Chapel: an HPC language in a mainstream multicore world

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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
- ***global-view* abstractions**
- ***multiresolution* design**
- **control of locality**
- **reduce gap between mainstream & parallel languages**

Chapel's Setting: HPCS

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

- Goal: Raise HEC user productivity by 10× for the year 2010
- 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 – 2010)
  - Implement the systems and technologies resulting from phase II
  - (Sun also continues work on Fortress, without HPCS funding)

HPC vs. Mainstream Multicore

- Differences:
  - machine scale
  - performance requirements (?)
  - memory requirements (?)
  - robustness requirements (?)
  - workloads
  - programming community sizes and expertise areas

- Some interesting HPC(S) trends:
  - growing desire for software productivity, programmability
  - desire to better support nontraditional users
    - students just out of school with no C/Fortran/vi/emacs experience
    - scientists without strong parallel CS background
  - desire to leverage multicore technologies in larger systems
    - ideally without requiring hybrid programming models
  - and others that match opinions expressed in this meeting…

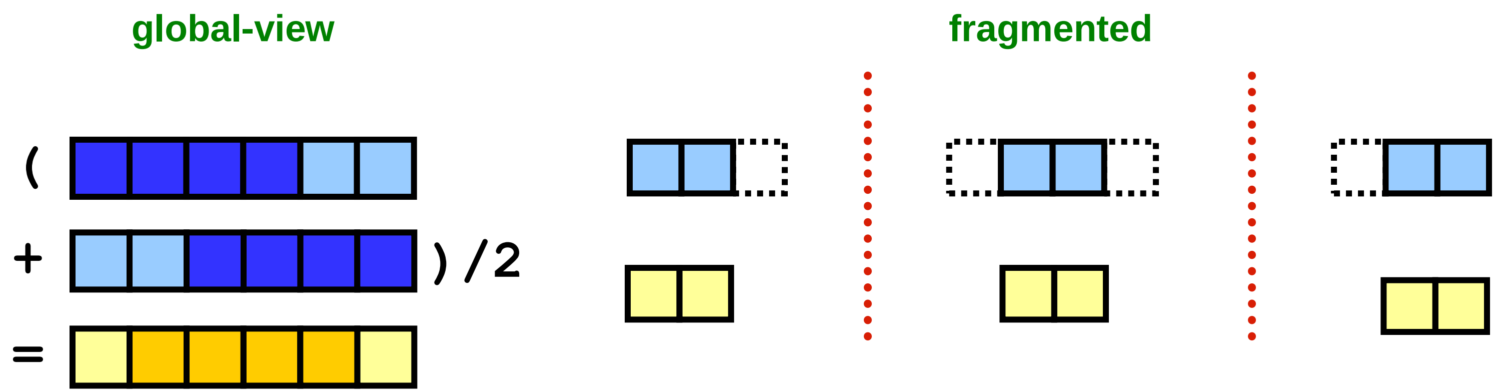
Outline

- ✓ Chapel Context
- ➢ Defining my terms
- ❑ Some Chapel features
- ❑ Wrap-up

(with an emphasis on themes and topics from this meeting)

