Unified Parallel C (UPC)

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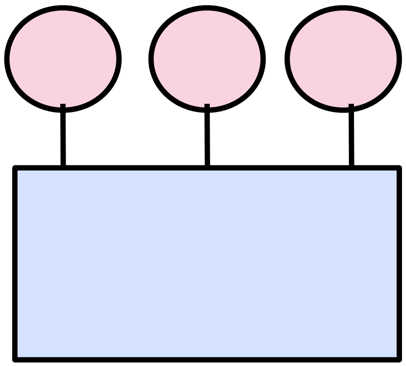
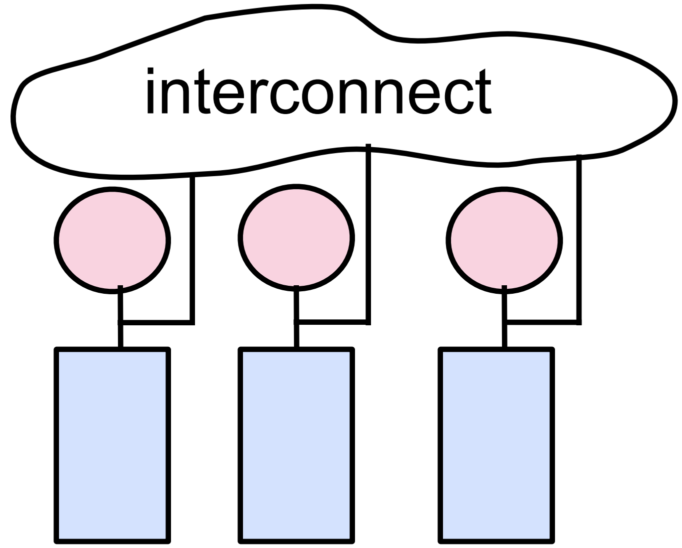
Idealized Parallel Architectures



