PACT 08

Productive Parallel Programming in PGAS

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Outline

1. Overview of the PGAS programming model
2. Scalability and performance considerations
3. Compiler optimizations
4. Examples of performance tuning
5. Conclusions

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1. Overview of the PGAS programming model

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Partitioned Global Address Space

- **Explicitly parallel, shared-memory like programming model**
- **Global addressable space**
  - Allows programmers to declare and “directly” access data distributed across the machine
- **Partitioned address space**
  - Memory is logically partitioned between *local* and *remote* (a two-level hierarchy)
  - Forces the programmer to pay attention to data locality, by exposing the inherent NUMA-ness of current architectures
- **Single Processor Multiple Data (SPMD) execution model**
  - All threads of control execute the **same** program
  - Number of threads fixed at startup
  - Newer languages such as X10 escape this model, allowing fine-grain threading
- **Different language implementations:**
  - **UPC** (C-based), CoArray Fortran (Fortran-based), Titanium and X10 (Java-based)

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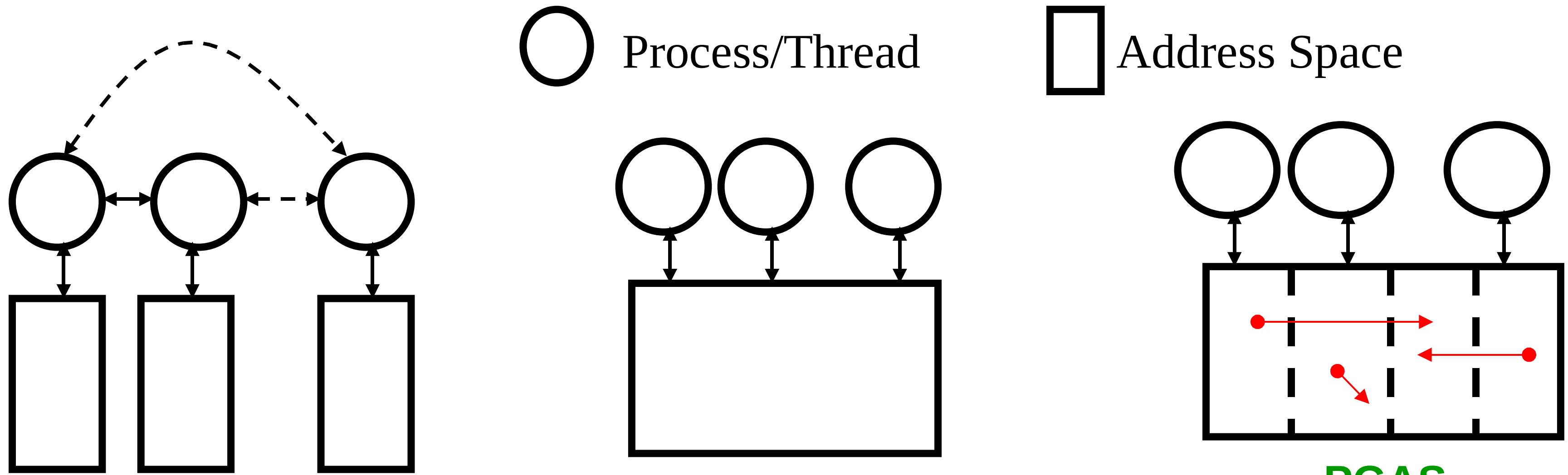
Partitioned Global Address Space



Message passing

MPI

Shared Memory

OpenMP

PGAS

UPC, CAF, X10

- **Computation is performed in multiple places.**
- **A place contains data that can be operated on remotely.**
- **Data lives in the place it was created, for its lifetime.**
- **A datum in one place may point to a datum in another place.**
- **Data-structures (e.g. arrays) may be distributed across many places.**
- **Places may have different computational properties (mapping to a hierarchy of compute engines)**

A place expresses locality.

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UPC Overview and Design Philosophy

- **Unified Parallel C (UPC) is:**
  - An explicit parallel extension of ANSI C
  - A partitioned global address space language
- **Similar to the C language philosophy**
  - Programmers are clever and careful, and may need to get close to hardware
    - to get performance, but
    - can get in trouble
  - Concise and efficient syntax
- **Common and familiar syntax and semantics for parallel C with simple extensions to ANSI C**
- **Based on ideas in Split-C, AC, and PCP**

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UPC Execution Model

- **A number of threads working independently in a SPMD fashion**
  - Number of threads available as program variable THREADS
  - MYTHREAD specifies thread index (0..THREADS-1)
  - upc_barrier is a global synchronization: all wait
  - There is a form of parallel loop that we will see later
- **There are two compilation modes**
  - **Static Threads mode:**
    - THREADS is specified at compile time by the user (compiler option)
    - The program may use THREADS as a compile-time constant
    - The compiler generates more efficient code
  - **Dynamic threads mode:**
    - Compiled code may be run with varying numbers of threads
    - THREADS is specified at runtime time by the user (via env. variable)

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Hello World in UPC

- Any legal C program is also a legal UPC program
- If you compile and run it as UPC with N threads, it will run N copies of the program (Single Program executed by all threads).

```
#include <upc.h>
#include <stdio.h>

int main() {
  printf("Thread %d of %d: Hello UPC world\n", MYTHREAD,
THREADS);
  return 0;
}
```

```
hello > xlupc helloWorld.upc
hello > env UPC_NTHREADS=4 ./a.out
Thread 1 of 4: Hello UPC world
Thread 0 of 4: Hello UPC world
Thread 3 of 4: Hello UPC world
Thread 2 of 4: Hello UPC world
```

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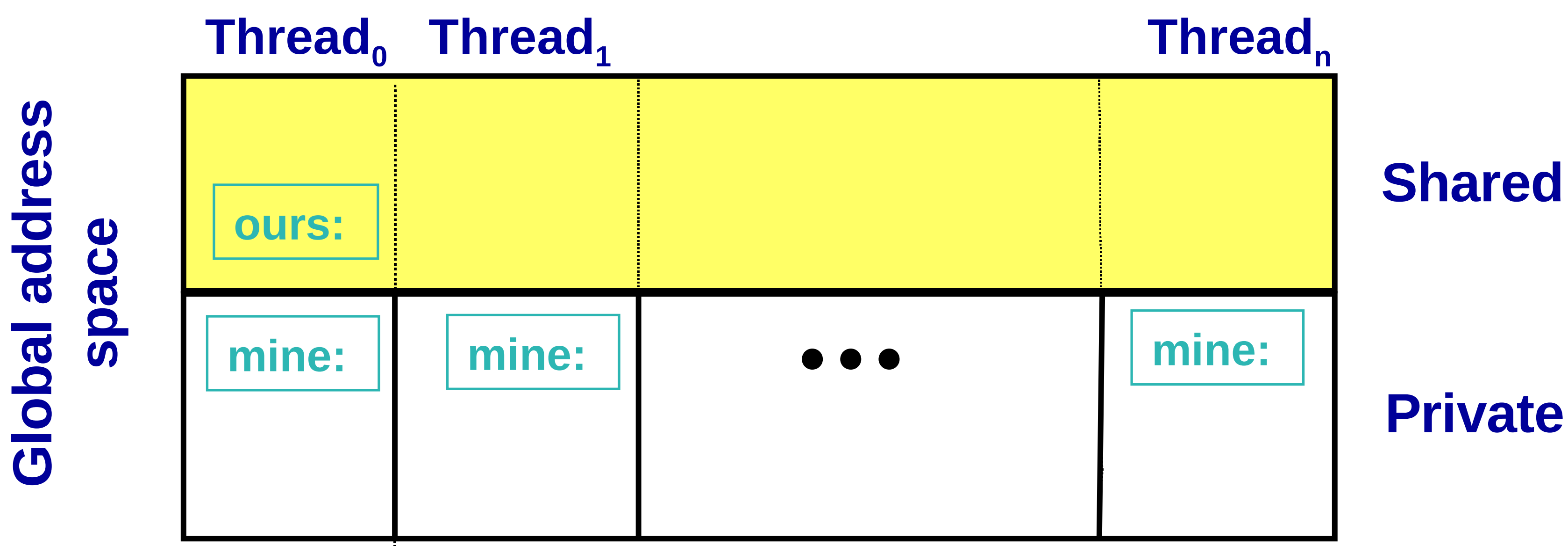
Private vs. Shared Variables in UPC

- **Normal C variables and objects are allocated in the private memory space for each thread.**
- **Shared variables are allocated only once, with thread 0**

```
shared int ours;
int mine;
```

- **Shared variables may not be declared automatic, i.e., may not occur in a in a function definition, except as static. Why?**



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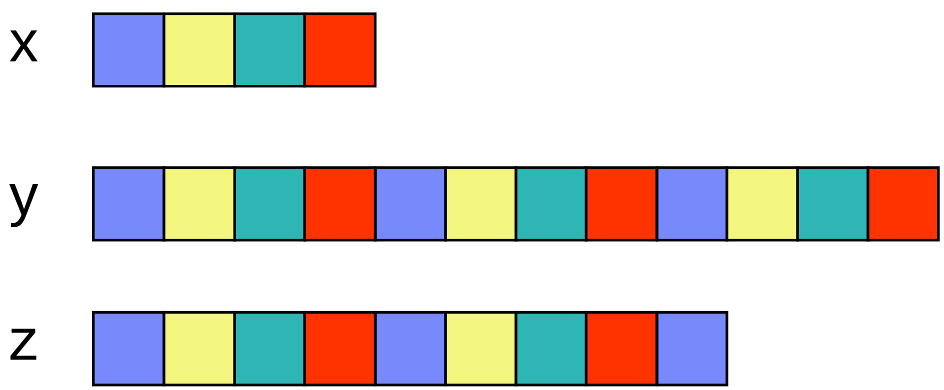
Shared Arrays

- **Shared arrays are spread over the threads, distributed in a cyclic fashion**

```
shared int x[THREADS];          /* 1 element per thread */
shared int y[3][THREADS];       /* 3 elements per thread */
shared int z[3][3];             /* 2 or 3 elements per thread */
```

- **Assuming THREADS = 4:**



Think of a linearized C array, then map round-robin on THREADS

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Work Sharing with upc_forall()

- **The owner computes rule is very common in parallel programming**
  - Loop over all; work on those owned by this proc
- **UPC adds a special type of loop**

```
upc_forall(init; test; loop; affinity)
    statement;
```

- **Programmer indicates the iterations are independent**
  - Undefined if there are dependencies across threads
- **Affinity expression indicates which iterations to run on each thread. It may have one of two types:**
  - **Integer:** `affinity%THREADS` is `MYTHREAD`

    ```
    upc_forall(i=0; i<N; ++i; i)
    ```

  - **Pointer:** `upc_threadof(affinity)` is `MYTHREAD`

    ```
    upc_forall(i=0; i<N; ++i; &A[i])
    ```

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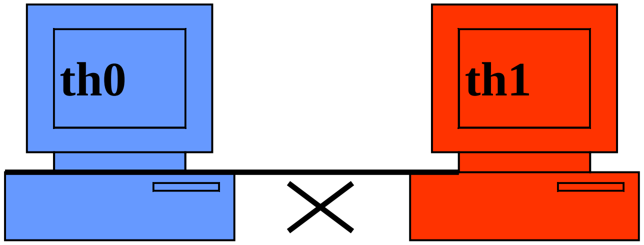
Work Sharing with upc_forall()

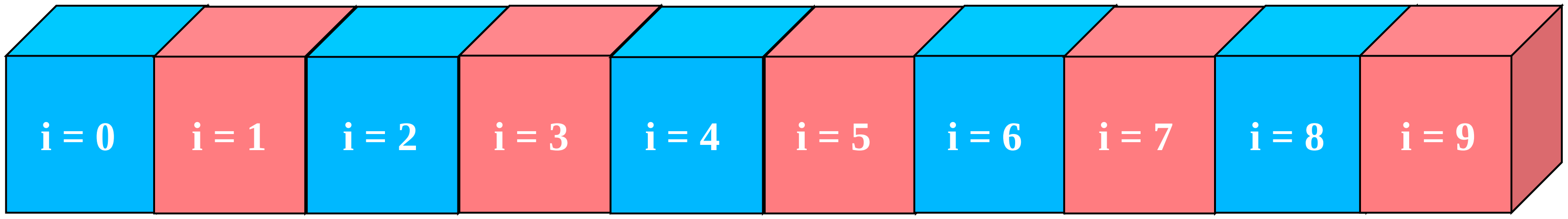
- Similar to C for loop, 4th field indicates the affinity
- Thread that "owns" elem. A[i] executes iteration

```
shared int A[10],B[10],C[10];
upc_forall(i=0; i < 10; i++; &A[i]) {
    A[i] = B[i] + C[i];
}
```



No communication

2 threads



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Vector Addition with upc_forall

```
#define N 100*THREADS

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

void main() {
    int i;
    upc_forall(i=0; i<N; i++; i)

        sum[i]=v1[i]+v2[i];
}
```

- Equivalent code could use "&sum[i]" for affinity
- The code would be correct but slow if the affinity expression were i+1 rather than i.

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UPC Global Synchronization

- **Controls relative execution of threads**
- **UPC has two basic forms of barriers:**
  - Barrier: block until all other threads arrive
    `upc_barrier`
  - Split-phase barriers
    `upc_notify;` this thread is ready for barrier
    do computation unrelated to barrier
    `upc_wait;` wait for others to be ready
- **Optional labels allow for debugging**

```
#define MERGE_BARRIER 12
if (MYTHREAD%2 == 0) {
   ...
   upc_barrier MERGE_BARRIER;
} else {
   ...
   upc_barrier MERGE_BARRIER;
}
```

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Recap: Shared Variables, Work sharing and Synchronization

- **With what you've seen until now, you can write a bare-bones data-parallel program**
- **Shared variables are distributed and visible to all threads**
  - Shared scalars have affinity to thread 0
  - Shared arrays are distributed (cyclically by default) on all threads
  - We shall look next at how to control memory layouts, shared pointers, etc.
- **Execution model is SPMD with the `upc_forall` provided to share work**
- **Barriers and split barriers provide global synchronization**

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Blocked Layouts in UPC

- **The cyclic layout is typically stored in one of two ways**
  - Distributed memory: each processor has a chunk of memory
    - Thread 0 would have: 0,THREADS, THREADS*2,… in a chunk
  - Shared memory machine: all data may be on one chunk
    - Shared memory would have: 0,1,2,…THREADS,THREADS+1,…
- **Vector addition example can be rewritten as follows**

```
#define N 100*THREADS
shared int [*] v1[N], v2[N], sum[N];
void main() {
   int i;
   upc_forall(i=0; i<N; i++; &a[i])
        sum[i]=v1[i]+v2[i];
}
```

blocked layout

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Layouts in General

- **All non-array objects have affinity with thread zero.**
- **Array layouts are controlled by layout specifiers:**
  - Empty (cyclic layout)
  - [*] (blocked layout)
  - [0] or [] (indefinitely layout, all on 1 thread)
  - [b] or [b1][b2]…[bn] = [b1*b2*…bn] (fixed block size)
- **The affinity of an array element is defined in terms of:**
  - block size, a compile-time constant
  - and THREADS.
- **Element i has affinity with thread**

  (i / block_size) % THREADS

- **In 2D and higher, linearize the elements as in a C representation, and then use above mapping**

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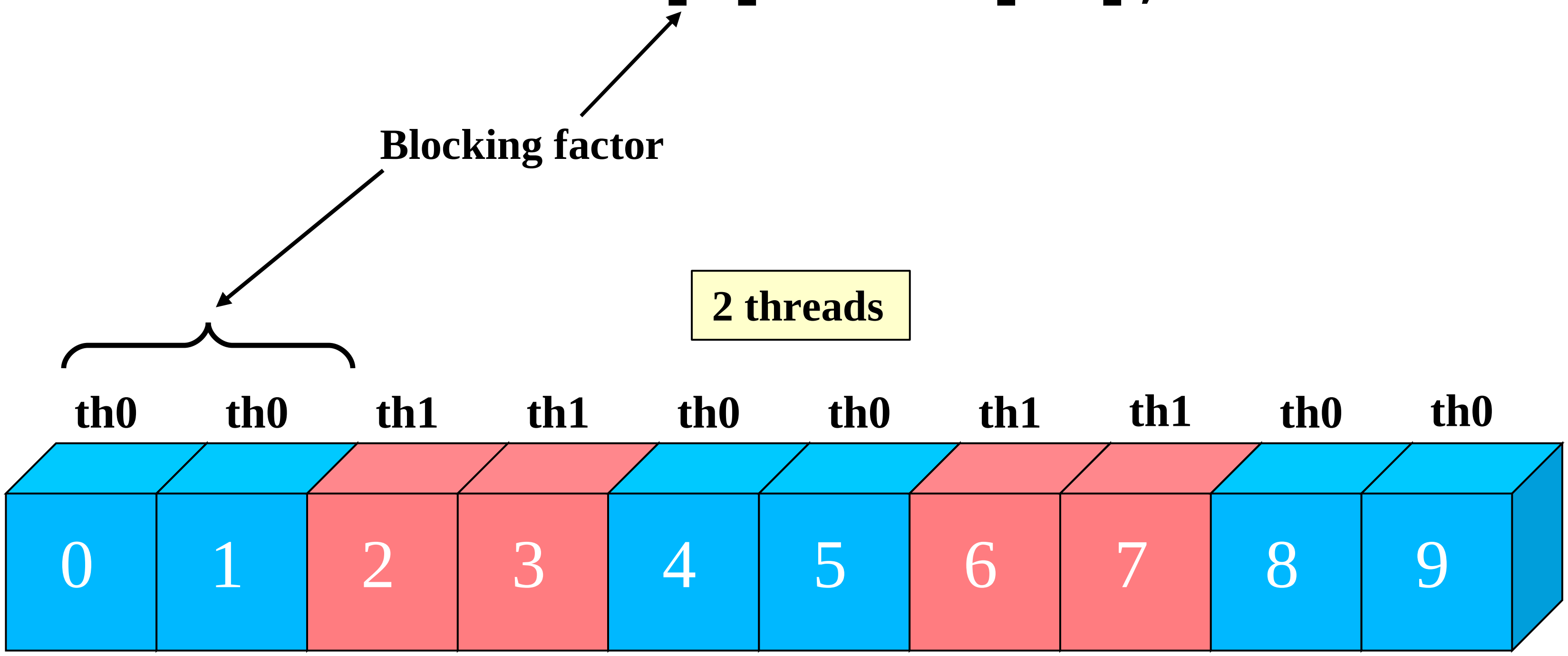
Distribution of a shared array in UPC

- Elements are distributed in block-cyclic fashion
- Each thread “owns” blocks of adjacent elements

```
shared [2] int X[10];
```



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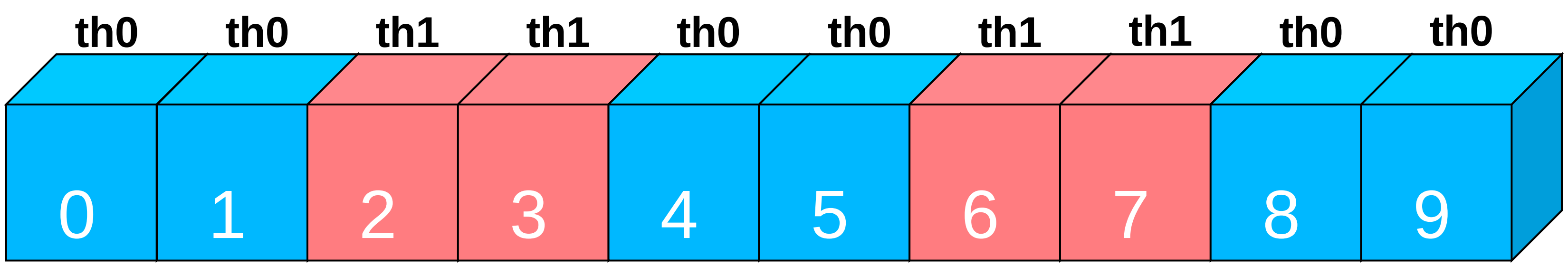
Physical layout of shared arrays

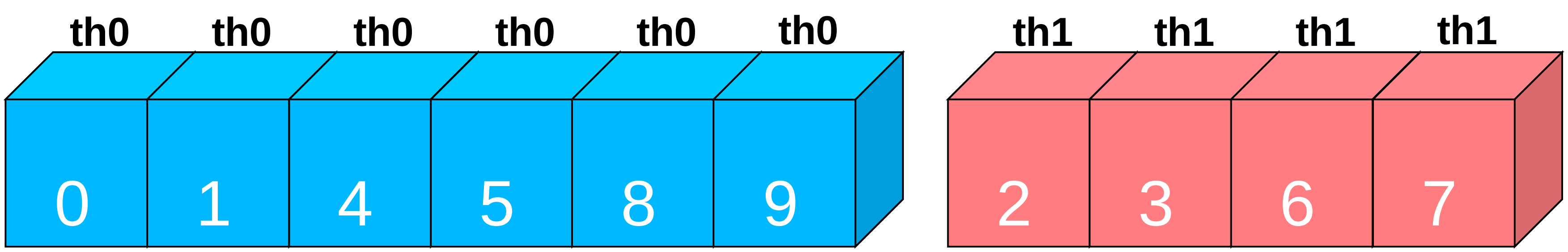
```
shared [2] int X[10];
```

2 threads

Logical Distribution



Physical Distribution



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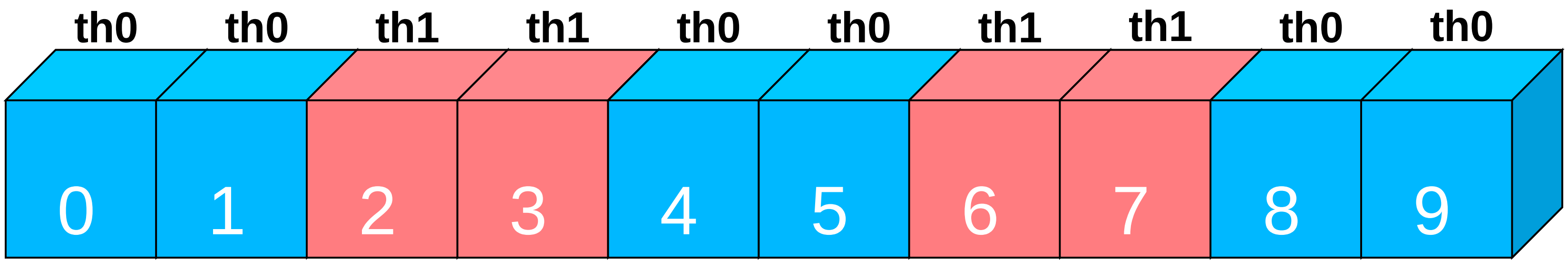
Terminology

```
shared [2] int X[10];
```



- **upc_threadof(&a[i])**
  - Thread that owns a[i]
- **upc_phaseof(&a[i])**
  - The position of a[i] within its block
- **course(&a[i])**
  - The block index of a[i]

Examples

upc_threadof(&a[2]) = 1

upc_threadof(&a[5]) = 0

upc_phaseof(&a[2]) = 0

upc_phaseof(&a[5]) = 1

course(&a[2]) = 0

course(&a[5]) = 1

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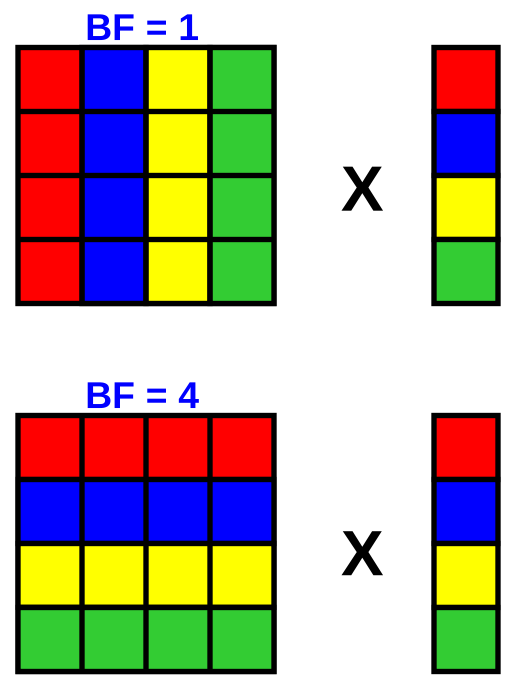
UPC Matrix Vector Multiplication Code

- **Matrix-vector multiplication with matrix stored by rows**

```
#define N   THREADS
shared [BF] int a[N][N];
shared int b[N], c[N];


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



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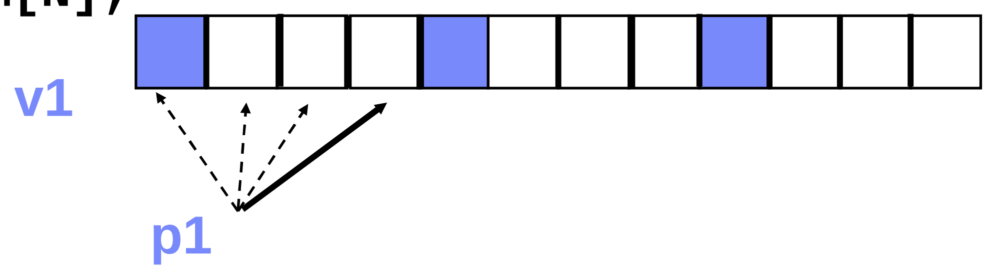
Pointers to Shared vs. Arrays

- In the C tradition, array can be access through pointers
- Here is the vector addition example using pointers

