OpenMP and the PGAS Model

CMSC714 – Sept 15, 2015

Guest Lecturer: Ray Chen

Last Time: Message Passing

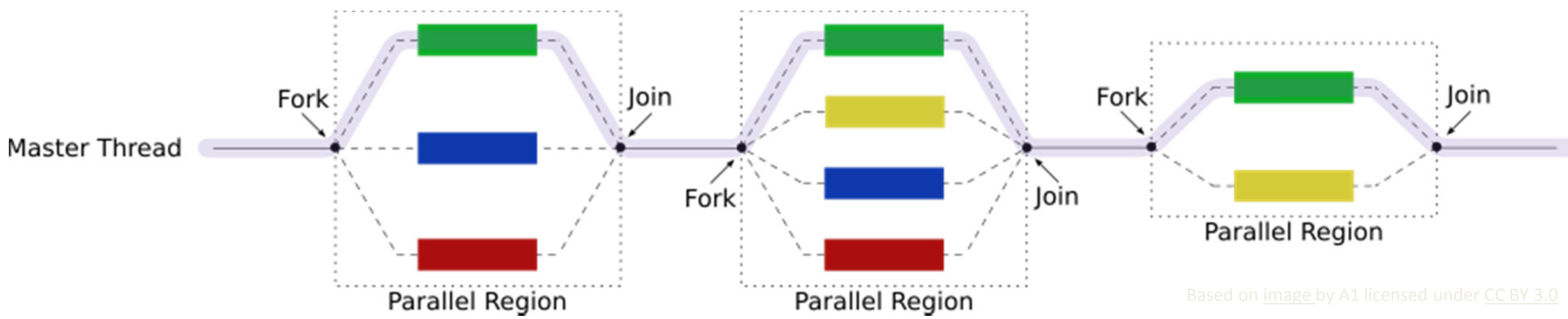
- Natural model for distributed-memory systems
  - Remote ("far") memory must be retrieved before use
  - Programmer responsible for specifying:
    - Participants (Single peer, collective communication, etc.)
    - Data types (MPI_CHAR, MPI_DOUBLE, etc.)
    - Logical synchronization
- How about shared-memory systems?
  - All processors can directly access any memory

OpenMP: Open Multi-Processing

- Portable interface for multiple processor systems
  - Agnostic to architecture or language
- Alternative to POSIX threads
  - Thread management too low-level for HPC applications
  - Task parallelism vs. data parallelism
- Not a language
  - Extends existing language (C/C++/Fortran)
  - Compiler responsible for low-level thread management
  - Allows for incremental approach to parallelism

OpenMP Fork/Join Model

- Single master thread executes until parallel region
- When a parallel region is reached
  - At start, N-1 additional threads are spawned (Fork)
  - All N threads execute the same code
    - Different code paths achieved through unique thread ID
  - At end, threads are synchronized via barrier (Join)



OpenMP Syntax

- Compiler directives
  - Express parallel structure of code
  - Clauses modify directives

```
#pragma omp <directive> <clauses>
{
    // Code region affected by directive.
}
```

- Run-time library routines

```
#include <omp.h>
…
int id = omp_get_thread_num();
```

OpenMP `parallel` Directive

- Begin a new parallel region

```
#include <stdio.h>
#include <omp.h>

int main(int argc, char* argv[])
{
  #pragma omp parallel
  {
    printf("Thread %d of %d.\n",
           omp_get_thread_num(),
           omp_get_num_threads());
  }
  return 0;
}
```

```
$ gcc -fopenmp a.c
$ ./a.out
Thread 0 of 4
Thread 3 of 4
Thread 2 of 4
Thread 1 of 4
```

OpenMP Data Environment

- All variables have a data-sharing attribute
  - Shared: all threads use the same copy
  - Private: all threads use local storage for this variable
  - Firstprivate: Like private, but value is initialized on fork
  - Lastprivate: Like private, but value updated on join
- In general:
  - Variables defined inside a parallel region are private
  - Variables defined outside a parallel region are shared
  - Not always true: more details available in the spec
- Data-sharing attributes can be overridden

