CS 267
Unified Parallel C (UPC)

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Slides adapted from some by Tarek El-Ghazawi (GWU)

UPC Outline

1. Background
2. UPC Execution Model
3. Basic Memory Model: Shared vs. Private Scalars
4. Synchronization
5. Collectives
6. Data and Pointers
7. Dynamic Memory Management
8. Programming Examples
9. Performance Tuning and Early Results
10. Concluding Remarks

Context

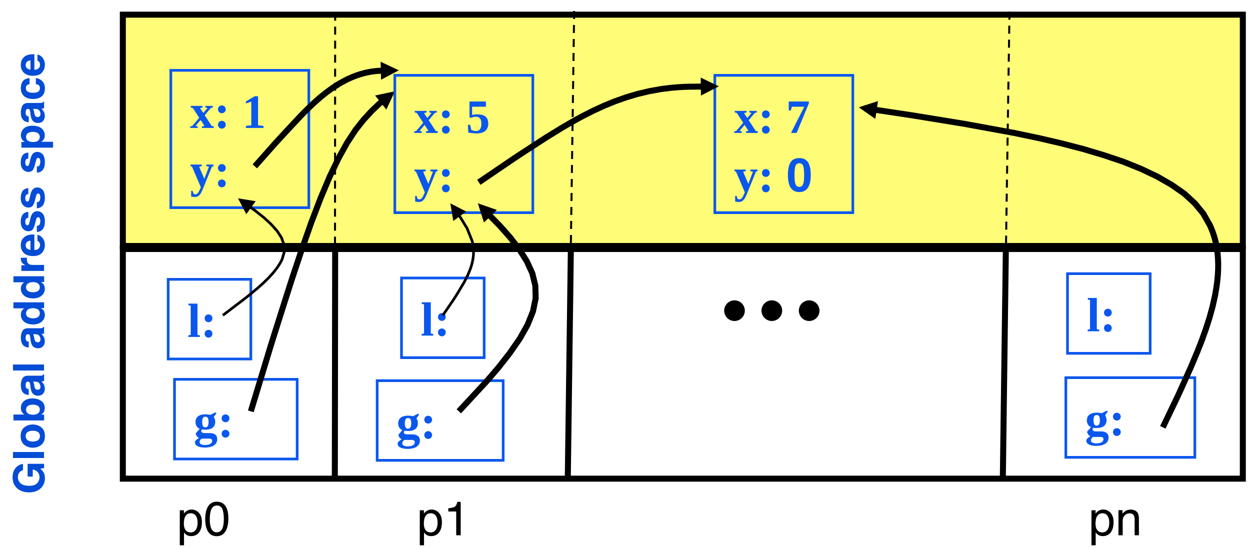
- Most parallel programs are written using either:
  - Message passing with a SPMD model
    - Usually for scientific applications with C++/Fortran
    - Scales easily
  - Shared memory with threads in OpenMP, Threads+C/C++/F or Java
    - Usually for non-scientific applications
    - Easier to program, but less scalable performance
- Global Address Space (GAS) Languages take the best of both
  - global address space like threads (programmability)
  - SPMD parallelism like most MPI programs (performance)
  - local/global distinction, i.e., layout matters (performance)

History of UPC

- Initial Tech. Report from IDA in collaboration with LLNL and UCB in May 1999 (led by IDA).
  - UCB based on Split-C
    - based on course project, motivated by Active Messages
  - IDA based on AC:
    - think about "GUPS" or histogram; "just do it" programs
- UPC consortium of government, academia, and HPC vendors coordinated by GMU, IDA, LBNL.
- The participants (past and present) are:
  - ARSC, Compaq, CSC, Cray Inc., Etnus, GMU, HP, IDA CCS, Intrepid Technologies, LBNL, LLNL, MTU, NSA, SGI, Sun Microsystems, UCB, U. Florida, US DOD

PGAS Languages

- *Global address space:* thread may directly read/write remote data
  - "Virtualizes" or hides the distinction between shared/distributed memory
- *Partitioned:* data is designated as local or global
  - Does not hide this: critical for locality and scaling



- *UPC, CAF, Titanium: Static parallelism (1 thread per proc)*
  - Does not virtualize processors; main difference from HPCS languages which have many/dynamic threads

What Makes a Language/Library PGAS?

- Support for distributed data structures
  - Distributed arrays; local and global pointers/references
- One-sided shared-memory "communication"
  - Simple assignment statements: **x[i] = y[i];** or **t = *p;**
  - Bulk operations: memory copy or array copy
  - Optional: remote invocation of functions
- Control over data layout
  - PGAS is not the same as (cache-coherent) "shared memory"
  - Remote data stays remote in the performance model
- Synchronization
  - Global barriers, locks, memory fences
- Collective Communication, IO libraries, etc.

UPC Overview and Design Philosophy

- Unified Parallel C (UPC) is:
  - An explicit parallel extension of ANSI C
  - A partitioned global address space language
  - Sometimes called a GAS 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

UPC Execution Model

UPC Execution Model

- A number of threads working independently in a SPMD fashion
  - Number of threads specified at compile-time or run-time; 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
    - The program may use THREADS as a compile-time constant
  - Dynamic threads mode:
    - Compiled code may be run with varying numbers of threads

Hello World in UPC

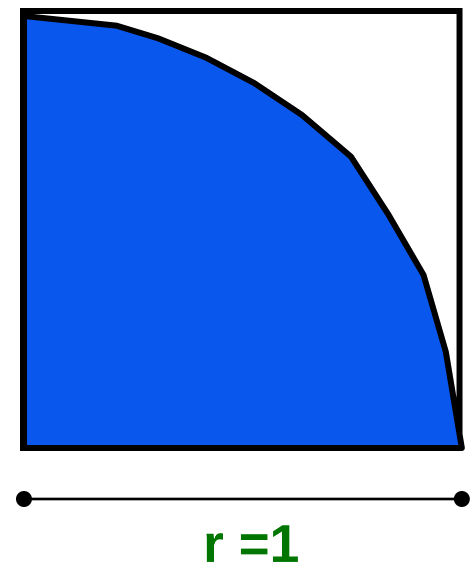
- Any legal C program is also a legal UPC program
- If you compile and run it as UPC with P threads, it will run P copies of the program.
- Using this fact, plus the identifiers from the previous slides, we can parallel hello world:

```
#include <upc.h>  /* needed for UPC extensions */
#include <stdio.h>

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

Example: Monte Carlo Pi Calculation

- Estimate Pi by throwing darts at a unit square
- Calculate percentage that fall in the unit circle
  - Area of square = $r^2 = 1$
  - Area of circle quadrant = $\frac{1}{4} * \pi r^2 = \pi/4$
- Randomly throw darts at x,y positions
- If $x^2 + y^2 < 1$, then point is inside circle
- Compute ratio:
  - # points inside / # points total
  - $\pi = 4*\text{ratio}$



Pi in UPC

- Independent estimates of pi:

```
main(int argc, char **argv) {
  int i, hits, trials = 0;
  double pi;

  if (argc != 2)trials = 1000000;
  else trials = atoi(argv[1]);

  srand(MYTHREAD*17);

  for (i=0; i < trials; i++) hits += hit();
  pi = 4.0*hits/trials;
  printf("PI estimated to %f.", pi);
}
```

Each thread gets its own copy of these variables

Each thread can use input arguments

Initialize random in math library

Each thread calls “hit” separately

Helper Code for Pi in UPC

- Required includes:

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

- Function to throw dart and calculate where it hits:

```
int hit(){
  int const rand_max = 0xFFFFFF;
  double x = ((double) rand()) / RAND_MAX;
  double y = ((double) rand()) / RAND_MAX;
  if ((x*x + y*y) <= 1.0) {
       return(1);
  } else {
       return(0);
  }
}
```

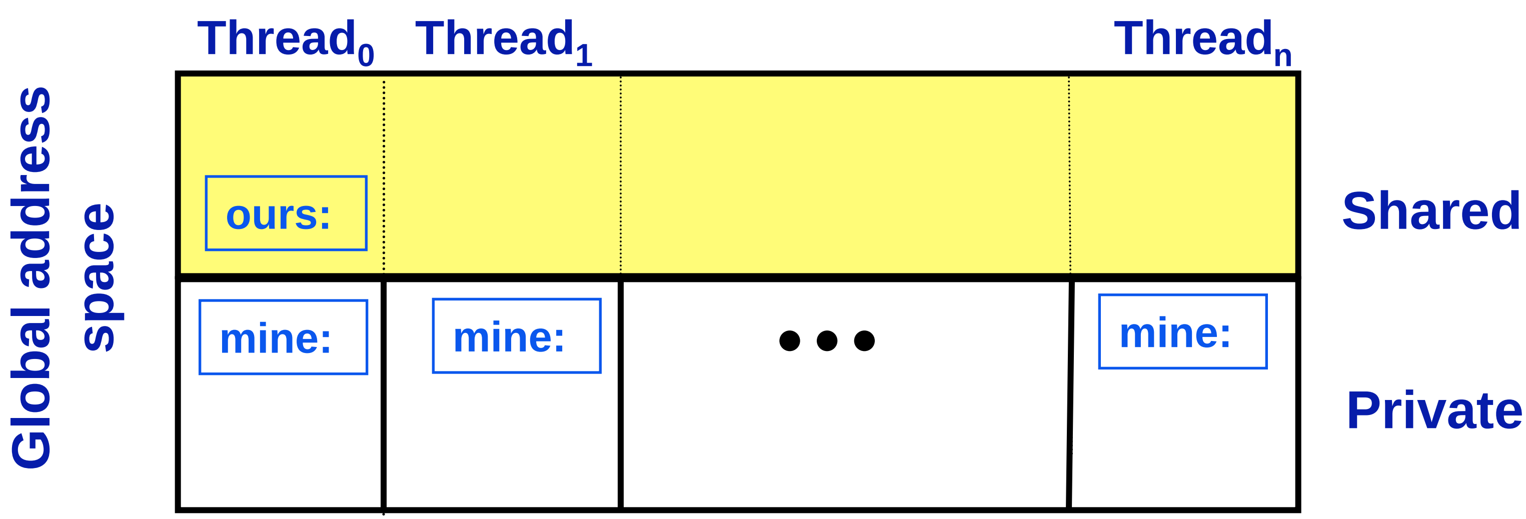
Shared vs. Private Variables

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;  // use sparingly: performance
int mine;
```

- Shared variables may not have dynamic lifetime: may not occur in a in a function definition, except as static. Why?



Pi in UPC: Shared Memory Style

- **Parallel computing of pi, but with a bug**

```
shared int hits;
main(int argc, char **argv) {
    int i, my_trials = 0;
    int trials = atoi(argv[1]);
    my_trials = (trials + THREADS - 1)/THREADS;
    srand(MYTHREAD*17);
    for (i=0; i < my_trials; i++)
      hits += hit();
    upc_barrier;
    if (MYTHREAD == 0) {
      printf("PI estimated to %f.", 4.0*hits/trials);
    }
}
```

shared variable to record hits

divide work up evenly

accumulate hits

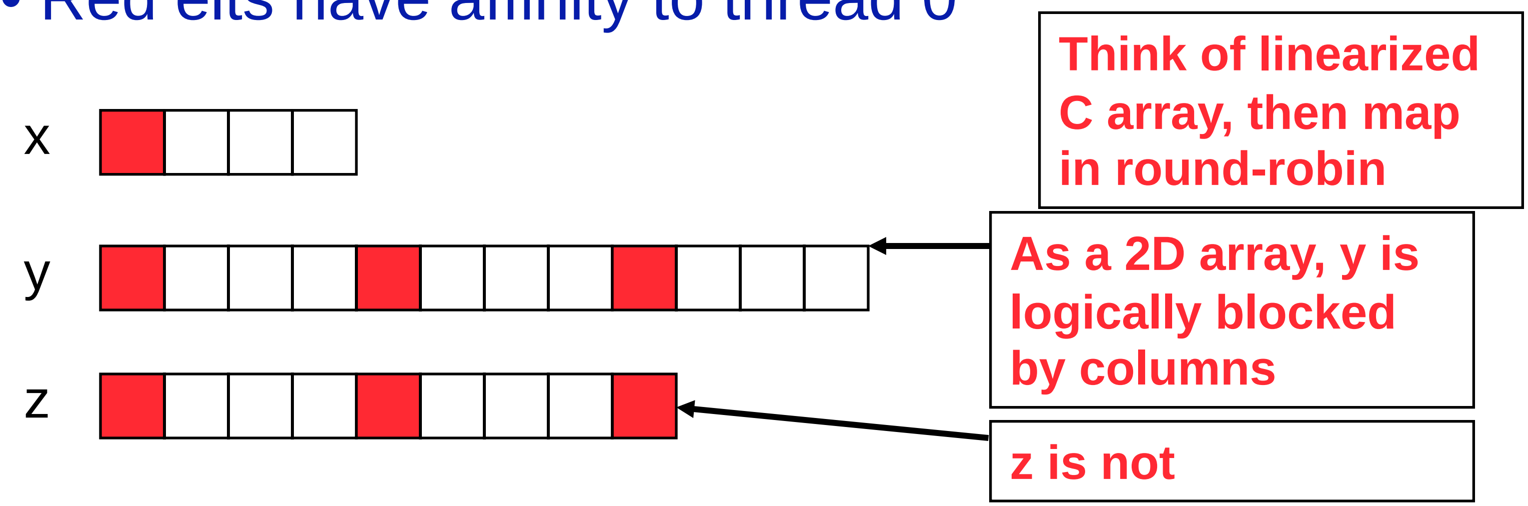
What is the problem with this program?

Shared Arrays Are Cyclic By Default

- Shared scalars always live in thread 0
- Shared arrays are spread over the threads
- Shared array elements are spread across the threads

```
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 */
```

- In the pictures below, assume THREADS = 4
  - Red elts have affinity to thread 0



Pi in UPC: Shared Array Version

- Alternative fix to the race condition
- Have each thread update a separate counter:
  - But do it in a shared array
  - Have one thread compute sum

```
shared int all_hits [THREADS];
main(int argc, char **argv) {
  … declarations an initialization code omitted
  for (i=0; i < my_trials; i++)
    all_hits[MYTHREAD] += hit();
  upc_barrier;
  if (MYTHREAD == 0) {
    for (i=0; i < THREADS; i++) hits += all_hits[i];
    printf("PI estimated to %f.", 4.0*hits/trials);
  }
}
```

all_hits is shared by all processors, just as hits was

update element with local affinity

UPC Synchronization

UPC Global Synchronization

- 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;
}
```

Synchronization - Locks

- Locks in UPC are represented by an opaque type:

  `upc_lock_t`

- Locks 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 one thread

- 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);`

Pi in UPC: Shared Memory Style

- **Parallel computing of pi, without the bug**

```
shared int hits;
main(int argc, char **argv) {
    int i, my_hits, my_trials = 0;
    upc_lock_t *hit_lock = upc_all_lock_alloc();
    int trials = atoi(argv[1]);
    my_trials = (trials + THREADS - 1)/THREADS;
    srand(MYTHREAD*17);
    for (i=0; i < my_trials; i++)
       my_hits += hit();
    upc_lock(hit_lock);
    hits += my_hits;
    upc_unlock(hit_lock);
    upc_barrier;
    if (MYTHREAD == 0)
      printf("PI: %f", 4.0*hits/trials);
}
```

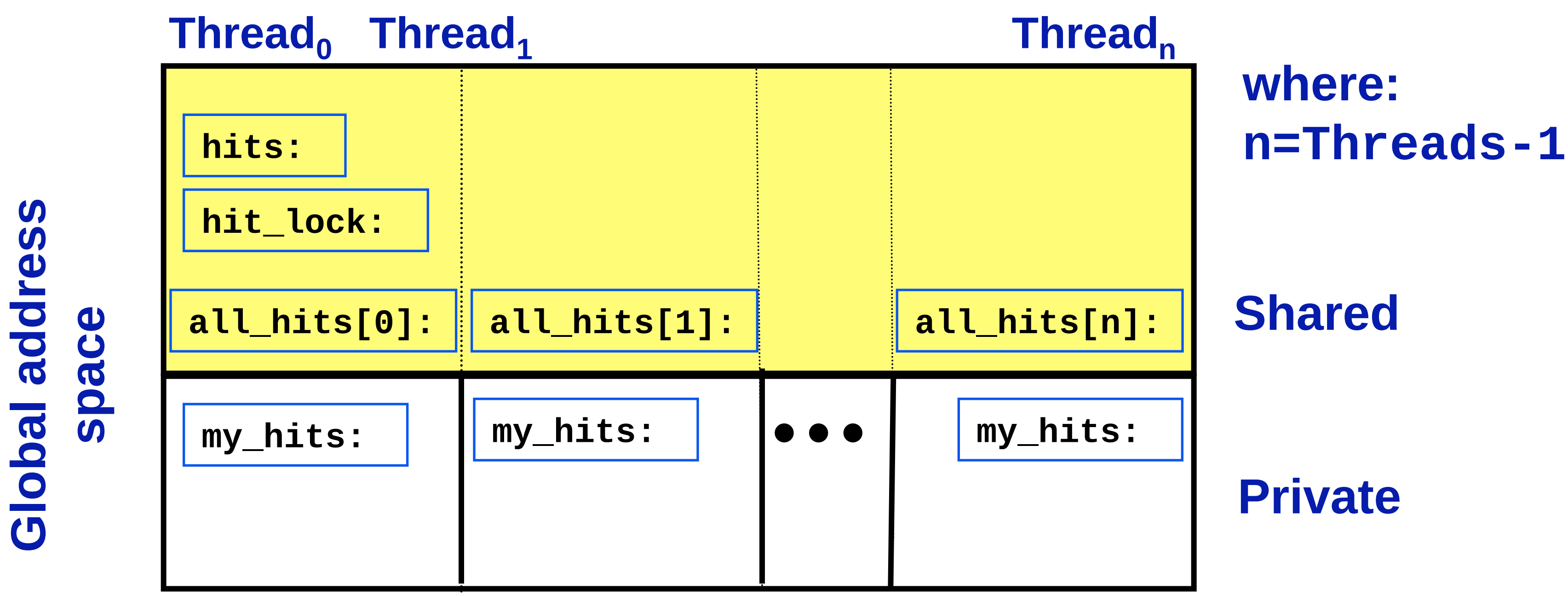
create a lock

accumulate hits locally

accumulate across threads

Recap: Private vs. Shared Variables in UPC

- We saw several kinds of variables in the pi example
  - Private scalars (`my_hits`)
  - Shared scalars (`hits`)
  - Shared arrays (`all_hits`)
  - Shared locks (`hit_lock`)



UPC Collectives

UPC Collectives in General

- The UPC collectives interface is in the language spec:
  - http://upc.lbl.gov/docs/user/upc_spec_1.2.pdf
- It contains typical functions:
  - Data movement: broadcast, scatter, gather, …
  - Computational: reduce, prefix, …
- Interface has synchronization modes:
  - Avoid over-synchronizing (barrier before/after is simplest semantics, but may be unnecessary)
  - Data being collected may be read/written by any thread simultaneously
- Simple interface for collecting scalar values (int, double,…)
  - Berkeley UPC value-based collectives
  - Works with any compiler
  - http://upc.lbl.gov/docs/user/README-collectivev.txt

Pi in UPC: Data Parallel Style

- **The previous version of Pi works, but is not scalable:**
  - **On a large # of threads, the locked region will be a bottleneck**
- **Use a reduction for better scalability**