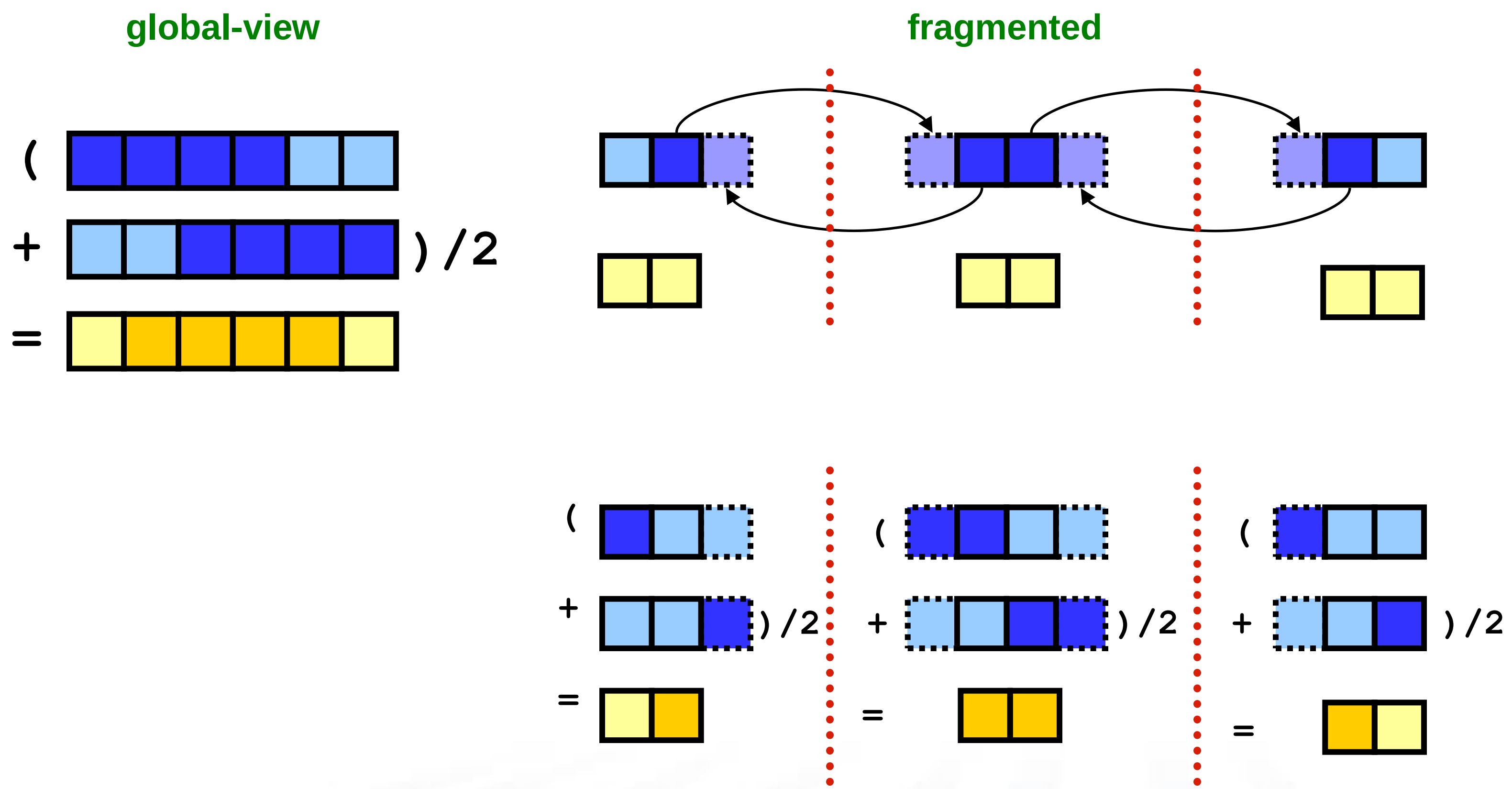
Global-view vs. Fragmented

Problem: “Apply 3-pt stencil to vector”



Global-view vs. Fragmented

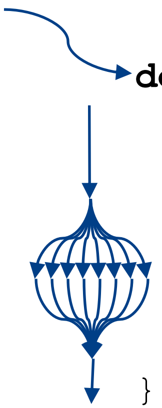
Problem: "Apply 3-pt stencil to vector"



Global-view vs. SPMD Code

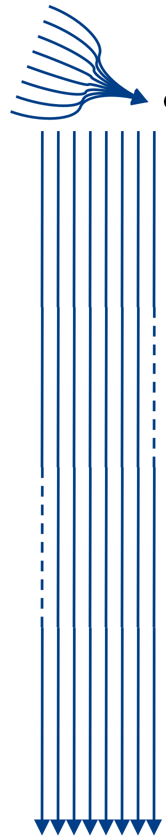
Problem: "Apply 3-pt stencil to vector"

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



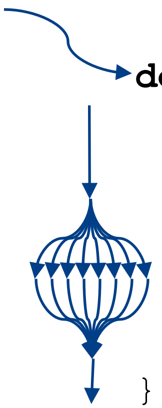
```
def main() {
  var n: int = 1000;
  var locN: int = n/numProcs;
  var a, b: [0..locN+1] real;

  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

Problem: "Apply 3-pt stencil to vector"

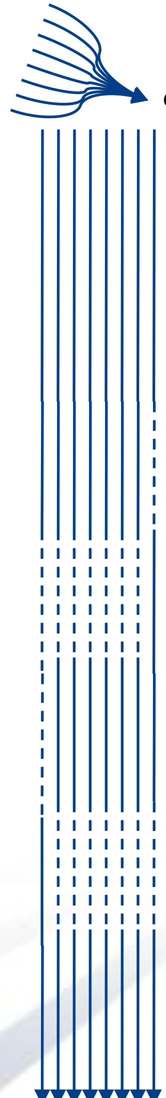
Assumes *numProcs* divides *n*; a more general version would require additional effort

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;
  }
}
```

