Chapel:
Parallel Programming Made Productive

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Cray Inc.

Seattle University — May 2nd, 2012

What is Parallel Computing?

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Parallel Computing: Using multiple processors and their memories to execute a computation.

Why would we do this?

What is Parallel Computing?

Parallel Computing: Using multiple processors and their memories to execute a computation.

Why would we do this?

- To execute a program more quickly than you otherwise could
- Or, potentially, to execute a larger program (in terms of data) than you otherwise could

Parallel Computations Vary in Difficulty

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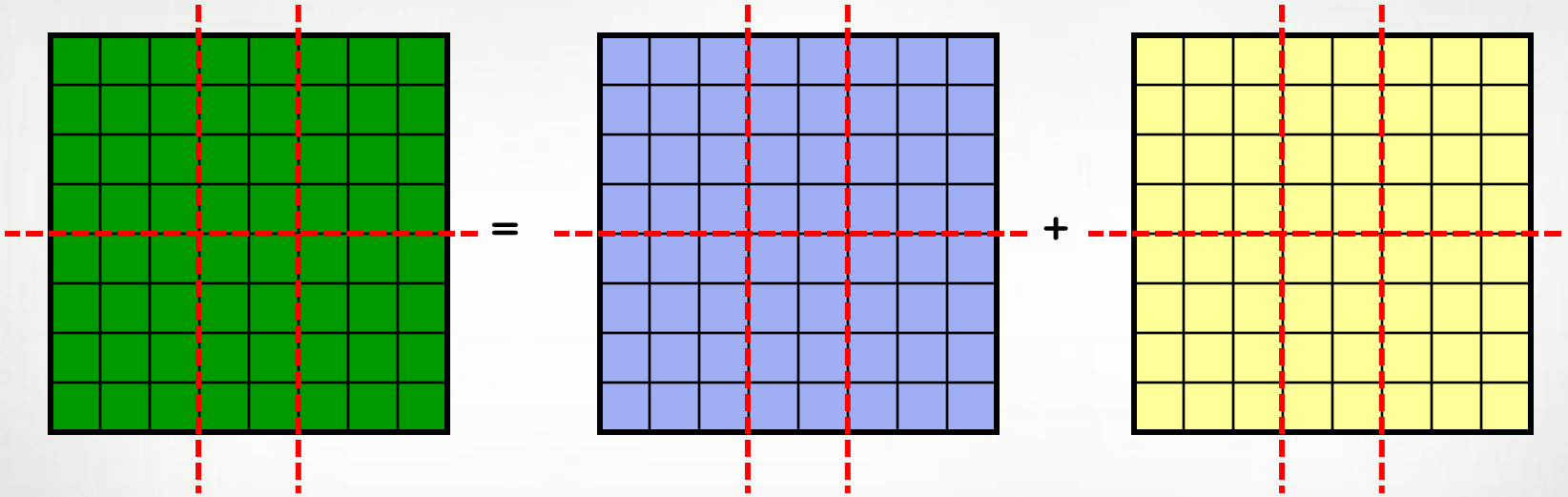
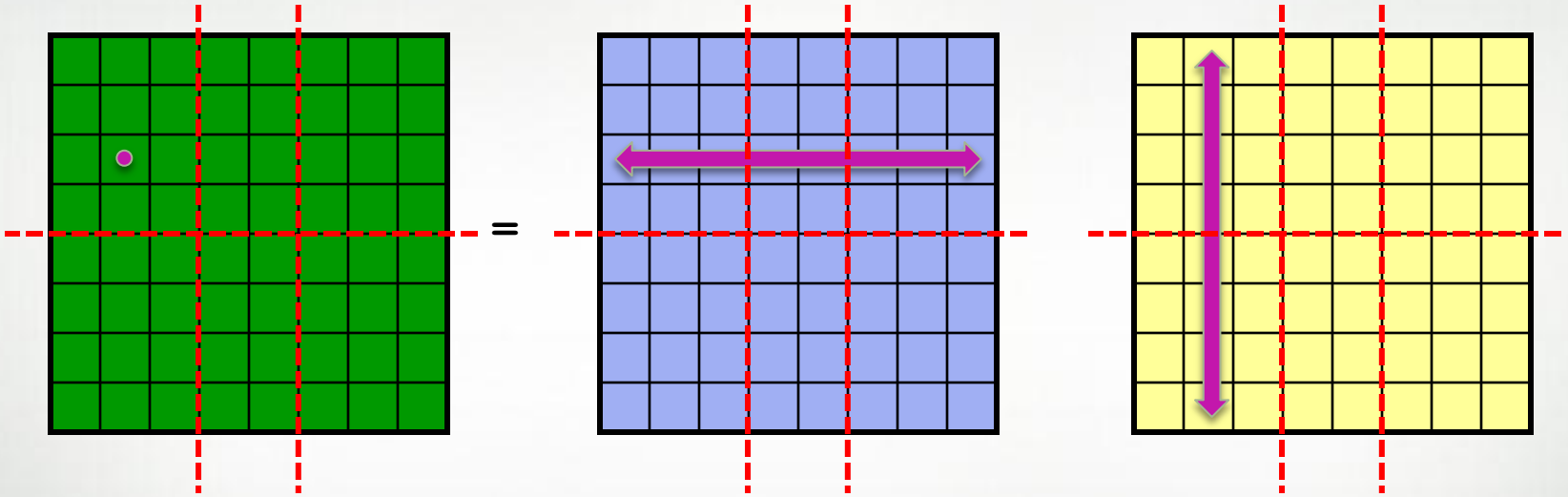
Matrix Addition: Quite straightforward



Parallel Computations Vary in Difficulty

Matrix Multiplication: Far more involved



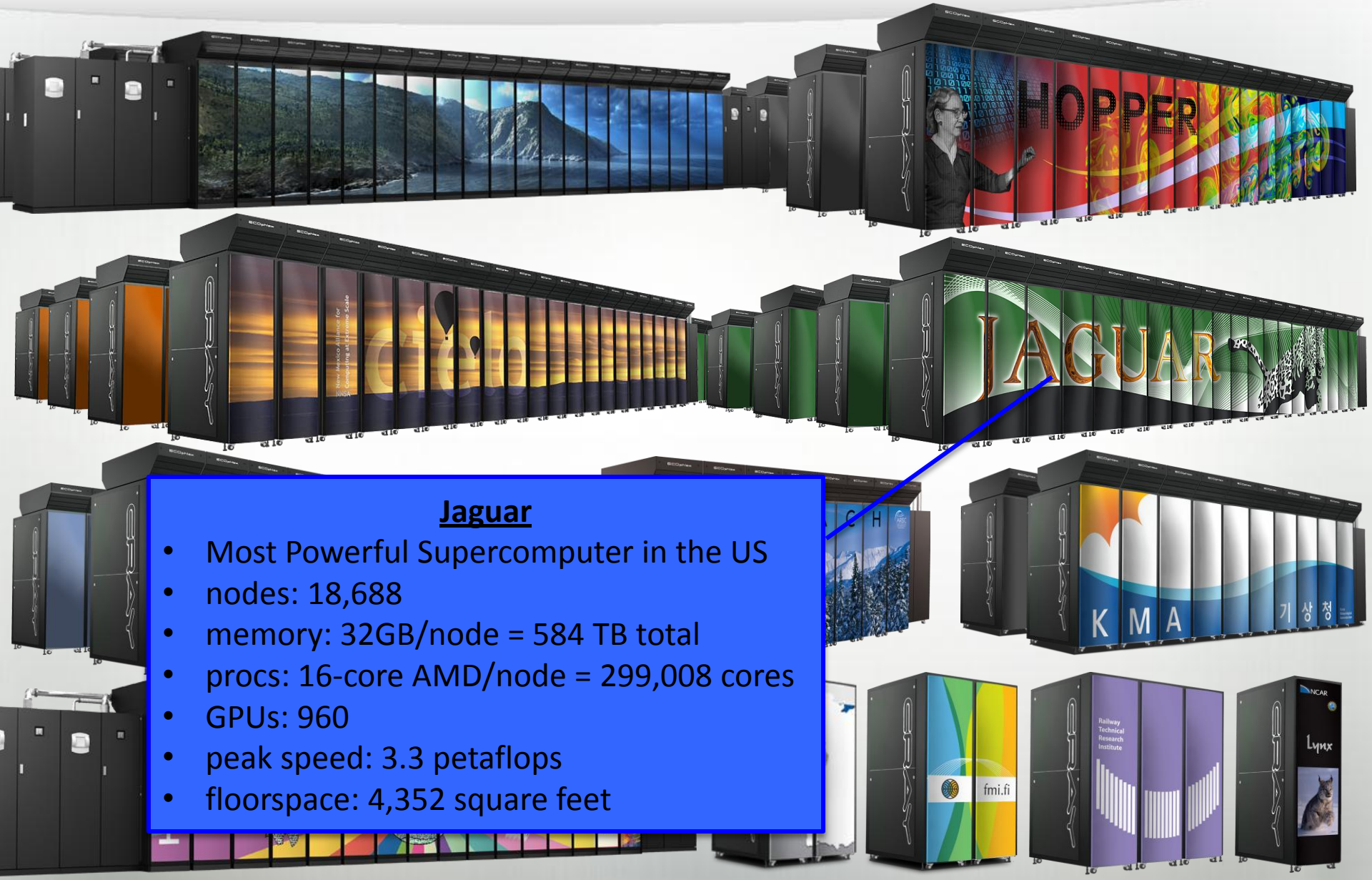
Some Terminology

processor core (or simply "core"): the unit of a computer that has a PC, executes instructions, etc.

node: a group of cores and memories that must go over the network to communicate with any others

network: the wires and chips that permit nodes to communicate with one another

Cray: The Supercomputer Company



Jaguar

- Most Powerful Supercomputer in the US
- nodes: 18,688
- memory: 32GB/node = 584 TB total
- procs: 16-core AMD/node = 299,008 cores
- GPUs: 960
- peak speed: 3.3 petaflops
- floorspace: 4,352 square feet

Top500: Simply One Piece of the Puzzle

- Rates the 500 fastest computers twice a year
- Measured using the LINPACK benchmark
  - Solves an LU factorization
  - Flops dominate runtime
- Yet, other factors limit most real applications
  - e.g., memory bandwidth

TOP500 SUPERCOMPUTER SITES

PROJECT | LISTS | STATISTICS | RESOURCES | NEWS

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TOP500 List - November 2011 (1-100)

R_{max} and R_{peak} values are in TFlops. For more details about other fields, check the TOP500 description.