```
#include <bupc_collectivev.h>
// shared int hits;
main(int argc, char **argv) {
    ...
    for (i=0; i < my_trials; i++)
       my_hits += hit();
    my_hits =          // type, input, thread, op
       bupc_allv_reduce(int, my_hits, 0, UPC_ADD);
    // upc_barrier;
    if (MYTHREAD == 0)
      printf("PI: %f", 4.0*my_hits/trials);
}
```

Berkeley collectives

no shared variables

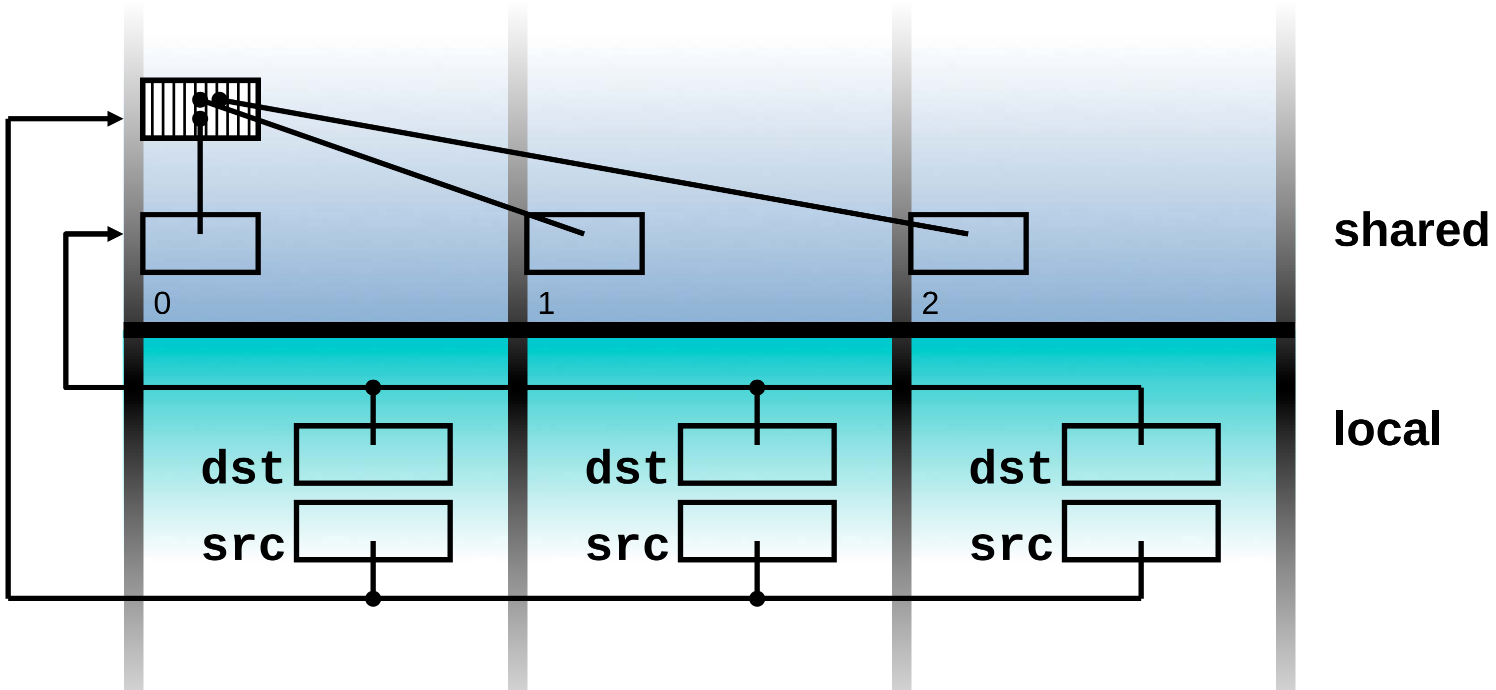
barrier implied by collective

UPC (Value-Based) Collectives in General

- General arguments:
  - rootthread is the thread ID for the root (e.g., the source of a broadcast)
  - All 'value' arguments indicate an l-value (i.e., a variable or array element, not a literal or an arbitrary expression)
  - All 'TYPE' arguments should the scalar type of collective operation
  - upc_op_t is one of: UPC_ADD, UPC_MULT, UPC_AND, UPC_OR, UPC_XOR, UPC_LOGAND, UPC_LOGOR, UPC_MIN, UPC_MAX
- Computational Collectives
  - TYPE bupc_allv_reduce(TYPE, TYPE value, int rootthread, upc_op_t reductionop)
  - TYPE bupc_allv_reduce_all(TYPE, TYPE value, upc_op_t reductionop)
  - TYPE bupc_allv_prefix_reduce(TYPE, TYPE value, upc_op_t reductionop)
- Data movement collectives
  - TYPE bupc_allv_broadcast(TYPE, TYPE value, int rootthread)
  - TYPE bupc_allv_scatter(TYPE, int rootthread, TYPE *rootsrcarray)
  - TYPE *bupc_allv_gather(TYPE, TYPE value, int rootthread, TYPE *rootdestarray)
    - Gather a 'value' (which has type TYPE) from each thread to 'rootthread', and place them (in order by source thread) into the local array 'rootdestarray' on 'rootthread'.
  - TYPE *bupc_allv_gather_all(TYPE, TYPE value, TYPE *destarray)
  - TYPE bupc_allv_permute(TYPE, TYPE value, int tothreadid)
    - Perform a permutation of 'value's across all threads. Each thread passes a value and a unique thread identifier to receive it - each thread returns the value it receives.

Full UPC Collectives

- Value-based collectives pass in and return scalar values
- But sometimes you want to collect over arrays
- When can a collective argument begin executing?
  - Arguments with affinity to thread *i* are ready when thread *i* calls the function; results with affinity to thread *i* are ready when thread *i* returns.
  - This is appealing but it is incorrect: In a broadcast, thread 1 does not know when thread 0 is ready.



UPC Collective: Sync Flags

- In full UPC Collectives, blocks of data may be collected
- A extra argument of each collective function is the sync mode of type upc_flag_t.
- Values of sync mode are formed by or-ing together a constant of the form UPC_IN_*X*SYNC and a constant of the form UPC_OUT_*Y*SYNC, where *X* and *Y* may be NO, MY, or ALL.
- If sync_mode is (UPC IN_*X*SYNC | UPC OUT *Y*SYNC), then if *X* is:
  - NO the collective function may begin to read or write data when the first thread has entered the collective function call,
  - MY the collective function may begin to read or write only data which has affinity to threads that have entered the collective function call, and
  - ALL the collective function may begin to read or write data only after all threads have entered the collective function call
- and if *Y* is
  - NO the collective function may read and write data until the last thread has returned from the collective function call,
  - MY the collective function call may return in a thread only after all reads and writes of data with affinity to the thread are complete3, and
  - ALL the collective function call may return only after all reads and writes of data are complete.

Work Distribution Using `upc_forall`

Example: Vector Addition

- Questions about parallel vector additions:
  - How to layout data (here it is cyclic)
  - Which processor does what (here it is “owner computes”)

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

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

cyclic layout

owner computes

Work Sharing with upc_forall()

- The idiom in the previous slide is very common
  - 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`
  - Pointer: `upc_threadof(affinity)` is `MYTHREAD`
- **`Syntactic sugar for loop on previous slide`**
  - *Some* compilers *may* do better than this, e.g.,

```
for(i=MYTHREAD; i<N; i+=THREADS)
```

  - Rather than having all threads iterate N times:

```
for(i=0; i<N; i++) if (MYTHREAD == i%THREADS)
```

Vector Addition with upc_forall

- The **vadd** example can be rewritten as follows
  - 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**.

