Chapel:
Productive Parallel Programming at Scale

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What You Will Learn

● Concepts of distributed parallel programming models
  ● MPI, SPMD
  ● CUDA, SIMT
  ● PGAS

● What is the Chapel programming language?
  ● Learn enough to get started writing programs

● How does the Chapel language fit in to the landscape of parallel programming tools?
About Me
High Performance Computing (HPC)
Programming Models by Example
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):
#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);
STREAM Triad: MPI

```c
#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 );

    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);
}
```

"SPMD": Single Program Multiple Data
#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 );

    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);
STREAM Triad: MPI+OpenMP

```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_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);
```

"Hybrid" multiple models of parallelism
STREAM Triad: MPI+OpenMP vs. 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);
    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];
}
```

#define N 2000000

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

cu malloc((void**)&d_a, sizeof(float)*N);
cu malloc((void**)&d_b, sizeof(float)*N);
cu malloc((void**)&d_c, sizeof(float)*N);

dim3 dimBlock(128);
dim3 dimGrid(N/dimBlock.x);
if( N % dimBlock.x != 0 ) dimGrid

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);
cuda threadSynchronize();

cu free(d_a);
cu free(d_b);
cu free(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];
}
Why do we need so much code? Why so many programming models?

STREAM Triad: MPI+OpenMP vs. CUDA

```
#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 );
    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);
return 0;
}
```

```
#include <hpcc.h>
#pragma omp parallel for
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;
    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];
    }
```
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.

<table>
<thead>
<tr>
<th>Type of HW Parallelism</th>
<th>Programming Model</th>
<th>Unit of Parallelism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inter-node</td>
<td>MPI</td>
<td>executable</td>
</tr>
<tr>
<td>Intra-node/multicore</td>
<td>OpenMP / pthreads</td>
<td>iteration/task</td>
</tr>
<tr>
<td>Instruction-level vectors/threads</td>
<td>pragmas, intrinsics</td>
<td>iteration</td>
</tr>
<tr>
<td>GPU/accelerator</td>
<td>CUDA / Open[CL</td>
<td>MP</td>
</tr>
</tbody>
</table>

benefits: lots of control; decent generality; easy to implement
downsides: lots of user-managed detail; brittle to changes
Motivation for Chapel

Q: Can a single language be...
   ...as productive as Python?
   ...as fast as Fortran?
   ...as portable as C?
   ...as scalable as MPI?
   ...as fun as <your favorite language here>?

A: We believe so.
What is Chapel?

**Chapel:** A productive parallel programming language
- portable
- open-source
- a collaborative effort

**Goals:**
- Support general parallel programming
  - “any parallel algorithm on any parallel hardware”
- Make parallel programming at scale 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 need, implemented in a language as attractive as recent graduates want.”
Rewinding a few slides...

Why do we need so much code?

Why so many programming models?
STREAM Triad: 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 for Chapel
- Survey of Chapel Concepts
  - Chapel Project and Characterizations
  - Chapel Resources
**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
Base Language
Base Language Features, by example

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

```java
config const n = 10;
for f in fib(n) do
    writeln(f);
```

```
0
1
1
2
3
5
8
...
```
Base Language Features, by example

CLU-style iterators

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

```
config const n = 10;
for f in fib(n) do
    writeln(f);
```

0 1 1 2 3 5 8 ...

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Base Language Features, by example

Configuration declarations (to avoid command-line argument parsing)
./a.out -n=1000000

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

```plaintext
cfg const n = 10;

for f in fib(n) do
    writeln(f);
```

```
0
1
1
2
3
5
8
...
```
Base Language Features, by example

```go
// config const n = 10;

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

for f in fib(n) do
  writeln(f);
```

0
1
1
2
3
5
8
...
Base Language Features, by example

```cpp
iter fib(n) {
    var current = 0,
        next = 1;
    for i in 1..n {
        yield current;
        current += next;
        current <=> next;
    }
}
```

```cpp
config const n = 10;
for (i, f) in zip(0..#n, fib(n)) do writeln("fib #", i, " is ", f);
```

```
|         |         |
|---------+---------|
| fib #0  | 0       |
| fib #1  | 1       |
| fib #2  | 1       |
| fib #3  | 2       |
| fib #4  | 3       |
| fib #5  | 5       |
| fib #6  | 8       |
| ...     |         |
```
Base Language Features, by example

```ruby
iter fib(n) {
  var current = 0,
      next = 1;
  for i in 1..n {
    yield current;
    current += next;
    current <=> next;
  }
}
```

```ruby
config const n = 10;
for (i, f) in zip(0..#n, fib(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
...
Base Language Features, by example

```
iter fib(n) {
    var current = 0,
        next = 1;

    for i in 1..n {
        yield current;
        current += next;
        current <=> next;
    }
}
```

```
cfg const n = 10;

for (i,f) in zip(0..#n, fib(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 |
...
Base Language Features, by example

**Recursive Function: Fibonacci**

