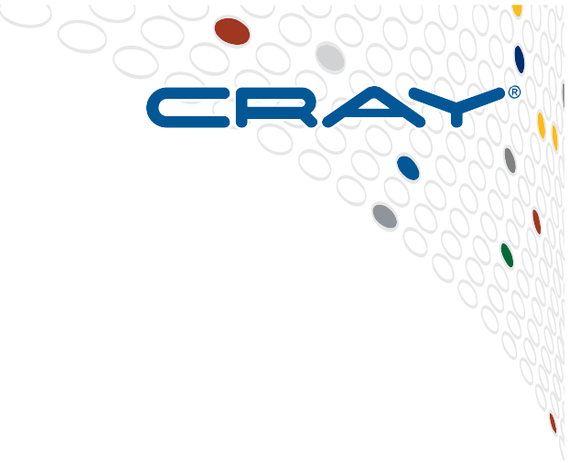


Data Parallelism with Locality:

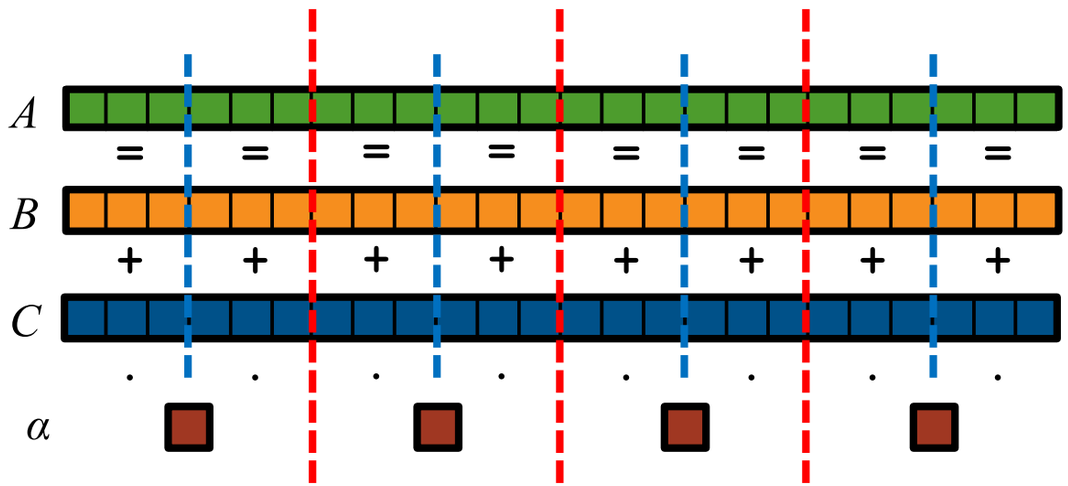
Domain Maps / Distributions (16x9 slides)

Scalable Parallel Programming Concerns

Q: What should scalable parallel programmers focus on?

A: ***Parallelism:*** What should execute simultaneously?

Locality: Where should those tasks execute?

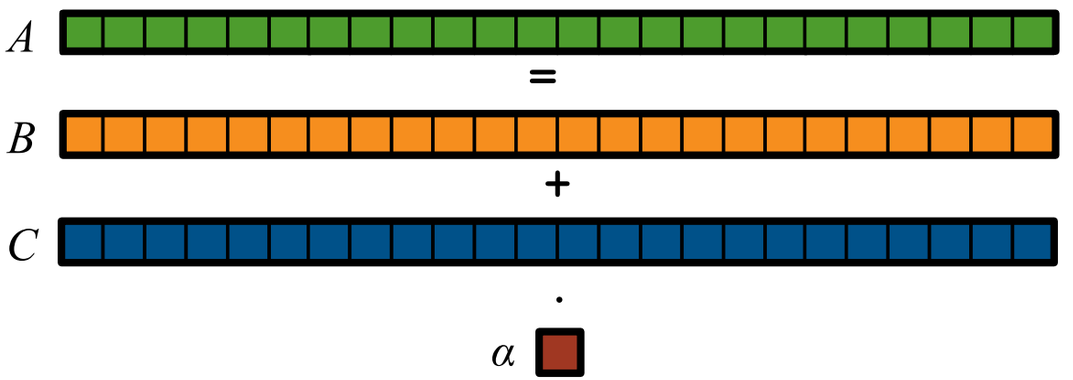


STREAM Triad: a trivial parallel computation

Given: m-element vectors A, B, C

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

In pictures:

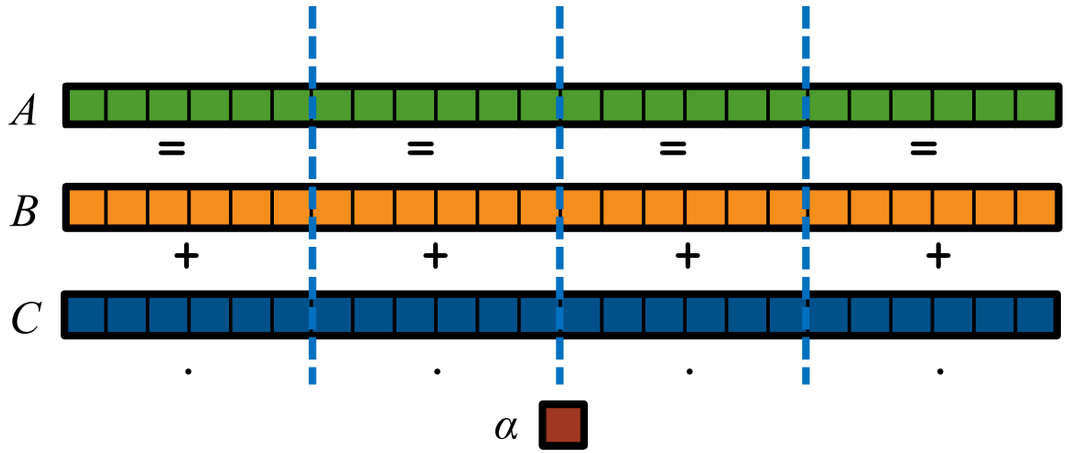


STREAM Triad: a trivial parallel computation

Given: m-element vectors A, B, C

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

In pictures, in parallel (shared memory / multicore):