```
#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];
  }
```

The cyclic data distribution may perform poorly on some machines

Distributed Arrays in UPC

Blocked Layouts in UPC

- If this code were doing nearest neighbor averaging (3pt stencil) the cyclic layout would be the worst possible layout.
- Instead, want a blocked layout
- Vector addition example can be rewritten as follows using a blocked layout

```
#define N 100*THREADS
   shared int [*] v1[N], v2[N], sum[N];

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

blocked layout

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 [] (indefinite 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

2D Array Layouts in UPC

- Array a1 has a row layout and array a2 has a block row layout.

```
shared [m] int a1 [n][m];
shared [k*m] int a2 [n][m];
```

- If (k + m) % THREADS = = 0 them a3 has a row layout

  shared int a3 [n][m+k];

- To get more general HPF and ScaLAPACK style 2D blocked layouts, one needs to add dimensions.
- Assume r*c = THREADS;

  shared [b1][b2] int a5 [m][n][r][c][b1][b2];

- or equivalently

  shared [b1*b2] int a5 [m][n][r][c][b1][b2];

UPC Matrix Vector Multiplication Code

- Matrix-vector multiplication with matrix stored by rows
- (Contrived example: problems size is PxP)

```
shared [THREADS] int a[THREADS][THREADS];
shared int b[THREADS], c[THREADS];

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

UPC Matrix Multiplication Code

```
/* mat_mult_1.c */
#include <upc_relaxed.h>

#define N  4
#define P  4
#define M 4

shared [N*P /THREADS] int a[N][P], c[N][M];
// a and c are row-wise blocked shared matrices

shared[M/THREADS] int b[P][M]; //column-wise blocking

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];
                }
        }
}
```

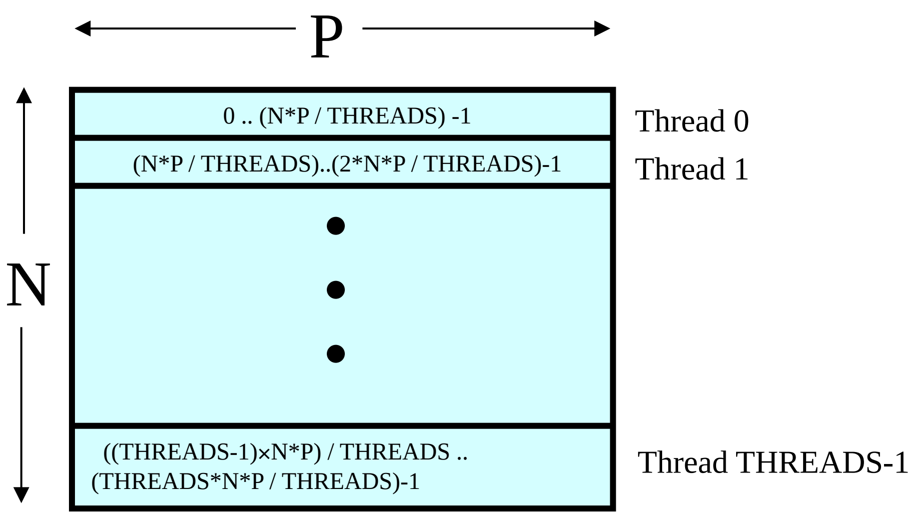
Notes on the Matrix Multiplication Example

- The UPC code for the matrix multiplication is almost the same size as the sequential code
- Shared variable declarations include the keyword shared
- Making a private copy of matrix B in each thread might result in better performance since many remote memory operations can be avoided
- Can be done with the help of upc_memget

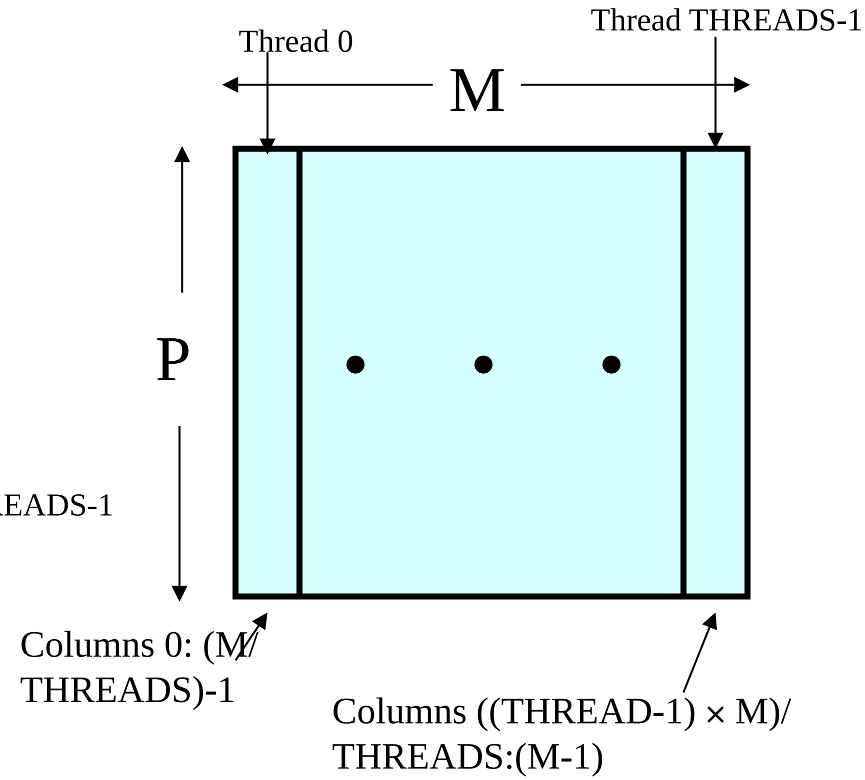
Domain Decomposition for UPC

- Exploits locality in matrix multiplication

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



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



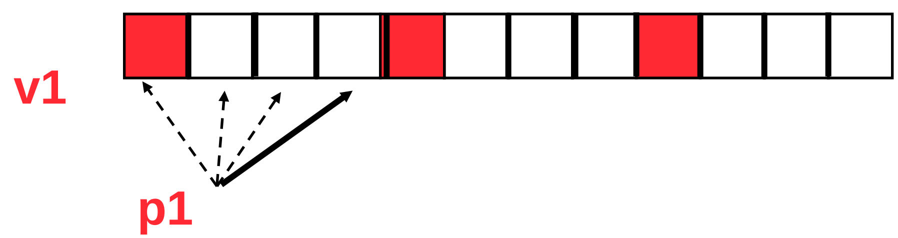
•**<u>Note:</u>** N and M are assumed to be multiples of THREADS

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;
   }
```



UPC Pointers

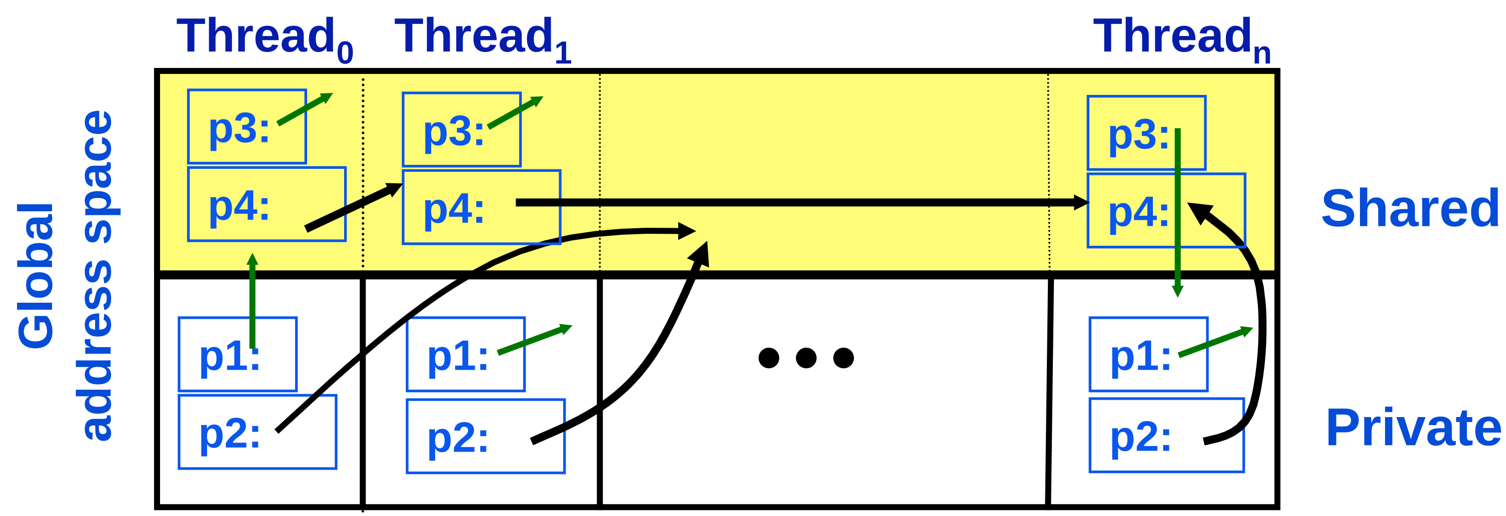
Where does the pointer point?

