Chapel

Productive Parallel Programming at Scale

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DARPA HPCS CRAY THE SUPERCOMPUTER COMPANY

Scalability at Cray

Cray's business: Allowing customers to achieve sustained high performance at large machine scales

My job: Enabling users to program our machines more *productively* through innovative language design

Productivity = Performance
+ Programmability
+ Portability
+ Robustness

Scalability Limiters in HPC Programming Models

- Restricted programming and execution models (*e.g.*, SPMD)
- Exposure of low-level implementation mechanisms
- Lack of programmability: ability to ________________ code

…write…
…read…
…modify…
…tune…
…maintain…
…experiment with…

Chapel

Chapel: a new parallel language being developed by Cray Inc.

Themes:

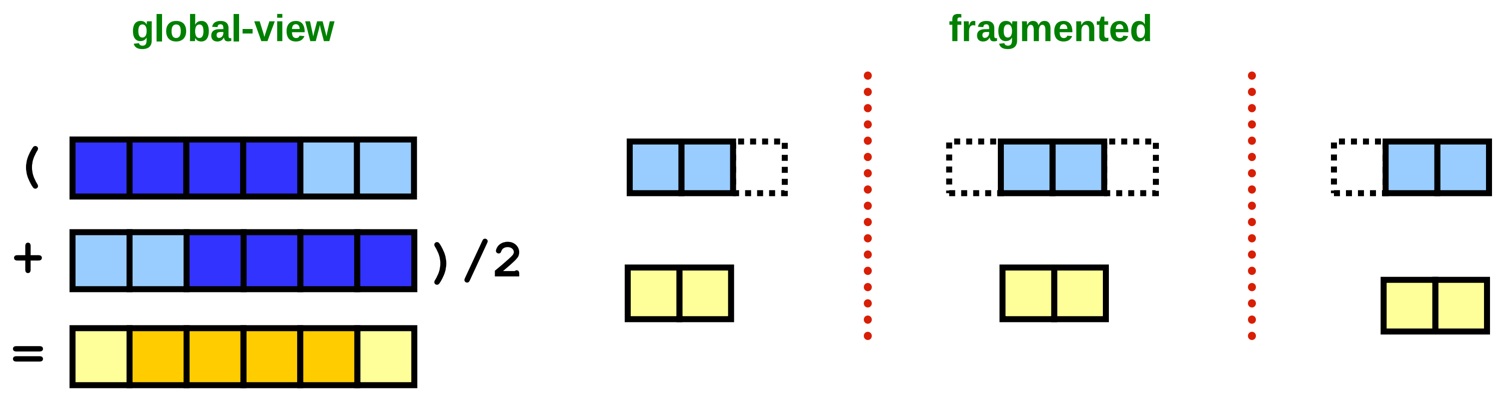
- **general parallel programming**
  - data-, task-, and nested parallelism
  - express general levels of software parallelism
  - target general levels of hardware parallelism
- **reduce gap between mainstream & parallel languages**
- ***global-view* abstractions**
- **control of locality**
- ***multiresolution design***

Outline

- ✓ Motivation for Chapel
- ➢ Global-view Programming Models and Scalability
- ❑ Language Overview
- ❑ Wrap-up

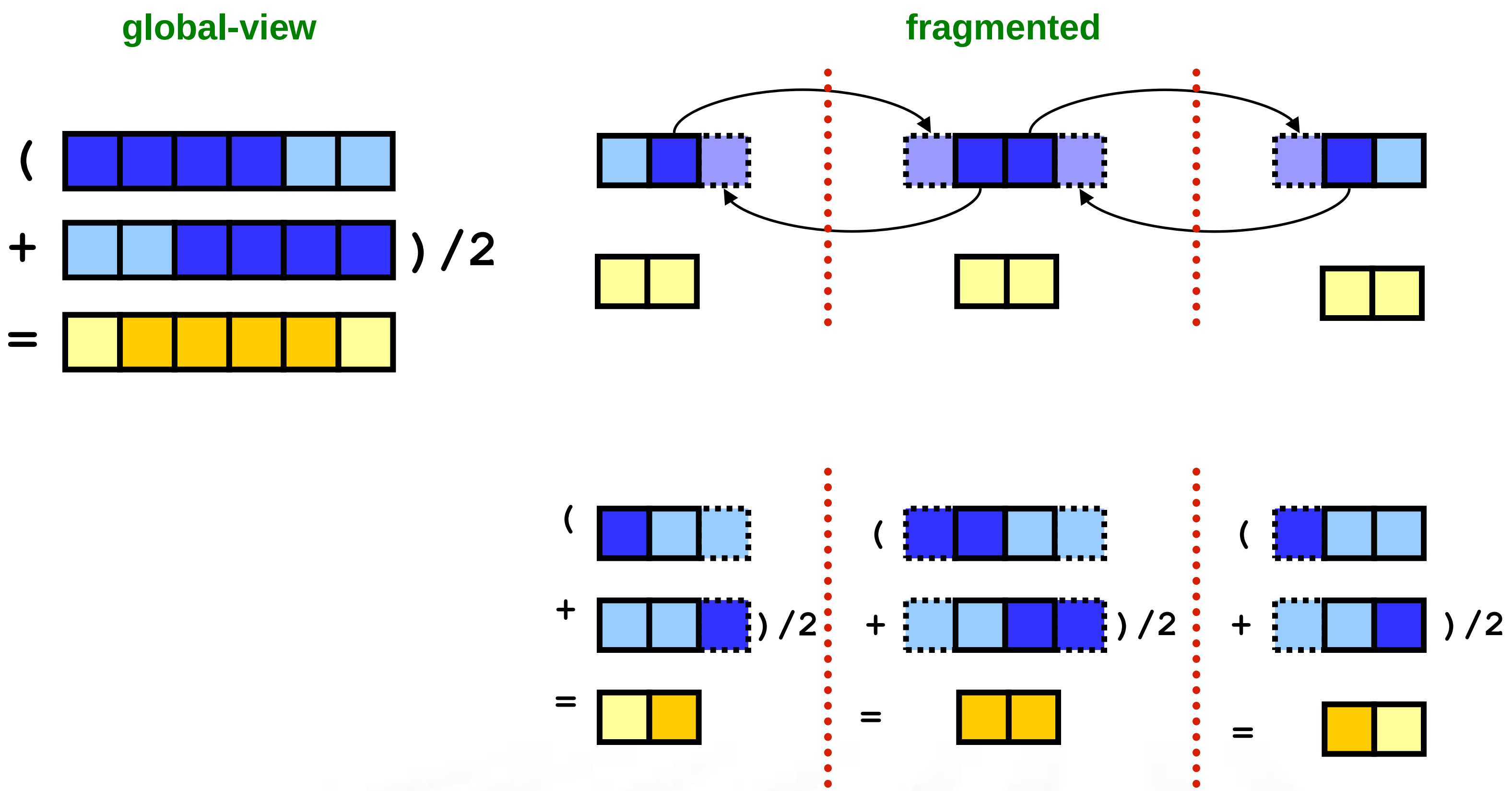
Global-view vs. Fragmented

Problem: "Apply 3-pt stencil to vector"



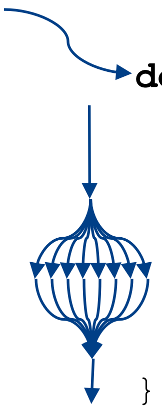
Global-view vs. Fragmented

Problem: "Apply 3-pt stencil to vector"



