PGAS09

Unified Parallel C – UPC Tutorial

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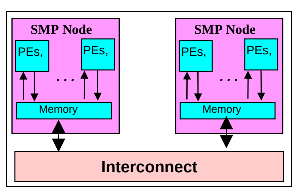
Overview

A. **Introduction to PGAS**
B. Unified Parallel C - UPC
C. Discussion

A. Introduction to PGAS

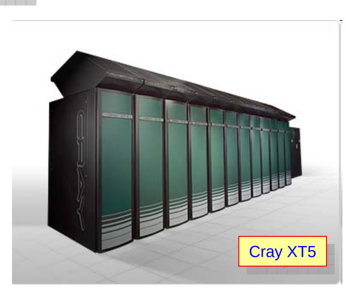
The common architectural landscape

SMP Clusters



Massively Parallel Processor Systems

IBM Blue Gene



Cray XT5

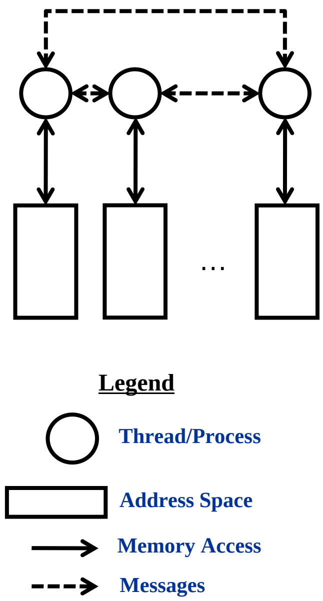
Programming Models

- What is a programming model?
  - The logical interface between architecture and applications
- Why Programming Models?
  - Decouple applications and architectures
    - Write applications that run effectively across architectures
    - Design new architectures that can effectively support legacy applications
- Programming Model Design Considerations
  - Expose modern architectural features to exploit machine power and improve performance
  - Maintain Ease of Use

Examples of Parallel Programming Models

- Message Passing
- Shared Memory (Global Address Space)
- Partitioned Global Address Space (PGAS)

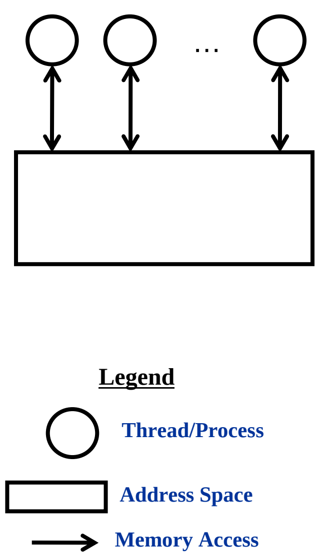
The Message Passing Model



- Concurrent sequential processes
- Explicit communication, two-sided
- Library-based
- Positive:
  - Programmers control data and work distribution.
- Negative:
  - Significant communication overhead for small transactions
  - Excessive buffering
  - Hard to program in
- Example: MPI

7

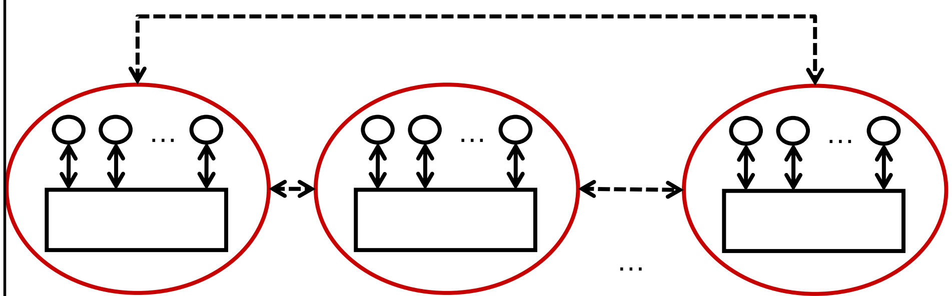
The Shared Memory Model

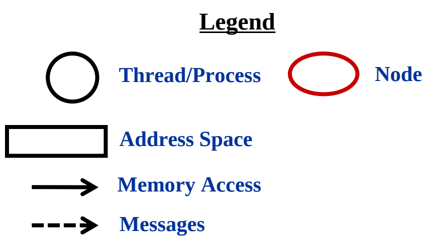


- Concurrent threads with shared space
- Positive:
  - Simple statements
  - Read remote memory via an expression
  - Write remote memory through assignment
- Negative:
  - Manipulating shared data leads to synchronization requirements
  - Does not allow locality exploitation
- Example: OpenMP, Java

8

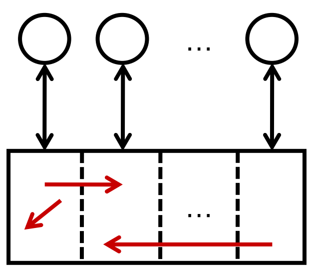
Hybrid Model(s)
Example: Shared + Message Passing

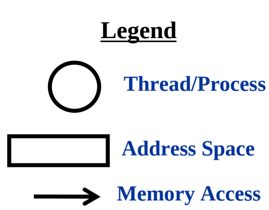




- Example: OpenMP at the node (SMP), and MPI in between

The PGAS Model





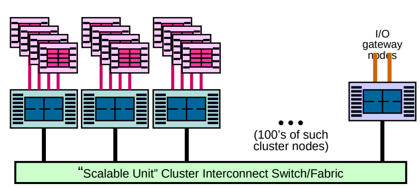
- Concurrent threads with a partitioned shared space
  - A datum may reference data in other partitions
  - Global arrays have fragments in multiple partitions
- Positive:
  - Helps in exploiting locality
  - Simple statements as shared memory
- Negative:
  - sharing all memory can result in subtle bugs and race conditions
  - Examples: UPC, X10, Chapel, CAF, Titanium

PGAS vs. other programming models/languages

	UPC, X10, Chapel, CAF, Titanium	MPI	OpenMP
Memory model	PGAS (Partitioned Global Address Space)	Distributed Memory	Shared Memory
Notation	Language	Library	Annotations
Global arrays?	Yes	No	No
Global pointers/references?	Yes	No	No
Locality Exploitation	Yes	Yes, necessarily	No

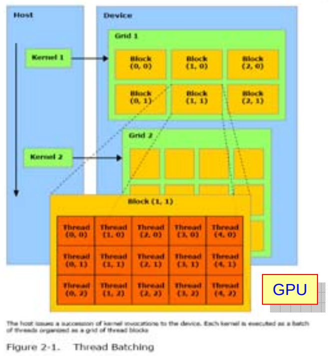
The heterogeneous/accelerated architectural landscape

