Chapel: Background

Sustained Performance Milestones

1 GF – 1988: Cray Y-MP; 8 Processors

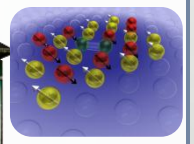
- Static finite element analysis

1 TF – 1998: Cray T3E; 1,024 Processors

- Modeling of metallic magnet atoms

1 PF – 2008: Cray XT5; 150,000 Processors

- Superconductive materials



1 EF – ~2018: Cray ____; ~10,000,000 Processors

- TBD

Sustained Performance Milestones

1 GF – 1988: Cray Y-MP; 8 Processors

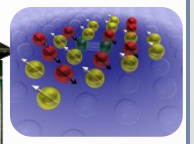
- Static finite element analysis
- Fortran77 + Cray autotasking + vectorization

1 TF – 1998: Cray T3E; 1,024 Processors

- Modeling of metallic magnet atoms
- Fortran + MPI (?)

1 PF – 2008: Cray XT5; 150,000 Processors

- Superconductive materials
- C++/Fortran + MPI + vectorization



1 EF – ~2018: Cray ____; ~10,000,000 Processors

- TBD
- TBD: C/C++/Fortran + MPI + CUDA/OpenCL/OpenMP/??? or ???

Why Do HPC Programming Models Change?

HPC has traditionally given users…

…low-level, *control-centric* programming models

…ones that are closely tied to the underlying hardware

benefits: lots of control; decent generality; easy to implement

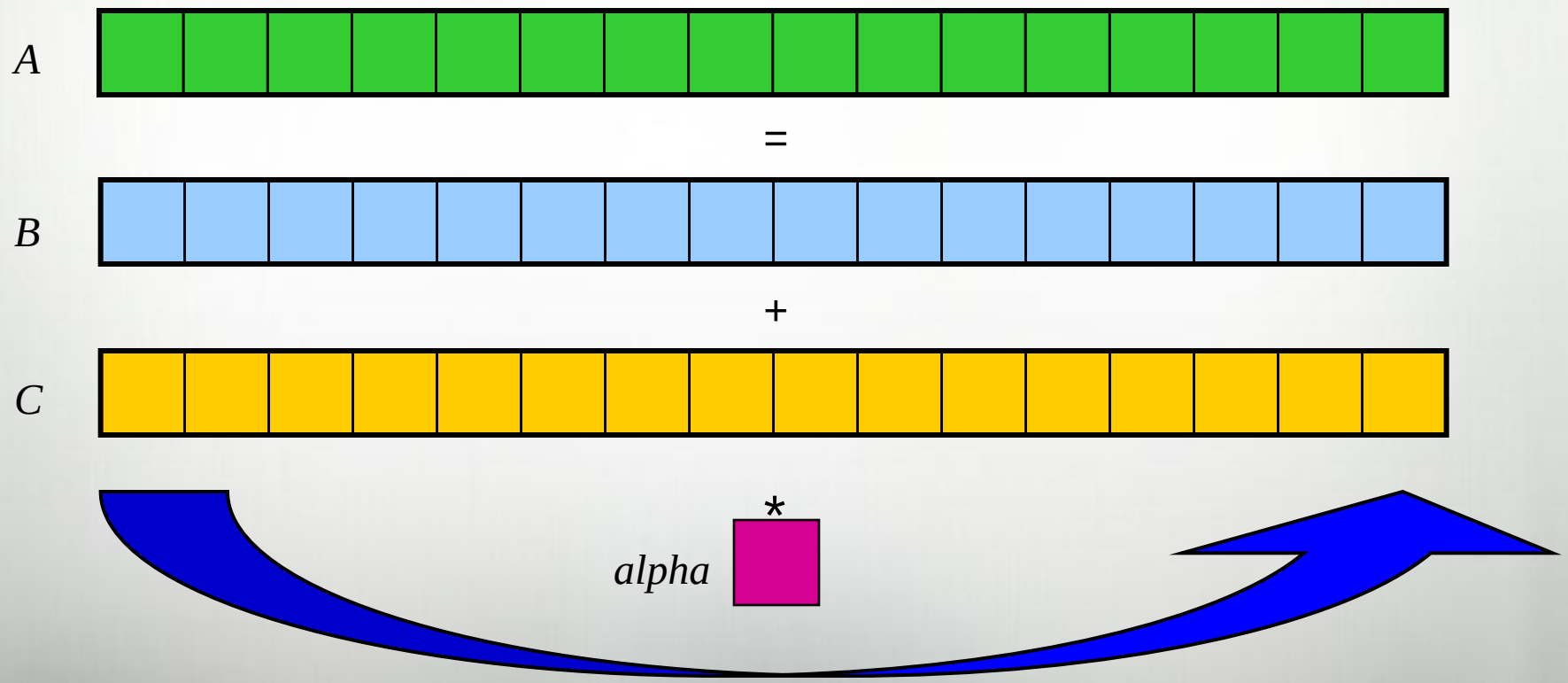
downsides: lots of user-managed detail; brittle to changes

Introduction to STREAM Triad

Given: m-element vectors A, B, C

Compute: $\forall i \in 1..m,\ A_i = B_i + \alpha \cdot C_i$

Pictorially:

