Lessons Learned in Array Programming: from ZPL to Chapel

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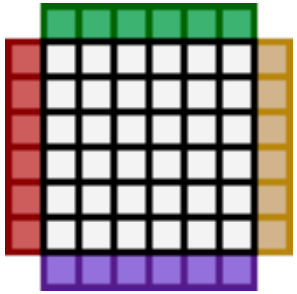
Chapel Team, Cray Inc.
ARRAY 2016, June 14, 2016



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My Background

Education:

- Earned Ph.D. from University of Washington CSE in 2001
- Remain associated with UW CSE as an Affiliate Professor

Industrial Experience:

- Currently a Principal Engineer at Cray Inc.
- Also spent an educational year at a start-up between UW and Cray

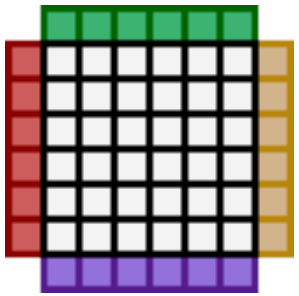
My R&D Interests

Designing and Implementing Parallel Languages

- targeting HPC (High-Performance Computing) system scales
- making use of array abstractions
  (as well as other abstractions)

Parallel Array Languages I've Worked on:

ZPL: at UW CSE

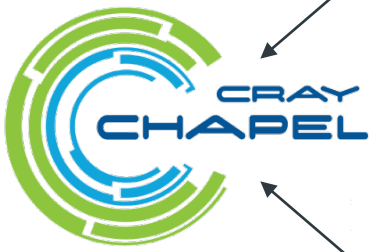


Chapel: at Cray

Chapel's Founders / Relationship to ZPL

Hans Zima
Vienna Fortran, HPF
Fortran-oriented
Performance
Minimal features

David Callahan
MTA C, Fortran
Multithreading
Generality
User-optimizable



Brad Chamberlain
ZPL
Array Programming
Syntactic performance model
SPMD execution

John Plevyak
D, Python, OCaml
Type inference
Generics
OOP

Today's Talk

Theme:

- Comparison of array features in ZPL vs. Chapel
  - and by extension, differences between academic vs. practical languages
    - **ZPL:** very pure, focused language ("array-based data parallelism")
    - **Chapel:** very general, intended for adoption ("any parallelism, including arrays")

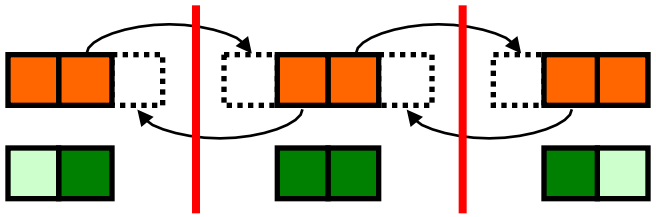
Outline:

- **Background**
- **ZPL**
  - Arrays in ZPL
  - ZPL's greatest hits
  - ZPL's drawbacks
- **Chapel arrays** (learning from ZPL's mistakes)
- **Q&A / Discussion**

Local-view vs. Global-view

Local-view:

- code describes per-task behavior
- programmer manages coordination details

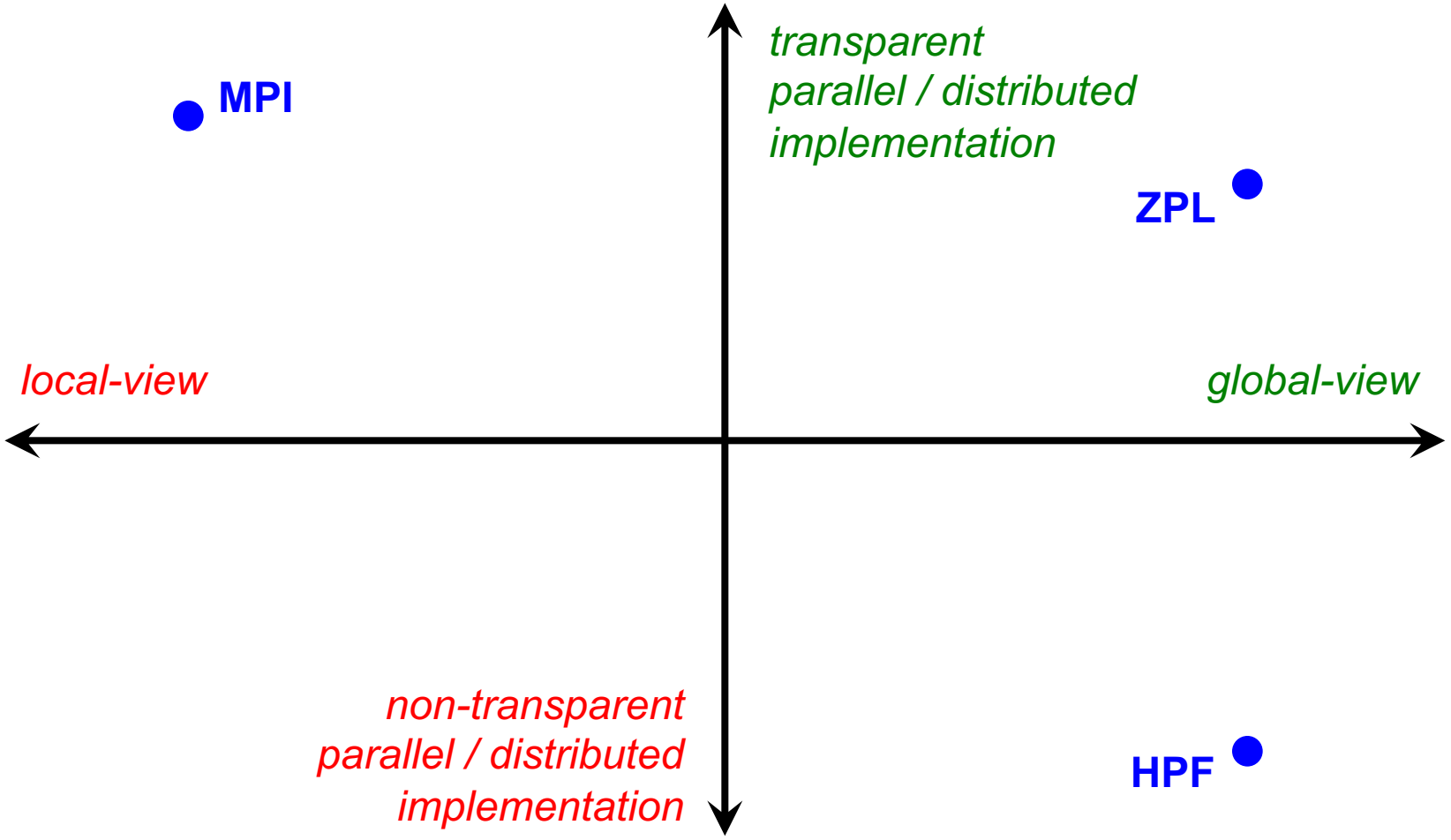


Global-view:

- code describes algorithm as a whole
- lower layers manage coordination

  (compiler, runtime, libraries)

Parallel Programming Stereotypes



ZPL Factsheet

ZPL: **an array-based data-parallel language**

Developed at: **University of Washington**

Timeframe: **1991 – 2003 (can still download today)**

Target systems: **1990's-era HPC systems**

- clusters of commodity processors or SMPs
- custom parallel architectures:
  - Cray T3E, KSR, SGI Origin, IBM SP2, Sun Enterprise, …

Related languages: **HPF**

Main concepts:

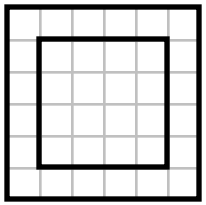
- abstract machine model: *the CTA*
- data parallelism via *regions* and arrays
- *WYSIWYG performance model*

Regions

Regions: index sets that…

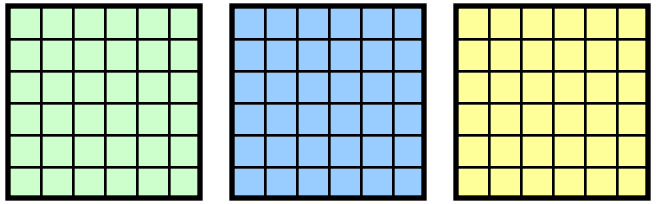
…can be named

```
region     R = [1..n  ,1..n  ];
       BigR = [0..n+1,0..n+1];
```



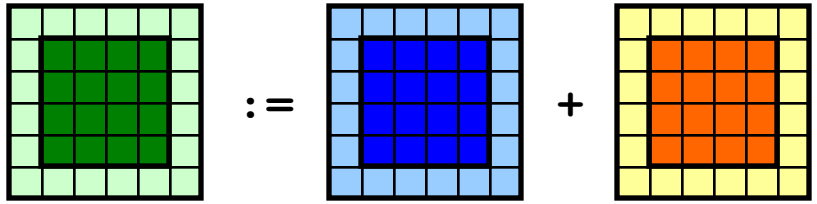
…are used to declare *parallel arrays*

```
var A, B, C:[BigR] integer;
```

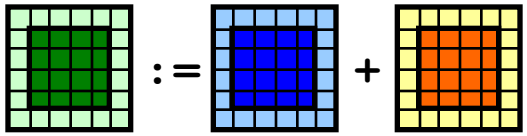


…specify indices for a statement's array references

```
[R] A := B + C;
```



Regions Eliminate Redundancy



C:

```
for (i=1; i<=n; i++) {
  for (j=1; j<=n; j++) {
    A[i][j] = B[i][j] + C[i][j];
  }
}
```

F90:

```
A(1:n,1:n) = B(1:n,1:n) + C(1:n,1:n)
```

ZPL:

```
[1..n,1..n] A := B + C;
```

or:

```
[R] A := B + C;
```

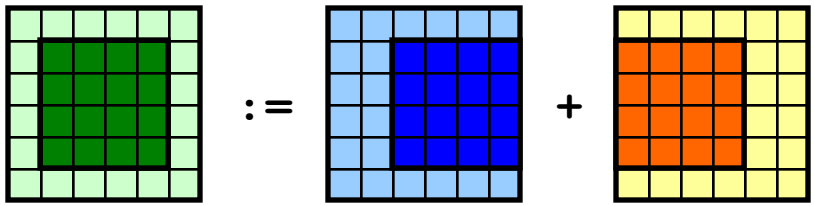
Array Operators

Array Operators: modify the current region's index set for an array reference

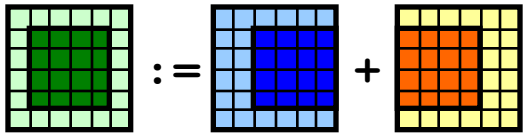
E.g., @-operator translates indices by a *direction*:

```
direction east = [0, 1];
          west = [0,-1];

[R] A := B@east + C@west;
```



Regions Emphasize Differences



C:

```
for (i=1; i<=n; i++) {
  for (j=1; j<=n; j++) {
    A[i][j] = B[i][j+1] + C[i][j-1];
  }
}
```

F90:

```
A(1:n,1:n) = B(1:n,2:n+1) + C(1:n,0:n-1)
```

ZPL:

```
[1..n,1..n] A := B@[0,1] + C@[0,-1];
```

or:

```
[R] A := B@east + C@west;
```

More on Regions / Parallel Arrays

- Region scopes can nest:

```
[R] begin
      A := Index1 + Index2 / 10.0;
      B := A@east;
      [i, 1..n] B := 0.0;
      foo(B);
    end;
```

- Constrained, by design:
  - Parallel arrays do not support “normal” indexing
  - Regions do not support direct iteration

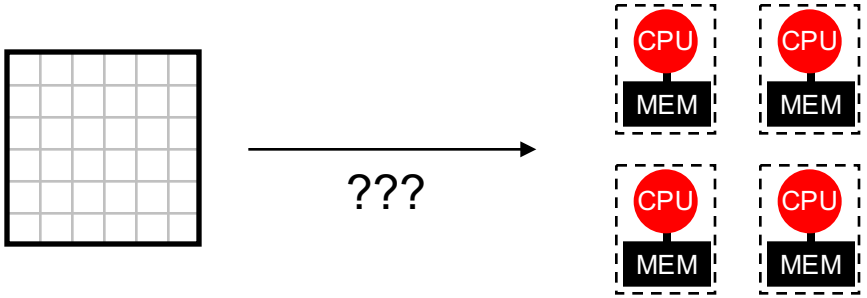
```
for (i,j) in R do A[i,j] = B[i,j+1];
```

Parallel Interpretation of Regions

- Users specify virtual processor grid at runtime

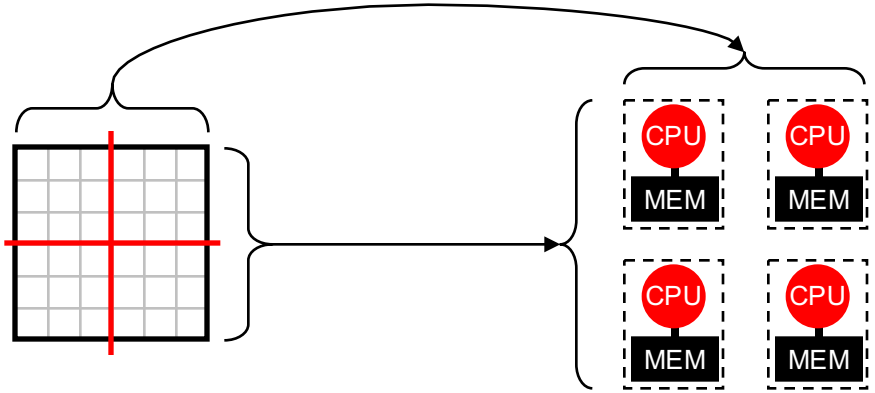
```
> ./a.out -p4          (uses a 2x2 grid  ⊡⊡ )
> ./a.out -p4 -r1      (uses a 1x4 grid  □□□□ )
```

- Region indices are distributed to this grid
  - defines data distribution for arrays
  - defines work distribution for computations



Region Distribution

1) Regions are block-distributed:



2) *Interacting regions* are distributed identically


```
[R] A := B + C;
```

ZPL's Performance Model

Distribution rules imply a performance model:

- Traditional operators are perfectly parallel

```
[R] A := B + C;
```

- Array operators indicate likely communication
  - of a particular style

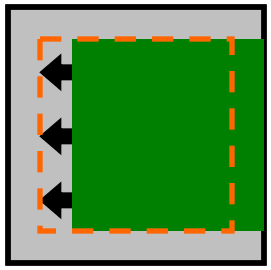
```
[R] A := B@east + C@west;
```

@-induced Communication

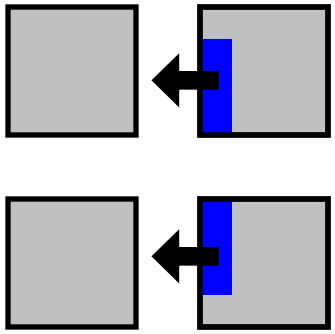
@ is used to refer to neighboring elements.

- data must be transferred to neighboring processors

```
[R] A := A@east;
```



global view



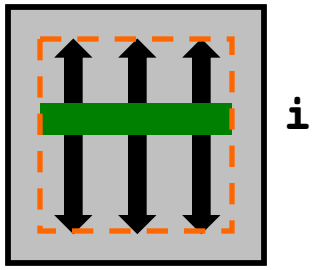
local view

Flood Communication

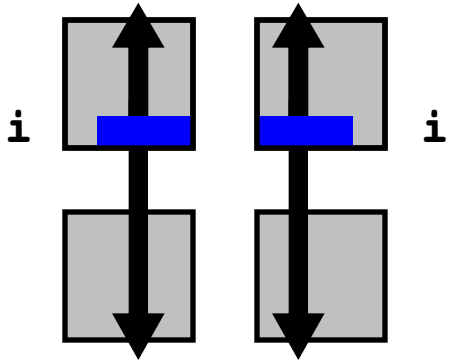
Floods replicate data across array dimensions

- data must be broadcast over sub-dimensions of the processor grid

```
[R] A := >>[i,] A;
```



global view



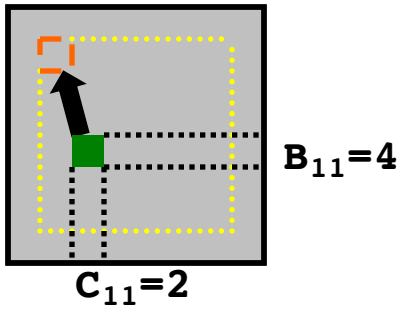
local view

Remap Communication

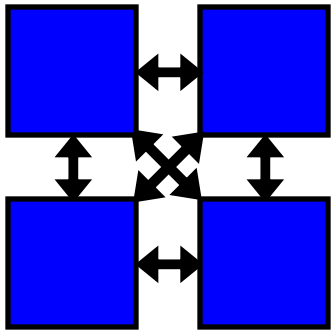
Remap arbitrarily re-arranges data

- indexes into an array with other arrays
- tends to require all-to-all communication

```
[R] A := A#[B,C];
```



global view



local view

Array Operator Summary

operator	effect	sample	communication
@	translate indices	`A@east`	point-to-point
flood	replicate array elements	`>>[i,] A`	sub-grid broadcast
reduction	collapse array elements	`+<<[R] A`	sub-grid reduction
scan	parallel scan	`+|| A`	parallel prefix
remap	arbitrary gather/scatter	`A#[X,Y]`	all-to-all

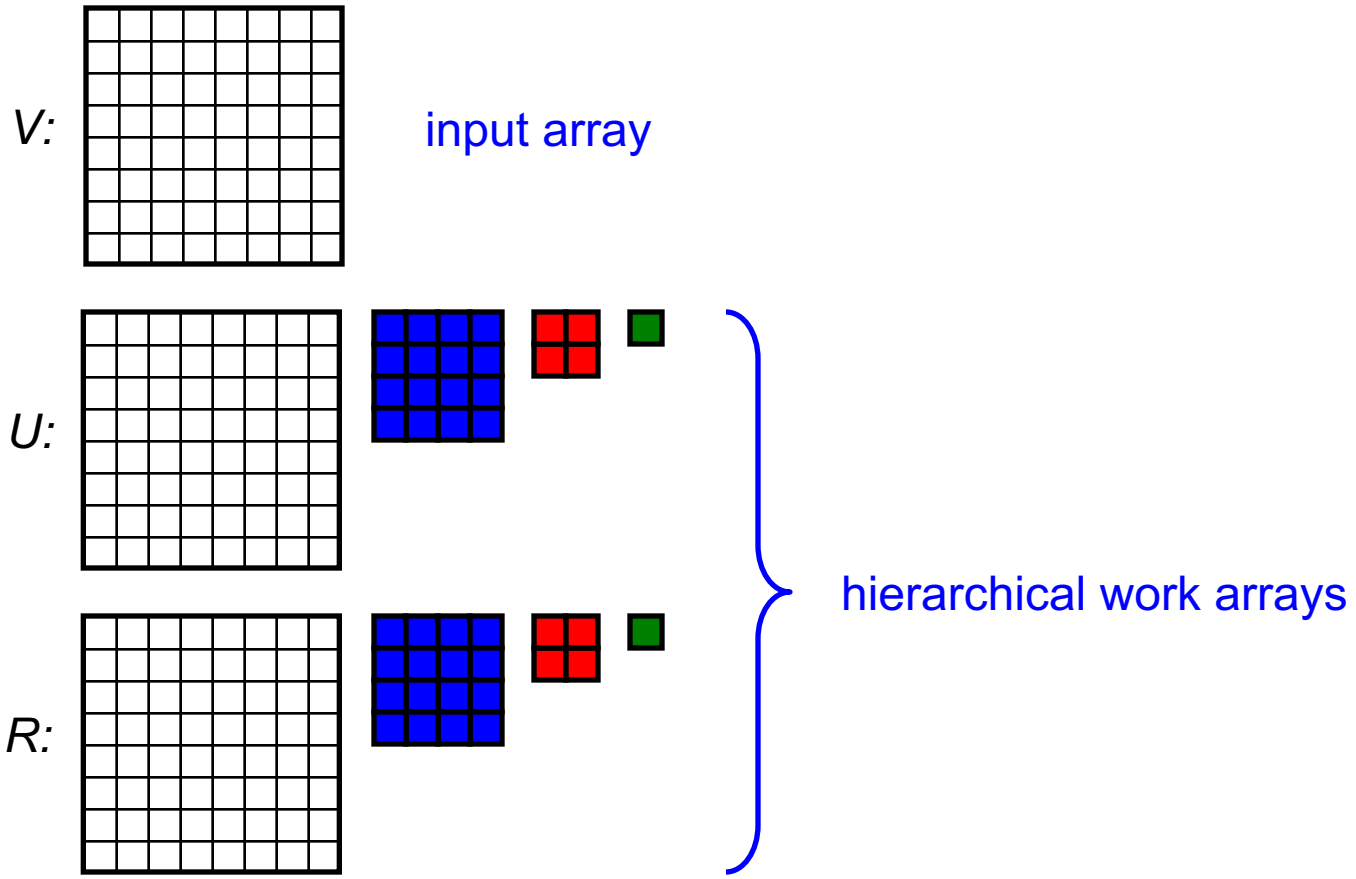
This is what we refer to as ZPL's *WYSIWYG performance model*:
Communication implications are visible in a program's syntax.

ZPL's Greatest Hits: Hierarchical Arrays in NAS MG

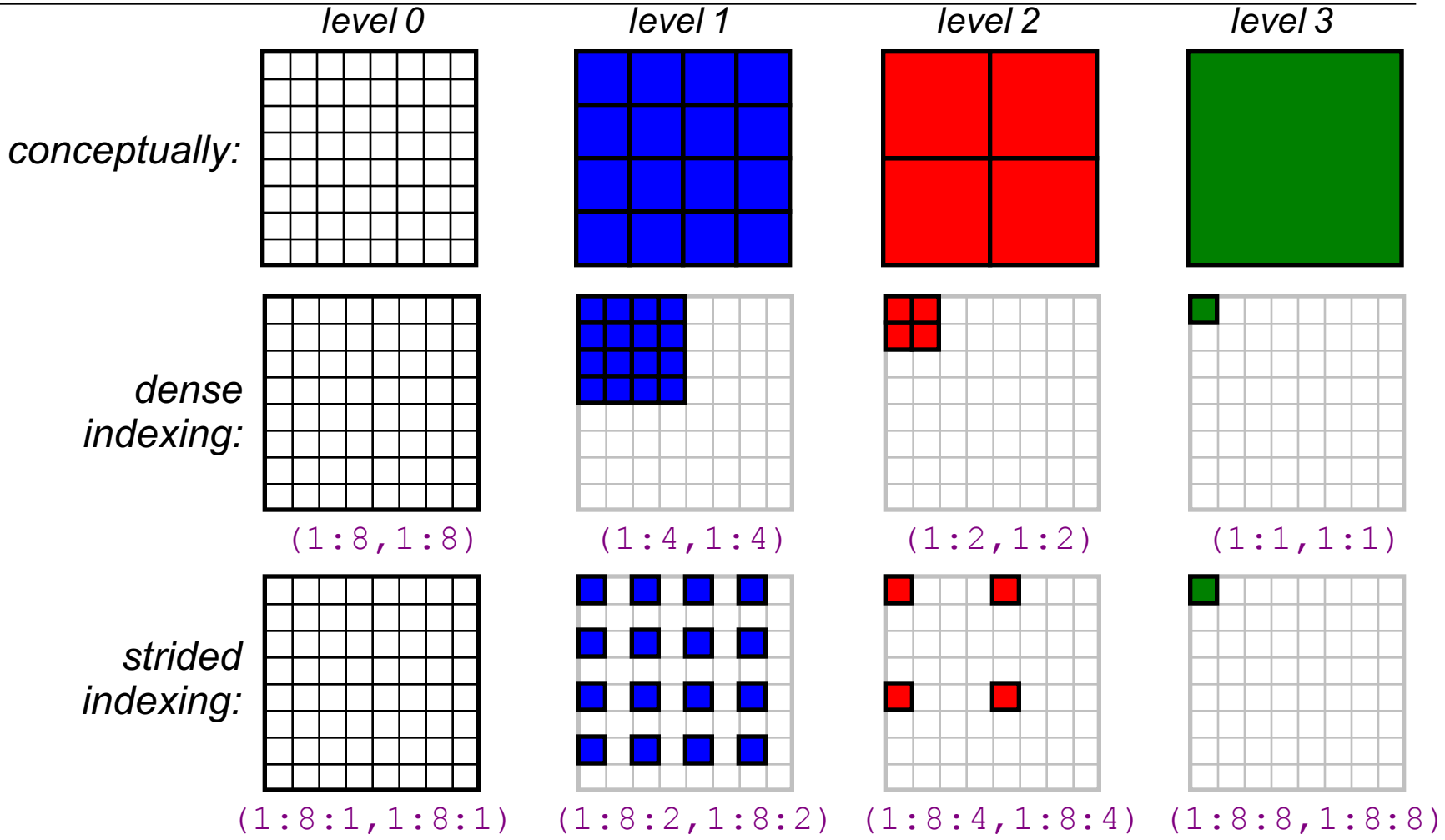
The NAS MG Benchmark

Mathematically: use a 3D multigrid method to find an approximate solution to a discrete Poisson problem ($\nabla^2 u = v$)

