Chapel: Global HPCC Benchmarks and Status Update

Brad Chamberlain

Chapel Team

CUG 2007

May 7, 2007

Chapel

Chapel: a new parallel language being developed by Cray

- Themes:
  - general parallelism
    - data-, task-, nested parallelism using *global-view* abstractions
    - general parallel architectures
  - locality control
    - data distribution
    - task placement (typically data-driven)
  - narrow gap between mainstream and parallel languages
    - object-oriented programming (OOP)
    - type inference and generic programming

Chapel's Setting: HPCS

- **HPCS:** High *Productivity* Computing Systems
  - Goal: Raise productivity by 10× for the year 2010
  - Productivity = Performance
    + Programmability
    + Portability
    + Robustness
- **Phase II**: Cray, IBM, Sun (July 2003 – June 2006)
  - Evaluation of the entire system architecture's impact on productivity…
    - processors, memory, network, I/O, OS, runtime, compilers, tools, …
    - …and new languages:
      - IBM: X10   Sun: Fortress   Cray: Chapel
- **Phase III**: Cray, IBM (July 2006 – 2010)
  - Implement the systems and technologies resulting from phase II

Chapel and Productivity

- Chapel's Productivity Goals:
  - vastly improve programmability over current languages/models
    - writing parallel codes
    - reading, modifying, maintaining, tuning them
  - support performance at least as good as MPI
    - competitive with MPI on generic clusters
    - better than MPI on more productive architectures like Cray's
  - improve portability compared to current languages/models
    - as ubiquitous as MPI, but with fewer architectural assumptions
    - more portable than OpenMP, UPC, CAF, …
  - improve code robustness via improved semantics and concepts
    - eliminate common error cases altogether
    - better abstractions to help avoid other errors

Outline

- ✓ Chapel Overview
- ➢ HPC Challenge Benchmarks in Chapel
  - STREAM Triad
  - Random Access
  - 1D FFT
- ❑ Project Status and User Activities

HPC Challenge Overview

Motivation: Growing realization that top-500 often fails to reflect practical/sustained performance

- measured using HPL, which essentially measures peak FLOP rate
- user applications often constrained by memory, network, …

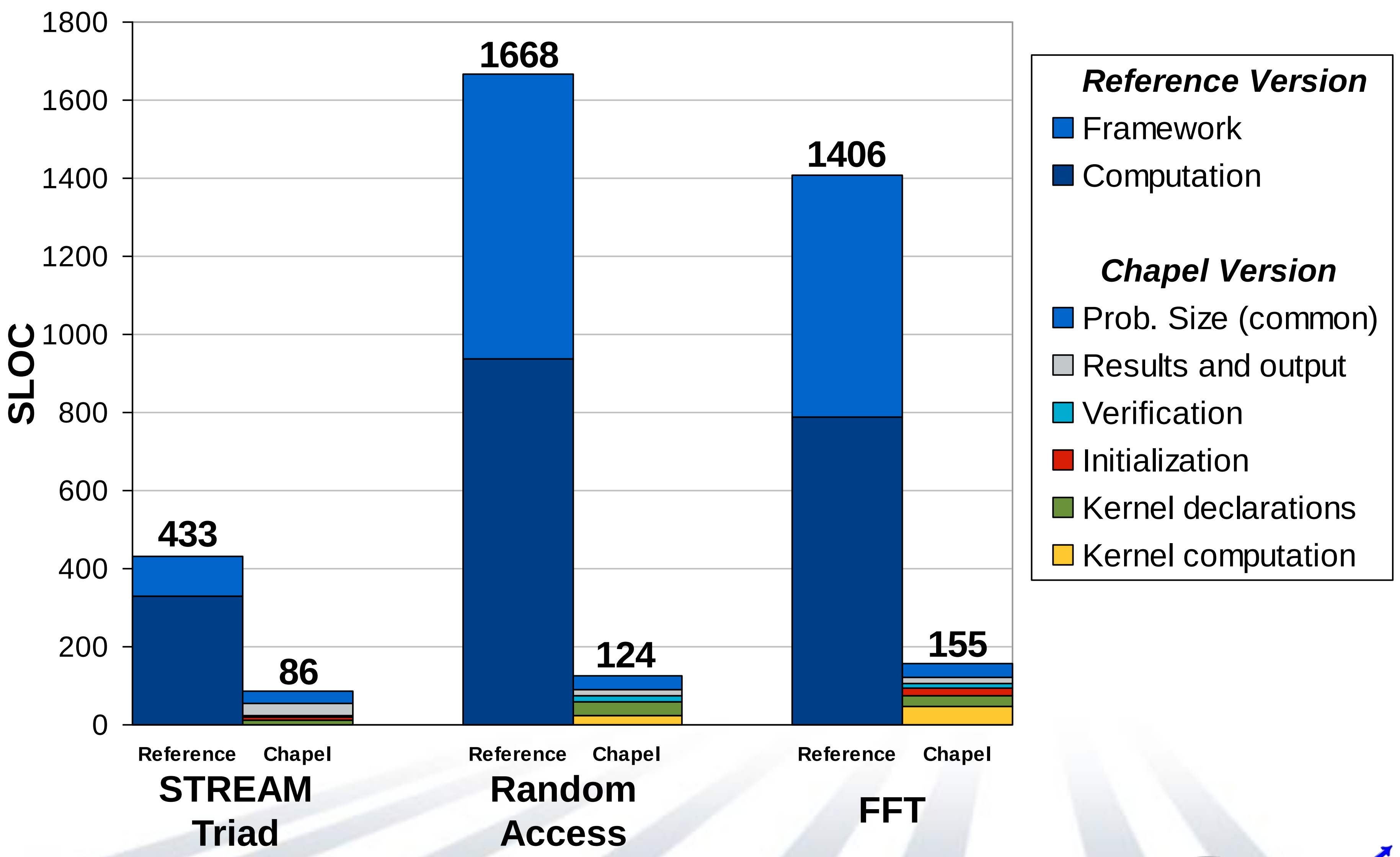
HPC Challenge (HPCC):