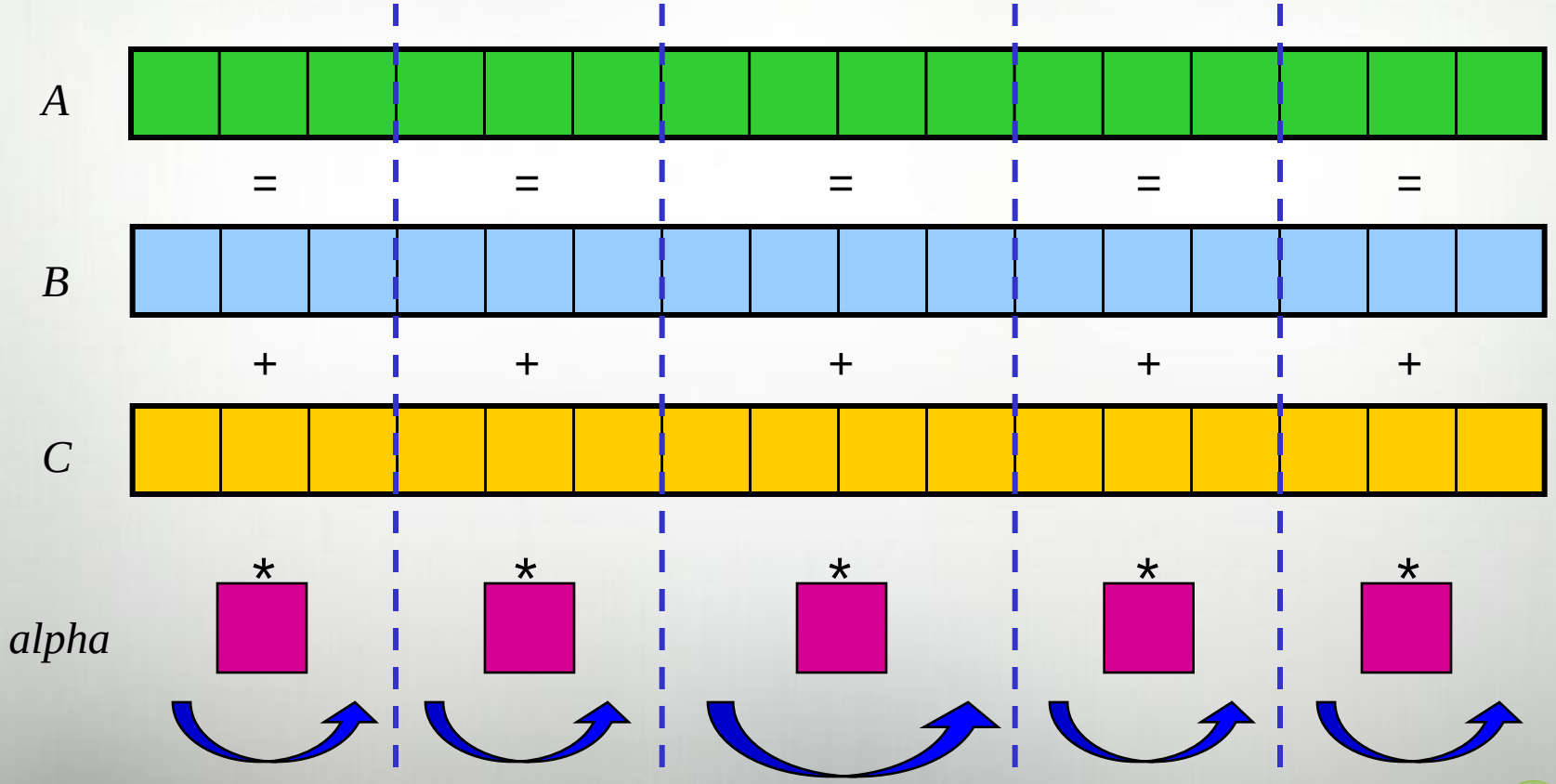


Introduction to STREAM Triad

Given: m-element vectors A, B, C

Compute: $\forall i \in 1..m,\ A_i = B_i + \alpha \cdot C_i$

Pictorially (in parallel):



A Few Versions of STREAM Triad

MPI

```
#include <hpcc.h>

static int VectorSize;
static double *a, *b, *c;

int HPCC_StarStream(HPCC_Params *params) {
  int myRank, commSize;
  int rv, errCount;
  MPI_Comm comm = MPI_COMM_WORLD;

  MPI_Comm_size( comm, &commSize );
  MPI_Comm_rank( comm, &myRank );

  rv = HPCC_Stream( params, 0 == myRank);
  MPI_Reduce( &rv, &errCount, 1, MPI_INT, MPI_SUM,
    0, comm );

  return errCount;
}

int HPCC_Stream(HPCC_Params *params, int doIO) {
  register int j;
  double  scalar;

  VectorSize = HPCC_LocalVectorSize( params, 3,
    sizeof(double), 0 );

  a = HPCC_XMALLOC( double, VectorSize );
  b = HPCC_XMALLOC( double, VectorSize );
  c = HPCC_XMALLOC( double, VectorSize );

  if (!a || !b || !c) {
    if (c) HPCC_free(c);
    if (b) HPCC_free(b);
    if (a) HPCC_free(a);
    if (doIO) {
      fprintf( outFile, "Failed to allocate memory
    (%d).\n", VectorSize );
      fclose( outFile );
    }
    return 1;
  }

  for (j=0; j<VectorSize; j++) {
    b[j] = 2.0;
    c[j] = 0.0;
  }

  scalar = 3.0;

  for (j=0; j<VectorSize; j++)
    a[j] = b[j]+scalar*c[j];

  HPCC_free(c);
  HPCC_free(b);
  HPCC_free(a);

  return 0;
}
```

A Few Versions of STREAM Triad

MPI + OpenMP

```
#include <hpcc.h>
#ifdef _OPENMP
#include <omp.h>
#endif

static int VectorSize;
static double *a, *b, *c;

int HPCC_StarStream(HPCC_Params *params) {
  int myRank, commSize;
  int rv, errCount;
  MPI_Comm comm = MPI_COMM_WORLD;

  MPI_Comm_size( comm, &commSize );
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    if (b) HPCC_free(b);
    if (a) HPCC_free(a);
    if (doIO) {
      fprintf( outFile, "Failed to allocate memory
    (%d).\n", VectorSize );
      fclose( outFile );
    }
    return 1;
  }

#ifdef _OPENMP
#pragma omp parallel for
#endif
  for (j=0; j<VectorSize; j++) {
    b[j] = 2.0;
    c[j] = 0.0;
  }

  scalar = 3.0;

#ifdef _OPENMP
#pragma omp parallel for
#endif
  for (j=0; j<VectorSize; j++)
    a[j] = b[j]+scalar*c[j];

  HPCC_free(c);
  HPCC_free(b);
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  return 0;
}
```

A Few Versions of STREAM Triad

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  if (!a || !b || !c) {
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    if (doIO) {
      fprintf( outFile, "Failed to allocate memory (%d).\n", VectorSize );
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    }
    return 1;
  }

#ifdef _OPENMP
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#endif
  for (j=0; j<VectorSize; j++) {
    b[j] = 2.0;
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  }

  scalar = 3.0;

#ifdef _OPENMP
#pragma omp parallel for
#endif
  for (j=0; j<VectorSize; j++)
    a[j] = b[j]+scalar*c[j];

  HPCC_free(c);
  HPCC_free(b);
  HPCC_free(a);

  return 0;
```

CUDA

```
#define N       2000000

int main() {
  float *d_a, *d_b, *d_c;
  float scalar;

  cudaMalloc((void**)&d_a, sizeof(float)*N);
  cudaMalloc((void**)&d_b, sizeof(float)*N);
  cudaMalloc((void**)&d_c, sizeof(float)*N);

  dim3 dimBlock(128);
  dim3 dimGrid(N/dimBlock.x );
  if( N % dimBlock.x != 0 ) dimGrid.x+=1;

  set_array<<<dimGrid,dimBlock>>>(d_b, .5f, N);
  set_array<<<dimGrid,dimBlock>>>(d_c, .5f, N);

  scalar=3.0f;
  STREAM_Triad<<<dimGrid,dimBlock>>>(d_b, d_c, d_a, scalar,  N);
  cudaThreadSynchronize();

  cudaFree(d_a);
  cudaFree(d_b);
  cudaFree(d_c);
}

__global__ void set_array(float *a,  float value, int len) {
  int idx = threadIdx.x + blockIdx.x * blockDim.x;
  if (idx < len) a[idx] = value;
}

