COMP 322: Fundamentals of Parallel Programming

Lecture 32: Partitioned Global Address Space (PGAS) programming models

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Worksheet #31 solution: PageRank Example

Name: _____ Net ID: _____

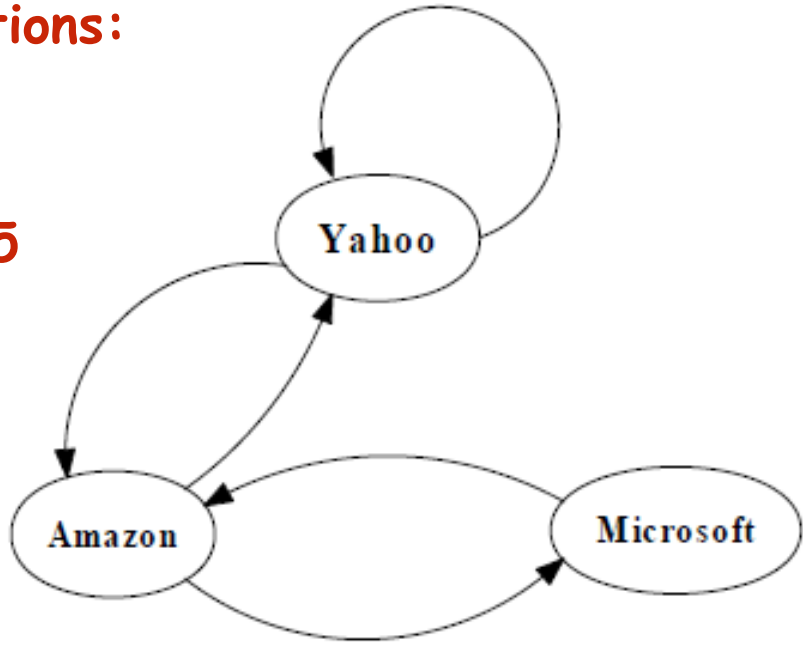
In the space below, indicate what you expect the relative ranking to be for the three pages below (with the given links). Show your computation (approximations are fine).

Final, after 7 iterations:

(1) Amazon = 1.22

(2) Yahoo = 1.15

(3) Microsoft = 0.65

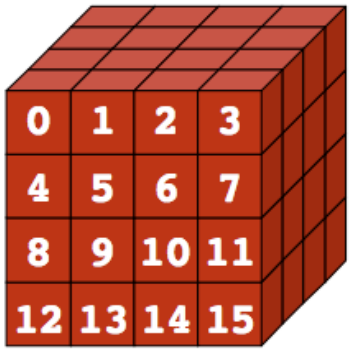


Partitioned Global Address Space Languages

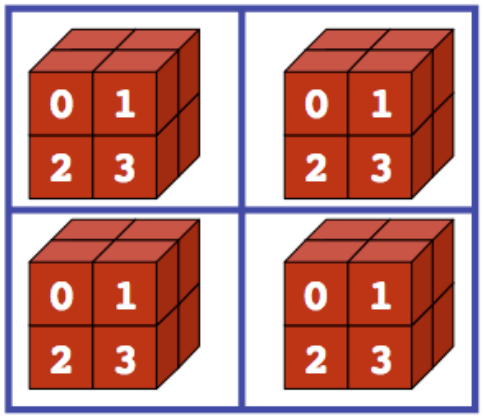
- Global address space
  - —one-sided communication (GET/PUT)
- Programmer has control over performance-critical factors
  - —data distribution and locality control
  - —computation partitioning
  - —communication placement
- Data movement and synchronization as language primitives
  - —amenable to compiler-based communication optimization
- "Global view" rather than "local view"

- simpler than two-sided message passing in MPI

- lacking in thread-based models
- HJ places (Lecture 34) help with locality control but not with data distribution



Global View



Local View (4 processes)