MPI SPMD pseudo-code

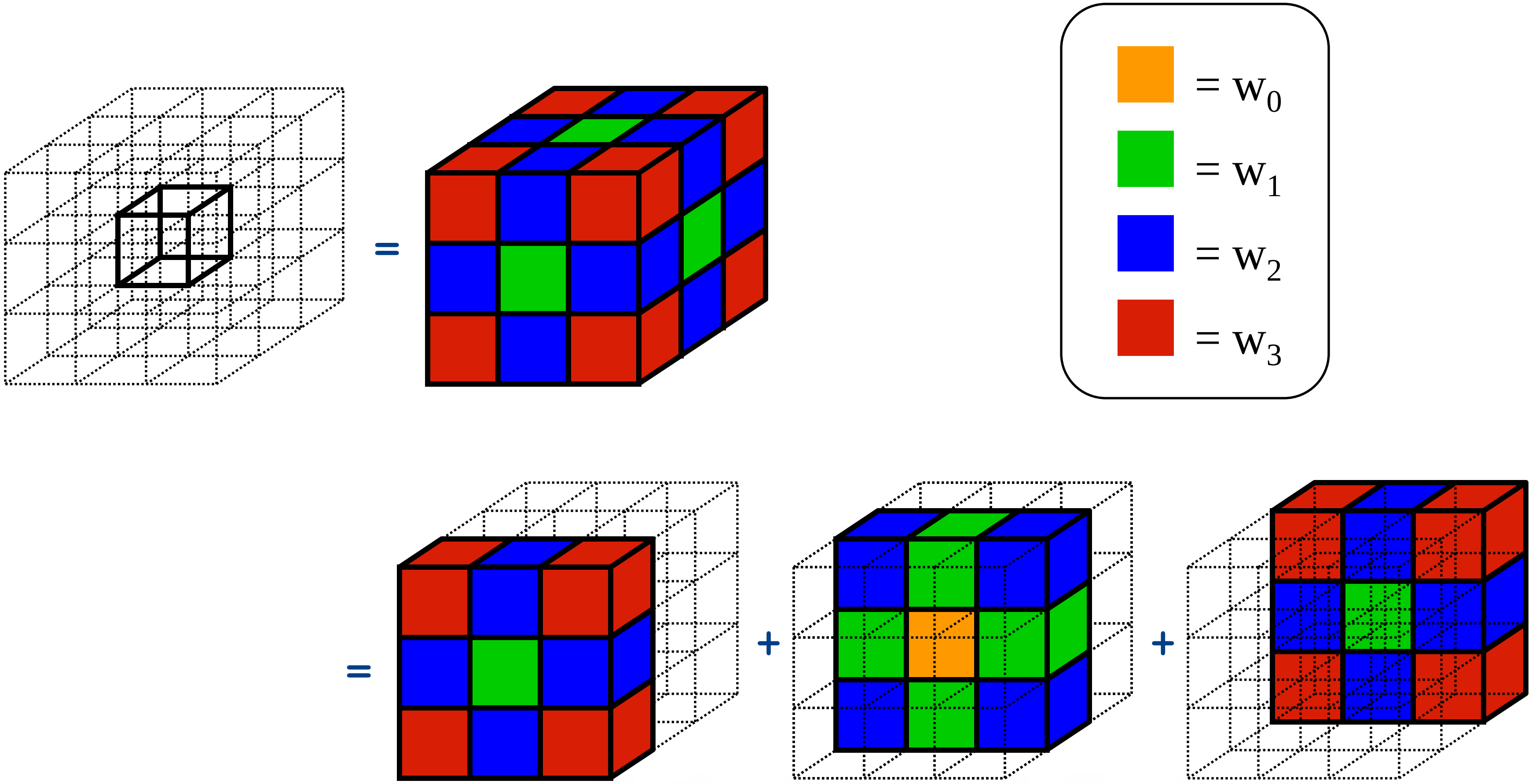
Problem: "Apply 3-pt stencil to vector"

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

NAS MG *rprj3* stencil



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
```

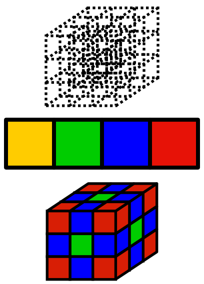
```
else if( dir .eq. +1 ) then