__global__ void STREAM_Triad( float *a, float *b, float *c,
                              float scalar, int len) {
  int idx = threadIdx.x + blockIdx.x * blockDim.x;
  if (idx < len) c[idx] = a[idx]+scalar*b[idx];
}
```

HPC suffers from too many distinct notations for expressing parallelism and locality

A Few Versions of STREAM Triad

MPI + OpenMP

```
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#ifdef _OPENMP
#include <omp.h>
#endif

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  rv = HPCC_Stream( params, 0 == myRan
  MPI_Reduce( &rv, &errCount, 1, MPI_I

  return errCount;
}

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  register int j;
  double  scalar;

  VectorSize = HPCC_LocalVectorSize( p

  a = HPCC_XMALLOC( double, VectorSize
  b = HPCC_XMALLOC( double, VectorSize
  c = HPCC_XMALLOC( double, VectorSize

  if (!a || !b || !c) {
    if (c) HPCC_free(c);
    if (b) HPCC_free(b);
    if (a) HPCC_free(a);
    if (doIO) {
      fprintf( outFile, "Failed to all
      fclose( outFile );
    }
    return 1;
  }

#ifdef _OPENMP
#pragma omp parallel for
#endif
  for (j=0; j<VectorSize; j++) {
    b[j] = 2.0;
    c[j] = 0.0;
  }

  scalar = 3.0;

#ifdef _OPENMP
#pragma omp parallel for
#endif
  for (j=0; j<VectorSize; j++)
    a[j] = b[j]+scalar*c[j];

  HPCC_free(c);
  HPCC_free(b);
  HPCC_free(a);

  return 0;
```

CUDA

```
#define N        2000000

int main() {
  float *d_a, *d_b, *d_c;
  float scalar;

;
;
;

N);
N);

d_c, d_a, scalar,  N);

value, int len) {
  int idx = threadIdx.x + blockIdx.x * blockDim.x;
  if (idx < len) a[idx] = value;
}

__global__ void STREAM_Triad( float *a, float *b, float *c,
                              float scalar, int len) {
  int idx = threadIdx.x + blockIdx.x * blockDim.x;
  if (idx < len) c[idx] = a[idx]+scalar*b[idx];
}
```

Chapel

```
config const m = 1000,
             alpha = 3.0;

const ProbSpace = [1..m] dmapped …;

var A, B, C: [ProbSpace] real;

B = …;
C = …;