```
#define N 100*THREADS

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

void main() {
   int i;
   shared int *p1, *p2;

   p1=v1; p2=v2;
   for (i=0; i<N; i++, p1++, p2++){

     if (i%THREADS == MYTHREAD)
       sum[i]= *p1 + *p2;

   }
}
```



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UPC Pointers

Where does the pointer point to?

Where does the pointer reside?

	Local	Shared
Private	PP (p1)	PS (p3)
Shared	SP (p2)	SS (p4)

```
int *p1;                /* private pointer to local memory */
shared int *p2;         /* private pointer to shared space */
int *shared p3;         /* shared pointer to local memory */
shared int *shared p4;  /* shared pointer to shared space */
```

Shared to private is not recommended. Why?

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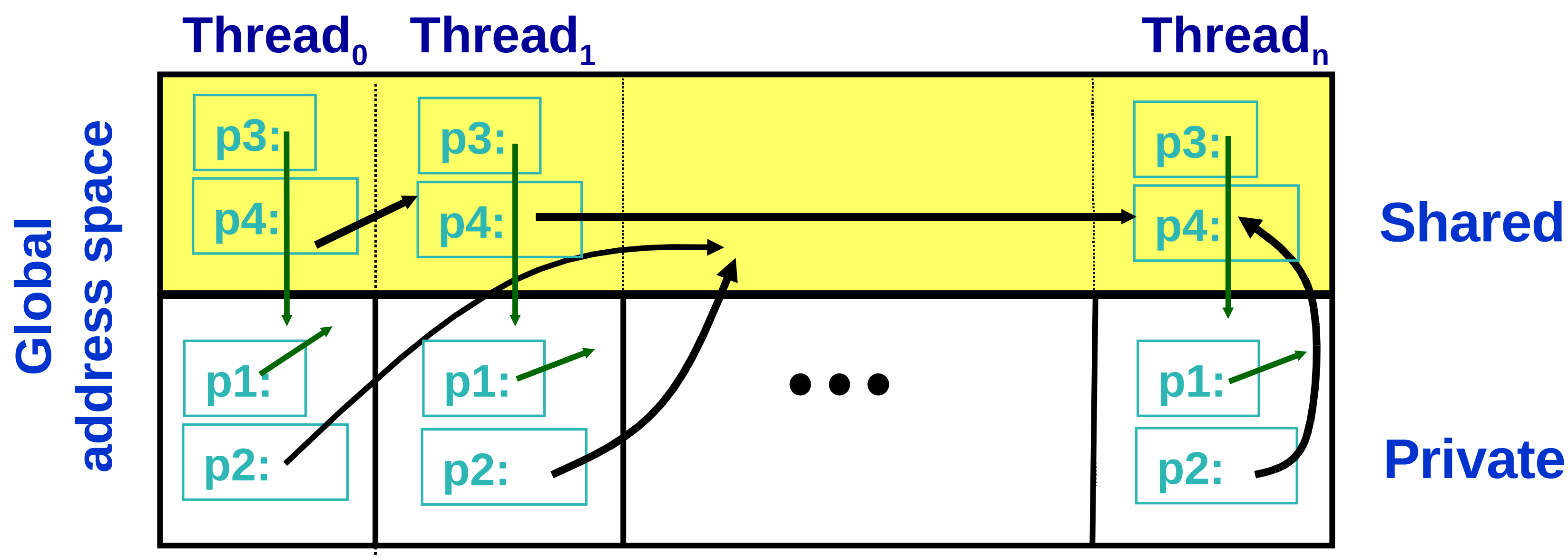
UPC Pointers




```
int *p1;                  /* private pointer to local memory */
shared int *p2;           /* private pointer to shared space */
int *shared p3;           /* shared pointer to local memory */
shared int *shared p4;    /* shared pointer to shared space */
```

Pointers to shared often require more storage and are more costly to dereference; they may refer to local or remote memory.

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Common Uses for UPC Pointer Types

```
int *p1;
```

- These pointers are fast (just like C pointers)
- Use to access local data in part of code performing local work
- Often cast a pointer-to-shared to one of these to get faster access to shared data that is local

```
shared int *p2;
```

- Use to refer to remote data
- Larger and slower due to test-for-local + possible communication

```
int * shared p3;
```

- Not recommended

```
shared int * shared p4;
```

- Use to build shared linked structures, e.g., a linked list

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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 shared to private is well defined only if the object pointed to by the pointer to shared has affinity with the thread performing the cast**

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Pointer Query Functions

- **size_t upc_threadof(shared void *ptr);**
  - returns the thread number that has affinity to the pointer to shared
- **size_t upc_phaseof(shared void *ptr);**
  - returns the index (position within the block)field of the pointer to shared
- **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

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Synchronization primitives

- We have seen upc_barrier, upc_notify and upc_wait
- UPC supports locks:
  - Represented by an opaque type: `upc_lock_t`
  - Must be allocated before use:

```
upc_lock_t *upc_all_lock_alloc(void);
```

allocates 1 lock, pointer to all threads

```
upc_lock_t *upc_global_lock_alloc(void);
```

allocates 1 lock, pointer to all threads

  - To use a lock:

```
void upc_lock(upc_lock_t *l)
void upc_unlock(upc_lock_t *l)
```

use at start and end of critical region

  - Locks can be freed when not in use

```
void upc_lock_free(upc_lock_t *ptr);
```

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Dynamic memory allocation

- **As in C, memory can be dynamically allocated**
- **UPC provides several memory allocation routines to obtain space in the shared heap**
  - shared void* upc_all_alloc(size_t nblocks, size_t nbytes)
    - a collective operation that allocates memory on all threads
    - layout equivalent to: shared [nbytes] char[nblocks * nbytes]
  - shared void* upc_global_alloc(size_t nblocks, size_t nbytes)
    - A non-collective operation, invoked by one thread to allocate memory on all threads
    - layout equivalent to: shared [nbytes] char[nblocks * nbytes]
  - shared void* upc_alloc(size_t nbytes)
    - A non-collective operation to obtain memory in the thread's shared section of memory
  - void upc_free(size_t nbytes)
    - A non-collective operation to free data allocated in shared memory
    - Why do we need just one version?

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Distributed arrays allocated dynamically

```
typedef shared [] int *sdblptr;
shared sdblptr directory[THREADS];

int main() {
  …
  directory[MYTHREAD] = upc_alloc(local_size*sizeof(int));
  upc_barrier;
  …
  /* use the array */
  upc_barrier;
  upc_free(directory[MYTHREAD]);
}
```

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Data movement

- Fine grain (array element, by array element access) are easy to program in an imperative way. However, especially on distributed memory machines, block transfers are more efficient
- UPC provides library functions for data movement and collective operations:
  - upc_memset
    - Set a block of values in shared memory
  - upc_memget, upc_memput
    - Transfer blocks of data from shared memory to/from private memory
  - upc_memcpy
    - Transfer blocks of data from shared memory to shared memory
- Collective operations (broadcast, reduce, etc.)
    - A set of function calls is specified in the standard, but it’s being reworked. More about this a bit later

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Memory Consistency

- The consistency model defines the order in which one thread may see another threads accesses to memory
  - If you write a program with unsychronized accesses, what happens?
  - Does this work?

```
data = …                    while (!flag) { };
flag = 1;                   … = data;   // use the data
```

- UPC has two types of accesses:
  - Strict: will always appear in order
  - Relaxed: may appear out of order to other threads
- There are several ways of designating the type, commonly:
  - Use the include file:

```
#include <upc_relaxed.h>
```

  - Which makes all accesses in the file relaxed by default
  - Use strict on variables that are used as synchronization (**flag**)

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Data movement Collectives

- Used to move shared data across threads:
  - upc_all_broadcast(shared void* dst, shared void* src, size_t nbytes, …)
    - A thread copies a block of memory it "owns" and sends it to all threads
  - upc_all_scatter(shared void* dst, shared void *src, size_t nbytes, …)
    - A single thread splits memory in blocks and sends each block to a different thread
  - upc_all_gather(shared void* dst, shared void *src, size_t nbytes, …)
    - Each thread copies a block of memory it "owns" and sends it to a single thread
  - upc_all_gather_all(shared void* dst, shared void *src, size_t nbytes, …)
    - Each threads copies a block of memory it "owns" and sends it to all threads
  - upc_all_exchange(shared void* dst, shared void *src, size_t nbytes, …)
    - Each threads splits memory in blocks and sends each block to all thread
  - upc_all_permute(shared void* dst, shared void *src, shared int* perm, size_t nbytes, …)
    - Each threads copies a block of memory and sends it to thread in perm[i]

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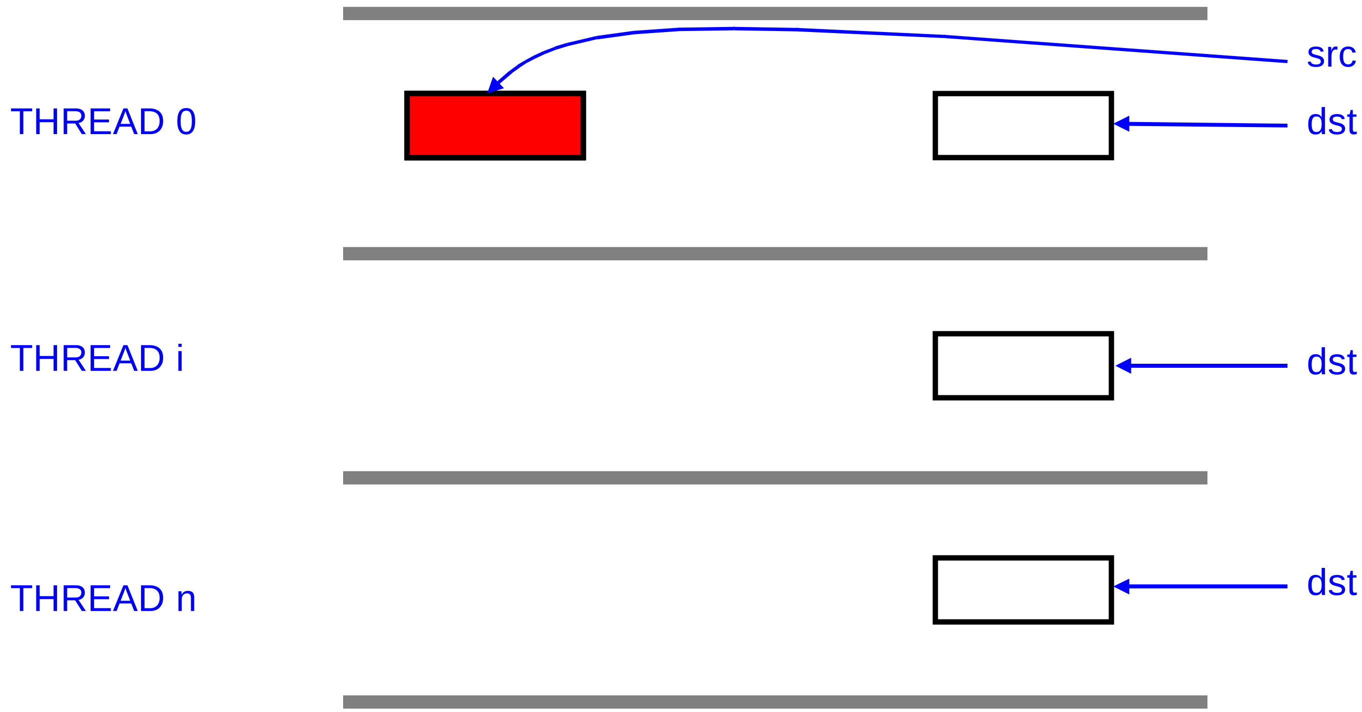
upc_all_broadcast



Thread 0 copies a block of memory and sends it to all threads

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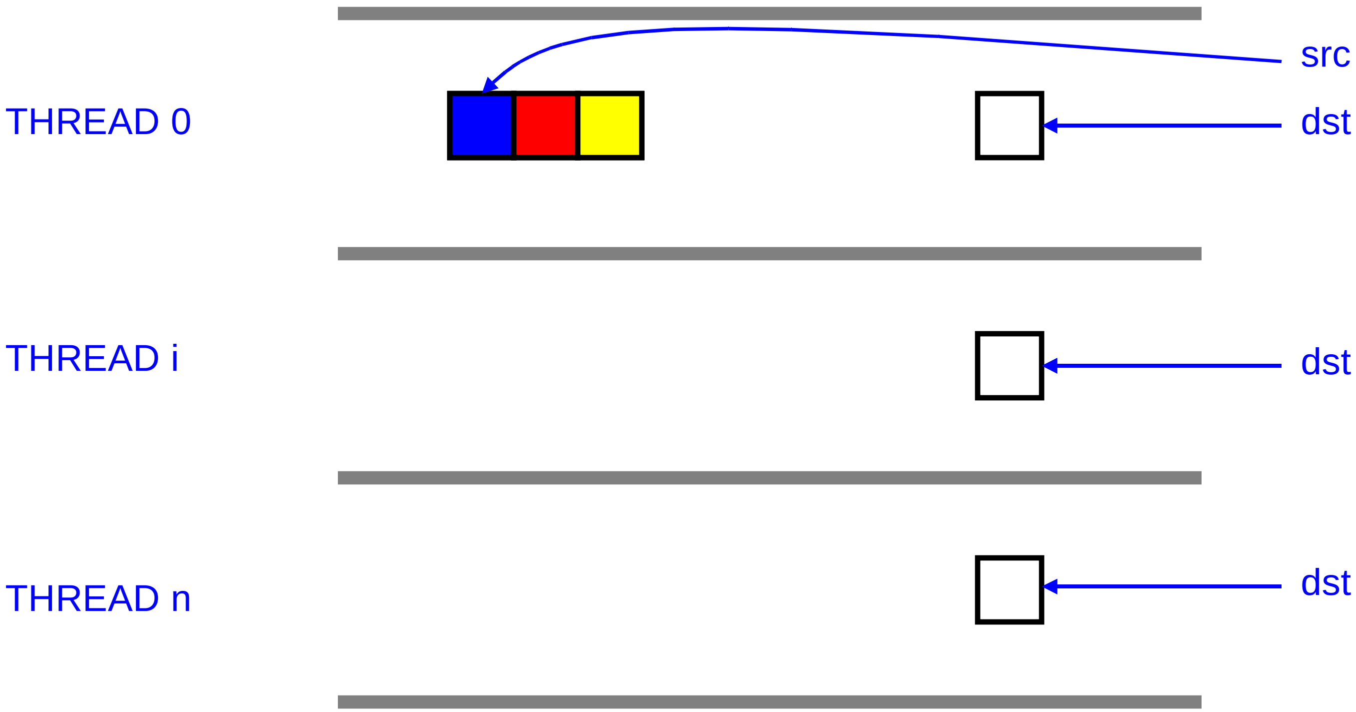
upc_all_scatter



Thread 0 sends a unique block to all threads

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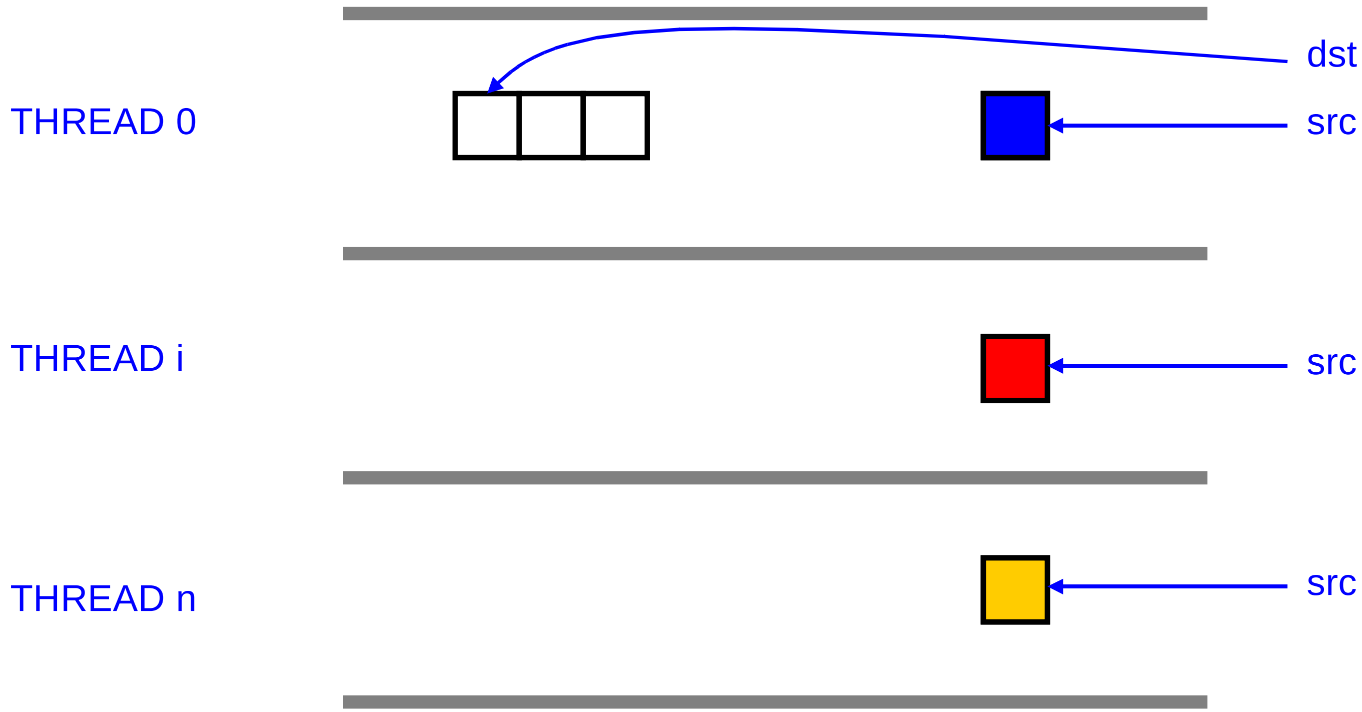
upc_all_gather



Each thread sends a block to thread 0

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Computational Collectives

- Used to perform data reductions
  - upc_all_reduceT(shared void* dst, shared void* src, upc_op_t op, …)
  - upc_all_prefix_reduceT(shared void* dst, shared void *src, upc_op_t op, …)
- One version for each type T (22 versions in total)
- Many operations are supported:
  - OP can be: +, *, &, |, xor, &&, ||, min, max
  - perform OP on all elements of src array and place result in dst array

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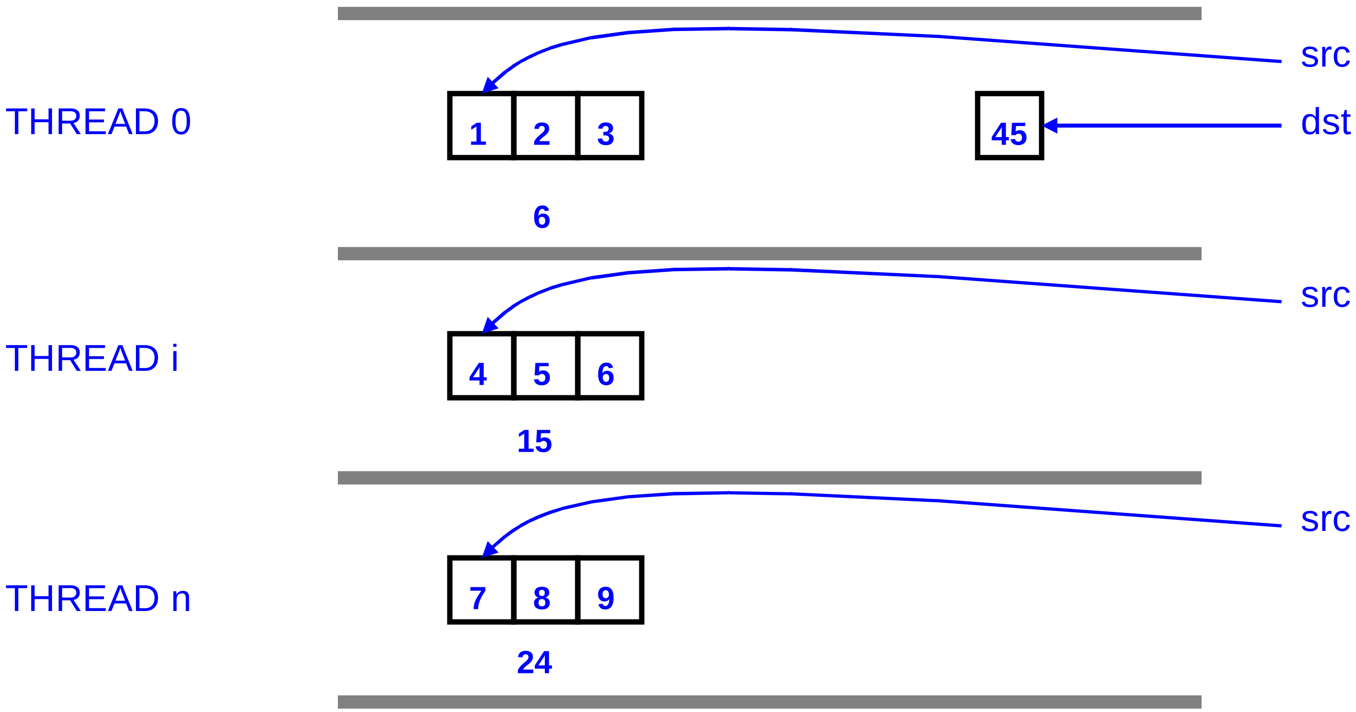
upc_all_reduce



Threads perform partial sums, each partial sum added and result stored on thread 0

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PACT 08

Scalability and performance considerations

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Scalability: Rules of thumb

- **Things to avoid:**
  - UPC tempts user into fine-grain communication
  - UPC tempts user into bad data layouts
  - The siren song of UPC locks
- **Things to take advantage of:**
  - Global view makes reasoning about program easier
    - The “G” ins PGAS
  - Collective communication

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Simple sum: Introduction

- Simple forall loop to add values into a sum

```
shared int values[N], sum;

sum = 0;
upc_forall (int i=0; i<N; i++; &values[i])
   sum += values[i];
```

- Is there a problem with this code ?
- Implementation is broken: “sum” is not guarded by a lock
- Write-after-write hazard; will get different answers every time

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Simple sum: using locks

- Easy you say … let’s use a lock !

```
shared int values[N], sum;
upc_lock_t mylock;

upc_forall (int i=0; i<N; i++; &values[i]) {
        upc_lock (&mylock);
        sum += values[i];
        upc_unlock (&mylock);
}
```

- Correct implementation ☺☺☺
- But horrible performance ☹☹☹
- Lock is used for every array value !!!

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Simple sum: minimizing lock use

- Better performance if N >> THREADS
- Still O(N) communication!