      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

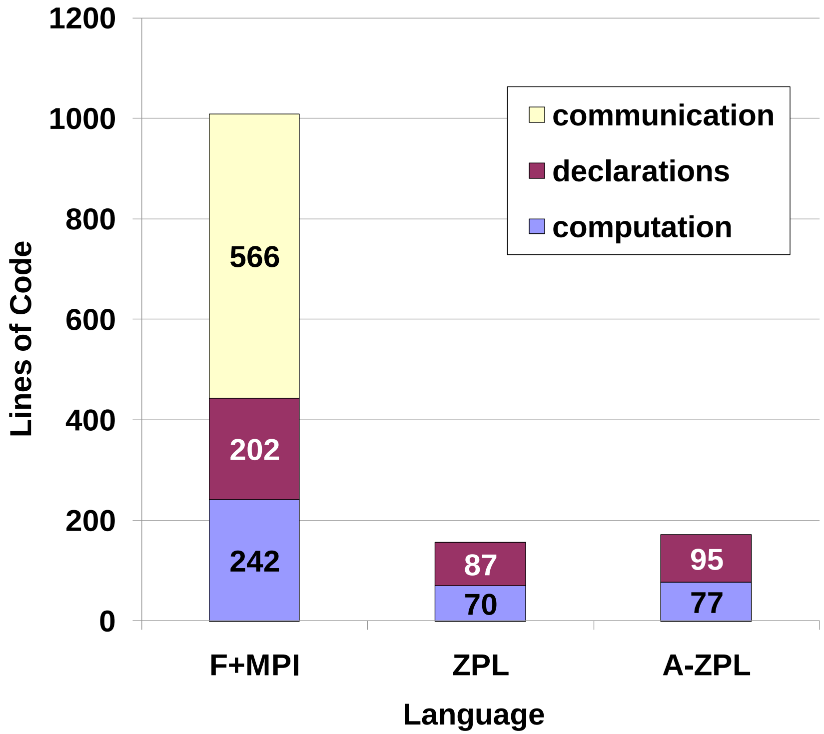
```
def rprj3(S, R) {
  param Stencil = [-1..1, -1..1, -1..1],
        w: [0..3] real = (0.5, 0.25, 0.125, 0.0625),
        w3d = [(i,j,k) in Stencil] w((i!=0) + (j!=0) + (k!=0));

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

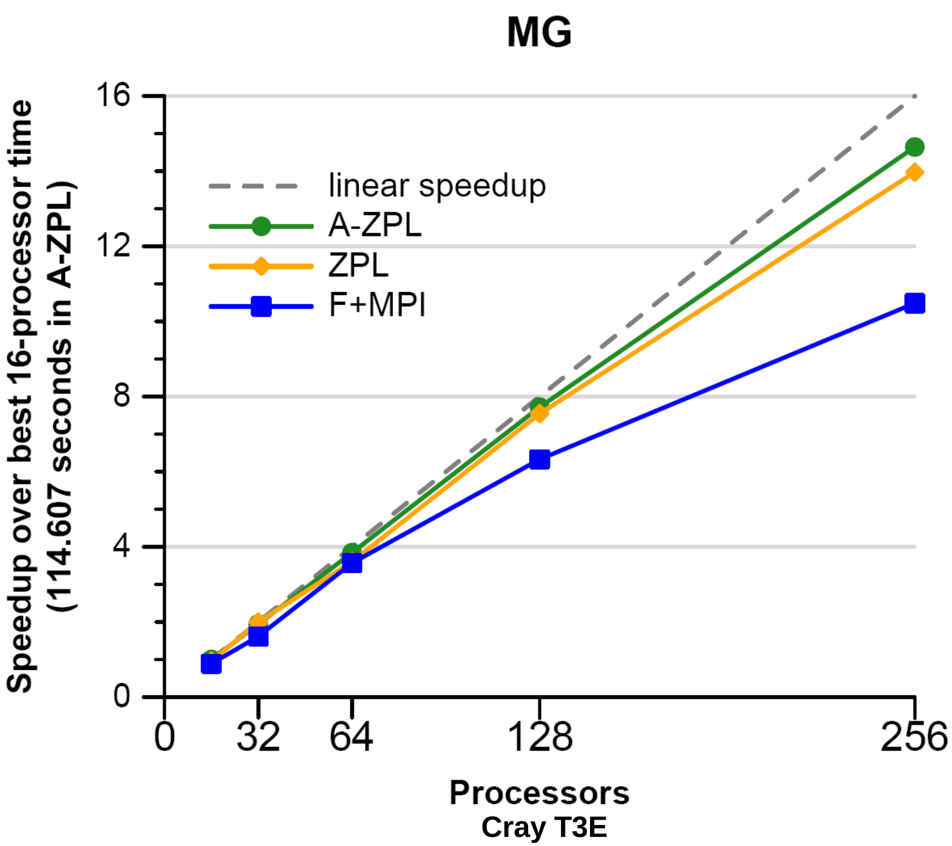


NAS MG *rprj3* stencil in ZPL

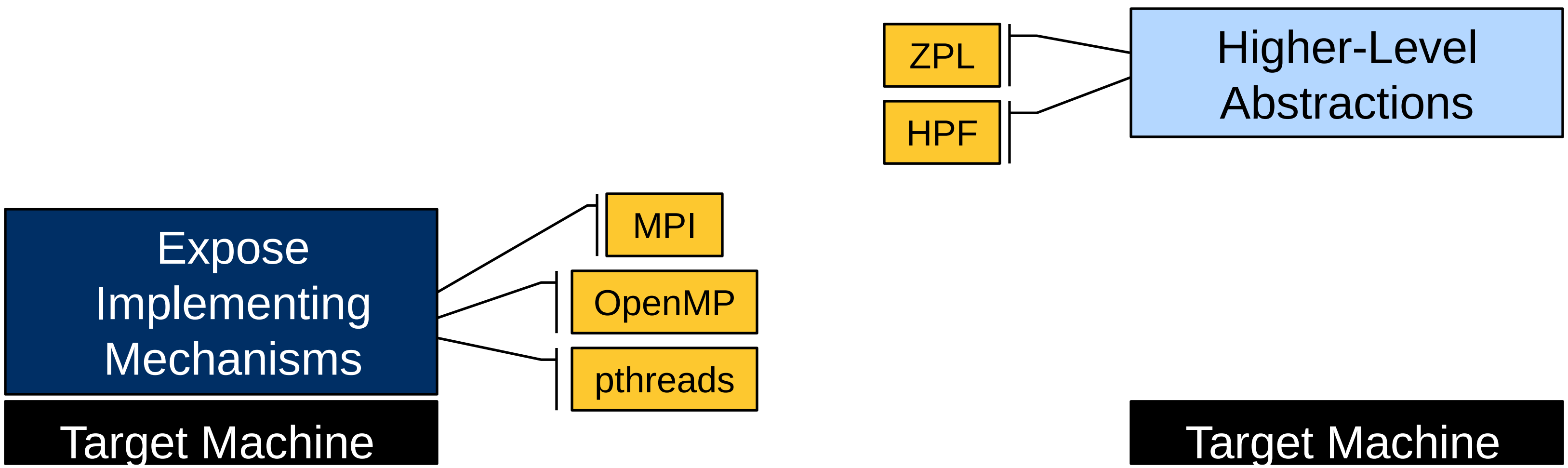
```
procedure rprj3(var S,R: [,,] double;
                 d: array [] of direction);
begin
  S := 0.5    *  R
     + 0.25   * (R@^d[ 1, 0, 0] + R@^d[ 0, 1, 0] + R@^d[ 0, 0, 1] +
                 R@^d[-1, 0, 0] + R@^d[ 0,-1, 0] + R@^d[ 0, 0,-1])
     + 0.125  * (R@^d[ 1, 1, 0] + R@^d[ 1, 0, 1] + R@^d[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





