The Audacity of Chapel:
Scalable Parallel Programming Done Right (director's cut, with outtakes)

Brad Chamberlain, Chapel Team, Cray Inc.

ACCU 2017, Bristol UK

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Fair Warning Statement

This keynote contains many slides and no guitar solos ☹

BUT… it does contain thematically relevant

UK rock lyrics trivia!!

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I am the egg man

Introductions

I am the Walrus
The Beatles
Magical Mystery Tour

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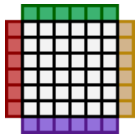
("Pssst… Who is this turkey?")

Hi, I'm Brad Chamberlain

- graduate of the University of Washington
  - worked on a data-parallel array language, ZPL



- principal engineer at Cray Inc.
  - founding member and technical lead of the Chapel project

- more of a practical parallel computing guy than a PL expert…

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The Context for My Work

HPC: High Performance Computing

- parallelism at large scales
  - lots of distributed processors and memories
- performance rules
  - and too often, is **all** that matters
- programmers are virtually living in the dark ages

CRAY: The Supercomputer Company

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Recent Highlighted Cray Systems

NNSA National Nuclear Security Administration | Sandia National Laboratories | Los Alamos National Laboratory | Lawrence Livermore National Laboratory

Next-Gen Cray XC
19k compute nodes
40+ PF, 2+ PB
80+PB File System
5200 sq ft

Cray/Intel partnership
50k+ compute nodes
180PF, 7+ PB
150+ PB File System

Argonne NATIONAL LABORATORY

CORAL COLLABORATION OAK RIDGE • ARGONNE • LIVERMORE

PGS Petroleum Geo-Services

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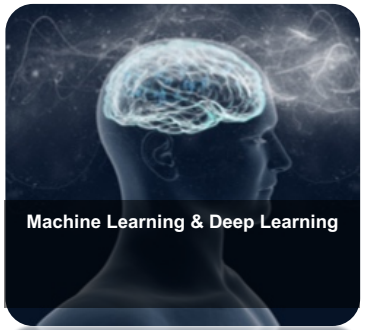
Cray Market Segments



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“I don’t really care about HPC programming...”

- **OK, but do you care about parallelism & concurrency?**
  - What about performance?
  - What about scaling up your data set sizes?
  - What about targeting next-generation processors?

Next-generation processors and computations are increasingly resembling traditional HPC.

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If you didn't care what happened to me,
And I didn't care for you,
We would zig zag our way
Through the boredom and pain…

Motivation for Chapel

Pigs on the Wing (part one)
Pink Floyd
Animals

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Motivation from Kathy Yelick (UC Berkeley, LBNL)

Why Consider New Languages at all?

- **Do we need a language? And a compiler?**
  - If higher level syntax is needed for productivity
    - We need a language
  - If static analysis is needed to help with correctness
    - We need a compiler (front-end)
  - If static optimizations are needed to get performance
    - We need a compiler (back-end)

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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

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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.”

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“The Audacity of Chapel”?

audacity (according to Google):

/ɔːˈdasɪti/

noun

1. a willingness to take bold risks.

   “I applaud the *audacity* of the Chapel team in attempting to create a new language given how hard it is for new languages to succeed.”

2. rude or disrespectful behaviour; impudence.

   “I can’t believe the Chapel team has the *audacity* to create a new language when we already have [C++ | Python | …]!”

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This Talk's Thesis

Programming language designers have, to date, largely failed the large-scale parallel computing community.

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This just feels like spinning plates
I'm living in cloud-cuckoo land

The Status Quo in HPC Programming

Like Spinning Plates
Radiohead
Amnesiac

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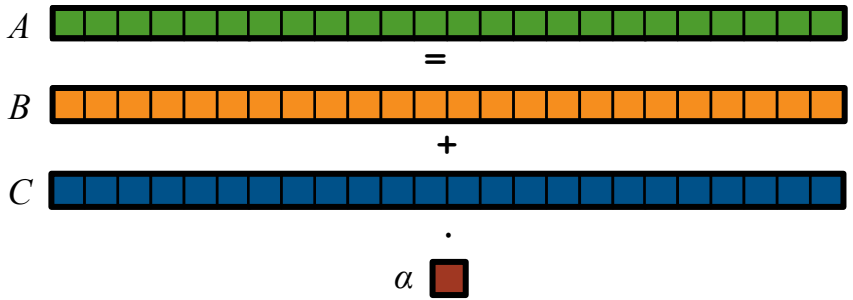
STREAM Triad: a trivial parallel computation

Given: m-element vectors A, B, C

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

In pictures:



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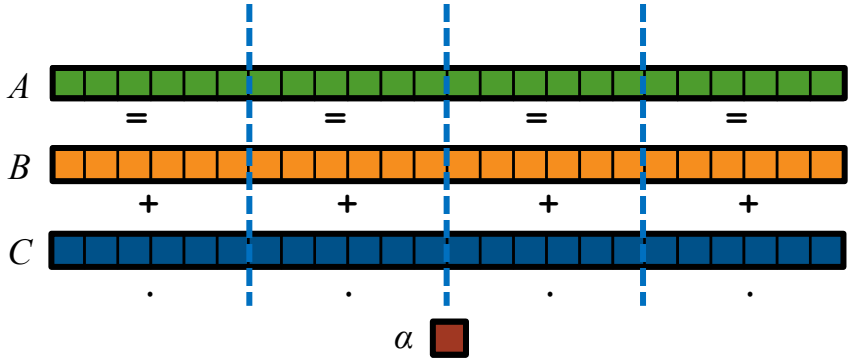
STREAM Triad: a trivial parallel computation

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 (shared memory / multicore):



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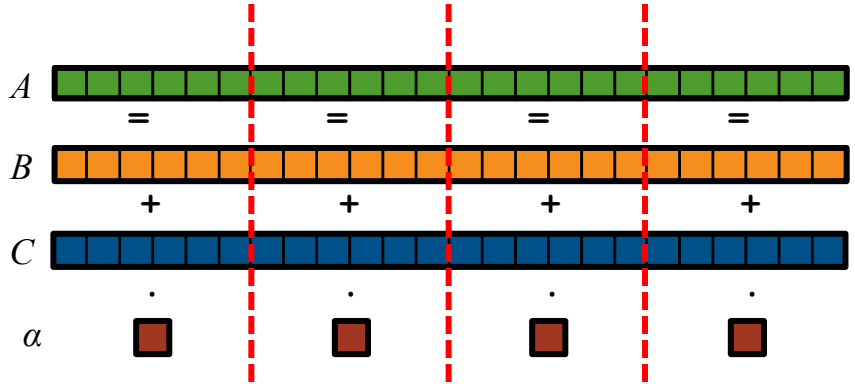
STREAM Triad: a trivial parallel computation

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):



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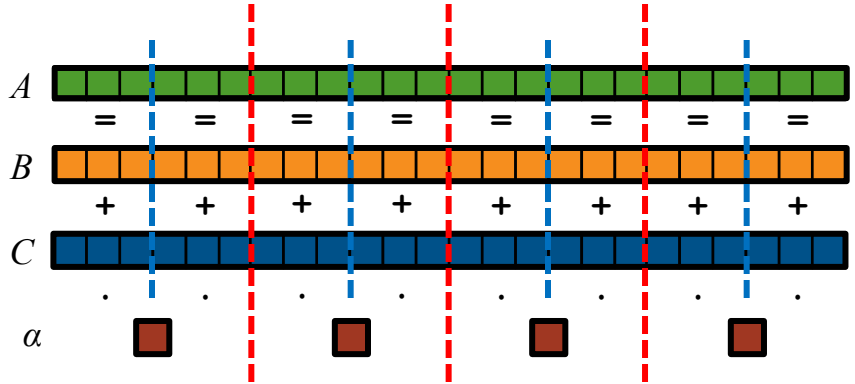
STREAM Triad: a trivial parallel computation

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 multicore):



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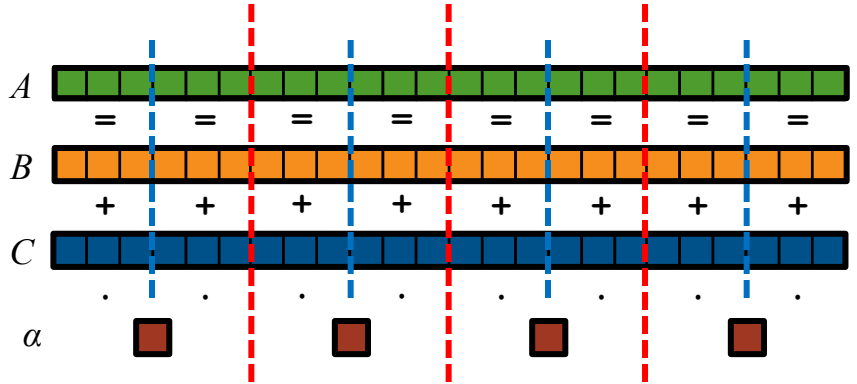
Scalable Parallel Programming Concerns

Q: What should scalable parallel programmers focus on?

A: *Parallelism:* What should execute simultaneously?

Locality: Where should those tasks execute?



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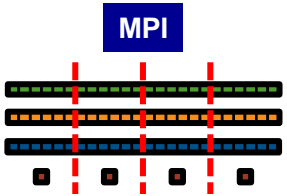
STREAM Triad: MPI




```
#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] = 1.0;
}
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);

return 0;  }
```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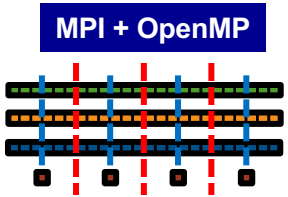
STREAM Triad: MPI+OpenMP




```
#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] = 1.0;
  }
  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;  }
```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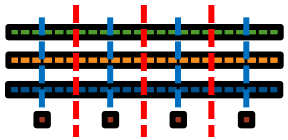
STREAM Triad: MPI+OpenMP

MPI + OpenMP



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#include <hpcc.h>
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#endif

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  MPI_Comm_rank( comm, &myRank );

  rv = HPCC_Stream( params, 0 == myRank);
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    0, comm );

  return errCount;
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    sizeof(double), 0 );

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

  if (!a || !b || !c) {
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    if (b) HPCC_free(b);
    if (a) HPCC_free(a);
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    return 1;
  }

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#endif
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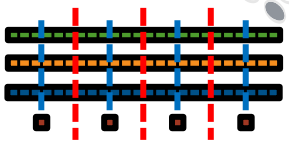
  }
  scalar = 3.0;

#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;
}
```

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];  }
```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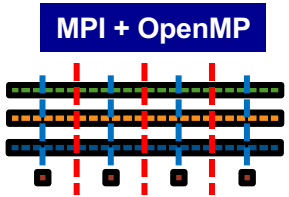
STREAM Triad: MPI+OpenMP




```
#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;
```

```
  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 );
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  c = HPCC_XMALLOC( double, VectorSize );
```

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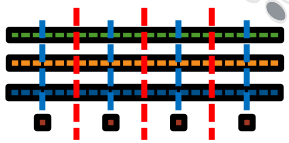
  if (b) HPCC_free(b);
  if (a) HPCC_free(a);
  if (doIO) {
    fprintf( outFile, "Failed to
      allocate memory (%d).\n",
      VectorSize );
    fclose( outFile );
  }
```

```
  for (j=0; j<VectorSize; j++) {
    b[j] = 2.0;
    c[j] = 1.0;
  }
  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;  }
```




```
#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);
```

```
  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];  }
```

HPC suffers from too many distinct notations for expressing parallelism and locality. This tends to be a result of bottom-up language design.

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Why so many programming models?

HPC tends to approach programming models bottom-up:

Given a system and its core capabilities…

…provide features that permit users to access the available performance.

- portability? generality? programmability? These are second- or third-order concerns, if that.

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	iteration
GPU/accelerator	CUDA / Open[MP|CL|ACC]	SIMD function/task

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

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STREAM Triad: Chapel

```
use …;

config const m = 1000,
             alpha = 3.0;

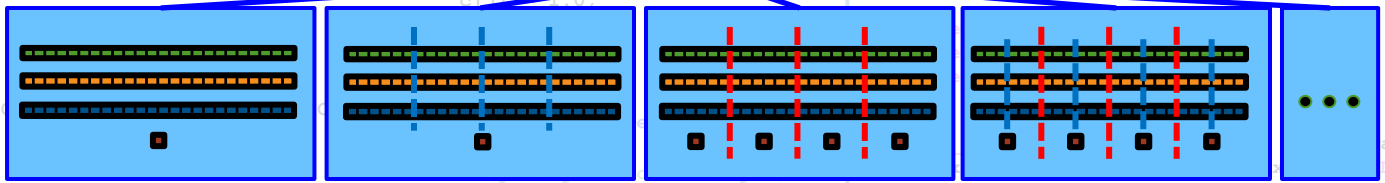
const ProblemSpace = {1..m} dmapped …;

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

B = 2.0;
C = 1.0;

A = B + alpha * C;
```

The special sauce:
How should this index set—and any arrays and computations over it—be mapped to the system?



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.

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This Talk's Takeaways

If you design a parallel programming language…

…don't tie yourself to low-level, architecture-specific mechanisms

- yet don't make them inaccessible either…
  - permit interoperating with such mechanisms
  - or support them as the "assembly" to your higher-level features

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It's so easy to laugh, it's so easy to hate
It takes guts to be gentle and kind

SPMD Programming Models like MPI

I Know It's Over
The Smiths
The Queen is Dead

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HPC's Status Quo: SPMD Programming

SPMD: Single Program, Multiple Data

- concept: write one program, run multiple copies of it in parallel
- a "bottom-up" programming model design
  - "HPC systems can run lots of programs, so let's get parallelism that way"
- often clumsy in practice

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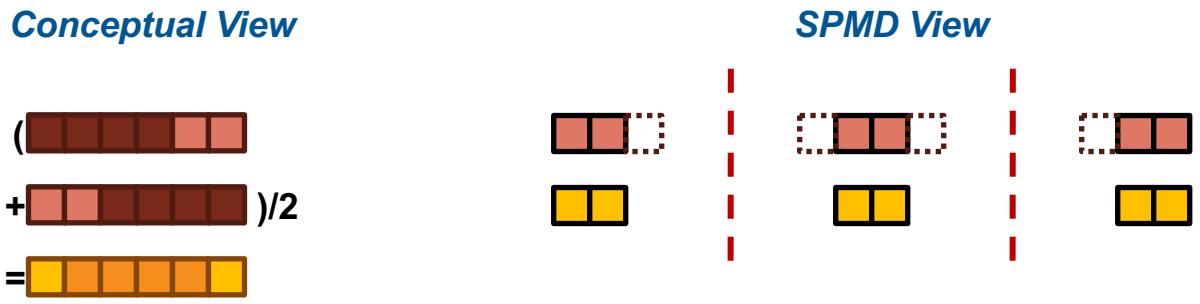
SPMD by Example (in pictures)

“Apply a 3-Point Stencil to a vector”



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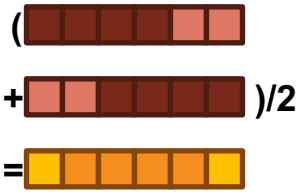
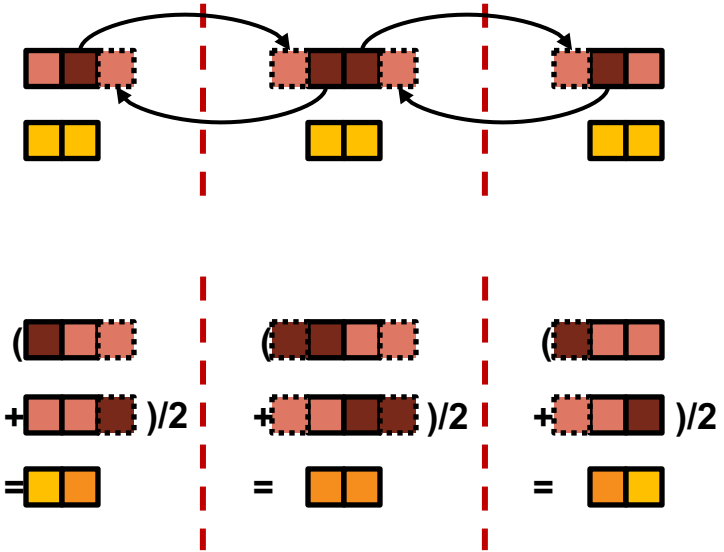
SPMD by Example (in pictures)

“Apply a 3-Point Stencil to a vector”

Conceptual View



SPMD View



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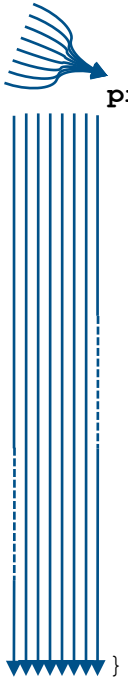
SPMD by Example (in code)

“Apply a 3-Point Stencil to a vector”

SPMD pseudo-code



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

  if (me < p-1) {
    send(me+1, A[myN]);
    recv(me+1, A[myN+1]);
  }
  if (me > 0) {
    send(me-1, A[1]);
    recv(me-1, A[0]);
  }
  forall i in 1..myN do
    B[i] = (A[i-1] + A[i+1])/2;
}
```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SPMD by Example (in code)

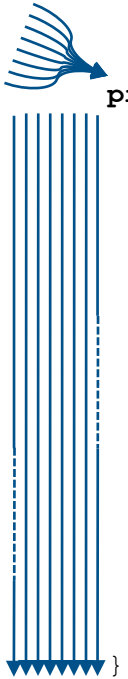
"Apply a 3-Point Stencil to a vector"

Global-view code (Chapel)

```
proc main() {
  const n = 1000,
        D = {1..n} dmapped Block(…);
  var A, B: [1..n] real;

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

SPMD pseudo-code



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

  if (me < p-1) {
    send(me+1, A[myN]);
    recv(me+1, A[myN+1]);
  }
  if (me > 0) {
    send(me-1, A[1]);
    recv(me-1, A[0]);
  }
  forall i in 1..myN do
    B[i] = (A[i-1] + A[i+1])/2;
}
```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SPMD by Example (in code)

"Apply a 3-Point Stencil to a vector"

Global-view code (Chapel)

```
proc main() {
  const n = 1000,
        D = {1..n} dmapped Block(…);
  var A, B: [1..n] real;

  forall i in 2..n-1 do
}
```

Bug: Refers to uninitialized values at ends of A

SPMD pseudo-code

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

  if (me < p-1) {
    send(me+1, A[myN]);
    recv(me+1, A[myN+1]);
  }
  if (me > 0) {
    send(me-1, A[1]);
    recv(me-1, A[0]);
  }
  forall i in 1..myN do
    B[i] = (A[i-1] + A[i+1])/2;
}
```


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SPMD by Example (in code)

"Apply a 3-Point Stencil to a vector"

Global-view code (Chapel)

