An Overview of the Chapel Programming Language

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What is Chapel?

- A new parallel language
  - Under development at Cray Inc.
  - Supported through the DARPA HPCS program
- Status
  - Version 1.1 released April 15, 2010
  - Open source via BSD license

    http://chapel.cray.com/

    http://sourceforge.net/projects/chapel/

The Chapel Team

- Brad Chamberlain 
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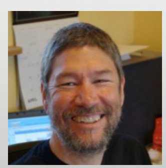
- Greg Titus 

- Former Team Members

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Goals For Today

- Introduce you to Chapel with a focus on
  - Data parallelism
  - Task parallelism
  - Execution on distributed-memory systems
- Discuss to-date performance
- Get your feedback on Chapel
- Point you towards resources to use after today

Rough Outline

8:00 – Welcome

8:05 – Background

8:30 – HPCC Performance in 10 Minutes

8:40 – Language Basics

9:05 – Data Parallelism

9:30 – Break

9:35 – Multi-Locale Execution

10:00 – Task Parallelism

10:20 – Wrap Up

Chapel: Background

Chapel Settings

- **HPCS**: **H**igh **P**roductivity **C**omputing **S**ystems (DARPA)
  - Goal: Raise HEC user productivity by 10x

    Productivity = Performance + Programmability + Portability + Robustness
- Phase II: Cray, IBM, Sun (July 2003 – June 2006)
  - Evaluated entire system architecture
  - Three new languages (Chapel, X10, Fortess)
- Phase III: Cray, IBM (July 2006 –)
  - Implement phase II systems
  - Work continues on all three languages

Chapel Productivity Goals

- Improve programmability over current languages
  - Writing parallel codes
  - Reading, changing, porting, tuning, maintaining, ...
- Support performance at least as good as MPI
  - Competitive with MPI on generic clusters
  - Better than MPI on more capable architectures
- Improve portability over current languages
  - As ubiquitous as MPI
  - More portable than OpenMP, UPC, CAF, ...
- Improve robustness via improved semantics
  - Eliminate common error cases
  - Provide better abstractions to help avoid other errors

Outline

- Chapel's Settings and Goals
- Chapel's Themes
  - Global-view abstractions
  - General parallel programming
  - Multiple levels of design
  - Control of locality
  - Mainstream language features

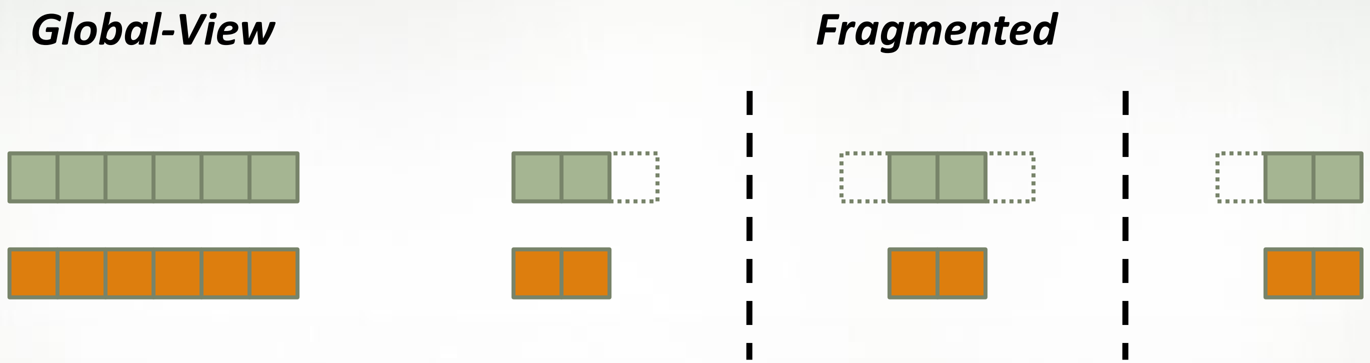
Global-View Abstractions

Definitions

- **Programming model**
  The mental model of a programmer
- **Fragmented model**
  Programmer takes point-of-view of a single processor/thread
- **SPMD models** (Single Program, Multiple Data)
  Fragmented models with multiple copies of one program
- **Global-view model**
  Programmer writes code to describe computation as a whole

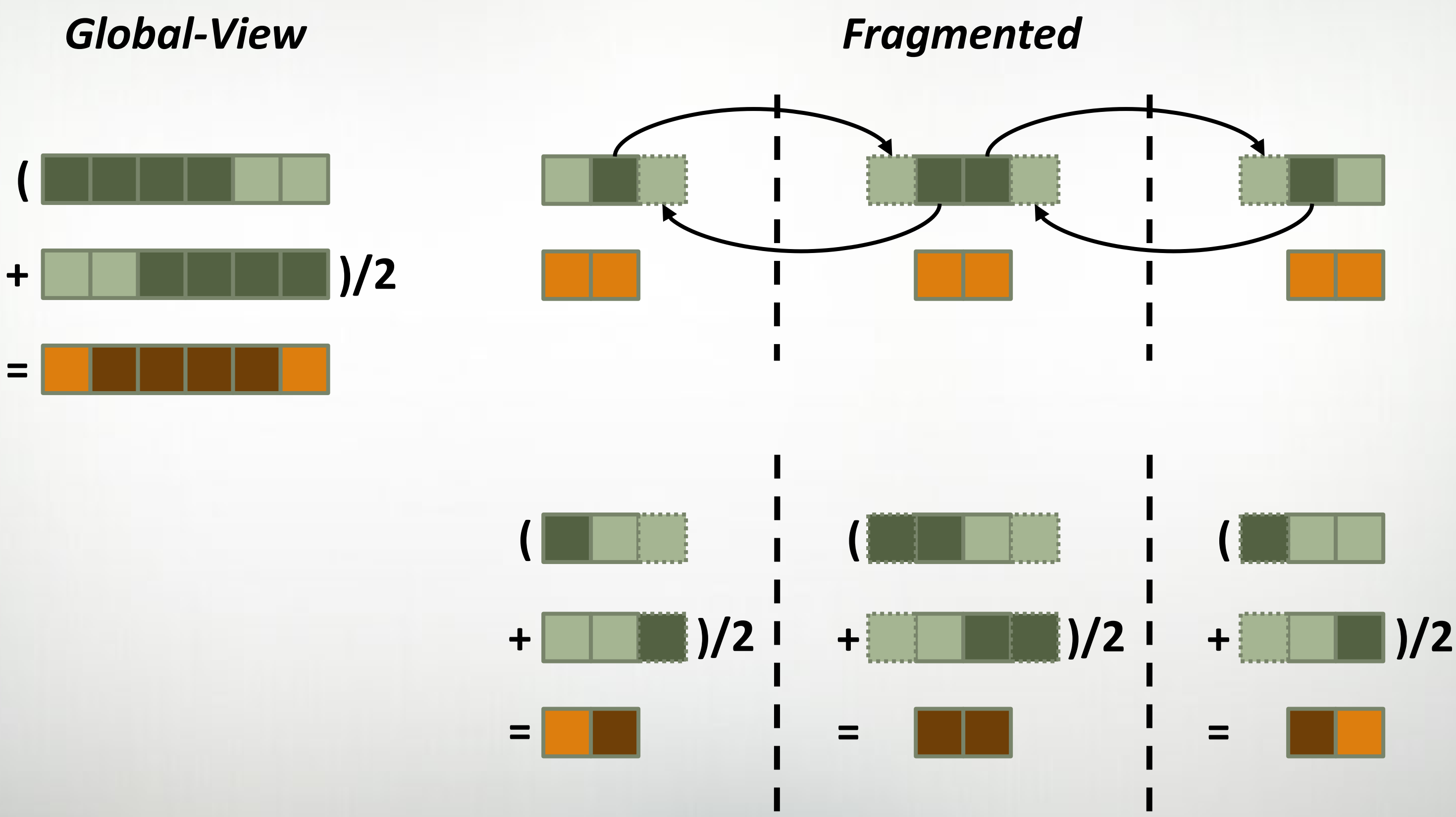
Global-View Abstractions

Example: 3-Point Stencil (Data Declarations)



Global-View Abstractions

Example: 3-Point Stencil (Computation)

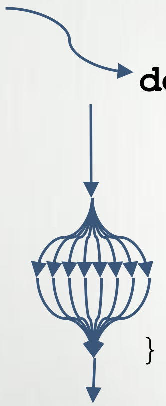


Global-View Abstractions

Example: 3-Point Stencil (Code)

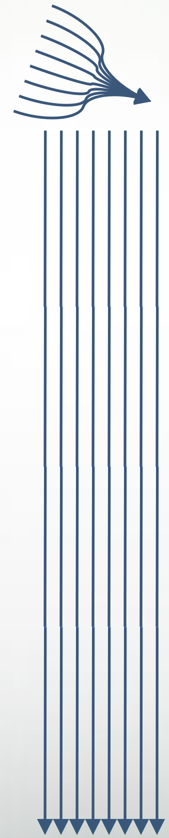
Assumes p divides n

Global-View



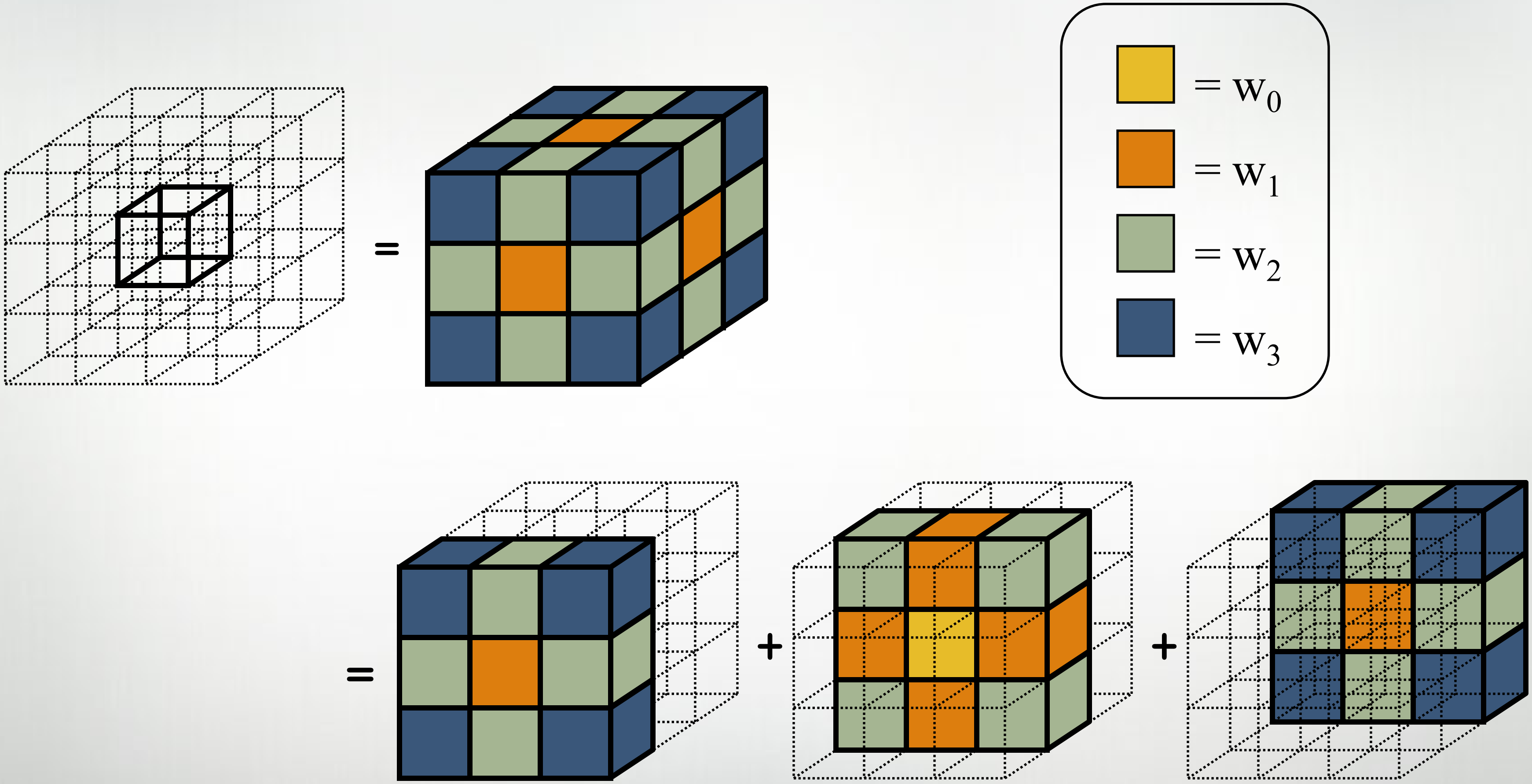
```
def main() {
  var n = 1000;
  var A, B: [1..n] real;

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

Fragmented



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

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

NAS MG Stencil



NAS MG Stencil in Fortran + MPI

```
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( nprocs .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 comm1p( 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'  subroutine
     comm3(u,n1,n2,n3,kk)

 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(axis
    ,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

 return
 end


 subroutine take3( axis, dir, u, n1, n2,
     n3 )
 use caf_intrinsics


 implicit none

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

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

 integer buff_id, indx

 integer i3, i2, i1

 buff_id = 3 + dir
 indx = 0

 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  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.  3 )then
    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