OpenMP Worksharing Constructs

- Used to parallelize loops
  - HPC programs contain computationally intensive loops

```
#pragma omp loop
for (i = 0; i < MAX; ++i) {
  …
}
```

- Restrictions
  - Loop iterations must be independent
  - Strict rules for loop initialization, test, and increment
  - Premature termination of loops not supported

OpenMP Example: Finding Primes

```c
#include <stdio.h>
#include <stdlib.h>

int main(int argc, char* argv[])
{
    int cap = atoi(argv[1]);
    int count = 0;
    int num = 0;

    #pragma omp parallel loop reduction(max:num) schedule(dynamic)
    for (int i = 0; i < cap; ++i) {

        int prime = 1;
        for (int j = 0; prime && j * j <= i; ++j)
            prime = i % j;

        if (prime) {
            #pragma omp atomic
            ++count;
            num = i;
        }
    }
    printf("Prime #%d is %d\n", count, num);
    return 0;
}
```

Parallelize the following loop.

Keep a private copy of num for each thread, and copy the maximum value back when the loop is finished.

Use a work queue to load-balance threads.

Synchronize the next line; count is a shared variable.

OpenMP Synchronization

```
#pragma omp barrier
```

Threads pause here until all reach this point

```
#pragma omp critical
```

Threads will execute one at a time

```
#pragma omp single
```

Only one thread will ever execute

- Other threads wait in an implied barrier at end of region

```
#pragma omp master
```

Only the master thread will execute

- Other threads skip the region without waiting

OpenMP Sync Puzzles

- Puzzle #1

```
int x = 1;
#pragma omp parallel num_threads(2)
{
  #pragma omp single
  {
    ++x;
  }
  printf("%d\n", x);
}
```

→

```
2
2
```

OpenMP Sync Puzzles

- Puzzle #2

```
int x = 1;
#pragma omp parallel num_threads(2)
{
  #pragma omp master
  {
    ++x;
  }
  printf("%d\n", x);
}
```

→

```
1
2
```

or

```
2
2
```

OpenMP Sync Puzzles

- Puzzle #3

```
int x = 1;
#pragma omp parallel num_threads(2)
{
  ++x;
  #pragma omp barrier
  printf(“%d\n”, x);
}
```

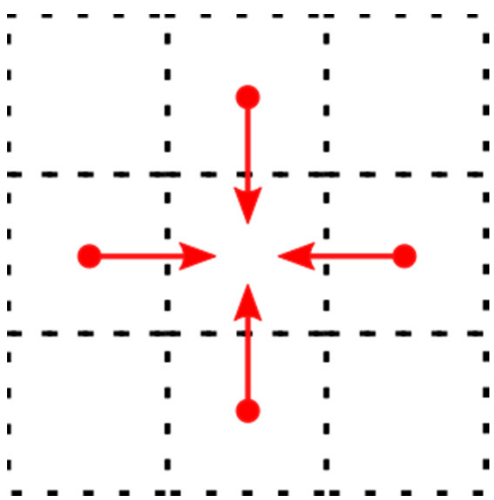
Shared variable access is not automatically synchronized. Behavior is undefined.

