Chapel
the Cascade High Productivity Language

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October 22, 2009

What is Chapel?

- A new parallel language being developed by Cray Inc.
- Part of Cray's entry in DARPA's HPCS program
- **Main Goal:** Improve programmer productivity
  - Improve the programmability of parallel computers
  - Match or beat the performance of current programming models
  - Provide better portability than current programming models
  - Improve robustness of parallel codes
- Target architectures:
  - multicore desktop machines
  - clusters of commodity processors
  - Cray architectures
  - systems from other vendors
- A work in progress

Chapel's Setting: HPCS

HPCS: High *Productivity* Computing Systems (DARPA *et al.*)

- Goal: Raise productivity of high-end computing users by 10×
- Productivity = Performance
  + Programmability
  + Portability
  + Robustness

- **Phase II**: Cray, IBM, Sun (July 2003 – June 2006)
  - Evaluated the entire system architecture's impact on productivity…
    - processors, memory, network, I/O, OS, runtime, compilers, tools, …
    - …and new languages:

      Cray: Chapel IBM: X10 Sun: Fortress

- **Phase III**: Cray, IBM (July 2006 –)
  - Implement the systems and technologies resulting from phase II
  - (Sun also continues work on Fortress, without HPCS funding)

Chapel: Motivating Themes

1) general parallel programming
2) *global-view* abstractions
3) *multiresolution* design
4) control of locality/affinity
5) reduce gap between mainstream & parallel languages

Outline

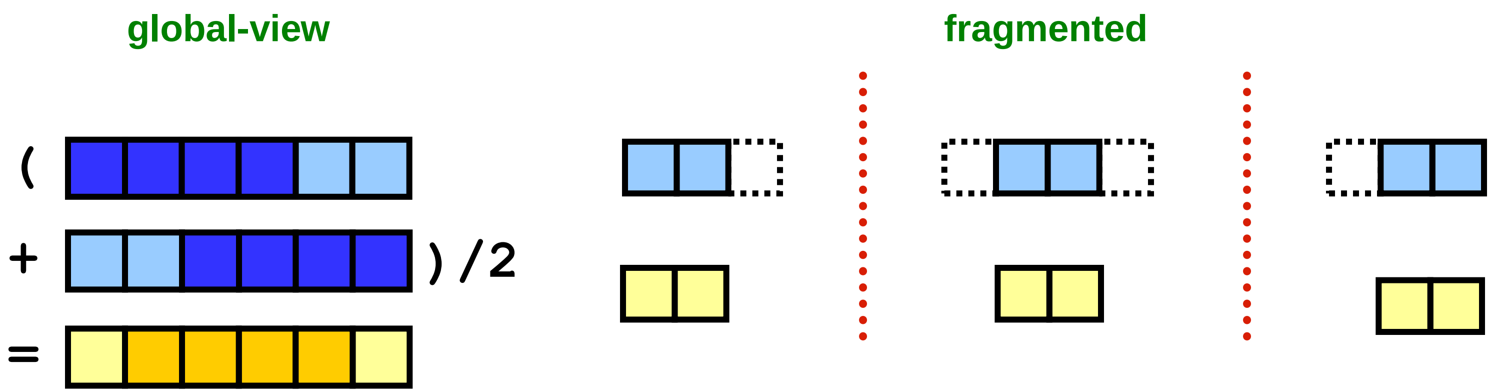
- ✓ Chapel Context
- ➢ Chapel Themes
- ❑ Language Overview
- ❑ Status, Collaborations, Future Work

1) General Parallel Programming

- **General software parallelism**
  - *Algorithms:* should be able to express any that come to mind
    - should never hit a limitation requiring the user to return to MPI
  - *Styles:* data-parallel, task-parallel, concurrent algorithms
    - as well as the ability to compose these naturally
  - *Levels:* module-level, function-level, loop-level, statement-level, …
- **General hardware parallelism**
  - *Types:* multicore desktops, clusters, HPC systems, …
  - *Levels:* inter-machine, inter-node, inter-core, vectors, multithreading

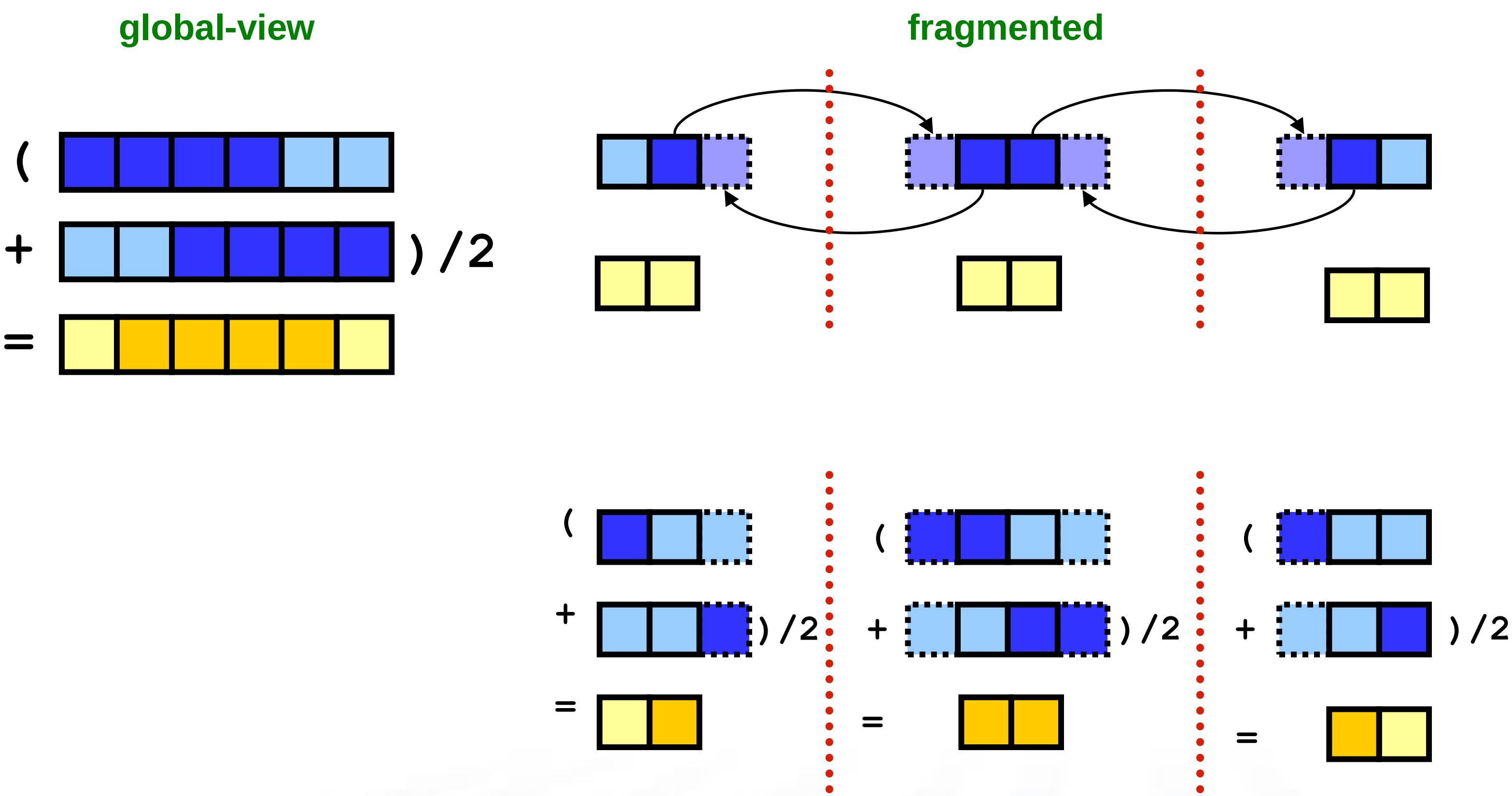
2) Global-view vs. Fragmented

Problem: "Apply 3-pt stencil to vector"



2) Global-view vs. Fragmented

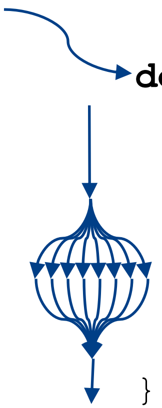
Problem: "Apply 3-pt stencil to vector"