    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

 return
 end


 subroutine comm1p( axis, u, n1, n2, n3,
     kk )
 use caf_intrinsics


 implicit none

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

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

 integer i3, i2, i1, buff_len,buff_id
 integer i, kk, indx

 dir = -1

 buff_id = 3 + dir
 buff_len = nm2

 do  i=1,nm2
    buff(i,buff_id) = 0.0D0
 enddo


 dir = +1

 buff_id = 3 + dir
 buff_len = nm2

 do  i=1,nm2
    buff(i,buff_id) = 0.0D0
 enddo

 dir = +1

 buff_id = 2 + dir
 buff_len = 0

 if( axis .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
 endif

 if( axis .eq.  2 )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
 endif

if( axis .eq.  3 )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
 endif

 dir = -1

 buff_id = 2 + dir
 buff_len = 0

 if( axis .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
 endif

 if( axis .eq.  2 )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
 endif

 if( axis .eq.  3 )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
 endif

 do  i=1,nm2
    buff(i,4) = buff(i,3)
    buff(i,2) = buff(i,1)
 enddo

 dir = -1

 buff_id = 3 + dir
 indx = 0

 if( axis .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
 endif

 if( axis .eq.  2 )then
    do  i3=2,n3-1
       do  i1=1,n1
          indx = indx + 1
          u(i1,n2,i3) = buff(indx,
     buff_id )
       enddo
    enddo
 endif

 if( axis .eq.  3 )then
    do  i2=1,n2
       do  i1=1,n1
          indx = indx + 1
          u(i1,i2,n3) = buff(indx,
     buff_id )
       enddo
    enddo
 endif

 dir = +1

 buff_id = 3 + dir
 indx = 0

 if( axis .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

if( axis .eq.  2 )then
    do  i3=2,n3-1
       do  i1=1,n1
          indx = indx + 1
          u(i1,1,i3) = buff(indx,
     buff_id )
       enddo
    enddo
 endif

 if( axis .eq.  3 )then
    do  i2=1,n2
       do  i1=1,n1
          indx = indx + 1
          u(i1,i2,1) = buff(indx,
     buff_id )
       enddo
    enddo
 endif

 return
 end

 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
```

NAS MG Stencil in Chapel

```
def rprj3(S, R) {
  const Stencil = [-1..1, -1..1, -1..1],
        W: [0..3] real = (0.5, 0.25, 0.125, 0.0625),
        W3D = [(i,j,k) in Stencil] W((i!=0)+(j!=0)+(k!=0));

  forall inds in S.domain do
    S(inds) =
      + reduce [offset in Stencil] (W3D(offset) *
                                     R(inds + offset*R.stride));
}
```

Our previous work in ZPL has shown that such compact codes can result in better performance than the Fortran + MPI.

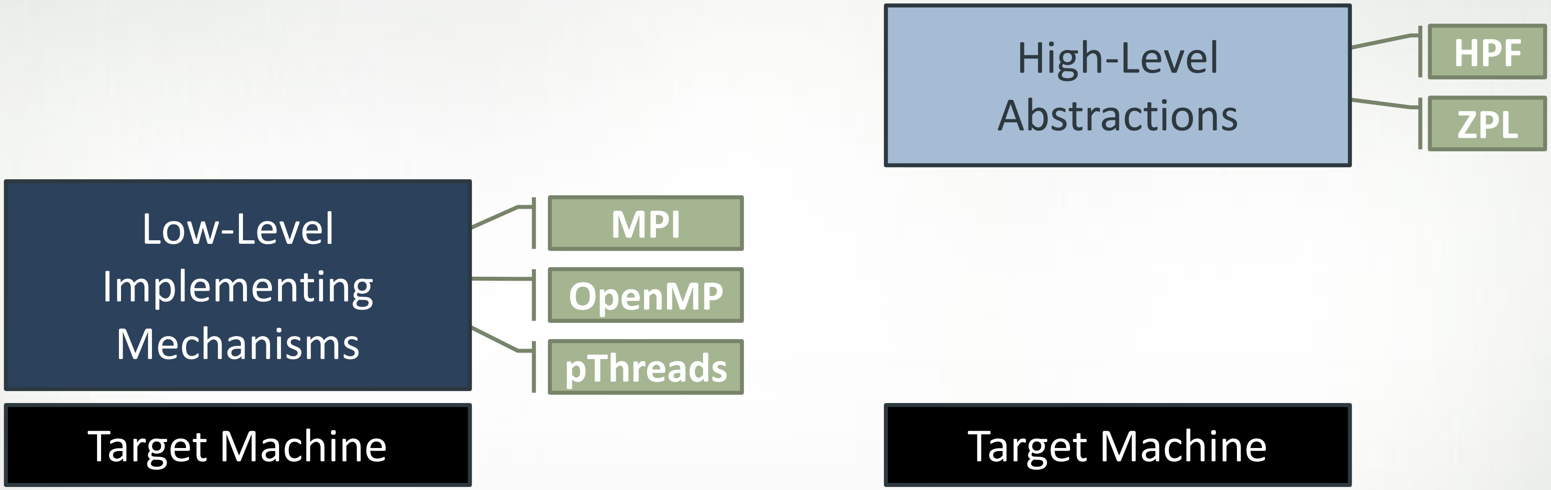
Summary of Current Programming Systems

	System	Data Model	Compute Model
Communication Libraries	MPI/MPI-2	Fragmented	Fragmented
	SHMEM	Fragmented	Fragmented
	ARMCI	Fragmented	Fragmented
	GASNet	Fragmented	Fragmented
Shared Memory	OpenMP, pThreads	Global-View (trivially)	Global-View (trivially)
PGAS Languages	Co-Array Fortran	Fragmented	Fragmented
	UPC	Global-View	Fragmented
	Titanium	Fragmented	Fragmented
HPCS Languages	Chapel	Global-View	Global-View
	X10 (IBM)	Global-View	Global-View
	Fortress (Sun)	Global-View	Global-View

General Parallel Programming

- Express all parallelism in the software
  - Forms: data, task, nested (arbitrary composition thereof)
  - Levels: module, function, loop, statement
- Target all parallelism in the hardware
  - Systems: multicore desktops, clusters, HPC systems
  - Types: multithreading, vector
  - Levels: across cores, across nodes, across systems

Multiple Levels of Design



“Why is everything so difficult?”

“Why can’t I optimize this?”

Multiple Levels of Design

Language Concepts

- Data Parallelism
- Distributions
- Task Parallelism
- Base Language
- Locality Control
- Target Machine

Task Scheduling

- Work Stealing
- Suspendable Tasks
- Task Pool
- Thread per Task
- Target Machine

Memory Management

- Garbage Collection
- Region-Based
- Per-Allocation Frees
- Target Machine

Control of Locality

Given

- Scalable systems tend to store memory with processors
- Remote accesses tend to take longer than local accesses

Therefore

- Placement of data relative to computation matters
- Programmers need control over data placement

Note

- As multi-core chips grow, locality may matter on desktops
- GPUs/accelerators expose node-level locality

Mainstream Language Features

- Object-oriented programming with value and reference classes
- Generic programming with types and compile-time constants
- Latent typing and a rich set of primitive types
- Modules for libraries and code organization
- Functions with nesting, overloading, and named arguments
- Multi-dimensional and associative arrays with slicing, etc.
- Classes, records, and unions
- Tuples, ranges, and domains
- Standard modules (*e.g.*, Math, Random, Time, BitOps, Norm)

Questions?

- Chapel's Settings and Goals
- Chapel's Design
  - Global-view abstractions
  - General parallel programming
  - Multiple levels of design
  - Control of locality
  - Mainstream language features

Chapel: HPCC Performance

Prologue

This is a reprise of a 10-minute presentation I gave at the HPCC Competition at Supercomputing 2009. The finalists were

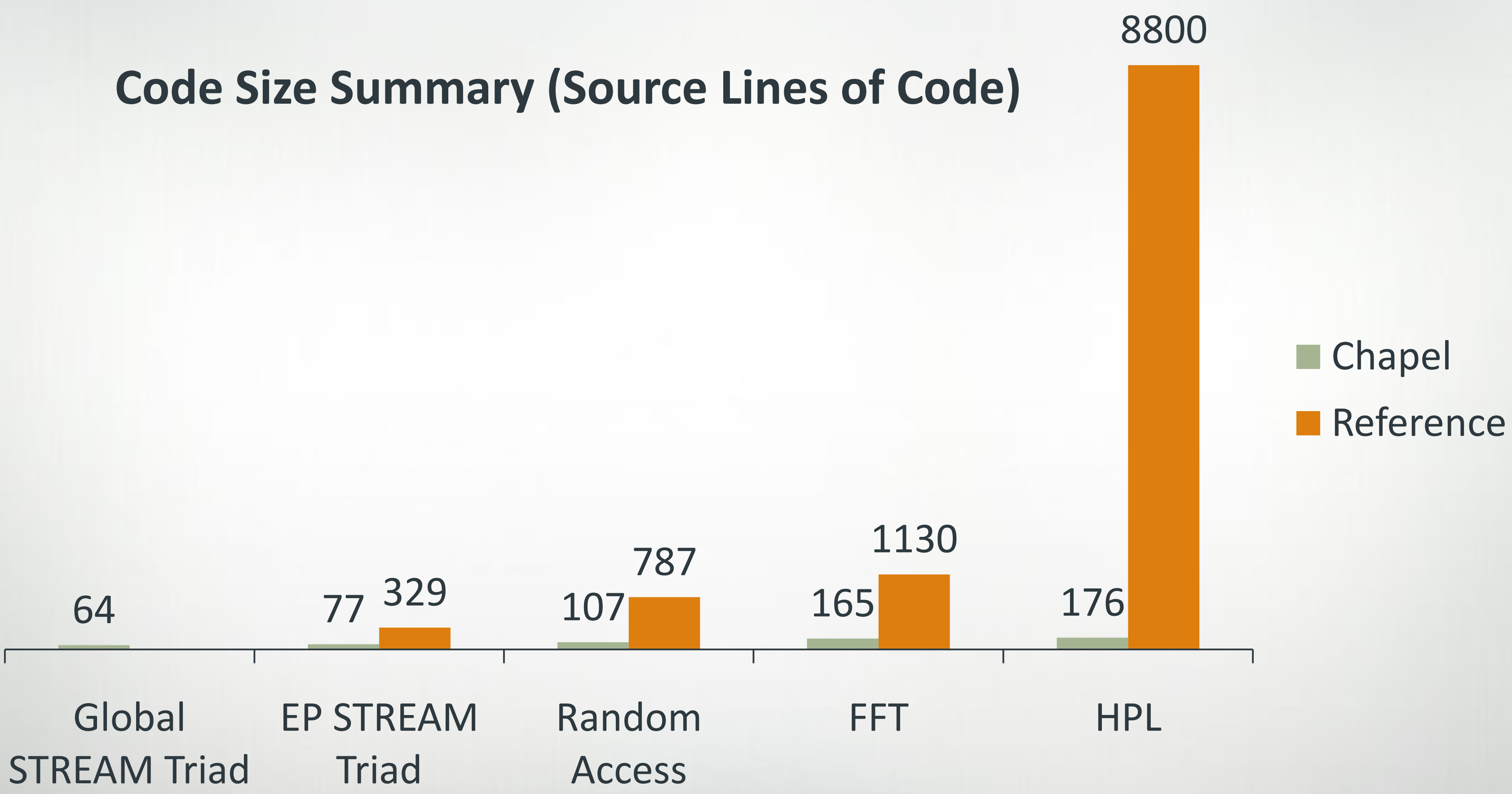
- Cray: Chapel
- IBM: X10
- University of Tsukuba: XcalableMP

The codes have been updated to version 1.1 of Chapel.

Highlights

- Global STREAM Triad 10.8 TB/s (6.4x over 2008)
  - Executed on 2048 nodes (up from 512 nodes in 2008)
  - Better scaling by eliminating extra communication
- EP STREAM Triad 12.2 TB/s
  - More similar to EP STREAM reference version
- Random Access 0.122 GUP/s (111x over 2008)
  - Executed on 2048 nodes (up from 64 nodes in 2008)
  - Optimized remote forks + better scaling as with STREAM
- A distributed-memory implementation of FFT
- A demonstration of portability
  - Cray XT4, Cray CX1, IBM pSeries 575, SGI Altix

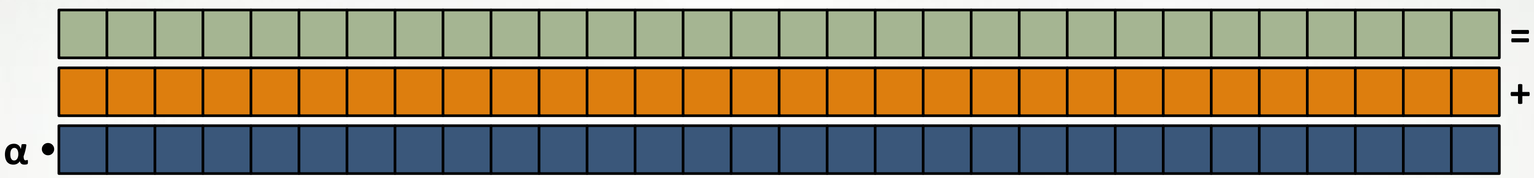
Chapel Implementation Characteristics



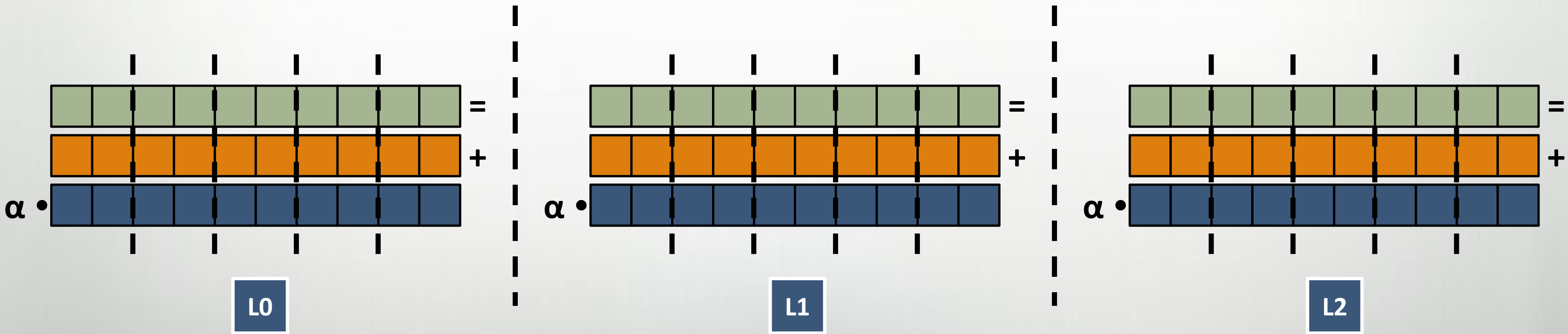
What is a Distribution?

A "recipe" for distributed arrays that...

Instructs the compiler how to map the global view...



...to a fragmented, per-processor implementation



Chapel Distributions

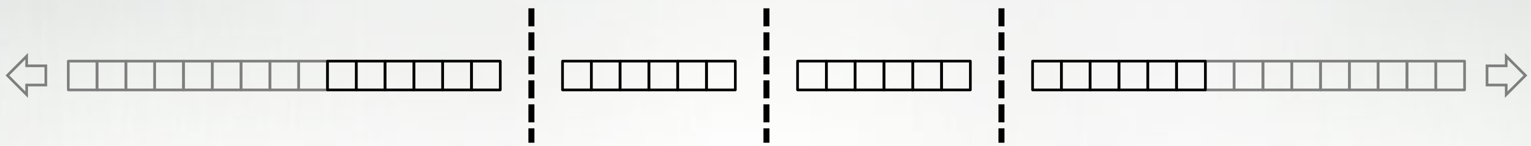
- Distributions are written entirely in Chapel
  - Advanced programmers can write their own
  - Classes define distributions, domains, and arrays
  - Compiler lowers code to a structural interface
  - Task-parallel constructs implement concurrency
- Standard distributions under development
  - Block
  - Cyclic
  - BlockCyclic
  - Associative
  - GPU

FFT and HPL in a Nutshell

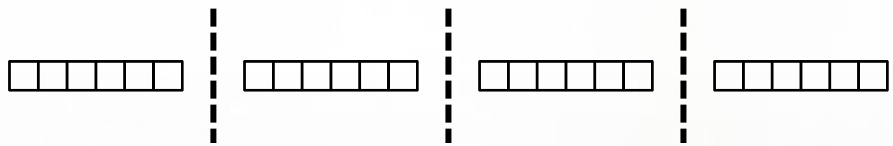
- FFT
  - Uses both Block and Cyclic distributions
  - Butterfly-patterned accesses are completely local
    - Communication with nearby neighbors is local with Block
    - Communication with far off neighbors is local with Cyclic
  - Executes on distributed memory, but is slow
- HPL
  - Implementation is ready for BlockCyclic distribution
  - Executes on single locale only, but is multi-threaded

Global STREAM Triad in Chapel (Excerpts)

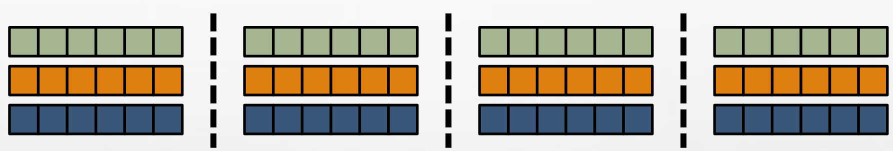
```
const BlockDist = new dmap(new Block(…));
```



