Unified Parallel C

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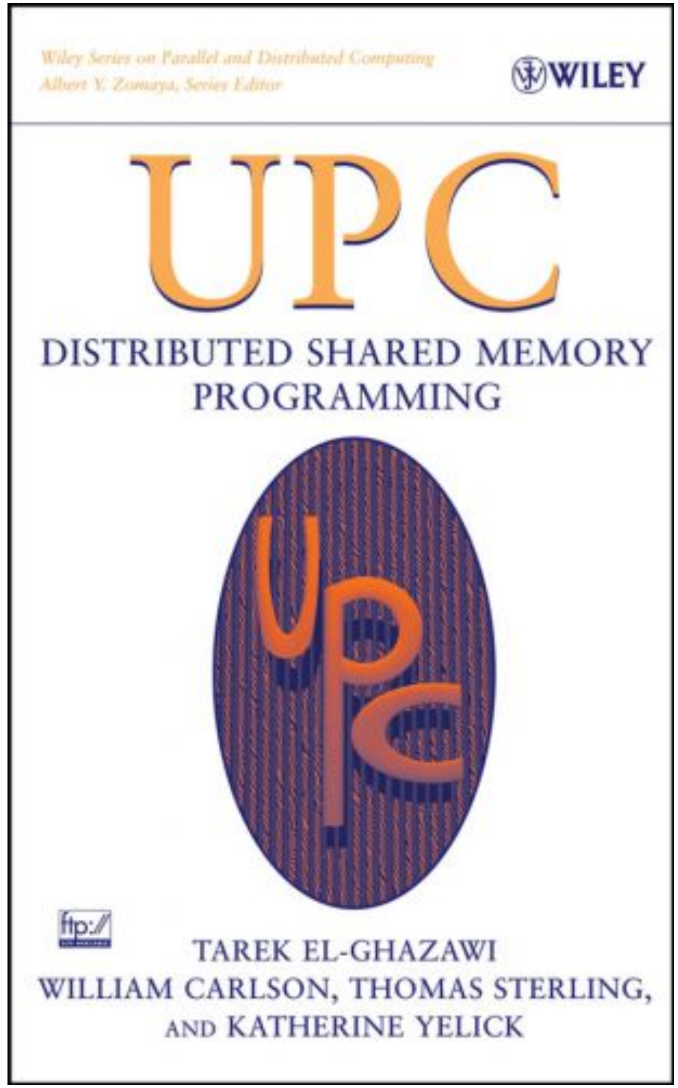
Wiley Series on Parallel and Distributed Computing
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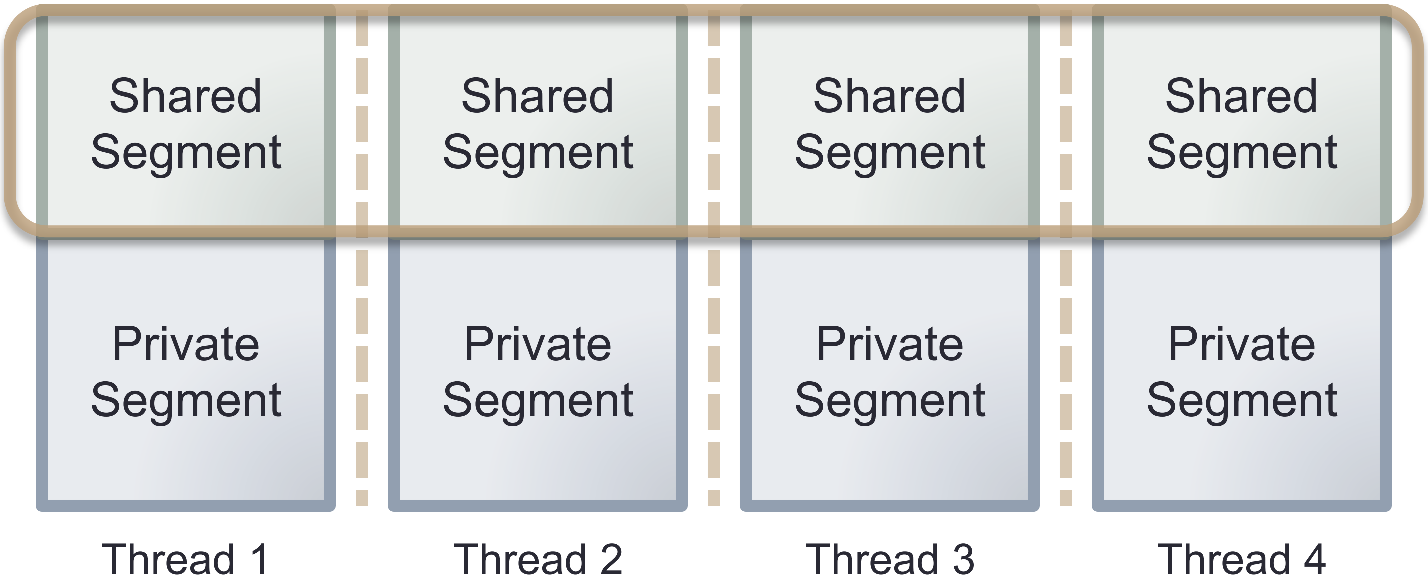
UPC
DISTRIBUTED SHARED MEMORY PROGRAMMING
UPC
TAREK EL-GHAZAWI
WILLIAM CARLSON, THOMAS STERLING,
AND KATHERINE YELICK

Outline

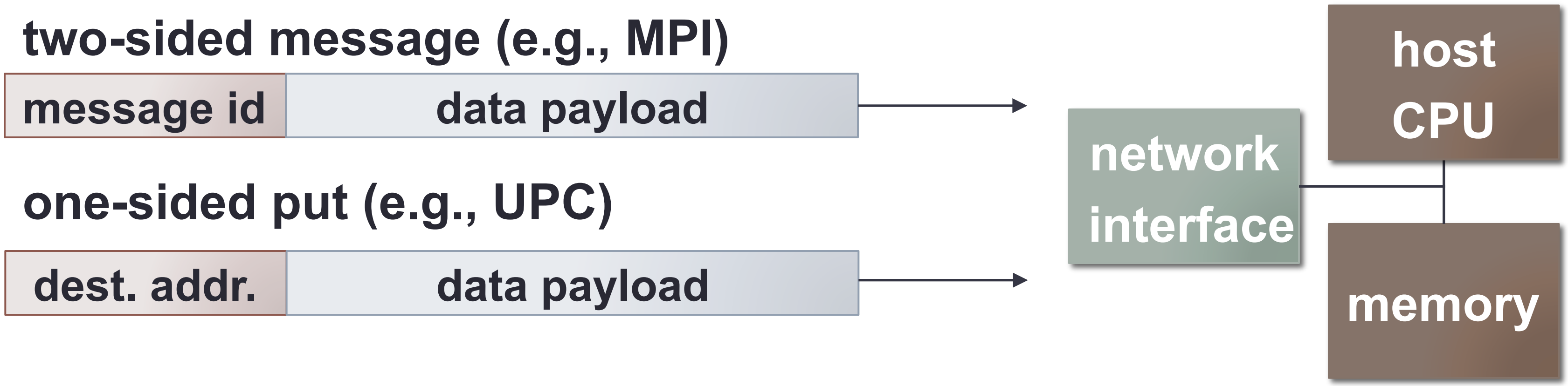
- Overview of UPC
- How does a UPC implementation work
- Examples
- Optimization tips and good practices
- Summary of tools and references

Partitioned Global Address Space In UPC



- Global data view abstraction for productivity
- Vertical partitions among threads for locality control
- Horizontal partitions between shared and private segments for data placement optimizations
- Friendly to non-cache-coherent architectures

One-Sided vs. Two-Sided Messaging



- Two-sided messaging
  - Message does not contain information about the final destination; need to look it up on the target node
  - Point-to-point synchronization implied with all transfers
- One-sided messaging
  - Message contains information about the final destination
  - Decouple synchronization from data movement

Overview of Unified Parallel C

- C99 extension (PGAS C)
  - Partitioned Global Address Space for data sharing
  - One-sided communication (Put/Get, Read/Write)
  - Loop-level parallelism (upc_forall)
- SPMD execution model
  - Total number of threads in the execution: THREADS
  - My thread id (0,…,THREADS-1): MYTHREAD
- Widely available
  - Open source: Berkeley UPC, GCC UPC
  - Commercial: Cray, IBM, HP, SGI
  - Platforms: Shared-memory, Ethernet, Infiniband, Cray, IBM, …

Why Use UPC?

