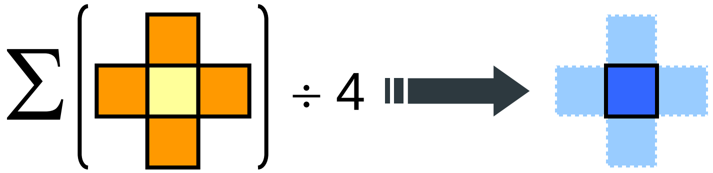
A

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,
             epsilon = 1.0e-5;
```

Compute maximum change

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

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

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

```
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,
             epsilon = 1.0e-5;

const BigD = {0..n+1, 0..n+1},
          D = BigD[1..n, 1..n],
[illegible]
```

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

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

```
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,
             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);
```

Write array to console

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;
```

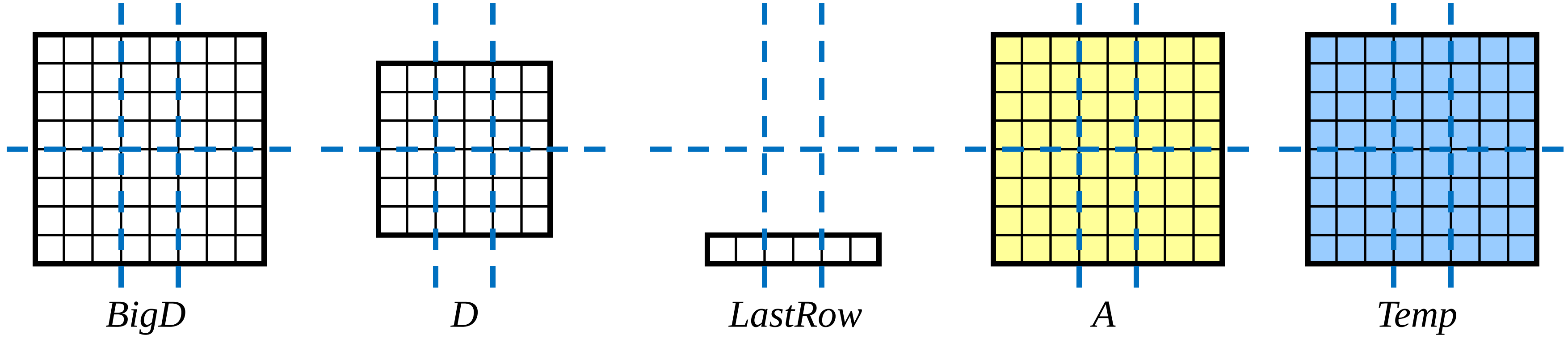
By default, domains and their arrays are mapped to a single locale.
Any data parallelism over such domains/ arrays will be executed by the cores on that locale.
Thus, this is a shared-memory parallel program.

```
    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



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;

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;
```