```
const ProblemSpace:
         domain(1,int(64)) dmapped BlockDist = [1..m];
```



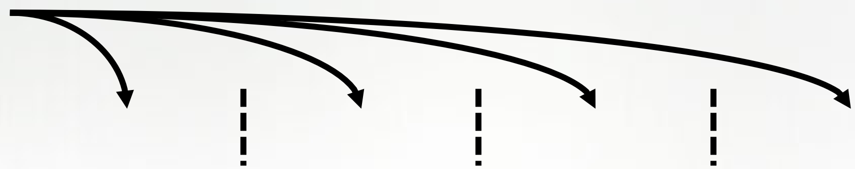
```
var A, B, C: [ProblemSpace] elemType;
```



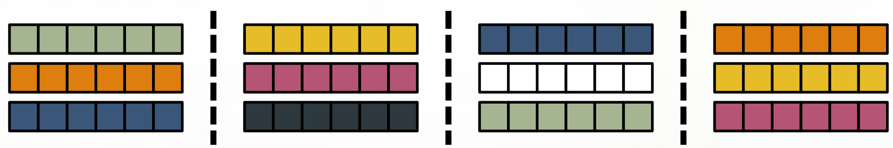
```
forall (a,b,c) in (A,B,C) do
  a = b + alpha * c;
```

EP STREAM Triad in Chapel (Excerpts)

```
coforall loc in Locales do on loc {
```



```
  local {
    var A, B, C: [1..m] elemType;
```



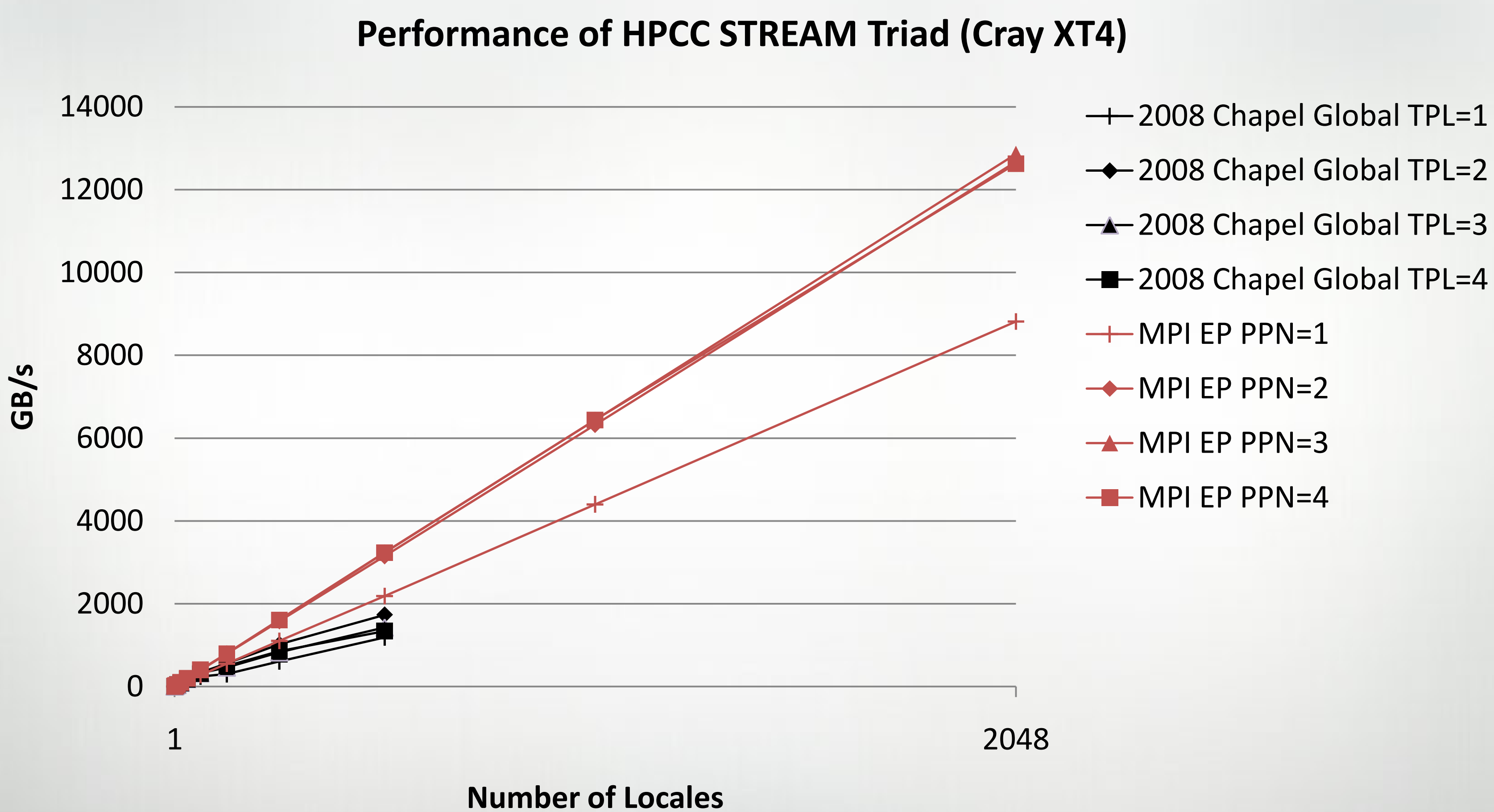
```
    forall (a,b,c) in (A,B,C) do
      a = b + alpha * c;
  }
}
```

Experimental Setup

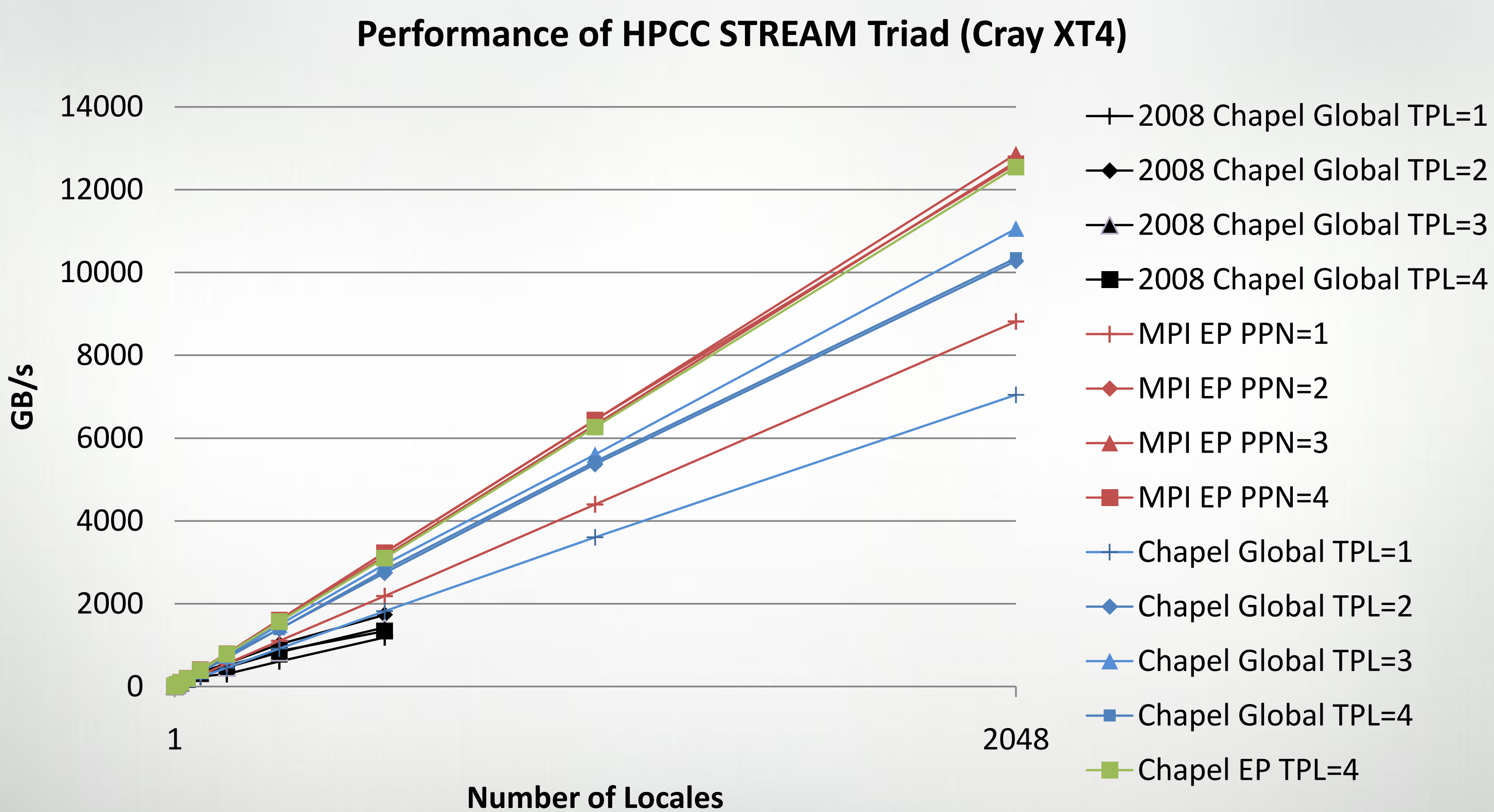
Machine Characteristics	
Model	Cray XT4
Location	ORNL
Nodes	7832
Processor	2.1 GHz Quadcore AMD Opteron
Memory	8 GB per node

Benchmark Parameters	
STREAM Triad Memory	Least value greater than 25% of memory
Random Access Memory	Least power of two greater than 25% of memory
Random Access Updates	2^{n-10} for memory equal to 2^n

STREAM Triad Performance



STREAM Triad Performance



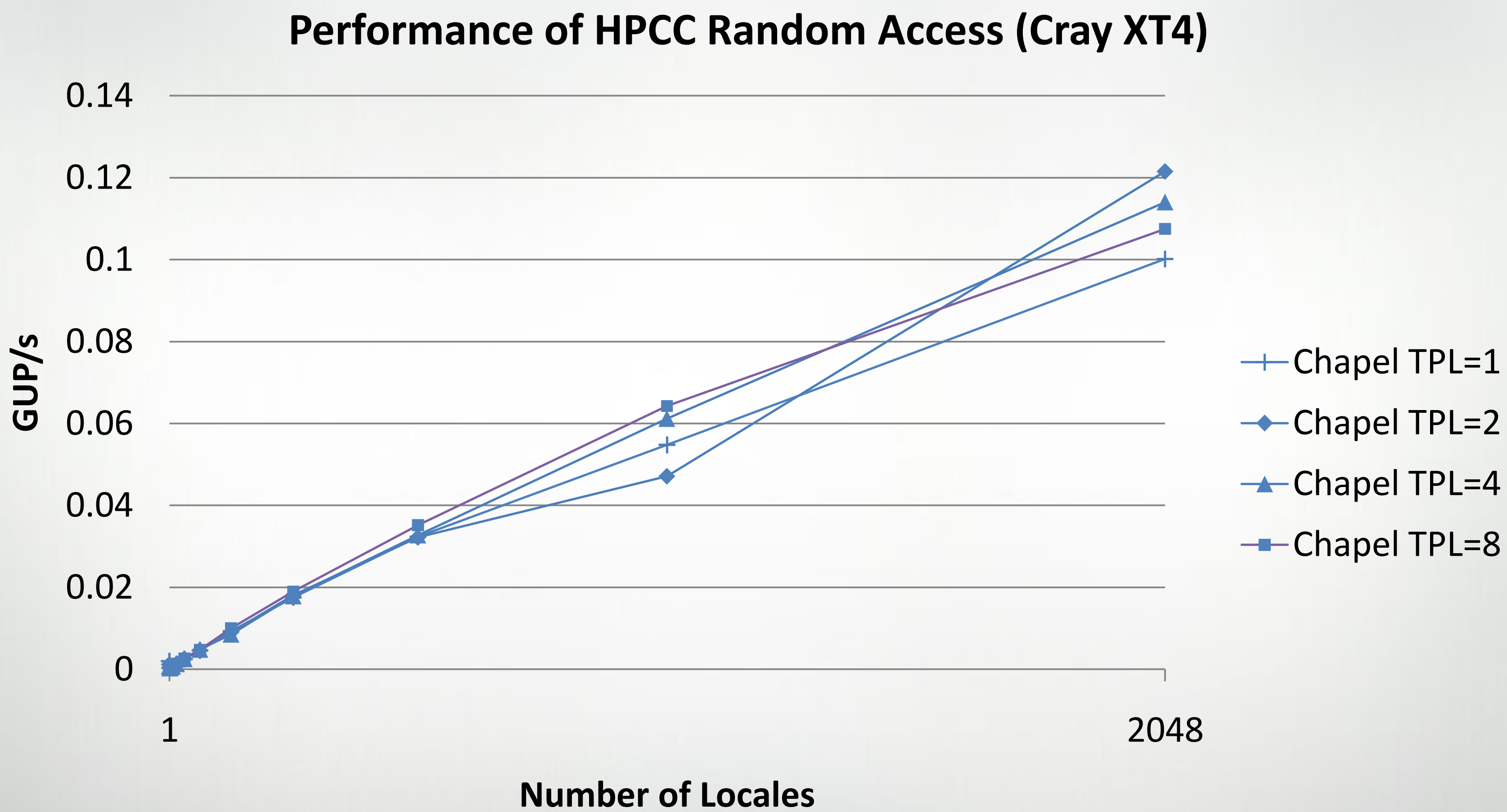
Global Random Access in Chapel (Excerpts)

