HPCC STREAM and RA in Chapel Performance and Potential

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What is Chapel?

- A new parallel language
  - Under development at Cray Inc.
  - Supported through the DARPA HPCS program
- Goals
  - **Improve programmer productivity**
  - Improve the programmability of parallel computers
  - Match or improve performance of MPI/UPC/CAF
  - Provide better portability than MPI/UPC/CAF
  - Improve robustness of parallel codes
  - Support multi-core and multi-node systems

Outline

- What is Chapel?
- Chapel's Parallel Programming Model
- HPCC STREAM Triad in Chapel
- HPCC RA in Chapel
- Summary and Future Work

Fragmented vs. Global-View: Definitions

- Programming model

  The mental model of a programmer
- Fragmented models

  Programmers take point-of-view of a single processor/thread
- SPMD models (Single Program, Multiple Data)

  Fragmented models with multiple copies of one program
- Global-view models

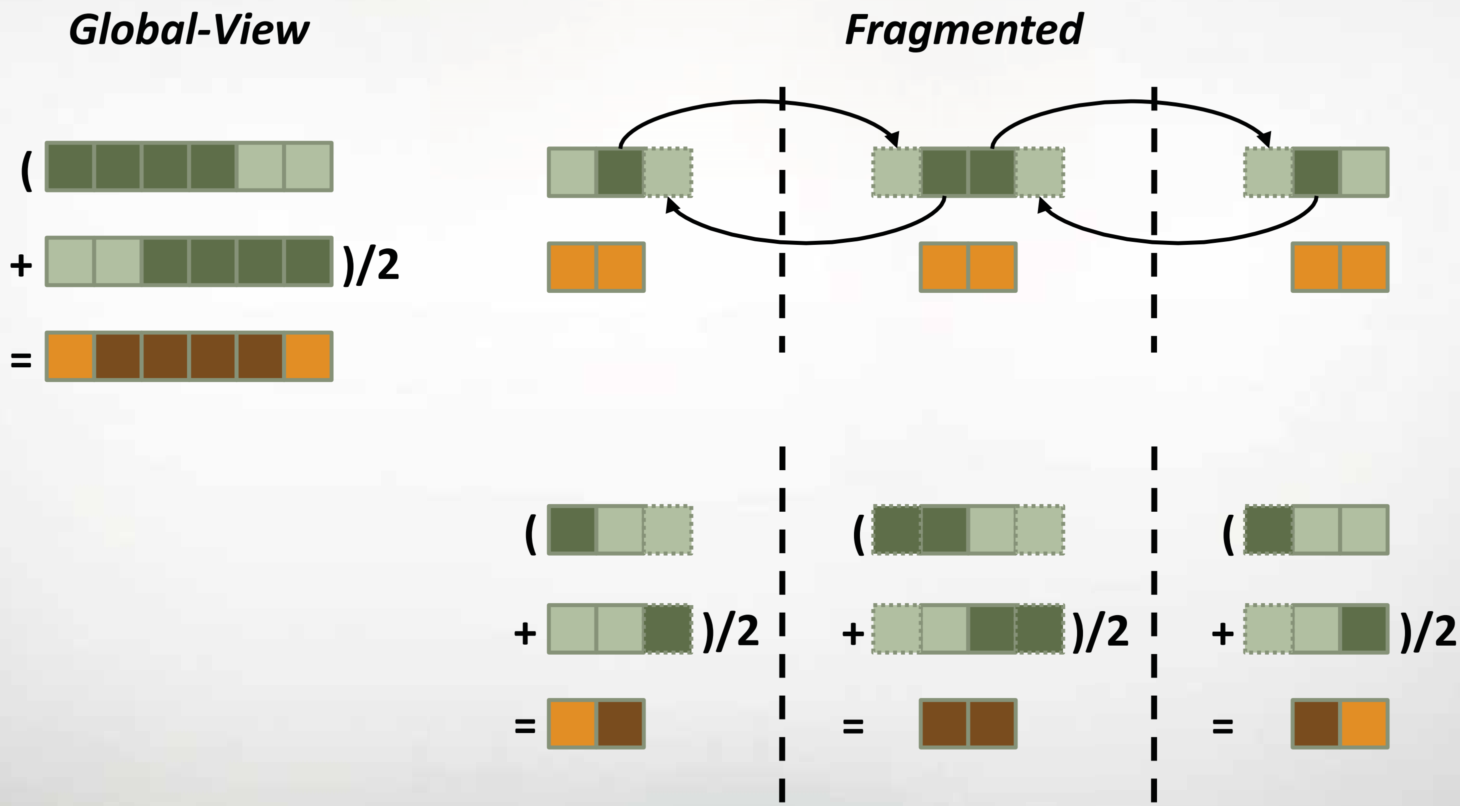
  Programmers write code to describe computation as a whole

3-Point Stencil Example (n=6)

	1					6
Initial state	2.0	0.0	0.0	0.0	0.0	12.0
Iteration 1	2.0	1.0	0.0	0.0	6.0	12.0
Iteration 2	2.0	1.0	0.5	3.0	6.0	12.0
Iteration 3	2.0	1.25	2.0	3.25	7.5	12.0
⋮						
Steady state	2.0	4.0	6.0	8.0	10.0	12.0

