Chapel Hands-On

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Discovery 2015: September 16th, 2011

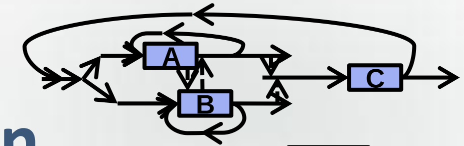
What is Chapel?

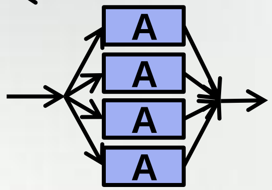
- A new parallel programming language
  - Design and development led by Cray Inc.
  - Started under the DARPA HPCS program
- **Overall goal:** Improve programmer productivity
  - Improve the programmability of parallel computers
  - Match or beat the performance of current programming models
  - Support better portability than current programming models
  - Improve the robustness of parallel codes
- A work-in-progress

Chapel's Implementation

- Being developed as open source at SourceForge
- Licensed as BSD software
- **Target Architectures:**
  - multicore desktops and laptops
  - commodity clusters
  - Cray architectures
  - systems from other vendors
  - (in-progress: CPU+accelerator hybrids, manycore, …)

Why Chapel?





Dynamic, arbitrary, multithreaded execution

- Contrast with UPC/SHMEM: single-threaded SPMD

Explicit parallel concepts in source code for (composable) data and task parallelism

- Contrast with UPC/SHMEM: all parallelism stems from implicitly running multiple copies of the program

Distinct concepts for locality vs. parallelism

- Contrast with UPC/SHMEM in which the program images represent locality in addition to parallelism

Productivity Features

- type inference, iterator functions, rich array types, OOP, …

Goals

This Session's Goals:

- Teach you about Chapel
  - current status
  - future directions
- Give you a chance to program in Chapel
- Answer your questions
- Get your feedback and suggestions

But realistically speaking…?

- You're about to be hit with a firehose of information
- You'll likely leave knowing just enough to be dangerous

  Plug: Come to our SC11 tutorial in Seattle for a more in-depth introduction!

Outline

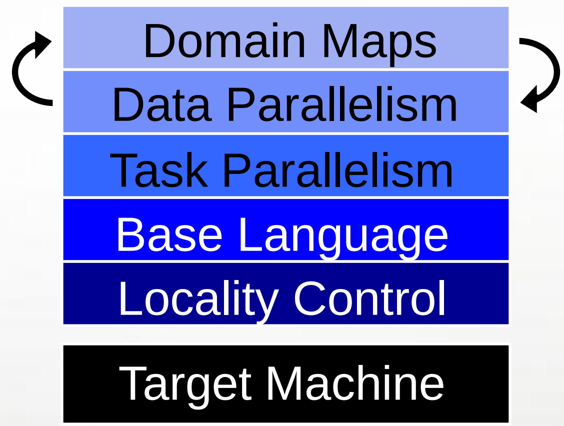
- ✓ Chapel Motivation
- ➢ Quick Tour of Some Chapel Features
- Project Status and Summary
- Bonus Topics

Chapel's Multiresolution Design

Multiresolution Design: Support multiple tiers of features

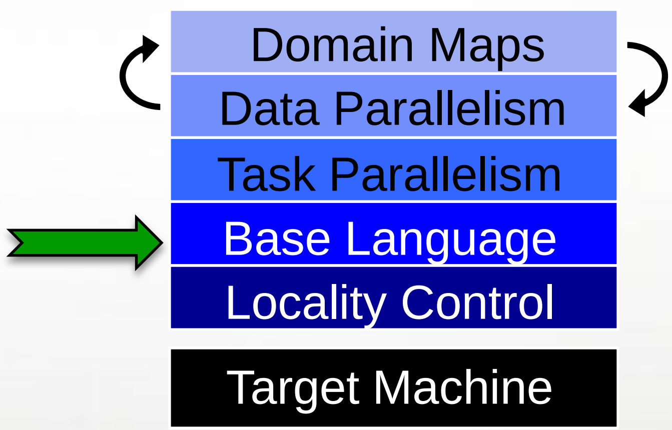
- higher levels for programmability, productivity
- lower levels for greater degrees of control

Chapel language concepts



- build the higher-level concepts in terms of the lower
- Permit users to intermix layers arbitrarily

Base Language Features



Static Type Inference

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


proc addem(x, y) {            // addem() is generic
  return x + y;
}

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

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

```
(4.14, bradford)
```

Configs

```
param intSize = 32;
type elementType = real(32);
const epsilon = 0.01:elementType;
var start = 1:int(intSize);
```

Configs

```
config param intSize = 32;
config type elementType = real(32);
config const epsilon = 0.01:elementType;
config var start = 1:int(intSize);
```

```
% chpl myProgram.chpl -sintSize=64 -selementType=real
% a.out --start=2 --epsilon=0.00001
```