Global-view vs. SPMD Code

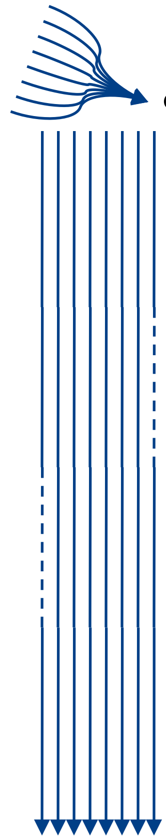
Problem: "Apply 3-pt stencil to vector"



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;
  }
}
```

Global-view vs. SPMD Code

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

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;
  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;
  }
}
```

MPI SPMD pseudo-code

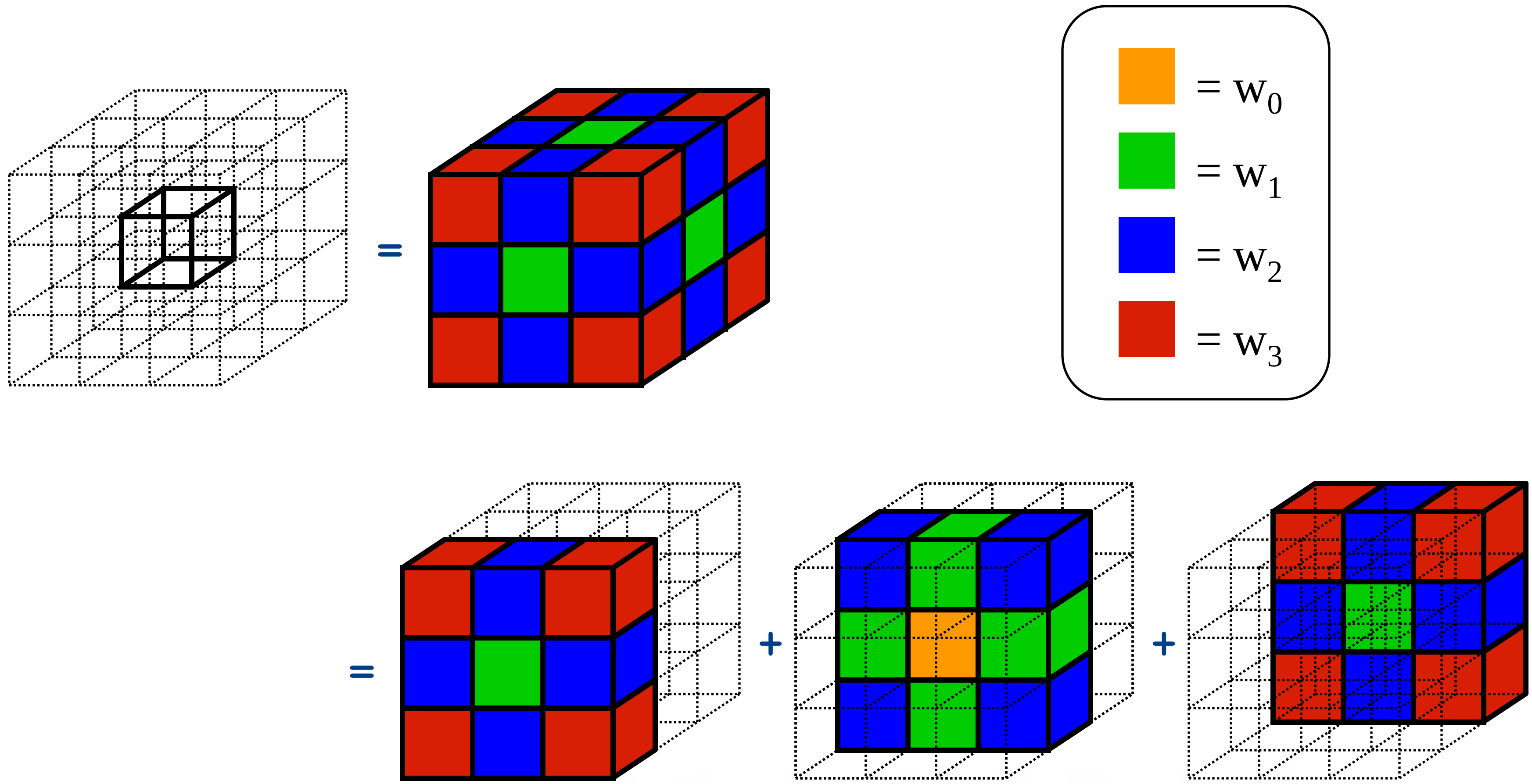
Problem: "Apply 3-pt stencil to vector"

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

rprj3 stencil from NAS MG

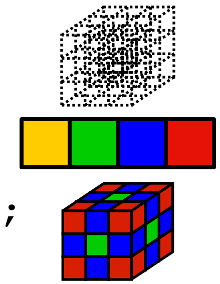


NAS MG *rprj3* stencil in Fortran + MPI

```
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
```

NAS MG *rprj3* stencil in Chapel

```
def rprj3(S, R) {
  param 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 + R.stride*offset));
}
```

