Chapel
Overview and Status

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Intel Extreme Scale Technical Review Meeting

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Safe Harbor Statement

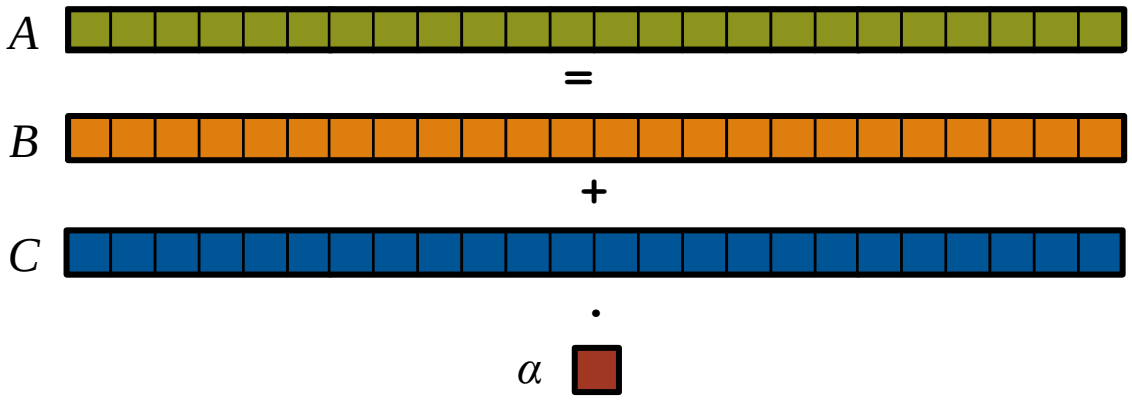
This presentation may contain forward-looking statements that are based on our current expectations. Forward looking statements may include statements about our financial guidance and expected operating results, our opportunities and future potential, our product development and new product introduction 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.

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:



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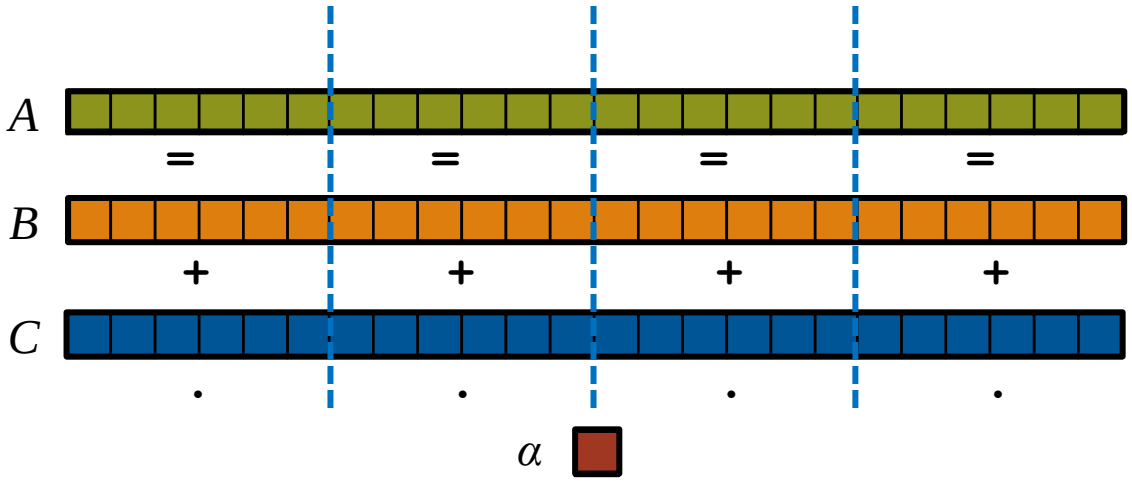

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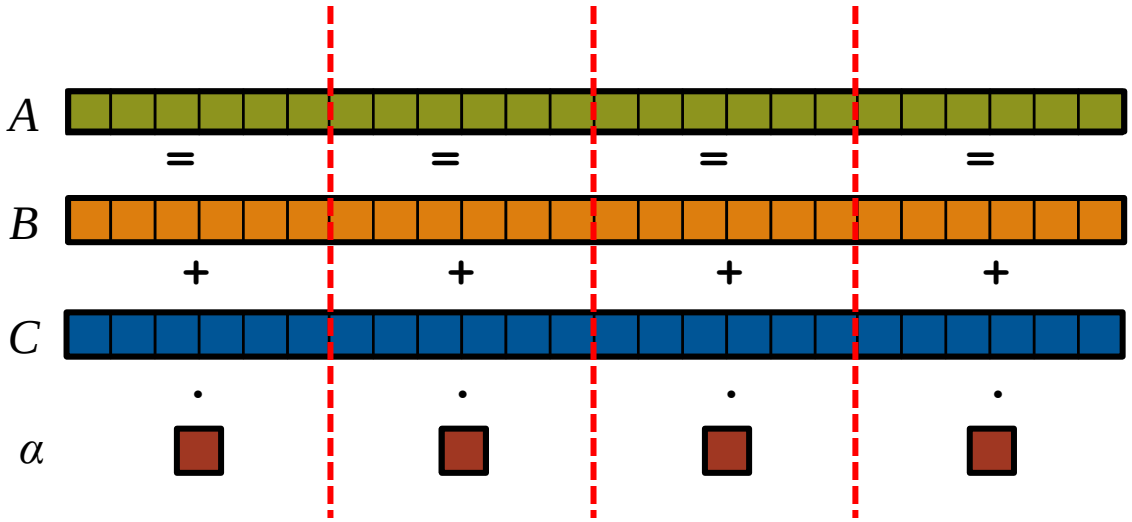

STREAM Triad: a trivial parallel computation

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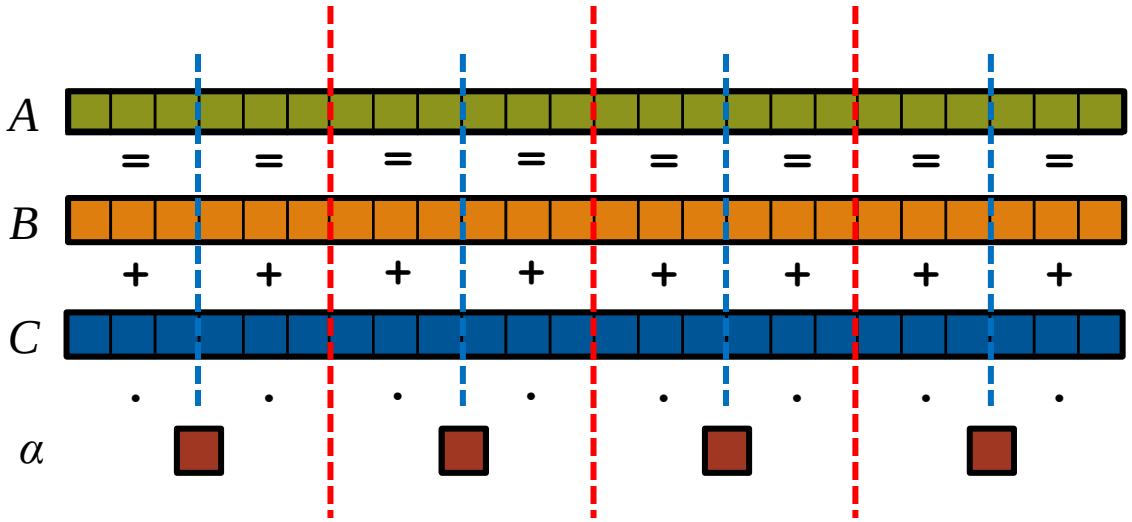
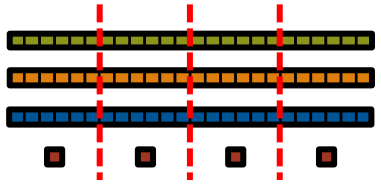


STREAM Triad: MPI



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);
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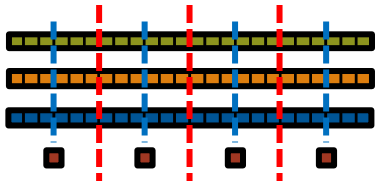
```

STREAM Triad: MPI+OpenMP



MPI + OpenMP

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

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int HPCC_StarStream(HPCC_Params *params) {
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    }
    return 1;
  }

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

  scalar = 3.0;

#ifdef _OPENMP
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    a[j] = b[j]+scalar*c[j];

  HPCC_free(c);
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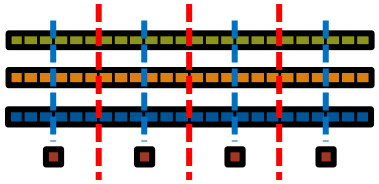
```

STREAM Triad: MPI+OpenMP vs. CUDA

MPI + OpenMP



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  scalar = 3.0;

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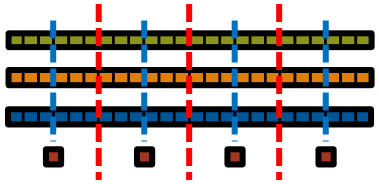
#endif
  for (j=0; j<VectorSize; j++)
    a[j] = b[j]+scalar*c[j];

  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.x+=1;

  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

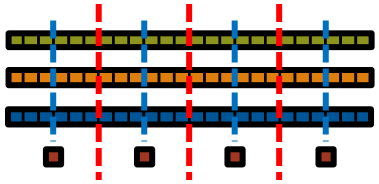
Type of HW Parallelism	Programming Model	Unit of Parallelism
Inter-node	MPI	executable
Intra-node/multicore	OpenMP/pthreads	iteration/task
Instruction-level vectors/threads	pragmas	iteration
GPU/accelerator	CUDA/OpenCL/OpenACC	SIMD function/task

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

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

Rewinding a few slides…

MPI + OpenMP



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#ifdef _OPENMP
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    a[j] = b[j]+scalar*c[j];

  HPCC_free(c);
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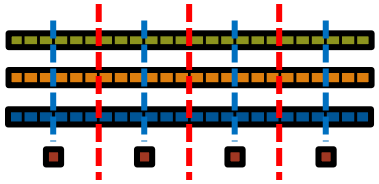
  return 0;
}
```

CUDA



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STREAM Triad: Chapel

MPI + OpenMP

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  rv = HPCC_Stream( params, 0 == myR
  MPI_Reduce( &rv, &errCount, 1, MPI

  return errCount;
}

int HPCC_Stream(HPCC_Params *params,
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  VectorSize = HPCC_LocalVectorSize(

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    if (a) HPCC_free(a);
    if (doIO) {
      fprintf( outFile, "Failed to allocate memory (%d).\n", VectorSi
      fclose( outFile );
```

Chapel

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

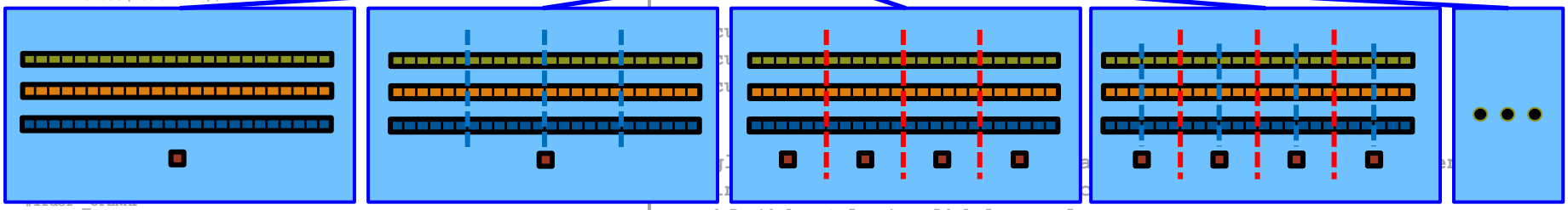
const ProblemSpace = {1..m} dmapped …;

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

B = 2.0;
C = 3.0;