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(D, 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)
```

Range Types and Algebra

```
const r = 1..10;

printVals(r # 3);
printVals(r # -3);
printVals(r by 2);
printVals(r by 2 align 2);
printVals(r by -2);
printVals(r by 2 # 3);
printVals(r # 3 by 2);

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

```
1 2 3
8 9 10
1 3 5 7 9
2 4 6 8 10
10 8 6 4 2
1 3 5
1 3
```

Zipper Iteration

```
var A: [0..9] real;

for (i,j,a) in (1..10, 2..20 by 2, A) do
  a = j + i/10.0;

writeln(A);
```

```
2.1 4.2 6.3 8.4 10.5 12.6 14.7 16.8 18.9 21.0
```

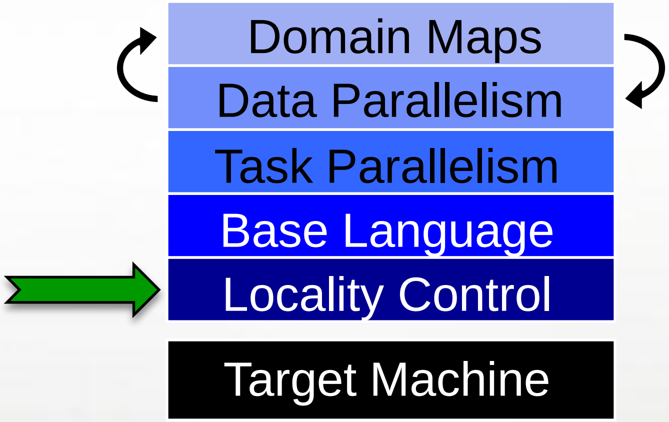
Default and Named Arguments

```
proc foo(name="joe", weight=175, age) {
  …
}

foo("brad", age=101);
```

Other Base Language Features

- tuple types
- compile-time features for meta-programming
  - e.g., compile-time functions to compute types and params
- rank-independent programming features
- value- and reference-based OOP
- overloading, where clauses
- modules (for namespace management)
- …

Locality Features



The Locale

- **Definition**
  - Abstract unit of target architecture
  - Capable of running tasks and storing variables
    - i.e., has processors and memory
  - Supports reasoning about locality
- **Properties**
  - a locale's tasks have ~uniform access to local data
  - Other locales' data is also accessible, but at a price
- **Locale Examples**
  - A multi-core processor
  - An SMP node

Coding 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 LocaleSpace = [0..#numLocales];
const Locales: [LocaleSpace] locale;
```

Locales:

L0	L1	L2	L3	L4	L5	L6	L7

Locale Operations

- Locale methods support reasoning about machine resources:

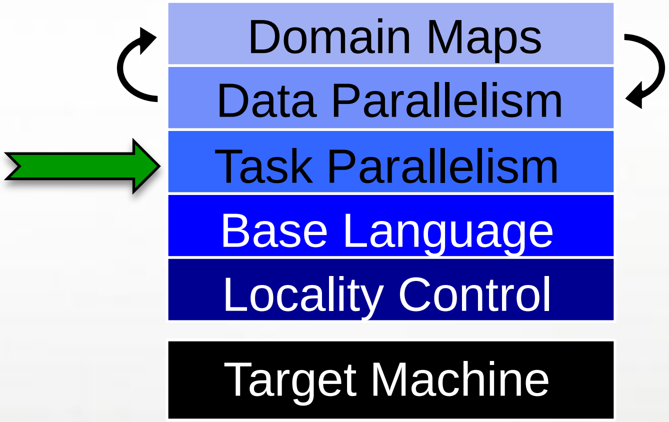
```
proc locale.physicalMemory(…) { … }
proc locale.numCores(…) { … }
proc locale.name(…) { … }
```

- *On-clauses* support placement of computations:

```
writeln("on locale 0");
on Locales[1] do
  writeln("now on locale 1");
writeln("on locale 0 again");
```

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

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

Task Parallel Features



Task Creation

```
begin myNewTask(); // fire-and-forget
whileOriginalTaskContinues();

cobegin {
  myFirstTask();
  mySecondTask();
}  // wait for these two tasks to complete

coforall tid in 0..#numTasks {
  executeTask(tid);
}  // wait for these numTasks tasks to complete
```

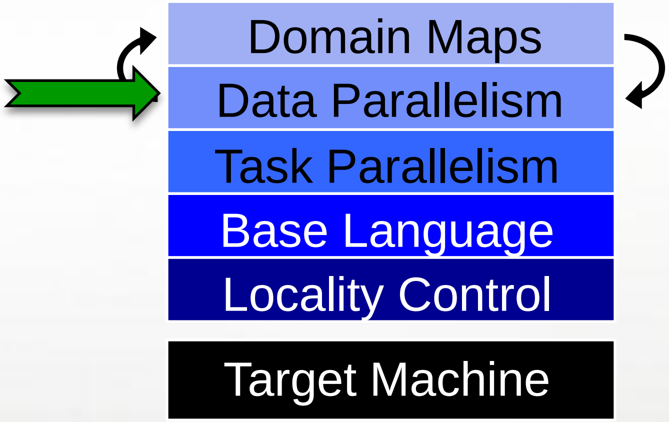
Task Synchronization: Sync Vars

