Chapel: Productive, Multiresolution Parallel Programming

Brad Chamberlain, Chapel Team, Cray Inc.
ATPESC: Argonne Training Program for Exascale Computing
August 6th, 2015
Chapel: HPC Programmers Deserve Nice Things Too

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Chapel Motivation

Q: Why doesn’t parallel programming have an equivalent to Python / Matlab / Java / C++ / (your favorite programming language here) ?
   ● one that makes it easy to quickly get codes up and running
   ● one that is portable across system architectures and scales
   ● one that bridges the HPC, data analysis, and mainstream communities

A: We believe this is due not to any particular technical challenge, but rather a lack of sufficient...
   …long-term efforts
   …resources
   …community will
   …co-design between developers and users
   …patience

Chapel is our attempt to change this
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 want,
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, …
Sustained Performance Milestones

1 GF – 1988: Cray Y-MP; 8 Processors
- Static finite element analysis
- Fortran77 + Cray autotasking + vectorization

1 TF – 1998: Cray T3E; 1,024 Processors
- Modeling of metallic magnet atoms
- Fortran + MPI (Message Passing Interface)

1 PF – 2008: Cray XT5; 150,000 Processors
- Superconductive materials
- C++/Fortran + MPI + vectorization

1 EF – ~20__: Cray ____; ~10,000,000 Processors
- TBD
- TBD: C/C++/Fortran + MPI + OpenMP/OpenACC/CUDA/OpenCL?

Or, perhaps something completely different?
STREAM Triad: a trivial parallel computation

**Given:** $m$-element vectors $A$, $B$, $C$

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

**In pictures:**

- $A$
- $B$
- $C$
- $\alpha$

$A \quad = \quad B \quad + \quad C \cdot \alpha$
STREAM Triad: a trivial parallel computation

**Given:** $m$-element vectors $A, B, C$

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

**In pictures, in parallel:**

\[
\begin{align*}
A & \quad = \quad = \quad = \quad = \\
B & \quad + \quad + \quad + \\
C & \quad . \quad . \quad . \quad . \\
\end{align*}
\]

\[\alpha\]
STREAM Triad: a trivial parallel computation

**Given:** $m$-element vectors $A$, $B$, $C$

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

**In pictures, in parallel (distributed memory):**

\[
\begin{align*}
A &= & & & & & \\
B &= + & & + & & + \\
C &= \cdot & & \cdot & & \cdot \\
\alpha &= & & & & \\
\end{align*}
\]
STREAM Triad: a trivial parallel computation

**Given:** $m$-element vectors $A$, $B$, $C$

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

In pictures, in parallel (distributed memory multicore):

![Diagram showing the computation process]
#include <hpcc.h>

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

int HPCC_StarStream(HPCC_Params *params) {
    int myRank, commSize;
    int rv, errCount;
    MPI_Comm comm = MPI_COMM_WORLD;
    MPI_Comm_size( comm, &commSize );
    MPI_Comm_rank( comm, &myRank );

    rv = HPCC_Stream( params, 0 == myRank);
    MPI_Reduce( &rv, &errCount, 1, MPI_INT, MPI_SUM, 0, comm );

    return errCount;
}

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

    VectorSize = HPCC_LocalVectorSize( params, 3, sizeof(double), 0 );

    a = HPCC_XMALLOC( double, VectorSize );
    b = HPCC_XMALLOC( double, VectorSize );
    c = HPCC_XMALLOC( double, VectorSize );

    if (!a || !b || !c) {
        if (c) HPCC_free(c);
        if (b) HPCC_free(b);
        if (a) HPCC_free(a);
        if (doIO) {
            fprintf( outFile, "Failed to allocate memory (%d). \n", VectorSize );
            fclose( outFile );
        }
        return 1;
    }

    for (j=0; j<VectorSize; j++) {
        b[j] = 2.0;
        c[j] = 0.0;
    }
    scalar = 3.0;

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

    HPCC_free(c);
    HPCC_free(b);
    HPCC_free(a);
#include <hpcc.h>
#ifdef _OPENMP
#include <omp.h>
#endif

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

int HPCC_StarStream(HPCC_Params *params) {
    int myRank, commSize;
    int rv, errCount;
    MPI_Comm comm = MPI_COMM_WORLD;