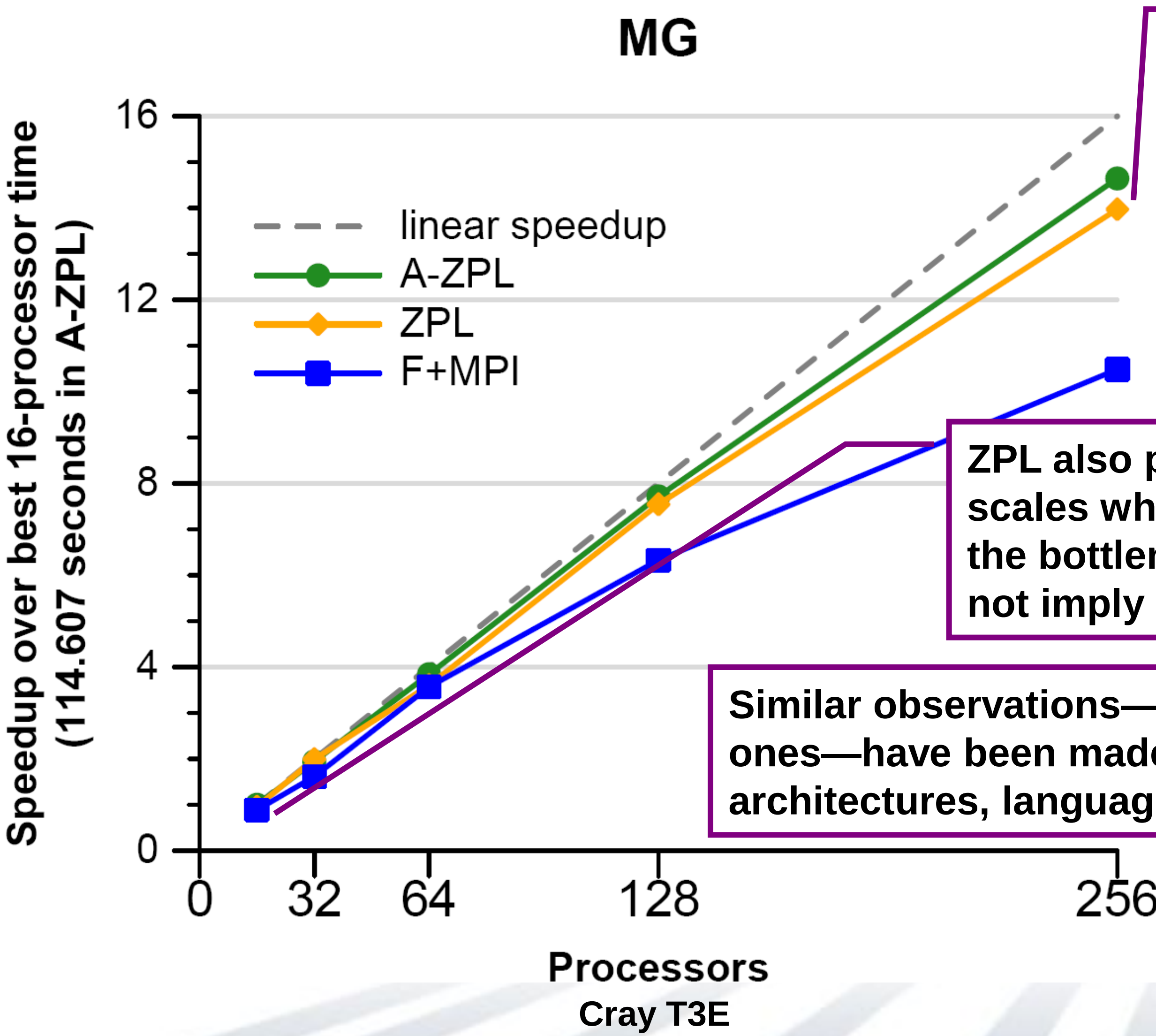


- Unfortunately, Chapel is a work in progress, so I do not have scalability results to show today
- However, these Chapel features are based on our previous work in ZPL, for which I do have scalability results

NAS MG *rprj3* stencil in ZPL

```
procedure rprj3(var S,R: [,,] double;
                d: array [] of direction);
begin
  S := 0.5     *  R
     + 0.25    * (R@^d[ 1, 0, 0] + R@^d[ 0, 1, 0] + R@^d[ 0, 0, 1] +
                  R@^d[-1, 0, 0] + R@^d[ 0,-1, 0] + R@^d[ 0, 0,-1])
     + 0.125   * (R@^d[ 1, 1, 0] + R@^d[ 1, 0, 1] + R@^d[ 0, 1, 1] +
                  R@^d[ 1,-1, 0] + R@^d[ 1, 0,-1] + R@^d[ 0, 1,-1] +
                  R@^d[-1, 1, 0] + R@^d[-1, 0, 1] + R@^d[ 0,-1, 1] +
                  R@^d[-1,-1, 0] + R@^d[-1, 0,-1] + R@^d[ 0,-1,-1])
     + 0.0625  * (R@^d[ 1, 1, 1] + R@^d[ 1, 1,-1] +
                  R@^d[ 1,-1, 1] + R@^d[ 1,-1,-1] +
                  R@^d[-1, 1, 1] + R@^d[-1, 1,-1] +
                  R@^d[-1,-1, 1] + R@^d[-1,-1,-1]);
end;
```

NAS MG Speedup: ZPL vs. Fortran + MPI

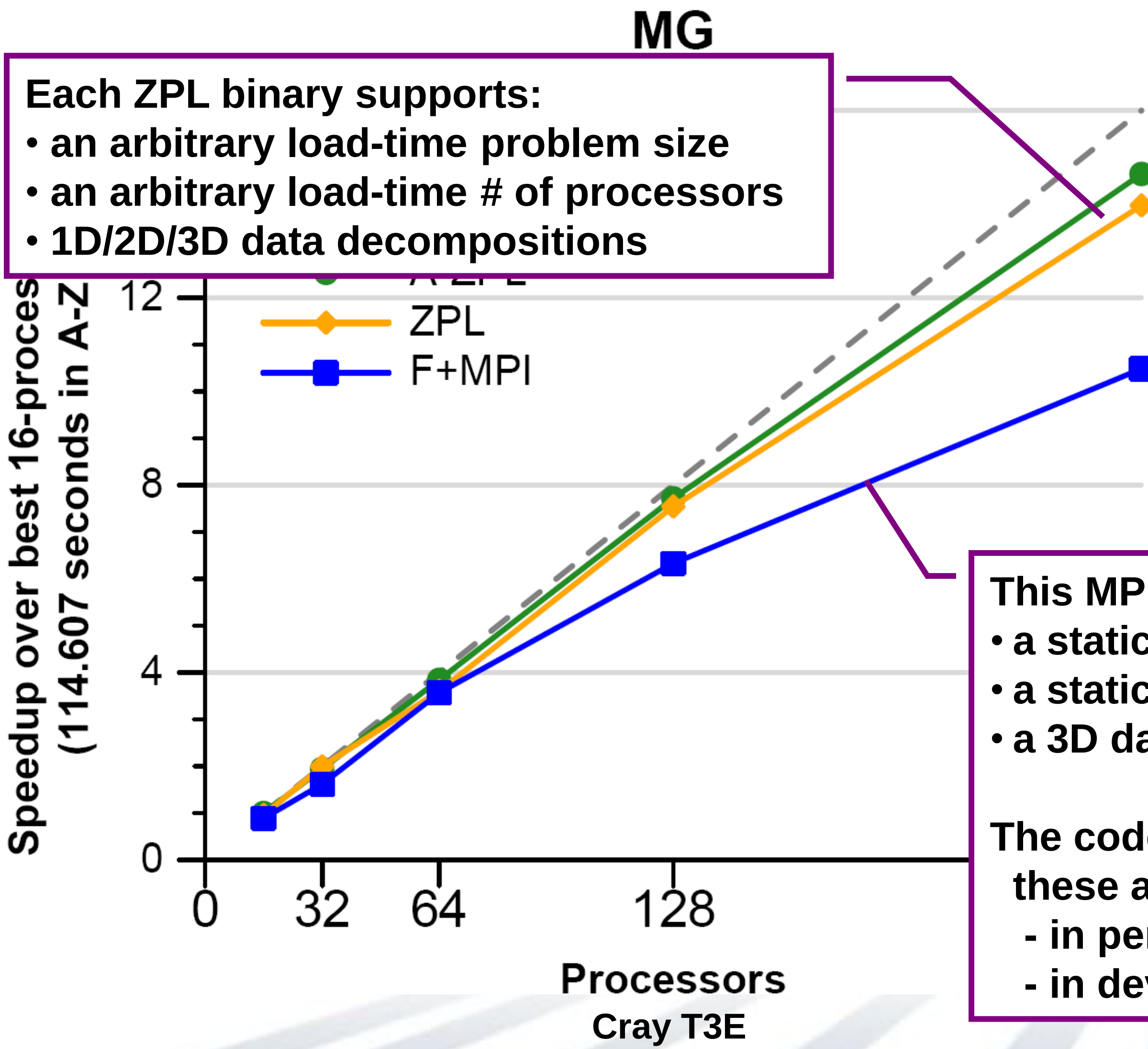


ZPL scales better than MPI since its communication is expressed in an implementation-neutral way; this permits the compiler to use SHMEM on this Cray T3E but MPI on a commodity cluster

ZPL also performs better at smaller scales where communication is not the bottleneck ⇒ new languages need not imply performance sacrifices

Similar observations—and more dramatic ones—have been made using more recent architectures, languages, and benchmarks