Shared Memory



Distributed Memory

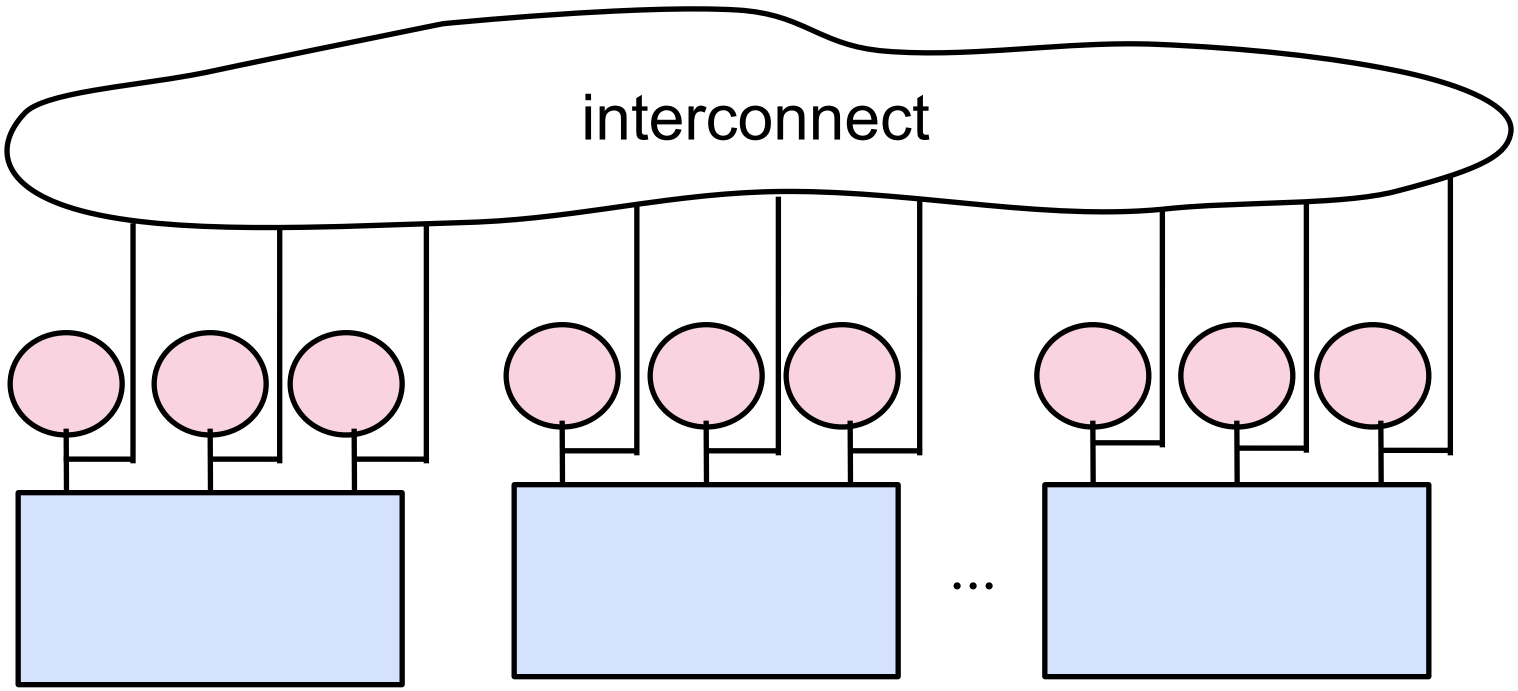
Programming Models

Cilk
OpenMP
Pthreads

MPI
UPC
CAF

Key: Process/Thread, Memory

Idealized Parallel Architectures of Today



Hybrid Shared + Distributed Memory

Programming Models

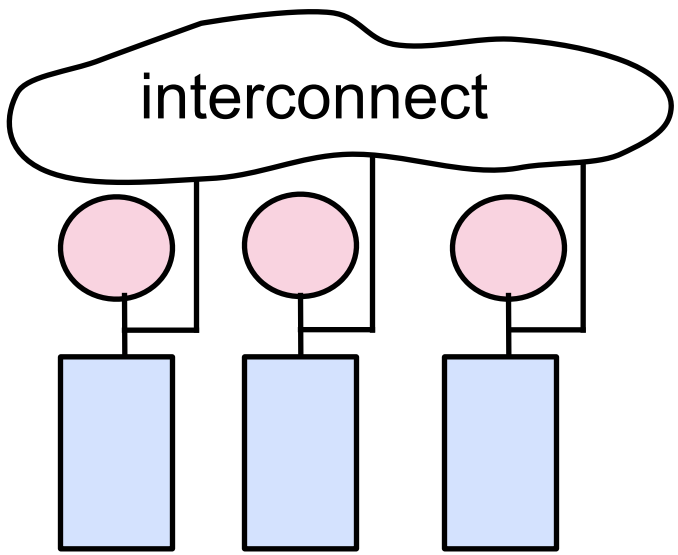
e.g., MPI + OpenMP
PGAS models

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

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**
  - **—computation partitioning**
  - **—communication placement**

lacking in OpenMP

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 Languages

- Unified Parallel C (C) http://upc.wikinet.org
- Titanium (Java) http://titanium.cs.berkeley.edu
- Coarray Fortran 2.0 (Fortran) http://caf.rice.edu

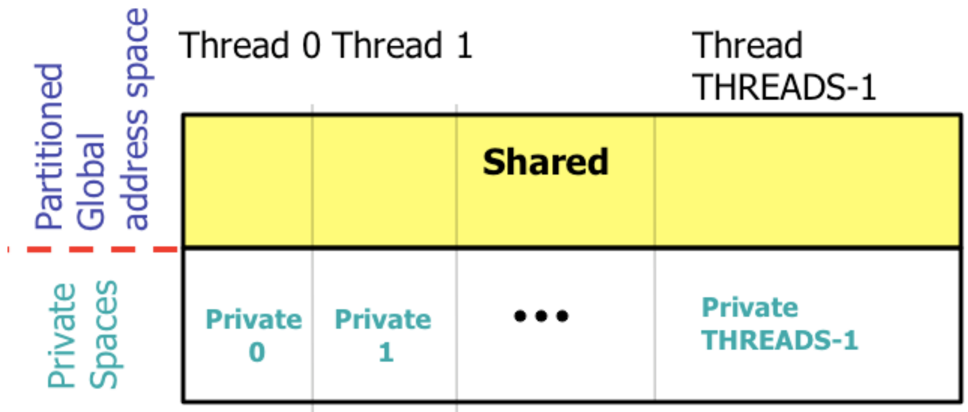
- Related efforts: HPCS Languages
  - X10 (http://x10-lang.org)
  - Chapel (http://chapel.cray.com)
  - Fortress (https://projectfortress.java.net)

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 using**
  - **—synchronization primitives**
  - **—shared variables**

Shared and Private Data

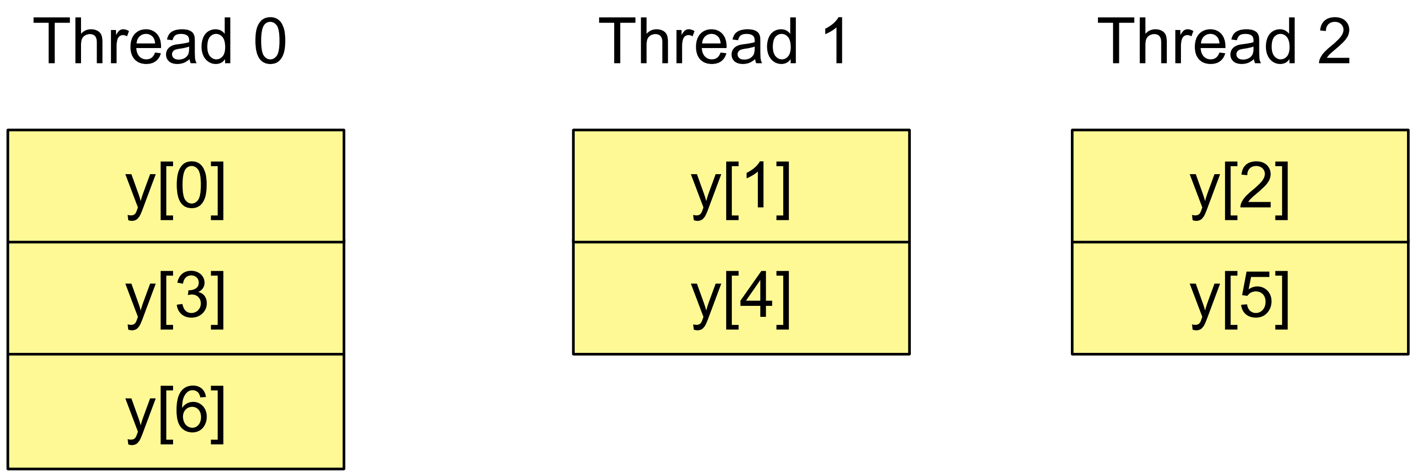
- **Static and dynamic memory allocation of each type of data**
- **Shared objects placed in memory based on affinity**
  - **shared scalars have affinity to thread 0**
    - **here, a scalar means a singleton instance of any type**
  - **elements of shared arrays are allocated round robin among memory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