- Pros
  - A global address space for shared-memory programming
  - One-sided communication is a good match for hardware RDMA
  - Can safely reuse non-pthread-safe legacy sequential libraries
- Cons
  - Memory consistency model is complicated
    - Good news: most users don't need to worry for common use patterns
  - Performance tuning is as hard as other programming models

Example: Hello World

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

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

```
> upcc helloworld.upc
> upcrun –n 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
```

How to use UPC on Cray XE / XK

- module swap PrgEnv-pgi PrgEnv-cray
- cc -h upc helloworld.upc
- aprun -n 8 ./a.out

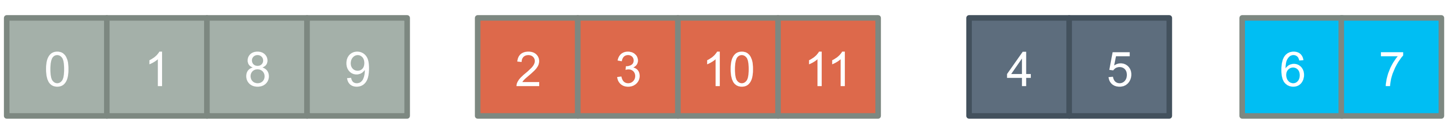
UPC is simple

- 5 necessary keywords:
  - shared
  - upc_fence // non-collective
  - upc_barrier // imply a fence
  - THREADS
  - MYTHREAD
- Communication is implicit
  - shared int s;
  - s = 5; // write (put)
  - a = s; // read (get)

Sharing Data

- Static shared data defined in file scope
  - shared int j; /* shared scalar variable resides on thread 0 */
  - shared int a[10]; /* shared array distributed in round-robin */
- Shared arrays are distributed in a 1-D block-cyclic fashion over all threads
  - shared [blocking_factor] int array[size];
  - Example: shared [2] int b[12]; on 4 UPC threads
    - logical data layout

    - physical data layout



Data Layouts in a Nutshell

- Static non-array objects have affinity with thread 0
- Array layouts are controlled by the blocking factor:
  - Empty or [1] (cyclic layout)

    shared int == shared [1] int
  - [*] (blocked layout)

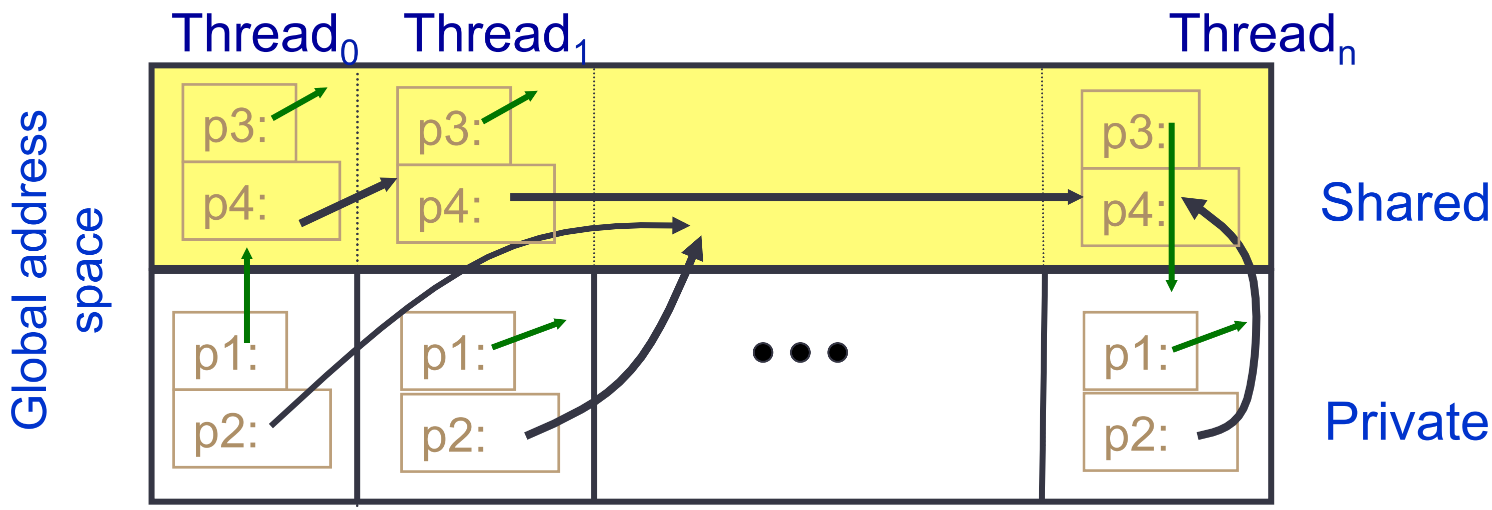
    shared [*] int a[sz] == shared [sz/THREADS] int a[sz]
  - [0] or [] (indefinite layout, all on 1 thread)

    shared [] int == shared [0] int
  - [b] (fixed block size, aka block-cyclic)
- The affinity of an array element A[i] is determined by:

```
(i / block_size) % THREADS
```

- M-D arrays linearize elements in row-major format

UPC Pointers

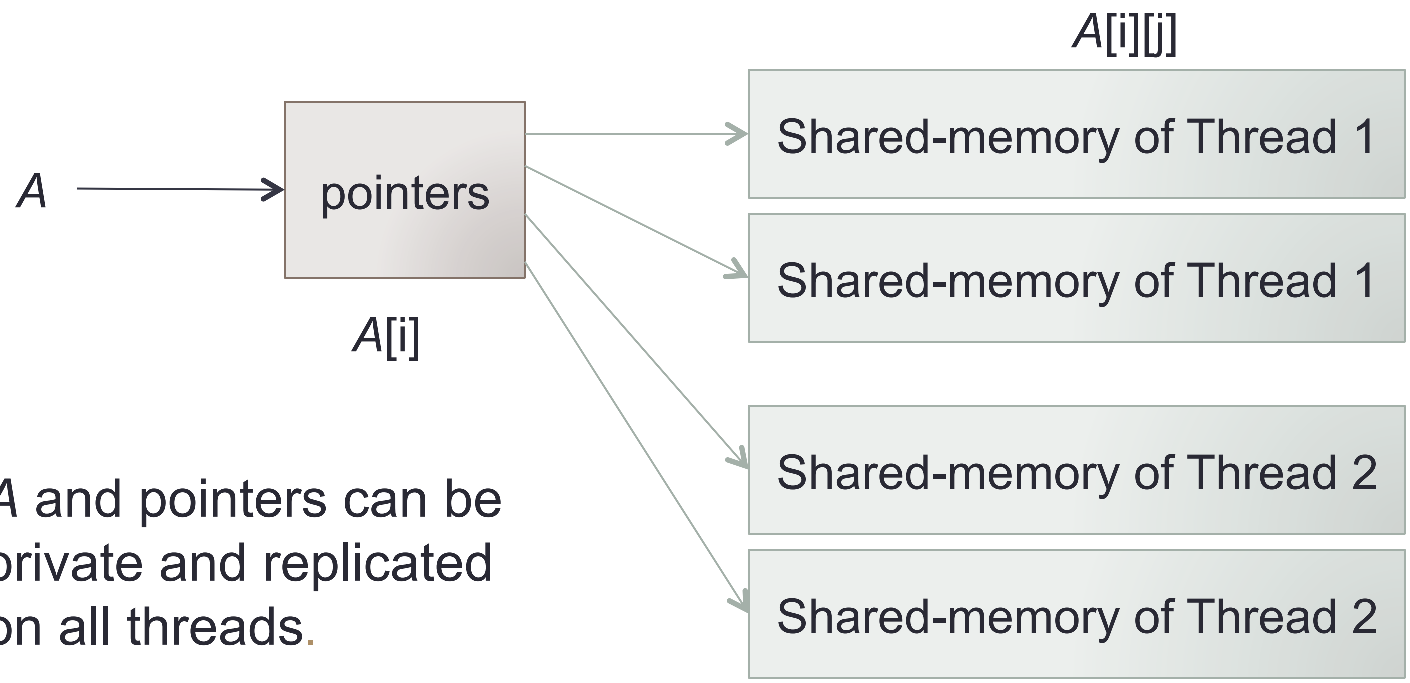



```
int *p1;              /* private pointer to local memory */
shared int *p2; /* private pointer to shared space */
int *shared p3; /* shared pointer to local memory */
shared int *shared p4; /* shared pointer to shared space */
```

