Unified Parallel C (UPC)

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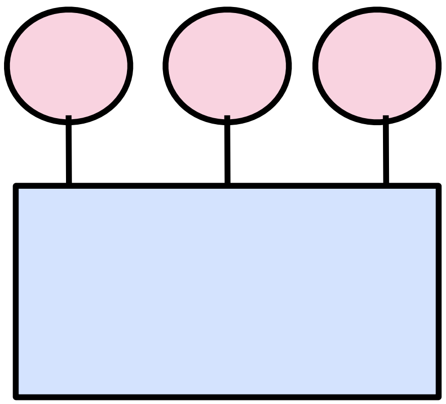
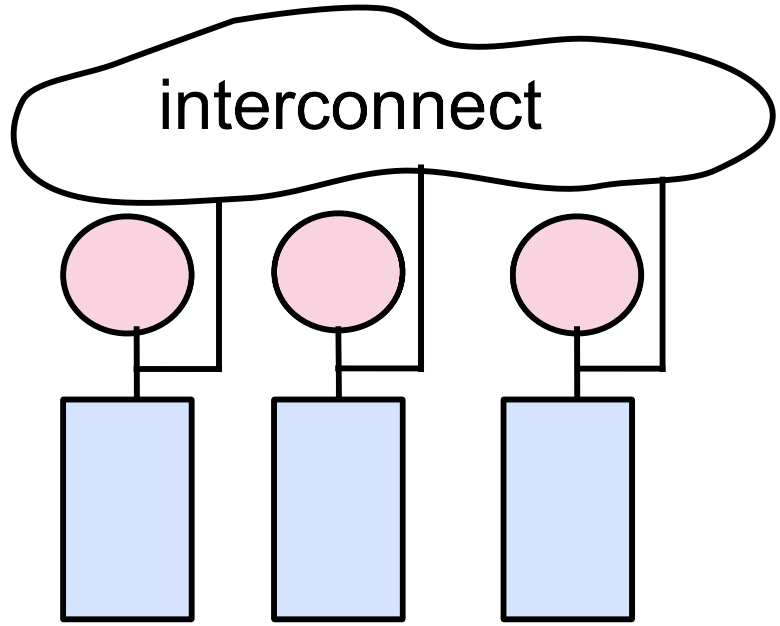
Idealized Parallel Architectures



Shared Memory



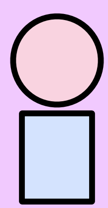
Distributed Memory

Programming Models

Cilk
OpenMP
Pthreads

MPI

Key:



Process/Thread

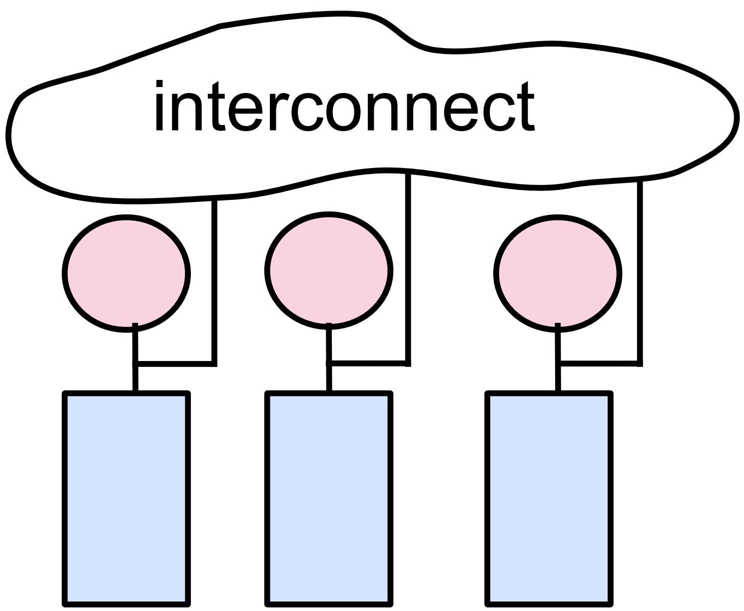
Memory

Performance Concerns for Distributed Memory

Data movement and synchronization are expensive

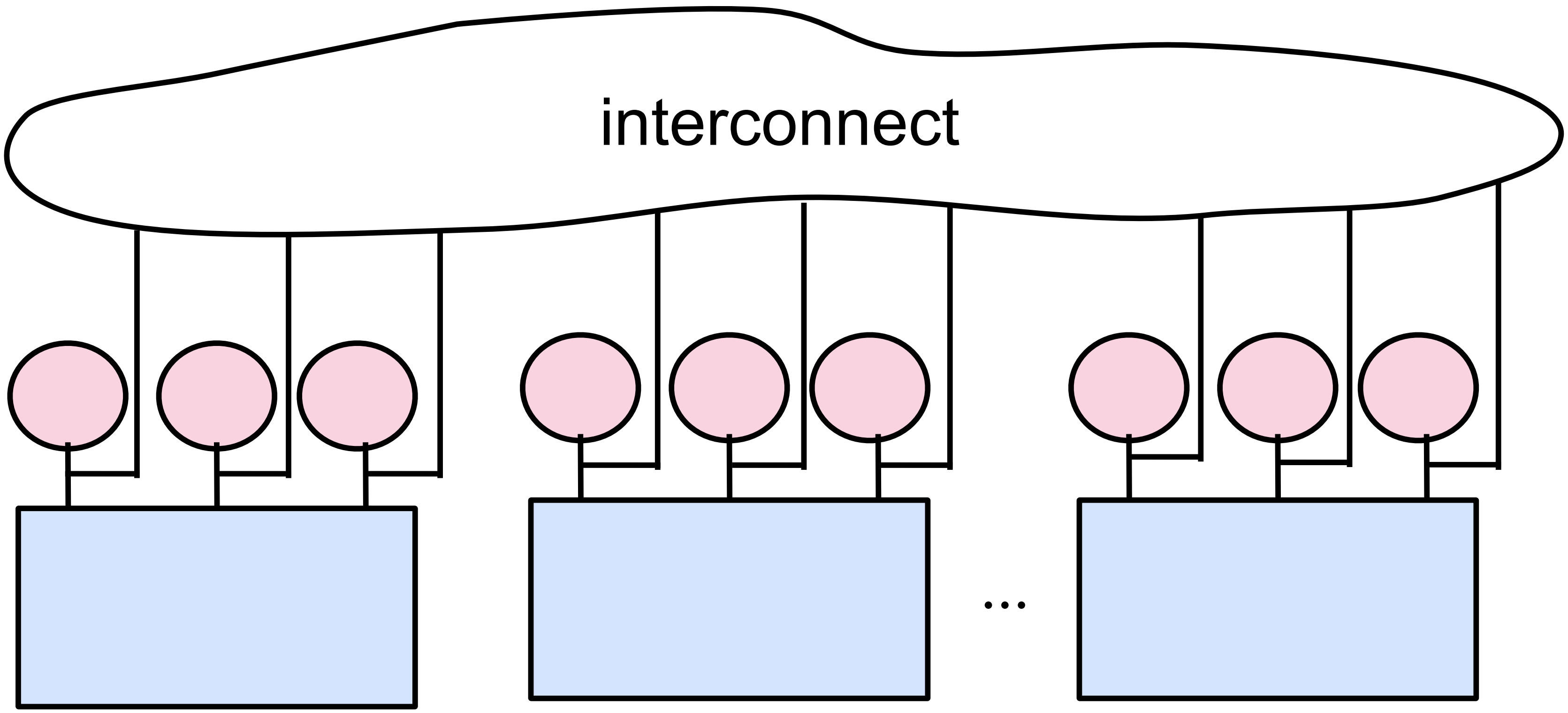
To minimize overheads

- **Co-locate data with processes**
- **Aggregate multiple accesses to remote data**
- **Overlap communication with computation**