- suite of 7 benchmarks to measure various system characteristics
- annual competition based on 4 of the HPCC benchmarks
  - class 1: best performance (award per benchmark)
  - class 2: most productive
    - 50% performance
    - 50% code elegance, size, clarity

For more information:

- HPCC Benchmarks: http://icl.cs.utk.edu/hpcc/
- HPCC Competition: http://www.hpcchallenge.org

Code Size Summary



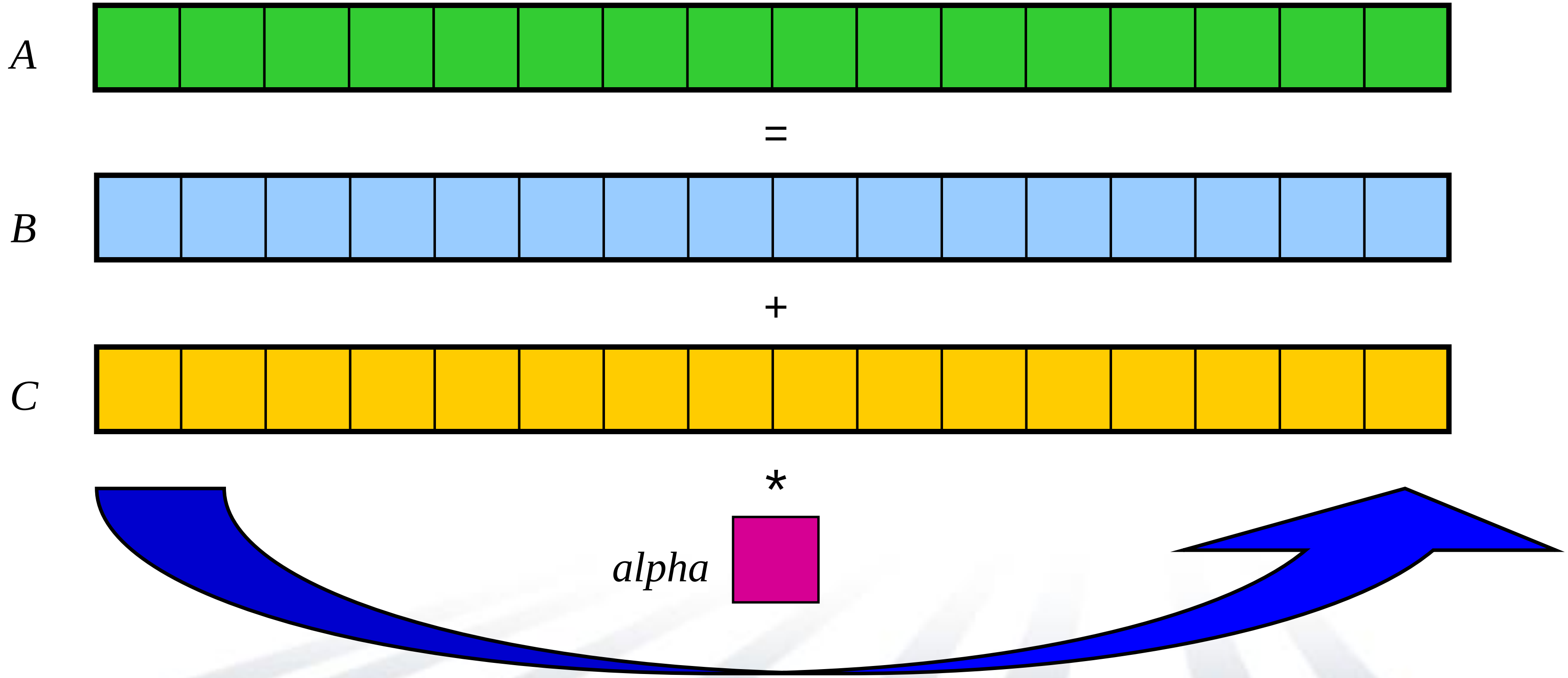
STREAM Triad

Introduction to STREAM Triad

Given: m-element vectors A, B, C

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

Pictorially:

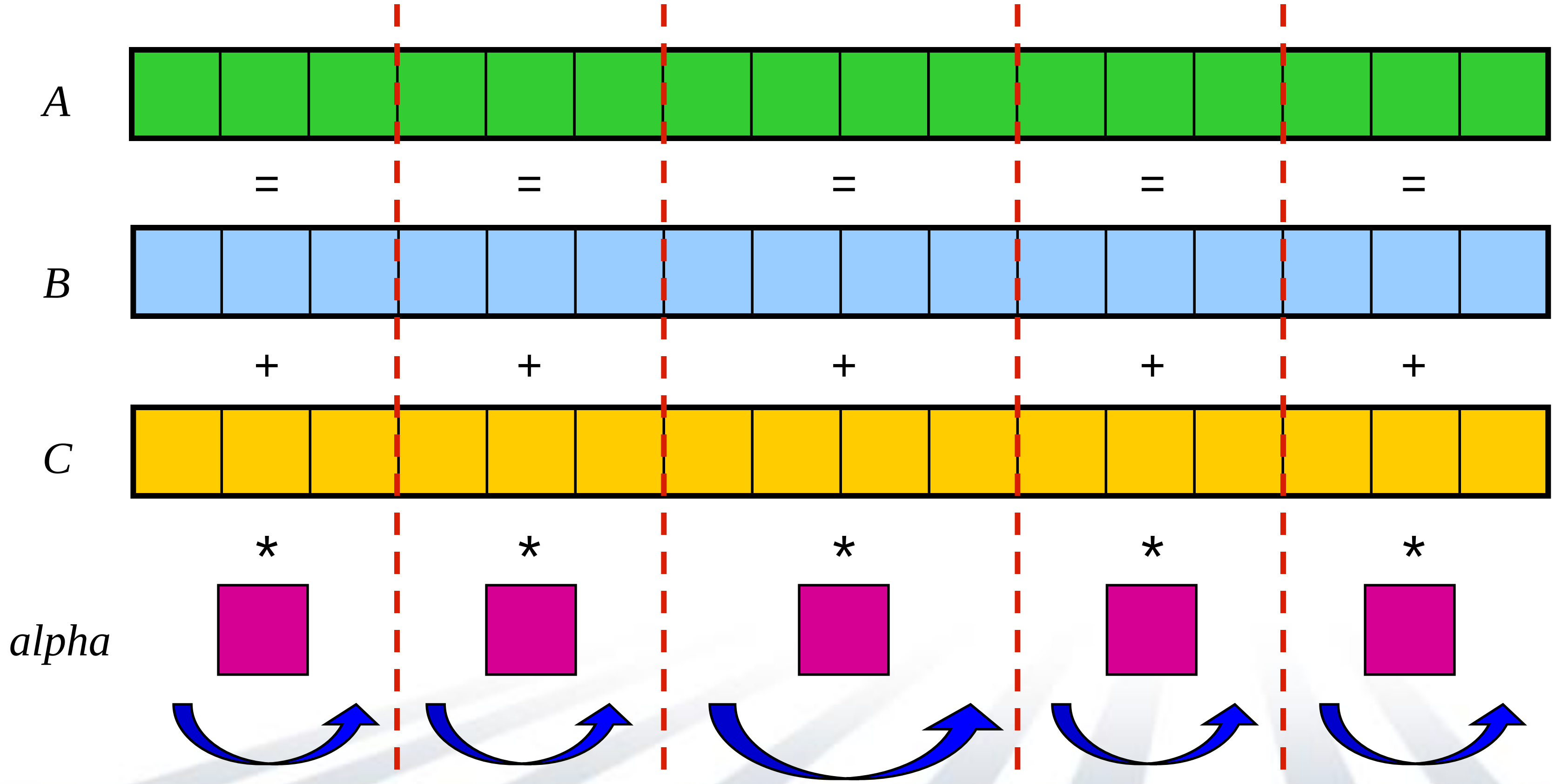


Introduction to STREAM Triad

Given: m-element vectors A, B, C

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

Pictorially (in parallel):



STREAM Triad: Some Declarations

```
const m = computeProblemSize(elemType, numVectors),
      alpha = 3.0;
```

STREAM Triad: Some Declarations

```
const m = computeProblemSize(elemType, numVectors),
      alpha = 3.0;
```

Chapel Variable Declarations

{ **var** | **const** | **param** } <*name*> [: <*definition*>] [= <*initializer*>]

- **var** ⇒ can change values
- **const** ⇒ a run-time constant (can't change values after initialization)
- **param** ⇒ a compile-time constant

May omit definition or initializer, but not both

- If definition omitted, type inferred from initializer
- If initializer omitted, variable initialized using type's default value

Here, *m* has no definition, so its type is inferred using the return type of computeProblemSize() -- an int

Similarly, *alpha* is inferred to be a real floating point value

STREAM Triad: Some Declarations

```
config const m = computeProblemSize(elemType, numVectors),
             alpha = 3.0;
```

Configuration Variables

Preceding a variable declaration with **config** allows it to be initialized on the command-line, overriding its default initializer

config const/var ⇒ can be overridden on executable command-line
config param ⇒ can be overridden on compiler command-line

prompt> `stream --m=10000 --alpha=3.14159265`

STREAM Triad: Core Computation

```
const ProblemSpace: domain(1) distributed(Block) = [1..m];
var A, B, C: [ProblemSpace] elemType;


  A = B + alpha * C;
```

STREAM Triad: Core Computation

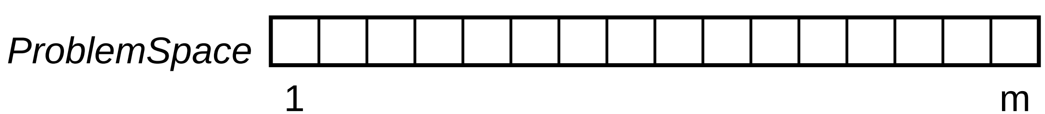
```
const ProblemSpace: domain(1) distributed(Block) = [1..m];
var A, B, C: [ProblemSpace] elemType;

  A =
```

Declare a domain

domain: a first-class index set, potentially distributed
(think of it as the size and shape of an array)

domain(1) ⇒ 1D arithmetic domain, indices are integers

[1..m] ⇒ a 1D arithmetic domain literal defining the index set:
{1, 2, …, *m*}



STREAM Triad: Core Computation

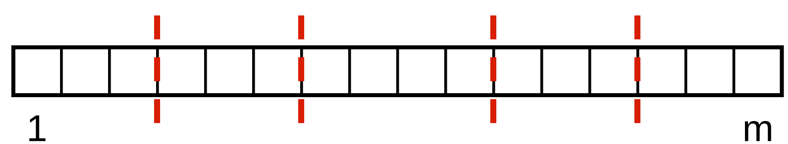
```
const ProblemSpace: domain(1) distributed(Block) = [1..m];
var A, B, C: [ProblemSpace] elemType;

  A
```

Specify the domain's distribution

distribution: describes how to map the domain indices to locales, and how to implement domains (and their arrays)

distributed(Block) ⇒ break the indices into *numLocales* consecutive blocks

ProblemSpace



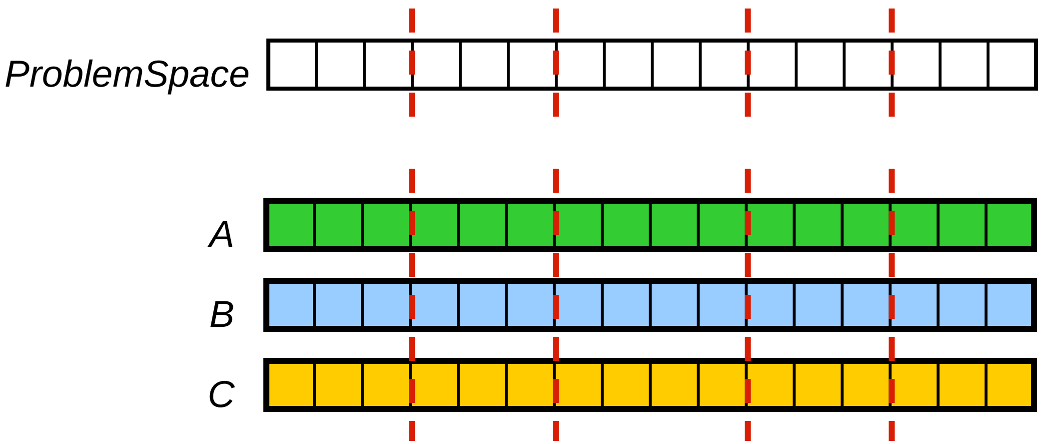
STREAM Triad: Core Computation

```
const ProblemSpace: domain(1) distributed(Block) = [1..m];
var A, B, C: [ProblemSpace] elemType;
```