2) Global-view vs. SPMD Code

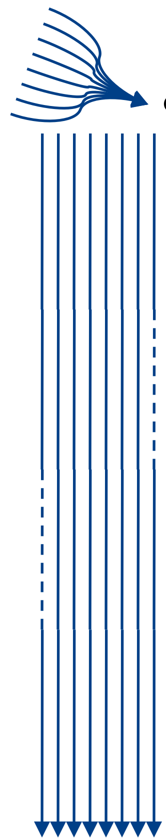
Problem: "Apply 3-pt stencil to vector"

global-view



```
def main() {
  var n: int = 1000;
  var a, b: [1..n] real;

  forall i in 2..n-1 {
    b(i) = (a(i-1) + a(i+1))/2;
  }
}
```

SPMD



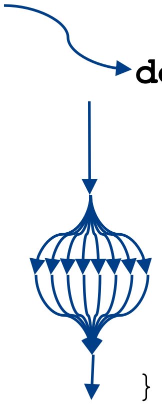
```
def main() {
  var n: int = 1000;
  var locN: int = n/numProcs;
  var a, b: [0..locN+1] real;

  if (iHaveRightNeighbor) {
    send(right, a(locN));
    recv(right, a(locN+1));
  }
  if (iHaveLeftNeighbor) {
    send(left, a(1));
    recv(left, a(0));
  }
  forall i in 1..locN {
    b(i) = (a(i-1) + a(i+1))/2;
  }
}
```

2) Global-view vs. SPMD Code

Problem: "Apply 3-pt stencil to vector"

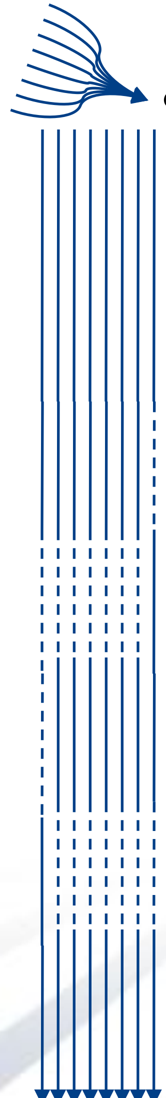
Assumes *numProcs* divides *n*; a more general version would require additional effort

global-view



```
def main() {
  var n: int = 1000;
  var a, b: [1..n] real;

  forall i in 2..n-1 {
    b(i) = (a(i-1) + a(i+1))/2;
  }
}
```

SPMD



```
def main() {
  var n: int = 1000;
  var locN: int = n/numProcs;
  var a, b: [0..locN+1] real;
  var innerLo: int = 1;
  var innerHi: int = locN;

  if (iHaveRightNeighbor) {
    send(right, a(locN));
    recv(right, a(locN+1));
  } else {
    innerHi = locN-1;
  }
  if (iHaveLeftNeighbor) {
    send(left, a(1));
    recv(left, a(0));
  } else {
    innerLo = 2;
  }
  forall i in innerLo..innerHi {
    b(i) = (a(i-1) + a(i+1))/2;
  }
}
```

2) SPMD pseudo-code + MPI

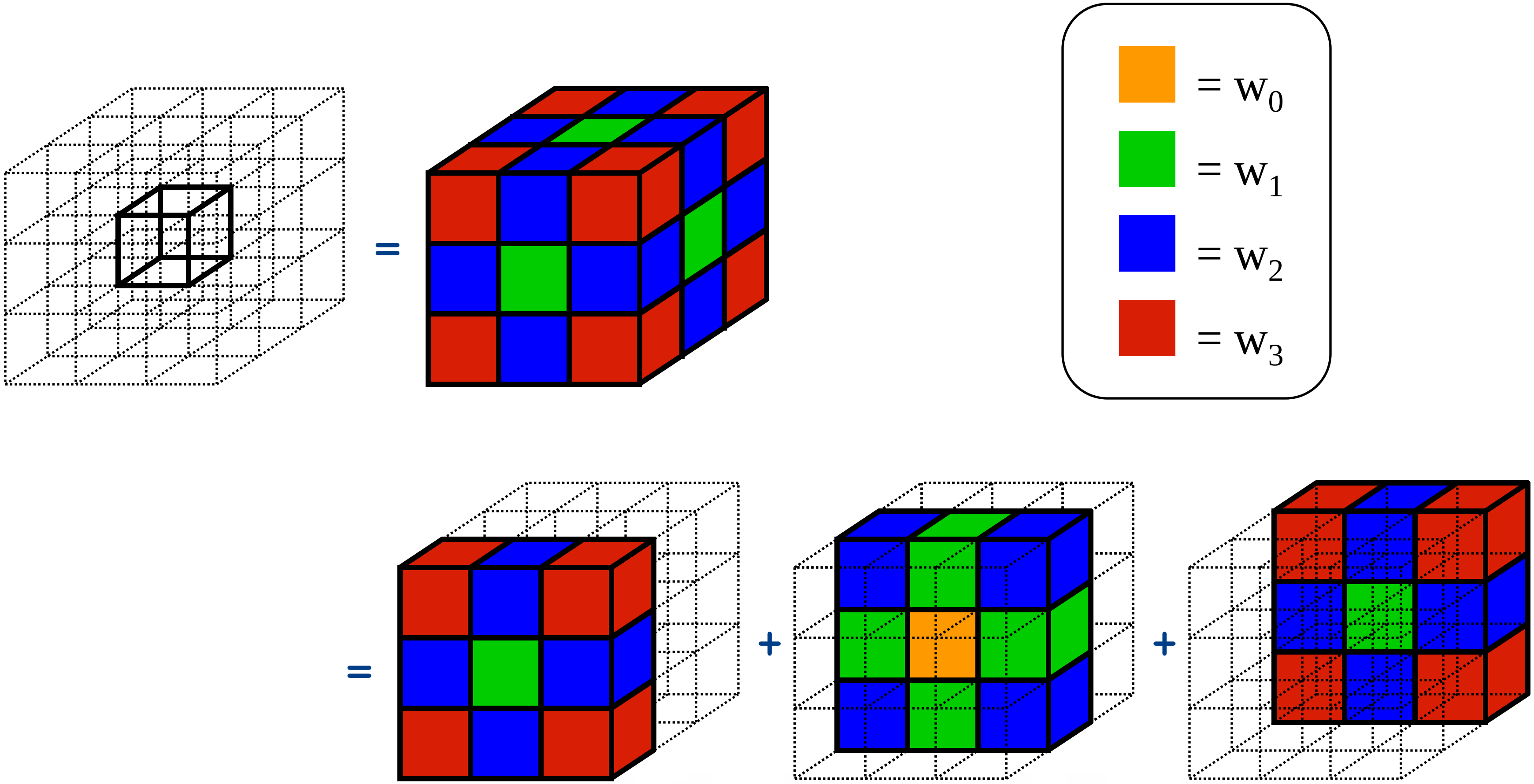
Problem: "Apply 3-pt stencil to vector"

SPMD (pseudocode + MPI)

```
var n: int = 1000, locN: int = n/numProcs;
var a, b: [0..locN+1] real;
var innerLo: int = 1, innerHi: int = locN;
var numProcs, myPE: int;
var retval: int;
var status: MPI_Status;

MPI_Comm_size(MPI_COMM_WORLD, &numProcs);
MPI_Comm_rank(MPI_COMM_WORLD, &myPE);
if (myPE < numProcs-1) {
  retval = MPI_Send(&(a(locN)), 1, MPI_FLOAT, myPE+1, 0, MPI_COMM_WORLD);
  if (retval != MPI_SUCCESS) { handleError(retval); }
  retval = MPI_Recv(&(a(locN+1)), 1, MPI_FLOAT, myPE+1, 1, MPI_COMM_WORLD, &status);
  if (retval != MPI_SUCCESS) { handleErrorWithStatus(retval, status); }
} else
  innerHi = locN-1;
if (myPE > 0) {
  retval = MPI_Send(&(a(1)), 1, MPI_FLOAT, myPE-1, 1, MPI_COMM_WORLD);
  if (retval != MPI_SUCCESS) { handleError(retval); }
  retval = MPI_Recv(&(a(0)), 1, MPI_FLOAT, myPE-1, 0, MPI_COMM_WORLD, &status);
  if (retval != MPI_SUCCESS) { handleErrorWithStatus(retval, status); }
} else
  innerLo = 2;
forall i in (innerLo..innerHi) {
  b(i) = (a(i-1) + a(i+1))/2;
}
```

Communication becomes geometrically more complex for higher-dimensional arrays

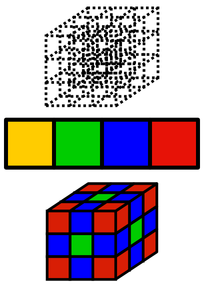
2) *rprj3* stencil from NAS MG



2) NAS MG *rprj3* stencil in Fortran + MPI

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

implicit none

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

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

if( .not. dead(kk) )then
   do  axis = 1, 3
      if( 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'

