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
8. Performance Tuning and Early Results
9. Concluding Remarks

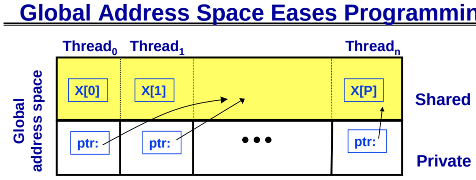
Context

- 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 MPI (performance)
  - local/global distinction, i.e., layout matters (performance)

Partitioned Global Address Space Languages

- Explicitly-parallel programming model with SPMD parallelism
  - Fixed at program start-up, typically 1 thread per processor
- Global address space model of memory
  - Allows programmer to directly represent distributed data structures
- Address space is logically partitioned
  - Local vs. remote memory (two-level hierarchy)
- Programmer control over performance critical decisions
  - Data layout and communication
- Performance transparency and tunability are goals
  - Initial implementation can use fine-grained shared memory
- Multiple PGAS languages: UPC (C), CAF (Fortran), Titanium (Java)

Global Address Space Eases Programming



- The languages share the global address space abstraction
  - Shared memory is logically partitioned by processors
  - Remote memory may stay remote: no automatic caching implied
  - One-sided communication: reads/writes of shared variables
  - Both individual and bulk memory copies
- Languages differ on details
  - Some models have a separate private memory area
  - Distributed array generality and how they are constructed

Current Implementations of PGAS Languages

- A successful language/library must run everywhere
- UPC
  - Commercial compilers available on Cray, SGI, HP machines
  - Open source compiler from LBNL/UCB (source-to-source)
  - Open source gcc-based compiler from Intrepid
- CAF
  - Commercial compiler available on Cray machines
  - Open source compiler available from Rice
- Titanium
  - Open source compiler from UCB runs on most machines
- Common tools
  - Open64 open source research compiler infrastructure
  - ARMCI, GASNet for distributed memory implementations
  - Pthreads, System V shared memory

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

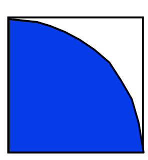
- Any legal C program is also a legal UPC program
- If you compile and run it as UPC with P threads, it will run P copies of the program.
- Using this fact, plus the identifiers from the previous slides, we can parallel hello world:

```
#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
  - π = 4*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);
  }
}
```

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Shared vs. Private Variables

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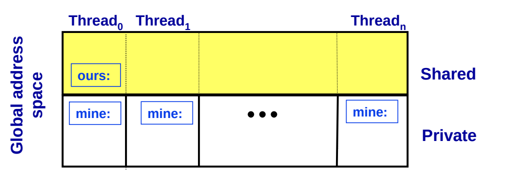
Private vs. Shared Variables in UPC

- 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;  // 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?



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Pi in UPC: Shared Memory Style

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

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

What is the problem with this program?

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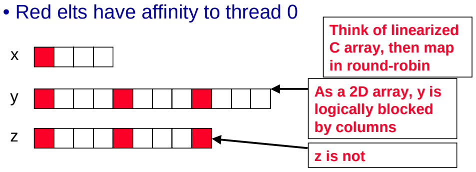
Shared Arrays Are Cyclic By Default

- 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



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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];    // all_hits is shared by all processors, just as hits was
main(int argc, char **argv) {
  ... declarations an initialization code omitted
  for (i=0; i < my_trials; i++)
    all_hits[MYTHREAD] += hit();   // update element with local affinity
  upc_barrier;
  if (MYTHREAD == 0) {
    for (i=0; i < THREADS; i++) hits += all_hits[i];
    printf("PI estimated to %f.", 4.0*hits/trials);
  }
}
```

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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

UPC Collectives

UPC Collectives in General

- The UPC collectives interface is available from:
  - http://www.gwu.edu/~upc/docs/
- 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

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>             Berkeley collectives
// shared int hits;                       no shared variables
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;                       barrier implied by collective
    if (MYTHREAD == 0)
      printf("PI: %f", 4.0*my_hits/trials);
}
```

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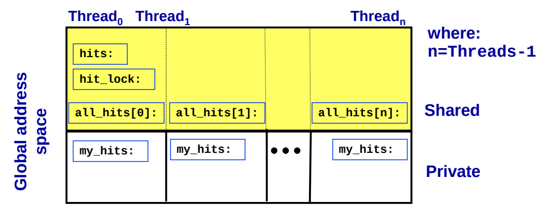
Recap: Private vs. Shared Variables in UPC

- 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`)



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Work Distribution Using `upc_forall`

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

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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)`

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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
                                         The cyclic data
  shared int v1[N], v2[N], sum[N];       distribution may
                                         perform poorly on
  void main() {                          some machines
       int i;
       upc_forall(i=0; i<N; i++; i)
              sum[i]=v1[i]+v2[i];
  }
```

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Distributed Arrays in UPC

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: each thread has a logical chunk
    - Shared memory would have: 0,1,2,…THREADS,THREADS+1,…
  - What performance problem is there with the latter?
  - What is this code was instead doing nearest neighbor averaging?
- Vector addition example can be rewritten as follows

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

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


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

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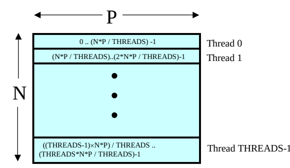
Domain Decomposition for UPC

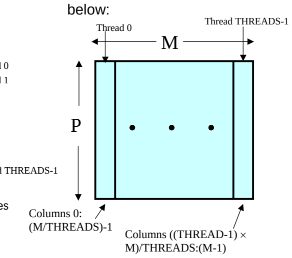
- Exploits locality in matrix multiplication

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



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

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



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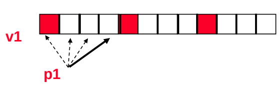
Pointers to Shared vs. Arrays

- 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?

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.

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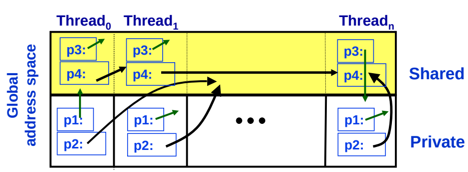
UPC Pointers