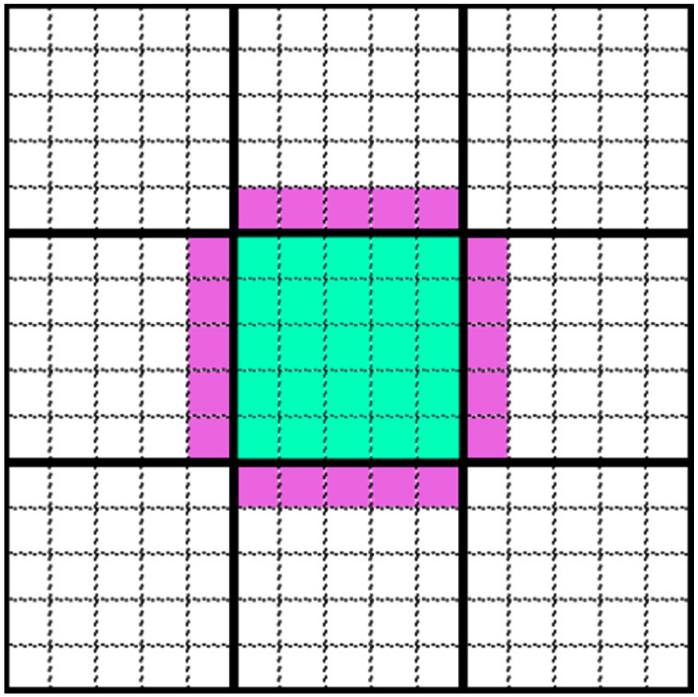
Limitations of OpenMP

- Not fool-proof
  - Data dependencies, conflicts, race conditions
  - Gives you plenty of rope to hang yourself with
- OpenMP and Amdahl's Law
  - What is Dagum and Menon take on this issue?
- Computational Problem Size
  - USA #1 supercomputer (Titan) has 32GB/node
  - World #1 supercomputer (Tianhe-2) has 64GB/node
  - What if our datasets are larger than 64GB?
    - "You're gonna need a bigger boat…"

MPI + OpenMP

- Programming in MPI + OpenMP is hard
  - Necessary for today's large distributed memory systems





PGAS Programming Model

- Partitioned Global Address Space
- Presents an abstracted shared address space
  - Simplifies the complexity of MPI + OpenMP
- Exposes data/task locality for performance
- Several languages use this model
  - UPC, Fortress, HPF, X10, etc.
  - Ever heard of these?

Chapel Themes

- Designed from scratch
  - Blank slate as opposed to a language extension
  - Allows for clearer, more expressive language semantics
- Multi-resolution design
  - Higher-level abstractions built from lower-level ones
  - Allows users to mix and match as needed
- Global-view programming
  - Data can be declared using global problem size
  - Data can be accessed using global indices