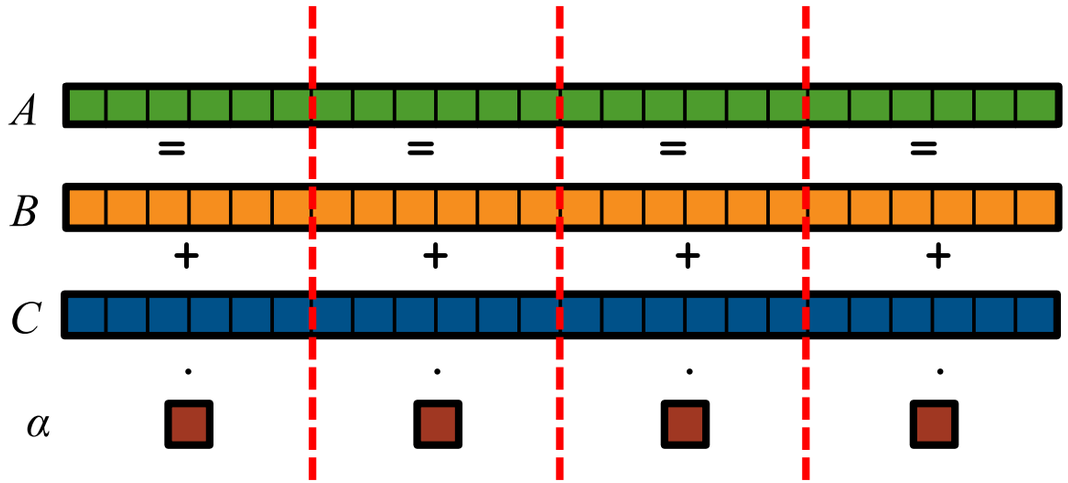


STREAM Triad: a trivial parallel computation

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):

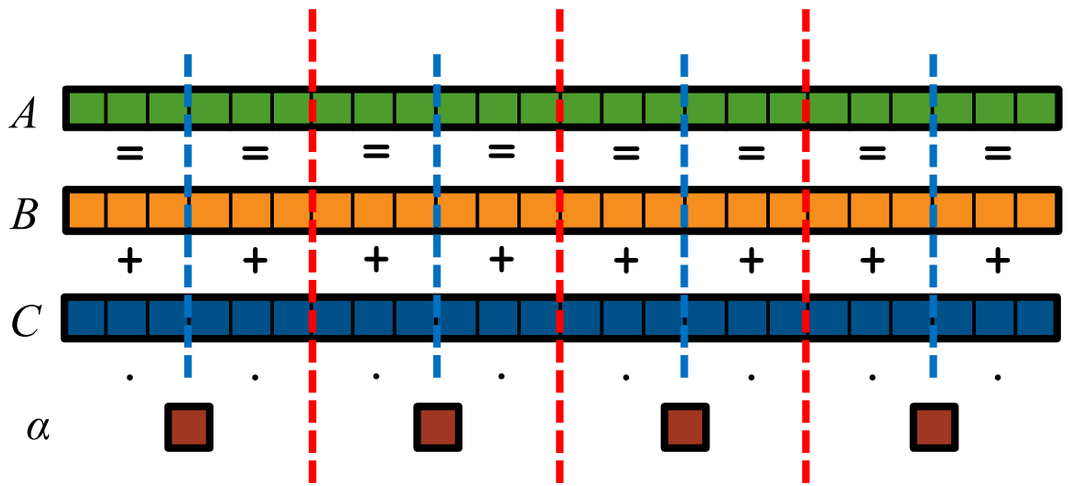


STREAM Triad: a trivial parallel computation

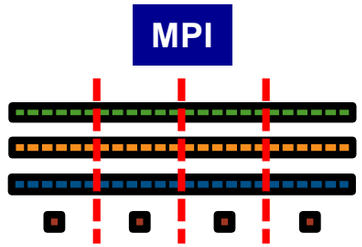
Given: m-element vectors A, B, C

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

In pictures, in parallel (distributed memory multicore):

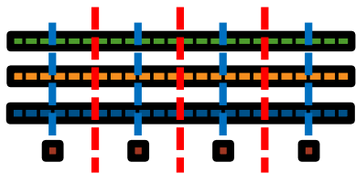


STREAM Triad: MPI

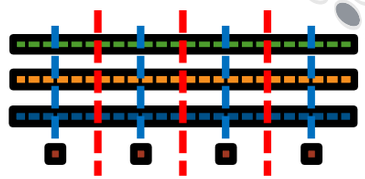



```
#include <hpcc.h>

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] = 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;  }
```