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

STREAM Triad: Chapel

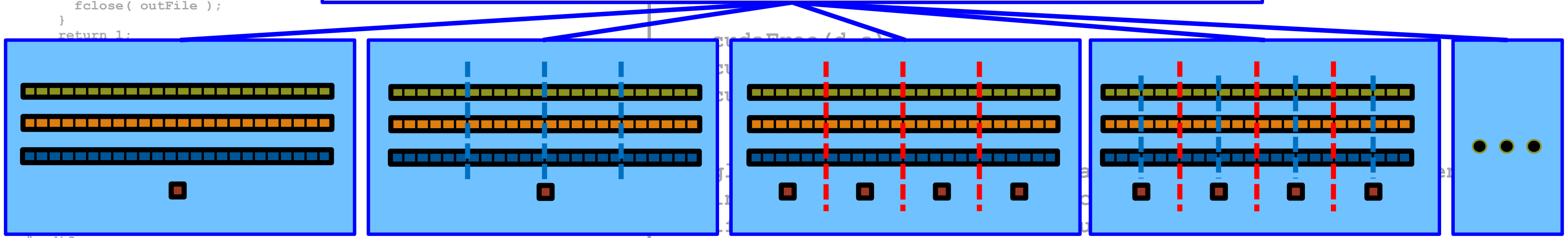
MPI + OpenMP

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

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

int HPCC_StarStream(HPCC_Params *par
  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 a
      fclose( outFile );
    }
    return 1;
```

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

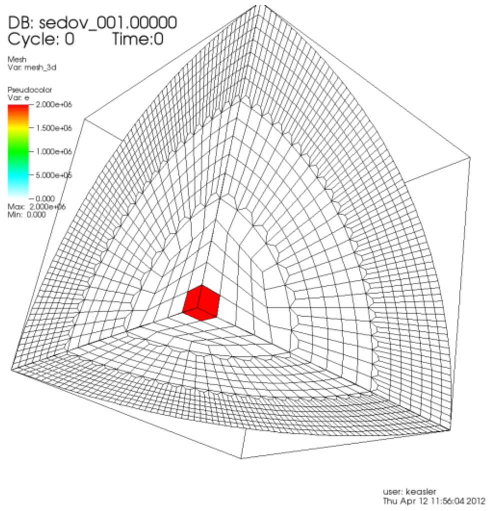


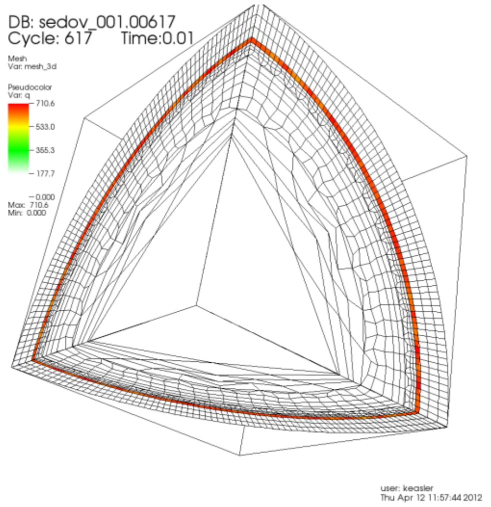
```
#endif
  for
    a[