Distributed Memory

Idealized Parallel Architectures of Today



Hybrid Shared + Distributed Memory

Programming Models

e.g., MPI + OpenMP
PGAS models

Partitioned Global Address Space Model

- A global address space that is logically distributed
- A collection of threads operating within the address space
- Each thread has affinity with a portion of the address space
- Each thread has private data as well

Partitioned Global Address Space Languages

- Global address space
  - one-sided communication (GET/PUT) simpler than msg passing
- Programmer has control over performance-critical factors
  - data distribution and locality control lacking in OpenMP
  - computation partitioning
  - communication placement

  mostly up to the compiler & runtime system for OpenMP and Cilk
- Data movement and synchronization as language primitives
  - amenable to compiler-based communication optimization

Partitioned Global Address Space Models

• Unified Parallel C	(C)	http://upc.wikinet.org
• Titanium	(Java)	http://titanium.cs.berkeley.edu
• UPC++	(C++)	https://bitbucket.org/upcxx

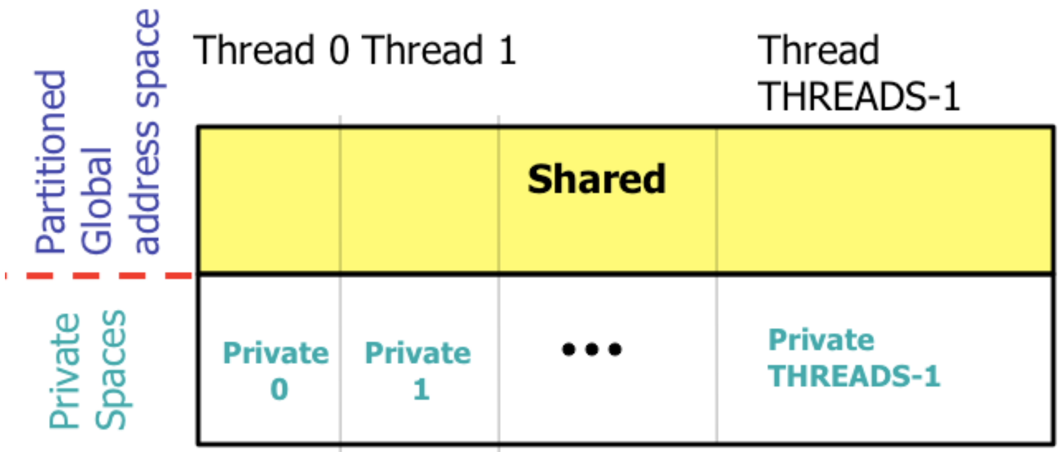
- Related efforts: HPCS Languages
  - X10 (http://x10-lang.org)
  - Chapel (http://chapel.cray.com)
  - Fortress (https://projectfortress.java.net)

Unified Parallel C (UPC)

- An explicit parallel extension of the C language
  - a few extra keywords
    - shared, MYTHREAD, THREADS, upc_forall
- Language features
  - partitioned global address space for shared data
    - part of shared data co-located with each thread
  - threads created at application launch
    - each bound to a hardware thread / core
    - each has some private data
  - a memory model
    - defines semantics of interleaved accesses to shared data
  - synchronization primitives
    - barriers
    - locks
    - load/store

UPC Execution Model

- Multiple threads work independently in a SPMD fashion
  — MYTHREAD specifies thread index (0..THREADS-1)
  — # threads specified at compile-time or program launch
- Address Space



- Threads synchronize as necessary using
  — synchronization primitives
  — shared variables

Shared and Private Data

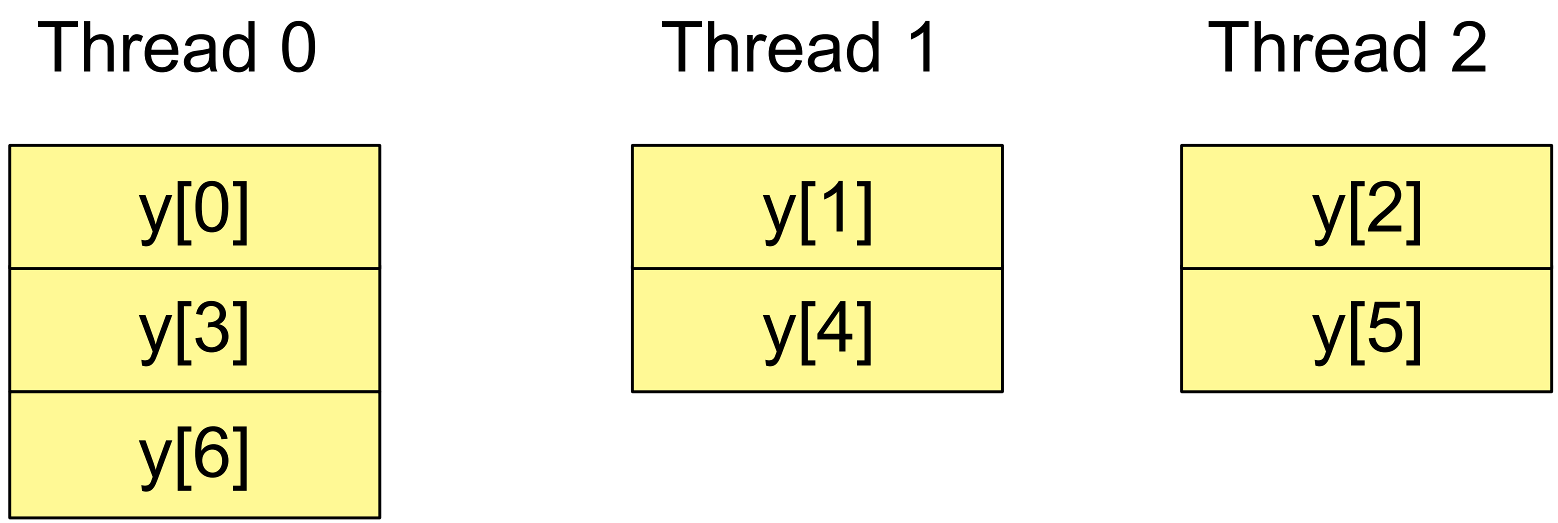
- Static and dynamic memory allocation of each type of data
- Shared objects placed in memory based on affinity
  - shared scalars have affinity to thread 0
    - here, a scalar means a singleton instance of any type
  - elements of shared arrays are allocated round robin among memory modules co-located with each thread

A One-dimensional Shared Array

Consider the following data layout directive

```
shared int y[2 * THREADS + 1];
```