Declare arrays

arrays: mappings from domains (index sets) to variables. Several flavors:

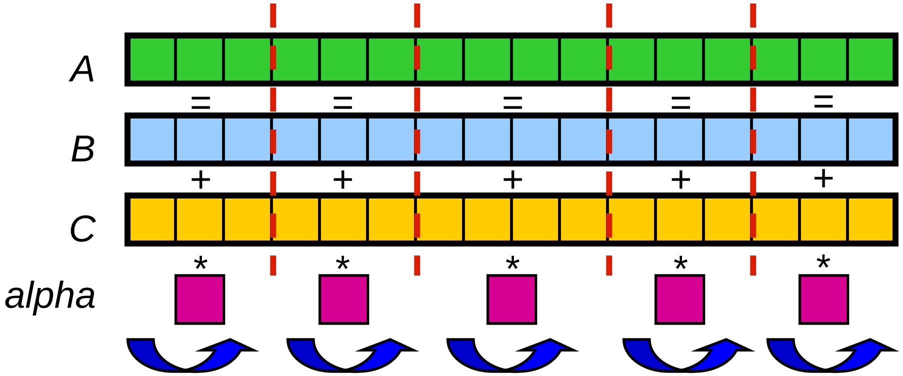
- dense and sparse rectilinear (indexed by integer tuples)
- associative arrays (indexed by value types)
- opaque arrays (indexed anonymously to represent sets & graphs)



STREAM Triad: Core Computation

Expressing the computation

whole-array operations: support standard scalar operations on arrays in an element-wise manner



[1..m];

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

STREAM Triad: Core Computation

```
const ProblemSpace: domain(1) distributed(Block) = [1..m];
var A, B, C: [ProblemSpace] elemType;


  A = B + alpha * C;
```

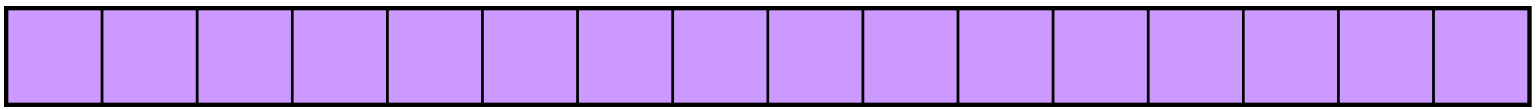
Random Access

Introduction to Random Access

Given: m-element table T (where $m = 2^n$ and initially $T_i = i$)

Compute: N_U random updates to the table using bitwise-xor

Pictorially:

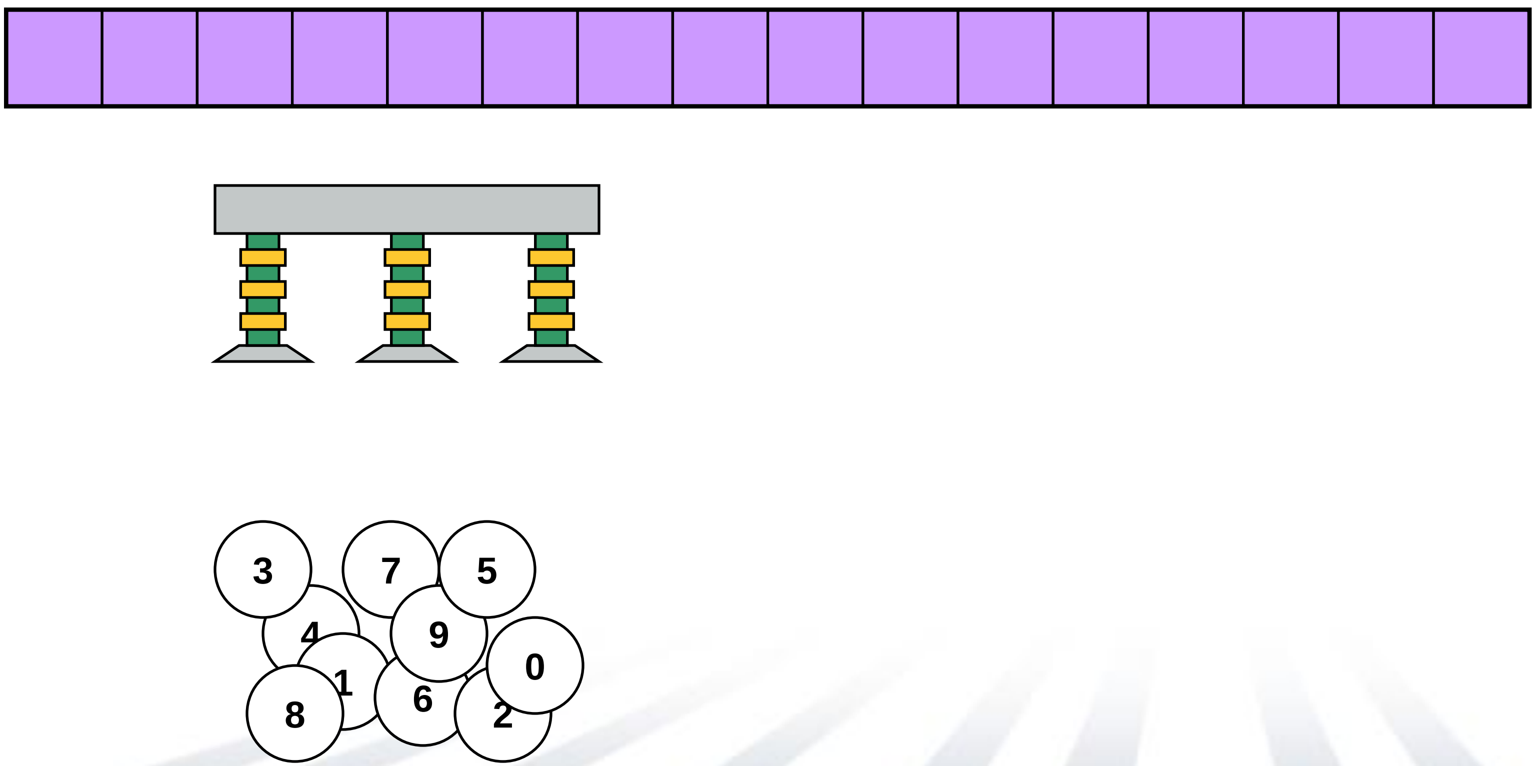


Introduction to Random Access

Given: m-element table T (where $m = 2^n$ and initially $T_i = i$)

Compute: N_U random updates to the table using bitwise-xor

Pictorially:

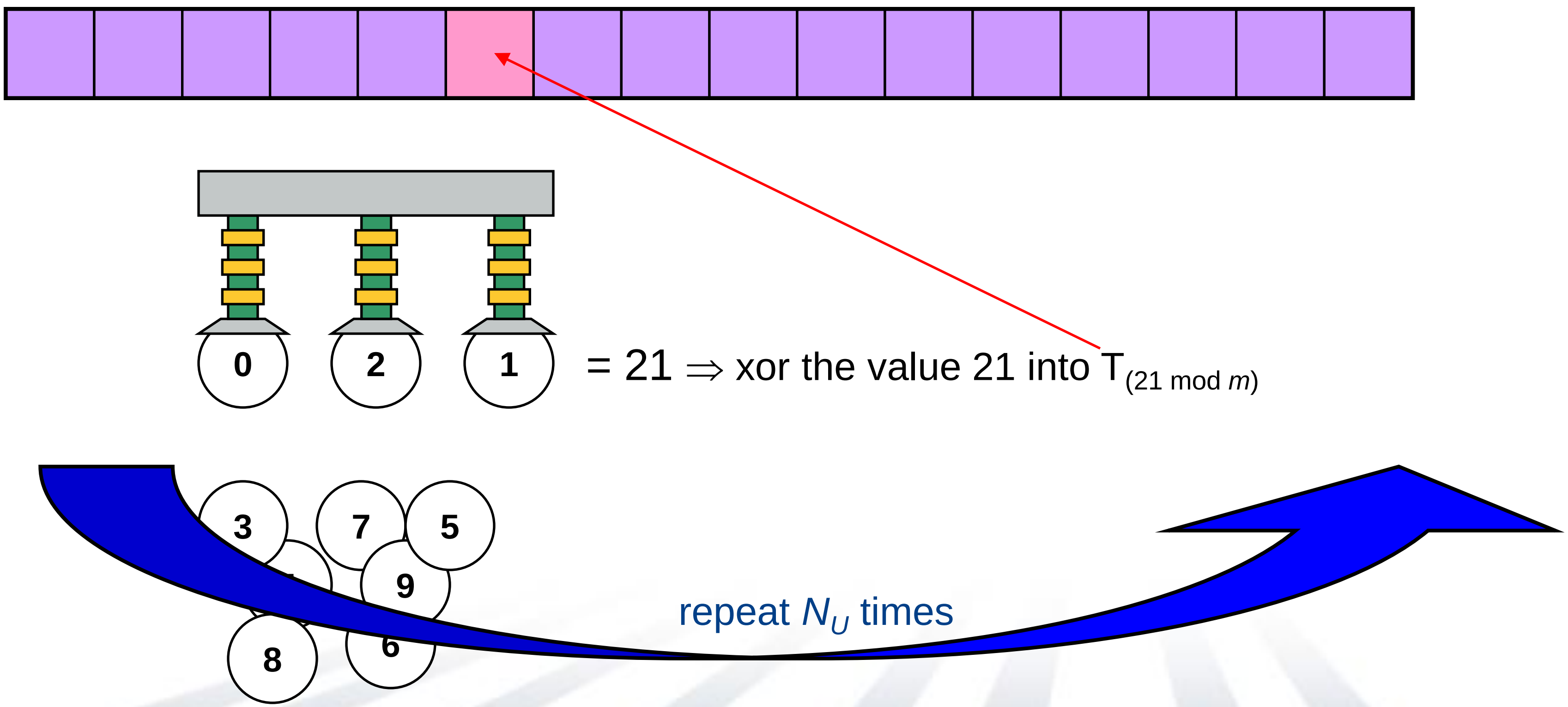


Introduction to Random Access

Given: m-element table T (where $m = 2^n$ and initially $T_i = i$)

Compute: N_U random updates to the table using bitwise-xor

Pictorially:

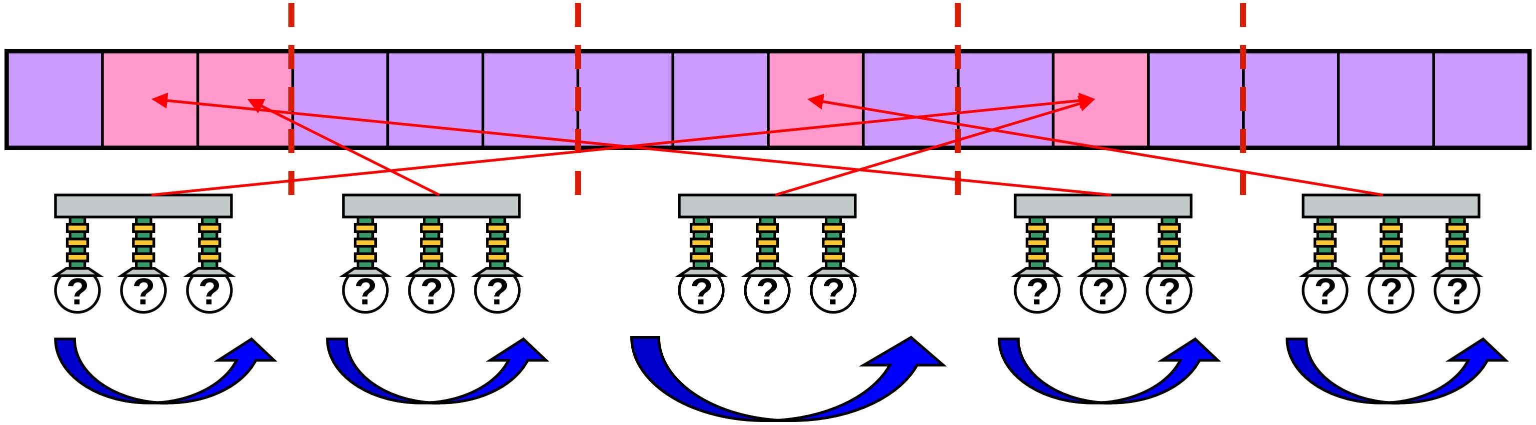


Introduction to Random Access

Given: m-element table T (where $m = 2^n$ and initially $T_i = i$)

Compute: N_U random updates to the table using bitwise-xor

Pictorially (in parallel):

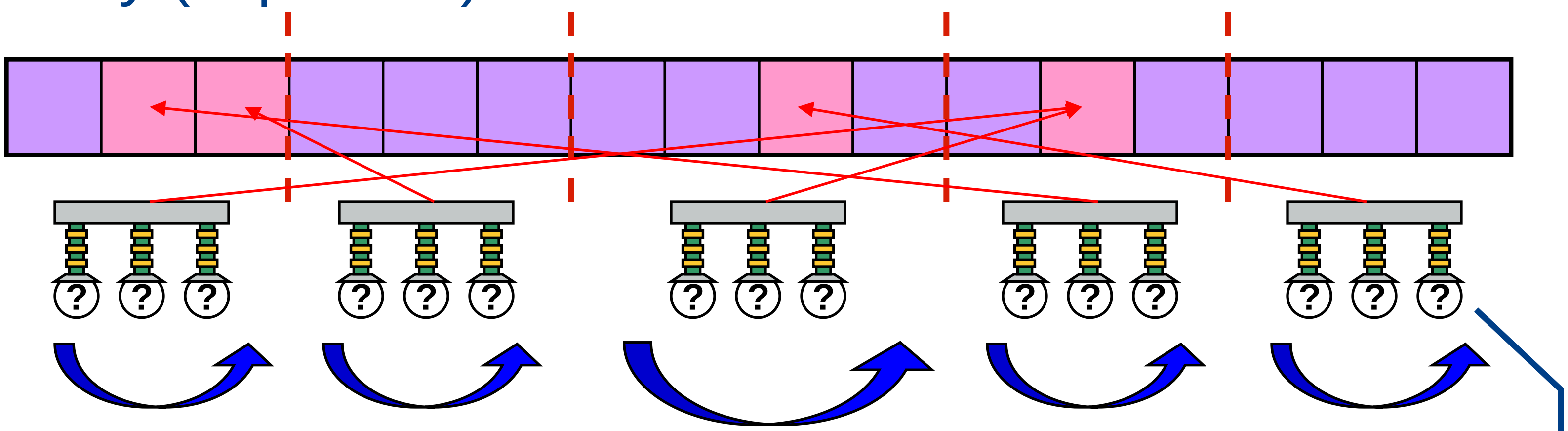


Introduction to Random Access

Given: m-element table T (where $m = 2^n$ and initially $T_i = i$)

Compute: N_U random updates to the table using bitwise-xor

Pictorially (in parallel):



Random Numbers

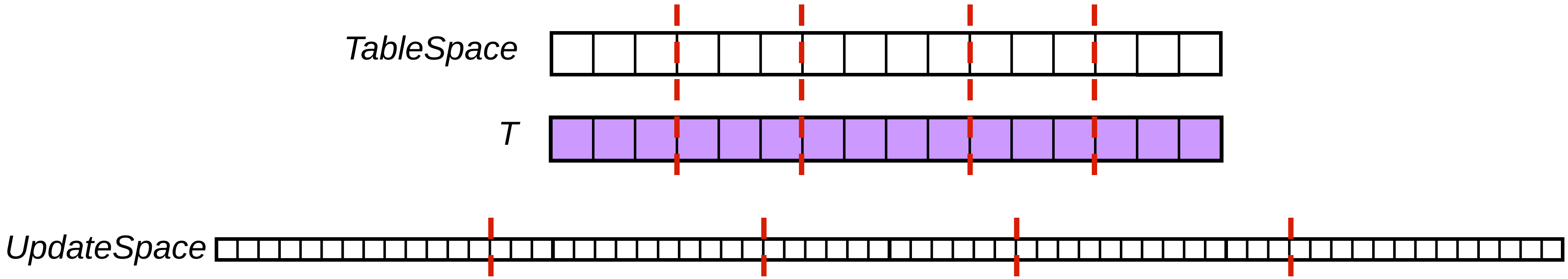
Not actually generated using lotto ping-pong balls!

Instead, implement a pseudo-random stream:

- *k*th random value can be generated at some cost
- given the *k*th random value, can generate the (*k*+1)-st much more cheaply

Random Access: Domains and Arrays

```
const TableSpace: domain(1) distributed(Block) = [0..m);
var T: [TableSpace] elemType;

const UpdateSpace: domain(1) distributed(Block) = [0..N_U);
```



Random Access: Random Value Iterator

```
iterator RAStream(block) {
  var val = getNthRandom(block.low);
  for i in block {
    getNextRandom(val);
    yield val;
  }
}


def getNthRandom(in n) { … }


def getNextRandom(inout x) { … }
```

Random Access: Random Value Iterator

```
iterator RAStream(block) {
  var val = getNthRandom(block.low);
  for i in block {
    getNextRandom(val);
    yield val;
  }
}
```

def

def

Defining an iterator

iterator: similar to a function but generates a stream of return values; invoked using **for** and **forall** loops

yield: like a return statement but the iterator's execution continues logically after returning the value