```
shared int values[N], sum;
shared int partialsums[THREADS];

partialsum[MYTHREAD]=0;
upc_forall (int i=0; i<N; i++; &values[i]) {
  partialsum[MYTHREAD] += values[i];
}

upc_forall (int i=0; i<THREADS; i++; partialsums[i]) {
  upc_lock (&mylock);
  sum += partialsums[i];
  upc_unlock (&mylock);
}
```

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Simple sum: avoiding locks

- **Assuming N = k * THREADS (or array padded with zeroes)**

```
shared int values[N], sum;

upc_all_reduceI (&sum,
                 values,
                 UPC_ADD,
                 THREADS,
                 N/THREADS,
                 NULL,
                 UPC_IN_ALLSYNC|UPC_OUT_ALLSYNC);
```

- **Typical O(log(n)) scalability (like MPI reductions)**
- **Your lesson: avoid locks! There is almost always a better solution**

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Access Granularity: Stencil

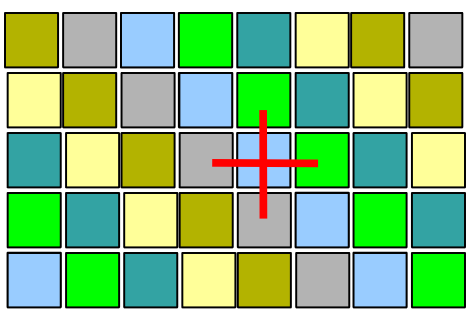
Communication traffic:
4 * N * N * THREADS elements
4 * N * N * THREADS accesses

Naive solution:

```
shared double A[N][N];

upc_forall (i=1; i<N-1; i++; continue)
  upc_forall (j=1; j<N-1; j++; &A[i][j])
    A[i][j] = 0.25 *(A[i-1][j]+A[i+1][j]+A[i][j-1]+A[i][j+1];
```

This is bad because all accesses right of 0.25 are likely non-local.



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Access Granularity: Banded Stencil

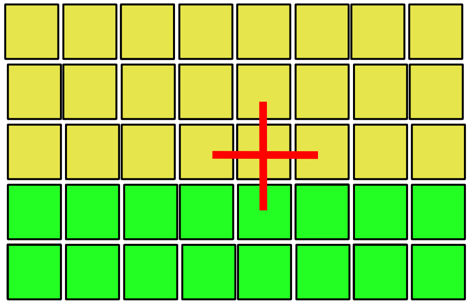
Communication traffic:
2 * N * THREADS elements
2 * N * THREADS accesses

Better solution: banded layout

```
shared [N*N/THREADS] double A[N][N];

upc_forall (i=1; i<N-1; i++; continue)
  upc_forall (j=1; j<N-1; j++; &A[i][j])
    A[i][j] = 0.25 *(A[i-1][j]+A[i+1][j]+A[i][j-1]+A[i][j+1];
```

Better, because only 2*N accesses per thread are non-local



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Access Granularity: Shadow Exchange

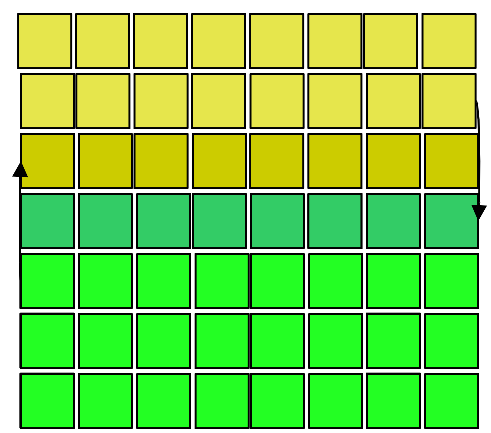
Communication traffic:
2 * N * THREADS elements
2 * THREADS accesses

Banded layout with shadow regions:

```
#define B (N*(N+2*THREADS)/THREADS)
shared [B] double A[N+2*THREADS][N];

/* exchange shadows (code incomplete, no bounds checks!) */
int l=MYTHREAD*B;              /* lower shadow */
upc_memget (&A[l][0], &A[l-2][0], N*sizeof(double));
int u=(MYTHREAD+1)*B-1;        /* upper shadow row */
upc_memget (&A[u][0], &A[u+2][0], N*sizeof(double));

/* stencil code as usual */
...
```



Shadow region exchange

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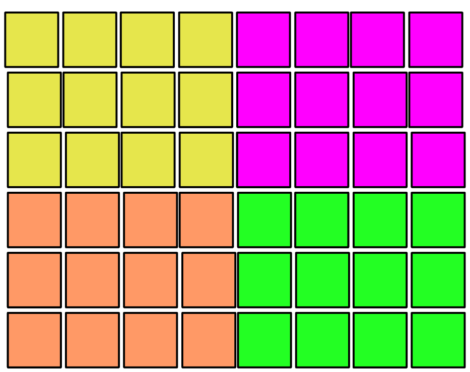
Access Granularity: Tiled layout

Communication traffic:
4 * N * sqrt(T) elements
4 * T accesses

Tiled layout (UPC extension)

```
#define B
shared [B][B] double A[N][N];
```

- **Very complicated code (exchange buffers are not contiguous) (*)**
- **Highly scalable: per-thread communication costs <u>decrease</u> with scaling**



(*) compiler aggregation optimization can help keep code small

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Matrix multiplication: Introduction

```
shared double A[M][P], B[P][N], C[M][N];

forall (i=0; i<M; i++; continue)
  forall (j=0; j<N; j++; &C[i][j])
     for (k=0; k<P; k++)
        C[i][j] += A[i][k]*B[k][j];
```

Problem:

- **Accesses to A and B are mostly non-local**
- **Fine grain remote access == bad performance!**

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Matrix multiplication: Block matrices

```
shared struct { int x[B][B]; } A[M1][P1], B[P1][N1], C[M1]
  [N1];

forall (i=0; i<M1; i++; continue)
  forall (j=0; j<N1; j++; &C[i][j])
     for (k=0; k<P1; k++) {
        upc_memget (alocal, &A[i][k], B*B*sizeof(double));
        upc_memget (blocal, &B[k][j], B*B*sizeof(double));
        dgemm (alocal, blocal, &C[i][j]);
     }
```

– **Good:**
  - **Fewer accesses, large granularity**
  - **Improved single-node performance (ESSL library call)**
– **Bad:**
  - **Code has changed significantly**
  - **Still not scalable performance: O(n^3) communication**

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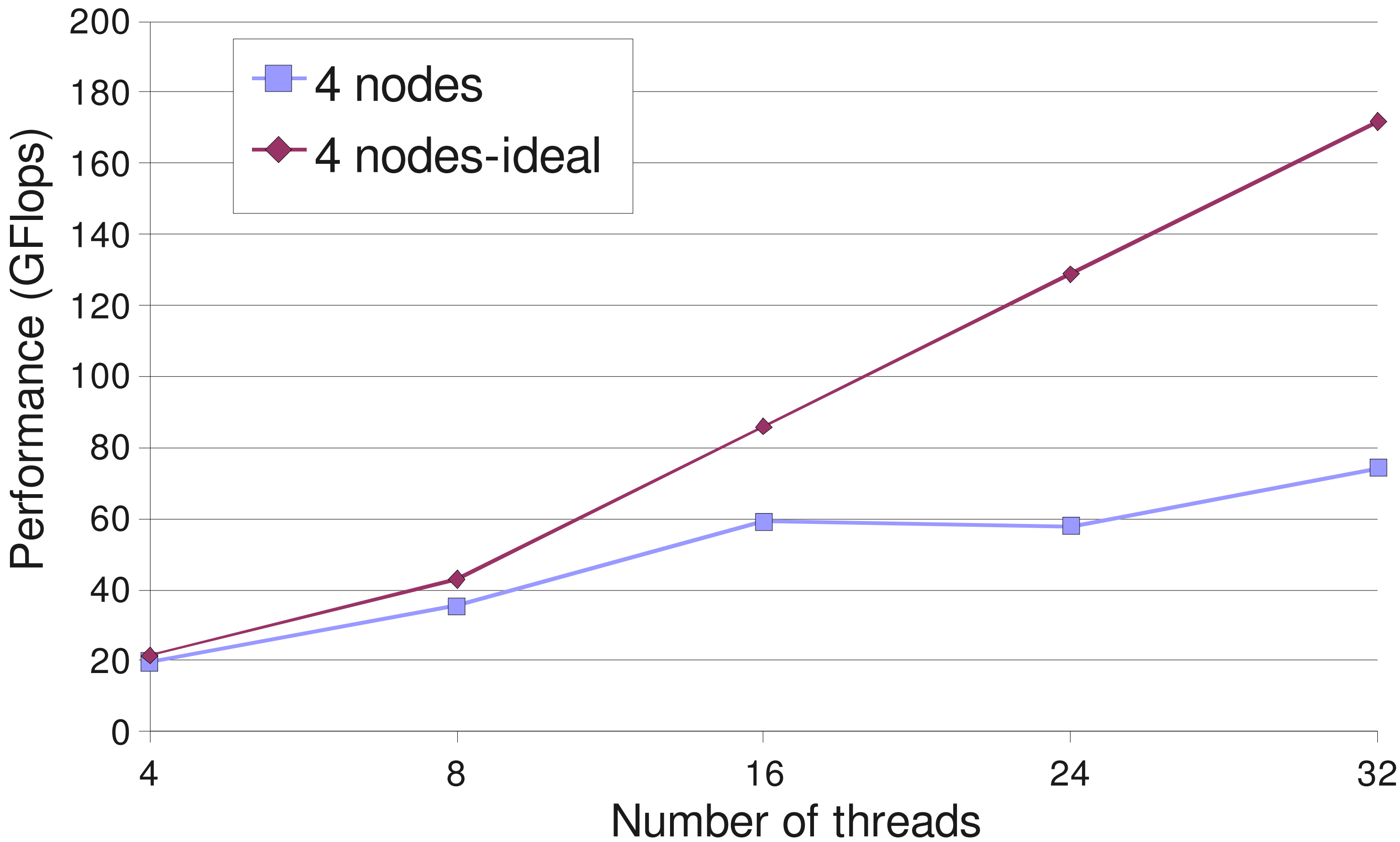
Blocked Matrix Multiply scaling
P5 cluster, 4 nodes x 8 threads/node



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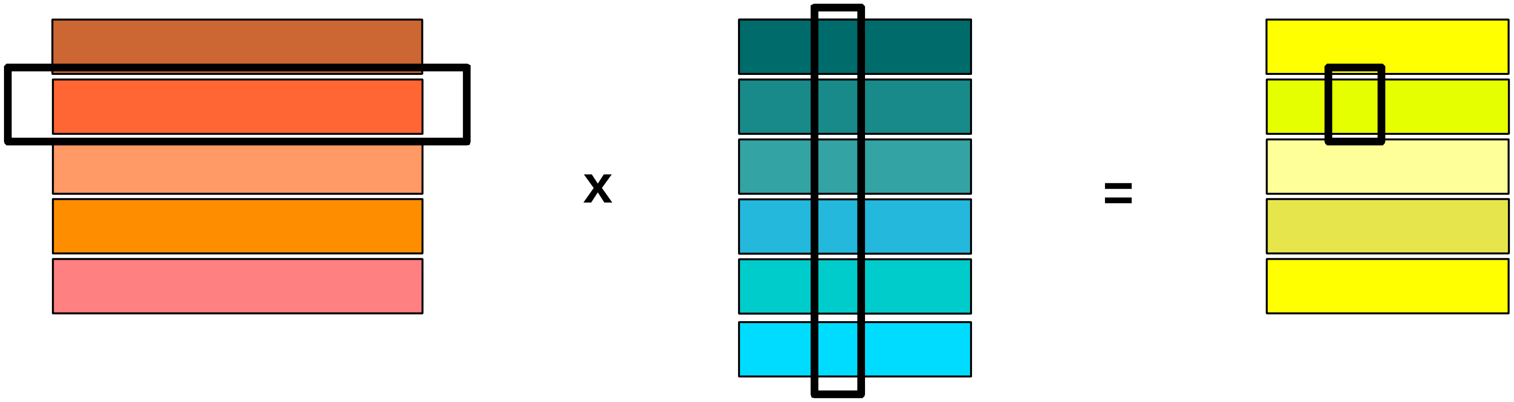
Matrix multiplication: New Layout

```
typedef shared { int x[B][B]; } Block;
shared [M1*sizeof(Block)] Block A[M1][P1];
shared [P1*sizeof(Block)] Block B[P1][N1];
shared [M1*sizeof(Block)] Block C[M1][N1];
```

Good:

- no locality issues on A and C (traversing the same way)

- Bad:
  - B is traversed across block layout (communication!)



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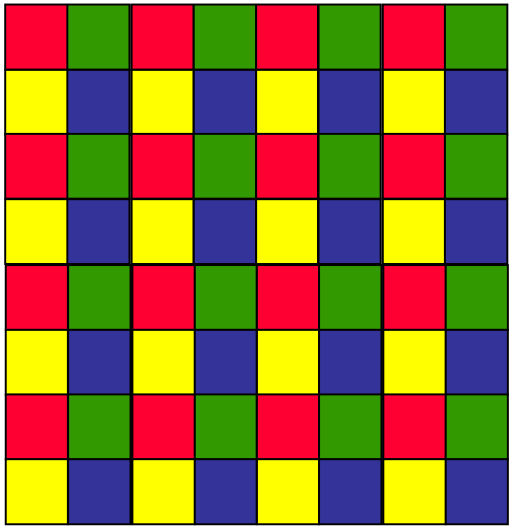
Matrix Multiplication: Tiled Layouts

```
#pragma processors C(Tx, Ty)
shared [B][B] double C[M][N];
```

- **Good:**
  - **Allows control of block placement on processor grid**
  - **Allows C to be accessed as array, not as struct**
  - **Allows communication among rows, cols of processors (scalable communication)**
- **Bad:**
  - **UPC extension: not available in vanilla UPC**
  - **Not <u>yet</u> available in IBM UPC**
- **Good:**
  - **Attempting to add this into standard**



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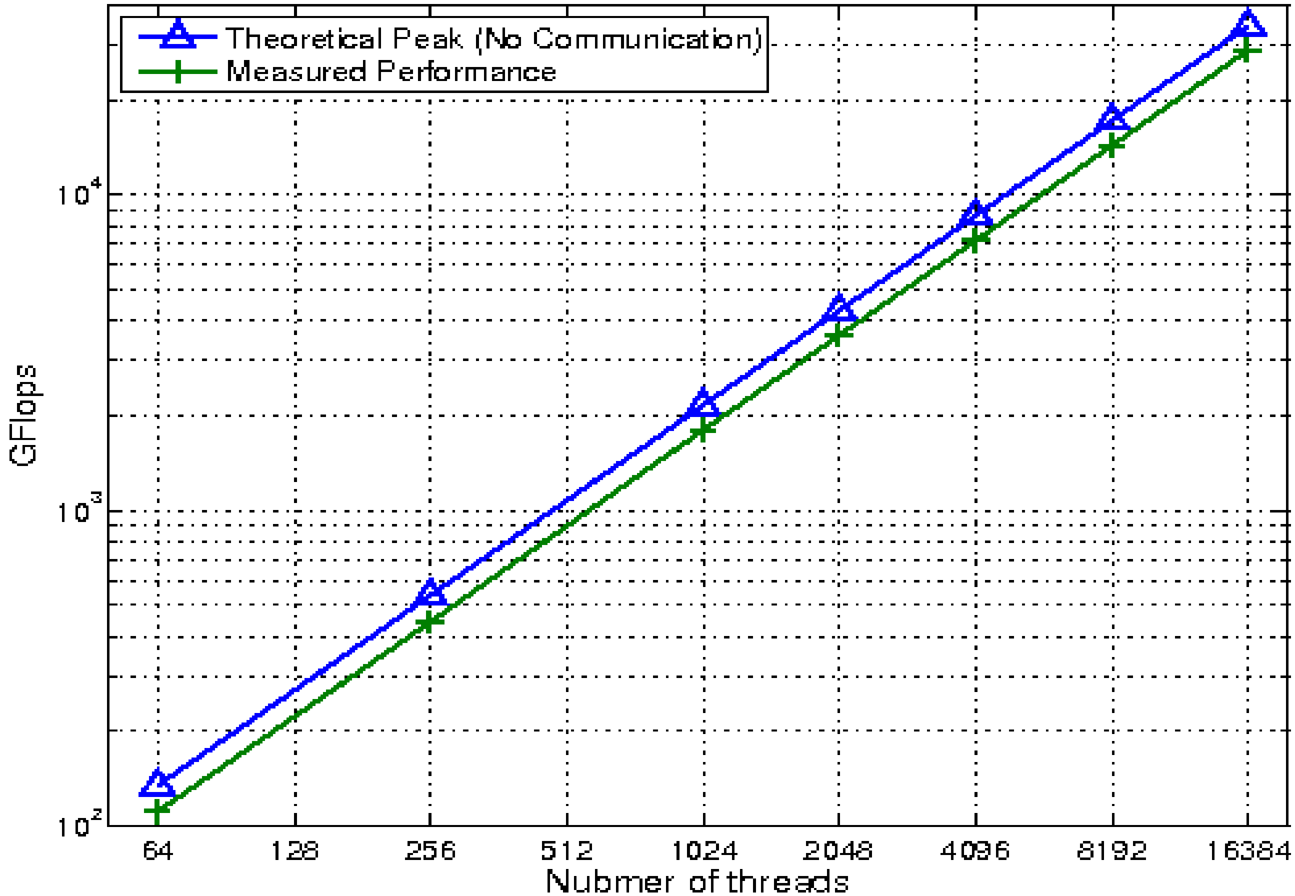
Scalability: Matrix multiplication: Tiled layout key to performance



UPC matrix multiplication on a 16-rack Blue Gene/L

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3. Compiler optimizations

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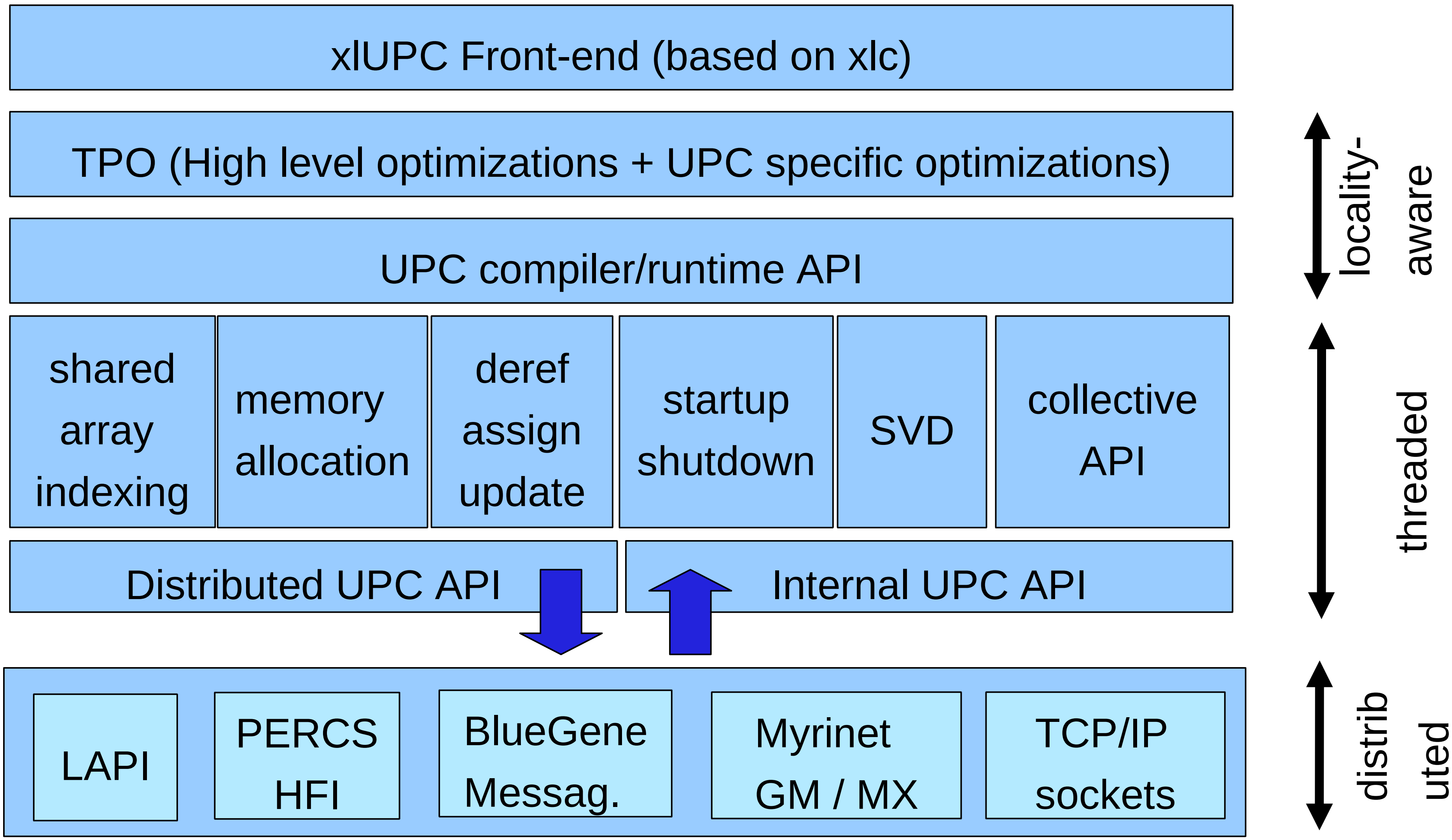
IBM

UPC hybrid runtime stack



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XL-UPC Runtime System

- **Designed for scalability**
- **Implementations available for**
  - SMP using pthreads
  - Clusters using LAPI
  - BlueGene/L using the BG/L message layer
- **Provides a unique API to the compiler for all the above implementations**
- **Provides management of and access to shared data in a scalable manner using the Shared Variable Directory**

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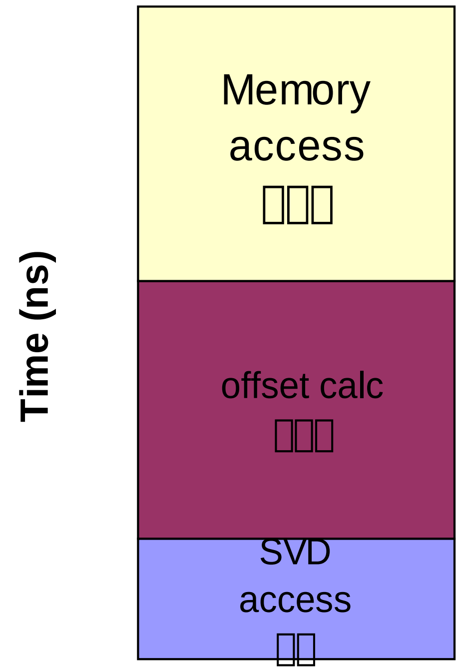
Anatomy of a shared access

```
shared [BF] int A[N],B[N],C[N];
upc_forall (i=0; i < N, ++i; &A[i])
    A[i] = B[i] + C[i];
```

Generated code (loop body):

```
__xlupc_deref_array(C_h, __t1, i, sizeof(int), …);
__xlupc_deref_array(B_h, __t2, i, sizeof(int), …);
__t3 = __t1 + __t2;
__xlupc_assign_array(A_h, __t3, i, sizeof(int), …);
```

Anatomy of a runtime call



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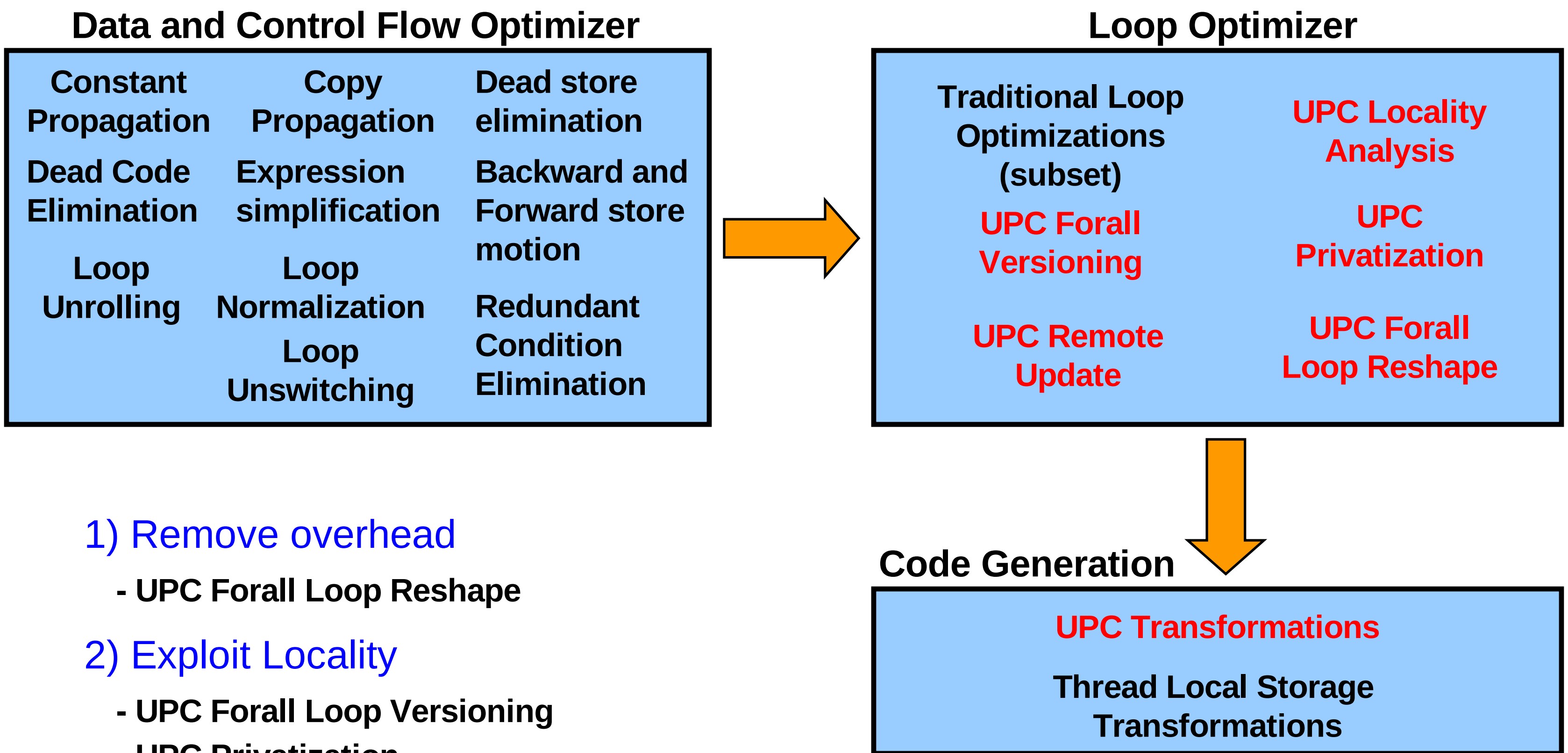
UPC Optimizer Infrastructure



1) Remove overhead
   - **UPC Forall Loop Reshape**

2) Exploit Locality
   - **UPC Forall Loop Versioning**
   - **UPC Privatization**

3) Reduce communication
   - **UPC Remote Update**

Optimizer infrastructure applicable to other PGAS languages (Co-Array Fortran)

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Optimizing Shared Object Accesses

- **When shared data is accessed, function calls to the RTS are used to set or get the shared data**
- **The calls to the RTS use the Shared Variable Directory (SVD) to locate the shared data**
  - This lookup requires several pointer dereferences and is expensive
- **When the compiler can determine the *relative* thread that owns each shared reference, it can perform several different optimizations to reduce the overhead of RTS calls**

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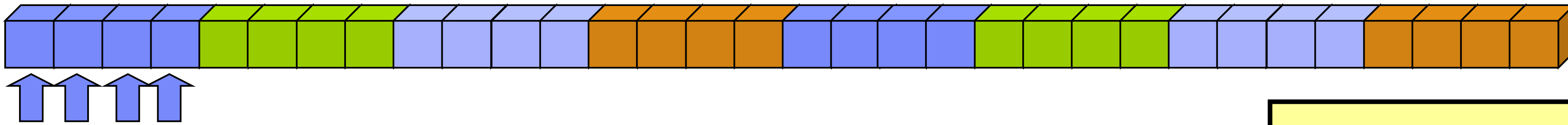
UPC Locality Analysis



4 UPC Threads