Parallel Programming Models: Two Camps



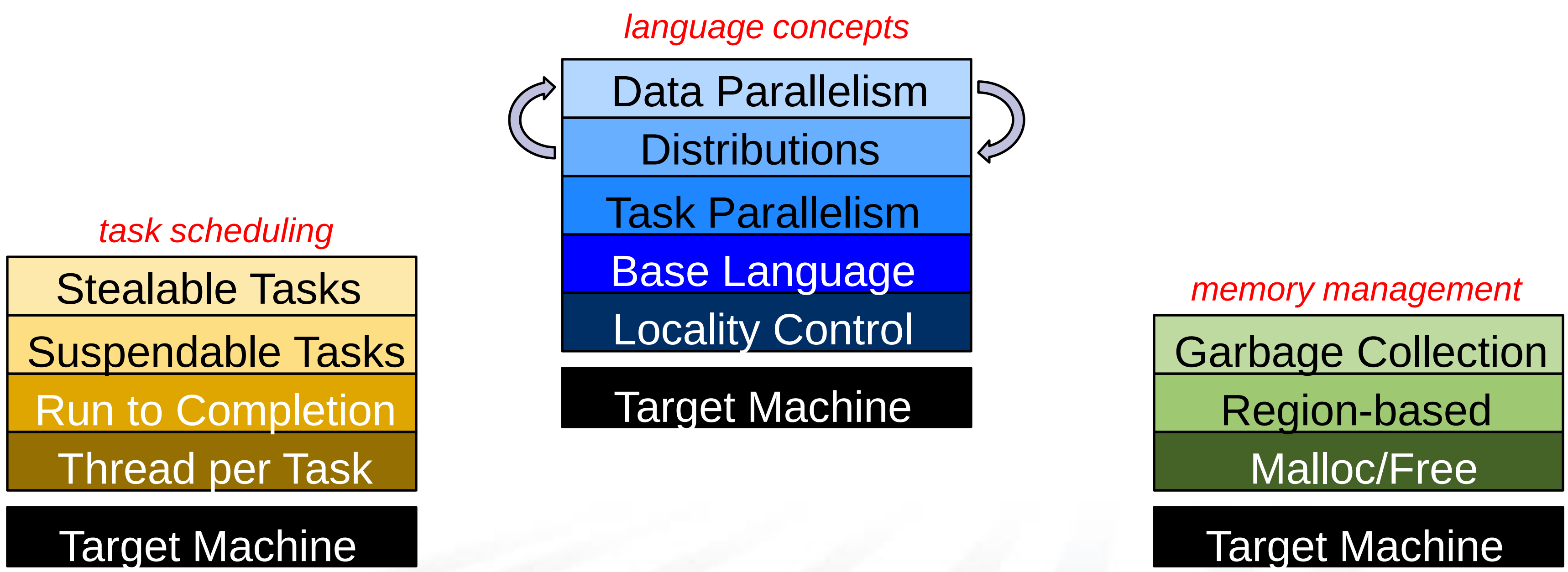
"Why is everything so painful?"