    MPI_Comm_size( comm, &commSize );
    MPI_Comm_rank( comm, &myRank );

    rv = HPCC_Stream( params, 0 == myRank);
    MPI_Reduce( &rv, &errCount, 1, MPI_INT, MPI_SUM, 0, comm );

    return errCount;
}

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

    VectorSize = HPCC_LocalVectorSize( params, 3, sizeof(double), 0 );

    a = HPCC_XMALLOC( double, VectorSize );
    b = HPCC_XMALLOC( double, VectorSize );
    c = HPCC_XMALLOC( double, VectorSize );

    #ifdef _OPENMP
    #pragma omp parallel for
    #endif
    for (j=0; j<VectorSize; j++) {
        b[j] = 2.0;
        c[j] = 0.0;
    }

    scalar = 3.0;

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

    HPCC_free(c);
    HPCC_free(b);
    HPCC_free(a);

    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;
    }
    return 0;
}
STREAM Triad: MPI+OpenMP vs. CUDA

MPI + OpenMP

```c
#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];
}
```

CUDA

```c
#include <hpcc.h>
#include <omp.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;
    }
    __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];
    }
    return 0;
}
```

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

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<th>Programming Model</th>
<th>Unit of Parallelism</th>
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</tr>
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<td>GPU/accelerator</td>
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<td>CL</td>
</tr>
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</table>

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

**downsides:** lots of user-managed detail; brittle to changes
Rewinding a few slides...

**MPI + OpenMP**

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

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

int HPCC_StarStream(HPCC_Params *params) {
    int myRank, commSize;
    int rv, errCount;
    MPI_Comm comm = MPI_COMM_WORLD;
    MPI_Comm_size( comm, &commSize );
    MPI_Comm_rank( comm, &myRank );
    rv = HPCC_Stream( params, 0 == myRank);
    MPI_Bcast( &rv, 1, MPI_INT, 0, comm );
    return errCount;
}

VectorSize = HPCC_LocalVectorSize( params, 3, sizeof(double), 0 );

a = HPCC_XMALLOC( double, VectorSize );
if (!a) HPCC_free(a);

b = HPCC_XMALLOC( double, VectorSize );
if (!b) HPCC_free(b);

c = HPCC_XMALLOC( double, VectorSize );
if (!c) HPCC_free(c);

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).

    }
    return 1;
}
#endif
#pragma omp parallel for
for (j=0; j<VectorSize; j++) {
    b[j] = 2.0;
    c[j] = 0.0;
}
scalar = 3.0;
```

**CUDA**

```c
#include <hpcc.h>

#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, 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);
    
    cudaFree(d_a);
    cudaFree(d_b);
    cudaFree(d_c);
}
```

HPC suffers from too many distinct notations for expressing parallelism and locality.
**STREAM Triad: Chapel**

```
#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];
}
```

**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
  ● Project Status and Next Steps

● This evening: Chapel hands-on session
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
Motivating Chapel Themes

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

With a unified set of concepts...

...express any parallelism desired in a user’s program
  ● **Styles:** data-parallel, task-parallel, concurrency, nested, ...
  ● **Levels:** model, function, loop, statement, expression

...target any parallelism available in the hardware
  ● **Types:** machines, nodes, cores, instruction

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<td>GPU/accelerator</td>
<td>Chapel</td>
<td>SIMD function/task</td>
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</table>
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*

- Domain Maps
- Data Parallelism
- Task Parallelism
- Base Language
- Locality Control
- Target Machine

- 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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- Project Status and Next Steps
const pi = 3.14, // pi is a real
    coord = 1.2 + 3.4i, // coord is a complex...
    coord2 = pi*coord, // ...as is coord2
    name = "brad", // name is a string
    verbose = false; // verbose is boolean

proc addem(x, y) { // addem() has generic arguments
    return x + y; // and an inferred return type
}

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

writeln((sum, fullname));

(4.14, bradford)
const r = 1..10;

printVals(r);
printVals(r # 3);
printVals(r by 2);
printVals(r by -2);
printVals(r by 2 # 3);
printVals(r # 3 by 2);
printVals(0.. # n);

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

1 2 3 4 5 6 7 8 9 10
1 2 3
1 3 5 7 9
10 8 6 4 2
1 3 5
1 3
0 1 2 3 4 ... n-1
Iterators