Generality Notes

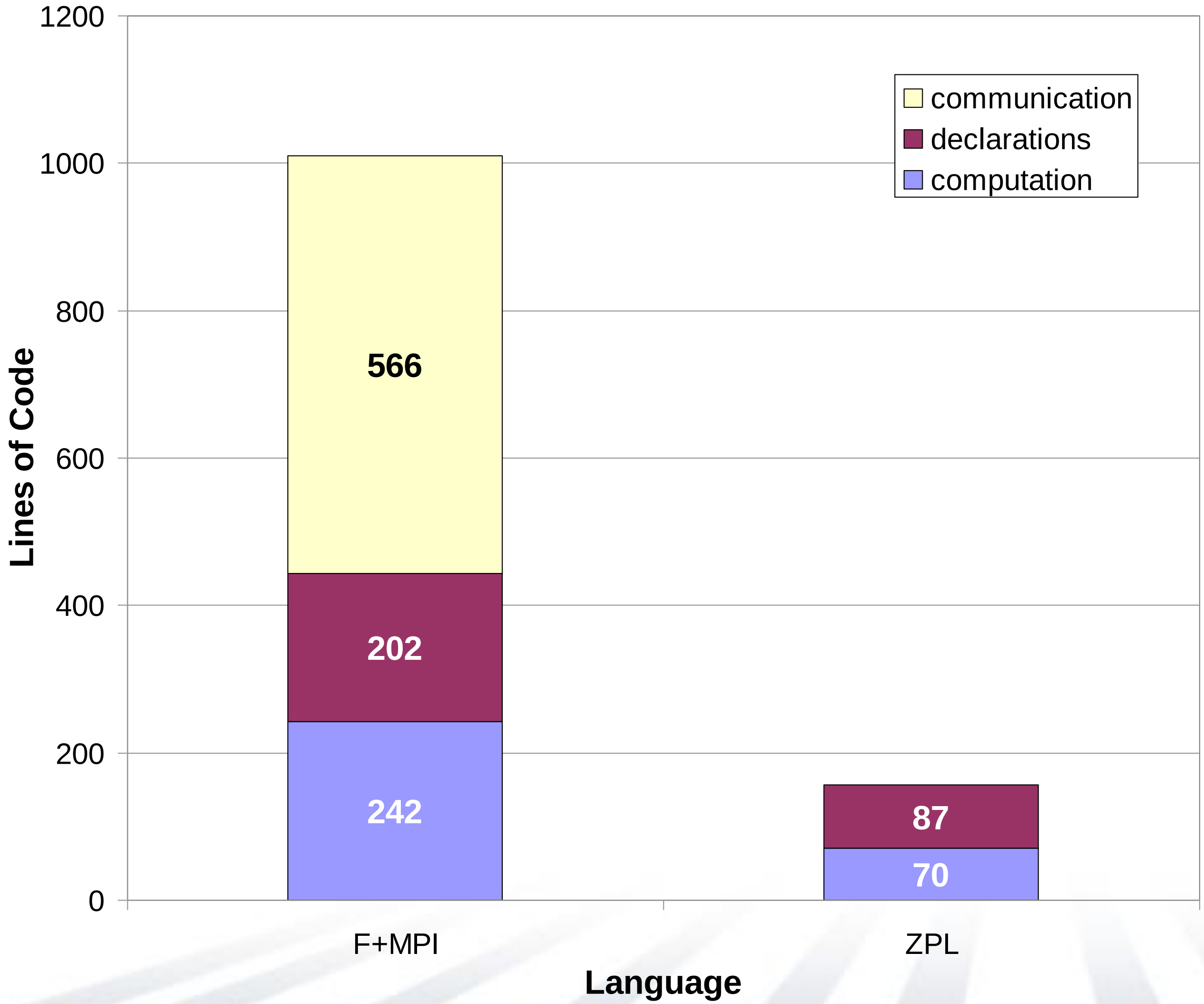


Each ZPL binary supports:
- **an arbitrary load-time problem size**
- **an arbitrary load-time # of processors**
- **1D/2D/3D data decompositions**

This MPI binary only supports:
- **a static 2*****k*** **problem size**
- **a static 2*****j*** **# of processors**
- **a 3D data decomposition**

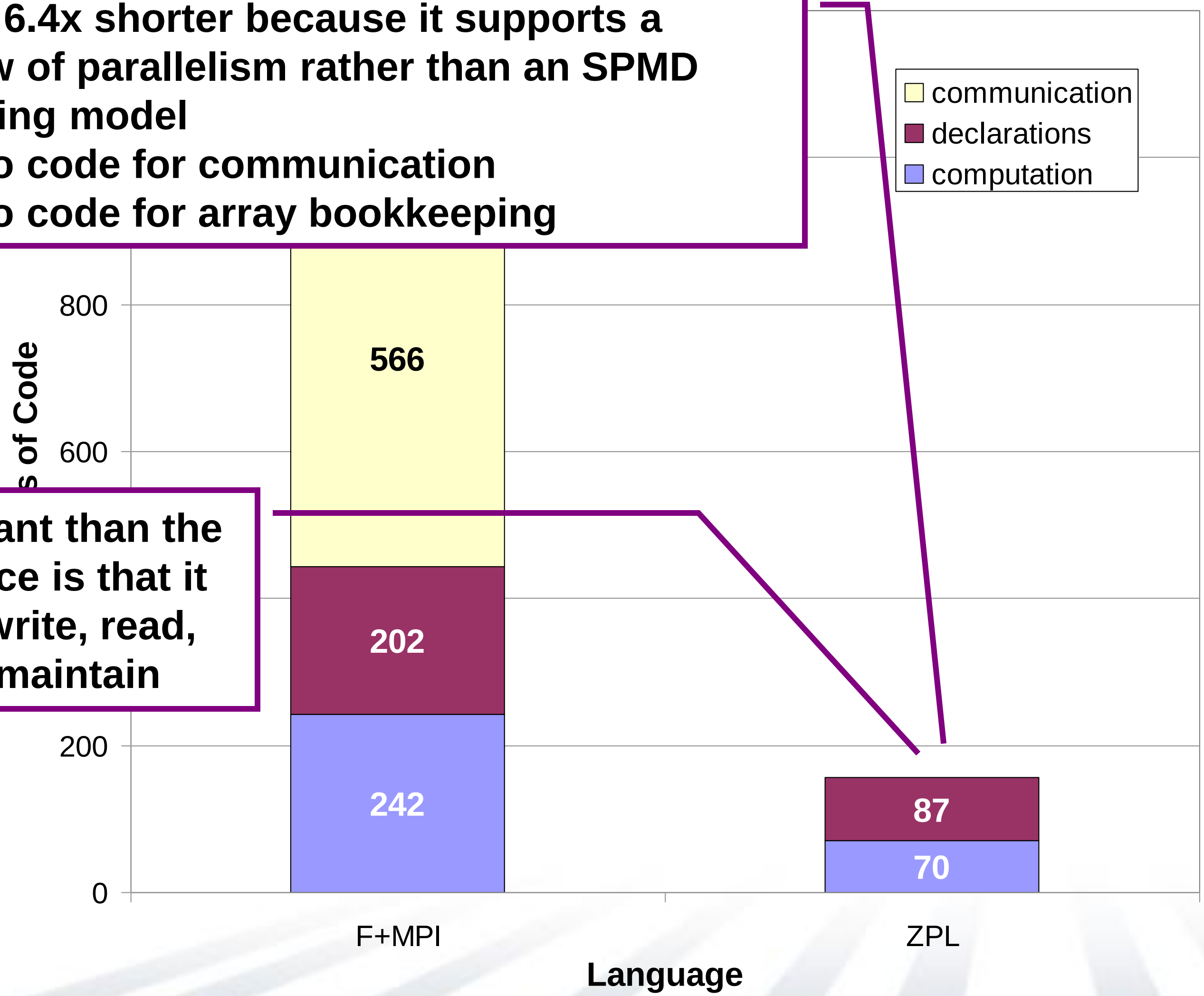
The code could be rewritten to relax these assumptions, but at what cost?
- **in performance?**
- **in development effort?**

Code Size Notes



Code Size Notes

- the ZPL is 6.4x shorter because it supports a global view of parallelism rather than an SPMD programming model
  - ⇒ little/no code for communication
  - ⇒ little/no code for array bookkeeping