Where does the pointer reside?	Local	Shared
Private	p1	p2
Shared	p3	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 local memory (p3) is not recommended.

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.

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

UPC Pointers

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

Virtual Address	Thread	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 pointer-to-local, the thread number of the pointer to shared may be lost
- Casting of shared to local is well defined only if the object pointed to by the pointer to shared has affinity with the thread performing the cast

Special 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
- shared void *upc_resetphase(shared void *ptr); resets the phase to zero

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

Global Memory Allocation

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

`nblocks :` **number of blocks**
`nbytes :` **block size**

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

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]

Memory Freeing

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

Distributed Arrays Directory Style

- Some high performance UPC programmers avoid the UPC style arrays
  - Instead, build directories of distributed objects
  - Also more general

```
typedef shared [] double *sdblptr;
shared sdblptr directory[THREADS];
directory[i]=upc_alloc(local_size*sizeof(double));
upc_barrier;
```

Memory Consistency in UPC

- 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`**)

Synchronization- Fence

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

Performance of UPC

PGAS Languages have Performance Advantages

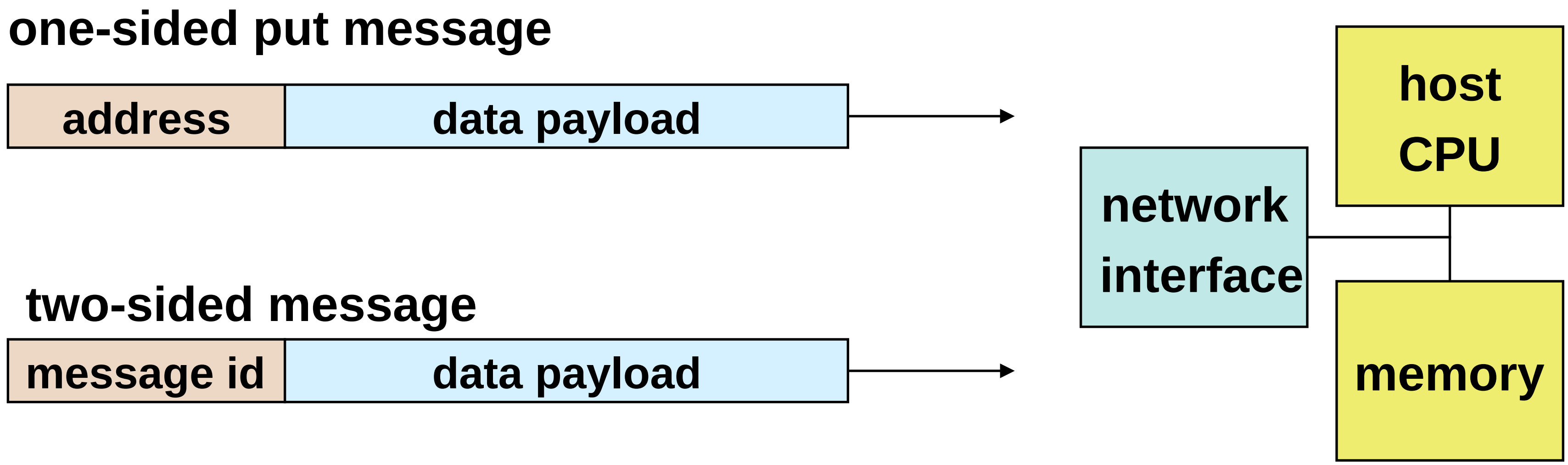
Strategy for acceptance of a new language

- Make it run faster than anything else

Keys to high performance

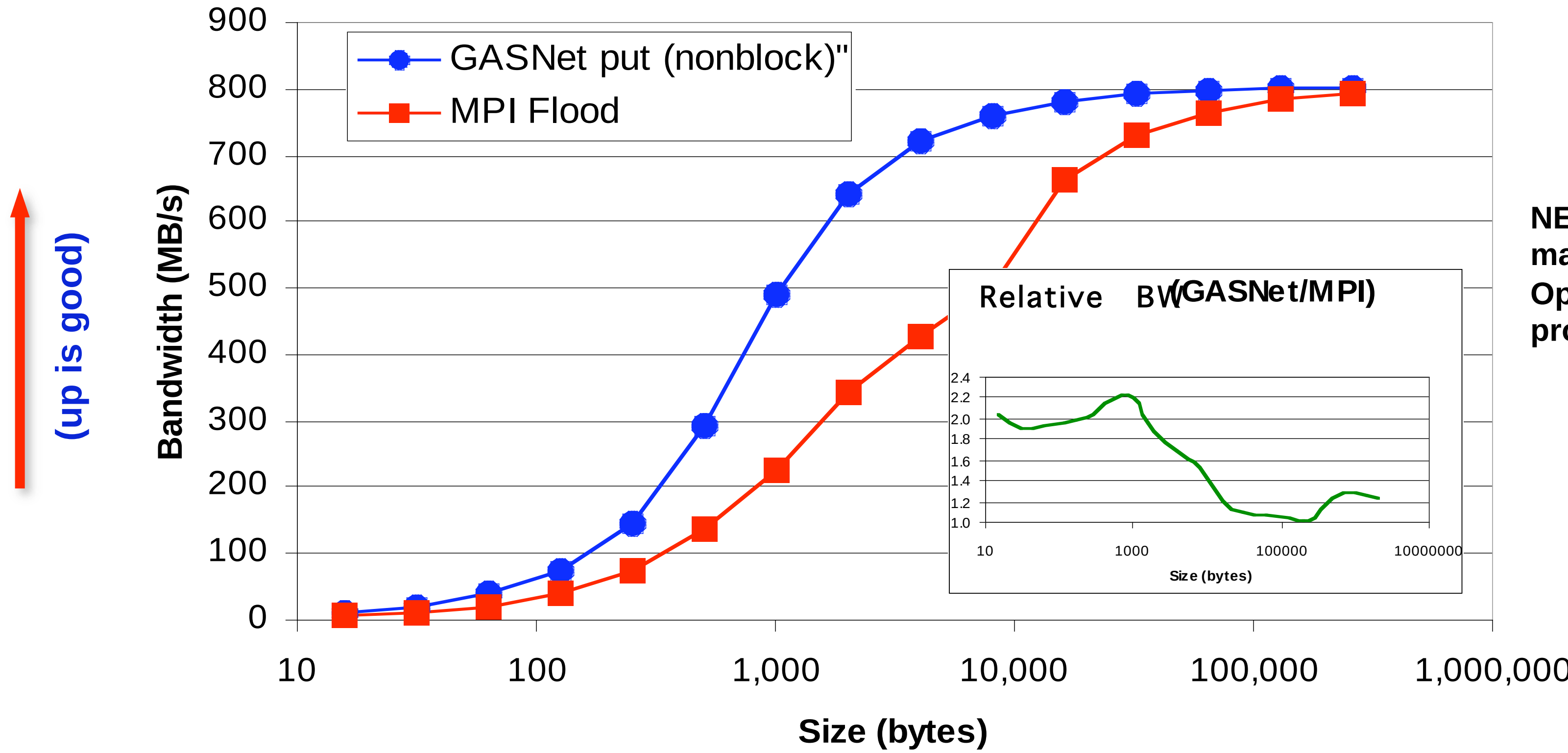
- Parallelism:
  - Scaling the number of processors
- Maximize single node performance
  - Generate friendly code or use tuned libraries (BLAS, FFTW, etc.)
- Avoid (unnecessary) communication cost
  - Latency, bandwidth, overhead
  - Berkeley UPC and Titanium use GASNet communication layer
- Avoid unnecessary delays due to dependencies
  - Load balance; Pipeline algorithmic dependencies