Cray XT5h: FPGA/Vector-accelerated Opteron



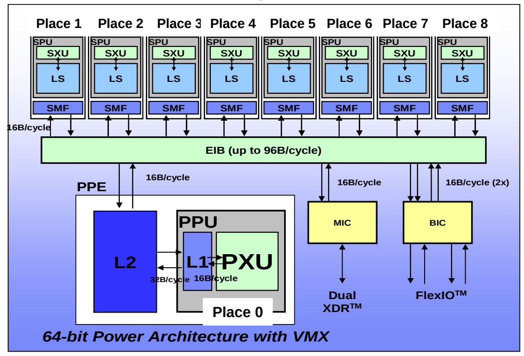
Road Runner: Cell-accelerated Opteron

Example accelerator technologies

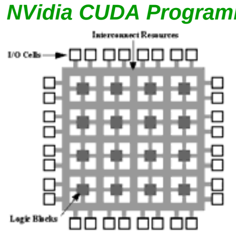


GPU

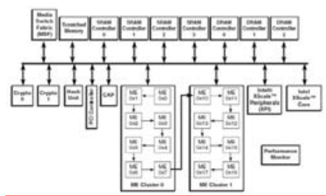
From NVidia CUDA Programming Guide



Cell Processor



FPGA

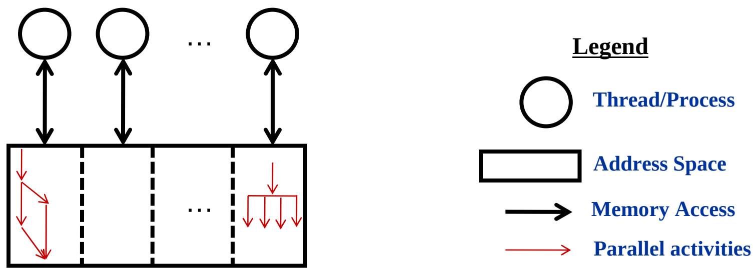


Multi-core w/ accelerators *(Intel IXP 2850)*

The current architectural landscape

- **Substantial architectural innovation is anticipated over the next ten years.**
  - **Hardware situation remains murky, but programmers need stable interfaces to develop applications**
- **Heterogenous accelerator-based systems will exist, raising serious programmability challenges.**
  - **Programmers must choreograph interactions between heterogenous processors, memory subsystems.**
- **Multicore systems will dramatically raise the number of cores available to applications.**
  - **Programmers must understand concurrent structure of their applications.**
- **Applications seeking to leverage these architectures will need to go beyond data-parallel, globally synchronizing MPI model.**
- **These changes, while most profound for HPC now, will change the face of commercial computing over time.**

PGAS with dynamic parallelism



X10, Chapel

- Explicit concurrency
- SPMD is a special case
- Asynchronous activities can be started and stopped in a given space partition

- Asynchronous activities can be used for active messaging
  - DMAs,
  - fork/join concurrency, do-all/do-across parallelism

Concurrency is made explicit and programmable.

How do we realize dynamic parallelism in PGAS?

- Through a dynamic PGAS library in C, Fortran, Java (co-habiting with MPI) which implements
  - remote references
  - global data-structures
  - inter-place messaging
  - global and/or collective operations
  - intra-place concurrency
  - atomic operations

- Through languages
  - Asynchronous CAF
    - extension of CAF with asyncs
  - Asynchronous UPC
    - extension of UPC with asyncs
  - X10 (already asynchronous)
    - extension of sequential Java
  - Chapel (already asynchronous)
- Leveraged runtimes such as XL UPC runtime, GASNet, ARMCI, LAPI, DCMF, DaCS, Cilk runtime, Chapel runtime
- Libraries reduce cost of adoption, languages offer enhanced productivity benefits

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C. Discussion

B. Unified Parallel C
UPC

UPC Overview

1) UPC in a nutshell
   - Memory model
   - Execution model
   - UPC Systems

2) Data Distribution and Pointers
   - Shared vs Private Data
   - Examples of data distribution
   - UPC pointers

3) Workload Sharing
   - upc_forall

4) Advanced topics in UPC
   - Dynamic Memory Allocation
   - Synchronization in UPC
   - UPC Libraries

5) UPC Productivity
   - Code efficiency

Introduction

- UPC – Unified Parallel C
- Set of specs for a parallel C
  - v1.0 completed February of 2001
  - v1.1.1 in October of 2003
  - v1.2 in May of 2005
- Compiler implementations by vendors and others
- Consortium of government, academia, and HPC vendors including IDA CCS, GWU, UCB, MTU, UMN, ARSC, UMCP, U of Florida, ANL, LBNL, LLNL, DoD, DoE, HP, Cray, IBM, Sun, Intrepid, Etnus, …

Introduction cont.

- UPC compilers are now available for most HPC platforms and clusters
  - Some are open source
- A debugger (Totalview from Etnus), a performance analysis tool (PPW from Univ. of Florida), Eclipse development environment (IBM)
- Benchmarks, programming examples, and compiler testing suite(s) are available
- Visit www.upcworld.org or upc.gwu.edu for more information

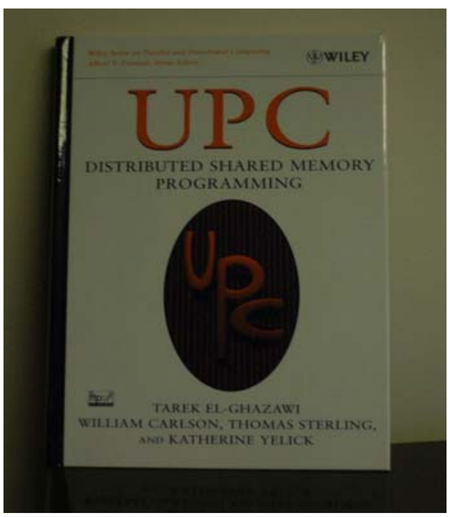
UPC Systems

- Current UPC Compilers
  - Hewlett-Packard
  - Cray
  - IBM
  - Berkeley
  - Intrepid (GCC UPC)
  - MTU
- UPC application development tools
  - Totalview
  - PPW from UF
  - Eclipse tools from IBM

UPC Home Page

http://www.upc.gwu.edu

UPC textbook now available



- *UPC: Distributed Shared Memory Programming*
  - Tarek El-Ghazawi
  - William Carlson
  - Thomas Sterling
  - Katherine Yelick
- Wiley, May, 2005
- ISBN: 0-471-22048-5

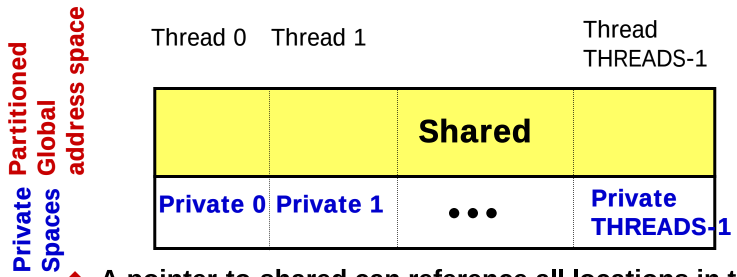
What is UPC?