```plaintext
iter fibonacci(n) {
    var current = 0,
        next = 1;
    for 1..n {
        yield current;
        current += next;
        current <=> next;
    }
}
```

```plaintext
for f in fibonacci(7) do writeln(f);
0
1
1
2
3
5
8
```

```plaintext
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;
}
```

```plaintext
for ij in tiledRMO({1..m, 1..n}, 2) do
    write(ij);
(1,1) (1,2) (2,1) (2,2)
(1,3) (1,4) (2,3) (2,4)
(1,5) (1,6) (2,5) (2,6)
...
(3,1) (3,2) (4,1) (4,2)
```
Zippered Iteration

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

fib #0 is 0
fib #1 is 1
fib #2 is 1
fib #3 is 2
fib #4 is 3
fib #5 is 5
fib #6 is 8
...
```
Other Base Language Features

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

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● Project Status and Next Steps
Defining our Terms

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

**Task Parallelism:** a style of parallel programming in which parallelism is driven by programmer-specified tasks

(in contrast with):

**Data Parallelism:** a style of parallel programming in which parallelism is driven by computations over collections of data elements or their indices
Task Parallelism: Begin Statements

// create a fire-and-forget task for a statement
begin writeln(“hello world”);
writeln(“goodbye”);

Possible outputs:

- hello world
- goodbye
- hello world
- goodbye
// create a task per iteration
coforall t in 0..#numTasks {
  writeln("Hello from task ", t, " of ", numTasks);
} // implicit join of the numTasks tasks here

writeln("All tasks done");

Sample output:

Hello from task 2 of 4
Hello from task 0 of 4
Hello from task 3 of 4
Hello from task 1 of 4
All tasks done
Other Task Parallel Concepts

- **cobegins**: create tasks using compound statements
- **atomic variables**: support atomics ops, similar to modern C++
- **sync/single variables**: support producer/consumer patterns
- **sync statements**: join unstructured tasks
- **serial statements**: conditionally squash parallelism
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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

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

- Chapel provides built-in locale variables

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

```
Locales    L0  L1  L2  L3  L4  L5  L6  L7
```

- User’s `main()` begins executing on locale #0
Locale Operations

- Locale methods support queries about the target system:

  ```chapel
  proc locale.physicalMemory(...) { ... }
  proc locale.numCores { ... }
  proc locale.id { ... }
  proc locale.name { ... }
  ```

- **On-clauses** support placement of computations:

  ```chapel
  writeln(“on locale 0”);
  on Locales[1] do
    writeln(“now on locale 1”);
  writeln(“on locale 0 again”);
  ```

  ```chapel
  on A[i,j] do
    bigComputation(A);
  on node.left do
    search(node.left);
  ```
Parallelism and Locality: Orthogonal in Chapel

- This is a **parallel**, but local program:

```
begin writeln("Hello world!");
writeln("Goodbye!");
```

- This is a **distributed**, but serial program:

```
writeln("Hello from locale 0!");
on Locales[1] do writeln("Hello from locale 1!");
writeln("Goodbye from locale 0!");
```

- This is a **distributed** and **parallel** program:

```
begin on Locales[1] do writeln("Hello from locale 1!");
on Locales[2] do begin writeln("Hello from locale 2!");
writeln("Goodbye from locale 0!");
```
Partitioned Global Address Space (PGAS) Languages

(Or perhaps: partitioned global namespace languages)

- **abstract concept:**
  - support a shared namespace on distributed memory
    - permit parallel tasks to access remote variables by naming them
  - establish a strong sense of ownership
    - every variable has a well-defined location
    - local variables are cheaper to access than remote ones

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

<table>
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<th>partitioned space</th>
<th>shared name/address space</th>
<th>private space 0</th>
<th>private space 1</th>
<th>private space 2</th>
<th>private space 3</th>
<th>private space 4</th>
</tr>
</thead>
</table>
Chapel and PGAS

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

Locales (think: “compute nodes”)
Chapel: Scoping and Locality

```chapel
var i: int;
```

Locales (think: “compute nodes”)
var i: int;
on Locales[1] {

Locales (think: “compute nodes”)
var i: int;
on Locales[1] {
    var j: int;
}

**Locales** (think: “compute nodes”)

<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>j</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Chapel: Scoping and Locality