For THREADS = 3, we get the following layout



A Multi-dimensional Shared Array

```
shared int A[4][THREADS];
```

For THREADS = 3, we get the following layout

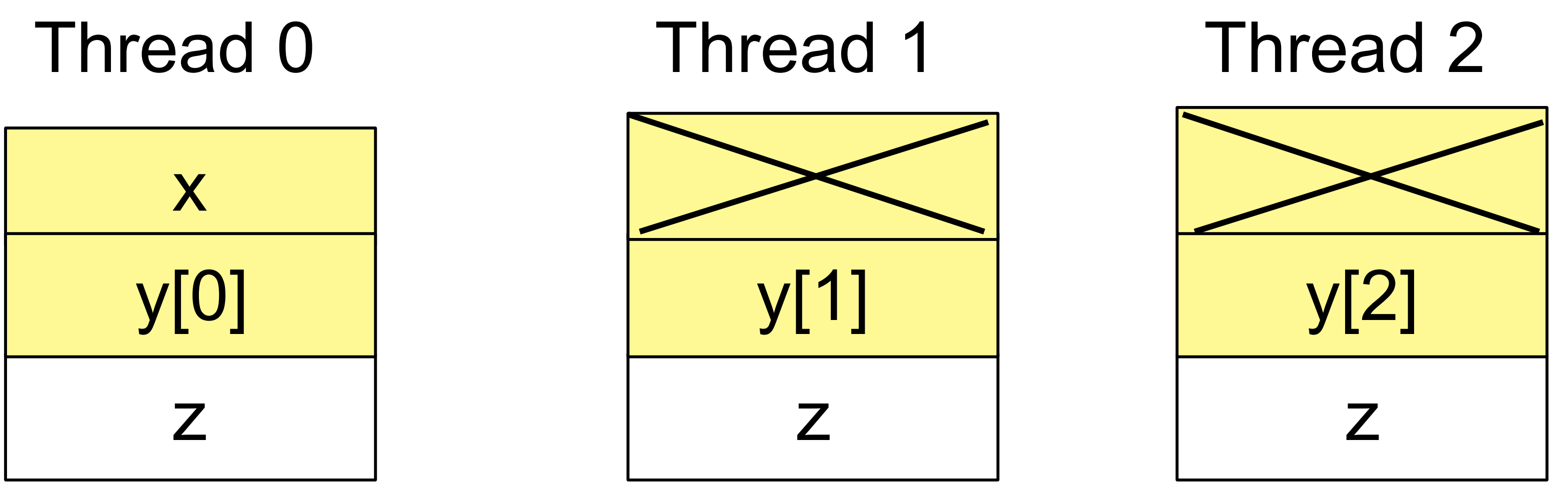
Thread 0	Thread 1	Thread 2
A[0][0]	A[0][1]	A[0][2]
A[1][0]	A[1][1]	A[1][2]
A[2][0]	A[2][1]	A[2][2]
A[3][0]	A[3][1]	A[3][2]

Shared and Private Data

Consider the following data layout directives

```
shared int x; // x has affinity to thread 0
shared int y[THREADS];
int z;          // private
```

For THREADS = 3, we get the following layout



Controlling the Layout of Shared Arrays

- Can specify a blocking factor for shared arrays
  - default block size is 1 element
- Shared arrays are distributed on a block per thread basis, round robin allocation of block size chunks
- Example layout using block size specifications
  - e.g., `shared [2] int a[16]`

block size

Thread 0	Thread 1	Thread 2
a[0]	a[2]	a[4]
a[1]	a[3]	a[5]
a[6]	a[8]	a[10]
a[7]	a[9]	a[11]
a[12]	a[14]	
a[13]	a[15]	

Blocking of Shared Arrays

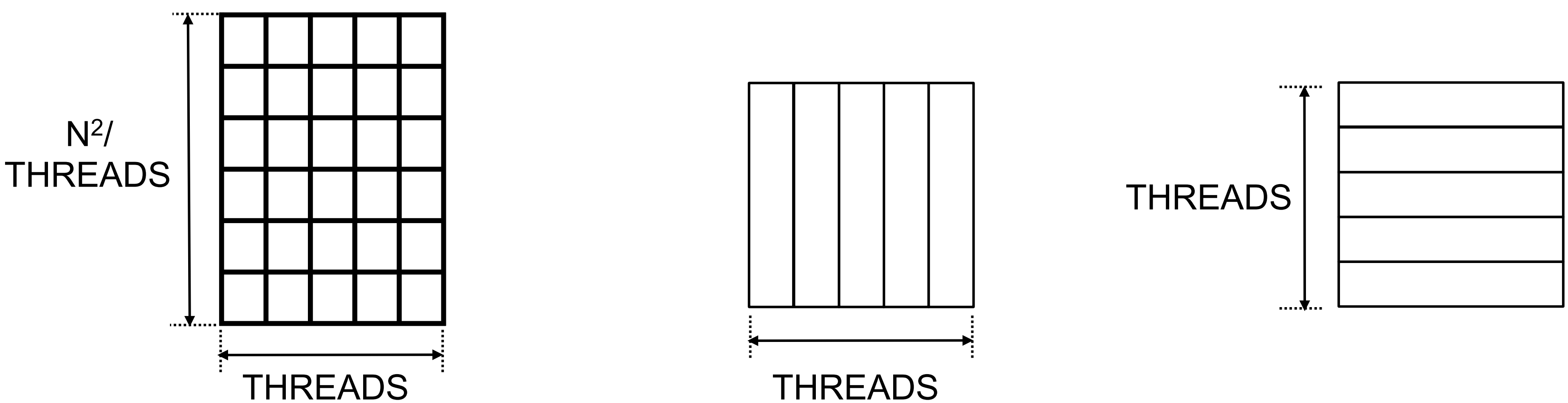
- **Block size and THREADS determine *affinity***
  - **with which thread will a datum be co-located**
- **Element i of a blocked array has affinity to thread:**

$$\left\lfloor \frac{i}{blocksize} \right\rfloor \bmod THREADS$$

Blocking Multi-dimensional Data I

- **Manage the interaction between**
  - **contiguous memory layout of C multi-dimensional arrays**
  - **blocking factor for shared layout**
- **Consider layouts for different block sizes for**
  - **shared [BLOCKSIZE] double grids[N][N];**

For the case where N = K * THREADS:



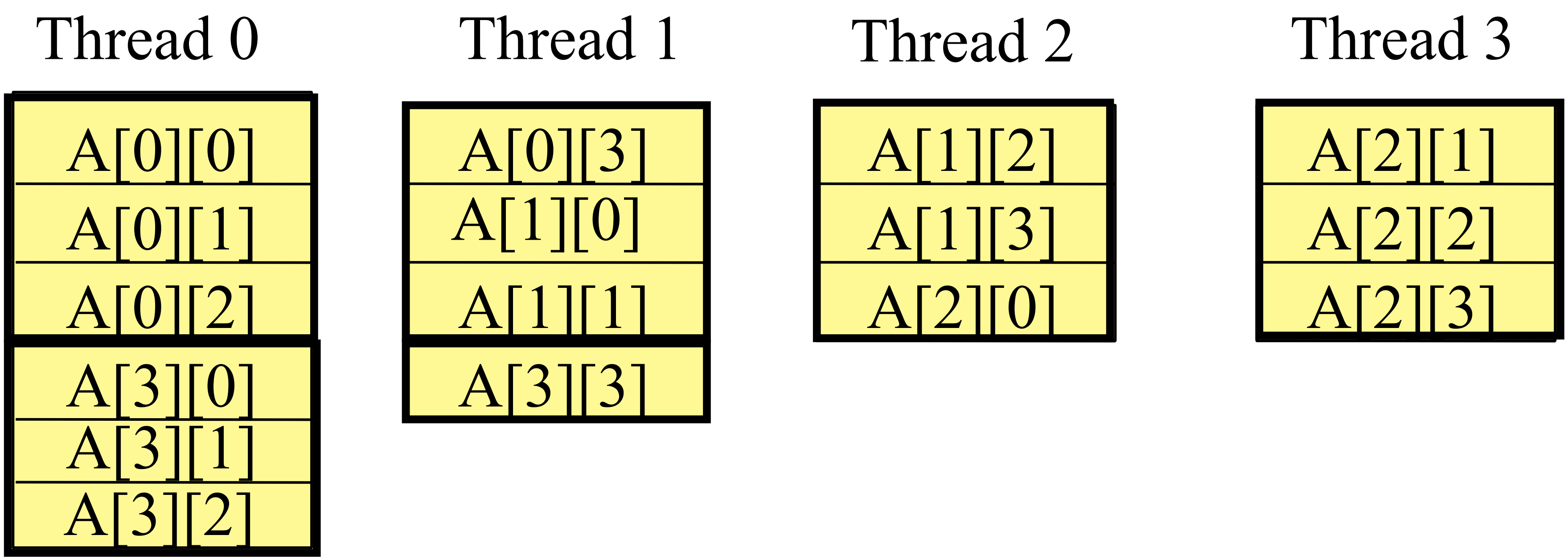
Default
BLOCKSIZE=1

Column Blocks
BLOCKSIZE=N/THREADS

Distribution by Row
BLOCKSIZE=N

Blocking Multi-dimensional Data II

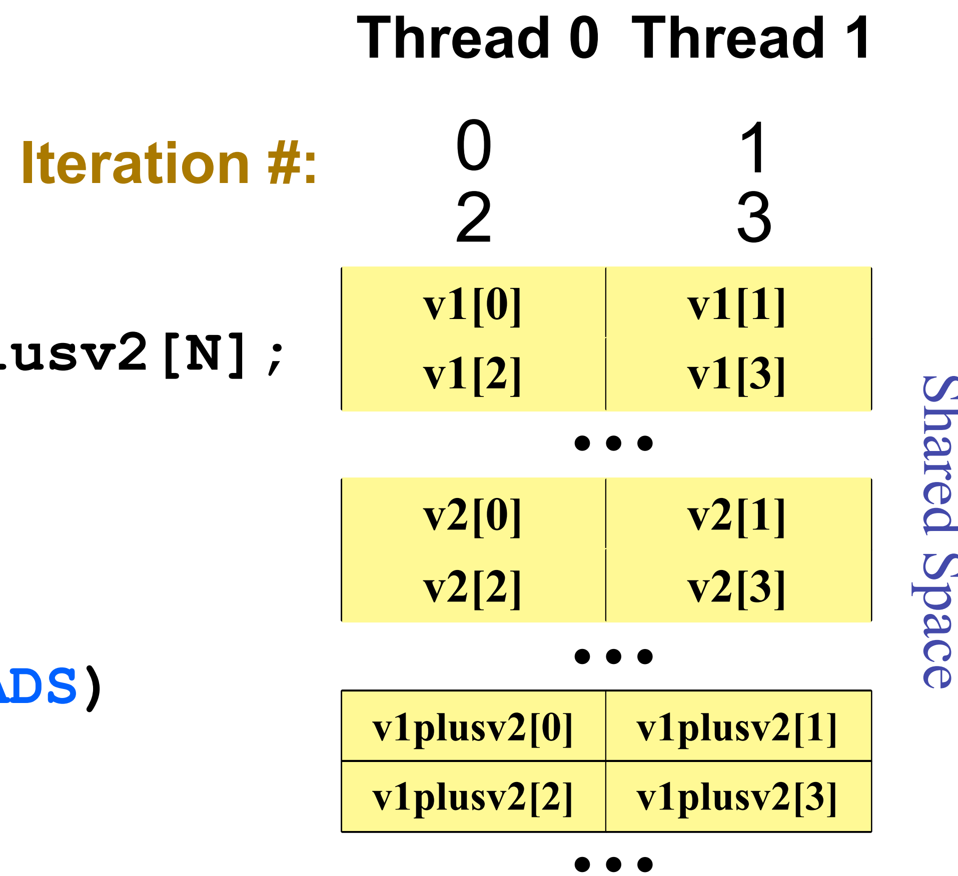
- **Consider the data declaration**
  - `shared [3] int A[4][THREADS];`
- **When THREADS = 4, this results in the following data layout**



The mapping is not pretty when the rightmost dimensions aren't a multiple of THREADS

A Simple UPC Program: Vector Addition

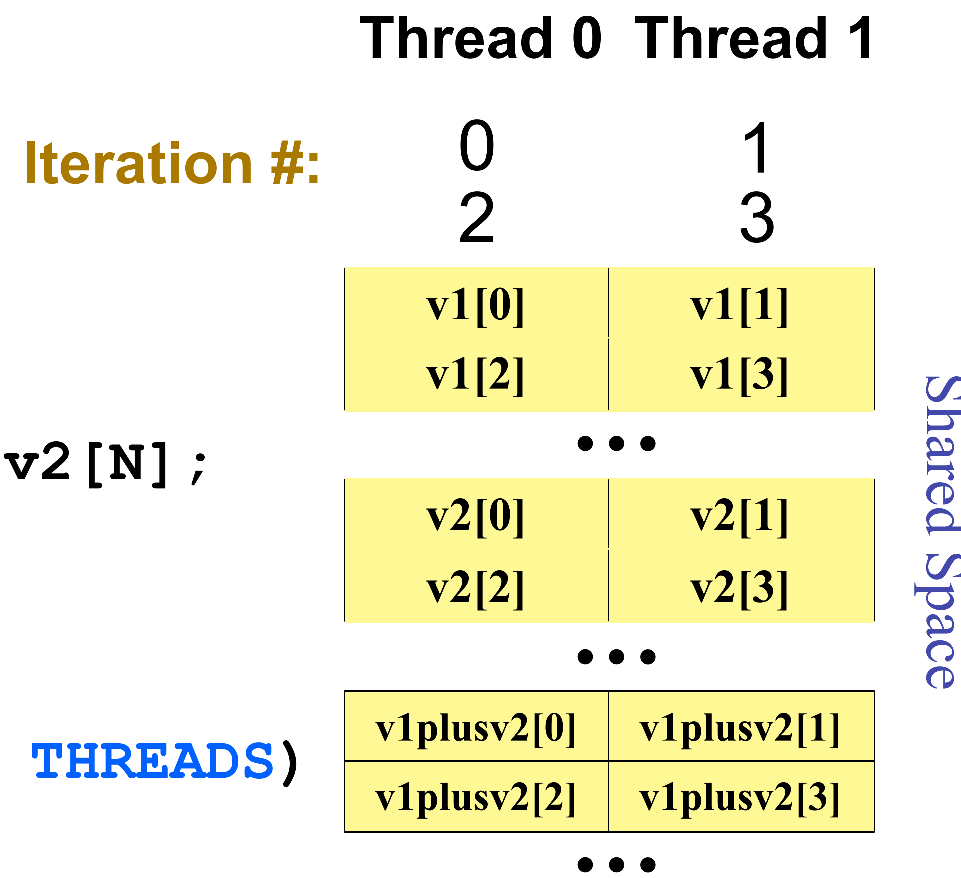
```
//vect_add.c
#include <upc_relaxed.h>
#define N 100*THREADS

shared int v1[N], v2[N], v1plusv2[N];

void main() {
  int i;
  for(i=0; i<N; i++)
    if (MYTHREAD == i % THREADS)
  v1plusv2[i]=v1[i]+v2[i];
}
```



Each thread executes each iteration to check if it has work

A More Efficient Vector Addition

```
//vect_add.c
#include <upc_relaxed.h>
#define N 100*THREADS

shared int v1[N], v2[N], v1plusv2[N];

void main() {
  int i;
  for(i = MYTHREAD; i < N; i += THREADS)
    v1plusv2[i]=v1[i]+v2[i];
}
```



Each thread executes only its own iterations

Worksharing with `upc_forall`

- Distributes independent iterations across threads
- Simple C-like syntax and semantics
  - `upc_forall(init; test; loop; affinity)`
- Affinity is used to enable locality control
  - usually, map iteration to thread where the iteration's data resides
- Affinity can be
  - an integer expression, or a
  - reference to (address of) a shared object

Work Sharing + Affinity with `upc_forall`

- **Example 1: explicit affinity using shared references**

```
shared int a[100],b[100], c[100];
int i;
upc_forall (i=0; i<100; i++; &a[i])
    a[i] = b[i] * c[i];
```