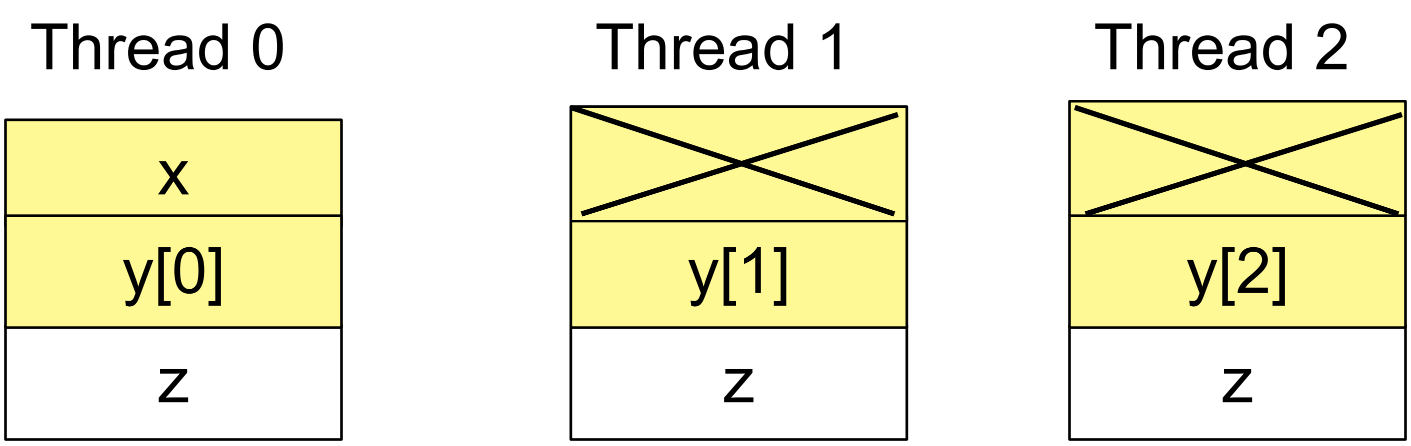
Thread 0	Thread 1	Thread 2
A[0][0]	A[0][1]	A[0][2]
A[1][0]	A[1][1]	A[1][2]
A[2][0]	A[2][1]	A[2][2]
A[3][0]	A[3][1]	A[3][2]