RAStream(): an iterator that generates a random value for each index in *block*

e.g., to iterate over the entire stream sequentially, one could use:

```
for r in RAStream([0..N_U)) { … }
```

Random Access: Random Value Iterator

```
iterator RAStream(block) {
  var val = getNthRandom(block.low);
  for i in block {
    getNextRandom(val);
    yield val;
  }
}


def getNthRandom(in n) { … }


def getNextRandom(inout x) { … }
```

Random Access: Computation

```
[i in TableSpace] T(i) = i;

forall block in UpdateSpace.subBlocks do
  for r in RAStream(block) do
    T(r & indexMask) ^= r;
```

Random Access: Computation

```
[i in TableSpace] T(i) = i;

forall block in UpdateSpace.subBlocks do
  for r in RAStream(block) do
    T(r & indexMask) ^= r;
```

Initialization

Uses *forall expression* to initialize table

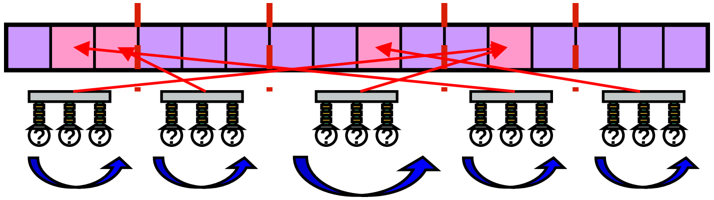
Computing the Updates

Express table updates by invoking iterators:

subBlocks: a standard iterator that generates blocks of indices appropriate for the target machine's parallelism

RAStream(): our iterator for generating random values

Effectively: generate parallel chunks of work; iterate over chunks serially performing updates



Random Access: Computation

```
[i in TableSpace] T(i) = i;

forall block in UpdateSpace.subBlocks do
  for r in RAStream(block) do
    T(r & indexMask) ^= r;
```

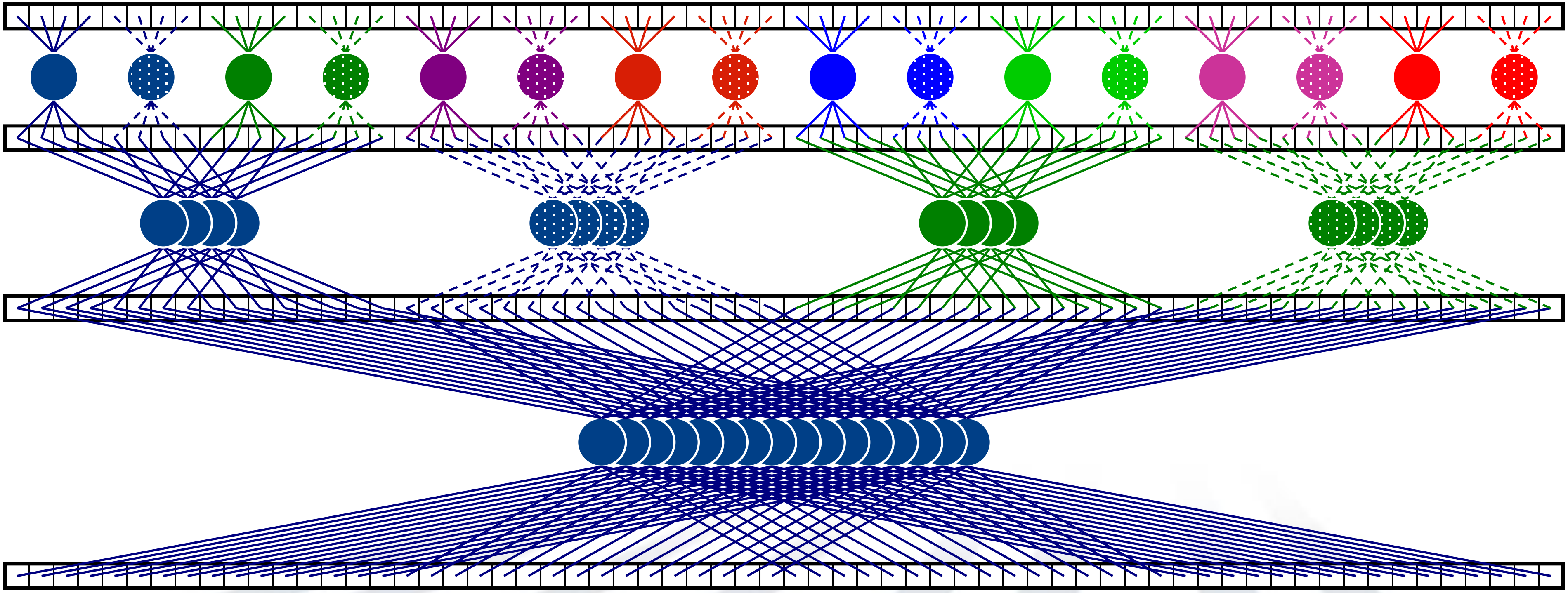
FFT

Introduction to FFT

Given: m-element vector z of complex numbers (where $m = 2^n$)

Compute: 1D Discrete Fourier Transform of z

Pictorially (using a radix-4 algorithm):



FFT: Computation

```
for i in [2..log2(numElements)) by 2 {
  const m = radix*span, m2 = 2*m;

  forall (k,k1) in (Adom by m2, 0..) {
    var wk2 = …, wk1 = …, wk3 = …;

    forall j in [k..k+span) do
      butterfly(wk1, wk2, wk3, A[j..j+3*span by span]);

    wk1 = …; wk3 = …; wk2 *= 1.0i;

    forall j in [k+m..k+m+span) do
      butterfly(wk1, wk2, wk3, A[j..j+3*span by span]);
  }
  span *= radix;
}

def butterfly(wk1, wk2, wk3, inout A:[1..radix]) { … }
```