"Why do my hands feel tied?"

Multiresolution Language Design

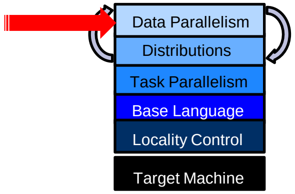
Our Approach: Permit the language to be utilized at multiple levels, as required by the problem/programmer

- 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



Outline

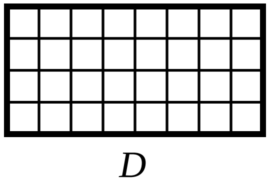
- ✓ Chapel Context
- ✓ Defining my terms
- ➢ Some Chapel features
- ❑ Wrap-up



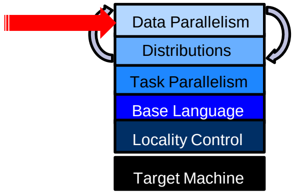
Domains

domain: a first-class index set

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

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

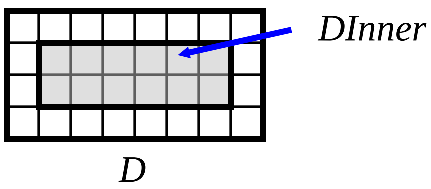


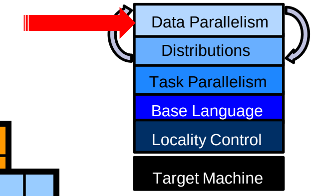
Domains



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];
```

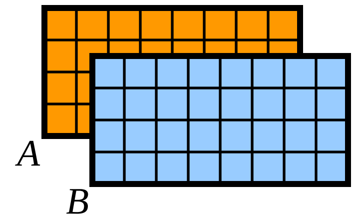




Domains: Some Uses

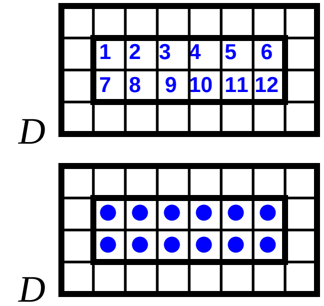
- Declaring arrays:

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



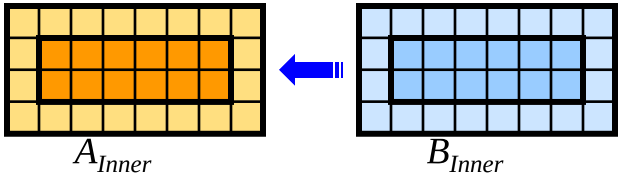
- Iteration (sequential or parallel):

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



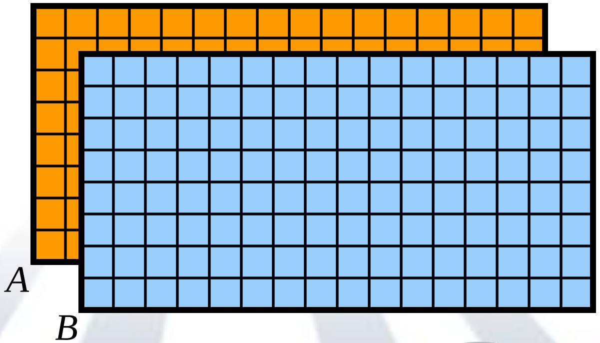
- Array Slicing:

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

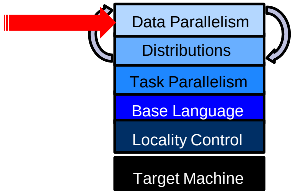


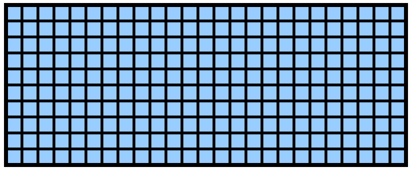
- Array reallocation:

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

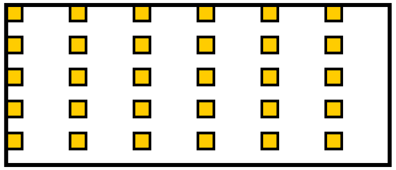


Domains: Different Flavors

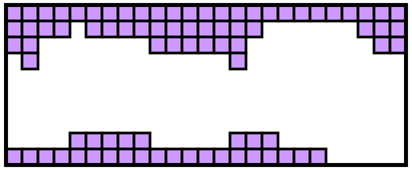




dense

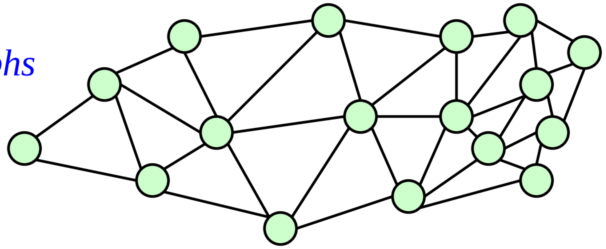


strided

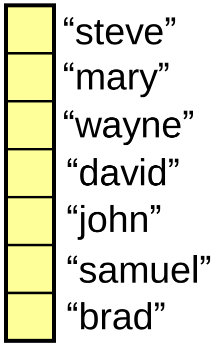


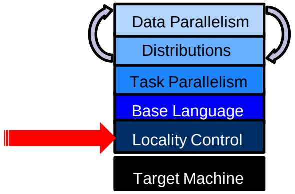
sparse

graphs



associative

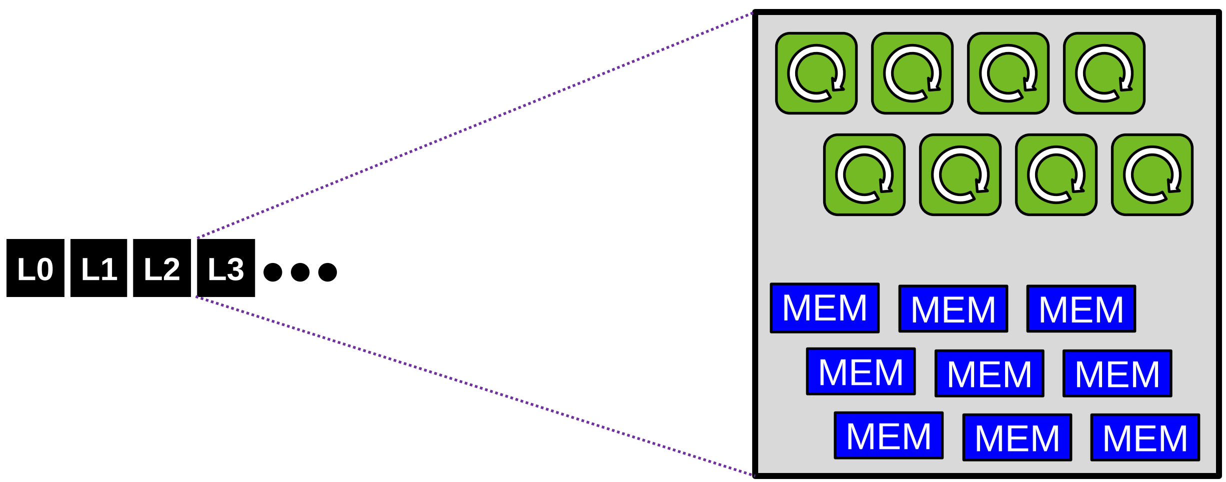




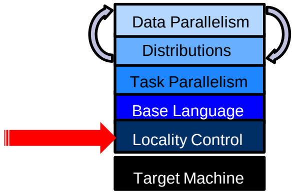
Locality: Locales

locale: architectural unit of locality

- has capacity for processing and storage
- 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 could be a locale



Locality: Locales



- user specifies # locales on executable command-line