  HPCC
  HPCC
  HPCC

  retu
}
```

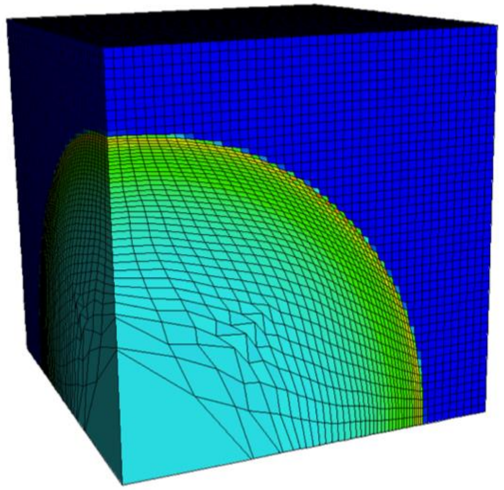
Philosophy: Good language design can tease details of locality and parallelism away from an algorithm, permitting the compiler, runtime, applied scientist, and HPC expert to each focus on their strengths.

LULESH: a DOE Proxy Application

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







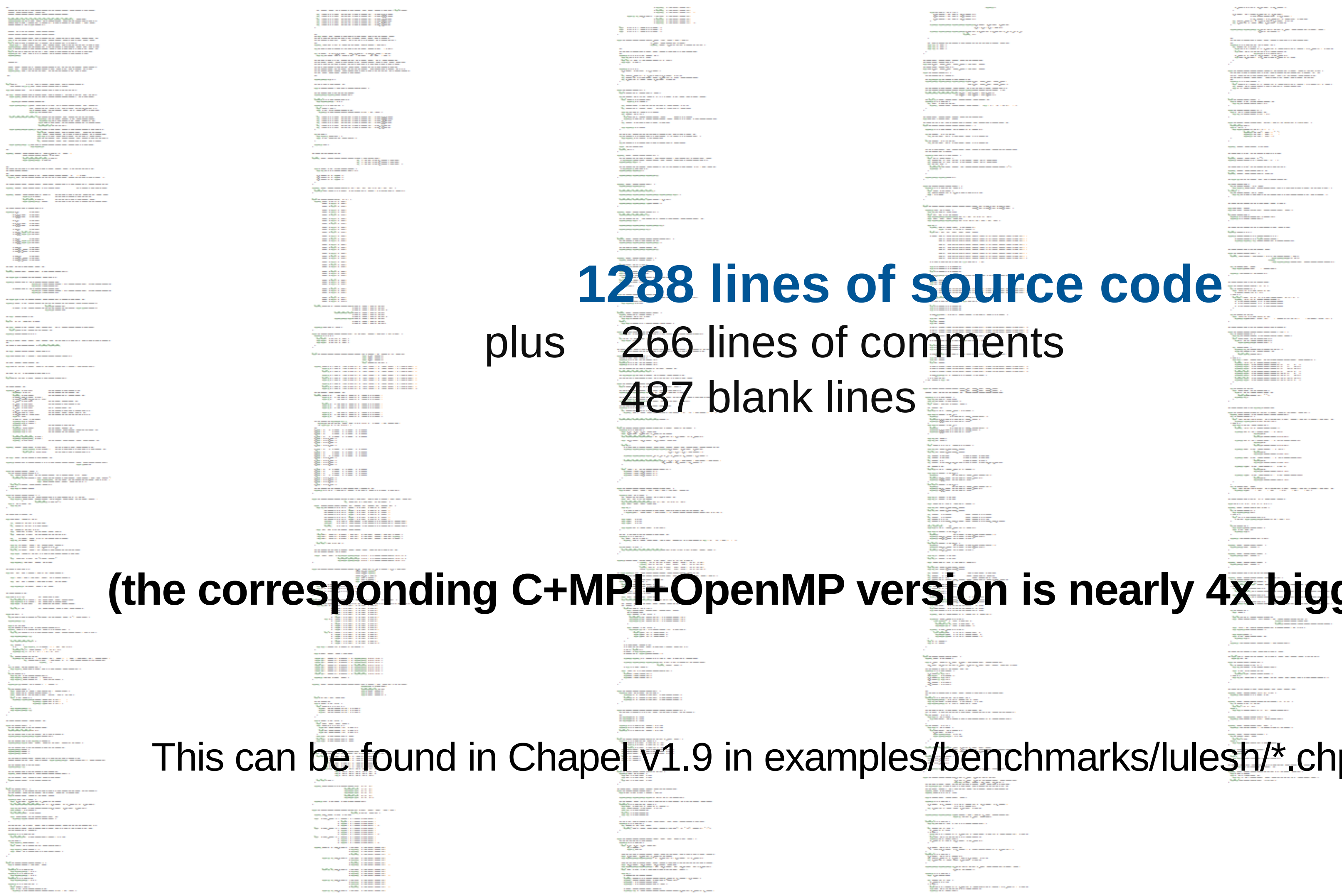
pictures courtesy of Rob Neely, Bert Still, Jeff Keasler, LLNL

LULESH in Chapel

[illegible]