```
// 'sync' types store full/empty state along with value

var result$: sync int;                       // initially empty
result$ = begin computeSomething();          // writes fill
computeSomethingElse();
computeThirdThingUsingResult(result$);       // reads empty
```

Bounded Buffer Producer/Consumer Example

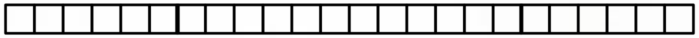
```
cobegin {
  producer();
  consumer();
}

var buff$: [0..#buffersize] sync real;

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

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

Data Parallel Features

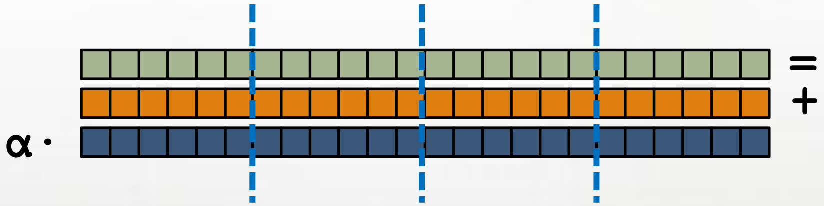


STREAM Triad: Chapel (multicore)

```
const ProblemSpace = [1..m];
```



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




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

Chapel Domain/Array Operations

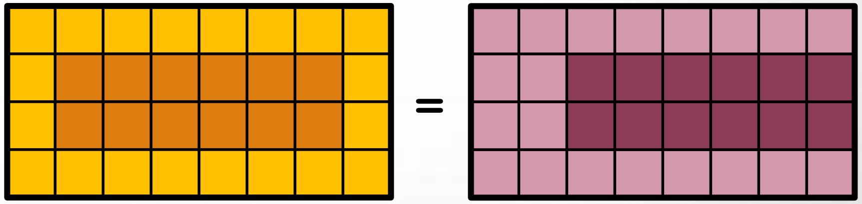
- Parallel and Serial Iteration

```
A = forall (i,j) in D do (i + j/10.0);
```

1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8
2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8
3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8
4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8

- Array Slicing; Domain Algebra

```
A[InnerD] = B[InnerD+(0,1)];
```



- Promotion of Scalar Functions and Operators

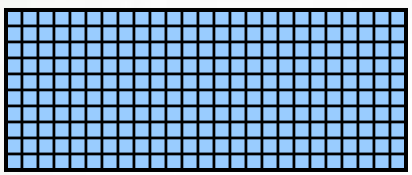
```
A = B + alpha * C;
```

```
A = exp(B, C);
```

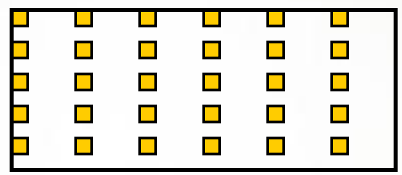
- And several other operations: indexing, reallocation, set operations, reindexing, aliasing, queries, …

Chapel Domain/Array Types

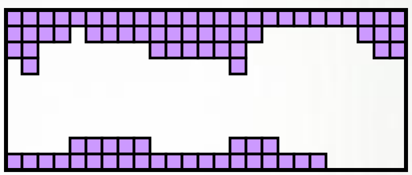
Chapel supports several types of domains and arrays:



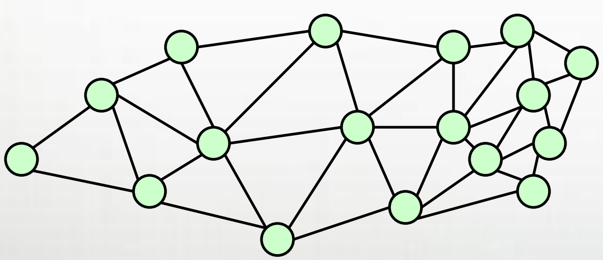
dense



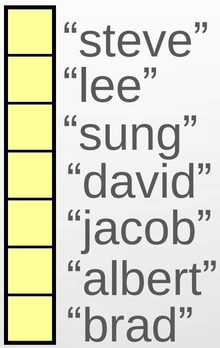
strided



sparse

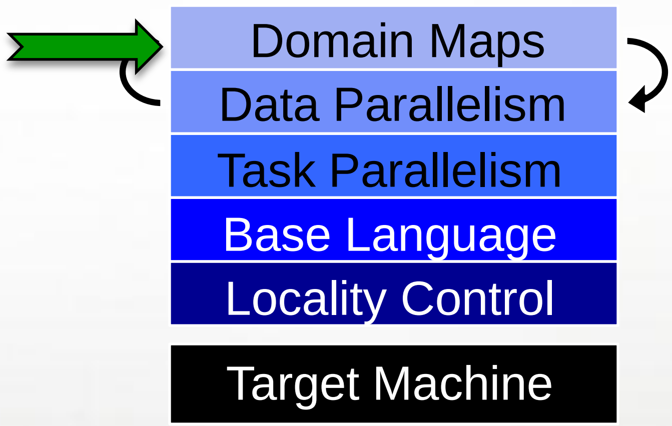


unstructured



associative

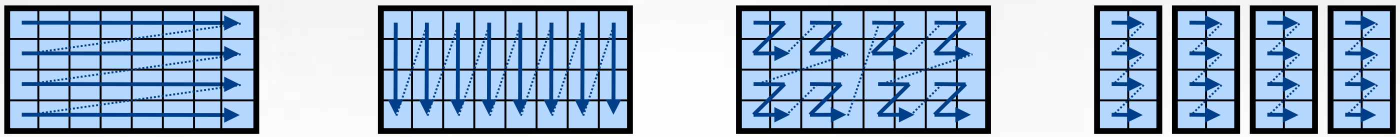
Data Parallel Features



Data Parallelism: Implementation Qs

Q1: How are arrays laid out in memory?

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

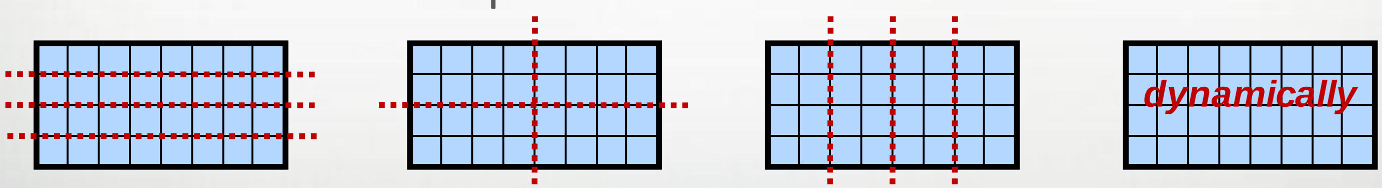


…?

- What data structure is used to store sparse arrays? (COO, CSR, …?)

Q2: How are data parallel operators implemented?

- How many tasks?
- How is the iteration space divided between the tasks?



…?

Data Parallelism: Implementation Qs

Q3: How are arrays distributed between locales?

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

Q4: What architectural features will be used?

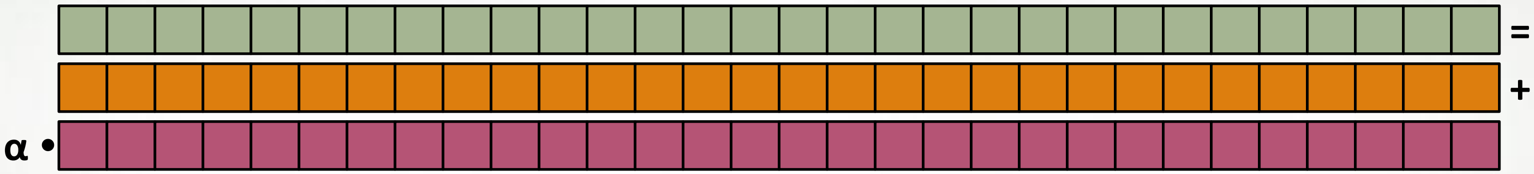
- Can/Will the computation be executed using CPUs? GPUs? both?
- What memory type(s) is the array stored in? CPU? GPU? texture? …?

A1: In Chapel, any of these could be the correct answer

A2: Chapel's *domain maps* are designed to give the user full control over such decisions