```
proc main() {
  const n = 1000,
        D = {1..n} dmapped Block(…);
  var A, B: [1..n] real;

  forall
    B[i]
}
```

Communication becomes geometrically more complex for higher-dimensional arrays

SPMD pseudo-code

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

  if (me < p-1) {
    send(me+1, A[myN]);
    recv(me+1, A[myN+1]);
  } else
    myHi = myN-1;
  if (me > 0) {
    send(me-1, A[1]);
    recv(me-1, A[0]);
  } else
    myLo = 2;
  forall i in myLo..myHi do
    B[i] = (A[i-1] + A[i+1])/2;
}
```

Assumes p divides n

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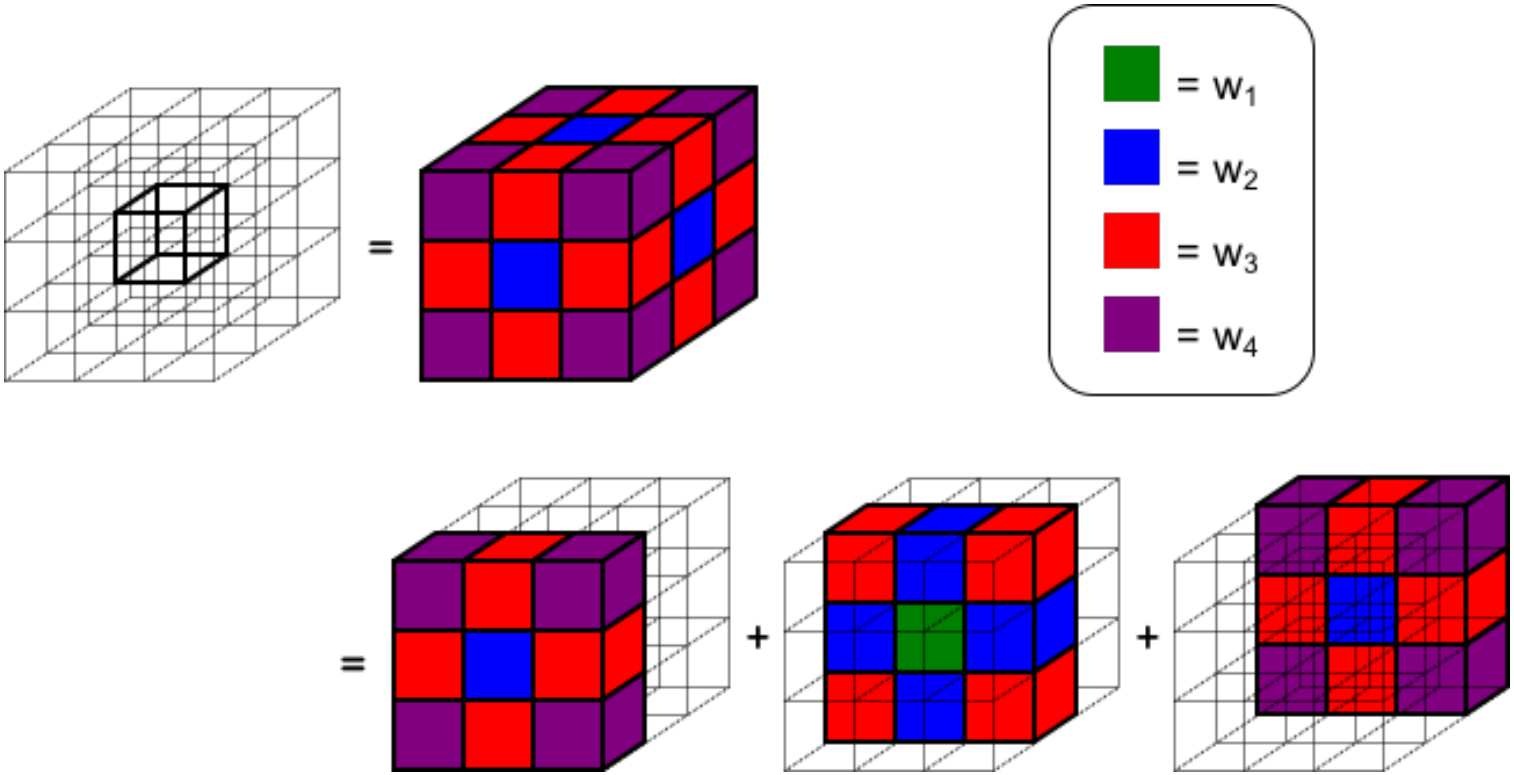
27-point stencils (*rprj3* from NAS MG)



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rprj3 in Fortran + MPI

```
      subroutine rprj3(r,m1k,m2k,m3k,s,m1j,m2j,m3j,k)
      implicit none
      include 'cafnpb.h'
      include 'globals.h'

      integer m1k, m2k, m3k, m1j, m2j, m3j,k

      double precision r(m1k,m2k,m3k), s(m1j,m2j,m3j)
      integer j3, j2, j1, i3, i2, i1, d1, d2, d3, j
      double precision x1(m), y1(m), x2,y2

      if(m1k.eq.3)then
        d1 = 2
      else
        d1 = 1
      endif

      if(m2k.eq.3)then
        d2 = 2
      else
        d2 = 1
      endif

      if(m3k.eq.3)then
        d3 = 2
      else
        d3 = 1
      endif
```

```
        do  j3=2,m3j-1
         i3 = 2*j3-d3
         do  j2=2,m2j-1
           i2 = 2*j2-d2
           do j1=2,m1j
            i1 = 2*j1-d1
            x1(i1-1) = r(i1-1,i2-1,i3  ) + r(i1-1,i2+1,i3  )
     >               + r(i1-1,i2,  i3-1) + r(i1-1,i2,  i3+1)
            y1(i1-1) = r(i1-1,i2-1,i3-1) + r(i1-1,i2-1,i3+1)
     >               + r(i1-1,i2+1,i3-1) + r(i1-1,i2+1,i3+1)
           enddo
           do  j1=2,m1j-1
            i1 = 2*j1-d1
            y2 = r(i1,  i2-1,i3-1) + r(i1,  i2-1,i3+1)
     >         + r(i1,  i2+1,i3-1) + r(i1,  i2+1,i3+1)
            x2 = r(i1,  i2-1,i3  ) + r(i1,  i2+1,i3  )
     >         + r(i1,  i2,  i3-1) + r(i1,  i2,  i3+1)
            s(j1,j2,j3) =
     >          0.5D0 * r(i1,i2,i3)
     >        + 0.25D0 * (r(i1-1,i2,i3) + r(i1+1,i2,i3) + x2)
     >        + 0.125D0 * ( x1(i1-1) + x1(i1+1) + y2)
     >        + 0.0625D0 * ( y1(i1-1) + y1(i1+1) )
           enddo
         enddo
        enddo
        j = k-1
        call comm3(s,m1j,m2j,m3j,j)
        return
        end
```


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rprj3 in Fortran + MPI

```
subroutine rprj3(r,m1k,m2k,m3k,s,m1j,m2j,m3j,k)
implicit none
include 'cafnpb.h'
include 'globals.h'

integer m1k, m2k, m3k, m1j, m2j, m3j,k

double precision r(m1k,m2k,m3k), s(m1j,m2j,m3j)
integer j3, j2, j1, i3, i2, i1, d1, d2, d3, j
double precision x1(m), y1(m), x2,y2

if(m1k.eq.3)then
  d1 = 2
else
  d1 = 1
endif

if(m2k.eq.3)then
  d2 = 2
else
  d2 = 1
endif

if(m3k.eq.3)then
  d3 = 2
else
  d3 = 1
endif
```

```
  do  j3=2,m3j-1
   i3 = 2*j3-d3
   do  j2=2,m2j-1
     i2 = 2*j2-d2
     do j1=2,m1j
      i1 = 2*j1-d1
      x1(i1-1) = r(i1-1,i2-1,i3  ) + r(i1-1,i2+1,i3  )
>              + r(i1-1,i2,  i3-1) + r(i1-1,i2,  i3+1)
      y1(i1-1) = r(i1-1,i2-1,i3-1) + r(i1-1,i2-1,i3+1)
>              + r(i1-1,i2+1,i3-1) + r(i1-1,i2+1,i3+1)
     enddo
     do  j1=2,m1j-1
      i1 = 2*j1-d1
      y2 = r(i1,  i2-1,i3-1) + r(i1,  i2-1,i3+1)
>        + r(i1,  i2+1,i3-1) + r(i1,  i2+1,i3+1)
      x2 = r(i1,  i2-1,i3  ) + r(i1,  i2+1,i3  )
>        + r(i1,  i2,  i3-1) + r(i1,  i2,  i3+1)
      s(j1,j2,j3) =
>         0.5D0 * r(i1,i2,i3)
>       + 0.25D0 * (r(i1-1,i2,i3) + r(i1+1,i2,i3) + x2)
>       + 0.125D0 * ( x1(i1-1) + x1(i1+1) + y2)
>       + 0.0625D0 * ( y1(i1-1) + y1(i1+1) )
     enddo
   enddo
  enddo
  j = k-1
  call comm3(s,m1j,m2j,m3j,j)
  return
  end
```


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comm3: the communication for *rprj3*

```
subroutine comm3(u,n1,n2,n3,kk)
use caf_intrinsics

implicit none

include 'cafnpb.h'
include 'globals.h'

integer n1, n2, n3, kk
double precision u(n1,n2,n3)
integer axis

if( .not. dead(kk) )then
   do  axis = 1, 3
      if( nproces .ne. 1) then
         call sync_all()
         call give3( axis, +1, u, n1,
     n2, n3, kk )
         call give3( axis, -1, u, n1,
     n2, n3, kk )
         call sync_all()
         call take3( axis, -1, u, n1,
     n2, n3 )
         call take3( axis, +1, u, n1,
     n2, n3 )
      else
         call commlp( axis, u, n1, n2,
     n3, kk )
      endif
   enddo
else
   do  axis = 1, 3
      call sync_all()
      call sync_all()
   enddo
   call zero3(u,n1,n2,n3)
endif
return
end


subroutine give3( axis, dir, u, n1, n2,
     n3, k )
use caf_intrinsics


implicit none

include 'cafnpb.h'
include 'globals.h'

integer axis, dir, n1, n2, n3, k, ierr
double precision u( n1, n2, n3 )

integer i3, i2, i1, buff_len,buff_id

buff_id = 2 + dir
buff_len = 0

if( axis .eq.  1 )then
   if( dir .eq. -1 )then

      do  i3=2,n3-1
         do  i2=2,n2-1
            buff_len = buff_len + 1
            buff(buff_len,buff_id ) =
     u( 2,  i2,i3)
         enddo
      enddo


      buff(1:buff_len,buff_id+1)[nbr(axi
     s,dir,k)] =
     >      buff(1:buff_len,buff_id)

      else if( dir .eq. +1 ) then

         do  i3=2,n3-1
            do  i2=2,n2-1
               buff_len = buff_len +
     1
               buff(buff_len,
     buff_id ) = u( n1-1, i2,i3)
            enddo
         enddo


      buff(1:buff_len,buff_id+1)[nbr
     (axis,dir,k)] =
     >      buff(1:buff_len,buff_id)

      endif
   endif

   if( axis .eq.  2 )then
      if( dir .eq. -1 )then

do  i3=2,n3-1
            do  i1=1,n1
               buff_len = buff_len +
     1
               buff(buff_len,
     buff_id ) = u( i1,  2,i3)
            enddo
         enddo


      buff(1:buff_len,buff_id+1)[nbr
     (axis,dir,k)] =
     >      buff(1:buff_len,buff_id)

      else if( dir .eq. +1 ) then

         do  i3=2,n3-1
            do  i1=1,n1
               buff_len = buff_len +
     1
               buff(buff_len,
     buff_id ) = u( i1,n2-1,i3)
            enddo
         enddo


      buff(1:buff_len,buff_id+1)[nbr
     (axis,dir,k)] =
     >      buff(1:buff_len,buff_id)

      endif
   endif

   if( axis .eq.  3 )then
      if( dir .eq. -1 )then

         do  i2=1,n2
            do  i1=1,n1
               buff_len = buff_len +
     1
               buff(buff_len,
     buff_id ) = u( i1,i2,2)
            enddo
         enddo


      buff(1:buff_len,buff_id+1)[nbr
     (axis,dir,k)] =
     >      buff(1:buff_len,buff_id)

      else if( dir .eq. +1 ) then

         do  i2=1,n2
            do  i1=1,n1
               buff_len = buff_len +
     1
               buff(buff_len,
     buff_id ) = u( i1,i2,n3-1)
            enddo
         enddo


      buff(1:buff_len,buff_id+1)[nbr
     (axis,dir,k)] =
     >      buff(1:buff_len,buff_id)

      endif
   endif

   if( axis .eq.  2 )then
      if( dir .eq. -1 )then

         do  i3=2,n3-1
            do  i1=1,n1
               indx = indx + 1
               u(i1,n2,i3) =
     buff(indx, buff_id )
            enddo
         enddo

      else if( dir .eq. +1 ) then

         do  i3=2,n3-1
            do  i1=1,n1
               indx = indx + 1
               u(i1,1,i3) =
     buff(indx, buff_id )
            enddo
         enddo

      endif
   endif

   if( axis .eq.  1 )then
      if( dir .eq. -1 )then

         do  i3=2,n3-1
            do  i2=2,n2-1
               indx = indx + 1
               u(n1,i2,i3) =
     buff(indx, buff_id )
            enddo
         enddo

      else if( dir .eq. +1 ) then

         do  i3=2,n3-1
            do  i2=2,n2-1
               indx = indx + 1
               u(1,i2,i3) =
     buff(indx, buff_id )
            enddo
         enddo

      endif
   endif

   if( axis .eq.  2 )then
      if( dir .eq. -1 )then

         do  i3=2,n3-1
            do  i1=1,n1
               indx = indx + 1
               u(i1,n2,i3) =
     buff(indx, buff_id )
            enddo
         enddo

      else if( dir .eq. +1 ) then

         do  i2=1,n2
            do  i1=1,n1
               indx = indx + 1
               u(i1,n2,i3) =
     buff(indx, buff_id )
            enddo
         enddo

      endif
   endif

   if( axis .eq.  3 )then
      if( dir .eq. -1 )then

         do  i3=2,n3-1
            do  i1=1,n1
               indx = indx + 1
               u(i1,i2,3) =
     buff(indx, buff_id )
            enddo
         enddo

      else if( dir .eq. +1 ) then

         do  i2=1,n2
            do  i1=1,n1
               indx = indx + 1
               u(i1,i2,n3) =
     buff(indx, buff_id )
            enddo
         enddo

      endif
   endif

   if( axis .eq.  2 )then
      if( dir .eq. -1 )then

         do  i3=2,n3-1
            do  i1=1,n1
               indx = indx + 1
               u(i1,n2,i3) =
     buff(indx, buff_id )
            enddo
         enddo

      else if( dir .eq. +1 ) then

         do  i2=1,n2
            do  i1=1,n1
               indx = indx + 1
               u(i1,i2,n3) =
     buff(indx, buff_id )
            enddo
         enddo

      endif
   endif

   if( axis .eq.  1 )then
      if( dir .eq. -1 )then

         do  i3=2,n3-1
            do  i1=1,n1
               indx = indx + 1
               u(i1,i2,i3) =
     buff(indx, buff_id )
            enddo
         enddo

      else if( dir .eq. +1 ) then

         do  i3=2,n3-1
            do  i1=1,n1
               indx = indx + 1
               u(i1,i2,i3) =
     buff(indx, buff_id )
            enddo
         enddo

      endif
   endif

   if( axis .eq.  3 )then
      if( dir .eq. -1 )then

         do  i3=2,n3-1
            do  i1=1,n1
               indx = indx + 1
               u(i1,1,i3) =
     buff(indx, buff_id )
            enddo
         enddo

      else if( dir .eq. +1 ) then

         do  i2=1,n2
            do  i1=1,n1
               indx = indx + 1
               u(i1,i2,n3) =
     buff(indx, buff_id )
            enddo
         enddo

      endif
   endif

   if( axis .eq.  2 )then
      if( dir .eq. -1 )then

         do  i3=2,n3-1
            do  i1=1,n1
               indx = indx + 1
               u(i1,1,i3) =
     buff(indx, buff_id )
            enddo
         enddo

      else if( dir .eq. +1 ) then

         do  i2=1,n2
            do  i1=1,n1
               indx = indx + 1
               u(i1,i2,1) =
     buff(indx, buff_id )
            enddo
         enddo

      endif
   endif

   if( axis .eq.  1 )then
      if( dir .eq. -1 )then

         do  i3=2,n3-1
            do  i2=2,n2-1
               indx = indx + 1
               u(n1,i2,i3) =
     buff(indx, buff_id )
            enddo
         enddo

      else if( dir .eq. +1 ) then

         do  i3=2,n3-1
            do  i2=2,n2-1
               indx = indx + 1
               u(1,i2,i3) =
     buff(indx, buff_id )
            enddo
         enddo

      endif
   endif

   if( axis .eq.  3 )then
      if( dir .eq. -1 )then

         do  i2=1,n2
            do  i1=1,n1
               indx = indx + 1
               u(i1,i2,1) =
     buff(indx, buff_id )
            enddo
         enddo

      else if( dir .eq. +1 ) then

         do  i1=1,n1
            do  i2=1,n2
               indx = indx + 1
               u(i1,i2,n3) =
     buff(indx, buff_id )
            enddo
         enddo

      endif
   endif

   if( axis .eq.  2 )then
      if( dir .eq. -1 )then

         do  i1=1,n1
            do  i2=1,n2
               indx = indx + 1
               u(i1,1,i3) =
     buff(indx, buff_id )
            enddo
         enddo

      else if( dir .eq. +1 ) then

         do  i1=1,n1
            do  i2=1,n2
               indx = indx + 1
               u(i1,i2,1) =
     buff(indx, buff_id )
            enddo
         enddo

      endif
   endif

   if( axis .eq.  1 )then
      if( dir .eq. -1 )then

         do  i1=1,n1
            do  i2=1,n2
               indx = indx + 1
               u(i1,i2,i3) =
     buff(indx, buff_id )
            enddo
         enddo

      else if( dir .eq. +1 ) then

         do  i1=1,n1
            do  i2=1,n2
               indx = indx + 1
               u(i1,i2,i3) =
     buff(indx, buff_id )
            enddo
         enddo

      endif
   endif
```


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Being Gutsy, Gentle, and Kind to MPI

- **It's enabled the vast majority of HPC results for the past ~20 years**
- **It's very analogous to assembly programming**
  - explicitly move data from memory to registers

    vs.

    explicitly move data between compute nodes' memories
- **Just like assembly, it's an important technology**
  - for programming at low levels
  - for enabling higher-level technologies
- **Yet, as with assembly, we should develop higher-level alternatives**