STREAM Triad: MPI+OpenMP

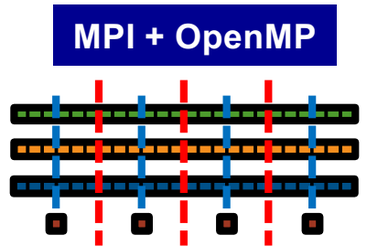



```
#include <hpcc.h>
#ifdef _OPENMP
#include <omp.h>
#endif

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;  }
```



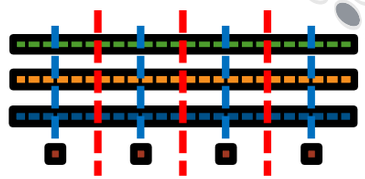

```
#define N 2000000
int main() {
  float *d_a, *d_b, *d_c;
  float scalar;

  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




```
#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;
  }

  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;  }
```

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




```
#define N 2000000

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

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

  dim3 dimBlock(128);
  dim3 dimGrid(N/dimBlock.x );
  if( N % dimBlock.x != 0 ) dimGrid.x+=1;

  set_array<<<dimGrid,dimBlock>>>(d_a, .5f, N);
  set_array<<<dimGrid,dimBlock>>>(d_b, 2.f, N);
  set_array<<<dimGrid,dimBlock>>>(d_c, .5f, N);

  scalar=3.f;
  STREAM_Triad<<<dimGrid,dimBlock>>>(d_b, d_c, d_a, scalar,  N);
  cudaThreadSynchronize();

  cudaFree(d_a);
  cudaFree(d_b);
  cudaFree(d_c);


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

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

Why so many programming models?

HPC tends to approach programming models bottom-up:

Given a system and its core capabilities…

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

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

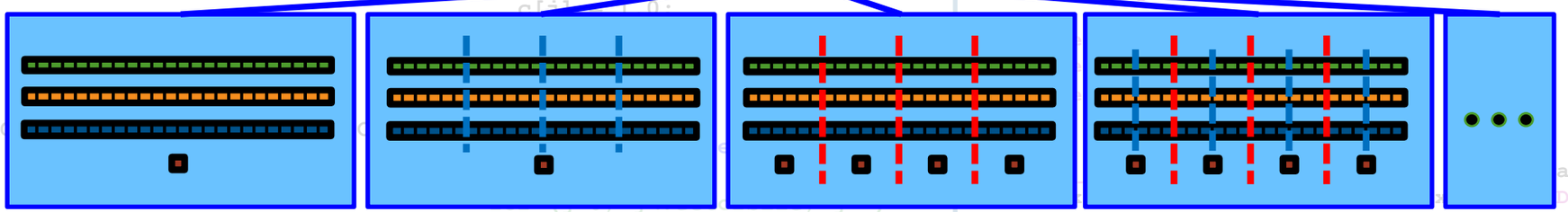
Type of HW Parallelism	Programming Model	Unit of Parallelism
Inter-node	MPI	executable
Intra-node/multicore	OpenMP / pthreads	iteration/task
Instruction-level vectors/threads	pragmas	iteration
GPU/accelerator	CUDA / Open[MP|CL|ACC]	SIMD function/task

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

STREAM Triad: Chapel

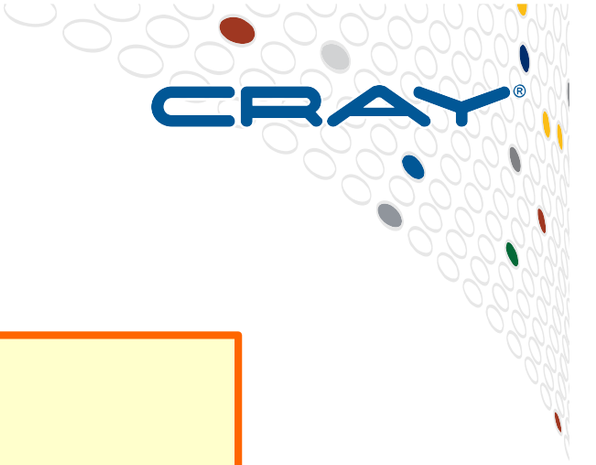
```
use …;

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.

Data Parallelism, by example



This is a shared memory program

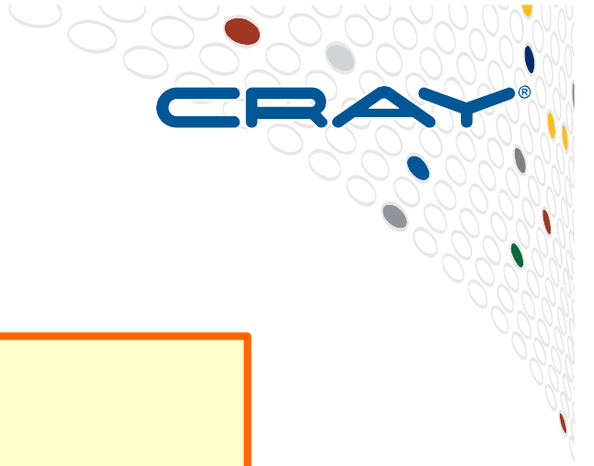
Nothing has referred to remote locales, explicitly or implicitly

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
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
```