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
```

2) NAS MG *rprj3* 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 ijk in S.domain do
    S(ijk) = + reduce [offset in Stencil]
                        (w3d(offset) * R(ijk + offset*R.stride));
}
```

Our previous work in ZPL showed that compact, global-view codes like these can result in performance that matches or beats hand-coded Fortran+MPI while also supporting more runtime flexibility

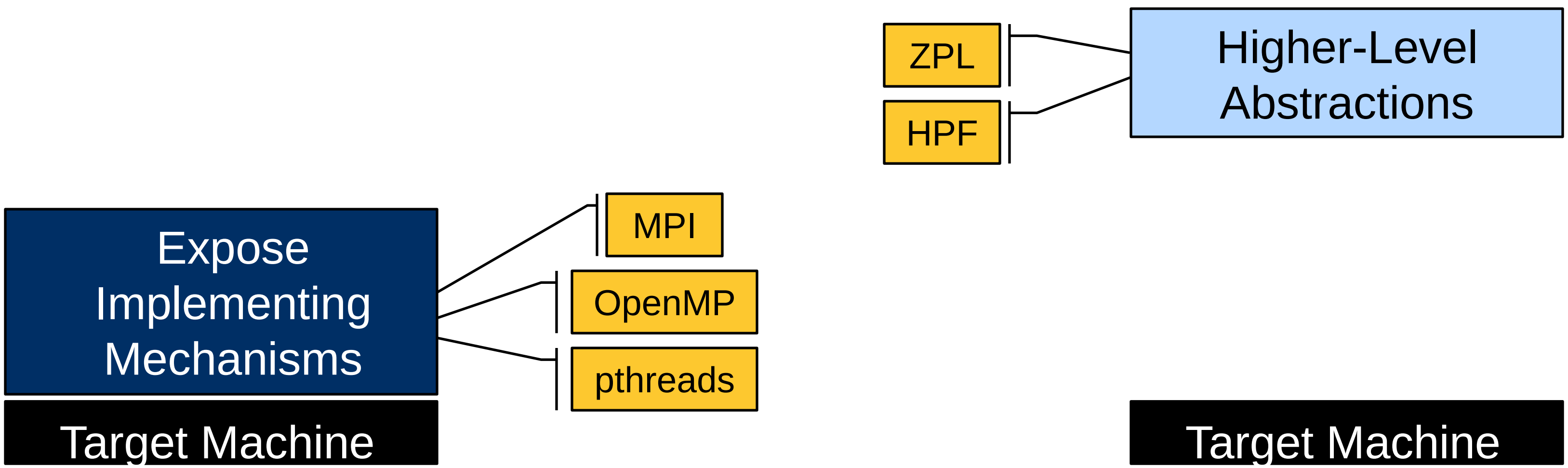
2) Classifying HPC Programming Notations

	data / control
communication libraries:	
• MPI, MPI-2	fragmented / fragmented/SPMD
• SHMEM, ARMCI, GASNet	fragmented / SPMD
shared memory models:	
• OpenMP, pthreads	global-view / global-view (trivially)
PGAS languages:	
• Co-Array Fortran	fragmented / SPMD
• UPC	global-view / SPMD
• Titanium	fragmented / SPMD
HPCS languages:	
• Chapel	global-view / global-view
• X10 (IBM)	global-view / global-view
• Fortress (Sun)	global-view / global-view

3) Multiresolution Languages: Motivation

Two typical camps of parallel language design:

low-level vs. high-level



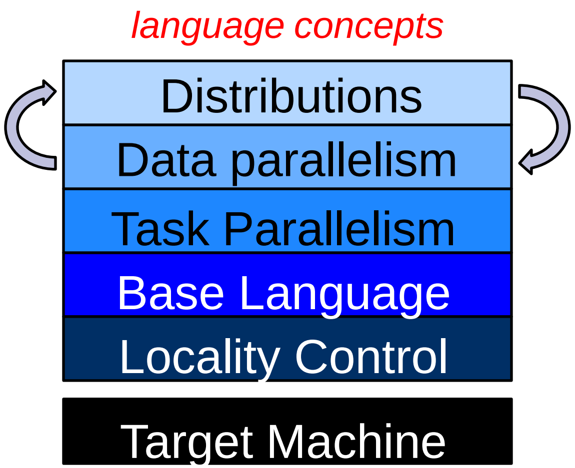
"Why is everything so tedious?"

"Why don't I have more control?"

3) Multiresolution Language Design

Our Approach: Structure the language in a layered manner, permitting it to be used at multiple levels as required/desired

- provide high-level features and automation for convenience
- provide the ability to drop down to lower, more manual levels
- use appropriate separation of concerns to keep these layers clean



4) Ability to Tune for Locality/Affinity

- Large-scale systems tend to locate memory w/ processors
  - a good approach for building scalable parallel systems
- Remote accesses tend to be significantly more expensive than local
- Therefore, placement of data relative to computation matters for scalable performance

  $\Rightarrow$ programmer should have control over placement of data, tasks
- As multicore chips grow in #cores, locality likely to become more important in mainstream parallel programming as well
  - GPUs/accelerators are another case where locality matters

5) Support for Modern Language Concepts

- students graduate with training in Java, Matlab, Perl, C#
- HPC community mired in Fortran, C (maybe C++) and MPI
- we'd like to narrow this gulf
  - leverage advances in modern language design
  - better utilize the skills of the entry-level workforce…

    …while not ostracizing traditional HPC programmers
- examples:
  - build on an imperative, block-structured language design
  - support object-oriented programming, but make its use optional
  - support for static type inference, generic programming to support…

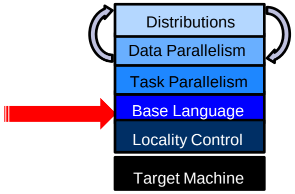
    …exploratory programming as in scripting languages

    …code reuse

Outline

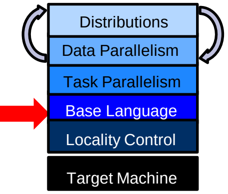
- ✓ Chapel Context
- ✓ Chapel Themes
- ➢ Language Overview
  - ➢ Base Language
  - ❑ Task Parallelism
  - ❑ Data Parallelism
  - ❑ Locality and Distributions
- ❑ Status, Collaborations, Future Work

Base Language: Design



- Block-structured, imperative programming
- Intentionally not an extension to an existing language
- Instead, select attractive features from others:
  - **ZPL, HPF:** data parallelism, index sets, distributed arrays
    (see also APL, NESL, Fortran90)
  - **Cray MTA C/Fortran:** task parallelism, lightweight synchronization
  - **CLU:** iterators (see also Ruby, Python, C#)
  - **ML:** latent types (see also Scala, Matlab, Perl, Python, C#)
  - **Java, C#:** OOP, type safety
  - **C++:** generic programming/templates (without adopting its syntax)
  - **C, Modula, Ada:** syntax
- Follow lead of C family of languages when useful
  (C, Java, C#, Perl, …)

Base Language: My Favorite Features



- **Rich compile-time language**
  - parameter values (compile-time constants)
  - folded conditionals, unrolled for loops, tuple expansions
  - type and parameter functions – evaluated at compile-time
- **Latent types**
  - ability to omit type specifications for convenience or code reuse
  - type specifications can be omitted from…

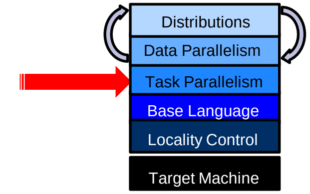
…variables	(inferred from initializers)
…class members	(inferred from constructors)
…function arguments	(inferred from callsite)
…function return types	(inferred from return statements)

- **Configuration variables** (and parameters)

```
config const n = 100;  // override with ./a.out --n=100000
```

- **Tuples**
- **Iterators** (in the CLU, Ruby sense)
- **Declaration Syntax**: more like Pascal/Modula than C

Task Parallelism: Task Creation



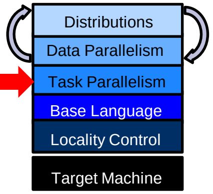
begin: creates a task for future evaluation

```
begin DoThisTask();
WhileContinuing();
TheOriginalThread();
```

sync: waits on all begins created within its dynamic scope

```
sync {
  begin treeSearch(root);
}

def treeSearch(node) {
  if node == nil then return;
  begin treeSearch(node.right);
  begin treeSearch(node.left);
}
```

Task Parallelism: Structured Tasks



cobegin: creates a task per component statement:

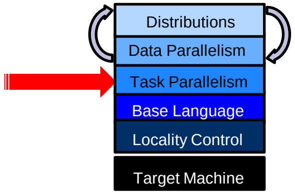
```
computePivot(lo, hi, data);
cobegin {
  Quicksort(lo, pivot, data);
  Quicksort(pivot, hi, data);
} // implicit join here
```

```
cobegin {
  computeTaskA(…);
  computeTaskB(…);
  computeTaskC(…);
} // implicit join
```

coforall: creates a task per loop iteration

```
coforall e in Edges {
  exploreEdge(e);
} // implicit join here
```

Task Parallelism: Task Coordination



sync variables: store full/empty state along with value

```
var result$: sync real;    // result is initially empty
sync {
  begin … = result$;       // block until full, leave empty
  begin result$ = …;       // block until empty, leave full
}
result$.readXX();          // read value, leave state unchanged;
                           // other variations also supported
```

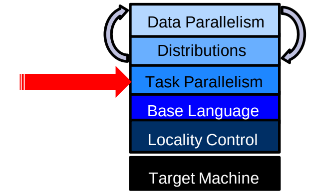
single-assignment variables: writable once only

```
var result$: single real = begin f(); // result initially empty
…                    // do some other things
total += result$;    // block until f() has completed
```

atomic sections: support transactions against memory

```
atomic {
  newnode.next = insertpt;
  newnode.prev = insertpt.prev;
  insertpt.prev.next = newnode;
  insertpt.prev = newnode;
}
```

Producer/Consumer example

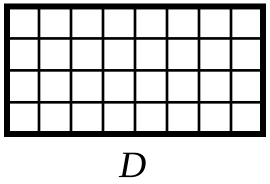



```
var buff$: [0..buffersize-1] sync int;

cobegin {
  producer();
  consumer();
}

def producer() {
  var i = 0;
  for … {
    i = (i+1) % buffersize;
    buff$(i) = …;
  }
}

def consumer() {
  var i = 0;
  while {
    i = (i+1) % buffersize;
    …buff$(i)…;
  }
}
```

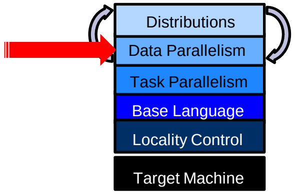
Data Parallelism: Domains

domain: a first-class index set

```
var m = 4, n = 8;

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

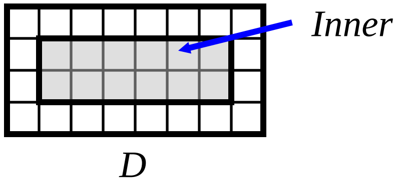


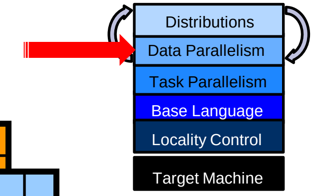
Data Parallelism: Domains



domain: a first-class index set

```
var m = 4, n = 8;

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

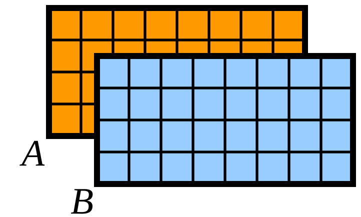




Domains: Some Uses

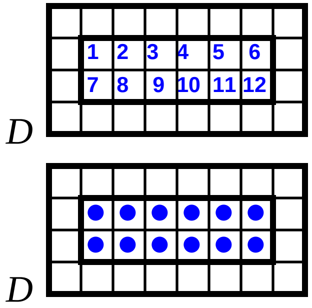
- Declaring arrays:

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



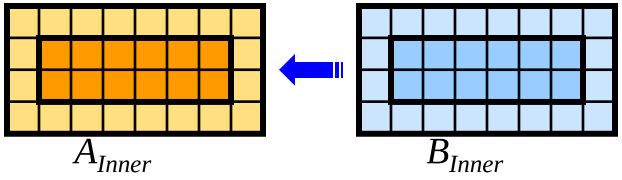
- Iteration (sequential or parallel):

```
    for    ij in Inner { … }
or: forall ij in Inner { … }
or: …
```



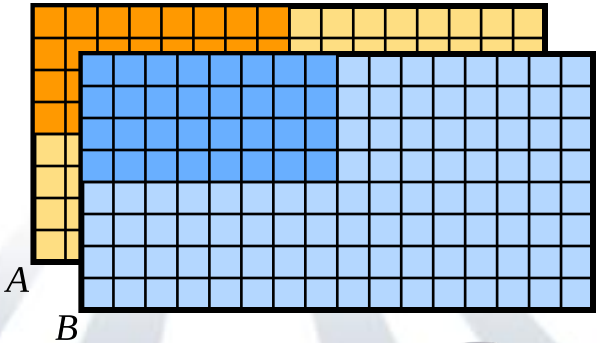
- Array Slicing:

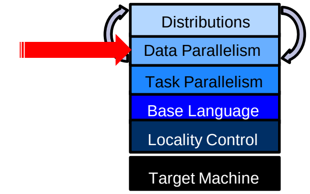
```
A[Inner] = B[Inner];
```



- Array reallocation:

```
D = [1..2*m, 1..2*n];
```

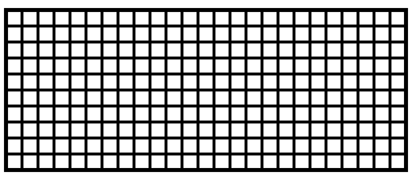




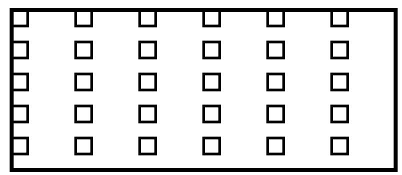
Data Parallelism: Domain Types

Chapel supports several domain types…

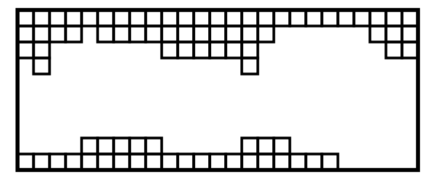
```
var OceanSpace = [0..#lat, 0..#long],
    AirSpace = OceanSpace by (2,4),
    IceSpace: sparse subdomain(OceanSpace) = genCaps();
```



dense

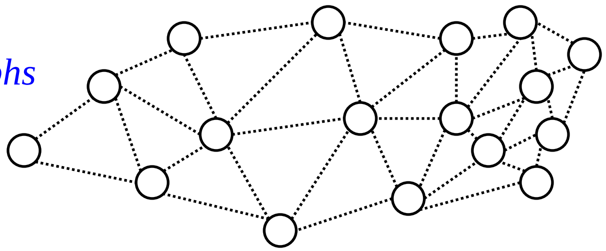


strided

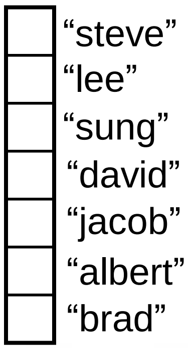


sparse

graphs



associative

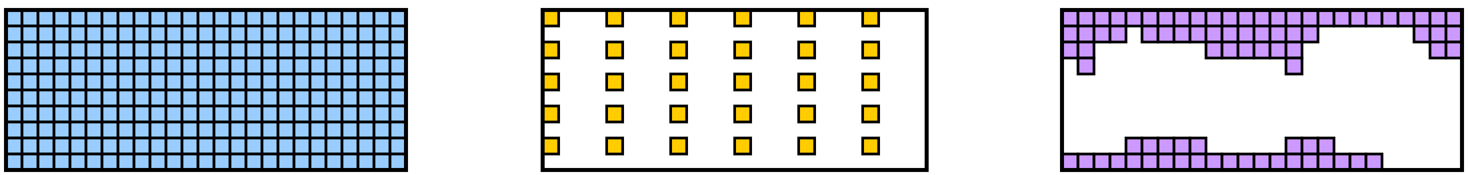


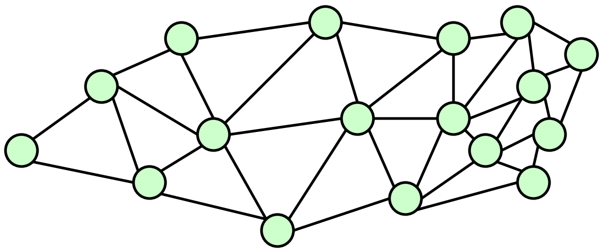

```
var Vertices: domain(opaque) = …,   People: domain(string) = …;
```