```
shared [4] int A[Z][Z], B[Z][Z], C[Z][Z];
int main ( ) {
   int k , l ;
   for (k =0; k<Z ; k++) {
         upc_forall (l=0; l < Z; l++;  &A[k][l]) {
               A[k][l] = 0 ;
               B[k][l+1] = m+2;
               C[k][l+14] = m*3;
         }
   }
}
```

All accesses of A[k][l] are local to executing thread

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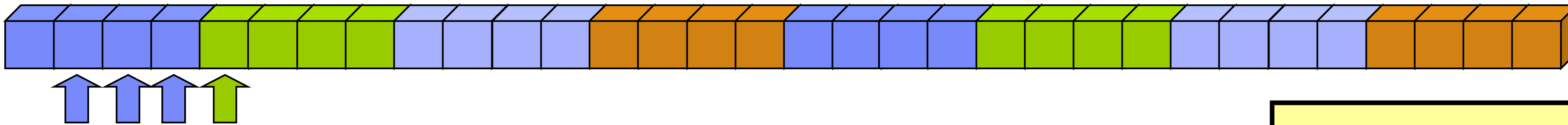
UPC Locality Analysis



```
shared [4] int A[Z][Z], B[Z][Z], C[Z][Z];
int main ( ) {
   int k , l ;
   for (k =0; k<Z ; k++) {
         upc_forall (l=0; l < Z; l++;  &A[k][l]) {
               A[k][l] = 0 ;
               B[k][l+1] = m+2;
               C[k][l+14] = m*3;
         }
   }
}
```

4 UPC Threads

Some accesses of A[k][l] are local, some are remote

The point where the locality changes is called the ***cut***

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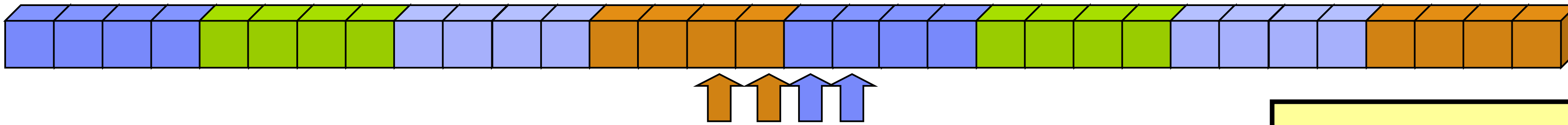
UPC Locality Analysis



4 UPC Threads

```
shared [4] int A[Z][Z], B[Z][Z], C[Z][Z];
int main ( ) {
  int k , l ;
  for (k =0; k<Z ; k++) {
      upc_forall (l=0; l < Z; l++;  &A[k][l]) {
          A[k][l] = 0 ;
          B[k][l+1] = m+2;
          C[k][l+14] = m*3;
      }
  }
}
```

Some accesses of A[k][l] are remote, some are local

Account for the block-cyclic distribution in UPC

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UPC Locality Analysis

- **Compiler refactors the original loop nest into regions where the locality is constant**
- **The regions are created using *cuts***
- **Once the loop is refactored, the compiler builds a *Shared Reference Map* that maps the shared references to the relative thread that owns them**

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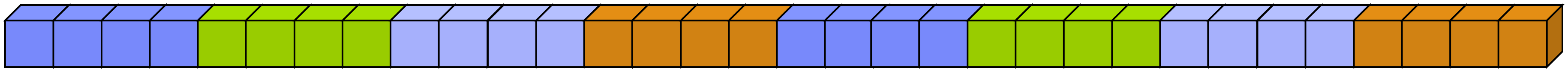
Shared Reference Map



```
shared [4] int A[N][N], B[N][N], C[N][N] ;
int main ( ) {
  int i, j ;
  for (i=0; i < N; i++) {
    upc_forall (j=0; j < N; j++; &A[i][j])  {
      if (j < 2) {
        A[i][j] = 0 ; / / A1
        B[i][j+1] = m+2; / / B1
        C[i][j+14] = m*3; / / C1
      } else if (j < 3) {
        A[i][j] = 0 ; / / A2
        B[i][j+1] = m+2; / / B2
        C[i][j+14] = m*3; / / C2
      } else {
        A[i][j] = 0 ; / / A3
        B[i][j+1] = m+2; / / B3
        C[i][j+14] = m*3; / / C3
      }
```

Region 2
Position [0,0]

Region 3
Position [0,2]

Region 4
Position [0,3]

Thread		Shared References
MYTHREAD	➡	A1 B1 A2 B2 C2 A3 C3
MYTHREAD+1	➡	B3
MYTHREAD+2	➡	
MYTHREAD+3	➡	C1

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Shared Reference Map

- **The shared reference map gives the compiler information about the relative thread that owns each shared reference**
- **The shared reference map is not concerned about machine configuration**
- **This information can then be used to perform locality optimizations**
  - **Privatization**: Local shared references can be accessed directly without requiring the RTS
  - **Coalescing**: Remote shared references owned by the same thread can be accessed in groups
  - **Scheduling**: Remote shared references that require communication

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Shared Object Access Privatization

- **All shared references that map to MYTHREAD in the SRM are *local* to the accessing thread**
- **Machine architecture can also be used to find accesses for co-located threads**
- **Compiler converts each local shared-object access into a traditional C pointer access**
  - Base address obtained from RTS ***once***
  - Offset computed based on index and shared array shape

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SOAP Example: Stream Triad

```
#define SCALAR 3.0
shared double a[N], b[N], c[N];
void StreamTriad() {
  int i;
  upc_forall(i=0;i<N;i++;&a[i])
    a[i] = b[i] + SCALAR*c[i];
}
```

```
#define SCALAR 3.0
shared double a[N], b[N], c[N];
void StreamTriad() {
  int i;
  upc_forall(i=0; i<N; i++; i) {
    __xlupc_deref_array(c_h, tmp1, i);
    __xlupc_deref_array(b_h, tmp2, i);
    tmp3 = tmp2 + 3.0*tmp1;
    __xlupc_assign_array(a_h, tmp3, i);
  }
}
```

Naïve transformation results in 3 calls to the UPC Runtime in every iteration

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SOAP Example: Stream Triad

Get base addresses outside of loop

```
#define SCALAR 3.0
shared double a[N], b[N], c[N];
void StreamTriad() {
  int i;
  upc_forall(i=0;i<N;i++;&a[i])
    a[i] = b[i] + SCALAR*c[i];
}
```

```
#define SCALAR 3.0
shared double a[N], b[N], c[N];
void StreamTriad() {
  int i;
  aBase = __xlupc_base_address(a_h);
  bBase = __xlupc_base_address(b_h);
  cBase = __xlupc_base_address(c_h);
  upc_forall(i=0;i<N;i++;&a[i]) {
    aOffset = ComputeOffset(i);
    bOffset = ComputeOffset(i);
    cOffset = ComputeOffset(i);
    *(aBase+aOffset) = *(bBase+bOffset) +
                  SCALAR*( *(cBase + cOffset));
  }
}
```

Traditional “C” pointer access

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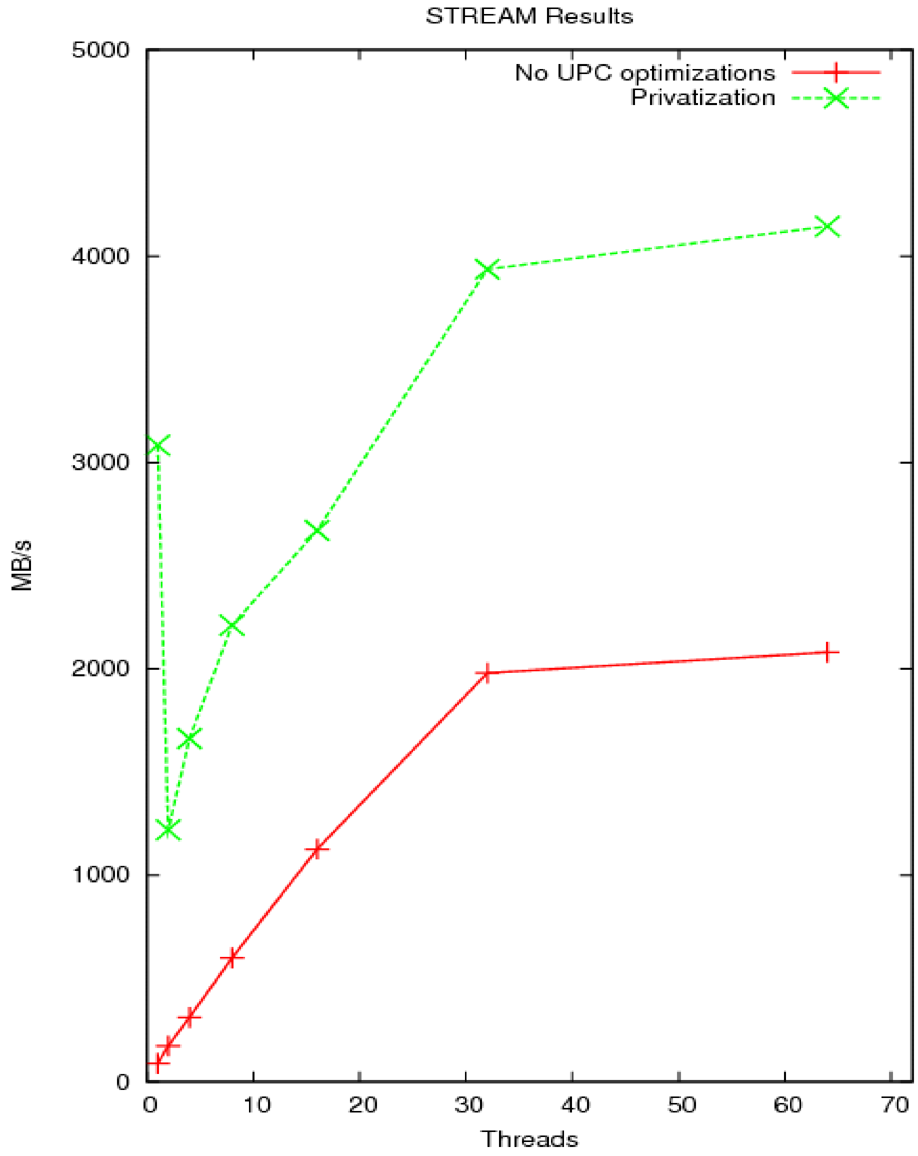
SOAP Example: Stream Triad



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Shared Object Access Coalescing

- **All shared references that map to the same remote thread can be *coalesced* together**
- **This reduces the number of messages, thereby reducing the execution time**
- **Requires support from the UPC Runtime**
- **Current runtime interface requires coalesced shared references to have**
  - The same base symbol
  - The same owner
  - The same type (read or write)

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SOAC Example: Sobel Edge Detection

```
shared [COLUMNS] BYTE orig[ROWS][COLUMNS];
shared [COLUMNS] BYTE edge[ROWS][COLUMNS];
int Sobel() {
  int i, j, gx, gy;
  double gradient;
  for (i=1; i < ROWS-1; i++) {
    upc_forall (j=1; j < COLUMNS-1; j++; &orig[i][j]) {
      gx =   (int) orig[i-1][j+1] - orig[i-1][j-1];
      gx += ((int) orig[i][j+1]   - orig[i][j-1]) * 2;
      gx +=  (int) orig[i+1][j+1] - orig[i+1][j-1];
      gy =   (int) orig[i+1][j-1] - orig[i-1][j-1];
      gy += ((int) orig[i+1][j]   - orig[i-1][j]) * 2;
      gy +=  (int) orig[i+1][j+1] - orig[i-1][j+1];
      gradient = sqrt((gx*gx) + (gy*gy));
      if (gradient > 255) gradient = 255;
      edge[i][j] = (BYTE) gradient;
    } } }
```

Shared arrays blocked by row

Loop body contains 12 shared array access

3 Local Accesses

9 Remote Accesses

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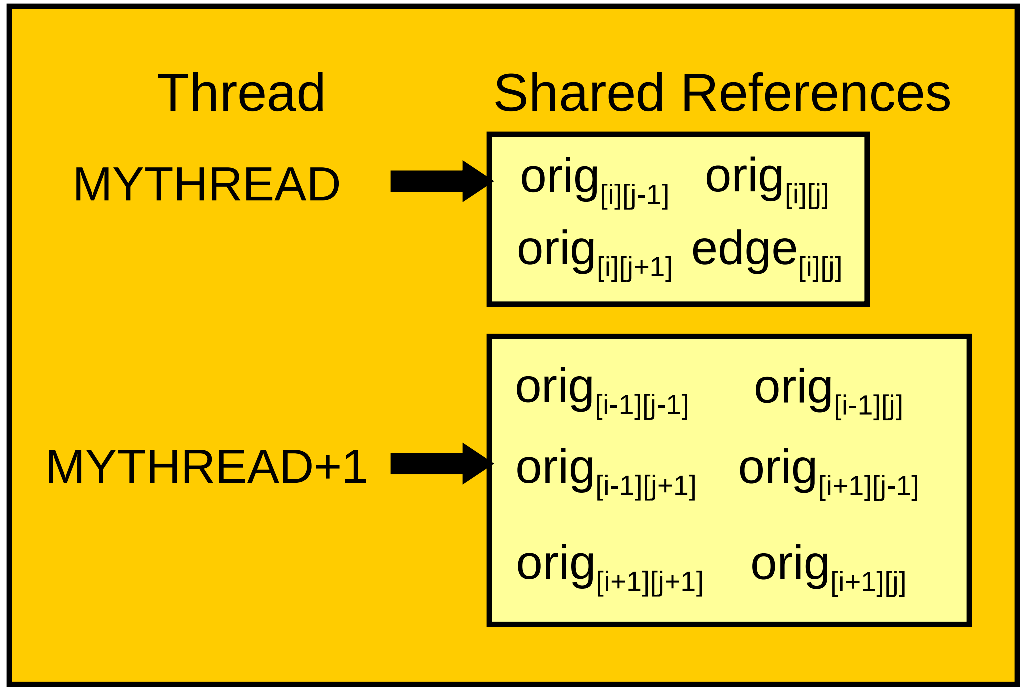
SOAC Example: Sobel Edge Detection

2 UPC Threads

```
shared [COLUMNS] BYTE orig[ROWS][COLUMNS];
shared [COLUMNS] BYTE edge[ROWS][COLUMNS];
int Sobel() {
  int i, j, gx, gy;
  double gradient;
  for (i=1; i < ROWS-1; i++) {
    upc_forall (j=1; j < COLUMNS-1; j++; &orig[i][j]) {
      gx =   (int) orig[i-1][j+1] - orig[i-1][j-1];
      gx += ((int) orig[i][j+1]   - orig[i][j-1]) * 2;
      gx +=  (int) orig[i+1][j+1] - orig[i+1][j-1];
      gy =   (int) orig[i+1][j-1] - orig[i-1][j-1];
      gy += ((int) orig[i+1][j]   - orig[i-1][j]) * 2;
      gy +=  (int) orig[i+1][j+1] - orig[i-1][j+1];
      gradient = sqrt((gx*gx) + (gy*gy));
      if (gradient > 255) gradient = 255;
      edge[i][j] = (BYTE) gradient;
  } } }
```



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SOAC Example: Sobel Edge Detection

2 UPC Threads

```
shared [COLUMNS] BYTE orig[ROWS][COLUMNS];
shared [COLUMNS] BYTE edge[ROWS][COLUMNS];
int Sobel() {
  int i, j, gx, gy;
  double gradient;
  for (i=1; i < ROWS-1; i++) {
    upc_forall (j=1; j < COLUMNS-1; j++; &orig[i][j]) {
      CoalescedRemoteAccess(tmp1, orig, ((i-1)*COLUMNS)+j-1, 3, 1);
      CoalescedRemoteAccess(tmp2, orig, ((i+1)*COLUMNS)+j-1,3, 1);
      gx = (int) tmp1[2] - tmp1[0];   gx += ((int) orig[i][j+1]   - orig[i][j-1]) * 2;
      gx += (int) tmp2[2] - tmp2[0];  gy = (int) tmp2[0] - tmp1[0];
      gy += ((int) tmp2[1] - tmp1[1] * 2;  gy += (int) tmp2[2] - tmp1[2];
      gradient = sqrt((gx*gx) + (gy*gy));
      if (gradient > 255) gradient = 255;
      edge[i][j] = (BYTE) gradient;
  } } }
```

Two calls to the UPC runtime to retrieve remote shared data

Temporary buffers created and managed by compiler

All accesses are now local

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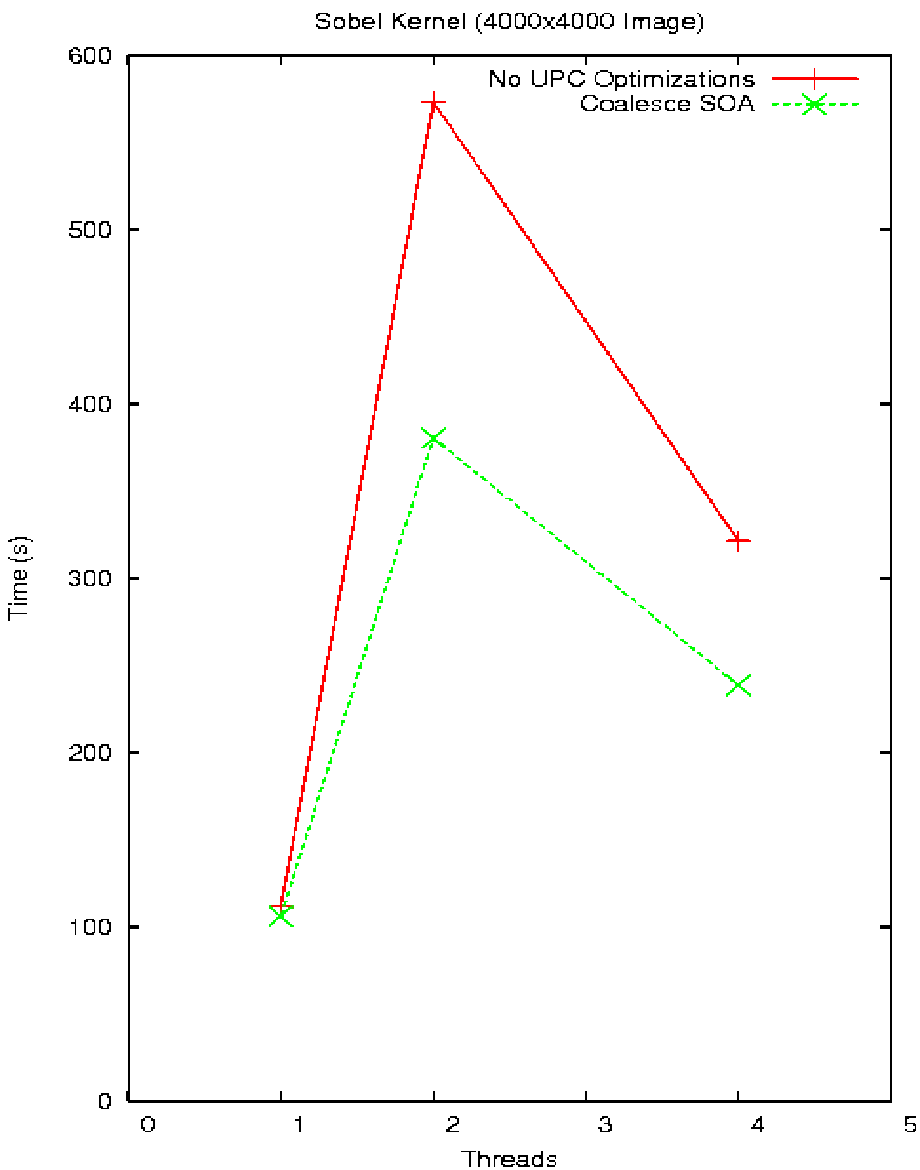
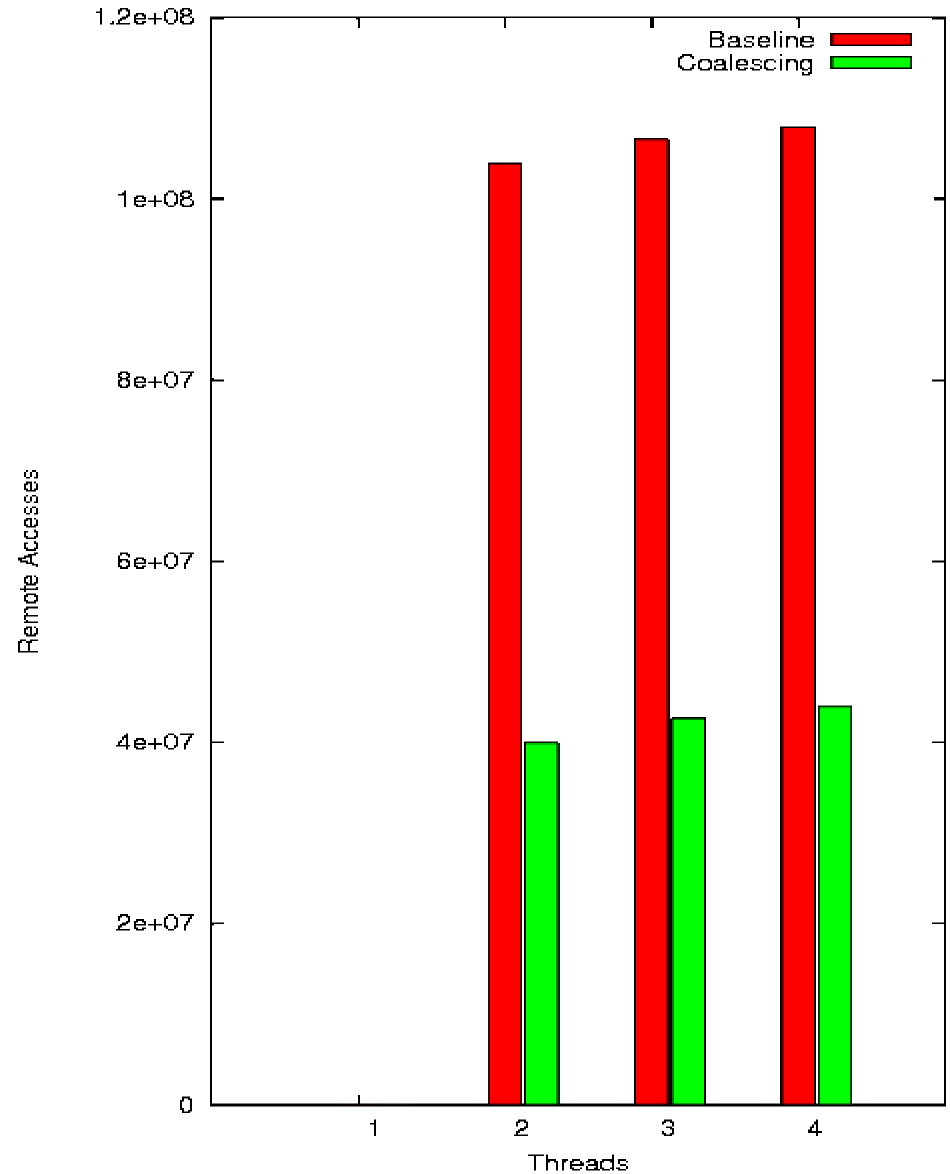
SOAC Example: Sobel Edge Detection





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Shared-Object Access Scheduling

- In UPC when a thread executes a runtime call it will wait until the call has been serviced.