A = B + alpha * C;
```

the special sauce



Philosophy: Good 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**
  - Quick run-through of basic concepts
  - Slightly more detail on advanced/research-y concepts
- **Project Status and Next Steps**
  - including “current events” section

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, …"

Seasoned HPC Programmers:

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

Computational Scientists:

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

Chapel Team:

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

Chapel's Implementation

- **Being developed as open source at GitHub**
  - Licensed as Apache v2.0 software

- **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, …

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

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1) General Parallel Programming

With a unified set of concepts...

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

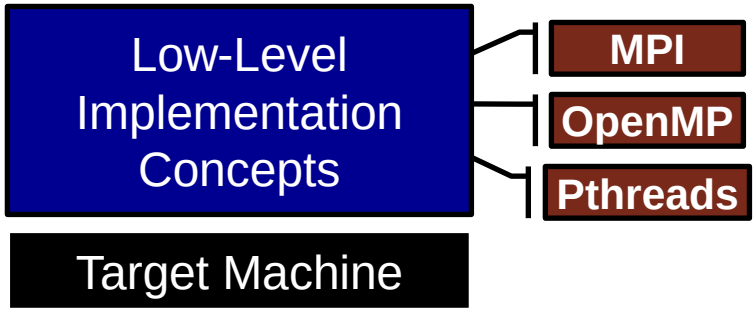
- **Styles:** data-parallel, task-parallel, concurrency, nested, …
- **Levels:** model, function, loop, statement, expression

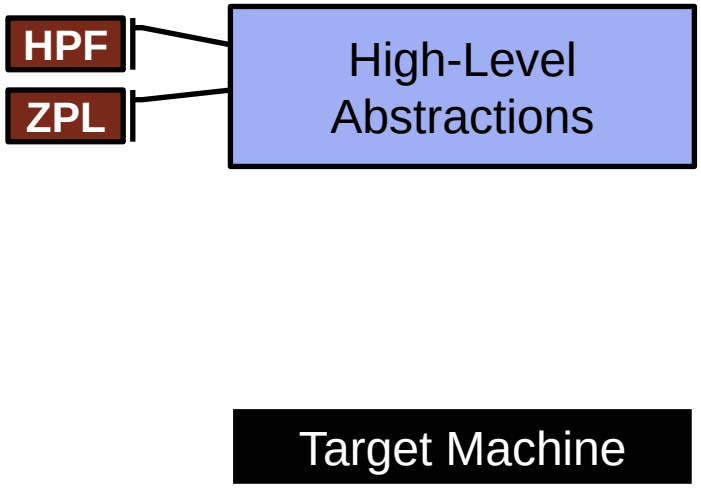
...target any parallelism available in the hardware

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

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

3) Multiresolution Design: Motivation





"Why is everything so tedious/difficult?"

"Why don't my programs port trivially?"

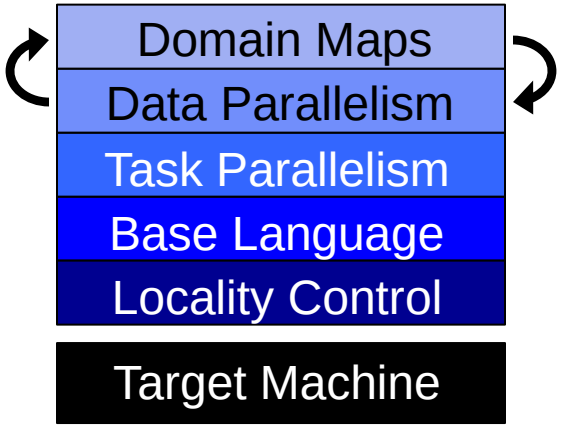
"Why don't I have more control?"

3) Multiresolution Design

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

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

Chapel language concepts



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

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

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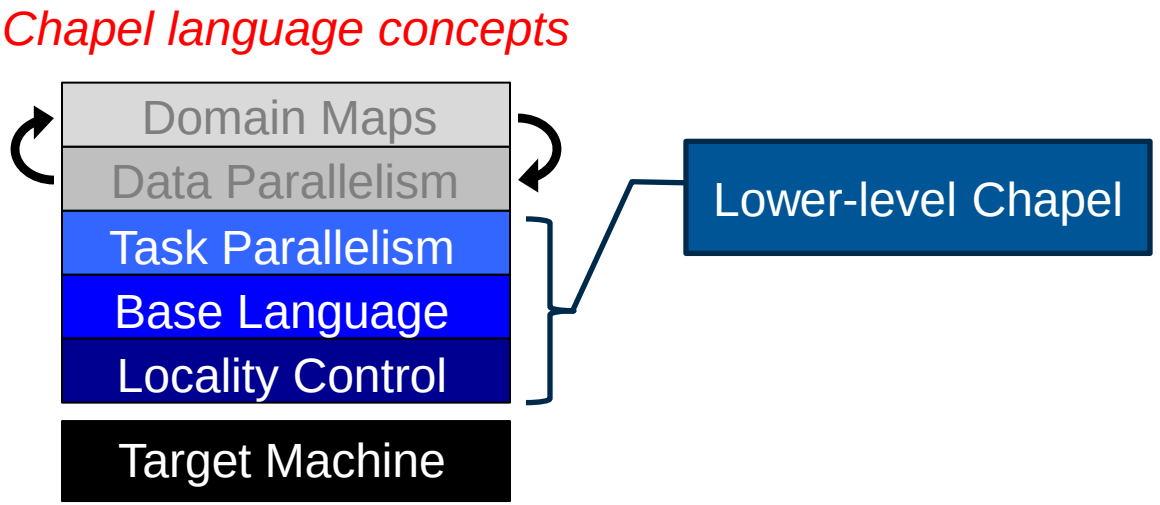
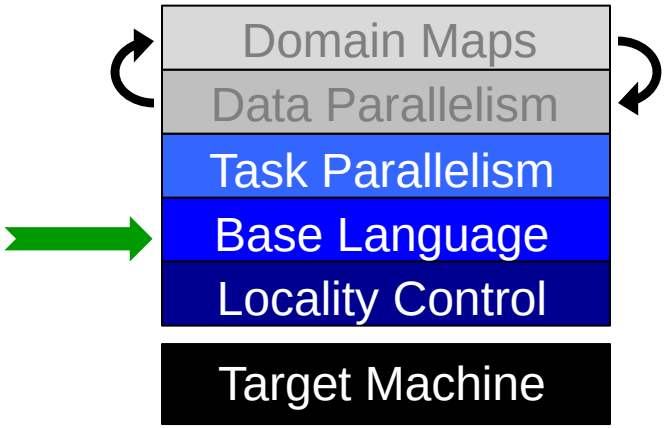
Lower-Level Features



Base Language Features



Sample Base Language Features

Static Type Inference for:
- arguments
- return types
- variables

CLU-style iterators

zippered iteration

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

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

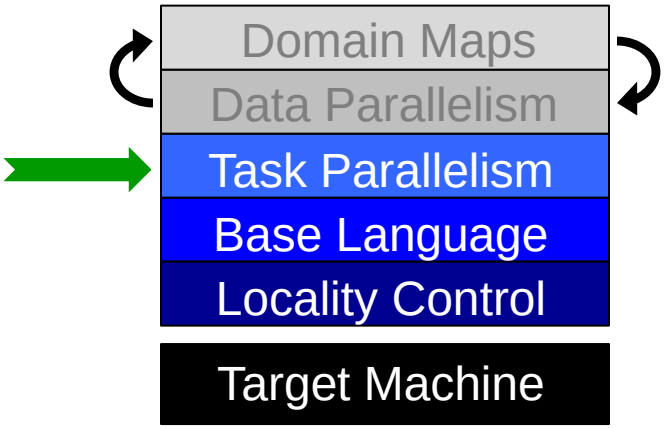
```
for (i,f) in zip(0..#n, fib(n)) do
  writeln("fib #", i, " is ", f);
```

```
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
...
```

swap operator

range types and operators

Task Parallel Features



Task Parallelism: Begin Statements

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

Possible outputs:

```
hello world
goodbye
```

```
goodbye
hello world
```

Sample Task Parallel Feature: Coforall Loops

```
coforall t in 0..#numTasks {   // create a task per iteration
  writeln("Hello from task ", t, " of ", numTasks);
}   // wait for its tasks to complete before proceeding

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
```

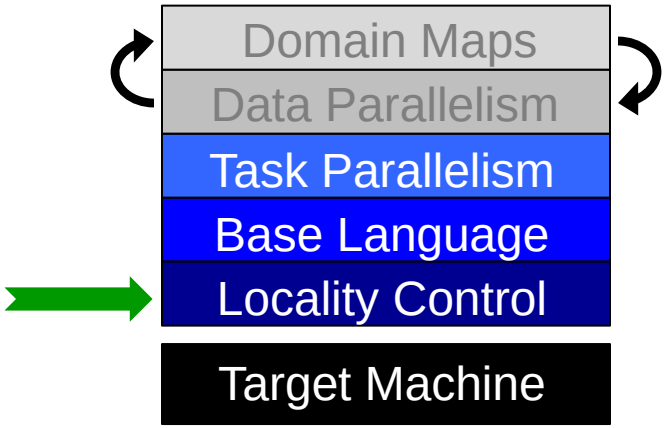
Task Parallelism: Data-Driven Synchronization

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

Locality Features



Theme 4: Control over Locality/Affinity

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);
```

Chapel and PGAS

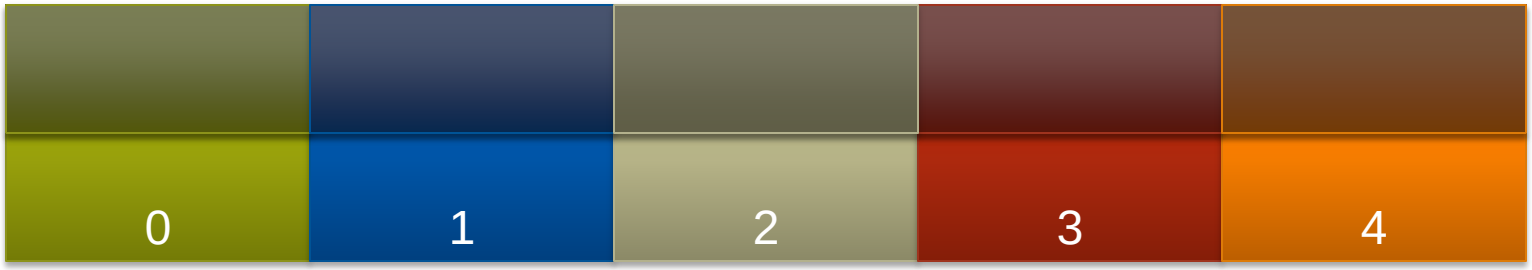
- **Chapel is a PGAS language…**

…but unlike most, it's not restricted to SPMD

⇒ never think in terms of "the other copies of the program"

⇒ "global name/address space" comes from lexical scoping

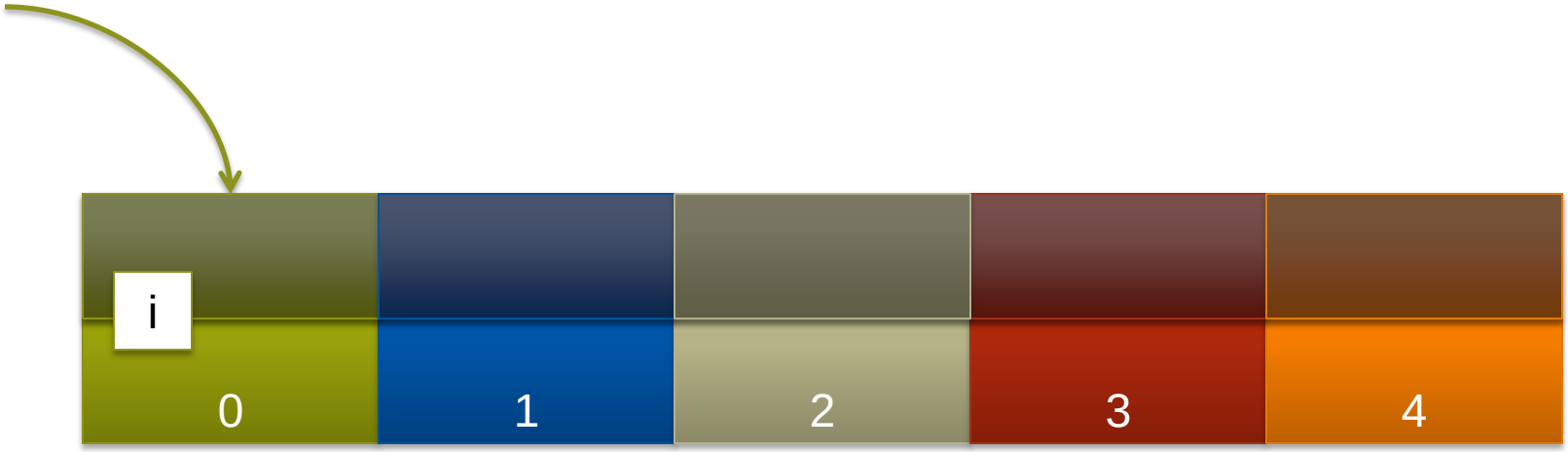
- as in traditional languages, each declaration yields one variable
- variables are stored on the locale where the task declaring it is executing



Locales (think: "compute nodes")

Chapel: Scoping and Locality

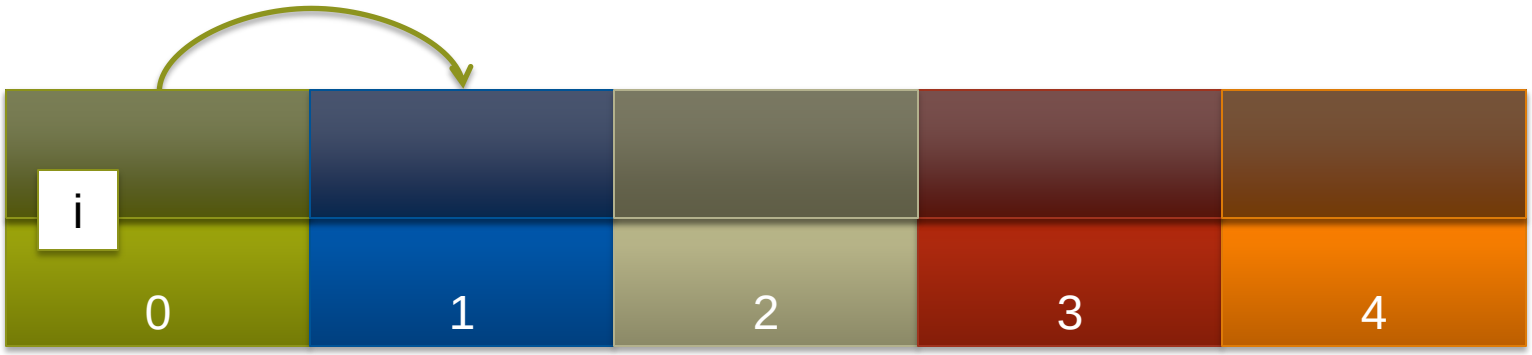
```
var i: int;
```



Locales (think: “compute nodes”)

Chapel: Scoping and Locality

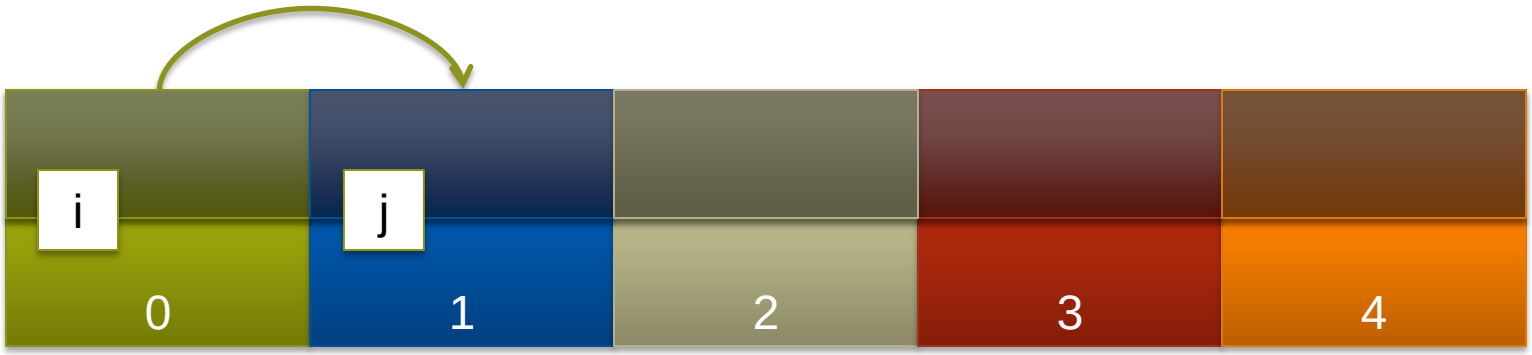
```
var i: int;
on Locales[1] {
```



Locales (think: “compute nodes”)

Chapel: Scoping and Locality

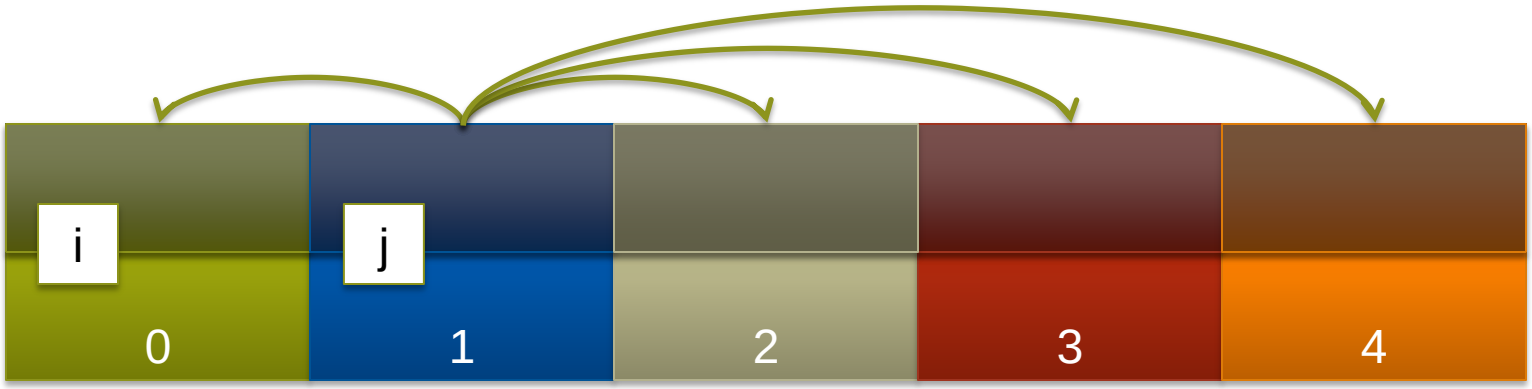
```
var i: int;
on Locales[1] {
  var j: int;
```