3-Point Stencil Example

Global-View vs. Fragmented Computation

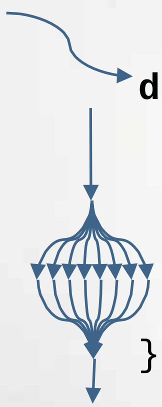


3-Point Stencil Example: Code

Global-View vs. Fragmented Code

Assumes p divides n

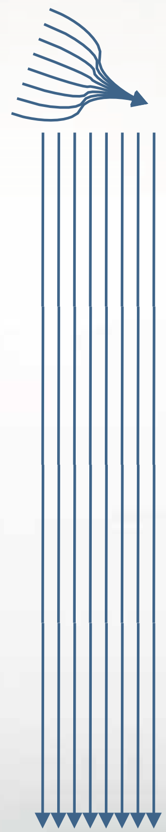
Global-View



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

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

Fragmented



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

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

NAS MG Stencil in Fortran + MPI, in Chapel

```fortran
use caf_intrinsics

 implicit none

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

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

 if( .not. dead(kk) )then
    do  axis = 1, 3
       if( nprocs .ne. 1) then
          call sync_all()
          call give3( axis, +1, u, n1, n2, n3,
      kk )
          call give3( axis, -1, u, n1, n2, n3,
      kk )
          call sync_all()
          call take3( axis, -1, u, n1, n2,
      n3 )
          call take3( axis, +1, u, n1, n2,
      n3 )
       else
          call comm1p( axis, u, n1, n2, n3,
      kk )
       endif
    enddo
 else
    do  axis = 1, 3
       call sync_all()
       call sync_all()
    enddo
    call zero3(u,n1,n2,n3)
 endif
 return
 end

 subroutine give3( axis, dir, u, n1, n2, n3,
      k )
 use caf_intrinsics


 implicit none

 include 'cafnpb.h'
 include 'globals.h'  subroutine
      comm3(u,n1,n2,n3,kk)

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

 integer i3, i2, i1, buff_len,buff_id

 buff_id = 2 + dir
 buff_len = 0

 if( axis .eq.  1 )then
    if( dir .eq. -1 )then

       do  i3=2,n3-1
          do  i2=2,n2-1
             buff_len = buff_len + 1
             buff(buff_len,buff_id ) = u( 2,
      i2,i3)
          enddo
       enddo

       buff(1:buff_len,buff_id+1)
      [nbr(axis,dir,k)] =
>      buff(1:buff_len,buff_id)

    else if( dir .eq. +1 ) then

       do  i3=2,n3-1
          do  i2=2,n2-1
             buff_len = buff_len + 1
             buff(buff_len, buff_id ) =
      u( n1-1, i2,i3)
             enddo
          enddo

          buff(1:buff_len,buff_id+1)
      [nbr(axis,dir,k)] =
>         buff(1:buff_len,buff_id)

       endif
    endif

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

     buff(1:buff_len,buff_id+1)[nbr(axis,dir,k)]
          =
>         buff(1:buff_len,buff_id)
 else if( dir .eq. +1 ) then

          do  i3=2,n3-1
             do  i1=1,n1
                buff_len = buff_len + 1
                buff(buff_len,  buff_id )=
          u( i1,n2-1,i3)
             enddo
          enddo

          buff(1:buff_len,buff_id+1)
          [nbr(axis,dir,k)] =
>         buff(1:buff_len,buff_id)

       endif
    endif

    if( axis .eq.  3 )then
       if( dir .eq. -1 )then

          do  i2=1,n2
             do  i1=1,n1
                buff_len = buff_len + 1
                buff(buff_len, buff_id ) =
          u( i1,i2,2)
             enddo
          enddo

          buff(1:buff_len,buff_id+1)
          [nbr(axis,dir,k)] =
>         buff(1:buff_len,buff_id)

       else if( dir .eq. +1 ) then

          do  i2=1,n2
             do  i1=1,n1
                buff_len = buff_len + 1
                buff(buff_len, buff_id ) =
          u( i1,i2,n3-1)
             enddo
          enddo

          buff(1:buff_len,buff_id+1)
          [nbr(axis,dir,k)] =
>         buff(1:buff_len,buff_id)

       endif
    endif

    return
    end


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

 implicit none

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

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

 integer buff_id, indx

 integer i3, i2, i1

 buff_id = 3 + dir
 indx = 0

 if( axis .eq.  1 )then
    if( dir .eq. -1 )then

       do  i3=2,n3-1
          do  i2=2,n2-1
             indx = indx + 1
             u(n1,i2,i3) = buff(indx,
    buff_id )
          enddo
       enddo

    else if( dir .eq. +1 ) then

       do  i3=2,n3-1
          do  i2=2,n2-1
             indx = indx + 1
             u(1,i2,i3) = buff(indx, buff_id )
          enddo
       enddo

    endif
 endif

 if( axis .eq.  2 )then
    if( dir .eq. -1 )then

       do  i3=2,n3-1
          do  i1=1,n1
             indx = indx + 1
             u(i1,n2,i3) = buff(indx,
    buff_id )
          enddo
       enddo

    else if( dir .eq. +1 ) then

       do  i3=2,n3-1
          do  i1=1,n1
             indx = indx + 1
             u(i1,1,i3) = buff(indx, buff_id )
          enddo
       enddo

    endif
 endif

 if( axis .eq.  3 )then
    if( dir .eq. -1 )then

       do  i2=1,n2
          do  i1=1,n1
             indx = indx + 1
             u(i1,i2,n3) = buff(indx,
    buff_id )
          enddo
       enddo

    else if( dir .eq. +1 ) then

       do  i2=1,n2
          do  i1=1,n1
             indx = indx + 1
             u(i1,i2,1) = buff(indx, buff_id )
          enddo
       enddo

    endif
 endif

 return
 end


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


 implicit none

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

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

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

 dir = -1

 buff_id = 3 + dir
 buff_len = nm2

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


 dir = +1

 buff_id = 3 + dir
 buff_len = nm2

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

 dir = +1

 buff_id = 2 + dir
 buff_len = 0

 if( axis .eq.  1 )then
    do  i3=2,n3-1
       do  i2=2,n2-1
          buff_len = buff_len + 1
          buff(buff_len, buff_id ) = u( n1-1,
     i2,i3)
       enddo
    enddo
 endif

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

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

 endif

 dir = -1

 buff_id = 2 + dir
 buff_len = 0

 if( axis .eq.  1 )then
    do  i3=2,n3-1
       do  i2=2,n2-1
          buff_len = buff_len + 1
          buff(buff_len,buff_id ) = u( 2,
    i2,i3)
       enddo
    enddo
 endif

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

 if( axis .eq.  3 )then
    do  i2=1,n2
       do  i1=1,n1
          buff_len = buff_len + 1
          buff(buff_len, buff_id ) =
     u( i1,i2,2)
       enddo
    enddo
 endif

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

 dir = -1

 buff_id = 3 + dir
 indx = 0

 if( axis .eq.  1 )then
    do  i3=2,n3-1
       do  i2=2,n2-1
          indx = indx + 1
          u(n1,i2,i3) = buff(indx, buff_id )
       enddo
    enddo
 endif

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

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

 dir = +1

 buff_id = 3 + dir
 indx = 0

 if( axis .eq.  1 )then
    do  i3=2,n3-1
       do  i2=2,n2-1
          indx = indx + 1
          u(1,i2,i3) = buff(indx, buff_id )
       enddo
    enddo
 endif

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

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

 return
 end

 subroutine
       rprj3(r,m1k,m2k,m3k,s,m1j,m2j,m3j,k)
 implicit none
 include 'cafnpb.h'
 include 'globals.h'

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

 double precision r(m1k,m2k,m3k),
       s(m1j,m2j,m3j)
 integer j3, j2, j1, i3, i2, i1, d1, d2, d3, j
 double precision x1(m), y1(m), x2,y2

 if(m1k.eq.3)then
    d1 = 2
 else
    d1 = 1
 endif

 if(m2k.eq.3)then
    d2 = 2
 else
    d2 = 1
 endif

 if(m3k.eq.3)then
    d3 = 2
 else
    d3 = 1
 endif

 do  j3=2,m3j-1
   i3 = 2*j3-d3
   do  j2=2,m2j-1
     i2 = 2*j2-d2
      do j1=2,m1j
        i1 = 2*j1-d1
        x1(i1-1) = r(i1-1,i2-1,i3  ) +
        r(i1-1,i2+1,i3  )
>                + r(i1-1,i2,  i3-1) +
        r(i1-1,i2,  i3+1)
        y1(i1-1) = r(i1-1,i2-1,i3-1) +
         r(i1-1,i2-1,i3+1)
>                 + r(i1-1,i2+1,i3-1) +
        r(i1-1,i2+1,i3+1)
     enddo
     do  j1=2,m1j-1
       i1 = 2*j1-d1
       y2 = r(i1,  i2-1,i3-1) + r(i1,
         i2-1,i3+1)
>        + r(i1,  i2+1,i3-1) + r(i1,
        i2+1,i3+1)
       x2 = r(i1,  i2-1,i3  ) + r(i1,
         i2+1,i3  )
>        + r(i1,  i2,  i3-1) + r(i1,  i2,
        i3+1)
       s(j1,j2,j3) =
>            0.5D0 * r(i1,i2,i3)
>         + 0.25D0 * (r(i1-1,i2,i3) +
         r(i1+1,i2,i3) + x2)
>         + 0.125D0 * ( x1(i1-1) + x1(i1+1) +
         y2)
>         + 0.0625D0 * ( y1(i1-1) + y1(i1+1) )
     enddo
   enddo
 enddo
 j = k-1
 call comm3(s,m1j,m2j,m3j,j)
 return
 end
```