Power data in KW for entire system

next

Rank	Site	Computer/Year Vendor	Cores	R_{max}	R_{peak}	Power
1	RIKEN Advanced Institute for Computational Science (AICS) Japan	K computer, SPARC64 VIIIfx 2.0GHz, Tofu interconnect / 2011 Fujitsu	705024	10510.00	11280.38	12659.9
2	National Supercomputing Center in Tianjin China	NUDT YH MPP, Xeon X5670 6C 2.93 GHz, NVIDIA 2050 / 2010 NUDT	186368	2566.00	4701.00	4040.0
3	DOE/SC/Oak Ridge National Laboratory United States	Cray XT5-HE Opteron 6-core 2.6 GHz / 2009 Cray Inc.	224162	1759.00	2331.00	6950.0
4	National Supercomputing Centre in Shenzhen (NSCS) China	Dawning TC3600 Blade System, Xeon X5650 6C 2.66GHz, Infiniband QDR, NVIDIA 2050 / 2010 Dawning	120640	1271.00	2984.30	2580.0
5	GSIC Center, Tokyo Institute of Technology Japan	HP ProLiant SL390s G7 Xeon 6C X5670, Nvidia GPU, Linux/Windows / 2010 NEC/HP	73278	1192.00	2287.63	1398.6
6	DOE/NNSA/LANL/SNL United States	Cray XE6, Opteron 6136 8C 2.40GHz, Custom / 2011 Cray Inc.	142272	1110.00	1365.81	3980.0
7	NASA/Ames Research Center/NAS United States	SGI Altix ICE 8200EX/8400EX, Xeon HT QC 3.0/Xeon 5570/5670 2.93 Ghz, Infiniband / 2011 SGI	111104	1088.00	1315.33	4102.0
8	DOE/SC/LBNL/NERSC United States	Cray XE6, Opteron 6172 12C 2.10GHz, Custom / 2010 Cray Inc.	153408	1054.00	1288.63	2910.0
9	Commissariat a l'Energie Atomique (CEA) France	Bull bullx super-node S6010/S6030 / 2010 Bull	138368	1050.00	1254.55	4590.0
10	DOE/NNSA/LANL United States	BladeCenter QS22/LS21 Cluster, PowerXCell 8i 3.2 Ghz / Opteron DC 1.8 GHz, Voltaire Infiniband / 2009 IBM	122400	1042.00	1375.78	2345.0

Sustained Performance Milestones

1 GF – 1988: Cray Y-MP; 8 Processors

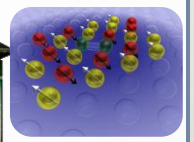
- Static finite element analysis

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

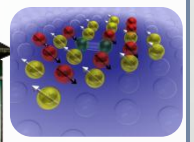
- Static finite element analysis
- Fortran77 + Cray autotasking + vectorization

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

- Modeling of metallic magnet atoms
- Fortran + MPI (Message Passing Interface)

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/OpenACC

Or Perhaps Something Completely Different?

STREAM Triad: a trivial parallel computation

Given: m-element vectors A, B, C

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

In pictures:

STREAM Triad: a trivial parallel computation

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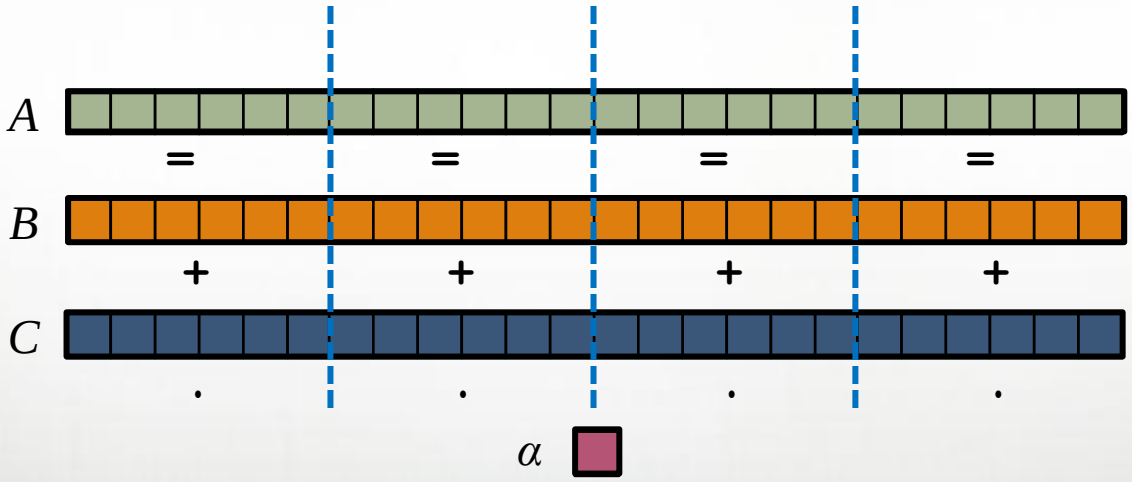
Compute: $\forall i \in 1..m, A_i = B_i + \alpha \cdot C_i$

In pictures, in parallel:



STREAM Triad: a trivial parallel computation

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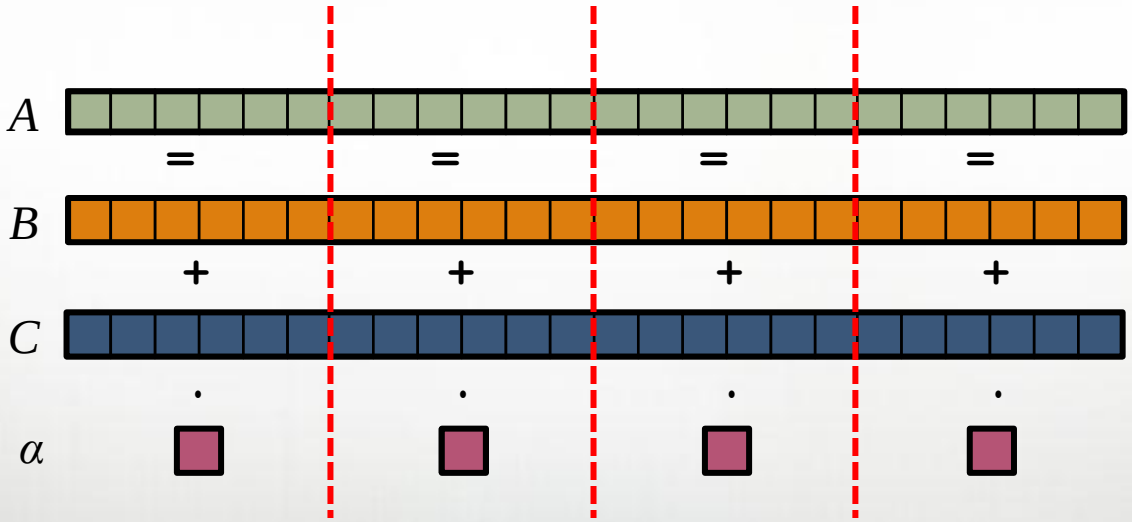
In pictures, in parallel (distributed memory):

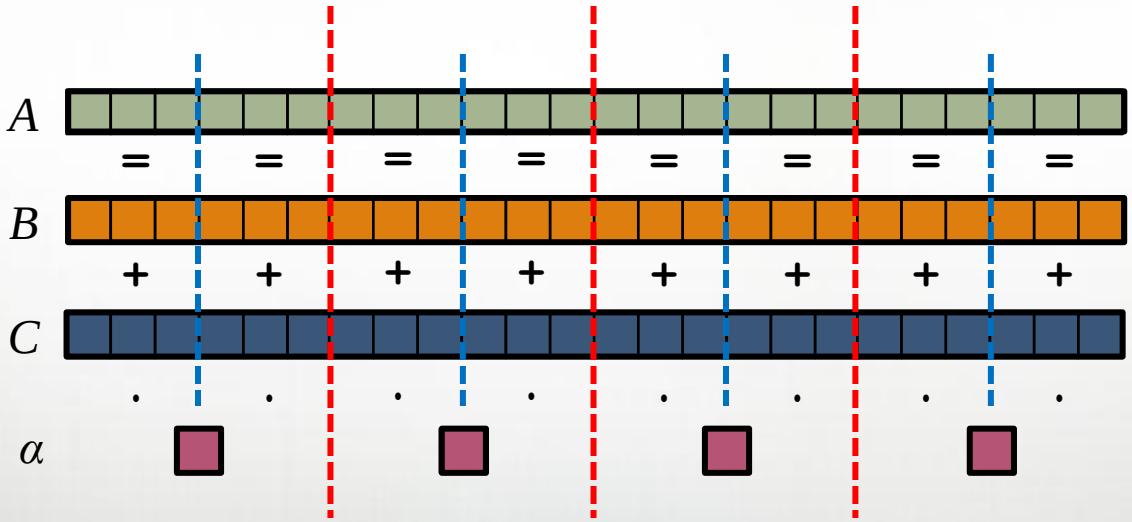


STREAM Triad: a trivial parallel computation

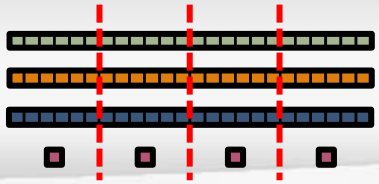
Given: m-element vectors A, B, C

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

In pictures, in parallel (distributed memory multicore):



STREAM Triad: MPI



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;
  }

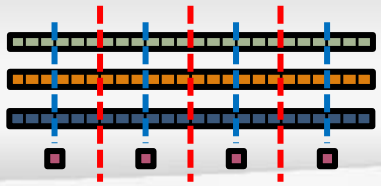
  scalar = 3.0;

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

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

  return 0;
}
```

STREAM Triad: MPI+OpenMP



MPI + OpenMP

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

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int HPCC_StarStream(HPCC_Params *params) {
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  if (!a || !b || !c) {
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    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;
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  }

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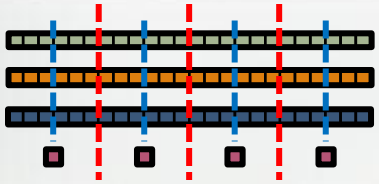
#ifdef _OPENMP
#pragma omp parallel for
#endif
  for (j=0; j<VectorSize; j++)
    a[j] = b[j]+scalar*c[j];

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

  return 0;
}
```

STREAM Triad: MPI+OpenMP vs. CUDA

MPI + OpenMP



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  scalar = 3.0;

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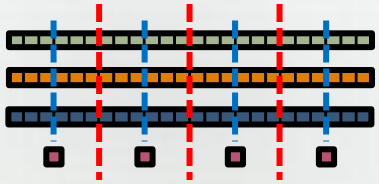
#endif
  for (j=0; j<VectorSize; j++)
    a[j] = b[j]+scalar*c[j];

  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

Why so many programming models?

HPC has traditionally given users…

- …low-level, *control-centric* programming models
- …ones that are closely tied to the underlying hardware
- …ones that support only a single type of parallelism

Examples:

Type of HW Parallelism	Programming Model	Unit of Parallelism
Inter-node	MPI	executable
Intra-node/multicore	OpenMP/pthreads	iteration/task
Instruction-level vectors/threads	pragmas	iteration
GPU/accelerator	CUDA/OpenCL/OpenAcc	SIMD function/task

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

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

("Glad I'm not an HPC Programmer!")

A Possible Reaction:

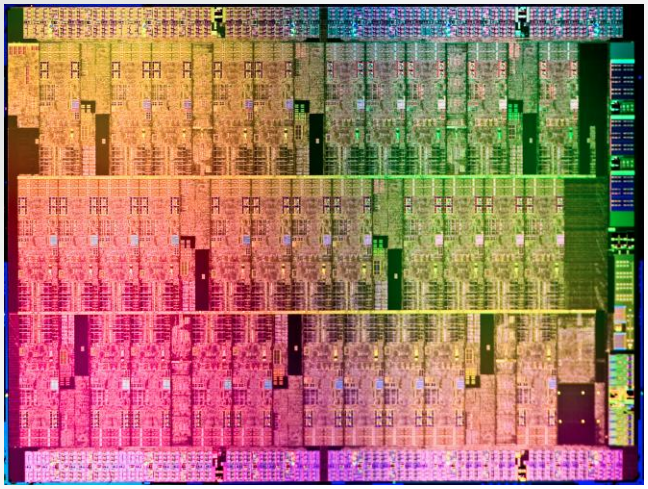
"This is all well and good for HPC users, but I'm a mainstream desktop programmer, so this is all academic for me."

The Unfortunate Reality:

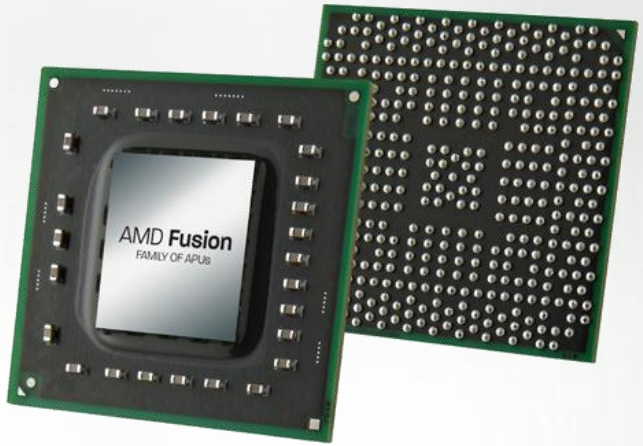
- Performance-minded mainstream programmers are forced to deal increasingly with parallelism too (due to multicore)
- And, as chips become more complex, locality too

and mainstream!