More important than the size difference is that it is easier to write, read, modify, and maintain

Summarizing Fragmented/SPMD Models

- Advantages:
  - fairly straightforward model of execution
  - relatively easy to implement
  - reasonable performance on commodity architectures
  - portable/ubiquitous
  - lots of important scientific work has been accomplished with them
- Disadvantages:
  - blunt means of expressing parallelism: cooperating executables
  - fails to abstract away architecture / implementing mechanisms
  - obfuscates algorithms with many low-level details
    - error-prone
    - brittle code: difficult to read, maintain, modify, *experiment*
    - "MPI: the assembly language of parallel computing"

Current HPC Programming Notations

- **communication libraries:**
  - MPI, MPI-2 (fragmented, typically SPMD)
  - SHMEM, ARMCI, GASNet (SPMD)

- **shared memory models:**
  - OpenMP, pthreads (global-view, trivially)

- **PGAS languages:**
  - Co-Array Fortran (SPMD)
  - UPC (SPMD)
  - Titanium (SPMD)

Scalability Limiters in HPC Programming Models

- Restricted programming and execution models
  - limits applicability to multiple levels of parallelism in HW and SW
- Exposure of low-level implementation mechanisms
  - exposes too much about implementation semantics

    e.g., saying "how" data should be communicated rather than simply "what" and possibly "when"
  - binds language too tightly to a particular implementation in hardware

    e.g., MPI for inter-node parallelism +
    OpenMP/pthreads for inter-core parallelism +
    directives for intra-core parallelism
- Lack of programmability
  - to a large degree, resulting from the previous two bullets
  - limits ability to modify code – a necessity to tune for these scales

Outline

- ✓ Motivation for Chapel
- ✓ Global-view Programming Models and Scalability
- Language Overview
  - Base Language
  - Parallel Features
    - Task Parallel
    - Data Parallel
  - Locality Features
- Wrap-up

Chapel 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

Base Language: Overview

- Syntax
  - adopt C family of syntax whenever possible/useful
  - main departures: declarations/casts, generics, for loops
- Language Elements
  - standard scalar types, expressions, statements
  - value- and reference-based OOP (optional)
  - no pointers, restricted opportunities for aliasing
  - argument intents similar to Fortran/Ada
- My favorite base language features
  - iterators (in the CLU/Ruby sense, not C++/Java)
  - tuples
  - latent types / simple static type inference
  - rich compile-time language
  - configuration variables

Task Parallelism: Task Creation

begin: creates a task for future evaluation

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

sync: waits on all begins created within a dynamic scope

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

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$.readFF();         // read when full, leave full;
                          // 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;
}
```

Task Parallelism: Structured Task Creation

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
```

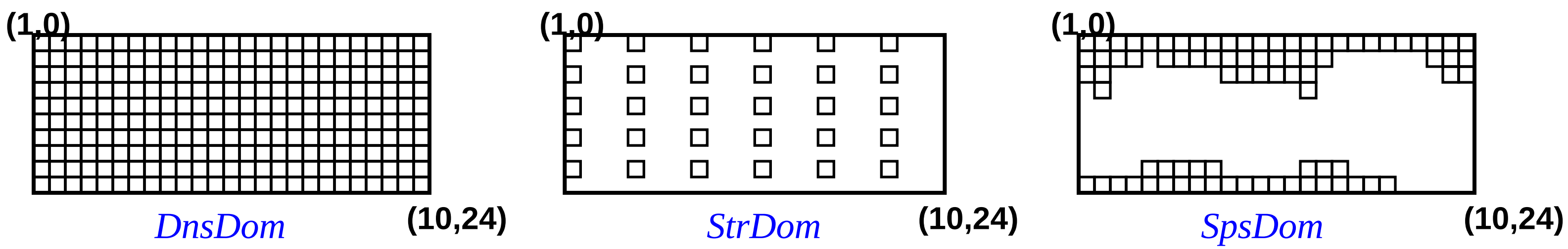
coforall: creates a task per loop iteration

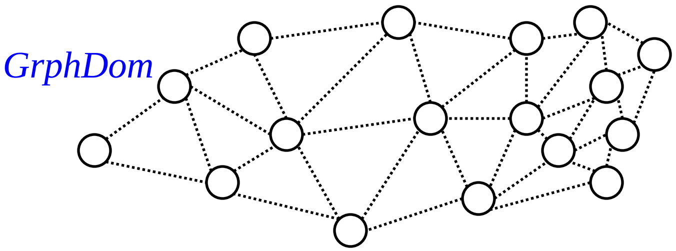
```
coforall e in Edges {
  exploreEdge(e);
} // implicit join here
```

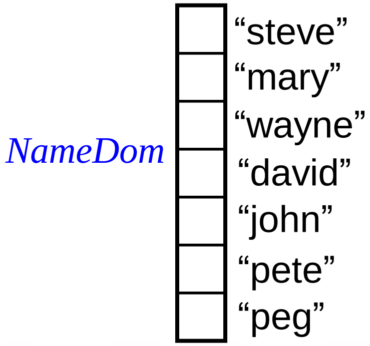
Data Parallelism: Domains

domains: first-class index sets, whose indices can be…

…integer tuples…



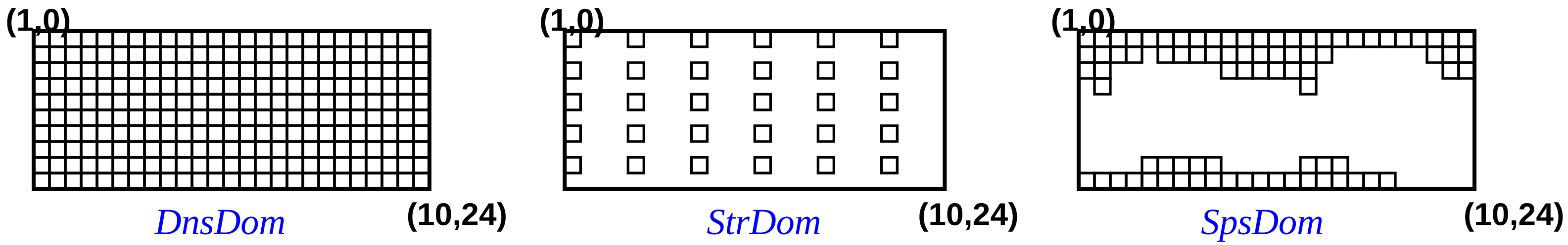


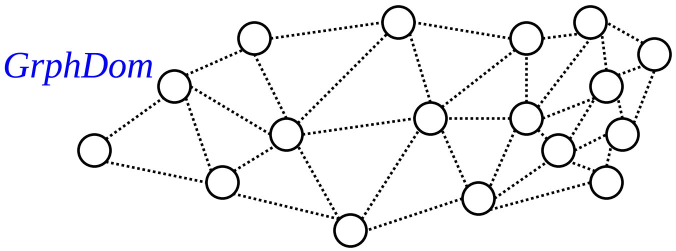


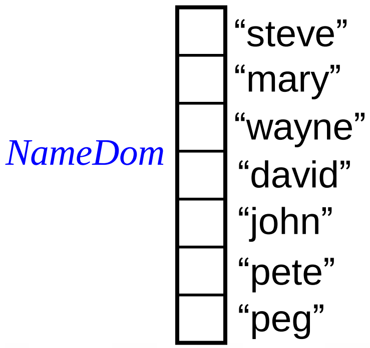
…anonymous… …or arbitrary values.