COMPUTE | STORE | ANALYZE

LULESH in Chapel



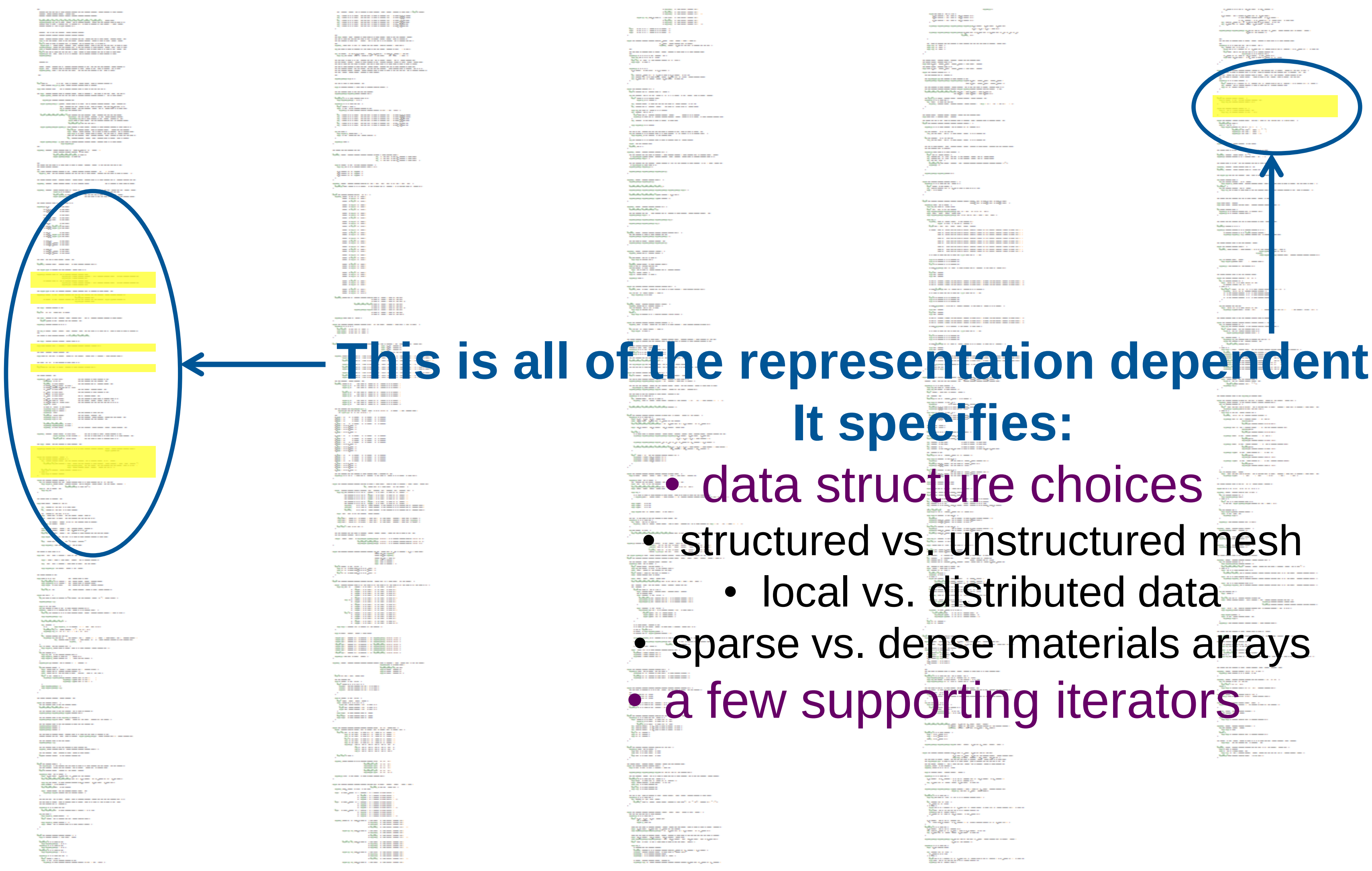
1288 lines of source code

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

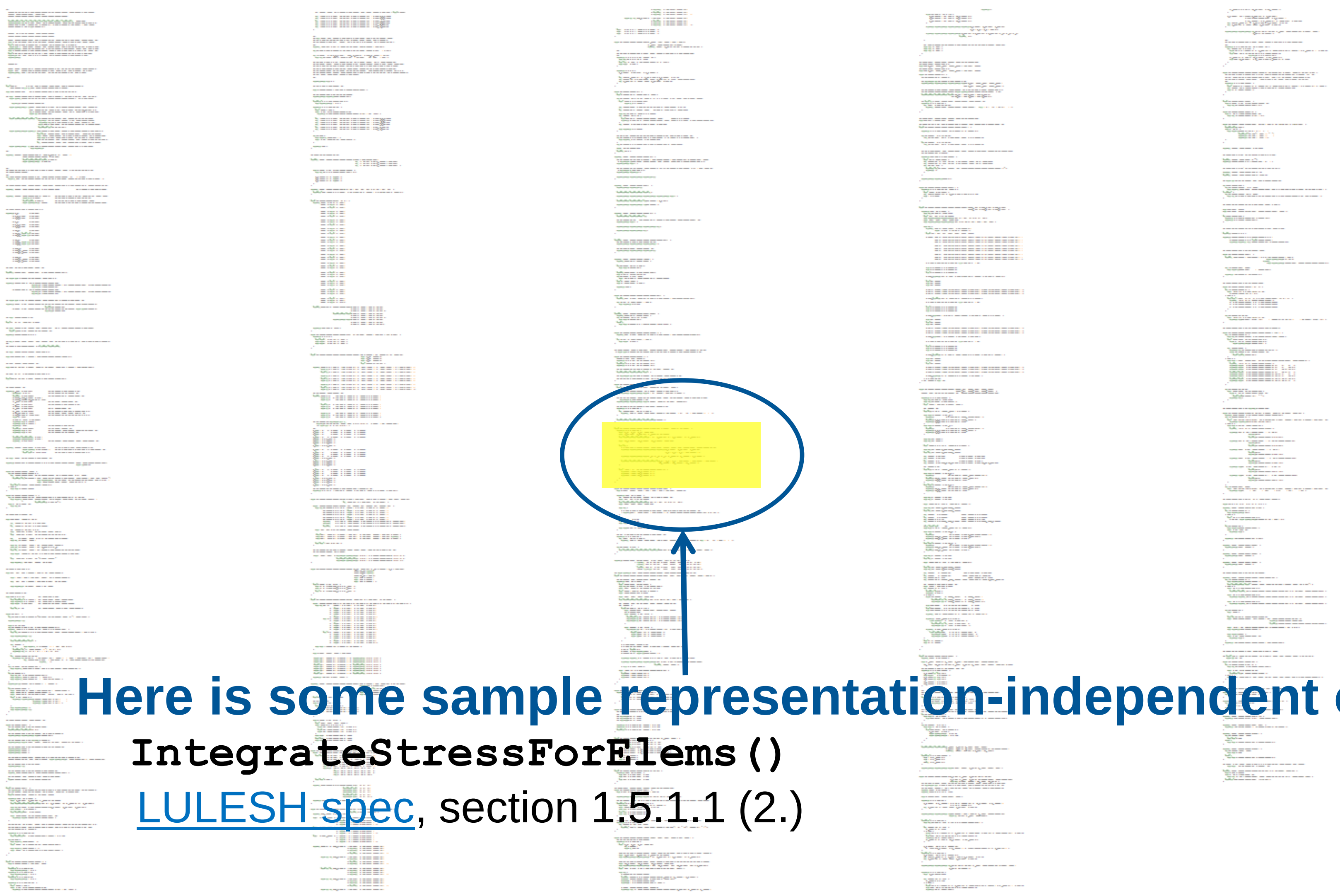


This is all of the representation dependent code.

It specifies:

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

LULESH in Chapel



Here is some sample representation-independent code

`IntegrateStressForElems()`

LULESH spec, section 1.5.1.1 (2.)

Representation-Independent Physics