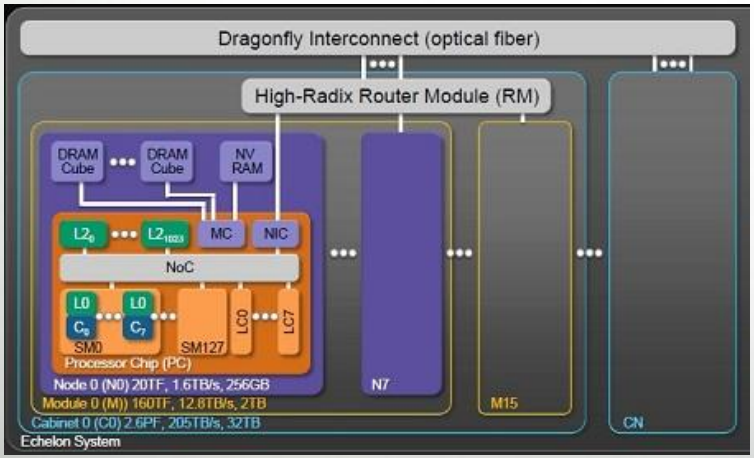
Next-generation HPC Processor Technologies



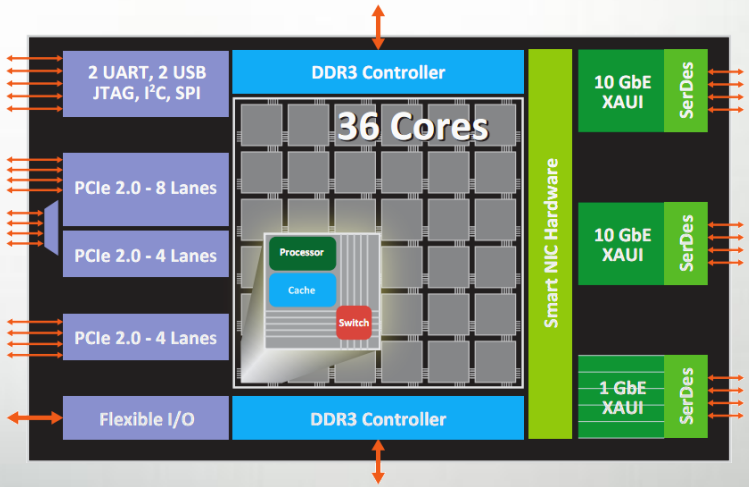
Intel MIC



AMD Fusion



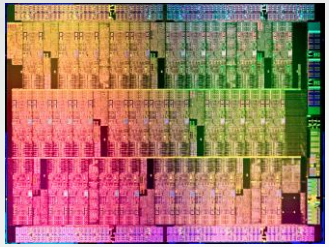
Nvidia Echelon

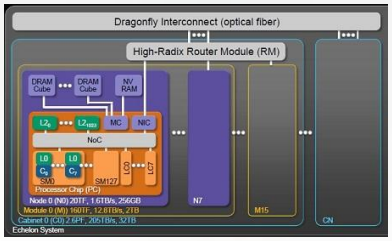


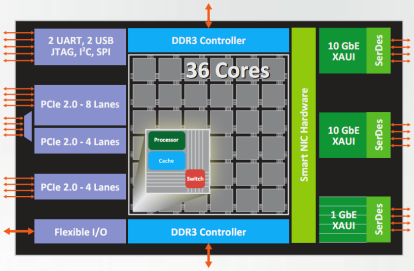
Tilera Tile-Gx

Sources: http://download.intel.com/pressroom/images/Aubrey_Isle_die.jpg, http://www.thinkcomputers.org/ces-2011-amds-fusion-apus/, http://insidehpc.com/2010/11/26/nvidia-reveals-details-of-echelon-gpu-designs-for-exascale/, http://tilera.com/sites/default/files/productbriefs/Tile-Gx%203036%20SB012-01.pdf

General Characteristics of These Architectures





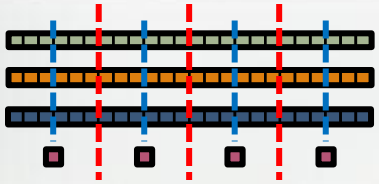


- Increased hierarchy and/or sensitivity to locality
- Heterogeneous processor and memory types

⇒ Both HPC and mainstream programmers will have a lot more to think about at the processor level

Rewinding a few slides…

MPI + OpenMP



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#include <omp.h>
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  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;
  }

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

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

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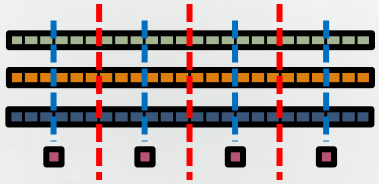
  return 0;
}
```

CUDA



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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

STREAM Triad: Chapel

MPI + OpenMP

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

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

int HPCC_StarStream(HPCC_Params *par
  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 == myR
  MPI_Reduce( &rv, &errCount, 1, MPI

  return errCount;
}

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

  VectorSize = HPCC_LocalVectorSize(

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

  if (!a || !b || !c) {
    if (c) HPCC_free(c);
    if (b) HPCC_free(b);
    if (a) HPCC_free(a);
    if (doIO) {
```

Chapel

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

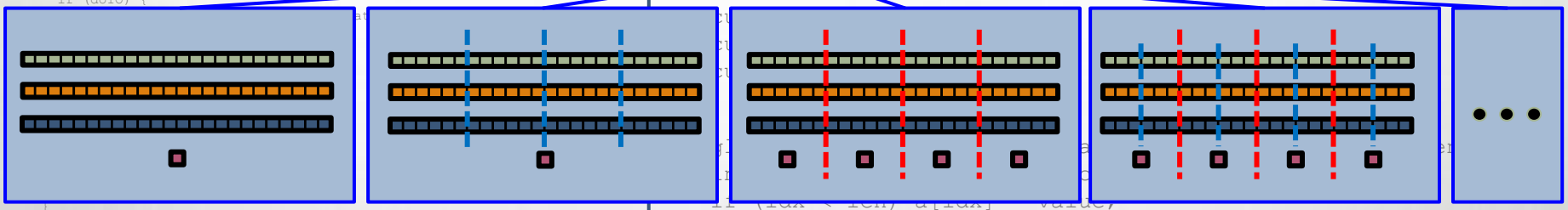
const ProblemSpace = [1..m] dmapped …;

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

B = 2.0;
C = 3.0;

A = B + alpha * C;
```

the special sauce



Philosophy: Good language design can tease details of locality and parallelism away from an algorithm, permitting the compiler, runtime, applied scientist, and HPC expert to each focus on their strengths.

Outline

- ✓ Motivation
- ➢ Chapel Background and Themes
- Tour of Chapel Concepts
- Project Status

What is Chapel?

- An emerging parallel programming language
  - Design and development led by Cray Inc.
    - in collaboration with academia, labs, industry
  - Initiated under the DARPA HPCS program

- **Overall goal:** Improve programmer productivity
  - Improve the programmability of parallel computers
  - Match or beat the performance of current programming models
  - Support better portability than current programming models
  - Improve the robustness of parallel codes

- A work-in-progress

Chapel's Implementation

- Being developed as open source at SourceForge
- Licensed as BSD software
- **Target Architectures:**
  - Cray architectures
  - multicore desktops and laptops
  - commodity clusters
  - systems from other vendors
  - *in-progress:* CPU+accelerator hybrids, manycore, …

Motivating Chapel Themes

1) General Parallel Programming
2) Global-View Abstractions
3) Multiresolution Design
4) Control over Locality/Affinity
5) Reduce HPC ↔ Mainstream Language Gap

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

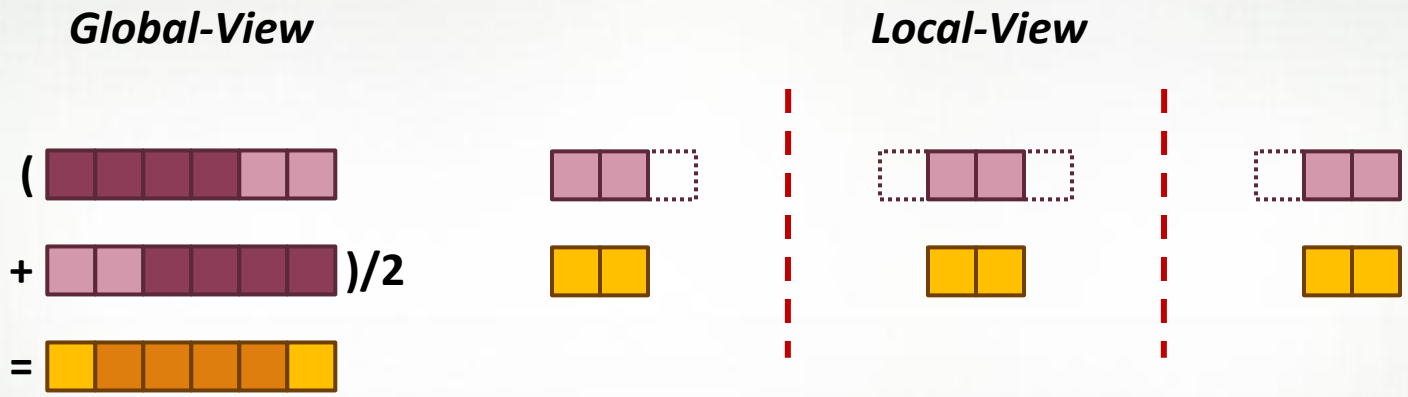
...target all parallelism available in the hardware

- **Types:** machines, nodes, cores, instructions

Style of HW Parallelism	Programming Model	Unit of Parallelism
Inter-node	Chapel	executable/task
Intra-node/multicore	Chapel	iteration/task
Instruction-level vectors/threads	Chapel	iteration
GPU/accelerator	Chapel	SIMD function/task

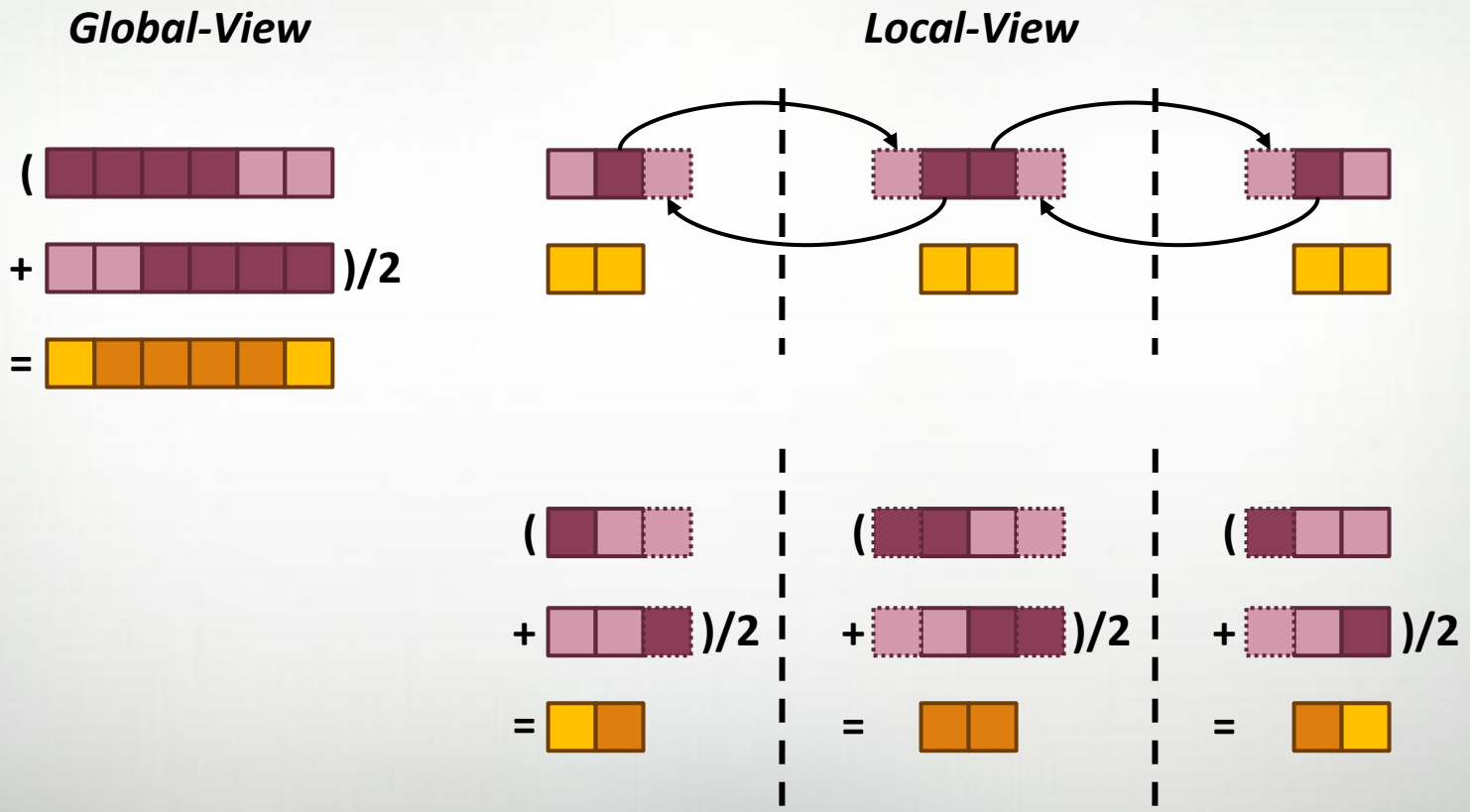
2) Global-View Abstractions

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



2) Global-View Abstractions

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



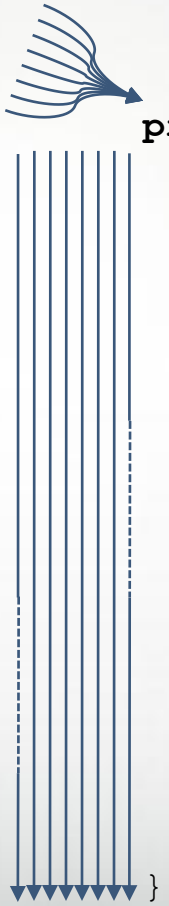
2) Global-View Abstractions

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)

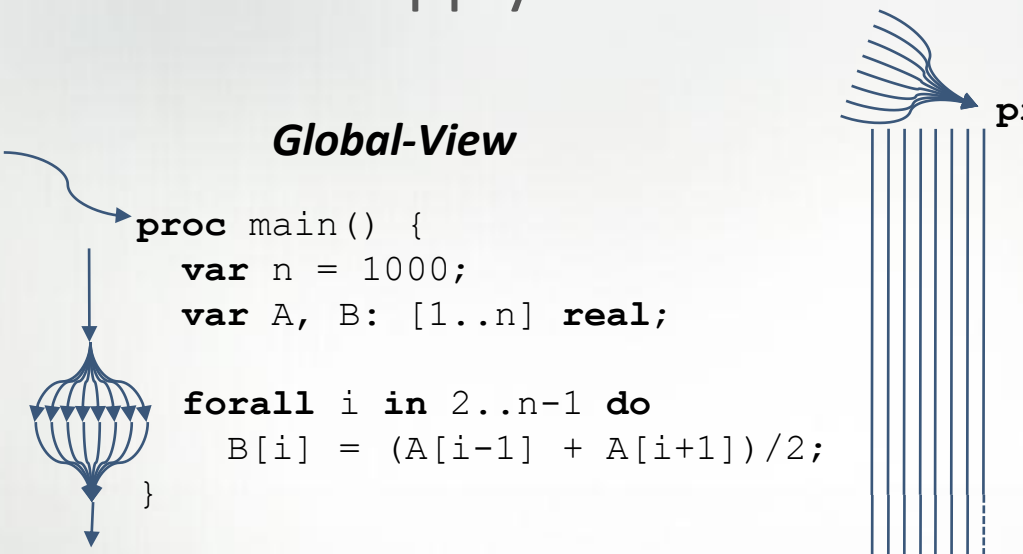
```
proc main() {
  var n = 1000;
  var p = numProcs(),
      me = myProc(),
      myN = n/p,
  var A, B: [0..myN+1] real;