Multi-Dimensional Arrays

Static 2-D array: shared [*] double A[M][N];

Dynamic 2-D array: shared [] double **A;



A and pointers can be private and replicated on all threads.

Loop level parallelism

- `upc_forall(init; test; loop; affinity)`
  `statement;`
- upc forall is a collective operation in which, for each execution of the loop body, the controlling expression and affinity expression are single-valued.
- Programmer asserts that the iterations are independent
- Affinity expression indicates which iterations will run on each thread. It may have one of two types:
  - Integer: `(affinity%THREADS) == MYTHREAD`
  - Pointer: `upc_threadof(affinity) == MYTHREAD`

```
upc_forall(i=0; i<N; i++; i)
      stmt;
equivalent to
for(i=0; i<N; i++)
      if (MYTHREAD == i % THREADS) stmt;
```

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);`
  collective call - allocates 1 lock, same pointer to all threads
  `upc_lock_t *upc_global_lock_alloc(void);`
  non-collective - allocates 1 lock per caller
- 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);`

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;
}
```

Bulk Data Movement and Nonblocking Communication

- Loops to perform element-wise data movement could potentially be slow because of network traffic per element
- Language introduces variants of memcpy to address this issue:

```
upc_memcpy (shared void * restrict dst,
            shared const void * restrict src, size_t n)
upc_memput (shared void * restrict dst,
            const void * restrict src, size_t n)
upc_memget (void * restrict dst,
            shared const void * restrict src, size_t n)
```

Data Movement Collectives

- upc_all_broadcast(shared void* dst, shared void* src, size_t nbytes, …)
- upc_all_scatter(shared void* dst, shared void *src, size_t nbytes, …)
- upc_all_gather(shared void* dst, shared void *src, size_t nbytes, …)
- upc_all_gather_all(shared void* dst, shared void *src, size_t nbytes, …)
- upc_all_exchange(shared void* dst, shared void *src, size_t nbytes, …)
- 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]

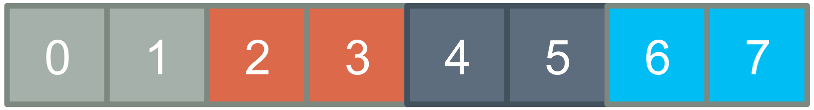
Computational Collectives

upc_all_reduceT(shared void* dst, shared void* src, upc_op_t op, …)

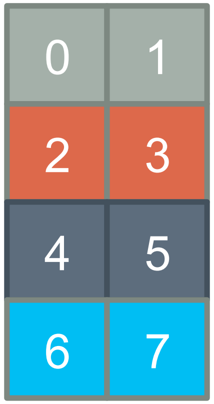
- data type T: char, short, int, float, double, long long double,…
- upc_op_t: +, *, &, |, xor, &&, ||, min, max

upc_all_reduceT computes:

$$\sum_{i=0}^{7} A[i]$$



Not



upc_all_prefix_reduceT(shared void* dst, shared void *src, upc_op_t op, …)

Example: Jacobi (5-point stencil)

```
shared [ngrid*ngrid/THREADS] double u[ngrid][ngrid];
shared [ngrid*ngrid/THREADS] double unew[ngrid][ngrid];
shared [ngrid*ngrid/THREADS] double f[ngrid][ngrid];

upc_forall( int i=1; i<n; i++; &unew[i][0] ) {
    for(int j=1; j<n; j++) {
      utmp = 0.25 * (u[i+1][j] + u[i-1][j] + u[i][j+1] + u[i][j-1] -
                 h*h*f[i][j]); /* 5-point stencil */
      unew[i][j] = omega * utmp + (1.0-omega)*u[i][j];
    }
  }
```

- Good spatial locality
- Mostly local memory accesses
- No explicit communication ghost-zone management

T0	T0	T0	T0
T1	T1	T1	T1
T2	T2	T2	T2
T3	T3	T3	T3

Example: Random Access (GUPS)

```
shared uint64 Table[TableSize]; /* cyclic distribution */
uint64 i, ran;

/* owner computes, iteration matches data distribution */
upc_forall (i = 0; i < TableSize; i++; i)    Table[i] = i;