- Unified Parallel C
- An explicit parallel extension of ISO C
- A partitioned shared memory parallel programming language

UPC Execution Model

- A number of threads working independently in a SPMD fashion
  - MYTHREAD specifies thread index (0..THREADS-1)
  - Number of threads specified at compile-time or run-time
- Synchronization when needed
  - Barriers
  - Locks
  - Memory consistency control

UPC Memory Model



- A pointer-to-shared can reference all locations in the shared space, but there is data-thread affinity
- A private pointer may reference addresses in its private space or its local portion of the shared space
- Static and dynamic memory allocations are supported for both shared and private memory

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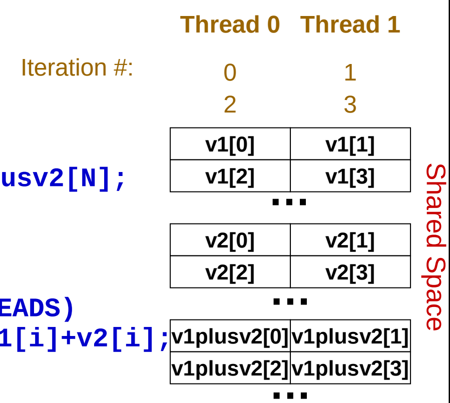
   - Shared vs. Private Data
   - Examples of data distribution
   - UPC pointers
3) Workload Sharing
   - upc_forall
4) Advanced topics in UPC
   - Dynamic Memory Allocation
   - Synchronization in UPC
   - UPC Libraries
5) UPC Productivity
   - Code efficiency

A First Example: 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];
}
```

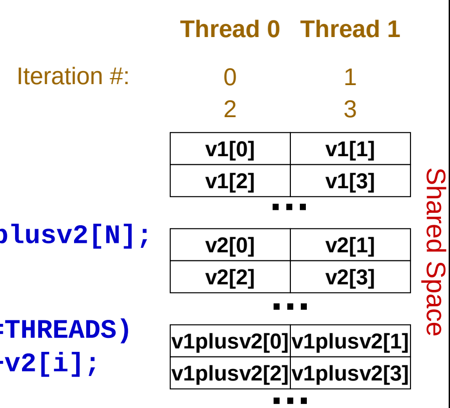


2nd Example: A More Efficient Implementation

```
//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];
}
```



3rd Example: A More Convenient Implementation with upc_forall

```
//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];
}
```

	Thread 0	Thread 1
Iteration #:	0	1
	2	3
	v1[0]	v1[1]
	v1[2]	v1[3]
	…	
	v2[0]	v2[1]
	v2[2]	v2[3]
	…	
	v1plusv2[0]	v1plusv2[1]
	v1plusv2[2]	v1plusv2[3]
	…	

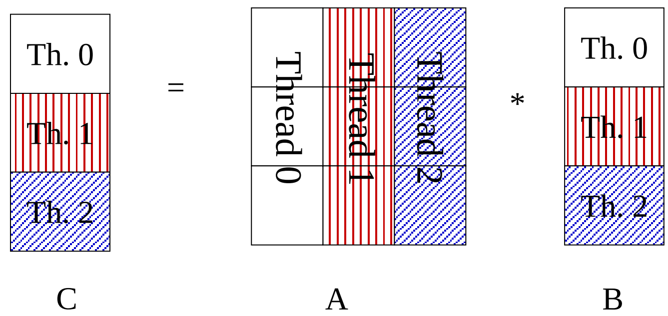
Shared Space

Example: UPC Matrix-Vector Multiplication- Default Distribution

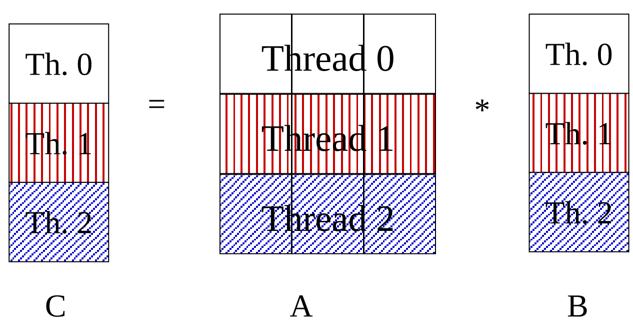
```
// vect_mat_mult.c
#include <upc_relaxed.h>

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];
      }
}
```

Data Distribution



A Better Data Distribution



Example: UPC Matrix-Vector Multiplication- The 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];
        }
}
```


Shared and Private Data

<u>Examples of Shared and Private Data Layout:</u>

Assume THREADS = 3

```
shared int x;  /*x will have affinity to thread 0 */
shared int y[THREADS];
int z;
```

will result in the layout:

Thread 0	Thread 1	Thread 2
x		
y[0]	y[1]	y[2]
z	z	z

Shared and Private Data

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

will result in the following data 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

```
shared int A[2][2*THREADS];
```

will result in the following data layout:

Thread 0	Thread 1	•••	Thread (THREADS-1)
A[0][0]	A[0][1]		A[0][THREADS-1]
A[0][THREADS]	A[0][THREADS+1]	•••	A[0][2*THREADS-1]
A[1][0]	A[1][1]		A[1][THREADS-1]
A[1][THREADS]	A[1][THREADS+1]		A[1][2*THREADS-1]

Blocking of Shared Arrays

- Default block size is 1
- Shared arrays can be distributed on a block per thread basis, round robin with arbitrary block sizes.
- A block size is specified in the declaration as follows:

```
shared [block-size] type array[N];
```

- **e.g.:** `shared [4] int a[16];`

Blocking of Shared Arrays

- Block size and THREADS determine affinity
- The term affinity means in which thread's local shared-memory space, a shared data item will reside
- Element i of a blocked array has affinity to thread:

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

Shared and Private Data

- Shared objects placed in memory based on affinity
- Affinity can be also defined based on the ability of a thread to refer to an object by a private pointer
- All non-array shared qualified objects, i.e. shared scalars, have affinity to thread 0
- Threads access shared and private data

Shared and Private Data

Assume THREADS = 4

```
shared [3] int A[4][THREADS];
```

will result in the following data layout:

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

Special Operators

- `upc_localsizeof(type-name or expression);`
  returns the size of the local portion of a shared object
- `upc_blocksizeof(type-name or expression);`
  returns the blocking factor associated with the argument
- `upc_elemsizeof(type-name or expression);`
  returns the size (in bytes) of the left-most type that is not an array

Usage Example of Special Operators

```
typedef shared int sharray[10*THREADS];
sharray a;
char i;
```

- `upc_localsizeof(sharray)` → `10*sizeof(int)`
- `upc_localsizeof(a)` →`10 *sizeof(int)`
- `upc_localsizeof(i)` →`1`
- `upc_blocksizeof(a)` →`1`
- `upc_elementsizeof(a)` →`sizeof(int)`

String functions in UPC

- UPC provides standard library functions to move data to/from shared memory
- Can be used to move chunks in the shared space or between shared and private spaces

String functions in UPC

- Equivalent of memcpy :
  - upc_memcpy(dst, src, size)
    - copy from shared to shared
  - upc_memput(dst, src, size)
    - copy from private to shared
  - upc_memget(dst, src, size)
    - copy from shared to private
- Equivalent of memset:
  - upc_memset(dst, char, size)
    - initializes shared memory with a character
- The shared block must be a contiguous with all of its elements having the same affinity

UPC Pointers

Where does it point to?