```
proc IntegrateStressForElems(sigxx, sigyy, sigzz, determ) {
  forall k in Elems {
    var b_x, b_y, b_z: 8*real;
    var x_local, y_local, z_local: 8*real;
    localizeNeighborNodes(k, x, x_local, y, y_local, z, z_local);

    var fx_local, fy_local, fz_local: 8*real;

    local {
      /* Volume calculation involves extra work for numerical consistency. */
      CalcElemShapeFunctionDerivatives(x_local, y_local, z_local,
                                                           b_x, b_y, b_z, determ[k]);

      CalcElemNodeNormals(b_x, b_y, b_z, x_local, y_local, z_local);

      SumElemStressesToNodeForces(b_x, b_y, b_z, sigxx[k], sigyy[k], sigzz[k],
                                                        fx_local, fy_local, fz_local);
    }

    for (noi, t) in elemToNodesTuple(k) {
      fx[noi].add(fx_local[t]);
      fy[noi].add(fy_local[t]);
      fz[noi].add(fz_local[t]);
    }
  }
}
```

parallel loop over elements

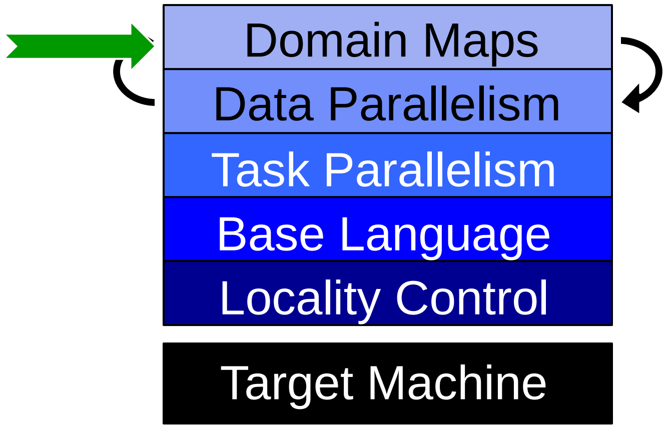
collect nodes neighboring this element; localize node fields

update node forces from element stresses

Because of domain maps, this code is independent of:
- structured vs. unstructured mesh
- shared vs. distributed data
- sparse vs. dense representation

Outline

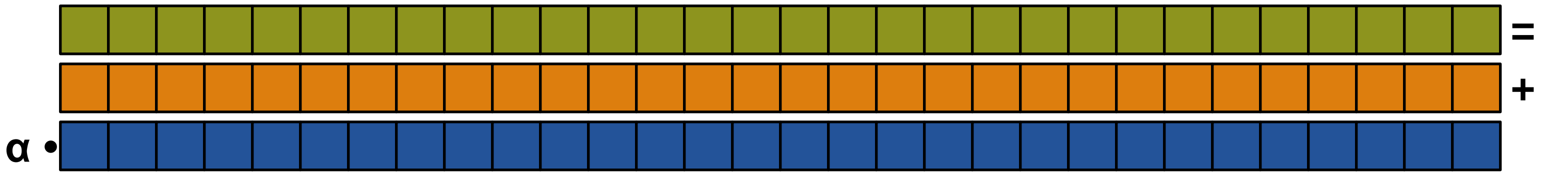
- ✓ Motivation
- ✓ Chapel Background and Themes
- ➢ Survey of Chapel Concepts



- ● Project Status and Next Steps