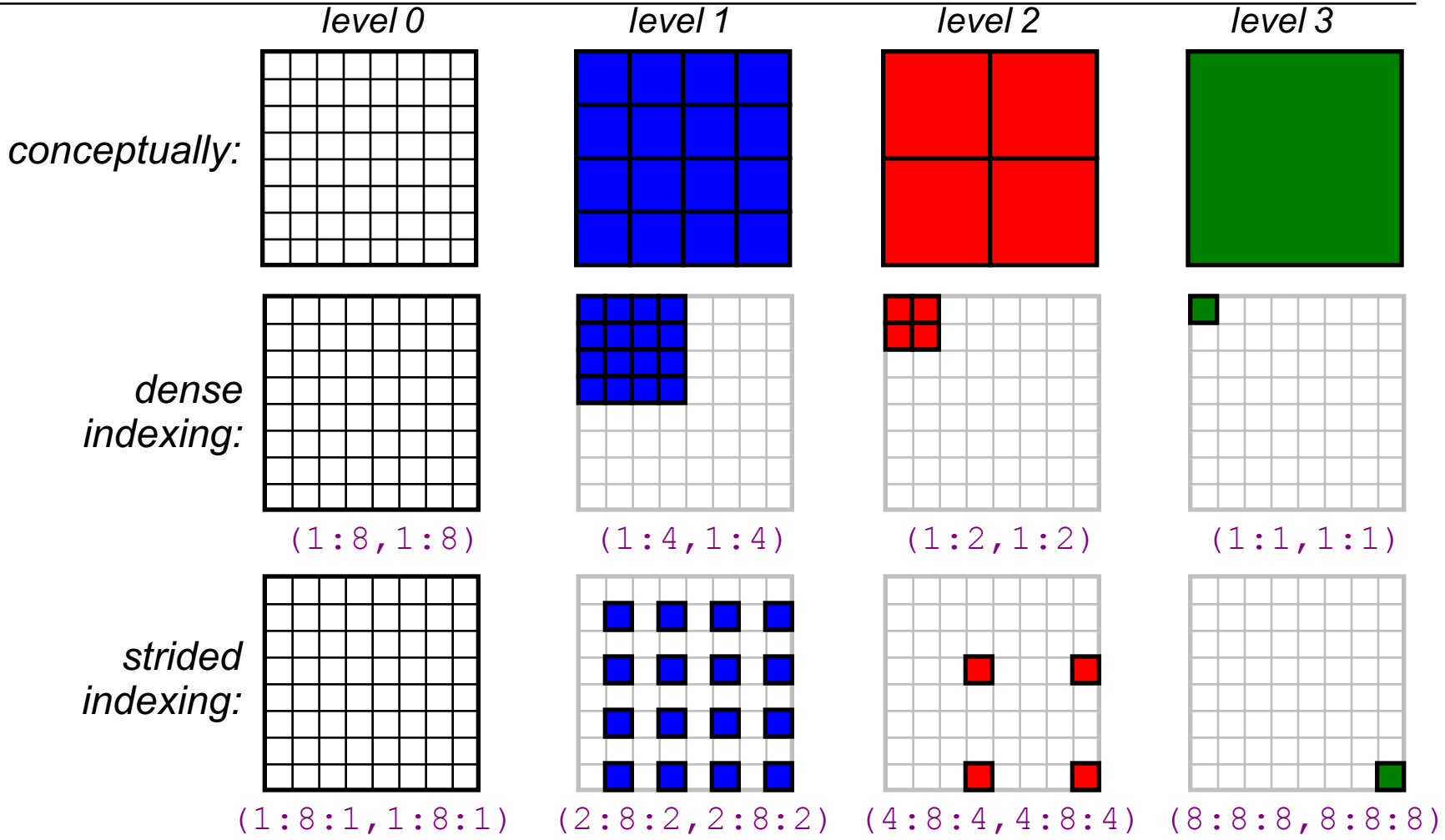
MG's arrays



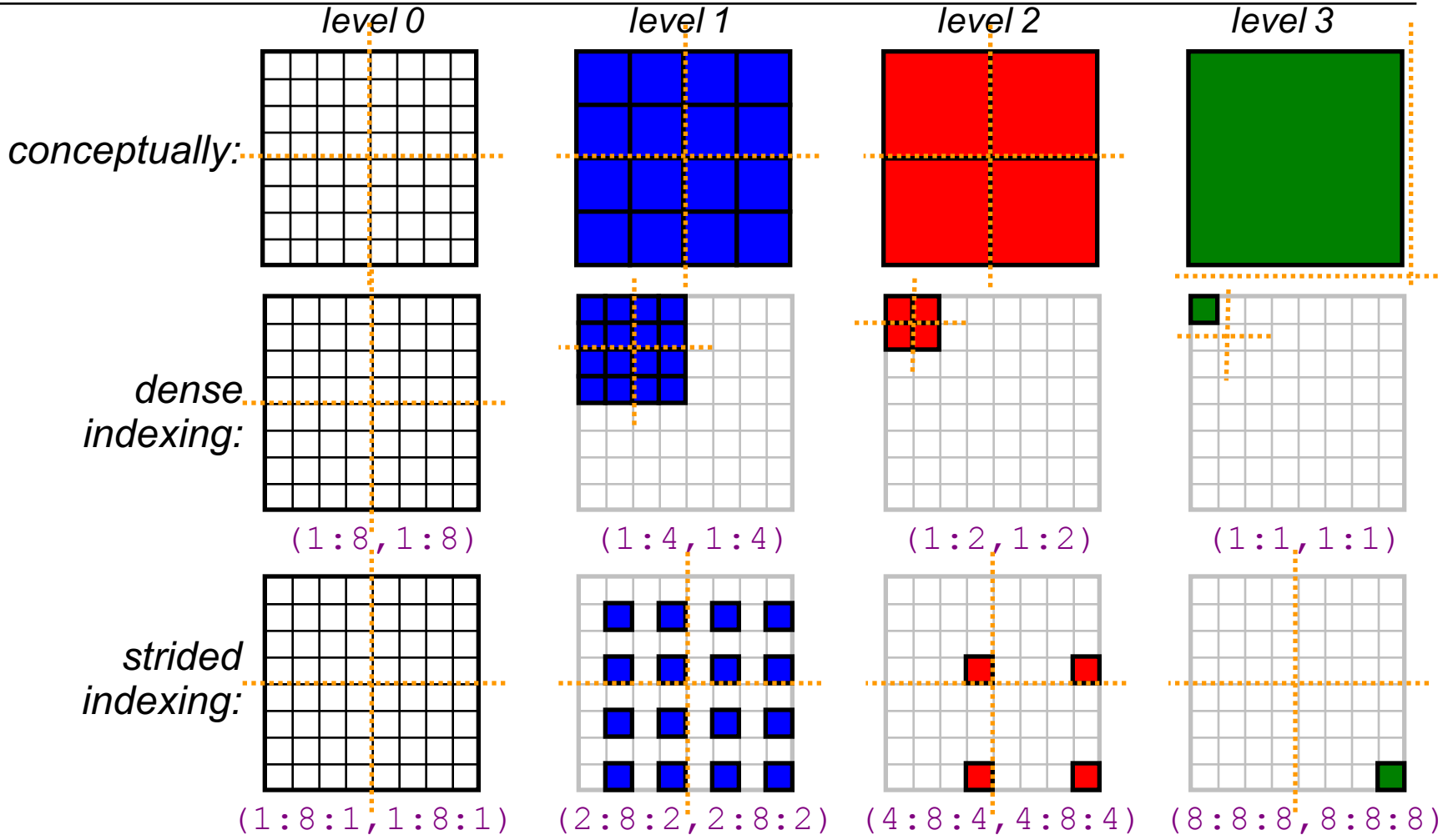
Hierarchical Arrays



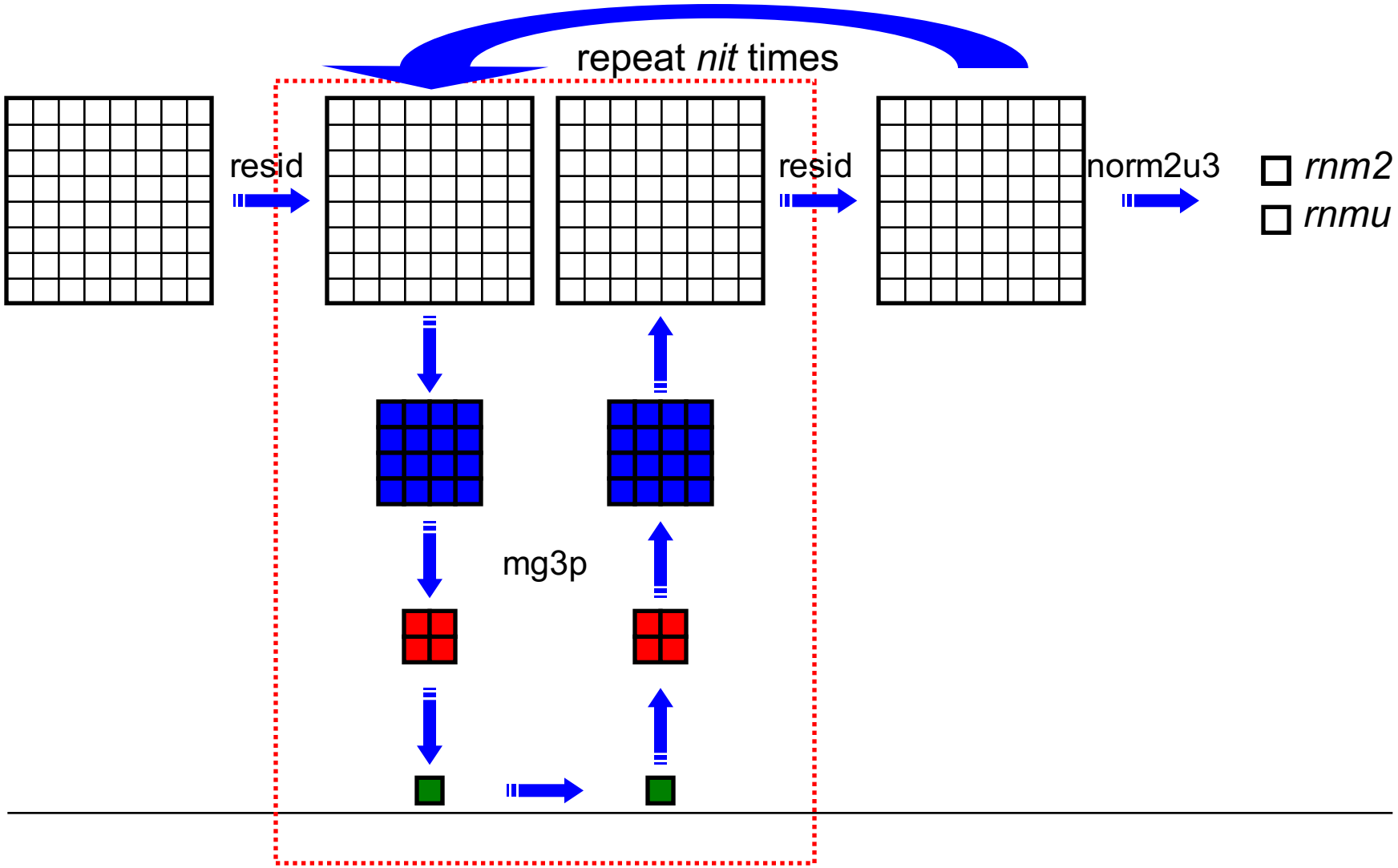
Hierarchical Arrays



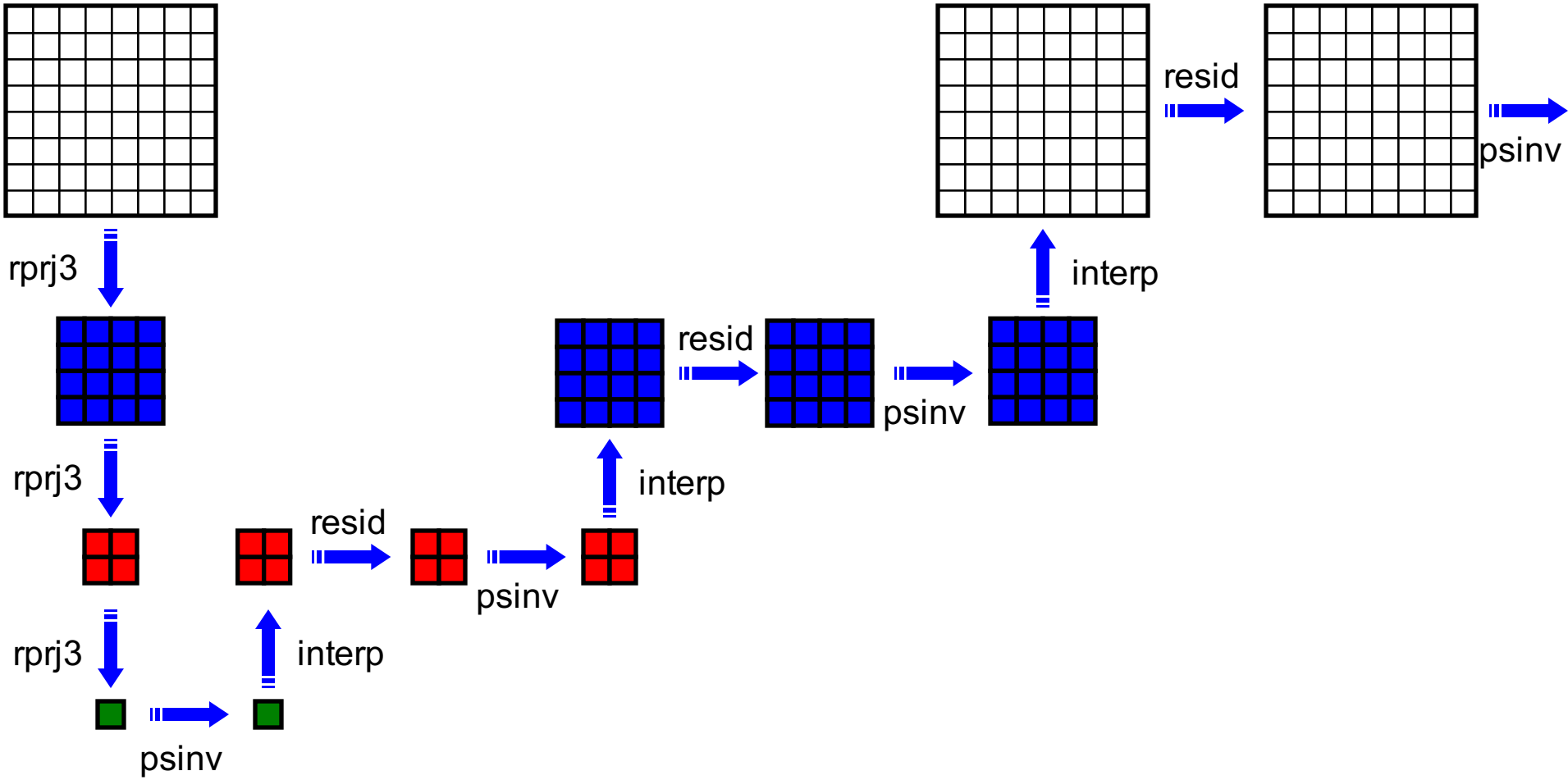
Distributed Hierarchical Arrays



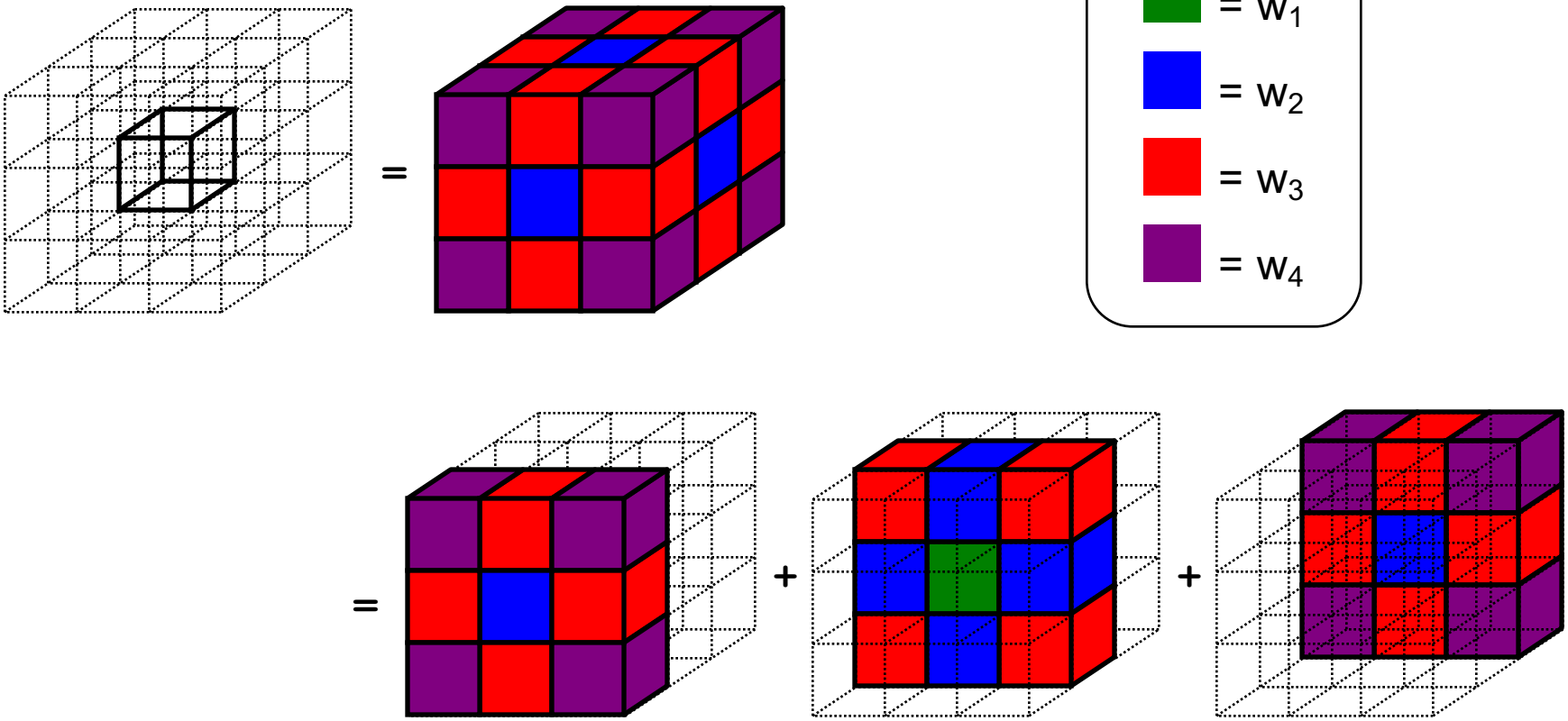
MG's Timed Portion



MG's Guts (*mg3P*)

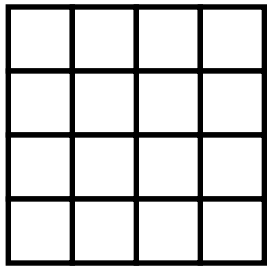


27-point stencils

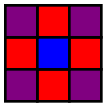


rprj3(S, R)

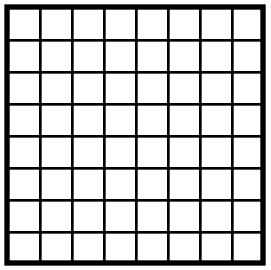
conceptually:



convolve(



,



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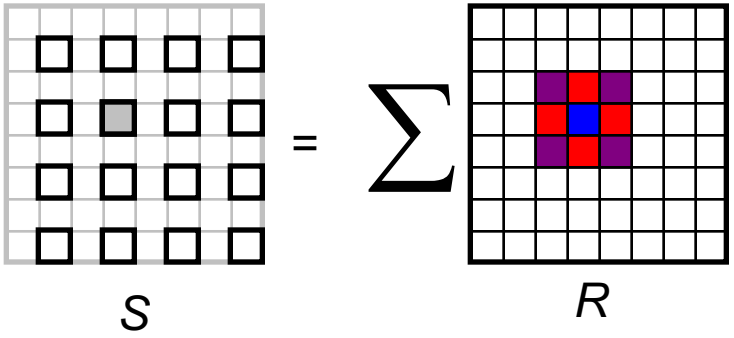
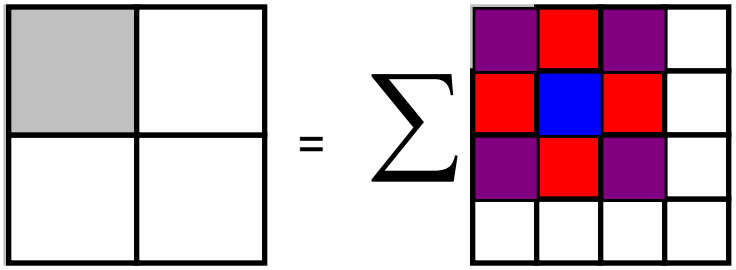
strided indexing:

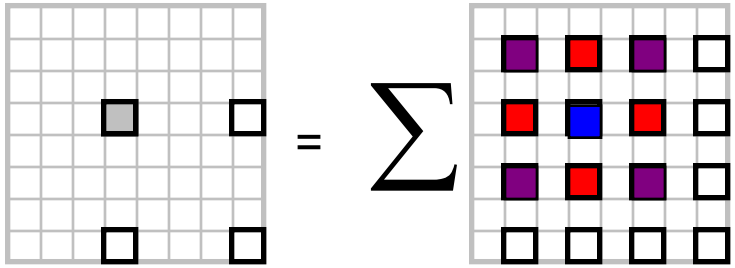


rprj3 at other levels

conceptually:



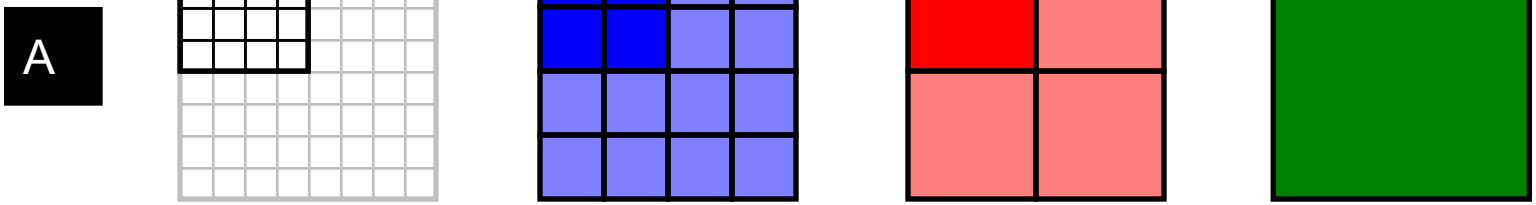
strided indexing:



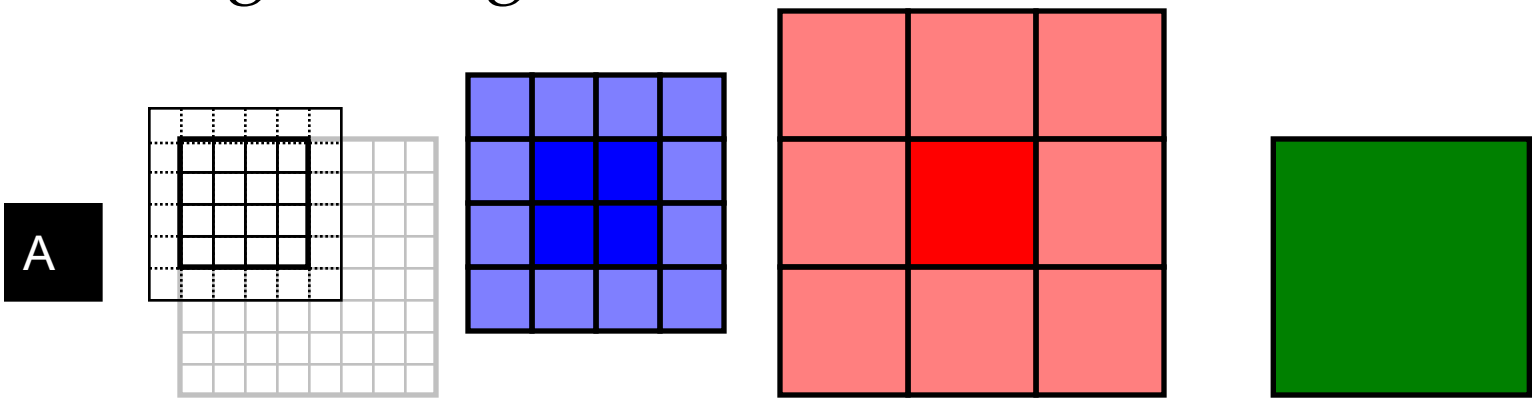
S *R*

Per-processor Data Allocation

In addition to its local block of values…

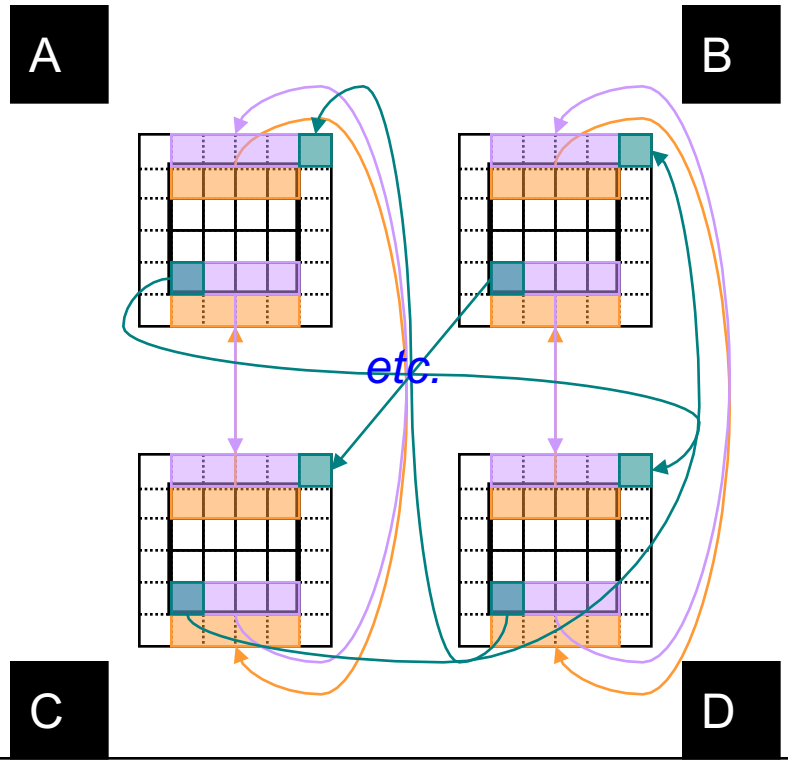


…each processor allocates ghost cells to cache neighboring values



Stencil Communication

Prior to computing a stencil, communication is typically required to refresh the ghost cells