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

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

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- Chapel's Parallel Programming Model
- HPCC STREAM Triad in Chapel
- HPCC RA in Chapel
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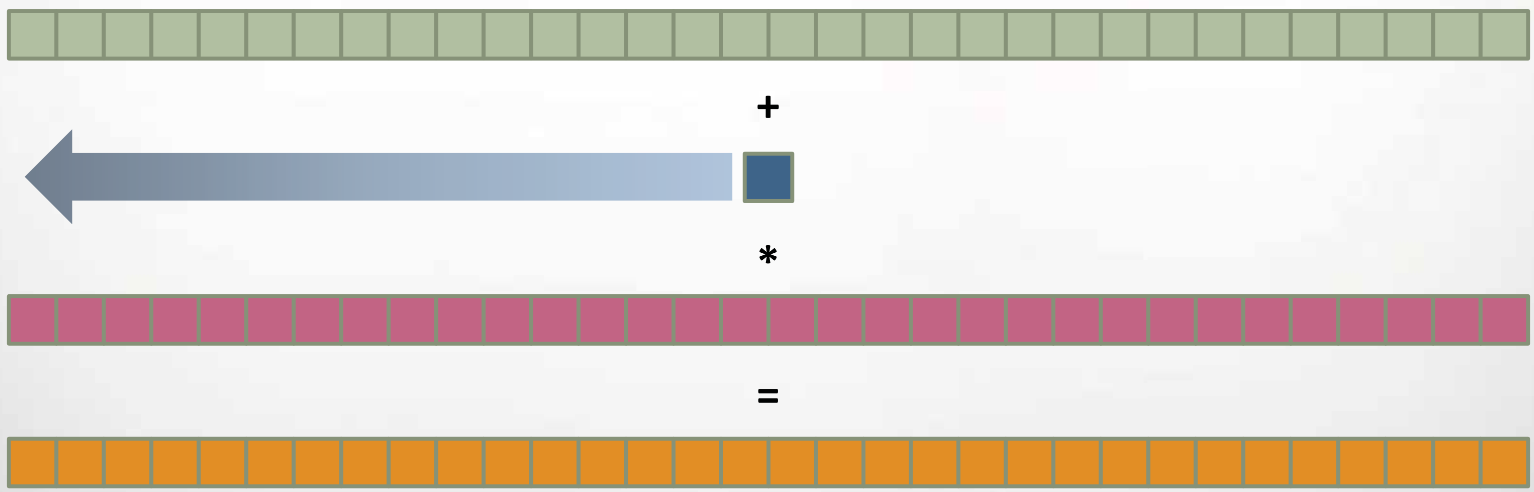
Introduction to STREAM Triad

Given: *m*-element vectors *A*, *B*, *C*

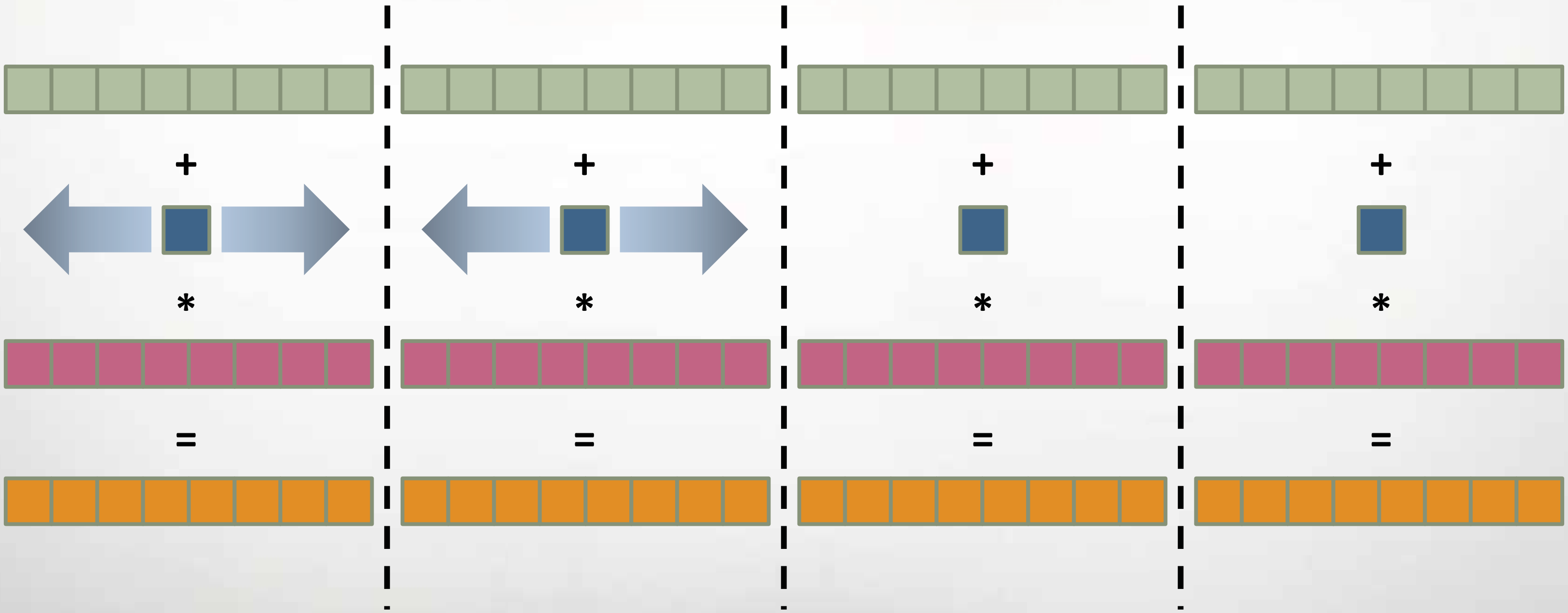
Compute:
```
forall i in 1..m do
   A(i) = B(i) + α * C(i);
```