Distributed Data Parallelism, by example

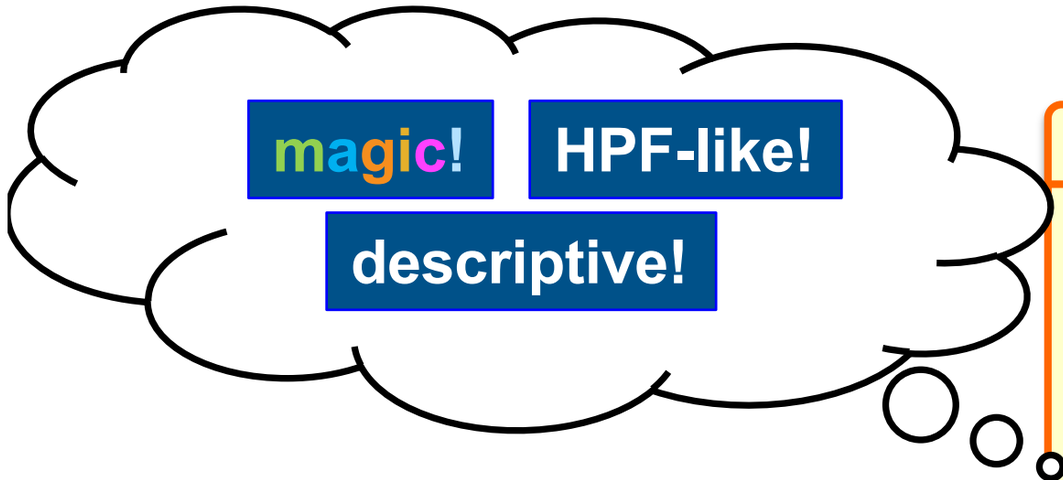


dataParallel.chpl

```
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
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
```

Distributed Data Parallelism, by example



dataParallel.chpl

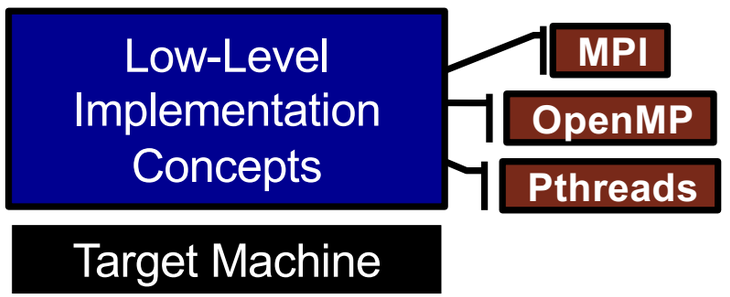
```
use CyclicDist;
config const n = 1000;
var D = {1..n, 1..n}
        dmapped Cyclic(startIdx = (1,1));
var A: [D] real;
forall (i,j) in D do
  A[i,j] = i + (j - 0.5)/n;
writeln(A);
```

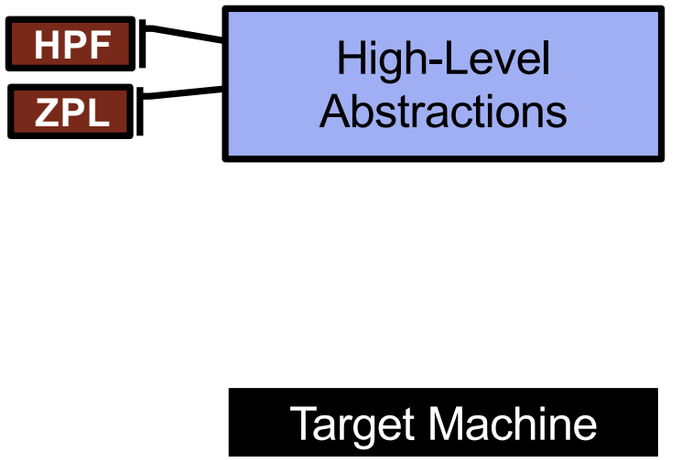
Not at all…

- Lowering of code is well-defined
- User can control details
- Part of Chapel's *multiresolution philosophy*…

```
prompt> chpl dataParallel.chpl
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
```

Chapel's Multiresolution Design: Motivation





"Why is everything so tedious/difficult?"

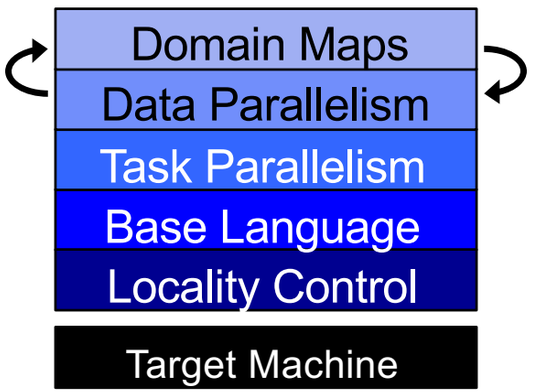
"Why don't my programs trivially port to new systems?"

"Why don't I have more control?"

Chapel's Multiresolution Philosophy

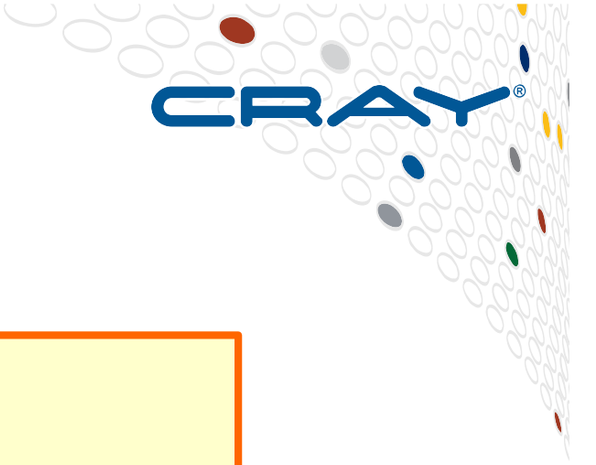
Multiresolution Design: Support multiple tiers of features