A = B + alpha * C;
```

the special sauce

Why Do HPC Programming Models Change?

HPC has traditionally given users…

…low-level, *control-centric* programming models

…ones that are closely tied to the underlying hardware

benefits: lots of control; decent generality; easy to implement

downsides: lots of user-managed detail; brittle to changes

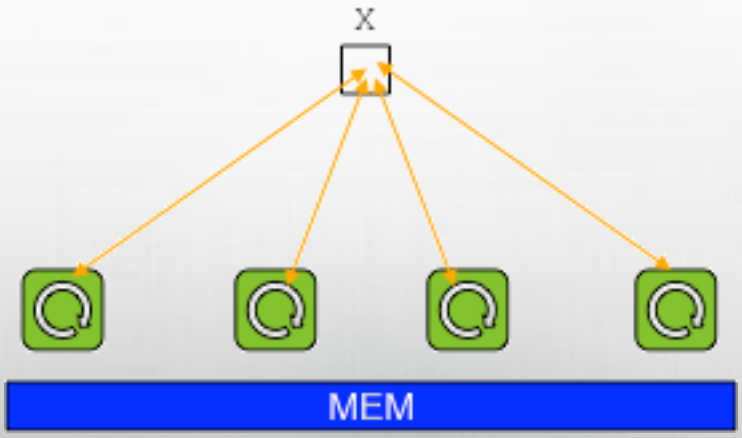
one characterization of Chapel's goals:

- Raise the level of abstraction to insulate parallel algorithms from underlying hardware when possible/practical
- Yet permit control over such details using appropriate abstraction and separation of concerns

Shared Memory Programming Models

e.g., OpenMP, pthreads

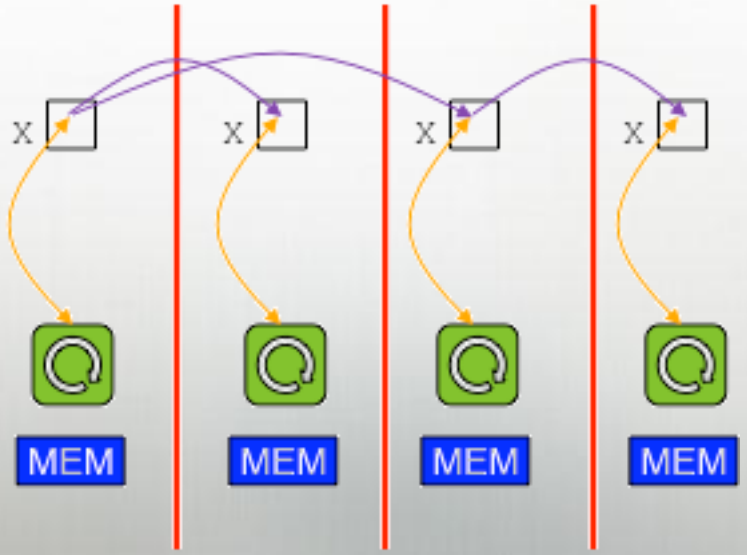
+ support dynamic, fine-grain parallelism
+ considered simpler, more like traditional programming
  - "if you want to access something, simply name it"
– no support for expressing locality/affinity; limits scalability
– bugs can be subtle, difficult to track down (race conditions)
– tend to require complex memory consistency models



Distributed Memory Programming Models

e.g., MPI

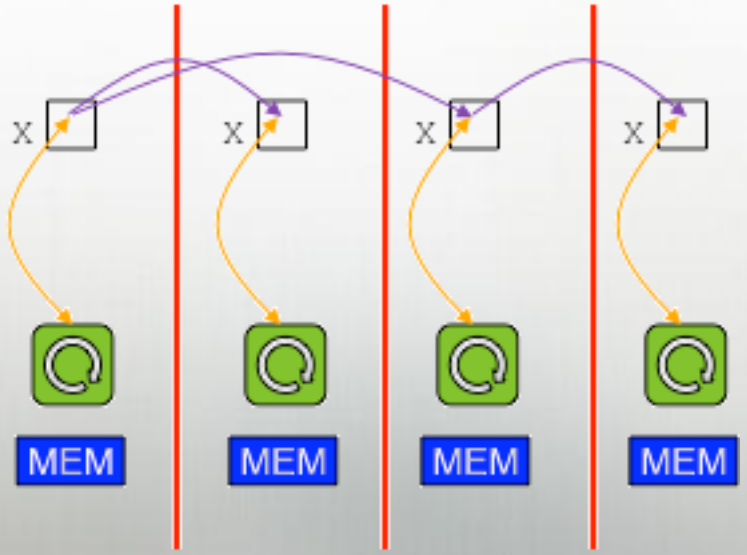
- a more constrained model; can only access local data
- run on most large-scale parallel platforms
  - and for many of them, can achieve near-optimal performance
- are relatively easy to implement
- can serve as a strong foundation for higher-level models
- users are able to get real work done with them



Distributed Memory Programming Models

e.g., MPI

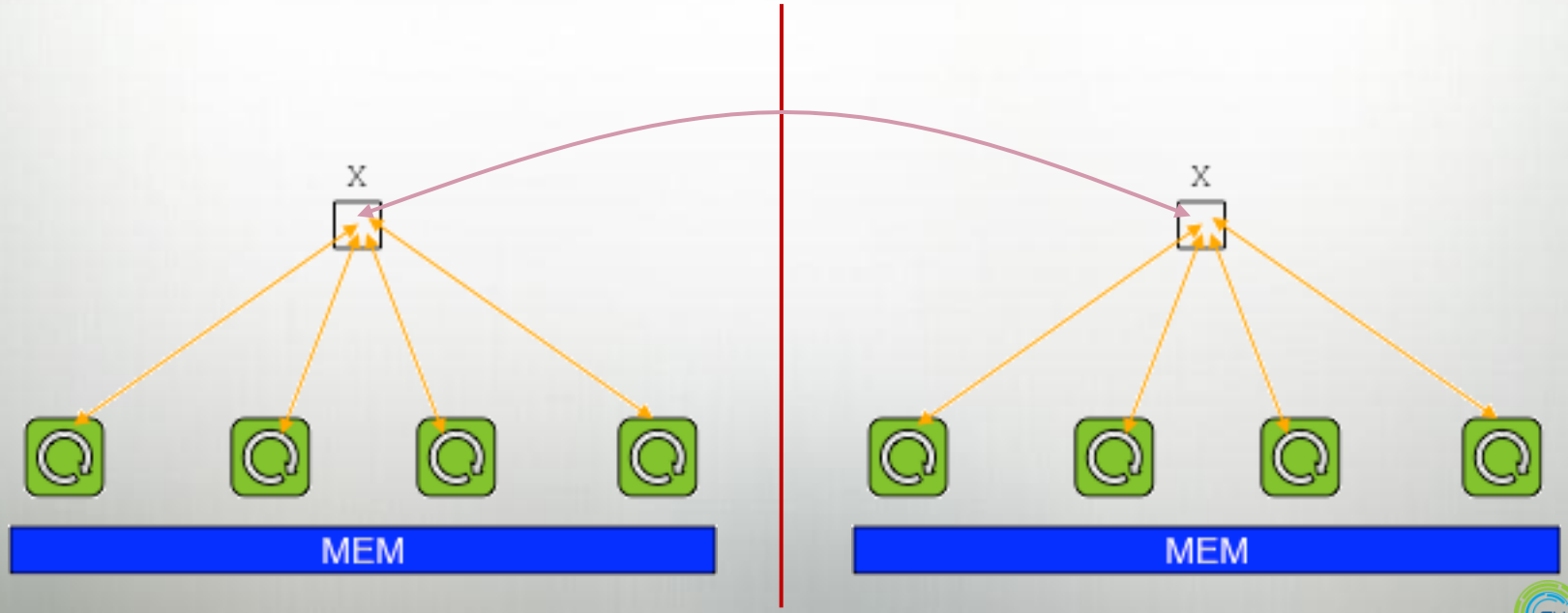
- communication must be used to get copies of remote data
  - and tends to reveal too much about *how* to transfer data, not simply *what*
- only supports "cooperating executable"-level parallelism
- couples data transfer and synchronization
- has frustrating classes of bugs of its own
  - e.g., mismatches between sends/recvs, buffer overflows, etc.



Hybrid Programming Models

***e.g.*, MPI+OpenMP, MPI+pthreads, MPI+CUDA, …**

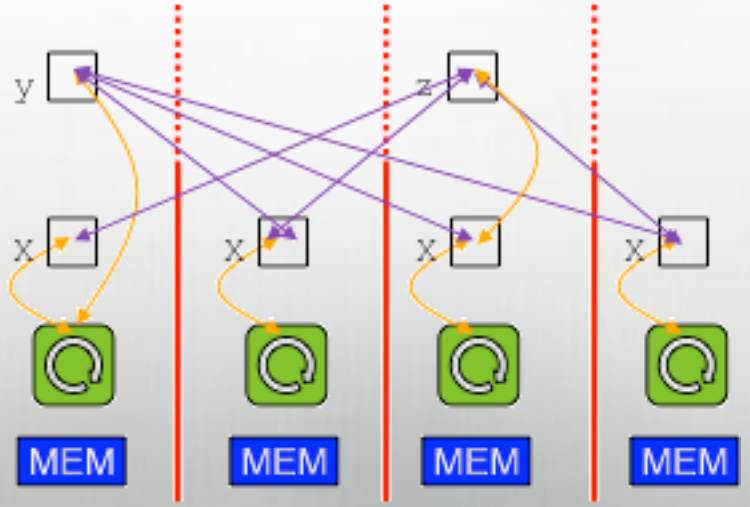
- + support a division of labor: each handles what it does best
- + permit overheads to be amortized across processor cores
- – require multiple distinct notations to express a single logical parallel algorithm, each with its own distinct semantics



PGAS (Partitioned Global Address Space) Models

e.g., Co-Array Fortran (CAF), Unified Parallel C (UPC)

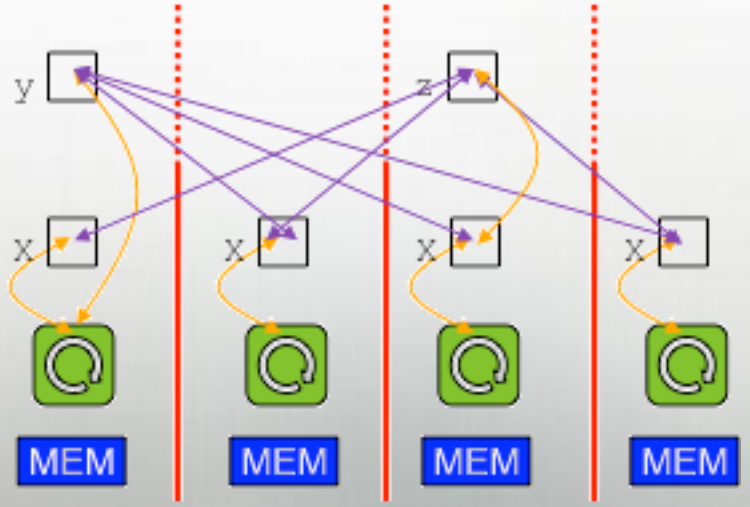
+ support a shared namespace, like shared-memory
+ support a strong sense of ownership and locality
  - each variable is stored in a particular memory segment
  - tasks can access any visible variable, local or remote
  - local variables are cheaper to access than remote ones
+ implicit communication eases user burden; permits compiler use best mechanisms available



PGAS (Partitioned Global Address Space) Models

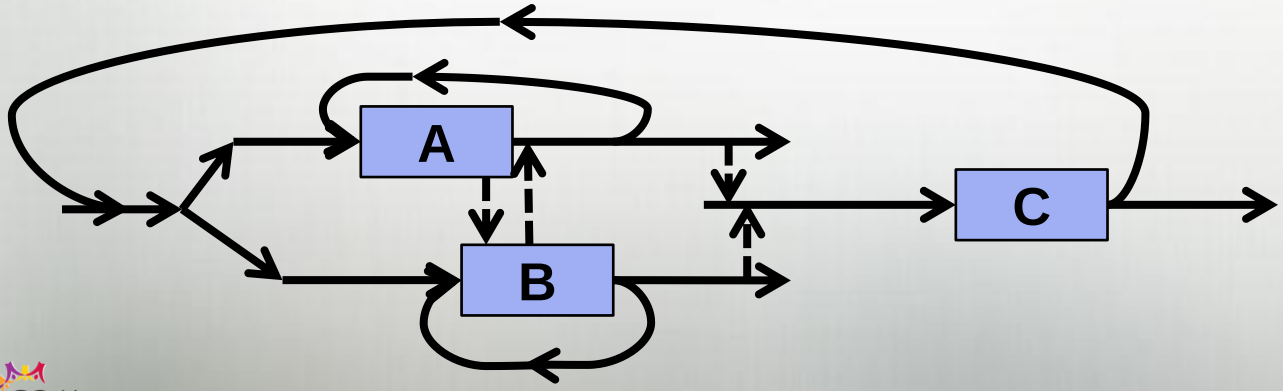