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
```

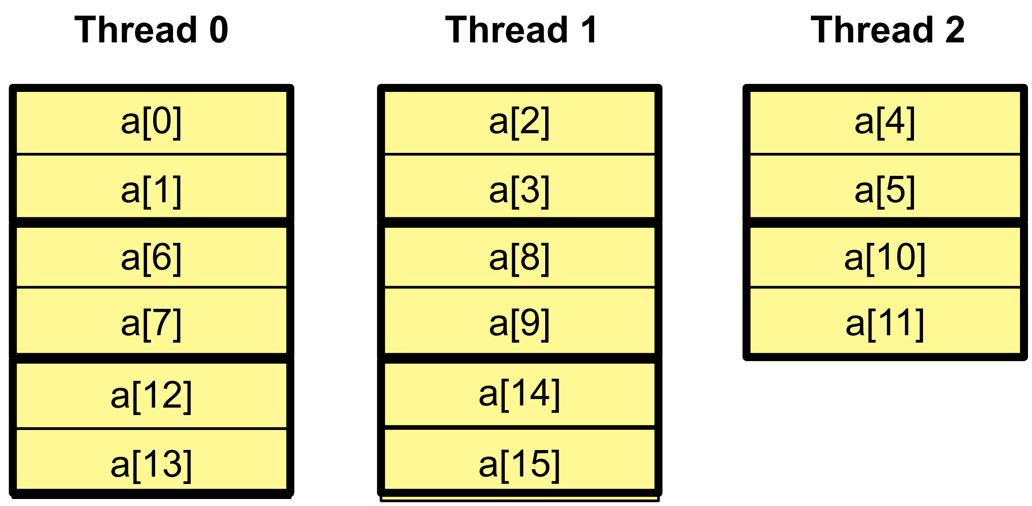
For THREADS = 3, we get the following layout



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



Blocking of Shared Arrays

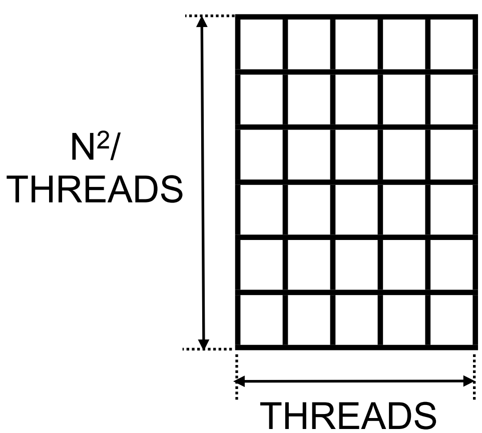
- **Block size and THREADS determine *affinity***
  - **—with which thread will a datum be co-located**
- **Element i of a blocked array has affinity to thread:**

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

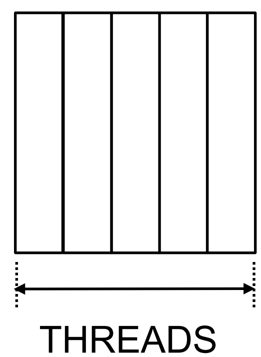
Blocking Multi-dimensional Data I

- **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];**

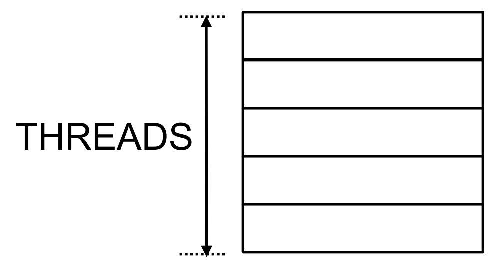
For the case where N = K * THREADS:



Default
BLOCKSIZE=1



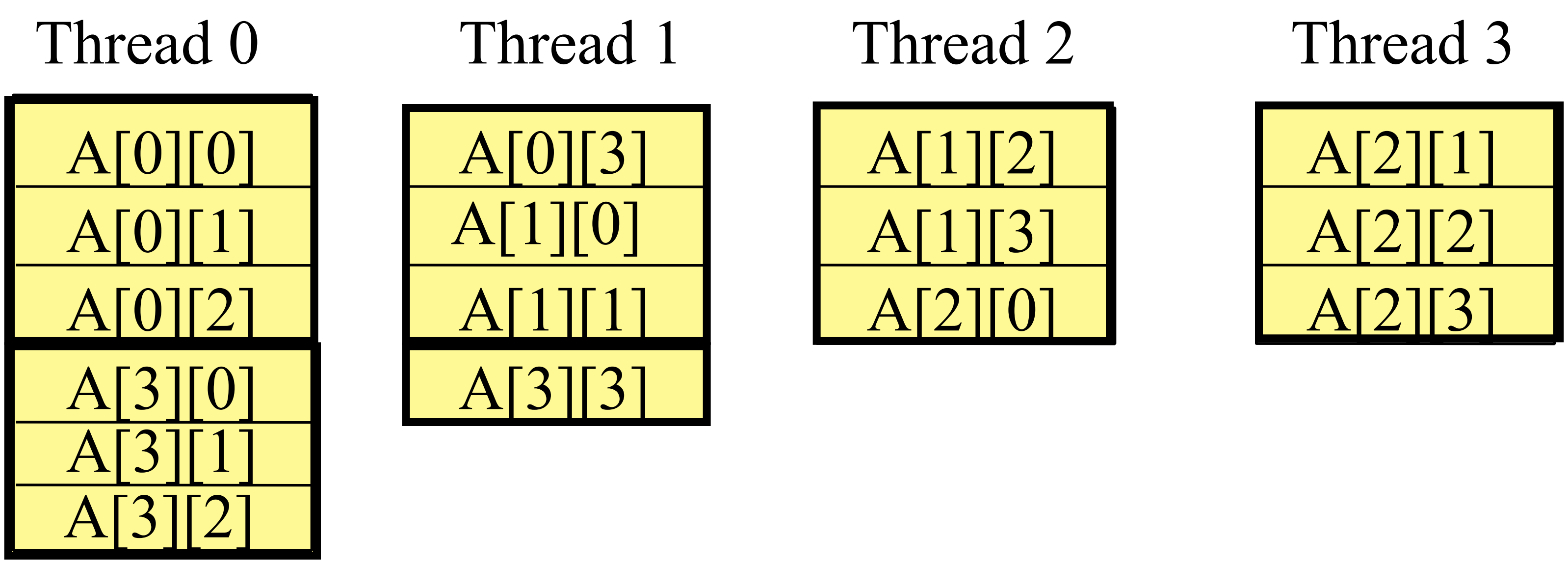
Column Blocks
BLOCKSIZE=N/THREADS



Distribution by Row
BLOCKSIZE=N

Blocking Multi-dimensional Data II

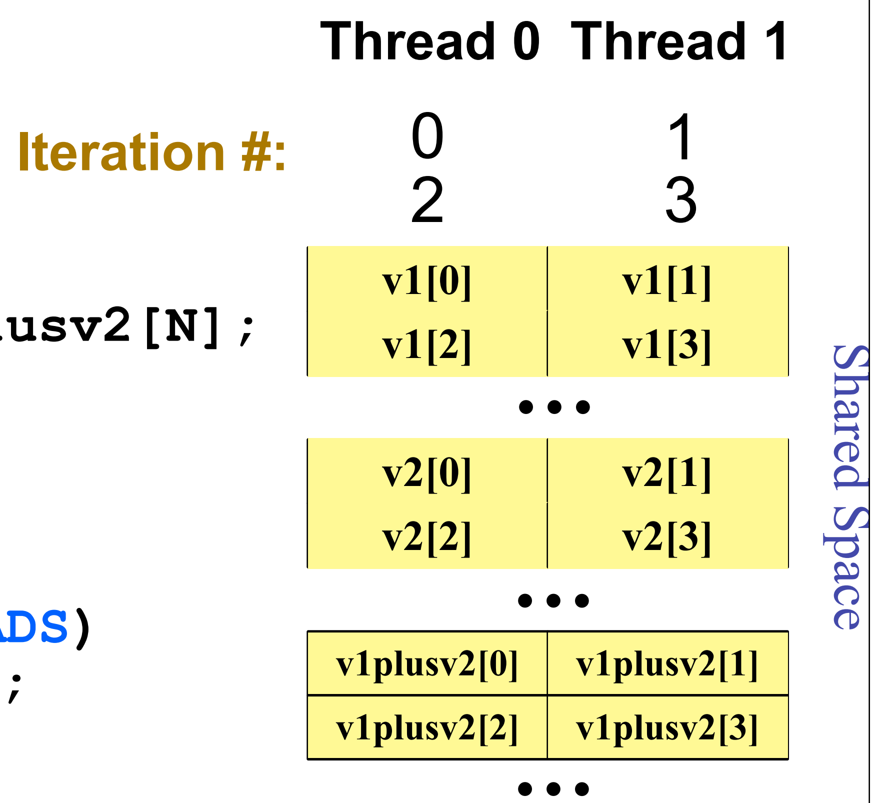
- **Consider the data declaration**
  - `shared [3] int A[4][THREADS];`
- **When THREADS = 4, this results in the following data layout**



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

A Simple UPC Program: Vector Addition

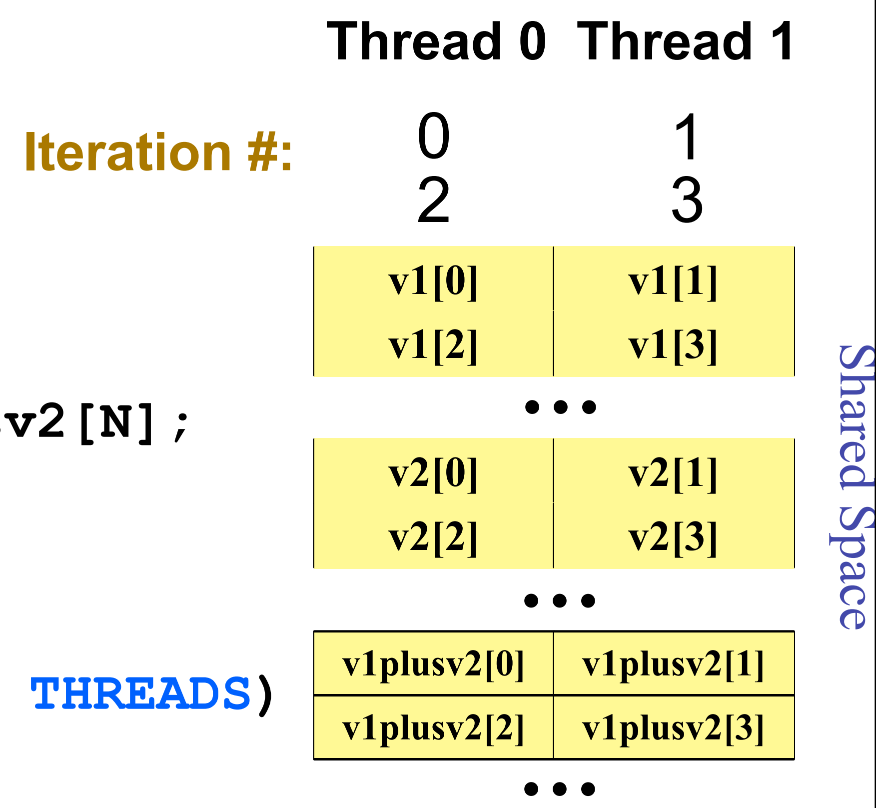
```
//vect_add.c
#include <upc_relaxed.h>
#define N 100*THREADS