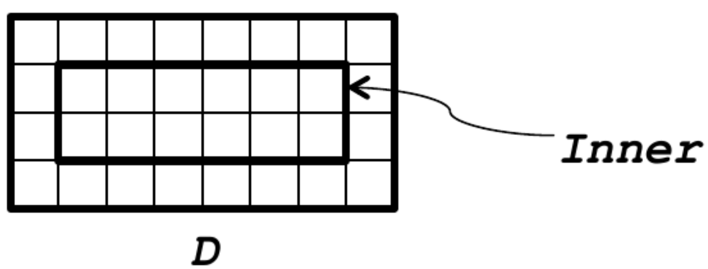
Data Parallelism, By Example

Domains

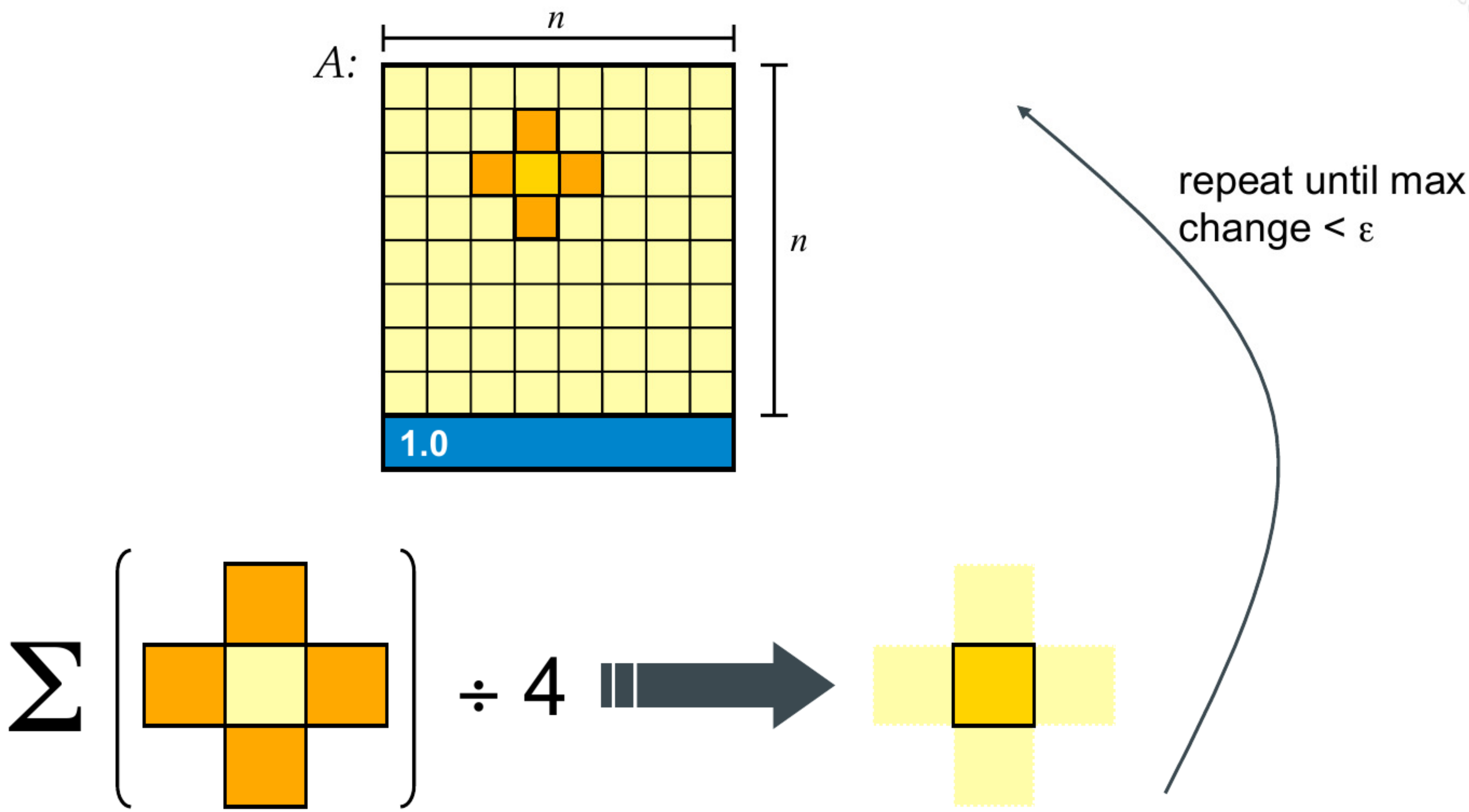
Domain:

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

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

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



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

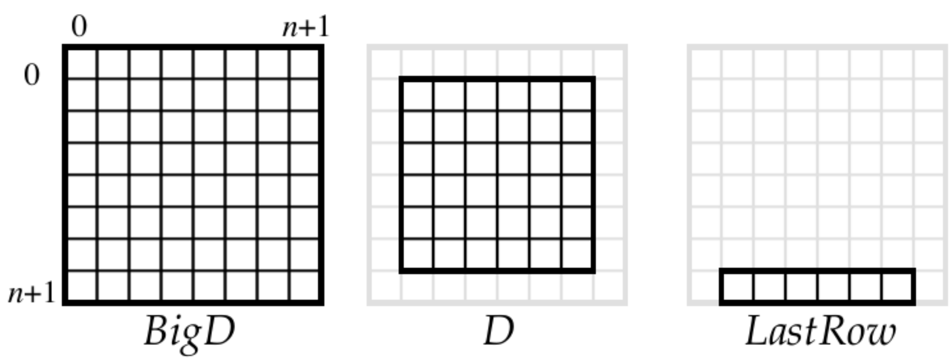
```
config const n = 6,
             epsilon = 1.0e-5;

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