Where does it reside?		Private	Shared
	Private	PP	PS
	Shared	SP	SS

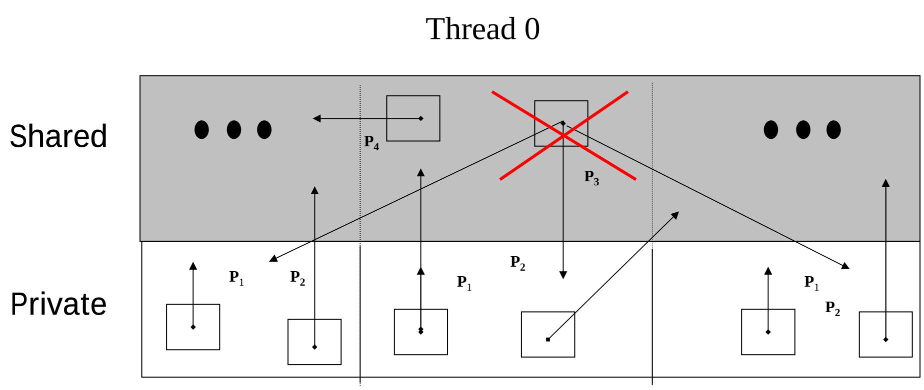
UPC Pointers

- **How to declare them?**

```
int *p1;     /* private pointer pointing locally */
shared int *p2;  /* private pointer pointing into
                    the shared space */
int *shared p3;  /* shared pointer pointing locally
  */
shared int  *shared p4; /* shared pointer pointing
  into the shared space */
```

- **You may find many using “shared pointer” to mean a pointer pointing to a shared object, e.g. equivalent to p2 but could be p4 as well.**

UPC Pointers



UPC Pointers

◆ **What are the common usages?**

- int *p1; /* access to private data or to local shared data */
- shared int *p2; /* independent access of threads to data in shared space */
- int *shared p3; /* not recommended*/
- shared int *shared p4; /* common access of all threads to data in the shared space*/

UPC Pointers

- In 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 Pointers

- 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 number of the pointer-to-shared may be lost
- Casting of a pointer-to-shared to a private pointer is well defined only if the pointed to object has affinity with the local thread

Special Functions

- size_t upc_threadof(shared void *ptr);
  returns the thread number that has affinity to the object pointed to by ptr
- size_t upc_phaseof(shared void *ptr);
  returns the index (position within the block) of the object which is pointed to by ptr
- size_t upc_addrfield(shared void *ptr);
  returns the address of the block which is pointed at by the pointer to shared
- shared void *upc_resetphase(shared void *ptr);
  resets the phase to zero
- size_t upc_affinitysize(size_t ntotal, size_t nbytes, size_t thr);
  returns the exact size of the local portion of the data in a shared object with affinity to a given thread

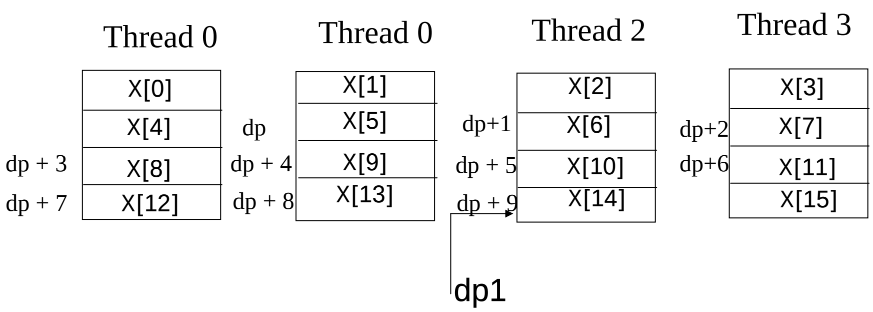
UPC Pointers

<u>pointer to shared Arithmetic Examples:</u>

Assume THREADS = 4

```
#define N 16
shared int x[N];
shared int *dp=&x[5], *dp1;
dp1 =  dp + 9;
```

UPC Pointers



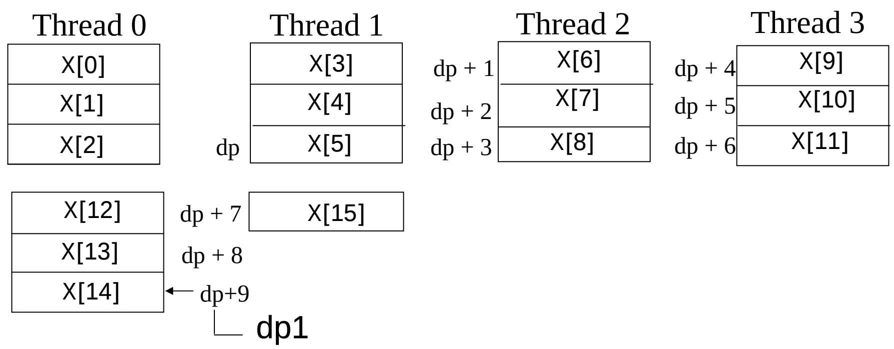
UPC Pointers

Assume THREADS = 4

shared[3] int x[N], *dp=&x[5], *dp1;

dp1 = dp + 9;

UPC Pointers



UPC Pointers

<u>Example Pointer Castings and Mismatched Assignments:</u>

- Pointer Casting

shared int x[THREADS];

int *p;

p = (int *) &x[MYTHREAD]; /* p points to x[MYTHREAD] */

- **Each of the private pointers will point at the x element which has affinity with its thread, i.e. MYTHREAD**

UPC Pointers

- **Mismatched Assignments**

Assume THREADS = 4

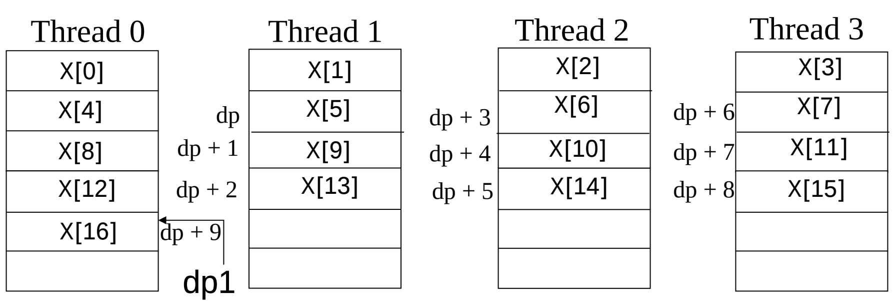
shared int x[N];

shared[3] int *dp=&x[5], *dp1;

dp1 = dp + 9;

  - **The last statement assigns to dp1 a value that is 9 positions beyond dp**
  - **The pointer will follow its own blocking and not that of the array**

UPC Pointers



UPC Pointers

- Given the declarations
  shared[3] int *p;
  shared[5] int *q;
- Then
  p=q; /* is acceptable (an implementation may require an explicit cast, e.g. p=(*shared [3])q;) */
- Pointer p, however, will follow pointer arithmetic for blocks of 3, not 5 !!
- A pointer cast sets the phase to 0

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5) UPC Productivity
   - Code efficiency

Worksharing with upc_forall

- Distributes independent iteration across threads in the way you wish– typically used to boost locality exploitation in a convenient way
- Simple C-like syntax and semantics

  upc_forall(init; test; loop; affinity)

  statement

  - Affinity could be an integer expression, or a
  - Reference to (address of) a shared object