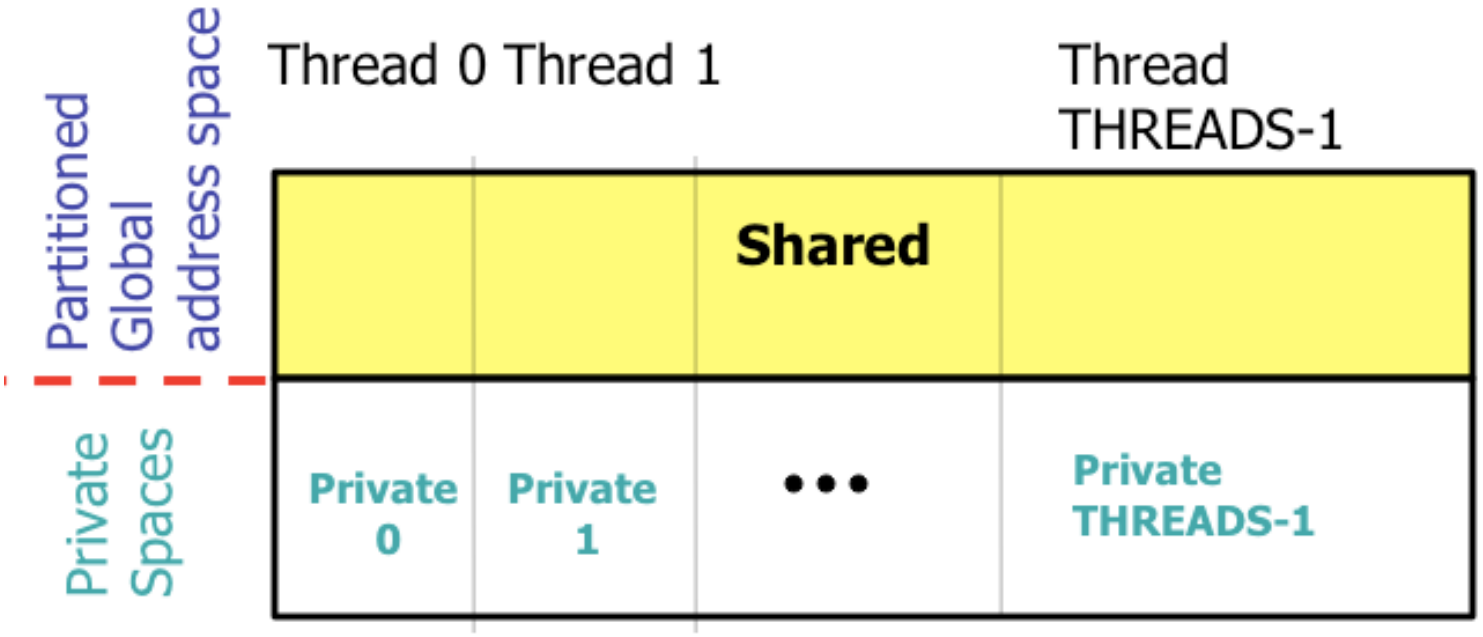
Partitioned Global Address Space (PGAS) Languages

- Unified Parallel C (C) http://upc.wikinet.org
- Titanium (early Java) http://titanium.cs.berkeley.edu
- Coarray Fortran 2.0 (Fortran) http://caf.rice.edu
- UPC++ (C++) https://bitbucket.org/upcxx
- Habanero-UPC++ (C++) http://habanero-rice.github.io/habanero-upc/

- **Related efforts: newer languages developed since 2003 as part of the DARPA High Productivity Computing Systems (HPCS) program**
  - **—IBM: X10 (starting point for Habanero-Java)**
  - **—Cray: Chapel**
  - **—Oracle/Sun: Fortress**

PGAS model

- A collection of "threads" (like MPI processes) operating in a partitioned global address space that is logically distributed across threads.
- Each thread has *affinity* with a portion of the *globally shared* address space. Each thread has also a *private* space.
- Elements in the partitioned global space co-located with a thread are said to have *affinity* to that thread.