```
va
A[
do
                                                    j+1]) / 4;
}
wr
```

Declare domains (first class index sets)

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

Dom1[Dom2] ⇒ computes the intersection of two domains



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

Jacobi Iteration in Chapel

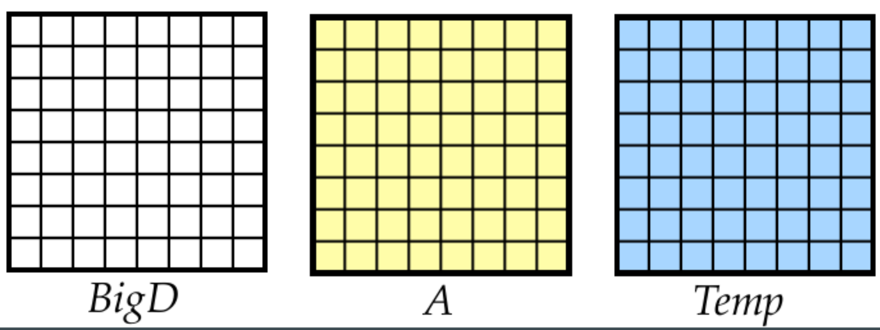
```
config const n = 6,
             epsilon = 1.0e-5;

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)



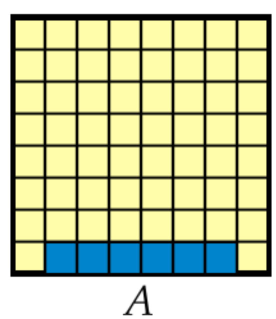

```
i,j+1]) / 4;
```

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]…”)



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],
   LastRow = D.exterior(1,0);
```

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);
```

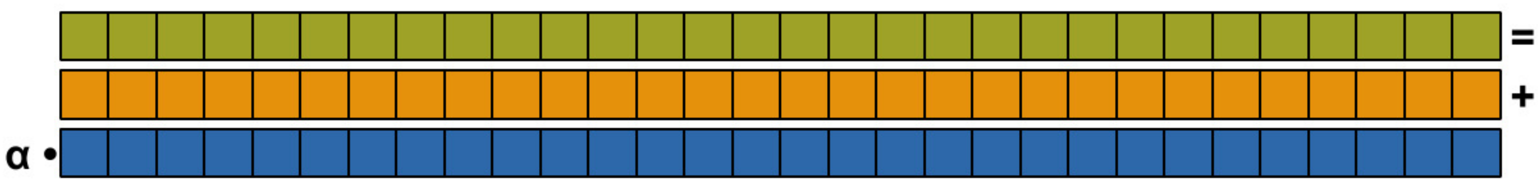
Write array to console

Jacobi Iteration in Chapel

```
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);
```

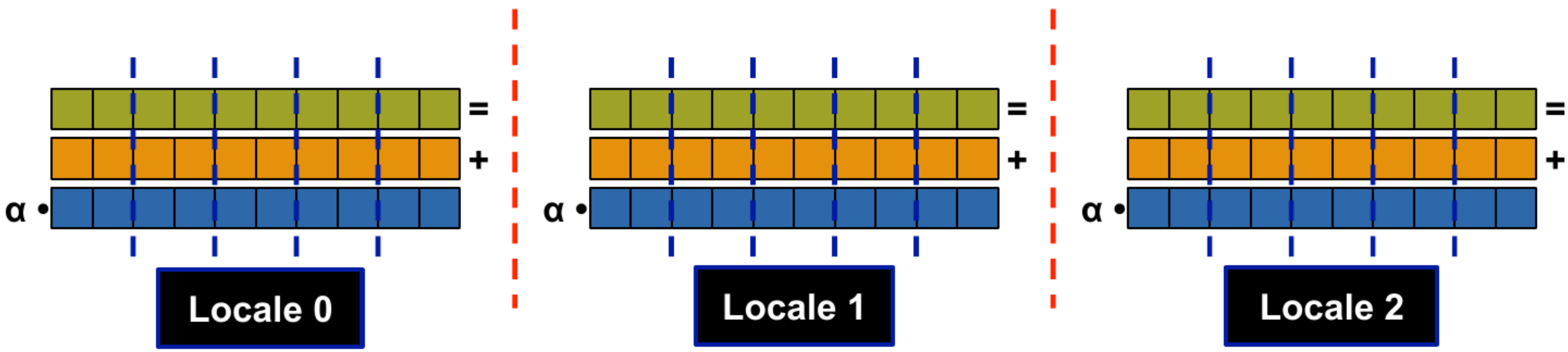
Domain Maps

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:



Shared Memory Data Parallel "Hello, world!"

```
config const numIters = 100000;

const D = {1..numIters};

forall i in D do
  writeln("Hello, world! ",
          "from iteration ", i, " of ", numIters);
```

Distributed Memory Data Parallel "Hello, world!"

```
config const numIters = 100000;

const D = {1..numIters} dmapped Cyclic(startIdx=1);

forall i in D do
  writeln("Hello, world! ",
          "from iteration ", i, " of ", numIters);
```

Layouts and Distributions

Domain Maps fall into two major categories:

layouts:

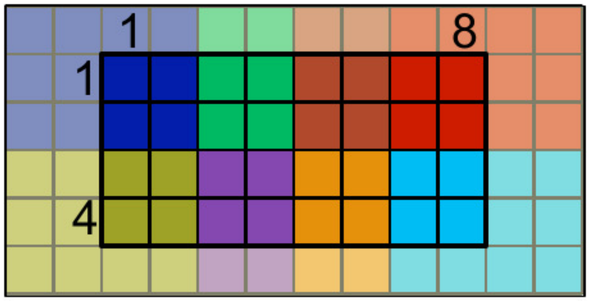
- target a shared memory
- **examples:** row- and column-major order, tilings, compressed sparse row, space-filling curves

distributions:

- map indices/elements to distributed memories
- **examples:** Block, Cyclic, Block-Cyclic, Recursive Bisection, …

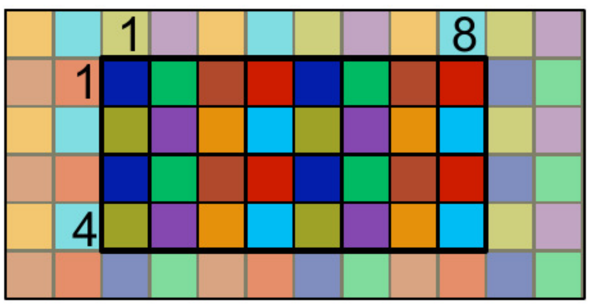
Sample Distributions: Block and Cyclic

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



distributed to

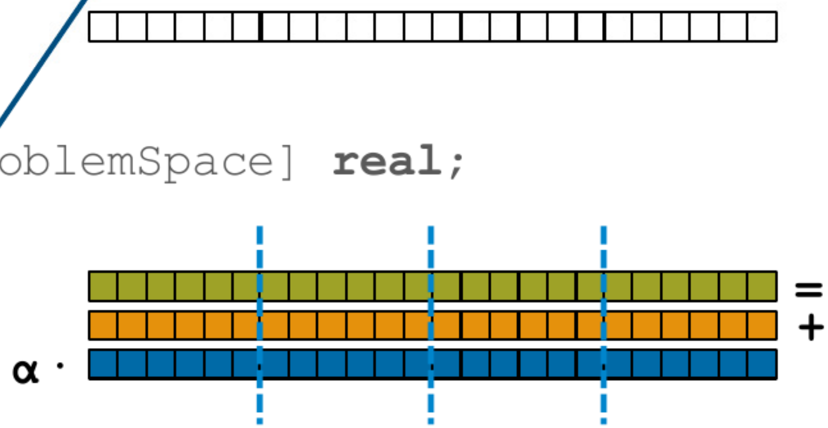

```
var Dom = {1..4, 1..8} dmapped Cyclic( startIdx=(1,1) );
```



distributed to

STREAM Triad: Chapel (multicore)