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**

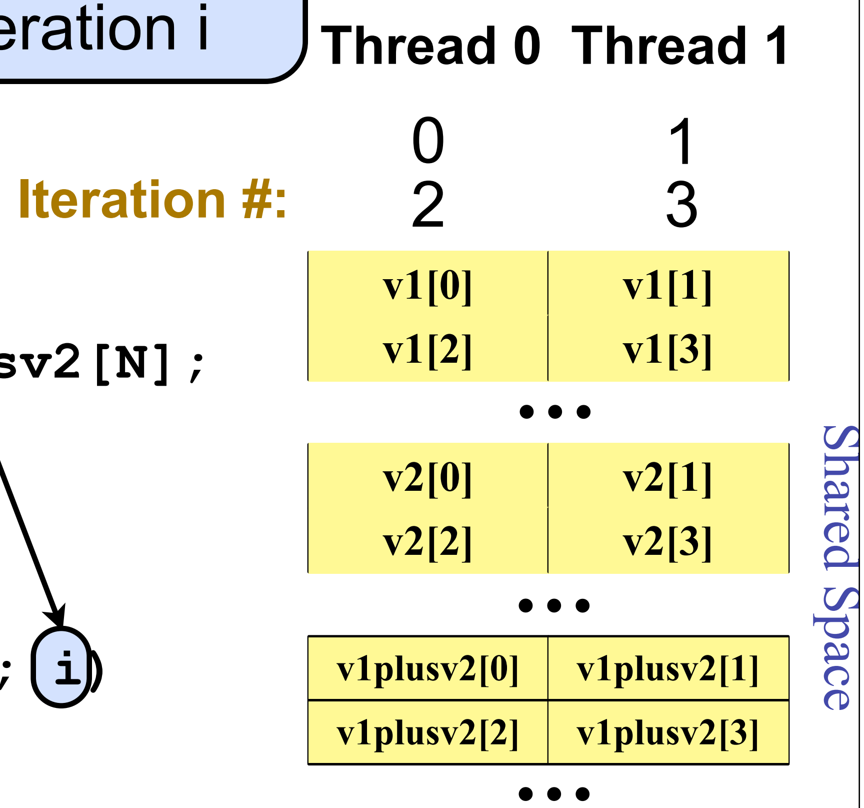
```
shared int a[100],b[100], c[100];
int i;
upc_forall (i=0; i<100; i++; i)
    a[i] = b[i] * c[i];
```

