# Chapel:
## Productive Parallel Programming at Scale

**Michael Ferguson, Chapel Team, Cray Inc.**

**Guest Lecture at CMSC 441**

**December 7th, 2017**

# Safe Harbor Statement

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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



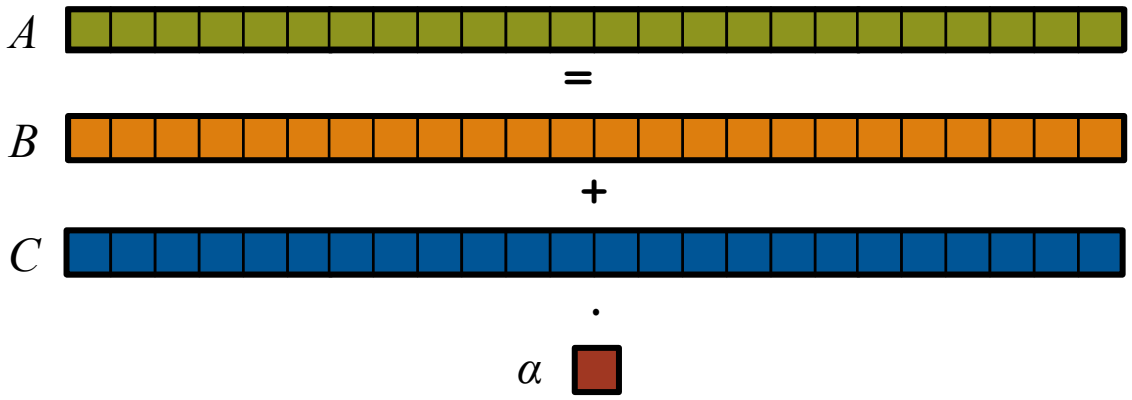
# High Performance Computing (HPC) Programming Models by Example

# 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 $A$, $B$, $C$

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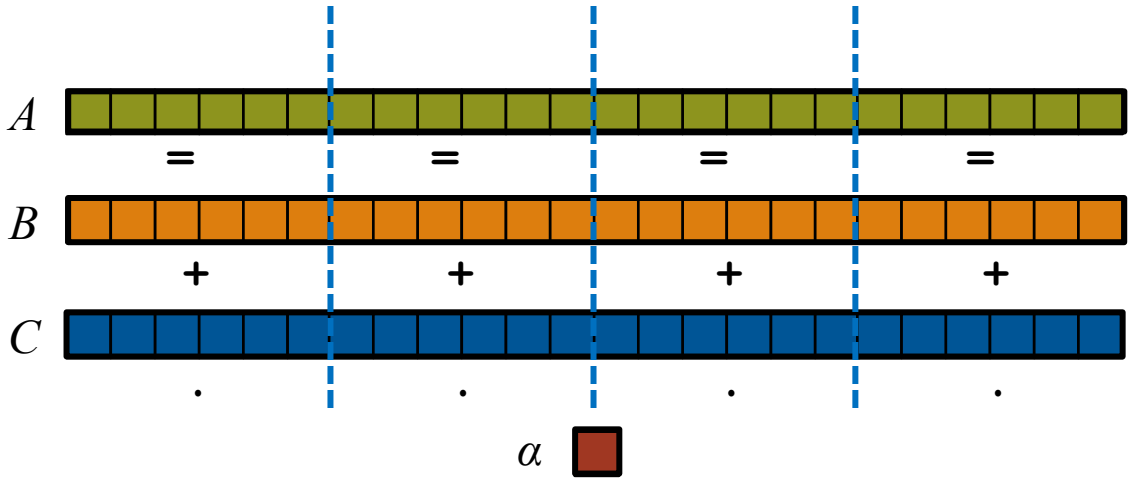
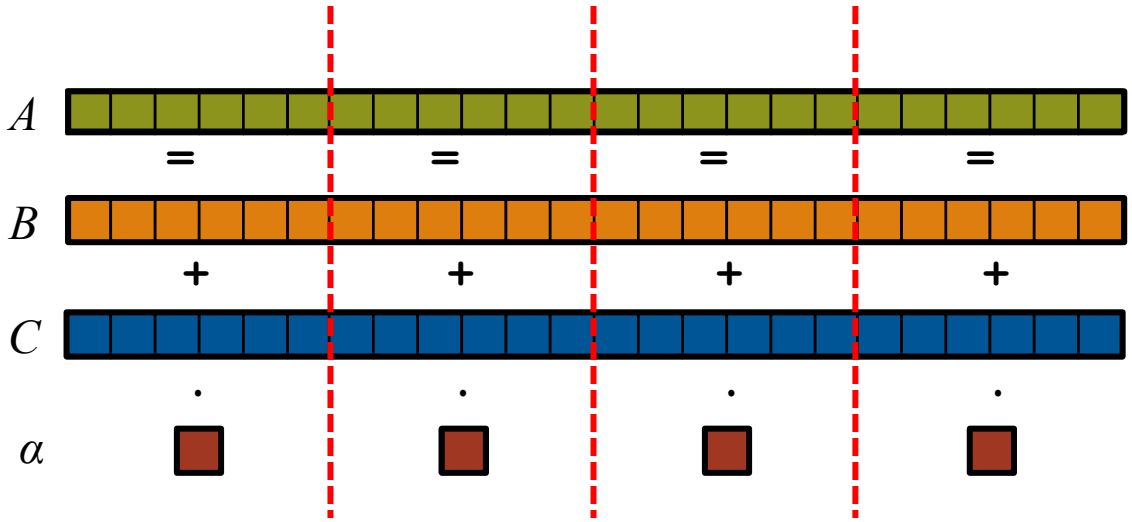


# STREAM Triad: a trivial parallel computation

**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):**

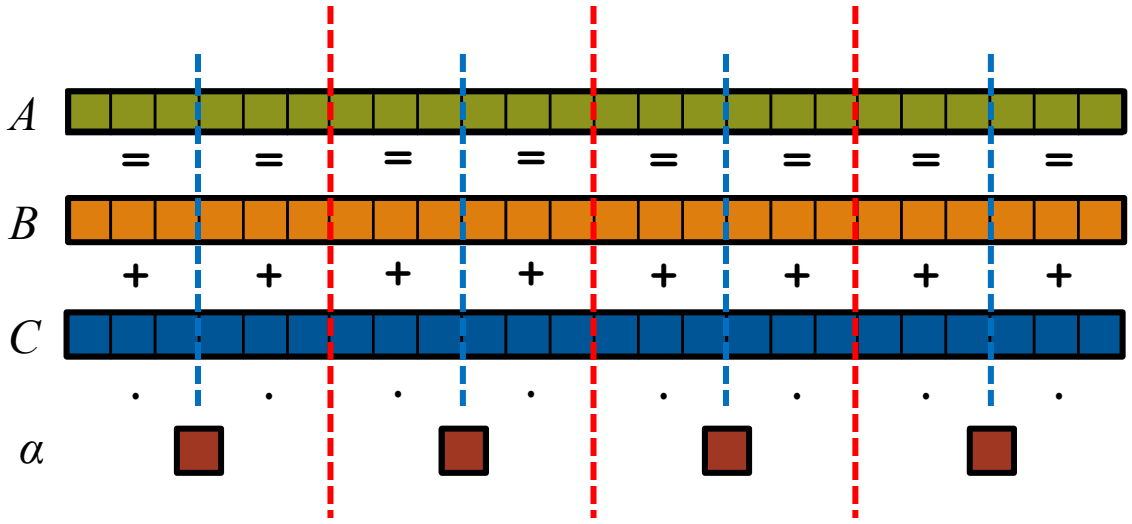


# STREAM Triad: a trivial parallel computation

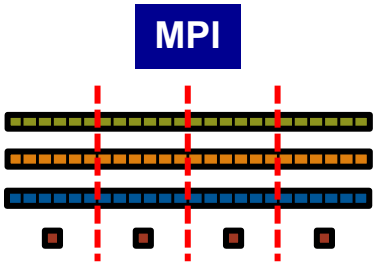
**Given:** $m$-element vectors $A$, $B$, $C$

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

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



# STREAM Triad: MPI



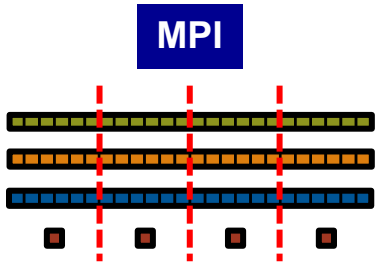

```
#include <hpcc.h>

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




"SPMD": Single Program Multiple Data

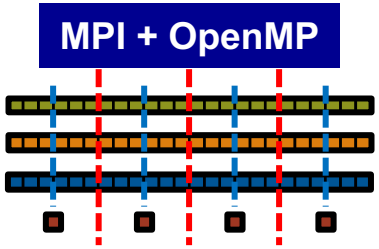
```
#include <hpcc.h>

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 |
  if (c)
  if (b)
  if (a)
  if (do
    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);
```

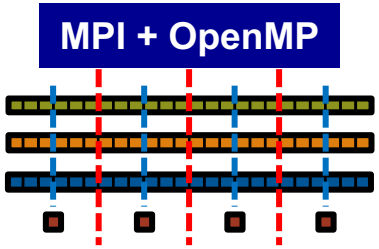
# STREAM Triad: MPI+OpenMP




```
#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

"Hybrid" multiple models of parallelism




```
#include <hpcc.h>
#ifdef _OPENMP
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#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 );
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  rv = HPCC_Stream( params, 0 == myRank);
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int HPCC_Stream(HPCC_Params *params, int doIO) {
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    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);
```
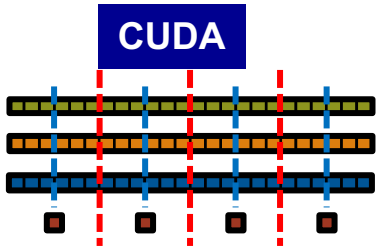
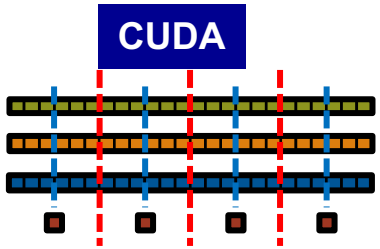

shared memory parallelism

# STREAM Triad: MPI+OpenMP vs. CUDA




```
#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

  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];
}
```