One-Sided vs Two-Sided



- A one-sided put/get message can be handled directly by a network interface with RDMA support
  - Avoid interrupting the CPU or storing data from CPU (preposts)
- A two-sided messages needs to be matched with a receive to identify memory address to put data
  - Offloaded to Network Interface in networks like Quadrics
  - Need to download match tables to interface (from host)
  - Ordering requirements on messages can also hinder bandwidth

One-Sided vs. Two-Sided: Practice

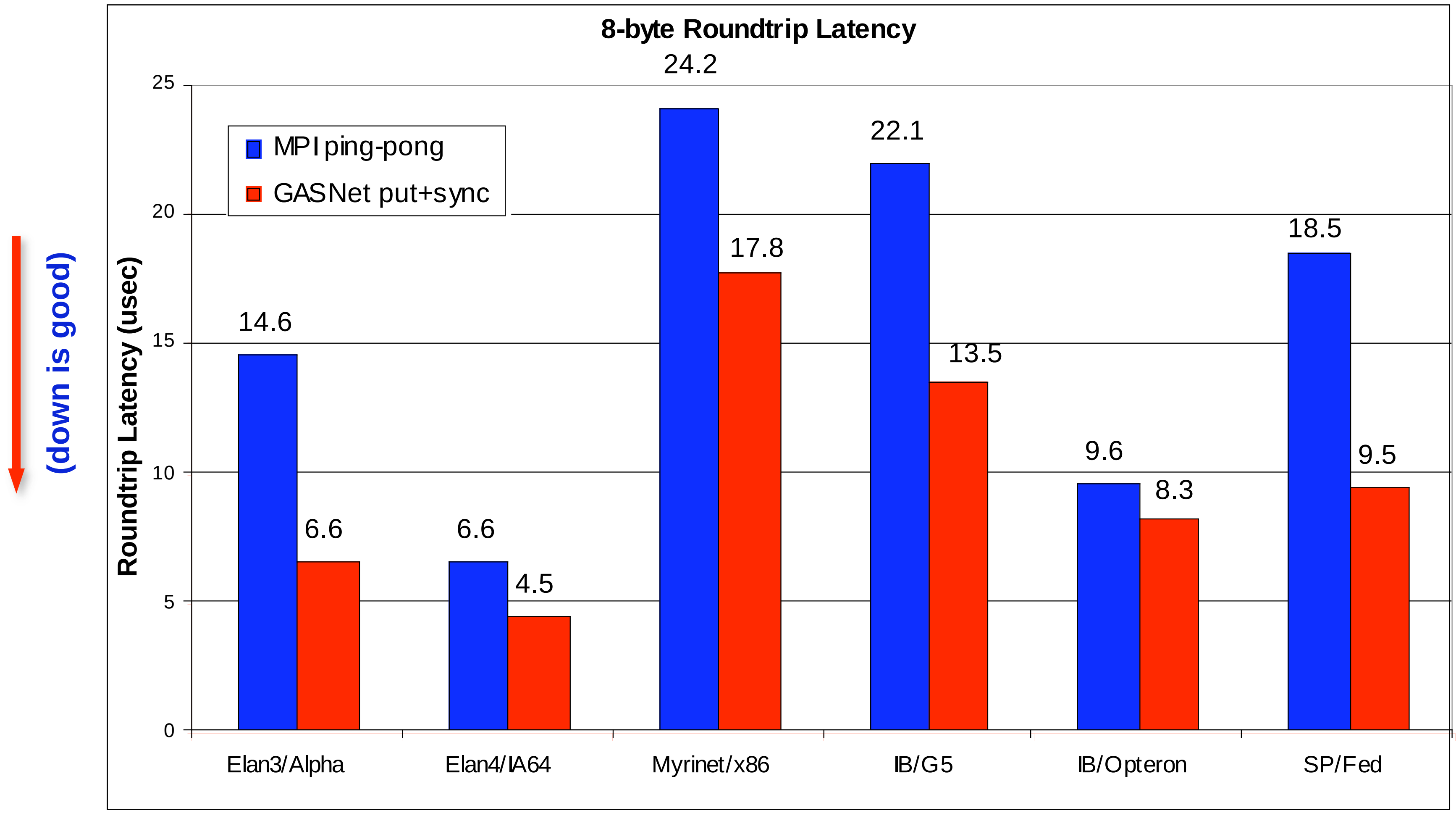


NERSC Jacquard machine with Opteron processors

- InfiniBand: GASNet vapi-conduit and OSU MVAPICH 0.9.5
- Half power point (N ½) differs by *one order of magnitude*
- This is not a criticism of the implementation!

Joint work with Paul Hargrove and Dan Bonachea

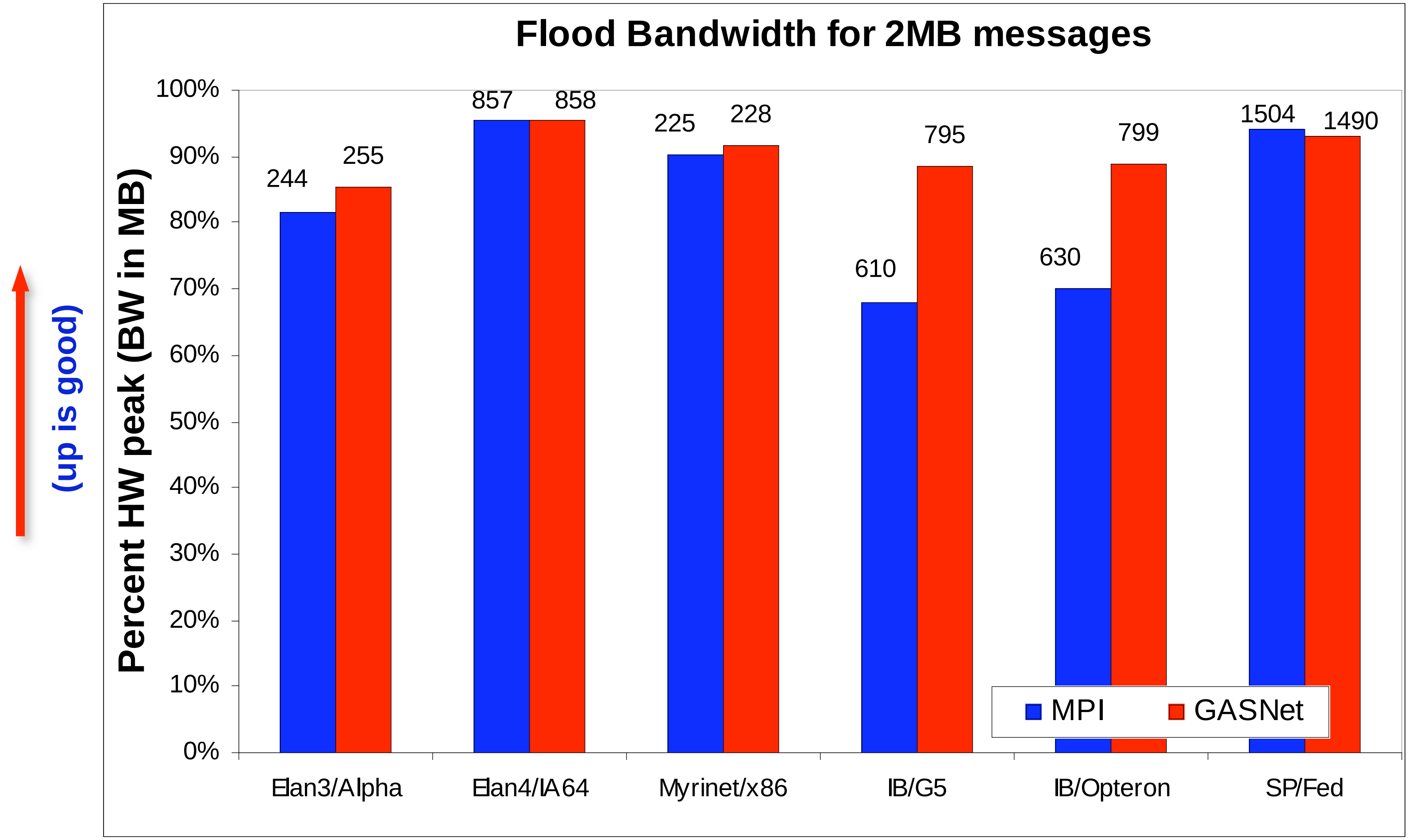
GASNet: Portability *and* High-Performance