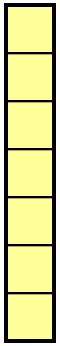
Data Parallelism: Domain Uses

All domain types can be used to declare arrays…

```
var Ocean: [OceanSpace] real,
    Air: [AirSpace] real,
    IceCaps[IceSpace] real;
```

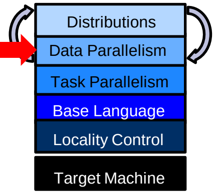






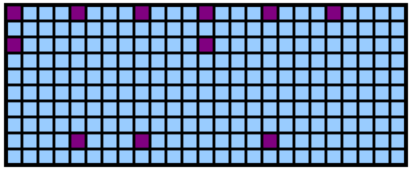

```
var Weight: [Vertices] real,        Age: [People] int;
```

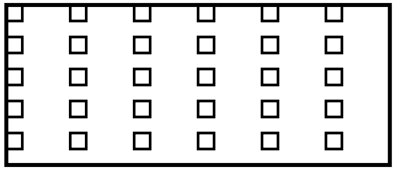
Data Parallelism: Domain Uses

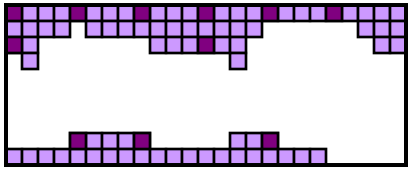


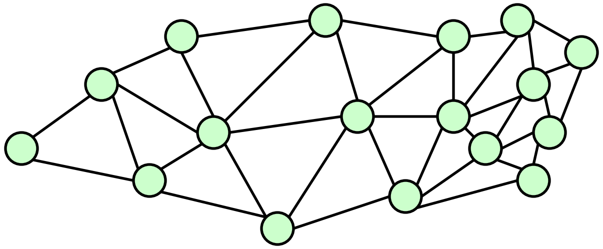
…to iterate over index sets…

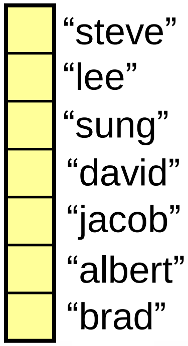
```
forall ij in AirSpace do
  Ocean(ij) += IceCaps(ij);
```











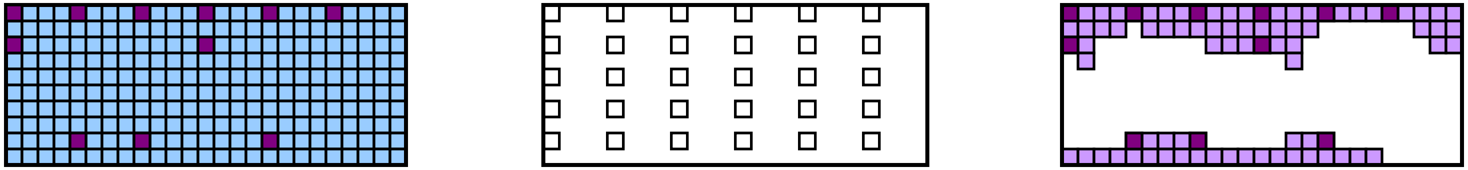

```
forall v in Vertices do
  Weight(v) = numEdges(v);
```

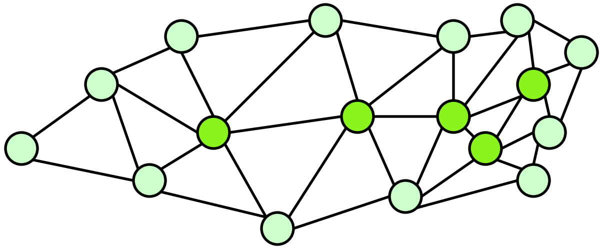
```
forall p in People do
  Age(p) += 1;
```

Data Parallelism: Domain Uses

…to slice arrays…

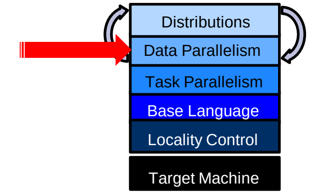
```
Ocean[AirSpace] += IceCaps[AirSpace];
```





…Vertices[Interior]…

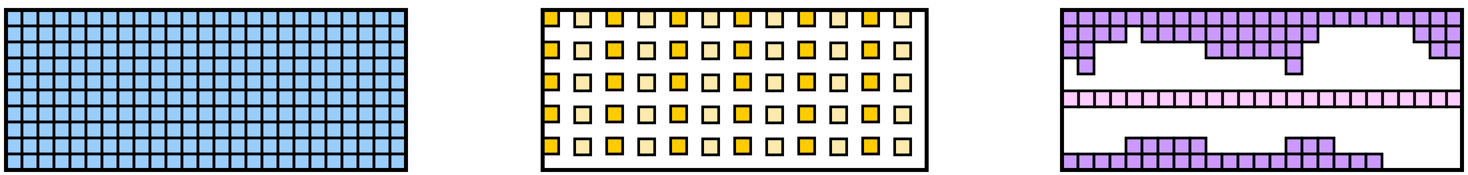
…People[Interns]…

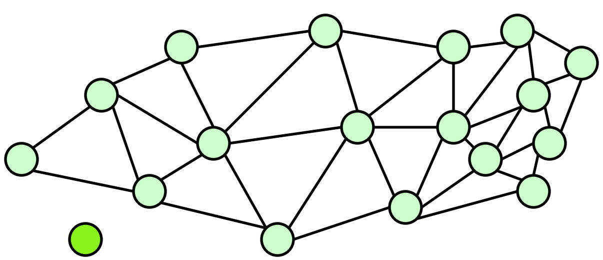


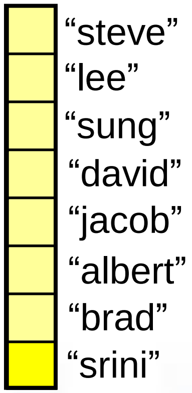
Data Parallelism: Domain Uses

…and to reallocate arrays

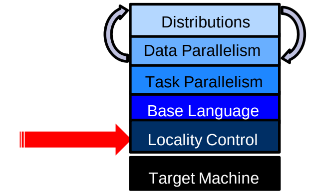
```
AirSpace = OceanSpace by (2,2);
IceSpace += genEquator();
```







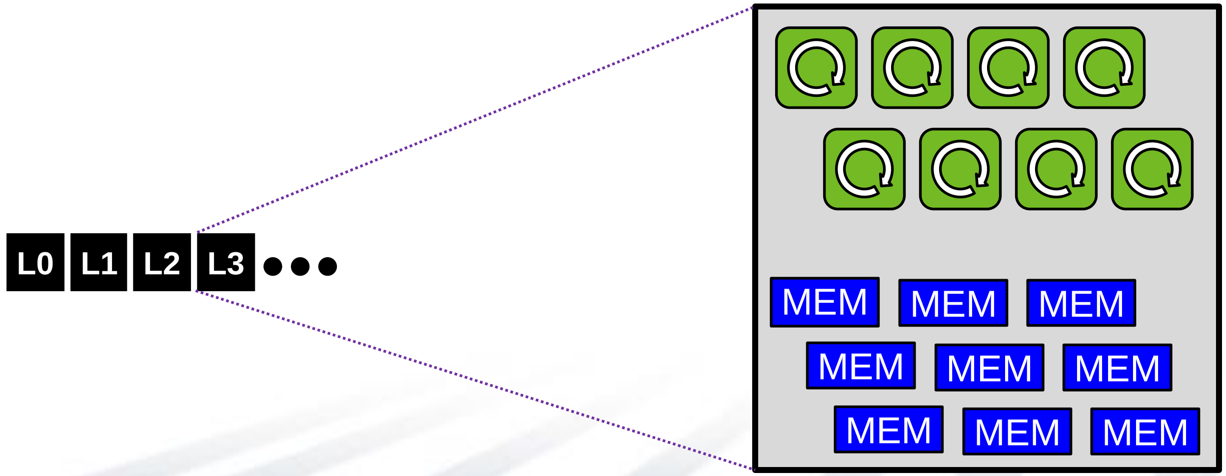

```
newnode = Vertices.create();    People += "srini";
```



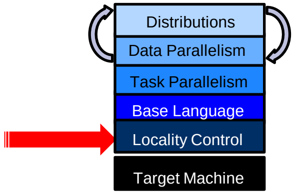
Locality: Locales

locale: An abstract unit of the target architecture

- supports reasoning about locality
- has capacity for processing and storage
- two threads in a given locale have similar access to a given address
  - addresses in that locale are ~uniformly accessible
  - addresses in other locales are also accessible, but at a price
- locales are defined for a given architecture by a Chapel compiler
  - e.g., a multicore processor or SMP node could be a locale