Locales (think: “compute nodes”)

Chapel: Scoping and Locality

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

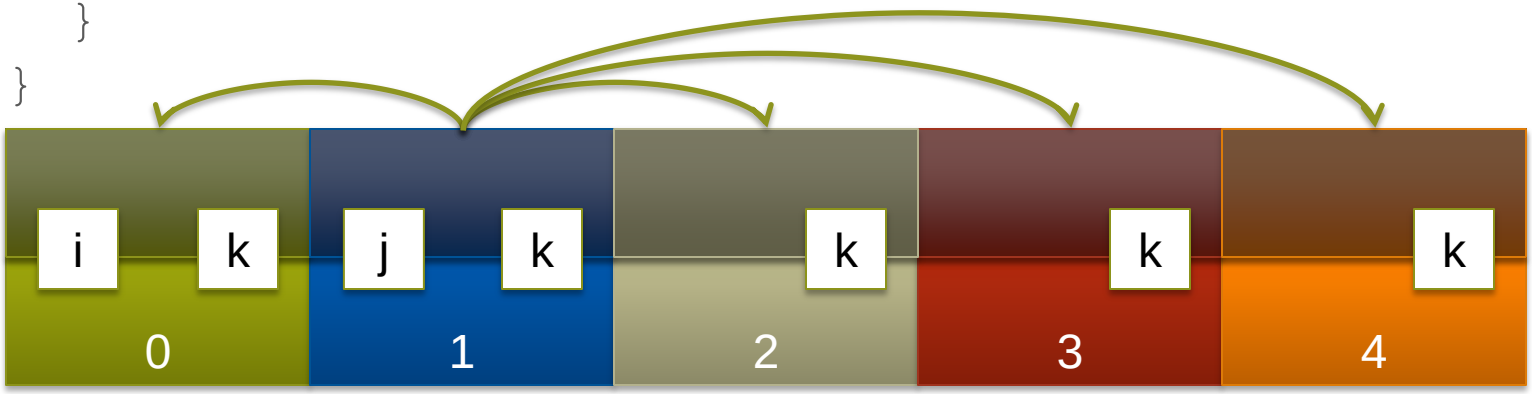


Locales (think: “compute nodes”)

Chapel: Scoping and Locality

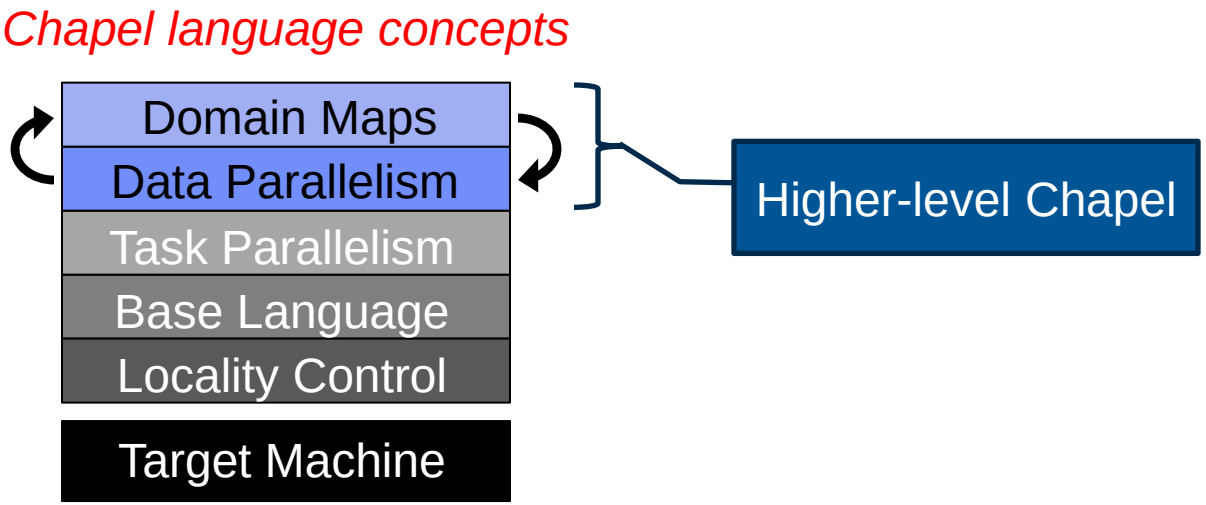
```
var i: int;
on Locales[1] {
  var j: int;
  coforall loc in Locales {
    on loc {
      var k: int;

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

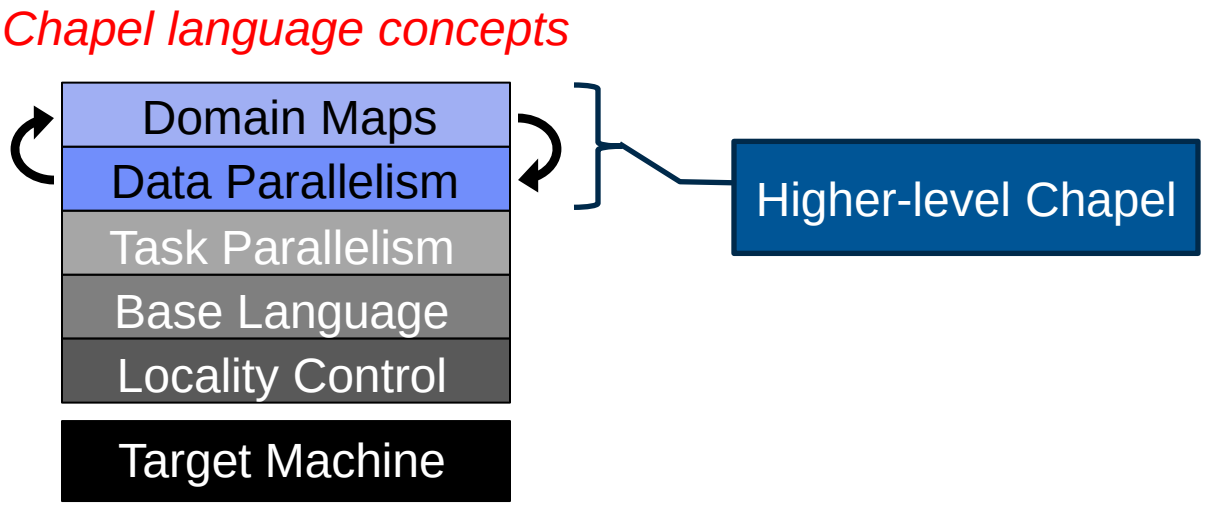


Locales (think: "compute nodes")

Higher-Level Features

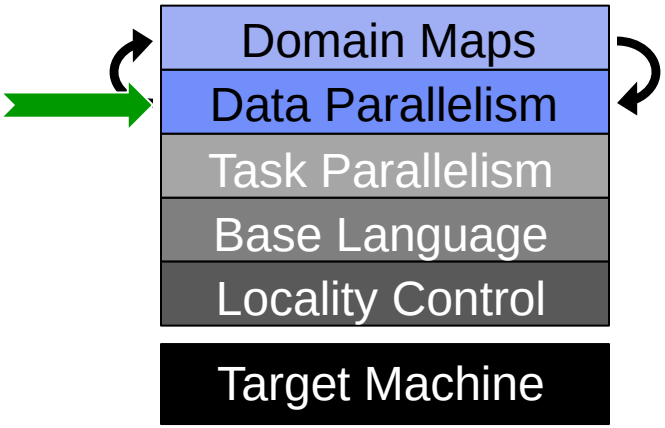


Higher-Level Features



Theme 2: Global-view Abstractions

Data Parallel Features (by example)



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 *pa
  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", VectorSi
      fclose( outFile );
```

Chapel

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

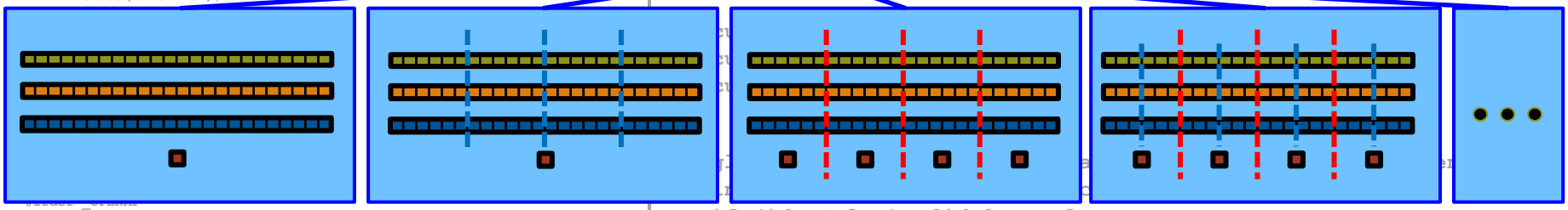
const ProblemSpace = {1..m} dmapped …;

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

B = 2.0;
C = 3.0;

A = B + alpha * C;
```

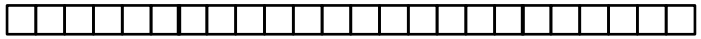
the special sauce



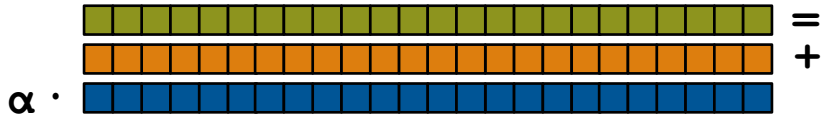
Philosophy: Good language design can tease details of locality and parallelism away from an algorithm, permitting the compiler, runtime, applied scientist, and HPC expert to each focus on their strengths.

STREAM Triad in Chapel

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



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



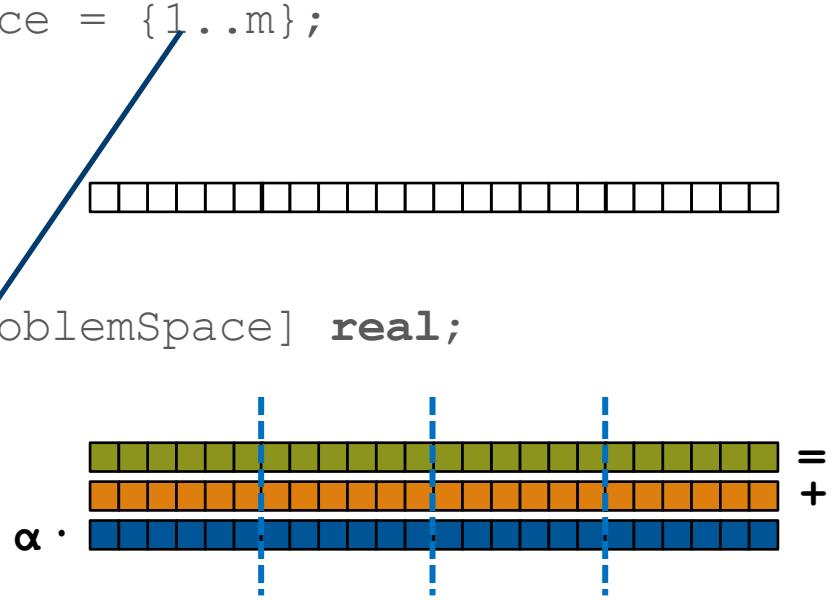

```
A = B + alpha * C;
```

STREAM Triad: Chapel (multicore)

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

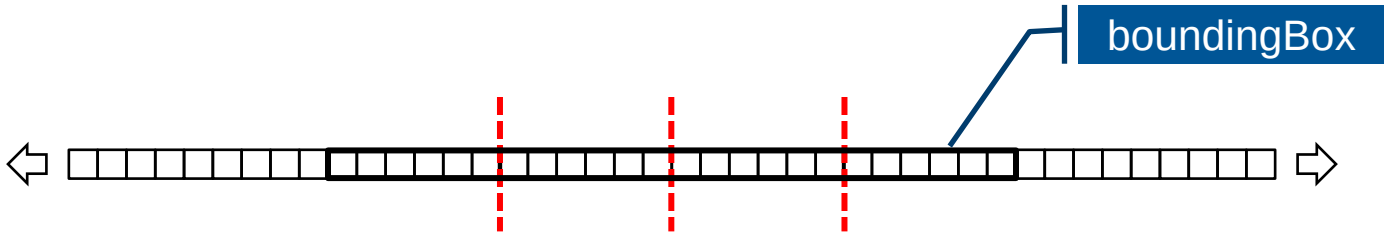
var A, B, C: [ProblemSpace] real;

A = B + alpha * C;
```

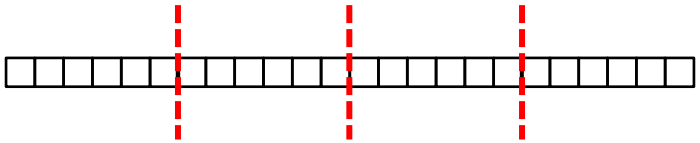


No domain map specified => use default layout
- current locale owns all domain indices and array values
- computation will execute using local processors only

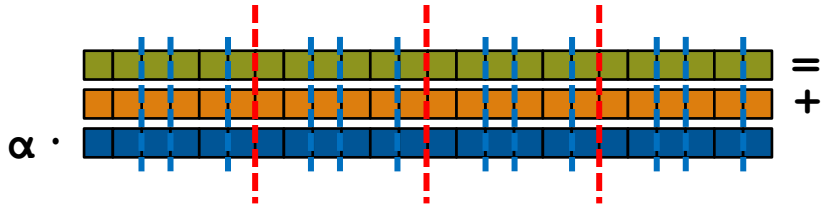
STREAM Triad: Chapel (multilocale, blocked)




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

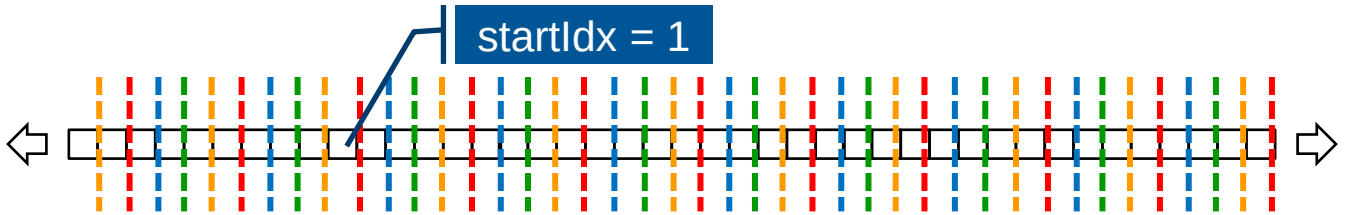


```
var A, B, C: [ProblemSpace] real;
```

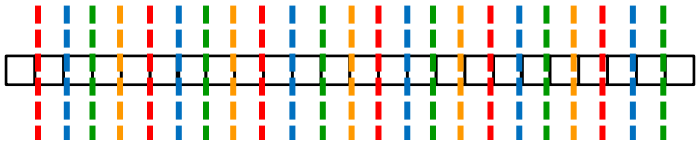



```
A = B + alpha * C;
```

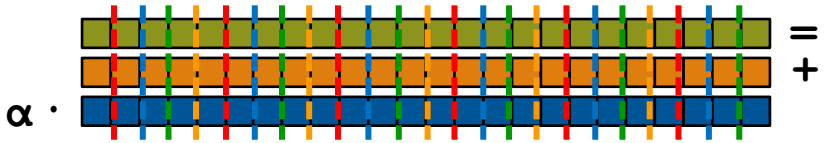
STREAM Triad: Chapel (multilocale, cyclic)