e.g., Co-Array Fortran (CAF), Unified Parallel C (UPC)

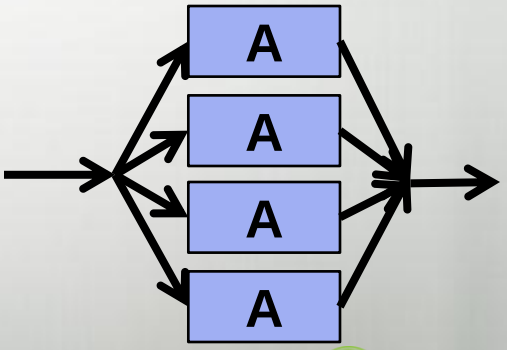
- retain many of the downsides of shared-memory
  - error cases, memory consistency models
- restricted to SPMD programming and execution models
- data structures not as flexible/rich as one might like



Chapel: A Next-Generation PGAS Language

- a PGAS language, but non-traditional:
  - more general/dynamic/multithreaded parallelism
  - concepts for composable data and task parallelism
  - distinct concepts for locality vs. parallelism
    - e.g., *locale* type represents architectural locality
  - productivity features
    - type inference, iterator functions, rich array types, OOP, …





Chapel's Origins

- **HPCS**: High Productivity Computing Systems
  - Overall goal: Raise high-end user productivity by 10x

    Productivity = Performance + Programmability + Portability + Robustness
- **Phase II:** Cray, IBM, Sun (July 2003 – June 2006)
  - Goal: Propose new productive system architectures
  - Each vendor created a new programming language
    - **Cray:** Chapel
    - **IBM:** X10
    - **Sun:** Fortress
- **Phase III:** Cray, IBM (July 2006 –)
  - Goal: Develop the systems proposed in phase II
  - Each vendor implemented a compiler for their language
    - Sun also continued their Fortress effort without HPCS funding

Chapel's Productivity Goals

- Vastly improve **programmability** over current languages
  - Writing parallel programs
  - Reading, modifying, porting, tuning, maintaining them
- Support **performance** at least as good as MPI
  - Competitive with MPI on generic clusters
  - Better than MPI on more capable architectures
- Improve **portability** over current languages
  - As ubiquitous as MPI but more abstract
  - More portable than OpenMP, UPC, and CAF are thought to be
- Improve **robustness** via improved semantics
  - Eliminate common error cases
  - Provide better abstractions to help avoid other errors

Outline

- Chapel's Context
- Chapel's Motivating Themes
  1. General parallel programming
  2. *Global-view* abstractions
  3. *Multiresolution* design
  4. Control over locality/affinity
  5. Reduce gap between mainstream & HPC languages

1) General Parallel Programming

With a unified set of concepts...

...express any parallelism desired in a user's program

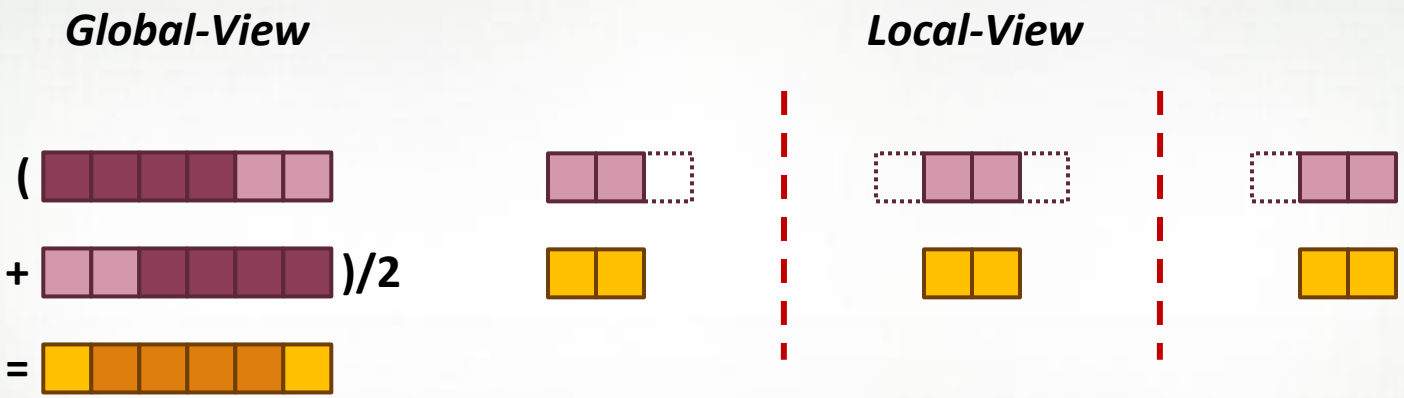
- **Styles:** data-parallel, task-parallel, concurrency, nested, …
- **Levels:** model, function, loop, statement, expression

...target all parallelism available in the hardware

- **Systems:** multicore desktops, clusters, HPC systems, …
- **Levels:** machines, nodes, cores, instructions

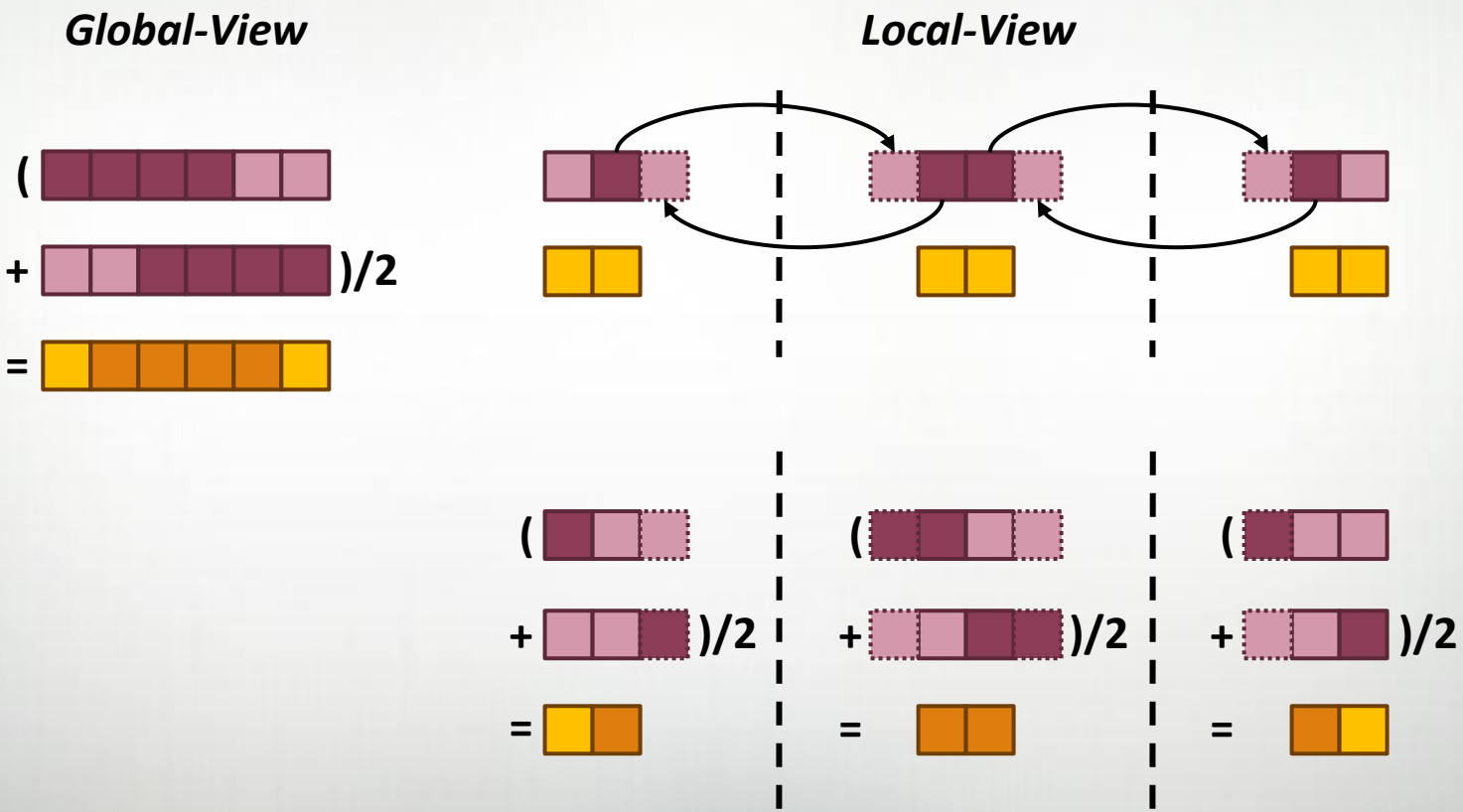
2) Global-View Abstractions

In pictures: "Apply a 3-Point Stencil to a vector"



2) Global-View Abstractions

In pictures: "Apply a 3-Point Stencil to a vector"



2) Global-View Abstractions

In code: "Apply a 3-Point Stencil to a vector"

Global-View