Note: both yield a round-robin distribution of iterations

Vector Addition Using `upc_forall`

thread affinity for work: have thread i execute iteration i

```c
//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**

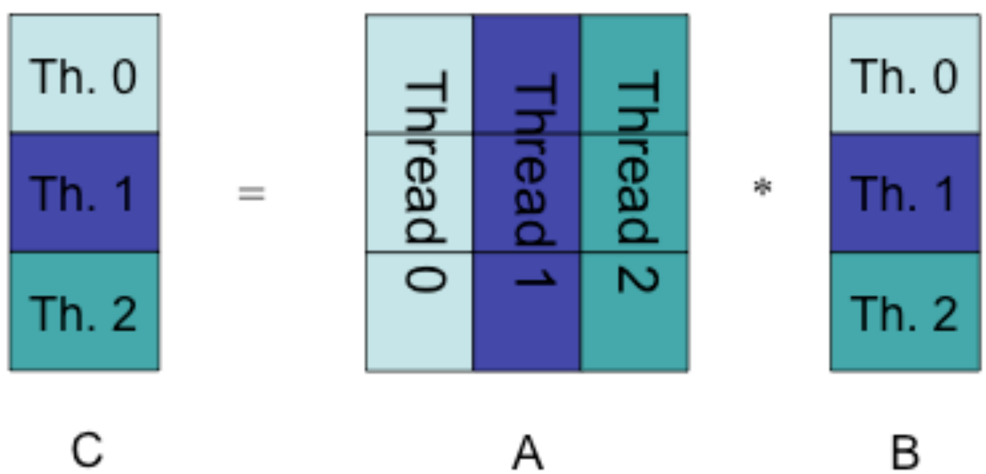
```
shared int a[100],b[100], c[100];
int i;
upc_forall (i=0; i<100; i++; (i*THREADS)/100)
    a[i] = b[i] * c[i];
```

- **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

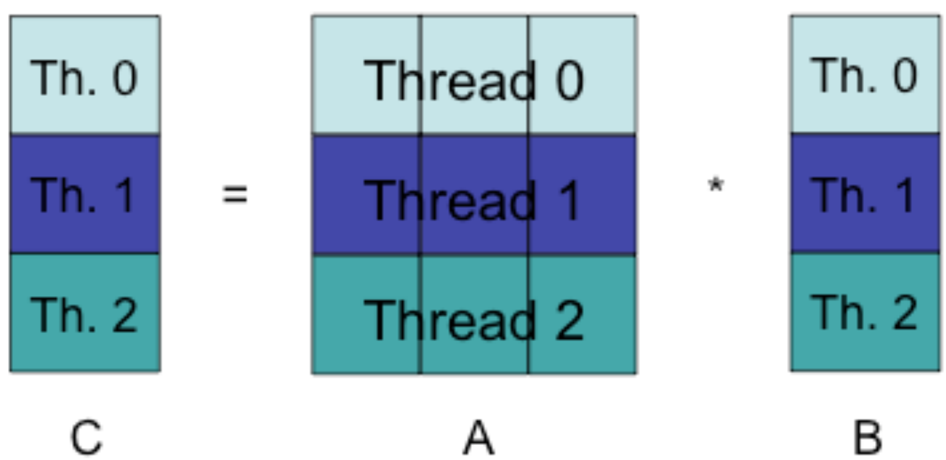
Matrix-Vector Multiply (Default Distribution)