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

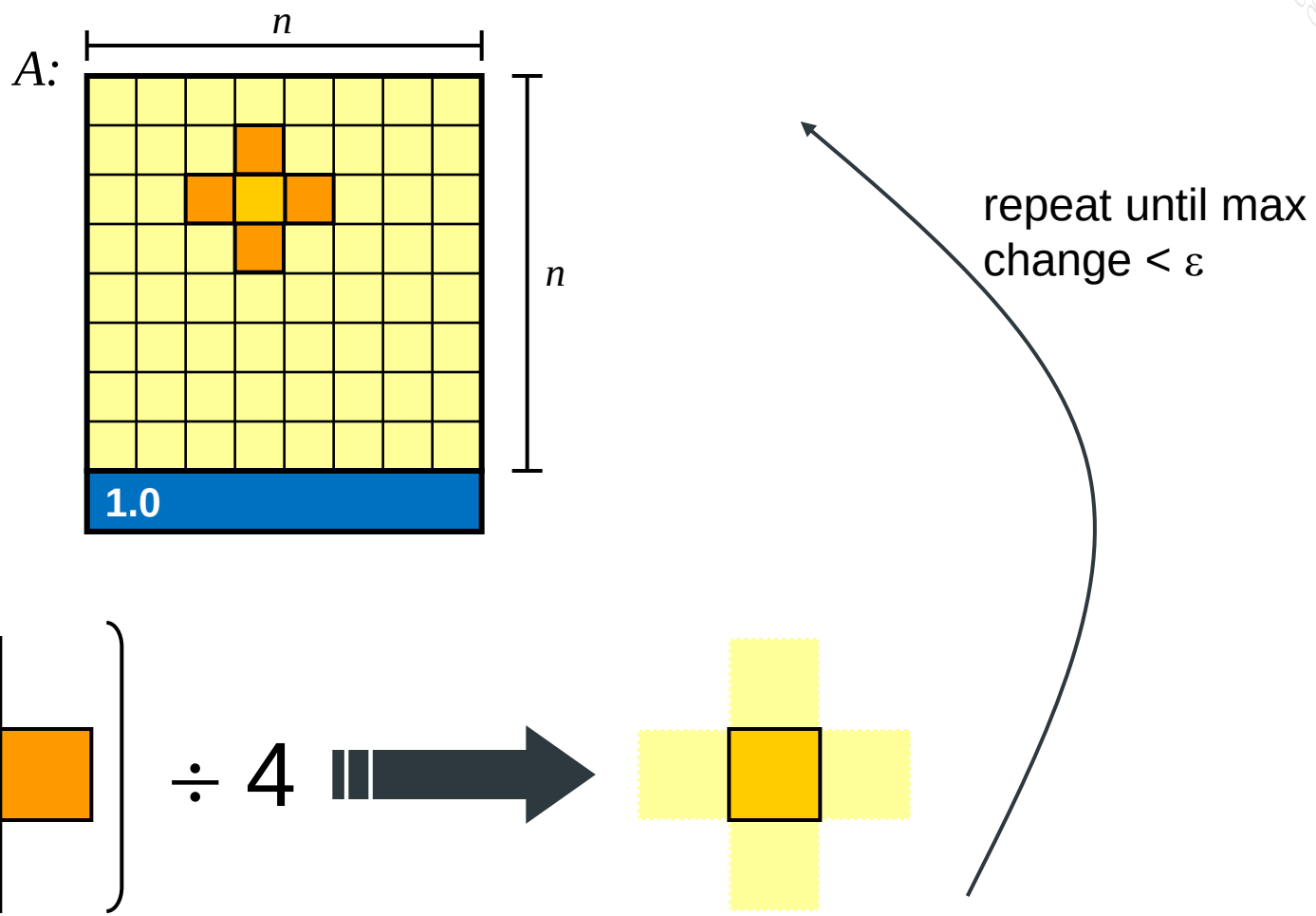


```
var A, B, C: [ProblemSpace] real;
```




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

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
```

Declare program parameters

const ⇒ can't change values after initialization

config ⇒ can be set on executable command-line

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

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

n ⇒ **default integer** (64 bits)

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

Jacobi Iteration in Chapel

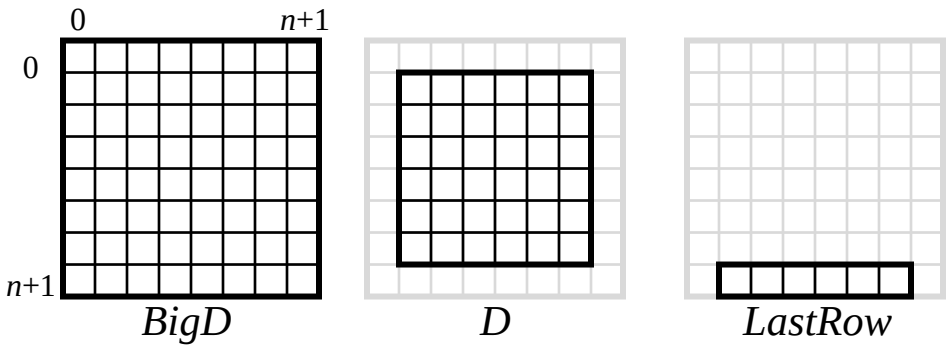
```
config const n = 6,
             epsilon = 1.0e-5;

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

Declare domains (first class index sets)

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

Dom1[Dom2] ⇒ computes the intersection of two domains



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

Jacobi Iteration in Chapel

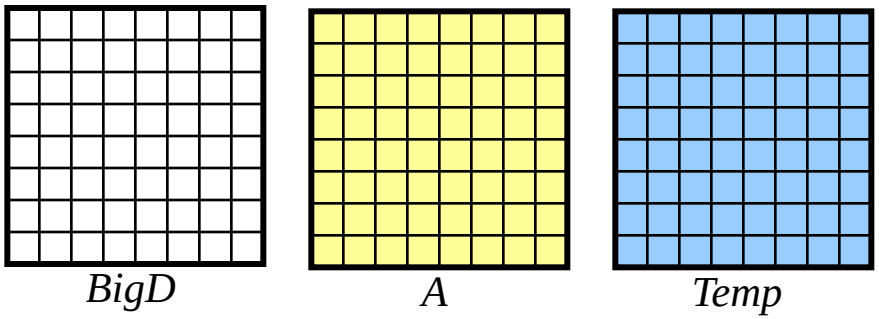
```
config const n = 6,
             epsilon = 1.0e-5;

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

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

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

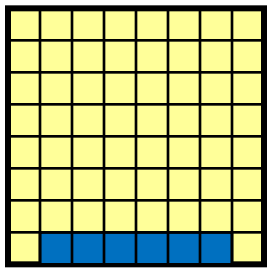
                                          j+1]) / 4;

}

wr
```

Set Explicit Boundary Condition

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



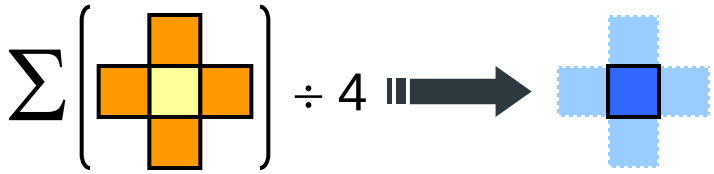
A

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],
```

Copy data back & Repeat until done

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 (shared memory)

```
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 (distributed memory)

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

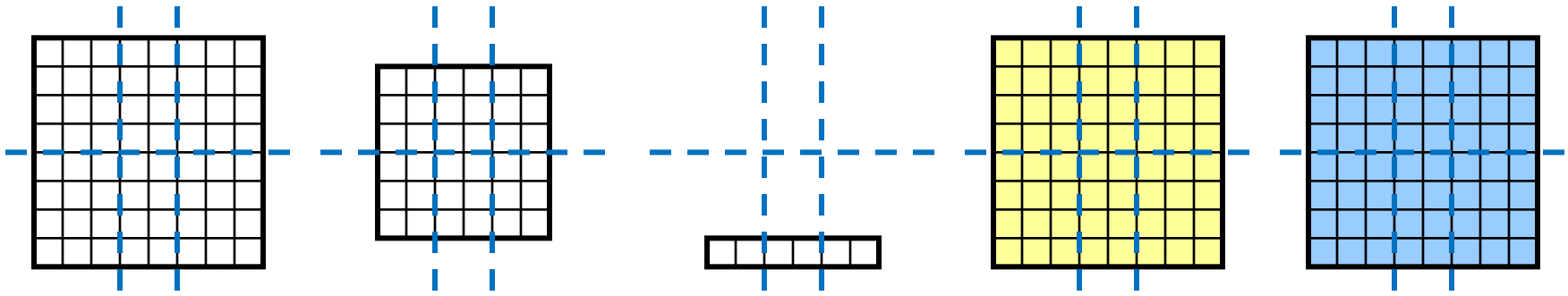
const BigD = {0..n+1, 0..n+1} dmapped Block({1..n, 1..n}),
          D = BigD[1..n, 1..n],
    LastRow = D.exterior(1,0);

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;

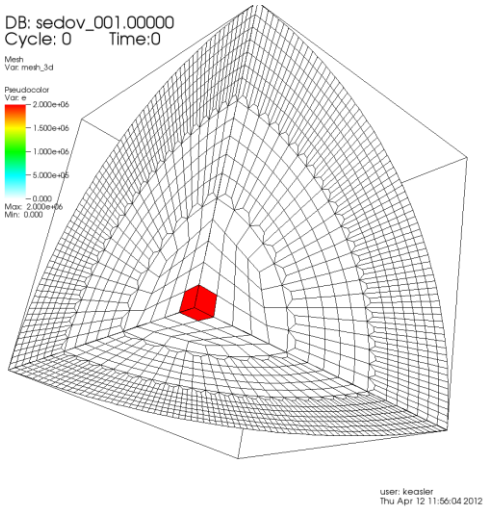
  const delta = max reduce abs(A[D] - Temp[D]);
  A[D] = Temp[D];
} while (delta > epsilon);

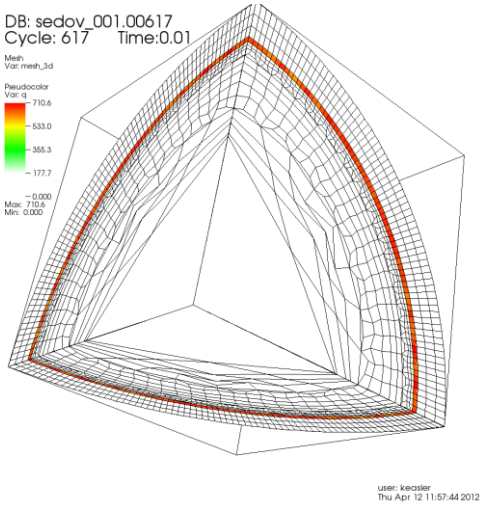
writeln(A);