```
proc 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;
}
```

Local-View (SPMD)

```
proc main() {
  var n = 1000;
  var p = numProcs(),
      me = myProc(),
      myN = n/p,
  var A, B: [0..myN+1] real;

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

Bug: Refers to uninitialized values at ends of A

2) Global-View Abstractions

In code: "Apply a 3-Point Stencil to a vector"

Global-View

```
proc 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;
}
```

Local-View (SPMD)

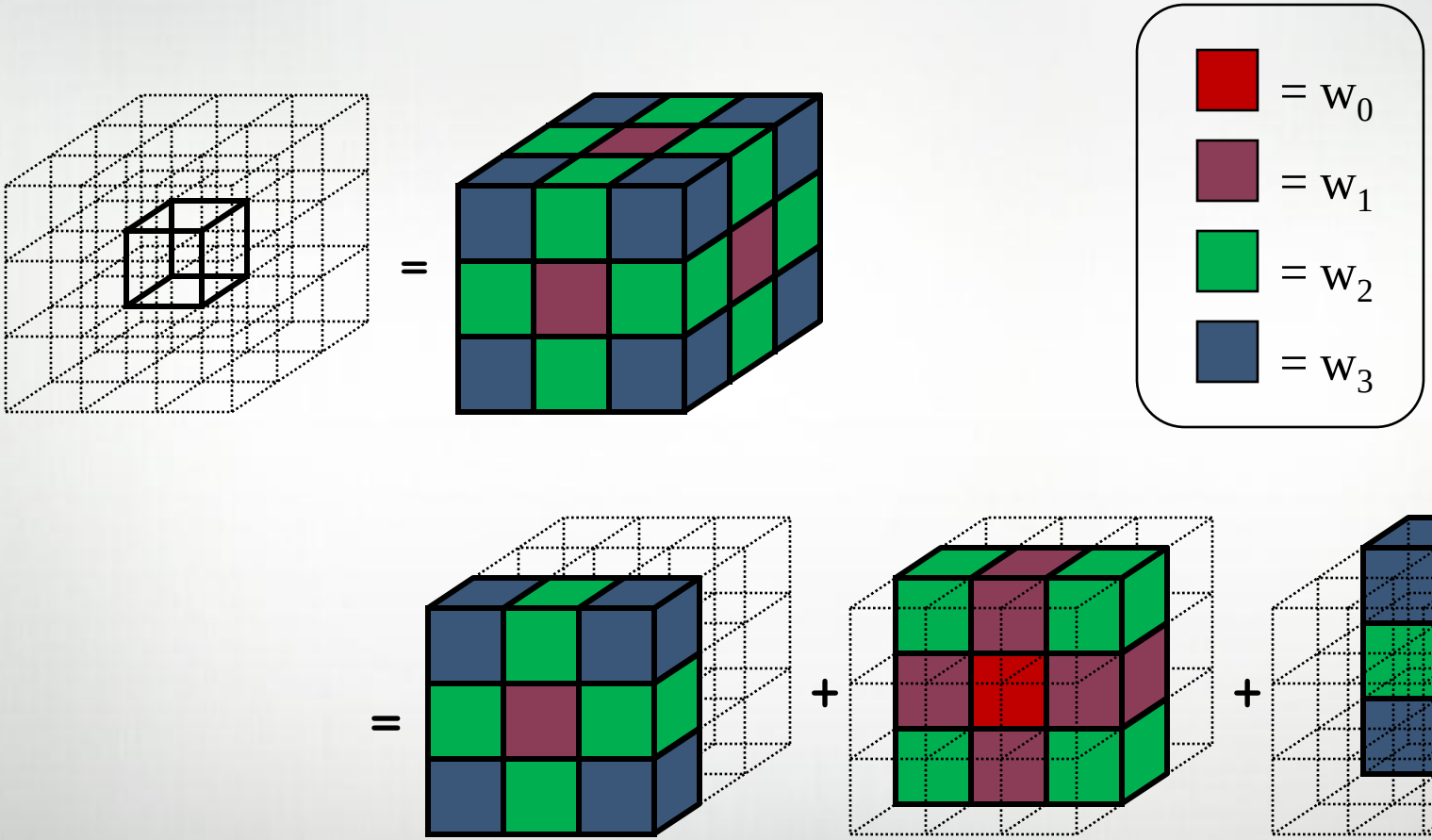
```
proc main() {
  var n = 1000;
  var p = numProcs(),
      me = myProc(),
      myN = n/p,
      myLo = 1,
      myHi = myN;
  var A, B: [0..myN+1] real;

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

Assumes p divides n

Communication becomes geometrically more complex for higher-dimensional arrays

2) *rprj3* Stencil from NAS MG



2) *rprj3* Stencil from NAS MG in Fortran + MPI