```
__xlupc_deref_array(C_h, __t1, i, sizeof(int), …);     ← wait
__xlupc_deref_array(B_h, __t2, i, sizeof(int), …);     ← wait again
__t3 = __t1 + __t2;
__xlupc_assign_array(A_h, __t3, i, sizeof(int), …);  ← wait again !
```

- Runtime calls are blocking, but we could use non-blocking pairs of calls (notify/wait)

```
req = __xlupc_deref_array_elt_post(…);
__xlupc_wait(req);
```

- Notify call initiates the RT access of the shared object
- Wait call should be placed before the first use

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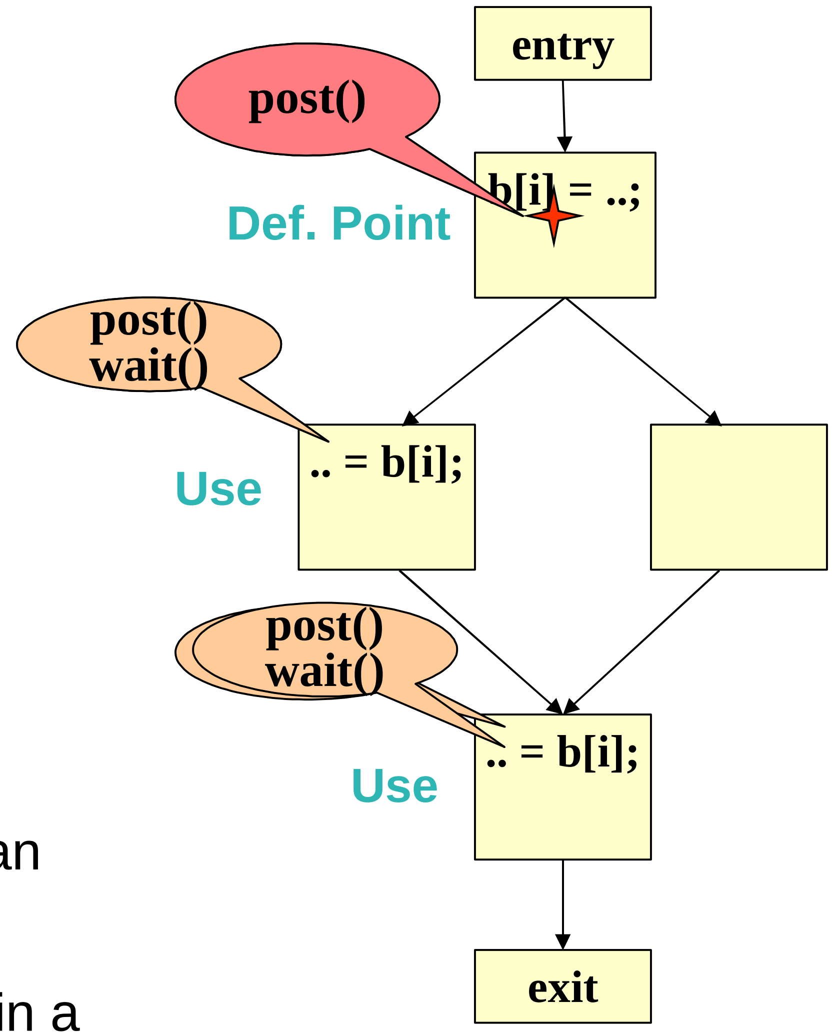
Scheduling of post/wait calls

Work in Progress

GOAL: place the post call as early as possible

- Collect shared loads used in a loop
- Split the blocking calls in a post/wait pair
- Find the definition point of the shared ref.
- *Move the post call to the earliest program point with the following properties:*
  - *shared ref. is executed on all paths from P to exit*
  - *P is dominated by its shared ref. definition*
- Redundant post calls for the same object can be eliminated
- Consecutive post calls may be aggregated in a bulk transfer



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SOAS Example: Synthetic Benchmark

```
shared double MySharedData[SDS], RemoteData[SDS];
double MyPrivateData[PDS];
void Compute() {
  int i, j, k;
  double sum=0.0;
  upc_forall (i=0; i < SHARED_DATA_SIZE; i++; &MySharedData[i]) {
    for (j=0; j < PRIVATE_DATA_SIZE; j++) {
      sum += MyPrivateData[j];
    }
    MySharedData[i] = sum * RemoteData[(i+1)%(SDS)];
  }
}
```

Local Computation

Remote access

Execution waits until access is finished

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SOAS Example: Synthetic Benchmark

```
shared double MySharedData[SDS], RemoteData[SDS];
double MyPrivateData[PDS];
void Compute() {
 int i, j, k;
 double sum=0.0;
 wait = deref_array_post(RemoteData_h, MYTHREAD);
 upc_forall (i=0; i < SHARED_DATA_SIZE; i++; &MySharedData[i]) {
  for (j=0; j < PRIVATE_DATA_SIZE; j++) {
   sum += MyPrivateData[j];
  }
  offset=THREADS;
  deref_array_wait(wait);
  tmp2 = tmp;
  if (i+THREADS) < SHARED_DATA_SIZE)
   wait = deref_array_post(RemoteData_h,&tmp,(i+THREADS+1)%SHARED_DATA_SIZE);
  MySharedData[i] = sum * tmp2;
 } }
```

Prefetch first iteration

Local Computation

Wait for data from previous iteration

Prefetch next iteration

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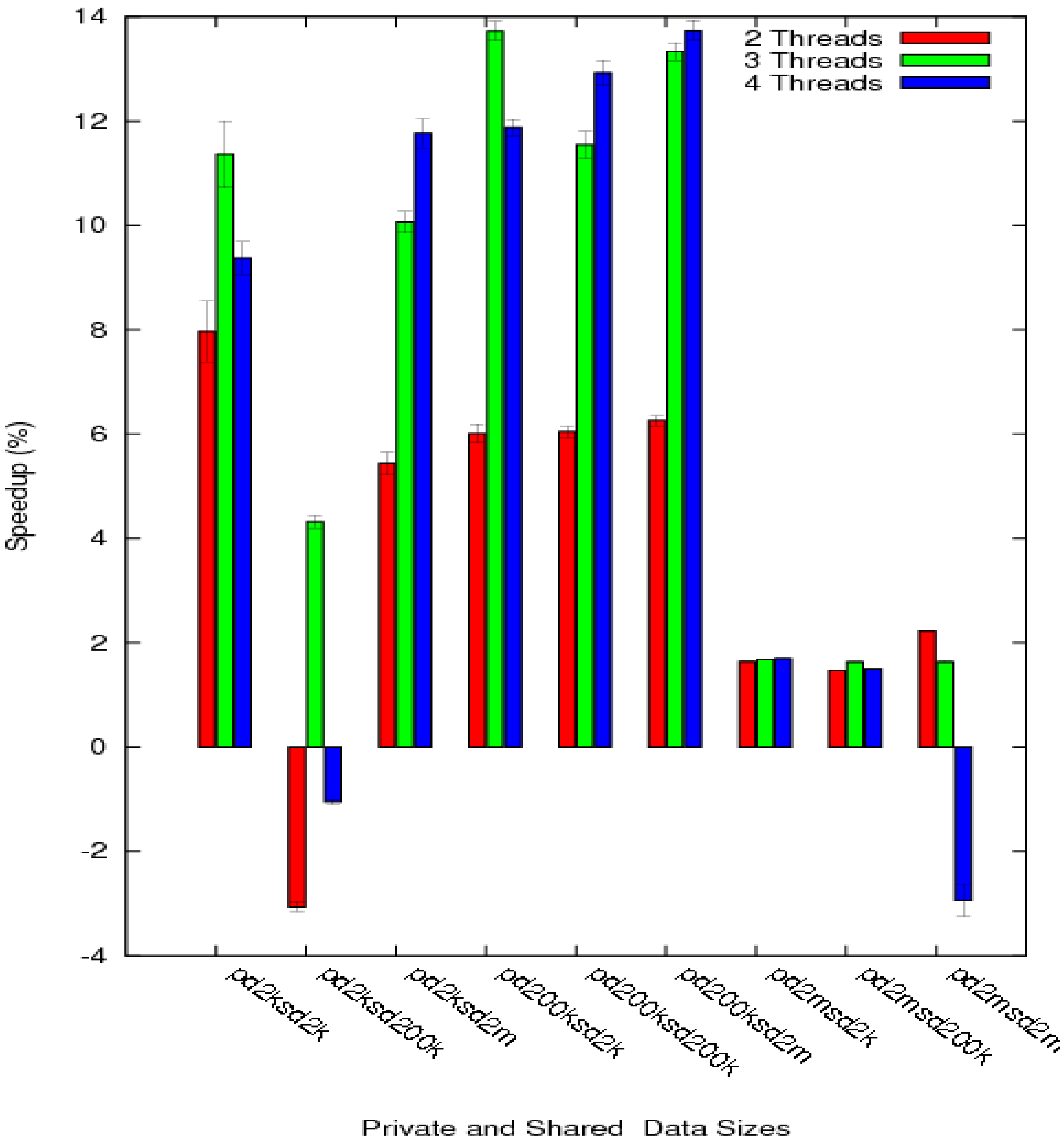
SOAC Example: Synthetic Benchmark



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The upc_forall work-sharing construct

- Similar to C for loop, 4th field indicates the affinity
  - *Integer affinity:* Thread with ID == affinity value executes the iteration
  - *Pointer-to-shared affinity:* thread that "owns" shared element executes the iteration
- Affinity test exec. on *each* iteration by all threads

Affinity Test

```
shared int A[N],B[N],C[N];
upc_forall(i=0; i < N; i++; i){
    A[i] = B[i] + C[i];
}
```

Branch

```
shared int A[N],B[N],C[N];
for (i=0; i < N; i++)  {
  if ((i % THREADS)== MYTHREAD)
     A[i] = B[i] + C[i];
}
```

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The upc_forall work-sharing construct

- Similar to C for loop, 4th field indicates the affinity
  - *Integer affinity:* Thread with ID == affinity value executes the iteration
  - *Pointer-to-shared affinity:* thread that "owns" shared element executes the iteration
- Affinity test exec. on *each* iteration by all threads

Affinity Test

```
shared [BF] int A[N],B[N],C[N];
upc_forall(i=0; i < N; i++; &A[i]) {
    A[i] = B[i] + C[i];
}
```

Branch

```
shared [BF] int A[N],B[N],C[N];
for (i=0; i < N; i++) {
  if (upc_threadof(A[i]) == MYTHREAD)
     A[i] = B[i] + C[i];
}
```

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Parallel Loop Reshaping (Integer Affinity)

- **Iteration space is partitioned**
- **Each thread starts executing at iteration *MYTHREAD***
- **Each thread executes every *THREADs* elements**

```
shared int A[N],B[N],C[N];
upc_forall(i=0; i < N; i++; i){
    A[i] = B[i] + C[i];
}
```

```
shared int A[N], B[N], C[N];
for (i=MYTHREAD; i < N; i+= THREADS) {
    A[i] = B[i]+C[i];
}
```

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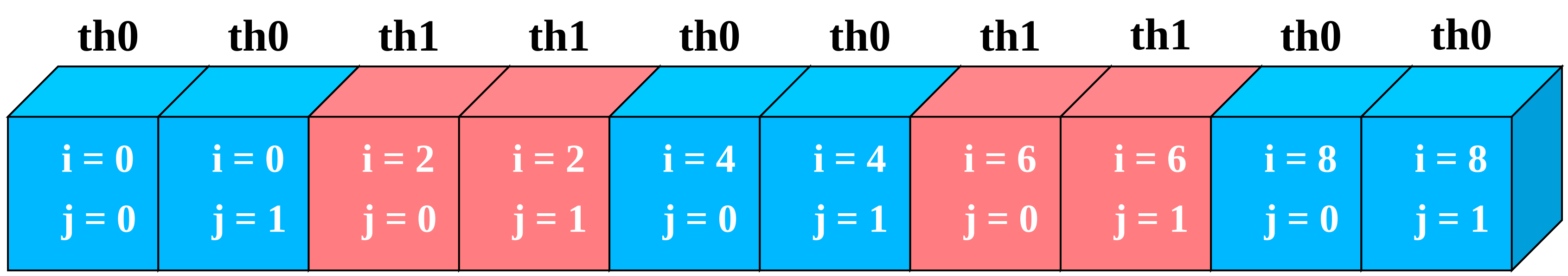
Parallel Loop Reshaping (Pointer-to-shared affinity)

- **Strip-mining optimization**
- **Create a 2-level loop nest**
  - Outer loop iterates over blocks owned by MYTHREAD
  - Inner loop iterates through each block element




```
shared [2] int A[N], B[N], C[N];
for (i=MYTHREAD * 2; i < N; i+= THREADS*2) {
    for (j=i; j < i+BF; j++)
        A[j] = B[i]+C[i];
}
```

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Parallel Loop Reshaping (Pointer-to-shared affinity)

- **Consider an upper-triangle parallel loop nest that uses pointer-to-shared affinity**
- **Shared array elements are initialized to -1**
- **Shared array elements are assigned the thread ID of their owner**

```
shared [ 2 ] double A[ 6 ] [ 6 ] ;

void UpperTriangularLoop ( ) {
  int  i , j ;

  for (i =0; i < 6 ; i ++)

    upc_forall (j=i; j<6; j++; &A[i][j])

      A[ i ] [ j ] = ( double ) MYTHREAD;
}
```

0	0	1	1	0	0
-1	1	0	0	1	1
-1	-1	1	1	0	0
-1	-1	-1	0	1	1
-1	-1	-1	-1	0	0
-1	-1	-1	-1	-1	1

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Parallel Loop Reshaping (Pointer-to-shared affinity)

- **For every iteration of the i loop, the upc_forall loop has a different iteration vector**
- **Thus, the compiler must compute the bounds of the new loop nest at runtime**

```
shared [ 2 ] double A[ 6 ] [ 6 ] ;

void UpperTriangularLoop ( ) {
  int  i , j ;

  for (i =0; i < 6 ; i ++)

      upc_forall (j=i; j<6; j++; &A[i][j])

           A[i] [j] = (double) MYTHREAD;
}
```

0	0	1	1	0	0
-1	1	0	0	1	1
-1	-1	1	1	0	0
-1	-1	-1	0	1	1
-1	-1	-1	-1	0	0
-1	-1	-1	-1	-1	1

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Parallel Loop Reshaping (Pointer-to-shared affinity)

- **The compute bound functions determine the iteraton vector for the new loop nests at runtime**
  - For each iteration of the i loop, compute the position of the next block owned by thread MYTHREAD

```
shared [ 2 ] double A[ 6 ] [ 6 ] ;

void UpperTriangularLoop() {
    int i, j;
    outerLB  = ComputeOuterLowerBound();
    outerUB = ComputeOuterUpperBound();
    innerLB  = ComputeInnerLowerBound();
    innerUB = ComputeInnerUpperBound();

    for (i=0; i<6 ;i++)
        for  (k=outerLB; k<outerUB; k++)
            for (l=innerLB; l < innerUB; l++)
                A[i] [k+l] = (double) MYTHREAD;
}
```

0	0	1	1	0	0
-1	1	0	0	1	1
-1	-1	1	1	0	0
-1	-1	-1	0	1	1
-1	-1	-1	-1	0	0
-1	-1	-1	-1	-1	1

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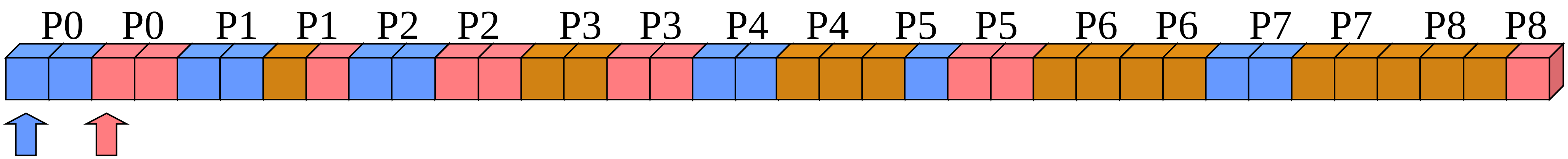
Parallel Loop Reshaping (Pointer-to-shared affinity)



	Thread 0	Thread 1
i=0	P=0, C=0	P=0, C=0
i=1		
i=2		
i=3		
i=4		
i=5		

0	0	1	1	0	0
-1	1	0	0	1	1
-1	-1	1	1	0	0
-1	-1	-1	0	1	1
-1	-1	-1	-1	0	0
-1	-1	-1	-1	-1	1

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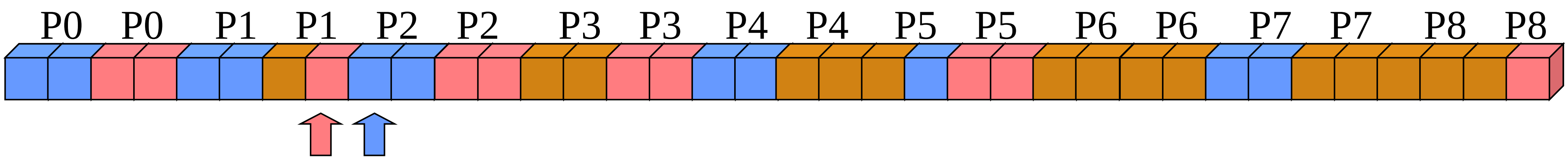
Parallel Loop Reshaping (Pointer-to-shared affinity)



	Thread 0	Thread 1
i=0	P=0, C=0	P=0, C=0
i=1	P=2, C=0	P=1, C=1
i=2		
i=3		
i=4		
i=5		

0	0	1	1	0	0
-1	1	0	0	1	1
-1	-1	1	1	0	0
-1	-1	-1	0	1	1
-1	-1	-1	-1	0	0
-1	-1	-1	-1	-1	1

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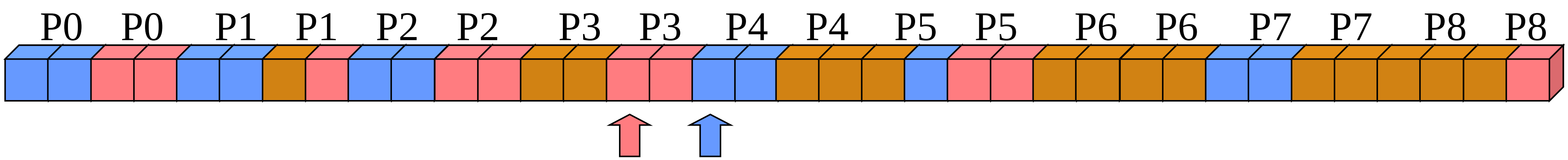
Parallel Loop Reshaping (Pointer-to-shared affinity)



	Thread 0	Thread 1
i=0	P=0, C=0	P=0, C=0
i=1	P=2, C=0	P=1, C=1
i=2	P=4, C=0	P=3, C=0
i=3		
i=4		
i=5		

0	0	1	1	0	0
-1	1	0	0	1	1
-1	-1	1	1	0	0
-1	-1	-1	0	1	1
-1	-1	-1	-1	0	0
-1	-1	-1	-1	-1	1

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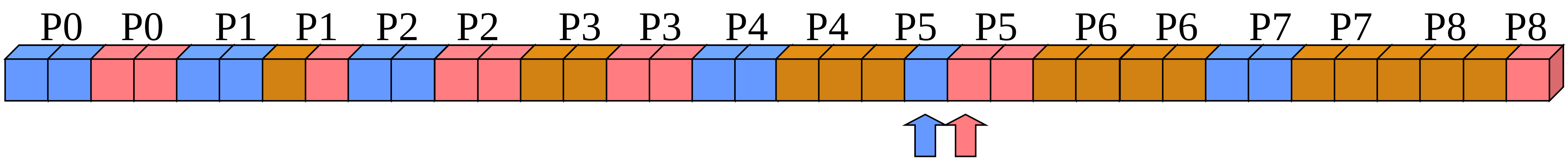
Parallel Loop Reshaping (Pointer-to-shared affinity)



	Thread 0	Thread 1
i=0	P=0, C=0	P=0, C=0
i=1	P=2, C=0	P=1, C=1
i=2	P=4, C=0	P=3, C=0
i=3	P=5, C=1	P=5, C=0
i=4		
i=5		

0	0	1	1	0	0
-1	1	0	0	1	1
-1	-1	1	1	0	0
-1	-1	-1	0	1	1
-1	-1	-1	-1	0	0
-1	-1	-1	-1	-1	1

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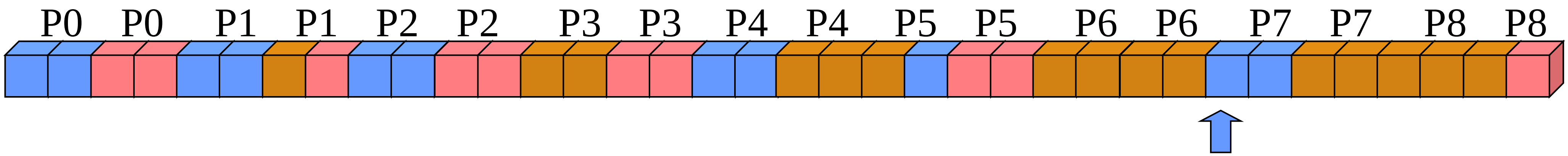
Parallel Loop Reshaping (Pointer-to-shared affinity)



	Thread 0	Thread 1
i=0	P=0, C=0	P=0, C=0
i=1	P=2, C=0	P=1, C=1
i=2	P=4, C=0	P=3, C=0
i=3	P=5, C=1	P=5, C=0
i=4	P=7, C=0	P=0, C=0
i=5		

0	0	1	1	0	0
-1	1	0	0	1	1
-1	-1	1	1	0	0
-1	-1	-1	0	1	1
-1	-1	-1	-1	0	0
-1	-1	-1	-1	-1	1

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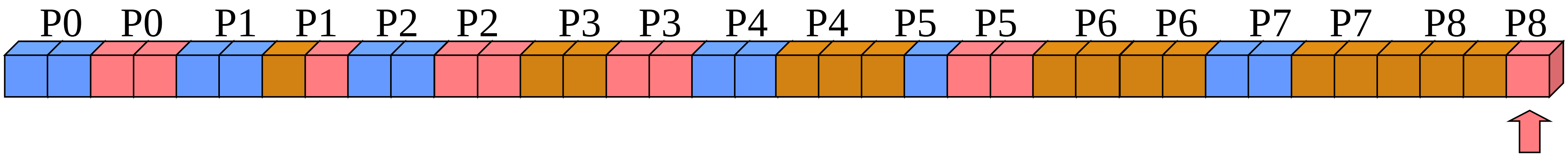
Parallel Loop Reshaping (Pointer-to-shared affinity)



	Thread 0	Thread 1
i=0	P=0, C=0	P=0, C=0
i=1	P=2, C=0	P=1, C=1
i=2	P=4, C=0	P=3, C=0
i=3	P=5, C=1	P=5, C=0
i=4	P=7, C=0	P=0, C=0
i=5	P=0, C=0	P=8, C=1

0	0	1	1	0	0
-1	1	0	0	1	1
-1	-1	1	1	0	0
-1	-1	-1	0	1	1
-1	-1	-1	-1	0	0
-1	-1	-1	-1	-1	1

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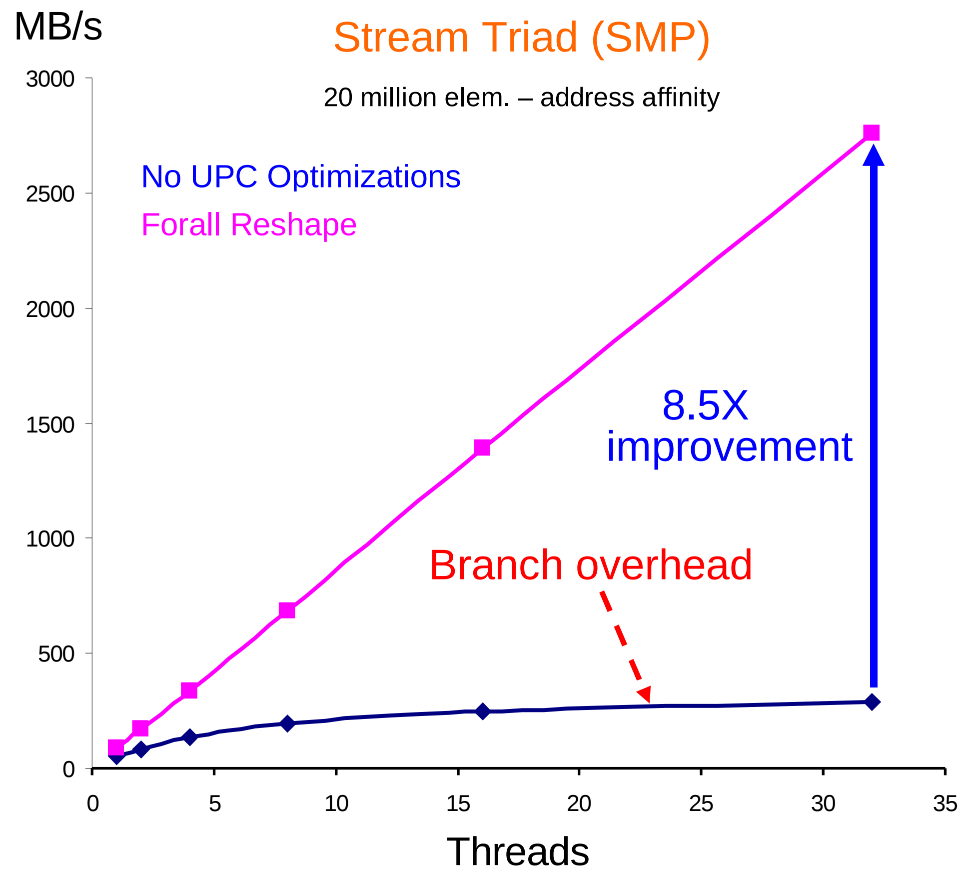
Parallel Loop Reshaping

Removed overhead

Objective: **remove branch overhead in naïve upc_forall translation**



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```
shared [BF] int A[N],B[N],C[N];
upc_forall (i=0; i < N; i++; &A[i])
    A[i] = B[i] + k*C[i];
```

naïve translation

```
shared [BF] int A[N],B[N],C[N];
for (i=0; i < N; i++)
  if (upc_threadof(A[i]) == MYTHREAD)
    A[i] = B[i] + k*C[i];
```

branch

optimized loop

```
shared [BF] int A[N], B[N], C[N];
for (i=MYTHREAD*BF; i<N; i+=THREADS*BF)
    for (j=i; j < i+BF; j++)
        A[j] = B[j] + k*C[j];
```