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

Locales (think: “compute nodes”)
Chapel: Scoping and Locality

```chapel
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”)

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Outline

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

● Project Status and Next Steps
Outline

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✓ Chapel Background and Themes

➢ Survey of Chapel Concepts

● Project Status and Next Steps
Data Parallelism by Example: Jacobi Iteration

A:

\[
\sum \left( \begin{array}{c}
\text{Orange}
\end{array} \right) \div 4
\]

\[\Sigma \left( \begin{array}{c}
\text{Orange}
\end{array} \right) \div 4\]

repeat until max change < \(\varepsilon\)
Jacobi Iteration in Chapel

```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

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

writeln(A);
```
Jacobi Iteration in Chapel

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

Declare program parameters

```plaintext
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
```plaintext
n ⇒ default integer (64 bits)
epsilon ⇒ default real floating-point (64 bits)
```
Jacobi Iteration in Chapel

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

**Declare domains (first class index sets)**

\{lo..hi, lo2..hi2\} \(\Rightarrow\) 2D rectangular domain, with 2-tuple indices

**Dom1[Dom2]** \(\Rightarrow\) computes the intersection of two domains

.\texttt{exterior}() \(\Rightarrow\) one of several built-in domain generators
Jacobi Iteration in Chapel

```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

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

**Set Explicit Boundary Condition**

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

![Diagram of matrix A with explicit boundary condition highlighted]
Jacobi Iteration in Chapel

```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)

\[
\sum \left( \begin{array}{c}
\text{\color{orange}{red}} \\
\text{\color{yellow}{yellow}} \\
\text{\color{green}{green}} \\
\text{\color{blue}{blue}} \\
\text{\color{navy}{navy}} \\
\end{array} \right) \div 4
\]

do { 
  forall (i,j) in D do 
  const delta = max reduce abs(A[D] - Temp[D]);
  A[D] = Temp[D];
} while (delta > epsilon);

writeln(A);
```
Jacobi Iteration in Chapel

```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

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

writeln(A);
```
Jacobi Iteration in Chapel

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

Copy data back & Repeat until done

uses slicing and whole array assignment
standard do...while loop construct
Jacobi Iteration in Chapel

```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

    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

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

writeln(A);
```

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.
Jacobi Iteration in Chapel

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

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

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

With this simple change, we specify a mapping from the domains and arrays to locales. Domain maps describe the mapping of domain indices and array elements to *locales*:

- specifies how array data is distributed across locales
- specifies how iterations over domains/arrays are mapped to locales

```
BigD  D  LastRow  A  Temp
```
Jacobi Iteration in Chapel

```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

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

writeln(A);

use BlockDist;
```
**STREAM Triad: Chapel**

The Chapel 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.

**Chapel**

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

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

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

B = 2.0;
C = 3.0;
A = B + alpha * C;
```