```
// 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];
      }
}
```



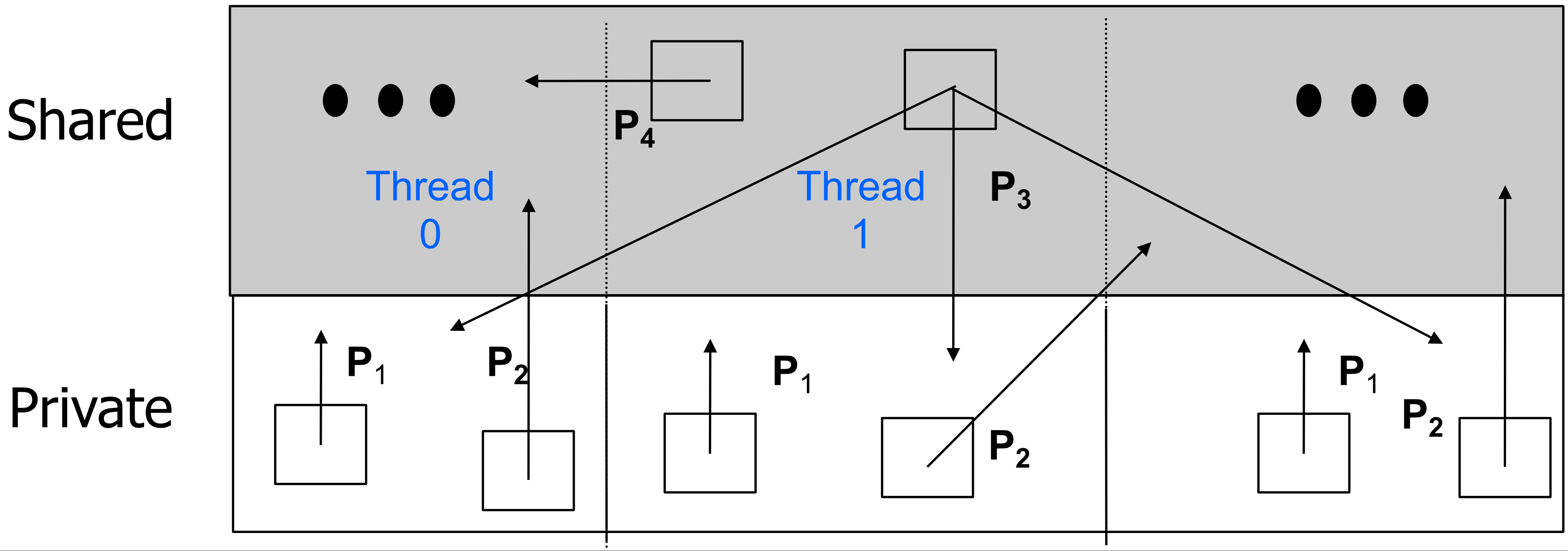
Matrix-Vector Multiply (Better Distribution)