Notes:

- Lots of optimization opportunities (e.g., comm/comp overlap, bulk transfers)
- Have to eventually start skipping processors at coarser levels

Distributed *rprj3* in Fortran + MPI

```
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
```

Local-view *rprj3* in Fortran + MPI

```
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
```

comm3: Communication in 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 commlp(  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  commlp(  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 i2=2,n2-1
         buff_len = buff_len + 1
         buff(buff_len, buff_id )= u( i1,n2-
     1,i3)
      enddo
   enddo
endif

if( axis .eq. 3 )then
   do i3=2,n3-1
      do i2=1,n2
         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
```

Global-view *rprj3* in ZPL

```
procedure rprj3(var S,R: [,,] double;
                d: array [] of direction);
begin
  S := 0.5000 * R +
       0.2500 * (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] +
       0.1250 * (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;
```

rprj3 kernel in Fortran, naively

```
   do  j3=2,m3j-1
    i3 = 2*j3-d3
    do  j2=2,m2j-1
      i2 = 2*j2-d2
      do  j1=2,m1j-1
       i1 = 2*j1-d1
       s(j1,j2,j3)  =
>          0.5D0 * r(i1,i2,i3)
>        + 0.25D0 * (r(i1-1,i2,i3)  + r(i1+1,i2,i3)
>                  + r(i1,   i2-1,i3   ) + r(i1,  i2+1,i3   )
>                  + r(i1,   i2,  i3-1) + r(i1,  i2,  i3+1))
>        + 0.125D0 * (r(i1-1,i2-1,i3   ) + r(i1-1,i2+1,i3   )
>                  + r(i1-1,i2,   i3-1) + r(i1-1,i2   ,i3+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))
>                  + r(i1,   i2-1,i3-1) + r(i1,   i2-1,i3+1)
>                  + r(i1,   i2+1,i3-1) + r(i1,   i2+1,i3+1))
>        + 0.0625D0 * (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)
>                   + 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
    enddo
  enddo
```

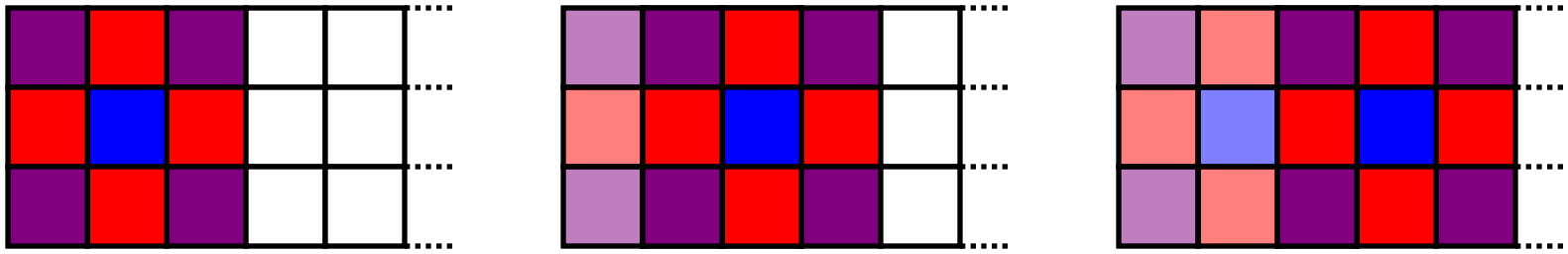
Actual *rprj3* Fortran code

```
subroutine rprj3(r,m1k,m2k,m3k,s,m1j,
implicit none
include 'cafnpb.h'
include 'globals.h'

integer m1k, m2k, m3k, m1j, m2j, m3j,

double precision r(m1k,m2k,m3k), s(m1
integer j3, j2, j1, i3, i2, i1, d1, d
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
```

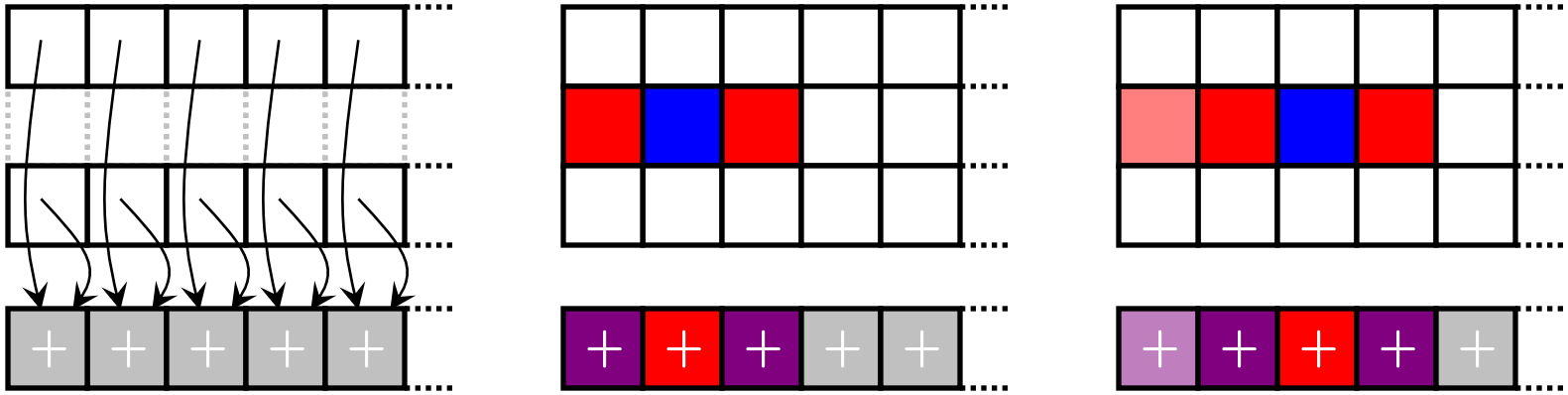
```
  do  j3=2,m3j-1
   i3 = 2*j3-d3
   do  j2=2,m2j-1
     i2 = 2*j2-d2
     do j1=2,m1j
      i1 = 2*j1-d1
      x1(i1-1) = r(i1-1,i2-1,i3   ) + r(i1-1,i2+1,i3   )
>              + r(i1-1,i2,   i3-1) + r(i1-1,i2,   i3+1)
      y1(i1-1) = r(i1-1,i2-1,i3-1) + r(i1-1,i2-1,i3+1)
>              + r(i1-1,i2+1,i3-1) + 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
```

Stencil Optimization (2D)

- Adjacent stencils use common subexpressions:

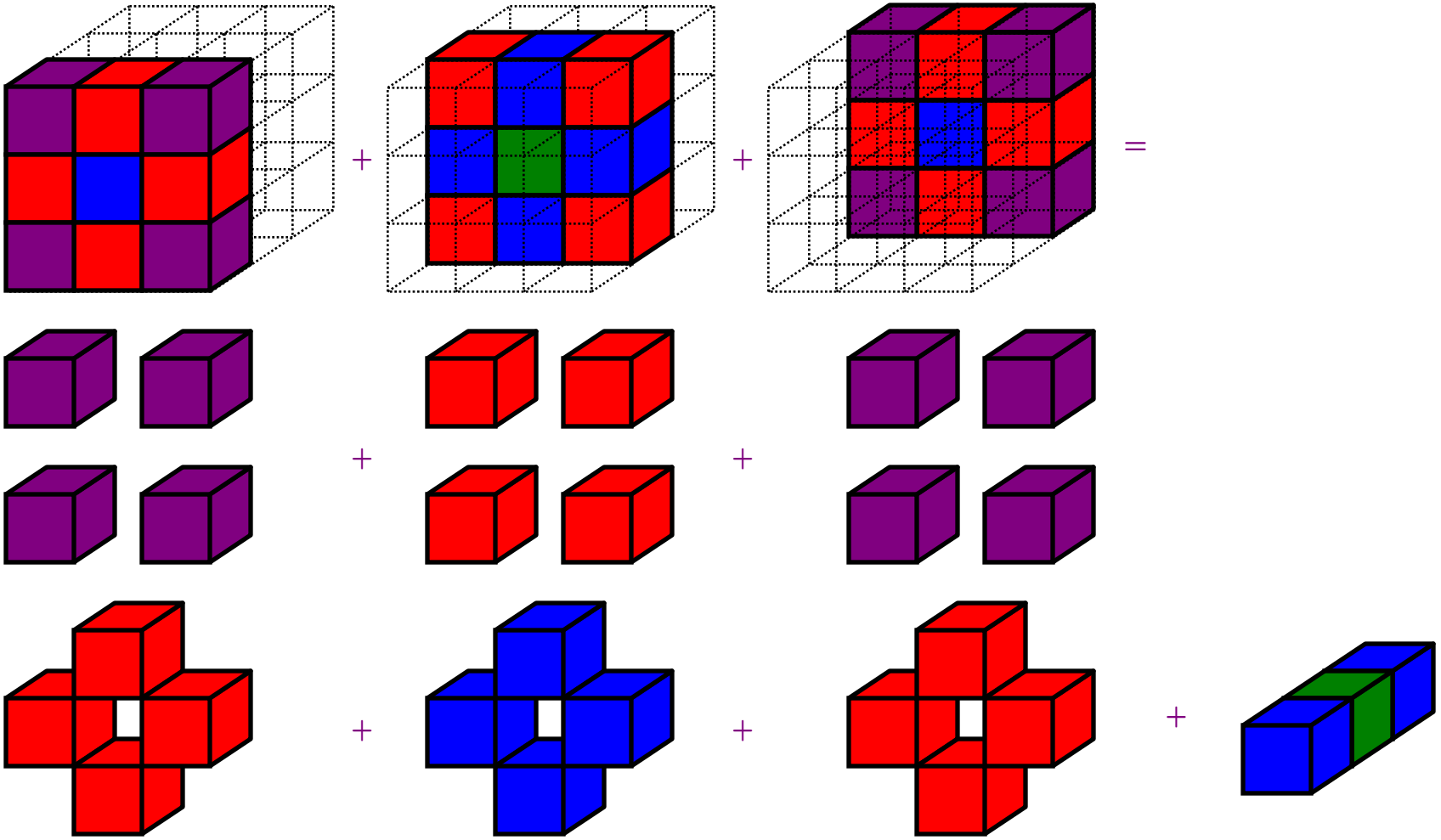


- Observation: Cache partial sums for reuse…

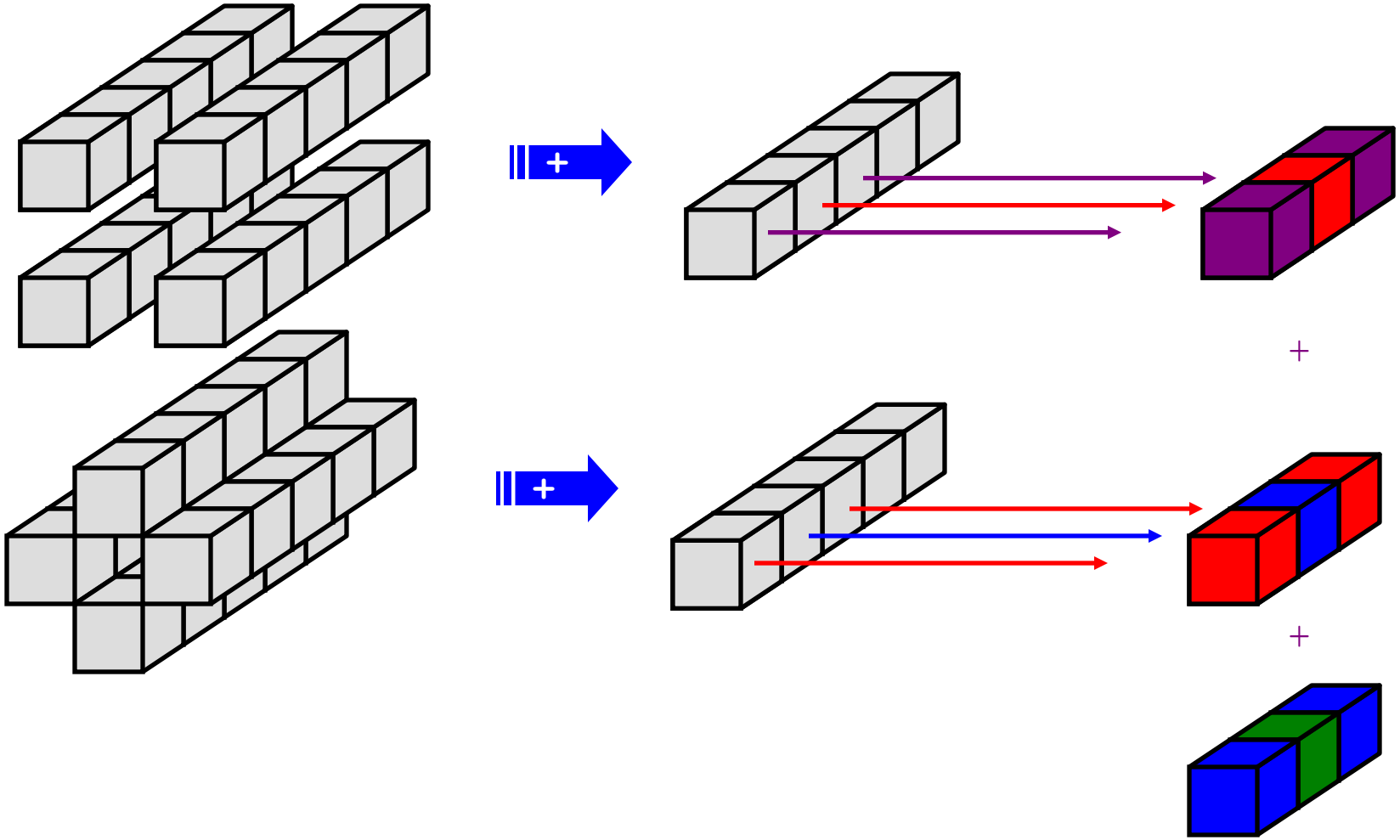


- Benefits are greater for 3D stencils…

MG Stencil Optimization



MG Stencil Optimization



Optimized stencil in Fortran

```
subroutine rprj3(r,m1k,m2k,m3k,s,m1j,
implicit none
include 'cafnpb.h'
include 'globals.h'

integer m1k, m2k, m3k, m1j, m2j, m3j,

double precision r(m1k,m2k,m3k), s(m1
integer j3, j2, j1, i3, i2, i1, d1, d
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
```

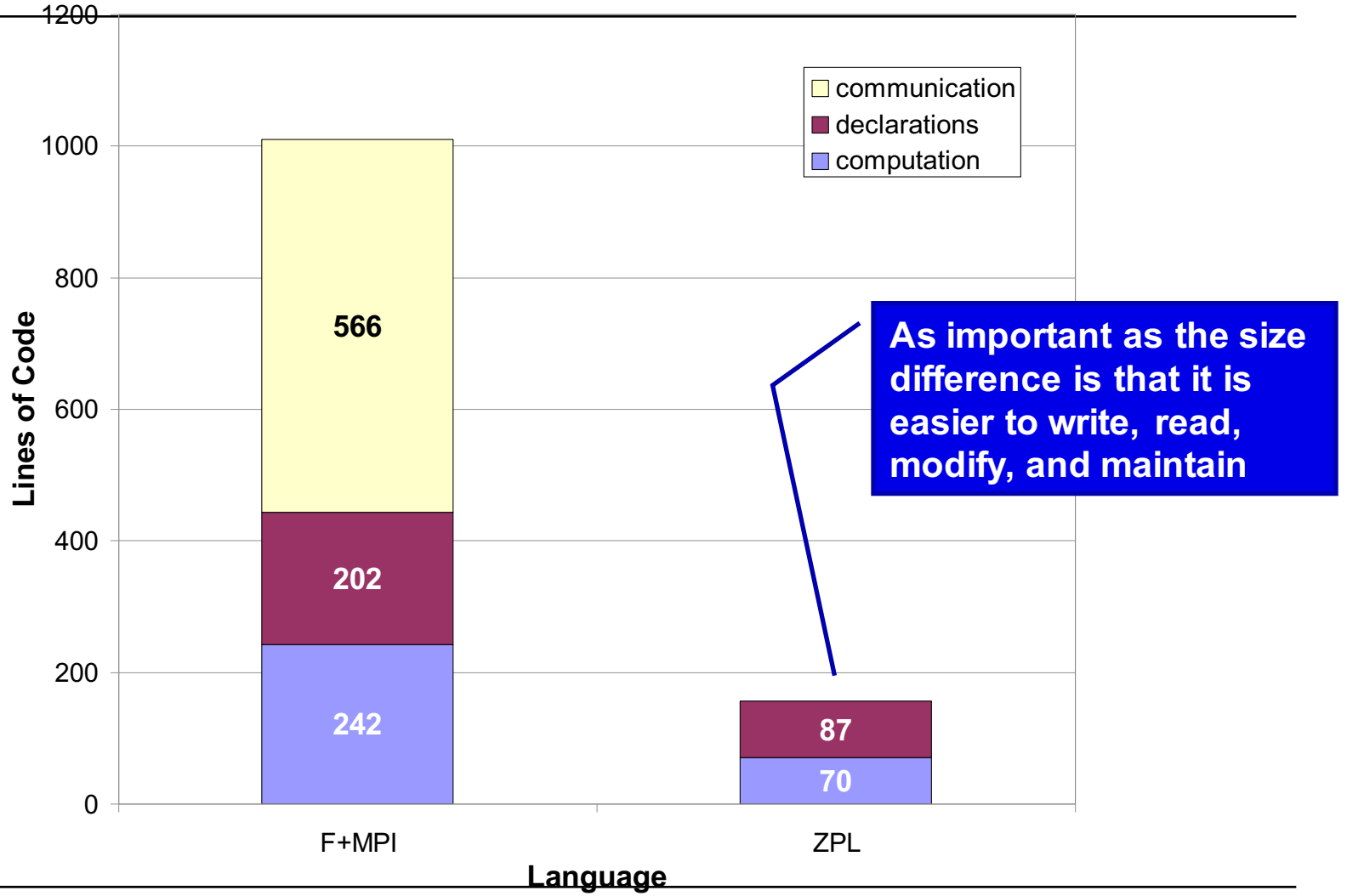
```
  do  j3=2,m3j-1
   i3 = 2*j3-d3
   do  j2=2,m2j-1
     i2 = 2*j2-d2
     do j1=2,m1j
      i1 = 2*j1-d1
      x1(i1-1) = r(i1-1,i2-1,i3   ) + r(i1-1,i2+1,i3   )
>              + r(i1-1,i2,   i3-1) + r(i1-1,i2,   i3+1)
      y1(i1-1) = r(i1-1,i2-1,i3-1) + r(i1-1,i2-1,i3+1)
>              + r(i1-1,i2+1,i3-1) + 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
```

Optimized stencil in ZPL

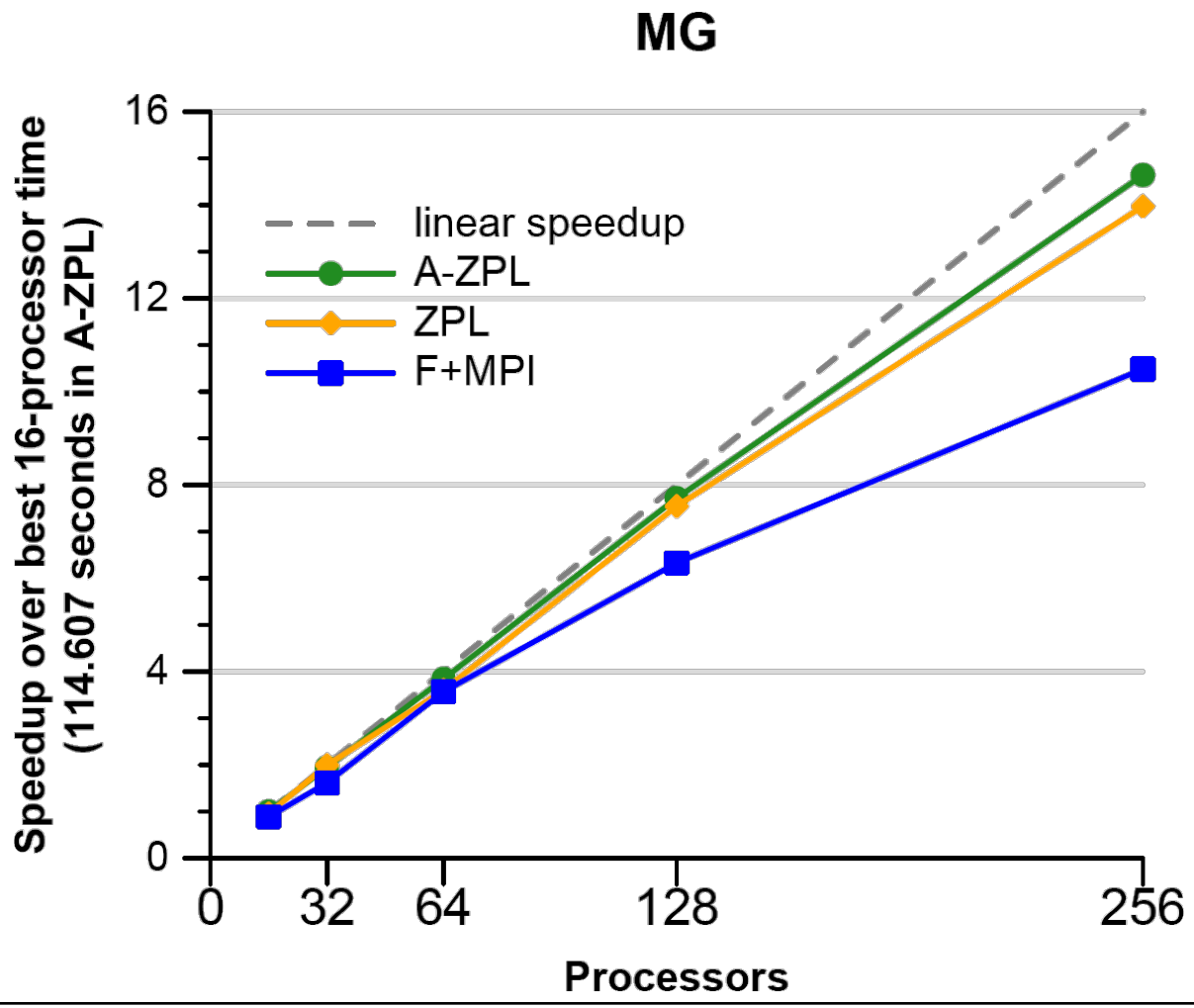
```
procedure rprj3(var S,R: [,,] double;
                d: array [] of direction);
begin
  S := 0.5000 * R +
       0.2500 * (R@^d[ 1, 0, 0] + R@^d[ 0, 1, 0] + R@^d[ 0, 0, 1] +
                 R@^d[-1, 0, 0] + R@^d[ 0,-1, 0] + R@^d[ 0, 0,-1] +
       0.1250 * (R@^d[ 1, 1, 0] + R@^d[ 1, 0, 1] + R@^d[ 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;
```

Compiler-optimized, thanks to rich semantic information about arrays (esp. relationship between hierarchical arrays and offsets)

Code Size Comparison



NAS MG Speedup: Cray T3E



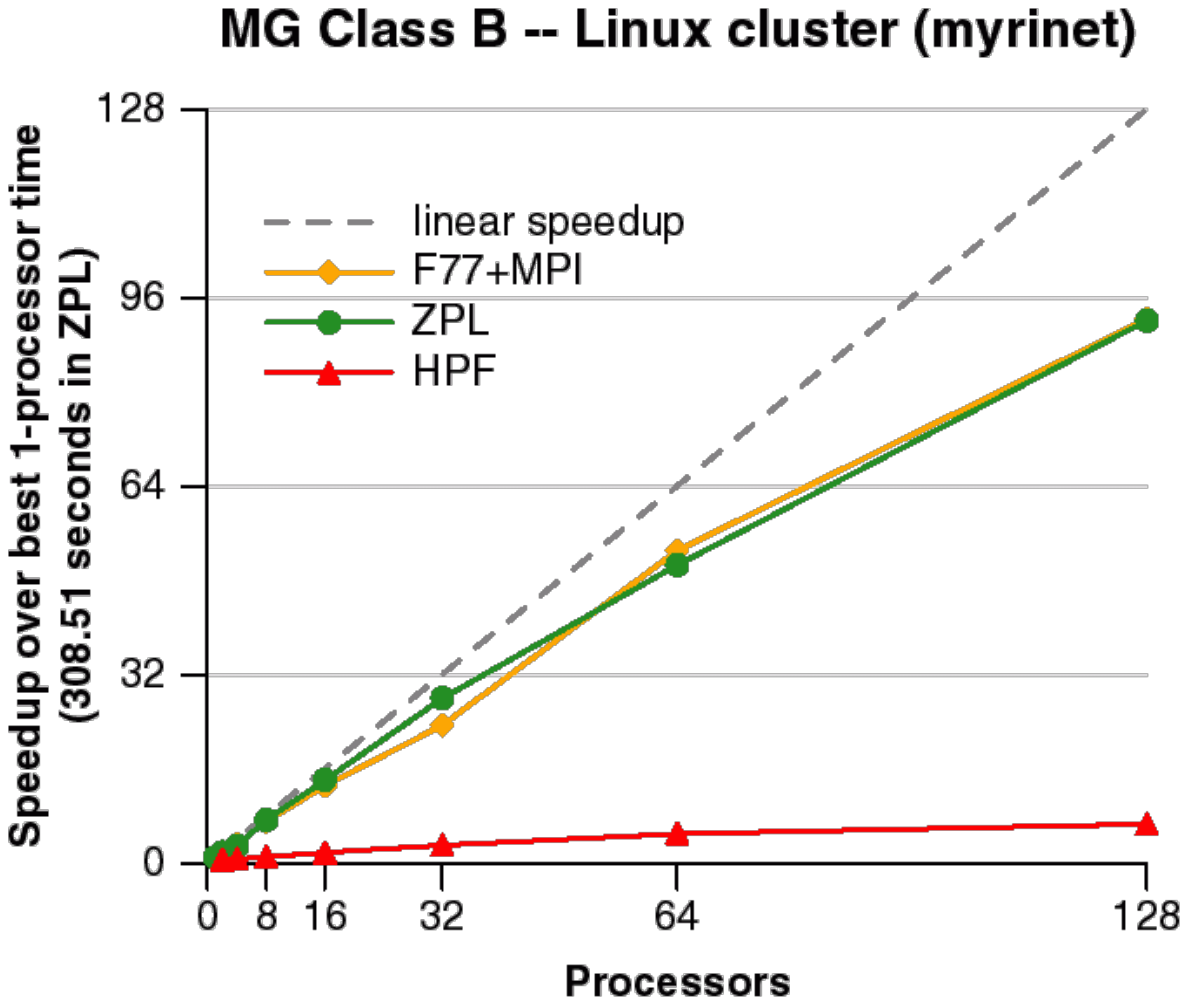
How did ZPL outperform MPI?

- MPI embeds specific communication idioms
  - non-blocking sends/receives
    - carries buffering & synchronization assumptions
- ZPL only expresses computation's intent
  - permits implementation to map to puts/gets
    - RDMA is the optimal choice on this Cray T3E
- Of course, MPI could use RDMA as well…

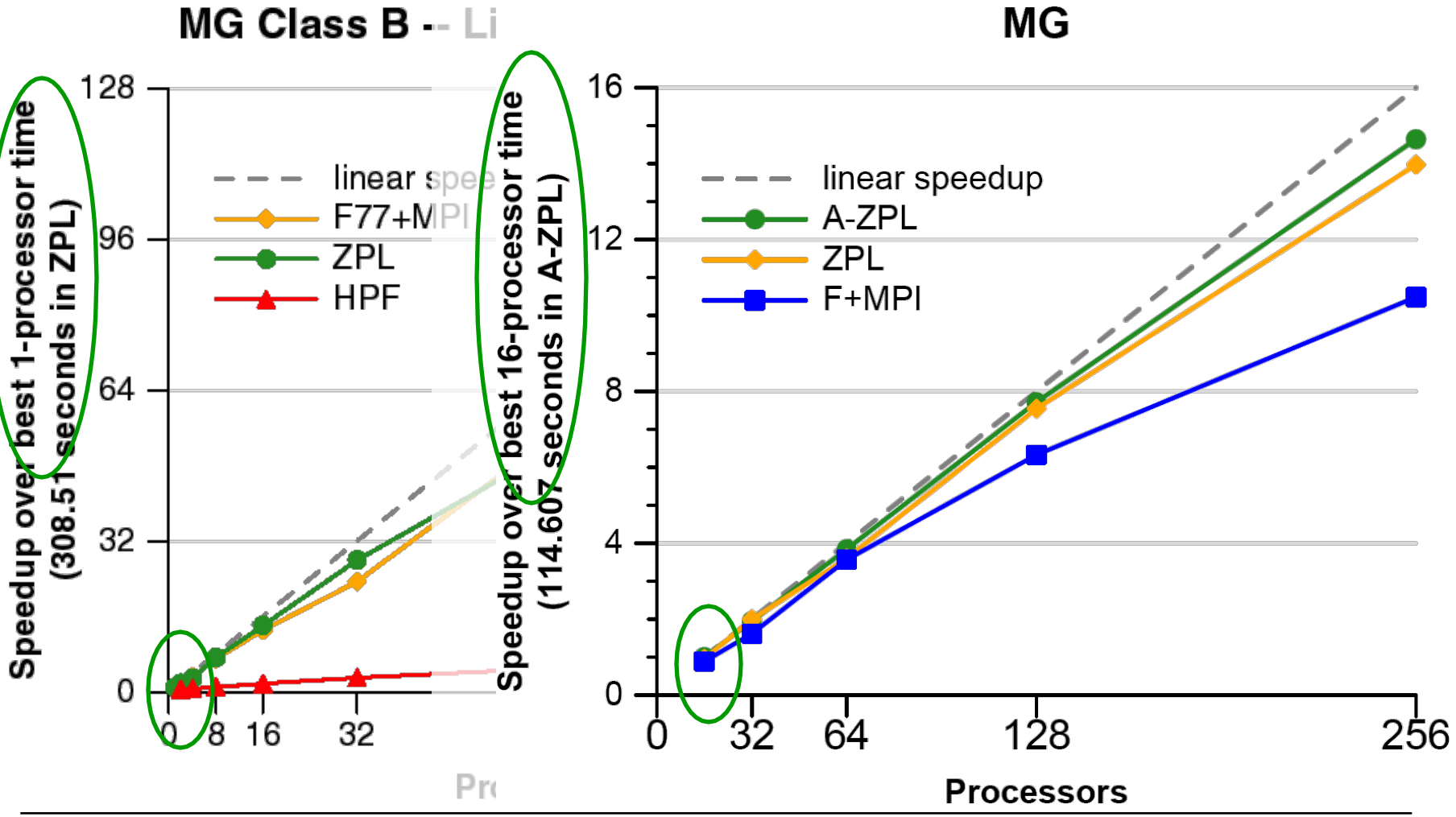
  ...but only via modifications to the code...

  ...and what would happen on non-RDMA systems?
- Meanwhile, ZPL can target MPI on clusters…

NAS MG Speedup: Myrinet cluster



ZPL was also fastest at small-scale



Code [In]Flexibility

The Fortran+MPI version…

- …only supports 2^k problem sizes
- …only supports running on 2^p compute nodes
  - moreover, both values must be specified at compile-time
- …only supports a single 3D data decomposition
- …could be rewritten to avoid these assumptions…
  - …but at what cost in terms of level of effort? code clarity?

In contrast, the ZPL version...

- …supports arbitrary problem sizes and node counts
  - and permits them to be specified at run-time
- …supports decomposing in 1, 2, or all 3 dimensions

NAS MG in ZPL: Summary

A resounding success for array programming!

- global-view of computation
- ability to reason about communication needs
- clear, concise, compact code
- optimized stencil computations
- system-specific communication idioms
- optimized communication (not described here)
- flexible parameterization (problem size, grid, …)

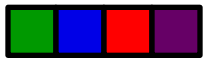
NAS MG in ZPL: Summary

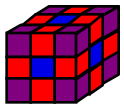
But also a significant downside:

- expression of stencil required O(*points*) code
  - OK for 27-point stencils
  - less so for, say, 216-point stencils in FMM

rprj3 stencil in Chapel