# STREAM Triad: MPI+OpenMP vs. CUDA

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  if (idx < len) a[idx] = value;
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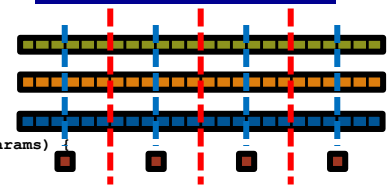
__global__ void STREAM_Triad( float *a, float *b, float *c,
                              float scalar, int len) {
  int idx = threadIdx.x + blockIdx.x * blockDim.x;
  if (idx < len) c[idx] = a[idx]+scalar*b[idx];
}
```

"SIMT"
Single Instruction Multiple Threads

kernels

# STREAM Triad: MPI+OpenMP vs. CUDA

## MPI + OpenMP



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#include <omp.h>
#endif

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static double *a, *b, *c;

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  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;
}
```
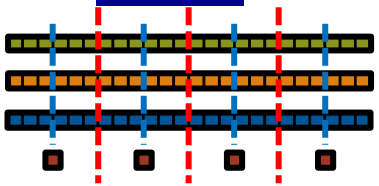

*Why do we need so much code?*

## CUDA



```
#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)+( N % dimBlock.x != 0 ));

  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?*

# 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 required.

| Type of HW Parallelism | Programming Model | Unit of Parallelism |
|---|---|---|
| Inter-node | MPI | executable |
| Intra-node/multicore | OpenMP / pthreads | iteration/task |
| Instruction-level vectors/threads | pragmas, intrinsics | iteration |
| GPU/accelerator | CUDA / Open[CL\|MP\|ACC] | iteration |

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:**

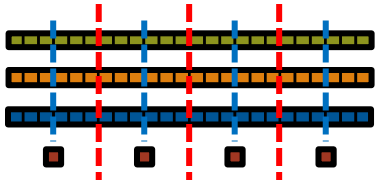
"something that lets me express my parallel computations without having to wrestle with architecture-specific details"

**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…

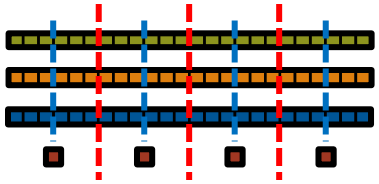
## MPI + OpenMP



```
#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;
}
```

*Why do we need so much code?*

## CUDA



```
#define N       2000000

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

  cudaMalloc((void**)&d_a, sizeof(float)*N);
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  dim3 dimBlock(128);
  dim3 dimGrid((N/dimBlock.x)+( !(N % dimBlock.x == 0) ? 1 : 0));
  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);
  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?*

# STREAM Triad: Chapel

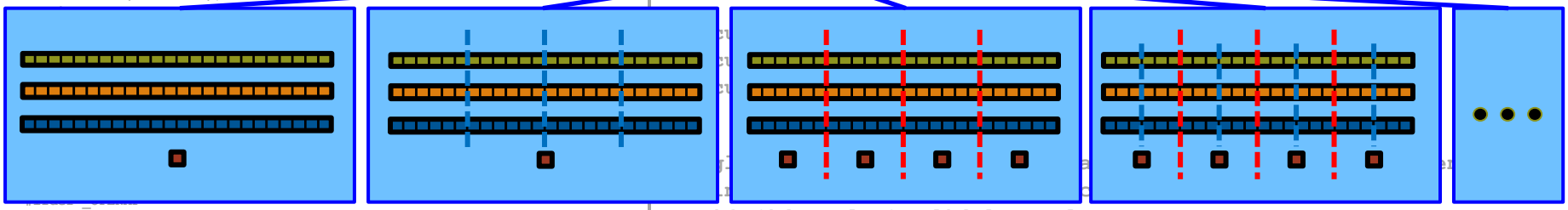
MPI + OpenMP

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

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

int HPCC_StarStream(HPCC_Params *pa
  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 == myR
  MPI_Reduce( &rv, &errCount, 1, MPI

  return errCount;
}

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

  VectorSize = HPCC_LocalVectorSize(

  a = HPCC_XMALLOC( double, VectorSi
  b = HPCC_XMALLOC( double, VectorSi
  c = HPCC_XMALLOC( double, VectorSi

  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"
      fclose( outFile );
```

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;
```

the special sauce



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

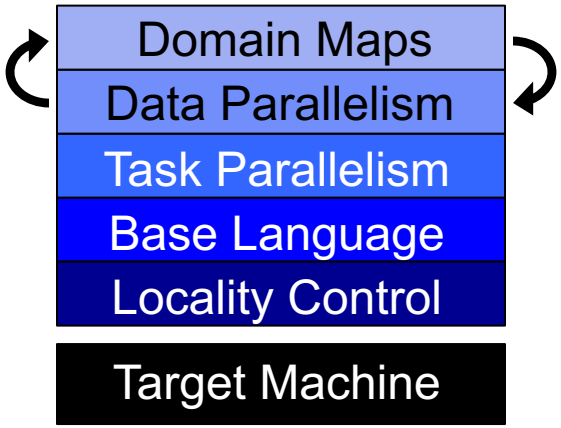
- ✓ Motivation for Chapel
- ➢ Survey of Chapel Concepts
- Chapel Project and Characterizations
- Chapel Resources

# Chapel's Multiresolution Philosophy

***Multiresolution Design:*** **Support multiple tiers of features**

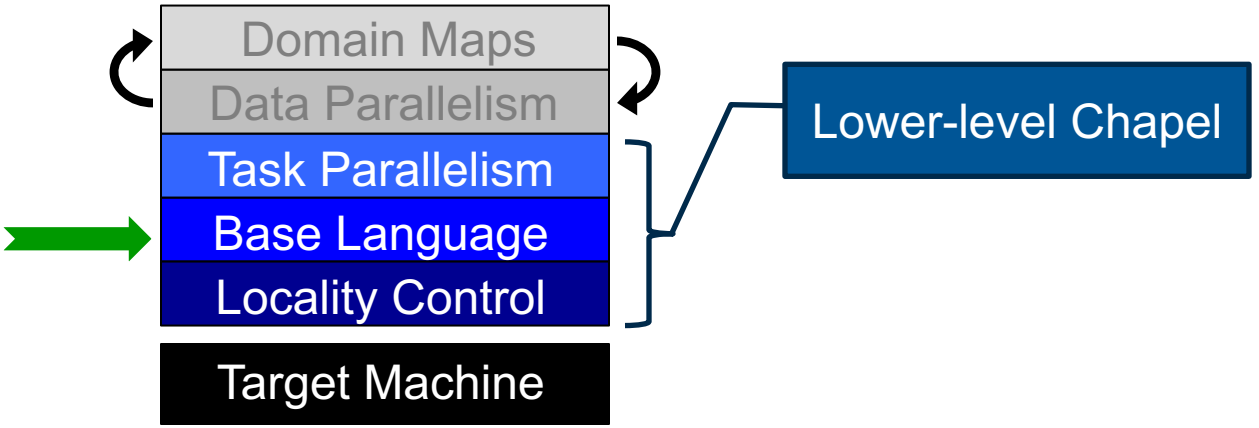
- higher levels for programmability, productivity
- lower levels for greater degrees of control

*Chapel language concepts*




- 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;
  }
}
```

```
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
...
```

# Base Language Features, by example

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

```
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
...
```

# Base Language Features, by example

Static type inference for:
- arguments
- return types
- variables

```
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
...
```

# Base Language Features, by example

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

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

Zippered iteration

```
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

Range types and operators

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

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

```
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;
  }
}
```

tuples

```
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;
  }
}
```

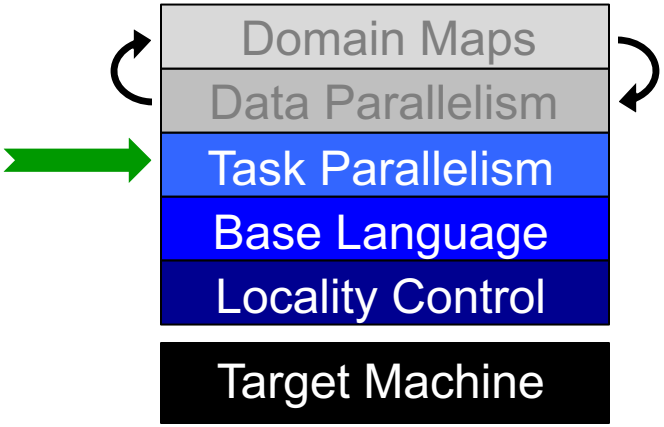
```
config const n = 10;

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
```

```
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
```

# Task Parallelism: Data-Driven Synchronization

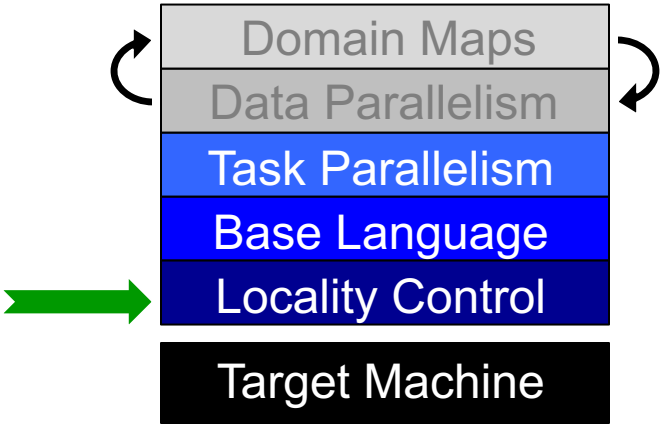
- **atomic variables:** support atomic operations
  - e.g., compare-and-swap; atomic sum, multiply, etc.
  - similar to C/C++

- **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 = …;
```


- `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:

```
coforall i in 1..msgs do
  writeln("Hello from task ", i);
```

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