  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)

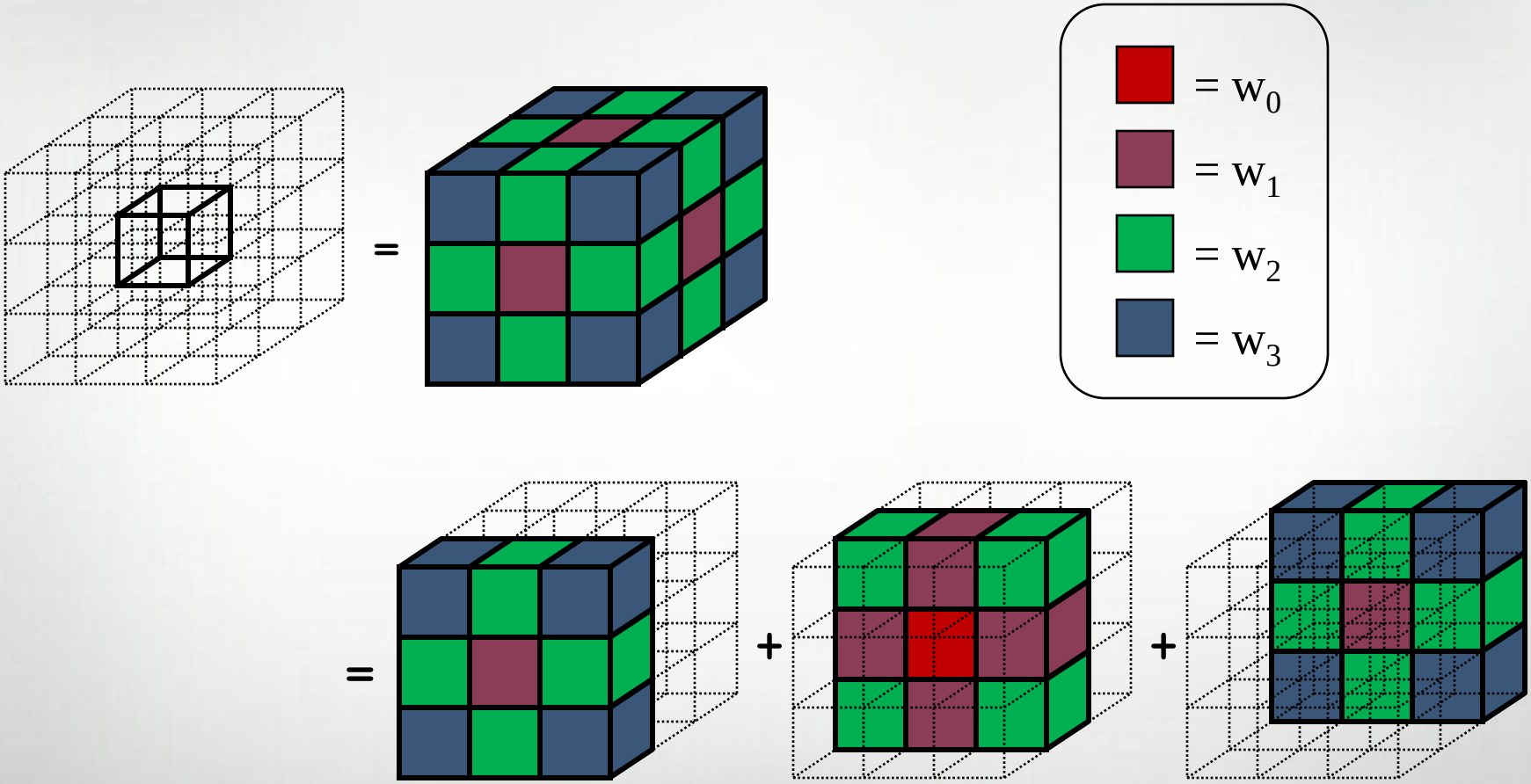
```
proc main() {
  var n = 1000;
  var p = numProcs(),
      me = myProc(),
      myN = n/p,
      myLo = 1,
      myHi = myN;
  var A, B: [0..myN+1] real;

  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,mlk,m2k,m3k,s,mlj,m2j,m3j,k )

      implicit none

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

      integer mlk, m2k, m3k, mlj, m2j, m3j,k
      double precision r(mlk,m2k,m3k), s(mlj,m2j,m3j)
      integer j3, j2, j1, i3, i2, i1, d1, d2, d3, j

      double precision x1(m), y1(m) , x2,y2


      if(mlk.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,mlj
               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,mlj-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,mlj,m2j,m3j,j)

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

      if( debug_vec(4) .ge. k )then
         call showall(s,mlj,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

      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,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 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

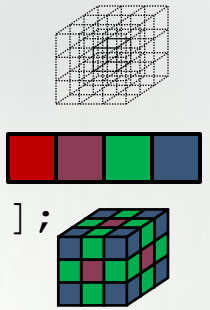
      do  i3=1,n3
         do  i2=1,n2
            do  i1=1,n1
               z(i1,i2,i3)=0.0D0
            enddo
         enddo
      enddo

      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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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

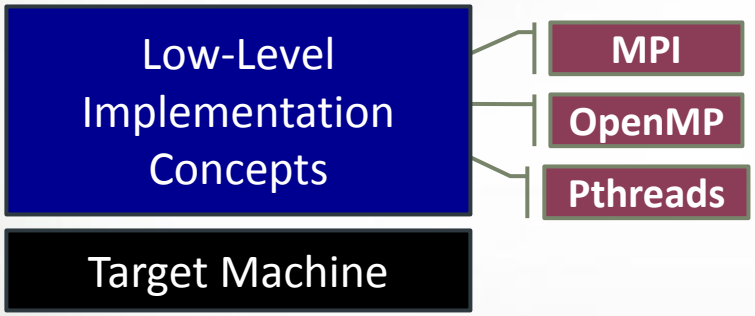
2) Global-View Programming: A Final Note

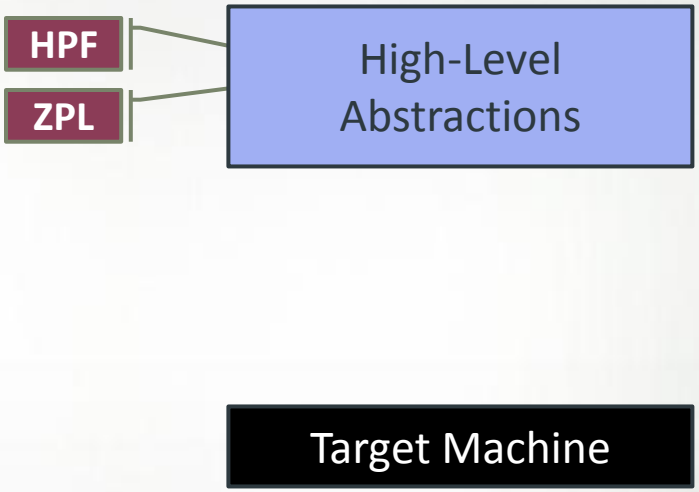
- A language may support both global- and local-view programming — in particular, Chapel does

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

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

3) Multiresolution Design: Motivation





"Why is everything so tedious/difficult?"

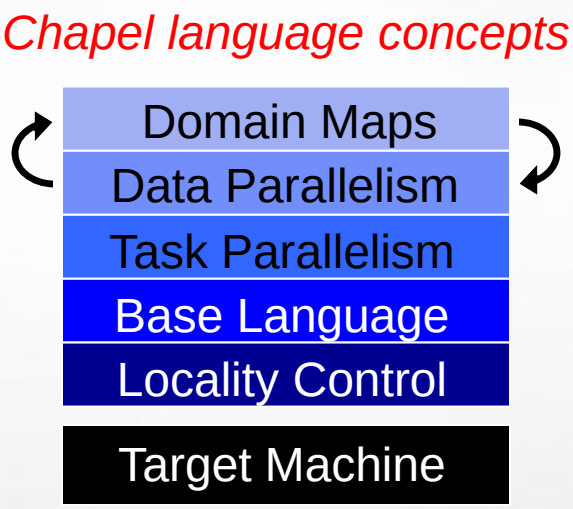
"Why don't my programs port trivially?"

"Why don't I have more control?"

3) Multiresolution Design

Multiresolution Design: Support multiple tiers of features

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



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

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 performance and scalability
- Give programmers control of data and task placement

5) Reduce HPC ↔ Mainstream Language Gap

Consider:

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

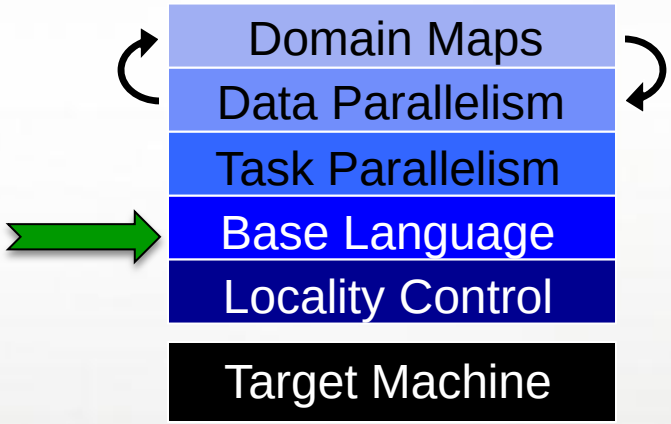
We'd like to narrow this gulf with Chapel:

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

Outline

- ✓ Motivation
- ✓ Chapel Background and Themes
- ➢ Tour of Chapel Concepts
- ● Project Status

Base Language Features



Static Type Inference