```
proc rprj3(S: [?SD], R) {
  const Stencil = {-1..1, -1..1, -1..1},

        w = (0.5, 0.25, 0.125, 0.0625),

        w3d: [Stencil] real
           = [(i,j,k) in Stencil]
               w((i!=0) + (j!=0) + (k!=0));

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

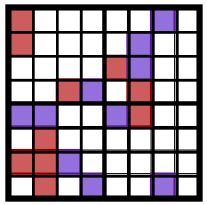




ZPL's Greatest Hits: Sparse Arrays in NAS CG

Sparse Arrays

- Good sparse arrays are a must for scientific computation
  - should be built-in
  - should be semantically similar to dense arrays



- NAS CG in a nutshell:
  - lots of sparse matrix-vector multiplications in a loop

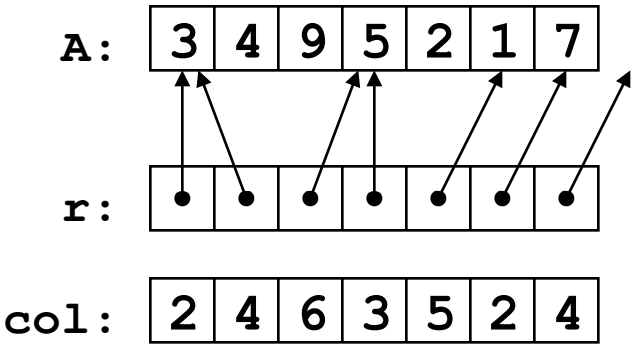
Compressed Sparse Row (CSR) Format

A:

0	0	0	0	0	0
0	3	0	4	0	9
0	0	0	0	0	0
0	0	5	0	2	0
0	1	0	0	0	0
0	0	0	7	0	0

= dense data vector

\+ structure information



Fortran Mat-Vect Multiplication

Dense Matrix-Vector Multiplication:

```
integer n
real*8 A(n,n)
real*8 t, V(n), S(n)


do i = 1,n
   t = 0.d0
   do j = 1,n
      t = t + A(i,j)*V(j)
   enddo
   S(i) = t
enddo
```

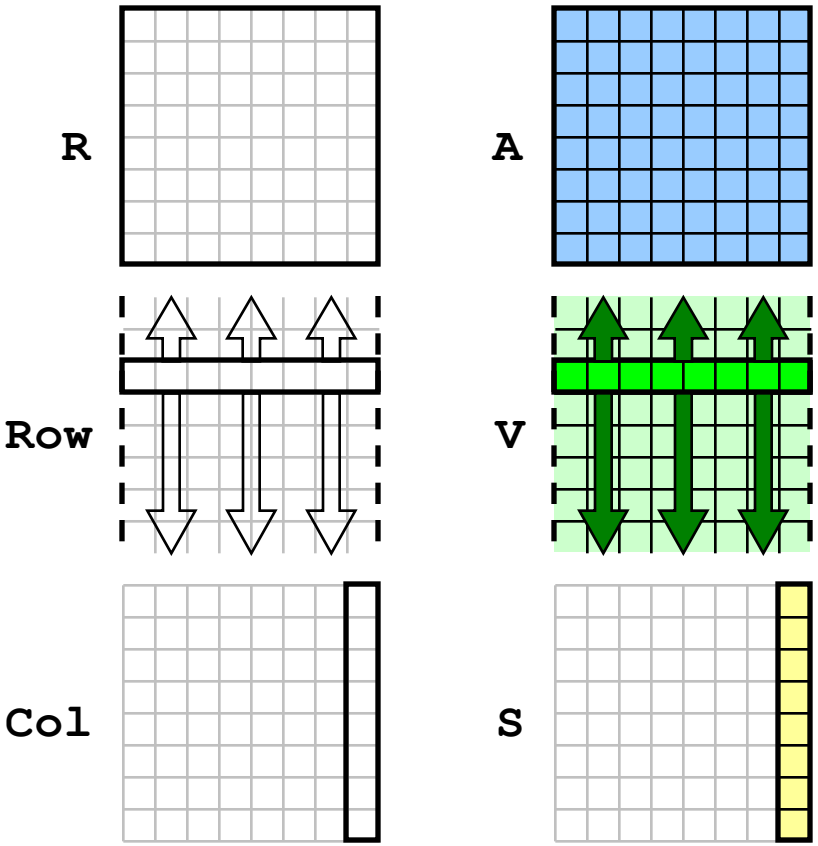
Sparse Matrix-Vector Multiplication:

```
integer n, nnz
real*8 A(nnz)
real*8 t, V(n), S(n)
integer r(n+1),col(nnz)

do i = 1,n
   t = 0.d0
   do j = r(i),r(i+1)-1
      t = t + A(j)*V(col(j))
   enddo
   S(i) = t
enddo
```

ZPL Mat-Vect Multiplication

declarations:

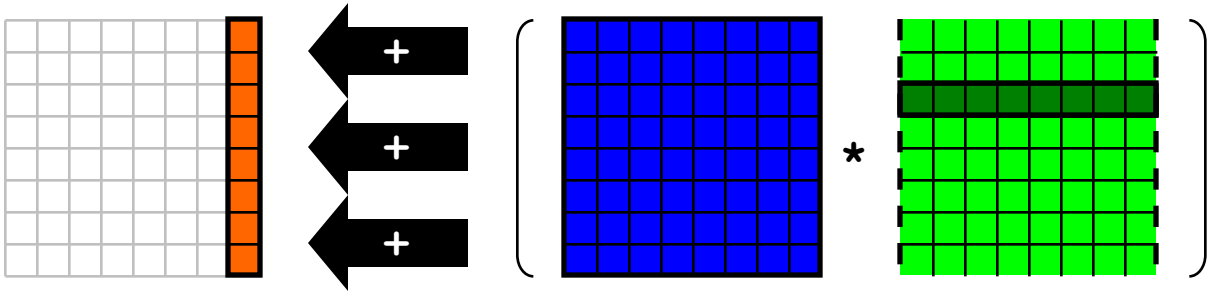
```
region R = [1..n,1..n];
       Row = [*,1..n];
       Col = [1..n,n];

var A:[R] double;
    V:[Row] double;
    S:[Col] double;
```



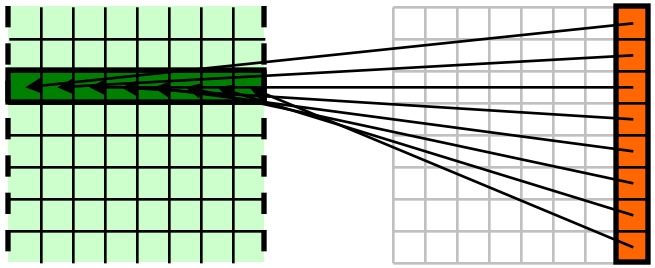
ZPL Mat-Vect Multiplication

computation:

```
[Col] S := +<<[R] (A*V);
```



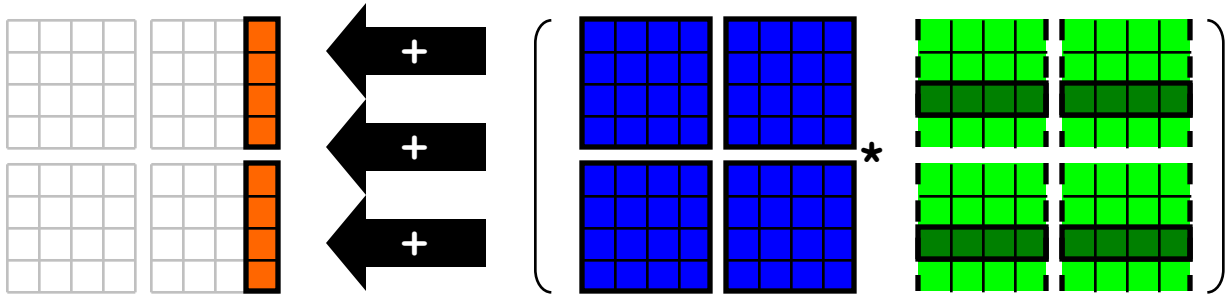

```
[Row] V := S#[n,Index1];
```



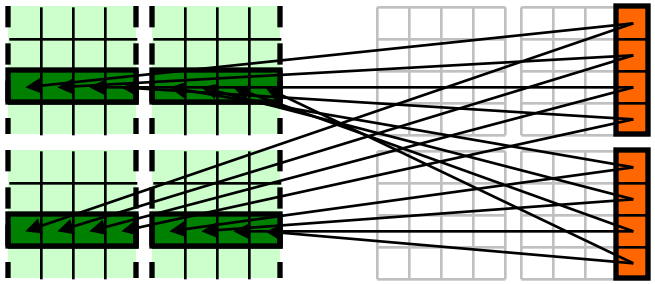
ZPL Mat-Vect Multiplication

computation (in parallel):

```
[Col] S := +<<[R] (A*V);
```




```
[Row] V := S#[n,Index1];
```



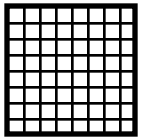
ZPL Mat-Vect Multiplication

Dense Matrix-Vector Multiplication:

```
region R = [1..n, 1..n];
       Row = [*, 1..n];
       Col = [1..n, n];


var A:[R] double;
    V:[Row] double;
    S:[Col] double;

[Col] S := +<<[R] (A*V);
```

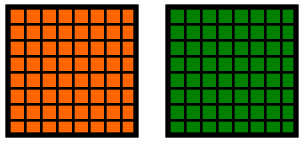
Sparse Regions and Arrays

```
region Rd = [1..n,1..n];
```

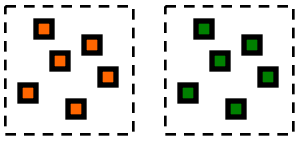


```
region Rs = Rd where <pattern>;
```

```
var Ad, Bd: [Rd] double;
```



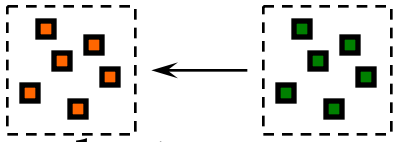
```
    As, Bs: [Rs] double;
```



Sparse Assignments

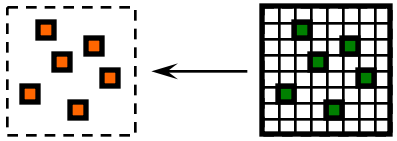
- Sparse assignment

```
[Rs] As := Bs;
```

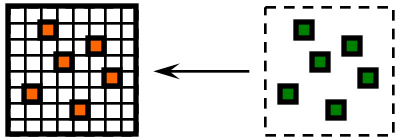


- Sparse assignment with dense array

```
[Rs] As := Bd;
```

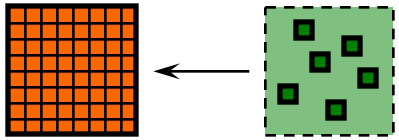


```
[Rs] Ad := Bs;
```



- Dense read of sparse array

```
[Rd] Ad := Bs;
```



- Dense assignment of sparse array – *illegal*

~~`[Rd] As := Bd;`~~

ZPL Mat-Vect Multiplication

Dense Matrix-Vector Multiplication:

```
region R = [1..n, 1..n];
       Row = [*, 1..n];
       Col = [1..n, n];


var A:[R] double;
    V:[Row] double;
    S:[Col] double;

[Col] S := +<<[R] (A*V);
```

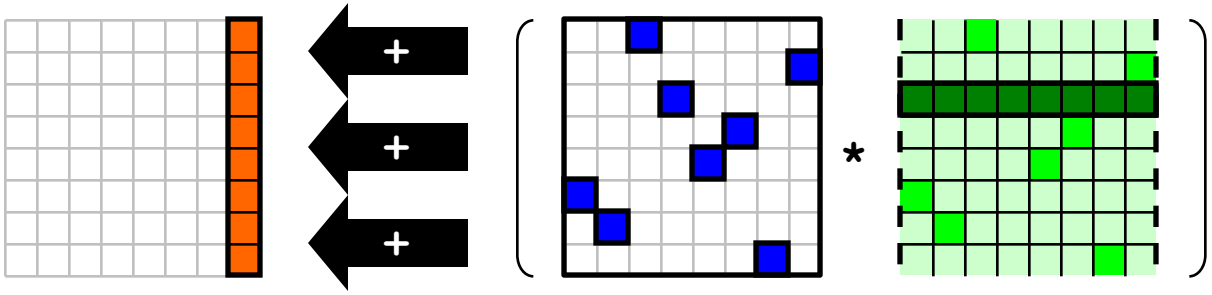
Sparse Matrix-Vector Multiplication:

```
region R = [1..n, 1..n];
       Row = [*, 1..n];
       Col = [1..n, n];
       Rs = R where …;

var A:[Rs] double;
    V:[Row] double;
    S:[Col] double;

[Col] S := +<<[Rs] (A*V);
```

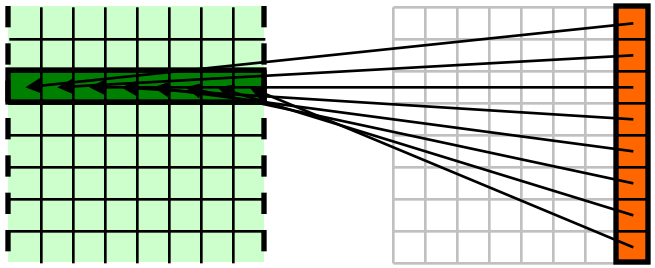
ZPL Mat-Vect Multiplication

Sparse Matrix-Vector Multiplication:

```
[Col] S := +<<[Rs] (A*V);
```




```
[Row] V := S#[n,Index1];
```



Sparse Arrays in ZPL

sparse array...

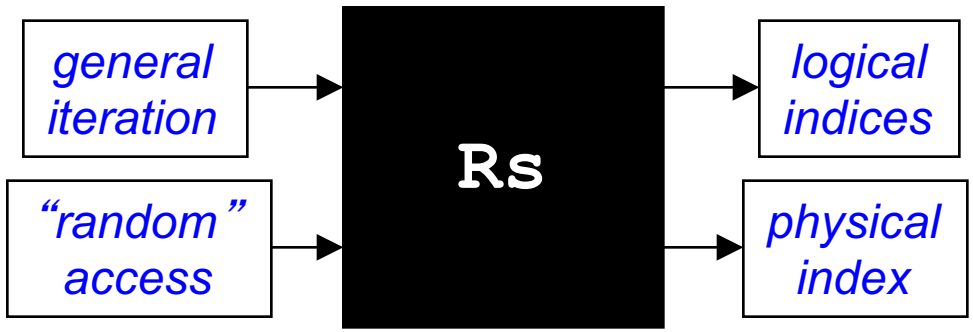
A:

0	0	0	0	0	0
0	3	0	4	0	9
0	0	0	0	0	0
0	0	5	0	2	0
0	1	0	0	0	0
0	0	0	7	0	0

= 1D dense array + sparse region

A:

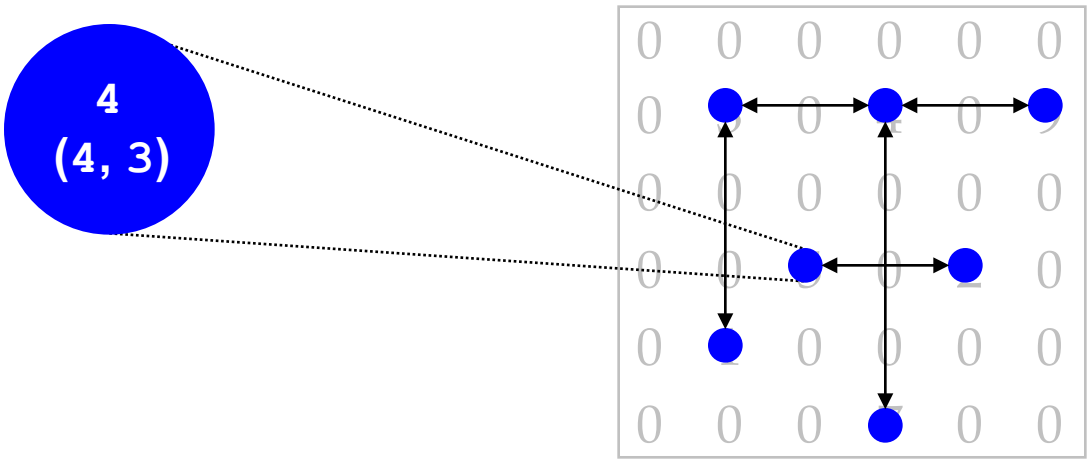
0	3	4	9	5	2	1	7



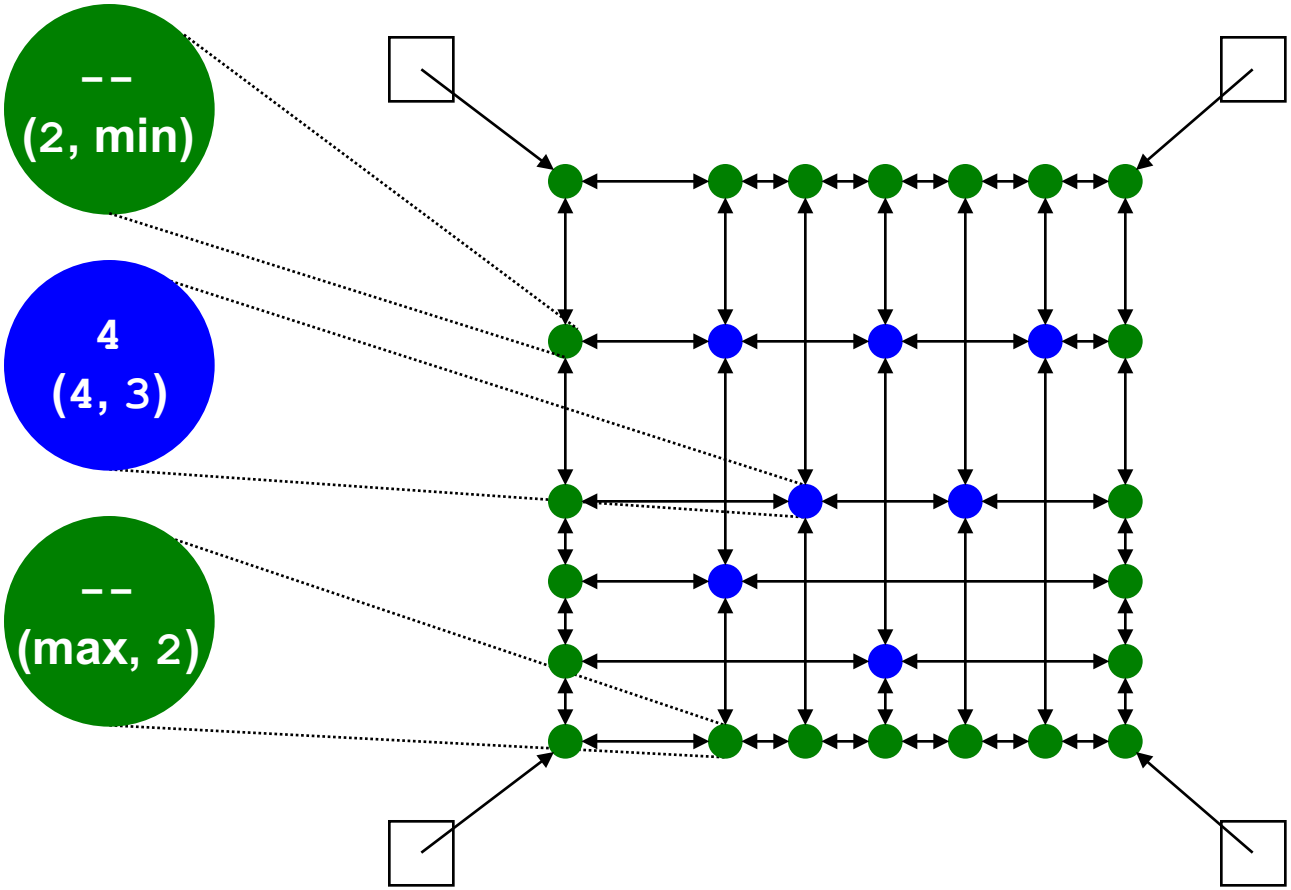
General Sparse Region Format

0	0	0	0	0	0
0	3	0	4	0	9
0	0	0	0	0	0
0	0	5	0	2	0
0	1	0	0	0	0
0	0	0	7	0	0

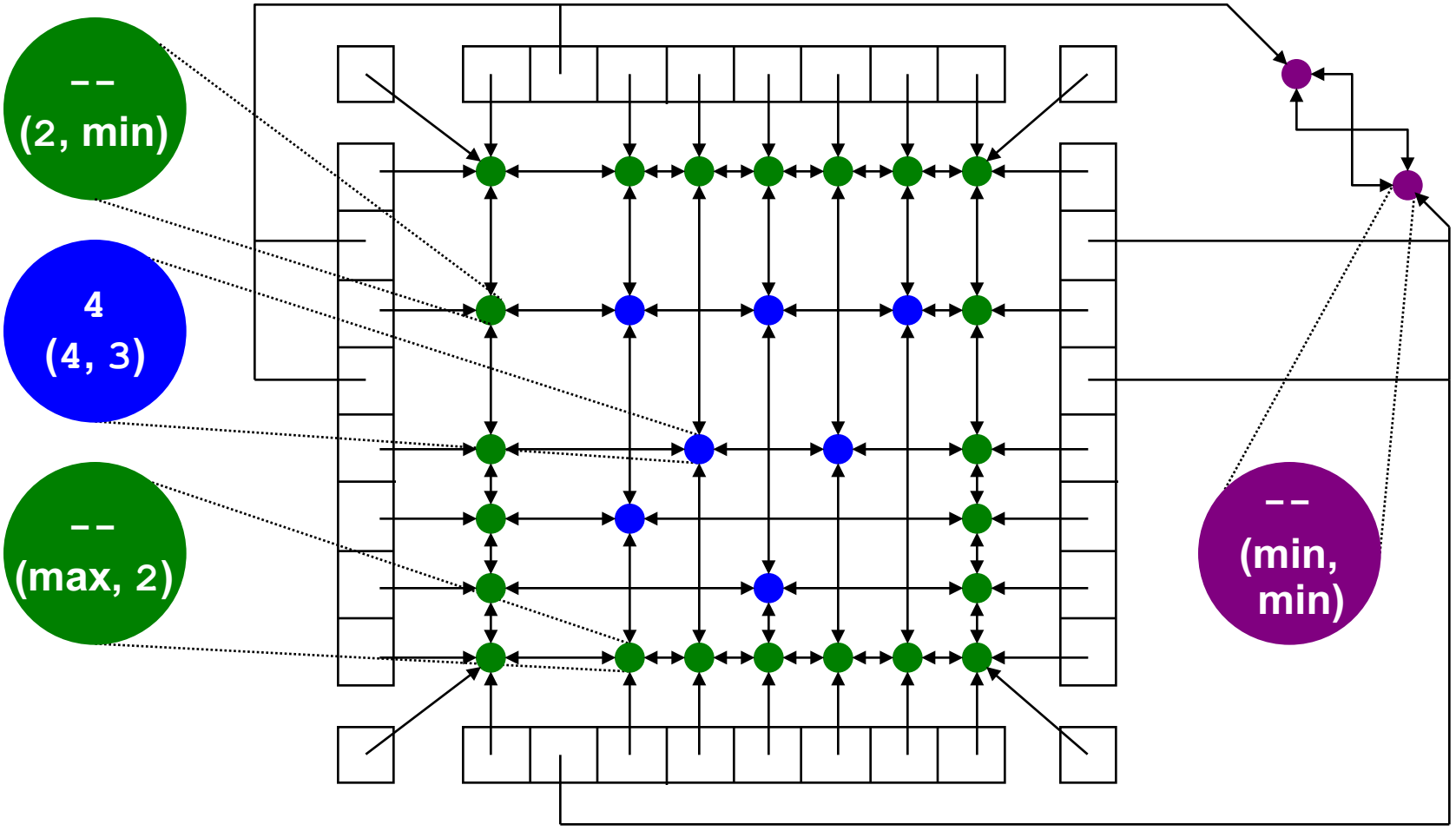
General Sparse Region Format



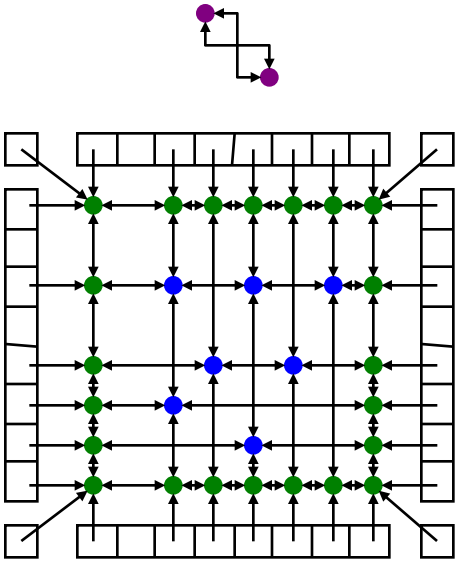
General Sparse Region Format

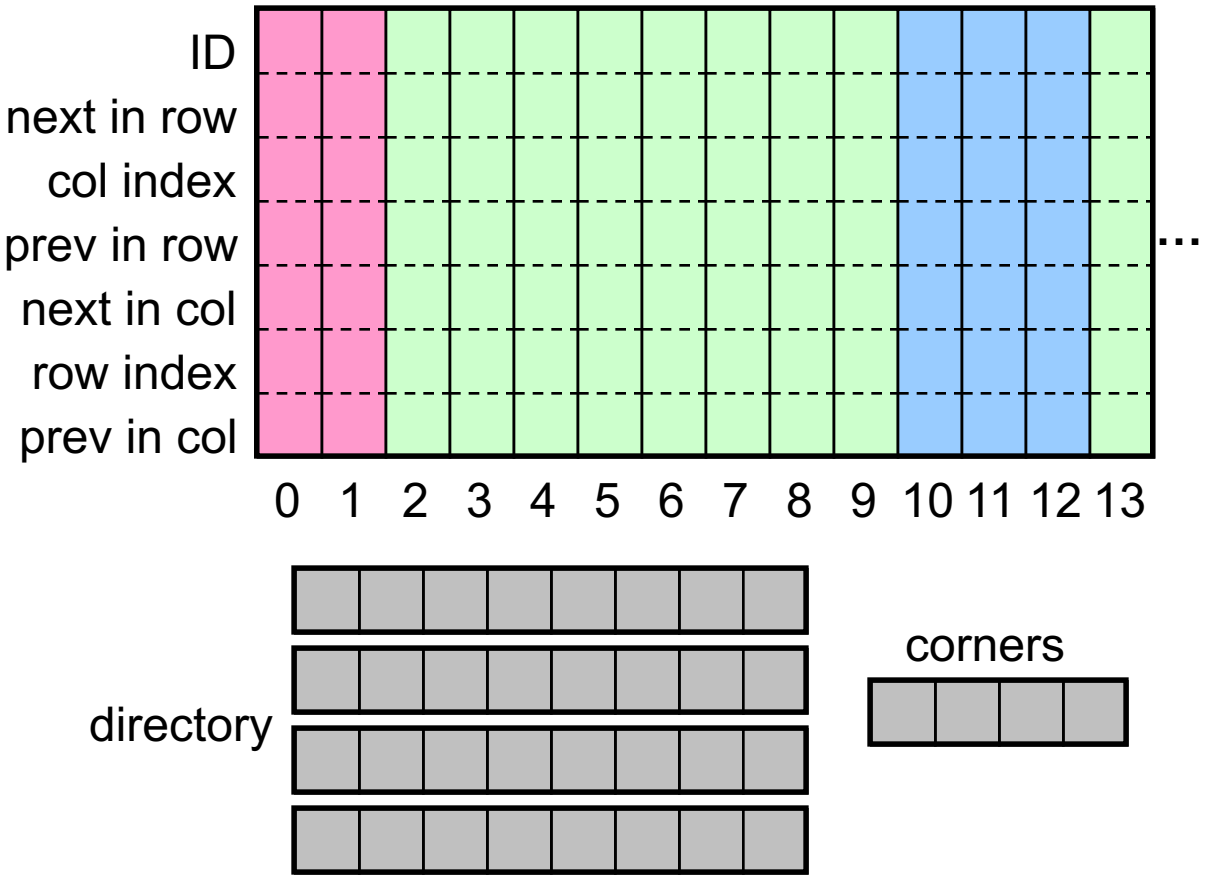


General Sparse Region Format

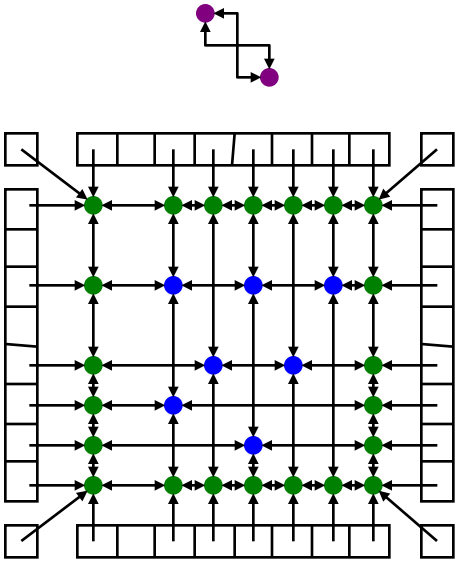


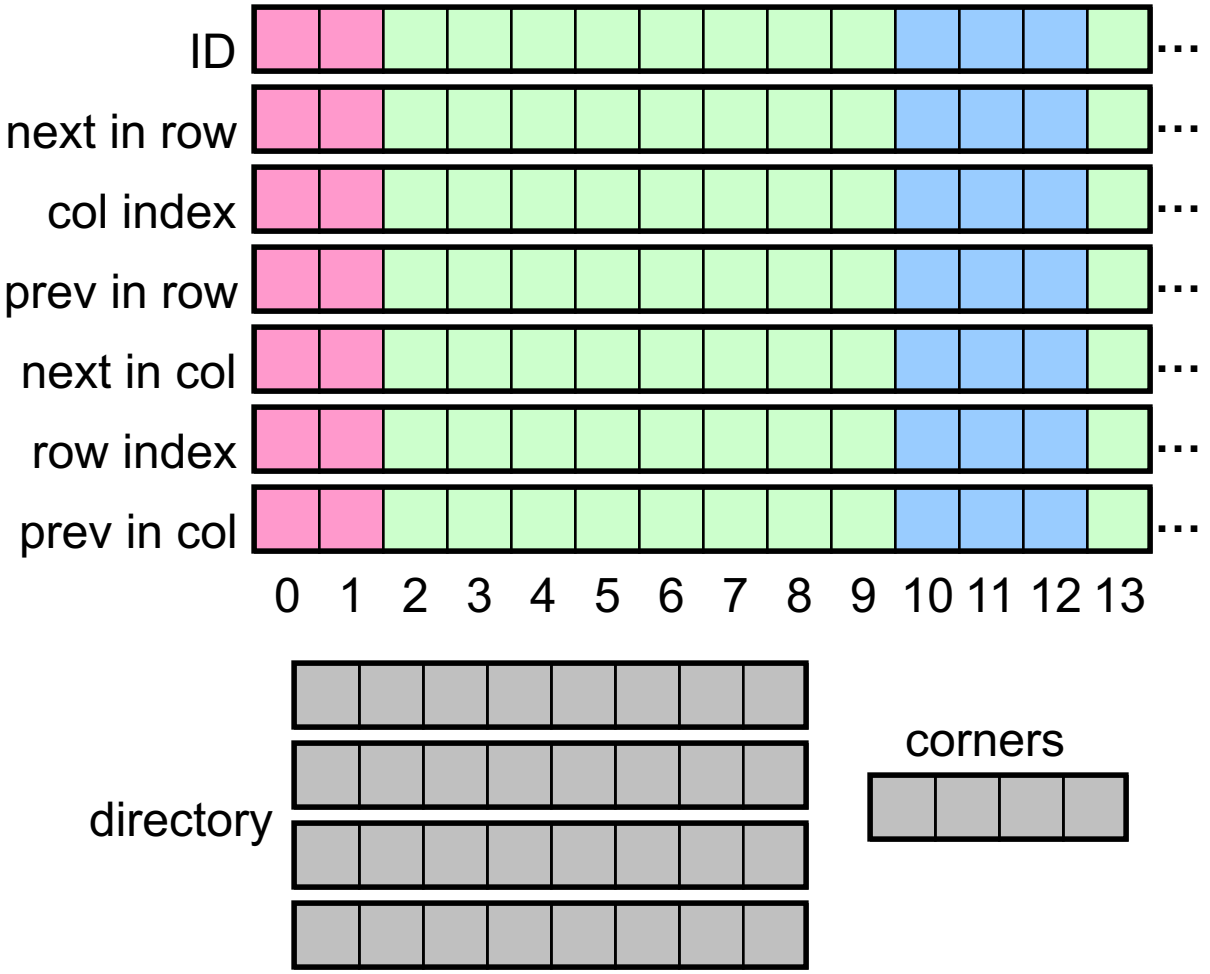
Sparse Format: Array of Records



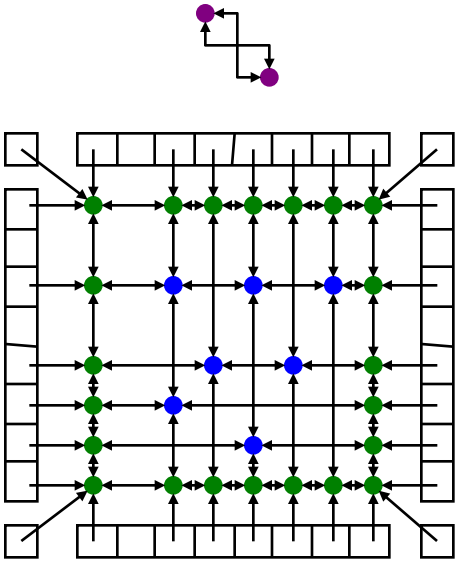


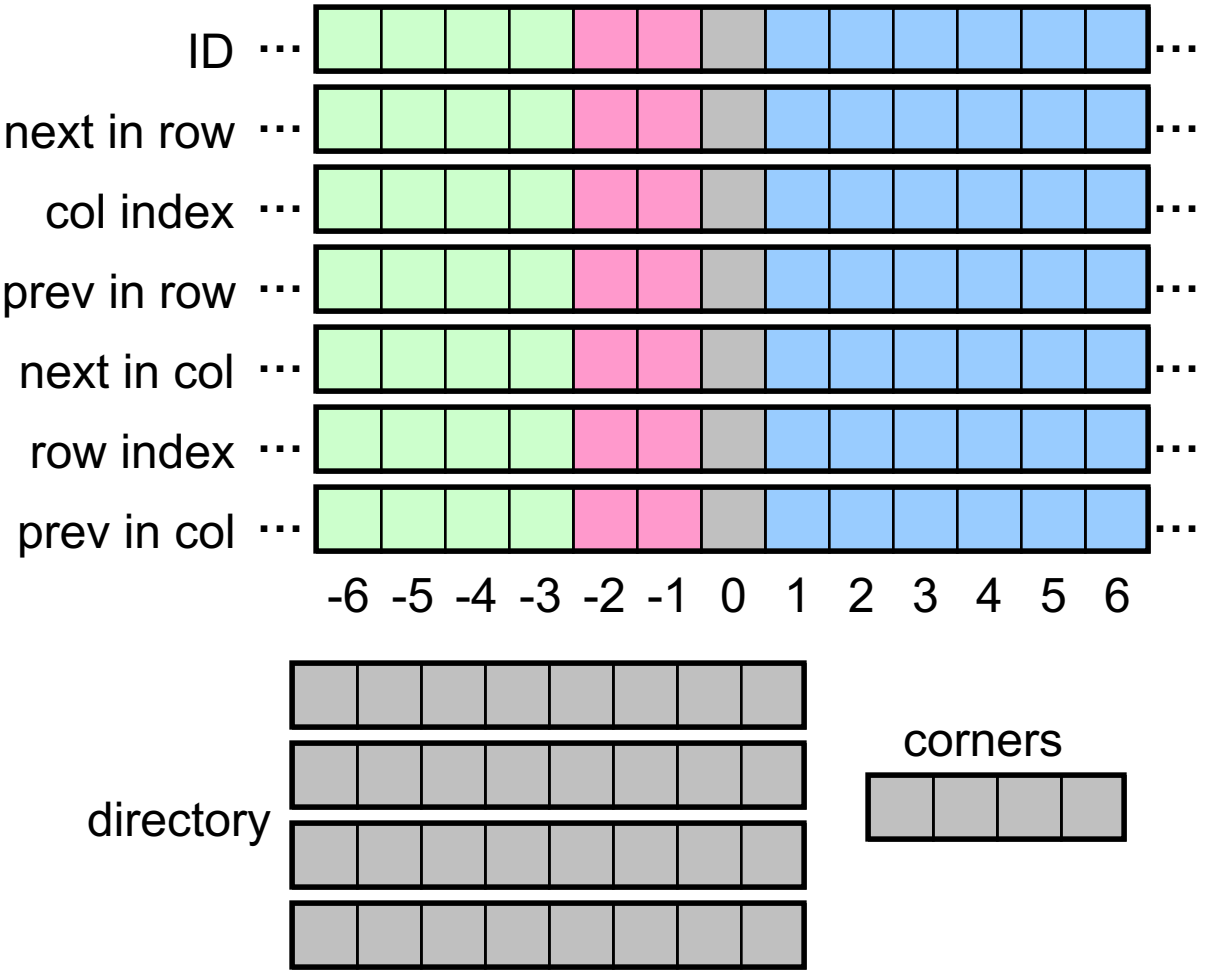
Sparse Format: Record of Arrays



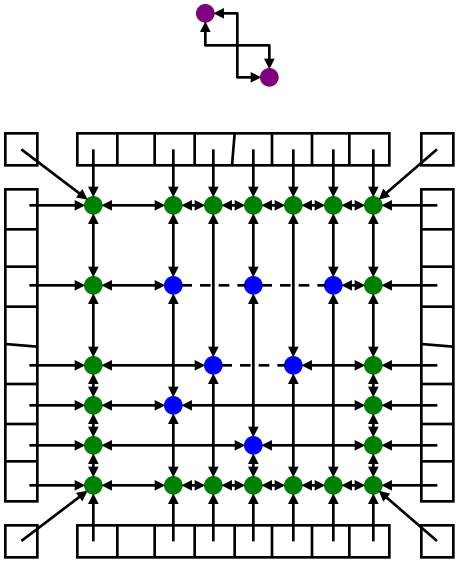


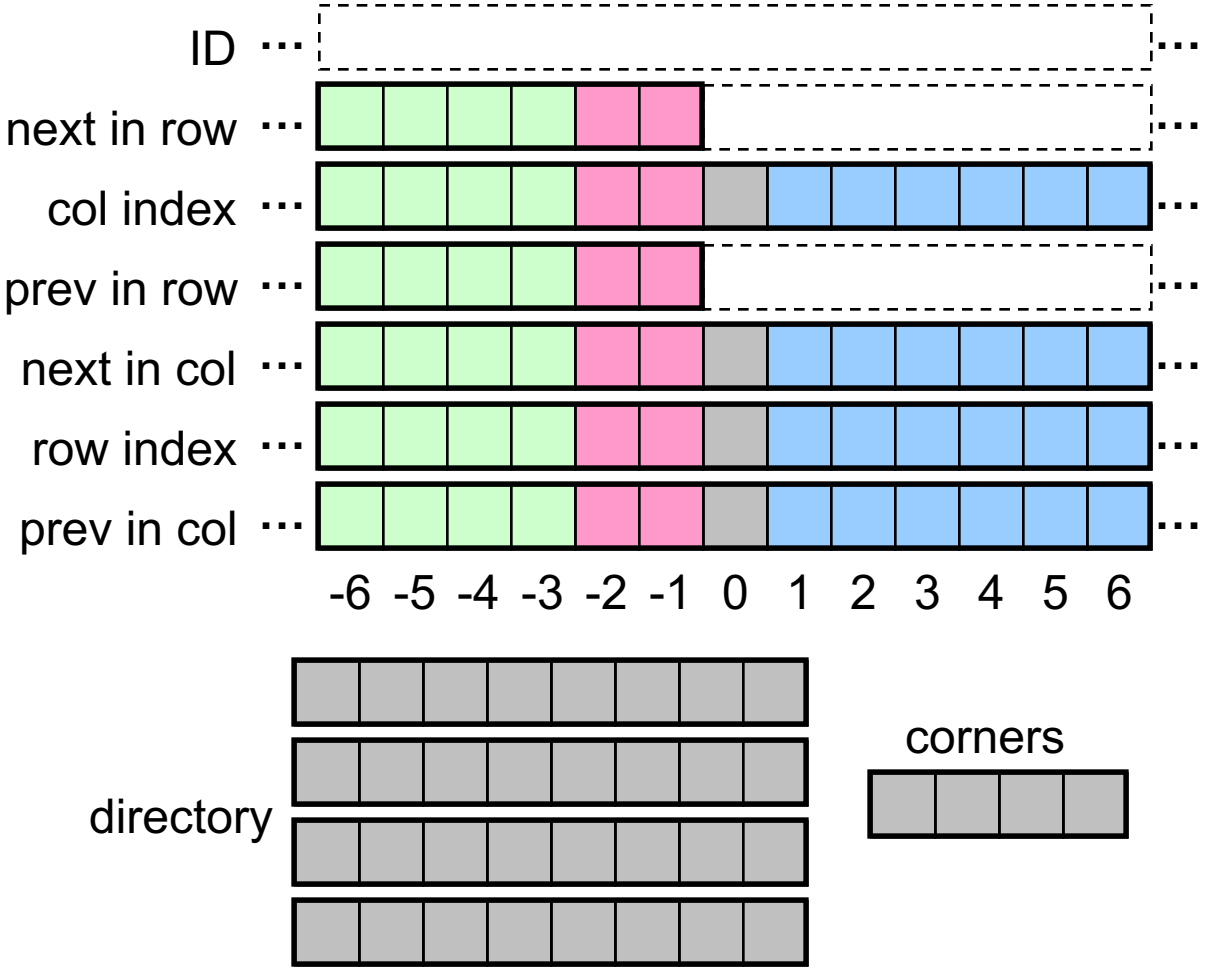
Sparse Format: Reordered



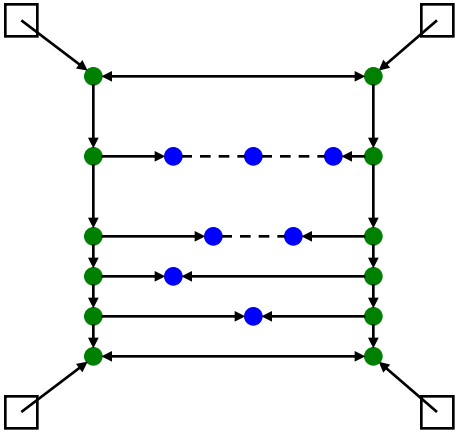


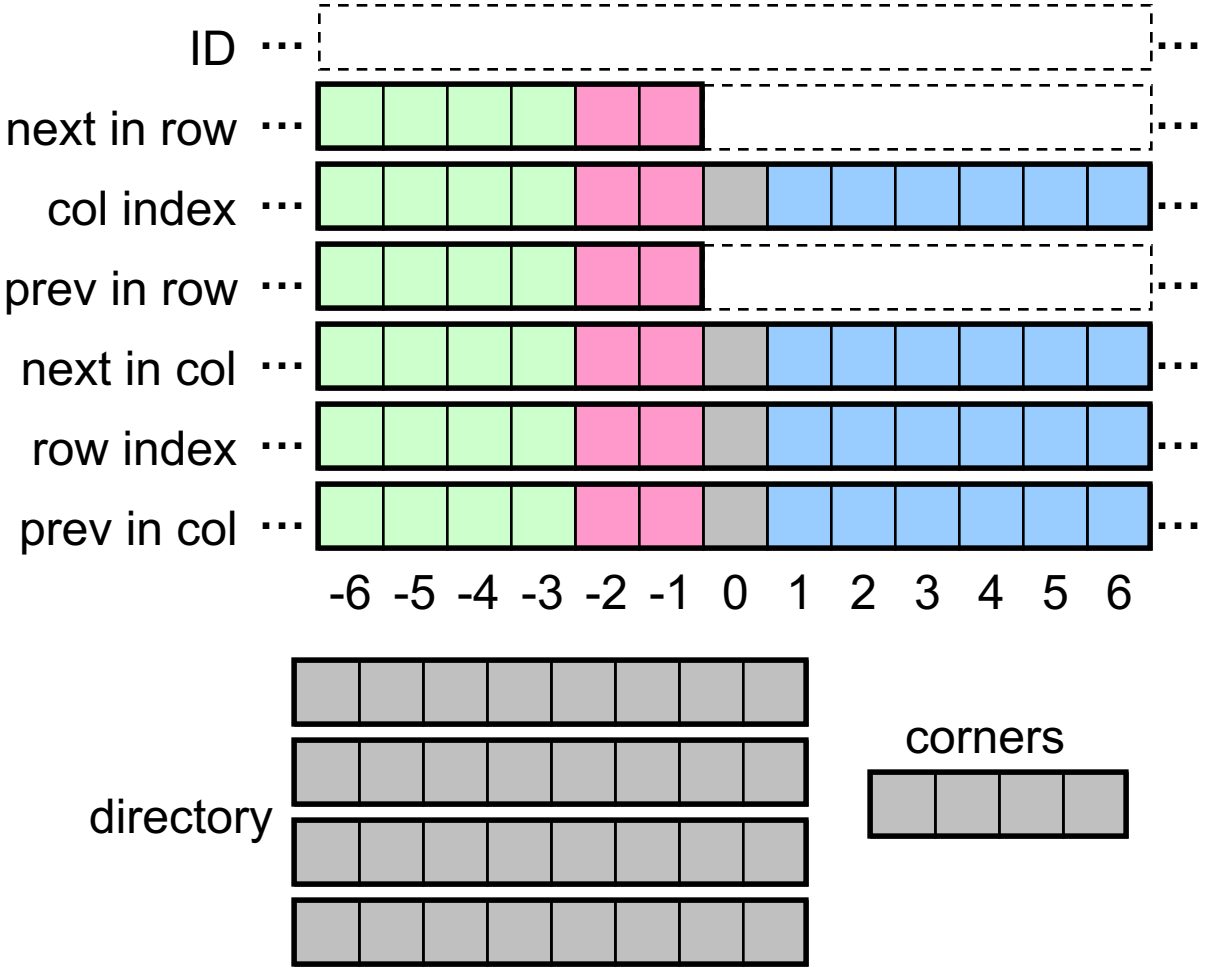
Sparse Format: Optimized



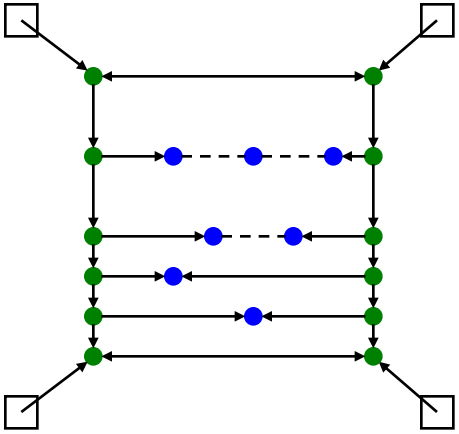


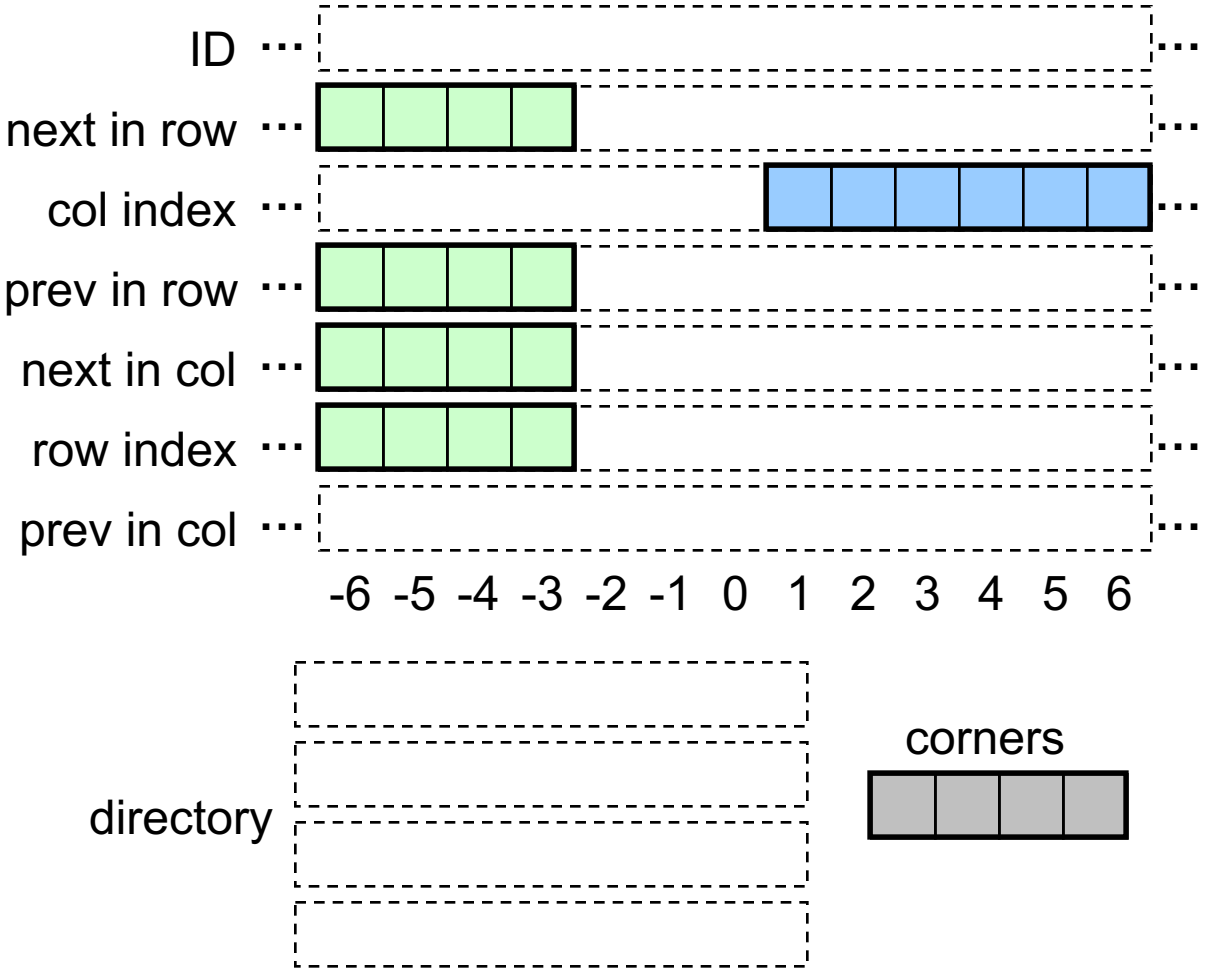