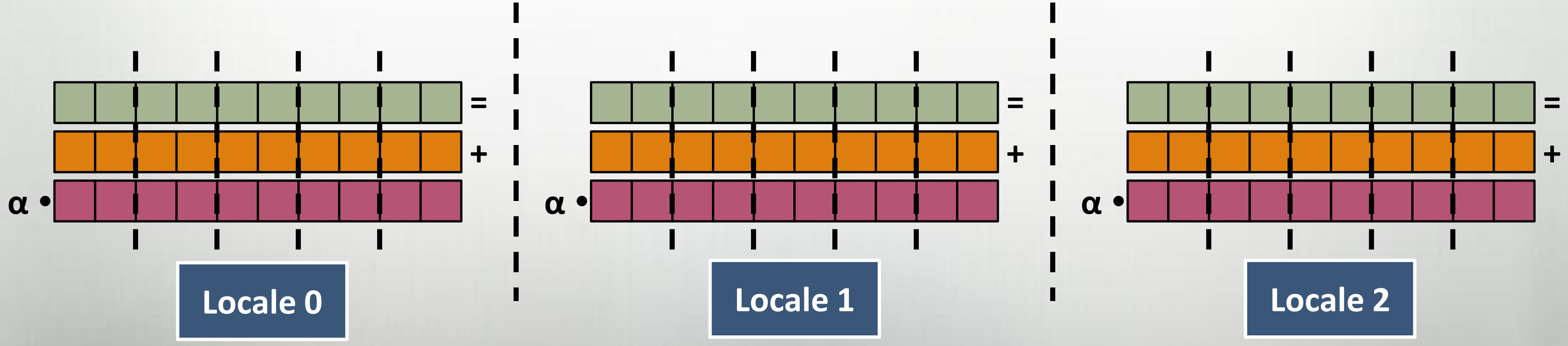
Domain Maps

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:



Domain Maps

Domain Maps: "recipes for implementing parallel/ distributed arrays and domains"

They define data storage:

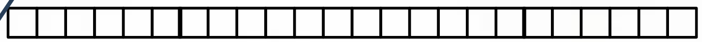
- Mapping of domain indices and array elements to locales
- Layout of arrays and index sets in each locale's memory

…as well as operations:

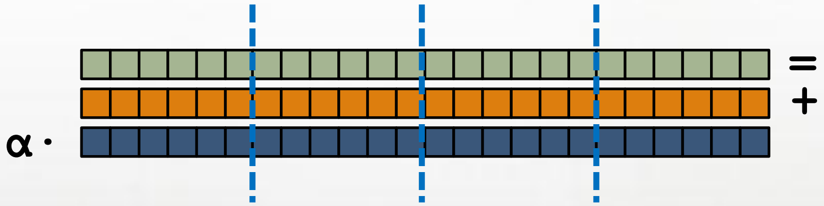
- random access, iteration, slicing, reindexing, rank change, …
- the Chapel compiler generates calls to these methods to implement the user's array operations

STREAM Triad: Chapel (multicore)

```
const ProblemSpace = [1..m];
```



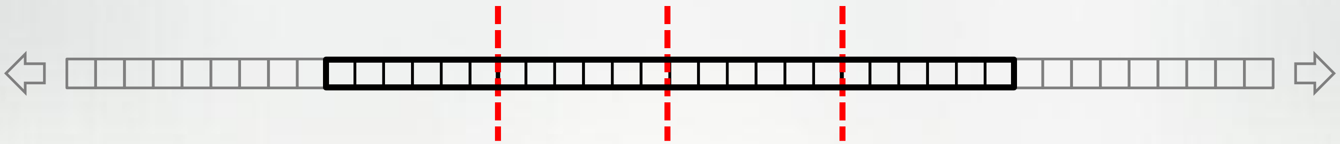
```
var A, B, C: [ProblemSpace] real;
```



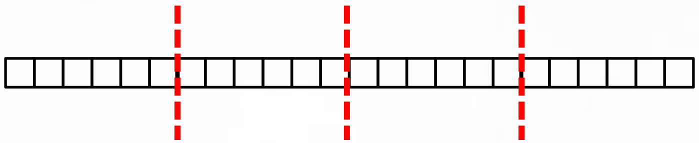

```
A = B + alpha * C;
```

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

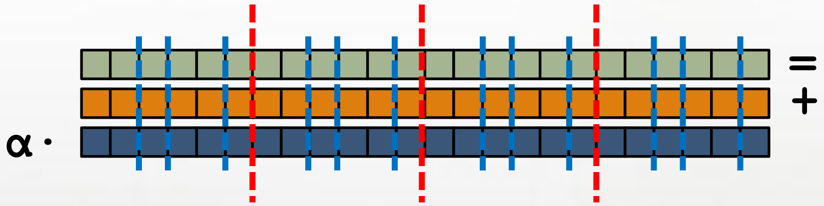
STREAM Triad: Chapel (multinode, blocked)



```
const ProblemSpace = [1..m]
                           dmapped Block(boundingBox=[1..m]);
```

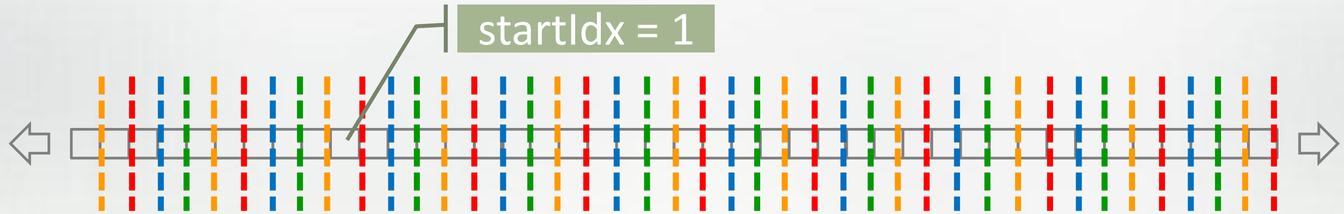


```
var A, B, C: [ProblemSpace] real;
```