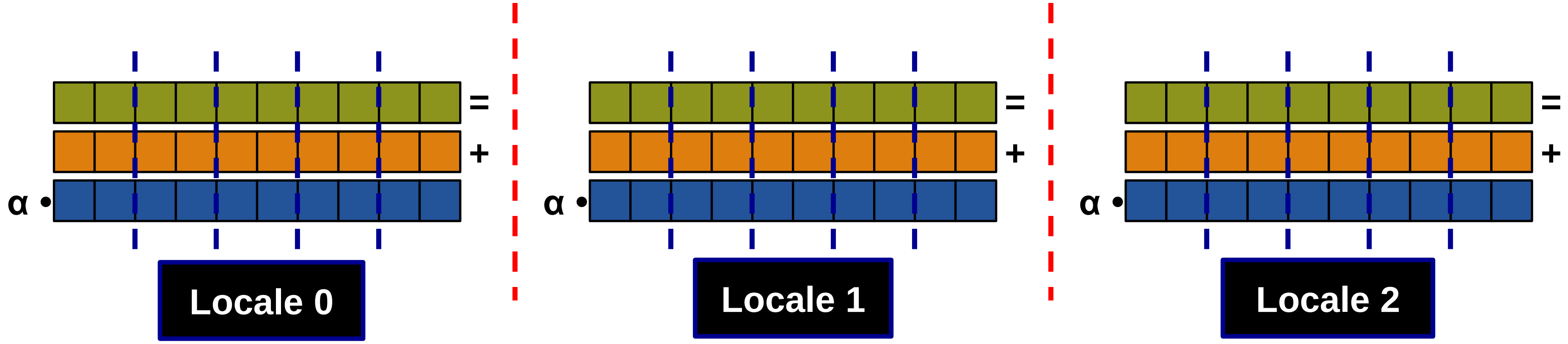
Domain Maps

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



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

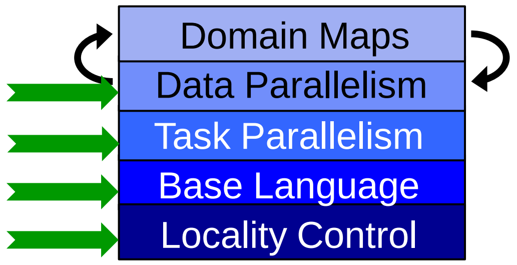
…to the target locales’ memory and processors:



Chapel's Domain Map Philosophy

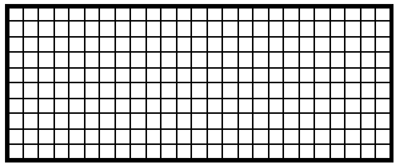
1. **Chapel provides a library of standard domain maps**
   - to support common array implementations effortlessly

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

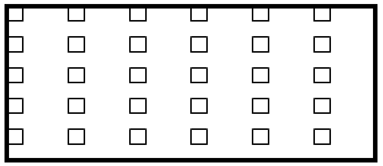


3. **Chapel's standard domain maps are written using the same end-user framework**
   - to avoid a performance cliff between "built-in" and user-defined cases

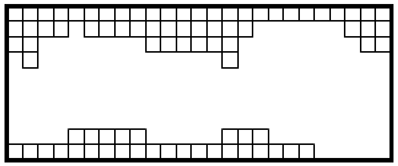
Chapel Domain Types



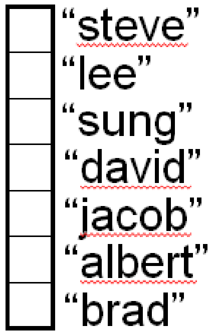
dense



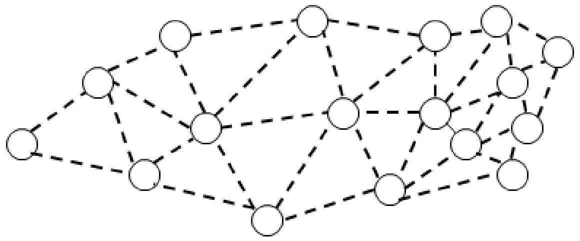
strided



sparse

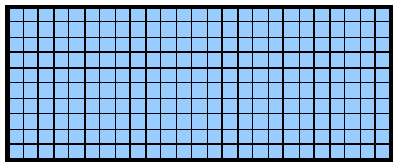


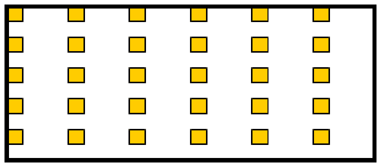
associative



unstructured

Chapel Array Types


dense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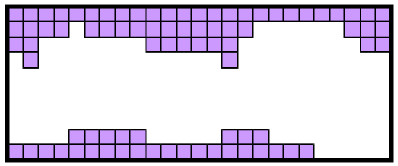
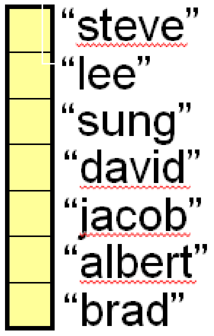
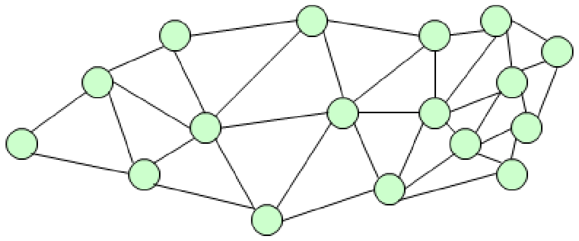
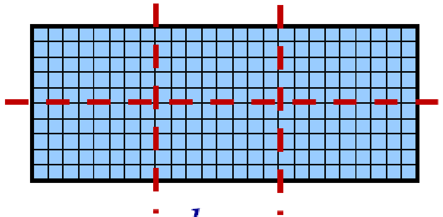

sparse

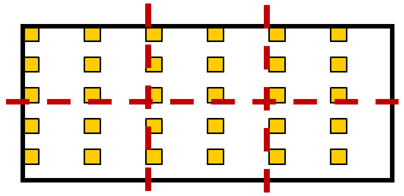


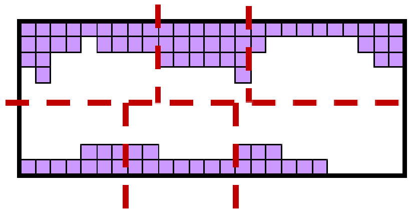
associative

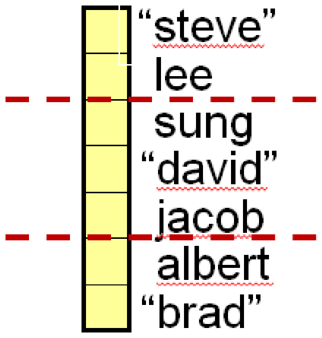

unstructured

All Domain Types Support Domain Maps