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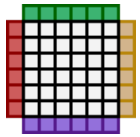
rprj3 in ZPL



```
procedure rprj3(var S,R: [,,] double;
                d: array [] of direction);
begin
  S := 0.5000 * R +
       0.2500 * (R@^d[ 1, 0, 0] + R@^d[ 0, 1, 0] + R@^d[ 0, 0, 1] +
                 R@^d[-1, 0, 0] + R@^d[ 0,-1, 0] + R@^d[ 0, 0,-1] +
       0.1250 * (R@^d[ 1, 1, 0] + R@^d[ 1, 0, 1] + R@^d[ 0, 1, 1] +
                 R@^d[ 1,-1, 0] + R@^d[ 1, 0,-1] + R@^d[ 0, 1,-1] +
                 R@^d[-1, 1, 0] + R@^d[-1, 0, 1] + R@^d[ 0,-1, 1] +
                 R@^d[-1,-1, 0] + R@^d[-1, 0,-1] + R@^d[ 0,-1,-1])+
       0.0625 * (R@^d[ 1, 1, 1] + R@^d[ 1, 1,-1] +
                 R@^d[ 1,-1, 1] + R@^d[ 1,-1,-1] +
                 R@^d[-1, 1, 1] + R@^d[-1, 1,-1] +
                 R@^d[-1,-1, 1] + R@^d[-1,-1,-1]);
end;
```

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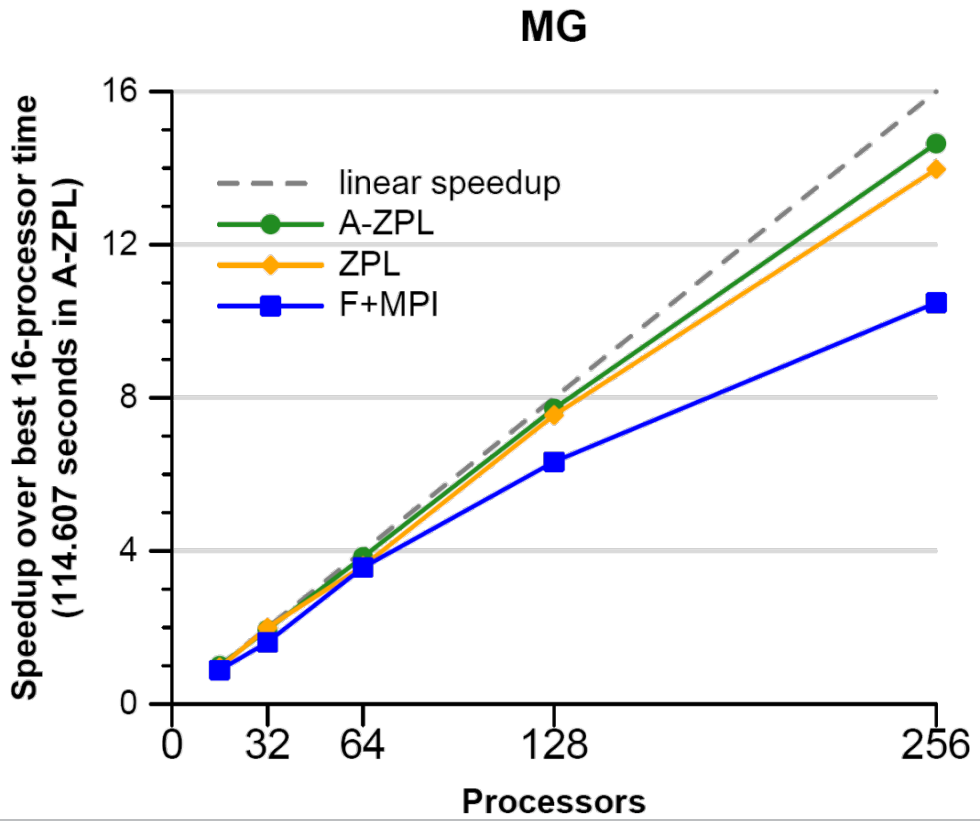
NAS MG Speedup: Cray T3E



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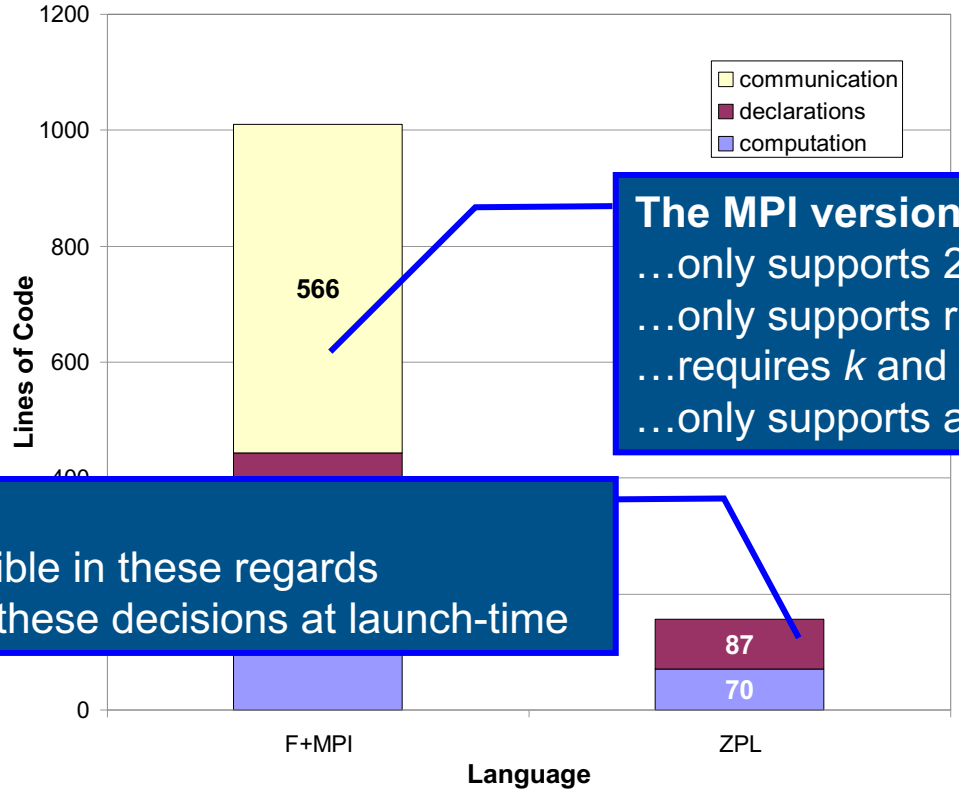
Code Size Comparison



The MPI version…
…only supports 2^k problem sizes
…only supports running on 2^p nodes
…requires *k* and *p* to be specified statically
…only supports a single 3D distribution

The ZPL version…
…is completely flexible in these regards
…supports making these decisions at launch-time

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This Talk's Takeaways

If you design a parallel programming language…

…don't base your model for parallelism and locality on SPMD

- instead, support a global view of parallelism and locality (like ZPL)

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Epilogue: So why was ZPL not adopted?

- **Too restricted in terms of generality:**
  - only a single level of array-based data parallelism
  - only a single parallel array type: block-distributed
  - lack of “manual overrides” to drop down closer to the system
  - choices that were dated (no OOP, modula-based syntax, …)
- **Great academic project, not a great practical language**
  - however, ZPL’s experiences informed Chapel’s design greatly

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And now for something
completely different.

[Instrumental]

Chapel Characteristics

The Liberty Bell March
John Philip Sousa
(unreleased?)

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Chapel's Goal

To create a language that is…

…as productive as Python

…as fast as Fortran

…as portable as C

…as scalable as MPI

…as fun as [*insert your favorite language here*]

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The Challenge

Q: So why don't we already have such a language already?

A: ~~Technical challenges?~~

- while they exist, we don't think this is the main issue…

A: Due to a lack of…

…long-term efforts

…resources

…community will

…co-design between developers and users

…patience

Chapel is our attempt to reverse this trend

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Chapel is Portable

- **Chapel's design and implementation are hardware-independent**
- **The current release requires:**
  - a C/C++ compiler
  - a *NIX environment: Linux, Mac OS X, Windows 10 w/ bash, Cygwin, …
  - POSIX threads
  - UDP, MPI, or RDMA (if distributed memory execution is desired)
- **Chapel runs 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

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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

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The Chapel Team at Cray (May 2016)

14 full-time employees + 2 summer interns + occasional visiting academics
(one of each started after photo taken)

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Chapel Community R&D Efforts

(and several others…)

http://chapel.cray.com/collaborations.html

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You say you got a real solution
Well, you know
We'd all love to see the plan

Chapel in a Nutshell

Revolution
The Beatles
The Beatles

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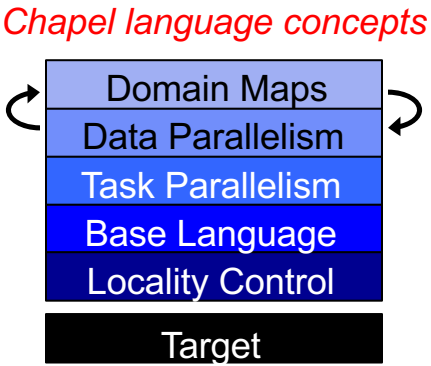
Chapel language feature areas



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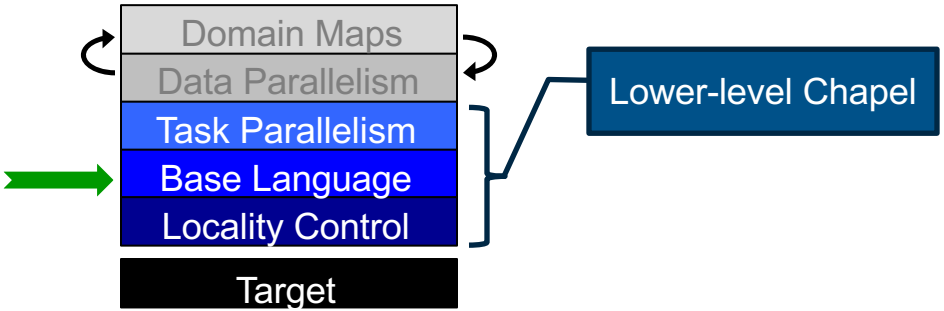
Base Language



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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
...
```


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Base Language Features, by example

Modern 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`

```
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

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
...
```


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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
…
```


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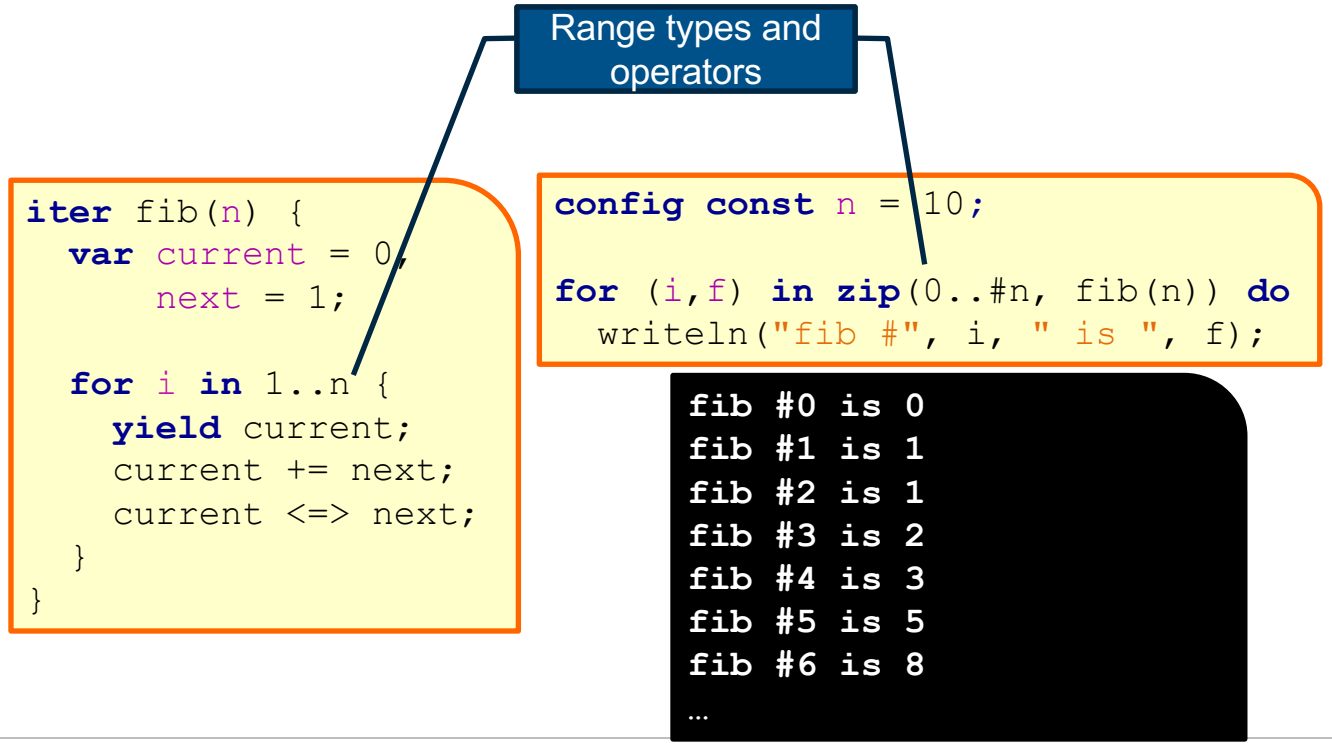
Base Language Features, by example



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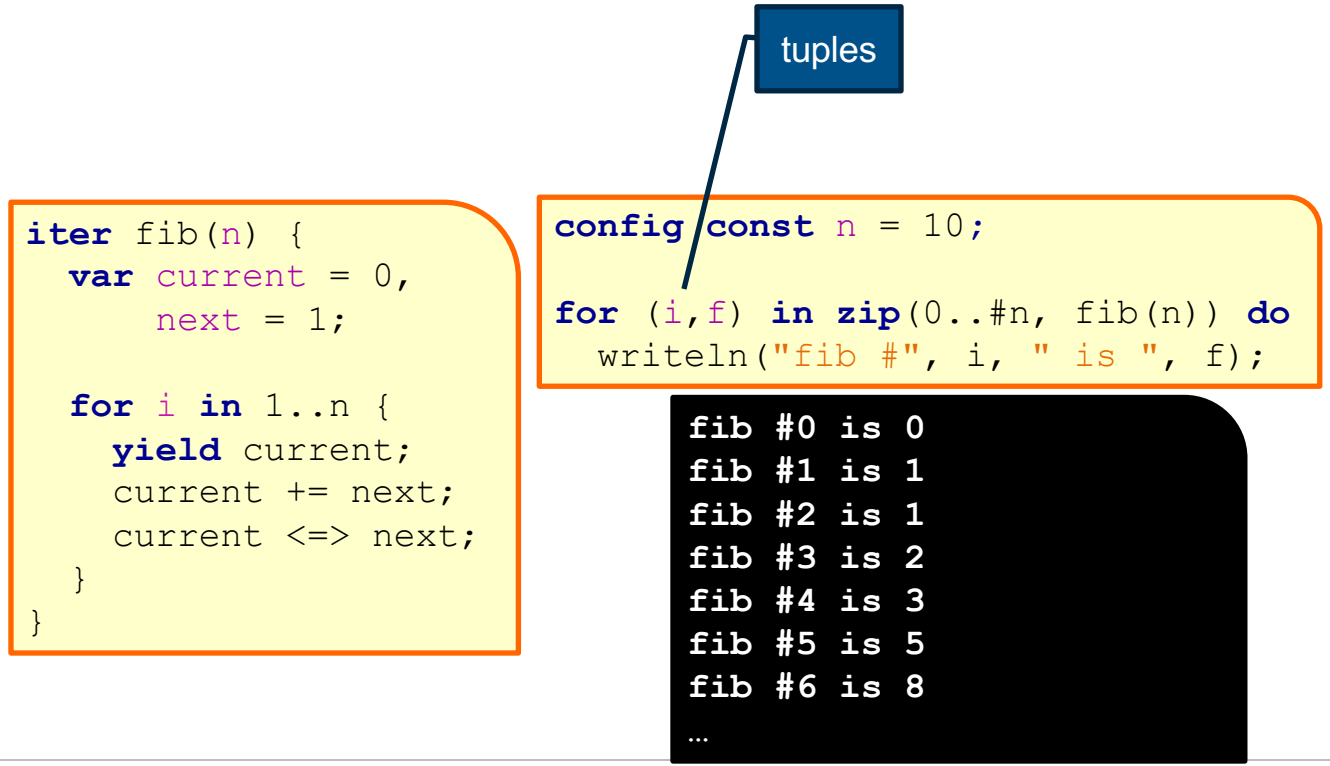
Base Language Features, by example



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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
…
```


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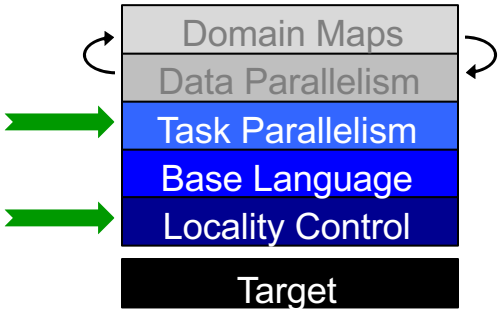
Task Parallelism and Locality Control



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Task Parallelism and Locality, by example

taskParallel.chpl

```
coforall loc in Locales do
  on loc {
    const numTasks = here.maxTaskPar;
    coforall tid in 1..numTasks do
      writef("Hello from task %n of %n "+
             "running on %s\n",
             tid, numTasks, here.name);
  }
```