upc_barrier; /* synchronization */

ran = starts(NUPDATE / THREADS * MYTHREAD); /* ran. seed */

for (i = MYTHREAD; i < NUPDATE; i+=THREADS) /* SPMD */
  {
    ran = (ran << 1) ^ (((int64_1) ran < 0) ? POLY : 0);
    Table[ran & (TableSize-1)] = Table[ran & (TableSize-1)] ^ ran;
  }
upc_barrier; /* synchronization */
```

The MPI version is about 150 lines due to message aggregation.

UPC Compiler Implementation

Source-to-source translator

UPC code

↓

UPC source-to-source translator

↓

C code

- Pros: portable
- Cons: may lose program information in two-phase compilation
- Example: Berkeley UPC

Source-to-object-code compiler

UPC code

↓

UPC source-to-object code complier

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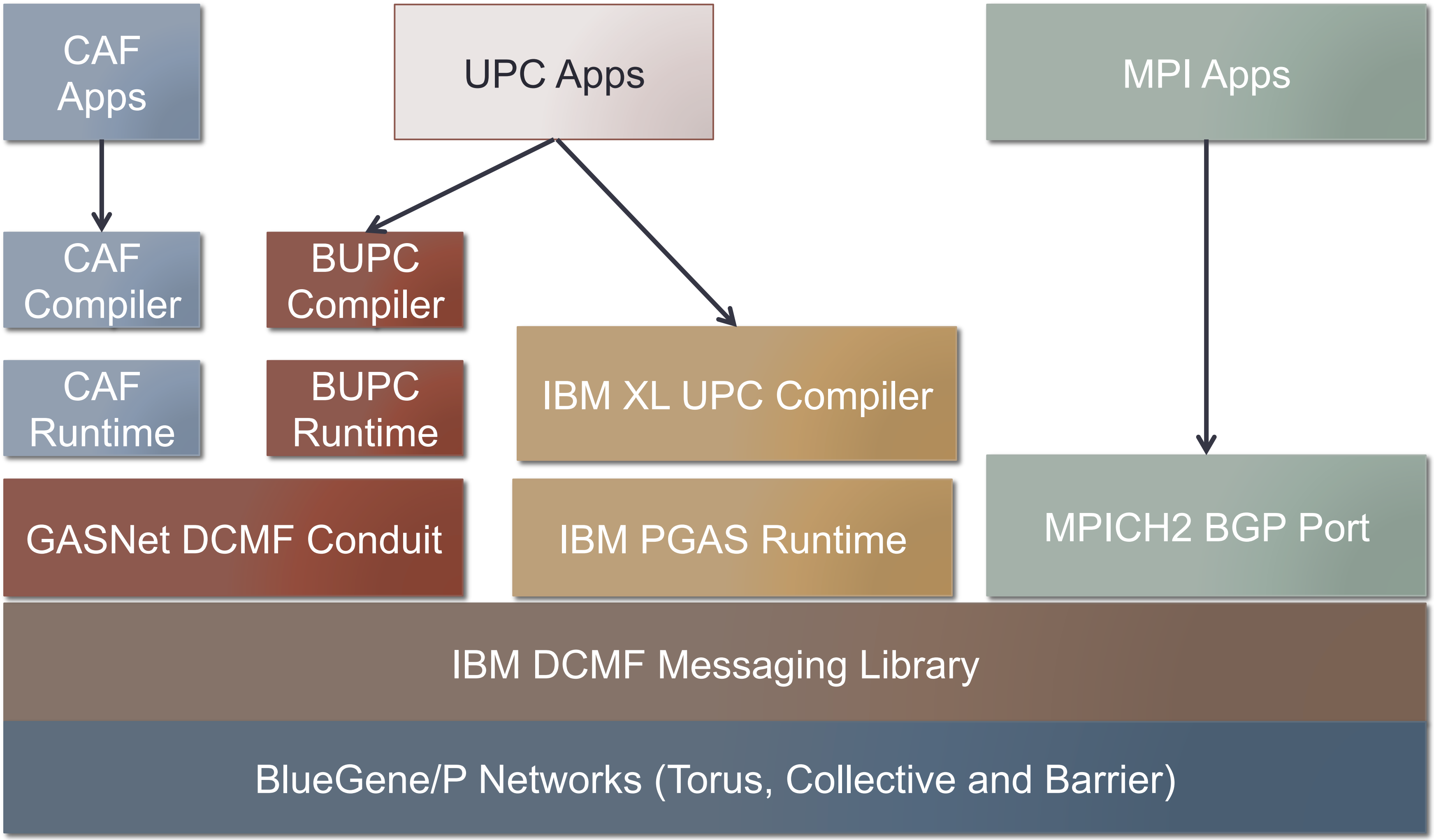
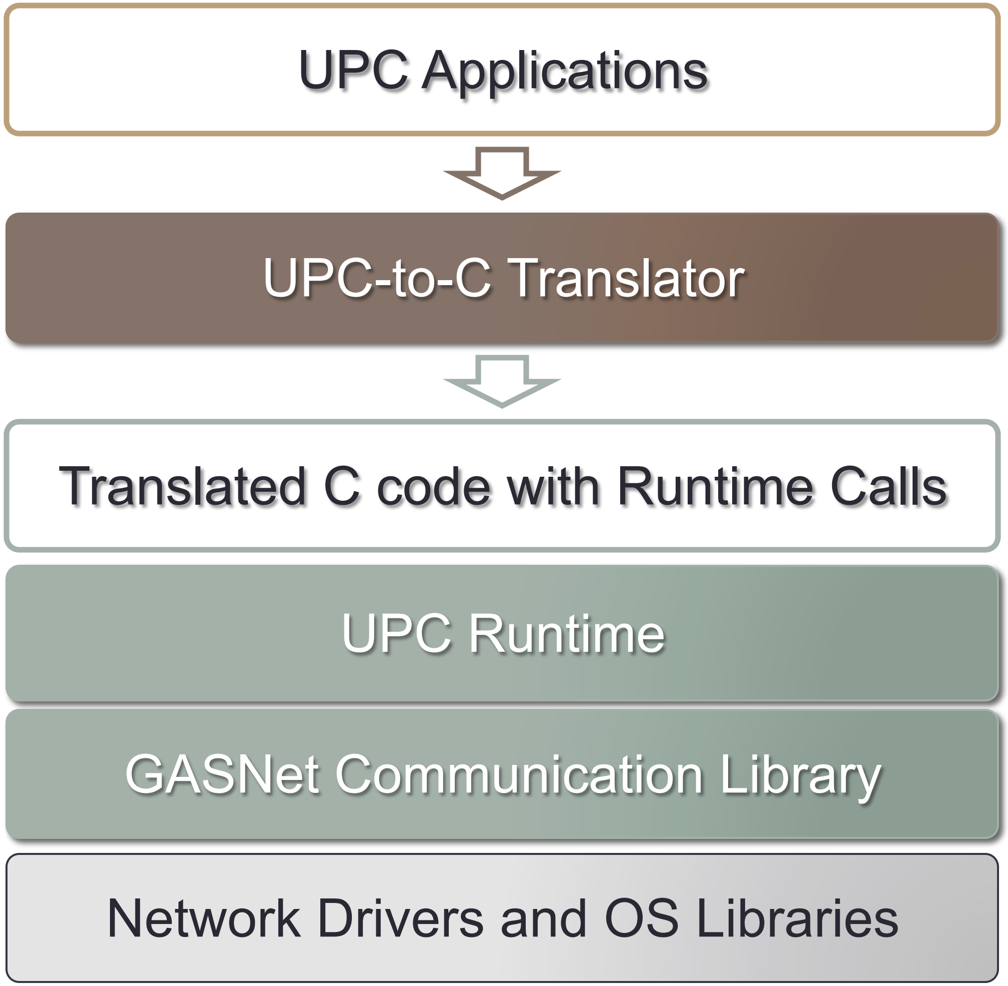
Assembly code

- Pros: easier to implement UPC specific optimization
- Cons: less portable
- Example: GCC UPC and most vendor UPC

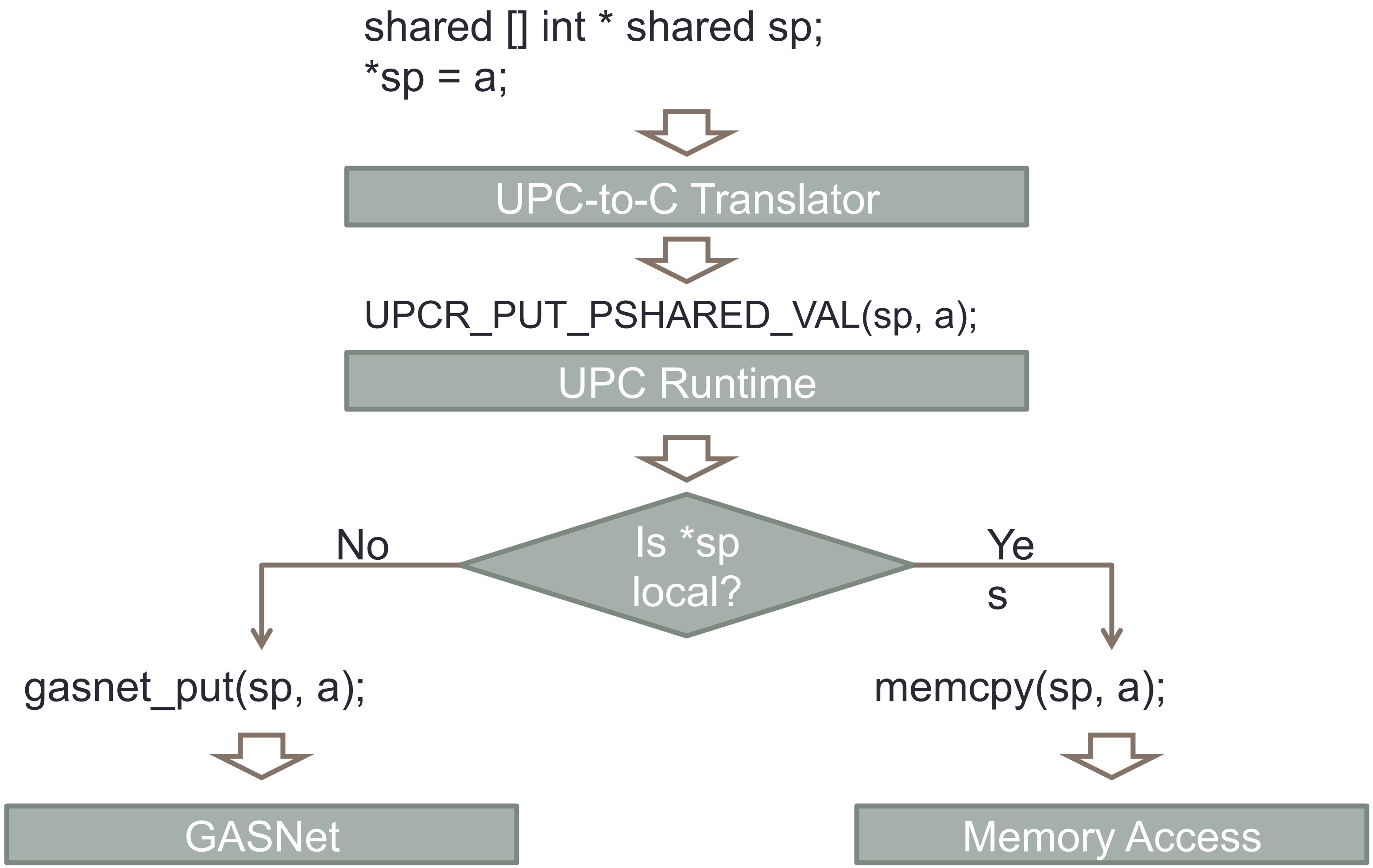
Programming models on BlueGene/P



Berkeley UPC Software Stack



Translation and Call Graph Example



Casting Shared-Pointer to Local

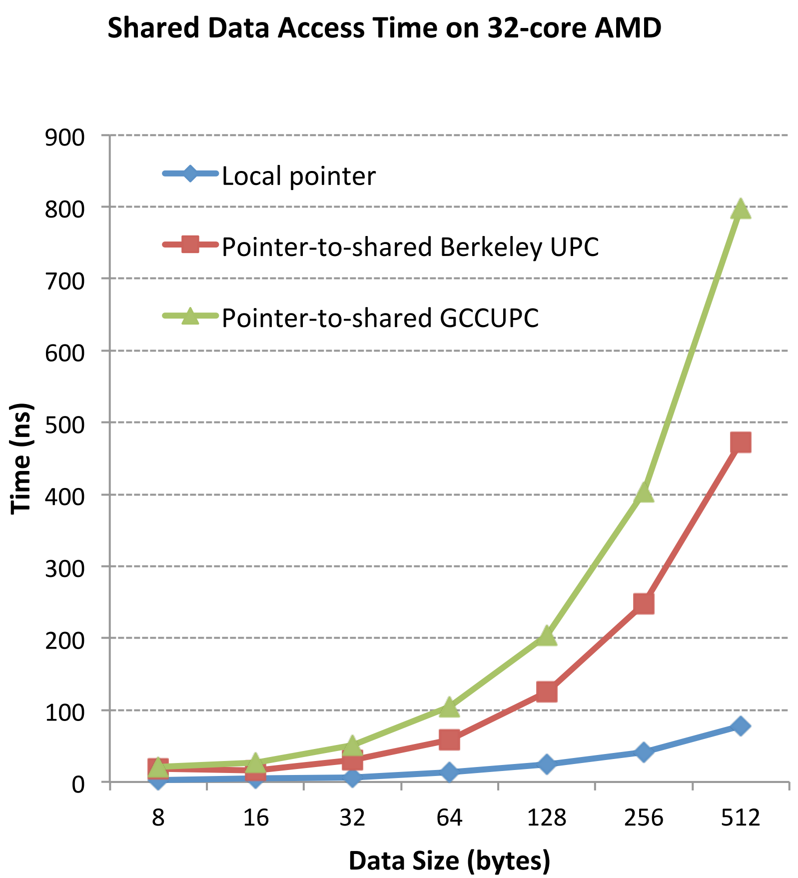
Kernel code of the STREAM benchmark using shared-pointers

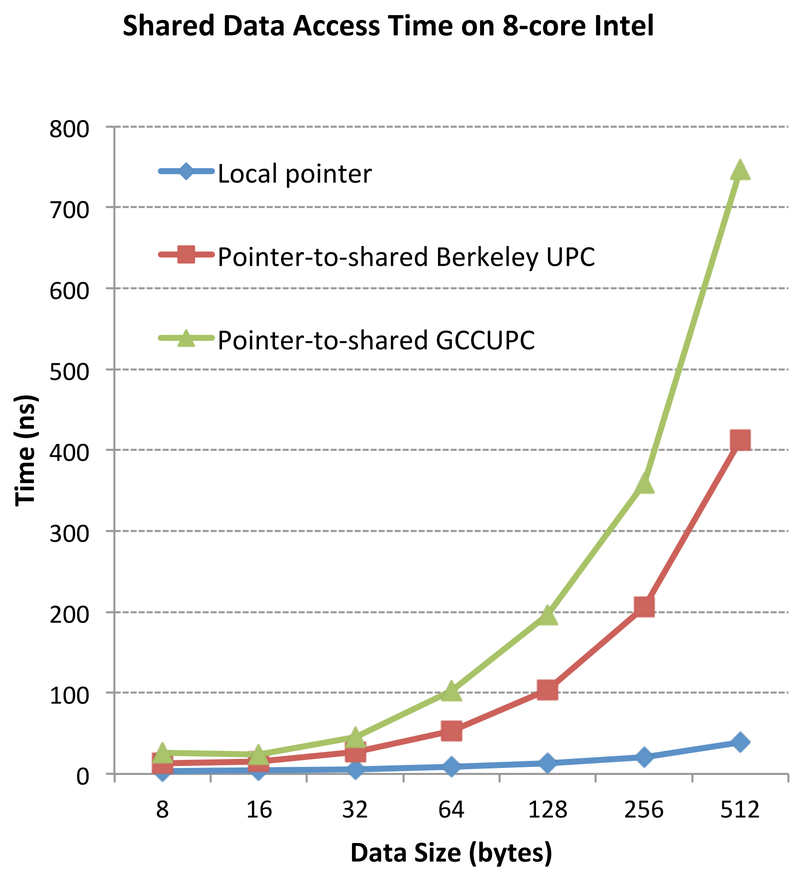
```
shared [] double *sa, *sb, *sc;
for (i=0; i<nelems; i++) {
  sa[i] = sb[i] + alpha * sc[i];
}
```

Kernel code of the STREAM benchmark using local pointers