```
// 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];
      }
}
```



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 Memory

- 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

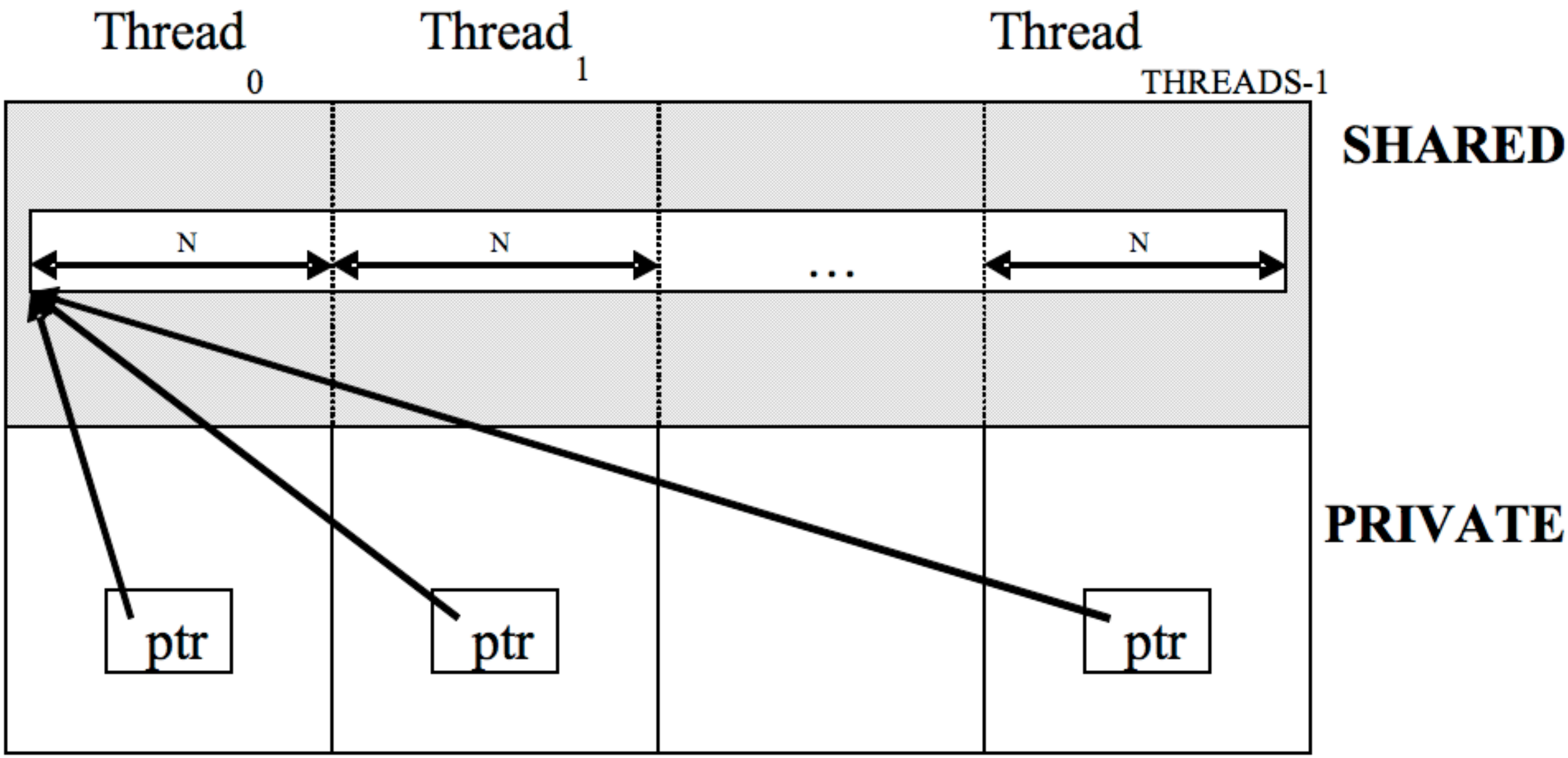
- Collective allocation function: must be called by all threads
  - shared void *upc_all_alloc(size_t nblocks, size_t nbytes)

    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**
  1. declarations
  2. pragmas
  3. program level

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

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**

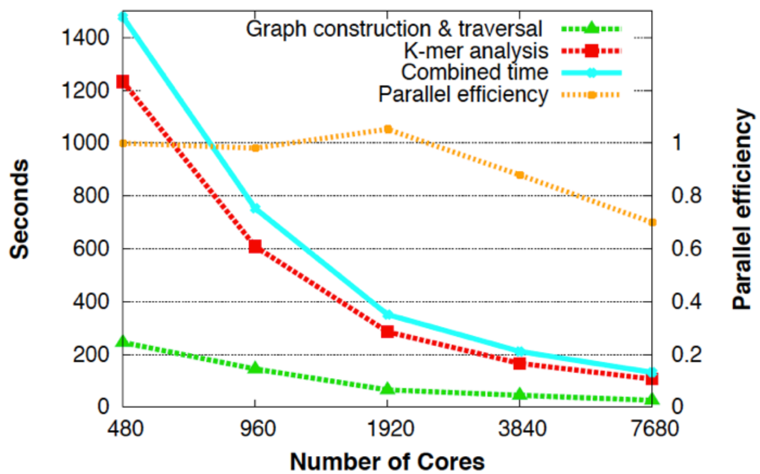


Fig. 1: Performance and strong scaling of our de Bruijn graph construction & traversal and k-mer analysis steps on Cray XC30 for the human genome. The top three timing curves are with respect to the first y-axis (left) whereas the parallel efficiency curve is with respect to the second y-axis (right).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

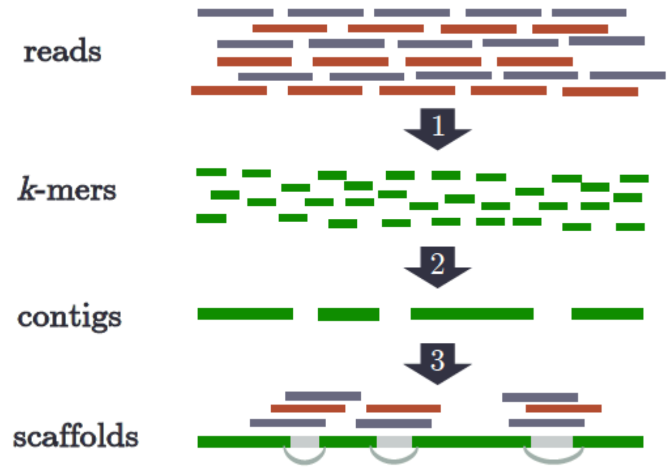


Fig. 2: Meraculous assembly flow chart.

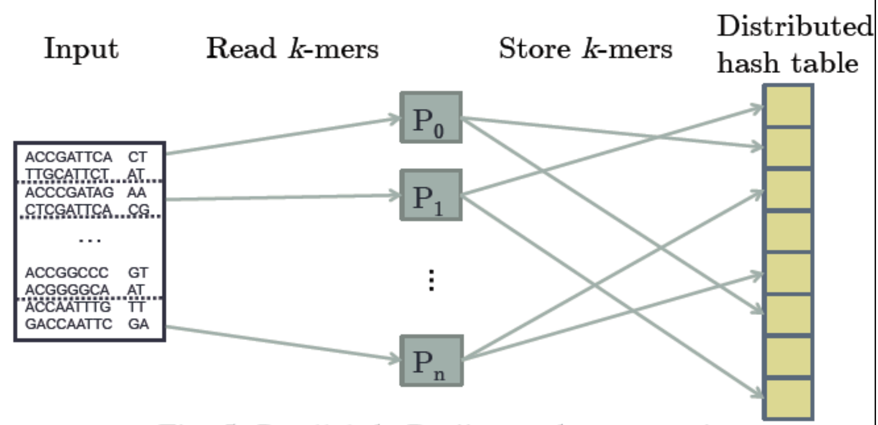


Fig. 5: Parallel de Bruijn graph construction.

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

Ongoing Work in UPC

- Interoperability support for multicore
  - —UPC always has run on clusters of shared memory
  - —Desire to run UPC on 1-n nodes for small n, within MPI
- Adding hierarchy to memory (socket, node, cab?,..)
- Use unique network features (atomics, DMA, etc.)
- PGAS/UPC for GPUs (P = CPU/GPU partition + nodes)
  - —First step: GASnet on CPU clusters
  - —Can put/get from GPU or CPU to/from GPU or CPU
  - —(Illusion is a single address space; ugly on current hw)
- SPMD PGAS + dynamic load balancing
  - —Dynamic load balancing is mostly useful for load imbalance in the apps, and cost across nodes is high
  - —So apps choose to add tasking on top of UPC
- Teams and autotuned collectives in UPC

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

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