Unified Parallel C (UPC) Execution Model

- Multiple threads working independently in a SPMD fashion
  - —MYTHREAD specifies thread index (0..THREADS-1)
    - – Like MPI processes and ranks
  - —# threads specified at compile-time or program launch time
- Partitioned Global Address Space (different from MPI)
  - A pointer-to-shared can reference all locations in the shared space
  - A pointer-to-local ("plain old C pointer") may only reference addresses in its private space or addresses in its portion of the shared space
  - Static and dynamic memory allocations are supported for both shared and private memory
- Threads synchronize as necessary using
  - —synchronization primitives
  - —shared variables

Shared and Private Data

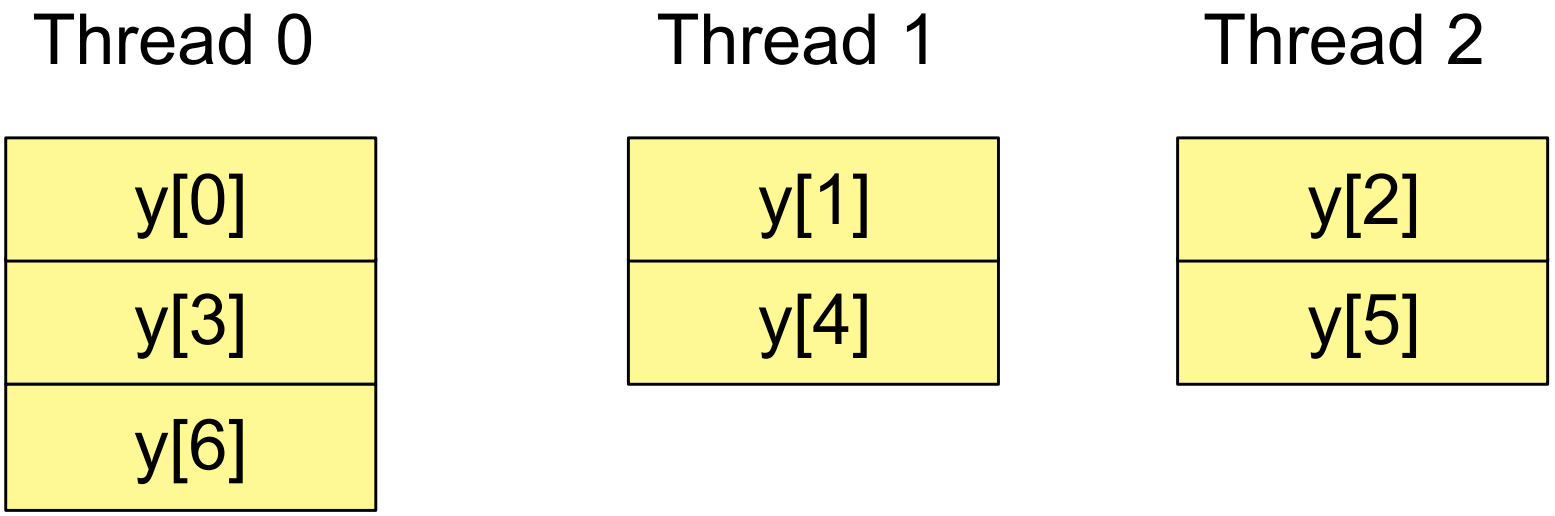
- Static and dynamic memory allocation of each type of data
- Shared objects placed in memory based on affinity
  - shared scalars have affinity to thread 0
    - here, a scalar means a non-array instance of any type (could be a struct, for example)
  - by default, elements of shared arrays are allocated "round robin" among memory modules co-located with each thread (cyclic distribution)
    - each shared array's distribution starts with the first element assigned to thread 0