```
const TableDist = new dmap(new Block(…0..m…)),
      UpdateDist = new dmap(new Block(…0..N_U…));

const TableSpace: domain … dmapped TableDist = …,
      Updates: domain … dmapped UpdateDist = …;

var T: [TableSpace] elemType;

forall ( ,r) in (Updates,RAStream()) do
  on TableDist.idxToLocale(r & indexMask) {
    const myR = r;
    local T(myR & indexMask) ^= myR;
  }
```

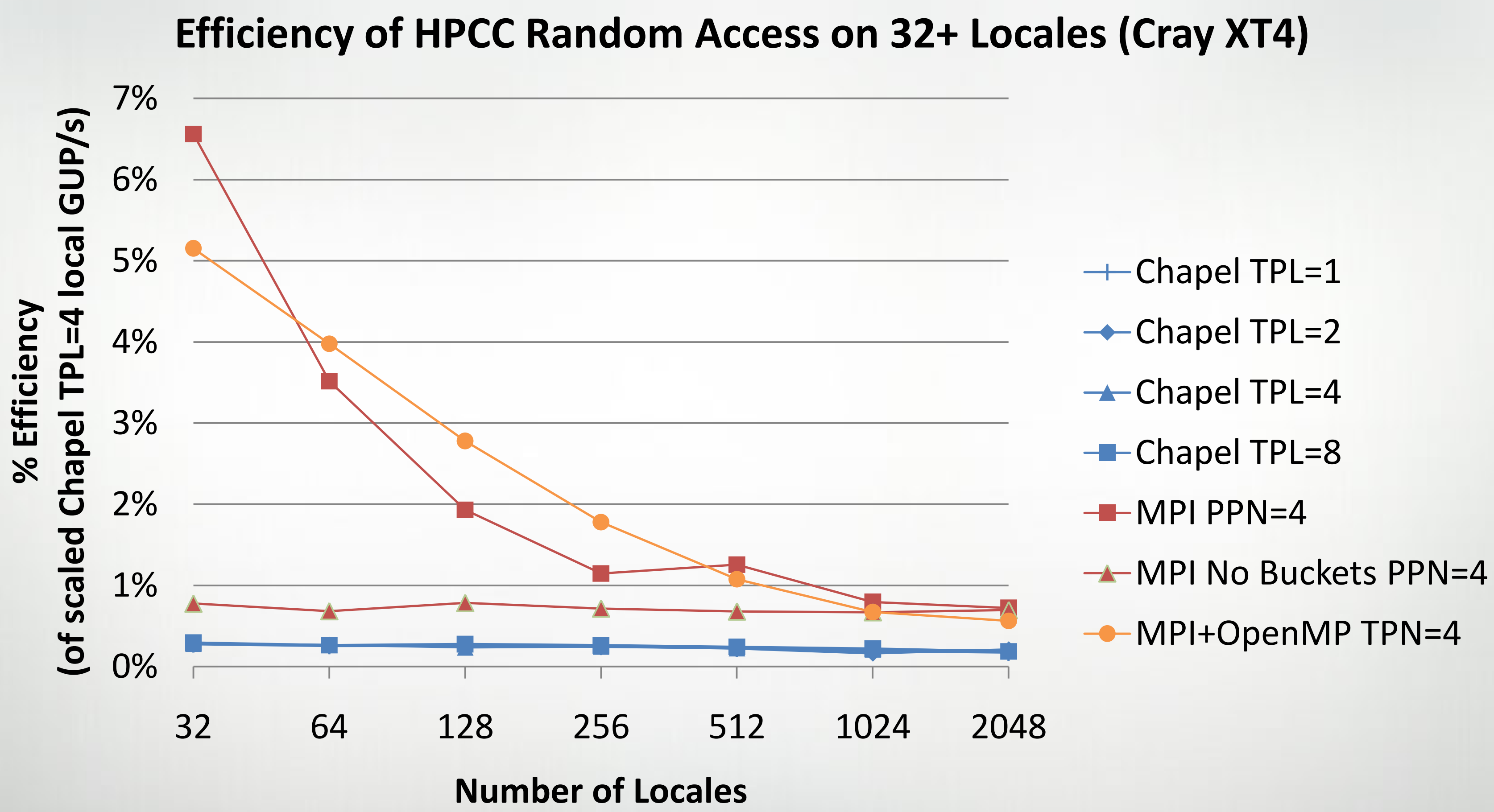
More elegant on-block

```
on T(r&indexMask) do
  T(r&indexMask) ^= r;
```

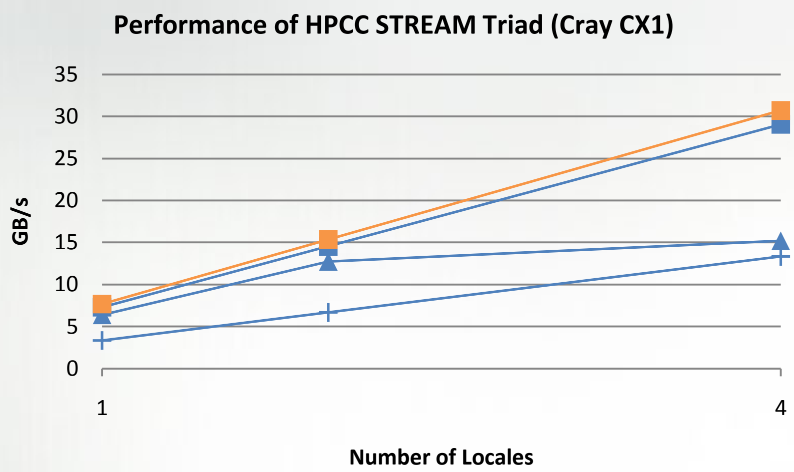
Random Access Performance

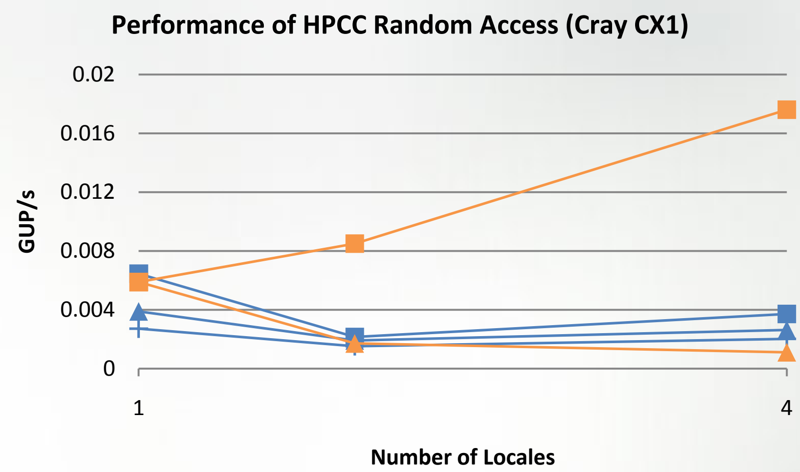


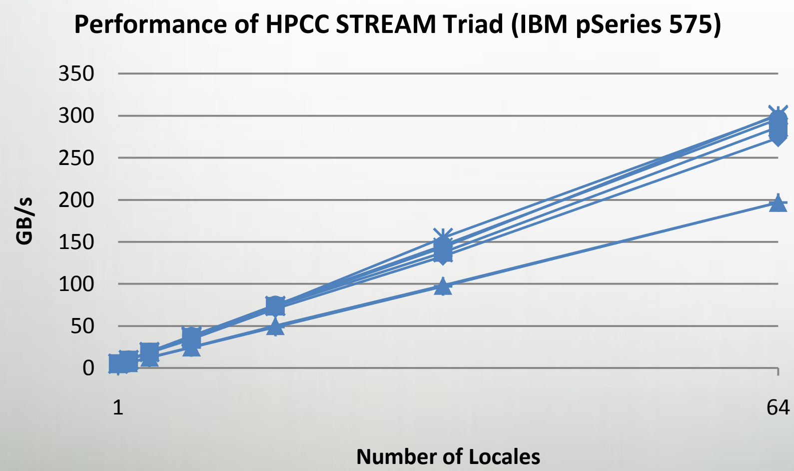
Random Access Efficiency on 32+ Nodes

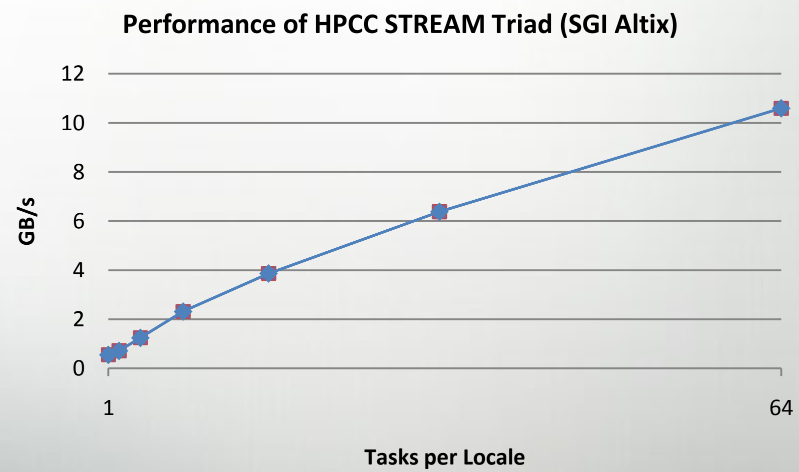


Portability Results









Summary

- Chapel is a work-in-progress
  - Performance is improving
  - Development of distributions is progressing

Score Card	Elegance	Performance
Global STREAM Triad	64 SLOC	10.8 TB/s
EP STREAM Triad	77 SLOC	12.2 TB/s
Random Access	107 SLOC	0.11 GUP/s
FFT	165 SLOC	0.00015 Gflop/s
HPL	176 SLOC	Multi-threaded, single-locale

No library routines were used in this entry.

Epilogue

The prize was split as follows

- $1000 Most Elegant Implementation: Chapel
- $1000 Best Performance: X10
- Honorable Mention: XcalableMP

Chapel: Language Basics

The Hello World Program

- Fast prototyping