Data Parallelism: Domain Declarations

```
var DnsDom: domain(2) = [1..10, 0..24],
    StrDom: subdomain(DnsDom) = DnsDom by (2,4),
    SpsDom: subdomain(DnsDom) = genIndices();
```





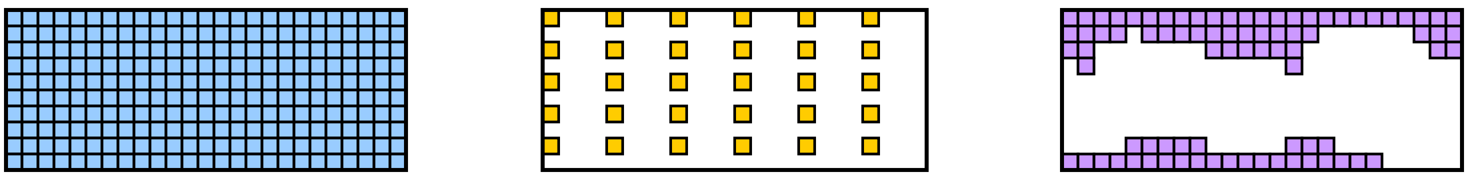


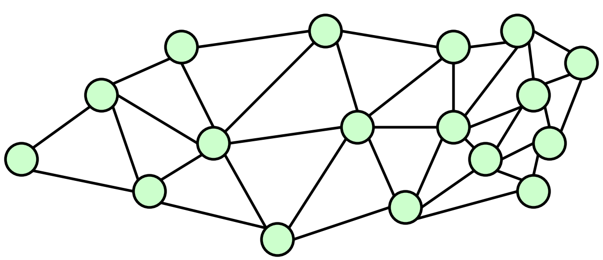

```
var GrphDom: domain(opaque),
    NameDom: domain(string) = readNames();
```

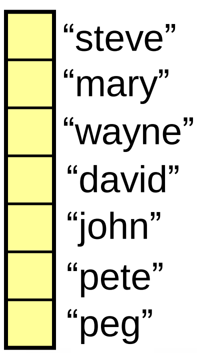
Data Parallelism: Domains and Arrays

Domains are used to declare arrays…

```
var DnsArr: [DnsDom] complex,
    SpsArr: [SpsDom] real;
…
```



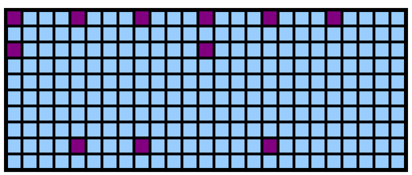


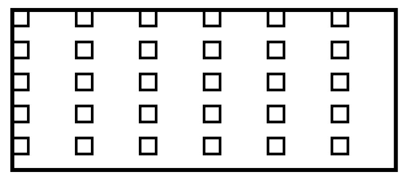


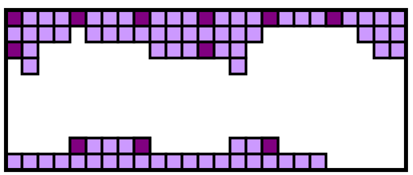
Data Parallelism: Domain Iteration

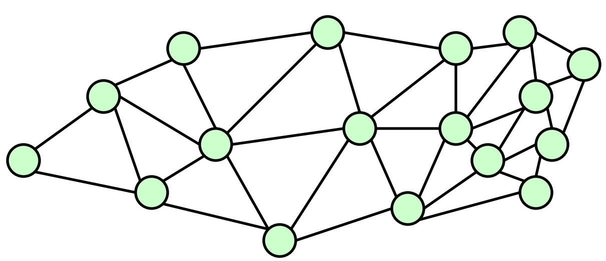
…to iterate over index spaces…

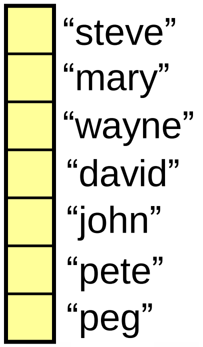
```
forall ij in StrDom {
  DnsArr(ij) += SpsArr(ij);
}
```