Distributed Parallelization of STREAM Triad

Given: *m*-element vectors *A*, *B*, *C*

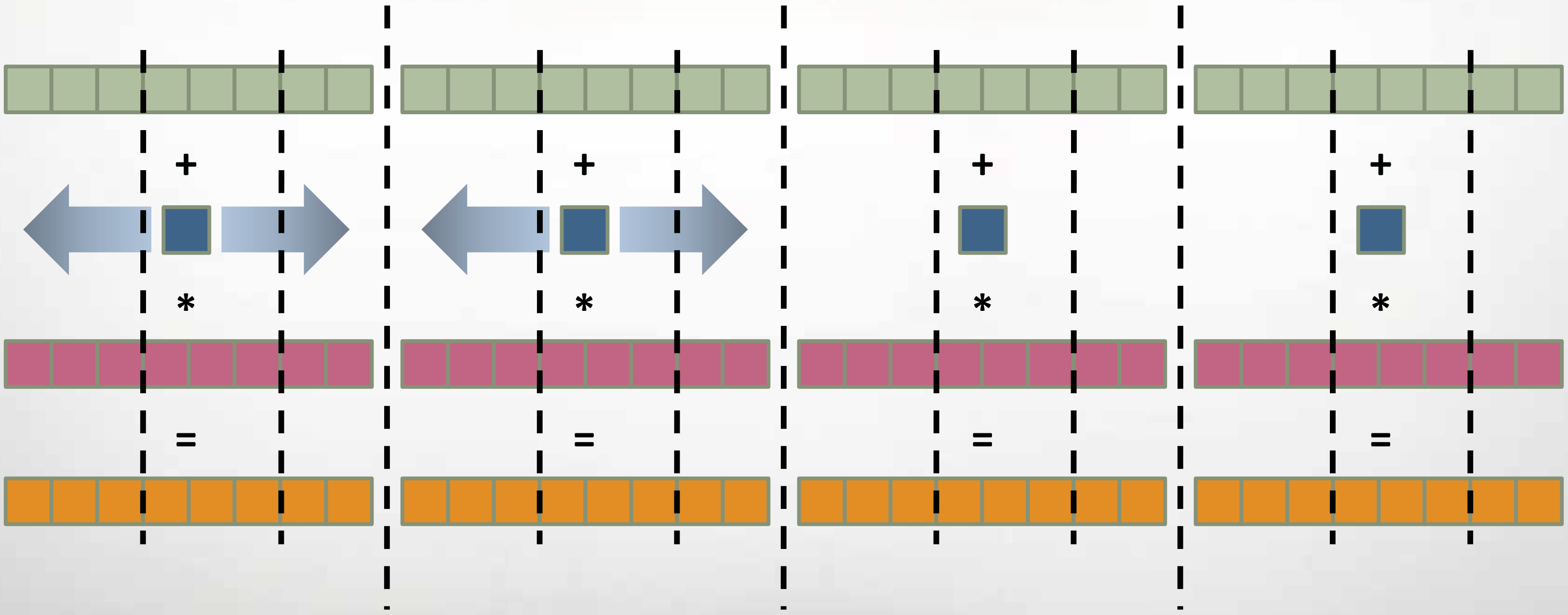
Compute:
```
forall i in 1..m do
  A(i) = B(i) + α * C(i);
```



Further Parallelization of STREAM Triad

Given: *m*-element vectors *A*, *B*, *C*

Compute:
```
forall i in 1..m do
   A(i) = B(i) + α * C(i);
```



STREAM Triad in Chapel: Single Locale

Given: *m*-element vectors *A*, *B*, *C*

Compute:
```
forall i in 1..m do
  A(i) = B(i) + α * C(i);
```

```
config const m: int(64) = ...;
const alpha: real = 3.0;
const ProblemSpace: domain(1,int(64)) = [1..m];
var A, B, C: [ProblemSpace] real;

forall i in ProblemSpace do
  A(i) = B(i) + alpha * C(i);
```

STREAM Triad in Chapel: Single Locale

Given: *m*-element vectors *A*, *B*, *C*

Compute:
```
forall i in 1..m do
   A(i) = B(i) + α * C(i);
```

```
config const m: int(64) = ...;
const alpha: real = 3.0;
const ProblemSpace: domain(1,int(64)) = [1..m];
var A, B, C: [ProblemSpace] real;

A = B + alpha * C;
```

More concise variation using whole array operations

STREAM Triad in Chapel: Single Locale

Given: *m*-element vectors *A*, *B*, *C*

Compute:
```
forall i in 1..m do
   A(i) = B(i) + α * C(i);
```

```
config const m: int(64) = ...;
const alpha: real = 3.0;
const ProblemSpace: domain(1,int(64)) = [1..m];
var A, B, C: [ProblemSpace] real;

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

Variation that iterates directly over the arrays

STREAM Triad in Chapel: Multi-Locale

Given: *m*-element vectors *A*, *B*, *C*

Compute:
```
forall i in 1..m do
    A(i) = B(i) + α * C(i);
```

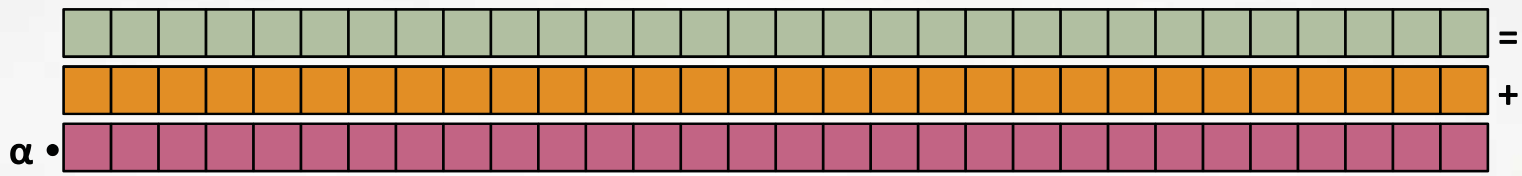
```
config const m: int(64) = ..., tpl = ...;
const alpha: real = 3.0;
const BlockDist = new Block(1,int(64),[1..m],tpl);
const ProblemSpace: domain(1, int(64))
                        distributed BlockDist = [1..m];
var A, B, C: [ProblemSpace] real;

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

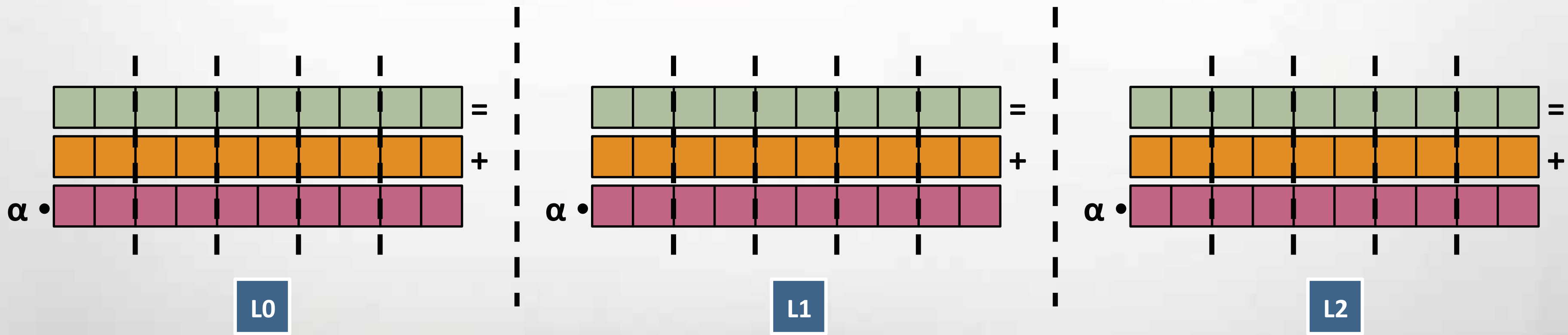
What is a Distribution?

A “recipe” for distributed arrays that...