FFT: Computation

```
for i in [2..log2(numElements)) by 2 {
  const m = radix*span, m2 = 2*m;

  forall (k,k1) in (Adom by m2, 0..) {
    var wk2 = …, wk1 = …, wk3 = …;

    forall j in [k..k+span) do
      butterfly(wk1, wk2, wk3, A[j..j+3*span by span]);

    wk1 = …; wk3 = …; wk2 *= 1.0i;

    forall j in [k+m..k+m+span) do
      butterfly(wk1, wk2, wk3, A[j..j+3*span by span]);
  }
  span *= radix;
}

def butterfly(wk1, wk2, wk3, inout A:[1..radix]) { … }
```

Sequential loop to express phases of computation

Nested forall loops to express a phase's parallel butterflies

Support for complex and imaginary types simplifies math

Generic arguments allow butterfly() to be called with complex, real, or imaginary twiddle factors

FFT: Computation

```
for i in [2..log2(numElements)) by 2 {
  const m = radix*span, m2 = 2*m;

  forall (k,k1) in (Adom by m2, 0..) {
    var wk2 = …, wk1 = …, wk3 = …;

    forall j in [k..k+span) do
      butterfly(wk1, wk2, wk3, A[j..j+3*span by span]);

    wk1 = …; wk3 = …; wk2 *= 1.0i;

    forall j in [k+m..k+m+span) do
      butterfly(wk1, wk2, wk3, A[j..j+3*span by span]);
  }
  span *= radix;
}

def butterfly(wk1, wk2, wk3, inout A:[1..radix]) { … }
```

HPCC Status, Next Steps

HPCC Status:

- all codes compile and run today
- current compiler only targets a single node
- serial performance approaching hand-coded C on a daily basis
- CUG paper…

  …contains full source listings

  …covers codes in more detail

  …describes performance advantages and challenges in Chapel

What's Next?

- demonstrate performance for these codes
  - continue optimizing serial performance
  - add compiler support for targeting multiple nodes
- finish implementing HPL

HPCC Summary

- Chapel supports HPCC codes attractively
  - clear, concise, general
  - parallelism expressed in architecturally-neutral way
  - benefit from Chapel's global-view parallelism
  - utilizes generic programming and modern SW Engineering principles
  - should serve as an excellent reference for future HPCC competitors
- Note that HPCC benchmarks are relatively simple
  - all data structures are 1D vectors
  - locality very data driven
  - minimal task- & nested parallelism
  - little need for OOP, abstraction

…HPCC designed to stress systems, not languages

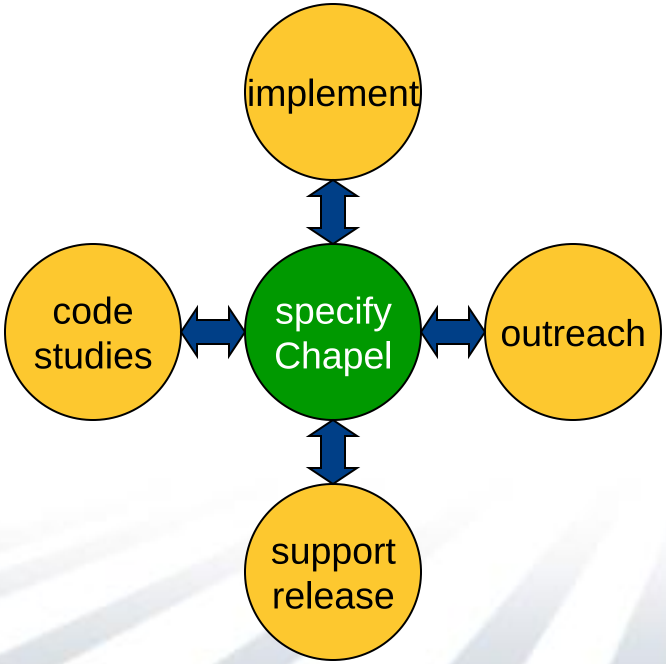
- would like to see similar competitions emerge for richer computations

Outline

- ✓ Chapel Overview
- ✓ HPC Challenge Benchmarks in Chapel
  - ✓ STREAM Triad
  - ✓ Random Access
  - ✓ 1D FFT
- ➢ Project Status and User Activities

Chapel Work

- Chapel Team's Focus:
  - specify Chapel syntax and semantics
  - implement prototype Chapel compiler
  - code studies of benchmarks, applications, and libraries in Chapel
  - community outreach to inform and learn from users
  - support users evaluating the language
  - refine language based on these activities



Project Status, Next Steps

- **Chapel specification:**
  - revised draft language specification available on Chapel website
  - editing to add additional examples & rationale; improve clarity
- **Compiler implementation:**
  - improving serial performance
  - starting on distributed memory implementation
  - adding missing serial features
- **Code studies:**
  - **NAS Parallel Benchmarks:** CG (well underway), IS, FT, MG
  - **Linear Algebra routines:** block LU, block Cholesky, matrix mult.
  - **Other applications of interest:** Fast Multipole Method, SSCA2, …
- **Release:**
  - made a preliminary release to government team December 2006
  - initial response from those users has been positive, encouraging
  - next release due Summer 2007

Notable User Studies

- Two main efforts to date, both at ORNL:
  - Robert Harrison, Wael Elwasif, David Bernholdt, Aniruddha Shet
    - Fock matrix computations using producer-consumer parallelism
    - coupled model idioms (e.g., for use in CCSM)
  - Richard Barrett, Stephen Poole, Philip Roth
    - stencil idioms: 2D, 3D, sparse
    - sweep3D & wavefront-style computations

- In both cases…

  …great technical discussions and feedback

  …valuable sanity-check for language and implementation

  …studies comparing with Fortress, X10 forthcoming

Chapel Contributors

- **Current:**
  - Brad Chamberlain
  - Steven Deitz
  - Mary Beth Hribar
  - David Iten
  - (Your name here? We're hiring…)

- **Alumni:**
  - David Callahan
  - Hans Zima (CalTech/JPL)
  - John Plevyak
  - Wayne Wong
  - Shannon Hoffswell
  - Roxana Diaconescu (CalTech)
  - Mark James (JPL)
  - Mackale Joyner (2005 intern, Rice University)
  - Robert Bocchino (2006 intern, UIUC)

For More Information…

BOF today at 4pm

chapel_info@cray.com

bradc@cray.com

http://chapel.cs.washington.edu

Your feedback desired!