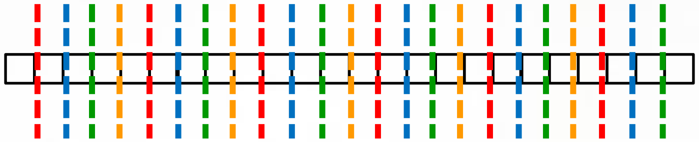



```
A = B + alpha * C;
```

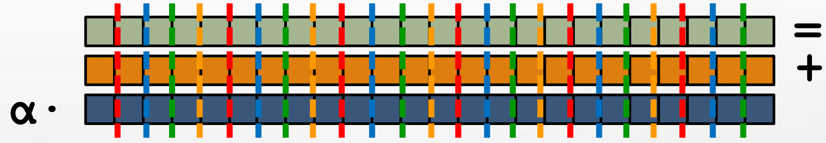
STREAM Triad: Chapel (multinode, cyclic)




```
const ProblemSpace = [1..m]
                        dmapped Cyclic(startIdx=1);
```

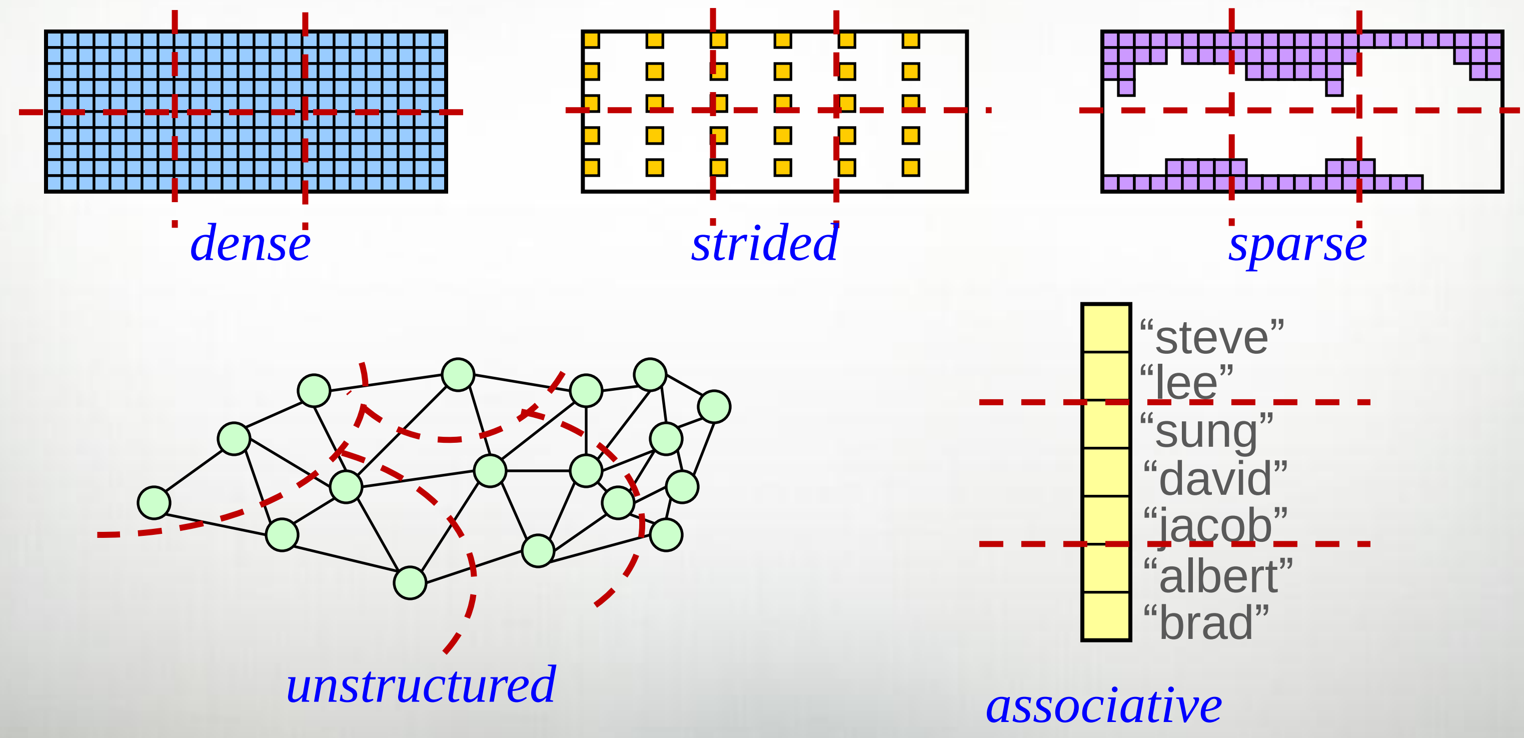


```
var A, B, C: [ProblemSpace] real;
```