63

Work Sharing and Exploiting Locality via 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 and distribution in a round-robin fashion**

```
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: Examples 1 and 2 result in the same distribution

64

Work Sharing: upc_forall()

- Example 3: Implicitly with distribution 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

UPC Overview

1) **UPC in a nutshell**
   - Memory model
   - Execution model
   - UPC Systems

2) **Data Distribution and Pointers**
   - Shared vs Private Data
   - Examples of data distribution
   - UPC pointers

3) **Workload Sharing**
   - upc_forall

4) **Advanced topics in UPC**
   - Dynamic Memory Allocation
   - Synchronization in UPC
   - UPC Libraries

5) **UPC Productivity**
   - Code efficiency

Dynamic Memory Allocation in UPC

- Dynamic memory allocation of shared memory is available in UPC
- Functions can be collective or not
- A collective function has to be called by every thread and will return the same value to all of them
- As a convention, the name of a collective function typically includes “all”

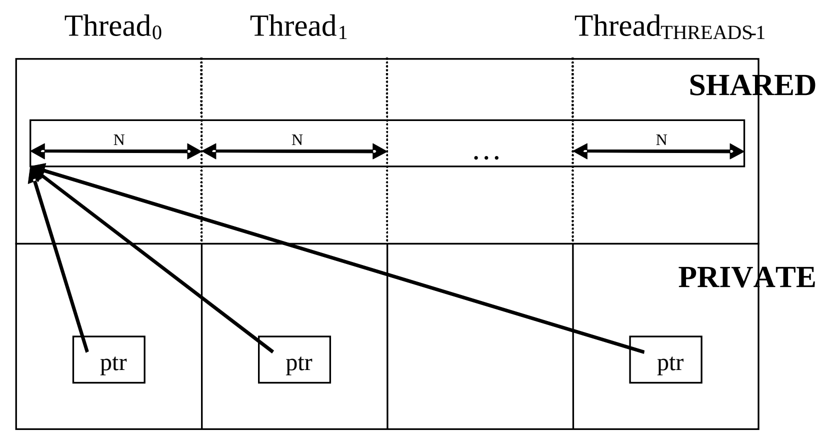
Collective Global Memory Allocation

```
shared void *upc_all_alloc
         (size_t nblocks, size_t nbytes);
```

nblocks: number of blocks
nbytes: block size

- **This function has the same result as** upc_global_alloc. **But this is a collective function, which is expected to be called by all threads**
- **All the threads will get the same pointer**
- **Equivalent to :**
  shared [nbytes] char[nblocks * nbytes]

Collective Global Memory Allocation




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


Global Memory Allocation

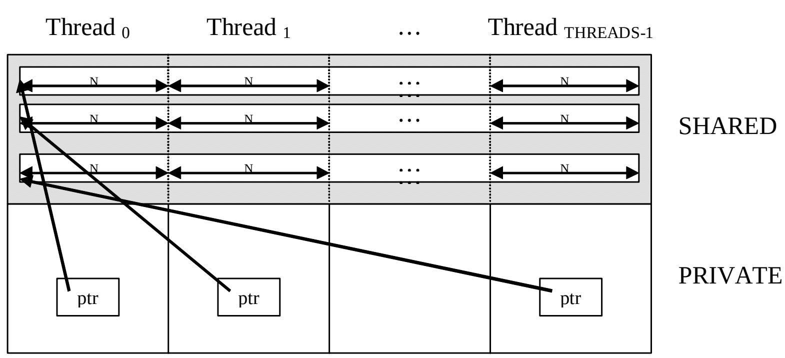
shared void *upc_global_alloc
(size_t nblocks, size_t nbytes);

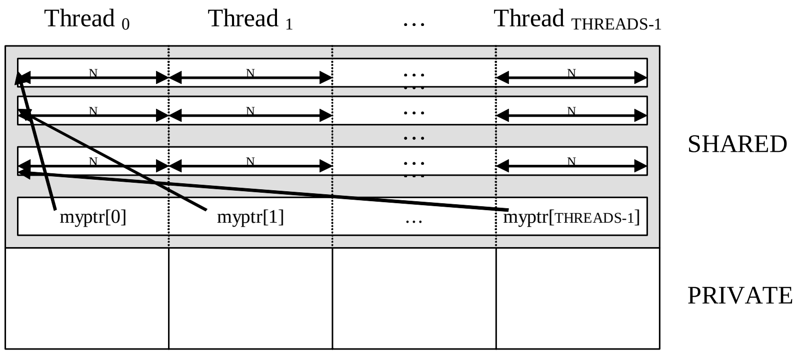
nblocks : number of blocks
nbytes : block size

- **Non collective, expected to be called by one thread**
- **The calling thread allocates a contiguous memory region in the shared space**
- **Space allocated per calling thread is equivalent to :**
  shared [nbytes] char[nblocks * nbytes]
- **If called by more than one thread, multiple regions are allocated and each calling thread gets a different pointer**

Global Memory Allocation

```
shared [N] int *ptr;

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



 shared [N] int *shared
   myptr[THREADS];

 myptr[MYTHREAD] =
   (shared [N] int *)
   upc_global_alloc( THREADS, N*sizeof( int ));
```



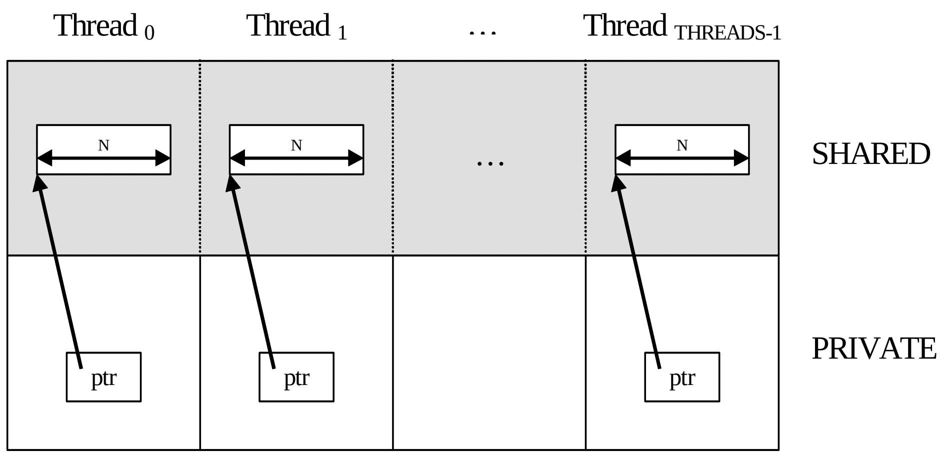
Local-Shared Memory Allocation

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

nbytes: block size

- **Non collective, expected to be called by one thread**
- **The calling thread allocates a contiguous memory region in the local-shared space of the calling thread**
- **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**

Local-Shared Memory Allocation




```
shared [] int *ptr;
ptr = (shared [] int *)upc_alloc(N*sizeof( int ));
```


Memory Space Clean-up

```
void upc_free(shared void *ptr);
```

- **The upc_free function frees the dynamically allocated shared memory pointed to by ptr**
- **upc_free is not collective**

Example: Matrix Multiplication in UPC

- Given two integer matrices A(NxP) and B(PxM), we want to compute C =A x B.
- Entries c_{ij} in C are computed by the formula:

$$c_{ij} = \sum_{l=1}^{p} a_{il} \times b_{lj}$$

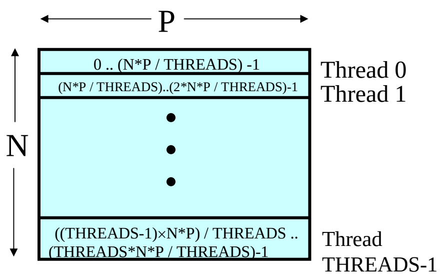
Doing it in C