```javascript
iter fib(n) {
    var current = 0,
        next = 1;
    for i in 1..n {
        yield current;
        current += next;
        current <=> next;
    }
}
```

**Configuration Example**

```javascript
config const n = 10;
for (i,f) in zip(0..#n, fib(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

- interoperability features
- OOP (value- and reference-based)
- overloading, where clauses
- argument intents, default values, match-by-name
- compile-time features for meta-programming
  - e.g., compile-time functions to compute types, values; reflection
- modules (for namespace management)
- rank-independent programming features
- …
Task Parallelism
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
Task Parallelism: Coforall Loops

```cpp
// 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
```
Task Parallelism: Data-Driven Synchronization

- **atomic variables**: support atomic operations
  - e.g., compare-and-swap; atomic sum, multiply, etc.
  - similar to C/C++

- **sync variables**: store full-empty state along with value
  - by default, reads/writes block until full/empty, leave in opposite state
Other Task Parallel Concepts

- **cobegins**: create tasks using compound statements
- **single variables**: like sync variables, but write-once
- **sync statements**: join unstructured tasks
- **serial statements**: conditionally squash parallelism
Locality Control
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
```

- main() starts execution as a task on locale #0
Locale Operations

- Locale methods support queries about the target system:
  - `proc locale.physicalMemory(...) { ... }`
  - `proc locale.numCores { ... }`
  - `proc locale.id { ... }`
  - `proc locale.name { ... }`

- On-clauses support placement of computations:
  - `writeln("on locale 0");`
  - `on Locales[1] do writeln("now on locale 1");`
  - `writeln("on locale 0 again");`
  - `on A[i,j] do bigComputation(A);`
  - `on node.left do search(node.left);`
Parallelism and Locality: Orthogonal in Chapel

- This is a **parallel**, but local program:
  
  ```chapel
coforall i in 1..msgs do
  writeln("Hello from task ", i);
  ```

- This is a **distributed**, but serial program:
  
  ```chapel
writeln("Hello from locale 0!");
on Locales[1] do writeln("Hello from locale 1!");
on Locales[2] do writeln("Hello from locale 2!");
  ```

- This is a **distributed parallel** program:
  
  ```chapel
coforall i in 1..msgs do
  on Locales[i%numLocales] do
  writeln("Hello from task ", i, " running on locale ", here.id);
  ```
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: Fortran Co-Arrays, UPC
**SPMD PGAS Languages** *(using a pseudo-language, not Chapel)*

```plaintext
shared int i(*);  // declare a shared variable i
```
SPMD PGAS Languages (using a pseudo-language, not Chapel)

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

shared int i(*);  // declare a shared variable i
function main() {
    i = 2*this_image();  // each image initializes its copy
}

private int j;  // declare a private variable j
SPMD PGAS Languages (using a pseudo-language, not Chapel)

```plaintext
shared int i(*); // declare a shared variable i

function main() {
    i = 2*this_image(); // each image initializes its copy
    barrier();

    private int j; // declare a private variable j
    j = i( (this_image()+1) % num_images() ); // access our neighbor's copy of i
    // communication implemented by compiler + runtime

    // How did we know our neighbor had an i?
    // Because it's SPMD - we're all running the same
    // program. (Simple, but restrictive)
```

![Diagram showing variable assignments for i and j across different image slots.](image)
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”)
Chapel: Scoping and Locality

```chapel
var i: int;
on Locales[1] {
```

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

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

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

```chapel
var i: int;
on Locales[1] {
    var j: int;
    coforall loc in Locales {
        on loc {
            print(i, j);
        }
    }
}
```

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;
      ...
    }
  }
}
```

Locales (think: “compute nodes”)

<table>
<thead>
<tr>
<th>i</th>
<th>k</th>
<th>j</th>
<th>k</th>
<th>k</th>
<th>k</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>
Chapel: Scoping and Locality

```chapel
var i: int;
on Locales[1] {
    var j: int;
    coforall loc in Locales {
        on loc {
            var k: int;
            k = 2*i + j;
        }
    }
}
```

OK to access `i`, `j`, and `k` wherever they live

![Diagram showing scoping and locality in Chapel](image)

Locales (think: “compute nodes”)
```
var i: int;
on Locales[1] { 
  var j: int;
  coforall loc in Locales { 
    on loc { 
      var k: int;
      k = 2*i + j;
    }
  }
}
```

Here, \( i \) and \( j \) are remote, so the compiler + runtime will transfer their values.

$$k = 2*i + j;$$
Chapel: Locality queries

```chapel
var i: int;
on Locales[1] {
  var j: int;
  coforall loc in Locales {
    on loc {
      var k: int;
      ...
      // query the locale on which this task is running
      ...
      j.locale...
      // query the locale on which j is stored
    }
  }
}
```