- 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

Distributed Data Parallelism, by example



Chapel's prescriptive approach:

```
forall (i,j) in D do…
```

⇒ invoke and inline D's default parallel iterator

- defined by D's type / domain map

default domain map

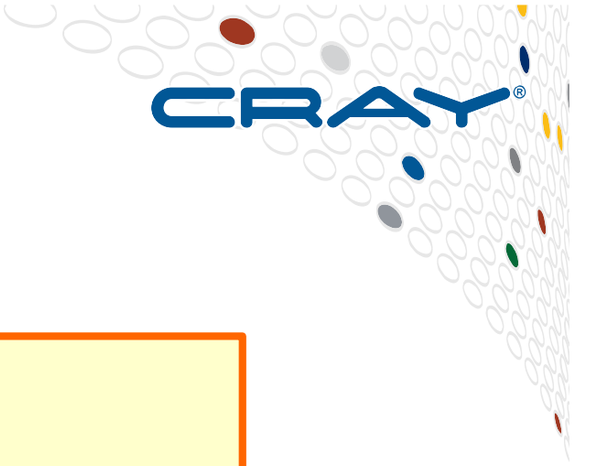
- create a task per local core
- block indices across tasks

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
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
```

Distributed Data Parallelism, by example



Chapel's prescriptive approach:

```
forall (i,j) in D do…
```

⇒ invoke and inline D's default parallel iterator

- defined by D's type / domain map

default domain map

cyclic domain map

on each target locale…

- create a task per core
- block local indices across tasks

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
prompt> ./dataParallel --n=5 --numLocales=4
1.1 1.3 1.5 1.7 1.9
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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
```
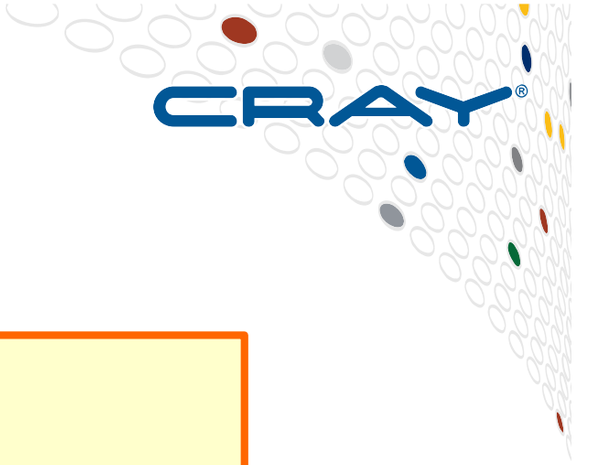

Distributed Data Parallelism, by example



Chapel's prescriptive approach:

```
forall (i,j) in D do…
```

⇒ in

- d
  domain map

What if I don't like D's iteration strategy?

dataParallel.chpl

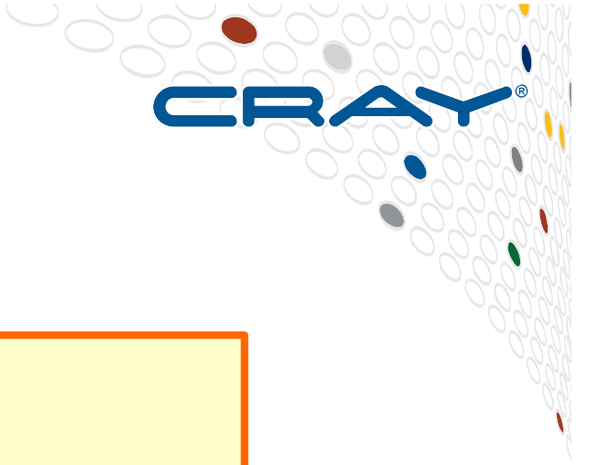
```
use CyclicDist;
config const n = 1000;
var D = {1..n, 1..n}
        dmapped Cyclic(startIdx = (1,1));
var A: [D] real;
forall (i,j) in D do
  A[i,j] = i + (j - 0.5)/n;
```

- Write and call your own parallel iterator:

```
forall (i,j) in myParIter(D) do…
```

```
rallel.chpl
lel --n=5 --numLocales=4
```

Distributed Data Parallelism, by example



Chapel's prescriptive approach:

```
forall (i,j) in D do…
```

⇒ in

- d
  domain map

What if I don't like D's iteration strategy?

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;
```

- Write and call your own parallel iterator:

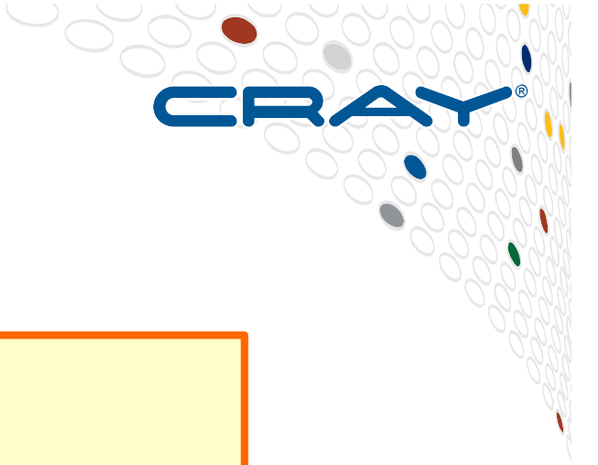
```
forall (i,j) in myParIter(D) do…
```

- Or, use a different domain map:

```
var D = {1..n, 1..n} dmapped Block(…);
```

```
rallel.chpl
lel --n=5 --numLocales=4
```

Distributed Data Parallelism, by example



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- Write and call your own parallel iterator:

```
forall (i,j) in myParIter(D) do…
```

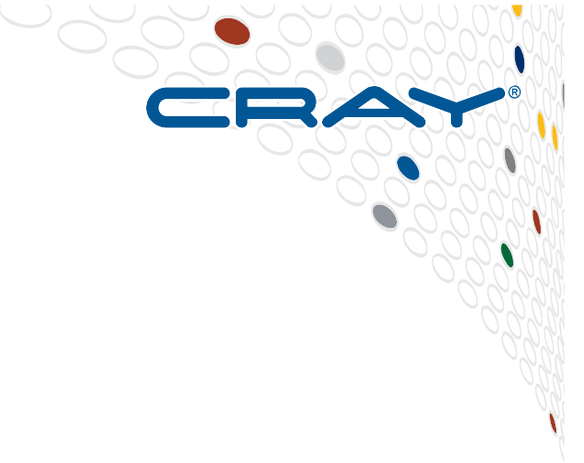
- Or, use a different domain map:

```
var D = {1..n, 1..n} dmapped Block(…);
```

- Or, write and use your own domain map:

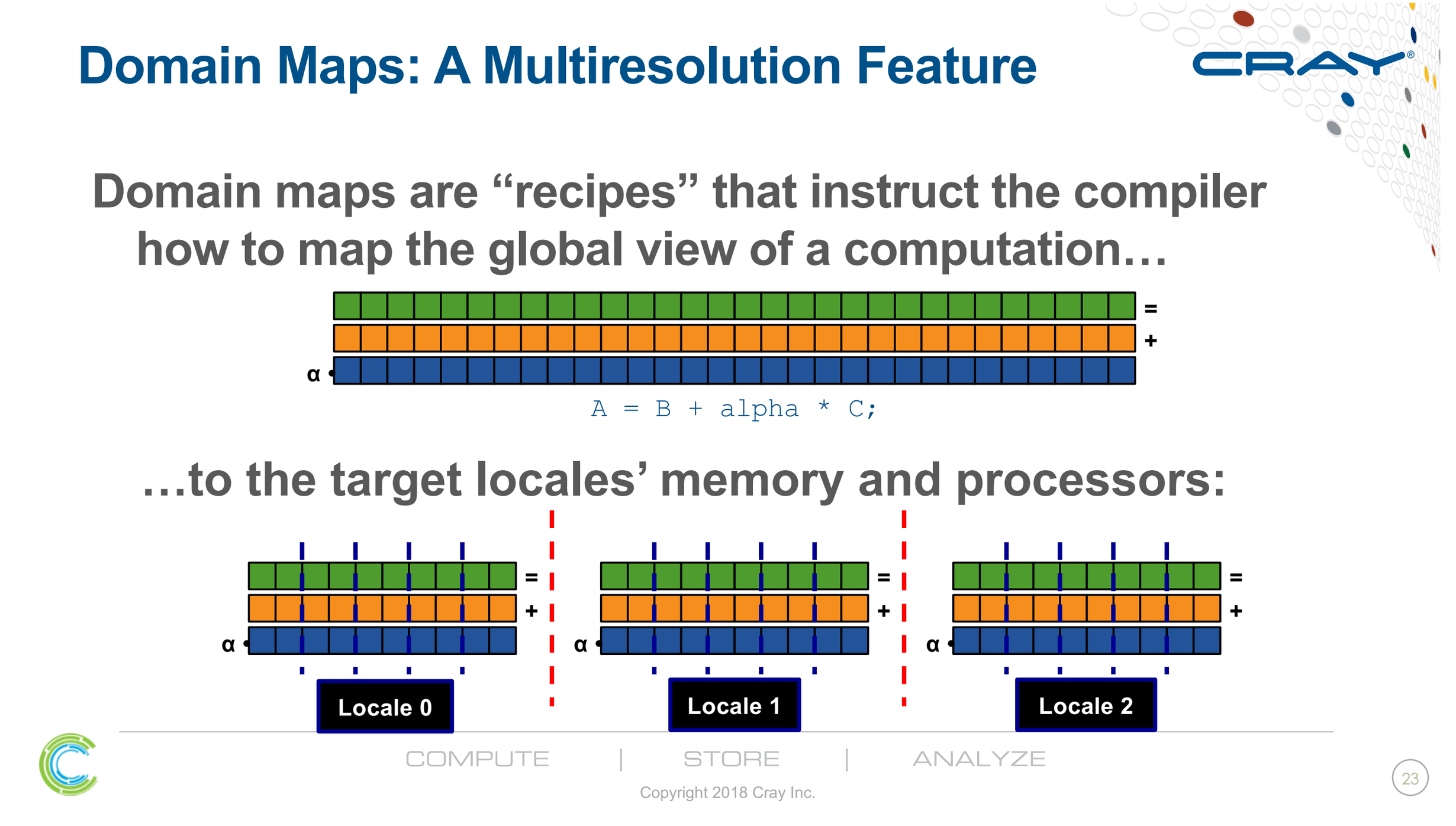
```
var D = {1..n, 1..n} dmapped MyDomMap(…);
```