```
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

- 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

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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;
```

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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`)

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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

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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

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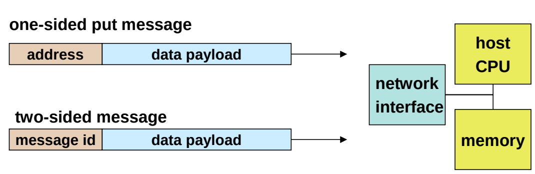
One-Sided vs Two-Sided



- 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

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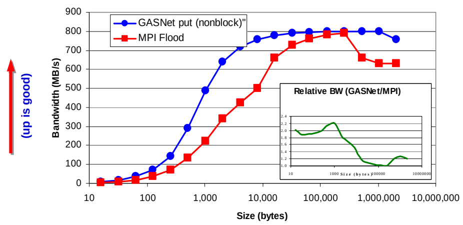
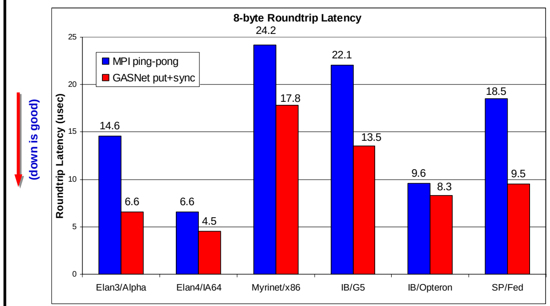
Performance Advantage of One-Sided Communication



- Opteron/InfiniBand (Jacquard at NERSC):
  - GASNet's vapi-conduit and OSU MPI 0.9.5 MVAPICH
  - This is a very good MPI implementation – it's limited by semantics of message matching, ordering, etc.
- Half power point (N ½) differs by *one order of magnitude*

Joint work with Paul Hargrove and Dan Bonachea

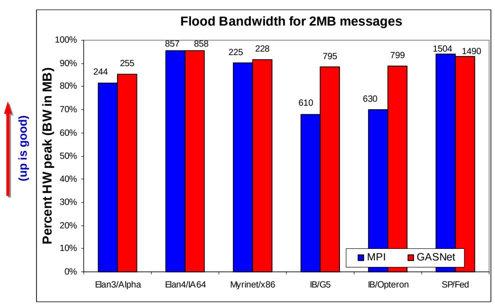
GASNet: Portability *and* High-Performance



GASNet better for latency across machines

Joint work with UPC Group; GASNet design by Dan Bonachea

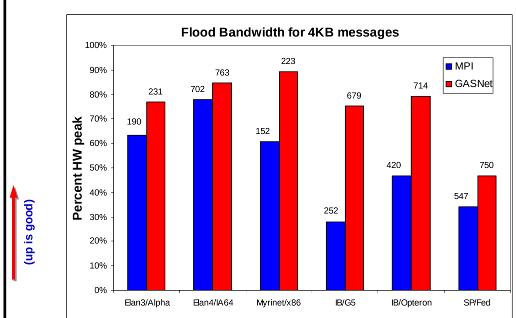
GASNet: Portability *and* High-Performance



GASNet at least as high (comparable) for large messages

Joint work with UPC Group; GASNet design by Dan Bonachea

GASNet: Portability *and* High-Performance

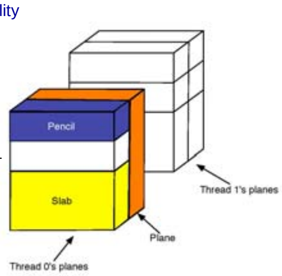


GASNet excels at mid-range sizes: important for overlap

Joint work with UPC Group; GASNet design by Dan Bonachea

Case Study 2: NAS FT

- Performance of Exchange (Alltoall) is critical
  - 1D FFTs in each dimension, 3 phases
  - Transpose after first 2 for locality
  - Bisection bandwidth-limited
    - Problem as #procs grows



- Three approaches:
  - **Exchange:**
    - wait for 2nd dim FFTs to finish, send 1 message per processor pair
  - **Slab:**
    - wait for chunk of rows destined for 1 proc, send when ready
  - **Pencil:**
    - send each row as it completes

Joint work with Chris Bell, Rajesh Nishtala, Dan Bonachea

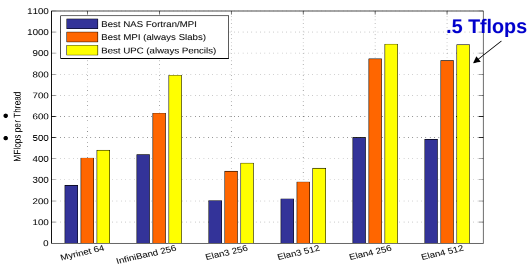
Overlapping Communication

- 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



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Joint work with Chris Bell, Rajesh Nishtala, Dan Bonachea

Case Study 2: 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

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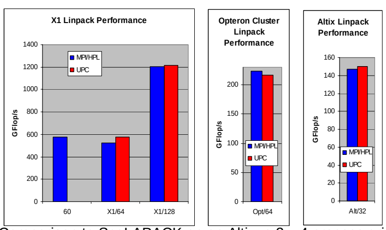
Joint work with Parry Husbands

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

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

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