```
#include <stdlib.h>

#define N  4
#define P  4
#define M 4
int a[N][P] =  {1,2,3,4,5,6,7,8,9,10,11,12,14,14,15,16}, c[N][M];
int b[P][M] = {0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1};

void main (void) {
     int i, j , l;
     for (i = 0 ; i<N ; i++) {
        for (j=0 ; j<M ;j++) {
               c[i][j] = 0;
               for (l = 0 ; l<P ; l++) c[i][j] += a[i][l]*b[l][j];
        }
     }
}
```

Domain Decomposition for UPC

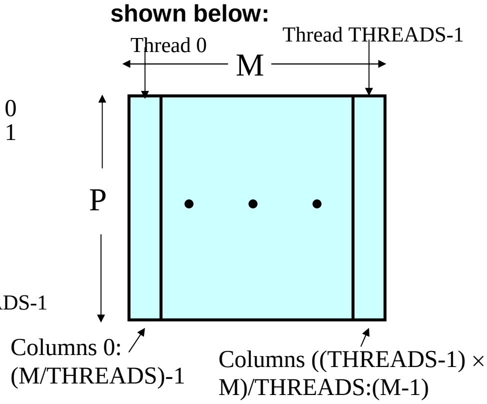
Exploiting locality in matrix multiplication

- A (N × P) is decomposed row-wise into blocks of size (N × P) / THREADS as shown below:



•**Note:** N and M are assumed to be multiples of THREADS

- B(P × M) is decomposed column-wise into M/ THREADS blocks as shown below:



UPC Matrix Multiplication Code

```
#include <upc_relaxed.h>
#define N  4
#define P  4
#define M  4

shared [N*P /THREADS] int a[N][P];
shared [N*M /THREADS] int c[N][M];
/* a and c are blocked shared matrices, initialization is not
   currently implemented */
shared[M/THREADS] int b[P][M];
void main (void) {
   int i, j , l; // private variables

   upc_forall(i = 0 ; i<N ; i++; &c[i][0]) {
        for (j=0 ; j<M ;j++) {
                c[i][j] = 0;
                for (l= 0 ; l<P ;l++) c[i][j] += a[i][l]*b[l][j];
        }
  }
}
```

UPC Matrix Multiplication Code with Privatization

```
#include <upc_relaxed.h>
#define N  4
#define P  4
#define M  4

shared [N*P /THREADS] int a[N][P]; // N, P and M divisible by THREADS
shared [N*M /THREADS] int c[N][M];
shared [M/THREADS]    int b[P][M];
int *a_priv, *c_priv;
void main (void) {
   int i, j , l; // private variables
   upc_forall(i = 0 ; i<N ; i++; &c[i][0]) {
        a_priv = (int *)a[i]; c_priv = (int *)c[i];
        for (j=0 ; j<M ;j++) {
                c_priv[j] = 0;
                for (l= 0 ; l<P ; l++)
                        c_priv[j] += a_priv[l]*b[l][j];
}  }    }
```


UPC Matrix Multiplication Code with block copy

```
#include <upc_relaxed.h>
shared [N*P /THREADS] int a[N][P];
shared [N*M /THREADS] int c[N][M];
/* a and c are blocked shared matrices, initialization is not
   currently implemented */
shared[M/THREADS] int b[P][M];
int b_local[P][M];

void main (void) {
   int i, j , l; // private variables
   for( i=0; i<P; i++ )
        for( j=0; j<THREADS; j++ )
                upc_memget(&b_local[i][j*(M/THREADS)],
                        &b[i][j*(M/THREADS)], (M/THREADS)*sizeof(int));
   upc_forall(i = 0 ; i<N ; i++; &c[i][0]) {
        for (j=0 ; j<M ;j++) {
                c[i][j] = 0;
                for (l= 0 ; l<P ; l++) c[i][j] +=a[i][l]*b_local[l][j];
        }
   }
}
```

UPC Matrix Multiplication Code with Privatization and Block Copy

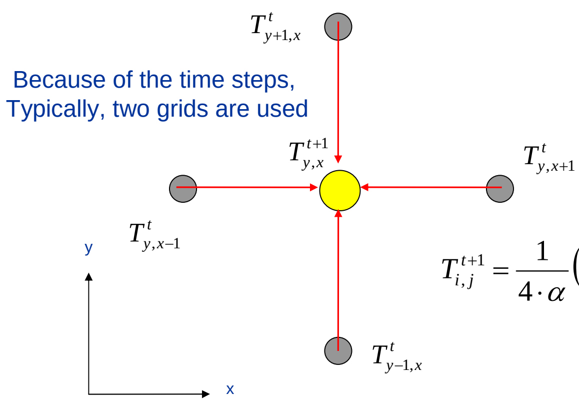
```
#include <upc_relaxed.h>
shared [N*P /THREADS] int a[N][P]; // N, P and M divisible by
   THREADS
shared [N*M /THREADS] int c[N][M];
shared[M/THREADS] int b[P][M];
int *a_priv, *c_priv, b_local[P][M];
void main (void) {
   int i, priv_i, j , l; // private variables
   for( i=0; i<P; i++ )
        for( j=0; j<THREADS; j++ )
        upc_memget(&b_local[i][j*(M/THREADS)],
        &b[i][j*(M/THREADS)], (M/THREADS)*sizeof(int));
   upc_forall(i = 0 ; i<N ; i++; &c[i][0]) {
        a_priv = (int *)a[i]; c_priv = (int *)c[i];
        for (j=0 ; j<M ;j++) {
                c_priv[j] = 0;
                for (l= 0 ; l<P ; l++)
                        c_priv[j] += a_priv[l]*b_local[l][j];
} }   }
```


Matrix Multiplication with dynamic memory

```
#include <upc_relaxed.h>
shared [N*P /THREADS] int *a;
shared [N*M /THREADS] int *c;
shared [M/THREADS] int *b;

void main (void) {
  int i, j , l; // private variables
  a = upc_all_alloc(THREADS,(N*P/THREADS)
       *upc_elemsizeof(*a));
  c=upc_all_alloc(THREADS,(N*M/THREADS)*
       upc_elemsizeof(*c));
  b=upc_all_alloc(P*THREADS,(M/THREADS)*
       upc_elemsizeof(*b));