```
writeln("Hello from locale 0!");
on Locales[1] do writeln("Hello from locale 1!");
on Locales[2] do writeln("Hello from locale 2!");
```

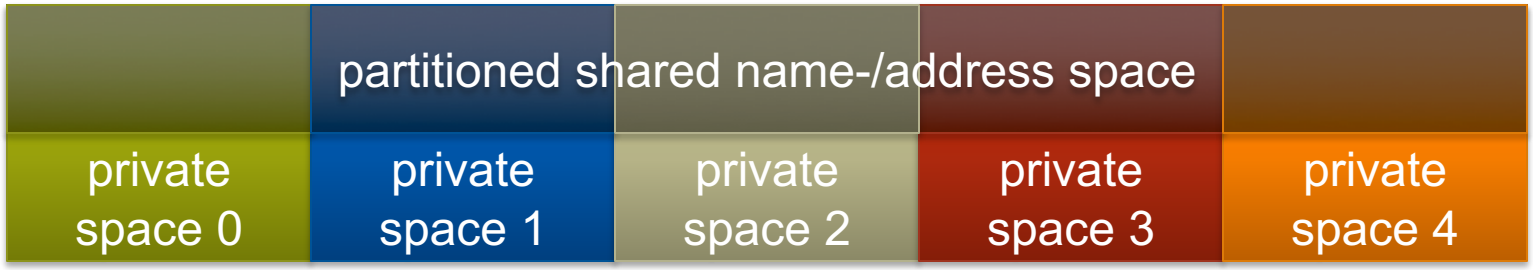
- This is a **distributed parallel** program:

```
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)

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

# SPMD PGAS Languages (using a pseudo-language, not Chapel)

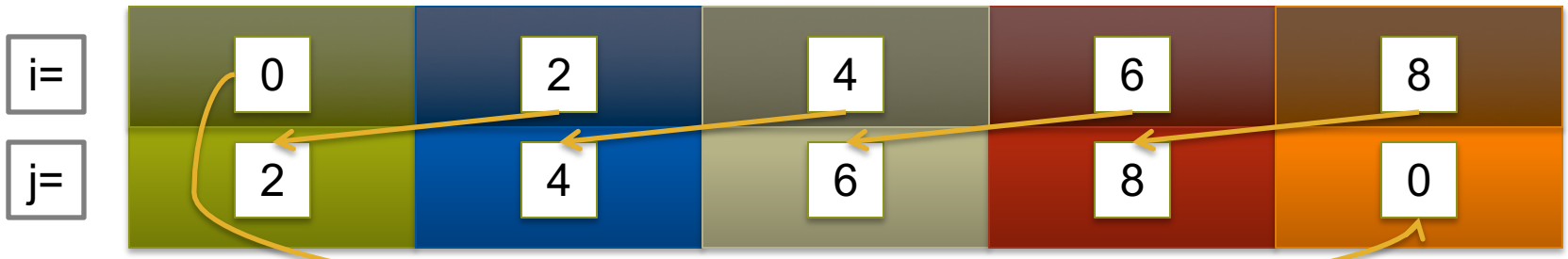
```
shared int i(*);    // declare a shared variable i
function main() {
  i = 2*this_image();  // each image initializes its copy
```

# 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
```

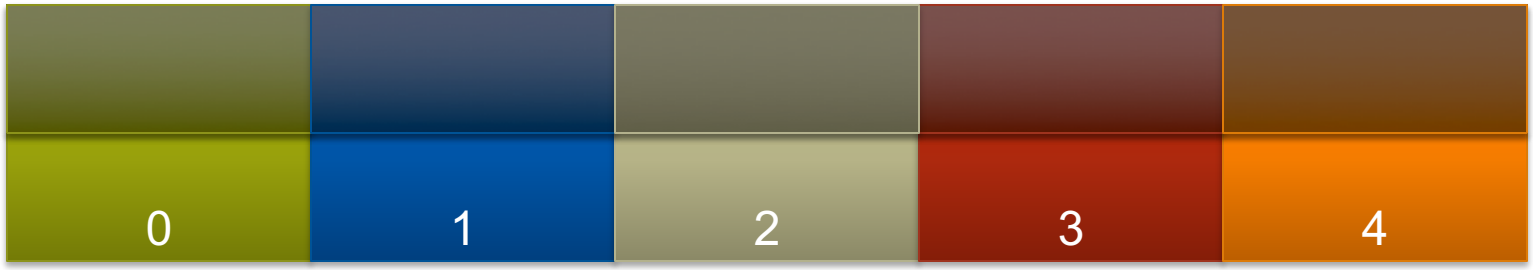
# SPMD PGAS Languages (using a pseudo-language, not Chapel)