```
      subroutine rprj3( r,m1k,m2k,m3k,s,m1j,m2j,m3j,k )

      implicit none

      include 'mpinpb.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)
     >              + 0.062D0 * ( y1(i1-1) + y1(i1+1) )
            enddo

         enddo
      enddo


      j = k-1
      call comm3(s,m1j,m2j,m3j,j)

      if( debug_vec(0) .ge. 1 )then
         call rep_nrm(s,m1j,m2j,m3j,'   rprj3',k-1)
      endif

      if( debug_vec(4) .ge. k )then
         call showall(s,m1j,m2j,m3j)
      endif

      return
      end


      subroutine norm2u3(r,n1,n2,n3,rnm2,rnmu,nx,ny,nz)

      implicit none

      include 'mpinpb.h'

      integer n1, n2, n3, nx, ny, nz
      double precision rnm2, rnmu, r(n1,n2,n3)
      double precision s, a, ss
      integer i3, i2, i1, ierr

      double precision dn

      dn = 1.0d0*nx*ny*nz

      s=0.0D0
      rnmu = 0.0D0
      do  i3=2,n3-1
         do  i2=2,n2-1
            do  i1=2,n1-1
               s=s+r(i1,i2,i3)**2
               a=abs(r(i1,i2,i3))
               if(a.gt.rnmu)rnmu=a
            enddo
         enddo
      enddo

      call mpi_allreduce(rnmu,ss,1,dp_type,
     >   mpi_max,mpi_comm_world,ierr)
      rnmu = ss
      call mpi_allreduce(s, ss, 1, dp_type,
     >   mpi_sum,mpi_comm_world,ierr)
      s = ss
      rnm2=sqrt( s / dn )

      return
      end


      subroutine rep_nrm(u,n1,n2,n3,title,kk)

      implicit none

      include 'mpinpb.h'
      include 'globals.h'

      integer n1, n2, n3, kk
      double precision u(n1,n2,n3)
      character*8 title

      double precision rnm2, rnmu

      call norm2u3(u,n1,n2,n3,rnm2,rnmu,nx(kk),ny(kk),nz(kk))
      if( me .eq. root )then
         write(*,7)kk,title,rnm2,rnmu
7        format(' level',i2,' in ',a8,': norms =',D21.14,D21.14)
      endif

      return
      end


      subroutine comm3(u,n1,n2,n3,kk)

      implicit none

      include 'mpinpb.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 ready( axis, -1, kk )
               call ready( axis, +1, kk )

               call give3( axis, +1, u, n1, n2, n3, kk )
               call give3( axis, -1, u, n1, n2, n3, kk )

               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
         call zero3(u,n1,n2,n3)
      endif
      return
      end


      subroutine ready( axis, dir, k )

      implicit none

      include 'mpinpb.h'
      include 'globals.h'

      integer axis, dir, k
      integer buff_id,buff_len,i,ierr

      buff_id = 3 + dir
      buff_len = nm2

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

      msg_id(axis,dir,1) = msg_type(axis,dir) +1000*me

      call mpi_irecv( buff(1,buff_id), buff_len,
     >     dp_type, nbr(axis,-dir,k), msg_type(axis,dir),
     >     mpi_comm_world, msg_id(axis,dir,1), ierr)
      return
      end


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

      implicit none

      include 'mpinpb.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

      dir = -1
      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

            call mpi_send(
     >           buff(1, buff_id ), buff_len,dp_type,
     >           nbr( axis, dir, k ), msg_type(axis,dir),
     >           mpi_comm_world, ierr)

         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

            call mpi_send(
     >           buff(1, buff_id ), buff_len,dp_type,
     >           nbr( axis, dir, k ), msg_type(axis,dir),
     >           mpi_comm_world, ierr)

         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

            call mpi_send(
     >           buff(1, buff_id ), buff_len,dp_type,
     >           nbr( axis, dir, k ), msg_type(axis,dir),
     >           mpi_comm_world, ierr)

         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

            call mpi_send(
     >           buff(1, buff_id ), buff_len,dp_type,
     >           nbr( axis, dir, k ), msg_type(axis,dir),
     >           mpi_comm_world, ierr)

         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

            call mpi_send(
     >           buff(1, buff_id ), buff_len,dp_type,
     >           nbr( axis, dir, k ), msg_type(axis,dir),
     >           mpi_comm_world, ierr)

         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

            call mpi_send(
     >           buff(1, buff_id ), buff_len,dp_type,
     >           nbr( axis, dir, k ), msg_type(axis,dir),
     >           mpi_comm_world, ierr)

         endif
      endif

      return
      end


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

      implicit none

      include 'mpinpb.h'
      include 'globals.h'