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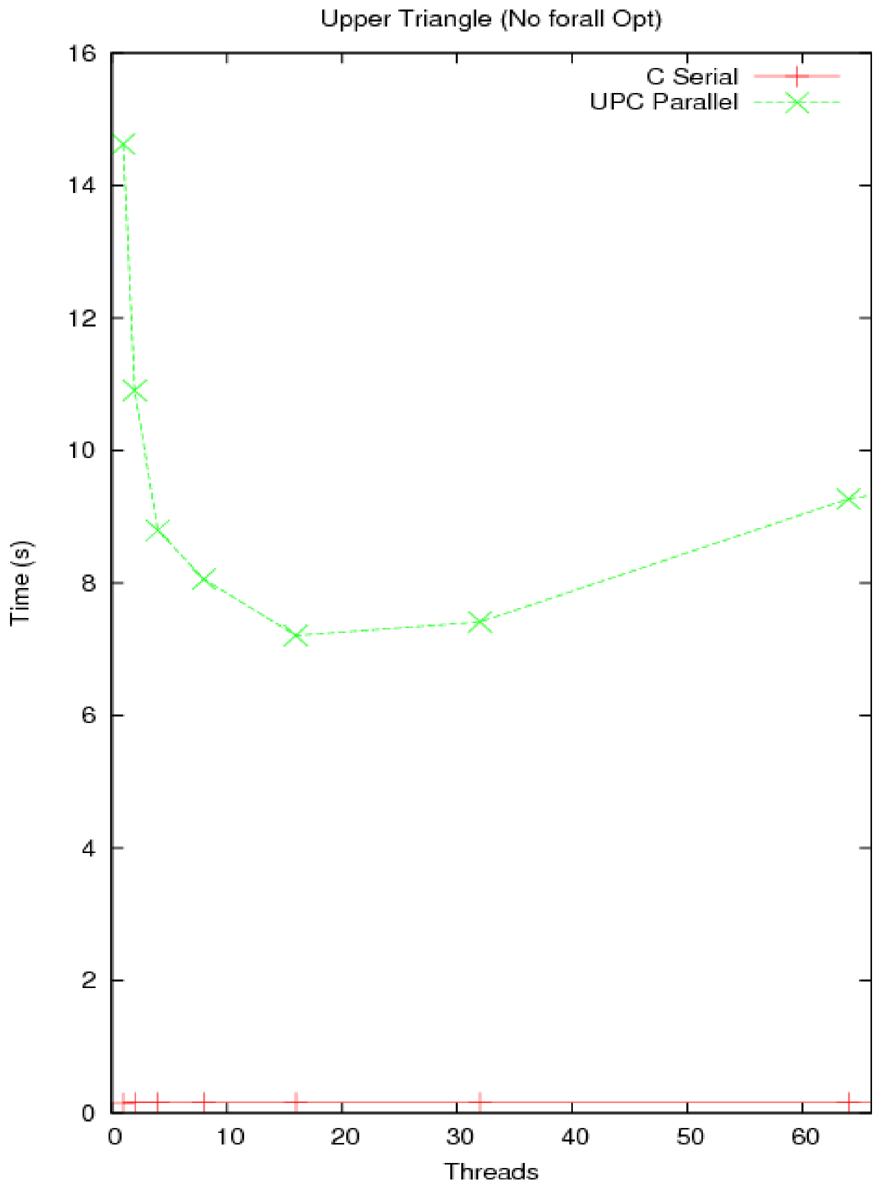
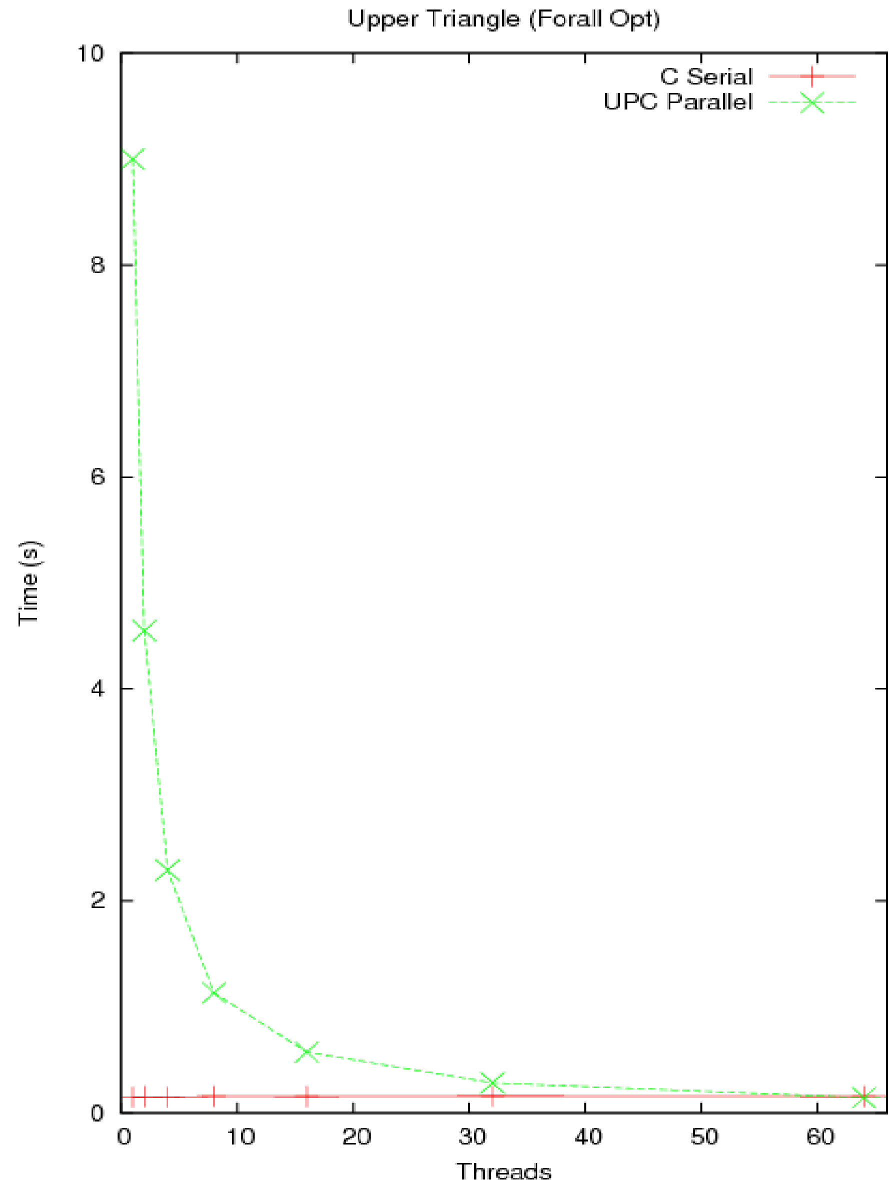
Parallel Loop Reshaping





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Locality Analysis for shared pointers

```
shared [BF] int B[N], C[N];
int main() {
  upc_forall(int i=0; i<N; ++i; &B[i])
      B[i] = C[i] = i*MYTHREAD;
  upc_barrier;

  shared [BF] int *pA = (shared [BF] int*)
    upc_all_alloc(N/BF*sizeof(int), BF);

  func1(pA, &C[0]);
  func2(pA, &C[0]);
}
void func1(shared int *pA, shared int *pC) {
  upc_forall (i=0; i < N; i++; &B[i])
      pA[i] = B[i]  op  k*pC[i];
}
void func2(shared int *pA, shared int *pC) {
  upc_forall (i=0; i < N; i++; &B[i])
      pA[i+BF] = B[i]  op  k*pC[i+BF];
}
```

Initialize arrays B and C

Allocate an array on N integers and blocking factor equal to BF

Pass the address of the 2 arrays

What do we know about the locality of the 2 pointers to shared in the called function ?

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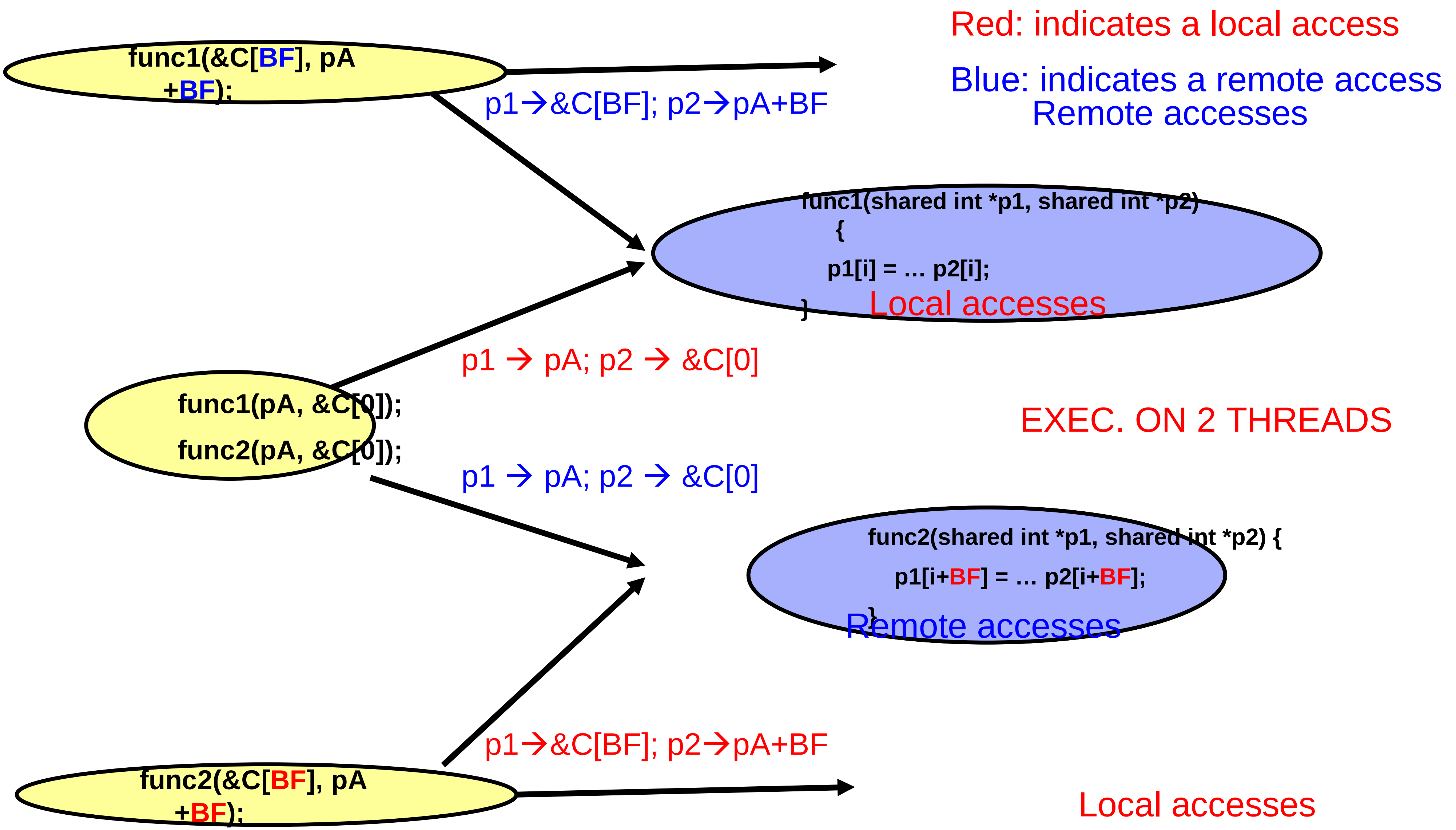
Possible approach: function cloning



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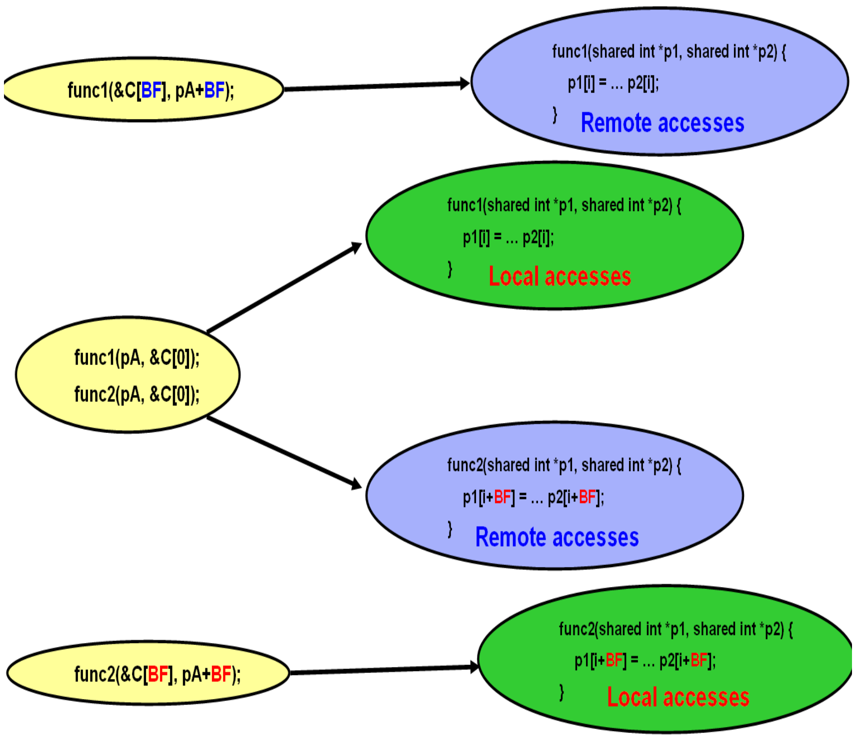
Possible approach: function cloning



Analysis:

- Create call graph
- Label call edges with arguments
- Merge call edges with same source and target and same actual arguments
- For each edge into a node identify privatization opportunities. If opportunities exist duplicate calee nodes and adjust edges
- Label privatizable shared references in a node

Drawbacks:

- This approach is an all program inter-procedural analysis
- Potentially large code growth: entire function code is cloned

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A second approach: loop versioning

Objective: privatize pointer-to-shared dereferences

```
shared [BF] int A[N], B[N], C[N];
void foo(shared int *pA, shared int *pC) {
  upc_forall (i=0; i < N; i++; &B[i])
      pA[i] = B[i]  op  k*pC[i];
}
```

- B[i] is a shared local access
- the target of pA, pC is not known until the program executes
- How can we determine the affinity of pA, pB ?

Analysis:

– gather candidate pointer dereferences in the upc_forall loops in the program
– candidate pointers must be loop invariant and have the same blocking factor as the affinity expression
– generate a copy of the original loop (version the loop)
– versioning condition uses UPC runtime calls in order to determine at runtime that pointers point to a shared array with appropriate layout

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UPC Forall Loop Versioning

```
void foo(shared int *pA, shared int *pC) {
   ver_pA = (upc_threadof(pA)==0) ? (upc_phaseof(pA)==0) ? 1 : 0;
   ver_pC = (upc_threadof(pC)==0) ? (upc_phaseof(pC)==0) ? 1 : 0;
   if (ver_pA && ver_pC) {
     upc_forall (i=0; i < N; i++; &B[i])
       pA[i] = B[i]  op  k*pC[i];
   } else if (ver_pA) {
     upc_forall (i=0; i < N; i++; &B[i])
       pA[i] = B[i]  op  k*pC[i];
   } else if (ver_pC) {
     upc_forall (i=0; i < N; i++; &B[i])
       pA[i] = B[i]  op  k*pC[i];
   } else {
     upc_forall (i=0; i < N; i++; &B[i])
       pA[i] = B[i]  op  k*pC[i];
   }
}
```

All 3 references can be privatized

2 references can be privatized

2 references can be privatized

Only reference B[j] can be privatized

Create versioning conditions

Version 1 of the loop: both pointers dereference access local memory

Version 2 of the loop: pA[i] access local memory

Version 3 of the loop: pC[i] access local memory

Original Loop

Advantages:

- Intra-procedural loop based analysis. Does not require all program knowledge.
- Code growth limited to upc_forall loops.
- Can limit code growth by using an all or nothing strategy: only one conditional branch is generated.
- Conditional branches can be folded by propagating information from the caller to the callee (inter-procedurally).

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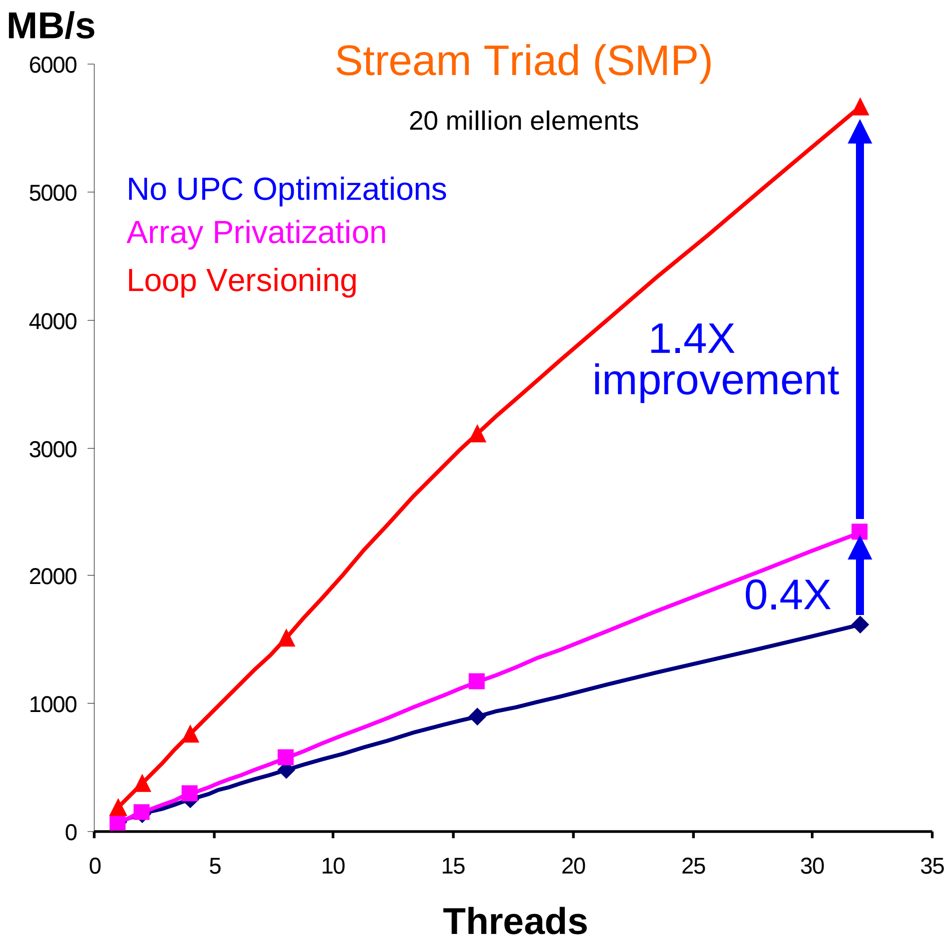
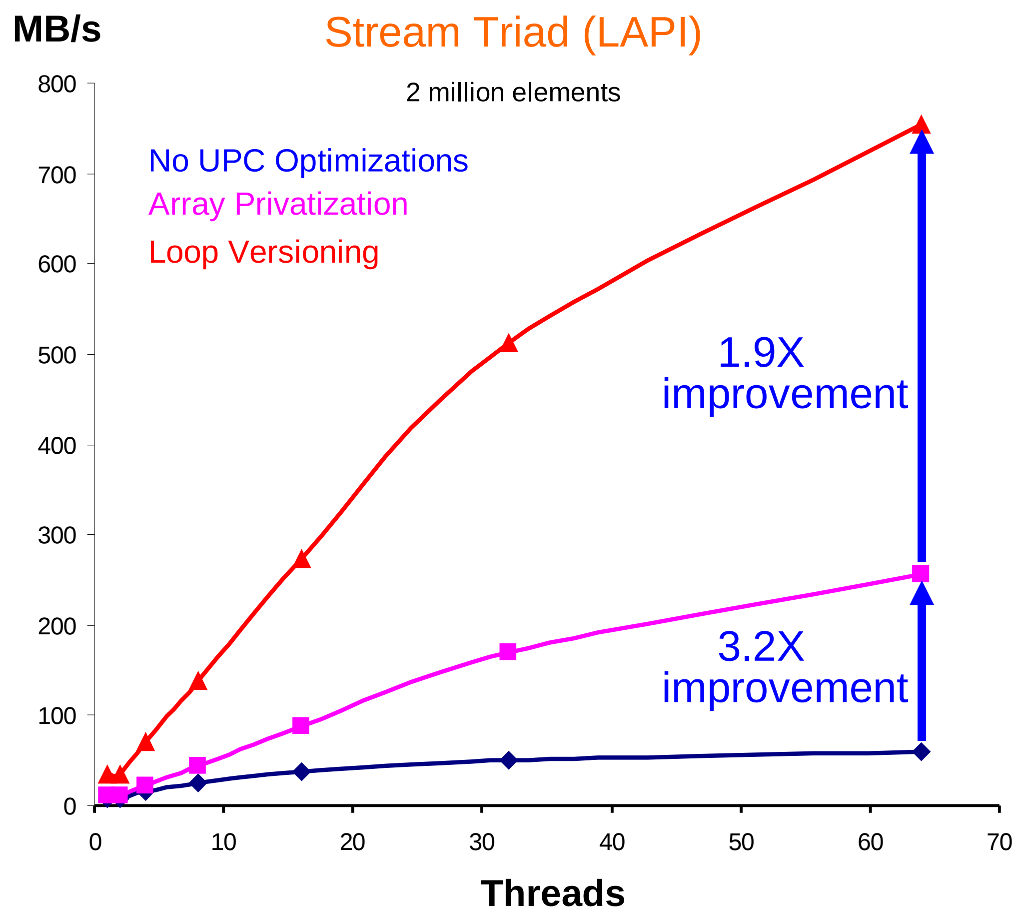
UPC Forall Loop Versioning

Exploited Locality





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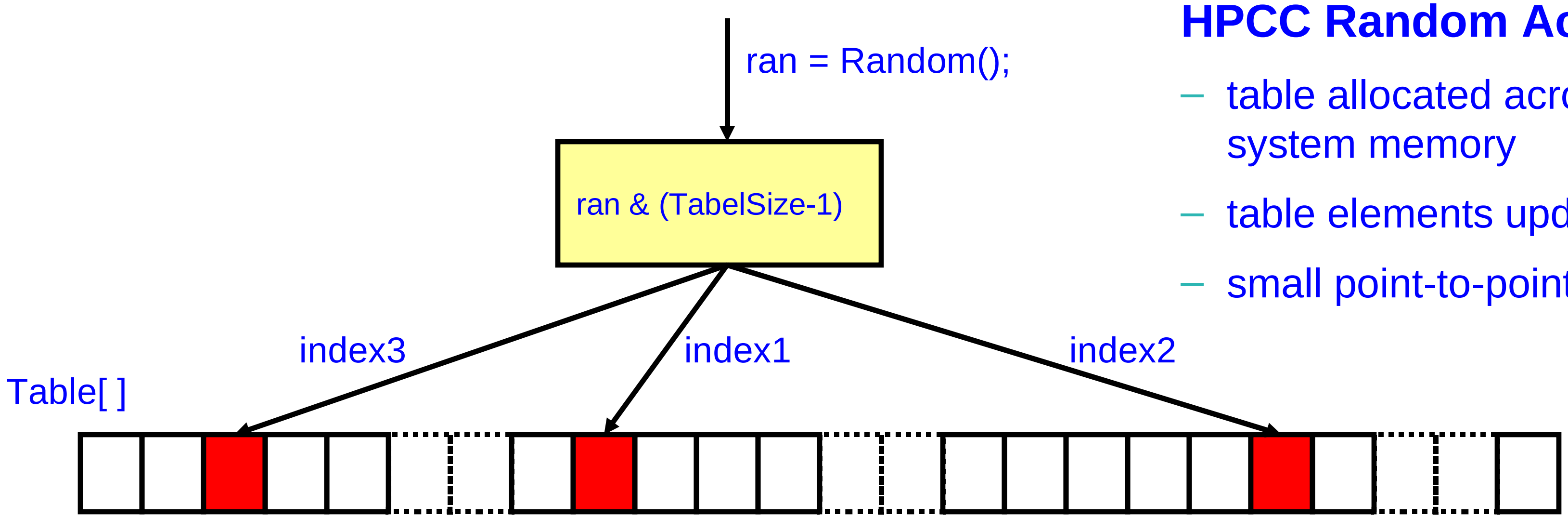
Remote Update Optimization

```
u64Int ran = starts(NUPDATE/THREADS * MYTHREAD);
upc_forall (i = 0; i < NUPDATE; i++; i) {
    ran = (ran << 1) ^ (((s64Int) ran < 0) ? POLY : 0);
    Table[ran & (TableSize-1)] ^= ran;
}
```



HPCC Random Access

- table allocated across distributed system memory
- table elements updated randomly ☹
- small point-to-point communication ☹