```
writeln("hello, world");
```

- Production-grade

```
module HelloWorld {
  def main() {
    writeln("hello, world");
  }
}
```

Characteristics of Chapel

- Syntax
  - Basics from C and Modula
  - Influences from many other languages
- Semantics
  - Imperative, block-structured
  - Optional object-oriented programming (OOP)
  - Elided types for convenience and generic coding
  - Static typing for performance and safety
- Design points
  - No pointers and few references
  - No compiler-inserted array temporaries

Chapel Influences

ZPL, HPF: data parallelism, index sets, distributed arrays

CRAY MTA C/Fortran: task parallelism, synchronization

CLU, Ruby, Python: iterators

ML, Scala, Matlab, Perl, Python, C#: latent types

Java, C#: OOP, type safety

C++: generic programming/templates

Outline

- High-Level Comments
- Elementary Concepts
  - Lexical structure
  - Types, variables, and constants
  - Input and output
- Data Structures and Control
- Miscellaneous

Lexical Structure

- Comments

```
/* standard
   C-style */
// standard C++ style
```

- Identifiers
  - Composed of A-Z, a-z, _, $, 0-9
  - Starting with A-Z, a-z, _, $
- Case-sensitive
- Whitespace-aware
  - Composed of spaces, tabs, and linefeeds
  - Separates tokens and ends //-comments

Primitive Types

Type	Description	Default Value	Default Bit Width	Supported Bit Widths
bool	logical value	false	impl-dep	8, 16, 32, 64
int	signed integer	0	32	8, 16, 32, 64
uint	unsigned integer	0	32	8, 16, 32, 64
real	real floating point	0.0	64	32, 64
imag	imaginary floating point	0.0i	64	32, 64
complex	complex floating points	0.0 + 0.0i	128	64, 128
string	character string	""	N/A	N/A

- Syntax

```
primitive-type:
   type-name [( bit-width )]
```

- Examples

```
int(64)    // 64-bit int
real(32)   // 32-bit real
uint       // 32-bit uint
```

Variables, Constants, and Parameters

- Syntax

```
declaration:
  var identifier [: type] [= init-expr]
  const identifier [: type] [= init-expr]
  param identifier [: type] [= init-expr]
```

- Semantics
  - Constness at runtime (**const**), at compile-time (**param**)
  - Omitted *init-expr*: value is assigned default for type
  - Omitted *type*: type is inferred from *init-expr*
- Examples

```
var count: int;              // initialized to 0
const pi: real = 3.14159;
param debug = true;          // inferred to be bool
```

Config Declarations

- Syntax

```
config-declaration:
  config declaration
```

- Semantics
  - Supports command-line overrides
  - Must be declared at module (file) scope
- Examples

```
config param intSize = 32;
config const start: int(intSize) = 1;
config var epsilon = 0.01;
```

```
% chpl -sintSize=16 myProgram.chpl
% a.out --start=2 --epsilon=0.001
```

Basic Operators and Precedence

<table>
<tr><th>Operator</th><th>Description</th><th>Associativity</th><th>Overloadable</th></tr>
<tr><td>:</td><td>cast</td><td>left</td><td>no</td></tr>
<tr><td>**</td><td>exponentiation</td><td>right</td><td>yes</td></tr>
<tr><td>! ~</td><td>logical and bitwise negation</td><td>right</td><td>yes</td></tr>
<tr><td>* / %</td><td>multiplication, division and modulus</td><td>left</td><td>yes</td></tr>
<tr><td>unary + -</td><td>positive identity and negation</td><td>right</td><td>yes</td></tr>
<tr><td>+ -</td><td>addition and subtraction</td><td>left</td><td>yes</td></tr>
<tr><td><< >></td><td>shift left and shift right</td><td>left</td><td>yes</td></tr>
<tr><td><= >= < ></td><td>ordered comparison</td><td>left</td><td>yes</td></tr>
<tr><td>== !=</td><td>equality comparison</td><td>left</td><td>yes</td></tr>
<tr><td>&</td><td>bitwise/logical and</td><td>left</td><td>yes</td></tr>
<tr><td>^</td><td>bitwise/logical xor</td><td>left</td><td>yes</td></tr>
<tr><td>|</td><td>bitwise/logical or</td><td>left</td><td>yes</td></tr>
<tr><td>&&</td><td>short-circuiting logical and</td><td>left</td><td>via isTrue</td></tr>
<tr><td>||</td><td>short-circuiting logical or</td><td>left</td><td>via isTrue</td></tr>
</table>

Assignments

Kind	Description
`=`	simple assignment

`+= -= *= /= %=`
`**= &= |= ^=`
`&&= ||= <<= >>=`
	compound assignment
	(*e.g.,* `x += y;` is equivalent to `x = x + y;`)

`<=>`	swap

Input and Output

- Input
  - read(expr-list): reads values into the arguments
  - read(type-list): returns values read of given types
  - readln(...) variant: also reads through new line
- Output
  - write(expr-list): writes arguments
  - writeln(...) variant: also writes new line
- Support for all types (including user-defined)
- File and string I/O via method variants of the above

Outline

- High-Level Comments
- Elementary Concepts
- Data Structures and Control
  - Tuples
  - Ranges
  - Arrays
  - For loops
  - Traditional constructs
- Miscellaneous

Tuple Values

- Syntax

```
tuple-expr:
  ( expr, expr-list )

expr-list:
  expr
  expr, expr-list
```

- Semantics
  - Light-weight first-class data structure
- Examples

```
var i3: (int, int, int) = (1, 2, 3);
var i3_2: 3*int = (4, 5, 6);
var triple: (int, string, real) = (7, "eight", 9.0);
```

Range Values

- Syntax

```
range-expr:
  [low] .. [high] [by stride]
```

- Semantics
  - Regular sequence of integers

    stride > 0: *low*, *low*+*stride*, *low*+2**stride*, ... ≤ *high*

    stride < 0: *high*, *high*+*stride*, *high*+2**stride*, ... ≥ *low*
  - Default *stride* = 1, default *low* or *high* is unbounded
- Examples

```
1..6 by 2       // 1, 3, 5
1..6 by -1      // 6, 5, 4, 3, 2, 1
3.. by 3        // 3, 6, 9, 12, ...
```

Array Types

- Syntax

```
array-type:
  [ index-set-expr ] elt-type
```

- Semantics
  - Stores an element of *elt-type* for each index
- Examples

```
var A: [1..3] int,          // 3-element array of ints
    B: [1..3, 1..5] real, // 2D array of reals
    C: [1..3][1..5] real; // array of arrays of reals
```

Much more on arrays in data parallelism part

For Loops

- Syntax

```
for-loop:
  for index-expr in iteratable-expr { stmt-list }
```

- Semantics
  - Executes loop body once per loop iteration
  - Indices in *index-expr* are new variables
- Examples

```
var A: [1..3] string = (" DO", " RE", " MI");

for i in 1..3 do write(A(i));        // DO RE MI
for a in A { a += "LA"; write(a); } // DOLA RELA MILA
```

Zipper "()" and Tensor "[]" Iteration

- Syntax

```
zipper-for-loop:
  for index-expr in ( iteratable-exprs ) { stmt-list }

tensor-for-loop:
  for index-expr in [ iteratable-exprs ] { stmt-list }
```

- Semantics
  - Zipper iteration is over all yielded indices pair-wise
  - Tensor iteration is over all pairs of yielded indices
- Examples

```
for i in (1..2, 1..2) do  // (1,1), (2,2)

for i in [1..2, 1..2] do  // (1,1), (1,2), (2,1), (2,2)
```

Traditional Control

- Conditional statements

```
if cond then computeA() else computeB();
```

- While loops

```
while cond {
  compute();
}
```

```
do {
  compute();
} while cond;
```

- Select statements

```
select key {
  when value1 do compute1();
  when value2 do compute2();
  otherwise compute3();
}
```

Outline

- High-Level Comments
- Elementary Concepts
- Data Structures and Control
- Miscellaneous
  - Functions and iterators
  - Records and classes
  - Generics
  - Other basic language features

Function Examples

- Example to compute the area of a circle

```
def area(radius: real)
  return 3.14 * radius**2;

writeln(area(2.0));    // 12.56
```

- Example of function arguments

```
def writeCoord(x: real = 0.0, y: real = 0.0) {
  writeln("(", x, ", ", y, ")");
}

writeCoord(2.0);       // (2.0, 0.0)
writeCoord(y=2.0);     // (0.0, 2.0)
```

What is an Iterator?

- An abstraction for loop control
  - Yields (generates) values for consumption
  - Otherwise, like a function
- Example

```
def string_chars(s: string) {
  for i in 1..length(s) do
    yield s.substring(i);
}

for c in string_chars(s) do ...
```

Records

- Value-based objects
  - Value-semantics (assignment copies fields)
  - Contain variable definitions (fields)
  - Contain function definitions (methods)
  - Similar to C++ classes
- Example

```
record circle { var x, y, radius: real; }
var c1, c2: circle;
c1.x = 1.0; c1.y = 1.0; c1.radius = 2.0;
c2 = c1; // copy of value
```

Classes

- Reference-based objects
  - Reference-semantics (assignment aliases)
  - Dynamic allocation
  - Dynamic dispatch
  - Similar to Java classes
- Example

```
class circle { var x, y, radius: real; }
var c1, c2: circle;
c1 = new circle(x=1.0, y=1.0, radius=2.0);
c2 = c1; // c2 is an alias of c1
delete c1;
```

Method Examples

Methods are functions associated with types.

```
def circle.area()
  return 3.14 * radius**2;

writeln(c1.area());
```

Methods can be defined for any type.

```
def int.square()
  return this**2;

writeln(5.square());
```

Generic Functions

Generic functions can be defined by explicit type and param arguments:

```
def foo(type t, x: t) { ...
def bar(param bitWidth, x: int(bitWidth)) { ...
```

Or simply by eliding an argument type (or type part):

```
def goo(x, y) { ...
def sort(A: []) { ...
```

Generic functions are replicated for each unique instantiation:

```
foo(int, x);    // copy of foo() with t==int
foo(string, x); // copy of foo() with t==string
goo(4, 2.2);    // copy of goo() with int and real args
```

Generic Types

Generic types can be defined by explicit type and param fields:

```
class Table { param numFields: int; ...
class Matrix { type eltType; ...
```

Or simply by eliding a field type (or type part):

```
record Triple { var x, y, z; }
```

Generic types are replicated for each unique instantiation:

```
// copy of Table with 10 fields
var myT: Table(10);
// copy of Triple with x:int, y:int, z:real
var my3: Triple(int,int,real) = new Triple(1,2,3.0);
```

Other Basic Language Features

- Unions
- Enumerated types
- Range and domain by and # operators
- Expression forms of conditionals and loops
- Type select statements
- Function instantiation constraints (where clauses)
- Formal argument intents (in, out, inout, const)
- User-defined compiler warnings and errors

Future Directions

- Fixed length strings
- Binary I/O
- Parallel I/O
- Interoperability with other languages
- More advanced OO features

Questions?

- High-Level Comments
- Elementary Concepts
  - Lexical structure
  - Types, variables, and constants
  - Input and output
- Data Structures and Control
  - Tuples
  - Ranges
  - Arrays
  - For loops
  - Traditional constructs
- Miscellaneous
  - Functions and iterators
  - Records and classes
  - Generics
  - Other basic language features

Chapel: Data Parallelism

Outline

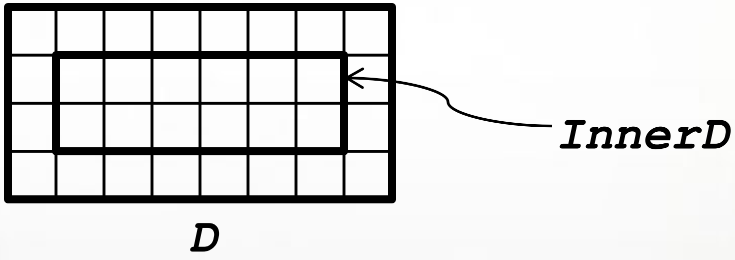
- Domains and Arrays
  - Overview
  - Arithmetic
- Other Domain Types
- Data Parallel Operations
- NAS MG Stencil Revisited

Domains

- A first-class index set
  - Specifies size and shape of arrays
  - Supports iteration, array operations
  - Potentially distributed across locales
- Three main classes
  - Arithmetic—indices are Cartesian tuples
  - Associative—indices are hash keys
  - Opaque—indices are anonymous
- Fundamental Chapel concept for data parallelism
- A generalization of ZPL's region concept

Sample Arithmetic Domains

```
config const m = 4, n = 8;

var D: domain(2) = [1..m, 1..n];

var InnerD: domain(2) = [2..m-1, 2..n-1];
```



Domains Define Arrays

- Syntax

```
array-type:
  [ domain-expr ] elt-type
```

- Semantics
  - Stores element for each index in *domain-expr*
- Example

```
var A, B: [D] real;
```

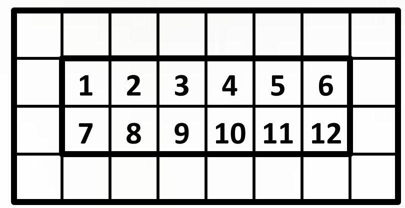
- Revisited example

```
var A: [1..3] int; // creates anonymous domain [1..3]
```

Domain Iteration

- For loops (discussed already)
  - Executes loop body once per loop iteration
  - Order is serial

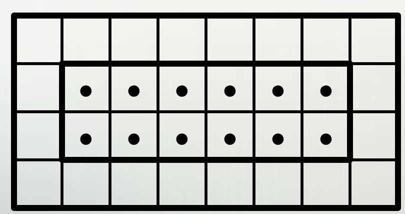
```
for i in InnerD do ...
```



D

- Forall loops
  - Executes loop body once per loop iteration
  - Order is parallel (must be *serializable*)

```
forall i in InnerD do ...
```



D

Other Forall Loops

Forall loops also support...

- A shorthand:

```
[(i,j) in D] A(i,j) = i + j/10.0;
```

1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8
2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8
3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8
4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8

A

- An expression-based form:

```
A = forall (i,j) in D do i + j/10.0;
```

- A shorthand expression-based form:

```
A = [(i,j) in D] i + j/10.0;
```

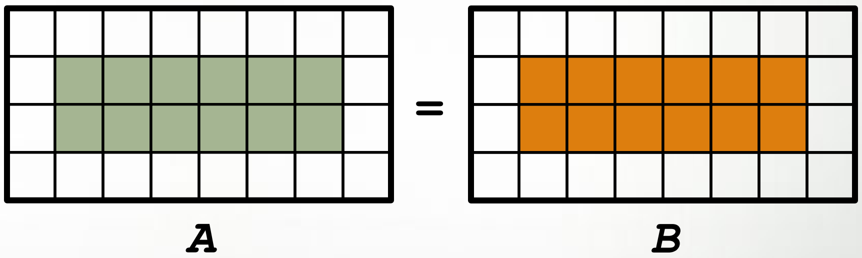
Data Parallelism Configuration Constants

- **--dataParTasksPerLocale=#**
  - Specify # of tasks to execute forall loops
  - Default: number of cores *(in current implementation)*
- **--dataParIgnoreRunningTasks=[true|false]**
  - If false, reduce # of forall tasks by # of running tasks
  - Default: true *(in current implementation)*
- **--dataParMinGranularity=#**
  - If > 0, reduce # of forall tasks if any task has fewer iterations
  - Default: 1 *(in current implementation)*

Other Domain Functionality

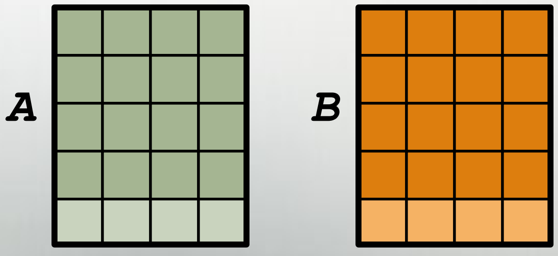
- Domain methods (exterior, interior, translate, ...)
- Domain slicing (intersection)
- Array slicing (sub-array references)

```
A(InnerD) = B(InnerD);
```



- Array reallocation
  - Reassign domain → change array
  - Values are preserved (new elements initialized)

```
D = [1..m+1, 1..m];
```



Array Arguments and Aliases

- Arrays are passed by reference

```
def f(A: []) { A = 0; }

f(A[InnerD]);
```

- Non-argument array alias of a slice

```
var AA => A(InnerD);
```

- Re-indexing arrays

```
def f(A: [1..n-2,1..m-2]);

f(A[2..n-1,2..m-1]);
```

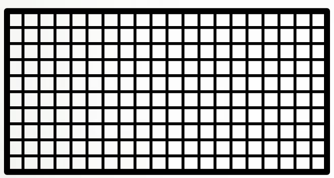
```
var AA: [1..n-2,1..m-2] => A[2..n-1,2..m-1];
```

Outline

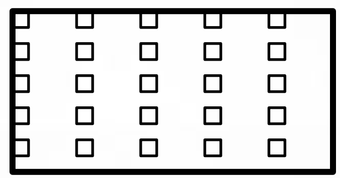
- Domains and Arrays
- Other Domain Types
  - Strided
  - Sparse
  - Associative
  - Opaque
- Data Parallel Operations
- NAS MG Stencil Revisited

The Varied Kinds of Domains

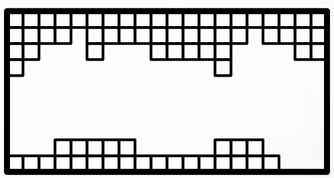
```
var Dense: domain(2) = [1..10, 1..20],
    Strided: domain(2) = Dense by (2, 4),
    Sparse: sparse subdomain(Dense) = genIndices(),
    Associative: domain(string) = readNames(),
    Opaque: domain(opaque);
```



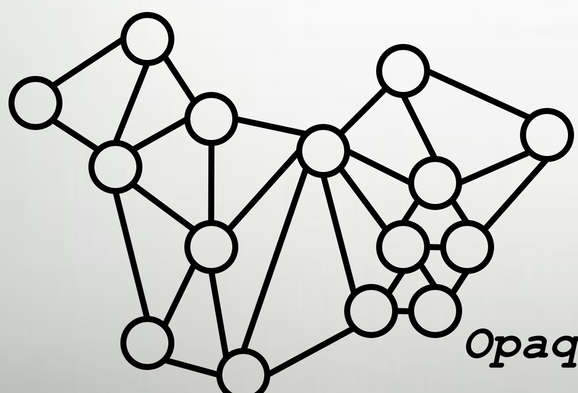
Dense



Strided



Sparse



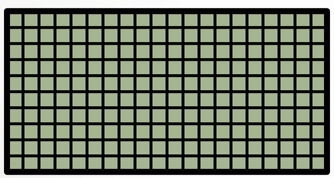
Opaque

George
John
Thomas
James
Andrew
Martin
William

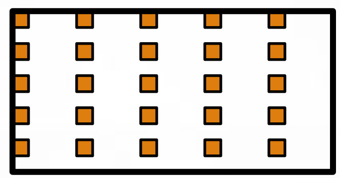
Associative

The Varied Kinds of Arrays

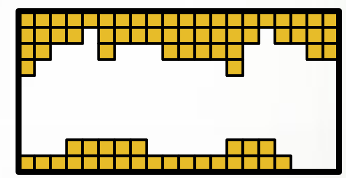
```
var DenseArr: [Dense] real,
    StridedArr: [Strided] real,
    SparseArr: [Sparse] real,
    AssociativeArr: [Associative] real,
    OpaqueArr: [Opaque] real;
```



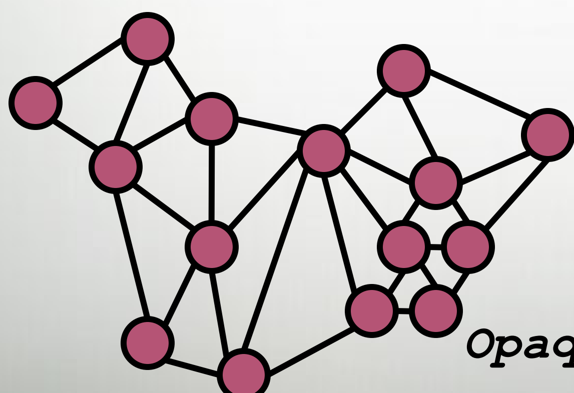
DenseArr



StridedArr



SparseArr

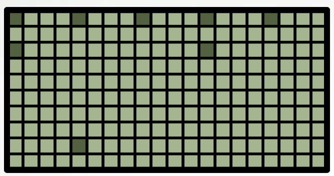


OpaqueArr

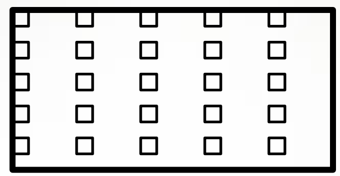
AssociativeArr

All Domains Support Iteration

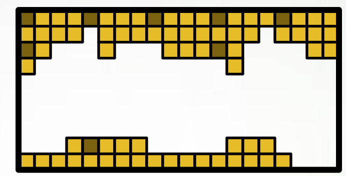
```
forall (i,j) in Strided {
  DenseArr(i,j) += SparseArr(i,j);
}
```



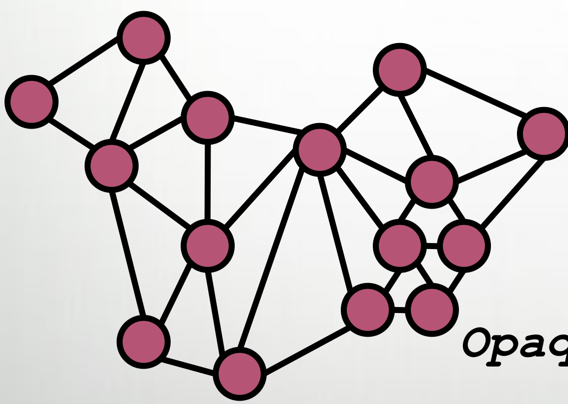
DenseArr



Strided



SparseArr



OpaqueArr

AssociativeArr

(Also, all domains support slicing, reallocation, ...)

Associative Domains and Arrays by Example

```
var Presidents: domain(string) =
        ("George", "John", "Thomas",
         "James", "Andrew", "Martin");

Presidents += "William";


var Ages: [Presidents] int,
    Birthdays: [Presidents] string;

Birthdays("George") = "Feb 22";


forall president in Presidents do
  if Birthdays(president) == today then
    Ages(president) += 1;
```

Presidents
George
John
Thomas
James
Andrew
Martin
William

Birthdays	*Ages*
Feb 22	277
Oct 30	274
Apr 13	266
Mar 16	251
Mar 15	242
Dec 5	227
Feb 9	236

Outline

- Domains and Arrays
- Other Domain Types
- Data Parallel Operations
  - Promotion
  - Reductions
  - Scans
- NAS MG Stencil Revisited

Data Parallel Promotion

Functions/operators expecting scalars can also take...

- Arrays, causing each element to be passed

```
sin(A)
2*A
```

≈

```
forall a in A do sin(a)
forall a in A do 2*a
```

- Domains, causing each index to be passed

```
foo(Sparse)
```

≈

```
forall i in Sparse do foo(i)
```

Multiple arguments can promote using either...

- Zipper promotion

```
pow(A, B)
```

≈

```
forall (a,b) in (A,B) do pow(a,b)
```

- Tensor product promotion

```
pow[A, B]
```

≈

```
forall (a,b) in [A,B] do pow(a,b)
```

Reductions

- Syntax

```
reduce-expr:
  reduce-op reduce iterator-expr
```

- Semantics
  - Combines iterated elements with *reduce-op*
  - *Reduce-op* may be built-in or user-defined
- Examples

```
total = + reduce A;
bigDiff = max reduce [i in InnerD] abs(A(i)-B(i));
```

Scans

- Syntax

```
scan-expr:
  scan-op scan iterator-expr
```

- Semantics
  - Computes parallel prefix of *scan-op* over elements
  - *Scan-op* may be any *reduce-op*
- Examples

```
var A, B, C: [1..5] int;
A = 1;                       // A:  1  1  1  1  1
B = + scan A;                // B:  1  2  3  4  5
B(3) = -B(3);                // B:  1  2 -3  4  5
C = min scan B;              // C:  1  1 -3 -3 -3
```

Reduction and Scan Operators

- Built-in
  - +, *, &&, ||, &, |, ^, min, max
  - minloc, maxloc

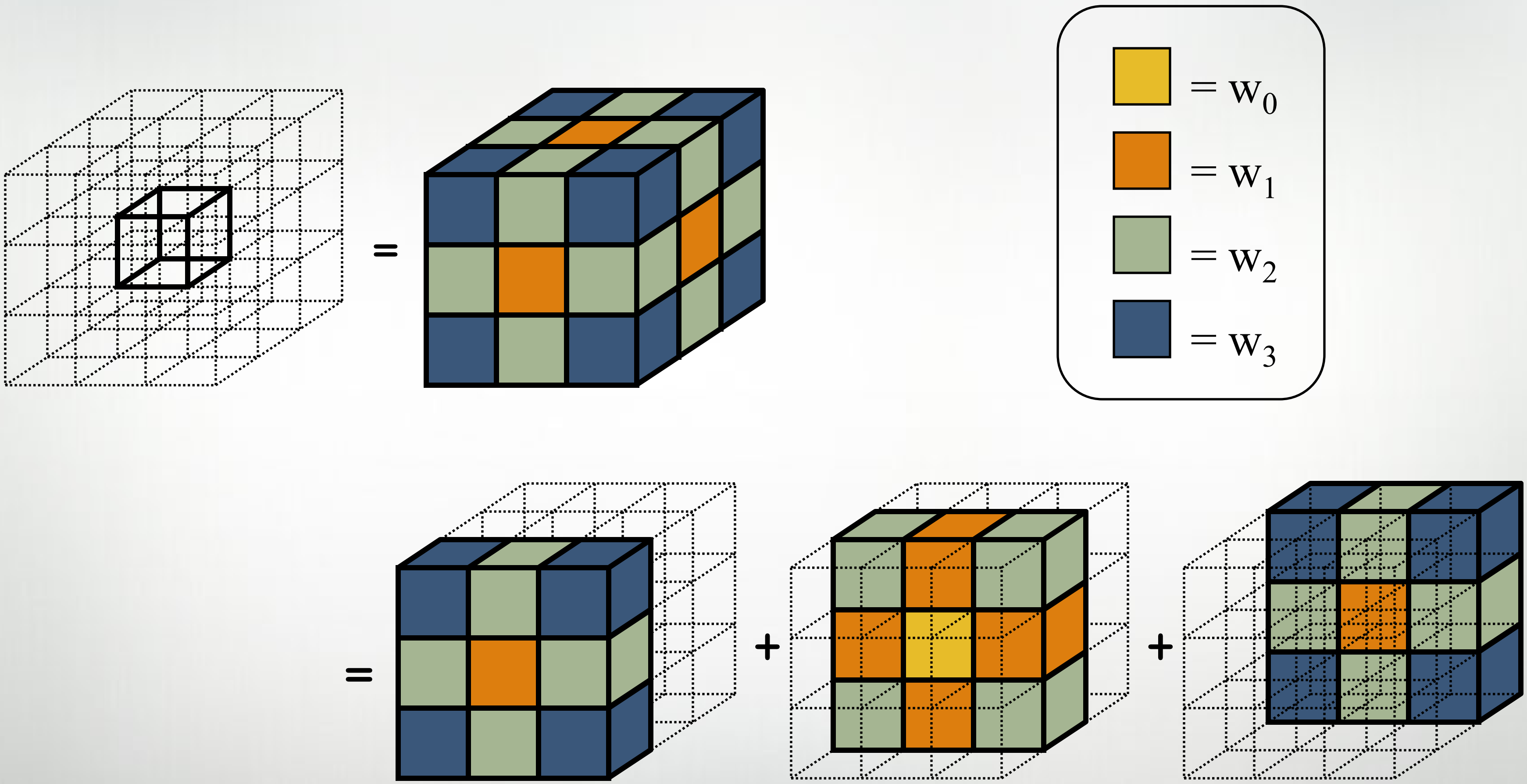
    (Generate a tuple of the min/max and its index)
- User-defined
  - Defined via a class that supplies a set of methods
  - Compiler generates code that calls these methods
  - More information:

    S. J. Deitz, D. Callahan, B. L. Chamberlain, and L. Snyder. *Global-view abstractions for user-defined reductions and scans*. In Proceedings of the Eleventh ACM SIGPLAN Symposium on Principles and Practices of Parallel Programming, 2006.

Outline

- Domains and Arrays
- Other Domain Types
- Data Parallel Operations
- NAS MG Stencil Revisited

NAS MG Stencil Revisited



NAS MG Stencil in Chapel Revisited