A One-dimensional Shared Array

Consider the following data layout directive

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

For THREADS = 3, we get the following "cyclic" layout



A Multi-dimensional Shared Array

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

For THREADS = 3, we get the following cyclic layout

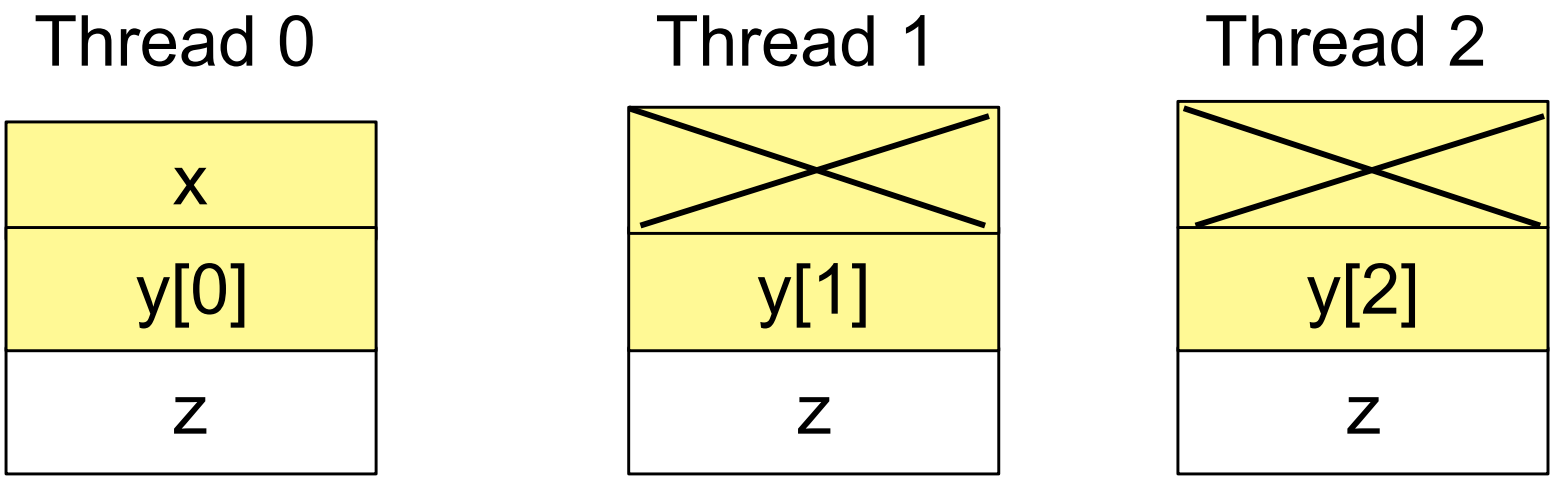
Thread 0	Thread 1	Thread 2
A[0][0]	A[0][1]	A[0][2]
A[1][0]	A[1][1]	A[1][2]
A[2][0]	A[2][1]	A[2][2]
A[3][0]	A[3][1]	A[3][2]