GASNet better for latency across machines

Joint work with UPC Group; GASNet design by Dan Bonachea

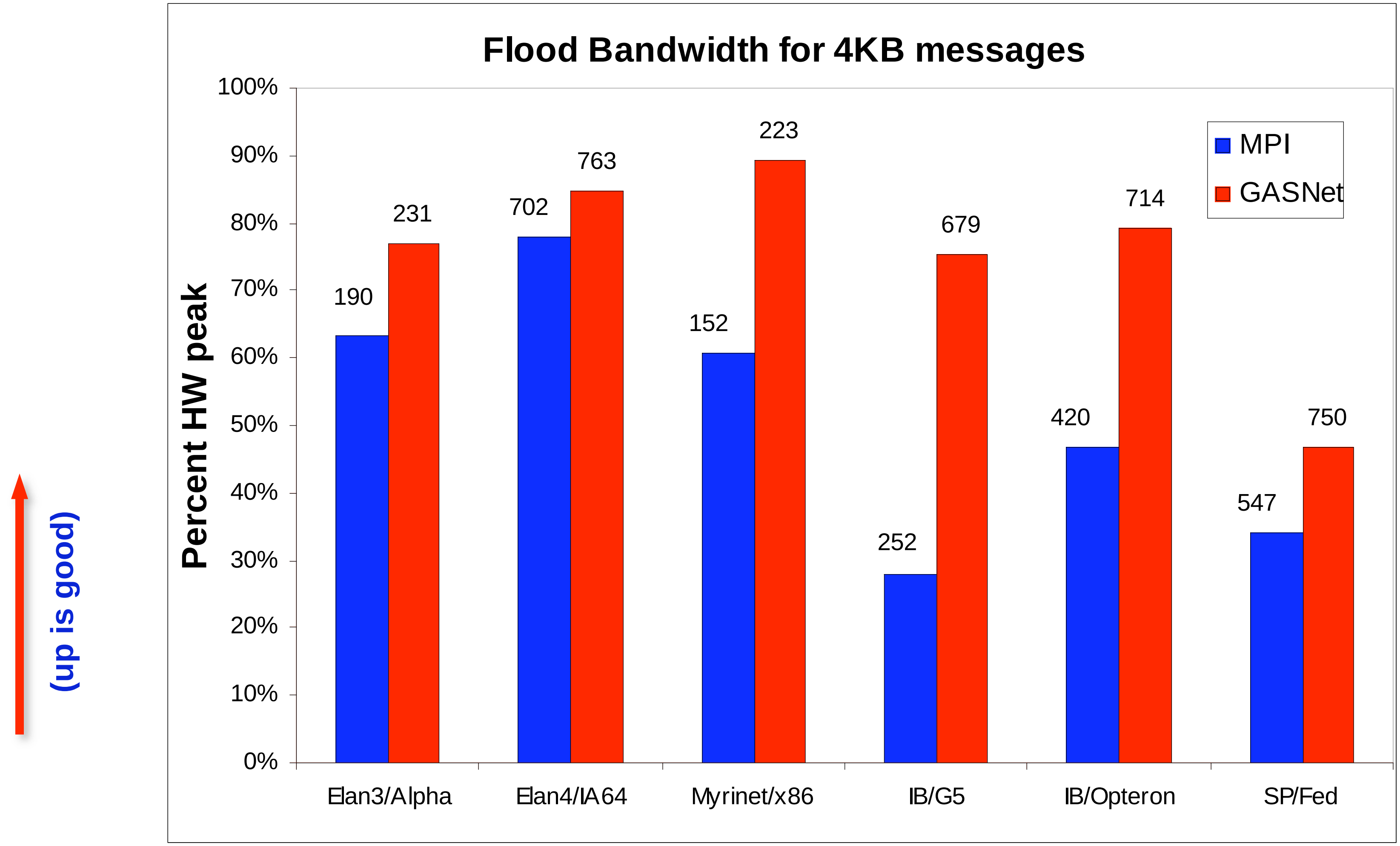
GASNet: Portability *and* High-Performance



GASNet at least as high (comparable) for large messages

Joint work with UPC Group; GASNet design by Dan Bonachea

GASNet: Portability *and* High-Performance

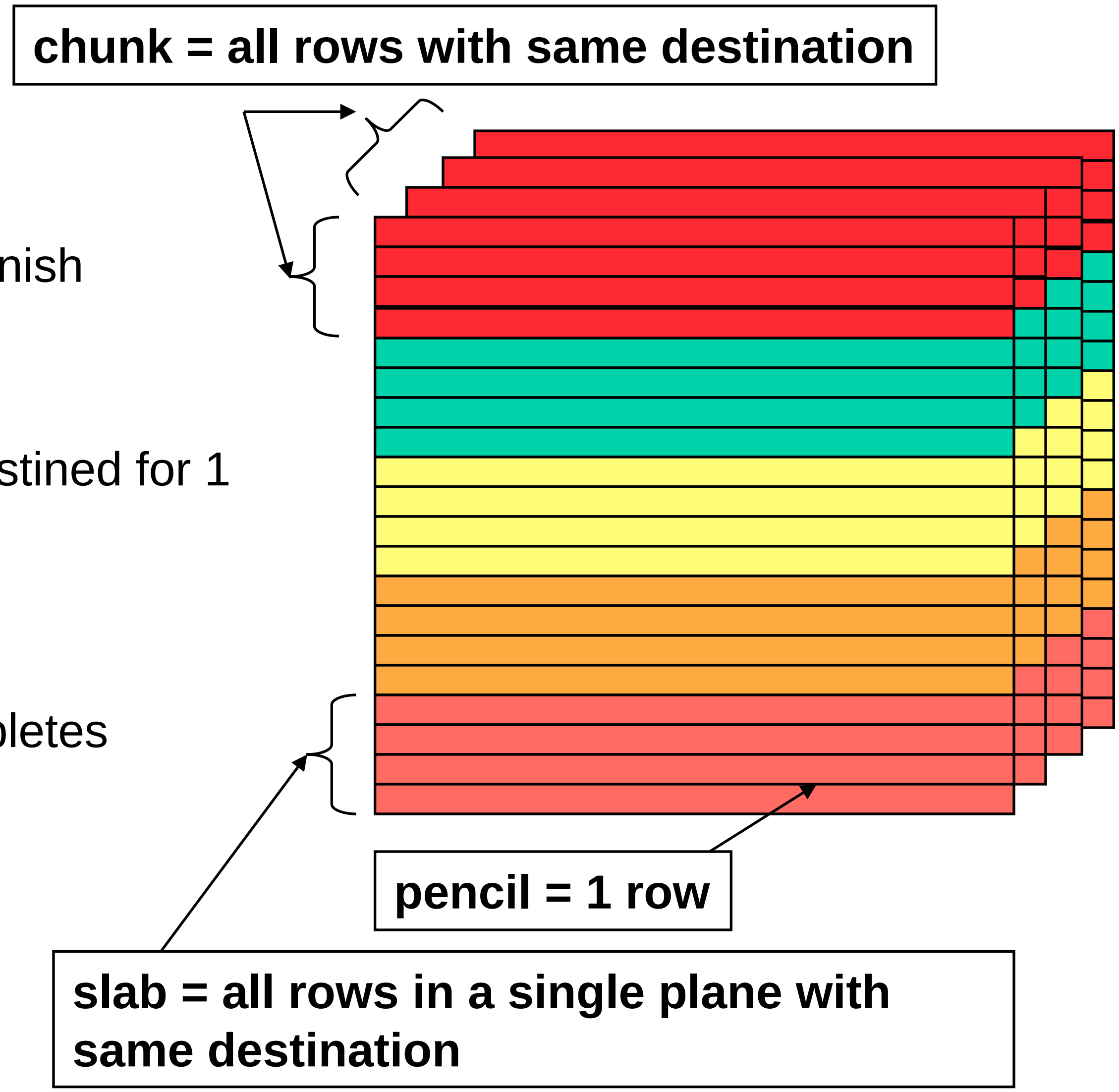


GASNet excels at mid-range sizes: important for overlap

Joint work with UPC Group; GASNet design by Dan Bonachea

Communication Strategies for 3D FFT

- Three approaches:
  - **Chunk:**
    - Wait for 2nd dim FFTs to finish
    - Minimize # messages
  - **Slab:**
    - Wait for chunk of rows destined for 1 proc to finish
    - Overlap with computation
  - **Pencil:**
    - Send each row as it completes
    - Maximize overlap and
    - Match natural layout