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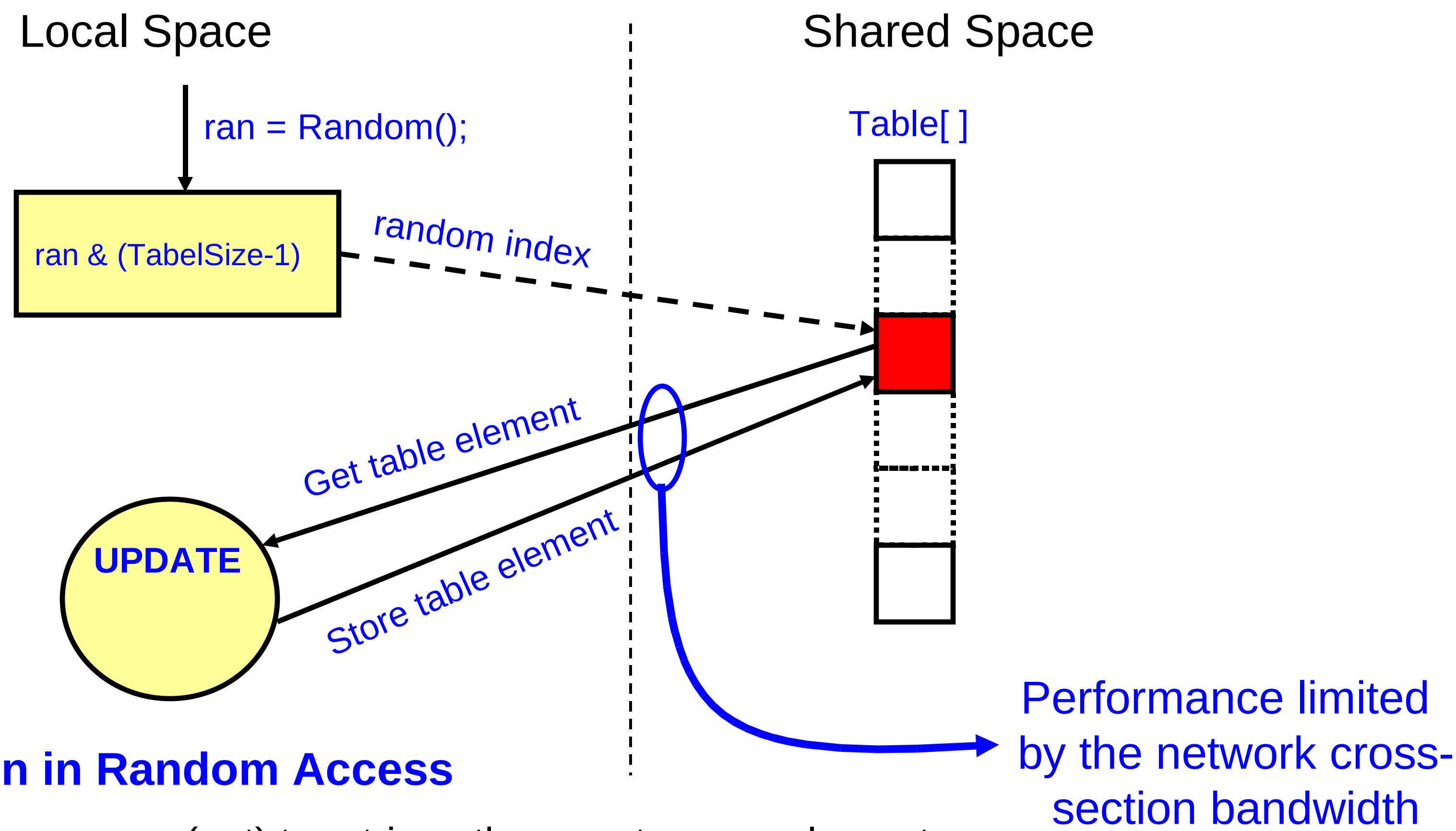
Remote Update Optimization



Communication in Random Access

– 1 fine grained messages (get) to retrieve the remote array element

– Update the array element locally

– 1 fine grained message (put) to store the updated value

– Compiler cannot predict whether the access is shared local or shared remote

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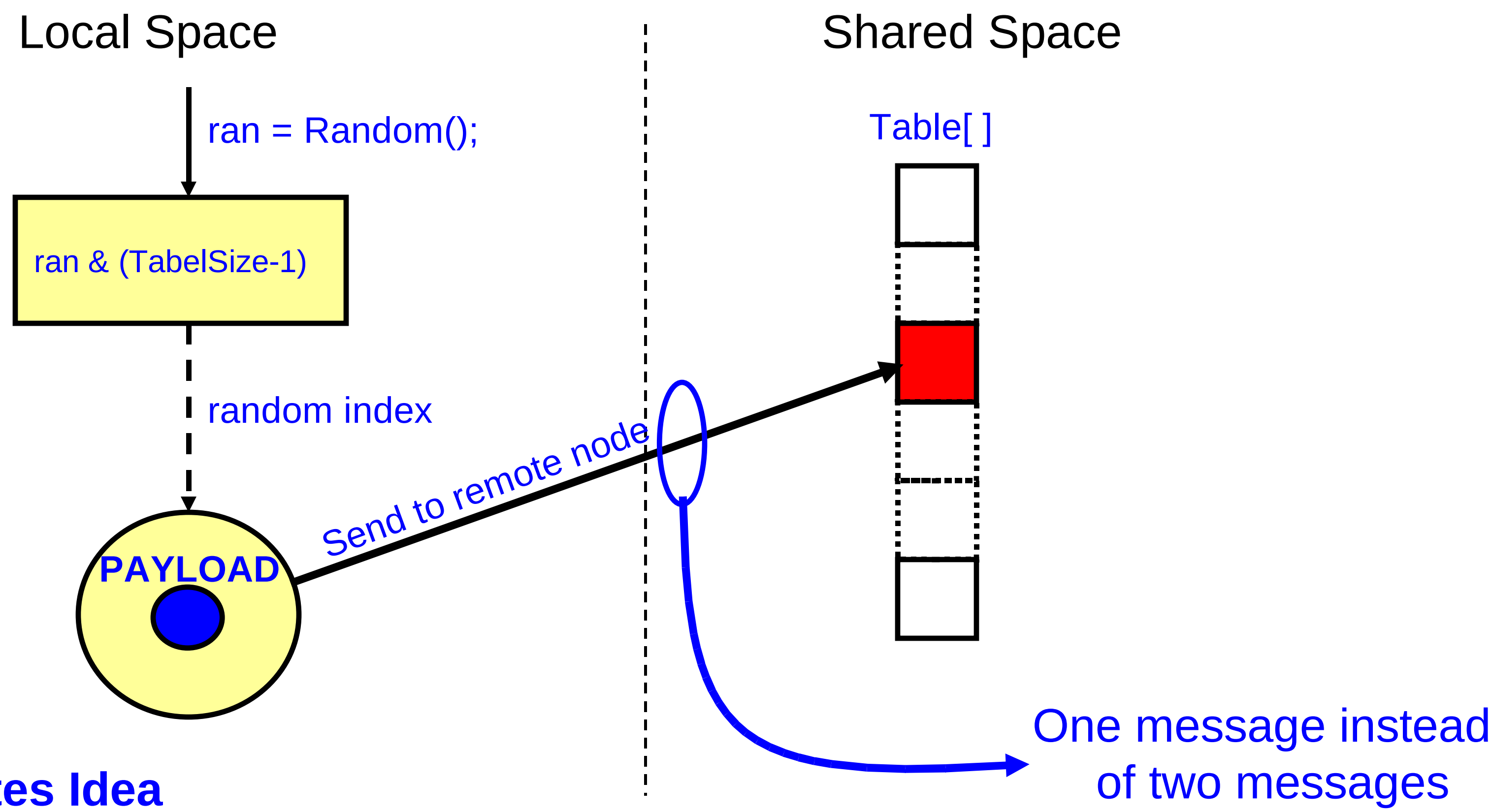
Remote Update Optimization



Owner computes Idea

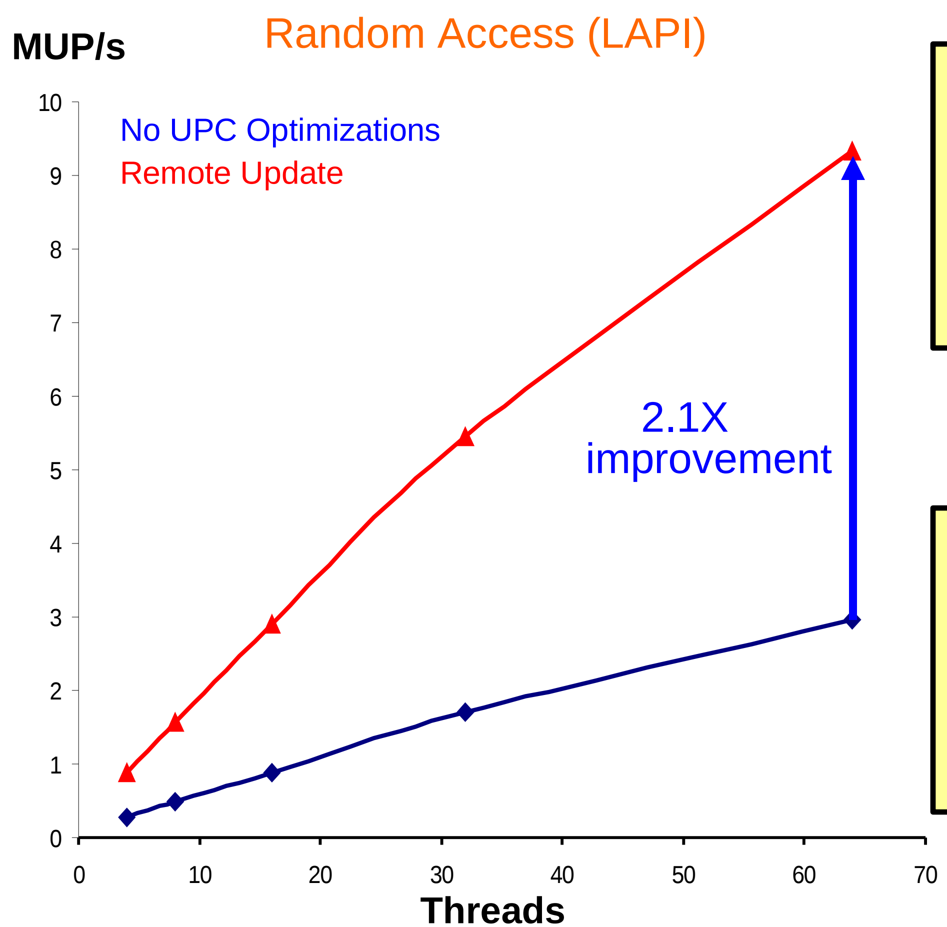
- Compiler recognize update pattern and issues 1 message:

  __xlupc_update(Table_h, index, ran, ^=);

- the update is now done on the **remote** node
- the communication overhead is reduced by half ☺

Remote Update Optimization

Reduced communication




```
u64Int ran = starts(NUPDATE/THREADS * MYTHREAD);
upc_forall (i = 0; i < NUPDATE; i++; i) {
    ran = (ran << 1) ^ (((s64Int) ran < 0) ? POLY : 0);
    Table[ran & (TableSize-1)] ^= ran;
}
```

```
u64Int ran = starts(NUPDATE/THREADS * MYTHREAD);
upc_forall (i = 0; i < NUPDATE; i++; i) {
    ran = (ran << 1) ^ (((s64Int) ran < 0) ? POLY : 0);
    __xlupc_update(Table_h, index, ran, ^=);
}
```

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Array Idiom Recognition

```
shared [BF] int A[N], B[N], C[N];
int a[N];

int main() {
  if (MYTHREAD == 0) {
    for (int i = 0; i < N; i++)
       A[i] = i;
    upc_barrier;
    for (int i = 0; i < N; i++)
       a[i] = A[i];
    for (int i = 0; i < N; i++)
       B[i] = a[i];
    upc_barrier;
    for (int i = 0; i < N; i++)
       C[i] = B[i];
}
```

Common array initialization idioms:

2. Initialize all shared array elements
3. Copy the shared array to a local array
4. Copy the local array to a second shared array
5. Copies one shared array to another shared array

Observations:

- Each operations requires fine grain communication
- How can we avoid the overhead of many small transfers to/from shared memory ?

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Array Idiom Recognition

```
shared [BF] int A[N];
int a[N];
int main() {
  if (MYTHREAD == 0)
    for (int i = 0; i < N; i++)
      A[i] = a[i];
}
```

```
shared [BF] int A[N];
int a[N];
int main() {
  if (MYTHREAD == 0)
    for (i = 0; i < N; i+=BF)
      upc_memput(&A[i], &a[i], BF*sizeof(a[i]));
}
```

Analysis:

2. Collect stride one accesses to shared array
3. Only non-strict accesses are considered
4. Classify the pattern into one of:
   - upc_memset: write same value to shared array
   - upc_memget: read from shared array to local array
   - upc_memput: write to shared array from local array
   - upc_memcpy: write from shared array to shared array
5. Generate the upc_mem* call and adjust the loop increment.

Extensions:

```
A[i+k] = a[i]  // how do we handle the offset ?

for(i=0; i<N; ++i) {
  if (i%BF < k)
    A[i] = a[i];  // first k accesses in block
  if (i%BF == k)
    upc_memput(&A[i], &a[i], (BF-k)*sizeof(a[i]));
}
```

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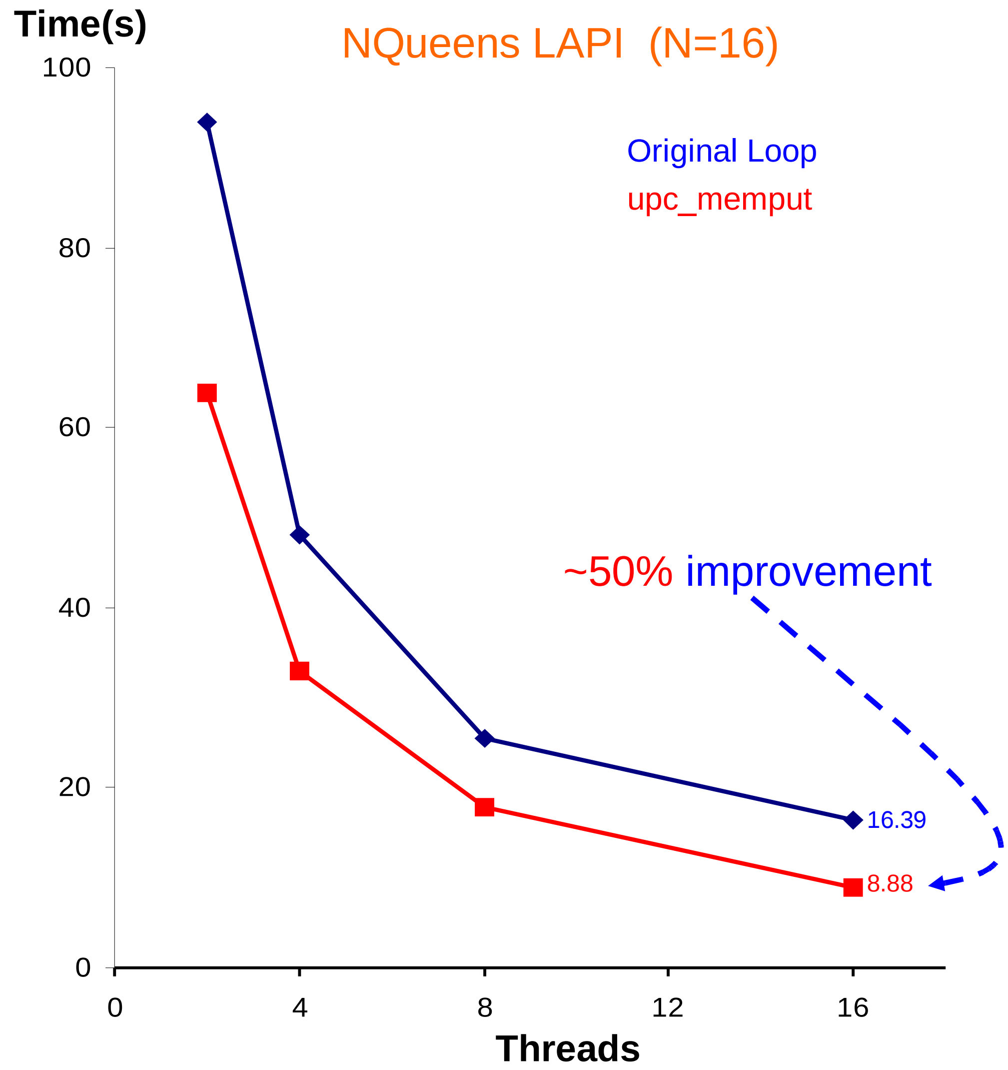
Array Idiom Recognition

Reduced communication



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```
shared [MAXTS] long int * finalPtr =
&FINALSOL[offset[MYTHREAD]];
step = SOLUT[MYTHREAD];
for (p = 0; p < step; p++)
  finalPtr[p] = ptr[p];
```