Shared and Private Data

Consider the following data layout directives

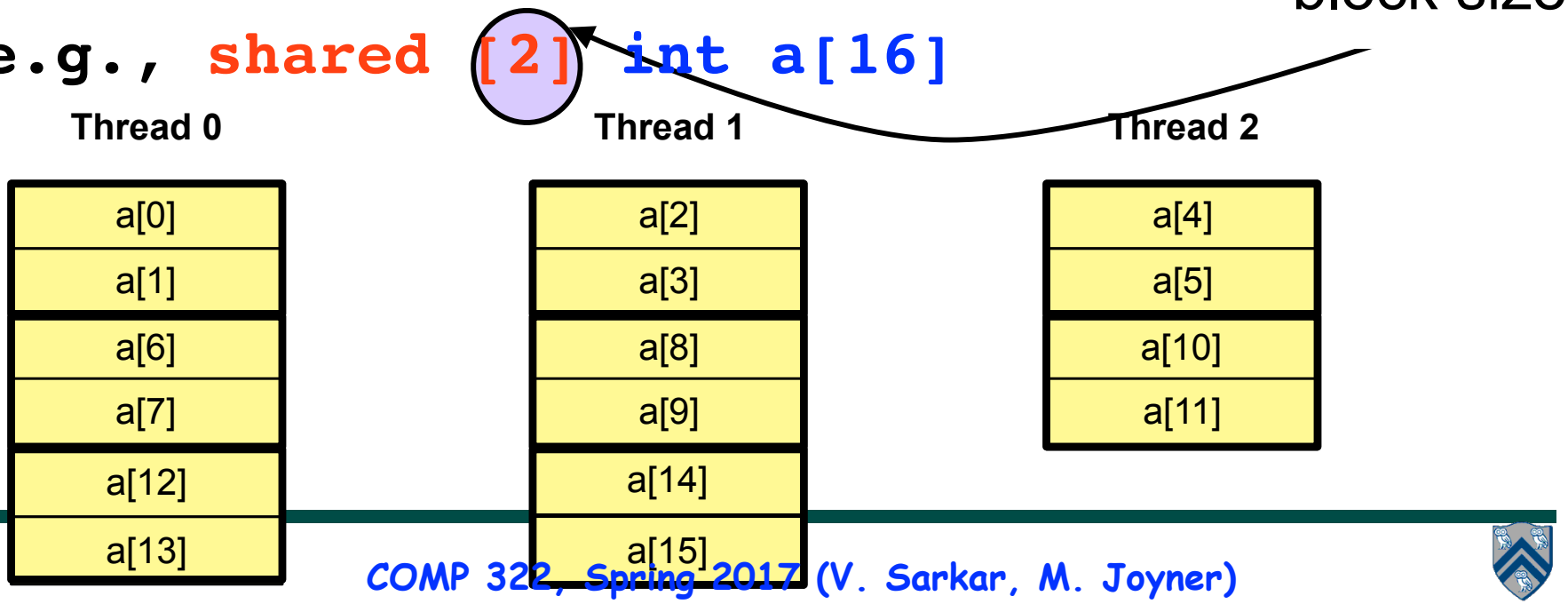
```
shared int x; // x has affinity to thread 0
shared int y[THREADS];
int z;          // private
```