```
shared [] double *sa, *sb, *sc;
double *a, *b, *c;
a=(double *)sa; b=(double *)sb; c=(double *)sc;
for (i=0; i<nelems; i++) {
  a[i] = b[i] + alpha * c[i];
}
```

Shared Data Access Performance: Local Pointer vs. Pointer-to-shared





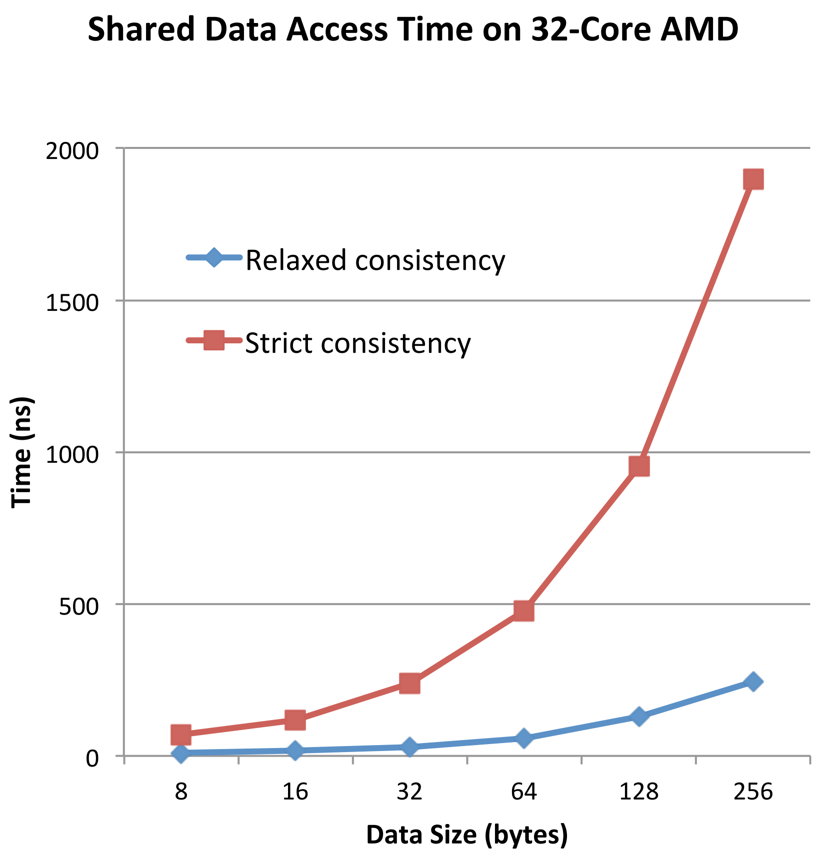
Use Physical Shared-Memory for Inter-Process Communication

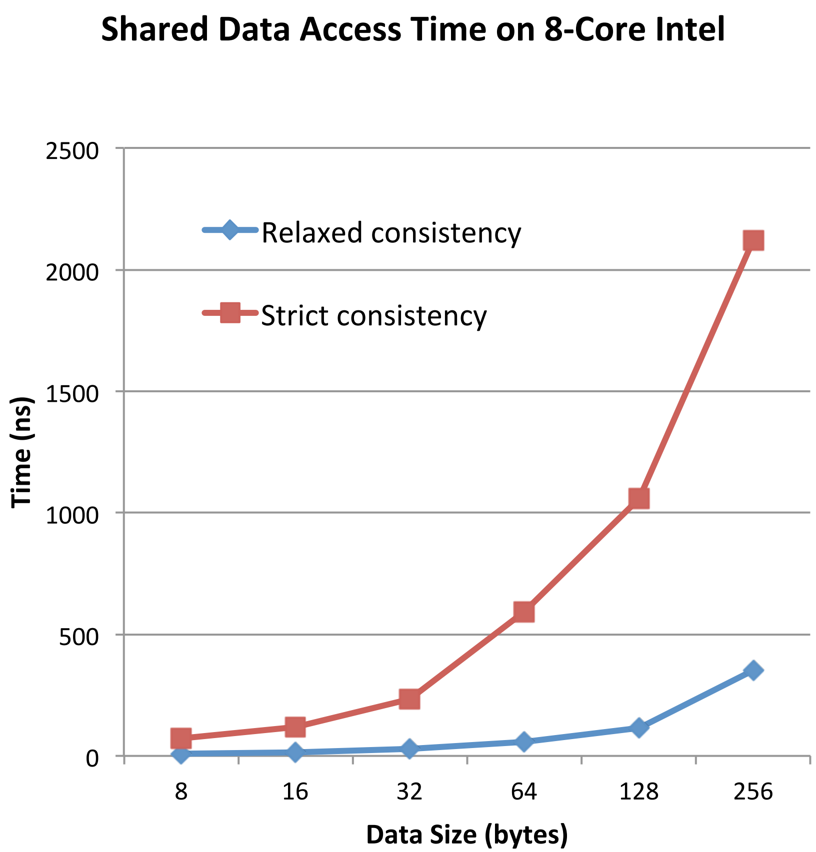
- Cast a pointer-to-shared affined to another thread but can be accessed directly by hardware load and store
  - void * upc_cast(shared void *ptr);
  - Castability query:
    - int upc_castable(shared void *ptr);
    - int upc_thread_castable(unsigned int threadnum);
- Implemented by cross-mapping physical memory to virtual address spaces of all processes sharing the node
- Save memory space and copy overheads that would be otherwise introduced by bounce-buffers

Memory Consistency Models

- UPC supports two memory consistency models: strict and relaxed
- Strict consistency
  - **Usage: #pragma upc strict** or **strict shared [ ] double *sa;**
  - Provide a total ordering for all memory accesses
  - Easy to reasoning about but takes a huge performance penalty
- Relaxed consistency
  - **Usage: #pragma upc relaxed** or **relaxed shared [ ] double *sa;**
  - Allow concurrent and out-of-order data accesses within a synchronization phase
  - Deliver better performance but may introduce data races if synchronization is done correctly
- In practice
  - Use the relaxed consistency model (default) until encountering errors
  - Use the strict consistency model for testing and debugging

Memory Consistency Performance: Relaxed vs. Strict





Example: Matrix Transpose

