Chapel: A Domain-Specific Language for Productive Parallel Programming at Scale

Brad Chamberlain, Chapel Team, Cray Inc. University of Washington, CSEP 590c
May 9th, 2016
Chapel: A Domain-Specific Language for Productive Parallel Programming at Scale

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Chapel:
An Extremely General Language for Productive Programming on Modern Systems

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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.
My Background

Affiliations:
- Graduated from UW in 2001 (and remain associated with UW as an affiliate professor)
- Spent a lost but educational year at a start-up
- Have worked at Cray Inc. since Fall 2002

R&D topics:
- Focus primarily on parallel language design & implementation
  - at UW: on the ZPL data-parallel language
  - at start-up: on a language for reconfigurable embedded computing
  - at Cray: on Chapel
- Most of my work has been in High-Performance Computing (HPC) (but, mainstream computing is becoming more and more like HPC)
  - parallel processors, GPU computing, cloud computing, data analytics, …
  - HPC challenges are becoming everyone’s challenges: parallelism & locality
The Chapel Team at Cray (Spring 2015)

(Our team currently has an open language/compiler developer position)
Motivation for Chapel

Q: Why doesn’t HPC programming have an equivalent to Python / Matlab / Java / C++ / (your favorite programming language here)?

● one that makes it easy to get programs up and running quickly
● 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 reverse this trend!
HPC’s Status Quo: SPMD Programming

SPMD = Single Program, Multiple Data

- concept: write one program, run multiple copies of it in parallel
- arguably a “bottom-up” programming model design
  - “HPC systems can run lots of programs, so let’s get parallelism that way”
- often clumsy in practice
In pictures: “Apply a 3-Point Stencil to a vector”

Conceptual View

\[
\frac{1}{2} \left( \begin{array}{ccc}
\text{red} & \text{red} & \text{red} \\
\text{red} & \text{red} & \text{red} \\
\end{array} \right)
+ \frac{1}{2} \left( \begin{array}{ccc}
\text{red} & \text{red} & \text{red} \\
\text{red} & \text{red} & \text{red} \\
\end{array} \right) = \left( \begin{array}{ccc}
\text{yellow} & \text{yellow} & \text{yellow} \\
\text{yellow} & \text{yellow} & \text{yellow} \\
\end{array} \right)
\]

SPMD View
In pictures: “Apply a 3-Point Stencil to a vector”
4) Global-View Abstractions

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

```
proc main() {
    var n = 1000;
    var p = numProcs(),
        me = myProc(),
        myN = n/p,
    var A, B: [0..myN+1] real;
    if (me < p-1) {
        send(me+1, A[myN]);
        recv(me+1, A[myN+1]);
    }
    if (me > 0) {
        send(me-1, A[1]);
        recv(me-1, A[0]);
    }
    forall i in 1..myN do
        B[i] = (A[i-1] + A[i+1])/2;
}
```

**SPMD pseudo-code**

Bug: Refers to uninitialized values at ends of A
4) Global-View Abstractions

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

```plaintext
proc main() {
    var n = 1000;
    var p = numProcs(),
        me = myProc(),
        myN = n/p,
        myLo = 1,
        myHi = myN;
    var A, B: [0..myN+1] real;
    if (me < p-1) {
        send(me+1, A[myN]);
        recv(me+1, A[myN+1]);
    } else
        myHi = myN-1;
    if (me > 0) {
        send(me-1, A[1]);
        recv(me-1, A[0]);
    } else
        myLo = 2;
    forall i in myLo..myHi do
        B[i] = (A[i-1] + A[i+1])/2;
}
```

Communication becomes geometrically more complex for higher-dimensional arrays

Assumes p divides n
What is Chapel?

**Chapel:** An emerging parallel programming language
- extensible
- portable
- open-source
- a collaborative effort
- a work-in-progress
- a top-down language design

**Goals:**
- Support general parallel programming
  - “any parallel algorithm on any parallel hardware”
- Make parallel programming far more productive
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.”
STREAM Triad: a trivial parallel computation

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

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

In pictures:
STREAM Triad: a trivial parallel computation

**Given:** \( m \)-element vectors \( A, B, C \)

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

In pictures, in parallel:
STREAM Triad: a trivial parallel computation

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

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

In pictures, in parallel (distributed memory):
STREAM Triad: a trivial parallel computation

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

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

In pictures, in parallel (distributed memory multicore):

![Diagram showing the computation of $A_i = B_i + \alpha \cdot C_i$]
#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>
#endif
#include <omp.h>
#endif

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

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

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

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

    return errCount;
}

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

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

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

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

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

    scalar = 3.0;

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

    HPCC_free(c);
    HPCC_free(b);
    HPCC_free(a);
STREAM Triad: MPI+OpenMP vs. CUDA