```
prompt> chpl taskParallel.chpl -o taskParallel
prompt> ./taskParallel --numLocales=2
Hello from task 1 of 2 running on n1033
Hello from task 2 of 2 running on n1032
Hello from task 2 of 2 running on n1033
Hello from task 1 of 2 running on n1032
```


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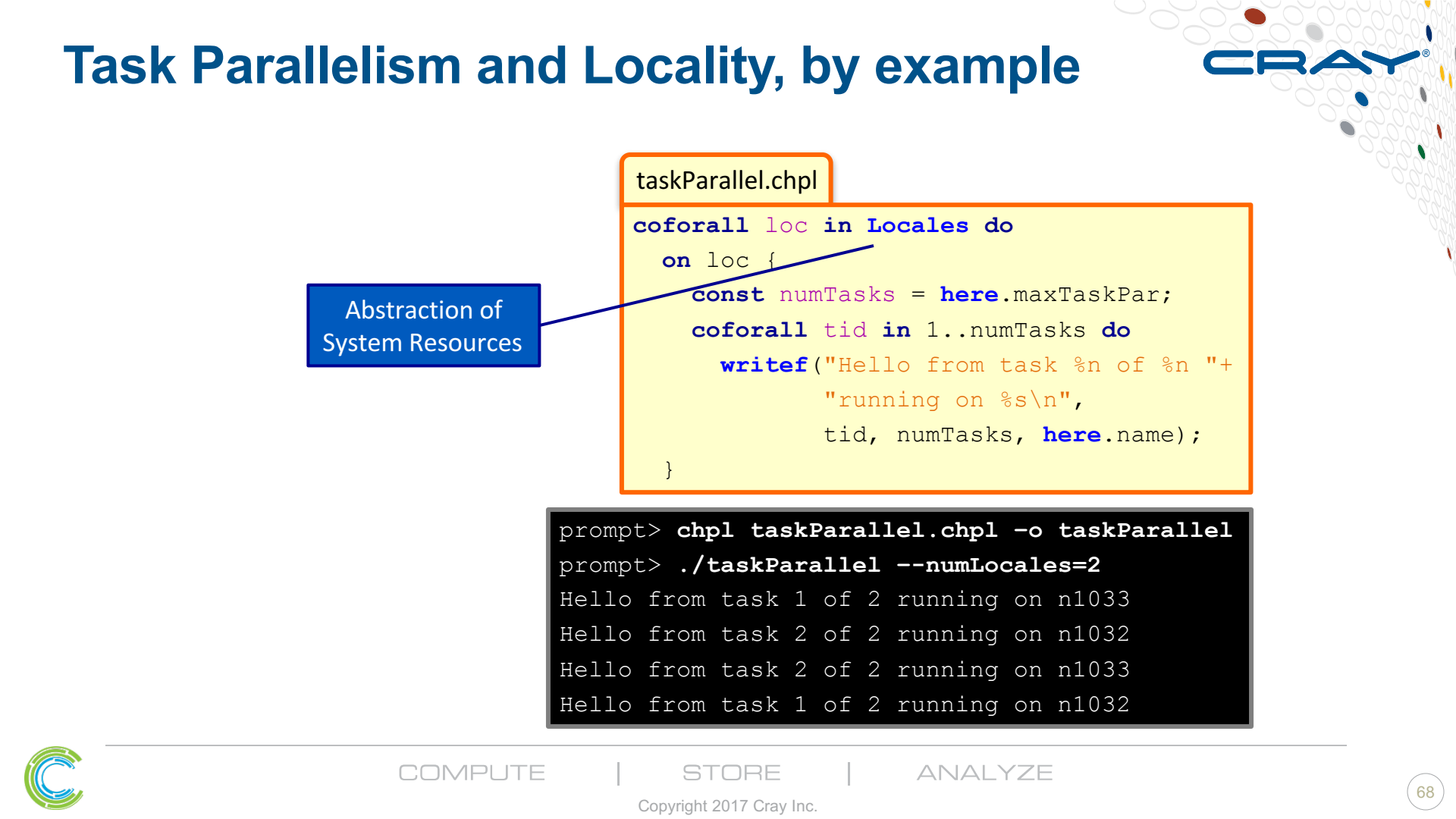
Task Parallelism and Locality, by example



taskParallel.chpl

```
coforall loc in Locales do
  on loc {
    const numTasks = here.maxTaskPar;
    coforall tid in 1..numTasks do
      writef("Hello from task %n of %n "+
             "running on %s\n",
             tid, numTasks, here.name);
  }
```

```
prompt> chpl taskParallel.chpl -o taskParallel
prompt> ./taskParallel --numLocales=2
Hello from task 1 of 2 running on n1033
Hello from task 2 of 2 running on n1032
Hello from task 2 of 2 running on n1033
Hello from task 1 of 2 running on n1032
```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Task Parallelism and Locality, by example

High-Level Task Parallelism

taskParallel.chpl

```
coforall loc in Locales do
  on loc {
    const numTasks = here.maxTaskPar;
    coforall tid in 1..numTasks do
      writef("Hello from task %n of %n "+
             "running on %s\n",
             tid, numTasks, here.name);
  }
```

```
prompt> chpl taskParallel.chpl -o taskParallel
prompt> ./taskParallel --numLocales=2
Hello from task 1 of 2 running on n1033
Hello from task 2 of 2 running on n1032
Hello from task 2 of 2 running on n1033
Hello from task 1 of 2 running on n1032
```


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Task Parallelism and Locality, by example

Control of Locality/Affinity

taskParallel.chpl

```
coforall loc in Locales do
  on loc {
    const numTasks = here.maxTaskPar;
    coforall tid in 1..numTasks do
      writef("Hello from task %n of %n "+
             "running on %s\n",
             tid, numTasks, here.name);
  }
```

```
prompt> chpl taskParallel.chpl -o taskParallel
prompt> ./taskParallel --numLocales=2
Hello from task 1 of 2 running on n1033
Hello from task 2 of 2 running on n1032
Hello from task 2 of 2 running on n1033
Hello from task 1 of 2 running on n1032
```


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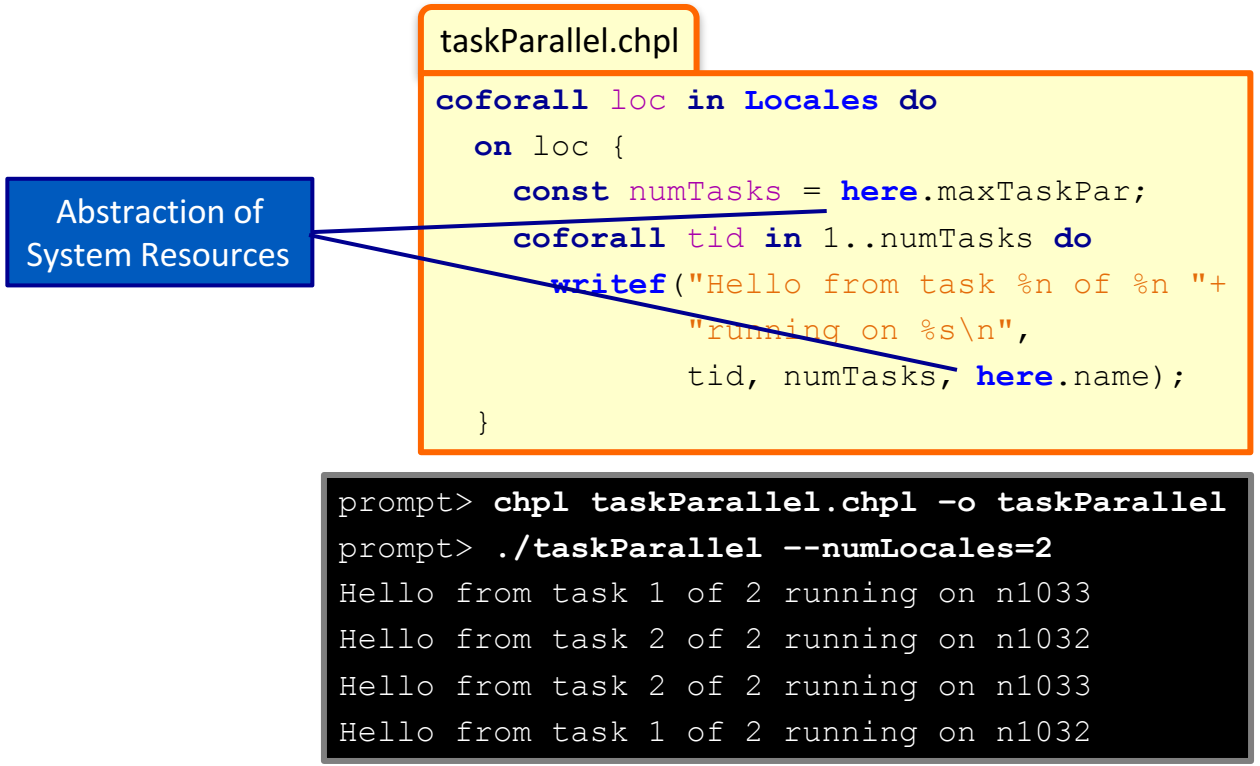
Task Parallelism and Locality, by example



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Task Parallelism and Locality, by example

High-Level Task Parallelism

taskParallel.chpl

```
coforall loc in Locales do
  on loc {
    const numTasks = here.maxTaskPar;
    coforall tid in 1..numTasks do
      writef("Hello from task %n of %n "+
             "running on %s\n",
             tid, numTasks, here.name);
  }
```

```
prompt> chpl taskParallel.chpl -o taskParallel
prompt> ./taskParallel --numLocales=2
Hello from task 1 of 2 running on n1033
Hello from task 2 of 2 running on n1032
Hello from task 2 of 2 running on n1033
Hello from task 1 of 2 running on n1032
```


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Task Parallelism and Locality, by example

taskParallel.chpl

```
coforall loc in Locales do
  on loc {
    const numTasks = here.maxTaskPar;
    coforall tid in 1..numTasks do
      writef("Hello from task %n of %n "+
             "running on %s\n",
             tid, numTasks, here.name);
  }
```

Not seen here:

Data-centric task coordination via atomic and full/empty vars

```
prompt> chpl taskParallel.chpl -o taskParallel
prompt> ./taskParallel --numLocales=2
Hello from task 1 of 2 running on n1033
Hello from task 2 of 2 running on n1032
Hello from task 2 of 2 running on n1033
Hello from task 1 of 2 running on n1032
```

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Task Parallelism and Locality, by example

taskParallel.chpl

```
coforall loc in Locales do
  on loc {
    const numTasks = here.maxTaskPar;
    coforall tid in 1..numTasks do
      writef("Hello from task %n of %n "+
             "running on %s\n",
             tid, numTasks, here.name);
  }
```

```
prompt> chpl taskParallel.chpl -o taskParallel
prompt> ./taskParallel --numLocales=2
Hello from task 1 of 2 running on n1033
Hello from task 2 of 2 running on n1032
Hello from task 2 of 2 running on n1033
Hello from task 1 of 2 running on n1032
```


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Parallelism and Locality: Distinct 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);
```


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Partitioned Global Address Space (PGAS) Languages
(Or more accurately: 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 2008's co-arrays, Unified Parallel C (UPC)

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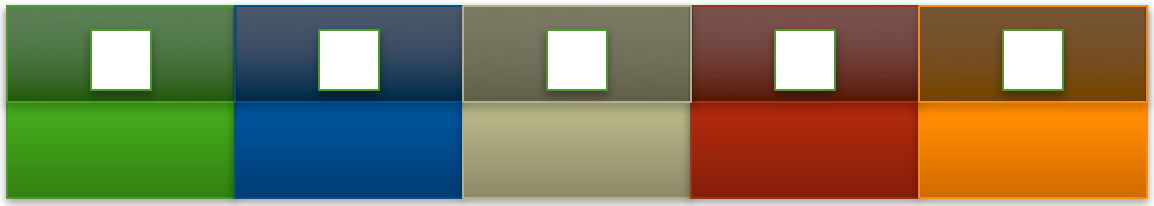
SPMD PGAS Languages (using a pseudo-language, not Chapel)

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

i =



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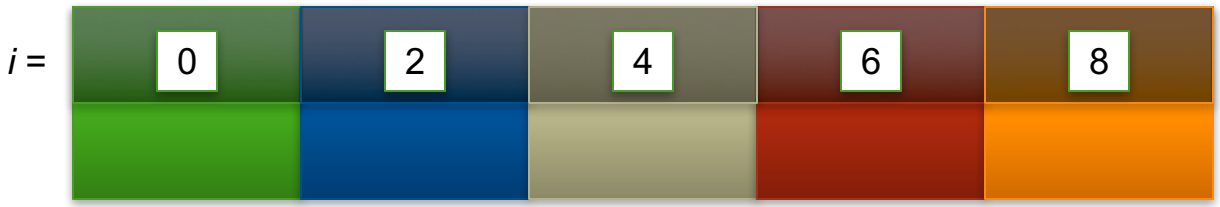
SPMD PGAS Languages (using a pseudo-language, not Chapel)

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



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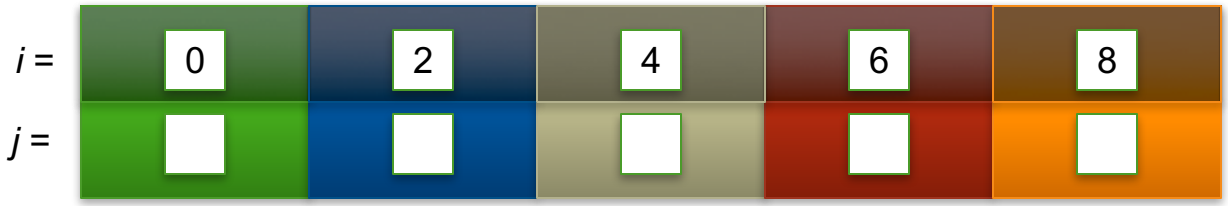
SPMD PGAS Languages (using a pseudo-language, not Chapel)

```
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
```



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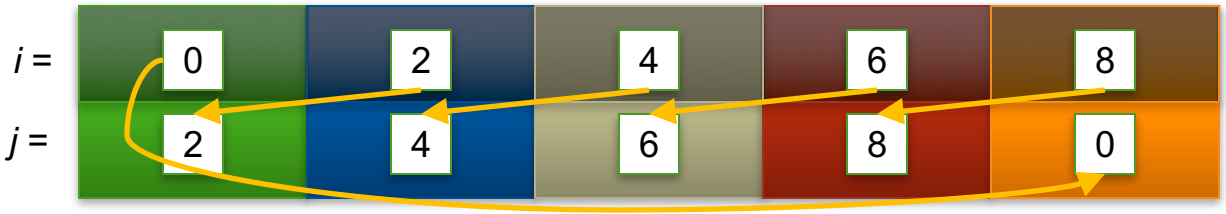
SPMD PGAS Languages (using a pseudo-language, not Chapel)

```
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; compiler and runtime implement the communication
    // Q: How did we know our neighbor had an i?
    // A: Because it's SPMD – we're all running the same program so if we have an i, so do they.
```



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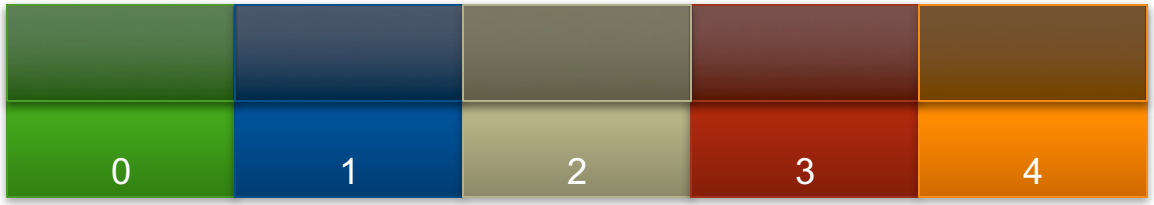
Chapel and PGAS

- **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")

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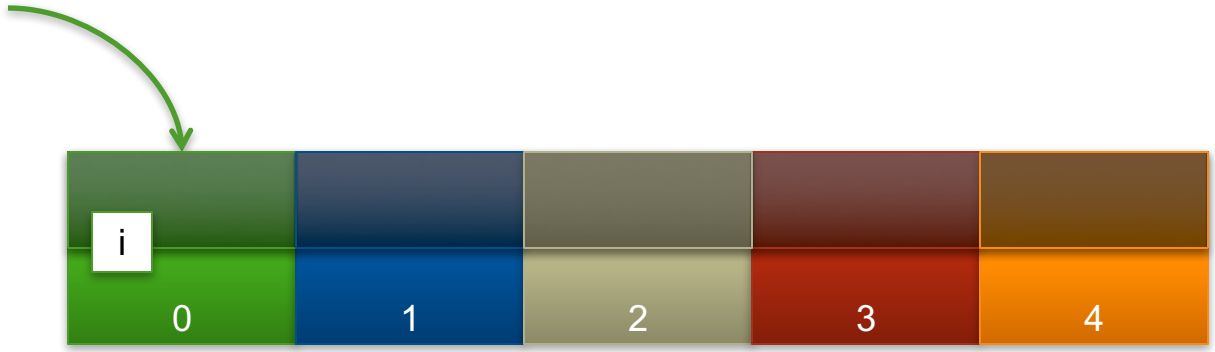
Chapel: Scoping and Locality

```
var i: int;
```



Locales (think: “compute nodes”)

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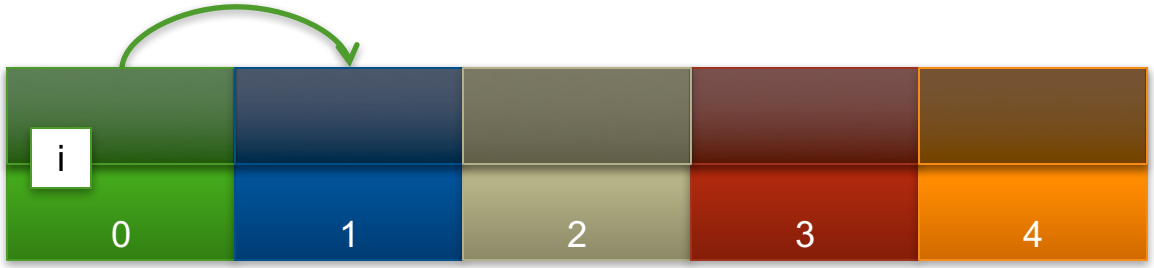
Chapel: Scoping and Locality

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



Locales (think: “compute nodes”)

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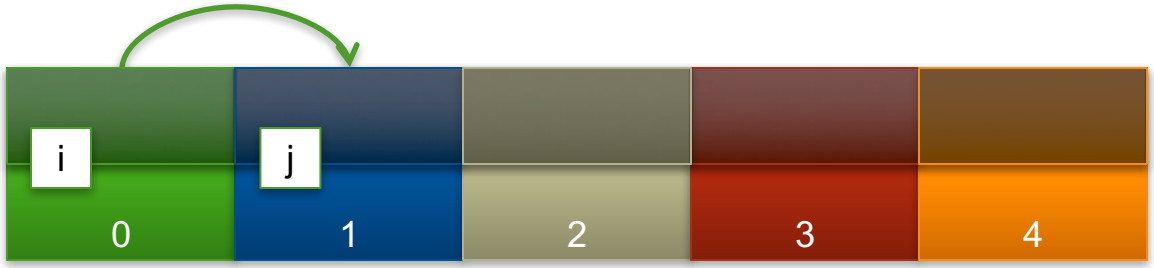
Chapel: Scoping and Locality

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



Locales (think: “compute nodes”)

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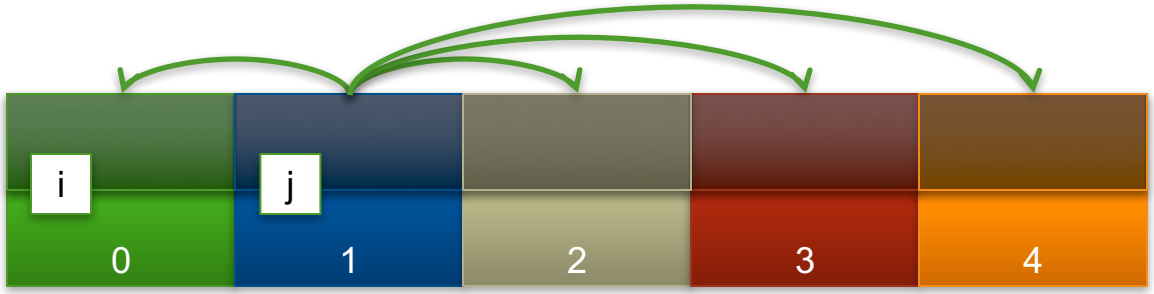
Chapel: Scoping and Locality

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



Locales (think: “compute nodes”)