```
shared double *sa, *sb;
size_t N;

upc_forall(i=0; i<N; i++; i)
{
    for (j=0; j<N; j++)
    {
        ij = i*N+j;
        ji = j*N+i;
        sb[ij] = sa[ji];
    }
  }
```

- Global array view may tempt you to use a naïve implementation
- Correct but very poor performance
  - All fine-grained accesses
  - No data locality
  - Difficult to vectorize

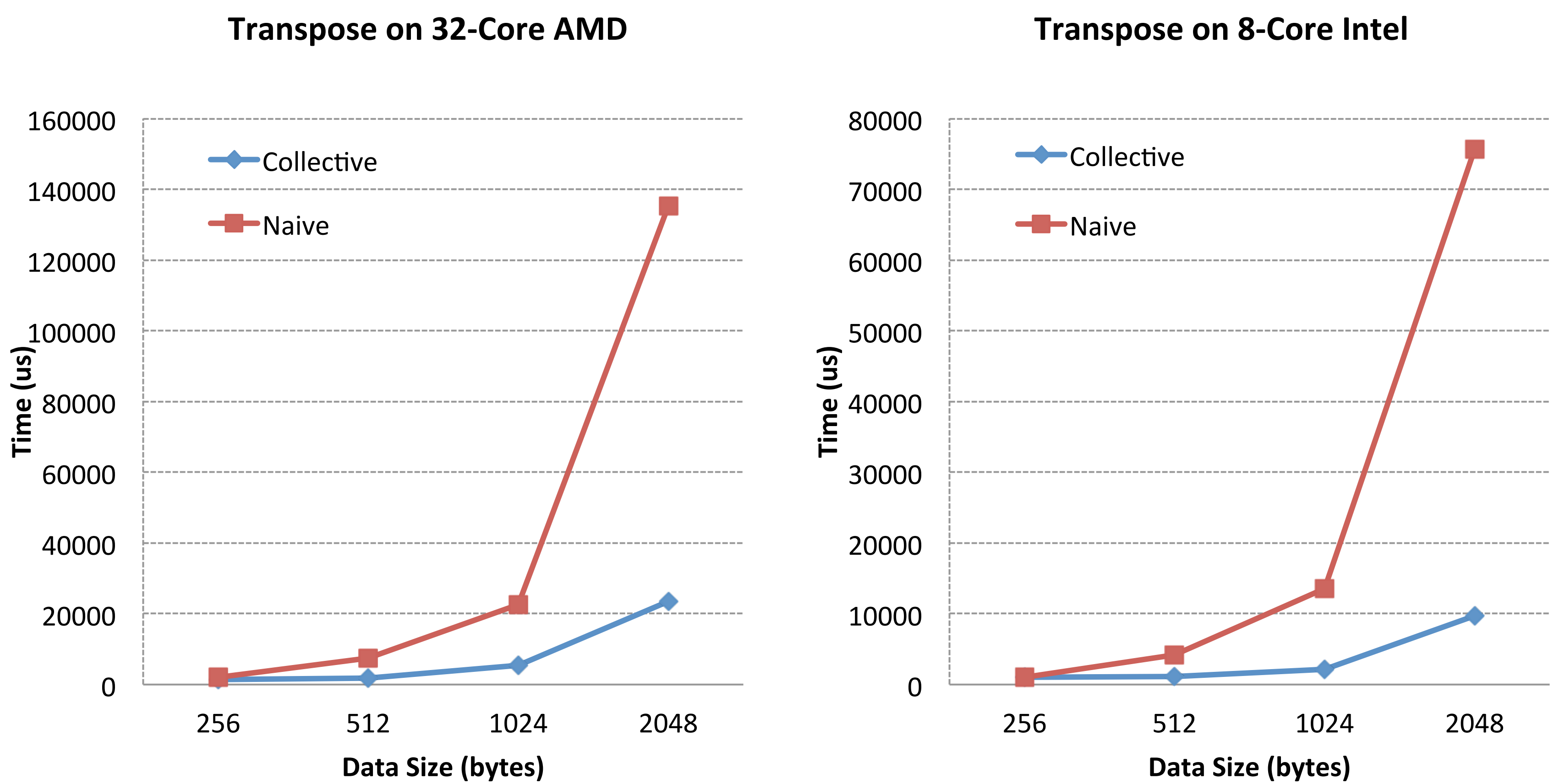
Example: Optimized Matrix Transpose

- Use a block data layout
- Transpose data blocks by a collective operation
- Transpose the elements in the block locally