```
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)
```



# Chapel and PGAS

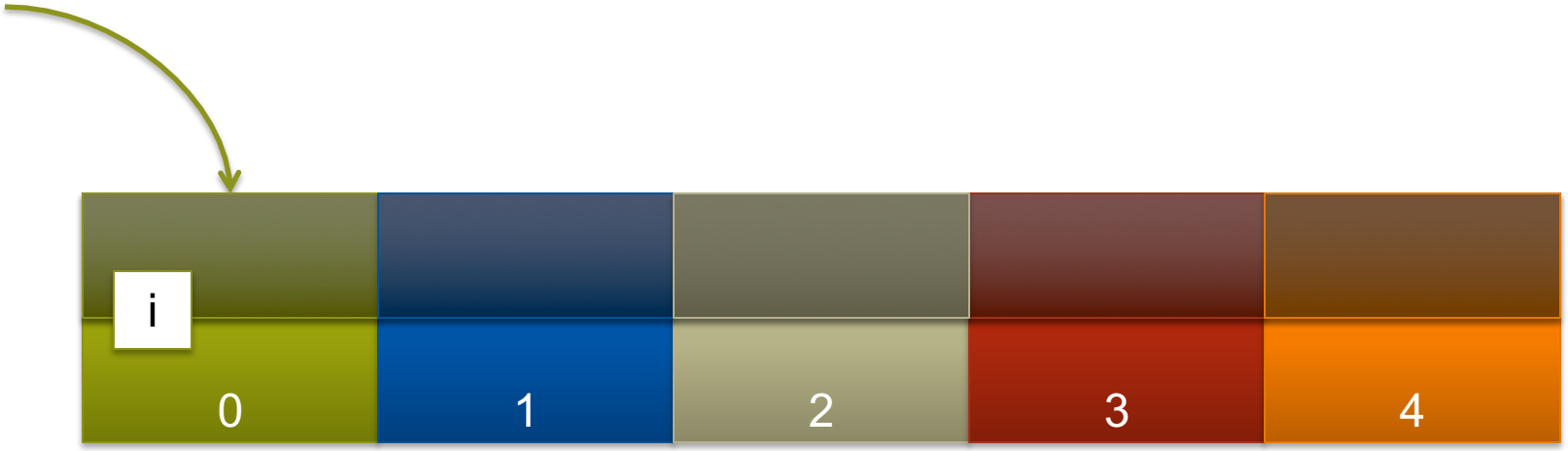
- **Chapel is PGAS, but unlike most, it's not inherently SPMD**
  - never think about "the other copies of the program"
  - "global name/address space" comes from lexical scoping
    - as in traditional languages, each declaration yields one variable
    - variables are stored on the locale where the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




*Locales* (think: "compute nodes")

# Chapel: Scoping and Locality

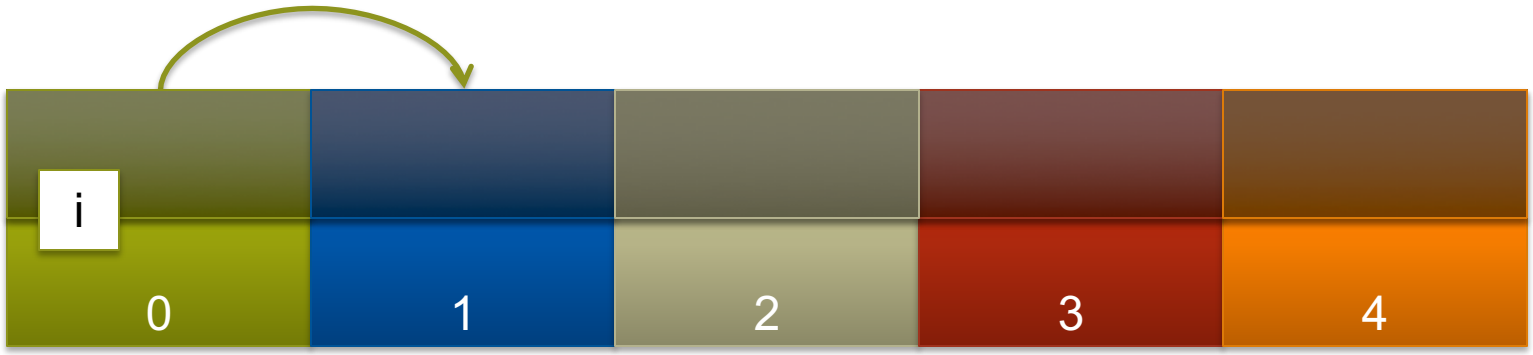
```
var i: int;
```




*Locales* (think: “compute nodes”)

# Chapel: Scoping and Locality

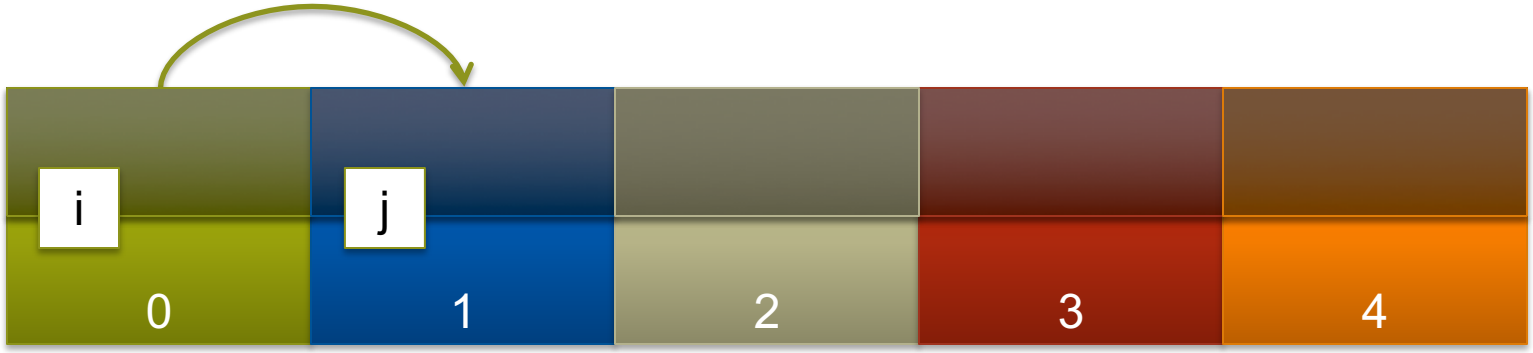
```
var i: int;
on Locales[1] {
```




*Locales* (think: “compute nodes”)

# Chapel: Scoping and Locality

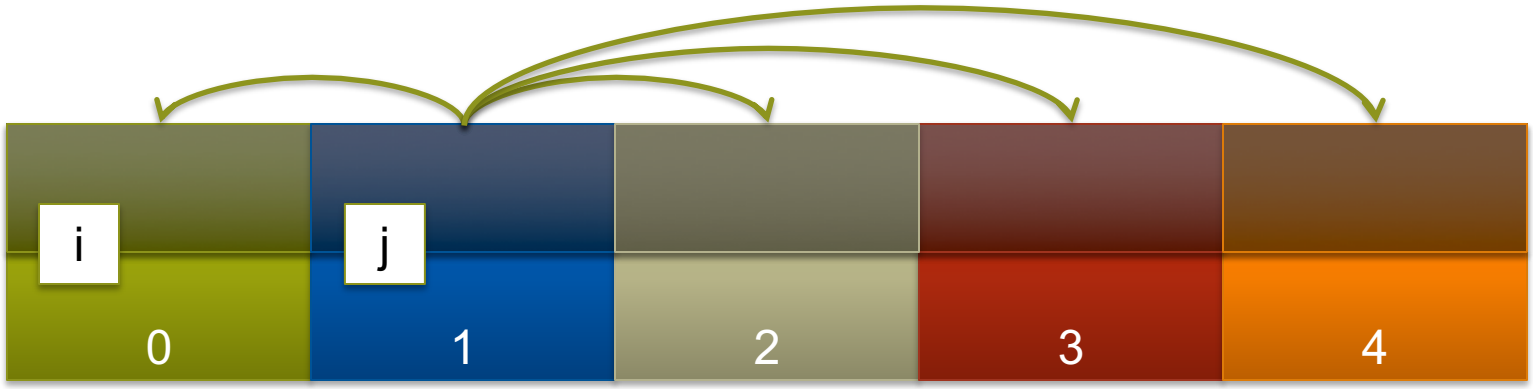
```
var i: int;
on Locales[1] {
  var j: int;
```




*Locales* (think: “compute nodes”)

# Chapel: Scoping and Locality

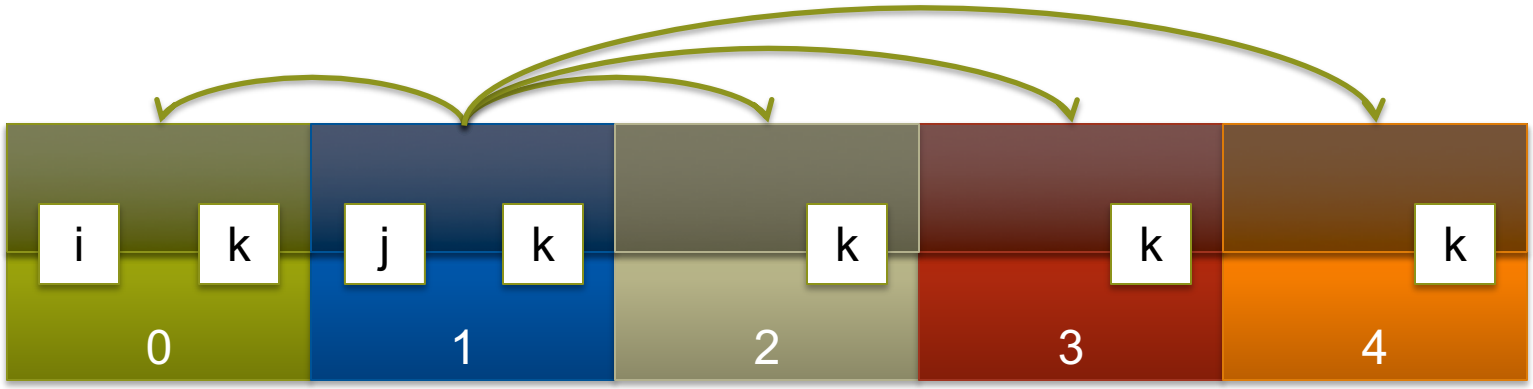
```
var i: int;
on Locales[1] {
  var j: int;
  coforall loc in Locales {
    on loc {
```




*Locales* (think: “compute nodes”)

# Chapel: Scoping and Locality

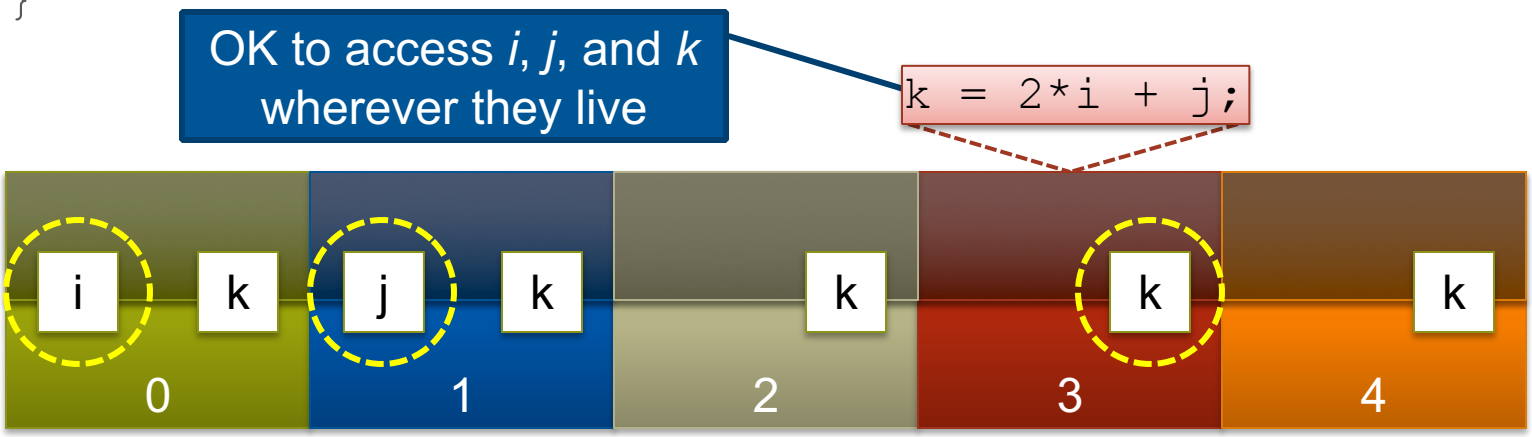
```
var i: int;
on Locales[1] {
  var j: int;
  coforall loc in Locales {
    on loc {
      var k: int;
      …
    }
  }
}
```




*Locales* (think: “compute nodes”)

# Chapel: Scoping and Locality

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

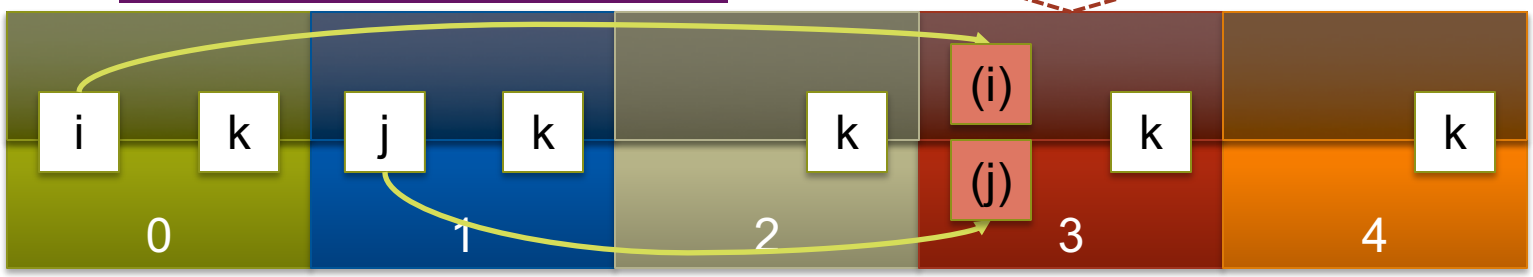



*Locales* (think: "compute nodes")

# Chapel: Scoping and Locality

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

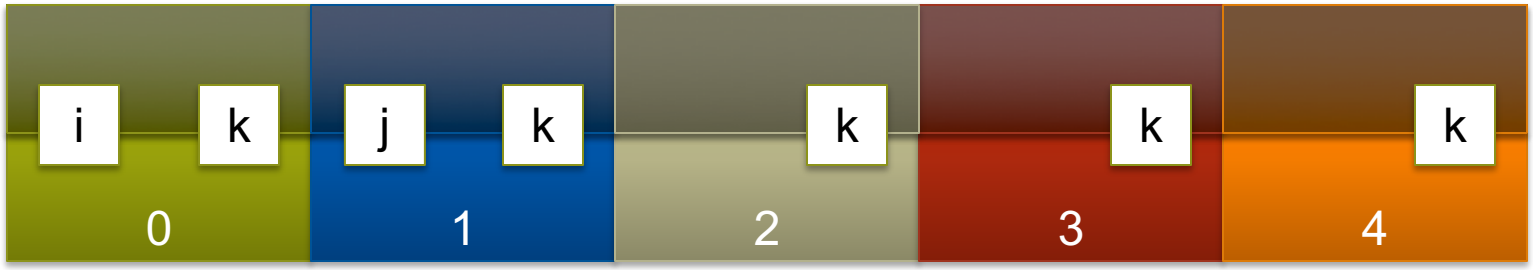
here, *i* and *j* are remote, so the compiler + runtime will transfer their values




*Locales* (think: "compute nodes")

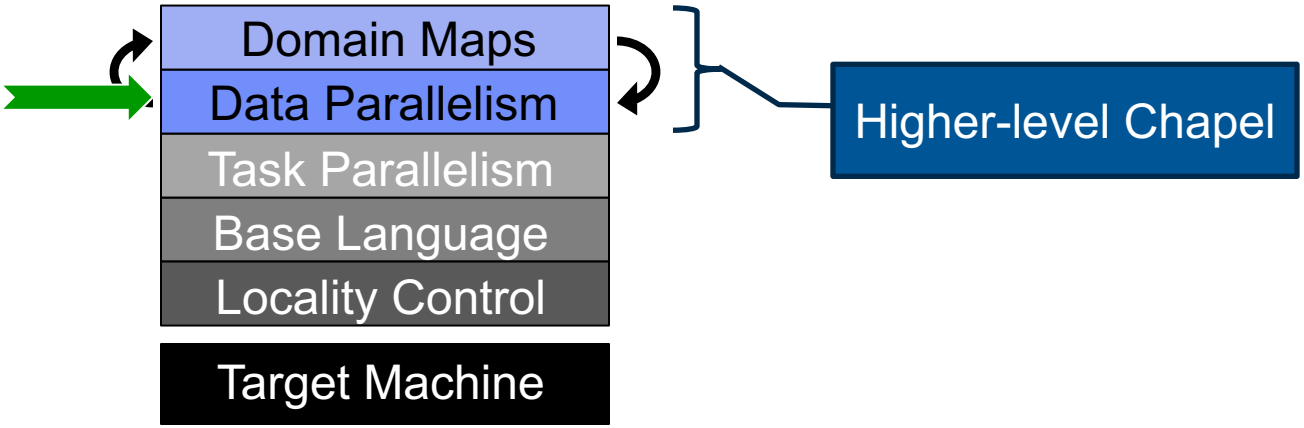
# Chapel: Locality queries