Sparse Format: True Requirements



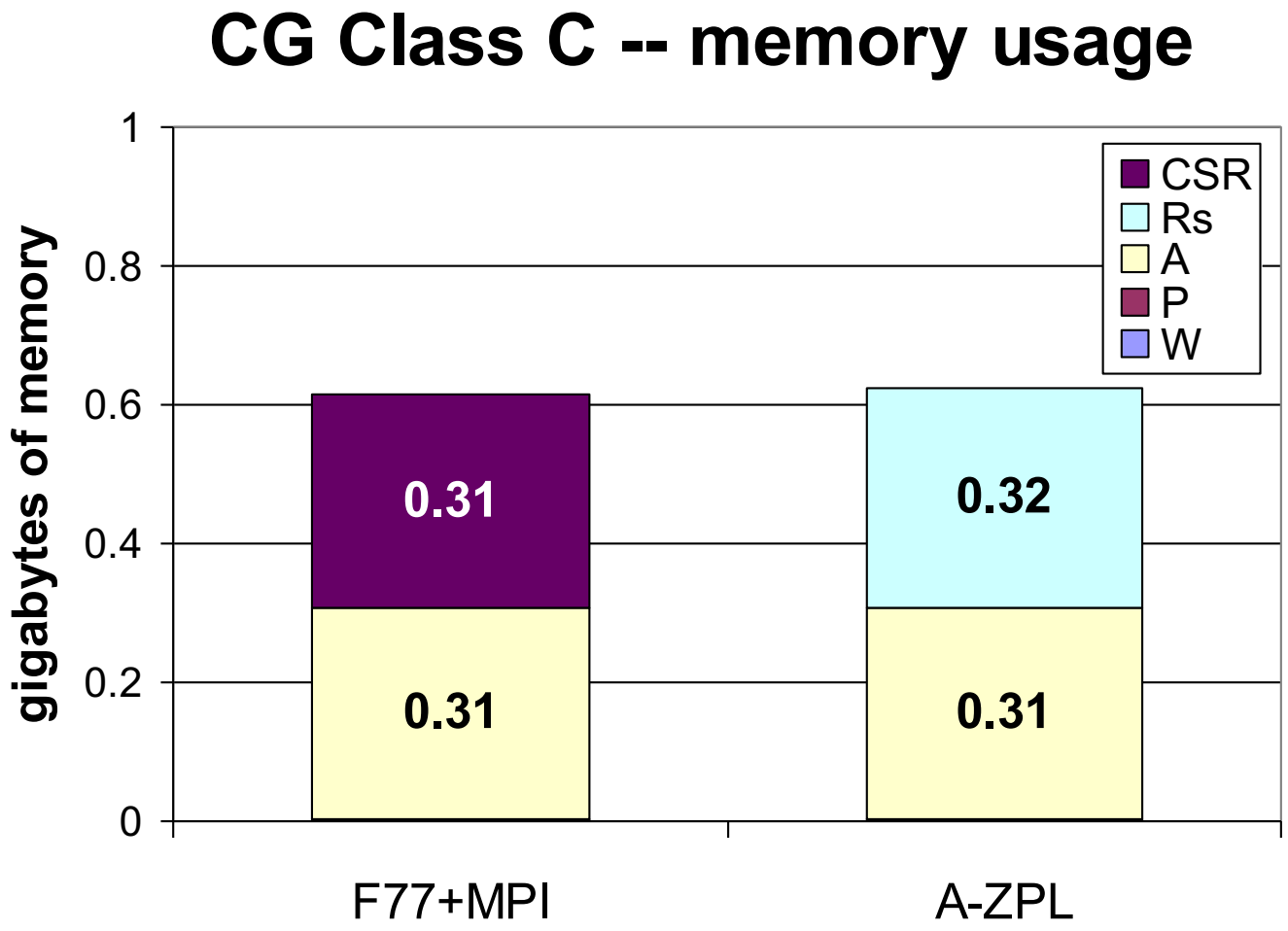


Sparse Format: Fully Optimized

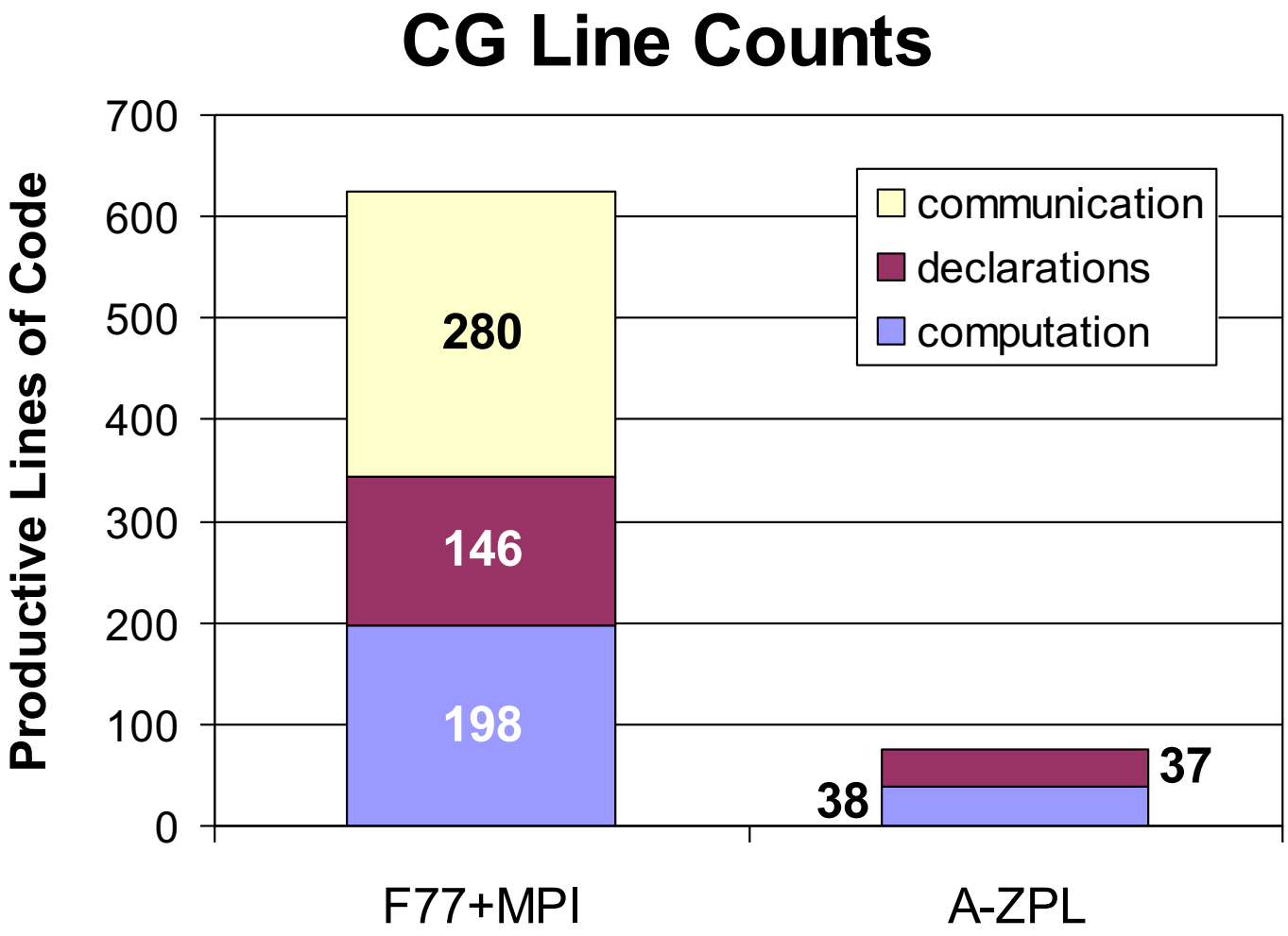


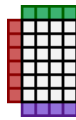


CG Memory Requirements

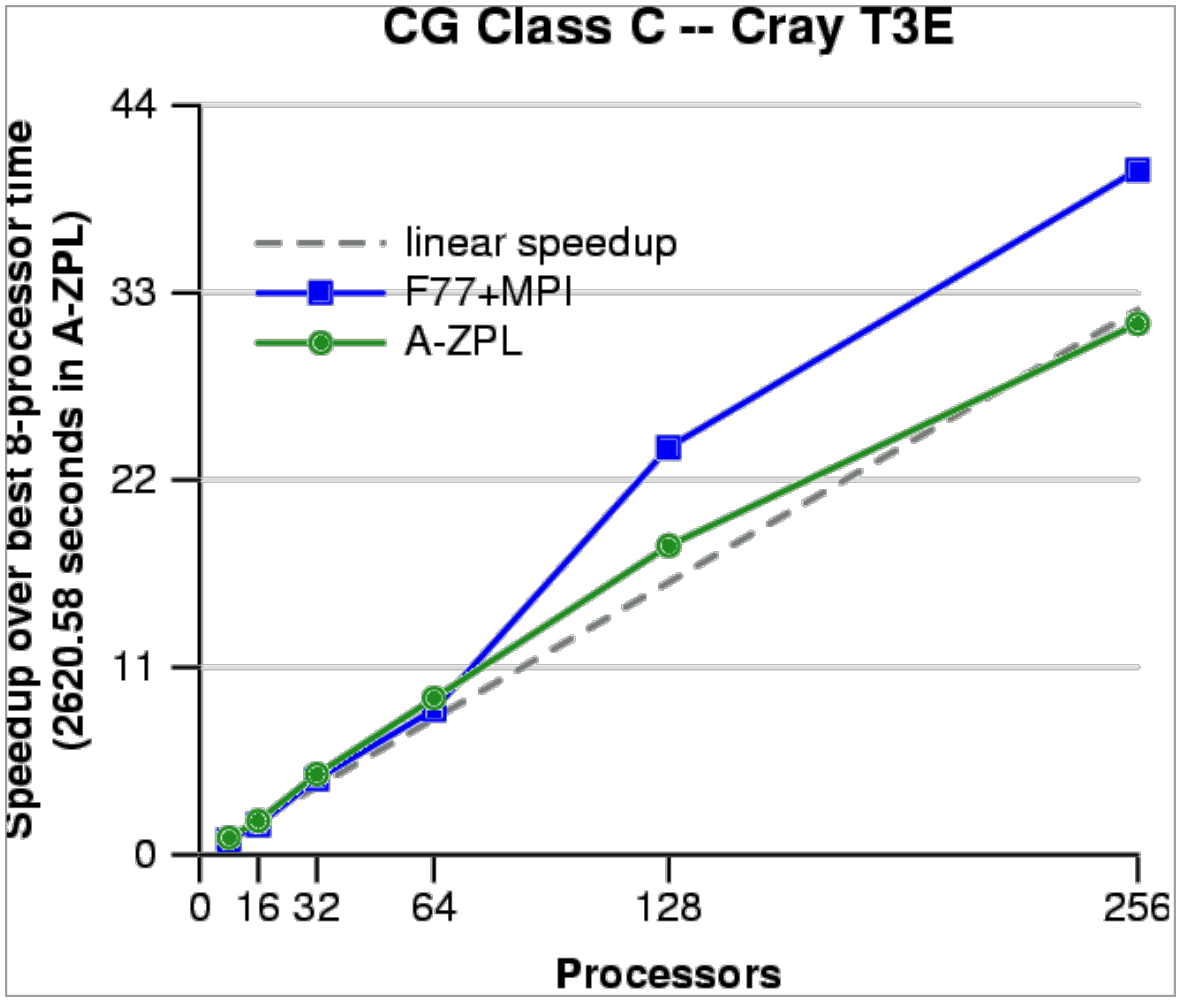


CG Code Size


CG Line Counts
Productive Lines of Code
700
600
500
400
300
200
100
0
communication
declarations
computation
280
146
198
38
37
F77+MPI
A-ZPL



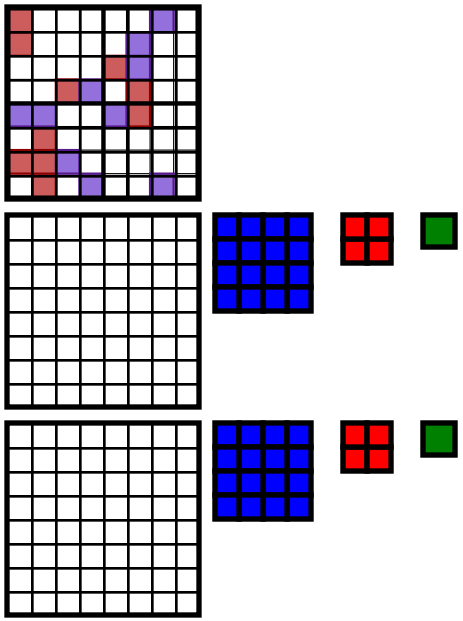
NAS CG Speedup: Cray T3E



though ZPL's sparsity pattern performed well at small node counts and scaled well, it couldn't beat hand-coded CSR at scale…

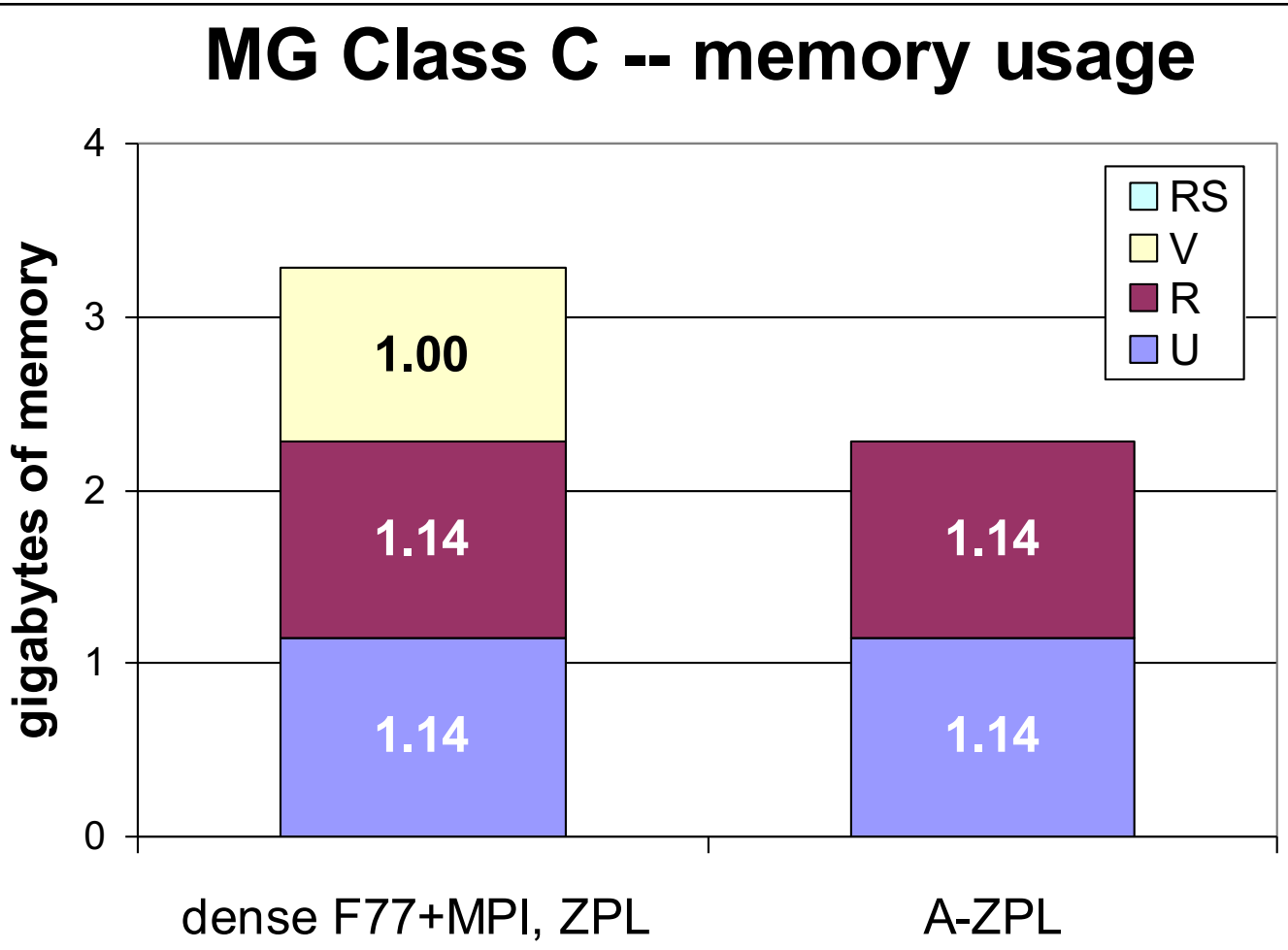
Sparse Arrays in MG

- MG's input array, *V*, has 20 non-zeroes regardless of problem size

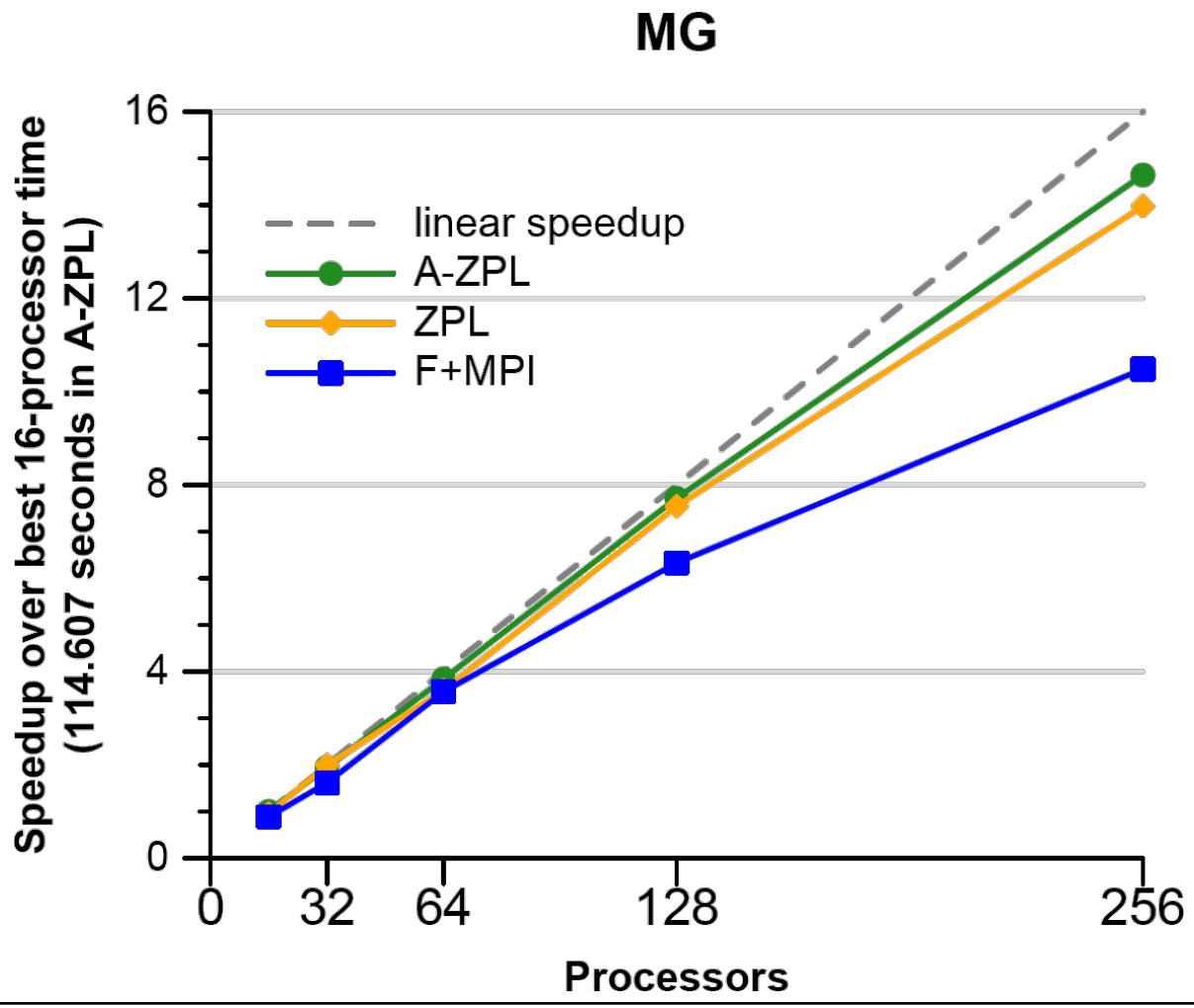


- Computes resid against *V* twice per iteration
- Wasted time and space

MG Memory Usage



NAS MG Speedup: Cray T3E



Another victory for arrays!