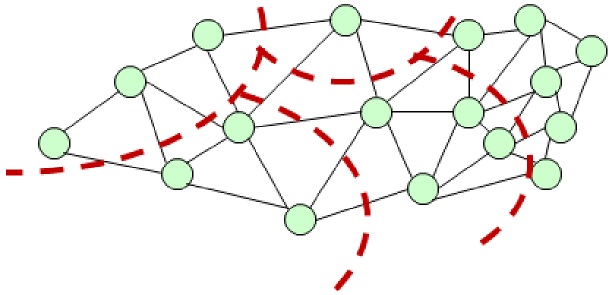

dense


strided


sparse



associative


unstructured

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 leader-follower 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.

…leader-follower 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)

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
    - leader-follower iterators and locale models are other examples
  - these avoid locking crucial policy decisions into the language

We believe Chapel can greatly improve productivity

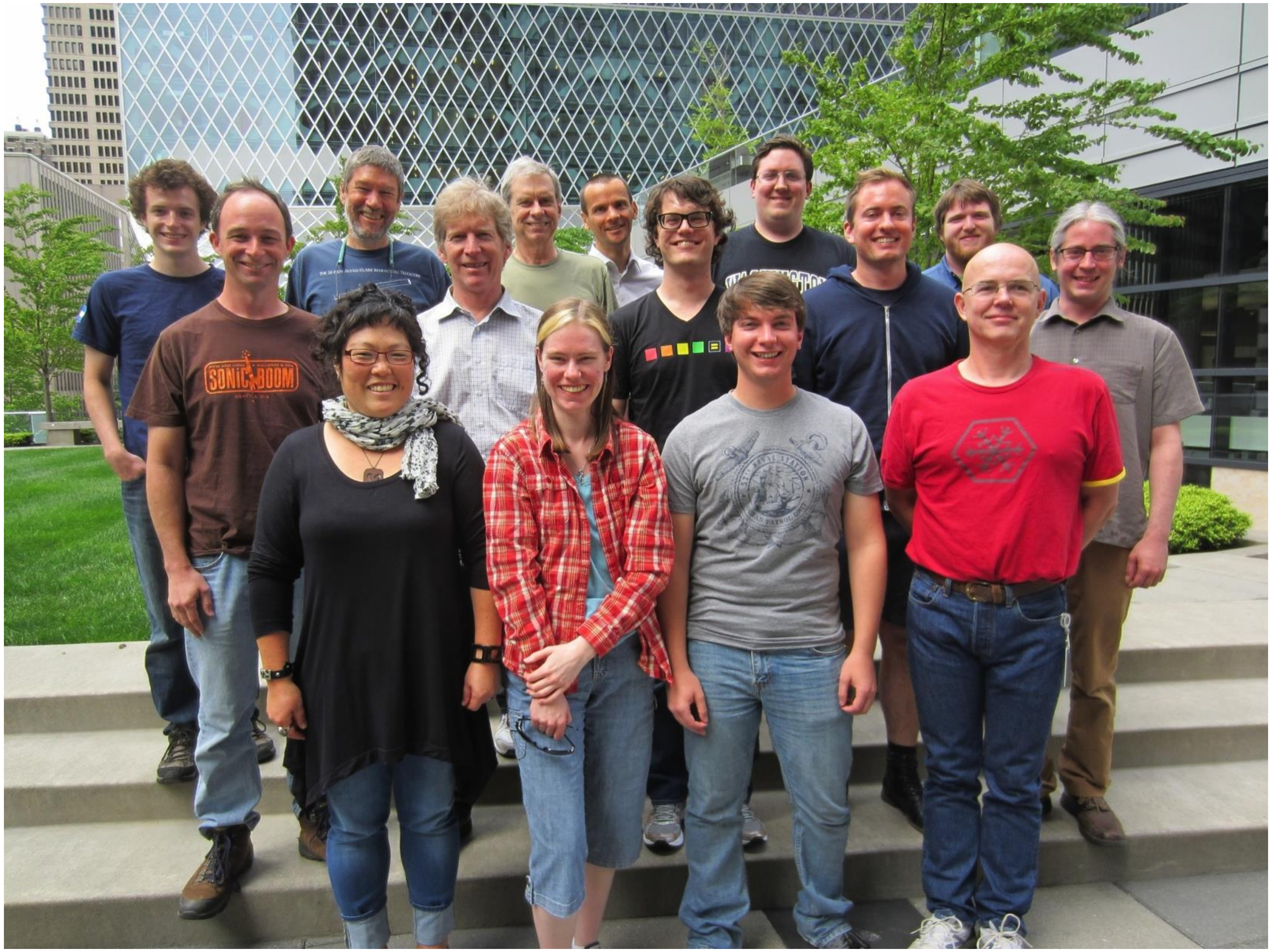
…for current and emerging HPC architectures

…for emerging mainstream needs for parallelism and locality

Outline

- ✓ Motivation
- ✓ Chapel Background and Themes
- ✓ Survey of Chapel Concepts
- ➢ **Project Status and Next Steps**

The Cray Chapel Team (Summer 2014)



Chapel…

…is a collaborative effort — join us!

CRAY

LTS Laboratory for Telecommunications Sciences

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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 next five years

- **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

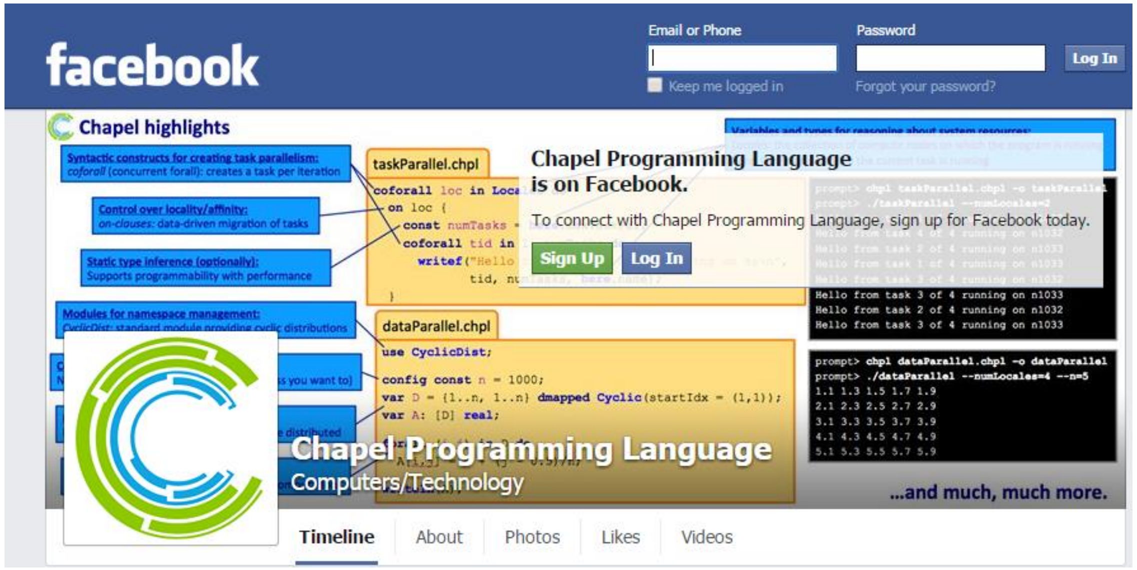
Chapel project page: http://chapel.cray.com

- 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



Syntactic constructs for creating task parallelism:
coforall (concurrent forall): creates a task per iteration

Control over locality/affinity:
on-clauses: data-driven migration of tasks

Static type inference (optionally):
Supports programmability with performance

Modules for namespace management:
CyclicDist: standard module providing cyclic distributions

Variables and types for reasoning about system resources:

taskParallel.chpl

```
coforall loc in Loca
  on loc {
    const numTasks =
    coforall tid in
      writef("Hello
             tid, nu
  }
```

dataParallel.chpl

```
use CyclicDist;

config const n = 1000;
var D = {1..n, 1..n} dmapped Cyclic(startIdx = (1,1));
var A: [D] real;
```

Chapel Programming Language is on Facebook.

To connect with Chapel Programming Language, sign up for Facebook today.

```
prompt> chpl taskParallel.chpl -o taskParallel
prompt> ./taskParallel --numLocales=2
Hello from task 4 of 4 running on n1032
Hello from task 2 of 4 running on n1033
Hello from task 1 of 4 running on n1033
Hello from task 3 of 4 running on n1032
Hello from task 3 of 4 running on n1033
Hello from task 2 of 4 running on n1032
Hello from task 3 of 4 running on n1033
```

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

…and much, much more.

Chapel Programming Language
Computers/Technology

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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CRAY THE SUPERCOMPUTER COMPANY

http://chapel.cray.com chapel_info@cray.com http://sourceforge.net/projects/chapel/