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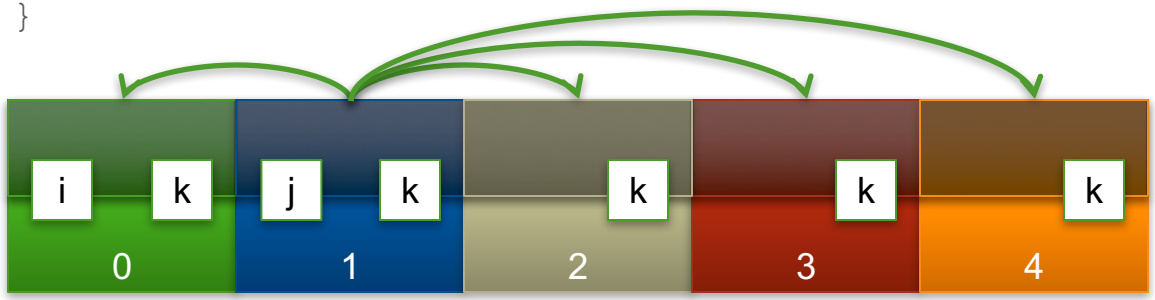
Chapel: Scoping and Locality

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



Locales (think: “compute nodes”)

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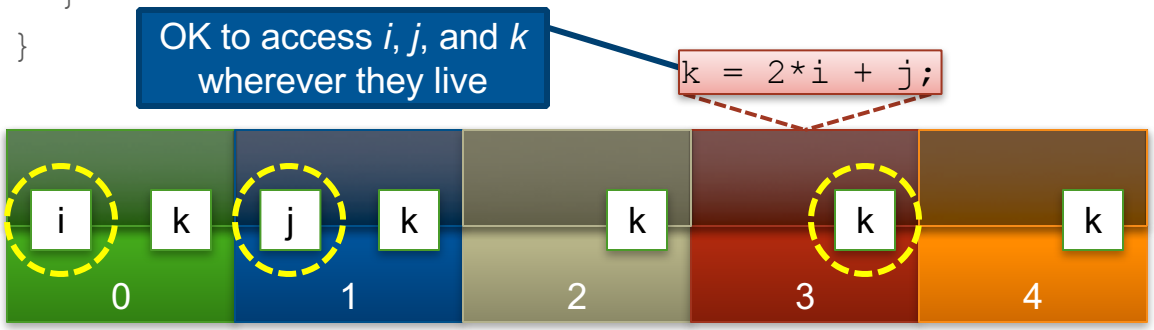
Chapel: Scoping and Locality

```
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")

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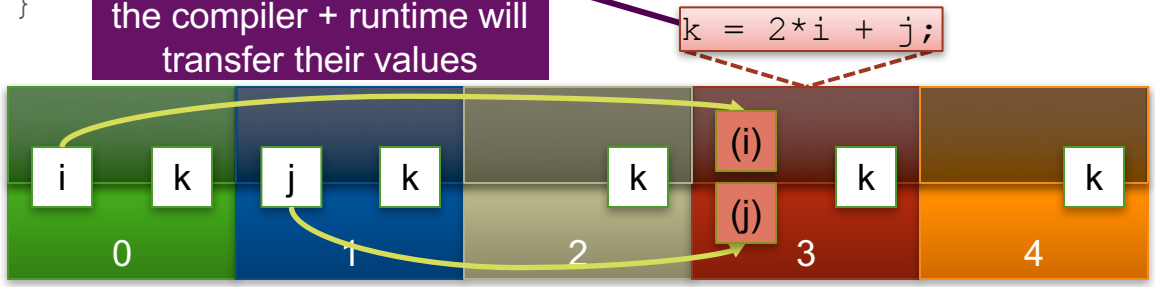
Chapel: Scoping and Locality

```
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")

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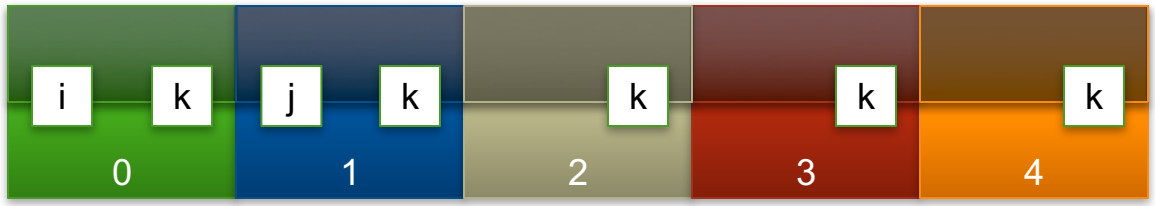
Chapel: Locality queries

```
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”)

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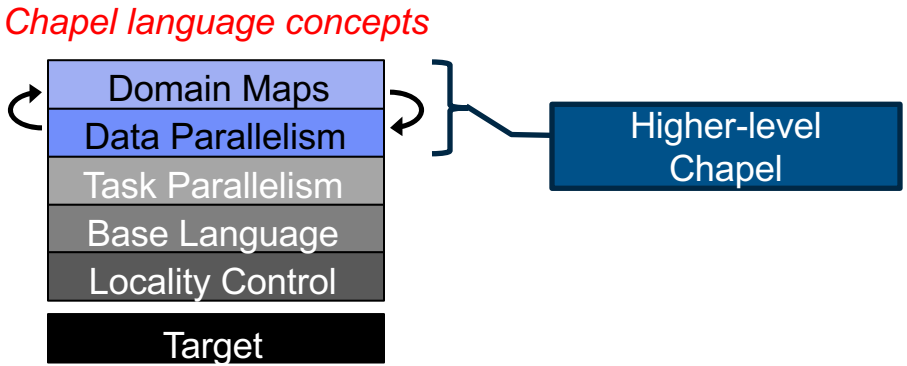
Higher-Level Features



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Data Parallelism, by example

dataParallel.chpl

```
config const n = 1000;
var D = {1..n, 1..n};

var A: [D] real;
forall (i,j) in D do
  A[i,j] = i + (j - 0.5)/n;
writeln(A);
```

```
prompt> chpl dataParallel.chpl -o dataParallel
prompt> ./dataParallel --n=5
1.1 1.3 1.5 1.7 1.9
2.1 2.3 2.5 2.7 2.9
3.1 3.3 3.5 3.7 3.9
4.1 4.3 4.5 4.7 4.9
5.1 5.3 5.5 5.7 5.9
```


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Data Parallelism, by example

Domains (Index Sets)

dataParallel.chpl

```
config const n = 1000;
var D = {1..n, 1..n};

var A: [D] real;
forall (i,j) in D do
  A[i,j] = i + (j - 0.5)/n;
writeln(A);
```

```
prompt> chpl dataParallel.chpl -o dataParallel
prompt> ./dataParallel --n=5
1.1 1.3 1.5 1.7 1.9
2.1 2.3 2.5 2.7 2.9
3.1 3.3 3.5 3.7 3.9
4.1 4.3 4.5 4.7 4.9
5.1 5.3 5.5 5.7 5.9
```


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Data Parallelism, by example

Arrays

dataParallel.chpl

```
config const n = 1000;
var D = {1..n, 1..n};

var A: [D] real;
forall (i,j) in D do
  A[i,j] = i + (j - 0.5)/n;
writeln(A);
```

```
prompt> chpl dataParallel.chpl -o dataParallel
prompt> ./dataParallel --n=5
1.1 1.3 1.5 1.7 1.9
2.1 2.3 2.5 2.7 2.9
3.1 3.3 3.5 3.7 3.9
4.1 4.3 4.5 4.7 4.9
5.1 5.3 5.5 5.7 5.9
```


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Data Parallelism, by example

Data-Parallel Forall Loops

dataParallel.chpl

```
config const n = 1000;
var D = {1..n, 1..n};

var A: [D] real;
forall (i,j) in D do
  A[i,j] = i + (j - 0.5)/n;
writeln(A);
```

```
prompt> chpl dataParallel.chpl -o dataParallel
prompt> ./dataParallel --n=5
1.1 1.3 1.5 1.7 1.9
2.1 2.3 2.5 2.7 2.9
3.1 3.3 3.5 3.7 3.9
4.1 4.3 4.5 4.7 4.9
5.1 5.3 5.5 5.7 5.9
```


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Distributed Data Parallelism, by example

Domain Maps
(Map Data Parallelism to the System)

dataParallel.chpl

```
use CyclicDist;
config const n = 1000;
var D = {1..n, 1..n}
        dmapped Cyclic(startIdx = (1,1));
var A: [D] real;
forall (i,j) in D do
  A[i,j] = i + (j - 0.5)/n;
writeln(A);
```

```
prompt> chpl dataParallel.chpl -o dataParallel
prompt> ./dataParallel --n=5 --numLocales=4
1.1 1.3 1.5 1.7 1.9
2.1 2.3 2.5 2.7 2.9
3.1 3.3 3.5 3.7 3.9
4.1 4.3 4.5 4.7 4.9
5.1 5.3 5.5 5.7 5.9
```


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Distributed Data Parallelism, by example

dataParallel.chpl

```
use CyclicDist;
config const n = 1000;
var D = {1..n, 1..n}
        dmapped Cyclic(startIdx = (1,1));
var A: [D] real;
forall (i,j) in D do
  A[i,j] = i + (j - 0.5)/n;
writeln(A);
```