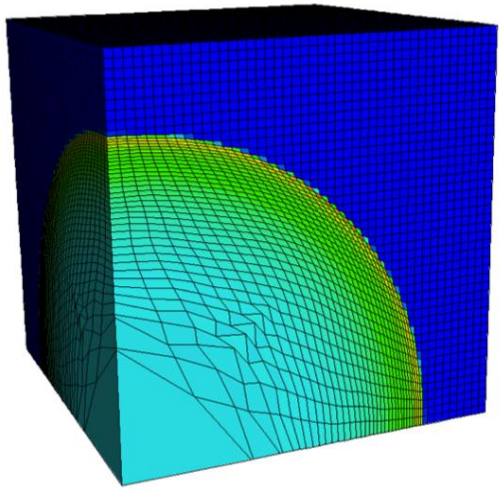
use BlockDist;
```

LULESH: a DOE Proxy Application

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



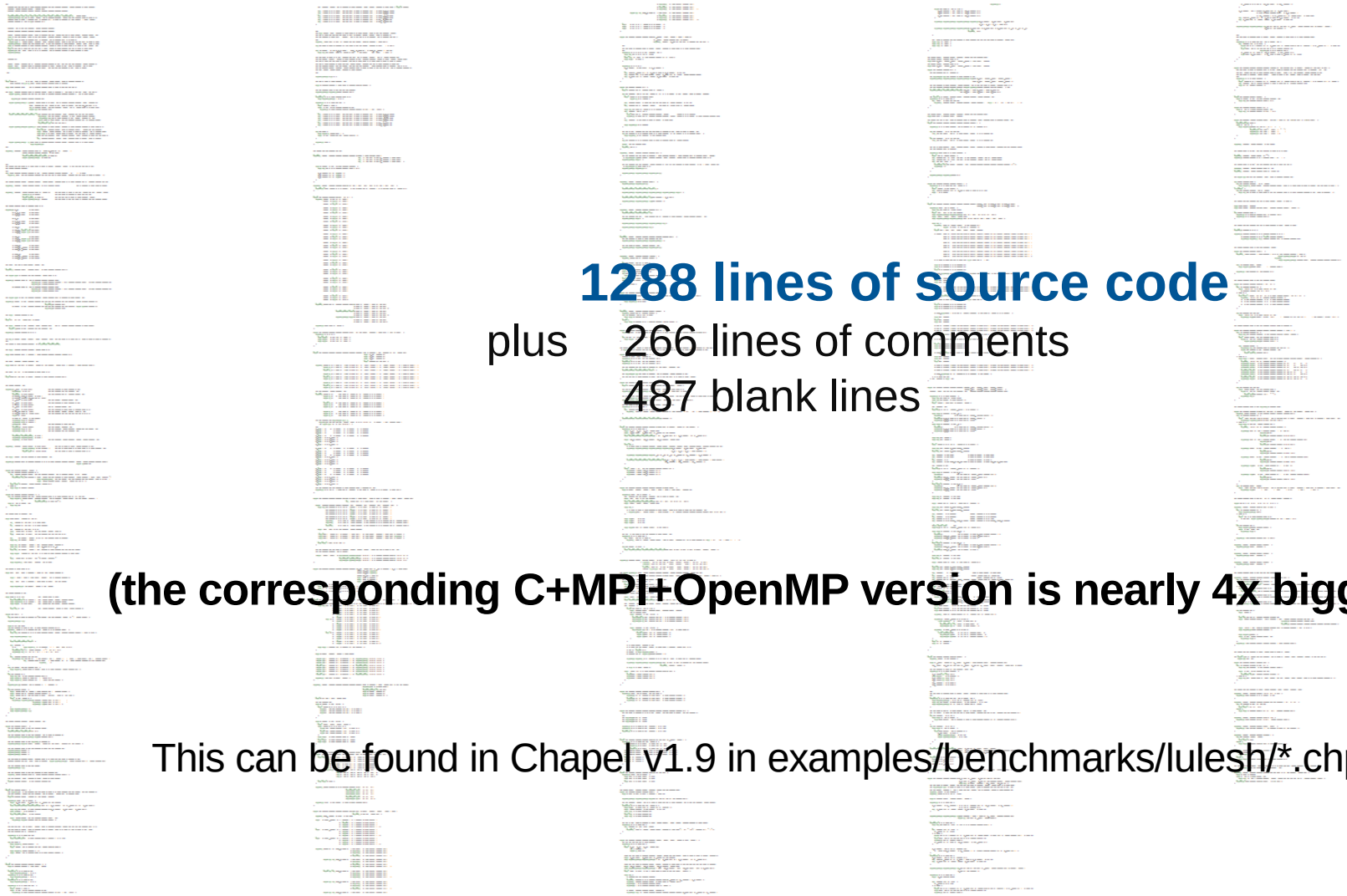




pictures courtesy of Rob Neely, Bert Still, Jeff Keasler, LLNL

LULESH in Chapel

LULESH in Chapel



1288 lines of source code

plus 266 lines of comments

487 blank lines

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

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

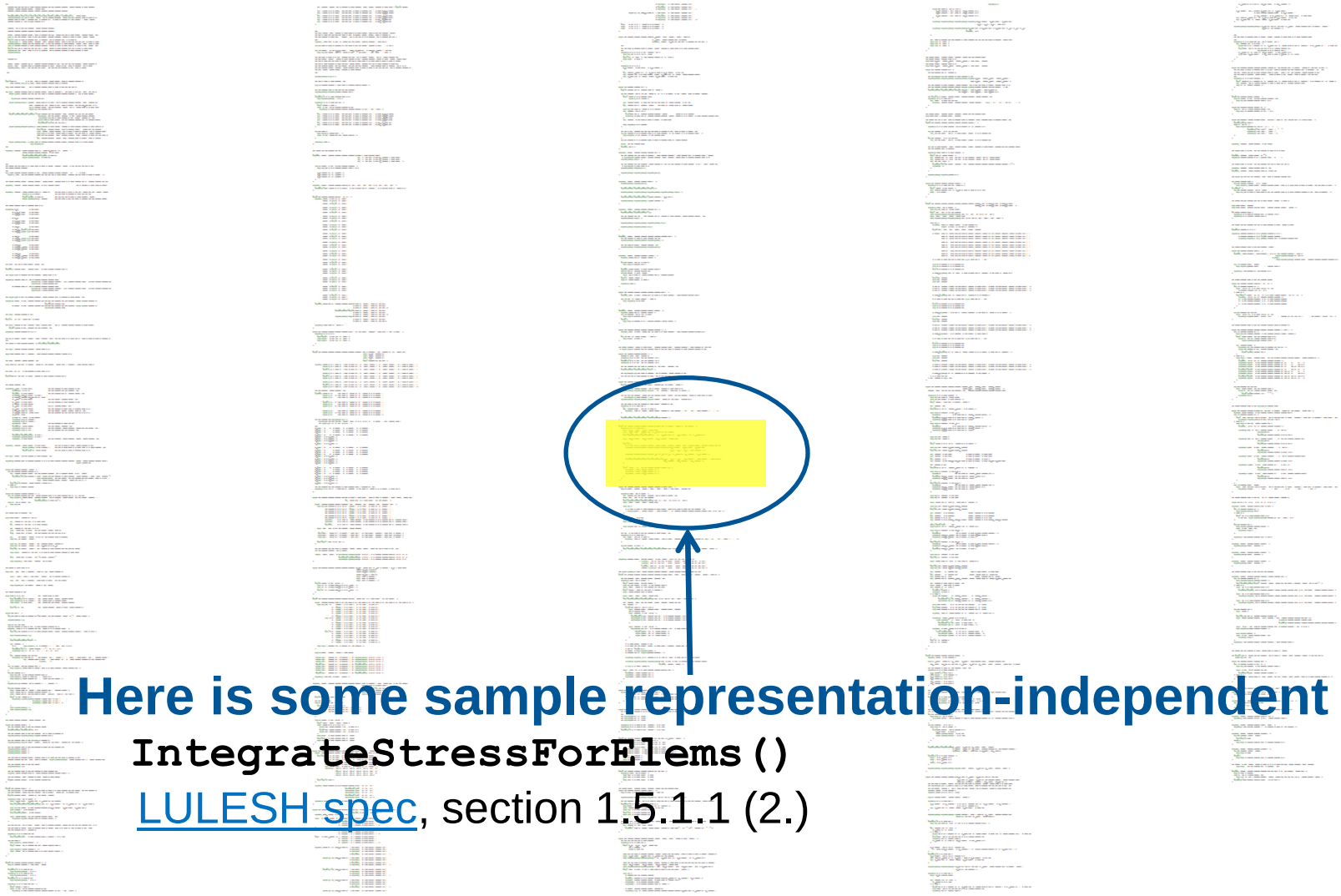
LULESH in Chapel

This is all of the representation dependent code.

It specifies:

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

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

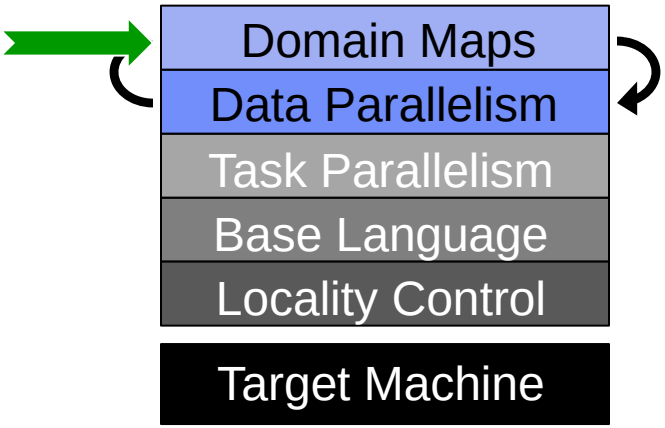
collect nodes neighboring this element; localize node fields

update node forces from element stresses

Because of domain maps, this code is independent of:

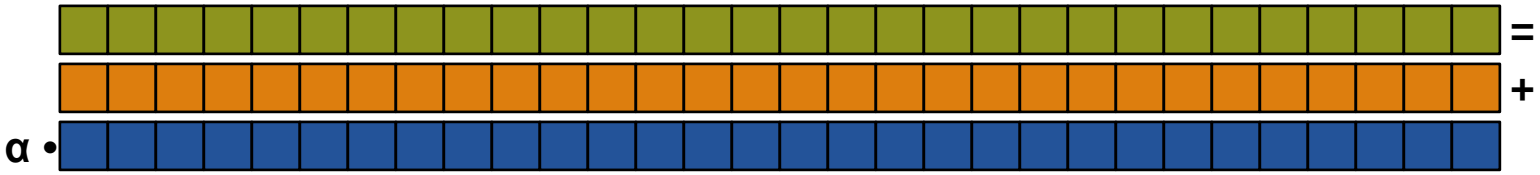
- structured vs. unstructured mesh
- shared vs. distributed data
- sparse vs. dense representation

Domain Maps



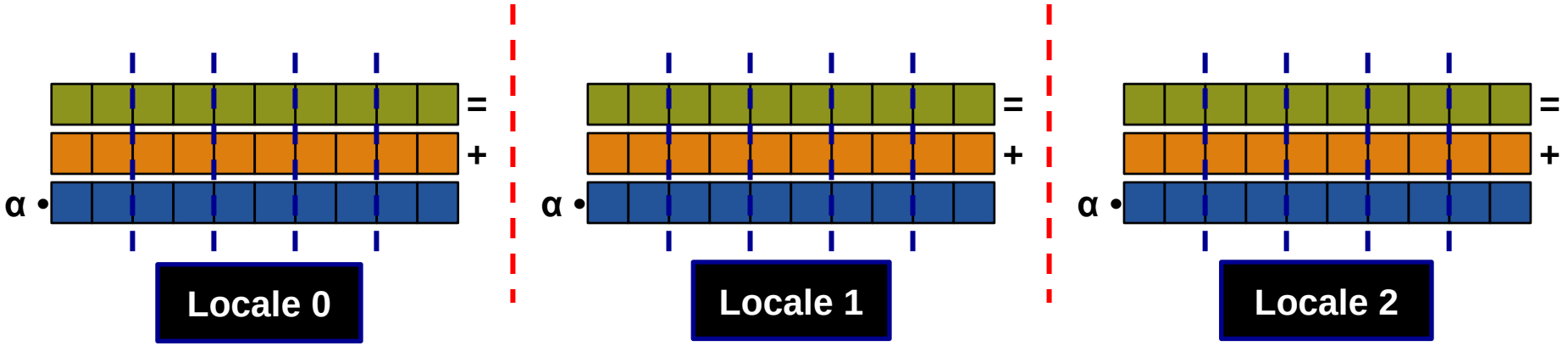
Domain Maps

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




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

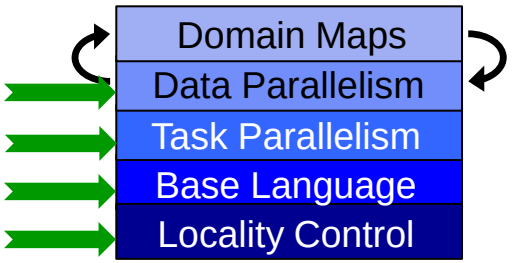
…to the target locales' memory and processors:



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

Domain Map Descriptors

Domain Map

Represents: a domain map value

Generic w.r.t.: index type

State: the domain map's representation

Typical Size: Θ(1)

Required Interface:
- create new domains

Domain

Represents: a domain

Generic w.r.t.: index type

State: representation of index set

Typical Size: Θ(1) → Θ(*numIndices*)

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

Array

Represents: an array

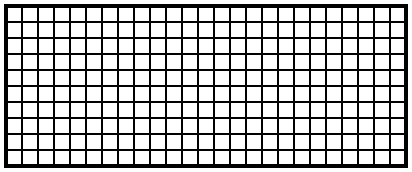
Generic w.r.t.: index type, element type

State: array elements

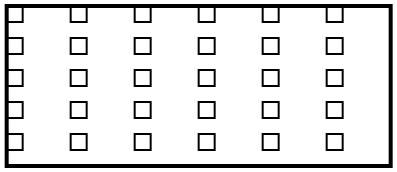
Typical Size: Θ(*numIndices*)

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

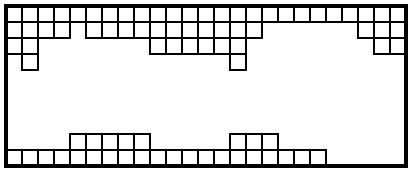
Chapel Domain Types



dense

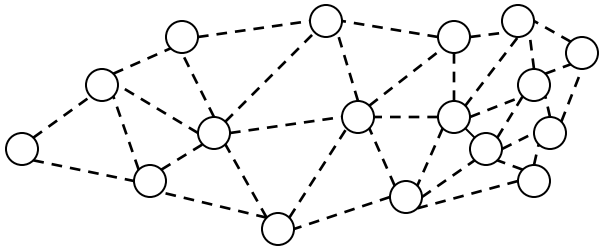


strided



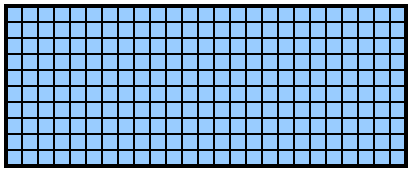
sparse

associative

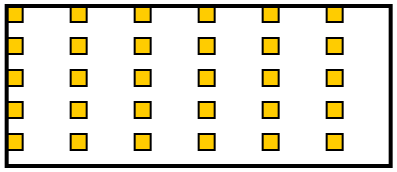


unstructured

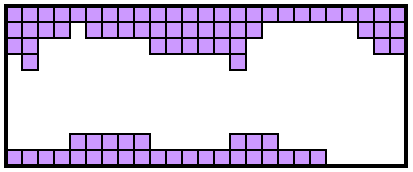
Chapel Array Types



dense

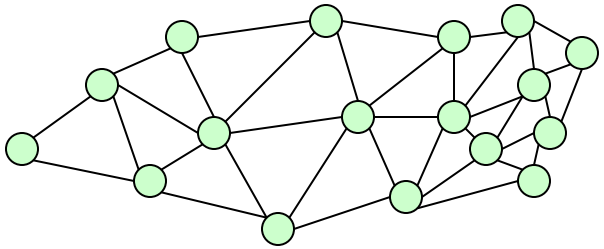


strided



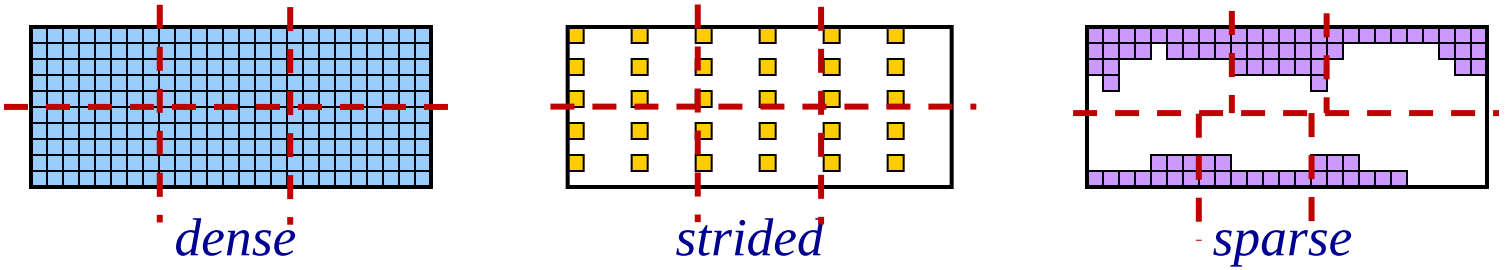
sparse

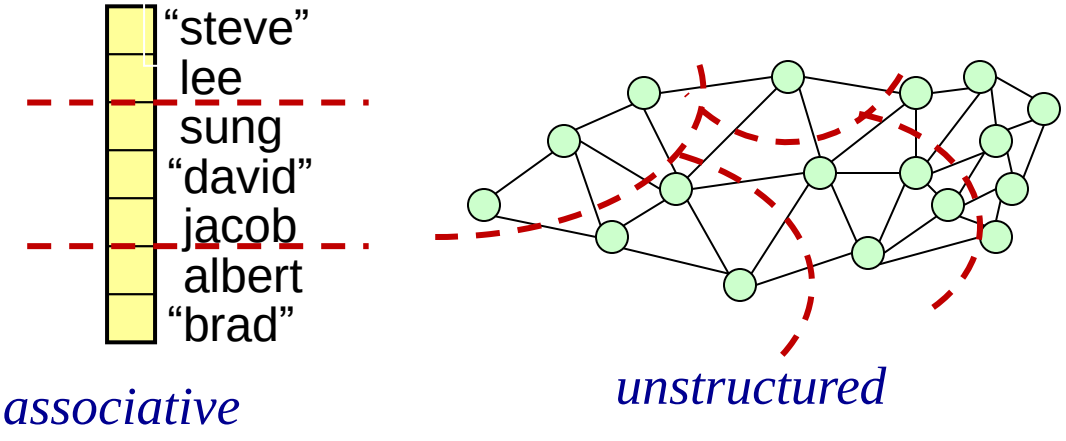
associative



unstructured

All Domain Types Support Domain Maps





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) **leader-follower 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, …

Implementing Data Parallel Loops

Q: How are parallel loops implemented?

(how many tasks? executing where? how are iterations divided up?)

```
forall k in Elems { … }
```

Q2: What about zippered data parallel operations?

(how to reconcile potentially conflicting parallel implementations?)