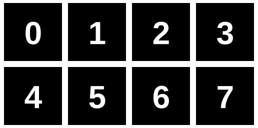
```
prompt> myChapelProg -nl=8
```

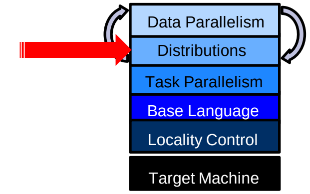
- Chapel programs have built-in domain/array of locales:

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

- Programmers can create their own locale views:

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

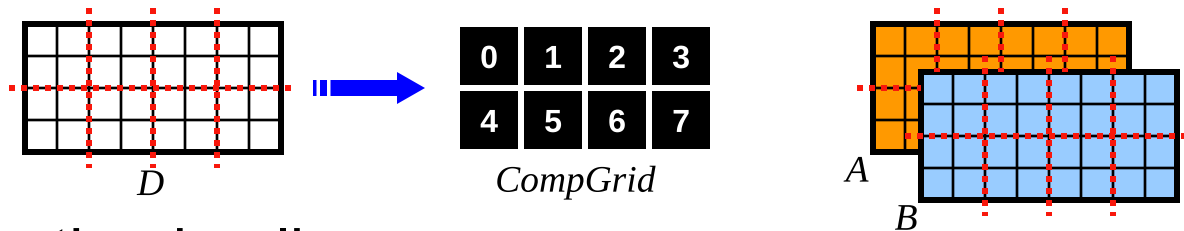




Distributions: Overview

Domains may be distributed across locales

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

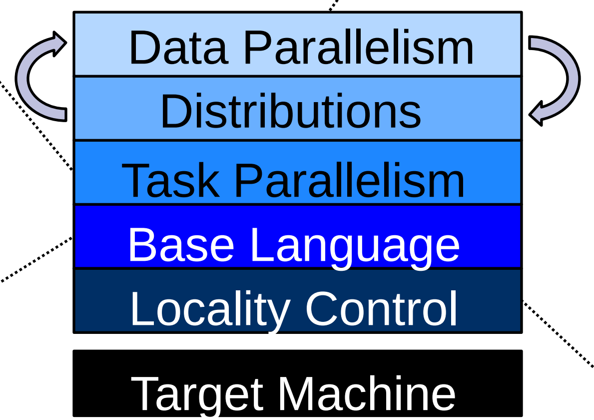


- A distribution implies…
  …ownership of the domain's indices (and its arrays' elements)
  …the default work ownership for operations on the domain/arrays
- Advanced users can write their own distributions
  (and standard distributions are written using the identical mechanism)
- A distribution must implement…
  …the mapping from indices to locales
  …the per-locale representation of domain indices and array elements
  …the compiler's target interface for lowering global-view operations

Other Chapel Features

- **unstructured task parallelism**
  - begins
  - sync statements
- **structured task parallelism**
  - cobegins
  - coforalls
- **synchronization**
  - sync/single variables
  - atomic blocks

- subdomains and index types
- zippered and tensor iteration
- scalar function promotion
- reductions and scans



- value- and reference-based OOP (optional)
- generic programming features
- latent types / shallow static type inference
- rich compile-time language
- iterators (generators)
- tuples

- fine-grain control over task and data placement via on clauses

Outline

- ✓ Chapel Context
- ✓ Defining my terms
- ✓ Some Chapel features
- ➢ Wrap-up

Chapel and Mainstream Multicore

- While Chapel doesn't specifically target mainstream multicore, it could be applicable
  - removes much tedium and nitpicky details from data parallelism
  - raises level of discourse for task parallelism beyond threads
  - though not a dialect of a mainstream language, not far afield either