```
prompt> chpl dataParallel.chpl -o dataParallel
prompt> ./dataParallel --n=5 --numLocales=4
1.1 1.3 1.5 1.7 1.9
2.1 2.3 2.5 2.7 2.9
3.1 3.3 3.5 3.7 3.9
4.1 4.3 4.5 4.7 4.9
5.1 5.3 5.5 5.7 5.9
```


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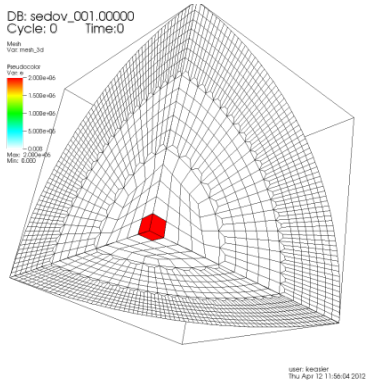
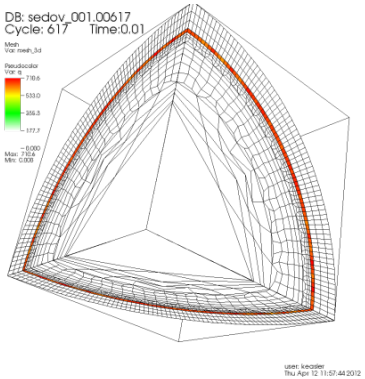
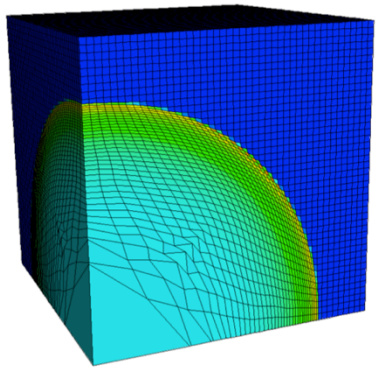
LULESH: a DOE Proxy Application

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







pictures courtesy of Rob Neely, Bert Still, Jeff Keasler, LLNL

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LULESH in Chapel

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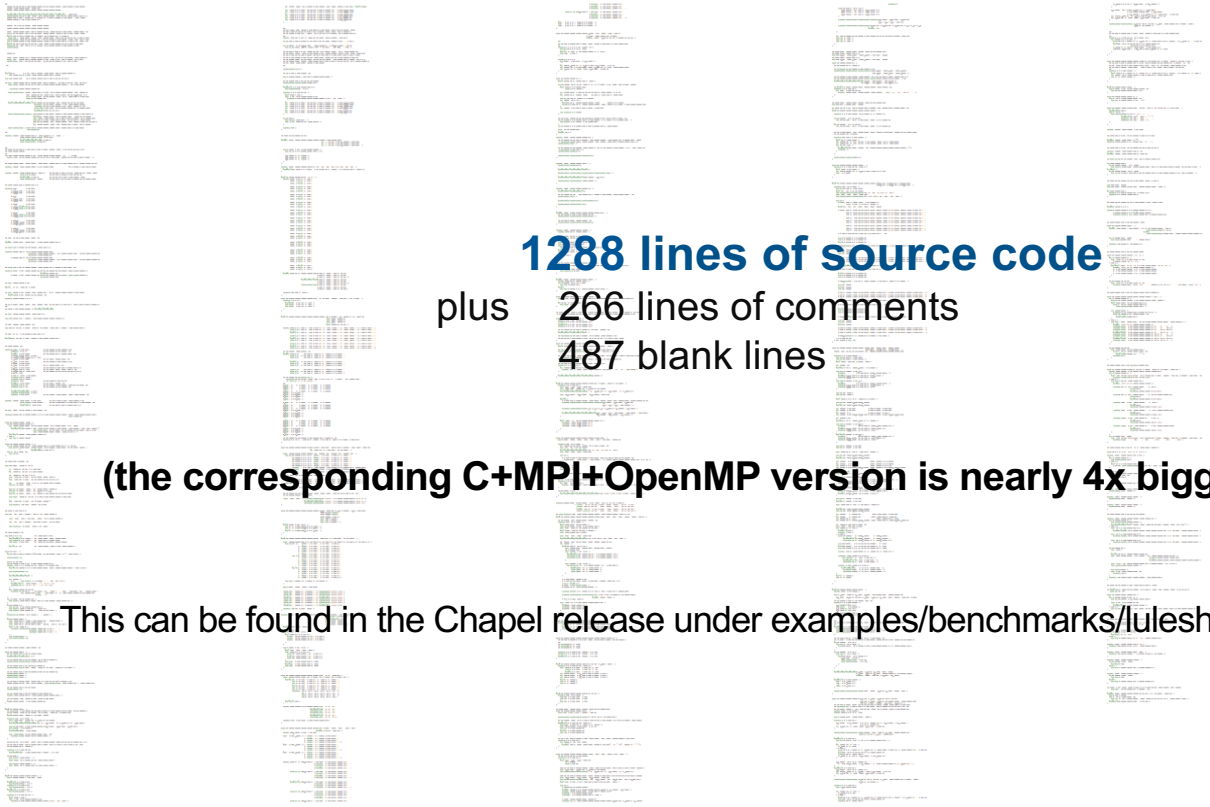
LULESH in Chapel



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 the Chapel release under examples/benchmarks/lulesh/*.chpl

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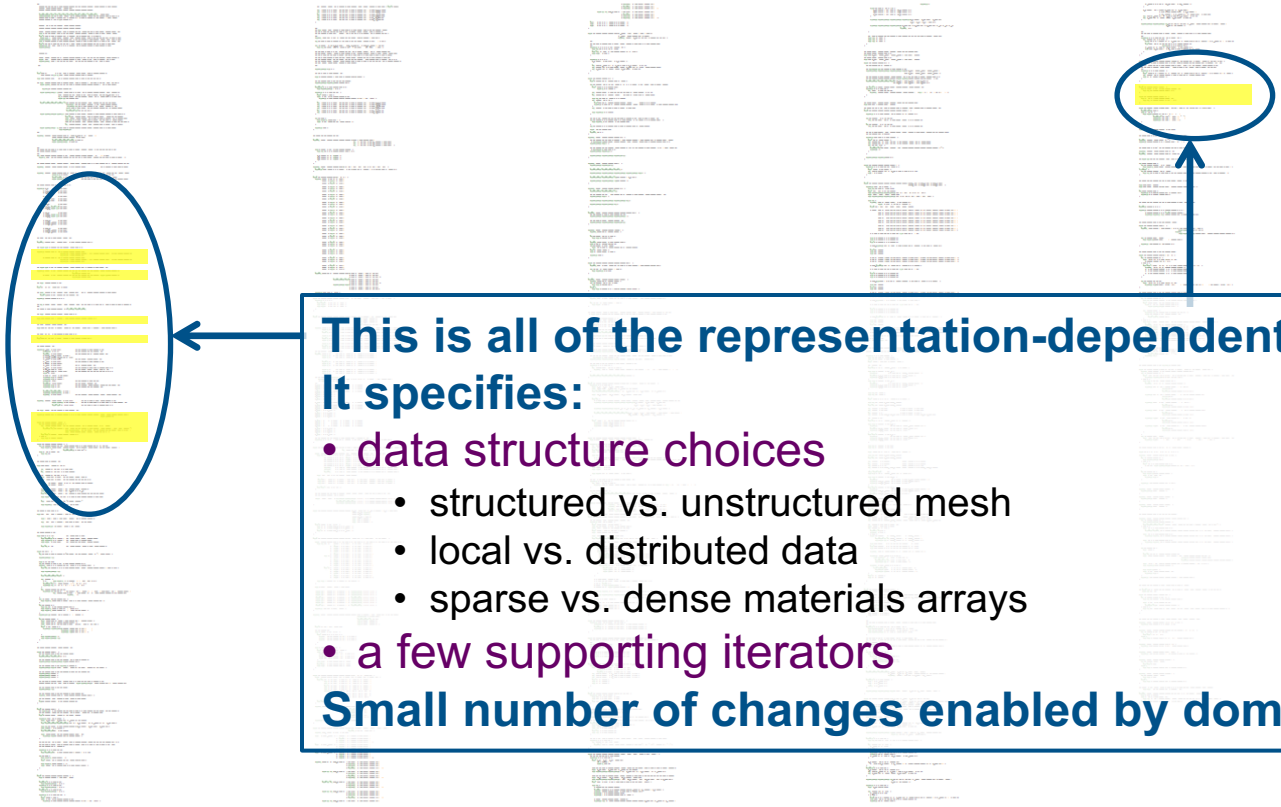
LULESH in Chapel



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

Small number of changes enabled by domain maps

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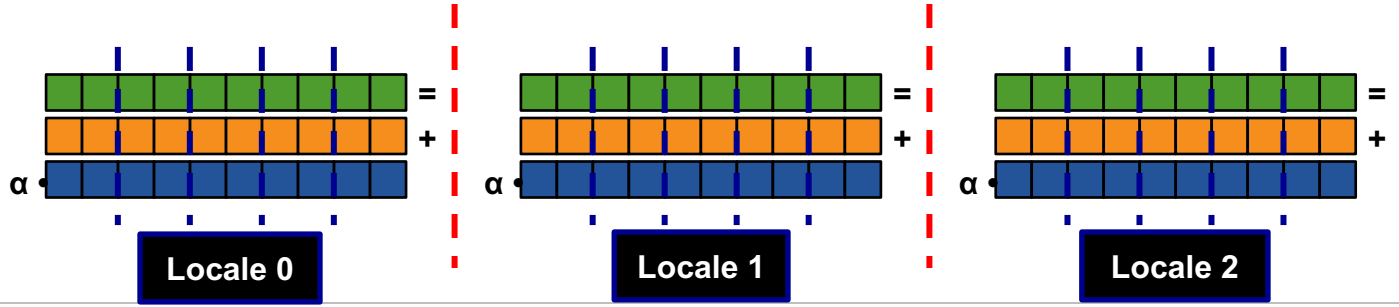
Domain Maps

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


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

…to the target locales’ memory and processors:



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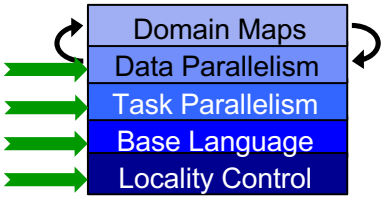
Chapel's Domain Map Philosophy

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 end-user framework**
   - to avoid a performance cliff between "built-in" and user-defined cases
   - in fact *every* Chapel array is implemented using this framework

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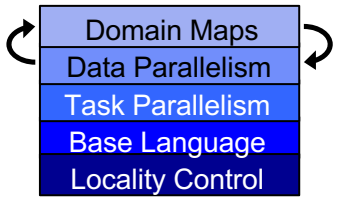
Chapel's Multiresolution Philosophy

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

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



- build the higher-level concepts in terms of the lower
- permit users to intermix layers arbitrarily

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Two Other Multiresolution Features

1) **parallel iterators:** User-specified forall-loop implementations
   - how many tasks to use and where they run
   - how iterations are divided between the tasks
   - how to zipper with other parallel iterators

2) **locale models:** User-specified locale types for new node architectures
   - how do I manage memory, create tasks, communicate, …

Like domain maps, these are…

…written in Chapel by expert users using lower-level features

…available to the end-user via higher-level abstractions

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This Talk's Takeaways

If you design a parallel programming language…

…create attractive ways of expressing parallelism and locality

- these are key concerns—shouldn't be yet another library call / pragma

…support first-class index sets

- very expressive concept for users (not seen here, today)
- enable the implementation to reason about alignment (ditto)

…support multiresolution features

- give users the ability to develop their own parallel policies

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Puttin' me down for thinking of someone new
Always the same
Playin' your game
Drive me insane…

Computer Language Benchmarks Game Results

Your Time is Gonna Come
Led Zeppelin
Led Zeppelin

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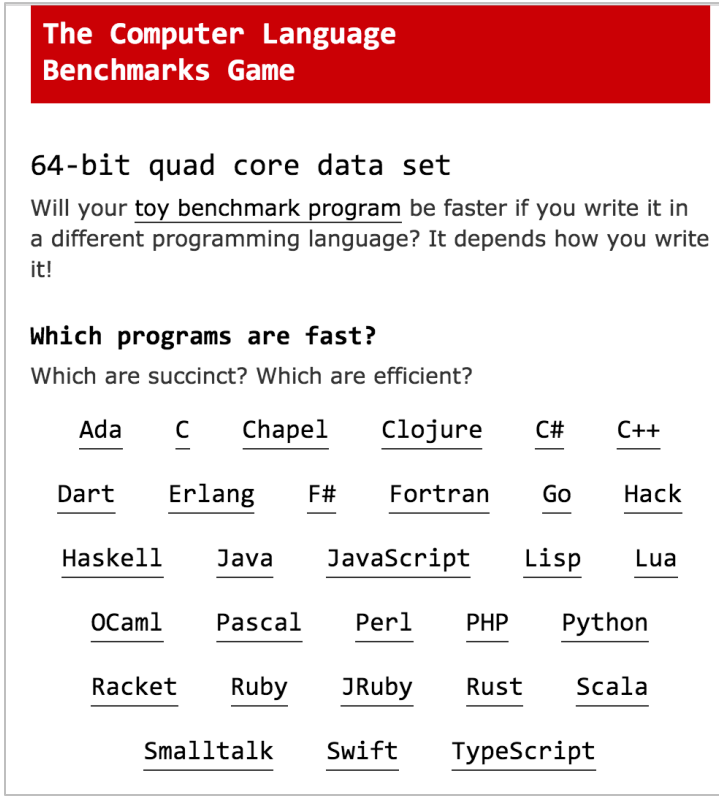
Computer Language Benchmarks Game (CLBG)



Website supporting cross-language comparisons

- 13 toy benchmark programs
  - exercise key computational idioms
  - specific approach prescribed

Take results with a grain of salt

- your mileage may vary

That said, it is one of the only such games in town…

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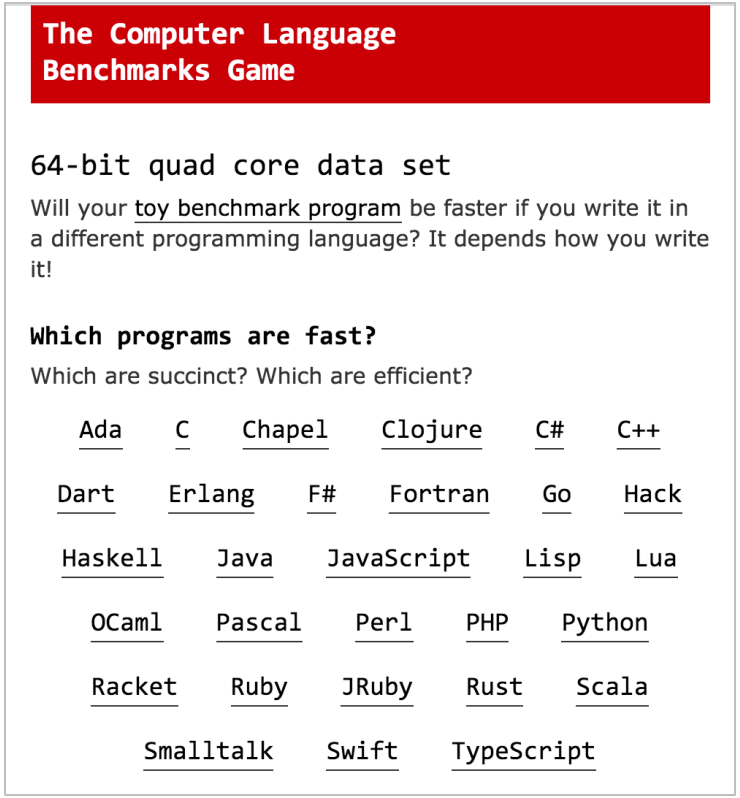
Computer Language Benchmarks Game (CLBG)



Chapel's approach to the CLBG:

- striving for elegance over heroism
  - ideally: "Want to learn how program xyz works? Read the Chapel version."

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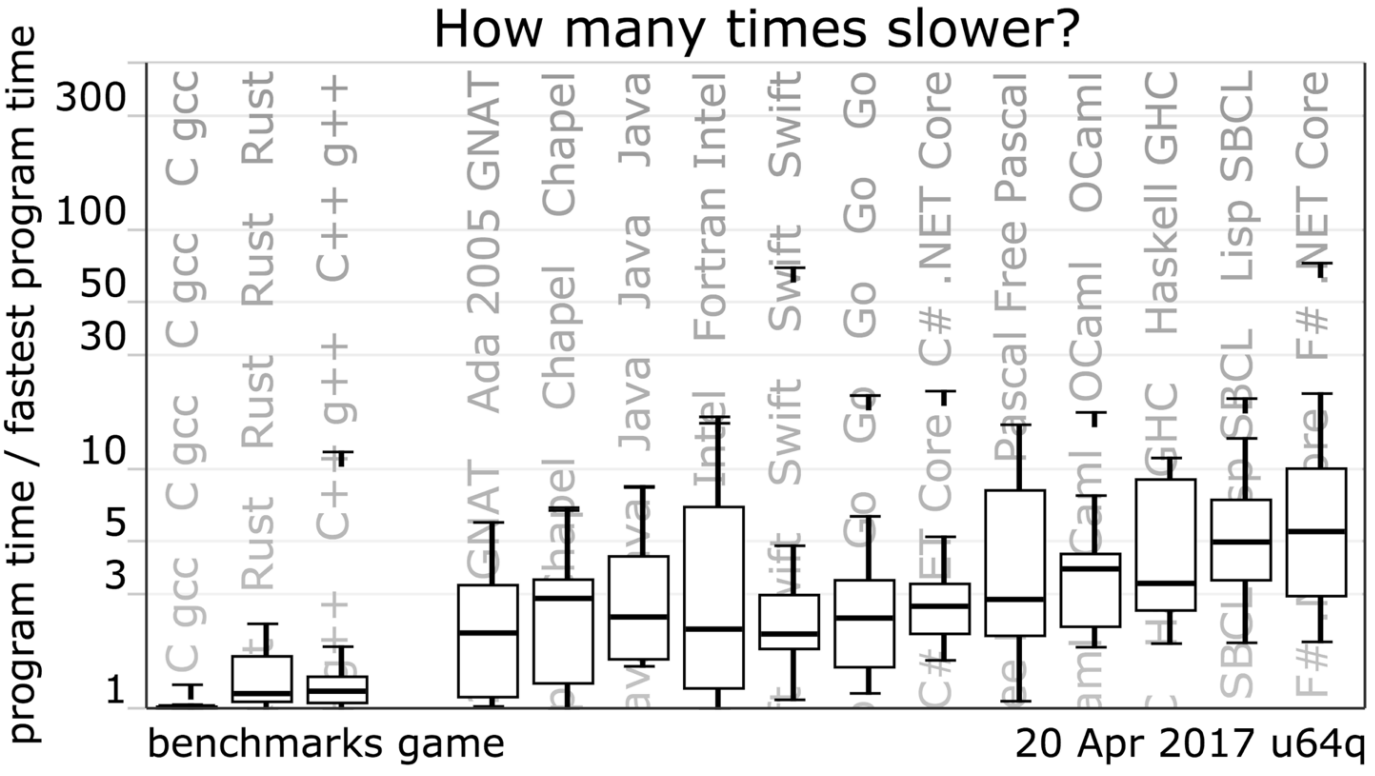
CLBG: Relative Performance Summary



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CLBG: Website

Can sort results by execution time, code size, memory or CPU use:

The Computer Language Benchmarks Game

chameneos-redux

description

program source code, command-line and measurements

×	source	secs	mem	gz	cpu	cpu load
1.0	**C** gcc #5	**0.60**	820	2863	2.37	100% 100% 98% 100%
1.2	**C++** g++ #5	**0.70**	3,356	1994	2.65	100% 100% 91% 92%
1.7	**Lisp** SBCL #3	**1.01**	55,604	2907	3.93	97% 96% 99% 99%
2.3	**Chapel** #2	**1.39**	76,564	1210	5.43	99% 99% 98% 99%
3.3	**Rust** #2	**2.01**	56,936	2882	7.81	97% 98% 98% 98%
5.6	C++ g++ #2	3.40	1,880	2016	11.88	100% 51% 100% 100%
6.8	Chapel	4.09	66,584	1199	16.25	100% 100% 100% 100%
8.0	**Java** #4	**4.82**	37,132	1607	16.73	98% 98% 54% 99%
8.5	**Haskell** GHC	**5.15**	8,596	989	9.26	79% 100% 2% 2%
10	Java	6.13	53,760	1770	8.78	42% 45% 41% 16%
10	Haskell GHC #4	6.34	6,908	989	12.67	99% 100% 2% 1%
11	**C#** .NET Core	**6.59**	86,076	1400	22.96	99% 82% 78% 91%
11	**Go**	**6.90**	832	1167	24.19	100% 96% 56% 100%
13	Go #2	7.59	1,384	1408	27.65	91% 99% 99% 78%
13	Java #3	7.94	53,232	1267	26.86	54% 96% 98% 94%

The Computer Language Benchmarks Game

chameneos-redux

description

program source code, command-line and measurements

×	source	secs	mem	gz	cpu	cpu load
1.0	**Erlang**	58.90	28,668	**734**	131.19	62% 60% 51% 53%
1.0	**Erlang** HiPE	59.39	25,784	**734**	131.58	60% 56% 56% 54%
1.1	**Perl** #4	5 min	14,084	**785**	7 min	40% 40% 29% 28%
1.1	**Racket**	5 min	132,120	**791**	5 min	1% 0% 0% 100%
1.1	Racket #2	175.88	116,488	842	175.78	100% 1% 1% 0%
1.2	**Python 3** #2	236.84	7,908	**866**	5 min	24% 48% 27% 45%
1.3	**Ruby**	90.52	9,396	**920**	137.53	35% 35% 35% 34%
1.3	**Ruby** JRuby	48.78	628,968	**928**	112.15	65% 60% 49% 58%
1.3	**Go** #5	11.05	832	**957**	32.48	75% 74% 75% 73%
1.3	**Haskell** GHC #4	6.34	6,908	**989**	12.67	99% 100% 2% 1%
1.3	Haskell GHC	5.15	8,596	989	9.26	79% 100% 2% 2%
1.6	**OCaml** #3					32% 38% 37% 39%
1.6	Go					100% 96% 56% 100%
1.6	**Chapel**					0% 100% 100% 100%
1.6	Chapel #2					99% 99% 98% 99%

gz == code size metric
strip comments and extra whitespace, then gzip

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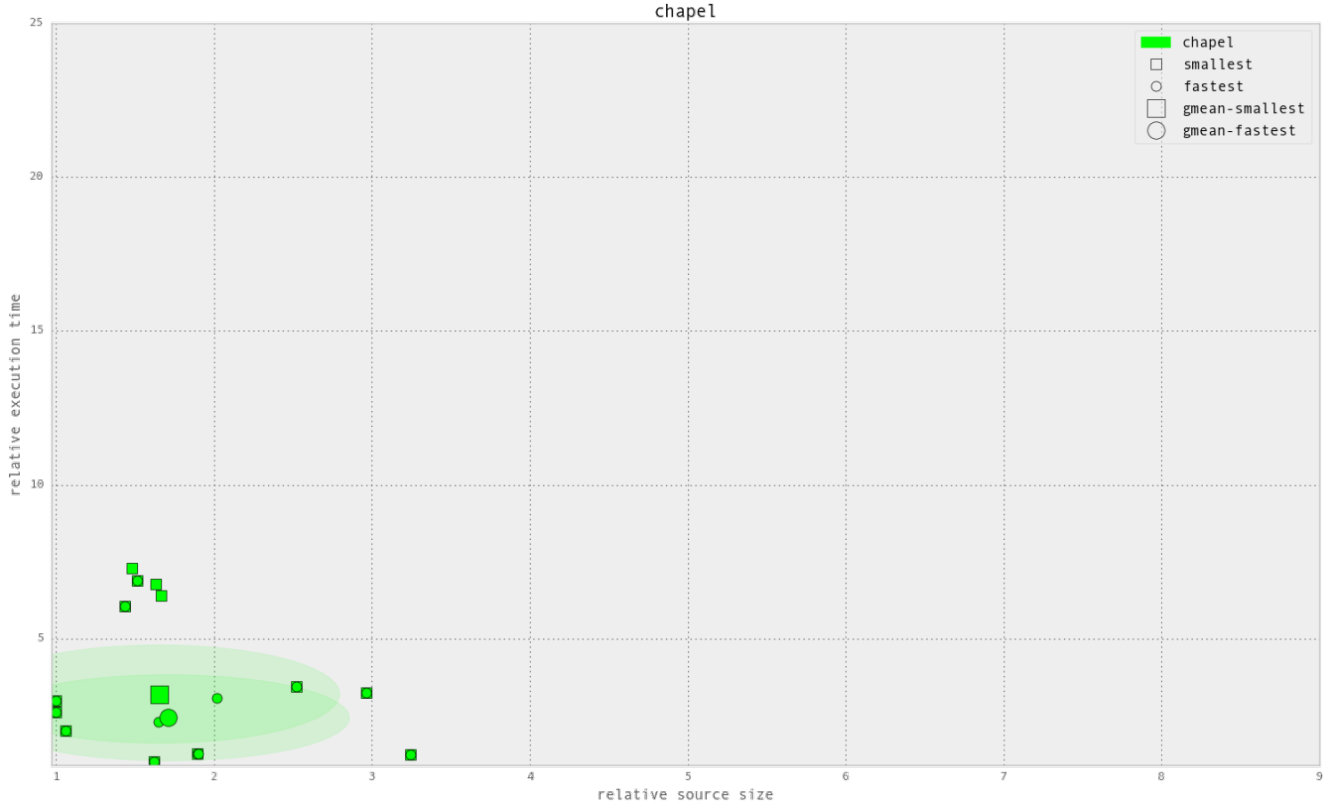
CLBG: Chapel entries



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CLBG: Chapel vs. 9 key languages

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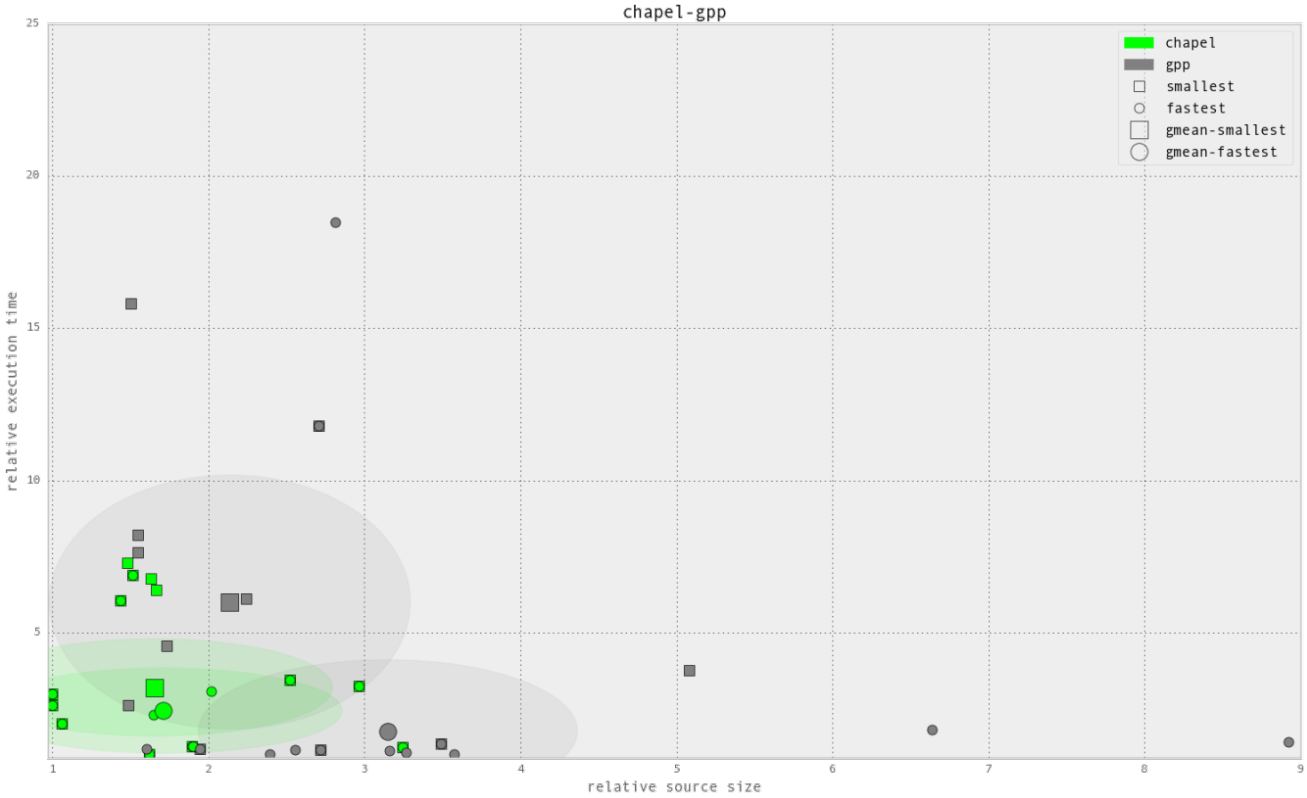
Chapel vs. C++



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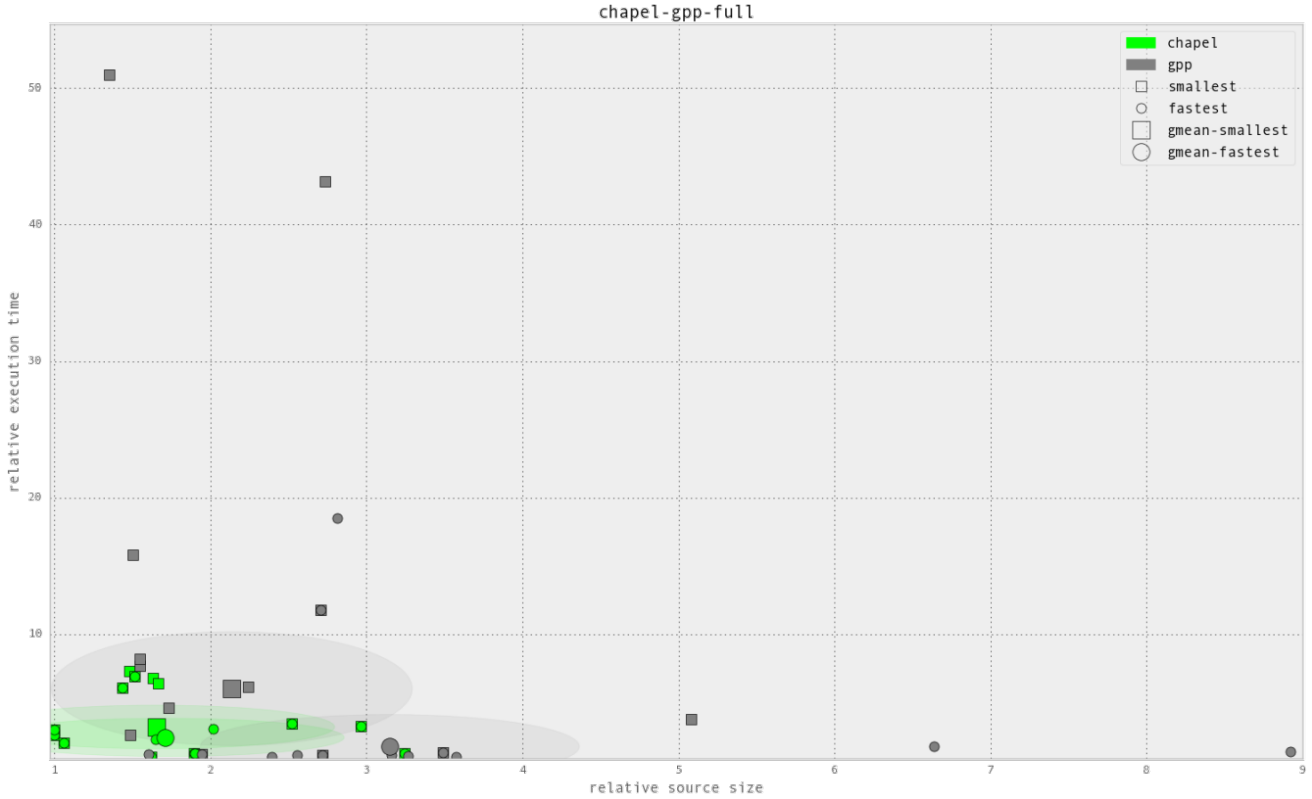
Chapel vs. C++ (zoomed out)



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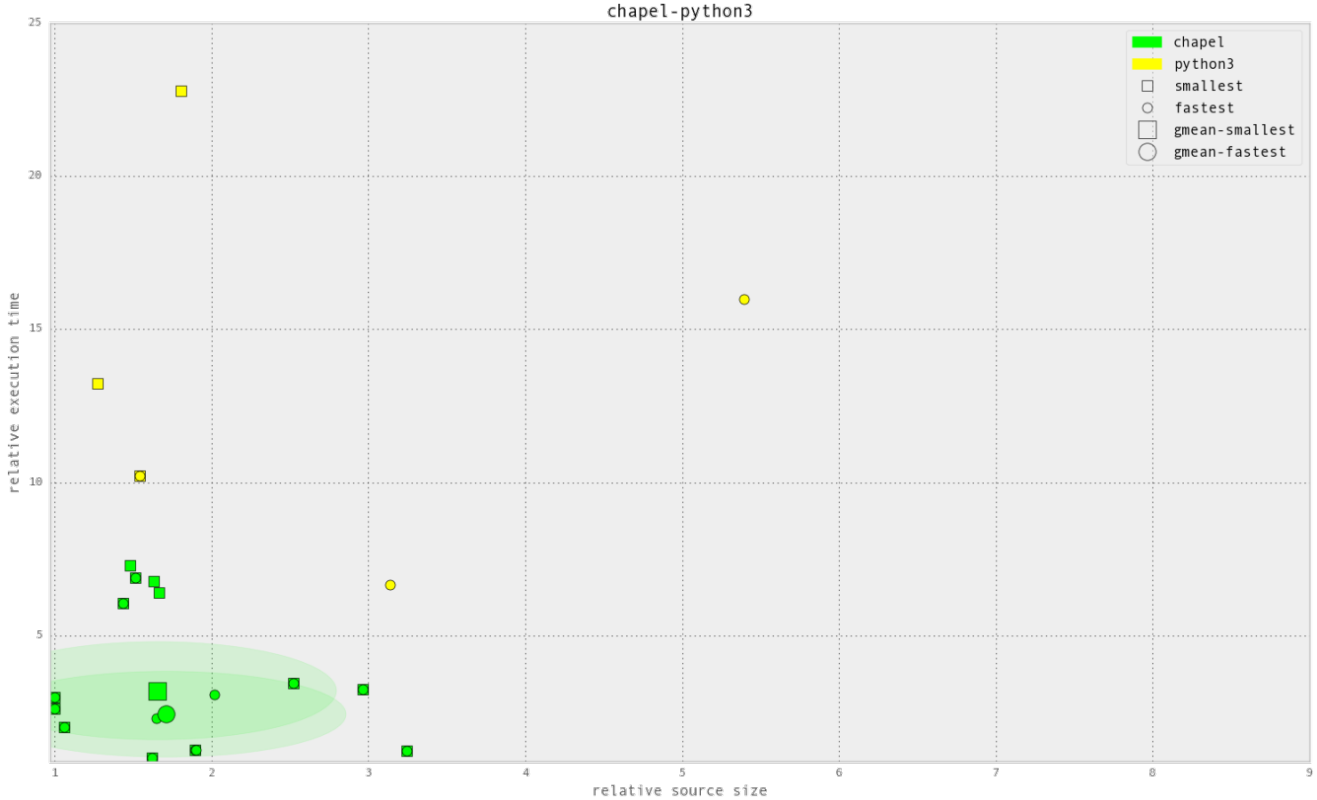
Chapel vs. Python



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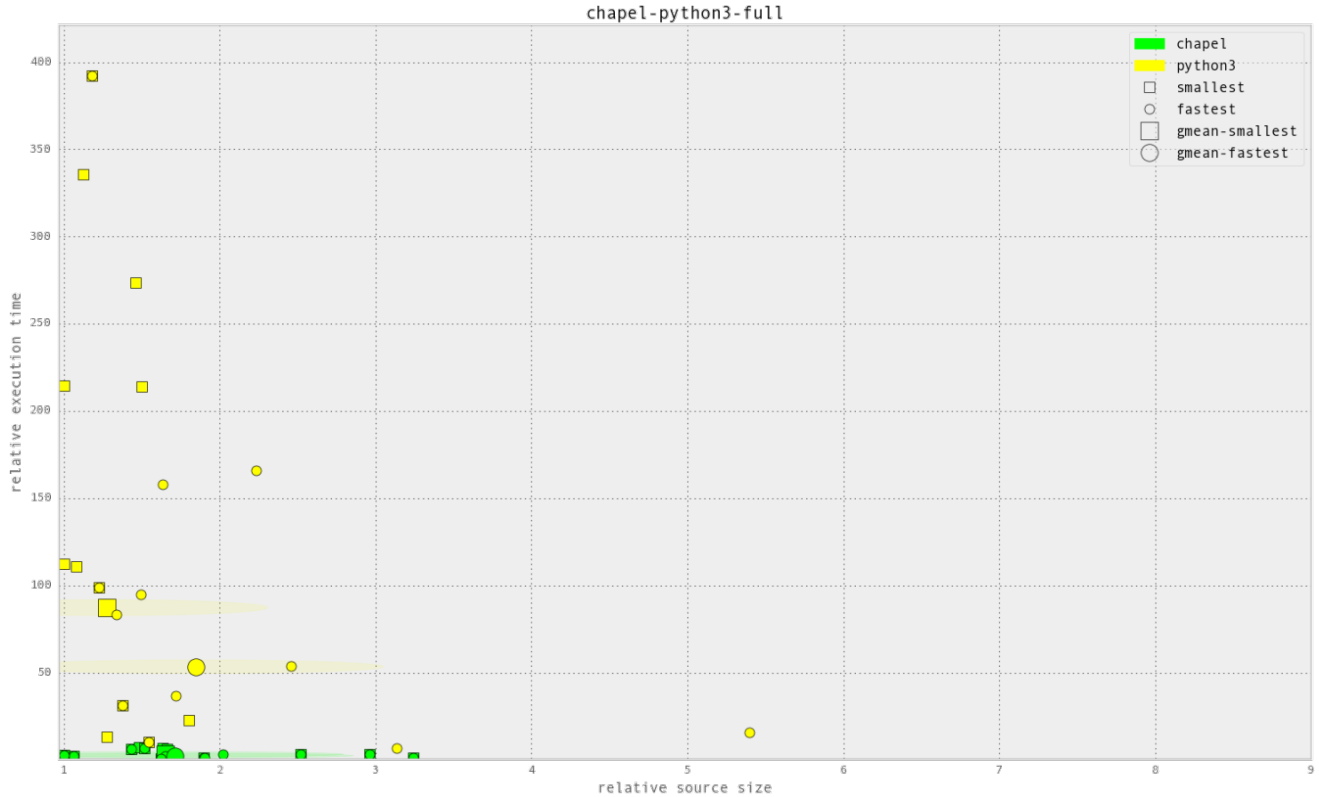
Chapel vs. Python (zoomed out)



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CLBG: Qualitative Comparisons

Can also browse program source code (but this requires actual thought):