MPI + OpenMP

```c
#define N 2000000

int main() {
    float *d_a, *d_b, *d_c;
    float scalar;

    cudaMemcpy((void**)&d_a, sizeof(float)*N);
    cudaMemcpy((void**)&d_b, sizeof(float)*N);
    cudaMemcpy((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);
    cudaMemcpy(d_a, (void**)&d_a, sizeof(float)*N);
    cudaMemcpy(d_b, (void**)&d_b, sizeof(float)*N);
    cudaMemcpy(d_c, (void**)&d_c, sizeof(float)*N);
}
```

CUDA

```c
#include <hpcc.h>

#define N 2000000

int main() {
    float *d_a, *d_b, *d_c;
    float scalar;

    cudaMemcpy((void**)&d_a, sizeof(float)*N);
    cudaMemcpy((void**)&d_b, sizeof(float)*N);
    cudaMemcpy((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);
    cudaMemcpy(d_a, (void**)&d_a, sizeof(float)*N);
    cudaMemcpy(d_b, (void**)&d_b, sizeof(float)*N);
    cudaMemcpy(d_c, (void**)&d_c, sizeof(float)*N);
}
```

HPC suffers from too many distinct notations for expressing parallelism and locality.
Why so many programming models?

HPC tends to approach programming models bottom-up: Given a system and its core capabilities...
...provide features that can access the available performance.
● portability, generality, programmability: not strictly necessary.

<table>
<thead>
<tr>
<th>Type of HW Parallelism</th>
<th>Programming Model</th>
<th>Unit of Parallelism</th>
</tr>
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<tbody>
<tr>
<td>Inter-node</td>
<td>MPI</td>
<td>executable</td>
</tr>
<tr>
<td>Intra-node/m multicore</td>
<td>OpenMP / pthreads</td>
<td>iteration/task</td>
</tr>
<tr>
<td>Instruction-level vectors/threads</td>
<td>pragmas</td>
<td>iteration</td>
</tr>
<tr>
<td>GPU/accelerator</td>
<td>CUDA / Open[CL</td>
<td>MP</td>
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**benefits:** lots of control; decent generality; easy to implement
**downsides:** lots of user-managed detail; brittle to changes
Rewinding a few slides…

HPC suffers from too many distinct notations for expressing parallelism and locality

```c
#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_StarStream(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;
    }
    if (a) {
        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;
    }
    int 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];
    }
```
**STREAM Triad: Chapel**

### 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, *top-down* language design can tease system-specific implementation details away from an algorithm, permitting the compiler, runtime, applied scientist, and HPC expert to each focus on their strengths.
Outline

✓ Motivation

➢ Chapel's Design Themes
  ● Survey of Chapel Concepts
  ● Project Status and Next Steps
Design Themes for Chapel

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

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

We’ll cover this one as we go
1) General Parallel Programming

With a unified set of concepts...

...target any hardware parallelism available in the system

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

...express any software parallelism desired by the user

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

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<td>Chapel</td>
<td>iteration</td>
</tr>
<tr>
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<td>Chapel</td>
<td>SIMD function/task</td>
</tr>
</tbody>
</table>
2) 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
3) Global-View Abstractions

In pictures: “Apply a 3-Point Stencil to a vector”
3) Global-View Abstractions

In pictures: “Apply a 3-Point Stencil to a vector”
3) Global-View Abstractions

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

Global-View

```chapel
proc main() {
    var n = 1000;
    var A, B: [1..n] real;

    forall i in 2..n-1 do
        B[i] = (A[i-1] + A[i+1])/2;
}
```

Local-View (SPMD)

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

    if (me < p-1) {
        send(me+1, A[myN]);
        recv(me+1, A[myN+1]);
    } else
        myHi = myN-1;

    if (me > 0) {
        send(me-1, A[1]);
        recv(me-1, A[0]);
    } else
        myLo = 2;

    forall i in myLo..myHi do
        B[i] = (A[i-1] + A[i+1])/2;
}
```
3) Global-View Abstractions: A Final Note

- A language may support both global- and local-view programming — in particular, Chapel does

```chapel
proc main() {
    coforall loc in Locales do
        on loc do
            MySPMMDProgram(loc.id, Locales.numElements);
}

proc MySPMMDProgram(myImageID, numImages) {
    ...
}
```
4) Multiresolution Design: Motivation

“Why is everything so tedious/difficult?”
“Why don’t my programs trivially port to new systems?”

“Why don’t I have more control?”
4) 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
Outline

✅ Motivation

✅ Chapel's Design Themes

➢ Survey of Chapel Concepts

● Project Status and Next Steps
Outline

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### Static Type Inference

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

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

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

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

`(4.14, bradford)`
Range Types, Values, and Operators

```chapel
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(i, " ");
        writeln();
}
```