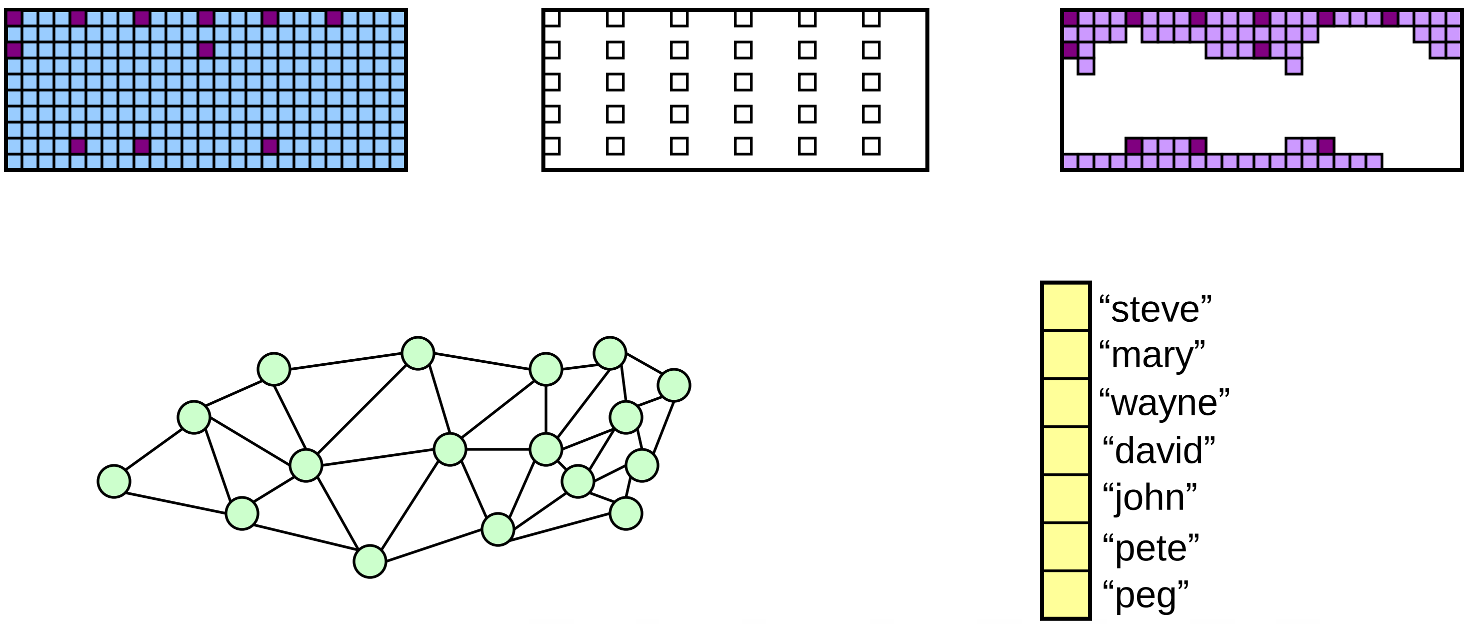




Data Parallelism: Array Slicing

…to slice arrays…

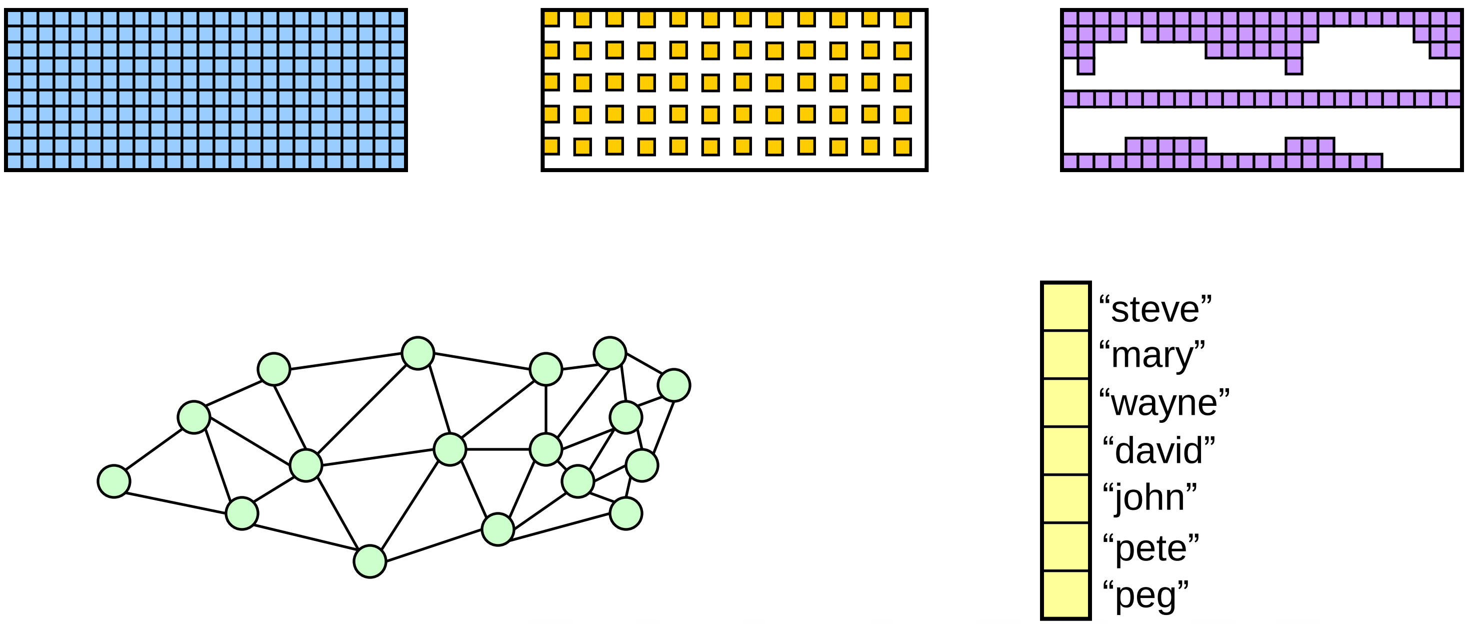
```
DnsArr[StrDom] += SpsArr[StrDom];
```



Data Parallelism: Array Reallocation

…and to reallocate arrays

```
StrDom = DnsDom by (2,2);
SpsDom += genEquator();
```



Locality: Locales

- *locale:* architectural unit of locality
  - has capacity for storage and processing
  - threads within a locale have ~uniform access to local memory
  - memory within other locales is accessible, but at a price
  - *e.g.*, a multicore processor or SMP node

Locality: Locales

- user specifies # locales on executable command-line

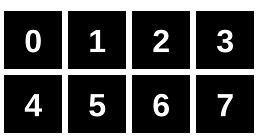
```
prompt> myChapelProg -nl=8
```

- Chapel programs have built-in locale variables:

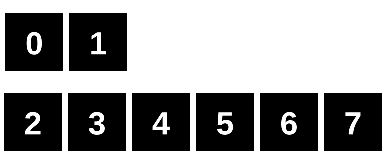
```
config const numLocales: int;
const LocaleSpace = [0..numLocales-1],
      Locales: [LocaleSpace] locale;
```

- Programmers can create their own locale views:

```
var CompGrid = Locales.reshape([1..GridRows,
                                 1..GridCols]);
```




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



Locality: Task Placement

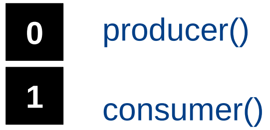
on clauses: indicate where tasks should execute

Either in a data-driven manner…

```
computePivot(lo, hi, data);
cobegin {
  on A(lo)     do Quicksort(lo, pivot, data);
  on A(pivot)  do Quicksort(pivot, hi, data);
}
```

…or by naming locales explicitly

```
cobegin {
  on Locales(0) do producer();
  on Locales(1) do consumer();
}
```

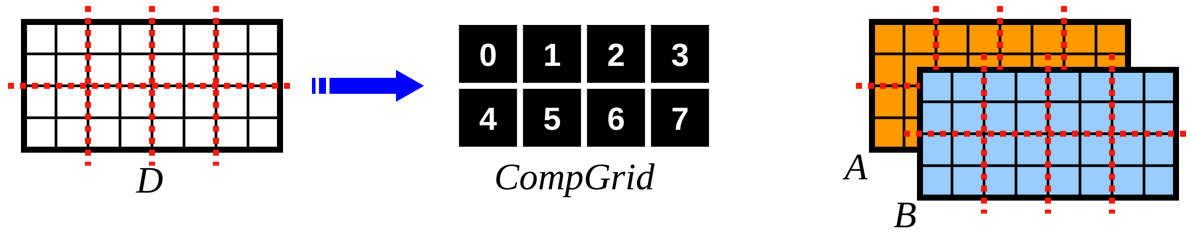



```
cobegin {
  on TaskALocs do computeTaskA(…);
  on TaskBLocs do computeTaskB(…);
  on Locales(0) do computeTaskC(…);
}
```

Locality: Domain Distribution

Domains may be distributed across locales

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



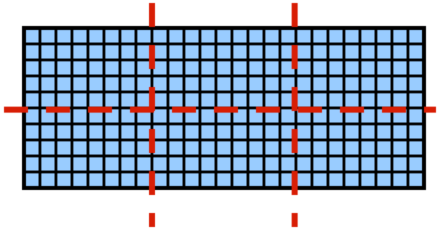
Locality: Domain Distributions

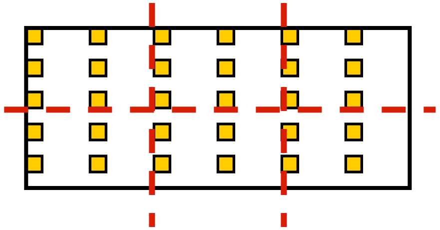
Distributions specify…

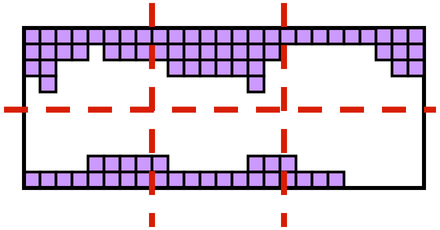
…a mapping of indices to locales

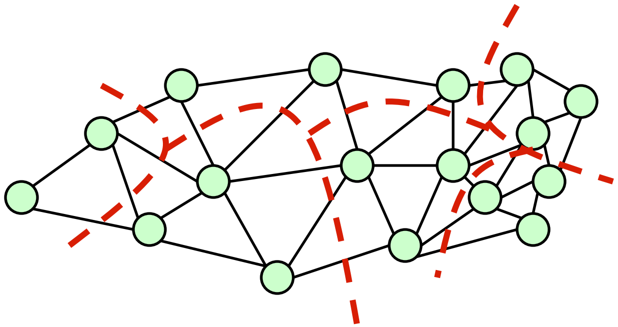
…per-locale storage for domain indices and array elements

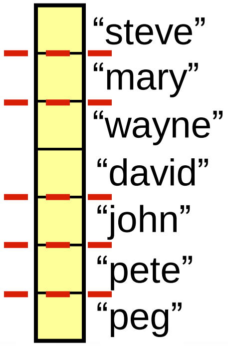
…the implementation of parallel operations on domains/arrays