```
proc main() {
  printColorEquations();

  const group1 = [i in 1..popSize1] new Chameneos(i, ((i-1)%3):Color);
  const group2 = [i in 1..popSize2] new Chameneos(i, colors10[i]);

  cobegin {
    holdMeetings(group1, n);
    holdMeetings(group2, n);
  }

  print(group1);
  print(group2);

  for c in group1 do delete c;
  for c in group2 do delete c;
}


//
// Print the results of getNewColor() for all color pairs.
//
proc printColorEquations() {
  for c1 in Color do
    for c2 in Color do
      writeln(c1, " + ", c2, " -> ", getNewColor(c1, c2));
  writeln();
}


//
// Hold meetings among the population by creating a shared meeting
// place, and then creating per-chameneos tasks to have meetings.
//
proc holdMeetings(population, numMeetings) {
  const place = new MeetingPlace(numMeetings);

  coforall c in population do            // create a task per chameneos
    c.haveMeetings(place, population);

  delete place;
}
```

excerpt from 1210 gz Chapel entry

```
void get_affinity(int* is_smp, cpu_set_t* affinity1, cpu_set_t* affinity2)
{
    cpu_set_t                   active_cpus;
    FILE*                       f;
    char                        buf [2048];
    char const*                 pos;
    int                         cpu_idx;
    int                         physical_id;
    int                         core_id;
    int                         cpu_cores;
    int                         apic_id;
    size_t                      cpu_count;
    size_t                      i;

    char const*                 processor_str       = "processor";
    size_t                      processor_str_len   = strlen(processor_str);
    char const*                 physical_id_str     = "physical id";
    size_t                      physical_id_str_len = strlen(physical_id_str);
    char const*                 core_id_str         = "core id";
    size_t                      core_id_str_len     = strlen(core_id_str);
    char const*                 cpu_cores_str       = "cpu cores";
    size_t                      cpu_cores_str_len   = strlen(cpu_cores_str);

    CPU_ZERO(&active_cpus);
    sched_getaffinity(0, sizeof(active_cpus), &active_cpus);
    cpu_count = 0;
    for (i = 0; i != CPU_SETSIZE; i += 1)
    {
        if (CPU_ISSET(i, &active_cpus))
        {
            cpu_count += 1;
        }
    }

    if (cpu_count == 1)
    {
        is_smp[0] = 0;
        return;
    }

    is_smp[0] = 1;
    CPU_ZERO(affinity1);
```

excerpt from 2863 gz C gcc entry

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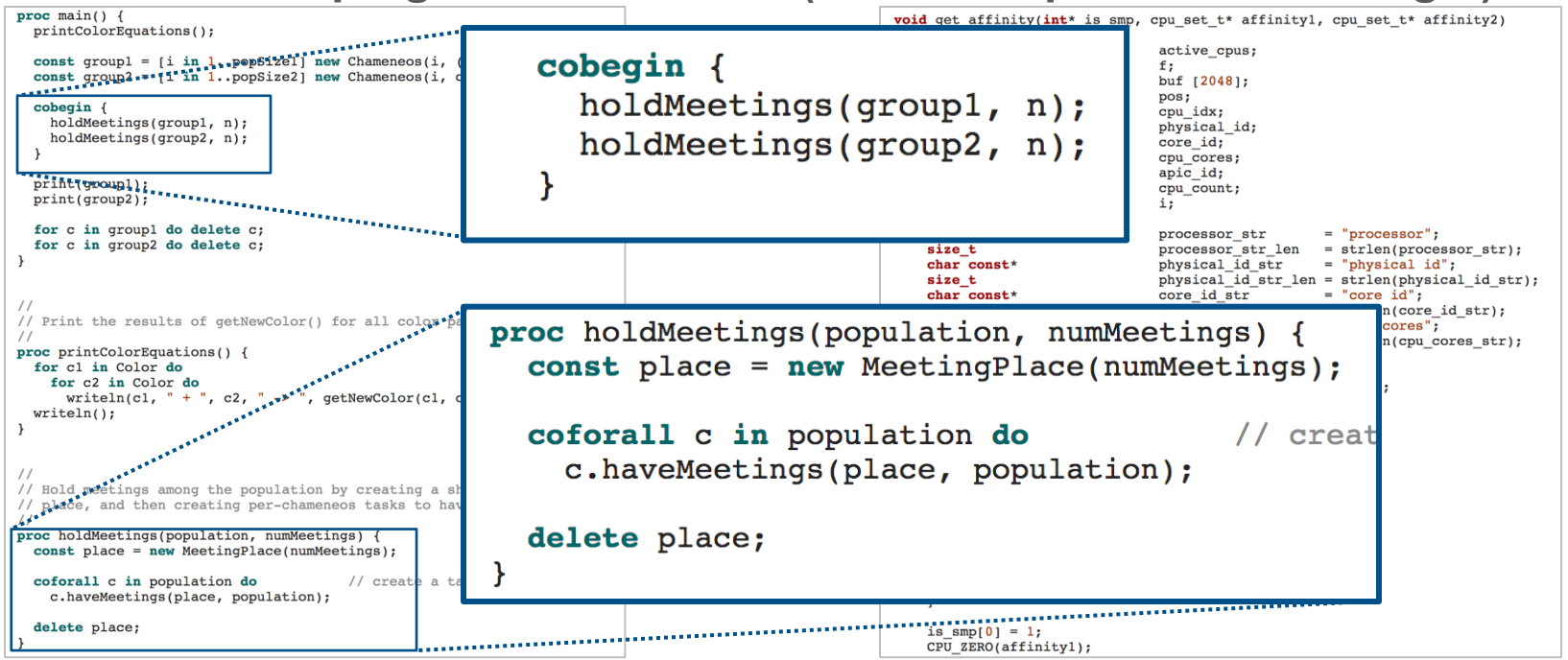
CLBG: Qualitative Comparisons

Can also browse program source code (but this requires actual thought):



excerpt from 1210 gz Chapel entry

excerpt from 2863 gz C gcc entry

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CLBG: Qualitative Comparisons

Can also browse program source code (but this requires actual thought):

```
proc main() {
char const*                     core_id_str          = "core id"
size_t                          core_id_str_len      = strlen(co
char const*                     cpu_cores_str        = "cpu core
size_t                          cpu_cores_str_len    = strlen(cp

CPU_ZERO(&active_cpus);
sched_getaffinity(0, sizeof(active_cpus), &active_cpus);
cpu_count = 0;
for (i = 0; i != CPU_SETSIZE; i += 1)
{
    if (CPU_ISSET(i, &active_cpus))
    {
        cpu_count += 1;
    }
}

if (cpu_count == 1)
{
    is_smp[0] = 0;
    return;
}
```

excerpt from 1210 gz Chapel entry

```
void get_affinity(int* is_smp, cpu_set_t* affinity1, cpu_set_t* affinity2)
{
    cpu_set_t                   active_cpus;
    FILE*                       f;
    char                        buf [2048];
    char const*                 pos;
    int                         cpu_idx;
    int                         physical_id;
    int                         core_id;
    int                         cpu_cores;
    int                         apic_id;
    size_t                      cpu_count;
    size_t                      i;

    char const*                 processor_str       = "processor";
    size_t                      processor_str_len   = strlen(processor_str);
    char const*                 physical_id_str     = "physical id";
    size_t                      physical_id_str_len = strlen(physical_id_str);
    char const*                 core_id_str         = "core id";
    size_t                      core_id_str_len     = strlen(core_id_str);
    char const*                 cpu_cores_str       = "cpu cores";
    size_t                      cpu_cores_str_len   = strlen(cpu_cores_str);