- **Example 2: implicit affinity with integer expressions**

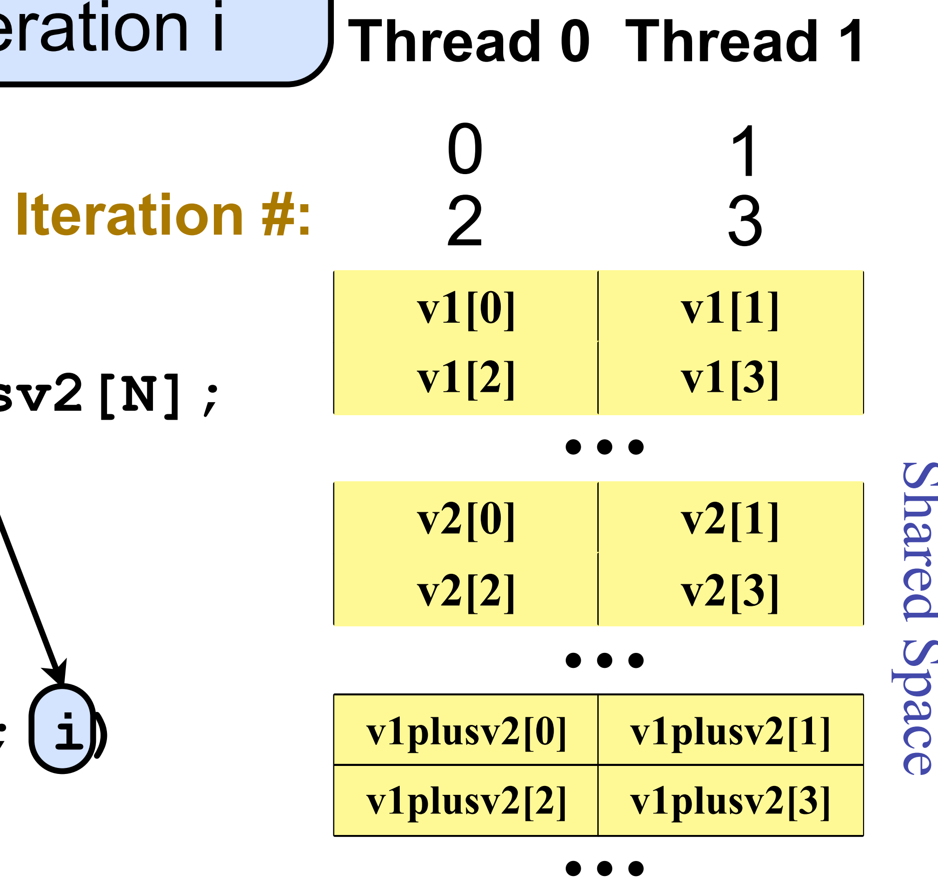
```
shared int a[100],b[100], c[100];
int i;
upc_forall (i=0; i<100; i++; i)
    a[i] = b[i] * c[i];
```

Note: both yield a round-robin distribution of iterations

Vector Addition Using upc_forall

thread affinity for work: have thread i execute iteration i

```
//vect_add.c
#include <upc_relaxed.h>
#define N 100*THREADS

shared int v1[N], v2[N], v1plusv2[N];

void main()
{
   int i;
   upc_forall(i = 0; i < N; i++; i)
      v1plusv2[i]=v1[i]+v2[i];
}
```



Each thread executes subset of global iteration space as directed by affinity clause

Work Sharing + Affinity with `upc_forall`

- **Example 3: implicit affinity by chunks**

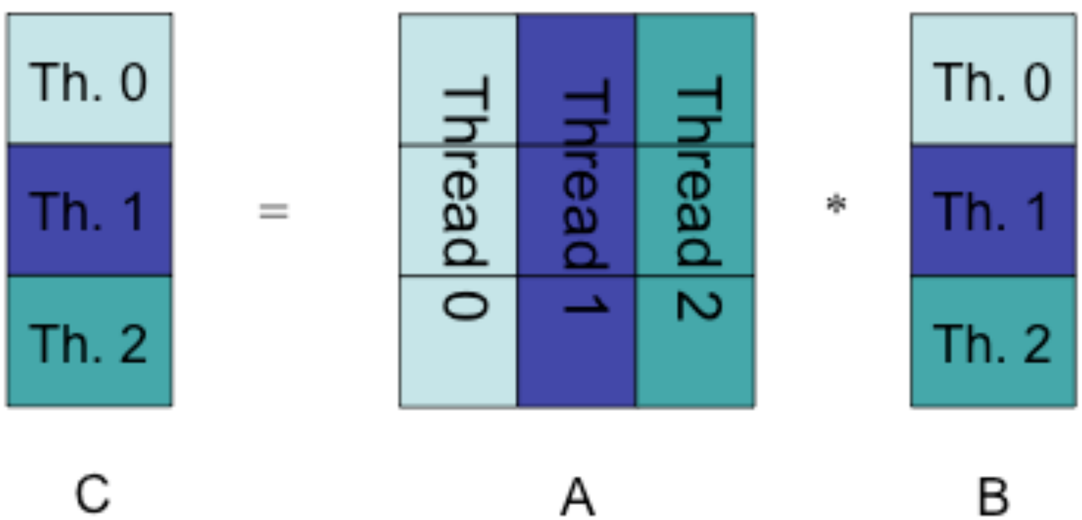
```
shared int a[100],b[100], c[100];
int i;
upc_forall (i=0; i<100; i++; (i*THREADS)/100)
   a[i] = b[i] * c[i];
```

- **Assuming 4 threads, the following results**

i	i*THREADS	i*THREADS/100
0..24	0..96	0
25..49	100..196	1
50..74	200..296	2
75..99	300..396	3

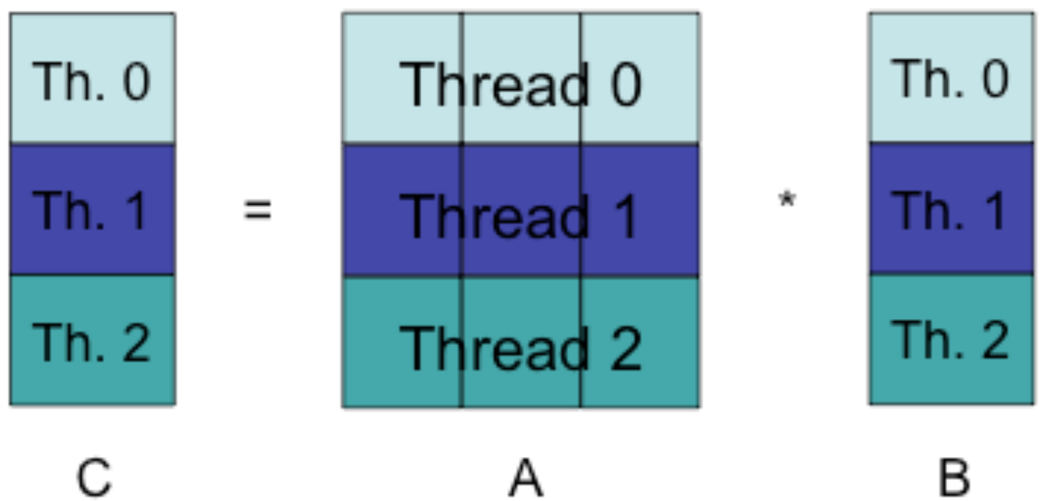
Matrix-Vector Multiply (Default Distribution)

```
// vect_mat_mult.c
#include <upc_relaxed.h>

shared int a[THREADS][THREADS];
shared int b[THREADS], c[THREADS];
void main (void) {
      int i, j;
      upc_forall(i = 0; i < THREADS; i++; i) {
            c[i] = 0;
            for ( j= 0 ; j < THREADS; j++)
                  c[i] += a[i][j]*b[j];
      }
}
```



Matrix-Vector Multiply (Better Distribution)

```
// vect_mat_mult.c
#include <upc_relaxed.h>

shared [THREADS] int a[THREADS][THREADS];
shared int b[THREADS], c[THREADS];
void main (void) {
        int i, j;
        upc_forall( i = 0 ; i < THREADS ; i++; i) {
                c[i] = 0;
                for ( j= 0 ; j< THREADS ; j++)
                        c[i] += a[i][j]*b[j];
        }
}
```



Meraculous De Novo Genome Assembler in UPC

- **Chop reads into k-mers that overlap by k-1**
- **Store k-mers in distributed hash table.**
  (key,value) =
  (k-mer, 2-char fwd/bwd extension [AGCT] [AGCT])
- **From selected k-mers, perform forward and reverse traversals to construct contigs**