Locales (think: “compute nodes”)
Data Parallelism

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

Higher-level Chapel
Data Parallelism By Example: STREAM Triad

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

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

forall (a,b,c) in zip(A,B,C) do
  a = b + alpha*c;
```
Data Parallelism By Example: STREAM Triad

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

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

A = B + alpha * C;  // equivalent to the zippered forall
```

// equivalent to the zippered forall
Other Data Parallel Features

- **Rich Domain/Array Types:**
  - multidimensional
  - strided
  - sparse
  - associative

- **Slicing:** Refer to subarrays using ranges/domains
  
  \[
  A[2..n-1, lo..#b] \\
  A[\text{ElementsOfInterest}]
  \]

- **Promotion:** Call scalar functions with array arguments
  \[
  \text{pow}(A, B) \quad // \text{equivalent to:} \quad \forall (a,b) \in \text{zip}(A,B) \quad \text{do} \quad \text{pow}(a,b)
  \]

- **Reductions/Scans:** Apply operations across collections
  \[
  + \text{reduce} \ A \\
  \text{myReduceOp} \text{ reduce} \ A
  \]
Domain Maps

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

Higher-level 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
const ProblemSpace = {1..m}

dmapped Cyclic(startIdx=1);

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

A = B + alpha * C;
STREAM Triad: Chapel (multilocale, blocked)

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

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

A = B + alpha * C;
```
### 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.
Parallel 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

We believe Chapel can greatly improve productivity
- ...for current and emerging parallel architectures
- ...for HPC users as well as mainstream uses of parallelism
Outline

✓ Motivation for Chapel
✓ Survey of Chapel Concepts
➢ Chapel Project and Characterizations
● Chapel Resources
Chapel was recently added to the game:

As of December 2017:

- **for performance:**
  - 1 top entries: pidigits
  - 4 top-5 entries:
    - fannkuch-redux, chameneos-redux, meteor, thread-ring
  - 2 top-10 entries: mandelbrot, fasta
  - 3 top-20 entries: spectral-norm, regex-redux

- **for code compactness:**
  - 2 top entries: n-body, thread-ring
  - 1 top-5 entries: spectral-norm
  - 2 top-10 entry: pidigits, regex-redux
  - 3 top-20 entries: mandelbrot, chameneos-redux, meteor
Scatter plots of CLBG code size x speed

Compressed Code Size (normalized to smallest entry)

Execution Time (normalized to fastest entry)
CLBG Cross-Language Summary
(Oct 2017 standings)
CLBG Cross-Language Summary
(Oct 2017 standings)
CLBG Cross-Language Summary
(Oct 2017 standings)

Compressed Code Size (normalized to smallest entry)

Execution Time (normalized to fastest entry)
Chapel is Portable

● Chapel is designed to be hardware-independent

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

● 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
The Chapel Team at Cray (Summer 2016)

14 full-time employees + 2 summer interns + 2–4 GSoC students
Chapel is a Collaborative Effort

(and several others…)

https://chapel-lang.org/collaborations.html
Chapel Status

- Currently being picked up by early adopters
  - over two releases, 3000+ downloads per year
  - Users who try it generally like what they see

- Most current features are functional and working well

- Performance is compelling in many cases
A notable early adopter

Chapel in the (Cosmological) Wild

Nikhil Padmanabhan, Yale University Professor, Physics & Astronomy

Abstract: This talk aims to present my personal experiences using Chapel in my research. My research interests are in observational cosmology; more specifically, I use large surveys of galaxies to constrain the evolution of the Universe. This involves measuring a number of spatial statistics of the distribution of galaxies, both on actual observations, but also on large numbers of simulated universes. I'll start by presenting a whirlwind introduction to cosmology, the problems that keep me up at night and our approaches to solving these. I'll then discuss what attracted me to Chapel—the ability to prototype algorithms quickly and the promised ease and flexibility of writing parallel programs. I'll then present a worked example of Chapel being used in a real-world application, discussing some of these aspects as well highlighting its interoperability with existing libraries, as well as some of the challenges. I'll conclude with what it would take for me to switch over to using Chapel all of the time.
Outline

✓ Motivation for Chapel
✓ Survey of Chapel Concepts
✓ Chapel Project and Characterizations
➢ Chapel Resources
Chapel Websites

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

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

Facebook: [https://www.facebook.com/ChapelLanguage](https://www.facebook.com/ChapelLanguage)

Twitter: [https://twitter.com/ChapelLanguage](https://twitter.com/ChapelLanguage)
Suggested Reading

Chapel chapter from *Programming Models for Parallel Computing*

- a detailed overview of Chapel’s history, motivating themes, features
- published by MIT Press, November 2015
- edited by Pavan Balaji (Argonne)
- chapter is now also available online

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.
- coverage of recent 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 mail the Cray team:**
- chapel_info@cray.com: contact the team at Cray
- chapel_bugs@cray.com: for reporting non-public bugs

or use IRC (#chapel on chat.freenode.net) or StackOverflow
Chapel: Productive Parallel Programming at Scale

Questions?