```
forall (k,d) in zip(Elems, determ) { … }
x += xd * dt;
```

A: Via Feature #2 (leader-follower iterators)…

Leader-Follower Iterators: Definition

- **Chapel defines forall loops using *leader-follower iterators*:**
  - *leader iterators:* create parallelism, assign iterations to tasks
  - *follower iterators:* serially execute work generated by leader

- **Given…**

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

…*A* is defined to be the *leader*

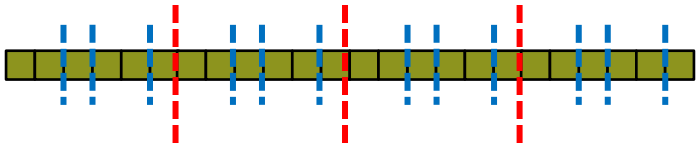
…*A, B,* and *C* are all defined to be *followers*

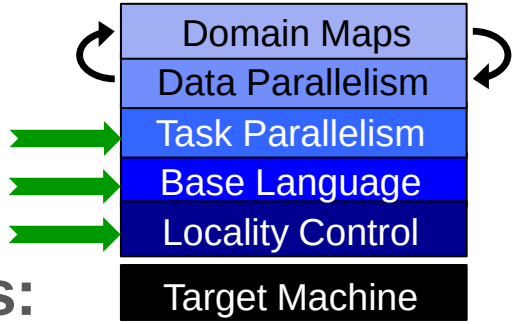
- **Domain maps support default leader-follower iterators**
  - specify parallel traversal of a domain's indices/array's elements
  - typically written to leverage affinity

Writing Leaders and Followers

Leader iterators are defined using task/locality features:

```
iter BlockArr.lead() {
  coforall loc in Locales do
    on loc do
      coforall tid in here.numCores do
        yield computeMyChunk(loc.id, tid);
}
```





Follower iterators simply use serial features:

```
iter BlockArr.follow(work) {
  for i in work do
    yield accessElement(i);
}
```

Leader-Follower Summary

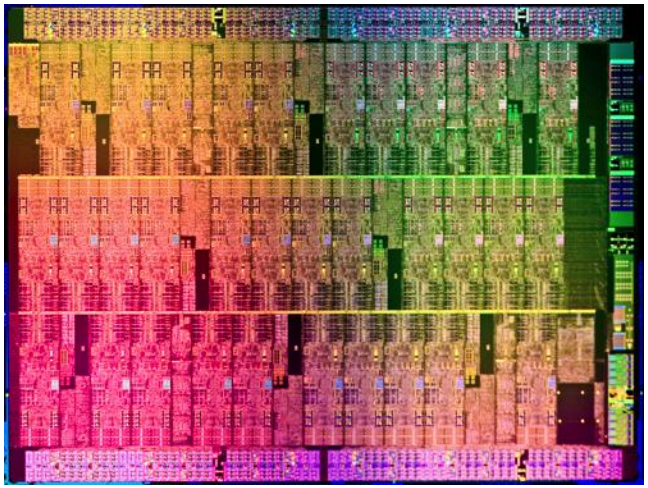
- **Data locality requires parallel loops to execute intelligently**
  - appropriate number and placement of tasks
  - good data-task affinity
- **Most languages define fixed parallel loop styles**
  - where “no parallel loops” is a common choice
- **Leader-follower iterators…**

  …move such policies into user-space

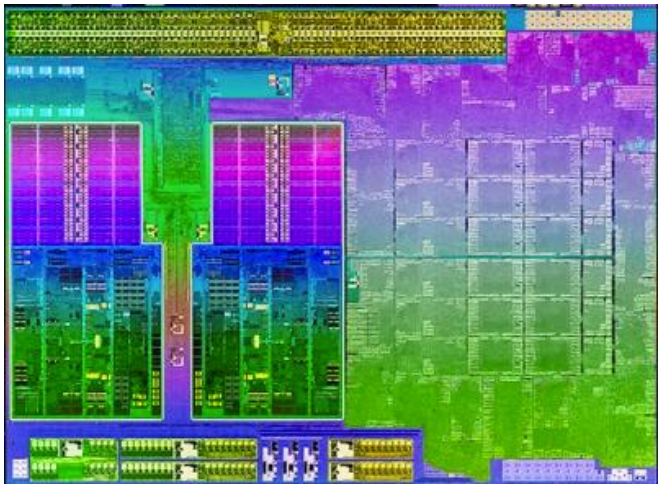
  …expose them to the end-user through data parallel abstractions

```
forall k in Elems { … }
x += xd * dt;
```

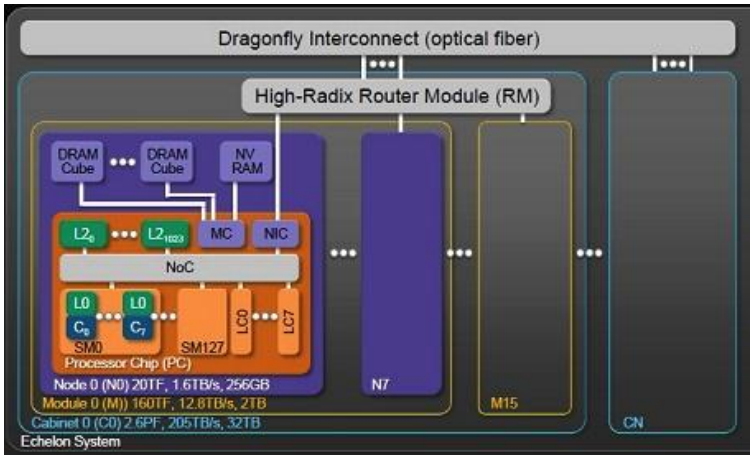
Prototypical Next-Gen Processor Technologies



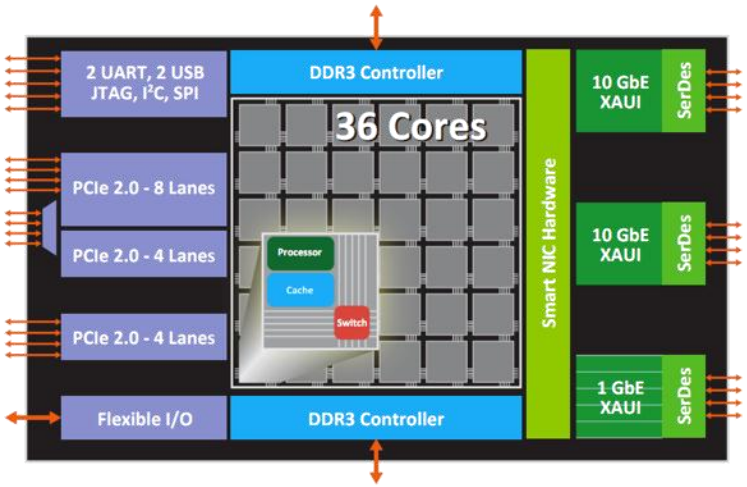
Intel Phi



AMD APU



Nvidia Echelon



Tilera Tile-Gx

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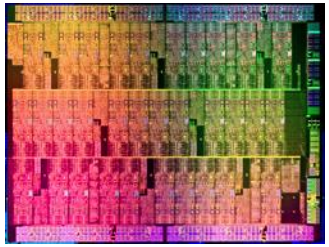
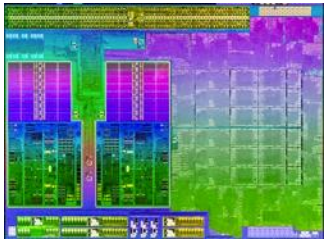
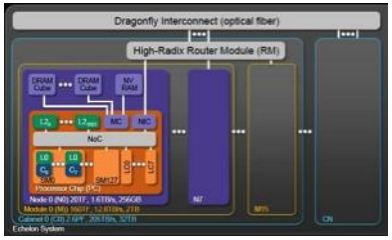
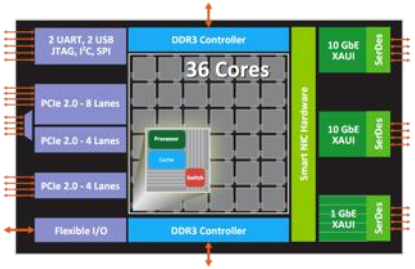
http://insidehpc.com/2010/11/26/nvidia-reveals-details-of-echelon-gpu-designs-for-exascale/ http://tilera.com/sites/default/files/productbriefs/Tile-Gx%203036%20SB012-01.pdf

Architectural Trends









Emerging compute node designs…

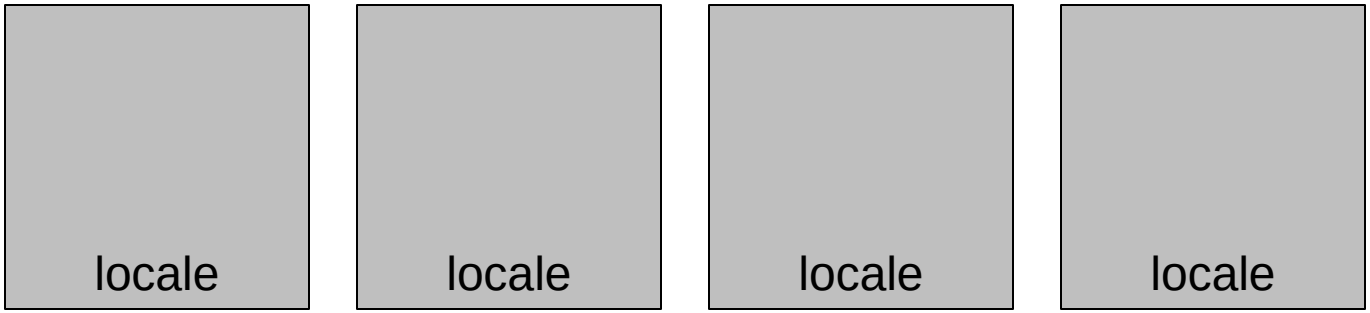
…are increasingly locality-sensitive

…potentially have multiple processor/memory types

Traditional Locales

Concept:

- Traditionally, Chapel has supported a 1D array of locales

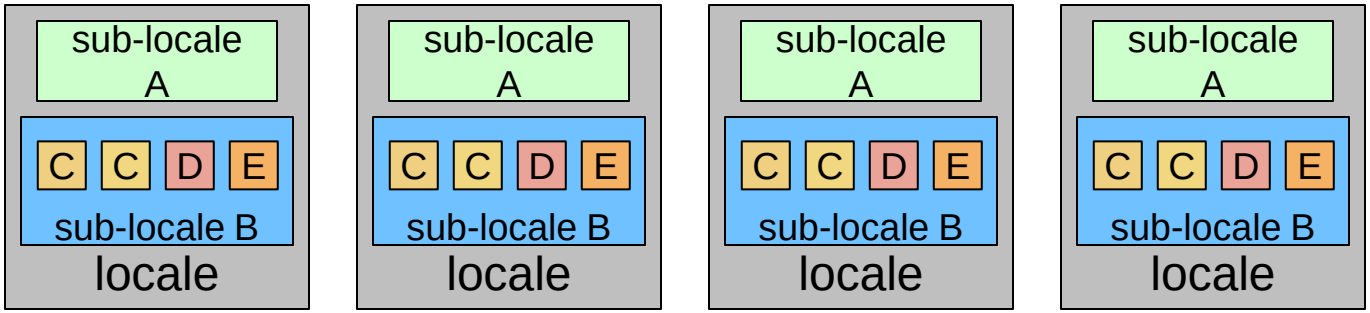


- Supports inter-node locality well, but not intra-node
  - (which, of course, is becoming increasingly important)

Recent Work: Hierarchical Locales

Concept:

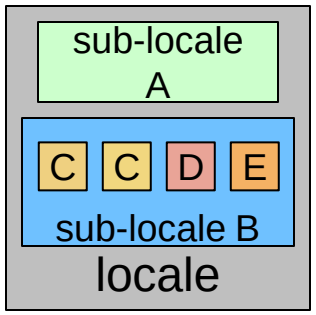
- Support locales within locales to describe architectural sub-structures within a node (e.g., memories, processors)



- As with top-level locales, *on-clauses* and *domain maps* map tasks and variables to sub-locales
- Locale models are defined using Chapel code

Defining Hierarchical Locales

1) Define the processor's abstract block structure



2) Define how to run a task on any sublocale

3) Define how to allocate/access memory on any sublocale

Hierarchical Locale Summary

- **Data locality requires flexibility w.r.t. future architectures**
  - due to uncertainty in processor design
  - to support portability between approaches
- **Most programming models assume certain features in the target architecture**
  - this is why MPI/OpenMP/UPC/CUDA/… have restricted applicability
- **Hierarchical Locales**

  …move the definition of new architectural models to user space

  …are exposed to the end-user via Chapel's traditional locality features