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



...to a fragmented, per-processor implementation



STREAM Triad in Chapel: Multi-Locale

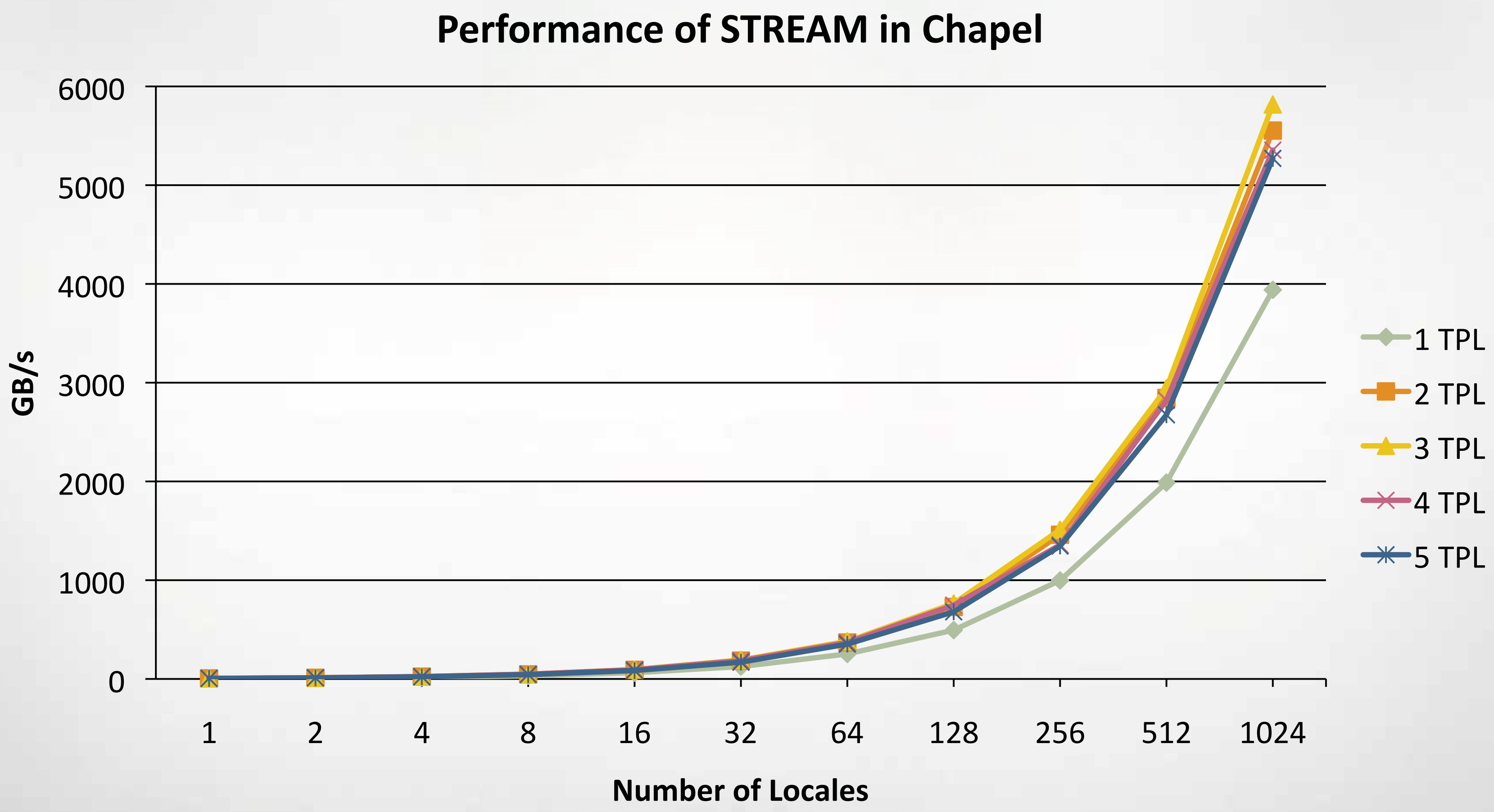
Given: *m*-element vectors *A*, *B*, *C*

Compute:
```
forall i in 1..m do
   A(i) = B(i) + α * C(i);
```

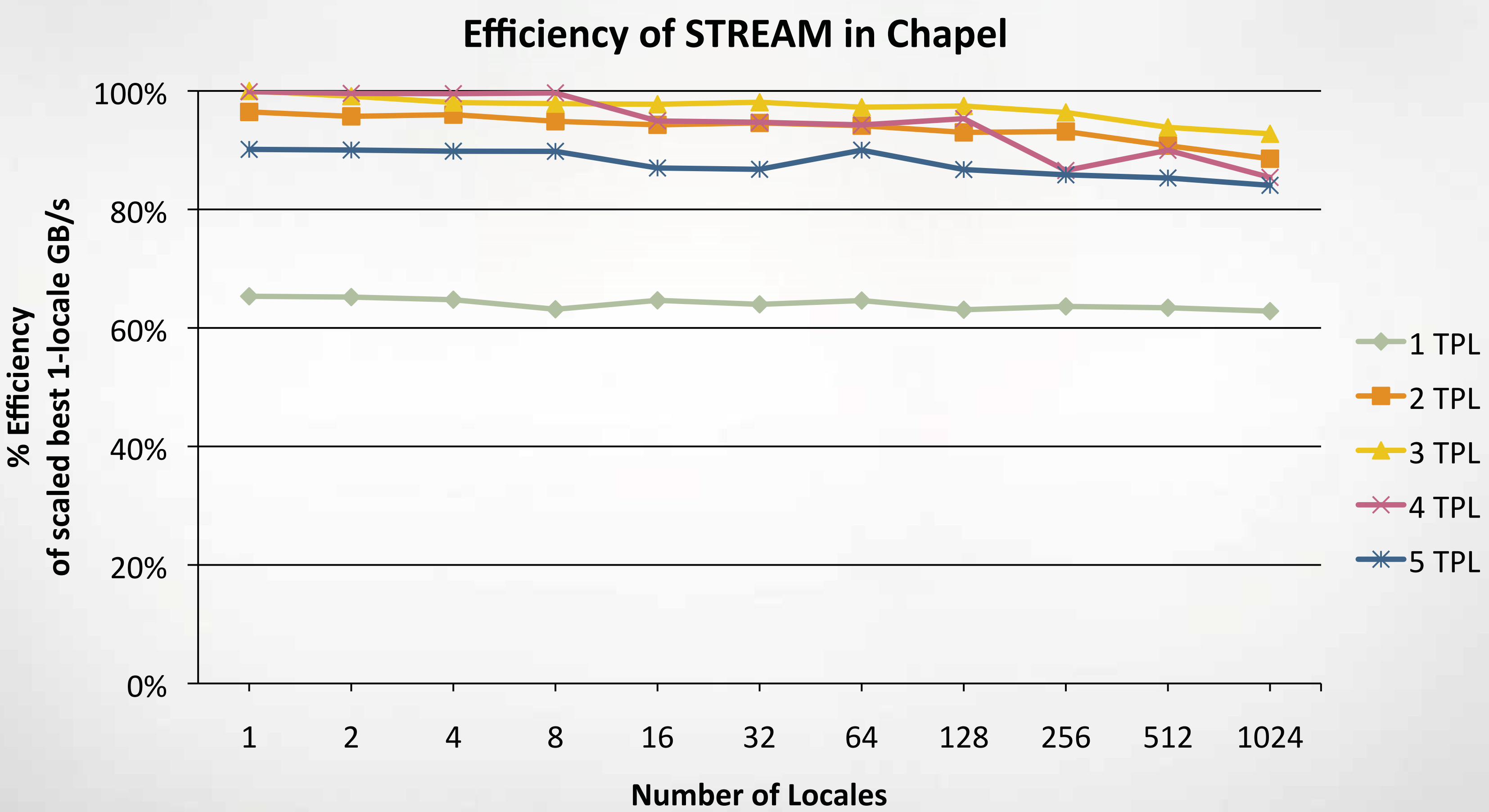
```
config const m: int(64) = ..., tpl = ...;
const alpha: real = 3.0;
const BlockDist = new Block(1,int(64),[1..m],tpl);
const ProblemSpace: domain(1, int(64))
                    distributed BlockDist = [1..m];
var A, B, C: [ProblemSpace] real;

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

HPCC STREAM Performance



HPCC STREAM Efficiency



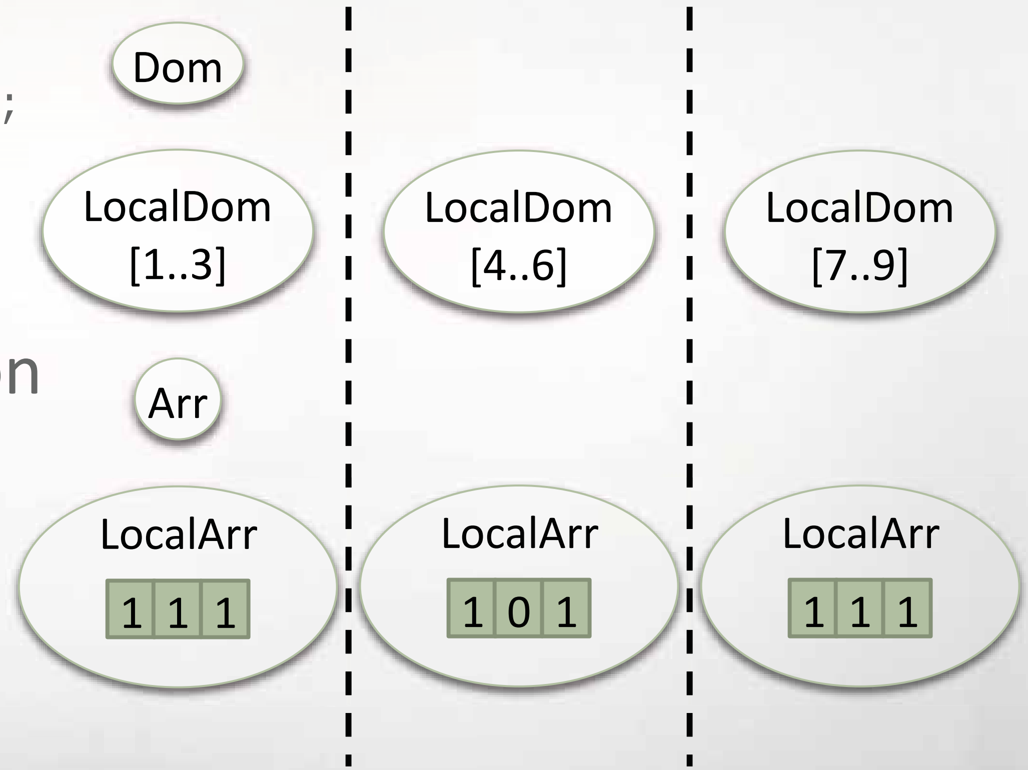
Optimization: Privatization

Simple example