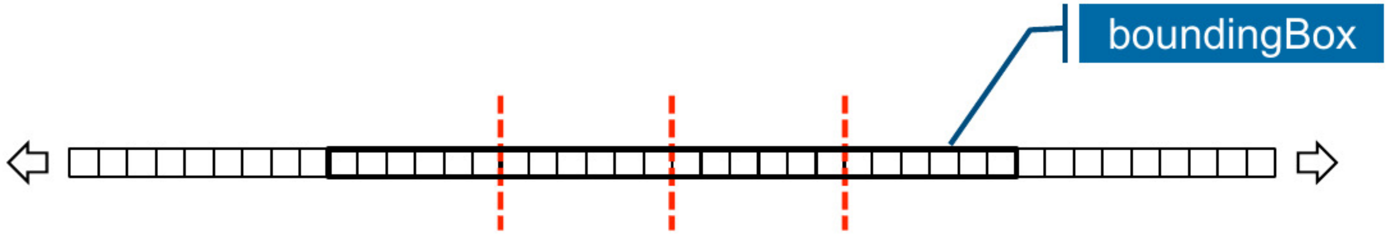
```
const ProblemSpace = {1..m};

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

A = B + alpha * C;
```



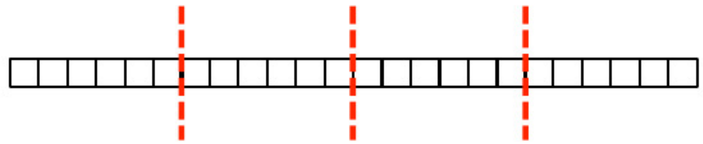
No domain map specified => use default layout

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

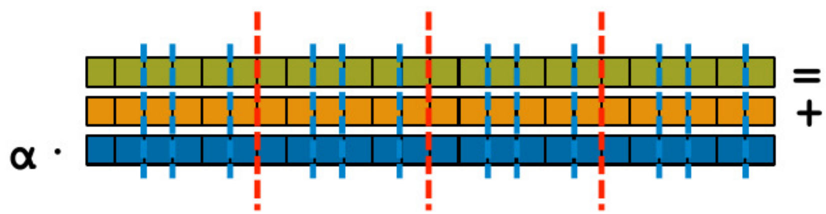
STREAM Triad: Chapel (distributed, blocked)




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

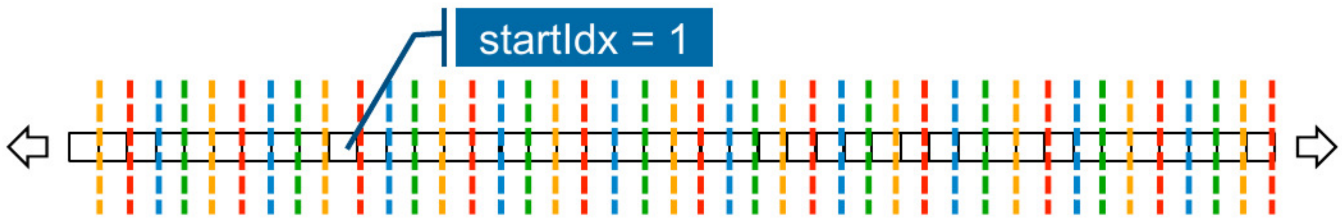


```
var A, B, C: [ProblemSpace] real;
```

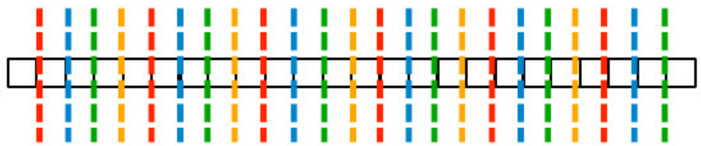



```
A = B + alpha * C;
```

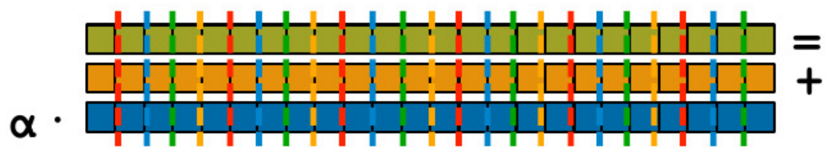
STREAM Triad: Chapel (distributed, cyclic)




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



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




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

Jacobi Iteration in Chapel (shared memory)