```
const pi = 3.14,              // pi is a real
      coord = 1.2 + 3.4i,     // coord is a complex…
      coord2 = pi*coord,      // …as is coord2
      name = "brad",          // name is a string
      verbose = false;        // verbose is boolean

proc addem(x, y) {            // addem() has generic arguments
  return x + y;               //   and an inferred return type
}

var sum = addem(1, pi),                 // sum is a real
    fullname = addem(name, "ford");     // fullname is a string

writeln((sum, fullname));
```

```
(4.14, bradford)
```

Range Types and Algebra

```
const r = 1..10;

printVals(r # 3);
printVals(r # -3);
printVals(r by 2);
printVals(r by 2 align 2);
printVals(r by -2);
printVals(r by 2 # 3);
printVals(r # 3 by 2);

proc printVals(r) {
  for i in r do
    write(r, " ");
  writeln();
}
```

```
1 2 3
8 9 10
1 3 5 7 9
2 4 6 8 10
10 8 6 4 2
1 3 5
1 3
```

Iterators

```
iter fibonacci(n) {
  var current = 0,
      next = 1;
  for 1..n {
    yield current;
    current += next;
    current <=> next;
  }
}
```

```
for f in fibonacci(7) do
  writeln(f);
```

```
0
1
1
2
3
5
8
```

```
iter tiledRMO(D, tilesize) {
  const tile = [0..#tilesize,
                0..#tilesize];
  for base in D by tilesize do
    for ij in D[tile + base] do
      yield ij;
}
```

```
for ij in tiledRMO(D, 2) do
  write(ij);
```

```
(1,1)(1,2)(2,1)(2,2)
(1,3)(1,4)(2,3)(2,4)
(1,5)(1,6)(2,5)(2,6)
…
(3,1)(3,2)(4,1)(4,2)
```

Zippered Iteration

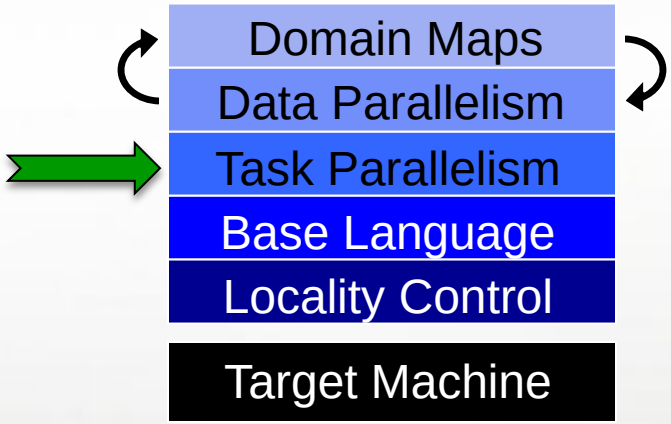
```
for (i,f) in (0..#n, fibonacci(n)) do
  writeln("fib #", i, " is ", f);
```

```
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
…
```

Other Base Language Features

- tuple types
- compile-time features for meta-programming
  - e.g., compile-time functions to compute types, params
- rank-independent programming features
- value- and reference-based OOP
- argument intents, default values, match-by-name
- overloading, where clauses
- modules (for namespace management)
- …

Task Parallel Features



Coforall Loops

```
coforall t in 0..#numTasks do
  writeln("Hello from task ", t, " of ", numTasks);

writeln("All tasks done");
```

```
Hello from task 2 of 4
Hello from task 0 of 4
Hello from task 3 of 4
Hello from task 1 of 4
All tasks done
```

Bounded Buffer Producer/Consumer Example

```
cobegin {
  producer();
  consumer();
}

// 'sync' types store full/empty state along with value
var buff$: [0..#buffersize] sync real;

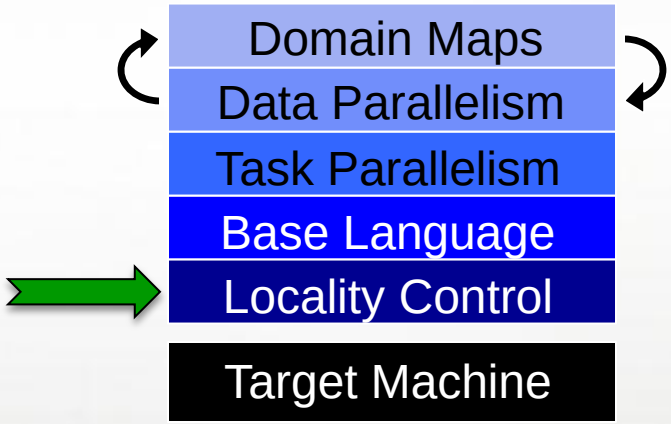
proc producer() {
  var i = 0;
  for … {
    i = (i+1) % buffersize;
    buff$[i] = …;    // reads block until empty, leave full
} }

proc consumer() {
  var i = 0;
  while … {
    i= (i+1) % buffersize;
    …buff$[i]…;     // writes block until full, leave empty
} }
```

Other Task Parallel Features

- *begin* statements for fire-and-forget tasks
- *atomic variables* for lock-free programming

Locality Features

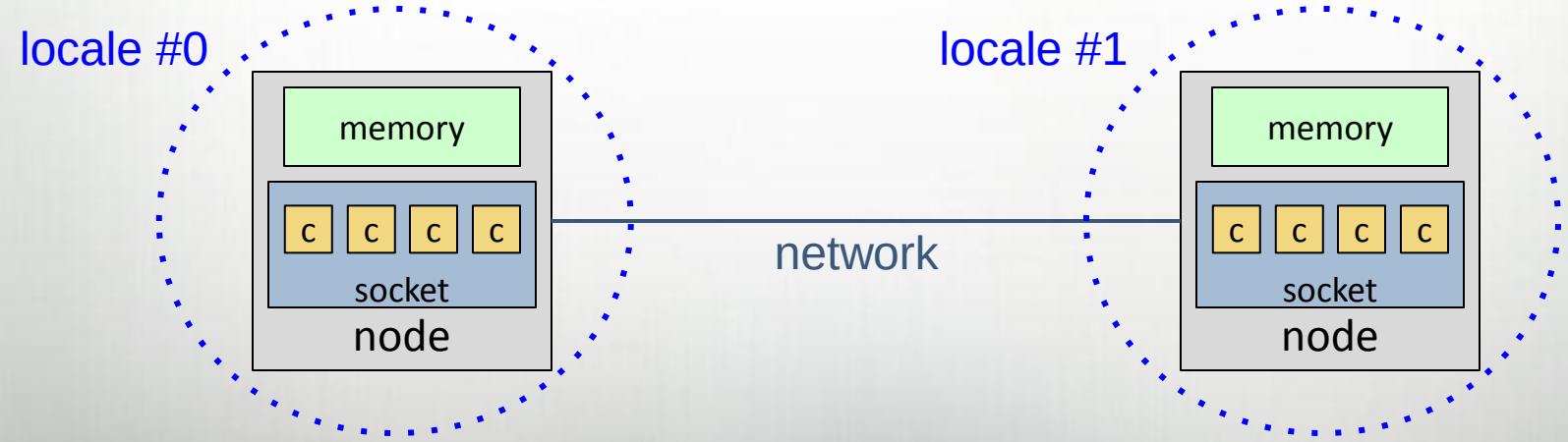


The Locale Type

Definition:

- Abstract unit of target architecture
- Supports reasoning about locality
- Capable of running tasks and storing variables
  - i.e., has processors and memory

Typically: A multi-core processor or SMP* node



*Symmetric Multiprocessor

Defining Locales

- Specify # of locales when running Chapel programs

```
% a.out --numLocales=8
```

```
% a.out -nl 8
```

- Chapel provides built-in locale variables

```
config const numLocales: int = …;
const Locales: [0..#numLocales] locale = …;
```

Locale Operations

- Locale methods support queries about target system:

```
proc locale.physicalMemory(…) { … }
proc locale.numCores { … }
proc locale.id { … }
proc locale.name { … }
```

- *On-clauses* support placement of computations:

```
writeln("on locale 0");

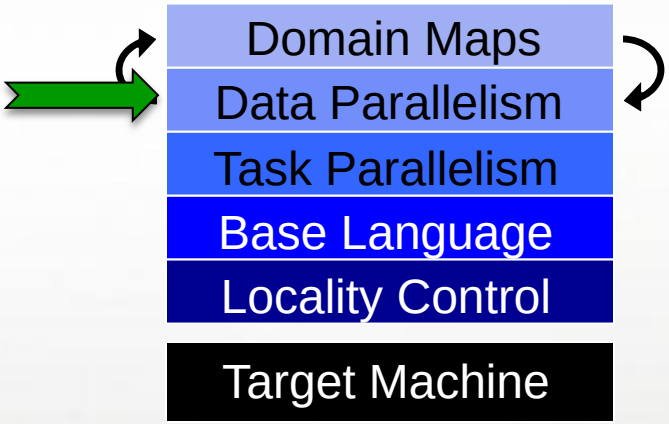
on Locales[1] do
  writeln("now on locale 1");

writeln("on locale 0 again");
```

```
cobegin {
  on A[i,j] do
    bigComputation(A);