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

      integer buff_id, indx

      integer status(mpi_status_size), ierr

      integer i3, i2, i1

      call mpi_wait( msg_id( axis, dir, 1 ),status,ierr)
      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 )

      implicit none

      include 'mpinpb.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,n3-1,i3)
            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 showall(z,n1,n2,n3)

      implicit none

      include 'mpinpb.h'

      integer n1,n2,n3,i1,i2,i3,i,ierr
      double precision z(n1,n2,n3)
      integer m1, m2, m3

      m1 = min(n1,18)
      m2 = min(n2,14)
      m3 = min(n3,18)

      write(*,*)'  '
      do  i=0,nprocs-1
         if( me .eq. i )then
            write(*,*)'id = ', me
            do  i3=1,m3
               do  i1=1,m1
                  write(*,6)(z(i1,i2,i3),i2=1,m2)
               enddo
               write(*,*)'- - - - - - - '
            enddo
            write(*,*)'  '
6           format(15f6.3)
         endif
         call mpi_barrier(mpi_comm_world,ierr)
      enddo

      return
      end


      subroutine zero3(z,n1,n2,n3)

      implicit none

      include 'mpinpb.h'

      integer n1, n2, n3
      double precision z(n1,n2,n3)
      integer i1, i2, i3

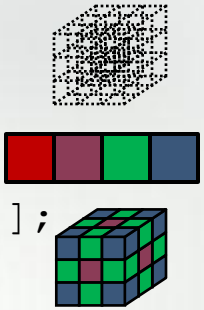
      do  i3=1,n3
         do  i2=1,n2
            do  i1=1,n1
               z(i1,i2,i3)=0.0D0
            enddo
         enddo
      enddo

      return
      end
bradc-lnx%
```

2) *rprj3* Stencil from NAS MG in Chapel

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

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



Our previous work in ZPL demonstrated that such compact codes can result in better performance than Fortran + MPI while also supporting more flexibility at runtime*.

****e.g.*, the Fortran + MPI *rprj3* code shown previously not only assumes *p* divides *n*, it also assumes that *p* and *n* are specified at compile-time and powers of two.**

2) Classifying Current Programming Models

	System	Data Model	Control Model
Communication Libraries	MPI/MPI-2	Local-View	Local-View
	SHMEM, ARMCI, GASNet	Local-View	SPMD
Shared Memory	OpenMP, Pthreads	Global-View (trivially)	Global-View (trivially)
PGAS Languages	Co-Array Fortran	Local-View	SPMD
	UPC	Global-View	SPMD
	Titanium	Local-View	SPMD
PGAS Libraries	Global Arrays	Global-View	SPMD

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	Titanium	Local-View	SPMD
PGAS Libraries	Global Arrays	Global-View	SPMD
HPCS Languages	Chapel	Global-View	Global-View
	X10 (IBM)	Global-View	Global-View
	Fortress (Sun)	Global-View	Global-View

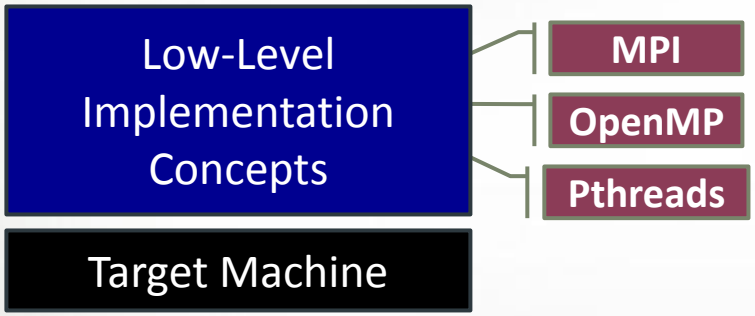
2) Global-View Programming: A Final Note

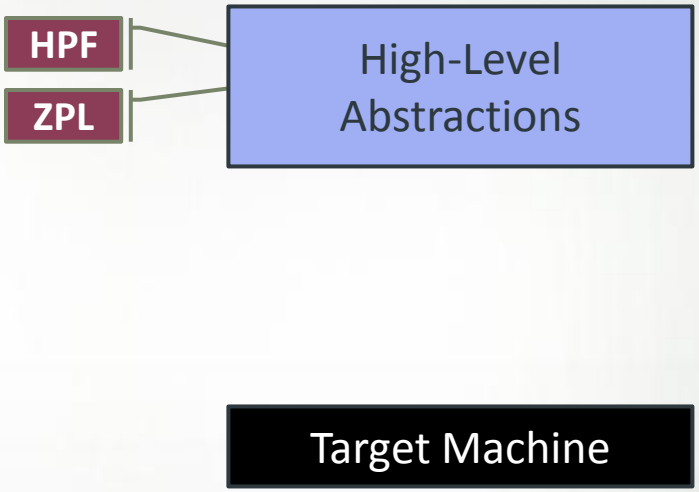
- A language may support both global- and local-view programming — in particular, Chapel does

```
proc main() {
  coforall loc in Locales do
    on loc do
      MySPMDProgram(loc.id, Locales.numElements);
}

proc MySPMDProgram(me, p) {
  ...
}
```

3) Multiresolution Language Design: Motivation





"Why is everything so difficult?"

"Why don't my programs port trivially?"

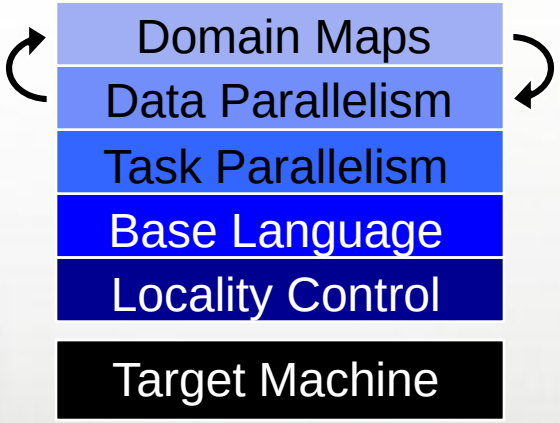
"Why don't I have more control?"

3) Multiresolution Language Design

Multiresolution Design: Support multiple tiers of features

- higher levels for programmability, productivity
- lower levels for performance, control
- build the higher-level concepts in terms of the lower

Chapel language concepts



- separate concerns appropriately for clean design

4) Control over Locality/Affinity

Consider:

- Scalable architectures package memory near processors
- Remote accesses take longer than local accesses

Therefore:

- Placement of data relative to computation affects scalability
- Give programmers control of data and task placement

Note:

- As core counts grow, locality will matter more on desktops
- GPUs and accelerators already expose node-level locality

5) Reduce Gap Between HPC & Mainstream Languages

Consider:

- Students graduate with training in Java, Matlab, Perl, Python
- Yet HPC programming is dominated by Fortran, C/C++, MPI

We'd like to narrow this gulf with Chapel:

- to leverage advances in modern language design
- to better utilize the skills of the entry-level workforce...
- ...while not ostracizing the traditional HPC programmer
  - e.g., support object-oriented programming, but make it optional

Questions?

- Chapel's Context
- Chapel's Motivating Themes
  1. General parallel programming
  2. *Global-view* abstractions
  3. *Multiresolution* design
  4. Control over locality/affinity
  5. Reduce gap between mainstream & HPC languages