```
rallel.chpl
lel --n=5 --numLocales=4
```



Use a Different Domain Map

Domain Maps: A Multiresolution Feature

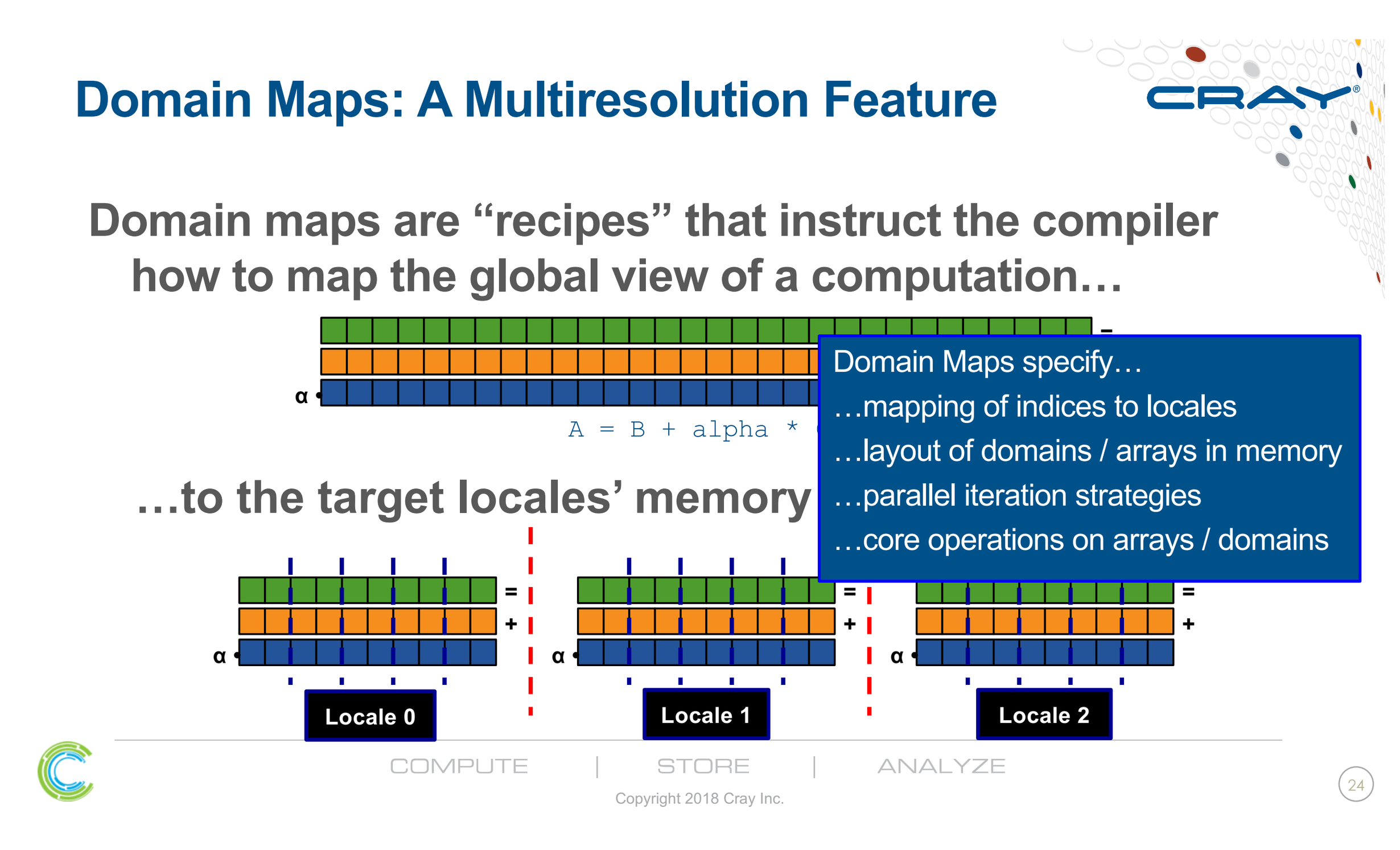


Domain maps are "recipes" that instruct the compiler how to map the global view of a computation…


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

…to the target locales' memory and processors:

Domain Maps: A Multiresolution Feature



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

```
A = B + alpha *
```

…to the target locales' memory

Domain Maps specify…

…mapping of indices to locales

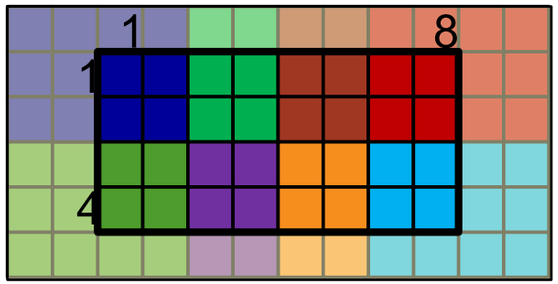
…layout of domains / arrays in memory

…parallel iteration strategies

…core operations on arrays / domains

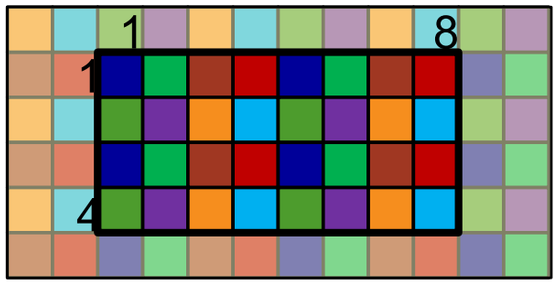
Sample Domain Maps: Block and Cyclic