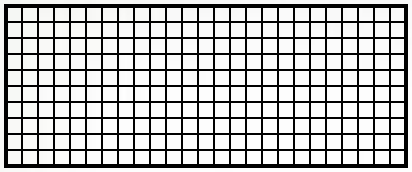
  on node.left do
    search(node.left);
}
```

Data Parallel Features

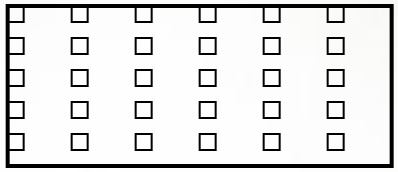


Chapel Domain Types

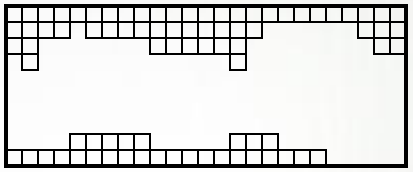
Chapel supports several types of domains (index sets) :



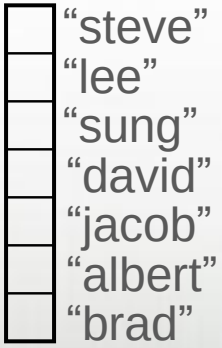
dense



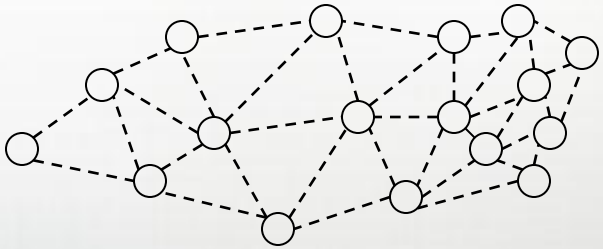
strided



sparse



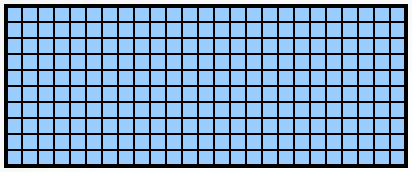
associative



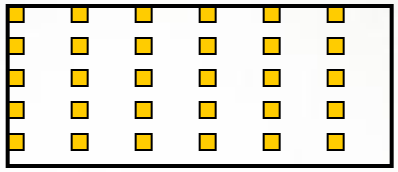
unstructured

Chapel Array Types

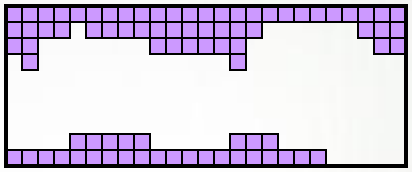
Each domain type can be used to declare arrays:



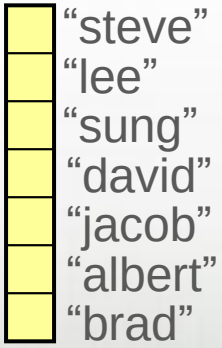
dense



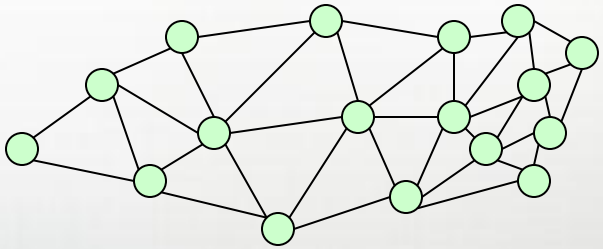
strided



sparse



associative



unstructured

Data Parallel Operations

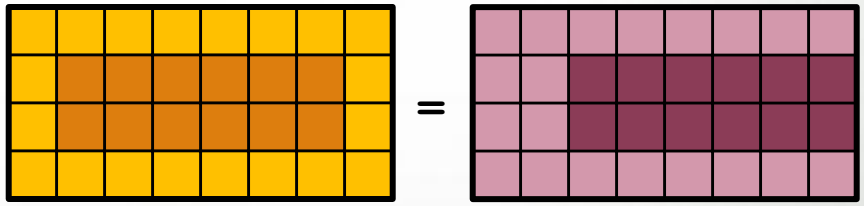
- Parallel Iteration via forall loops

```
A = forall (i,j) in D do (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)];
```



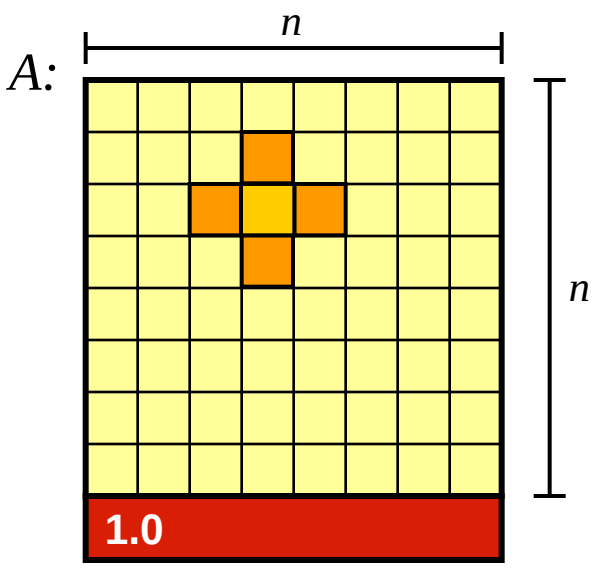
- Promotion of Scalar Operators and Functions

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

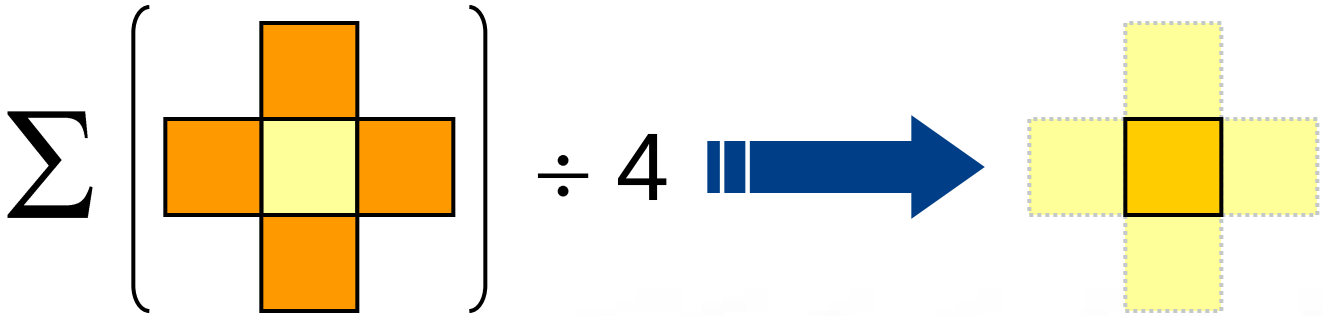
```
A = exp(B, C);
```

- And several others: indexing, reallocation, set operations, remapping, aliasing, queries, …

Jacobi Iteration in Pictures



repeat until max change < ε



Jacobi Iteration in Chapel

```
config const n = 6,
             epsilon = 1.0e-5;

const BigD: domain(2) = [0..n+1, 0..n+1],
          D: subdomain(BigD) = [1..n, 1..n],
    LastRow: subdomain(BigD) = D.exterior(1,0);

var A, Temp : [BigD] real;

A[LastRow] = 1.0;

do {
  [(i,j) in D] Temp(i,j) = (A[i-1,j] + A[i+1,j]
                          + A[i,j-1] + A[i,j+1]) / 4;

  const delta = max reduce abs(A[D] - Temp[D]);
  A[D] = Temp[D];
} while (delta > epsilon);

writeln(A);
```

Jacobi Iteration in Chapel

```
config const n = 6,
             epsilon = 1.0e-5;

const BigD: domain(2) = [0..n+1, 0..n+1],
          D: subdomain(BigD) = [1..n, 1..n],
   LastRow: subdomain(BigD) = D.exterior(1,0);

var A, Temp : [BigD] real;

A[Las

do {
  [(i

  con
  A[D
} whi

writeln(A);
```

Declare program parameters

const ⇒ can't change values after initialization

config ⇒ can be set on executable command-line

```
prompt> jacobi --n=10000 --epsilon=0.0001
```

note that no types are given; inferred from initializer

n ⇒ **default integer** (32 bits)

epsilon ⇒ **default real floating-point** (64 bits)

Jacobi Iteration in Chapel

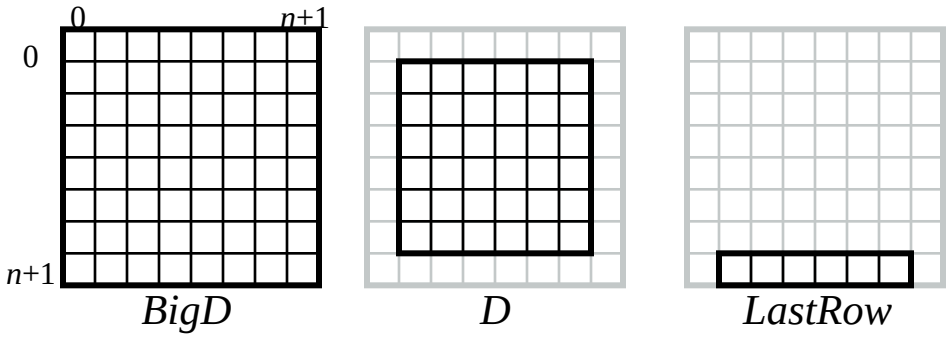
```
config const n = 6,
             epsilon = 1.0e-5;

const BigD: domain(2) = [0..n+1, 0..n+1],
          D: subdomain(BigD) = [1..n, 1..n],
   LastRow: subdomain(BigD) = D.exterior(1,0);
```

Declare domains (first class index sets)

domain(2) ⇒ 2D arithmetic domain, indices are integer 2-tuples

subdomain(*P*) ⇒ a domain of the same type as *P* whose indices are guaranteed to be a subset of *P*'s



exterior ⇒ one of several built-in domain generators

Jacobi Iteration in Chapel

```
config const n = 6,
             epsilon = 1.0e-5;

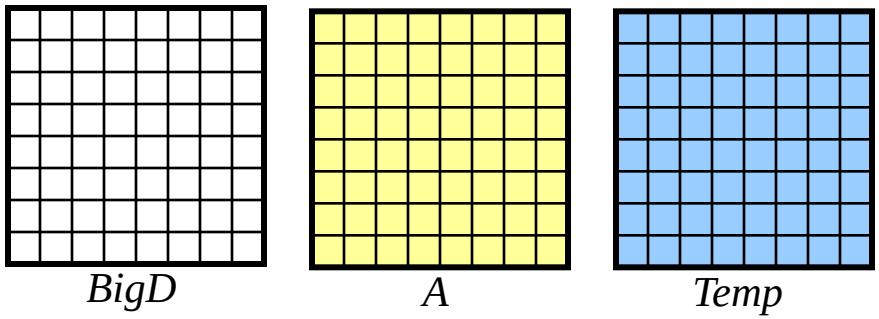
const BigD: domain(2) = [0..n+1, 0..n+1],
          D: subdomain(BigD) = [1..n, 1..n],
    LastRow: subdomain(BigD) = D.exterior(1,0);

var A, Temp : [BigD] real;

A[LastRow] = 1.0;
```

Declare arrays

var ⇒ can be modified throughout its lifetime
: ***[BigD] T*** ⇒ array of size *BigD* with elements of type *T*
(no initializer) ⇒ values initialized to default value (0.0 for reals)



Jacobi Iteration in Chapel

```
config const n = 6,
             epsilon = 1.0e-5;

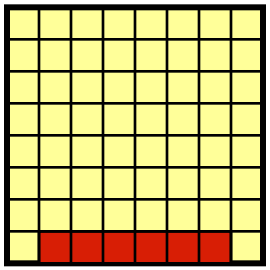
const BigD: domain(2) = [0..n+1, 0..n+1],
          D: subdomain(BigD) = [1..n, 1..n],
    LastRow: subdomain(BigD) = D.exterior(1,0);

var A, Temp : [BigD] real;

A[LastRow] = 1.0;
```

Set Explicit Boundary Condition

indexing by domain ⇒ slicing mechanism
array expressions ⇒ parallel evaluation



A

Jacobi Iteration in Chapel

```
config const n = 6,
             epsilon = 1.0e-5;
```

Compute 5-point stencil

[(*i,j*) in *D*] ⇒ parallel forall expression over *D*'s indices, binding them to new variables *i* and *j*