Joint work with Chris Bell, Rajesh Nishtala, Dan Bonachea

Overlapping Communication

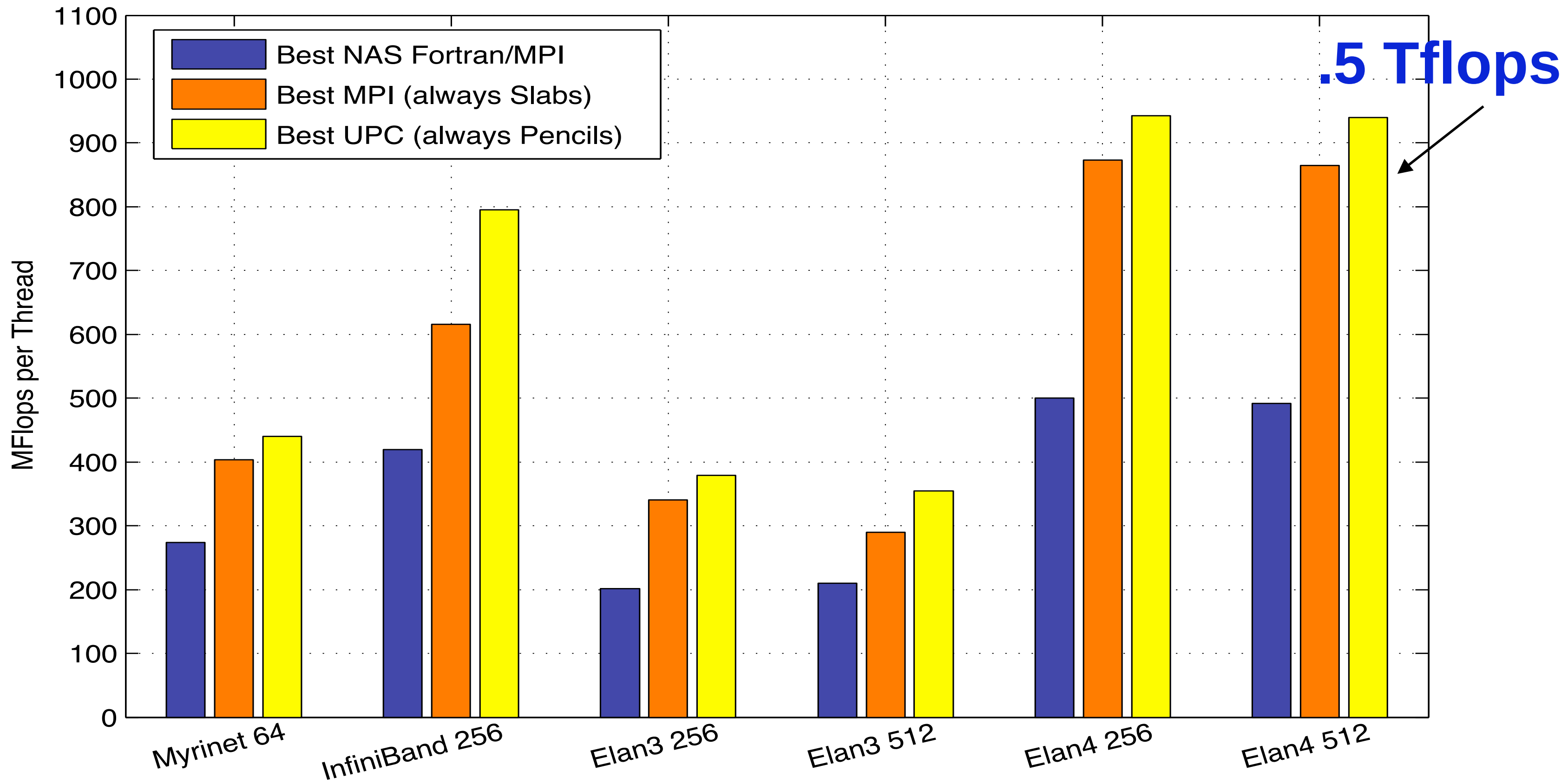
- Goal: make use of “all the wires all the time”
    - Schedule communication to avoid network backup
- Trade-off: overhead vs. overlap
    - Exchange has fewest messages, less message overhead
    - Slabs and pencils have more overlap; pencils the most
- Example: Class D problem on 256 Processors

Exchange (all data at once)	512 Kbytes
Slabs (contiguous rows that go to 1 processor)	64 Kbytes
Pencils (single row)	16 Kbytes

Joint work with Chris Bell, Rajesh Nishtala, Dan Bonachea

NAS FT Variants Performance Summary

-
-



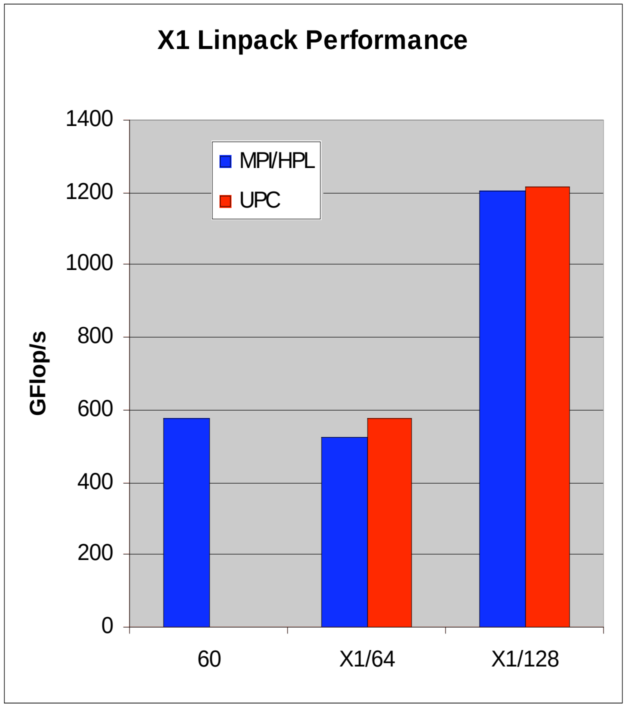
Joint work with Chris Bell, Rajesh Nishtala, Dan Bonachea

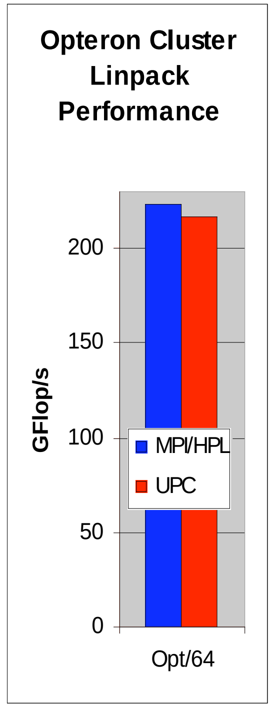
Case Study: LU Factorization

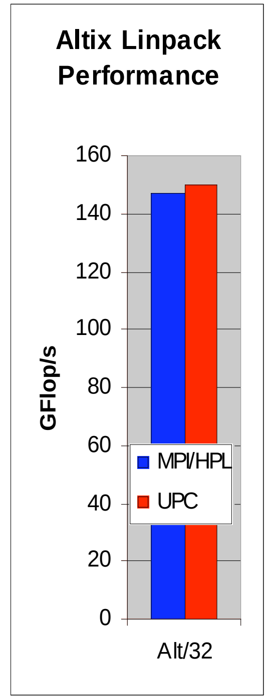
- Direct methods have complicated dependencies
  - Especially with pivoting (unpredictable communication)
  - Especially for sparse matrices (dependence graph with holes)
- LU Factorization in UPC
  - Use overlap ideas and multithreading to mask latency
  - Multithreaded: UPC threads + user threads + threaded BLAS
    - Panel factorization: Including pivoting
    - Update to a block of U
    - Trailing submatrix updates
- Status:
  - Dense LU done: HPL-compliant
  - Sparse version underway

Joint work with Parry Husbands

UPC HPL Performance







- **MPI HPL numbers from HPCC database**
- **Large scaling:**
  - 2.2 TFlops on 512p,
  - 4.4 TFlops on 1024p (Thunder)

- Comparison to ScaLAPACK on an Altix, a 2 x 4 process grid
  - ScaLAPACK (block size 64) 25.25 GFlop/s (tried several block sizes)
  - UPC LU (block size 256) - 33.60 GFlop/s, (block size 64) - 26.47 GFlop/s
- n = 32000 on a 4x4 process grid
  - ScaLAPACK - **43.34 GFlop/s** (block size = 64)
  - UPC - **70.26 Gflop/s** (block size = 200)

Joint work with Parry Husbands

Course Project Ideas

- Work with sparse Cholesky factorization code
  - Uses similar framework to dense LU, but more complicated: sparse, calls Fortran, scheduling TBD
- Experiment with threads package on another problem that has a non-trivial data dependence pattern
- Benchmarking (and tuning) UPC for Multicore / SMPs
  - Comparison to OpenMP and MPI (some has been done)
- Application/algorithm work in UPC
  - Delauney mesh generation
  - “AMR” fluid dynamics

Summary

- UPC designed to be consistent with C
  - Some low level details, such as memory layout are exposed
  - Ability to use pointers and arrays interchangeably
- Designed for high performance
  - Memory consistency explicit
  - Small implementation
- Berkeley compiler (used for next homework)

  http://upc.lbl.gov
- Language specification and other documents

  http://upc.gwu.edu