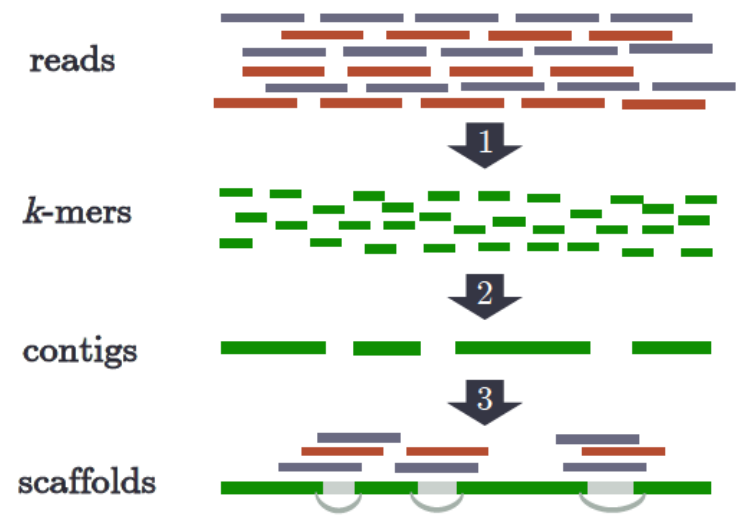


Fig. 2: Meraculous assembly flow chart.

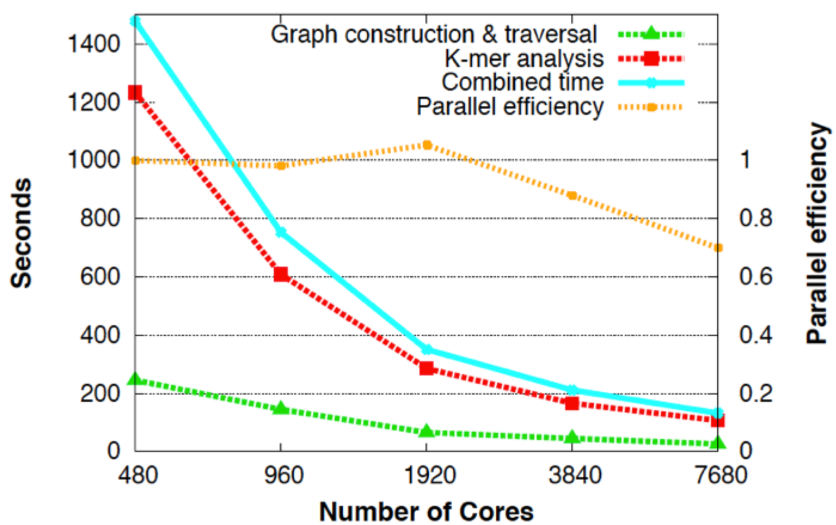


Fig. 1: Performance and strong scaling of our de Bruijn graph construction & traversal and k-mer analysis steps on Cray XC30 for the human genome. The top three timing curves are with respect to the first y-axis (left) whereas the parallel efficiency curve is with respect to the second y-axis (right). The x-axis uses a log scale.

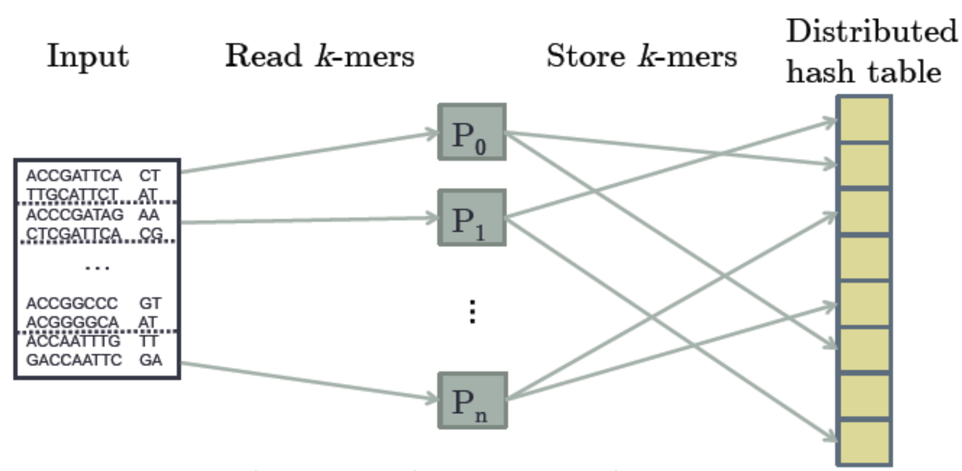


Fig. 5: Parallel de Bruijn graph construction.

E. Georganas et al., Parallel De Bruijn Graph Construction and Traversal for De Novo Genome Assembly, *SC14: International Conference for High Performance Computing, Networking, Storage and Analysis*, pp. 437-448, Nov. 2014 doi: 10.1109/SC.2014.41 URL: http://www.eecs.berkeley.edu/~egeor/sc14_genome.pdf

Imaging the earth's interior with seismic waves, supercomputers, and PGAS

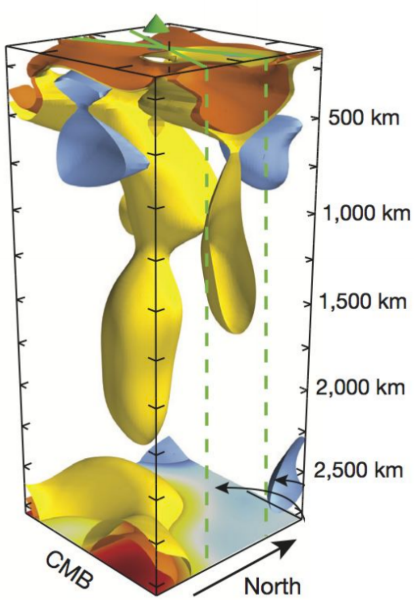
Scott French[1*] and Barbara Romanowicz[1,2]

[1] *Berkeley Seismological Laboratory, UC Berkeley, Berkeley, CA, USA*
[2] *Institut de Physique du Globe de Paris, Paris, France*
[*] *Now at: Google Inc.*

Whole Mantle Waveform Tomography

- **Objective: 3D model of material properties (elastic wave speed) throughout the earth's entire mantle (outer 2890 km)**
- **Observations: seismograms of natural earthquakes (100s)**
- **Predictions: numerical simulations of seismic wave propagation**

Scientific results: A whole-mantle model



Above: 3D rendering of shear-velocity structure beneath the Hawaii hotspot.

Geophysical Journal International
Geophys. J. Int. (2014) **199**, 1303–1327 doi: 10.1093/gji/ggu334
GJI Seismology

Whole-mantle radially anisotropic shear velocity structure from spectral-element waveform tomography

S. W. French[1,*] and B. A. Romanowicz[1,2,3]

LETTER

doi:10.1038/nature14876

Broad plumes rooted at the base of the Earth's mantle beneath major hotspots

Scott W. French[1]† & Barbara Romanowicz[1,2,3]

- The **first** whole-mantle seismic model based on waveform tomography using numerical wavefield simulations
- Reveals **new details** of earth structure not seen in previous models based on approximate forward modeling techniques (especially low shear-velocity structures)