```
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
    }
  }
}
```



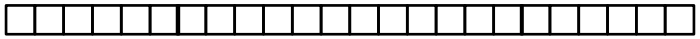

*Locales* (think: “compute nodes”)

# Data Parallelism

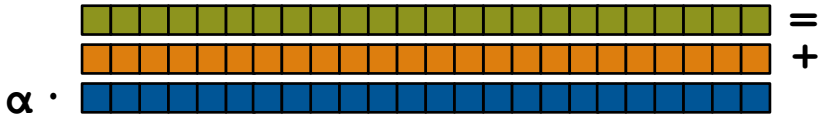


# Data Parallelism By Example: STREAM Triad

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



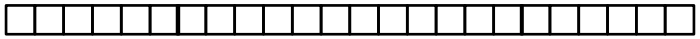
```
var A, B, C: [ProblemSpace] real;
```



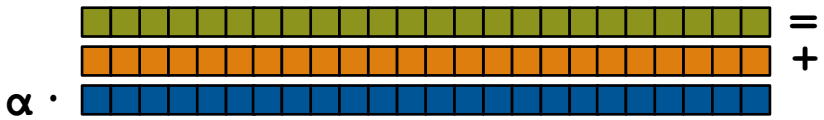

```
forall (a,b,c) in zip(A,B,C) do
  a = b + alpha*c;
```

# Data Parallelism By Example: STREAM Triad

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



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




```
A = B + alpha * C;  // 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[ElementsOfInterest] …
```

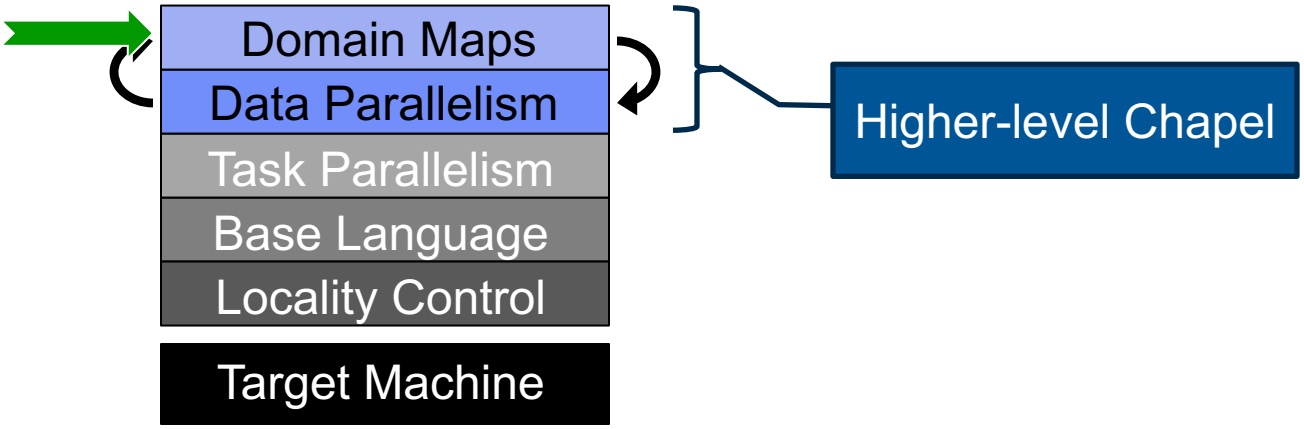
- **Promotion:** Call scalar functions with array arguments

```
… pow(A, B)…   // equivalent to: forall (a,b) in zip(A,B) do pow(a,b)
```

- **Reductions/Scans:** Apply operations across collections

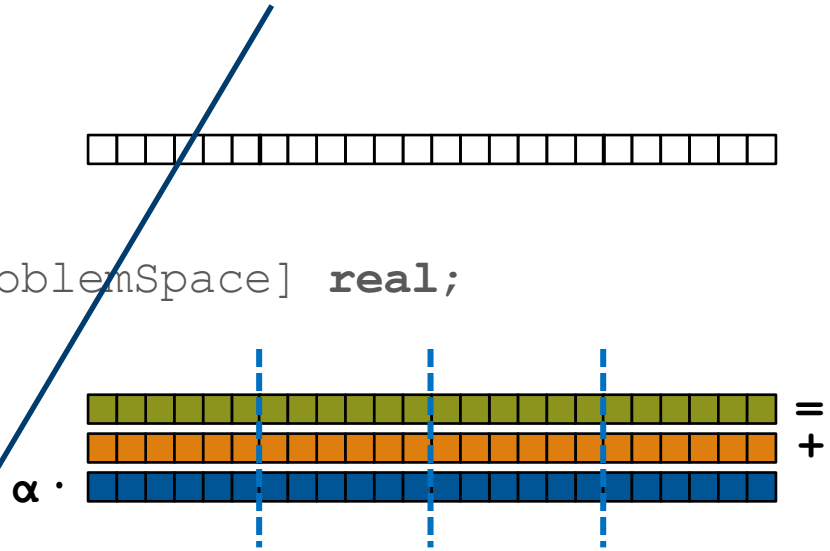
```
… + reduce A …
… myReduceOp reduce A …
```

# Domain Maps



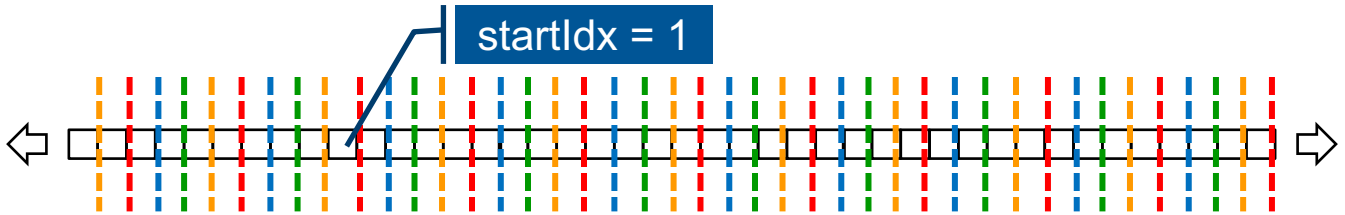
# STREAM Triad: Chapel (multicore)

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

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

A = B + alpha * C;
```

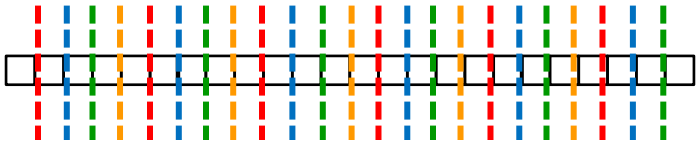



No domain map specified ⇒ use default layout
- current locale owns all domain indices and array values
- computation will execute using local processors only

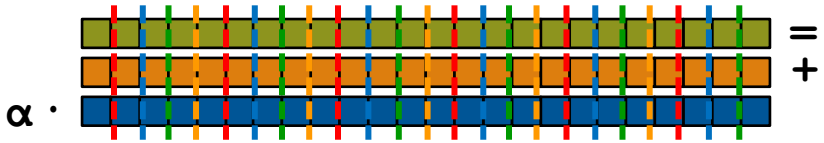
# STREAM Triad: Chapel (multilocale, cyclic)




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

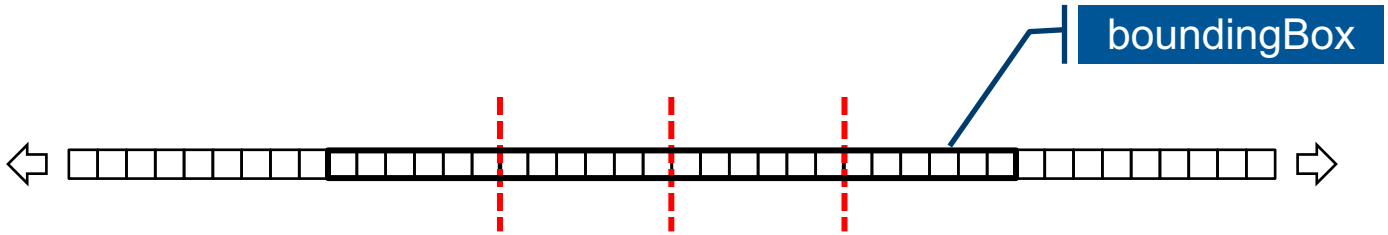


```
var A, B, C: [ProblemSpace] real;
```

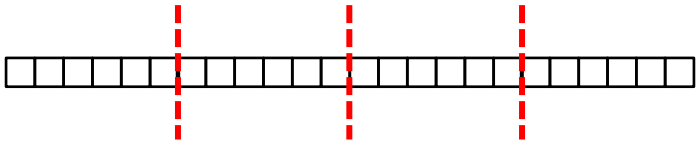



```
A = B + alpha * C;
```

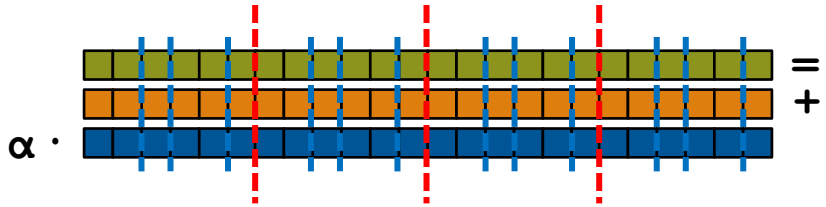
# STREAM Triad: Chapel (multilocale, blocked)