```
var Dist: Block(1,int(64));
var Dom: domain(1,int(64))
             distributed Dist;
var Arr: [Dom] int;
```

Reference to local data
requires communication

```
on Locales(1) {
  Arr(5) = 0;
}
```



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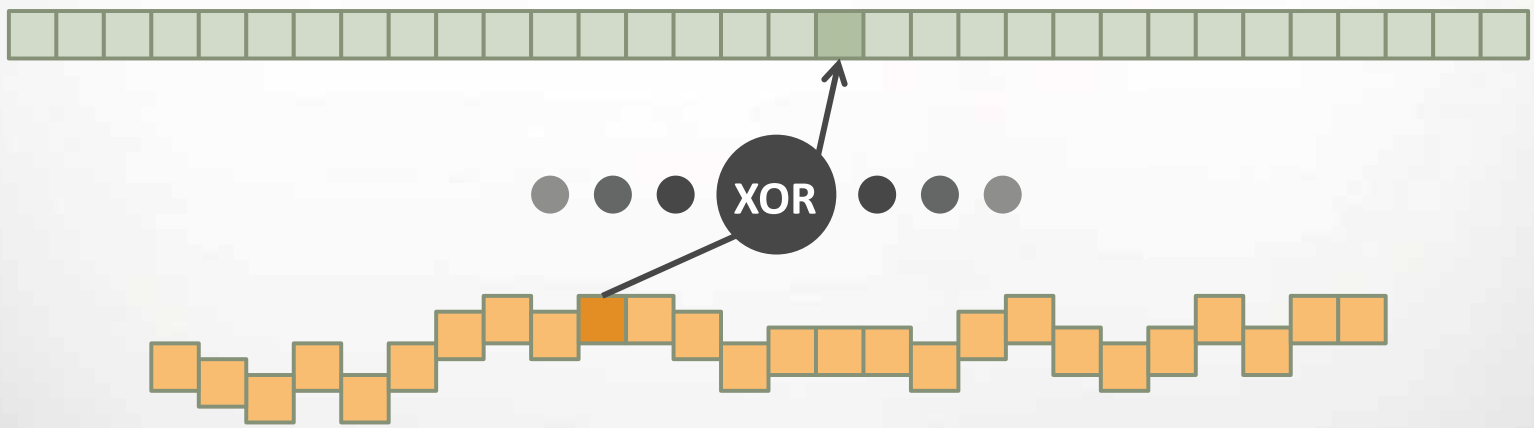
Introduction to RA

Given: *m*-element table *T* (where $m = 2^n$)

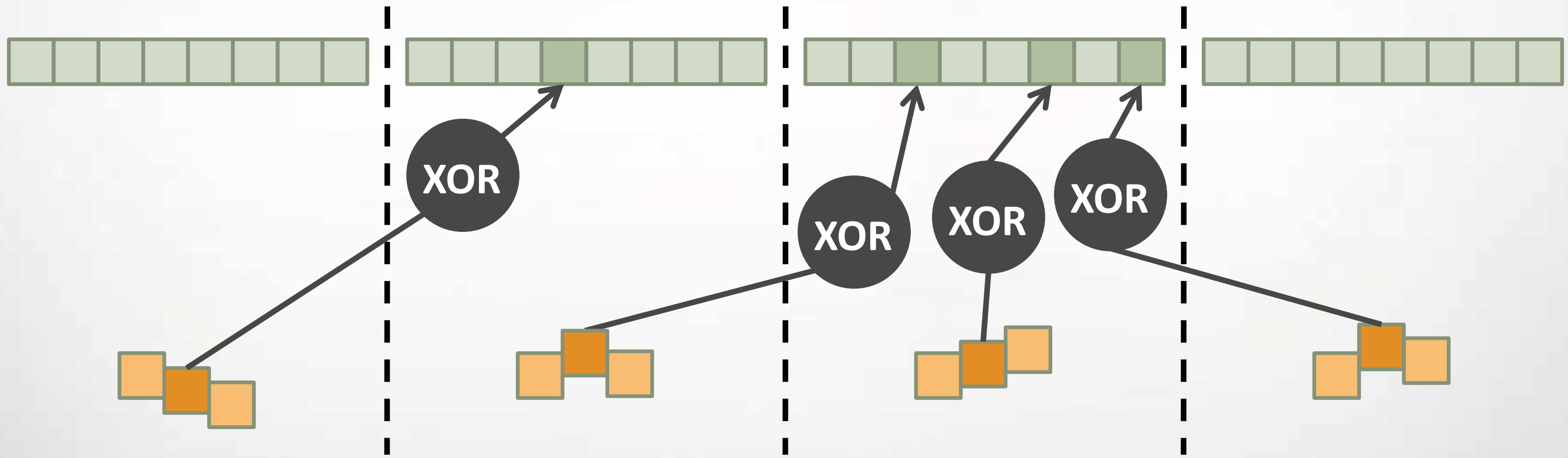
Compute:
```
forall r in RandomUpdates do
    T(r & (m-1)) ^= r;
```



Distributed Parallelization of RA

Given: *m*-element table *T* (where $m = 2^n$)

Compute:
```
forall r in RandomUpdates do
    T(r & (m-1)) ^= r;
```



RA in Chapel: Single Locale

Given: *m*-element table *T* (where $m = 2^n$)

Compute:
```
forall r in RandomUpdates do
  T(r & (m-1)) ^= r;
```