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

All Domain Types Support Domain Maps



Chapel's Domain Map Philosophy

1. Chapel provides a library of standard domain maps
   - to support common array implementations effortlessly
2. Advanced users can write their own domain maps in Chapel
   - to cope with shortcomings in our standard library
3. Chapel's standard layouts and distributions will be written using the same user-defined domain map framework
   - to avoid a performance cliff between "built-in" and user-defined domain maps
4. Domain maps should only affect implementation and performance, not semantics
   - to support switching between domain maps effortlessly

Outline

- ✓ Chapel Motivation
- ✓ Quick Tour of Some Chapel Features
- ➢ Project Status and Summary
- Bonus Topics

Status

- Everything you've heard about today works in the current compiler
  - (which is not to say that it's bug-free or feature-complete)

- Performance can still be hit or miss
  - a number of optimizations remain
    - some low-hanging, some more aggressive
  - generally speaking…

    …lower dimensional arrays perform better than higher-dimensional

    …single-locale performs better than multi-locale

    …multi-locale performs best with fine-grain, demand-driven communication patterns or embarrassingly parallel computations

Next Steps

No-brainers:

- Performance Optimizations
- Feature Improvements/Bug Fixes
- Complete HPCS deliverables
- Develop post-HPCS strategy/funding
- Support Collaborations and Users

Advanced Topics:

- Hierarchical Locales to target next-gen nodes
  - e.g., manycore, CPU+GPU hybrids, tiled processors, …
  - additional hierarchy and heterogeneity warrants it
- Atomic Operations Library (local and remote)

Potential Future Work (pending interest/funding)

- Resiliency/Fault Tolerance
- Task Teams
  - with collective operations: reductions, barriers, eurekas
  - permitting distinct scheduling policies
- Improved Interoperability, Libraries
- Re-work warts based on user feedback
  - strings
  - syntax: domain/array literals, zipper iteration
- Improved Tools:
  - performance analysis, debugging, editor support
  - Chapel interpreter
- …

Our Team

- Cray:


Brad Chamberlain


Sung-Eun Choi


Greg Titus


Vass Litvinov


Tom Hildebrandt

- External Collaborators:


Albert Sidelnik


Jonathan Turner


Srinivas Sridharan

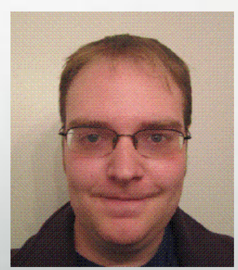
• • •

You? Your Friend/Student/ Colleague?

- Interns:


Jonathan Claridge


Hannah Hemmaplardh


Andy Stone


Jim Dinan


Rob Bocchino


Mack Joyner

• • •

Featured Collaborations (see http://chapel.cray.com/collaborations.html for more)

- **Sandia** (Kyle Wheeler, Rich Murphy): Chapel over Qthreads user threading
- **LTS** (Michael Ferguson): Improved I/O and strings
- **LLNL** (Tom Epperly et al.): Interoperability via Babel
- **UIUC** (David Padua, Albert Sidelnik, Maria Garzarán): CPU-GPU computing
- **U. Malaga** (Rafael Asenio, Maria Gonzales, Rafael Larossa): Parallel file I/O
- **CU Boulder** (Jeremy Siek, Jonathan Turner): Interfaces, concepts, generics
- **ORNL/Notre Dame** (Srinivas Sridharan, Jeff Vetter, Peter Kogge): Asynchronous software transactional memory over distributed memory
- **ORNL/ESSC** (Steve Poole, Matt Baker, …): portability, performance tuning
- **BSC/UPC** (Alex Duran): Chapel over Nanos++ user-level tasking
- **Argonne** (Rusty Lusk, Rajeev Thakur, Pavan Balaji): Chapel over MPICH
- (your name + idea here?)