- Sparse computation expressed like dense
- Compact, clean, comprehensible code again
  (not seen in this presentation)
- Code expresses algorithm, not implementation
  – compiler optimizes implementation based on need

ZPL Summary

ZPL's Successes

- **First-class concept for representing index sets**
  - makes clouds of scalars in array declarations and loops concrete
  - supports global-view of data and control; improved productivity
  - useful abstraction for user and compiler

  The Design and Implementation of a Region-Based Parallel Language. Bradford L. Chamberlain. PhD thesis, University of Washington, November 2001

- **Semantics constraining alignment of interacting arrays**
  - communication requirements visible to user and compiler in syntax

  ZPL's WYSIWYG performance model. Bradford L. Chamberlain, Sung-Eun Choi, E Christopher Lewis, Calvin Lin, Lawrence Snyder, and W. Derrick Weathersby. In *Proceedings of the IEEE Workshop on High-Level Parallel Programming Models and Supportive Environments*, 1998.

- **Implementation-neutral expression of communication**
  - supports implementation on each architecture using best paradigm

  A compiler abstraction for machine independent parallel communication generation. Bradford L. Chamberlain, Sung-Eun Choi, and Lawrence Snyder. In *Proceedings of the Workshop on Languages and Compilers for Parallel Computing*, 1997.

ZPL's Drawbacks

1) ZPL only supports one level of data parallelism

- No task parallelism / concurrent programming
- No nested parallelism (data or otherwise)
- ZPL's parallelism can never be very dynamic / unpredictable
  - single-threaded SPMD only

Takeaway:

Users want more general forms of parallelism (as do modern architectures and algorithms)

Challenge:

What would it take to meaningfully support general parallel programming with ZPL-like regions and arrays?

ZPL's Drawbacks

2) WYSIWYG depends on having two distinct array types:

i. parallel arrays, which you've been hearing about

ii. traditional arrays which support indexing, yet are serial / local only

```
var ThreeParArrs:     array [1..3] of [R] double;
var ParArrofTriples: [R] array [1..3] of double;

[R] TheeParArrs[2] := ParArrofTriples[2];
```

ZPL's Drawbacks

2) WYSIWYG depends on having two distinct array types:

i. parallel arrays, which you've been hearing about

ii. traditional arrays which support indexing, yet are serial / local only

```
var ThreeParArrs:     array [1..3] of [R] double;
var ParArrofTriples: [R] array [1..3] of double;
```

- this breaks code reuse and results in unfortunate code clones
  - "I need to rewrite this operation twice, once for each array type"
    - (or 2^k times for *k* array arguments?)

- there's a real tension here: WYSIWYG would be lost if…

  ...parallel arrays supported indexing

  ...serial arrays supported array operators

ZPL's Drawbacks

2) WYSIWYG depends on having two distinct array types:

i. parallel arrays, which you've been hearing about

ii. traditional arrays which support indexing, yet are serial / local only

```
var ThreeParArrs:     array [1..3] of [R] double;
var ParArrofTriples: [R] array [1..3] of double;
```

Takeaway:

Having distinct types for parallel vs. serial arrays is regrettable

Challenge:

How can ZPL's region/array benefits best be carried forward?

ZPL's Drawbacks

3) ZPL only supports Block-distributed arrays

- real algorithms may want other distributions: block-cyclic, MRB, …
- distribution baked into the compiler, not extensible
- memory layouts are also hard-coded
  - RMO for dense arrays
  - special ZPL format for sparse arrays

Takeaway:

While block is an important common case, it's not a panacea. Inability to get CSR sparse arrays hurt CG perforamnce.

Challenge:

How to support more general distributions and layouts without giving up performance?

ZPL's Drawbacks

4) Dated in several respects

- syntactically follows Modula rather than C (say)
- no support for OOP
- ...

- **a good example of academic vs. practical language design**
  - for academic work, such things may not matter (they didn't for ZPL)
  - for practical adoption, they can be show-stoppers (they were for ZPL)

Takeaway:

Users value attractive, modern, feature-rich language design.

Challenge:

How to keep the kitchen sink from dragging down a sleek design.

Main ZPL Sacrifice in moving to Chapel

Q: Any guesses?

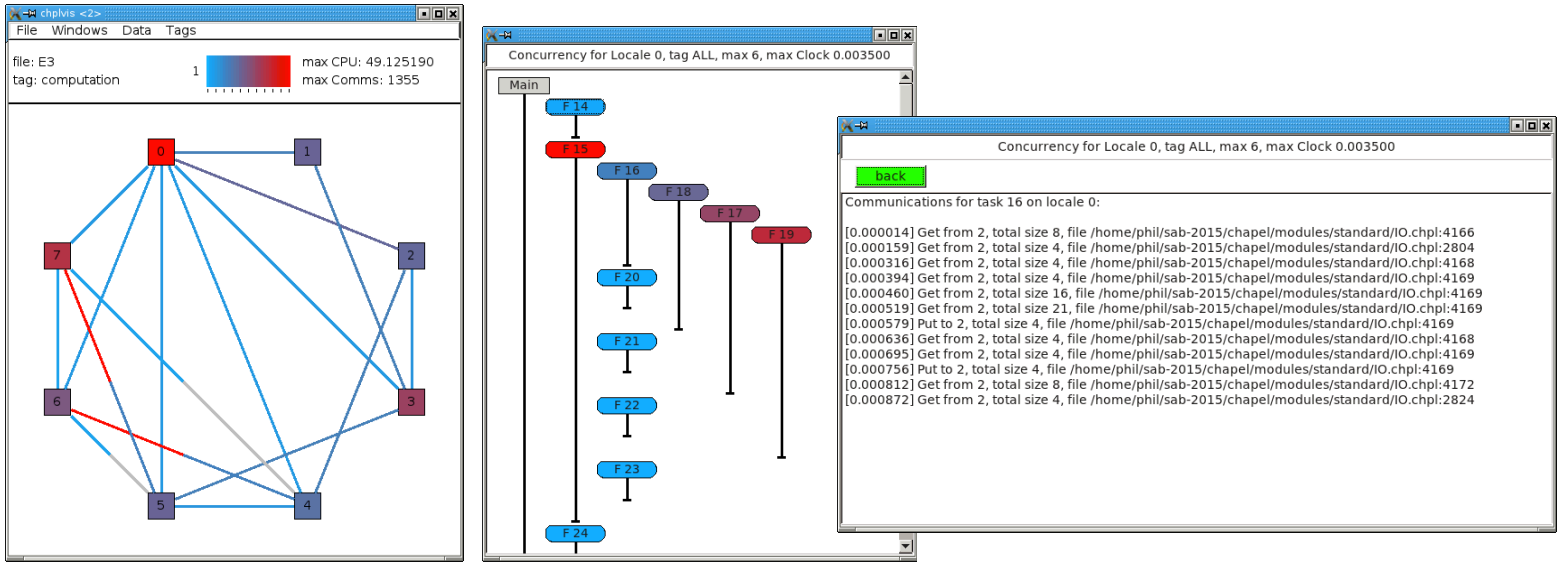
A: Chapel has no WYSIWYG model

- Chapel has one type of array for simplicity, code re-use
  - parallelism is a property of operators / loops, not arrays
  - distributed arrays support indexing
- Interacting arrays need not be distributed identically

```
var ThreeParArrs:    [1..3] [R] real;
var ParArrofTriples: [R] [1..3] real;

// ambiguous:
[1..3][i, 1..n] ThreeParArrs = ParArrofTriples;
// unless we use a tag to distinguish:
[i in 1..3] [jk in {i, 1..n}]
  ThreeParArrs[i][jk] = ParArrOfTriples[jk][i];
// which is essentially an index…
```

Life without WYSIWYG

- **Yet, Chapel users can still reason about communication**
  - semantic model is explicit about where data is placed / tasks execute
  - execution-time queries support reasoning about locality
    - `here` – where is this task running?
    - `x.locale` – where is x stored?
  - new **chplvis** tool supports visualization of communication
    - developed by Phil Nelson, WWU



ZPL vs. Chapel: Other Differences

ZPL	Chapel
data parallel only	task-, nested parallelism
built-in data distributions	user-defined data distributions
designed in an evolutionary manner "what can we do well today, tomorrow?"	designed in a blue-sky manner: "what would an ideal parallel language support?"
academic focus: pick one problem to address (array-based data parallelism)	market focus: what does a general, broad-market language require?
single-threaded, distributed-memory execution model	multithreaded, shared address space execution model
create something that matches today's architectures	create something productive; unproductive architectures may suffer

CRAY

Chapel

What is Chapel?

Chapel: An emerging parallel programming language

- portable
- open-source
- a collaborative effort
- a work-in-progress

Goals:

- Support general parallel programming
  - "any parallel algorithm on any parallel hardware"
- Make parallel programming far more productive
- Designed for practical adoption, not publications

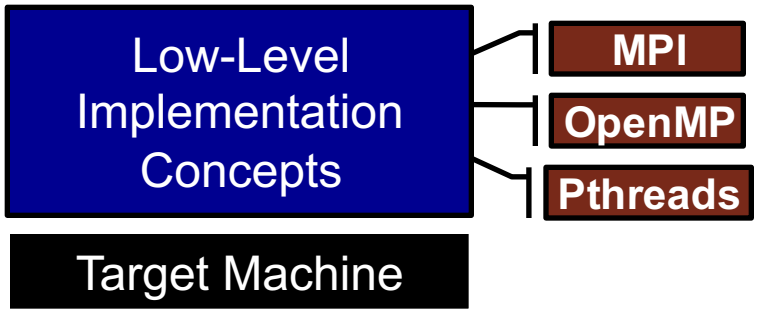
The Chapel Team at Cray (May 2016)

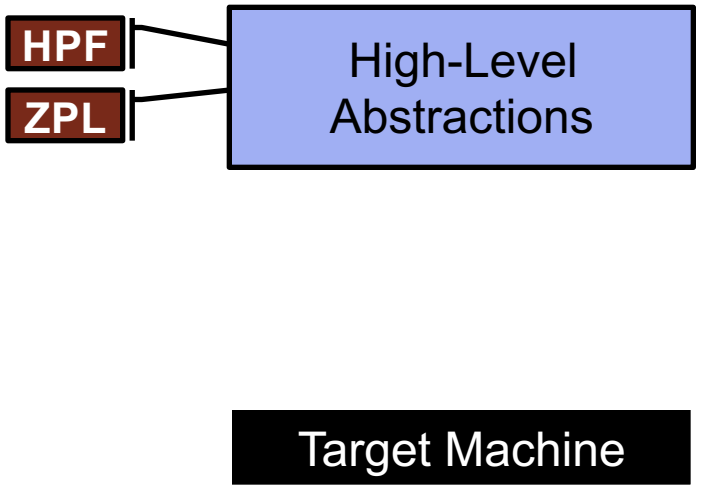
Chapel Community R&D Efforts

(and several others, some of whom you will hear from today…)

http://chapel.cray.com/collaborations.html

Chapel's Multiresolution Design: Motivation





"Why is everything so tedious/difficult?"

"Why don't my programs trivially port to new systems?"

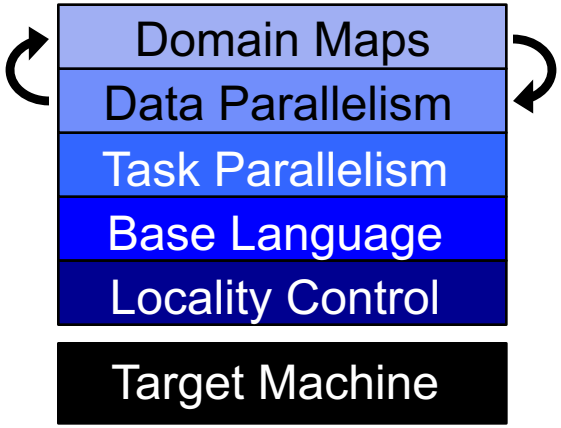
"Why don't I have more control?"

Chapel's Multiresolution Design

Multiresolution Design: **Support multiple tiers of features**

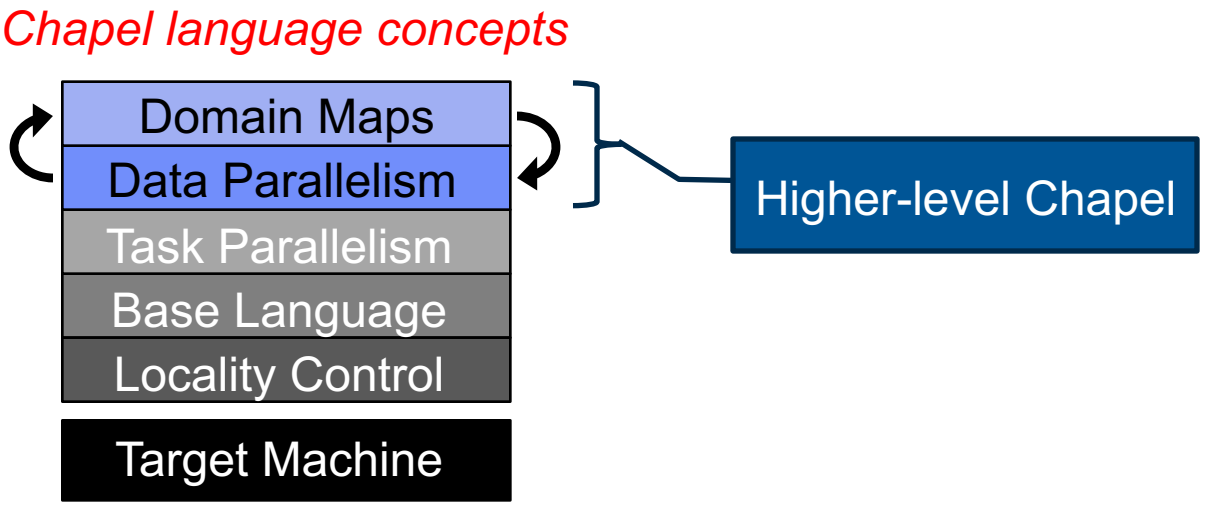
- higher levels for programmability, productivity
- lower levels for greater degrees of control

Chapel language concepts



- build the higher-level concepts in terms of the lower
- permit the user to intermix layers arbitrarily

Higher-Level Features



Data Parallelism, by example

dataParallel.chpl

```
config const n = 1000;
var D = {1..n, 1..n};

var A: [D] real;
forall (i,j) in D do
  A[i,j] = i + (j - 0.5)/n;
writeln(A);
```

```
prompt> chpl dataParallel.chpl -o dataParallel
prompt> ./dataParallel --n=5
1.1 1.3 1.5 1.7 1.9
2.1 2.3 2.5 2.7 2.9
3.1 3.3 3.5 3.7 3.9
4.1 4.3 4.5 4.7 4.9
5.1 5.3 5.5 5.7 5.9
```

Data Parallelism, by example

Domains (Chapel's *regions*)

dataParallel.chpl

```
config const n = 1000;
var D = {1..n, 1..n};

var A: [D] real;
forall (i,j) in D do
  A[i,j] = i + (j - 0.5)/n;
writeln(A);
```

```
prompt> chpl dataParallel.chpl -o dataParallel
prompt> ./dataParallel --n=5
1.1 1.3 1.5 1.7 1.9
2.1 2.3 2.5 2.7 2.9
3.1 3.3 3.5 3.7 3.9
4.1 4.3 4.5 4.7 4.9
5.1 5.3 5.5 5.7 5.9
```

Data Parallelism, by example

Arrays

dataParallel.chpl

```
config const n = 1000;
var D = {1..n, 1..n};

var A: [D] real;
forall (i,j) in D do
  A[i,j] = i + (j - 0.5)/n;
writeln(A);
```

```
prompt> chpl dataParallel.chpl -o dataParallel
prompt> ./dataParallel --n=5
1.1 1.3 1.5 1.7 1.9
2.1 2.3 2.5 2.7 2.9
3.1 3.3 3.5 3.7 3.9
4.1 4.3 4.5 4.7 4.9
5.1 5.3 5.5 5.7 5.9
```

Data Parallelism, by example

Data-Parallel Forall Loops

dataParallel.chpl

```
config const n = 1000;
var D = {1..n, 1..n};

var A: [D] real;
forall (i,j) in D do
  A[i,j] = i + (j - 0.5)/n;
writeln(A);
```

```
prompt> chpl dataParallel.chpl -o dataParallel
prompt> ./dataParallel --n=5
1.1 1.3 1.5 1.7 1.9
2.1 2.3 2.5 2.7 2.9
3.1 3.3 3.5 3.7 3.9
4.1 4.3 4.5 4.7 4.9
5.1 5.3 5.5 5.7 5.9
```

Distributed Data Parallelism, by example

Domain Maps
(Map Data Parallelism to the System)

dataParallel.chpl

```
use CyclicDist;
config const n = 1000;
var D = {1..n, 1..n}
        dmapped Cyclic(startIdx = (1,1));
var A: [D] real;
forall (i,j) in D do
  A[i,j] = i + (j - 0.5)/n;
writeln(A);
```

```
prompt> chpl dataParallel.chpl -o dataParallel
prompt> ./dataParallel --n=5 --numLocales=4
1.1 1.3 1.5 1.7 1.9
2.1 2.3 2.5 2.7 2.9
3.1 3.3 3.5 3.7 3.9
4.1 4.3 4.5 4.7 4.9
5.1 5.3 5.5 5.7 5.9
```

Distributed Data Parallelism, by example

dataParallel.chpl

```
use CyclicDist;
config const n = 1000;
var D = {1..n, 1..n}
        dmapped Cyclic(startIdx = (1,1));
var A: [D] real;
forall (i,j) in D do
  A[i,j] = i + (j - 0.5)/n;
writeln(A);
```

```
prompt> chpl dataParallel.chpl -o dataParallel
prompt> ./dataParallel --n=5 --numLocales=4
1.1 1.3 1.5 1.7 1.9
2.1 2.3 2.5 2.7 2.9
3.1 3.3 3.5 3.7 3.9
4.1 4.3 4.5 4.7 4.9
5.1 5.3 5.5 5.7 5.9
```

Chapel Data Parallel Operations

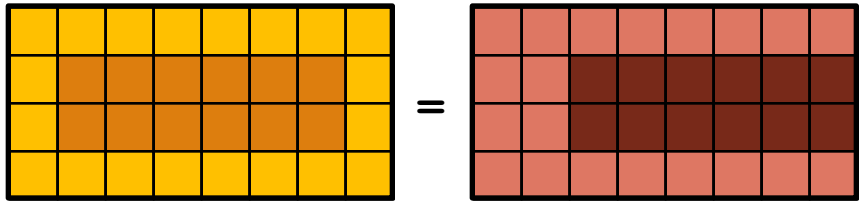
- **Data Parallel Iteration**

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

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

- **Array Slicing; Domain Algebra**

```
A[InnerD] = B[InnerD+(0,1)];
```



- **Promotion of Scalar Functions and Operators**

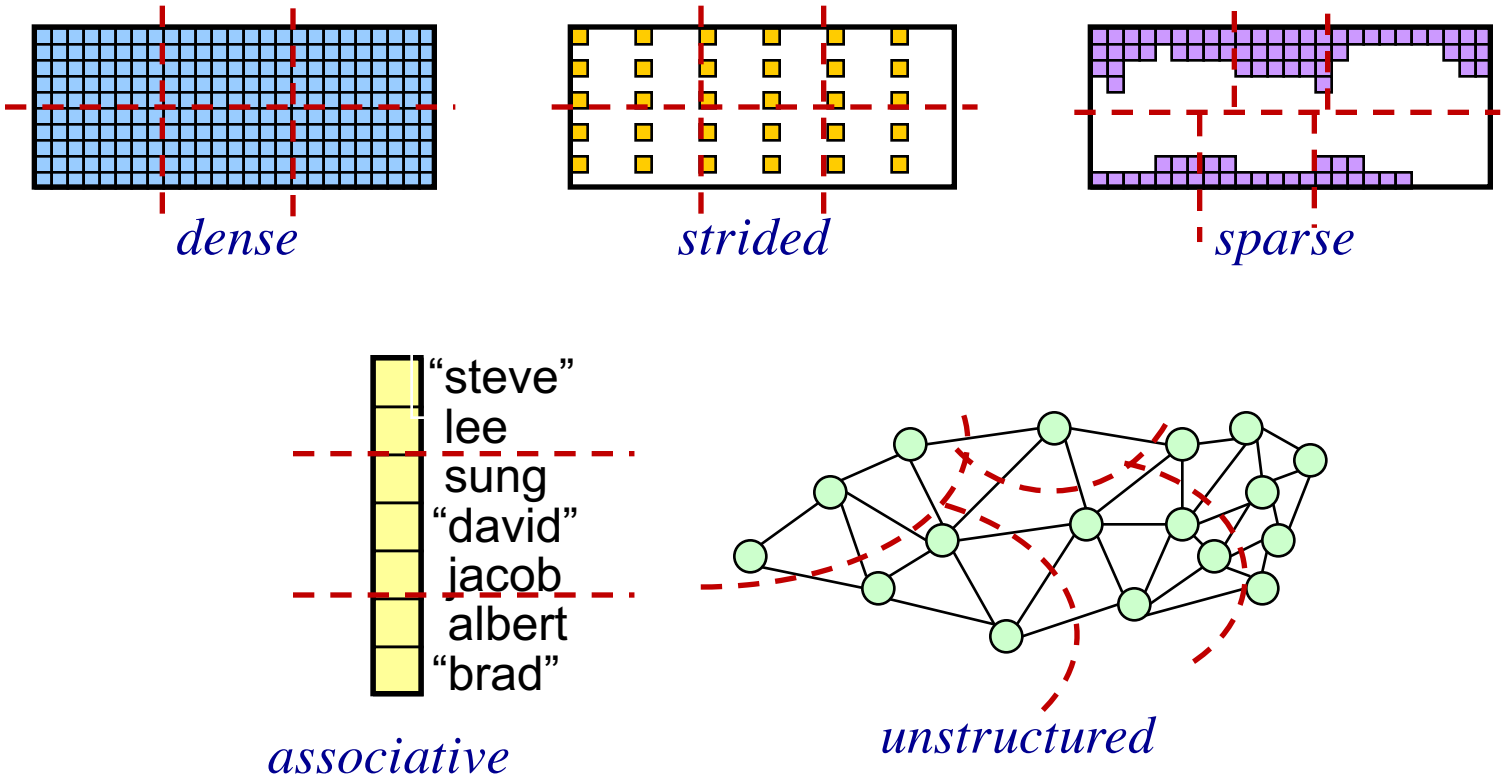
```
A = exp(B, C);
```

```
A = foo("hi", B, C);
```

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

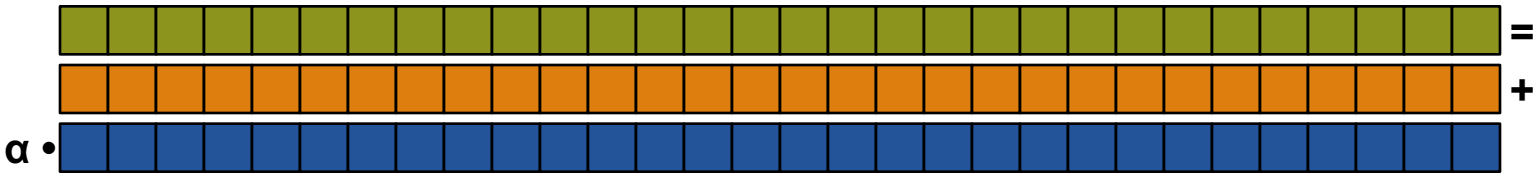
- **And many others: reductions, scans, reallocation, reshaping, remapping, set operations, aliasing, …**