```
config const m = ..., N_U = ...;
const TableSpace: domain(1,uint(64)) = [0..m-1],
      Updates: domain(1,uint(64)) = [0..N_U-1];
var T: [TableSpace] uint(64);

forall (i,r) in (Updates,RAStream()) do
  T(r & (m-1)) ^= r;
```

RA in Chapel: Multi-Locale

Given: *m*-element table *T* (where $m = 2^n$)

Compute:
```
forall r in RandomUpdates do
  T(r & (m-1)) ^= r;
```

```
config const m = ..., N_U = ..., tpl = ...;
const TableDist = new Block(1,uint(64),[0..m-1],tpl),
      UpdateDist = new Block(1,uint(64),[0..N_U-1],tpl),
      TableSpace: domain(1,uint(64))
                     distributed TableDist = [0..m-1],
      Updates: domain(1,uint(64))
                  distributed UpdateDist = [0..N_U-1];
var T: [TableSpace] uint(64);

forall (i,r) in (Updates,RAStream()) do
  on T(r & (m-1)) do
    T(r & (m-1)) ^= r;
```

RA in Chapel: Multi-Locale

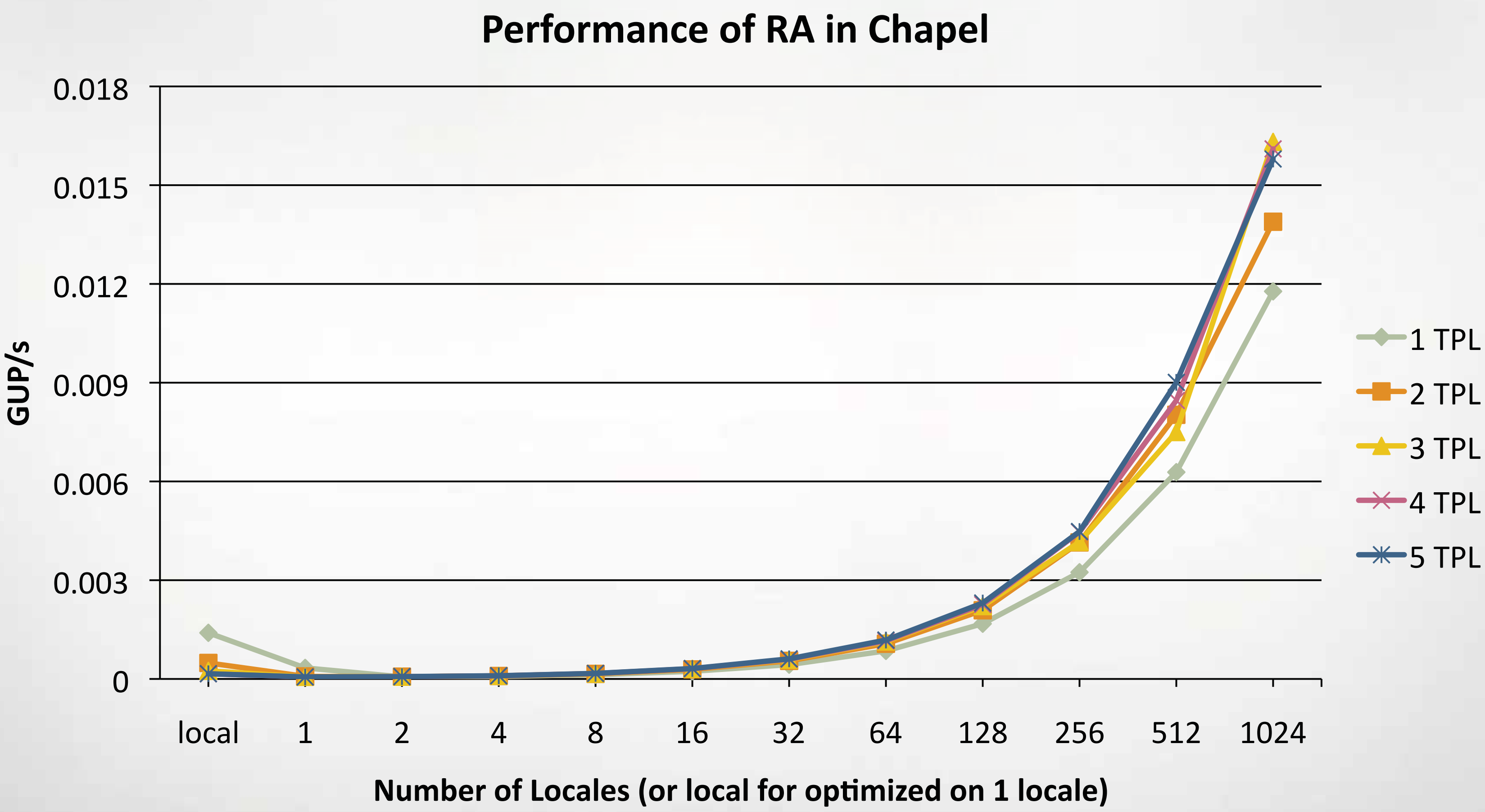
Given: *m*-element table *T* (where $m = 2^n$)

Compute:
```
forall r in RandomUpdates do
    T(r & (m-1)) ^= r;
```

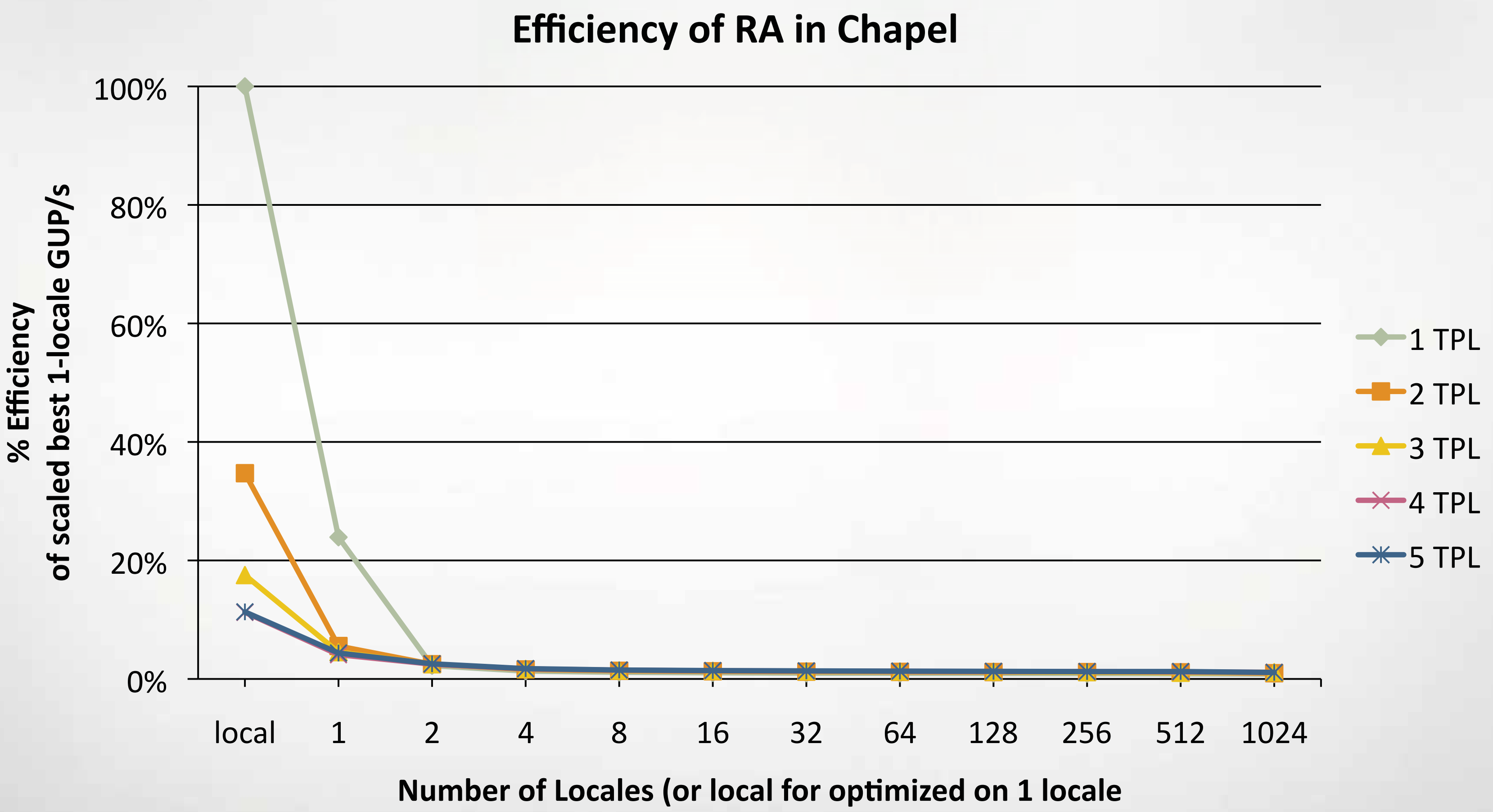
```
config const m = ..., N_U = ..., tpl = ...;
const TableDist = new Block(1,uint(64),[0..m-1],tpl),
      UpdateDist = new Block(1,uint(64),[0..N_U-1],tpl),
      TableSpace: domain(1,uint(64))
                     distributed TableDist = [0..m-1],
      Updates: domain(1,uint(64))
                  distributed UpdateDist = [0..N_U-1];
var T: [TableSpace] uint(64);