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

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

pictures courtesy of Rob Neely, Bert Still, Jeff Keasler, LLNL
LULESH in Chapel
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
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
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]);
    }
  }
}
```

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

parallel loop over elements
collect nodes neighboring this element; localize node fields
update node forces from element stresses
Domain maps are “recipes” that instruct the compiler how to map the global view of a computation...

\[ A = B + \alpha \times C; \]

...to the target locales’ memory and processors:
Chapel’s Domain Map Philosophy

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

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

3. Chapel’s standard domain maps are written using the same end-user framework
   ● to avoid a performance cliff between “built-in” and user-defined cases
Chapel Domain Types

- dense
- strided
- sparse
- associative
- unstructured
Chapel Array Types

- **dense**
- **strided**
- **sparse**

- **associative**
  - “steve”
  - “lee”
  - “sung”
  - “david”
  - “jacob”
  - “albert”
  - “brad”

- **unstructured**
All Domain Types Support Domain Maps

- Dense
- Strided
- Sparse
- Associative
- Unstructured
For More Information on Domain Maps

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

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

Chapel release:
- Current domain maps:
  - `$CHPL_HOME/modules/dists/*.chpl`
  - `layouts/*.chpl`
  - `internal/Default*.chpl`
- Technical notes detailing the domain map interface for implementers:
  - `$CHPL_HOME/doc/technotes/README.dsi`
Two Other Thematically Similar Features

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

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

Like domain maps, these are…

…written in Chapel by expert users using lower-level features
   - e.g., task parallelism, on-clauses, base language features, …

…available to the end-user via higher-level abstractions
   - e.g., forall loops, on-clauses, lexically scoped PGAS memory, …
Summary

**HPC programmers deserve better programming models**

**Higher-level programming models can help insulate algorithms from parallel implementation details**
- yet, without necessarily abdicating control
- Chapel does this via its multiresolution design
  - domain maps, parallel iterators, and locale models are all examples
  - avoids locking crucial policy decisions into the language definition

**We believe Chapel can greatly improve productivity**
...for current and emerging HPC architectures
...for HPC users and mainstream uses of parallelism at scale
Outline

✓ Motivation
✓ Chapel Background and Themes
✓ Survey of Chapel Concepts
➢ Project Status and Next Steps
Chapel’s 5-year push

● Based on positive user response to Chapel under HPCS, Cray undertook a five-year effort to improve it
  ● we’ve just started our third year

● Focus Areas:
  1. Improving performance and scaling
  2. Fixing immature aspects of the language and implementation
     ● e.g., strings, memory management, error handling, …
  3. Porting to emerging architectures
     ● Intel Xeon Phi, accelerators, heterogeneous processors and memories, …
  4. Improving interoperability
  5. Growing the Chapel user and developer community
     ● including non-scientific computing communities
  6. Exploring transition of Chapel governance to a neutral, external body
The Chapel Team at Cray (Spring 2015)
Chapel is a Collaborative, Community Effort

(and many others as well...)

http://chapel.cray.com/collaborations.html
A Year in the Life of Chapel

- **Two major releases per year** (April / October)
  - ~a month later: detailed release notes

- **SC** (Nov)
  - annual Lightning Talks BoF featuring talks from the community
  - annual CHUG (Chapel Users Group) happy hour
  - plus tutorials, panels, BoFs, posters, educator sessions, exhibits, …

- **CHIUW**: Chapel Implementers and Users Workshop (May/June)
  - CHIUW 2014 held at IPDPS (Phoenix, AZ)
  - CHIUW 2015 held at PLDI/FCRC (Portland, OR)

- **Talks, tutorials, research visits, blog posts, …** (year-round)
Implementation Status -- Version 1.11.0 (Apr 2015)

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

This is a great time to:
- Try out the language and compiler
- Use Chapel for non-performance-critical projects
- Give us feedback to improve Chapel
- Use Chapel for parallel programming education
Chapel and Education

● When teaching parallel programming, I like to cover:
  ● data parallelism
  ● task parallelism
  ● concurrency
  ● synchronization
  ● locality/affinity
  ● deadlock, livelock, and other pitfalls
  ● performance tuning
  ● …

● I don’t think there’s been a good language out there…
  ● for teaching *all* of these things
  ● for teaching *some* of these things well at all
  ● *until now*: We believe Chapel can play a crucial role here

Suggested Reading

Overview Papers:

  - *a detailed overview of Chapel’s history, motivating themes, features*

  - *a higher-level overview of the project, summarizing the HPCS period*
Blog Articles:

  - a short-and-sweet introduction to Chapel

- **Why Chapel?** (part 1, part 2, part 3), Cray Blog, June-October 2014.
  - a recent series of articles answering common questions about why we are pursuing Chapel in spite of the inherent challenges

  - a series of technical opinion pieces designed to combat standard arguments against the development of high-level parallel languages
Online Resources

**Project page:** [http://chapel.cray.com](http://chapel.cray.com)
- overview, papers, presentations, language spec, …

**GitHub page:** [https://github.com/chapel-lang](https://github.com/chapel-lang)
- download Chapel; browse source repository; contribute code

**Facebook page:** [https://www.facebook.com/ChapelLanguage](https://www.facebook.com/ChapelLanguage)
Community Resources

**SourceForge page:** [https://sourceforge.net/projects/chapel/](https://sourceforge.net/projects/chapel/)
- hosts community mailing lists
  (also serves as an alternate release download site to GitHub)

**Mailing Aliases:**

**write-only:**
- chapel_info@cray.com: contact the team at Cray

**read-only:**
- chapel-announce@lists.sourceforge.net: read-only announcement list

**read/write:**
- 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
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