```
B = N/THREADS;
nbytes = sizeof(double)*B*B;
upc_all_exchange(sb, sa, nbytes, UPC_IN_MYSYNC|UPC_OUT_MYSYNC);

/* local transpose */
for (t=0; t<THREADS; t++) {
  la = (double *)&sa[MYTHREAD] + B*B*t;
  lb = (double *)&sb[MYTHREAD] + B*B*t;
  local_transpose(la, lb, B);
}
```

Matrix Transpose Performance



Example : Matrix Multiplication

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

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

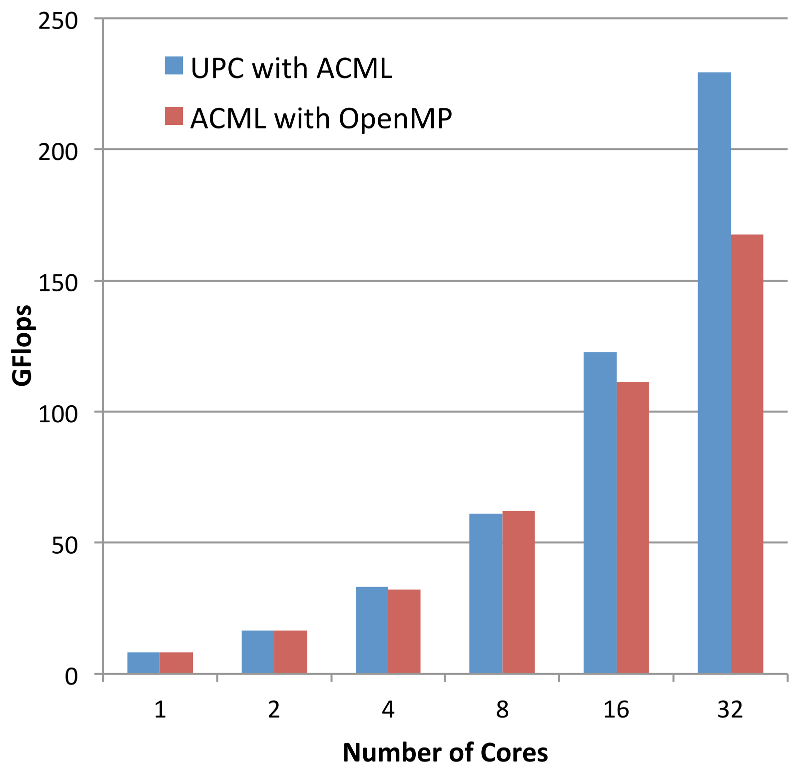
- Naïve implementation is very slow
  - Many fine-grained remote accesses
  - Recurring overheads in access through pointers-to-shared
  - Do not have optimization for the sequential part, such as register blocking , cache blocking and vectorization
- But it is really simply to write if you don’t care about performance (such as in prototyping or non-critical path)

Optimized UPC Parallel DGEMM

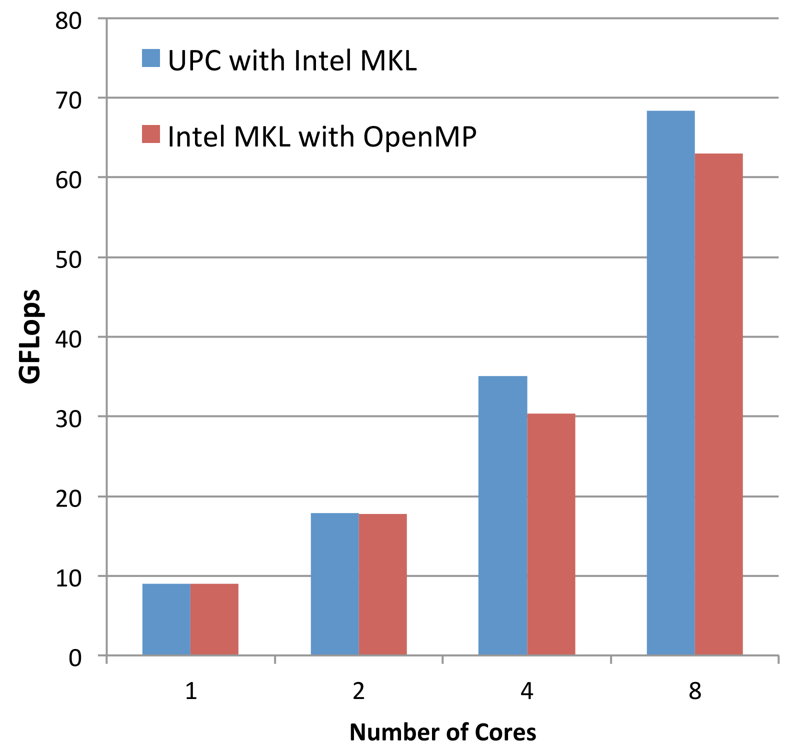
- 2-D block-cyclic data layout
- Use parallel algorithms such as SUMMA
- Transfer data in large blocks
- Use optimized BLAS dgemm (e.g., Intel MKL)
- Use non-blocking collective communication if available (e.g., row and column broadcasts)

Matrix Multiplication Performance

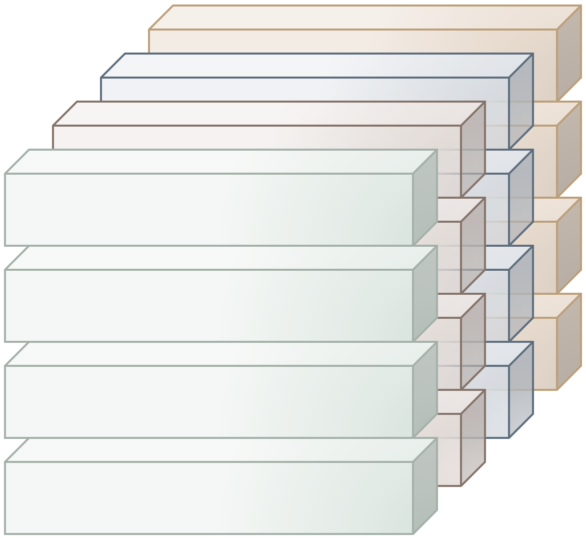
32-Core AMD (Opteron 8387)



8-Core Intel (Xeon E5530)



Example: 3-D FFT



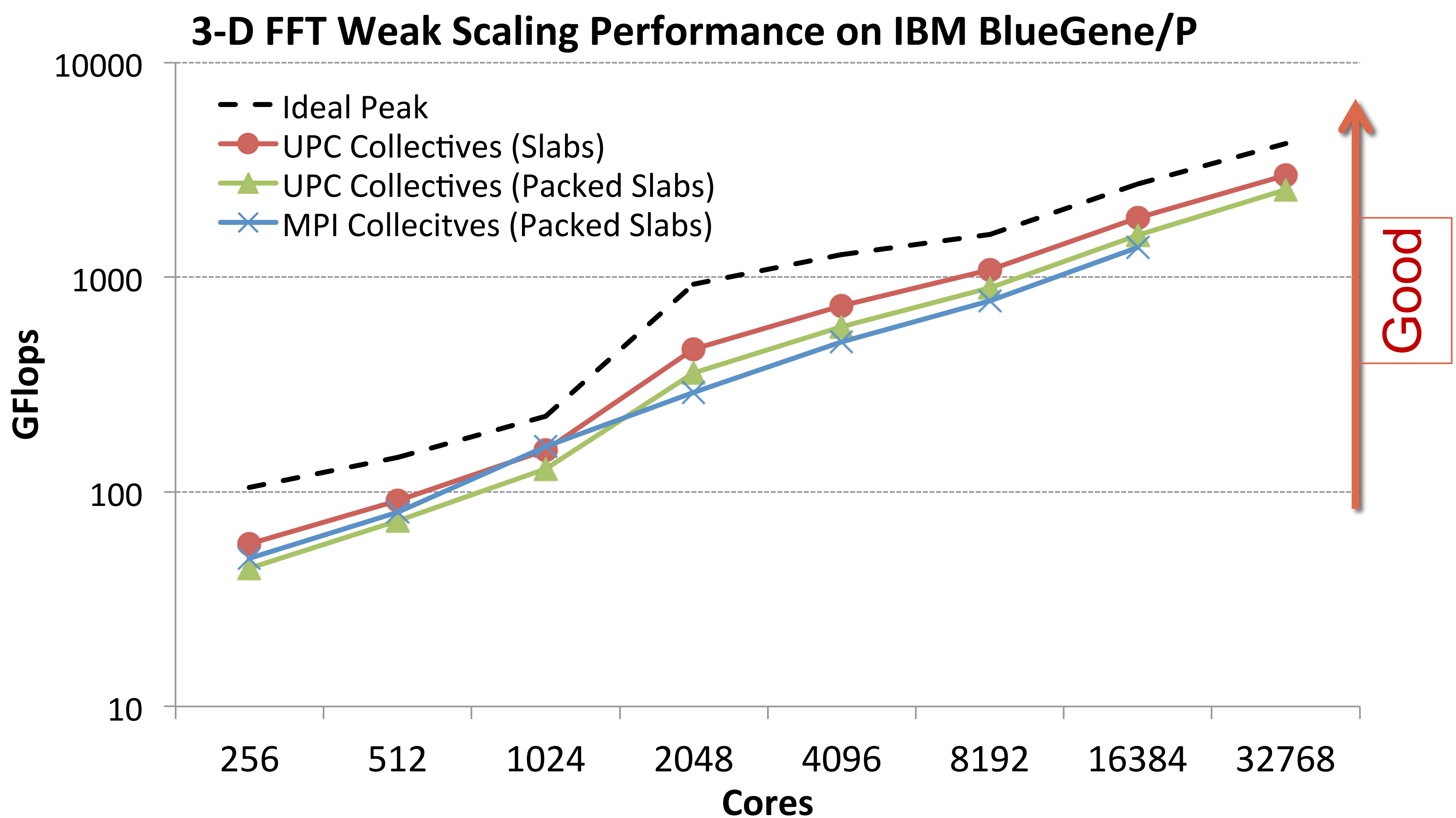
- 2-D Data Partitioning
- Row-column algorithm with overlapping local FFT and transpose (all-to-all communication)
- UPC non-blocking operations enabled fine-grained overlapping for better performance

FFT Performance on Multi-Core

Performance of 3D-FFT (512x256x256) on 32-core AMD (Mflops)

Threads	4	8	16	32
FFTW	4561.3	7338.7	8756.4	8365.5
UPC with FFTW	2306.61	4242.28	7210.87	**9849.7**

FFT Performance on BlueGene/P



Pitfalls in Programming with UPC

- Abuse fine-grained inter-node data accesses – generate tons of tiny data packets
- Flood data from many to one – congest the network
- Share everything and access data uniformly – forget about data localities and NUMA issues
- Use excessive locking/unlocking – lock operations are expensive, especially on distributed-memory systems
- Hand code common math functions (instead of using optimized libraries such as BLAS, FFTW, INTEL MKL, IBM ESSL,…)

Performance Penalty!

UPC Programming Tips

- Use local pointer to access the local part of shared data by casting pointer-to-shared to local pointer
- Leverage data affinity information and manage shared data layout to minimize remote accesses (both inter-node and NUMA)
- Use non-blocking communication if available
- Use collectives
- Use remote atomic operations if available

UPC one for two?

- Hybrid Programming Styles with UPC
  - fine-grained (shared memory style)
  - bulk synchronous (message passing style)
- Hybrid Execution with UPC
  - Map UPC threads hierarchically to groups of Pthreads
    - Threads within a process share resources and the same virtual address space
    - Processes within a node use physically shared memory for fast communication
    - Inter-node communication uses the network
  - Balance resource sharing and isolation
    - Too much sharing: resource contention (lower performance), prone to race conditions
    - No sharing: resource idling (lower throughput)

Interoperability: Mix it up

- UPC with other sequential languages: C++, FORTRAN
- MPI with UPC
  - Each MPI process is also a UPC thread
  - Each MPI process spawns a few UPC threads. MPI for inter-process communication and UPC for intra-process communication
- UPC with OpenMP
  - Map each UPC thread to an OS process and spawn OpenMP threads
- UPC with CUDA and OpenCL
  - Similar to MPI + CUDA/OpenCL

UPC 1.3

- Coming this Fall
- Main features
  - Non-blocking memory copy operations
    - Implicit non-blocking memory operations – fire and forget
    - upc_memcpy_nbi(…);
    - upc_fence;
  - UPC atomics
    - CAS
    - Op
    - Fetch and Op
  - High precision timers
  - Collective memory deallocation (upc_all_free)
- Many bug fixes and clarifications
- http://code.google.com/p/upc-specification/

Tools

- Eclipse **Parallel Tools Platform** (PTP)
  - http://www.eclipse.org/ptp/
- Parallel Performance Wizard (PPW)
  - http://ppw.hcs.ufl.edu/
- GDB UPC
  - http://www.gccupc.org/gdb-upc-info/debugging-with-gdb-upc
- Totalview
- Distributed Debugging Tool (DDT) from Allinea Software
- All other parallel computing tools for multi-process and multi-thread programs
  - Executing a UPC program is just like running a normal multi-process/multi-thread program from the OS's perspective.

Resources and Contacts

- Web sites::
  - UPC community portal: http://upc.gwu.edu
  - IBM XL UPC: http://www.alphaworks.ibm.com/tech/upccompiler
  - GCC UPC: http://www.gccupc.org
  - Berkeley UPC: http://upc.lbl.gov
- Email lists:
  - UPC Mailing Lists: http://upc.gwu.edu/upc_mail_group.html
  - public Berkeley UPC users list: upc-users@lbl.gov
  - Berkeley UPC/GASNet developers: upc-devel@lbl.gov

THANK YOU!