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



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




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

# STREAM Triad: Chapel

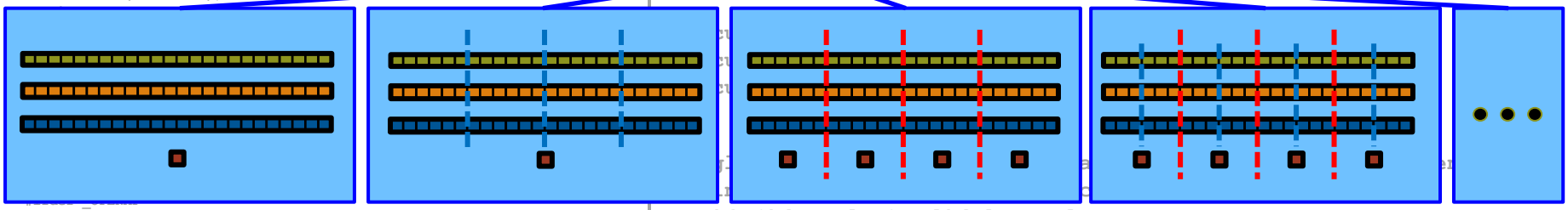
MPI + OpenMP

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

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

int HPCC_StarStream(HPCC_Params *pa
  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 == myR
  MPI_Reduce( &rv, &errCount, 1, MPI

  return errCount;
}

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

  VectorSize = HPCC_LocalVectorSize(

  a = HPCC_XMALLOC( double, VectorSi
  b = HPCC_XMALLOC( double, VectorSi
  c = HPCC_XMALLOC( double, VectorSi

  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"
      fclose( outFile );
```

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;
```

the special sauce



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.

# Language Summary

***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

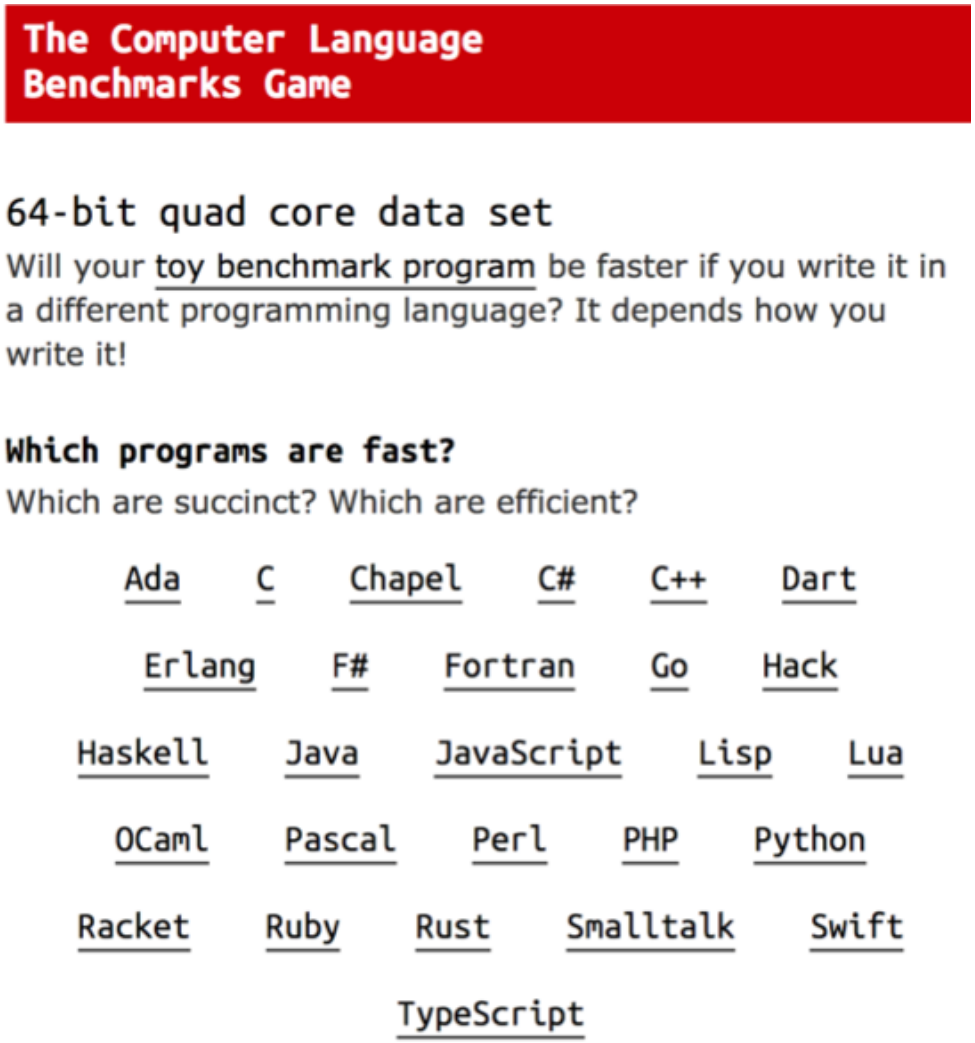
- ✓ Motivation for Chapel
- ✓ Survey of Chapel Concepts
- ➢ Chapel Project and Characterizations
- ● Chapel Resources

# Computer Language Benchmarks Game

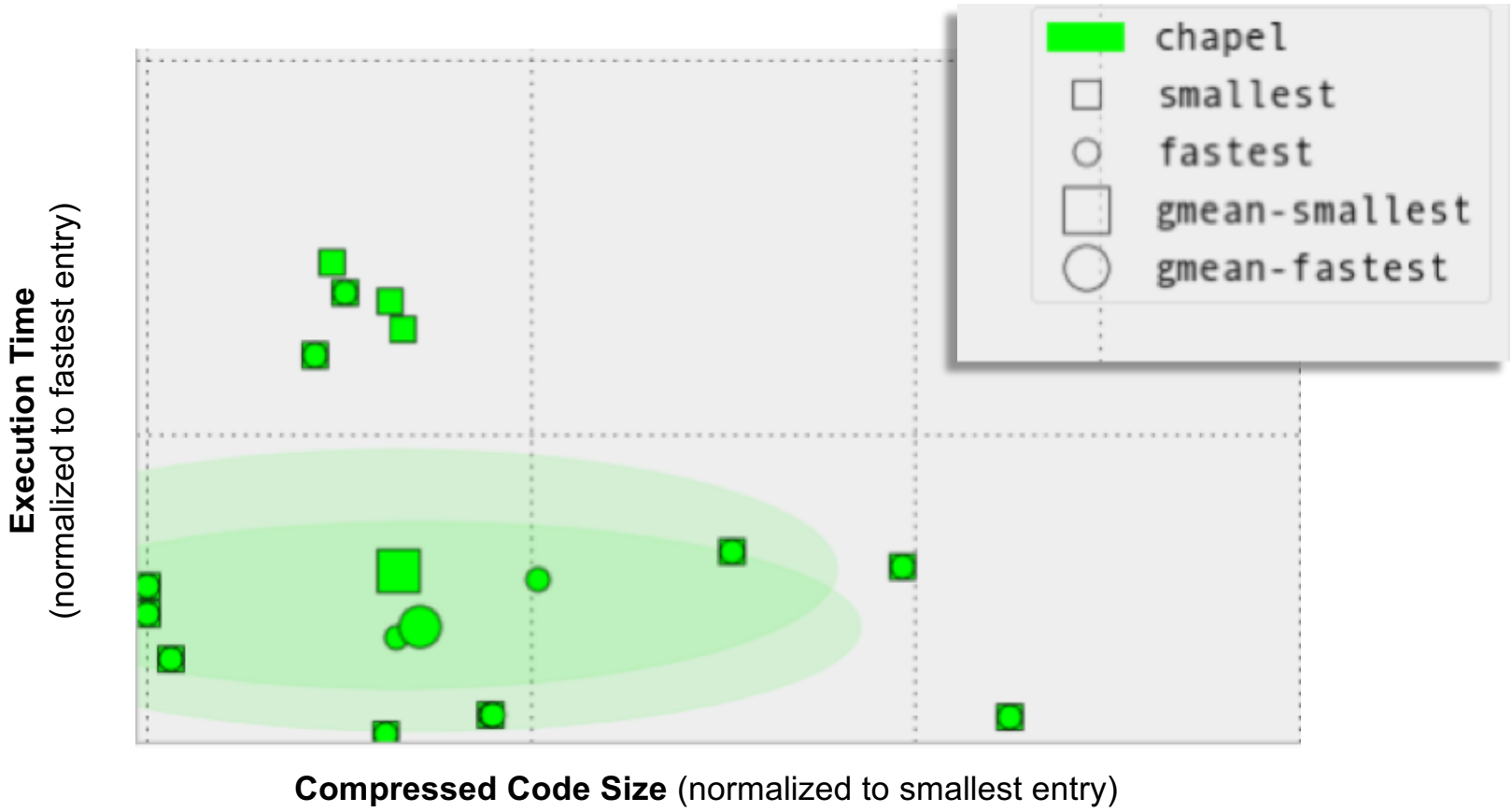
## Chapel was recently added to the game:

## As of December 2017:

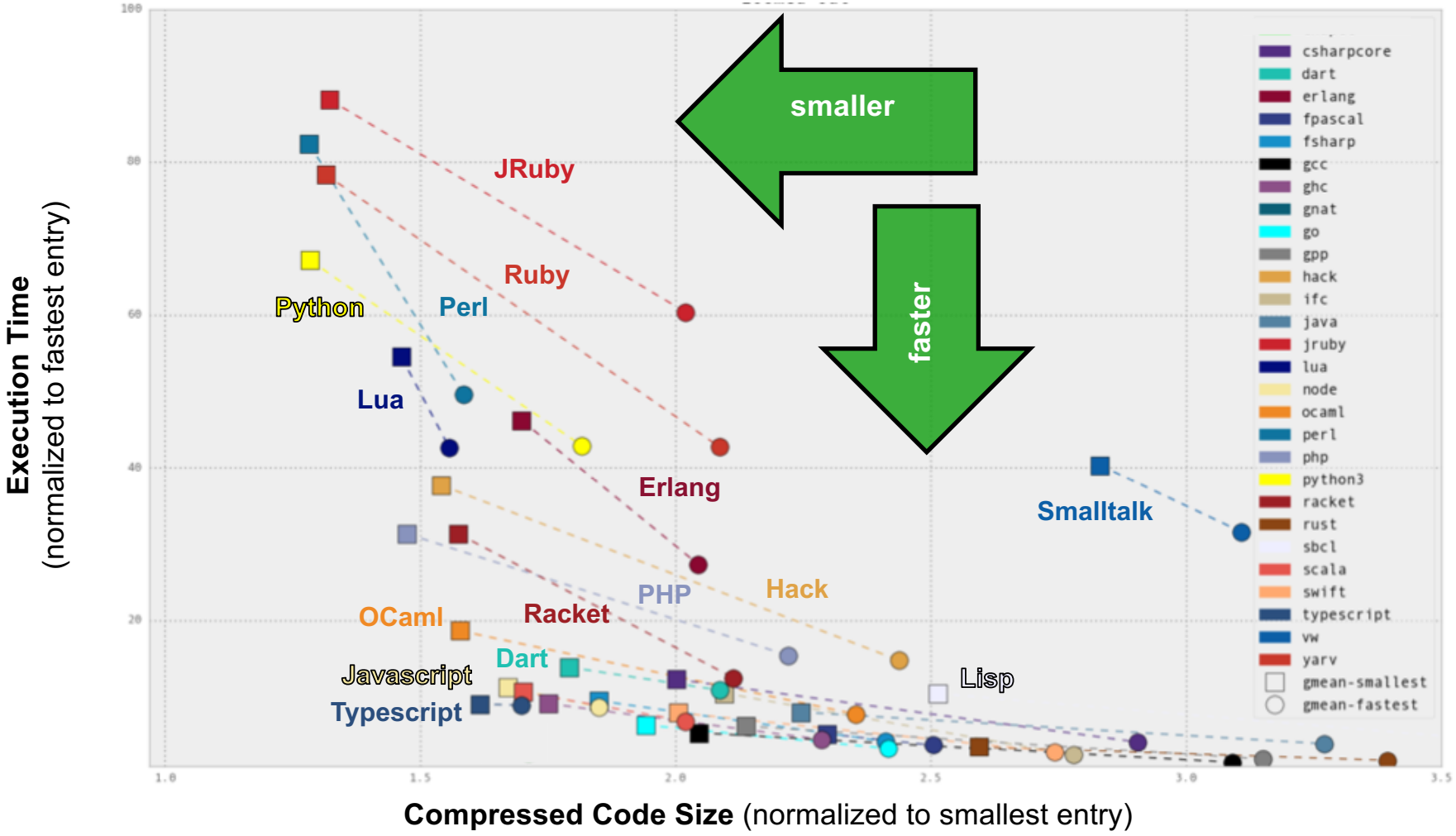
- **for performance:**
  - **1 top entries:** pidigits
  - **4 top-5 entries:** fannkuch-redux, chameneos-redux, meteor, thread-ring
  - **2 top-10 entries:**, mandelbrot, fasta
  - **3 top-20 entries:** spectral-norm, regex-redux
- **for code compactness:**
  - **2 top entries:** n-body, thread-ring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



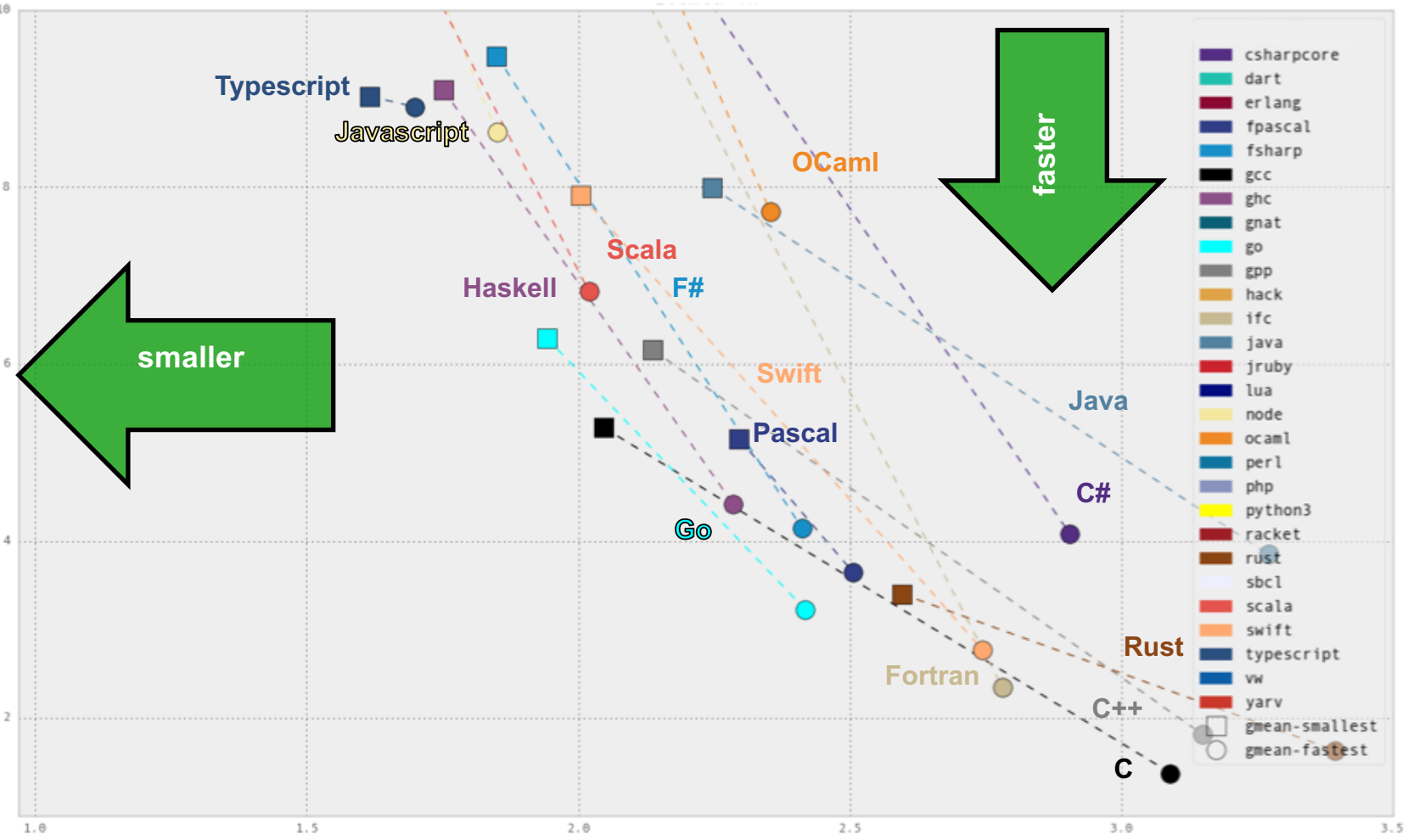
# Scatter plots of CLBG code size x speed



# CLBG Cross-Language Summary
(Oct 2017 standings)



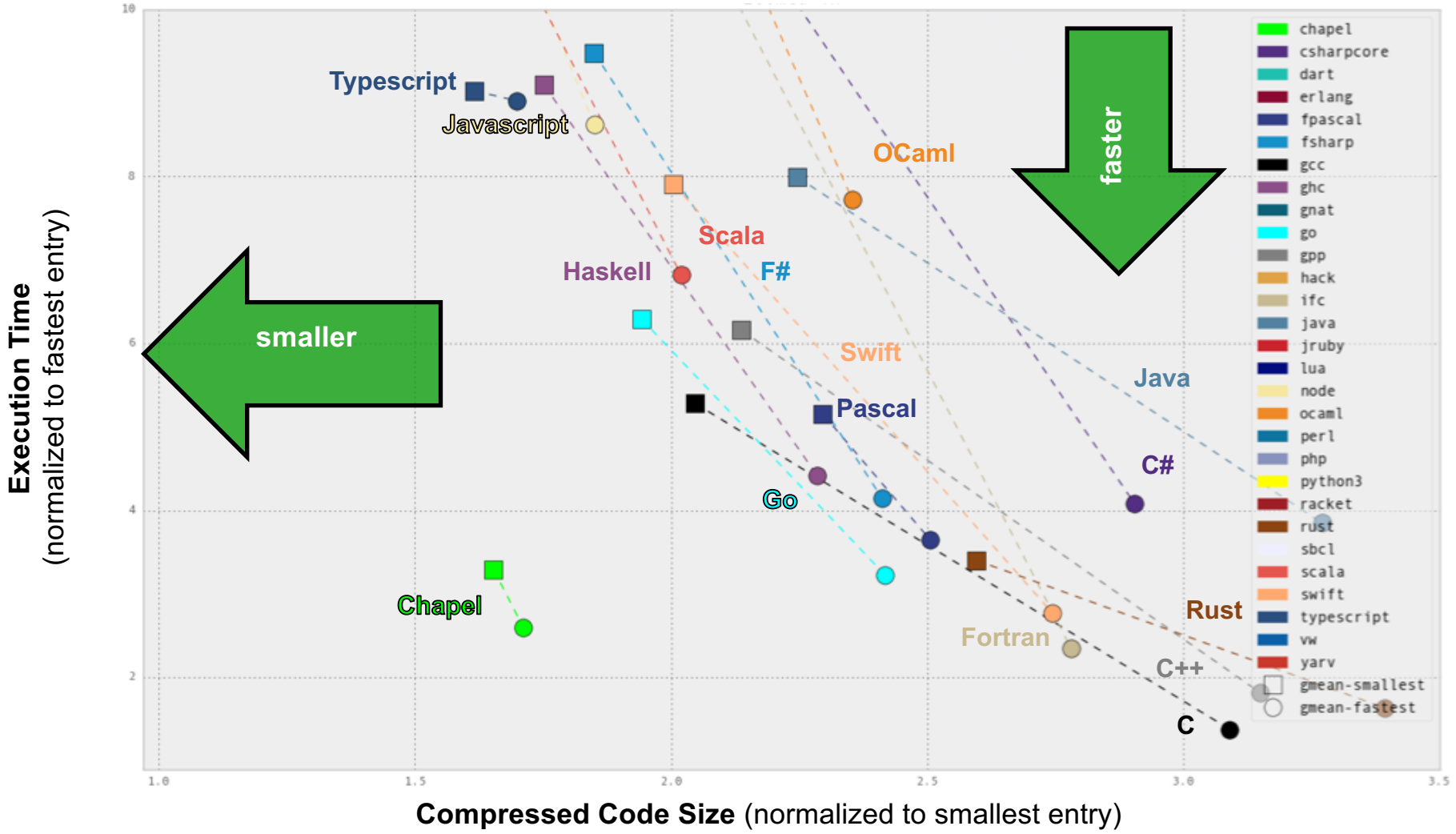
# CLBG Cross-Language Summary
(Oct 2017 standings)