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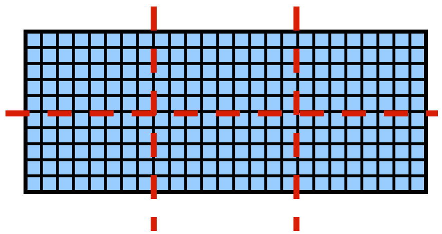
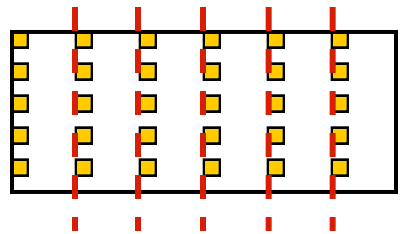
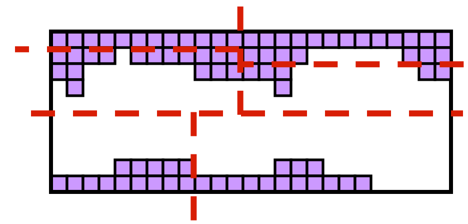
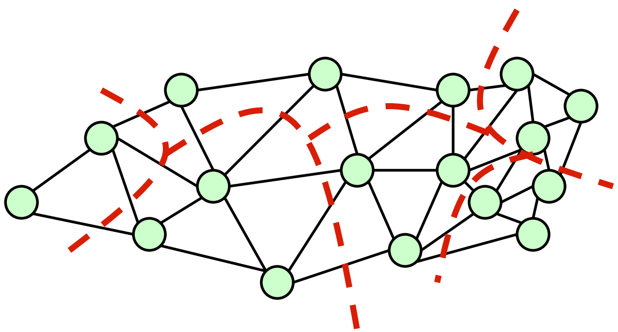
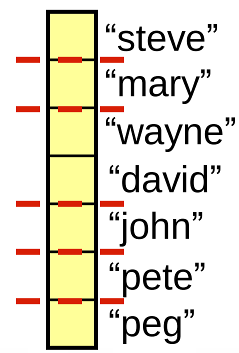






Locality: Distributions Overview

Distributions: "recipes for distributed arrays"

- Intuitively, distributions support the lowering…
  …from: the user's global view of a distributed array
  …to: the fragmented implementation on a distributed memory machine

- Users can implement custom distributions:
  - written using task parallel features, on clauses, domains/arrays
  - must implement standard interface:
    - **allocation/reallocation** of domain indices and array elements
    - **mapping functions** (*e.g.*, index-to-locale, index-to-value)
    - **iterators:** parallel/serial × global/local
    - optionally, communication idioms

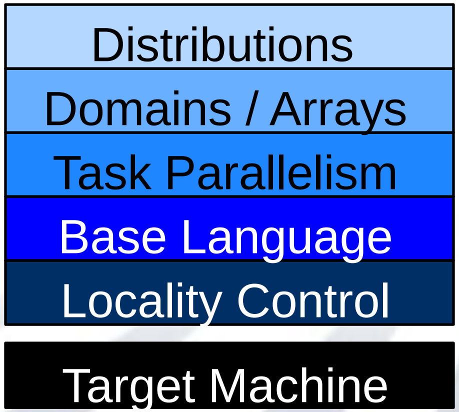
- Chapel provides a standard library of distributions…
  …written using the same mechanism as user-defined distributions
  …tuned for different platforms to maximize performance

Multiresolution Language Design

Conventional Wisdom: By providing higher-level concepts in a language, programmers' hands are tied, preventing them from manually optimizing for performance

My Belief: With appropriate design, this need not be the case

- provide high-level features and automation for convenience
  - knowledge of such features can aid in compiler optimization
- provide capabilities to drop down to lower, more manual levels
- use appropriate separation of concerns to keep this clean
  - support the 90/10 rule

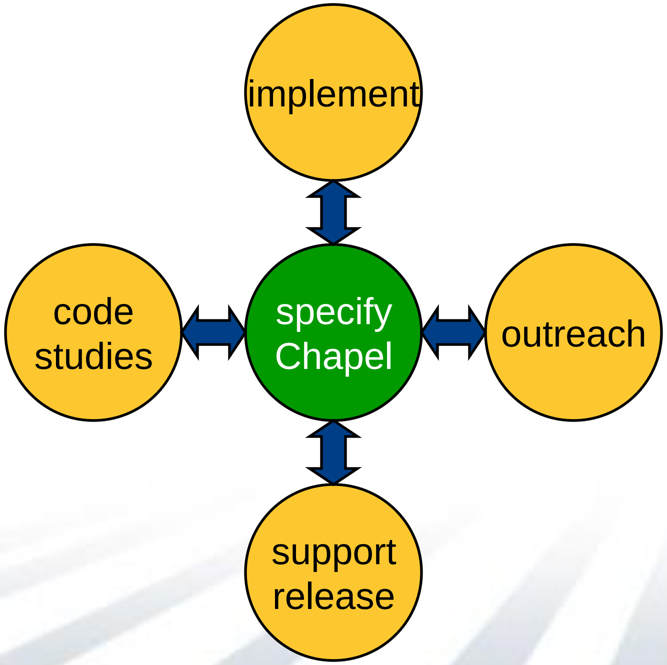


Outline

- ✓ Motivation for Chapel
- ✓ Global-view Programming Models and Scalability
- ✓ Language Overview
- ❑ Wrap-up

Chapel Work

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



Prototype Implementation

- Approach:
  - source-to-source compiler for portability (Chapel-to-C)
  - link against runtime libraries to hide machine details
    - threading layer currently implemented using pthreads
    - communication currently implemented using Berkeley's GASNet
- Status:
  - **base language:** solid, usable (a few gaps remain)
  - **task parallel:** multiple threads, multiple locales
  - **data parallel:** single-threaded, single-locale
  - **performance:** has received little effort (but much planning)
- Current Focus:
  - multi-threaded implementation of data parallel features
  - distributed domains and arrays
  - performance optimizations
- Early releases to ~40 users at ~20 sites (academic, gov't, industry)

HPC vs. Datacenter concerns

Concern	HPC	Datacenter*
Scalability	Crucial	Crucial
Locality/affinity	Crucial for performance	Crucial for performance
Portability to future technologies	Important	Important
Power/cooling	Increasingly an issue	Increasingly an issue
Flavor of Parallelism	Lots of data dependence, communication	Pleasingly parallel + reductions
Reliability/robustness	Checkpoint/restart	Redundancy + dynamic monitoring
Data types	Floating point (historically)	Strings, integers
Data structures	Multidimensional arrays / unstructured graphs	???
Memory Use	Lots (but generally in-core)	Lots (& generally out-of-core)

* Based on my rather limited understanding…

Chapel for Datacenter Computations?

Some appropriate features:

- large, distributed data structures ("arrays")
- application of scalar functions to arrays
- reductions: standard and user-defined
- ability to reason about locality, machine resources
- abstraction away from implementing mechanisms
- designed for generality

Yet also some areas requiring innovation/research:

- language-level support for redundancy/reliability?
- extend domains and distributions to out-of-core computations?
- interpreted Chapel for interactive data exploration?
- your ideas here…

A potentially interesting collaboration?

(We're open to others as well…)

Summary

Programming languages can help with scalability, given appropriate design and abstractions

- Abstractions must map well to hardware capabilities
  - capable of resulting in good performance
  - avoid encoding more about hardware than necessary
- Should support ability to drop to lower levels when required
- Should support ability to control and reason about locality
- Must be as general-purpose as target community requires

Chapel Team

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