```plaintext
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

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

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

```chapel
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;
}
```

```chapel
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

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

<table>
<thead>
<tr>
<th>fib #</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>8</td>
</tr>
</tbody>
</table>

...
Other Base Language Features

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

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➢ Survey of Chapel Concepts

● Project Status and Next Steps
Task Parallelism: Begin Statements

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

Possible outputs:

hello world  goodbye
goodbye  hello world
Task Parallelism: Coforall Loops

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

writeln("All tasks done");

Sample output:
Hello from task 2 of 4
Hello from task 0 of 4
Hello from task 3 of 4
Hello from task 1 of 4
All tasks done
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
**Outline**

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- Project Status and Next Steps

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

**Theme 5:** 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 = ...;
```

```
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:

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

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

  ```chapel
  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:

  ```chapel
  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!");
  ```
Time Check!
Do we have time for a sidebar on PGAS?

Yes?  No!
Global Address Space:

- permit parallel tasks to access variables by naming them
- regardless of whether they are local or remote
- compiler / library / runtime will take care of communication

OK to access \( i, j, \) and \( k \) wherever they live

\[
k = i + j;
\]
Global Address Space:
- permit parallel tasks to access variables by naming them
  - regardless of whether they are local or remote
  - compiler / library / runtime will take care of communication

Partitioned:
- establish a strong model for reasoning about locality
  - every variable has a well-defined location in the system
  - local variables are typically cheaper to access than remote ones

i and j are remote, so need to “get” their values

k = i + j;
PGAS Programming in a Nutshell

Global Address Space:
- permit parallel tasks to access variables by naming them
  - regardless of whether they are local or remote
  - compiler / library / runtime will take care of communication

Partitioned:
- establish a strong model for reasoning about locality
  - every variable has a well-defined location in the system
  - local variables are typically cheaper to access than remote ones

Images / Threads / Locales / Places / etc. (think: “compute nodes”)
proc main() {
    var i(*): int;    // declare a shared variable i
SPMD PGAS Languages (using a pseudo-language, not Chapel)

```plaintext
proc main() {
    var i(*): int; // declare a shared variable i
    i = 2*this_image(); // each image initializes its copy
}
```
SPMD PGAS Languages (using a pseudo-language, not Chapel)

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

---

<table>
<thead>
<tr>
<th>0</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>j</td>
<td>j</td>
<td>j</td>
<td>j</td>
<td>j</td>
</tr>
</tbody>
</table>
proc main() {
    var i(*): int;       // declare a shared variable i
    i = 2*this_image();  // each image initializes its copy
    var j: int;           // declare a private variable j
    j = i( (this_image()+1) % num_images() );
    // ^^^ access our neighbor’s copy of i
    // communication is implemented by the compiler + runtime

    // How did we know our neighbor had an i?
    // Because it’s SPMD – we’re all running the same program.
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”)
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;
}
Chapel: Scoping and Locality

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

Locales (think: “compute nodes”)}
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. For example:
      k = 2*i + j;
      // The implementation manages any communication.
    }
  }
}

Locales (think: “compute nodes”)

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Chapel: Locality queries

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

            ...here... // query the locale on which this task is running
            ...j.locale... // query the locale on which j is stored
        }
    }
}
```

Locales (think: “compute nodes”)

Outline

- Motivation
- Chapel's Design Themes
- Survey of Chapel Concepts

- Project Status and Next Steps
Outline

✔ Motivation
✔ Chapel's Design Themes
➢ Survey of Chapel Concepts

● Project Status and Next Steps
const ProblemSpace = {1..m};

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

A = B + alpha * C;
**STREAM Triad: Chapel (multicore)**

```chapel
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 (multilocal, blocked)

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

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

A = B + alpha * C;
```
STREAM Triad: Chapel (multilocation, cyclic)

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

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

A = B + alpha * C;
```
STREAM Triad: Chapel

```
#include <hpcc.h>
#ifdef _OPENMP
#include <omp.h>
#endif
static int VectorSize;
static double *a, *b, *c;
int HPCC_STAR_STREAM(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 (td)\n", VectorSize);
    fclose(outFile);
  }
  return 1;
}
#ifdef _OPENMP
#pragma omp parallel for
#endif
for (j=0; j<VectorSize; j++)
  b[j] = 2.0;
C = 3.0;
#ifdef _OPENMP
#pragma omp parallel for
#endif
for (j=0; j<VectorSize; j++)
  a[j] = b[j] + scalar * C;
HPCC_free(c);
HPCC_free(b);
HPCC_free(a);
return 0;
```
Chapel has Many Types of Domains/Arrays

- **dense**
- **strided**
- **sparse**
- **associative**
- **unstructured**
**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 the only 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**