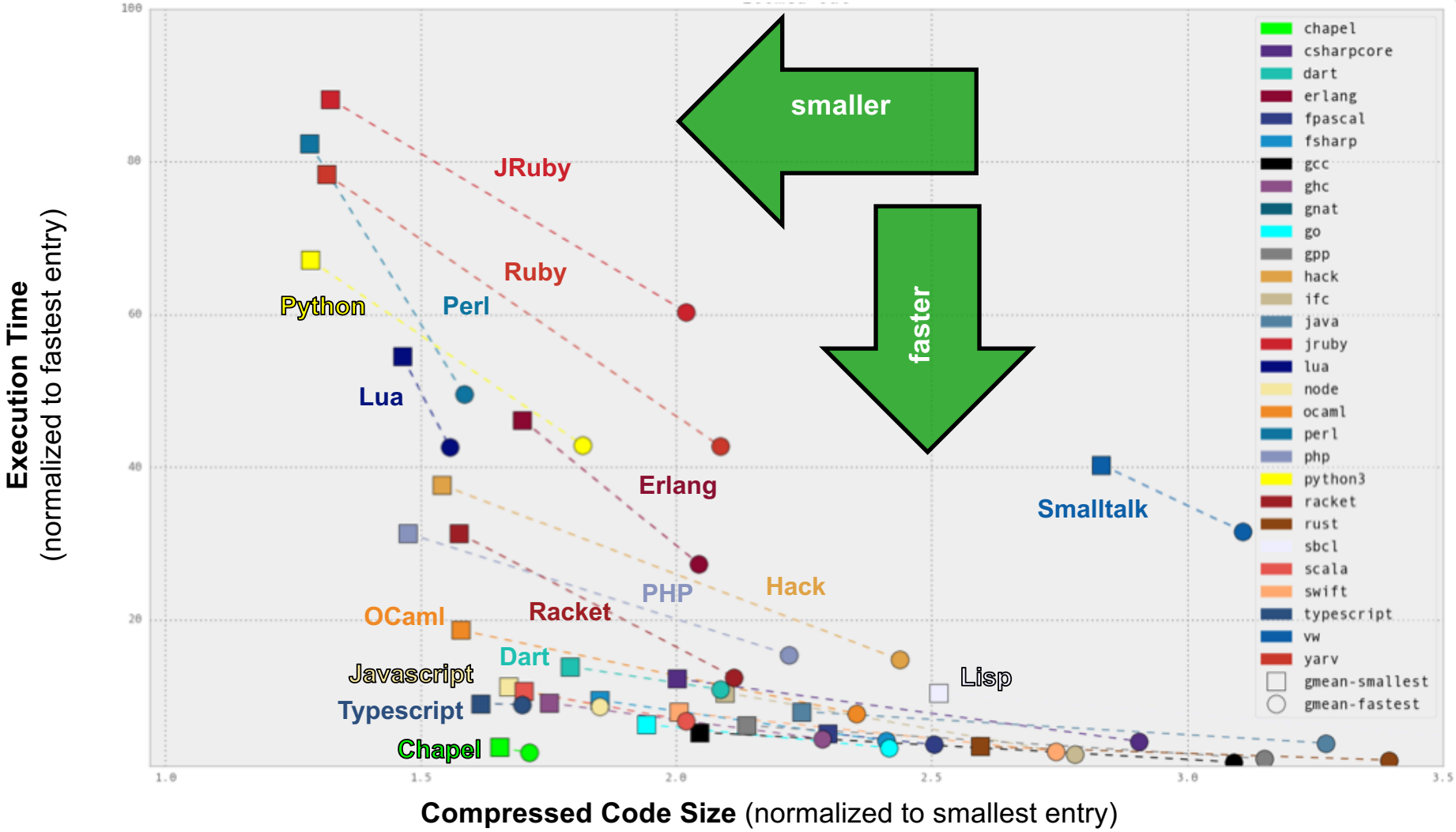

**Execution Time** (normalized to fastest entry)

**Compressed Code Size** (normalized to smallest entry)

# CLBG Cross-Language Summary
(Oct 2017 standings)



# CLBG Cross-Language Summary
(Oct 2017 standings)



# 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
- **Chapel is licensed as Apache v2.0 software**
- **Instructions for download + install are online**
  - see http://chapel.cray.com/download.html to get started

# The Chapel Team at Cray (Summer 2016)

# Chapel is a Collaborative Effort









Lawrence Berkeley
National Laboratory





(and several others…)

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

# Chapel Status

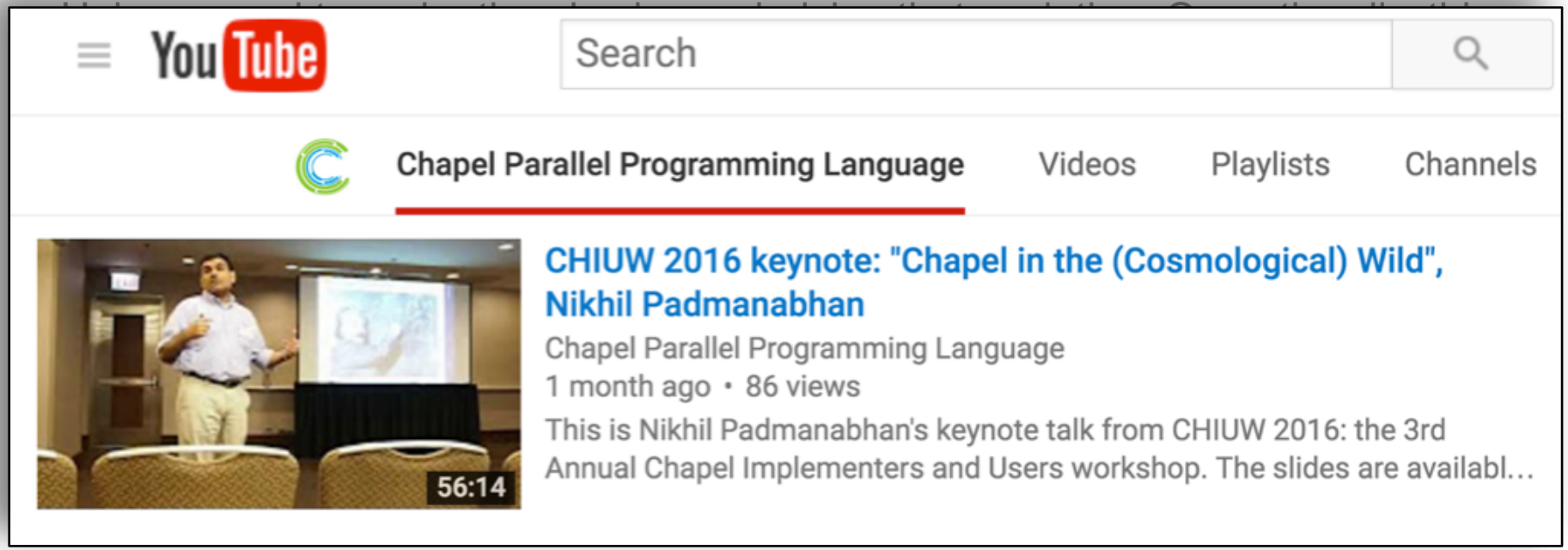
- **Currently being picked up by early adopters**
  - over two releases, 3000+ downloads per year
  - Users who try it generally like what they see
- **Most current features are functional and working well**
- **Performance is compelling in many cases**

# 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



# Outline

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

# 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

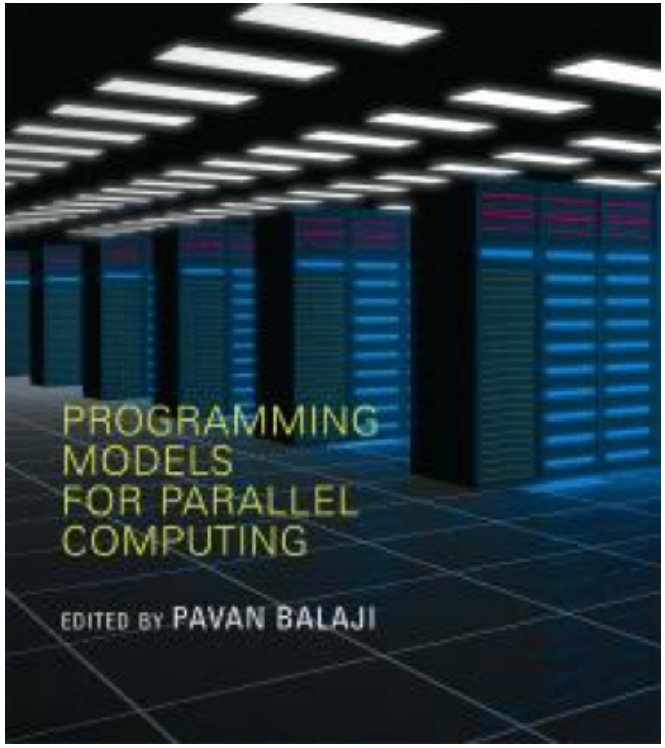
**Facebook:** https://www.facebook.com/ChapelLanguage

**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
- 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**

# Chapel Blog Articles

***Chapel: Productive Parallel Programming***, Cray Blog, May 2013.

- *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*

***[Ten] Myths About Scalable Programming Languages***, IEEE TCSC Blog (index available on chapel.cray.com "blog articles" page), Apr-Nov 2012.

- *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/)**

## 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?