For Further Information

- **Chapel Home Page** (papers, presentations, tutorials):
  http://chapel.cray.com
- **Chapel Project Page** (releases, mailing lists, code):
  http://sourceforge.net/projects/chapel/
- **General Questions/Info:**
  chapel_info@cray.com (or SourceForge chapel-users list)
- **Upcoming Events:**
  SC11 (November, Seattle WA):
  - Monday, Nov 14th: full-day comprehensive tutorial
  - Wednesday, Nov 16th: Chapel Lightning Talks BOF
  - Friday, Nov 18th: half-day broader engagement tutorial

  PGAS11 (October, Galveston, TX): leader/follower iterator talk

Outline

- ✓ Chapel Motivation
- ✓ Quick Tour of Some Chapel Features
- ✓ Project Status and Summary
- ➢ Bonus Topics
  - graph representations
  - atomic operations
  - collectives
  - I/O
  - tools

Graph Representation

- Graphs can be stored in a variety of ways in Chapel:
  - Edge lists
    - e.g., a 1D array of vertex objects, each of which stores an array of edges
  - Adjacency matrices
    - e.g., a 2D sparse *v* x *v* array whose entries represent connecting edges
  - “Pointer-based” representations
    - e.g., an unstructured/opaque array in which domain indices represent vertices and arrays of indices are used to represent edges
    - or, alternatively, a network of distributed, linked objects
  - …or any other sensible thing you can conceive of
- As with any data structure selection, choice should be motivated by use cases, expected operations
  - and at present, maturity of implementation

Atomic Operations: Low-level

Chapel currently has two main concepts for atomicity:

1) sync vars (low-level)

- use a sync var's full/empty state to guard critical sections
- essentially a sugared lock

```
enum owner = {foo, bar};
var lock$: sync owner;
proc foo() {                          proc bar() {
  lock$.writeEF(owner.foo);             lock$ = owner.bar;
  …critical operations…                 …critical operations…
  lock$.readFE();                       lock$;
}                                     }
```

- in many cases, these locks can be logically associated with algorithmic data (e.g., see earlier bounded buffer example)

Atomic Operations: High-level

2) atomic statements (high-level, not yet available)

- designed to execute a section of code atomically w.r.t. other tasks

```
atomic {
  newNode.next = node;
  newNode.prev = node.prev;
  node.prev.next = newNode;
  node.prev = newNode;
}
```

```
atomic A[i] += 1;
```

- intended that compiler would use HW-based mechanisms when applicable and fall back on SW when not (i.e., STM)
- but STM is very much an open research area (one that we have been pursuing jointly with U. Notre Dame & ORNL)

Atomic Operations: A Third Option?

Due to…

…the level of effort required to get general atomics working

…the desire to support lock-free programming now

…the observation that some HW atomic ops are awkward to code and have compilers recognize automatically (e.g., CAS)

…I've recently proposed pursuing a third, intermediate solution: a library of standard atomic ops

- e.g., atomic increments, compare and swap, math, …
- local and remote (use processor/network atomic ops.)
- intended as a stopgap until atomic statement is complete
  - though I expect it will continue to have utility then
- main challenges: portability, design

Collectives

- Many traditional collective operations don't make sense in a non-SPMD execution model
  - which of the arbitrarily many tasks should be involved?
- Some collective ops are supported via keywords on aggregates: `reduce`, `scan`
  - e.g., `sum = + reduce A;`
- Future work:
  - Introduction notion of task teams
  - Support collectives on teams
    - reductions, barriers, broadcasts, eurekas(?)

Input/Output

- Output
  - **write**(*expr-list*): writes the argument expressions
  - **writeln**(…) variant: writes a linefeed after the arguments
- Input
  - **read**(*expr-list*): reads values into the argument expressions
  - **read**(*type-list*): reads values of given types, returns as tuple
  - **readln**(…) variant: same, but skips through next linefeed
- Example:

```
var first, last: string;
write("what is your name? ");
read(first);
last = read(string);
writeln("Hi ", first, " ", last);
```

```
What is your name?
Chapel User
Hi Chapel User
```

- I/O to files and strings also supported

Input/Output: Current Work

While our current I/O story is for simple cases, it's a bit impoverished for real applications

- (moral: to get rich I/O, create benchmarks that require it)

Some of our collaborations are striving to improve this

- **Michael Ferguson** (LTS): Re-engineering the underpinnings of Chapel I/O to support I/O to memory buffers, sockets, data streams, etc. in addition to files and strings
  - existing console I/O interface unchanged; file I/O cleaned up
  - designed with parallel access in mind
  - initial version should be available in next 1-7 months
- **Rafael Asenjo** (U. Malaga): Working on adding support for writing distributed arrays to parallel file systems efficiently

Tools

- Tools have not been a major focus in the project so far
- Current status:
  - **IDEs:** vim and emacs Chapel modes available
    - see $CHPL_HOME/etc
  - **performance tuning / correctness debugging:** existing C tools can be applied to the generated code
    - Utility varies with style of code, sophistication of user
      - e.g., Codes with heavy overloading result in name mangling
    - Compiling with --cpp-lines supports Chapel source line numbers
  - **libraries/visualization:** little/no intrinsic support; support for ‘extern’ calls provides a path forward

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