For THREADS = 3, we get the following layout



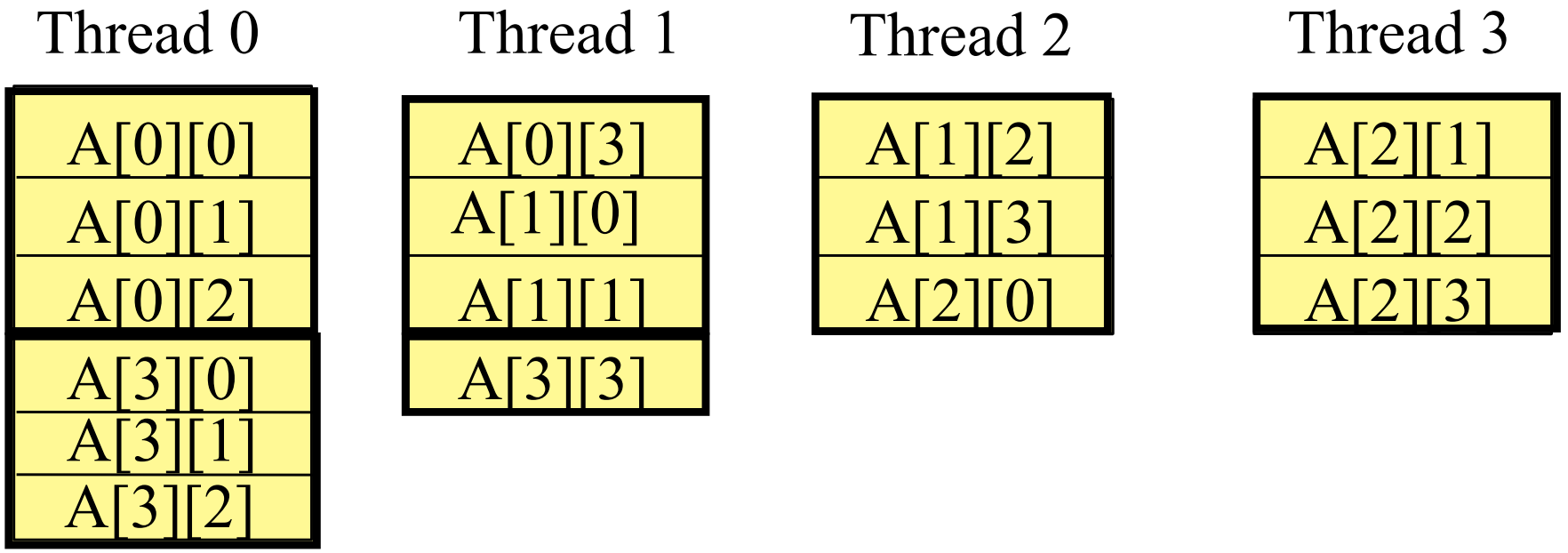
Controlling the Layout of Shared Arrays

- Can specify a blocking factor for shared arrays to obtain "block-cyclic" distributions
  - —default block size is 1 element ⇒ cyclic distribution
- 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]`



Blocking Multi-dimensional Data

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

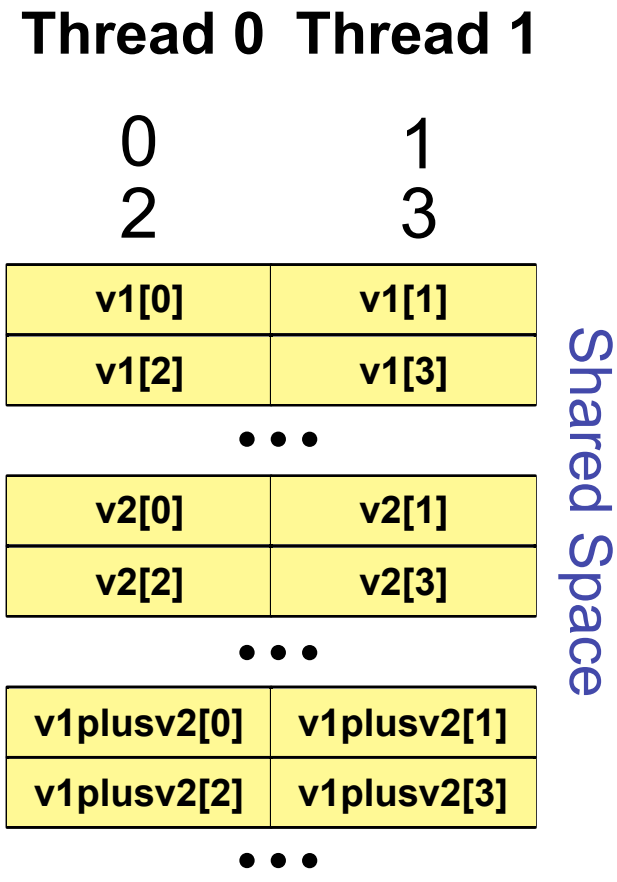


A Simple UPC Program: Vector Addition

```
//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];
}
```