    - programmers today seem more multilingual than in the past
    - interoperability more crucial than extending a language
- Chapel's locales and distributions are likely overkill for today's multicore processors
  - but what about for future generations of multicore?
- Chapel team does most of our development and testing on mainstream multicore machines
  - Linux, Mac, Windows, …
  - AMD, Intel, …

Takeaways

- Key themes for mainstream multicore languages
  - generality, to the extent possible
  - global-view abstractions (for Joe & Joan)
  - multiresolution design (for Steve & Stephanie)

- Other Lessons from HPC
  - abstract implementing mechanisms further from user's view than we traditionally have
  - SPMD: an execution case to optimize for, not the only tool in the box

Future Directions (with an eye on multicore)

- expand locale concept
  - hierarchical locales
    - to expose hierarchy within a node
  - heterogeneous locale types
    - to describe coarse-grain HW heterogeneity
  - dynamically varying numbers of locales

- equivalent of “distribution” concept for task parallelism
  - (Edward Lee’s directors?)

- and of course, many others…

Collaborations

UIUC (Vikram Adve and Rob Bocchino): Software Transactional Memory (STM) over distributed memory (PPoPP `08)

ORNL (David Bernholdt *et al.*): Chapel code studies – Fock matrix computations, MADNESS, Sweep3D, … (HIPS `08)

PNNL (Jarek Nieplocha *et al.*): ARMCI port of comm. layer

EPCC (Michele Weiland, Thom Haddow): performance study of single-locale task parallelism

CMU (Franz Franchetti): Chapel as portable parallel back-end language for SPIRAL

(Your name here?)

Chapel Contributors

- Current Team
  - Brad Chamberlain
  - Steve Deitz
  - Samuel Figueroa
  - David Iten
  - Andy Stone (not shown)
- Alumni
  - Robert Bocchino
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  - James Dinan
  - Roxana Diaconescu
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