```
on loc do
  coforall tid in here.numCores do
```

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**

Major Chapel Successes Under HPCS

SSCA#2 demonstration on the prototype Cray XC30

- unstructured graph compact application
- clean separation of computation from data structure choices
- fine-grain latency-hiding runtime
- use of XC30's network AMOs via Chapel's 'atomic' types

Clean, general parallel language design

- unified data-, task-, concurrent-, nested-parallelism
- distinct concepts for parallelism and locality
- multiresolution language design philosophy

Portable design and implementation

- while still being able to take advantage of Cray-specific features

Revitalization of Community Interest in Parallel Languages

- HPF-disenchantment became interest, cautious optimism, enthusiasm

Implementation Status -- Version 1.10.0 (Oct 2014)

Overall Status:

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

This is a good time to:

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

A Year in the Life of Chapel

- **Two major releases per year** (April / October)
  - **latest release:** version 1.10, October 2nd, 2014
  - **~a month later:** detailed release notes
    - version 1.10 release notes: http://chapel.cray.com/download.html#releaseNotes
- **CHIUW:** Chapel Implementers and Users Workshop (May-June)
  - talk-based workshop focusing on community efforts
- **SC** (Nov)
  - **Chapel tutorials** (most years)
  - **lightning talks BoF** (now in its 4th year)
  - **CHUG meet-up / happy hour** (now in its 5th year)
  - **emerging technology exhibit** (now in its 2nd year)
  - **educators forum** (past two years)
  - **talks, posters, panels, etc.** (whenever possible)
- **Talks, tutorials, research visits, blogs, …** (year-round)

CHIUW 2014 Talks and Speakers

User Experiences with a Chapel Implementation of UTS
Jens Breitbart, Technische Universität München

Evaluating Next Generation PGAS Languages for Computational Chemistry
Daniel Chavarria-Miranda, Pacific Northwest National Laboratory

Programmer-Guided Reliability in Chapel
David E. Bernholdt, Oak Ridge National Laboratory

Towards Interfaces for Chapel
Chris Wailes, Indiana University

Affine Loop Optimization using Modulo Unrolling in Chapel
Aroon Sharma, University of Maryland

Keynote: Walking to the Chapel
Robert Harrison, Stony Brook University / Brookhaven National Laboratory

LLVM Optimizations for PGAS Programs
Akihiro Hayashi, Rice University

Opportunities for Integrating Tasking and Communication Layers
Dylan T. Stark, Sandia National Laboratories

Caching in on Aggregation
Michael Ferguson, Laboratory for Telecommunication Sciences

Chapel at SC14

Chapel Tutorial (Sun @ 8:30)
- A Computation-Driven Introduction to Parallel Computing in Chapel

Emerging Technologies Booth on Show floor (all week)
- Booth #233: Chapel Hierarchical Locales poster, staffed by Chapel team

Chapel Lightning Talks BoF (Tues @ 12:15)
- 5-minute talks on Chapel + HSA, HDFS/Lustre/cURL, tilings, LLVM, ExMatEx, Python

Chapel Hierarchical Locales Talk (Tues @ 4:30)
- 30-minute talk describing the use of hierarchical locales in Chapel

Poster (Tues @ 5:15)
- Ian Bertolacci (Colorado State University) on advanced tilings in Chapel

Chapel Users Group BoF (Wed @ 5:30)
- Chapel intro + current events followed by community discussion

Happy Hour (Wed @ 7:15): *5th annual Chapel Users Group (CHUG) Happy Hour*
- at Mulate's (201 Julia St, just across the way): open to public, dutch treat

Participation in other BoFs:
- **LLVM in HPC** (Tues @ 12:15)
- **Programming Abstractions for Data Locality** (Wed @ 12:15)
- **PGAS: Partitioned Address Space Programming Model** (Wed @ 12:15)

Chapel Current Events

Chapel is Alive and Well

- **Based on positive customer response to Chapel under HPCS, Cray is undertaking a five-year effort to improve it**
  - we're currently partway into our second year

- **Focus Areas:**
  1. Improving performance and scaling
  2. Fixing immature aspects of the language and implementation
     - e.g., strings, RAII/memory model, error handling, …
  3. Porting to emerging architectures
     - Intel Phi, accelerators, heterogeneous processors and memories, …
  4. Improving interoperability
  5. Growing the Chapel user and developer community
     - including non-HPC communities
  6. Transitioning the governance to neutral, external group

The Cray Chapel Team has doubled in size

The Broader Chapel Community is also Growing

RICE

LTS Laboratory for Telecommunications Sciences

ETH Zürich

Sandia National Laboratories

Lawrence Livermore National Laboratory

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

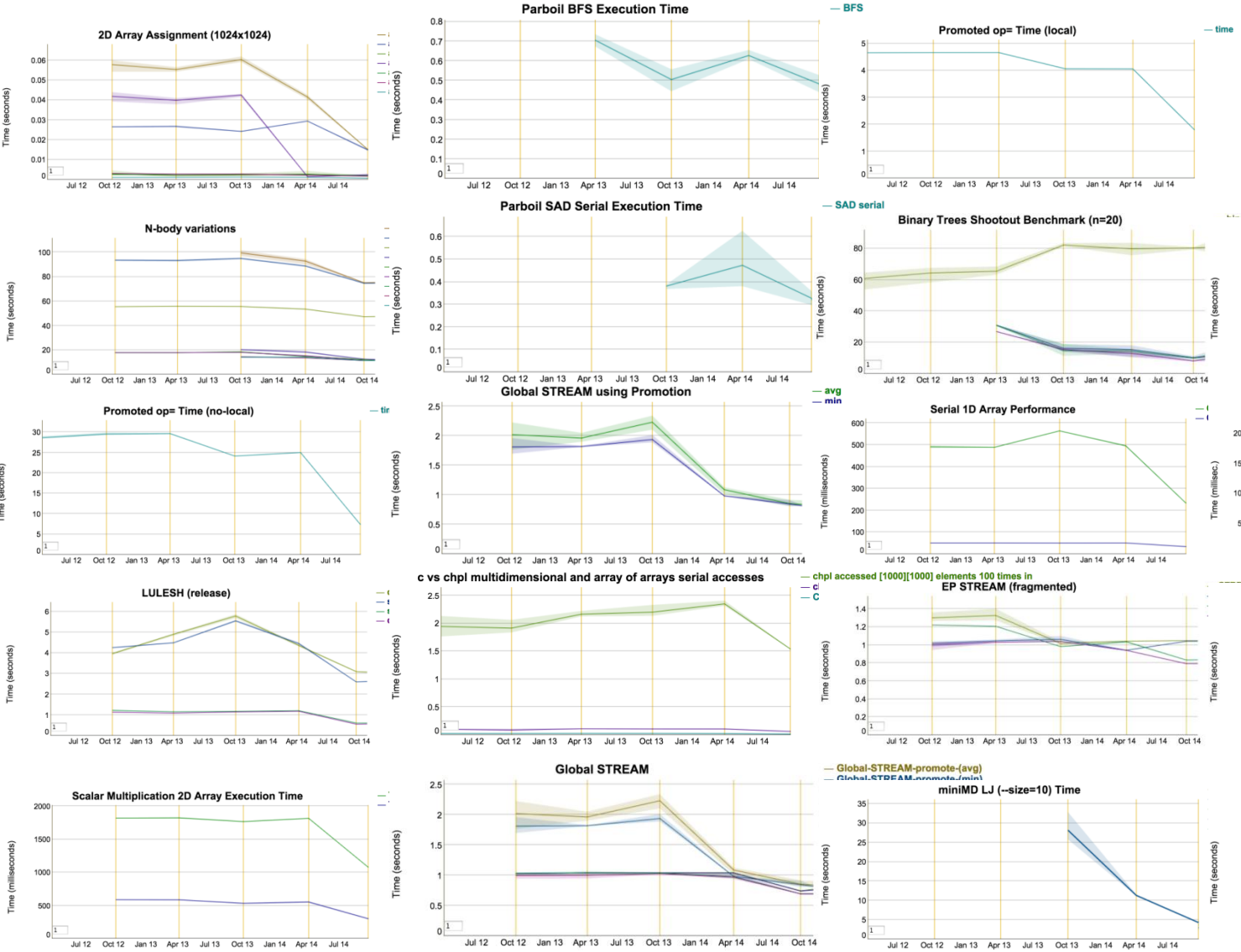
(there's been an uptick in interest from industrial users/developers as well)

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

Chapel version 1.10 is now available

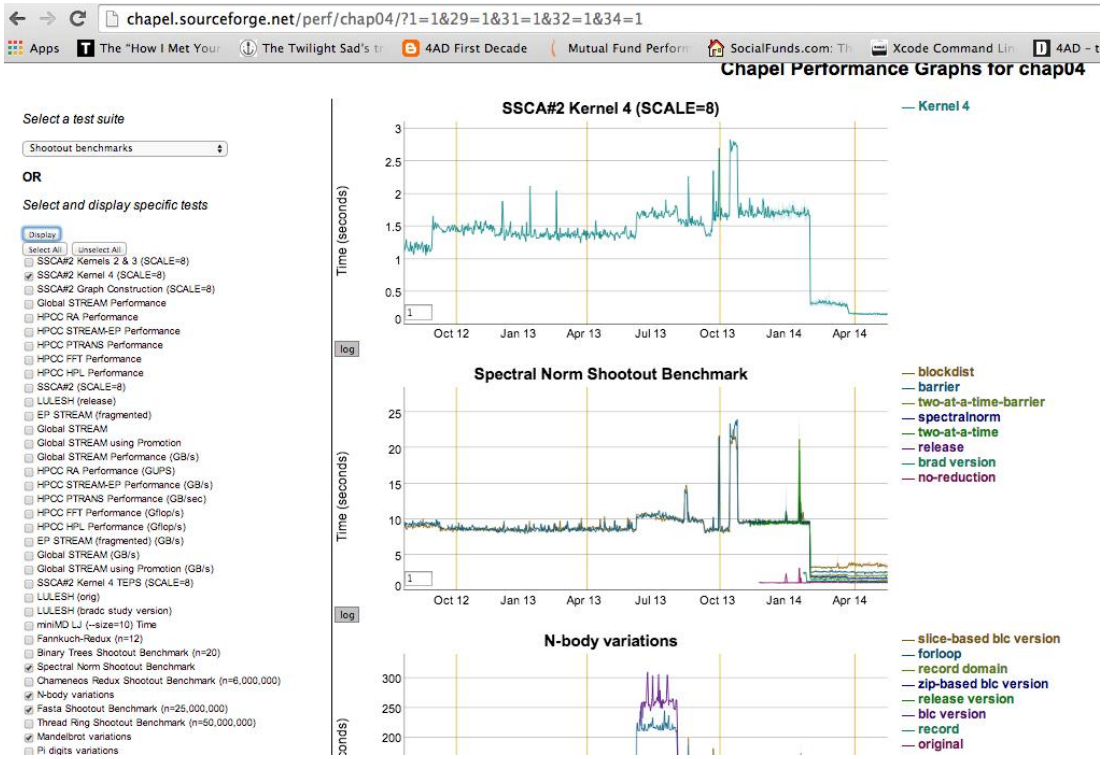
- **Highlights Include:**
  - lighter-weight tasking via Sandia's Qthreads
  - initial support for Intel Xeon Phil Knights Corner (KNC)
  - renewed focus on standard libraries
  - support for Lustre and cURL-based data channels
  - expanded array capabilities
  - improved semantic checks, bug fixes, third-party packages, …
  - significant performance improvements…

Execution Time is Improving (lower is better)



Nightly Performance Graphs are Now Public

- **What this means:**
  - You can stalk our performance changes over time