```
shared [MAXTS] long int * finalPtr =
&FINALSOL[offset[MYTHREAD]];
step = SOLUT[MYTHREAD];
for (p = 0; p < step; p+=MAXTS)
    upc_memput(finalPtr, ptr, …);
```

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Locality Optimizations and Forall Optimizations

- **Each of the optimizations presented has a reasonable impact on performance**
  - Reduce overhead of accessing shared data
  - Reduce overhead of executing parallel loop
- **However, when all optimizations are combined, they have a dramatic impact on performance**

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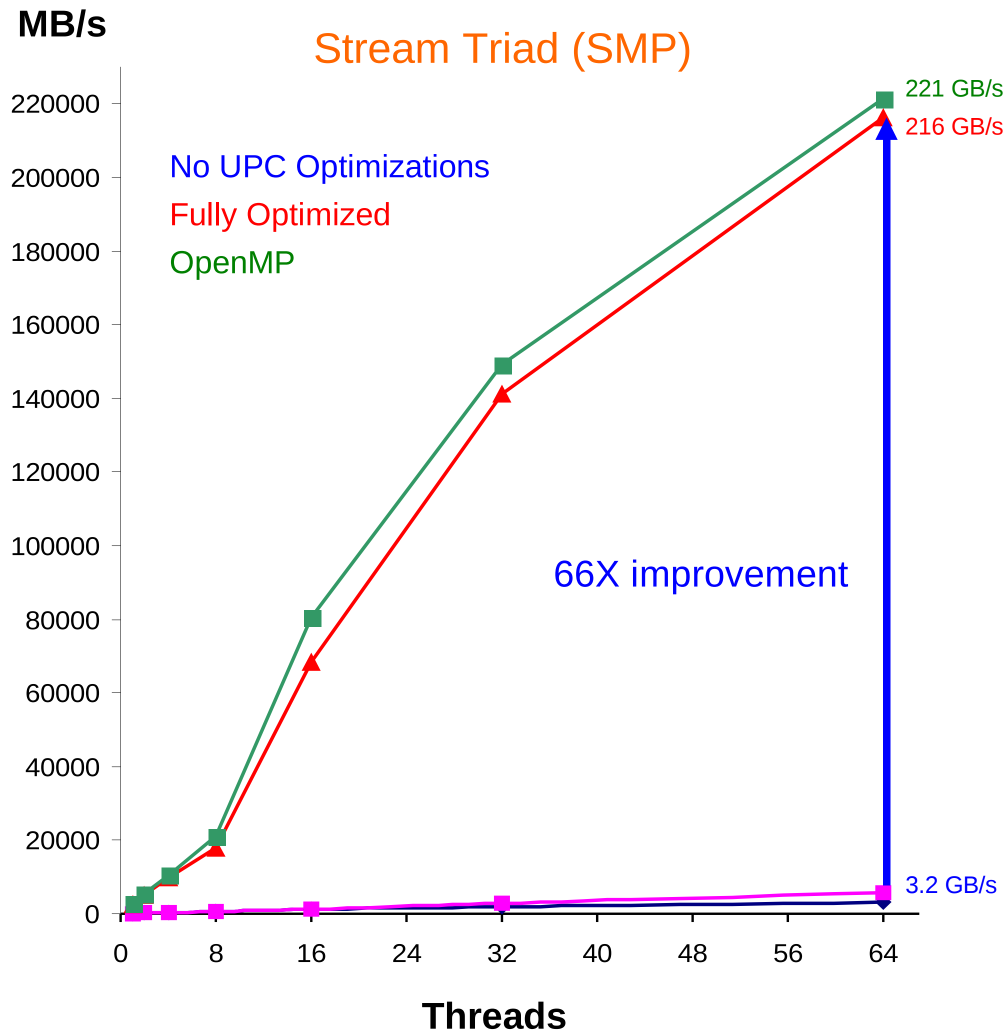
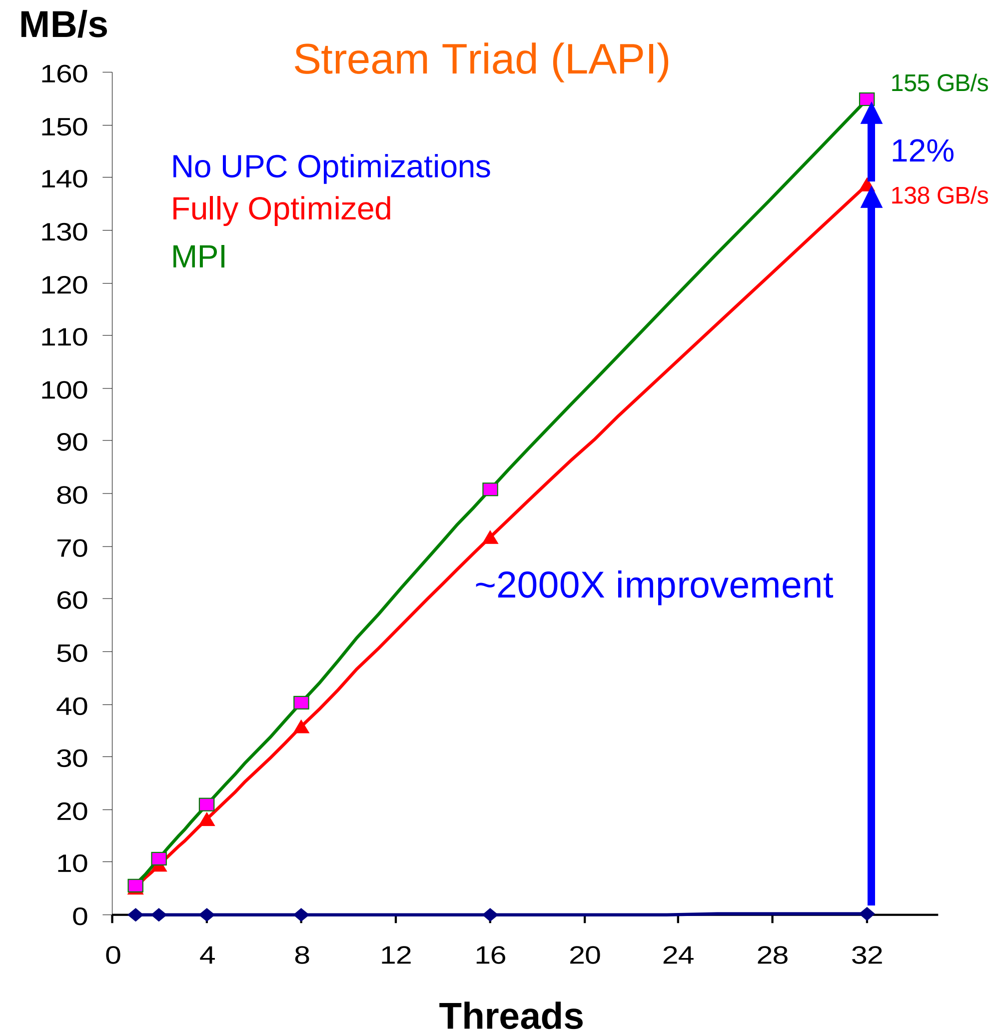
HPCC Stream Triad





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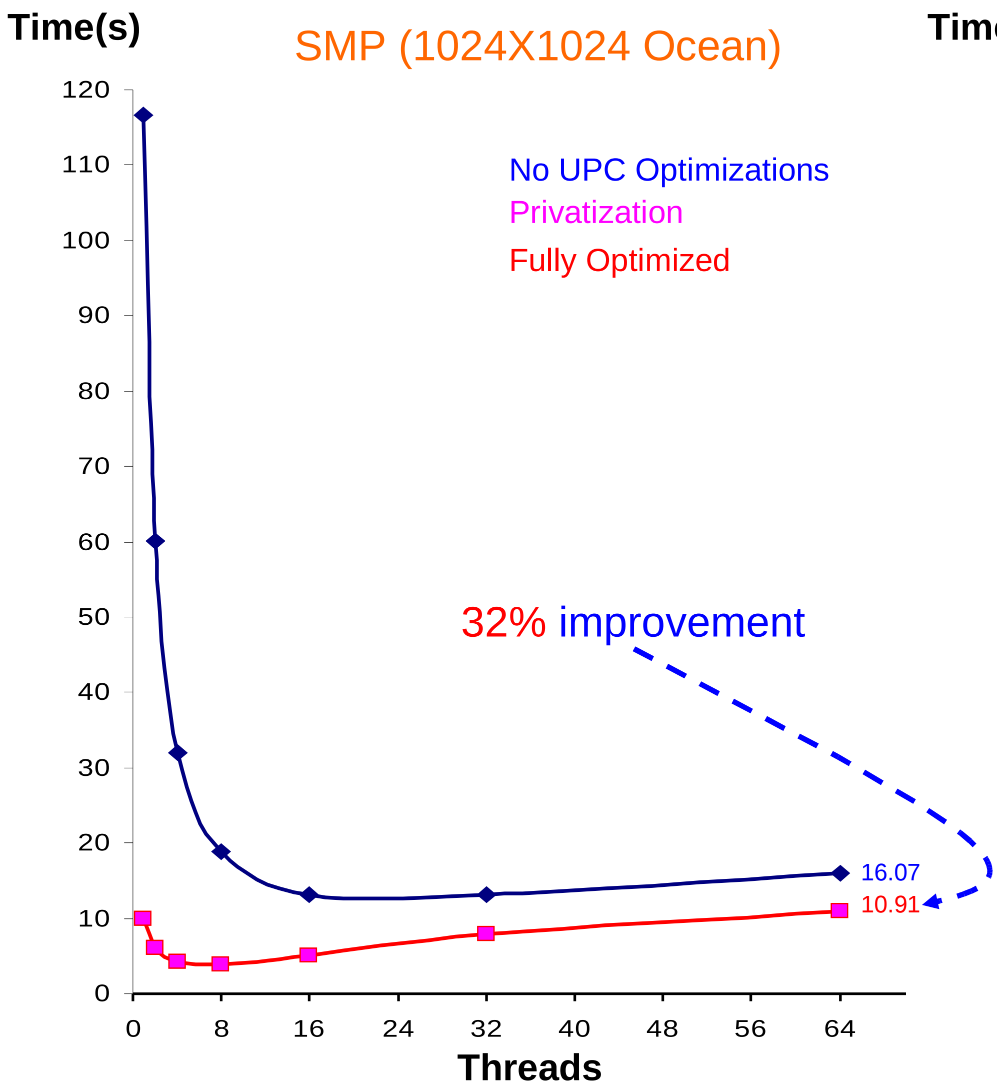
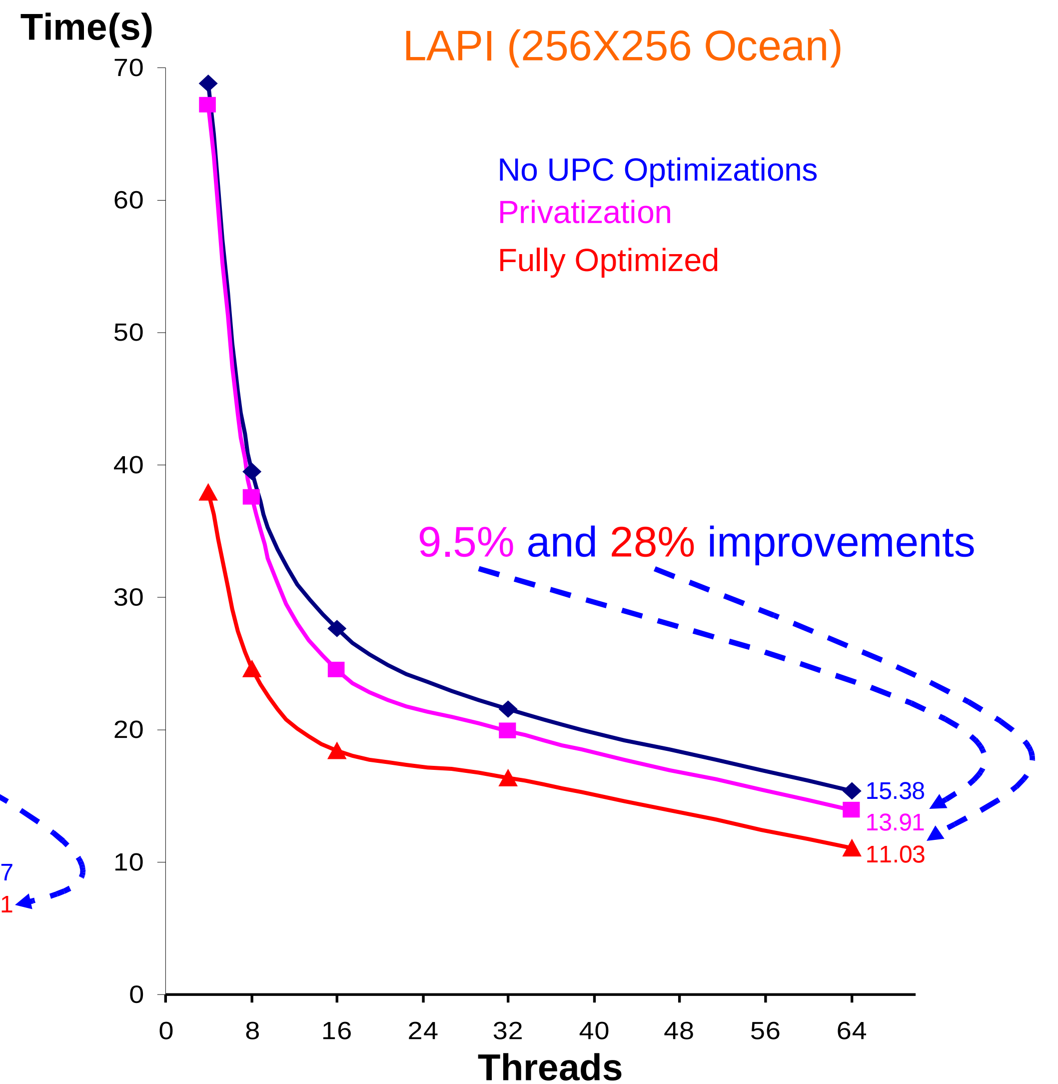
UPC Fish - Predator-prey model





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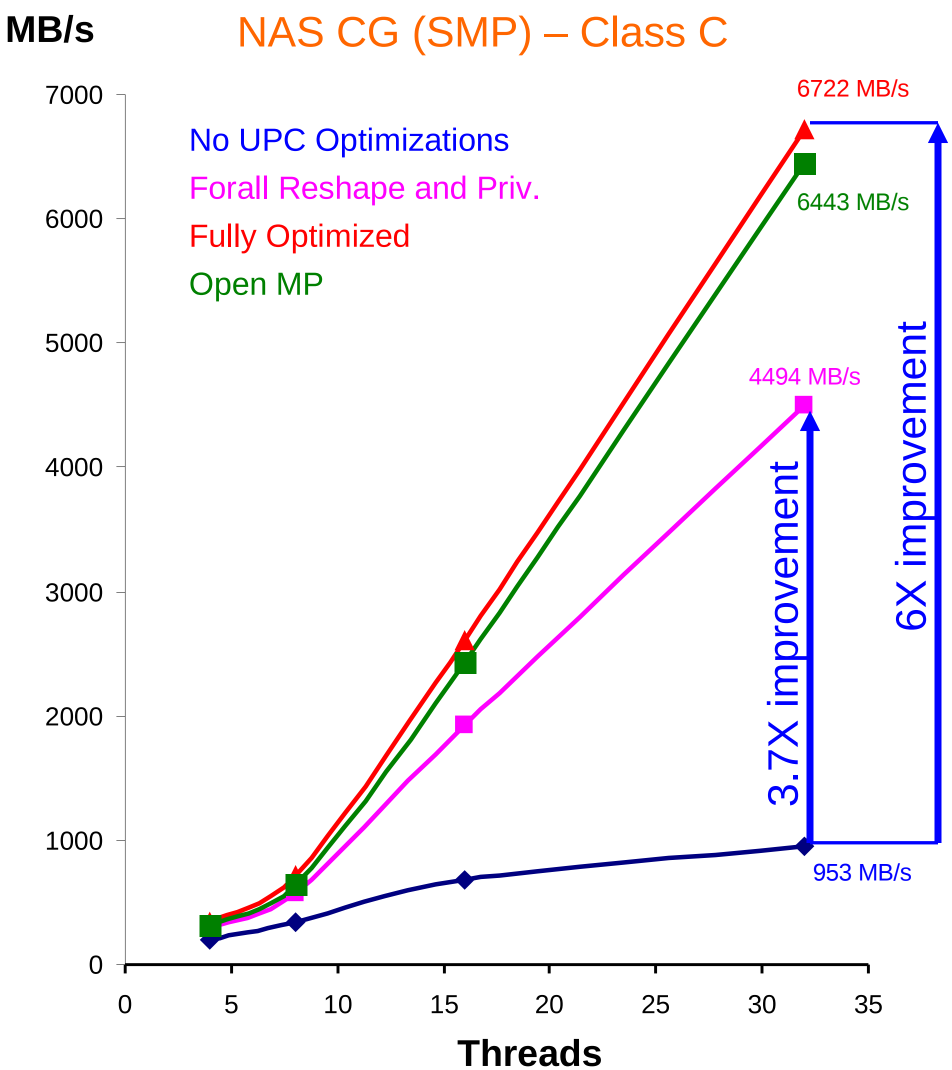
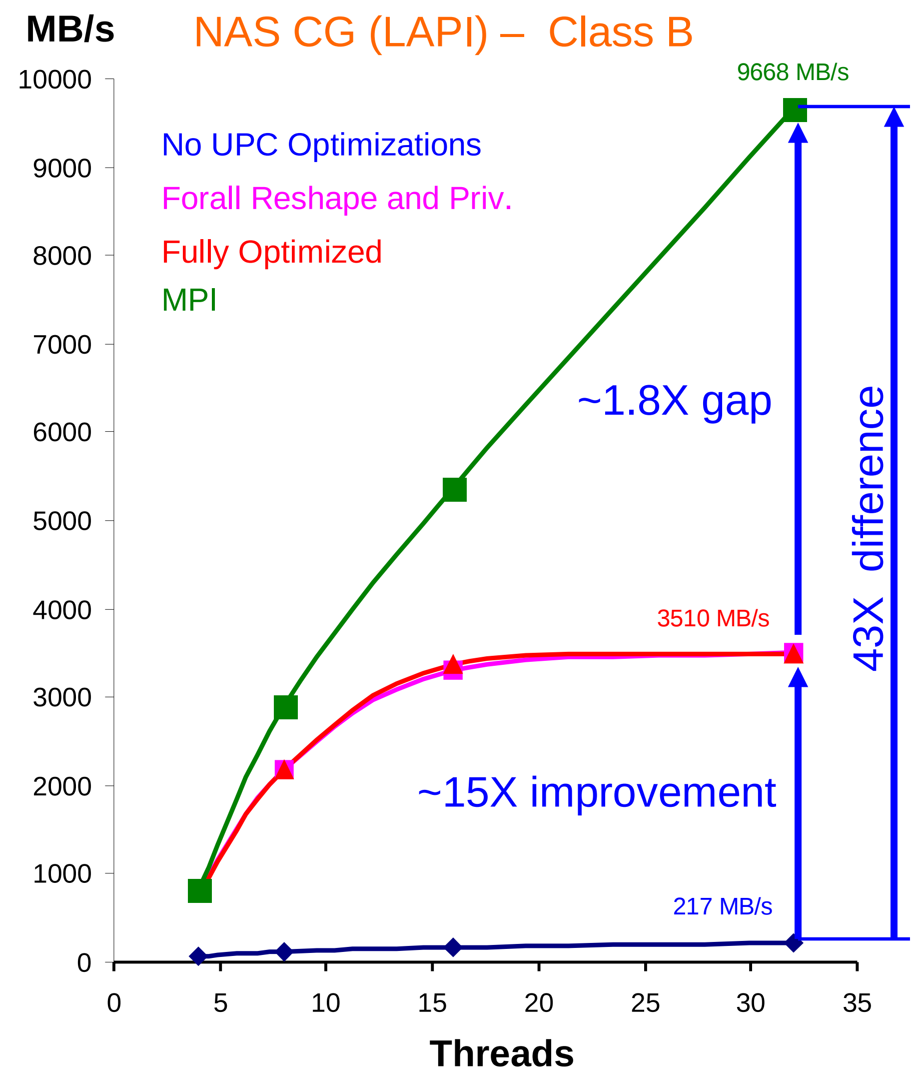
NAS 3.2 CG – UPC vs OMP and MPI





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4. Examples of performance tuning

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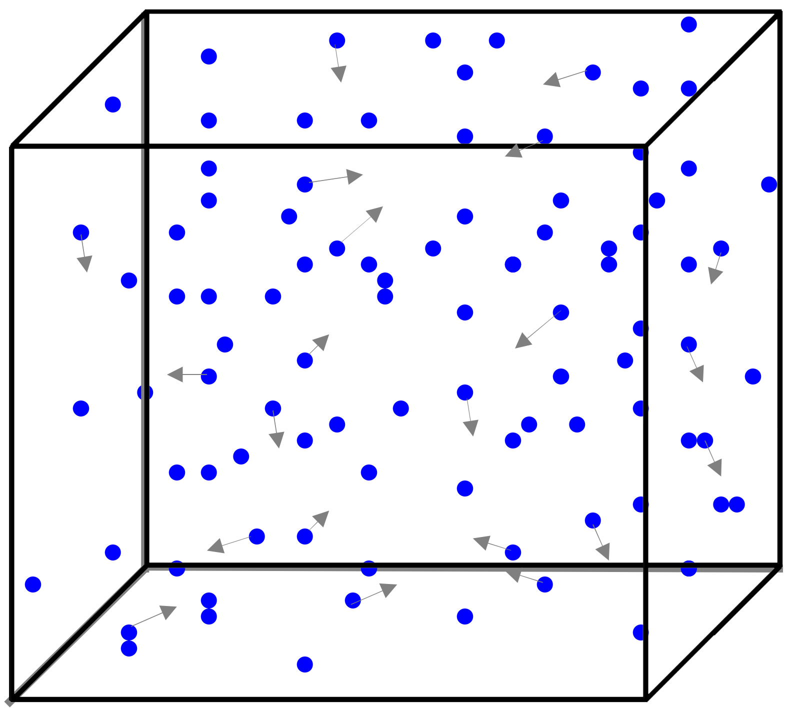
Molecular Dynamics

- N particles in 3D space interact with each other
- Compute particles new position, velocity, acceleration at each time step



- GOOD:
  - **Given force acting on each particle the computation of particles position, velocity, acceleration is an embarrassing parallel problem**
- BAD:
  - **Force acting on particle p.f[i] is a function of the gravitational attraction of all other particles …**

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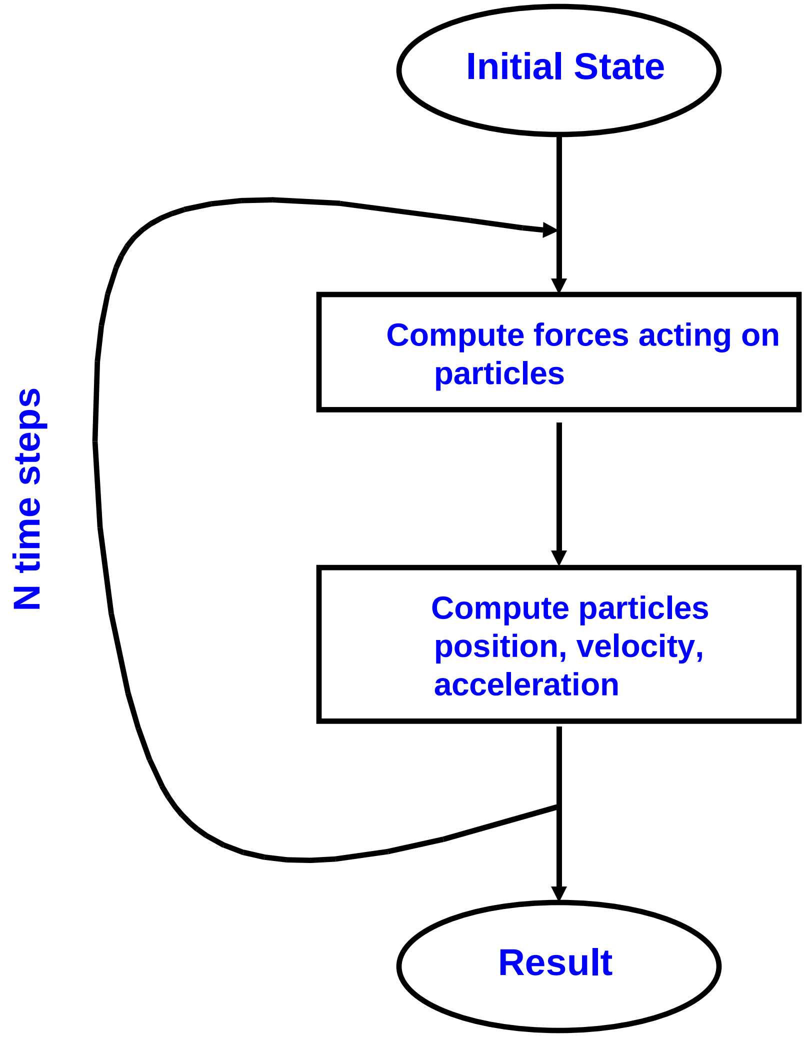
Molecular Dynamics




```
typedef struct {
  double p[3];   // particle position
  double v[3];   // particle velocity
  double a[3];   // particle acceleration
  double f[3]; // force acting on particle
} particle_t;

#define BF (NPARTS/THREADS)

shared [BF] particle_t PARTS[NPARTS];
shared [BF] double POT[NPARTS];
shared [BF] double KIN[NPARTS];
```

All Local access ☺

```
upc_forall(int i = 0; i < NPARTS; i++; &PARTS[i])
  for(int j = 0; j < NDIM; j++) {
    PARTS[i].p[j] += PARTS[i].v[j]*dt + 0.5*dt*dt*PARTS[i].a[j];
    PARTS[i].v[j] += 0.5*dt*(PARTS[i].f[j]*rmass + PARTS[i].a[j]);
    PARTS[i].a[j] = PARTS[i].f[j]*rmass;
  }
```

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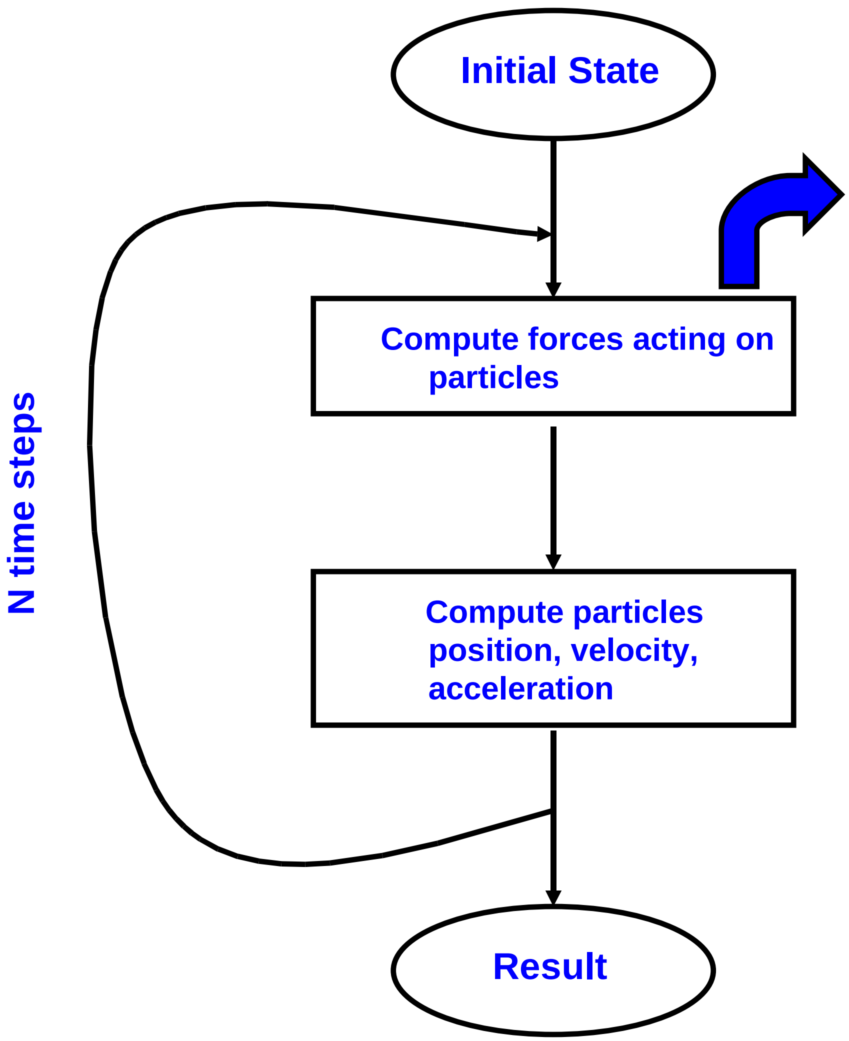
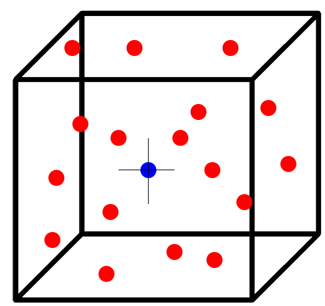
Molecular Dynamics




```
upc_forall (i = 0; i < NPARTS; i++; &PARTS[i]) {
  …
  for (j = 0; j < NPARTS; j++) {
    if (i != j) {
      d = dist(&PARTS[i].p[0], &PARTS[j].p[0], rij);
      POT[i] += 0.5*V(d);
      for (k = 0; k < NDIM; k++)
        PARTS[i].f[k] = PARTS[i].f[k] - rij[k]*DV(d)/d;
    }
  }

double dist (shared double *r1, shared double *r2, double *dr) {
  for (int i=0; i < NDIM; i++) {
    dr[i] = r1[i] - r2[i];
    d += dr[i]*dr[i];
  }
  return sqrt(d);
}
```

Remote accesses



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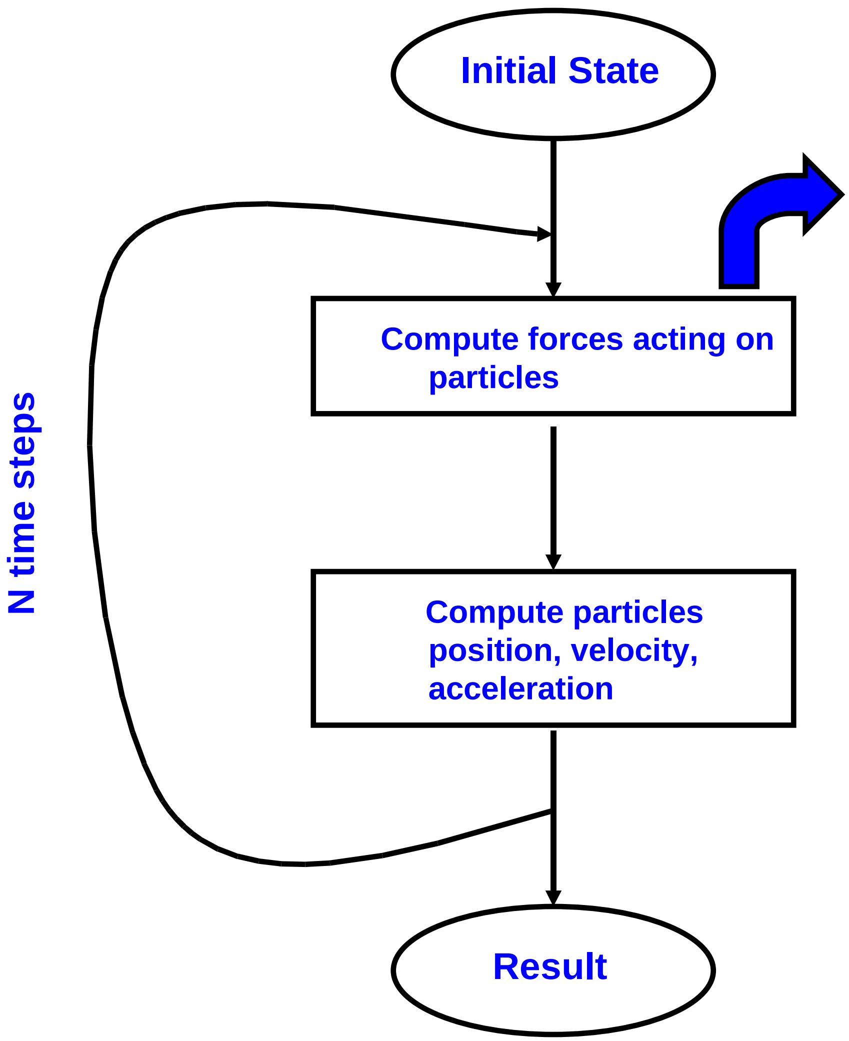
Molecular Dynamics




```
upc_forall (i = 0; i < NPARTS; i++; &PARTS[i]) {
  particle_t *p = (particle_t*) &PARTS[i];
  ...
  for (j = 0; j < NPARTS; j++) {
    if (i != j) {
      d = dist_local(&p->pos[0], &PARTS[j].pos[0], rij);
      POT[i] = POT[i] + 0.5*V(d);
      for (k = 0; k < NDIM; k++)
        p->f[k] = p->f[k] - rij[k]*DV(d)/d;
    }
  }
```

Local access

```
double dist _local (double *r1, shared double *r2, double *dr) {
  for (int i=0; i < NDIM; i++) {
    dr[i] = r1[i] - r2[i];
    d += dr[i]*dr[i];
  }
  return sqrt(d);
}
```

Further Improvements:

– Prefetch r2[i] with upc_memget ?

– Prefetch PARTS[j] in caller ?

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6. Conclusions

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Conclusions

UPC = Performance + Productivity

Performance

- Exploitation of data locality
- Coalescing of communication
- Overlapping communication and computation
- One-sided communication
- Optimized collective library

Productivity

- Simple syntax based on C
- Easy partitioning of shared data
- Work-sharing construct with locality information
- No explicit need to manage communication with function calls
- Simple thread synchronization

http://www.alphaworks.ibm.com/tech/upccompiler

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