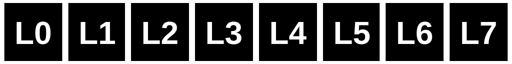


Locales and Program Startup



- Chapel users specify # locales on executable command-line

```
prompt> myChapelProg -nl=8      # run using 8 locales
```

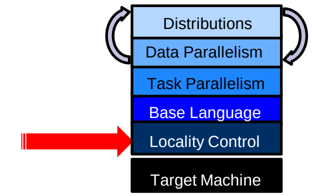


- Chapel launcher bootstraps program execution:
  - obtains necessary machine resources
    - *e.g.*, requests 8 nodes from the job scheduler
  - loads a copy of the executable onto the machine resources
  - starts running the program. *Conceptually…*

    …locale #0 starts running program's entry point (`main()`)

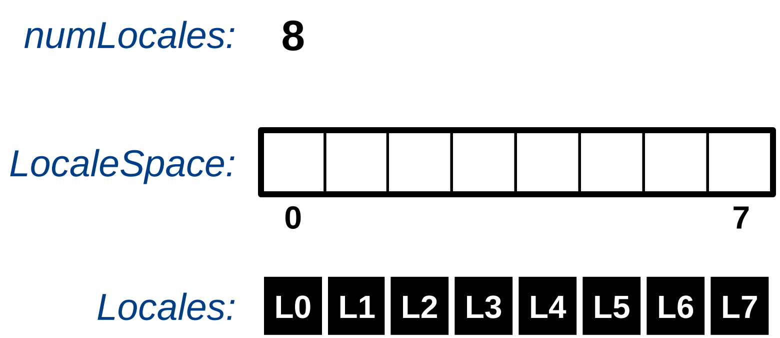
    …other locales wait for work to arrive

Locale Variables

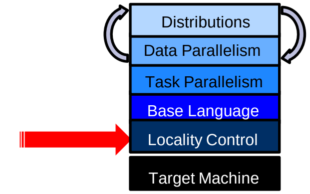


Built-in variables represent a program's locale set:

```
config const numLocales: int;                // number of locales
const LocaleSpace = [0..numLocales-1],       // locale indices
      Locales: [LocaleSpace] locale;         // locale values
```



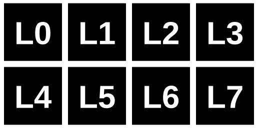
Locale Views



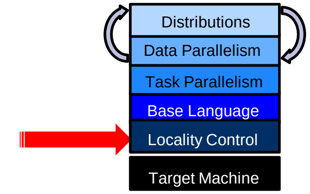
Using standard array operations, users can create their own locale views:

```
var TaskALocs = Locales[..numTaskALocs];
var TaskBLocs = Locales[numTaskALocs+1..];
```


```
var CompGrid = Locales.reshape([1..gridRows,
                                1..gridCols]);
```



Locale Methods



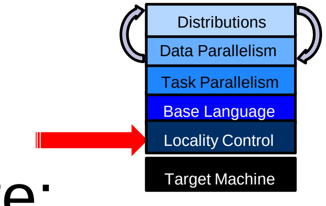
- The locale type supports built-in methods:

```
def locale.id: int;                      // index in LocaleSpace
def locale.name: string;                 // similar to uname -n
def locale.numCores: int;                // # of processor cores
def locale.physicalMemory(…): …;         // amount of memory
…
```

- Locale queries can also be made:

```
…myvar.locale…   // query the locale where myvar is stored
…here…           // query where the current task is running
```

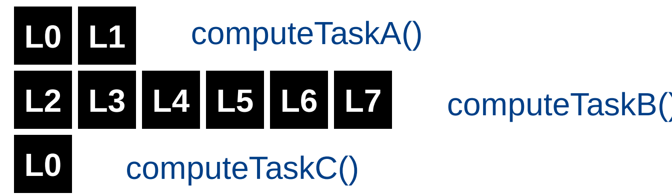
Locality: Task Placement



on clauses: indicate where statements should execute:

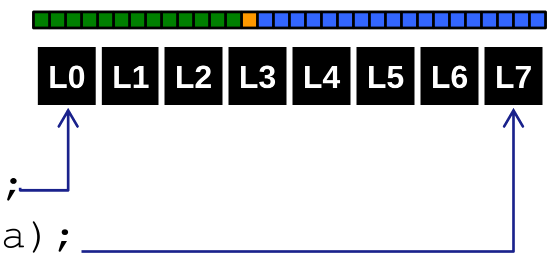
Either by naming locales explicitly…

```
cobegin {
  on TaskALocs do computeTaskA(…);
  on TaskBLocs do computeTaskB(…);
  on Locales(0) do computeTaskC(…);
}
```



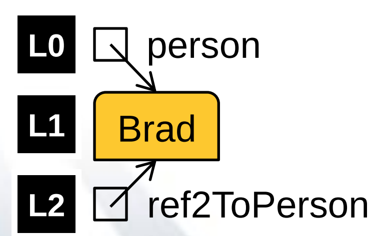
…or in a data-driven manner:

```
const pivot = computePivot(lo, hi, data);
cobegin {
  on data[lo] do Quicksort(lo, pivot, data);
  on data[hi] do Quicksort(pivot+1, hi, data);
}
```

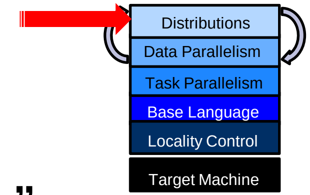


They can also control where data is allocated:

```
var person: Employee;
on Locales(1) do person = new Employee("Brad");
on Locales(2) do var ref2ToPerson = person;
```

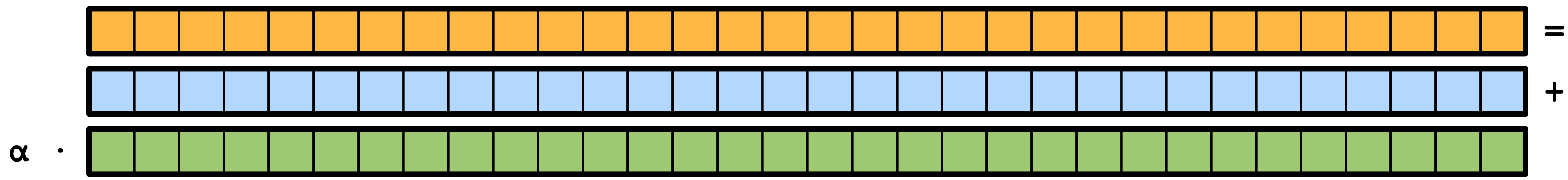


Chapel Distributions

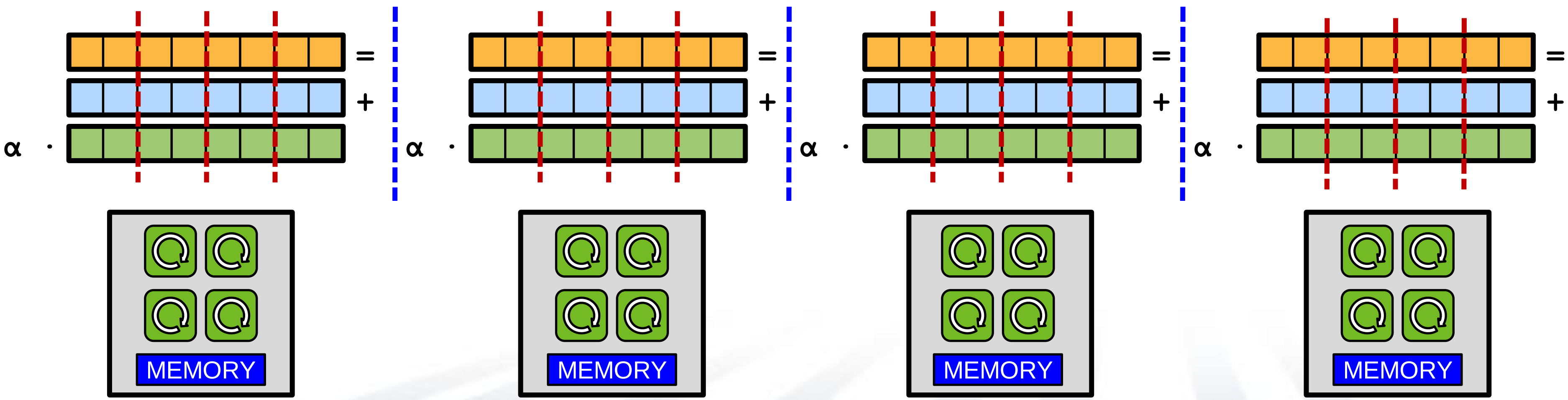


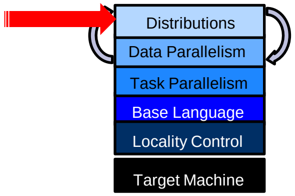
Distributions: "Recipes for parallel, distributed arrays"