  - You can submit your own performance tests and monitor them
  - You can see the performance impacts of patches you commit



http://chapel.sourceforge.net/perf/

Chapel Language Shootout* Entry Underway

benchmarksgame.alioth.debian.org/u32/performance.php?test=nbody

Apps | The "How I Met Your | The Twilight Sad's tr | 4AD First Decade | Mutual Fund Perform | SocialFunds.com: T

Ubuntu : Intel® Q6600® one core
Computer Language Benchmarks Game [[Play]]

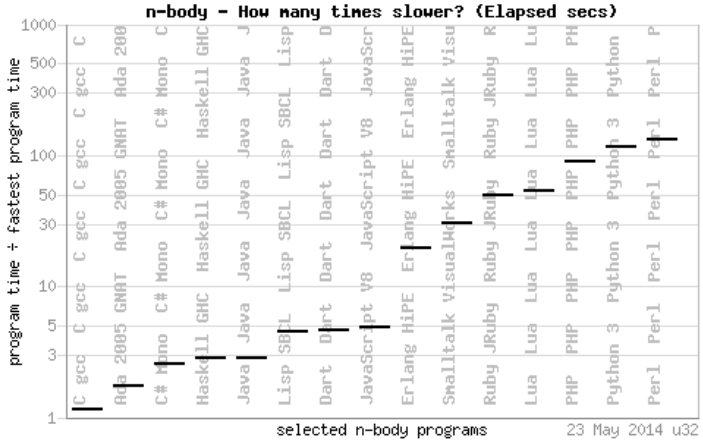
quad-core and one core, x86 and x64 measurements

ges - | x86 one core | Show

+1

n-body benchmark N=50,000,000

Each chart bar shows *how many times slower*, one ↓ **n-body** program was, compared to the fastest p



These are not the only programs that could be written. These are not the only compilers and interpret

Column × shows *how many times more* each program used compared to the benchmark program tha

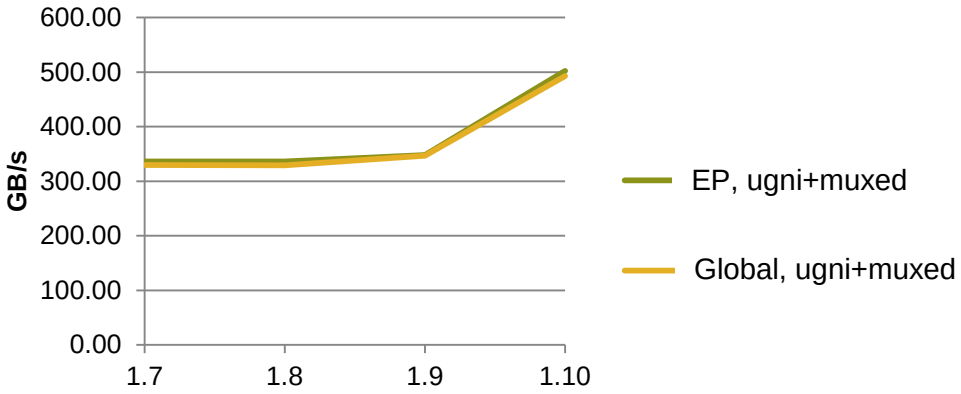
×	Program Source Code	CPU secs (sort)	Elapsed secs	Memory KB (sort)	Code B (sort)	≈ CPU Load
1.0	**Fortran** Intel #5	8.57	**8.57**	260	1659	0% 0% 0% 100%
1.1	**C++** g++ #8	9.08	**9.08**	336	1544	0% 0% 1% 100%
1.1	**C++** g++ #7	9.10	9.10	336	1545	2% 0% 5% 100%
1.2	**C** gcc #4	9.91	**9.92**	336	1490	0% 1% 1% 100%
1.2	**C++** g++ #3	9.94	9.95	620	1763	1% 0% 1% 100%
1.5	**C++** g++ #5	12.74	12.75	868	1749	0% 1% 1% 100%

* = ahem… The Computer Language Benchmarks Game
http://benchmarksgame.alioth.debian.org/

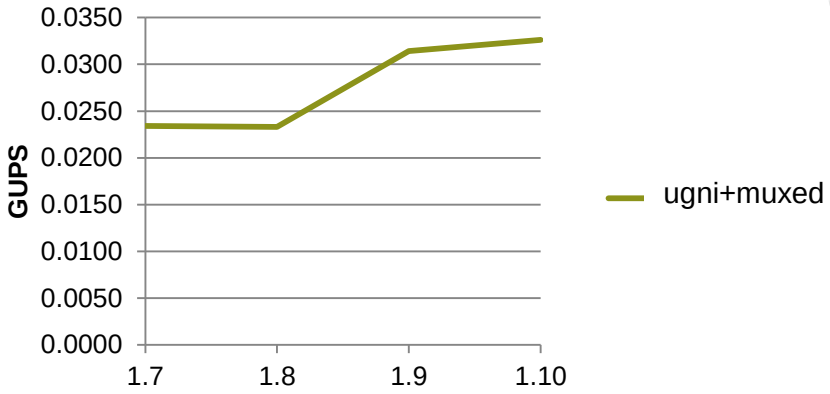
Shootout entry improving with each release

Multilocale Performance is also improving

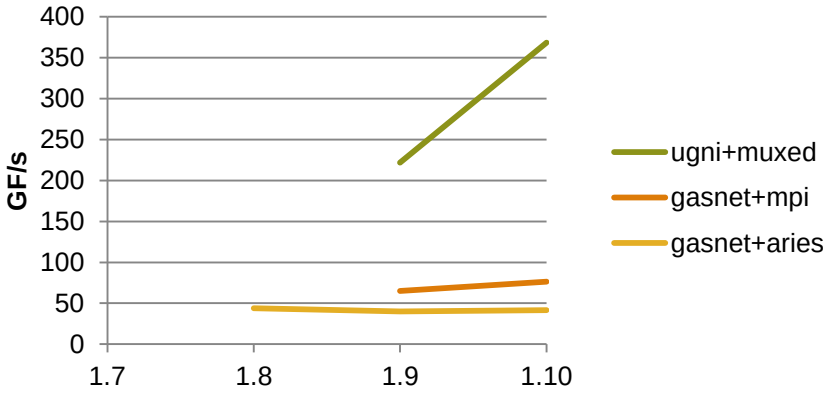
STREAM (GB/s)



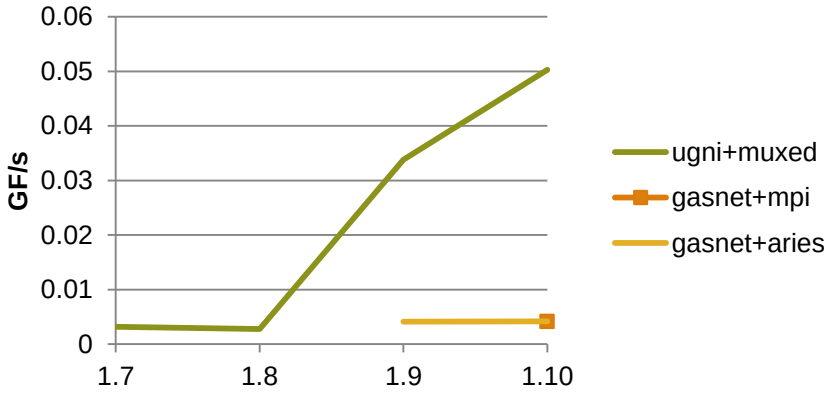
RA, atomic version (GUPS)



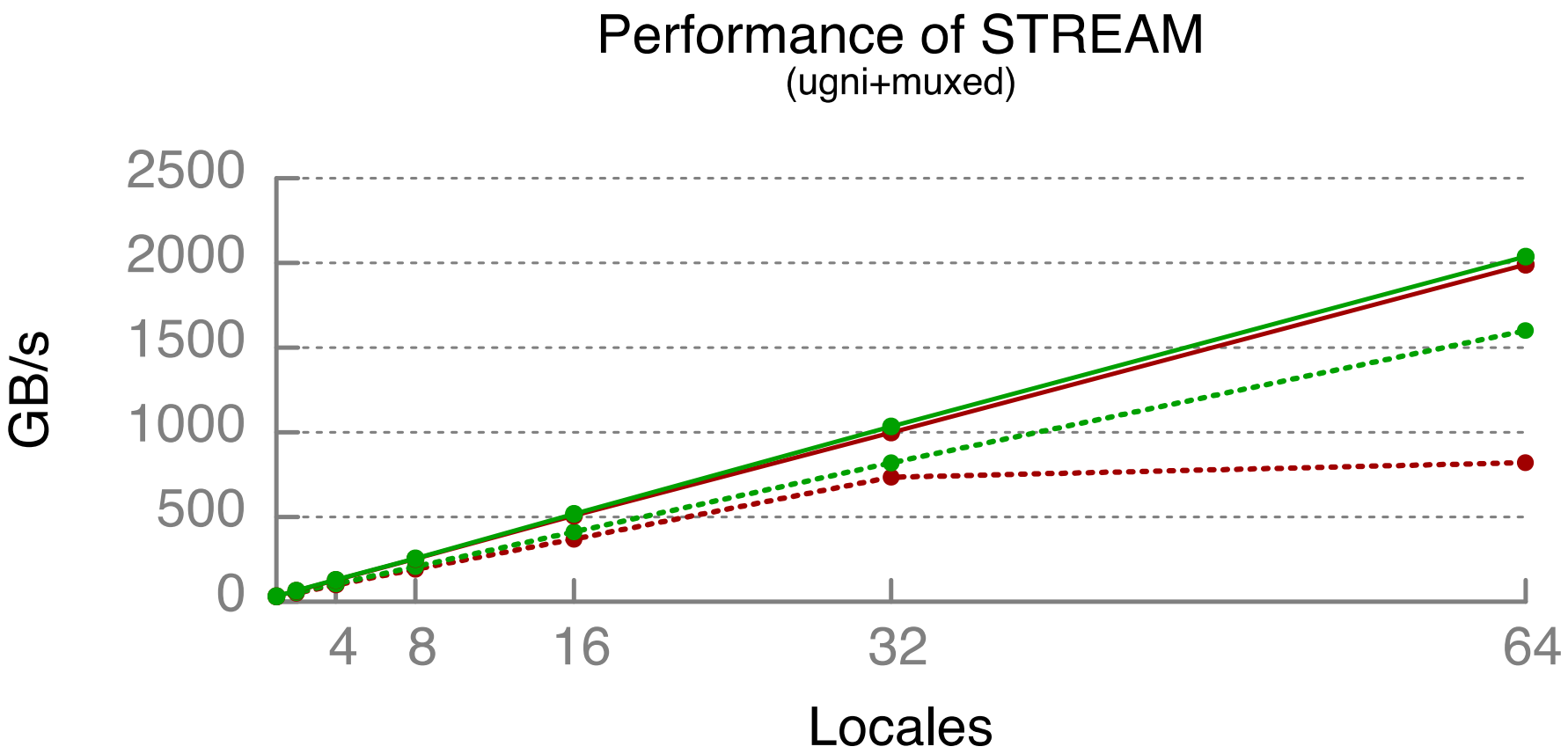
HPL, study version (GF/s)



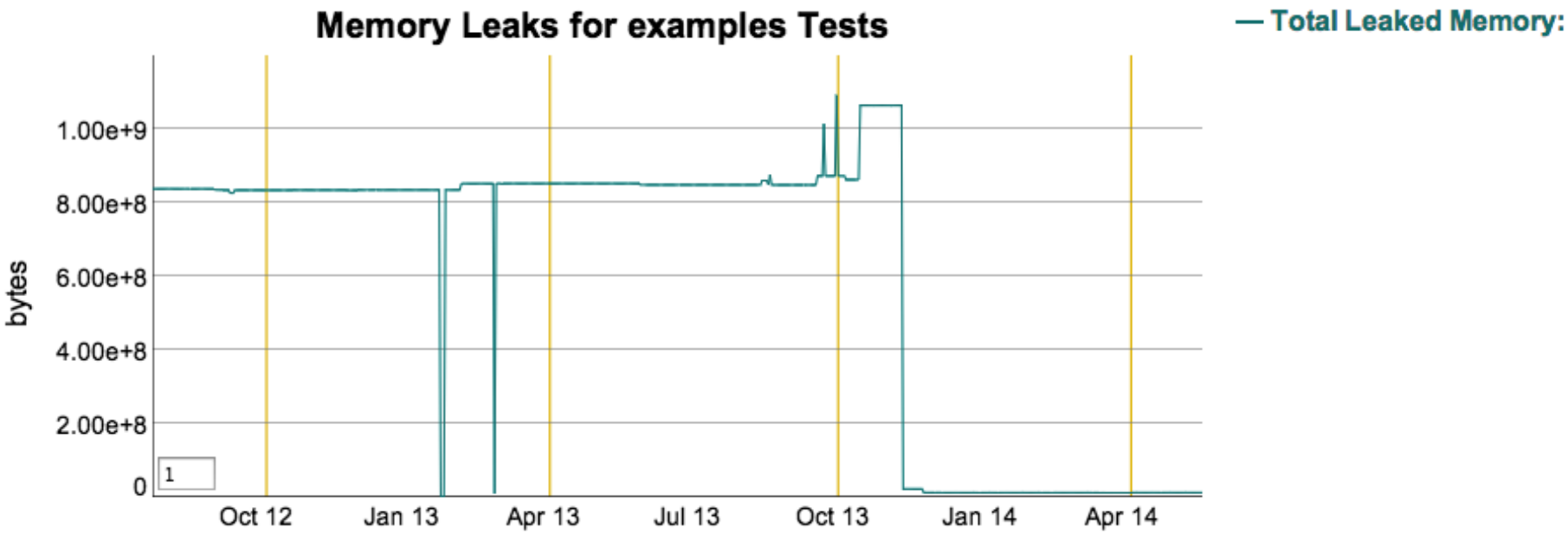
FFT (GF/s)



Scalability is Improving as well



Memory Leaks are Being Plugged



Correctness Testing Now Public Too

- **Nightly regression tests sent to SourceForge mailing lists:**
  - **chapel-test-results-regressions@…** the interesting results
  - **chapel-test-results-all@...** the complete results

http://sourceforge.net/p/chapel/mailman/

Chapel Developers Join 21st Century

- Migrated from SVN/SourceForge to Git/GitHub
- Converted testing from crontabs to Jenkins
- Began using Travis for pre-commit sanity checks
- Began using Coverity scan to catch code quality issues
- Started tracking tasks in Pivotal
- Kicked off a Facebook page
- Started a #chapel-developers IRC channel
- Created/Owned a Chapel project in OpenHUB

- Next up: Modern, online documentation and more…

Chapel is now Apache

Historically:

- **License:** BSD
- **Contributor Agreement:** Cray-specific

As of version 1.10:

- **License:** Apache v2.0
- **Contributor Agreement:** Apache v2.0

Rationale:

- BSD doesn't have a contributor agreement
- Cray agreement has been a stumbling block for some developers

http://www.apache.org/licenses/LICENSE-2.0.html

Chapel: It's not just for HPC anymore

- **"Big data" programmers want productive languages too**
  - MapReduce, Pig, Hive, HBase have their place, but also drawbacks
  - Wouldn't a general, locality-aware parallel language be nice here too?

- **Chapel support for HDFS*: A first step**
  - Developed by Tim Zakian (Indiana University), summer 2013
  - Summer 2014: extended support to include Lustre, cURL

- **Questions:**
  - What killer apps/demos to focus on?

*HDFS = Hadoop Distributed File System

http://chapel.cray.com/presentations/SC13/06-hdfs-ferguson.pdf

Chapel: Attractive for Education

For some time, we've claimed Chapel is ideal for education:

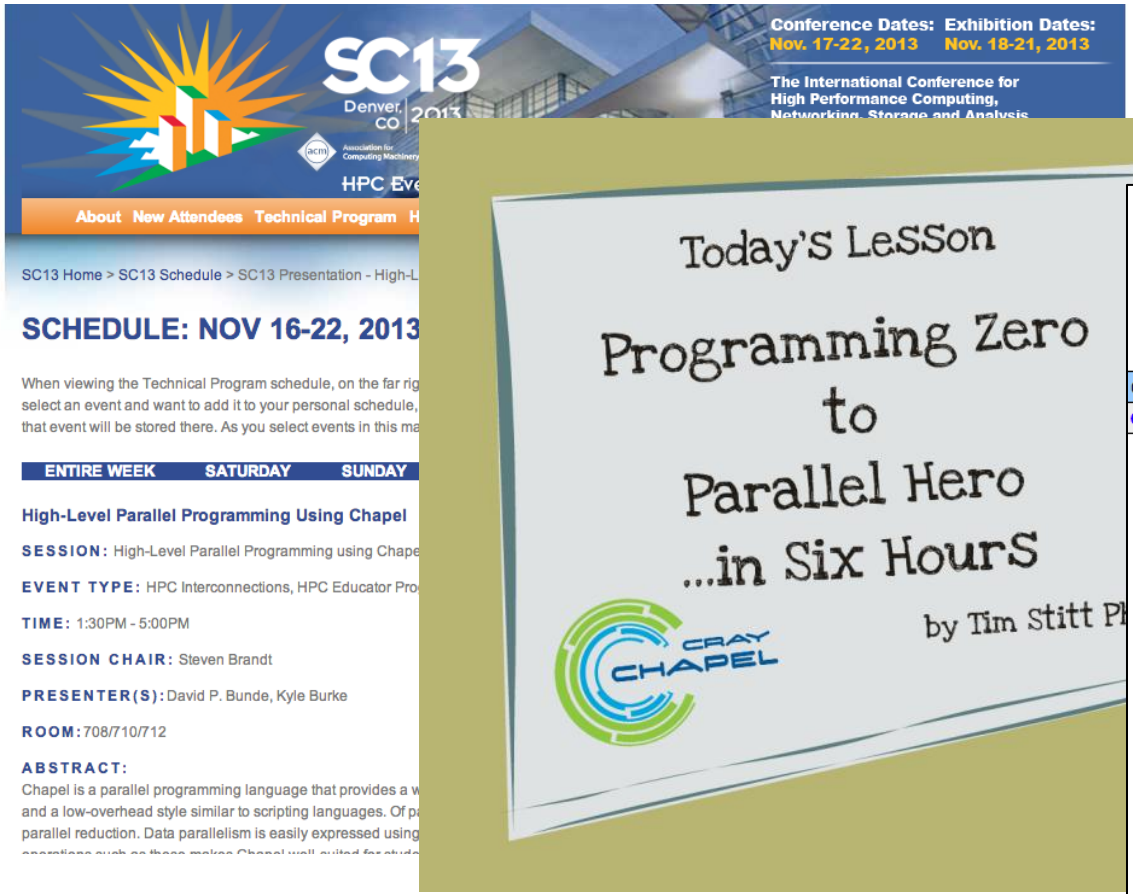
Chapel and Education

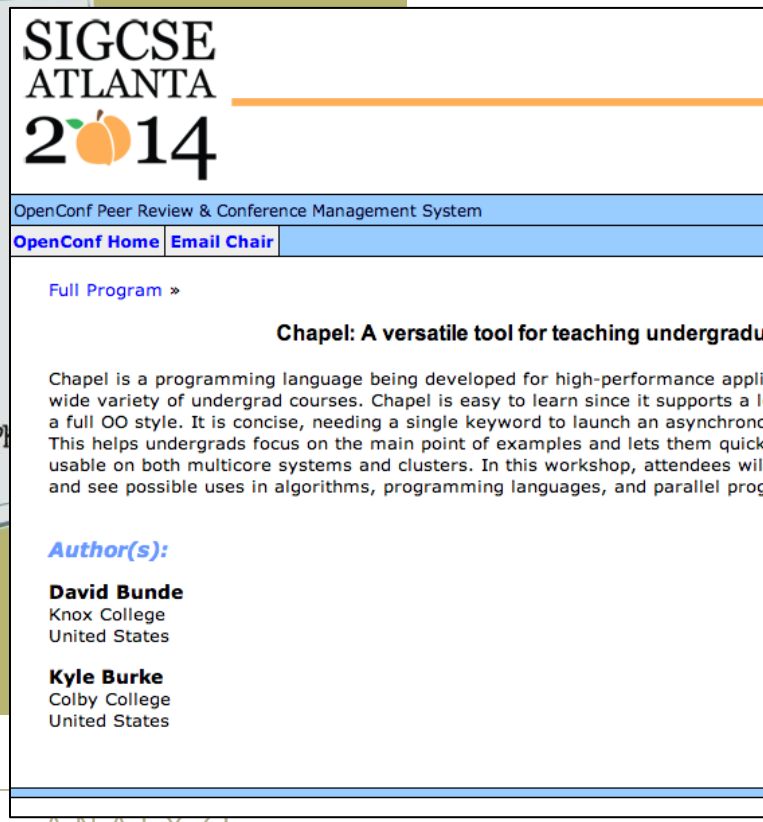
- **When teaching parallel programming, I like to cover:**
  - data parallelism
  - task parallelism
  - concurrency
  - synchronization
  - locality/affinity
  - deadlock, livelock, and other pitfalls
  - performance tuning
  - …
- **I don't think there's been a good language out there…**
  - for teaching *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: Attractive for Education

And now, educators are helping make the argument for us:





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

Interactive Chapel

- **What if you could work with Chapel interactively:**

```
chpl> var A: [1..n] real;
OK.
chpl> [i in 1..n] A = i / 2.0;
OK.
chpl> writeln(A);
0.5 1.0 1.5 2.0 2.5 3.0
chpl> proc foo(x) { x *= 2; }
OK.
```

- **What if this worked not only on your desktop, but by offloading onto compute nodes as well:**

```
chpl> var myLocales = getNodes(100);
OK.
chpl> var MyDist = new Block({1..1000000}, myLocales);
OK.
```

- **We've recently started an effort to implement such a capability**

Working toward "The Chapel Foundation"

- **If Chapel remains Cray-controlled, its chances of succeeding are much lower**
- **The intention has always been to "turn it over to the community" when it's ready**
  - finding the correct timing is tricky
- **We've started the brainstorming process of what such a model would look like ("The Chapel Foundation")**
  - membership roles
  - governance
  - funding models
- **If you have thoughts on this, we're interested in them**

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 1.10.0 release, browse source repository

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-October 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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