Chapel:
Productive, Multiresolution Parallel Programming

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ATPESC: Argonne Training Program for Exascale Computing
August 7th, 2014
Chapel:
Your New Favorite Parallel Language! :D

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Safe Harbor Statement

This presentation may contain forward-looking statements that are based on our current expectations. Forward looking statements may include statements about our financial guidance and expected operating results, our opportunities and future potential, our product development and new product introduction plans, our ability to expand and penetrate our addressable markets and other statements that are not historical facts. These statements are only predictions and actual results may materially vary from those projected. Please refer to Cray's documents filed with the SEC from time to time concerning factors that could affect the Company and these forward-looking statements.
Sustained Performance Milestones

1 GF – 1988: Cray Y-MP; 8 Processors
  • Static finite element analysis

1 TF – 1998: Cray T3E; 1,024 Processors
  • Modeling of metallic magnet atoms

1 PF – 2008: Cray XT5; 150,000 Processors
  • Superconductive materials

1 EF – ~2018: Cray ____; ~10,000,000 Processors
  • TBD
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 – ~2018: 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
```

$\alpha$
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):
#include <hpcc.h>

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

int HPCC_SharStream(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 _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 );

    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;
    }
#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);
    }
### 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);
}
```

```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
#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);
    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);
    cudaMemcpy(d_b);
    cudaMemcpy(d_c);
}
```

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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<td>pragmas</td>
<td>iteration</td>
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<td>GPU/accelerator</td>
<td>CUDA/OpenCL/OpenACC</td>
<td>SIMD function/task</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...

**CUDA**

```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);
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);
}

__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];
}
```

**MPI + OpenMP**

```c
//include <hpcc.h>
#define OPENMP
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;
}
#endif
#pragma omp parallel for
for (j=0; j<VectorSize; j++) {
    b[j] = 2.0;
    c[j] = 0.0;
}
scalar = 3.0;
#endif
#pragma omp parallel for
for (j=0; j<VectorSize; j++)
    a[j] = b[j]+scalar*c[j];
HPCC_free(c);
HPCC_free(b);
HPCC_free(a);
return 0;
#endif
```

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

● After dinner: Chapel and Charm++ hands-on session
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 BSD software (future releases will be Apache)

- Portable design and implementation, targeting:
  - multicore desktops and laptops
  - commodity clusters and the cloud
  - HPC systems from Cray and other vendors
  - in-progress: manycore processors, CPU+accelerator hybrids, …
Motivating Chapel Themes

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

1) General Parallel Programming
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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, instructions

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3) Multiresolution Design: Motivation

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

“Why don’t I have more control?”
**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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const pi = 3.14,
    coord = 1.2 + 3.4i,
    coord2 = pi*coord,
    name = “brad”,
    verbose = false;

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

var sum = addem(1, pi),
    fullname = addem(name, “ford”);

writeln((sum, fullname));

(4.14, bradford)
Range Types and Algebra

```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 by 2 # 3);
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

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

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

iter tiledRMO(D, tilesize) {
    const tile = {0..#tilesize, 0..#tilesize};
    for base in D by tilesize do
        for ij in D[tile + base] do
            yield ij;
}

for ij in tiledRMO({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)
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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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:

<table>
<thead>
<tr>
<th>hello world</th>
<th>goodbye</th>
</tr>
</thead>
<tbody>
<tr>
<td>goodbye</td>
<td>hello world</td>
</tr>
</tbody>
</table>
Task Parallelism: Coforall Loops

// create a task per iteration
cforall 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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Theme 4: Control over Locality/Affinity
The Locale Type

Definition:
- Abstract unit of target architecture
- Supports reasoning about locality
  - defines “here vs. there” / “local vs. remote”
- Capable of running tasks and storing variables
  - i.e., has processors and memory

Typically: A compute node (multicore processor or SMP)
Getting started with locales

- Specify # of locales when running Chapel programs

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

- Chapel provides built-in locale variables

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

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

Locales

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

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Locale Operations

Locale methods support queries about the target system:

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

On-clauses support placement of computations:

```plaintext
writeln("on locale 0");

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

```plaintext
begin on A[i,j] do
  bigComputation(A);
begin on node.left do
  search(node.left);
```
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
Chapel and PGAS

● Chapel is PGAS, but unlike most, it’s not restricted to 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
Chapel: Scoping and Locality

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

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

Locales (think: “compute nodes”)

i

0 1 2 3 4
var i: int;
on Locales[1] {
    var j: int;

 Locales (think: “compute nodes”)
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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Data Parallelism by Example: Jacobi Iteration

\[ A: \begin{bmatrix} \sum & 1.0 \end{bmatrix} \]

\[ \text{repeat until max change } < \varepsilon \]
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

```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 program parameters**

- **const** ⇒ can’t change values after initialization
- **config** ⇒ can be set on executable command-line

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

Note that no types are given; they’re inferred from initializers

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

```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\} ⇒ 2D rectangular domain, with 2-tuple indices

Dom1[Dom2] ⇒ computes the intersection of two domains

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

![Domain Diagrams](image-url)
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;
```

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]…”)

A

```
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)

$$
\sum \left( \begin{array}{c}
\text{+} \\
\text{+} \\
\text{+} \\
\text{+} \\
\end{array} \right) \div 4
$$

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

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);

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)
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
```
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);

call writeln(A);

use BlockDist;
```
### 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.
Goal: Solve one octant of the spherical Sedov problem (blast wave) using Lagrangian hydrodynamics for a single material.
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.)
Because of domain maps, this code is independent of:

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

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

● Project Status and Next Steps
Domain Maps

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**
- **unstructured**

All Chapel domain types support domain maps.
All Domain Types Support Domain Maps

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

- **associative**
- **unstructured**

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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) **leader-follower 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, …
Outline

✓ Motivation
✓ Chapel Background and Themes
✓ Survey of Chapel Concepts
➢ Project Status and Next Steps
Implementation Status -- Version 1.9.0 (Apr 2014)

Overall Status:

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

This is a good time to:

● Try out the language and compiler
● Use Chapel for non-performance-critical projects
● Give us feedback to improve Chapel
● 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

(see http://chapel.cray.com/education.html for more information and http://cs.washington.edu/education/courses/csep524/13wi/ for my use of Chapel in class)
Chapel: the next five years

● **Harden prototype to production-grade**
  ● add/improve lacking features
  ● optimize performance

● **Target more complex/modern compute node types**
  ● e.g., Intel MIC, CPU+GPU, AMD APU, …

● **Continue to grow the user and developer communities**
  ● including nontraditional circles: desktop parallelism, “big data”
  ● transition Chapel from Cray-managed to community-governed
Chapel…

…is a collaborative effort — join us!
Higher-level programming models can help insulate algorithms from parallel implementation details

- yet, without necessarily abdicating control
- Chapel does this via its multiresolution design
  - here, we saw it principally in domain maps
  - leader-follower iterators and locale models are other examples
  - these avoid locking crucial policy decisions into the language

We believe Chapel can greatly improve productivity

...for current and emerging HPC architectures
...for emerging mainstream needs for parallelism and locality
For More Information: Online Resources

Chapel project page: http://chapel.cray.com
  ● overview, papers, presentations, language spec, …

Chapel SourceForge page: https://sourceforge.net/projects/chapel/
  ● download 1.9.0 release, join community mailing lists

Chapel GitHub page: https://github.com/chapel-lang
  ● repository is hosted here

Mailing Aliases:
  ● chapel_info@cray.com: contact the team at Cray
  ● chapel-users@lists.sourceforge.net: user-oriented discussion list
  ● chapel-developers@lists.sourceforge.net: developer discussion
  ● chapel-education@lists.sourceforge.net: educator discussion
  ● chapel-bugs@lists.sourceforge.net: public bug forum
For More Information: Suggested Reading

Overview Papers:

  - a 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

  - a current 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
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