```
def rprj3(S, R) {
  const Stencil = [-1..1, -1..1, -1..1],
        W: [0..3] real = (0.5, 0.25, 0.125, 0.0625),
        W3D = [(i,j,k) in Stencil] W((i!=0)+(j!=0)+(k!=0));

  forall inds in S.domain do
    S(inds) =
      + reduce [offset in Stencil] (W3D(offset) *
                                     R(inds + offset*R.stride));
}
```

Questions?

- Domains and Arrays
  - Overview
  - Arithmetic
- Other Domain Types
  - Strided
  - Sparse
  - Associative
  - Opaque
- Data Parallel Operations
  - Promotion
  - Reductions
  - Scans
- NAS MG stencil revisited

Chapel: Multi-Locale Execution

The Locale Type

- Definition
  - Abstract unit of target architecture
  - Capacity for processing and storage
  - Supports reasoning about locality
- Properties
  - Locale’s tasks have uniform access to local memory
  - Other locale’s memory is accessible, but at a price
- Examples
  - A multi-core processor
  - An SMP node

Program Startup

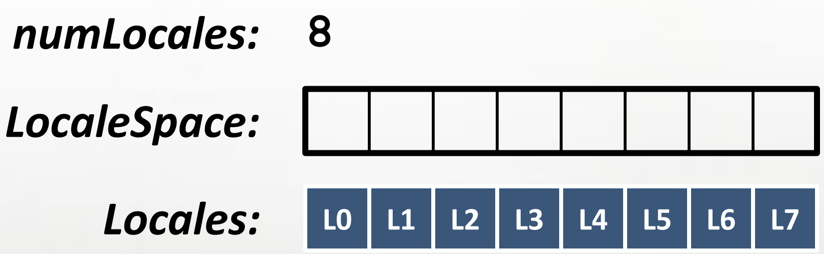
- Execution Context

```
config const numLocales: int;
const LocaleSpace: domain(1) = [0..numLocales-1];
const Locales: [LocaleSpace] locale;
```

- Specify # of locales when running executable

```
% a.out --numLocales=8
```

```
% a.out -nl 8
```



- Execution begins as a single task on a locale 0

Locale Methods

- ```
  def locale.id: int { ... }
  ```
  Returns index in LocaleSpace
- ```
  def locale.name: string { ... }
  ```
  Returns name of locale (like uname -a)
- ```
  def locale.numCores: int { ... }
  ```
  Returns number of cores available to locale
- ```
  def locale.physicalMemory(...) { ... }
  ```
  Returns physical memory available to user programs on locale

  Example

  ```
  const totalPhysicalMemory =
    + reduce Locales.physicalMemory();
  ```

The On Statement

- Syntax

```
on-stmt:
  on expr { stmt }
```

- Semantics
  - Executes *stmt* on the locale that stores *expr*
  - Does not introduce concurrency
- Example

```
var A: [LocaleSpace] int;
coforall loc in Locales do
  on loc do
    A(loc.id) = compute(loc.id);
```

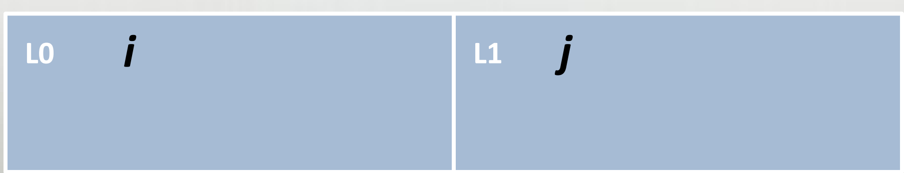
Querying a Variable's Locale

- Syntax

```
locale-query-expr:
  expr . locale
```

- Semantics
  - Returns the locale on which *expr* is stored
- Example

```
var i: int;
on Locales(1) {
  var j: int;
  writeln(i.locale.id, j.locale.id); // outputs 01
}
```



Here

- Built-in locale

```
const here: locale;
```

- Semantics
  - Refers to the locale on which the task is executing
- Example

```
writeln(here.id);     // outputs 0
on Locales(1) do
  writeln(here.id);   // outputs 1
```

Serial Example with Implicit Communication

```
var x, y: real;         // x and y allocated on locale 0

on Locales(1) {         // migrate task to locale 1
  var z: real;          // z allocated on locale 1

  z = x + y;            // remote reads of x and y

  on Locales(0) do      // migrate back to locale 0
    z = x + y;          // remote write to z
                        // migrate back to locale 1
  on x do               // data-driven migration to locale 0
    z = x + y;          // remote write to z
                        // migrate back to locale 1
}                       // migrate back to locale 0
```

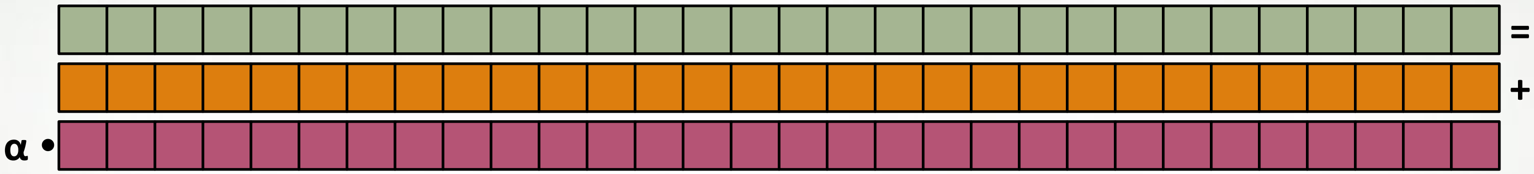
L0		L1	
	x		***z***
	y		

Outline

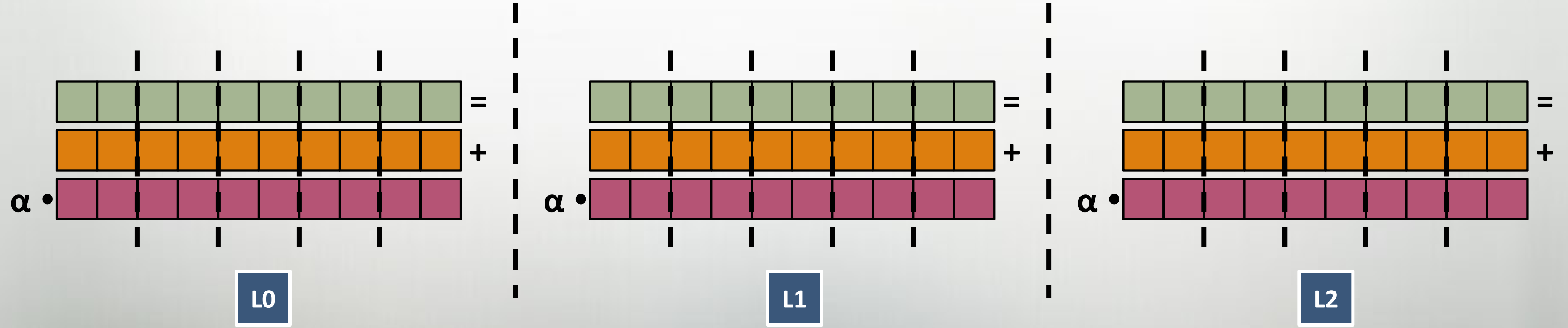
- Multi-Locale Basics
- Domain Maps
  - Layouts
  - Distributions
- Chapel Standard Layouts and Distributions
- User-defined Domain Maps

Domain Maps

Domain maps are a "recipe" that instructs the compiler how to map the global view…



…to memory and/or locales



More on Domain Maps

A domain map defines:

- Ownership of domain indices and array elements
- Underlying representation
- Standard set of operations on domains and arrays
  - E.g, slicing, reindexing, rank change
- How to farm out work
  - E.g., forall loops over distributed domains/arrays

Domain maps are built using language-level constructs

Using Domain Maps

- Syntax

```
dmap-type:
  dmap(dmap-class(...))
dmap-value:
  new dmap(new dmap-class(...))
```

- Semantics
  - Domain map classes are defined in Chapel
- Examples

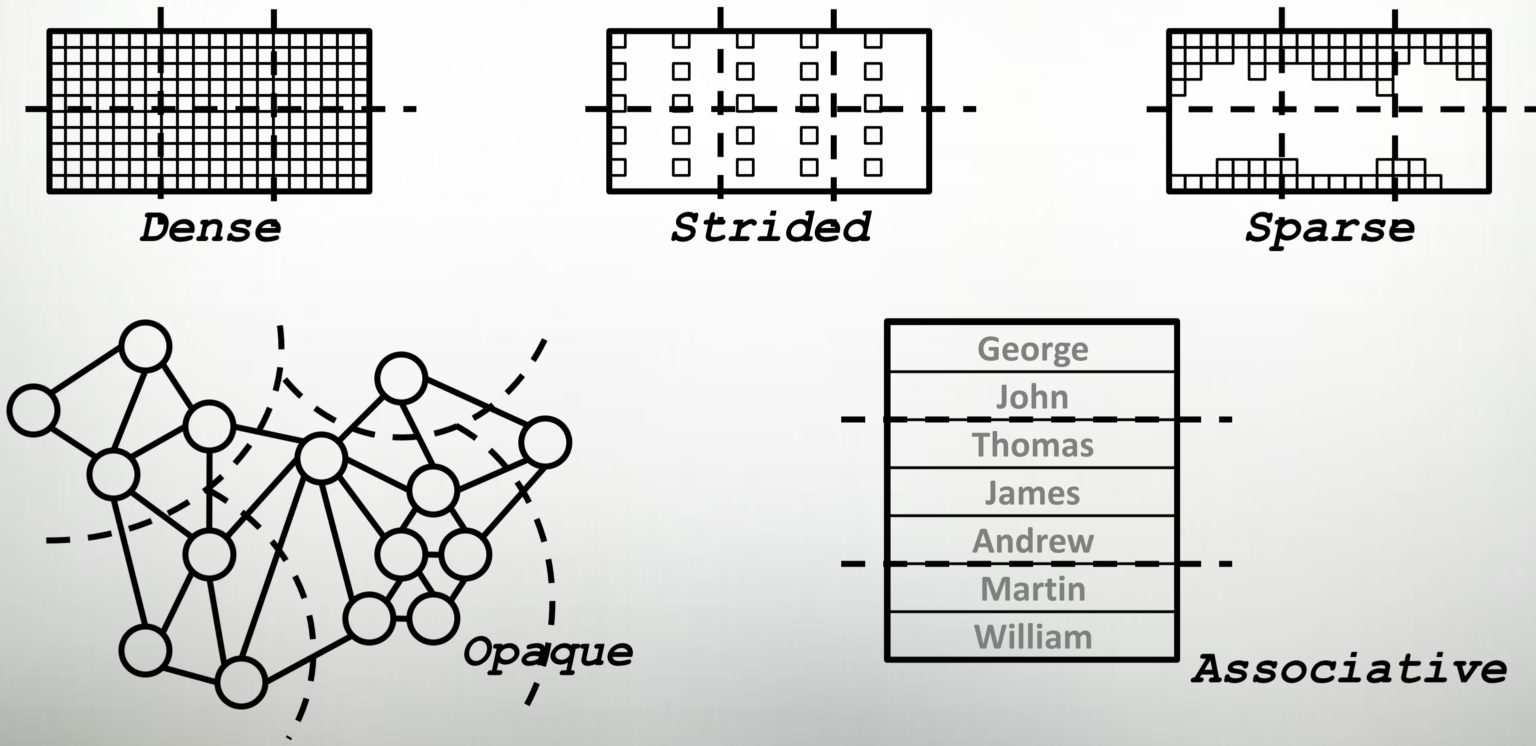
```
use myDMapMod;
var DMap: dmap(myDMap(...)) = new dmap(new myDMap(...));

var Dom: domain(...) dmapped DMap;
var A: [Dom] real;
```

Domain Map Types

All domain types can be dmapped.

Semantics are independent of domain map.

(Though performance and parallelism will vary...)



Layouts

Layouts are single-locale domain maps

- Uses begin, cobegin, coforall to implement data parallelism
- May take advantage of locale resources, *e.g.*, multiple cores

Examples

- Sparse CSR
- GPU

Distributions

Distributions are multi-locale domain maps

- Uses begin, cobegin, coforall to implement data parallelism
- Uses on to control data and task locality
- May use layouts for per-locale implementation

Examples

- Block
- Cyclic
- Block-Cyclic
- Block CSR
- Recursive bisection

Outline

- Domain Maps
- Chapel Standard Layouts and Distributions
  - Block
  - Cyclic
- User-defined Domain Maps

Chapel Standard Layouts and Distributions

Chapel provides a number of standard layouts and distributions

- All are written in Chapel

Examples

- Block distribution
- Cyclic distribution

The Block Distribution

The Block Distribution maps the indices of a domain in a dense fashion across the target Locales according to the `boundingBox` argument