- help the compiler map from the computation's global view…



…down to the *fragmented*, per-processor implementation

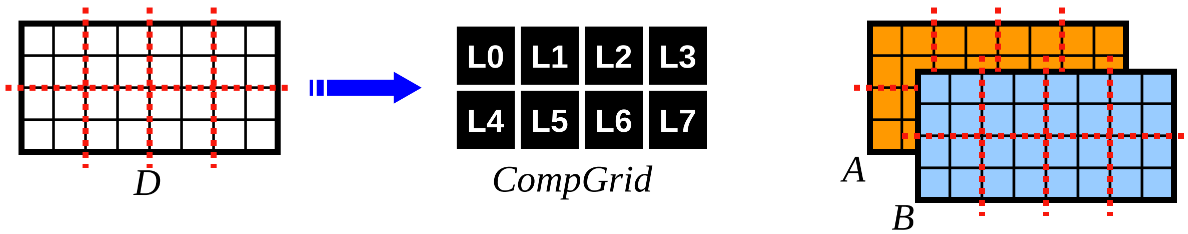




Domain Distribution

Domains may be distributed across locales

```
var D: domain(2) distributed Block on CompGrid = …;
```



A distribution implies…

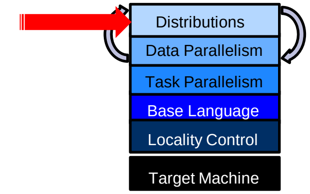
…ownership of the domain's indices (and its arrays' elements)

…the default work ownership for operations on the domains/arrays

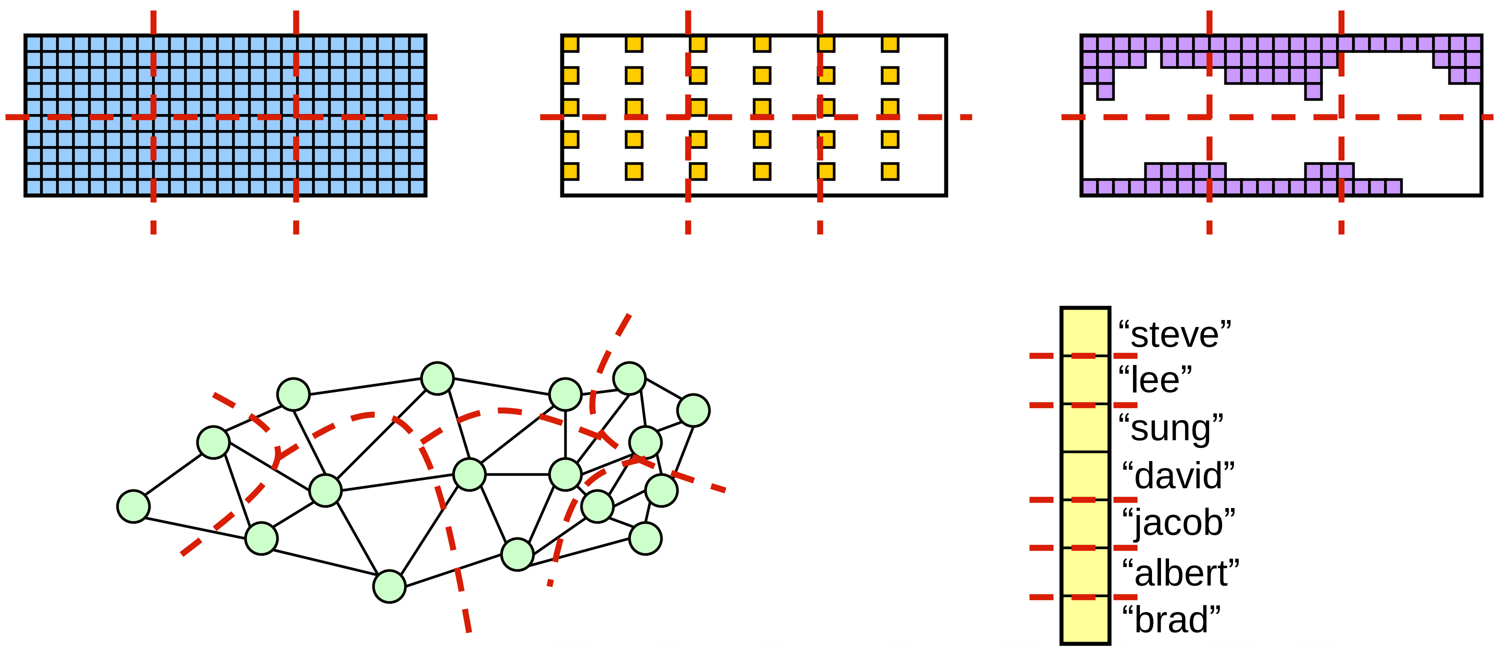
- e.g., forall loops or promoted operations

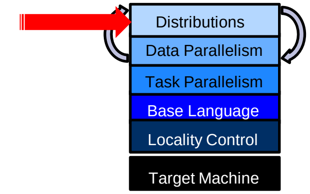
…the implementation of operations on its domains and arrays

Domain Distributions



- Any domain type may be distributed
- Distributions do not affect program semantics
  - only implementation details and therefore performance





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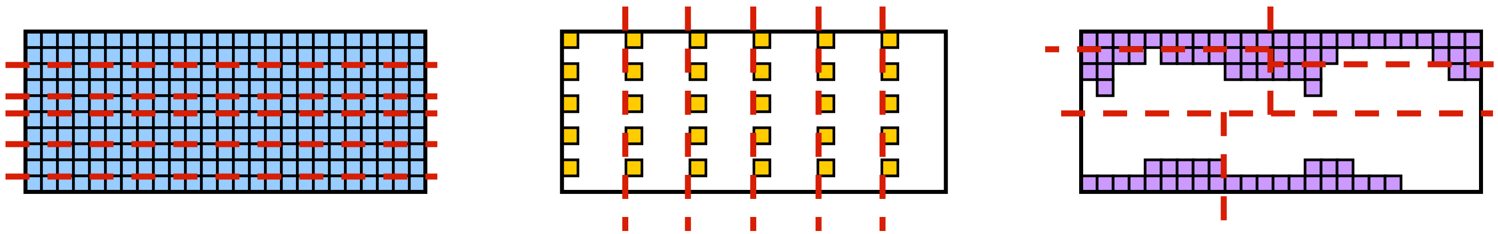
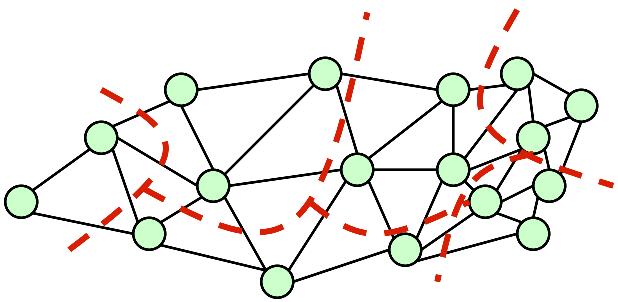
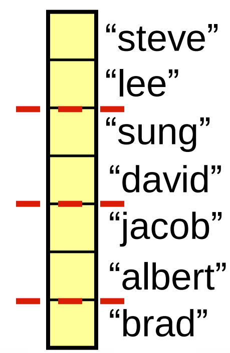






Distributions: Goals & Research

- Advanced users can write their own distributions
  - specified in Chapel using lower-level language features