  upc_forall(i = 0 ; i<N ; i++; &c[i*M]) {
     for (j=0 ; j<M ;j++) {
        c[i*M+j] = 0;
        for (l= 0;l<P; l++) c[i*M+j] += a[i*P+l]*b[l*M+j];
     }
  }
}
```

2D Heat Conduction Problem

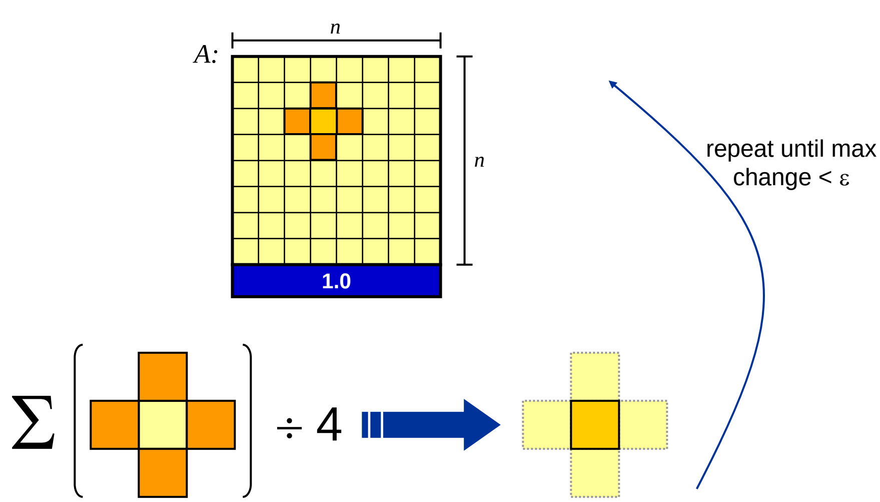
- **Based on the 2D Partial Differential Equation (1), 2D Heat Conduction problem is similar to a 4-point stencil operation, as seen in (2):**



$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \quad (1)$$

$$T^{t+1}_{i,j} = \frac{1}{4 \cdot \alpha}\left(T^t_{i-1,j} + T^t_{i+1,j} + T^t_{i,j-1} + T^t_{i,j+1}\right) \quad (2)$$

Heat Transfer in Pictures



Example: 2D Heat Conduction Problem

```
shared [BLOCKSIZE] double grids[2][N][N];
shared double dTmax_local[THREADS], dTmax_shared;
int x, y, nr_iter = 0, finished = 0;
int dg = 1, sg = 0;
double dTmax, dT, T, epsilon = 0.0001;
do {
   dTmax = 0.0;
   for( x=1; x<N-1; x++ ){
     upc_forall( y=1; y<N-1; y++; &grids[sg][x][y] ){
       T = (grids[sg][x-1][y] + grids[sg][x+1][y] +
         grids[sg][x][y-1] + grids[sg][x][y+1])
           / 4.0;
         dT = T – grids[sg][x][y];
         grids[dg][x][y] = T;
         if( dTmax < fabs(dT) )
           dTmax = fabs(dT);
     }
   }
```

Affinity field, used for work distribution

4-pt stencil

Example: 2D Heat Conduction Problem

```
dTmax_local[MYTHREAD]=dTmax;
upc_all_reduceD(
   &dTmax_shared,
   dTmax_local, UPC_MAX,
   THREADS, 1, NULL,
   UPC_IN_ALLSYNC |
   UPC_OUT_ALLSYNC );
```

reduction operation using UPC collectives library

```
 if( dTmax_shared < epsilon )
  finished = 1;
 else{
/*swapping the source &
  destination “pointers”*/
  dg = sg;
  sg = !sg;
 }
  nr_iter++;
} while( !finished );
upc_barrier;
```

Example: RandomAccess

<u>Description of the problem:</u>

Let T be a table of size 2^n and let S be a table of size 2^m filled with random 64-bit integers.

Let $\{A_i\}$ be a stream of 64-bit integers of length 2^{n+2} generated by the primitive polynomial over GF(2), X_{63}+1.

<u>For each a_i :</u>

$$T[LSB_{n-1\ldots0}(a_i)] = T[LSB_{n-1\ldots0}(a_i)] \text{ XOR } S[MSB_{m-1\ldots0}(a_i)]$$

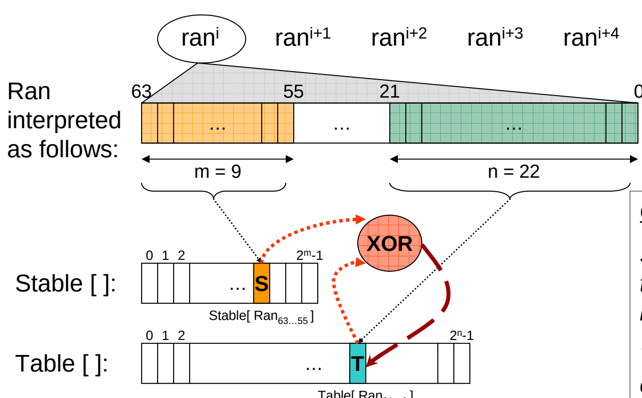
<u>2 Sets of typical problem sizes:</u>

(a) m=9, n=8, 9, max integer size possible

(b) m such as 2^m is half of the size of the cache

n such as 2^n is equal to half of the total memory

Example: RandomAccess



Sequence of 64-bit random numbers as described by Eq1 of length UPDATES = 2^{n+2}

<u>Objects:</u>

Stable = substitution table of size 2^m 64-bit integers

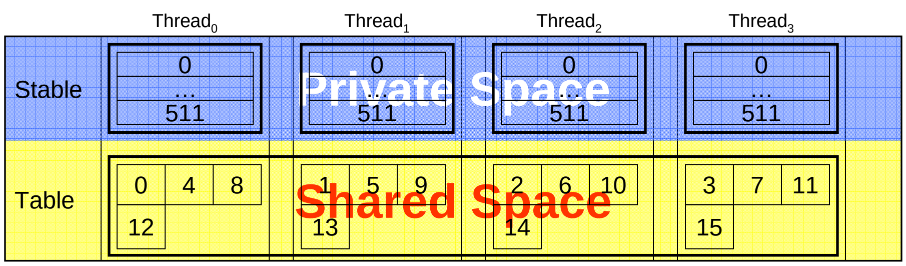
Table = data set array of size 2^n 64-bit integers

<u>Operation:</u> Update of T
T = T XOR S

<u>Eq1:</u> $ran^0 = 1$
$ran^n = 2 * ran^{n-1} \text{ XOR } [\, ran^{n-1}_{63} * 7\,]$

RandomAccess – UPC

```
u64Int Stable[STSIZE]; // private
shared u64Int *Table;  // shared
  // Table[] allocated dynamically at run-time by:
Table = (shared u64Int *)
    upc_all_alloc(TableSize,sizeof(u64Int));
  // STSIZE=2^m       where m=9,
  // TableSize=2^n    where n=4 in this example
…
Table[ran&(TableSize-1)] ^= Stable[ran>>B_SHR];
```



RandomAccess: Computational Core