```
const Dist = new dmap(new Block(boundingBox=[1..4, 1..8]));

var Dom: domain(2) dmapped Dist = [1..4, 1..8];
```

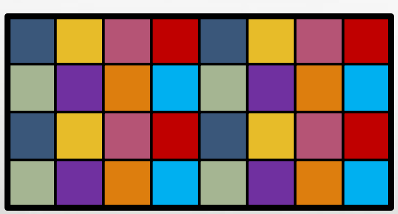
The Block class constructor

```
def Block(boundingBox: domain,
          targetLocales: [] locale = Locales,
          dataParTasksPerLocale = ...,
          dataParIgnoreRunningTasks = ...,
          dataParMinGranularity = ...,
          param rank = boundingBox.rank,
          type idxType = boundingBox.dim(1).eltType)
```

The Cyclic Distribution

The Cyclic Distribution maps the indices of a domain in a round-robin fashion across the target Locales according to the `startIdx` argument

```
const Dist = new dmap(new Cyclic(startIdx=(1,1)));

var Dom: domain(2) dmapped Dist = [1..4, 1..8];
```



distributed over

The Cyclic class constructor

```
def Cyclic(startIdx,
           targetLocales: [] locale = Locales,
           dataParTasksPerLocale = ...,
           dataParIgnoreRunningTasks = ...,
           dataParMinGranularity = ...,
           param rank: int = infered from startIdx,
           type idxType = infered from startIdx)
```

A little under the covers..

- Both the Block and Cyclic distributions use coforall and on to implement forall loops

```
coforall locDom in locDoms do on locDom {
  ... local portion ...
}
```

- Each locale's local portion uses the same knobs for intra-locale parallelism as default arrays and domains

Outline

- Domain Maps
- Chapel Standard Layouts and Distributions
- User-defined Domain Maps

User-defined Domain Maps

(Advanced) programmers can write domain maps

- The compiler uses a structural interface to build domain maps:
  - Create domains and arrays
  - Map indices to locales
  - Access array elements
  - Iterate over indices/elements sequentially, in parallel, zippered
  - ...

Standard Domain Maps ***are*** user-defined domain maps

Design goal: User-defined domain maps should perform as well as the Chapel Standard Domain Maps

Future Directions

- Heterogeneous locales
- Hierarchical locales
- GPU support via locales
- More standard distributions and layouts
- Specify interface for user-defined domain maps

Questions?

- Multi-Locale Basics
  - Locales
  - On, here, local, and communication
- Domain maps
  - Layouts
  - Distributions
- The Chapel Standard Distributions
  - Block Distribution
  - Cyclic Distribution
- User-defined Domain Maps

Chapel: Task Parallelism

Outline

- Primitive Task-Parallel Constructs
  - The **begin** statement
  - The **sync** types
- Structured Task-Parallel Constructs
- Atomic Transactions and Memory Consistency

Unstructured Task Creation: Begin

- Syntax

```
begin-stmt:
  begin stmt
```

- Semantics
  - Creates a concurrent task to execute *stmt*
  - Control continues immediately (no join)
- Example

```
begin writeln("hello world");
writeln("good bye");
```

- Possible output

```
hello world
good bye
```

```
good bye
hello world
```

Synchronization via Sync-Types

- Syntax

```
sync-type:
  sync type
```

- Semantics
  - Default read blocks until written (until “full”)
  - Default write blocks until read (until “empty”)
- Examples: Critical sections and futures

```
var lock$: sync bool;

lock$ = true;
critical();
lock$;
```

```
var future$: sync real;

begin future$ = compute();
computeSomethingElse();
useComputeResults(future$);
```

Sync-Type Methods

• **`readFE():t`**	wait until full, leave empty, return value
• **`readFF():t`**	wait until full, leave full, return value
• **`readXX():t`**	non-blocking, return value
• **`writeEF(v:t)`**	wait until empty, leave full, set value to `v`
• **`writeFF(v:t)`**	wait until full, leave full, set value to `v`
• **`writeXF(v:t)`**	non-blocking, leave full, set value to `v`
• **`reset()`**	non-blocking, leave empty, reset value
• **`isFull: bool`**	non-blocking, return true if full else false

- Defaults – read: **`readFE`**, write: **`writeEF`**

Outline

- Primitive Task-Parallel Constructs
- Structured Task-Parallel Constructs
  - The **cobegin** statement
  - The **coforall** loop
  - The **sync** statement
- Atomic Transactions and Memory Consistency
- Implementation Notes and Examples

Block-Structured Task Invocation: Cobegin

- Syntax

```
cobegin-stmt:
  cobegin { stmt-list }
```

- Semantics
  - Invokes a concurrent task for each listed *stmt*
  - Control waits to continue – implicit join
- Example

```
cobegin {
  consumer(1);
  consumer(2);
  producer();
}
```

Cobegin is Unnecessary

Any cobegin statement

```
cobegin {
  stmt1();
  stmt2();
  stmt3();
}
```

can be rewritten in terms of begin statements

```
var s1$, s2$, s3$: sync bool;
begin { stmt1(); s1$ = true; }
begin { stmt2(); s2$ = true; }
begin { stmt3(); s3$ = true; }
s1$; s2$; s3$;
```

but the compiler may miss out on optimizations.

Loop-Structured Task Invocation: Coforall

- Syntax

```
coforall-loop:
  coforall index-expr in iteratable-expr { stmt }
```

- Semantics
  - Loop over *iteratable-expr* invoking concurrent tasks
  - Control waits to continue – implicit join
- Example

```
begin producer();
coforall i in 1..numConsumers {
  consumer(i);
}
```

Usage of Begin, Cobegin, and Coforall

- Use begin when
  - Creating tasks with unbounded lifetimes
  - Load balancing requires dynamic task creation
  - Cobegin and coforall are insufficient for task structuring
- Use cobegin when
  - Invoking a fixed # of tasks (potentially heterogeneous)
  - The tasks have bounded lifetimes
- Use coforall when
  - Invoking a fixed or dynamic # of homogeneous task
  - The tasks have bounded lifetimes

Usage of For, Forall, and Coforall

- Use for when
  - A loop must be executed serially
  - One task is sufficient for performance
- Use forall when
  - The loop can be executed in parallel
  - The loop can be executed serially
  - Degree of concurrency << # of iterations
- Use coforall when
  - The loop must be executed in parallel
    (And not just for performance reasons!)
  - Each iteration has substantial work

Structuring Sub-Tasks: Sync-Statements

- Syntax

```
sync-statement:
  sync stmt
```

- Semantics
  - Executes *stmt*
  - Waits on all *dynamically-encountered* begins
- Example

```
sync {
  for i in 1..numConsumers {
    begin consumer(i);
  }
  producer();
}
```

Program Termination and Sync-Statements

Where the cobegin statement is static,

```
cobegin {
  functionWithBegin();
  functionWithoutBegin();
}
```

the sync statement is dynamic.

```
sync {
  begin functionWithBegin();
  begin functionWithoutBegin();
}
```

Program termination is defined by an implicit sync.

```
sync main();
```

Outline

- Primitive Task-Parallel Constructs
- Structured Task-Parallel Constructs
- Atomic Transactions and Memory Consistency
  - The **atomic** statement
  - Races and memory consistency
- Implementation Notes and Examples

Atomic Transactions (Unimplemented)

- Syntax

```
atomic-statement:
  atomic stmt
```

- Semantics
  - Executes stmt so it appears as a single operation
  - No other task sees a partial result
- Example

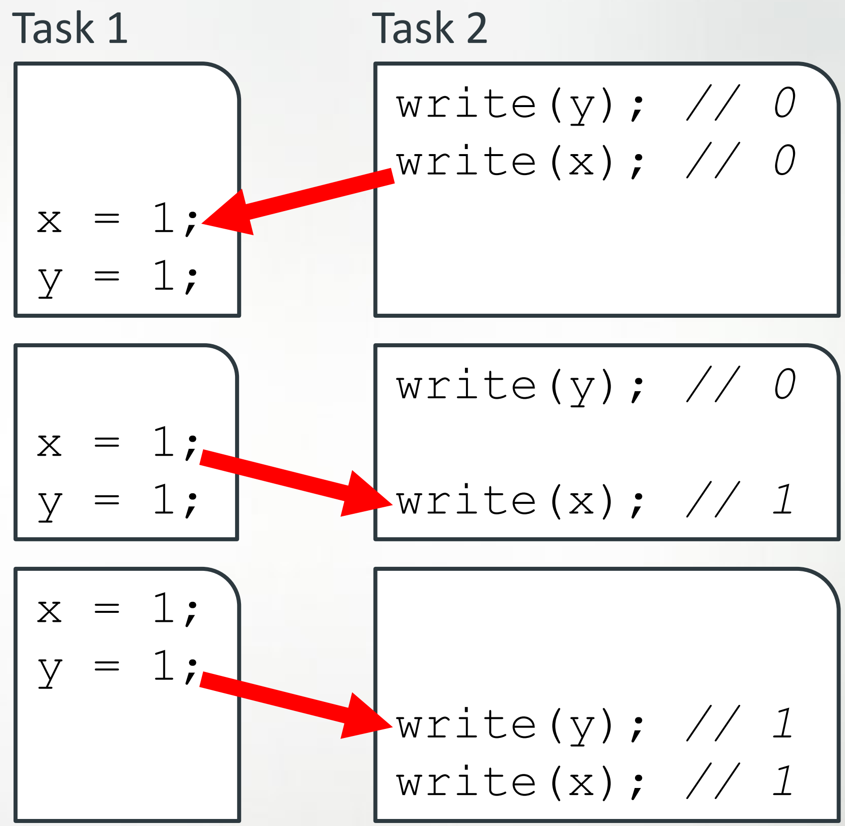
```
atomic A(i) = A(i) + 1;
```

```
atomic {
  newNode.next = node;
  newNode.prev = node.prev;
  node.prev.next = newNode;
  node.prev = newNode;
}
```

Races and Memory Consistency

- Example

```
var x = 0, y = 0;
cobegin {
  {
    x = 1;
    y = 1;
  }
  {
    write(y);
    write(x);
  }
}
```



- Could the output be 10? Or 42?

Data-Race-Free Programs (The Fine Print)

A program without races is sequentially consistent.

> A multi-processing system has sequential consistency if "*the results of any execution is the same as if the operations of all the processors were executed in some sequential order, and the operations of each individual processor appear in this sequence in the order specified by its program.*" – Leslie Lamport

The behavior of a program with races is undefined.

Synchronization is achieved in two ways:

- By reading or writing sync (or single) variables
- By executing atomic statements

Future Directions

- Task teams
- Suspendable tasks
- Work stealing, load balancing
- Eurekas
- Task-private variables

Questions?

- Primitive Task-Parallel Constructs
  - The **begin** statement
  - The **sync** types
- Structured Task-Parallel Constructs
  - The **cobegin** statement
  - The **coforall** loop
  - The **sync** statement
- Atomic Transactions and Memory Consistency
  - The **atomic** statement
  - Races and memory consistency

Chapel: Wrap Up

Outline

- About Chapel v1.1
- Implementation status
- External collaborations

Chapel Version 1.1

- Features
  - Open source at http://sourceforge.net/projects/chapel/
  - Distributed under the BSD Open Source license
  - Ported to Linux/Unix, Mac, Cygwin
- Contents
  - Compiler, runtime, standard modules, third-party libraries
  - Language spec, quick reference, numerous examples
- Highlights
  - Most data-parallel operations execute in parallel
  - Improved control of data parallelism
  - Completed Block and Cyclic distributions

Implementation Status

- Language Basics
  - No support for inheritance from multiple or generic classes
  - Incomplete support for sparse arrays and domains
  - No support for skyline arrays
  - Several internal memory leaks
- Task Parallelism
  - No support for atomic statements
  - Memory consistency model is not guaranteed
- Data Parallelism
  - Promoted functions/operators do not preserve shape
  - No partial scans or reductions

Collaborations I

- **Notre Dame/ORNL** (Peter Kogge, Srinivas Sridharan, Jeff Vetter)
  Asynchronous software transactional memory over distributed memory
- **UIUC** (David Padua, Albert Sidelnik, Maria Garzaran)
  Chapel for hybrid CPU-GPU computing
- **BSC/UPC** (Alex Duran)
  Chapel over Nanos++ user-level tasking
- **U. Malaga** (Rafa Asenio, Maria Gonzales, Rafael Larossa)
  Parallel file I/O for arrays
- **OSU** (Gagan Agrawal, Bin Ren)
  User-defined reductions over FREERIDE for data intensive computing

Collaborations II

- **U. Colorado** (Jeremy Siek, Jonathan Turner)
  Interfaces and modular generics for Chapel
- **PNNL/CASS-MT** (John Feo, Daniel Chavarria)
  Hybrid computing in Chapel; Cray XMT performance tuning; ARMCI port
- **ORNL** (David Bernholdt *et al.*, Steve Poole *et al.*)
  Code studies – Fock matrices, MADNESS, Sweep3D, coupled models, ...
- **Berkeley** (Dan Bonachea, Paul Hargrove *et al.*)
  Efficient GASNet support for Chapel; collective communication
- **U. Oregon/Paratools Inc.** (Sameer Shende)
  Performance analysis with Tau

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