```
  [(i,j) in D] Temp(i,j) = (A[i-1,j] + A[i+1,j]
                          + A[i,j-1] + A[i,j+1]) / 4;

  const delta = max reduce abs(A[D] - Temp[D]);
  A[D] = Temp[D];
} while (delta > epsilon);

writeln(A);
```

Jacobi Iteration in Chapel

```
config const n = 6,
             epsilon = 1.0e-5;

const BigD: domain(2) = [0..n+1, 0..n+1],
```

Compute maximum change

***op* reduce** ⇒ collapse aggregate expression to scalar using *op*

Promotion: *abs()* and – are scalar operators, automatically promoted to work with array operands

```
do {
  [(i,j) in D] Temp(i,j) = (A[i-1,j] + A[i+1,j]
                          + A[i,j-1] + A[i,j+1]) / 4;

  const delta = max reduce abs(A[D] - Temp[D]);
  A[D] = Temp[D];
} while (delta > epsilon);

writeln(A);
```

Jacobi Iteration in Chapel

```
config const n = 6,
             epsilon = 1.0e-5;

const BigD: domain(2) = [0..n+1, 0..n+1],
          D: subdomain(BigD) = [1..n, 1..n],
   LastRow: subdomain(BigD) = D.exterior(1,0);

var

A[La

do {
  [(i,j) in D] Temp(i,j) = (A[i-1,j] + A[i+1,j]
                          + A[i,j-1] + A[i,j+1]) / 4;

  const delta = max reduce abs(A[D] - Temp[D]);
  A[D] = Temp[D];
} while (delta > epsilon);

writeln(A);
```

Copy data back & Repeat until done

uses slicing and whole array assignment
standard *do…while* loop construct

Jacobi Iteration in Chapel

```
config const n = 6,
             epsilon = 1.0e-5;

const BigD: domain(2) = [0..n+1, 0..n+1],
          D: subdomain(BigD) = [1..n, 1..n],
   LastRow: subdomain(BigD) = D.exterior(1,0);

var A, Temp : [BigD] real;

A[LastRow] = 1.0;

do {
  [(i,j) in D] Temp(i,j) = (A[i-1,j] + A[i+1,j]
                          + A[i,j-1] + A[i,j+1]) / 4;

  const delta = max reduce abs(A[D] - Temp[D]);
  A[D] = Temp[D];
} while (delta > epsilon);

writeln(A);
```

Write array to console

Jacobi Iteration in Chapel

```
config const n = 6,
             epsilon = 1.0e-5;

const BigD = [0..n+1, 0..n+1] dmapped Block(…),
          D: subdomain(BigD) = [1..n, 1..n],
    LastRow: subdomain(BigD) = D.exterior(1,0);

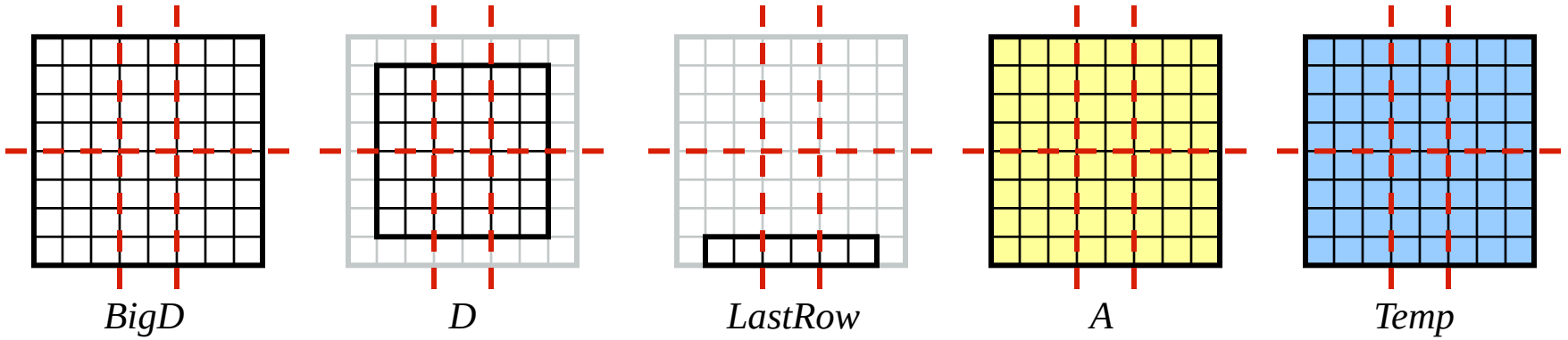
var A, Temp : [BigD] real;
```

With this change, same code runs in a distributed manner

Domain distribution maps indices to *locales*

⇒ decomposition of arrays & default mapping of iterations to locales

Subdomains inherit parent domain's distribution



Jacobi Iteration in Chapel

```
config const n = 6,
             epsilon = 1.0e-5;

const BigD = [0..n+1, 0..n+1] dmapped Block(…),
          D: subdomain(BigD) = [1..n, 1..n],
    LastRow: subdomain(BigD) = D.exterior(1,0);

var A, Temp : [BigD] real;

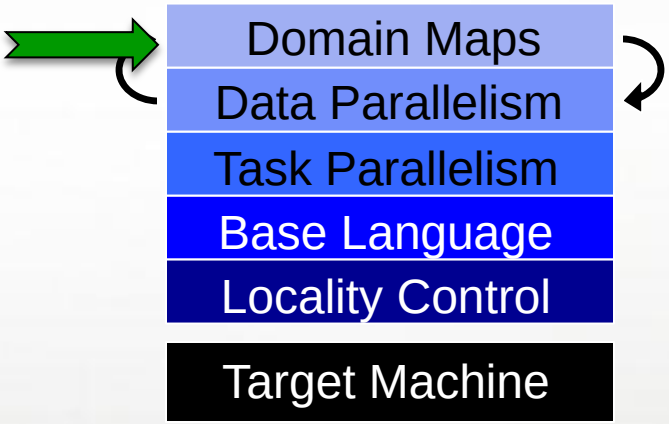
A[LastRow] = 1.0;

do {
  [(i,j) in D] Temp(i,j) = (A[i-1,j] + A[i+1,j]
                          + A[i,j-1] + A[i,j+1]) / 4;

  const delta = max reduce abs(A[D] - Temp[D]);
  A[D] = Temp[D];
} while (delta > epsilon);

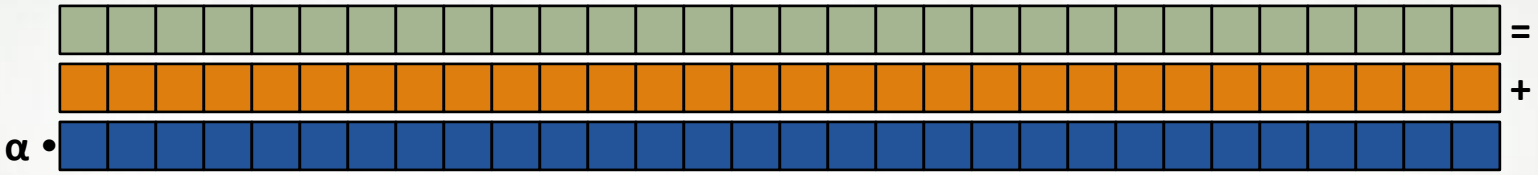
writeln(A);
```

Domain Maps


Domain Maps
Data Parallelism
Task Parallelism
Base Language
Locality Control
Target Machine

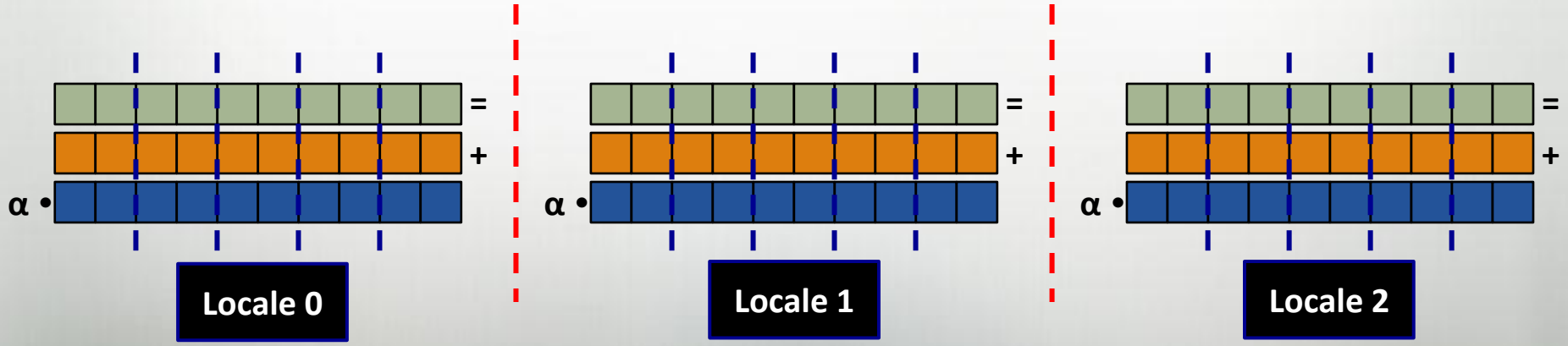
Domain Maps

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



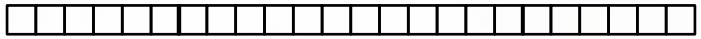

```
A = B + alpha * C;
```

…to the target locales’ memory and processors:

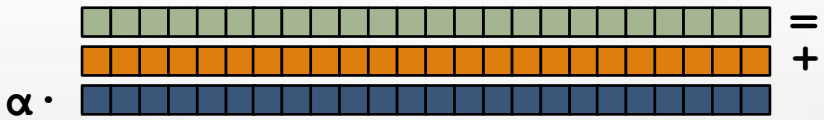


STREAM Triad: Chapel (multicore)

```
const ProblemSpace = [1..m];
```



```
var A, B, C: [ProblemSpace] real;
```



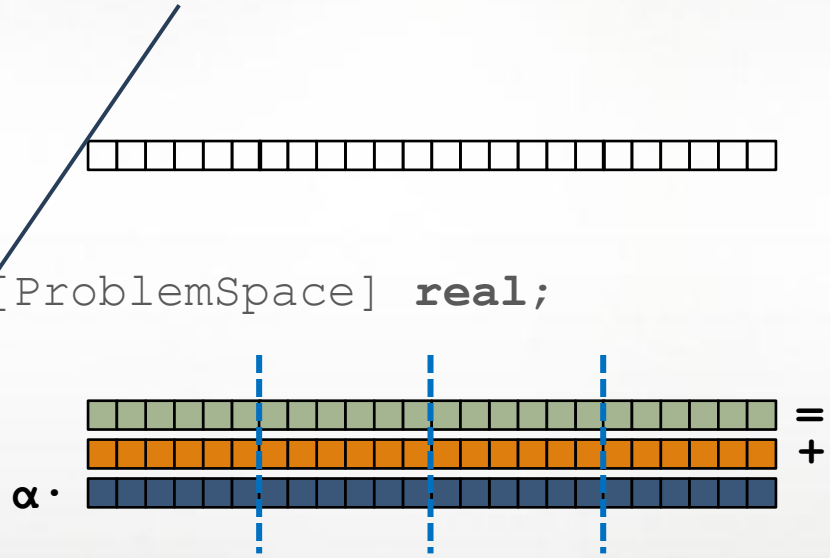

```
A = B + alpha * C;
```

STREAM Triad: Chapel (multicore)

```
const ProblemSpace = [1..m];