```
var Dom = {1..4, 1..8} dmapped Block( {1..4, 1..8} );
```



distributed to


```
var Dom = {1..4, 1..8} dmapped Cyclic( startIdx=(1,1) );
```



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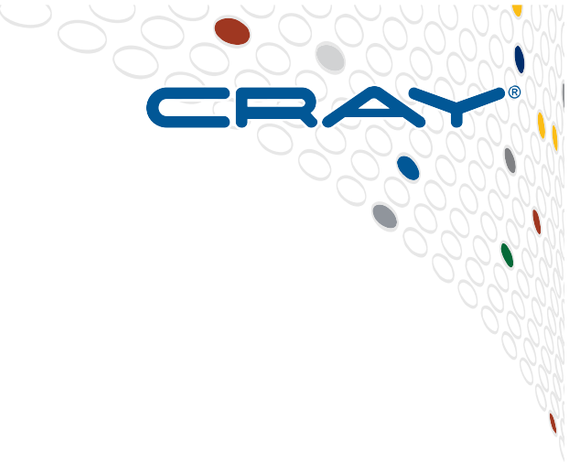
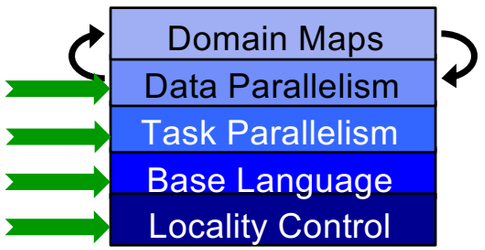


Write and Use Your Own Domain Map

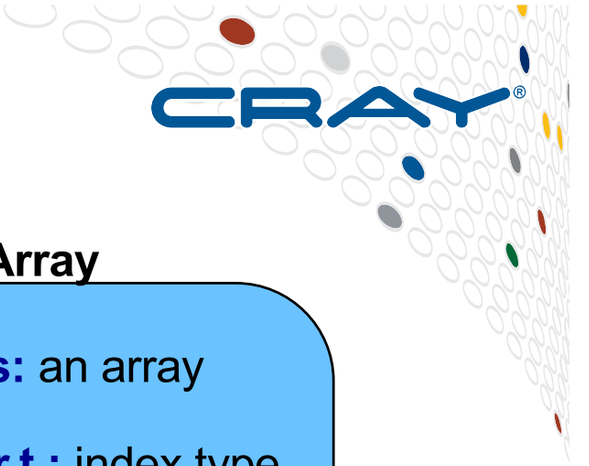
Chapel's Domain Map Philosophy

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

Domain Map Descriptors



Domain Map

Represents: a domain map value

Generic w.r.t.: index type

State: the domain map's representation

Typical Size: Θ(1) → Θ(*numLocales*)

Required Interface:

- create new domains
- which locale owns index *i*?

Domain

Represents: a domain

Generic w.r.t.: index type

State: representation of index set

Typical Size: Θ(1) → Θ(*numIndices*)

Required Interface:

- create new arrays
- queries: size, members
- iterators: serial, parallel
- domain assignment
- index set operations

Array

Represents: an array

Generic w.r.t.: index type, element type

State: array elements

Typical Size: Θ(*numIndices*)

Required Interface:

- (re-)allocation of elements
- random access
- iterators: serial, parallel
- get/set of sparse "zero" values
- …

Two Other Thematically Similar Features

1) **parallel iterators:** Permit users to specify the parallelism and work decomposition used by forall loops
   - including zippered forall loops
2) **locale models:** Permit users to model the target architecture and how Chapel should be implemented on it
   - e.g., how to manage memory, create tasks, communicate, …

Like domain maps, these are…

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

- e.g., task parallelism, on-clauses, base language features, …

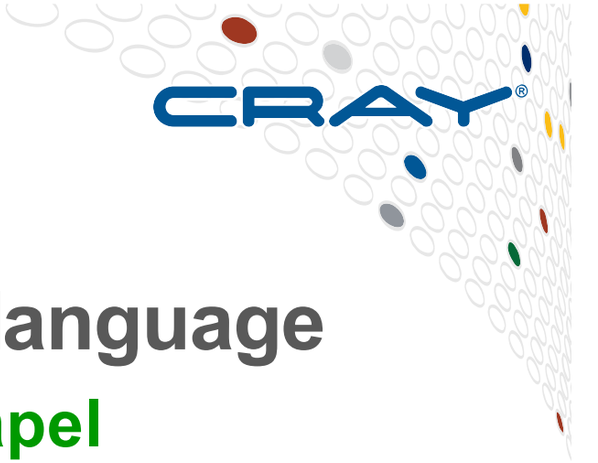
…available to the end-user via higher-level abstractions

- e.g., forall loops, on-clauses, lexically scoped PGAS memory, …

Chapel and Performance Portability

- **Avoid locking key policy decisions into the language**
  - Array memory layout?
  - Sparse storage format?
  - Parallel loop policies?

Chapel and Performance Portability



- **Avoid locking key policy decisions into the language**
  - Array memory layout? **not defined by Chapel**
  - Sparse storage format? **not defined by Chapel**
  - Parallel loop policies? **not defined by Chapel**
  - Abstract node architecture? **not defined by Chapel**
- **Instead, permit users to specify these in Chapel itself**
  - support performance portability through…

    …a separation of concerns

    …abstractions—known to the compiler, and therefore optimizable
  - **goal:** make Chapel a future-proof language

Summary of this Section

- **Chapel avoids locking crucial implementation decisions into the language specification**
  - local and distributed parallel array implementations
  - parallel loop scheduling policies
  - target architecture models
- **Instead, these can be…**

  …specified in the language by an advanced user

  …swapped between with minimal code changes
- **The result cleanly separates the roles of domain scientist, parallel programmer, and compiler/runtime**

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