forall (i,r) in (Updates,RAStream()) do
  on T.domain.dist.ind2loc(r & (m-1)) do
    T(r & (m-1)) ^= r;
```

Call ind2loc method directly

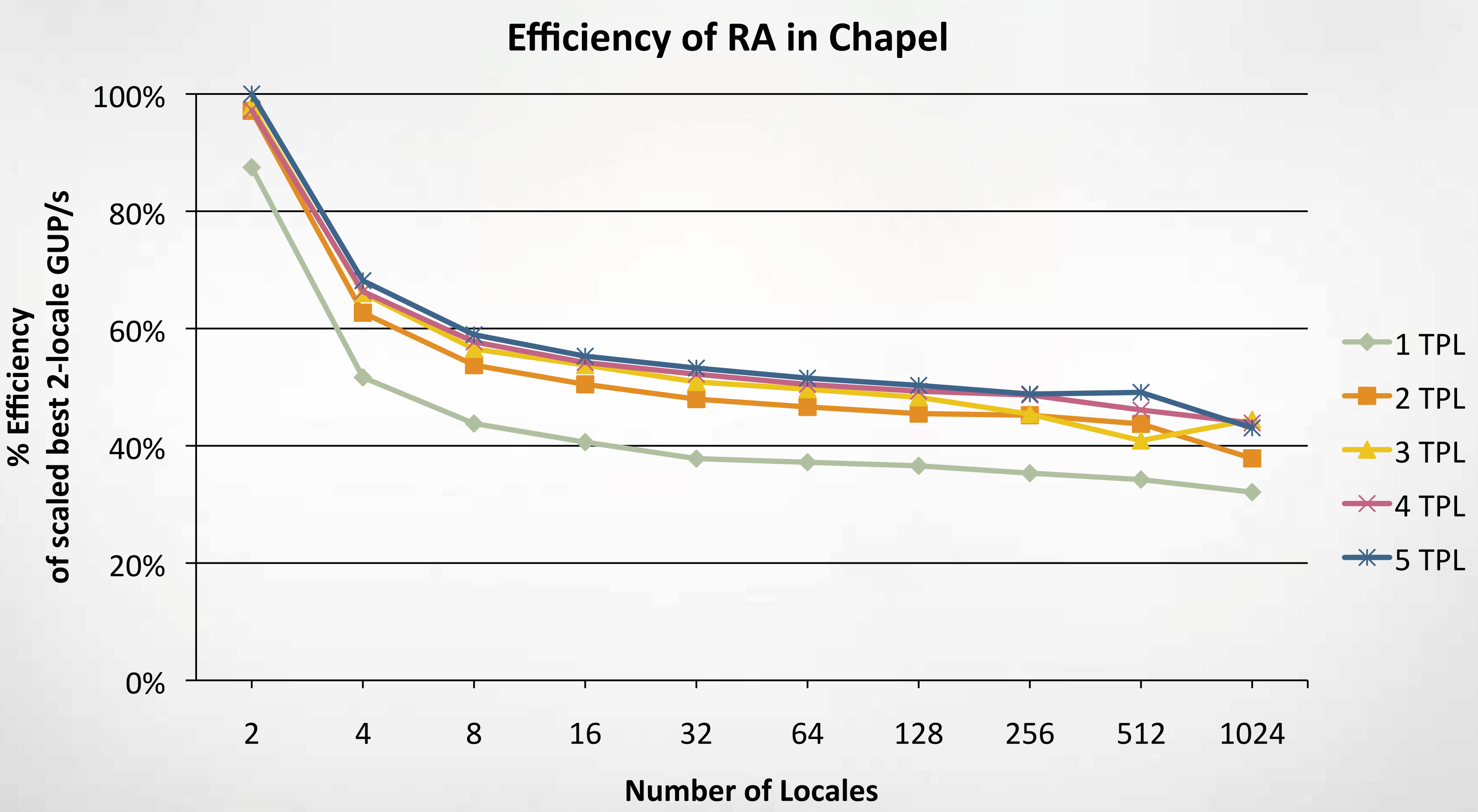
HPCC RA Performance



HPCC RA Efficiency I



HPCC RA Efficiency II



Optimization: Remote Value Forwarding

Simple example

```
var Arr: [Dom] int;
var r: int;
on Locales(1) {
  Arr(r) ^= r;
}
```

Outline

- What is Chapel?
- Chapel's Parallel Programming Model
- HPCC STREAM Triad in Chapel
- HPCC RA in Chapel
- Summary and Future Work

Summary

The global-view programming model is easy to use.

- Shorter, more concise code
- Separation of concerns (partitioning)
- Easy to change data distributions

Distributions implement the global-view model.

- Flexible mechanism for experimentation
- Implementation of distributions is in Chapel

Future Work

- Optimizations
  - Within the compiler
  - Within the runtime
  - Within the distributions
- Complete implementation of Block distribution
- Implement new distributions
  - Cyclic, BlockCyclic, RecursiveBisection
- Experiment with variations of STREAM and RA

Questions?