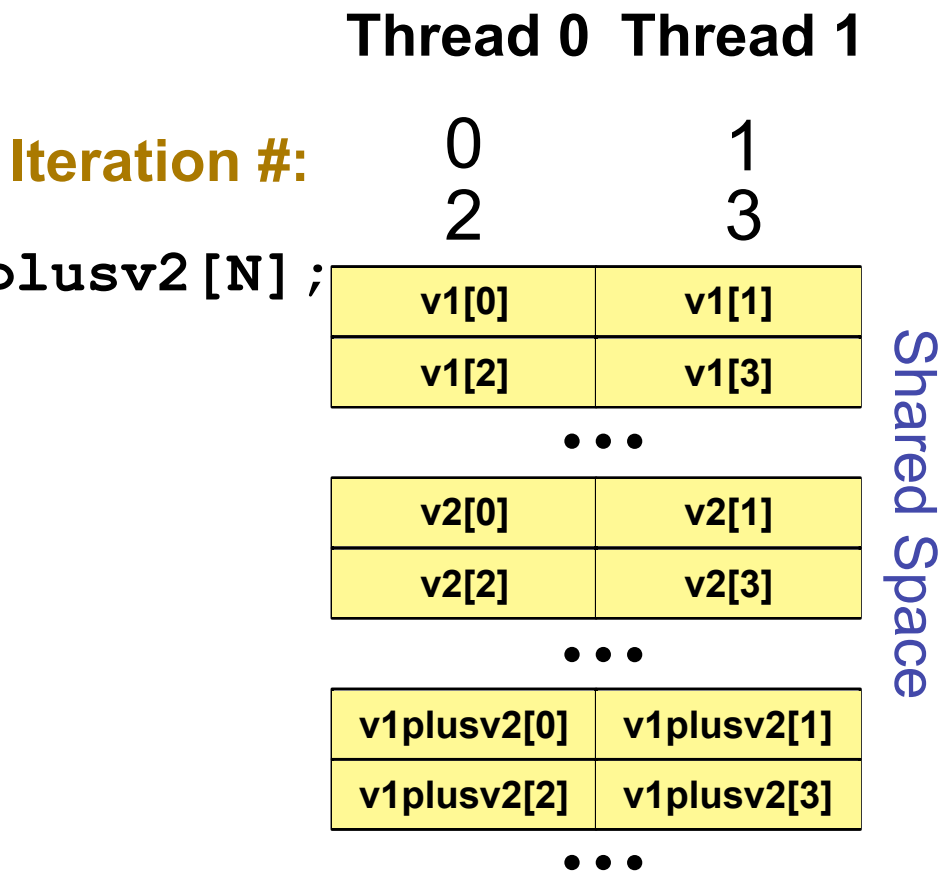
Each thread executes each iteration to check if it has work

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, the goal is to map iteration to thread where (all/most of) the iteration's data resides
- Affinity can be
  - an integer expression (with implicit mod on NUMTHREADS), or a
  - reference to (address of) a shared object

Work Sharing + Affinity with upc_forall

- Example 1: explicit data affinity using shared references

```
shared int a[100],b[100], c[100];
int i;
upc_forall (i=0; i<100; i++; &a[i])
  // Execute iteration i at a[i]'s thread
   a[i] = b[i] * c[i];
```