    CPU_ZERO(&active_cpus);
    sched_getaffinity(0, sizeof(active_cpus), &active_cpus);
    cpu_count = 0;
    for (i = 0; i != CPU_SETSIZE; i += 1)
    {
        if (CPU_ISSET(i, &active_cpus))
        {
            cpu_count += 1;
        }
    }

    if (cpu_count == 1)
    {
        is_smp[0] = 0;
        return;
    }

    is_smp[0] = 1;
    CPU_ZERO(affinity1);
```

excerpt from 2863 gz C gcc entry

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I have run
I have crawled
I have scaled…

Chapel Scalability Results

U2
I Still Haven't Found What I'm Looking For
The Joshua Tree

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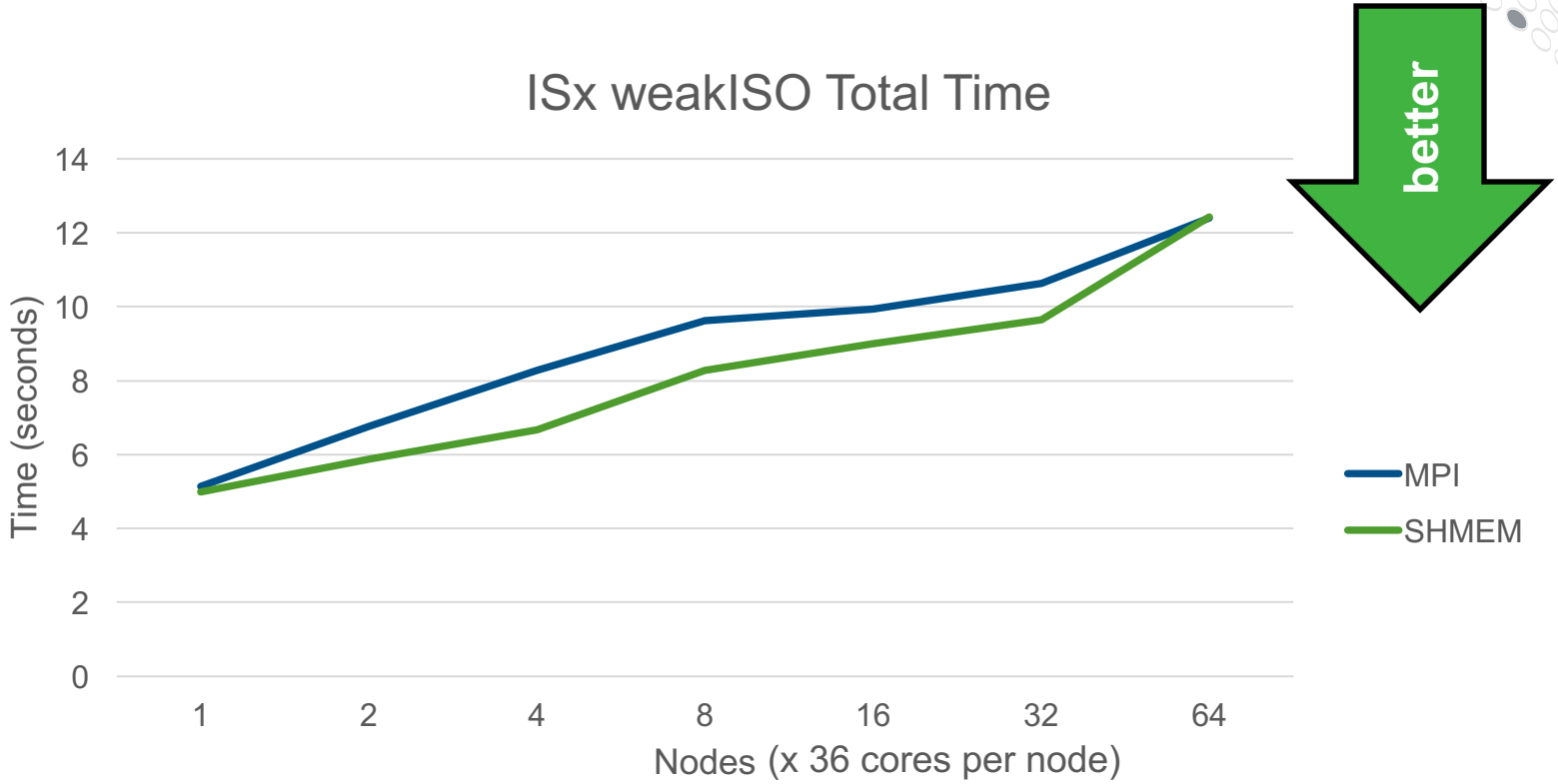
ISx Execution Time: MPI, SHMEM



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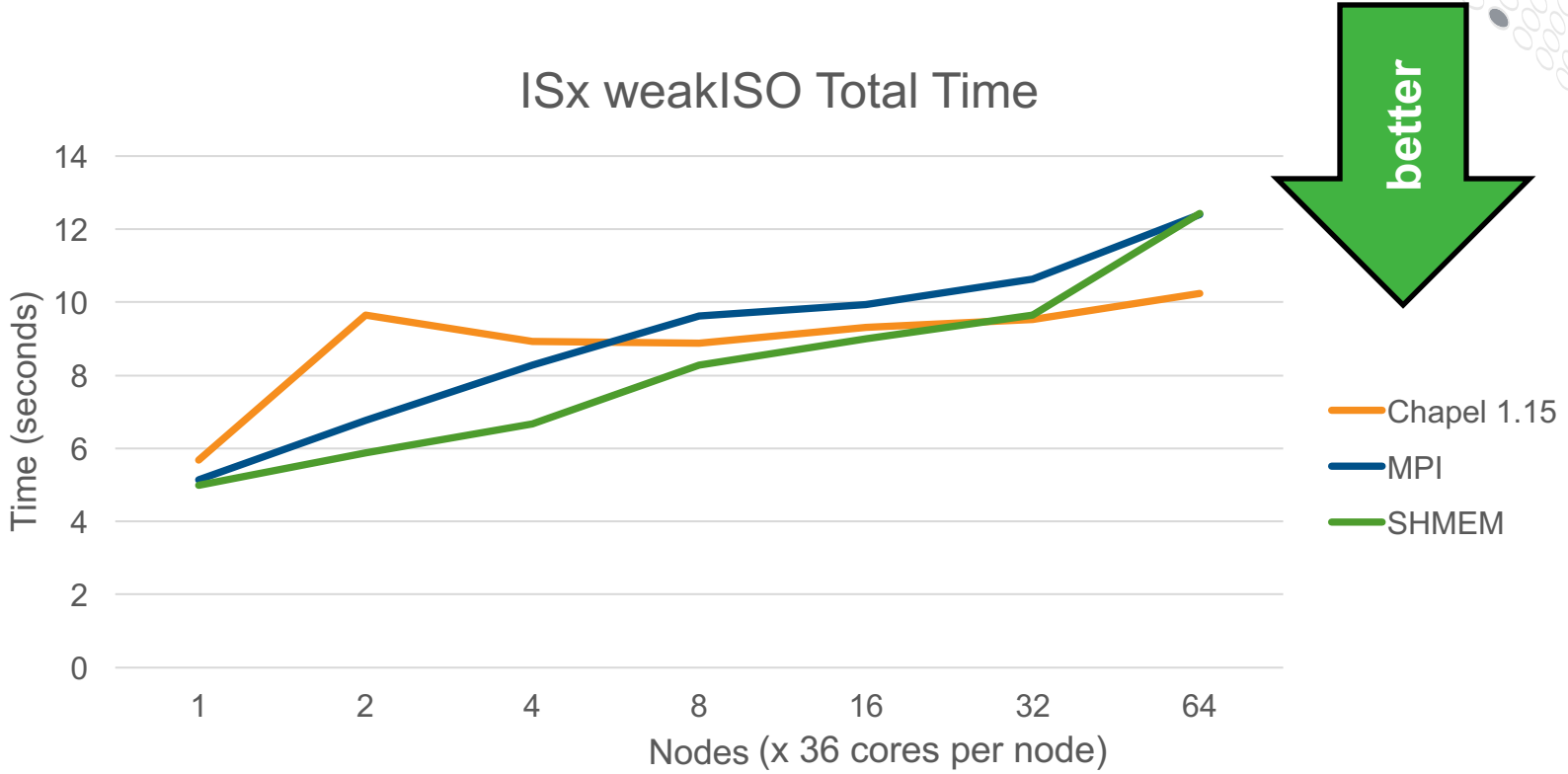
ISx Execution Time: MPI, SHMEM, Chapel



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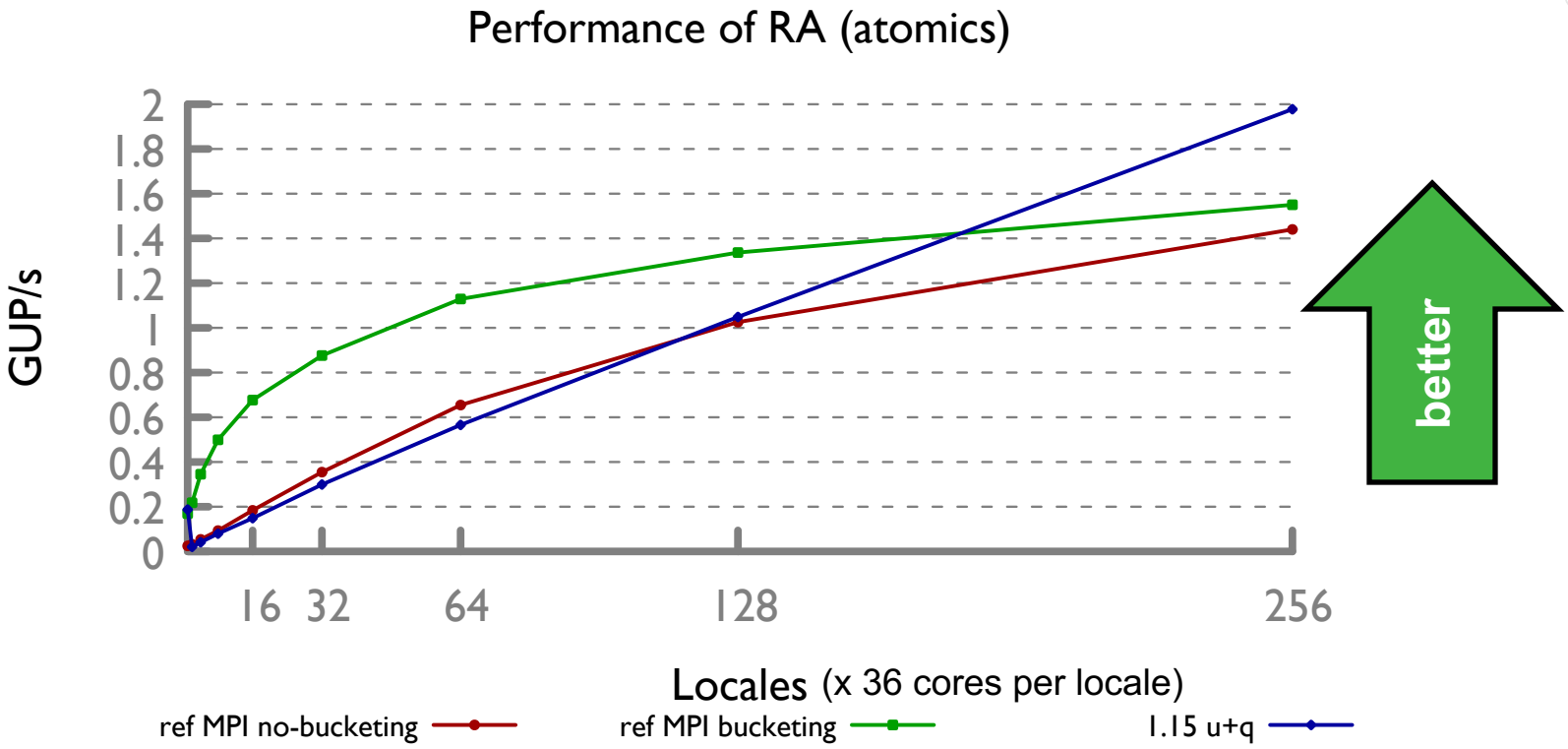
RA Performance: Chapel vs. MPI



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[At? And? Ah'm?] fourteen, and you know
That I've learned the easy way
Some stupid decisions
And with a...a broken heart

Summary

That Summer, at Home I Had Become The Invisible Boy
The Twilight Sad
Fourteen Autumns and Fifteen Winters

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This Talk's Thesis

Programming language designers have, to date, largely failed the large-scale parallel computing community.

- parallel features have historically been an afterthought
  - tacked on through libraries, pragmas, and extensions
  - rarely first-class
- even when languages are designed for parallelism…

  …most fail to consider scalable computing (distributed memory)

  …others tend to be domain-specific and not very general

We can do better!

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We think Chapel is an attractive candidate

- **Attractive language for end-users**
  - modern design
  - separates algorithmic specification from mapping to architecture
- **Able to achieve competitive performance**
  - though a good deal of tuning and optimization work remain…

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Recap of This Talk's Takeaways

If you design a parallel programming language…

…don't tie yourself to architecture-specific mechanisms

…don't base your model for parallelism and locality on SPMD

…create attractive ways of expressing parallelism and locality

…support first-class index sets

…support multiresolution features

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Chapel Challenges: Technical

- **design and optimization of multiresolution language features:**
  - domain maps
  - parallel iterators
  - locale models
- **compiler architecture: outgrowing the initial research prototype**
- **tools: classic chicken-and-egg problem**
  - IDE
  - debuggers
  - performance analysis
  - package manager
  - interactive development (interpreter, REPL, iPython, …)

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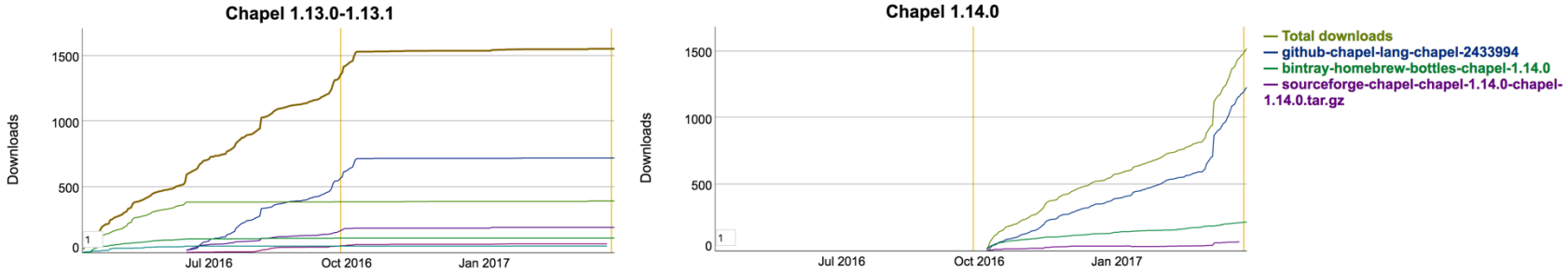
Chapel Challenges: Social

- **building up momentum in the user community**
  - lots of interest, but also lots of fear of being first / only adopter
  - 3000+ downloads / year for 2 releases



- **combatting impatience / numbness to our message and progress**
- **developing an aggressive language in a conservative field (HPC)**
- **engaging with peers in mainstream computing**

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Scratch my name on your arm with a fountain pen
This means you really love me

Further Resources

Rusholme Ruffians
The Smiths
Meat is Murder

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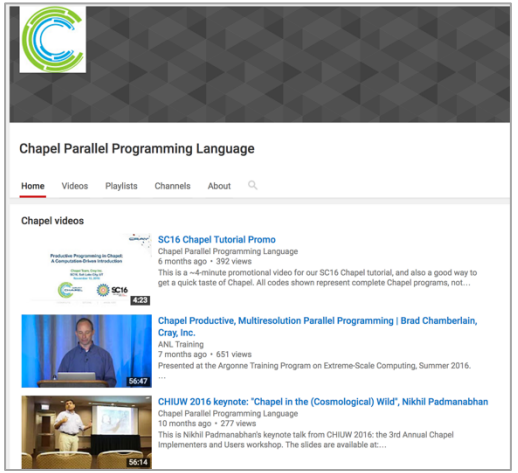
How to Stalk Chapel

http://facebook.com/ChapelLanguage

http://twitter.com/ChapelLanguage

https://www.youtube.com/channel/UCHmm27bYjhknK5mU7ZzPGsQ/

chapel-announce@lists.sourceforge.net



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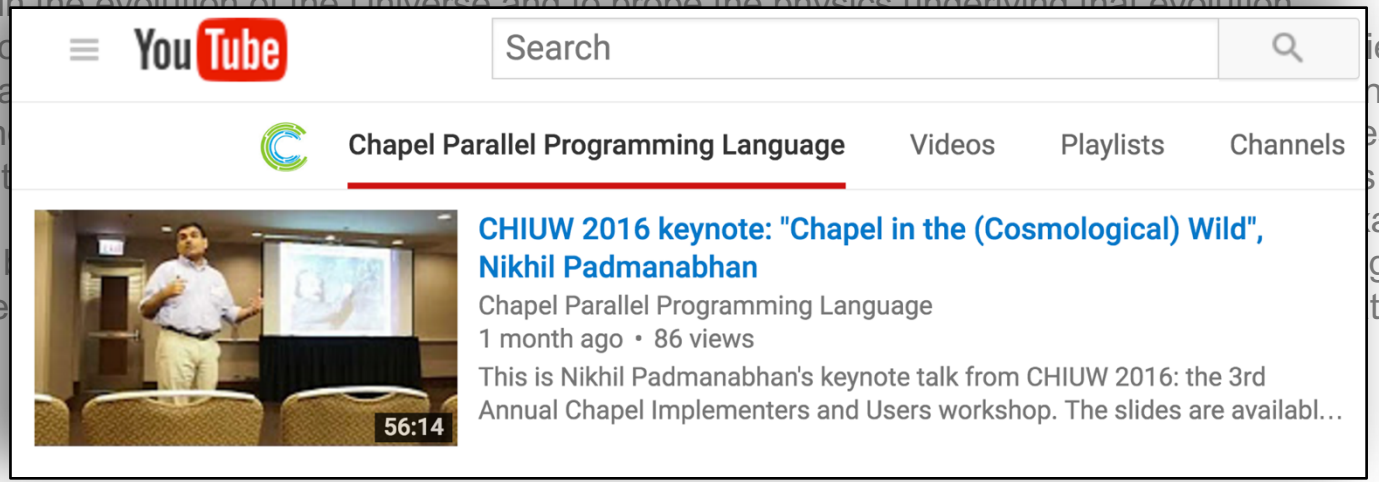
A Chapel talk to watch next (user perspective)

Chapel in the (Cosmological) Wild (CHIUW 2016 keynote)

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 and to probe the physics underlying that evolution. Operatic ies, both on actua ng a whirlwin es to solving t s quickly and the ample of Chapel l ghting its interope t it would take for



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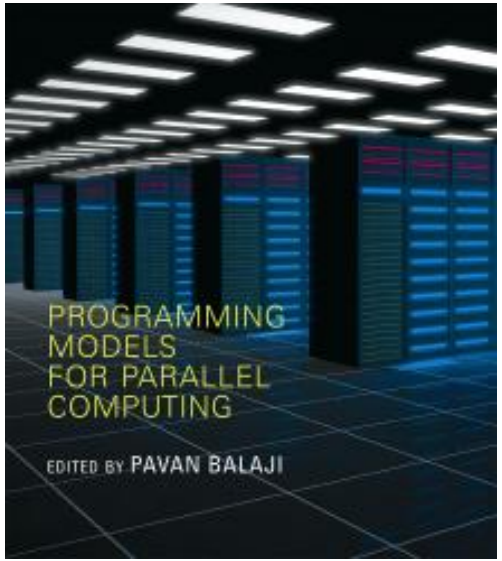
Suggested Reading (healthy attention spans)

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**

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Suggested Reading (short attention spans)

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

- *a short-and-sweet introduction to Chapel*

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*

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All we ever wanted was everything…

(I have Chapel swag to give you)

Get up
Eat jelly
sandwich bars, ….

(Have a good break and get some yummy snacks!)

ACCU 2017

All We Ever Wanted Was Everything
Bauhaus
The Sky's Gone Out

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