Domain maps insulate the rest of the application from these choices.
Domain Maps

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

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

...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 Components

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>Domain Maps</td>
<td></td>
</tr>
<tr>
<td>Data Parallelism</td>
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<tr>
<td>Task Parallelism</td>
<td></td>
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<tr>
<td>Base Language</td>
<td></td>
</tr>
<tr>
<td>Locality Control</td>
<td></td>
</tr>
</tbody>
</table>
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:
- Technical notes detailing the domain map interface for implementers: http://chapel.cray.com/docs/latest/technotes/dsi.html
- Current domain maps:
  - $CHPL_HOME/modules/dists/*.chpl
  - layouts/*.chpl
  - internal/Default*.chpl
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, …
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's Design Themes
✓ Survey of Chapel Concepts
➢ Project Status and Next Steps
Chapel is Portable

- Chapel’s design is intended to be hardware-independent

- The current release requires:
  - a C/C++ compiler
  - a *NIX environment (Linux, OS X, BSD, Cygwin, …)
  - POSIX threads
  - (for distributed execution): support for RDMA, MPI, or UDP

- Chapel can run on…
  ...laptops and workstations
  ...commodity clusters
  ...the cloud
  ...HPC systems from Cray and other vendors
  ...modern processors like Intel Xeon Phi, GPUs*, etc.

* = academic work only; not yet supported in the official release
Chapel is Open-Source

- Chapel’s development is hosted at GitHub
  - [https://github.com/chapel-lang](https://github.com/chapel-lang)

- Chapel is licensed as Apache v2.0 software

- Instructions for download + install are online
  - see [http://chapel.cray.com/download.html](http://chapel.cray.com/download.html) to get started
A Year in the Life of Chapel

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

- **CHIUW**: Chapel Implementers and Users Workshop (May/June)
  - (3rd annual) CHIUW 2016 will be held at IPDPS (Chicago, IL)

- **SC** (Nov)
  - tutorials, panels, BoFs, posters, educator sessions, exhibits, …
  - annual CHUG (Chapel Users Group) happy hour

- **Talks, tutorials, research visits, blog posts, …** (year-round)
Chapel is a Collaborative Effort

(and many others as well...)

http://chapel.cray.com/collaborations.html
Chapel is a Work-in-Progress

- Currently being picked up by early adopters
  - Users who try it generally like what they see
  - Last release got 1400+ downloads over six months

- Most features are functional and working well
  - some areas need improvements: strings, object-oriented features, …

- Performance can be hit-or-miss
  - shared memory performance is often competitive with C+OpenMP
  - distributed memory performance needs more work

- We are actively working to address these lacks
Stream-EP Performance Over Time

Stream EP Performance Across Chapel Releases
(128 nodes)

GB/s per node

Chapel version (six-months per release)

Chapel
MPI+OpenMP

v1.9 v1.10 v1.11 v1.12
Scalability: RA (atomics) Performance

- **RA (atomics) summary**
  - 5x better performance for ugni-qthreads
  - 3x better performance for ugni-muxed

![Graph showing performance of RA (atomics)]
Chapel Resources: For More Information
Chapel Websites

Project page: http://chapel.cray.com
- overview, papers, presentations, language spec, ...

GitHub: https://github.com/chapel-lang
- download Chapel; browse source repository; contribute code

Facebook: https://www.facebook.com/ChapelLanguage

Twitter: https://twitter.com/ChapelLanguage
Suggested Reading

Chapel chapter from *Programming Models for Parallel Computing*

- a detailed overview of Chapel’s history, motivating themes, features
- edited by Pavan Balaji, published by MIT Press
- an early draft is available online, entitled *A Brief Overview of Chapel*

Other Chapel papers/publications available at [http://chapel.cray.com/papers.html](http://chapel.cray.com/papers.html)
Chapel Blog Articles

- a short-and-sweet introduction to Chapel

**Chapel Springs into a Summer of Code**, Cray Blog, April 2016.
- a run-down of some current events

**Six Ways to Say “Hello” in Chapel** (parts 1, 2, 3), Cray Blog, Sep-Oct 2015.
- a series of articles illustrating the basics of parallelism and locality in Chapel

**Why Chapel?** (parts 1, 2, 3), Cray Blog, Jun-Oct 2014.
- a 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 argue against standard reasons given for not developing high-level parallel languages
Chapel Mailing Lists

**low-traffic (read-only):**
chapel-announce@lists.sourceforge.net: announcements about Chapel

**community lists:**
chapel-users@lists.sourceforge.net: user-oriented discussion list
chapel-developers@lists.sourceforge.net: developer discussions
chapel-education@lists.sourceforge.net: educator discussions
chapel-bugs@lists.sourceforge.net: public bug forum

*(subscribe at SourceForge: [http://sourceforge.net/p/chapel/mailman/](http://sourceforge.net/p/chapel/mailman/))*

**To contact the Cray team:**
chapel_info@cray.com: contact the team at Cray
chapel_bugs@cray.com: for reporting non-public bugs
Questions?
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