```
void RandomAccessUpdate(u64Int TableSize) {
  s64Int i;
  u64Int ran[128], ind;
  int j;
  /* Initialize main table */
  upc_forall( i=0; i<TableSize; i++; i )
    Table[i] = i;
  upc_barrier;
  for (j=0; j<128; j++)
    ran[j] = starts ((NUPDATE/128) * j);
  for (i=0; i<NUPDATE/128; i++ ){
    upc_forall( j=0; j<128; j++; j ){
       ran[j] = (ran[j] << 1) ^ ((s64Int) ran[j] < 0 ? POLY : 0);
       Table[ran[j] & (TableSize-1)] ^= Stable[ran[j] >>(64-LSTSIZE)];
     }
  }
}
```

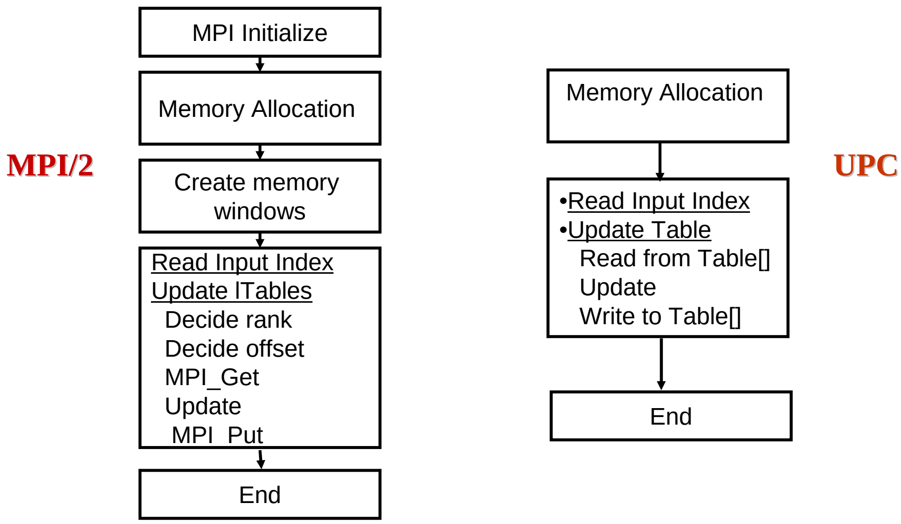
Initialize the **local** part of Table[]

Synchronization

Workload distribution

As-it-is in SEQ code

Expressing Memory Operations Efficiently: Large Histogram (HPCC RA)



Compact Code

	Random Access (#lines)	%Increase
C	144	-
UPC	158	9.72%
MPI/2	210	45.83%
MPI/1	344	138.89%

***Study done with HPCC 0.5alpha compliant code**

Less Conceptual Complexity

		Work Distr.	Data Distr.	Comm.	Synch. & Consist.	Misc. Ops	Sum	Overall Score
RandomAccess MPI/2	# Parameters	26	9	35	5	6	81	151
	# Function Calls	0	2	8	4	4	18	
	# Keywords with rank and np	15	6	8	0	2	31	
	# MPI Types	0	5	10	4	2	21	
	Notes	11 If 5 For	1 memalloc 1 window create	4 for collective operation 4 one-sided	1 fence 3 barriers (1 implicit)	mpi_init mpi_finalize mpi_comm_rank mpi_comm_size		
RandomAccess UPC	# Parameters	19	2	0	0	2	23	42
	# Function Calls	0	1	0	5	2	8	
	# Keywords	5	1	0	0	0	6	
	# UPC Constructs & UPC Types	3	2	0	0	0	5	
	Notes	3 forall 4 if 1 for	2 shared 1 upc_all_alloc		5 barriers	2 global_exit		

Synchronization

- **Explicit synchronization with the following mechanisms:**
  - **Barriers**
  - **Locks**
  - **Memory Consistency Control**
  - **Fence**

Synchronization - Barriers

- No implicit synchronization among the threads
- UPC provides the following barrier synchronization constructs:
  - 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

- In UPC, shared data can be protected against multiple writers :
  - void upc_lock(upc_lock_t *l)
  - int upc_lock_attempt(upc_lock_t *l) //returns 1 on success and 0 on failure
  - void upc_unlock(upc_lock_t *l)
- Locks are allocated dynamically, and can be freed
- Locks are properly initialized after they are allocated

Memory Consistency Models

- Has to do with ordering of shared operations, and when a change of a shared object by a thread becomes visible to others
- Consistency can be *strict* or *relaxed*
- Under the relaxed consistency model, the shared operations can be reordered by the compiler / runtime system
- The strict consistency model enforces sequential ordering of shared operations. (No operation on shared can begin before the previous ones are done, and changes become visible immediately)

Memory Consistency- Fence

- UPC provides a fence construct
  - Equivalent to a null strict reference, and has the syntax
    - upc_fence;
  - UPC ensures that all shared references are issued before the upc_fence is completed

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;                    }
```

- We 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.
- We could have used a fence in the same places. Affects shared references at all threads!
- The above works as an example of point to point synchronization.

UPC Libraries

- UPC Collectives
- UPC-IO

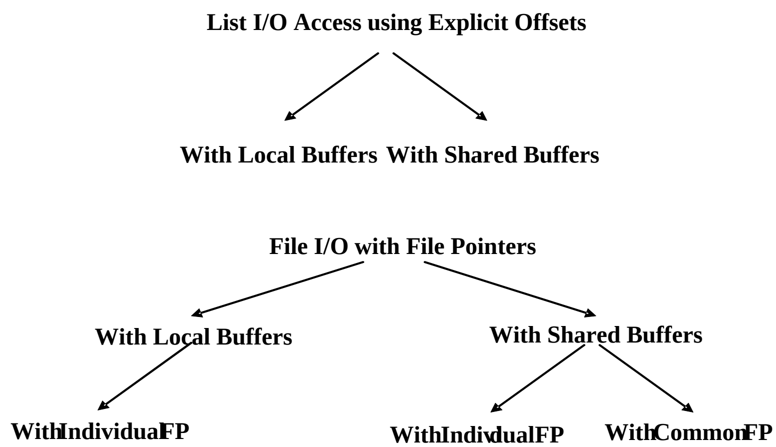
Overview UPC Collectives

- A collective function performs an operation in which *all* threads participate
- Recall that UPC includes the collectives:
  - `upc_barrier, upc_notify, upc_wait, upc_all_alloc, upc_all_lock_alloc`
- Collectives library include functions for bulk data movement and computation.
  - `upc_all_broadcast, upc_all_exchange, upc_all_prefix_reduce,` ***etc*.**

Overview of UPC-IO

- Most UPC-IO functions are collective
  - Function entry/exit includes implicit synchronization
  - Single return values for specific functions
- API provided through extension libraries
- UPC-IO data operations support:
  - shared or private buffers
  - Blocking (upc_all_fread_shared(), …)
  - Non-blocking (async) operations (upc_all_fread_shared_async(), …)
- Supports List-IO Access
- Several reference implementations by GWU

File Accessing and File Pointers



All Read/Write operations have blocking and asynchronous (non-blocking) variants

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   - UPC pointers

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   - upc_forall

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   - UPC Libraries

5) UPC Productivity
   - Code efficiency

Reduced Coding Effort is Not Limited to Random Access– NPB Examples

		SEQ1	UPC	SEQ2	MPI	UPC Effort (%)	MPI Effort (%)
NPB-CG	#lines	665	710	506	1046	6.77	106.72
	#chars	16145	17200	16485	37501	6.53	127.49
NPB-EP	#lines	127	183	130	181	44.09	36.23
	#chars	2868	4117	4741	6567	43.55	38.52
NPB-FT	#lines	575	1018	665	1278	77.04	92.18
	#chars	13090	21672	22188	44348	65.56	99.87
NPB-IS	#lines	353	528	353	627	49.58	77.62
	#chars	7273	13114	7273	13324	80.31	83.20
NPB-MG	#lines	610	866	885	1613	41.97	82.26
	#chars	14830	21990	27129	50497	48.28	86.14

$$UPC_{effort} = \frac{\#UPC - \#SEQ1}{\#SEQ1} \qquad MPI_{effort} = \frac{\#MPI - \#SEQ2}{\#SEQ2}$$

SEQ1 is C
SEQ2 is from NAS, all FORTRAN except for IS

C. Discussion