Whole Mantle Tomography: Under the Hood

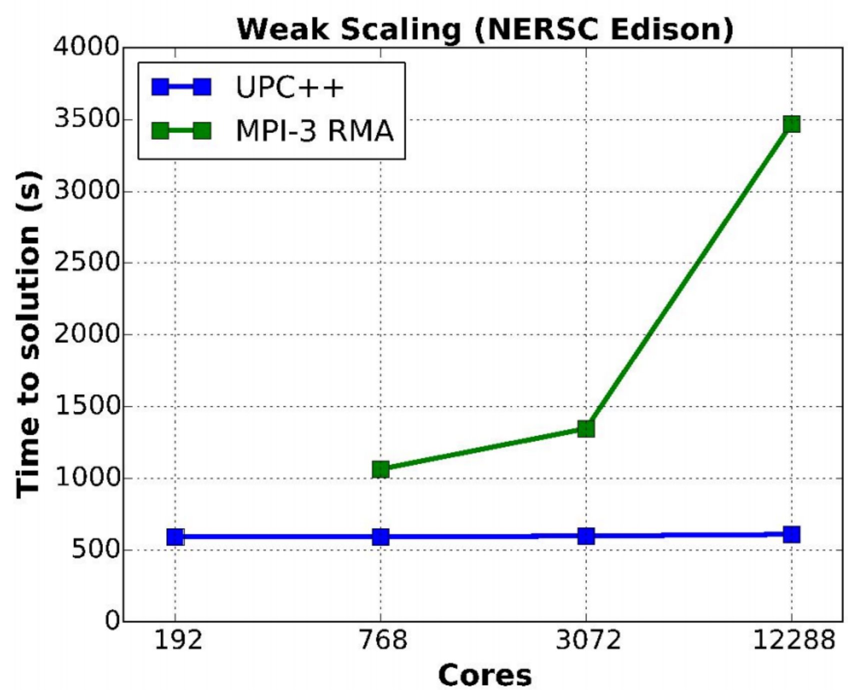
- **UPC++ Distributed matrix abstraction (French et al., IPDPS'15)**
  —excellent for distributed data structures + irregular accesses
- **Key to implementing one-sided updates optimized for our use case (+= only, associative / commutative, asynchronous)**
- **Distributed matrices use block-cyclic format**

Weak scaling vs. MPI (Hessian estimation)

- Distributed matrix size fixed (180 GB)
- Dataset size scaled w/ concurrency
  - 64 updates per MPI or UPC++ task + thread team (NUMA domain)

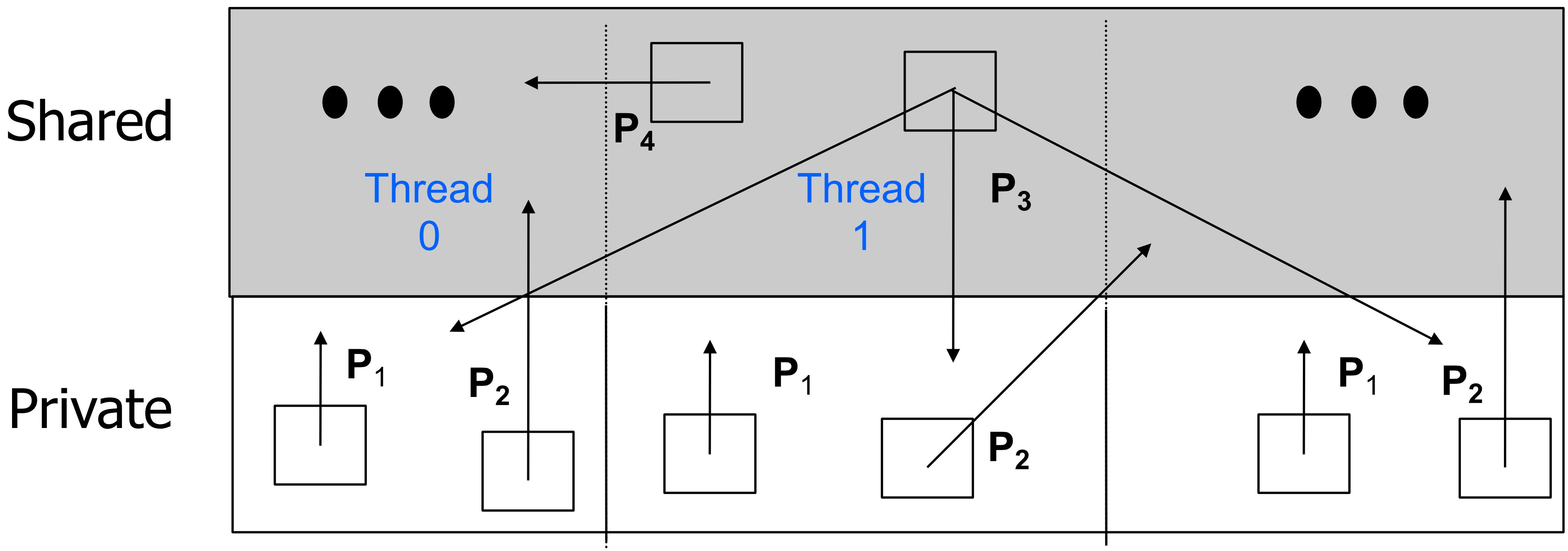
Setup

- NERSC Edison (Cray XC30)
- GNU Compilers 4.8.2 (-O3)
- Cray MPICH 7.0.3
- Up to 12,288 cores
- Matrix size: 180GB



UPC Pointers

- **Needed for expressive data structures**
- **Flavors**
  - **private pointers pointing to local**
    - **int *p1**
  - **private pointers pointing to shared**
    - **shared int *p2**
  - **shared pointers pointing to local**
    - **int *shared p3**
  - **shared pointers pointing to shared**
    - **shared int *shared p4**



UPC Pointer Implementation Requirements

- Handle shared data
- Support pointer arithmetic
- Support pointer casting

UPC Pointer Representation

- **UPC pointers to shared objects have three fields**
  - **thread number**
  - **local address of block**
  - **phase (specifies position in the block)**

Thread #	Block Address	Phase

- **Example: Cray T3E implementation**

Phase	Thread	Virtual Address
63 49	48 38	37 0

UPC Pointer Features

- **Pointer arithmetic**
  - —supports blocked and non-blocked array distributions
- **Casting of shared to private pointers is allowed**
  - —but not vice versa!
- **When casting a pointer-to-shared to a private pointer, the thread # of pointer-to-shared may be lost**
- **Casting of a pointer-to-shared to a private pointer**
  - —well defined only if the target object has affinity to local thread

Dynamic Memory Allocation of Shared

- Dynamic memory allocation of shared memory is available
- Functions can be collective or not
- Collective function
  - —called by every thread
  - —returns the same value to each of them
- Collective function names typically include "all"