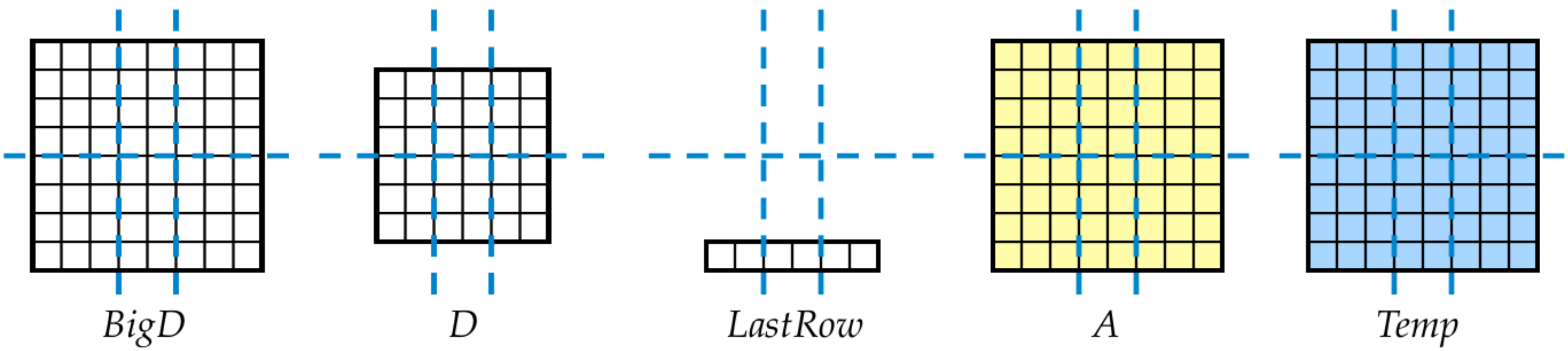
```
config const n = 6,
             epsilon = 1.0e-5;

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

var A, Temp : [BigD] real;

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 (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



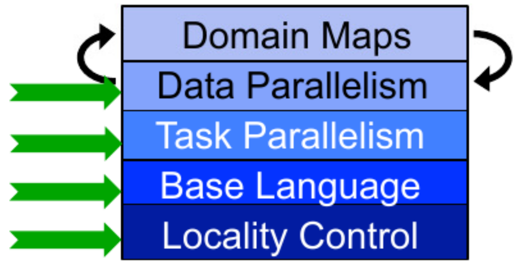
Jacobi Iteration in Chapel (distributed memory)

```
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;

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;
```

Chapel's Domain Map Philosophy

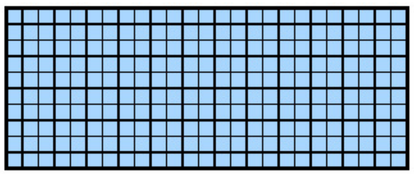
1. **Chapel provides a library of standard domain maps**
   - to support common array implementations effortlessly

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

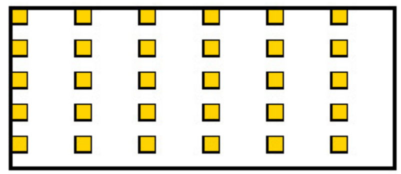


3. **Chapel's standard domain maps are written using the same end-user framework**
   - to avoid a performance cliff between "built-in" and user-defined cases

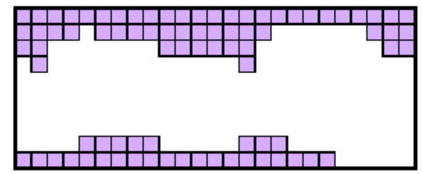
Chapel Array Types



dense

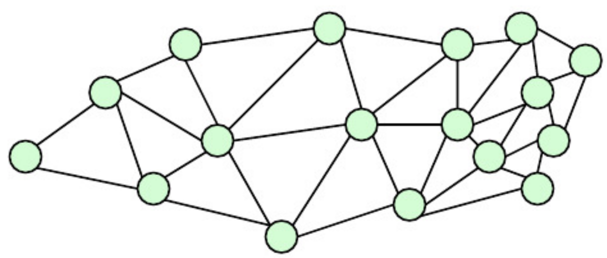


strided



sparse

associative



unstructured

All Domain Types Support Domain Maps