Chapel has Many Types of Domains/Arrays



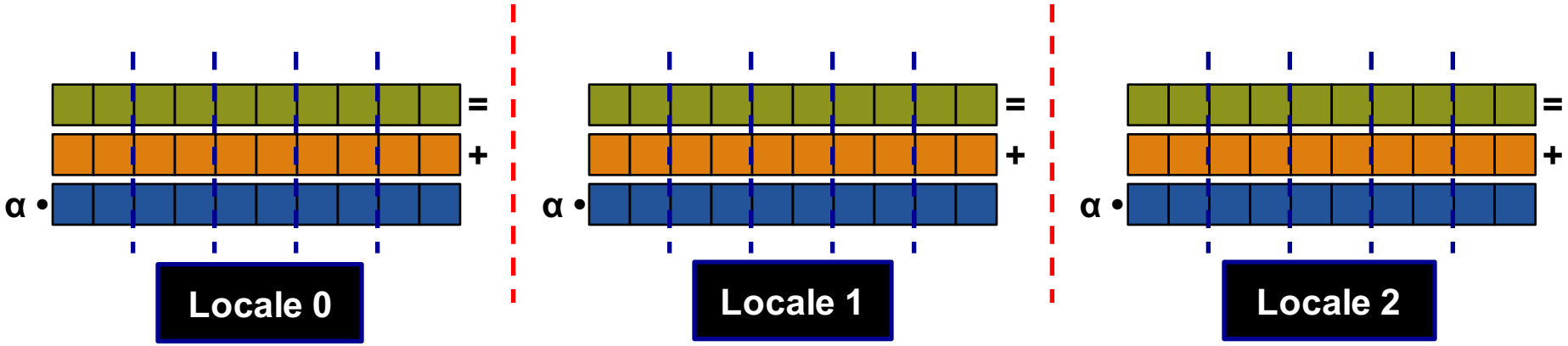
Domain Maps

Domain maps are "recipes" that instruct the compiler how to map the global view of a computation…




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

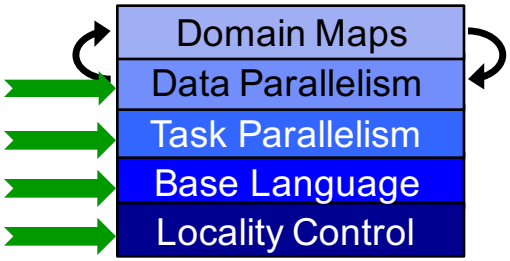
…to the target locales' memory and processors:



Chapel's Domain Map Philosophy

1. **Chapel provides a library of standard domain maps**
   - to support common array implementations effortlessly

2. **Expert users can write their own domain maps in Chapel**
   - to cope with any shortcomings in our standard library



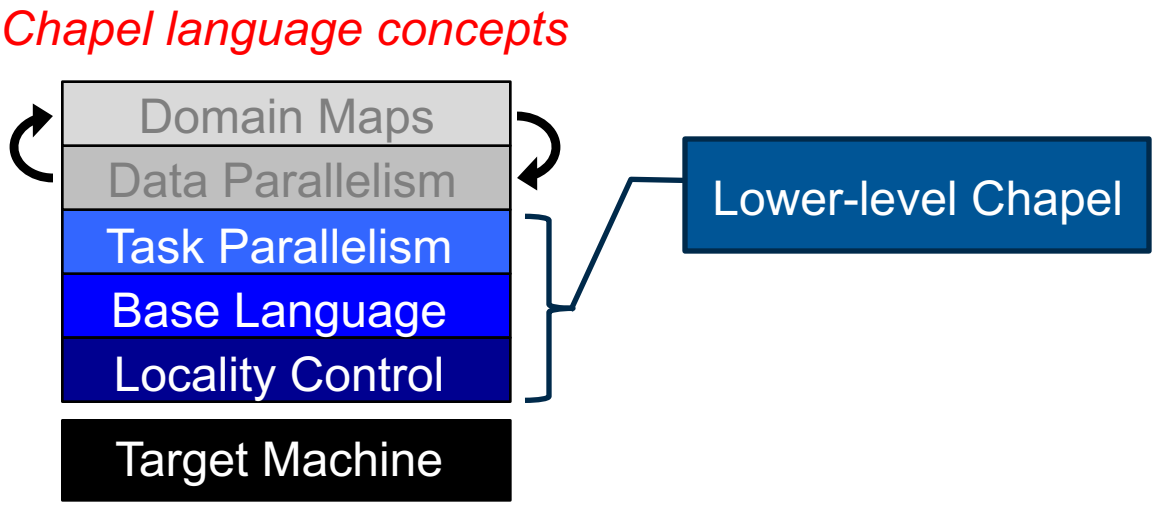
1. **Chapel's standard domain maps are written using the same end-user framework**
   - to avoid a performance cliff between "built-in" and user-defined cases

Impacts of Chapel's Domain Map Philosophy

- **Chapel supports both global- and local-view programming**
  - domain maps form a gateway between the two worldviews

- **Our approach put us at a performance disadvantage**
  - *all* Chapel arrays are written as Chapel code
    - compiler has no built-in knowledge of arrays, as in ZPL, Fortran, C
    - a distinct performance handicap compared to those languages
  - this has slowed our start, but we don't think it's inherently problematic
    - that said, we have not achieved parity with ZPL yet at scale
      - (though admittedly, our focus has been different)
    - nor have we re-implemented many key ZPL optimizations in Chapel (yet)
      - e.g., communication optimizations, stencil optimization that helped NAS MG

Lower-Level Features



Base Language Features, by example

```
iter fib(n) {
  var current = 0,
      next = 1;

  for i in 1..n {
    yield current;
    current += next;
    current <=> next;
  }
}
```

```
for (i,f) in zip(0..#n, fib(n)) do
  writeln("fib #", i, " is ", f);
```

```
fib #0 is 0
fib #1 is 1
fib #2 is 1
fib #3 is 2
fib #4 is 3
fib #5 is 5
fib #6 is 8
...
```

Base Language Features, by example

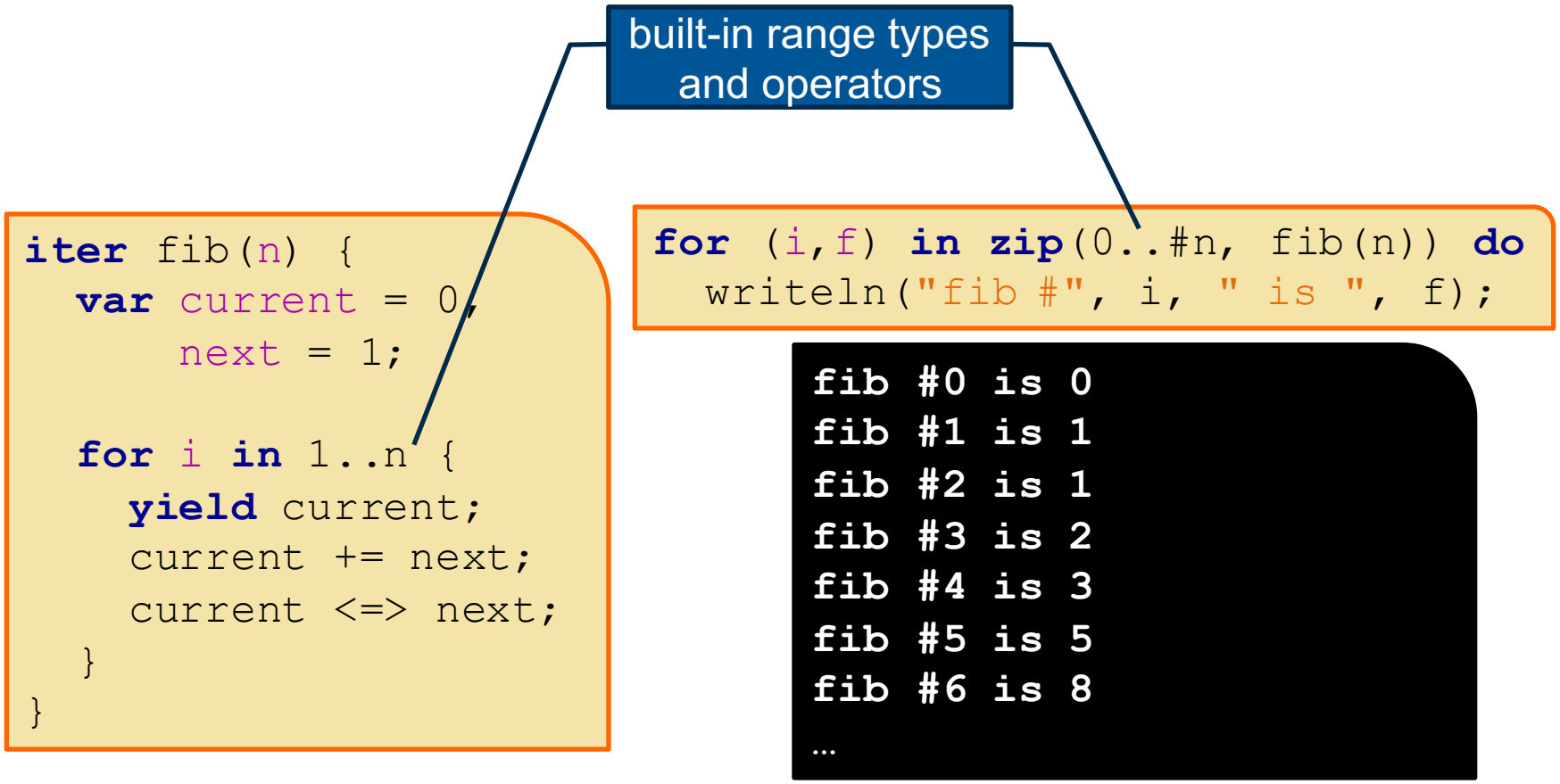
CLU-style iterators

```
iter fib(n) {
  var current = 0,
      next = 1;

  for i in 1..n {
    yield current;
    current += next;
    current <=> next;
  }
}
```

```
for (i,f) in zip(0..#n, fib(n)) do
  writeln("fib #", i, " is ", f);
```

```
fib #0 is 0
fib #1 is 1
fib #2 is 1
fib #3 is 2
fib #4 is 3
fib #5 is 5
fib #6 is 8
...
```

Base Language Features, by example



Base Language Features, by example

```
iter fib(n) {
  var current = 0,
      next = 1;

  for i in 1..n {
    yield current;
    current += next;
    current <=> next;
  }
}
```

zippered iteration

```
for (i,f) in zip(0..#n, fib(n)) do
  writeln("fib #", i, " is ", f);
```

```
fib #0 is 0
fib #1 is 1
fib #2 is 1
fib #3 is 2
fib #4 is 3
fib #5 is 5
fib #6 is 8
...
```

Base Language Features, by example

```
iter fib(n) {
  var current = 0,
      next = 1;

  for i in 1..n {
    yield current;
    current += next;
    current <=> next;
  }
}
```

tuples

```
for (i,f) in zip(0..#n, fib(n)) do
  writeln("fib #", i, " is ", f);
```

```
fib #0 is 0
fib #1 is 1
fib #2 is 1
fib #3 is 2
fib #4 is 3
fib #5 is 5
fib #6 is 8
...
```

Base Language Features, by example

Static Type Inference for:
- arguments
- return types
- variables

```
iter fib(n) {
  var current = 0,
      next = 1;

  for i in 1..n {
    yield current;
    current += next;
    current <=> next;
  }
}
```

```
for (i,f) in zip(0..#n, fib(n)) do
  writeln("fib #", i, " is ", f);
```

```
fib #0 is 0
fib #1 is 1
fib #2 is 1
fib #3 is 2
fib #4 is 3
fib #5 is 5
fib #6 is 8
...
```

Base Language Features, by example

```
iter fib(n) {
  var current = 0,
      next = 1;

  for i in 1..n {
    yield current;
    current += next;
    current <=> next;
  }
}
```

```
for (i,f) in zip(0..#n, fib(n)) do
  writeln("fib #", i, " is ", f);
```

```
fib #0 is 0
fib #1 is 1
fib #2 is 1
fib #3 is 2
fib #4 is 3
fib #5 is 5
fib #6 is 8
...
```

Task Parallelism, Locality Control, by example

taskParallel.chpl

```
coforall loc in Locales do
  on loc {
    const numTasks = here.maxTaskPar;
    coforall tid in 1..numTasks do
      writef("Hello from task %n of %n "+
             "running on %s\n",
             tid, numTasks, here.name);
  }
```

```
prompt> chpl taskParallel.chpl -o taskParallel
prompt> ./taskParallel --numLocales=2
Hello from task 1 of 2 running on n1033
Hello from task 2 of 2 running on n1032
Hello from task 2 of 2 running on n1033
Hello from task 1 of 2 running on n1032
```

Task Parallelism, Locality Control, by example

High-Level Task Parallelism

taskParallel.chpl

```
coforall loc in Locales do
  on loc {
    const numTasks = here.maxTaskPar;
    coforall tid in 1..numTasks do
      writef("Hello from task %n of %n "+
             "running on %s\n",
             tid, numTasks, here.name);
  }
```

```
prompt> chpl taskParallel.chpl -o taskParallel
prompt> ./taskParallel --numLocales=2
Hello from task 1 of 2 running on n1033
Hello from task 2 of 2 running on n1032
Hello from task 2 of 2 running on n1033
Hello from task 1 of 2 running on n1032
```

Task Parallelism, Locality Control, by example

taskParallel.chpl

```
coforall loc in Locales do
  on loc {
    const numTasks = here.maxTaskPar;
    coforall tid in 1..numTasks do
      writef("Hello from task %n of %n "+
             "running on %s\n",
             tid, numTasks, here.name);
  }
```

```
prompt> chpl taskParallel.chpl -o taskParallel
prompt> ./taskParallel --numLocales=2
Hello from task 1 of 2 running on n1033
Hello from task 2 of 2 running on n1032
Hello from task 2 of 2 running on n1033
Hello from task 1 of 2 running on n1032
```

Task Parallelism, Locality Control, by example

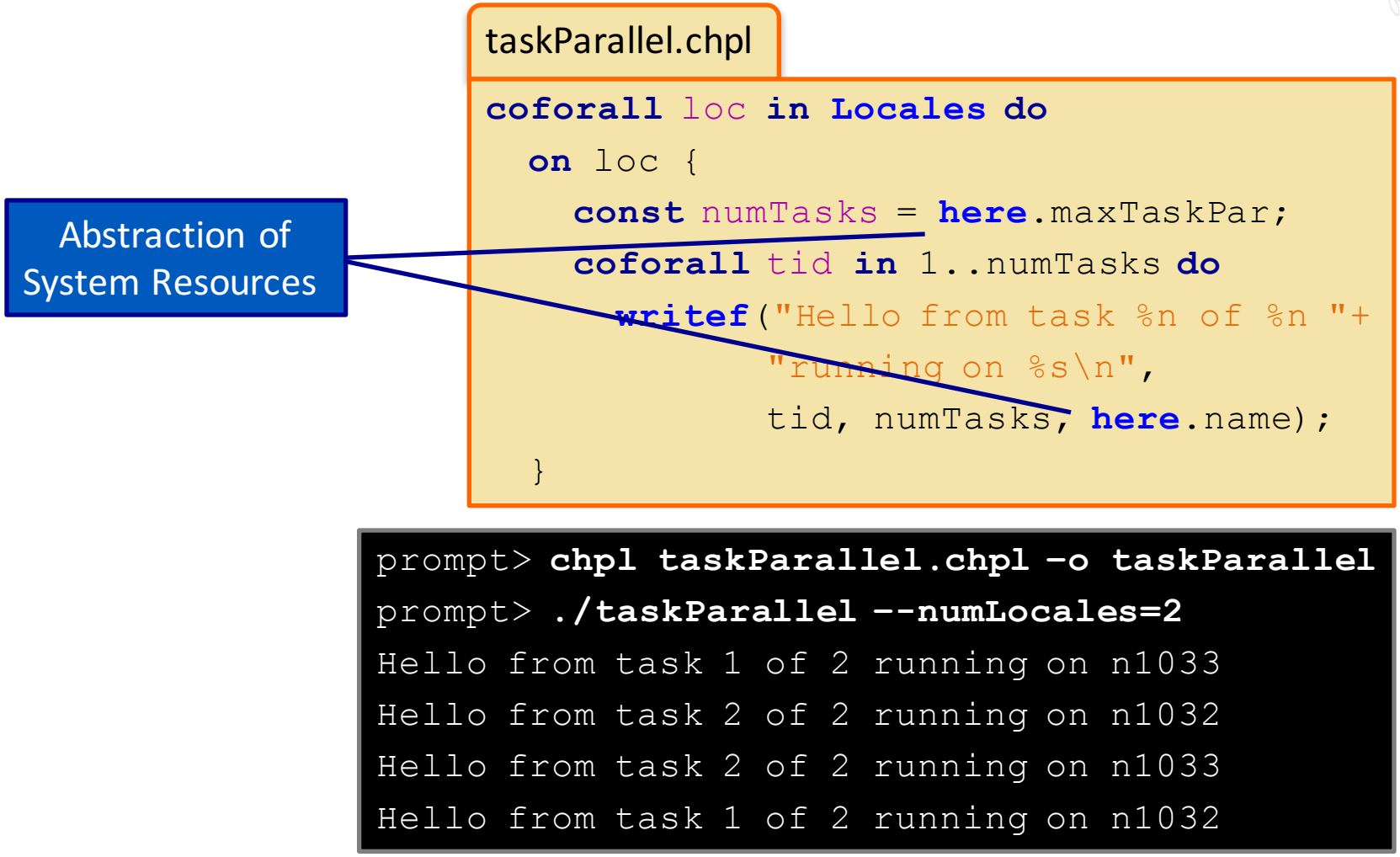
Control of Locality/Affinity

taskParallel.chpl

```
coforall loc in Locales do
  on loc {
    const numTasks = here.maxTaskPar;
    coforall tid in 1..numTasks do
      writef("Hello from task %n of %n "+
             "running on %s\n",
             tid, numTasks, here.name);
  }
```

```
prompt> chpl taskParallel.chpl -o taskParallel
prompt> ./taskParallel --numLocales=2
Hello from task 1 of 2 running on n1033
Hello from task 2 of 2 running on n1032
Hello from task 2 of 2 running on n1033
Hello from task 1 of 2 running on n1032
```

Task Parallelism, Locality Control, by example



Task Parallelism, Locality Control, by example

High-Level Task Parallelism

taskParallel.chpl

```
coforall loc in Locales do
  on loc {
    const numTasks = here.maxTaskPar;
    coforall tid in 1..numTasks do
      writef("Hello from task %n of %n "+
             "running on %s\n",
             tid, numTasks, here.name);
  }
```

```
prompt> chpl taskParallel.chpl -o taskParallel
prompt> ./taskParallel --numLocales=2
Hello from task 1 of 2 running on n1033
Hello from task 2 of 2 running on n1032
Hello from task 2 of 2 running on n1033
Hello from task 1 of 2 running on n1032
```

Task Parallelism, Locality Control, by example

taskParallel.chpl

```
coforall loc in Locales do
  on loc {
    const numTasks = here.maxTaskPar;
    coforall tid in 1..numTasks do
      writef("Hello from task %n of %n "+
             "running on %s\n",
             tid, numTasks, here.name);
  }
```

Not seen here:

Data-centric task coordination via atomic and full/empty vars

```
prompt> chpl taskParallel.chpl -o taskParallel
prompt> ./taskParallel --numLocales=2
Hello from task 1 of 2 running on n1033
Hello from task 2 of 2 running on n1032
Hello from task 2 of 2 running on n1033
Hello from task 1 of 2 running on n1032
```

Task Parallelism, Locality Control, by example

taskParallel.chpl

```
coforall loc in Locales do
  on loc {
    const numTasks = here.maxTaskPar;
    coforall tid in 1..numTasks do
      writef("Hello from task %n of %n "+
             "running on %s\n",
             tid, numTasks, here.name);
  }
```

```
prompt> chpl taskParallel.chpl -o taskParallel
prompt> ./taskParallel --numLocales=2
Hello from task 1 of 2 running on n1033
Hello from task 2 of 2 running on n1032
Hello from task 2 of 2 running on n1033
Hello from task 1 of 2 running on n1032
```

Parallelism and Locality: Orthogonal in Chapel

- This is a **parallel**, but local program:

```
coforall i in 1..msgs do
  writeln("Hello from task ", i);
```

- This is a **distributed**, but serial program:

```
writeln("Hello from locale 0!");
on Locales[1] do writeln("Hello from locale 1!");
on Locales[2] do writeln("Hello from locale 2!");
```

- This is a **distributed** **parallel** program:

```
coforall i in 1..msgs do
  on Locales[i%numLocales] do
    writeln("Hello from task ", i,
            " running on locale ", here.id);
```

ZPL and Chapel Resources

ZPL Resources

- **Project Page:**
  http://research.cs.washington.edu/zpl/home/index.html
- **Recommended Reading:**

  The Design and Development of ZPL. Lawrence Snyder. *HOPL III: Proceedings of the third ACM SIGPLAN conference on History of Programming Languages*, 8-1–8-37, 2007.

  The Design and Implementation of a Region-Based Parallel Language. Bradford Chamberlain. *Ph.D. Thesis*, University of Washington, September 2001.

Chapel Websites

Project page: http://chapel.cray.com

- overview, papers, presentations, language spec, …

GitHub: https://github.com/chapel-lang

- download Chapel; browse source repository; contribute code

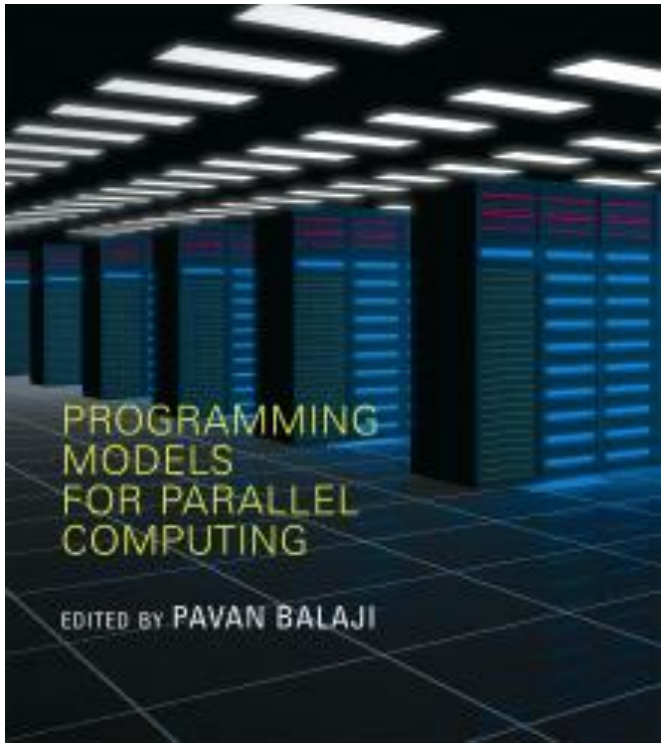
Facebook: https://www.facebook.com/ChapelLanguage

Twitter: https://twitter.com/ChapelLanguage

Suggested Reading

Chapel chapter from ***Programming Models for Parallel Computing***

- a detailed overview of Chapel's history, motivating themes, features
- edited by Pavan Balaji, published by MIT Press, November 2015
- chapter is now also available online



Other Chapel papers/publications available at **http://chapel.cray.com/papers.html**

Chapel Blog Articles

Chapel: Productive Parallel Programming, Cray Blog, May 2013.

- *a short-and-sweet introduction to Chapel*

Chapel Springs into a Summer of Code, Cray Blog, April 2016.

- *a run-down of some current events*

Six Ways to Say "Hello" in Chapel **(parts 1, 2, 3)**, Cray Blog, Sep-Oct 2015.

- *a series of articles illustrating the basics of parallelism and locality in Chapel*

Why Chapel? **(parts 1, 2, 3)**, Cray Blog, Jun-Oct 2014.

- *a series of articles answering common questions about why we are pursuing Chapel in spite of the inherent challenges*

[Ten] Myths About Scalable Programming Languages, IEEE TCSC Blog (index available on chapel.cray.com "blog articles" page), Apr-Nov 2012.

- *a series of technical opinion pieces designed to argue against standard reasons given for not developing high-level parallel languages*

Chapel Mailing Lists

low-traffic (read-only):

chapel-announce@lists.sourceforge.net: announcements about Chapel

community lists:

chapel-users@lists.sourceforge.net: user-oriented discussion list
chapel-developers@lists.sourceforge.net: developer discussions
chapel-education@lists.sourceforge.net: educator discussions
chapel-bugs@lists.sourceforge.net: public bug forum

(subscribe at SourceForge: http://sourceforge.net/p/chapel/mailman/**)**

To contact the Cray team:

chapel_info@cray.com: contact the team at Cray
chapel_bugs@cray.com: for reporting non-public bugs

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Questions?

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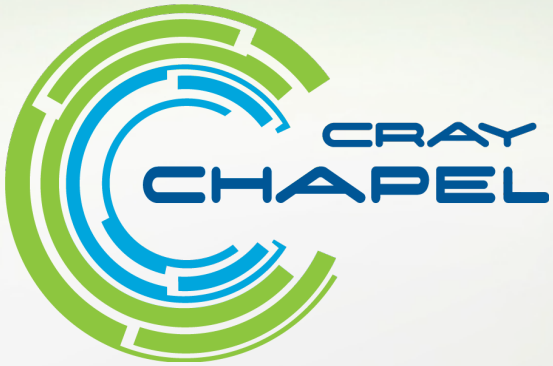

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