Global Allocation of Shared Memory

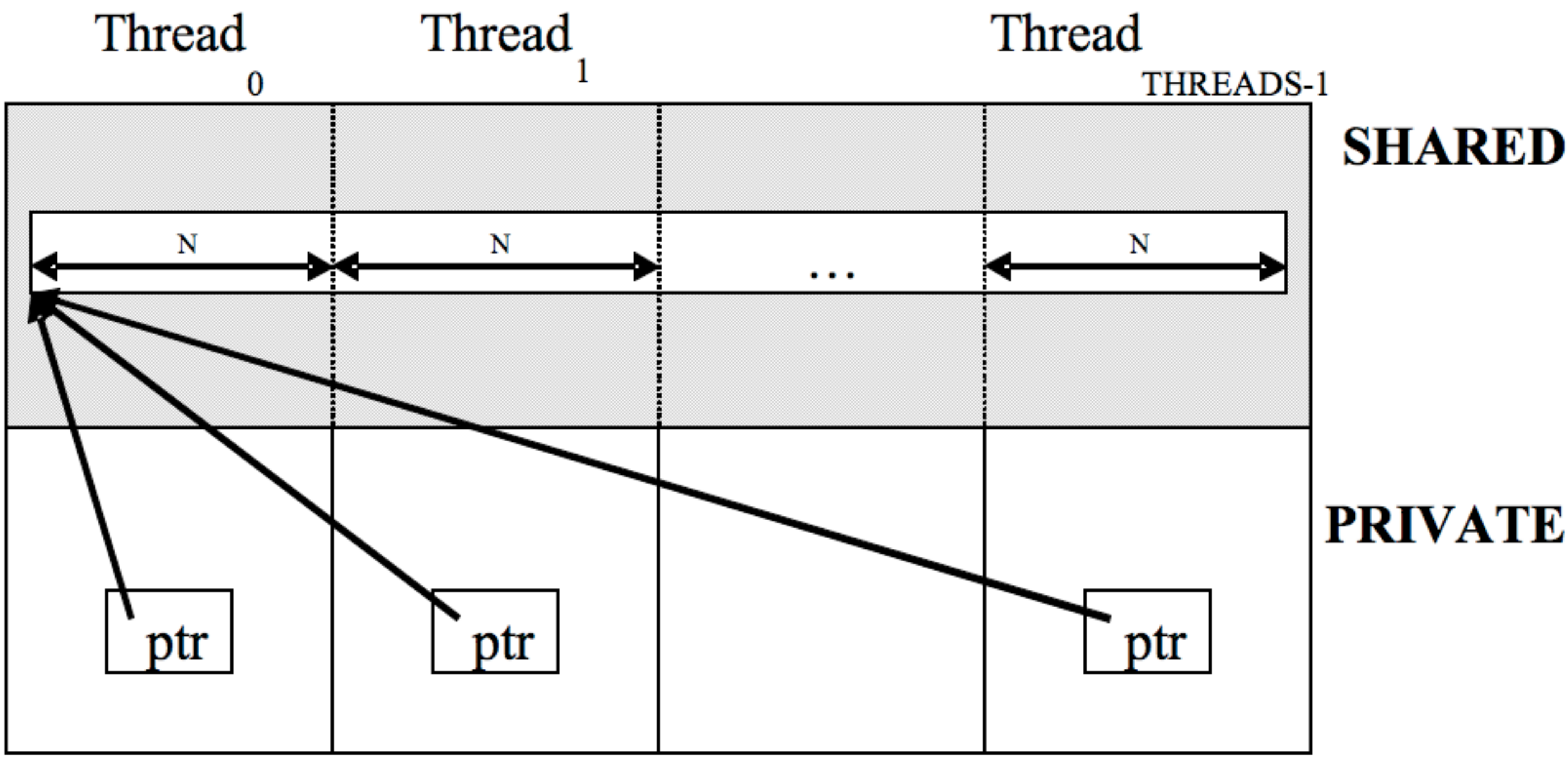
- **Collective allocation function: must be called by all threads**
  - **shared void *upc_all_alloc(size_t nblocks, size_t nbytes)**

    nblocks: number of blocks
    nbytes: block size
  - **each thread gets the same pointer**
  - **equivalent to :**

    shared [nbytes] char[nblocks * nbytes]
- **Non-collective version that yields the same layout**
  - **shared void *upc_global_alloc(size_t nblocks, size_t nbytes)**

    nblocks: number of blocks
    nbytes: block size

Global Allocation of Shared Memory




```
shared [N] int *ptr;
ptr = (shared [N] int *)
        upc_all_alloc( THREADS, N*sizeof( int ) );
```

Local-Shared Memory Allocation

```
shared void *upc_alloc (size_t nbytes)
```

—nbytes: block size

- Non collective; called by one thread
- Calling thread allocates a contiguous memory region in its local shared space
- Space allocated per calling thread is equivalent to shared [] char[nbytes]
- If called by more than one thread, multiple regions are allocated and each calling thread gets a different pointer

Synchronization

- **No implicit synchronization among the threads**
- **UPC provides the following synchronization mechanisms:**
  - **—barriers**
  - **—locks**

Synchronization - Barriers

- **Barriers (blocking)**
  - **upc_barrier expr_opt;**
- **Split-phase barriers (non-blocking)**
  - **upc_notify expr_opt;**
  - **upc_wait expr_opt;**
    - **note: upc_notify is not blocking upc_wait is**

Synchronization - Locks

- Lock primitives
  - void upc_lock(upc_lock_t *l)
  - int upc_lock_attempt(upc_lock_t *l) // success returns 1
  - void upc_unlock(upc_lock_t *l)
- Locks are allocated dynamically, and can be freed
- Locks are properly initialized after they are allocated

Dynamic Lock Allocation

- Collective lock allocation (à la upc_all_alloc)
  - upc_lock_t * upc_all_lock_alloc(void);
- Global lock allocation (à la upc_global_alloc)
  - upc_lock_t * upc_global_lock_alloc(void);
- Lock deallocation
  - void upc_lock_free(upc_lock_t *ptr);

Memory Consistency Model

- Dictates the ordering of shared operations
  - —when a change to a shared object by a thread becomes visible to others
- Consistency can be strict or relaxed
- Relaxed consistency model
  - —compiler & runtime can reorder accesses to shared data
- Strict consistency model
  - —enforce sequential ordering of operations on shared data
    - – no operation on shared can begin before previous ones are done
    - – changes become visible immediately

Memory Consistency

- Default behavior can be altered for a variable definition in the declaration using:
  - Type qualifiers: strict & relaxed
- Default behavior can be altered for a statement or a block of statements using
  - #pragma upc strict
  - #pragma upc relaxed
- Precedence order for memory consistency specifications
  - declarations

Memory Consistency Example

```
strict shared int flag_ready = 0;
shared int result0, result1;

if (MYTHREAD==0){
     results0 = expression1;
    flag_ready=1; //if not strict, it could be
     // switched with the above statement
} else if (MYTHREAD==1){
     while(!flag_ready); //Same note
         result1=expression2+results0;
}
```

- **Could have used a barrier between the first and second statement in the if and the else code blocks**
  - **expensive: affects all operations at all threads**
- **Above works as an example of point to point synchronization**

Forcing Memory Consistency via `upc_fence`

- **What is a memory fence?**
  - —all memory operations initiated before a fence operation must complete before the fence completes
- **UPC provides a fence construct**
  - —syntax
    - upc_fence;
  - —semantics
    - equivalent to a null strict reference

Library Operations for Bulk Data

- No flexible way to initiate bulk transfer operations in UPC
- Rely on library operations for bulk data transfer and set
  - `void upc_memcpy(shared void * restrict dst, shared const void * restrict src, size_t n)`
  - `void upc_memget(void * restrict dst, shared const void * restrict src, size_t n);`
  - `void upc_memput(shared void * restrict dst, const void * restrict src, size_t n);`
  - `void upc_memset(shared void *dst, int c, size_t n);`

Explicit Non-blocking Data Movement

- Get, Put, Copy
  - `upc_handle_t bupc_memcpy_async(shared void *dst, shared const void *src, size_tnbytes)`
  - `upc_handle_t bupc_memget_async(void *dst, shared const void *src, size_tnbytes)`
  - `upc_handle_t bupc_memput_async(shared void *dst, const void *src, size_tnbytes)`
    - same args and semantics as blocking variants
    - upc_handle_t: opaque handle representing the operation initiated
- Synchronize using one of two new functions
  - `void bupc_waitsync(upc_handle_t handle)`
    - blocking test for completion
  - `int bupc_trysync(upc_handle_t handle)`
    - non-blocking test for completion

References

Slides adapted from

Tarek El-Ghazawi, Steven Seidel. High Performance Parallel Programming with Unified Parallel C. SC05 Tutorial. http://upc.gwu.edu/tutorials/UPC-SC05.pdf

Book

Tarek El-Ghazawi, William Carlson, Thomas Sterling, Katherine Yelick. UPC: Distributed Shared Memory Programming. Wiley. 2005.

Meraculous De Novo Genome Assembler

E. Georganas et al., Parallel De Bruijn Graph Construction and Traversal for De Novo Genome Assembly, SC14: International Conference for High Performance Computing, Networking, Storage and Analysis, pp.437-448, Nov. 2014 doi: 10.1109/SC.2014.41
URL: http://www.eecs.berkeley.edu/~egeor/sc14_genome.pdf