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

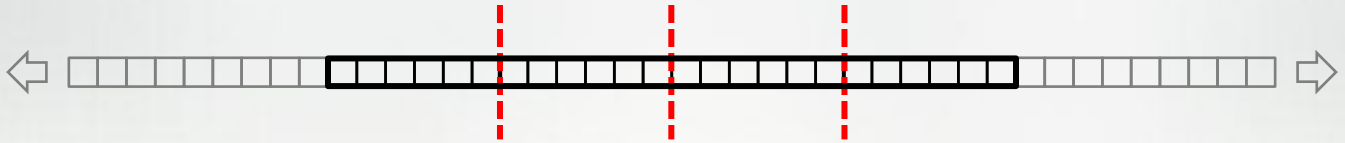
A = B + alpha * C;
```



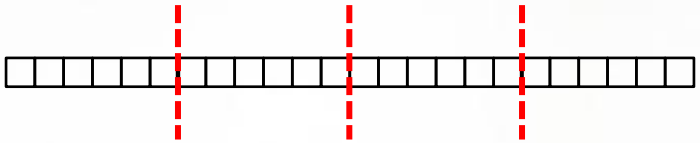
No domain map specified => use default layout

- current locale owns all indices and values
- computation will execute using local processors only

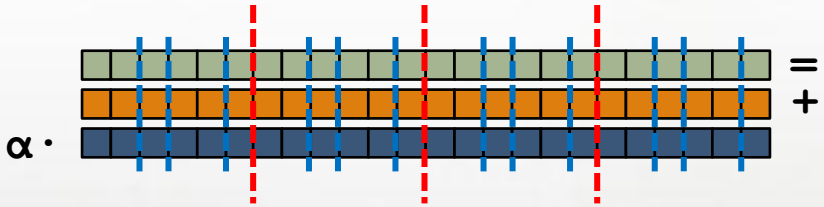
STREAM Triad: Chapel (multilocale, blocked)



```
const ProblemSpace = [1..m]
                     dmapped Block(boundingBox=[1..m]);
```

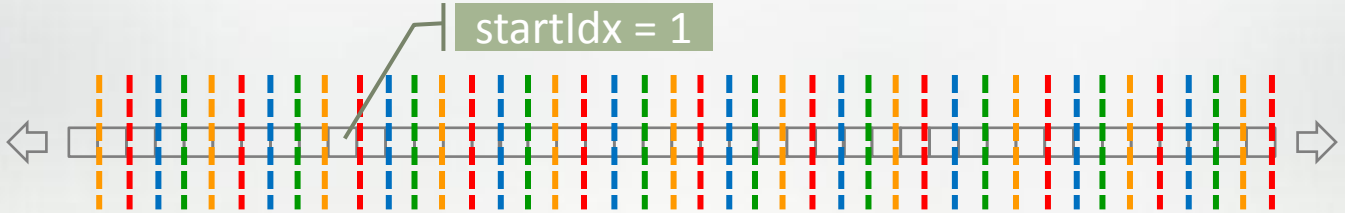


```
var A, B, C: [ProblemSpace] real;
```

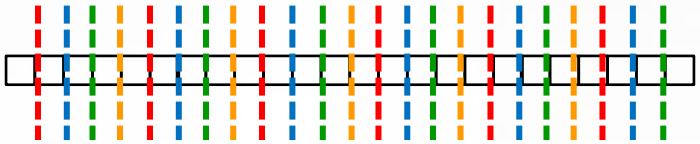



```
A = B + alpha * C;
```

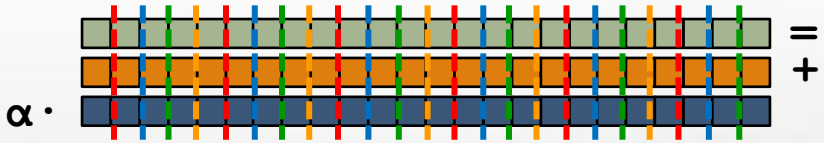
STREAM Triad: Chapel (multilocale, cyclic)




```
const ProblemSpace = [1..m]
                          dmapped Cyclic(startIdx=1);
```



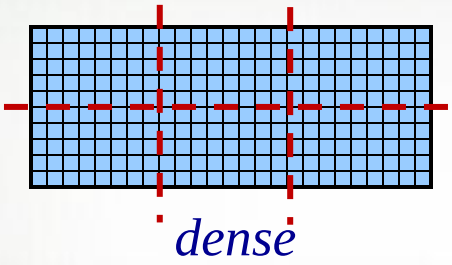
```
var A, B, C: [ProblemSpace] real;
```

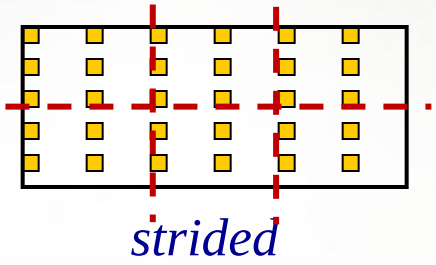


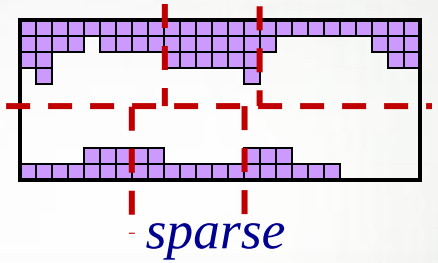

```
A = B + alpha * C;
```

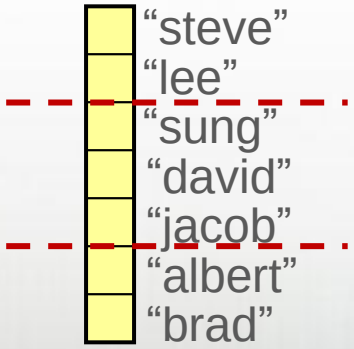
Domain Map Types

All Chapel domain types support domain maps

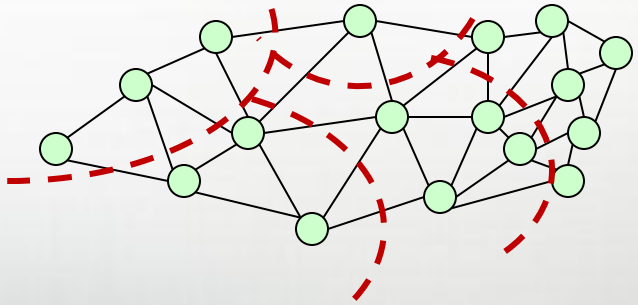








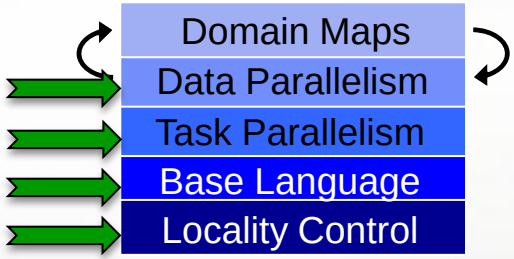
associative



unstructured

Chapel's Domain Map Philosophy

1. Chapel provides a library of standard domain maps
   - to support common array implementations effortlessly
2. Advanced users can write their own domain maps in Chapel
   - to cope with shortcomings in our standard library



3. 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

For More Information on Domain Maps

HotPAR'10: *User-Defined Distributions and Layouts in Chapel: Philosophy and Framework*
Chamberlain, Deitz, Iten, Choi; June 2010

CUG 2011: *Authoring User-Defined Domain Maps in Chapel*
Chamberlain, Choi, Deitz, Iten, Litvinov; May 2011

PGAS 2011: *User-Defined Parallel Zippered Iterators in Chapel,*
Chamberlain, Choi, Deitz, Navarro; October 2011

Chapel release:

- Technical notes detailing domain map interface for programmers:
  - $CHPL_HOME/doc/technotes/README.dsi
- Current domain maps:
  $CHPL_HOME/modules/dists/*.chpl
  layouts/*.chpl
  internal/Default*.chpl

Domain Map Summary

- Chapel avoids locking crucial implementation decisions into the language specification
  - local and distributed array implementations
  - parallel loop implementations
- Instead, these can be…

  …specified in the language by an advanced user

  …swapped in and out with minimal code changes
- The result separates the roles of domain scientist, parallel programmer, and implementation cleanly

Outline

- ✓ Motivation
- ✓ Chapel Background and Themes
- ✓ Tour of Chapel Concepts
- ➢ Project Status

Implementation Status -- Version 1.5.0 (Apr 19, 2012)

In a nutshell:

- Most features work at a functional level
- Many performance optimizations remain
  - particularly for distributed memory (multi-locale) execution

This is a good time to:

- Try out the language and compiler
- Use Chapel for non-performance-critical projects
- Give us feedback to improve Chapel
- Use Chapel for parallel programming education

Chapel and Education

- If I were teaching parallel programming, I'd want to cover:
  - data parallelism
  - task parallelism
  - concurrency
  - synchronization
  - locality/affinity
  - deadlock, livelock, and other pitfalls
  - performance tuning
  - memory consistency models
  - …
- I don't think there's been a good language out there…
  - for teaching *all* of these things
  - for teaching some of these things well at all
  - ***until now:*** We believe Chapel can potentially play a crucial role here

(see http://chapel.cray.com/education.html for more information)

Join Our Growing Community

- Cray:


Brad Chamberlain


Sung-Eun Choi


Greg Titus


Vass Litvinov


Tom Hildebrandt

(open positions)

- External Collaborators:


Albert Sidelnik
(UIUC)


Jonathan Turner
(CU Boulder)

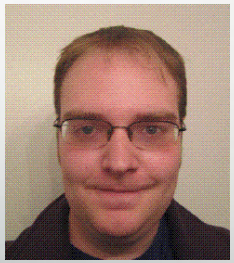

Kyle Wheeler
(Sandia)

You? Your Friend/Student/ Colleague?

- Interns:


Jonathan Claridge
(UW)


Hannah Hemmaplardh
(UW)


Andy Stone
(Colorado State)


Jim Dinan
(OSU)


Rob Bocchino
(UIUC)


Mackale Joyner
(Rice)

Featured Collaborations (see chapel.cray.com/collaborations.html for details)

- **CPU-GPU Computing:** UIUC (David Padua, Albert Sidelnik, Maria Garzarán)
  - **paper to appear at IPDPS 2012**
- **Tasking using Qthreads:** Sandia (Rich Murphy, Kyle Wheeler, Dylan Stark)
  - **paper at CUG, May 2011**
- **Interoperability using Babel/BRAID:** LLNL (Tom Epperly, Adrian Prantl, et al.)
  - **paper at PGAS, Oct 2011**
- **Dynamic Iterators:**
- **Bulk-Copy Opt:**
- **Parallel File I/O:**

  U Malaga (Rafael Asenjo, Maria Angeles Navarro, et al.)
  - **paper at ParCo, Aug 2011**
- **Improved I/O & Data Channels:** LTS (Michael Ferguson)
- **Interfaces/Generics/OOP:** CU Boulder (Jeremy Siek, Jonathan Turner)
- **Tasking over Nanos++:** BSC/UPC (Alex Duran)
- **Tuning/Portability/Enhancements:** ORNL (Matt Baker, Jeff Kuehn, Steve Poole)
- **Chapel-MPI Compatibility:** Argonne (Rusty Lusk, Pavan Balaji, Jim Dinan, et al.)

Summary

Higher-level programming models can help insulate algorithms from parallel implementation details

- yet, without necessarily abdicating control
- Chapel does this via its multiresolution design

We believe Chapel can greatly improve productivity

…for current and emerging HPC architectures

…and for the growing need for parallel programming in the mainstream

For More Information

Chapel project page: http://chapel.cray.com

- overview, papers, presentations, language spec, …

Chapel SourceForge page: https://sourceforge.net/projects/chapel/

- release downloads, public mailing lists, code repository, …

Mailing Lists:

- chapel_info@cray.com: contact the team
- chapel-users@lists.sourceforge.net: user-oriented discussion list
- chapel-developers@lists.sourceforge.net: dev.-oriented discussion
- chapel-education@lists.sourceforge.net: educator-oriented discussion
- chapel-bugs@lists.sourceforge.net: public bug forum
- chapel_bugs@cray.com: private bug mailing list

CRAY
THE SUPERCOMPUTER COMPANY

http://chapel.cray.com chapel_info@cray.com http://sourceforge.net/projects/chapel/