- Example 2: implicit data affinity with integer expressions

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

- Both yield a round-robin distribution of iterations

Work Sharing + Affinity with `upc_forall`

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

```
shared [25] 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 distribution of upc_forall iterations is as follows:**

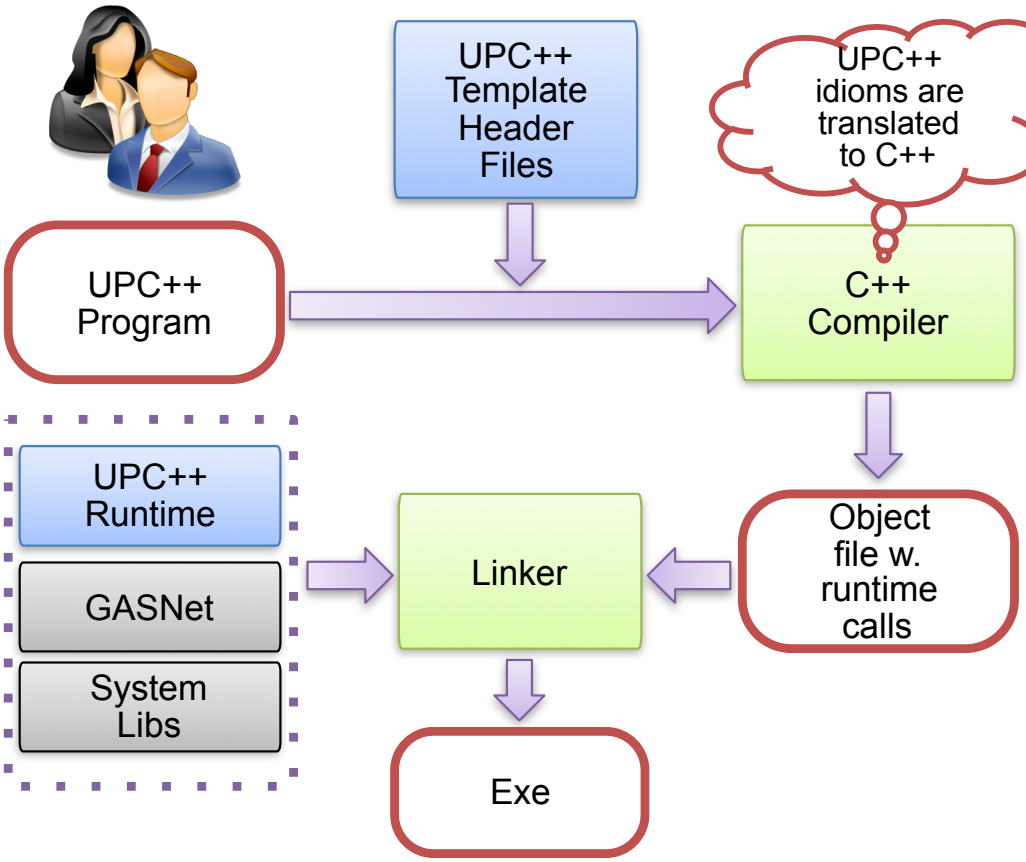
iteration i	i*THREADS	i*THREADS/100
0..24	0..96	0
25..49	100..196	1
50..74	200..296	2
75..99	300..396	3

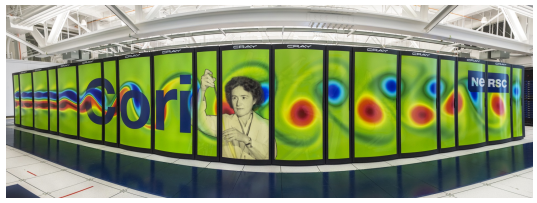
Synchronization in UPC

- Barriers (blocking)
  - upc_barrier
    - like "next" operation in HJ
- Split-phase barriers (non-blocking)
  - upc_notify
    - like explicit (non-blocking) signal on an HJ phaser
  - upc_wait
    - upc_wait is like explicit wait on an HJ phaser

- Lock primitives
  - void upc_lock(upc_lock_t *l)
  - int upc_lock_attempt(upc_lock_t *l) // like trylock()
  - void upc_unlock(upc_lock_t *l)

UPC++ library: a "Compiler-Free" Approach for PGAS (source: LBNL)





- Leverage C++ standards and compilers
  - Implement UPC++ as a C++ template library
  - C++ templates can be used as a mini-language to extend C++ syntax
- Many new features in C++11
  - E.g., type inference, variadic templates, lambda functions, r-value references
  - C++ 11 is well-supported by major compilers

Habanero-UPC++: Extending UPC++ with Task Parallelism (LBNL, Rice)

```
1. finish ( [capture_list1] () {
2.     // Any Habanero dynamic tasking constructs
3.     . . . // finish, async, asyncAwait
4.     . . .
5.     // Remote function invocation
6.     asyncAt ( destPlace, [capture_list2] ( ) {
7.           Statements;
8.     });
9.     . . .
10.    // Remote copy with completion signal in result
11.    asyncCopy ( src, dest, count, ddf=NULL );
12.    . . .
13.    asyncAwait(ddf, ….); // local
14.}); // waits for all local/remote async's to
   complete
```

"HabaneroUPC++: A Compiler-free PGAS Library." V. Kumar, Y. Zheng, V. Cavé, Z. Budimlić, V. Sarkar, PGAS 2015.

Example code structure from an application run on ORNL supercomputer (LSMS)

MPI version:

```
// Post MPI_IRecv() calls
. . .
// Post MPI_ISend() calls
. . .
// Perform all MPI_Wait()
// calls
. . .
// Perform tasks
// Each task needs results
// from two MPI_IRecv() calls
. . . async(…)
```

Habanero-UPC++ version:

```
// Issue one-sided
// asyncCopy() calls
. . .
// Issue data-driven tasks
// in any order without any
// wait/barrier operations
hcpp::asyncAwait(
      result1, result2,
      [=]() { task body });
. . .
```

MPI version waits for all IRecv() calls to complete before executing all tasks (like a barrier)

Habanero-UPC++ version specifies that each asyncAwait() task can complete when its two results become available from asyncCopy() calls