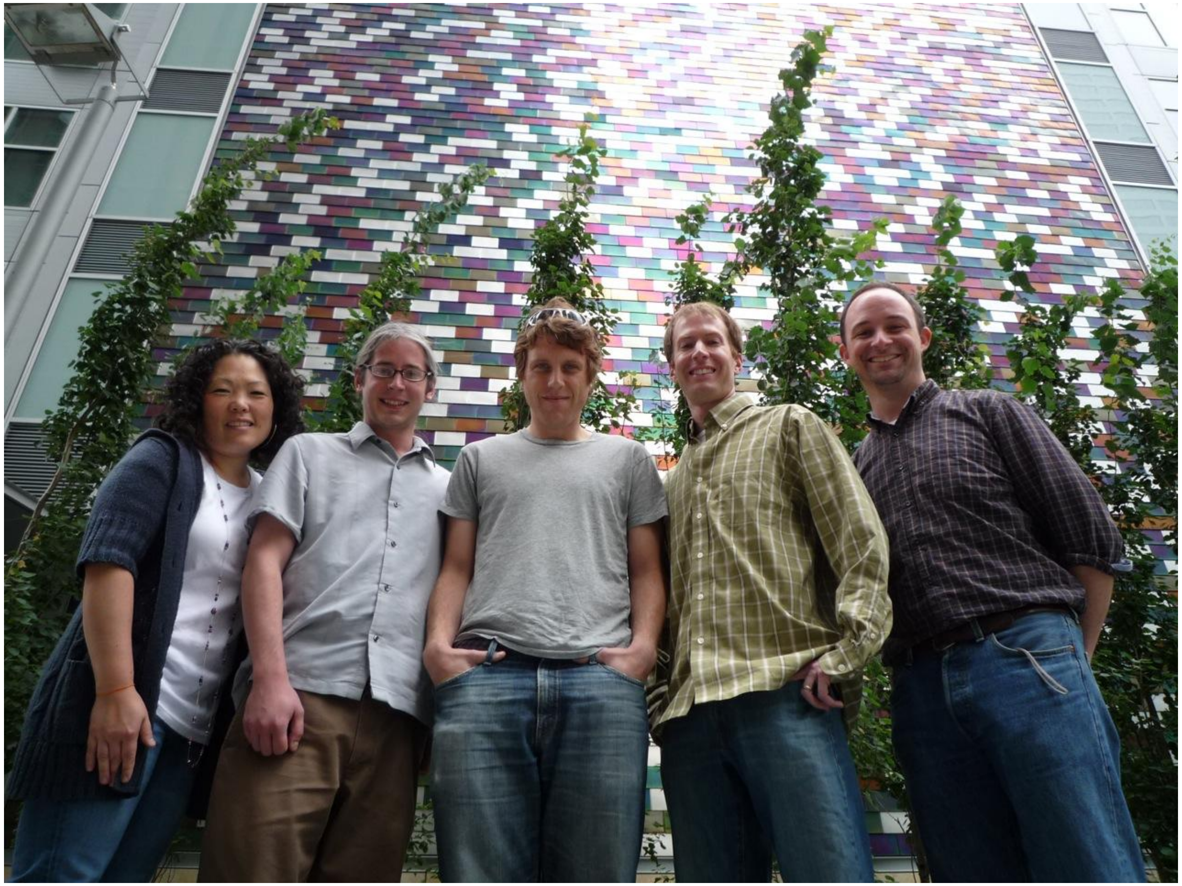
- Chapel will provide a standard library of distributions
  - written using the same user-defined distribution mechanism

(Draft paper describing user-defined distribution strategy available by request)

Outline

- ✓ Chapel Context
- ✓ Global-view Programming Models
- ✓ Language Overview
- ❑ Status, Collaborations, Future Work

The Chapel Team

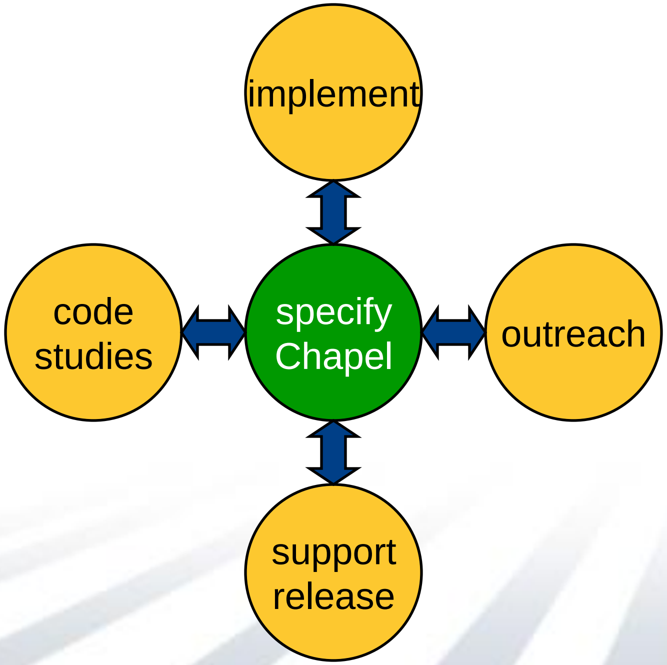


Sung-Eun Choi, David Iten, Lee Prokowich,
Steve Deitz, Brad Chamberlain

- Interns
  - Jacob Nelson (`09 – UW)
  - Albert Sidelnik (`09 – UIUC)
  - Andy Stone (`08 – Colorado St)
  - James Dinan (`07 – Ohio State)
  - Robert Bocchino (`06 – UIUC)
  - Mackale Joyner (`05 – Rice)
- Alumni
  - David Callahan
  - Roxana Diaconescu
  - Samuel Figueroa
  - Shannon Hoffswell
  - Mary Beth Hribar
  - Mark James
  - John Plevyak
  - Wayne Wong
  - Hans Zima

Chapel Work

- Chapel Team's Focus:
  - specify Chapel syntax and semantics
  - implement open-source prototype compiler for Chapel
  - perform code studies of benchmarks, apps, and libraries in Chapel
  - do community outreach to inform and learn from users/researchers
  - support users of code releases
  - refine language based on all these activities



Chapel Release

- **Current release:** version 1.0 (October 15th, 2009)
- Supported environments: UNIX/Linux, Mac OS X, Cygwin
- How to get started:
  1. Download from: http://sourceforge.net/projects/chapel
  2. Unpack tar.gz file
  3. See top-level README
     - for quick-start instructions
     - for pointers to next steps with the release
- Your feedback desired!
- Remember: a work-in-progress

  ⇒ it's likely that you will find problems with the implementation

  ⇒ this is still a good time to influence the language's design

Implementation Status (v1.0)

- **Base language:** stable (some gaps and bugs remain)
- **Task parallel:**
  - stable multi-threaded implementation of tasks, sync variables
  - atomic sections are an area of ongoing research with U. Notre Dame
- **Data parallel:**
  - stable multi-threaded data parallelism for dense domains/arrays
  - other domain types have a single-threaded reference implementation
- **Locality:**
  - stable locale types and arrays
  - stable task parallelism across multiple locales
  - initial support for some distributions: Block, Cyclic, Block-Cyclic
- **Performance:**
  - has received much attention in designing the language
  - yet not much implementation effort to date

Outreach: Active Collaborations

Notre Dame/ORNL (Peter Kogge, Srinivas Sridharan, Jeff Vetter):
Asynchronous STM over distributed memory

UIUC (David Padua, Albert Sidelnik):
Chapel for hybrid CPU-GPU computing

OSU (Gagan Agrawal, Bin Ren):
Data-intensive computing using Chapel's user-defined reductions

PNNL/CASS-MT (John Feo, Daniel Chavarria): Chapel extensions for hybrid computation; performance tuning for the Cray XMT; ARMCI port

ORNL (David Bernholdt *et al.*; Steve Poole *et al.*): Chapel code studies – Fock matrix computations, MADNESS, Sweep3D, coupled models, …

Berkeley (Dan Bonachea *et al.*): APGAS over GASNet; collectives

(Your name here?)

Collaboration Opportunities

- memory management policies/mechanisms
- dynamic load balancing: task throttling and stealing
- parallel I/O and checkpointing
- language interoperability
- application studies and performance optimizations
- index/subdomain semantics and optimizations
- targeting different back-ends (LLVM, MS CLR, …)
- runtime compilation
- library support
- tools
  - correctness debugging
  - performance debugging
  - IDE support
  - Chapel interpreter
  - visualizations, algorithm animations
- (your ideas here…)

Next Steps

- Expand our set of supported distributions
- Continue to improve performance
- Continue to add missing features
- Expand the set of codes that we are studying
- Expand the set of architectures that we are targeting
- Support the public release
- Continue to support collaborations and seek out new ones

Summary

Chapel strives to greatly improve Parallel Productivity

via its support for…

…general parallel programming
…global-view abstractions
…control over locality
…multiresolution features
…modern language concepts and themes

For More Information

chapel_info@cray.com

http://chapel.cray.com

http://sourceforge.net/projects/chapel

Parallel Programmability and the Chapel Language; Chamberlain, Callahan, Zima; International Journal of High Performance Computing Applications, August 2007, 21(3):291-312.

Questions?