Evaluating the Impact of Programming Language Features on the Performance of Parallel Applications on Cluster Architectures

Konstantin Berlin[1], Jun Huan[2], Mary Jacob[3], Garima Kochhar[3], Jan Prins[2], Bill Pugh[1], P. Sadayappan[3], Jaime Spacco[1], Chau-Wen Tseng[1]

[1] University of Maryland, College Park
[2] University of North Carolina, Chapel Hill
[3] Ohio State University

Motivation

- Irregular, fine-grain remote accesses
  - Several important applications
  - Message passing (MPI) is inefficient
- Language support for fine-grain remote accesses?
  - Less programmer effort than MPI
  - How efficient is it on clusters?

Contributions

- Experimental evaluation of language features
- Observations on programmability & performance
- Suggestions for efficient programming style
- Predictions on impact of architectural trends

Findings not a surprise, but we quantify penalties for language features for challenging applications

Outline

- Introduction
- Evaluation
  - Parallel paradigms
  - Fine-grain applications
  - Performance
- Observations & recommendations
- Impact of architecture trends
- Related work

Parallel Paradigms

- Shared-memory
  - Pthreads, Java threads, OpenMP, HPF
  - Remote accesses same as normal accesses
- Distributed-memory
  - MPI, SHMEM
  - Remote accesses through explicit (aggregated) messages
  - User distributes data, translates addresses
- Distributed-memory with special remote accesses
  - Library to copy remote array sections (Global Arrays)
  - Extra processor dimension for arrays (Co-Array Fortran)
  - Global pointers (UPC)
  - Compiler / run-time system converts accesses to messages

Global Arrays

- Characteristics
  - Provides illusion of shared multidimensional arrays
  - Library routines
    - Copy rectangular shaped data in & out of global arrays
    - Scatter / gather / accumulate operations on global array
  - Designed to be more restrictive, easier to use than MPI
- Example

```
NGA_Access(g_a, lo, hi, &table, &ld);
for (j = 0; j < PROCS; j++) {    for (i = 0; i < counts[j]; i++) {
      table[index-lo[0]] ^= stable[copy[i] >> (64-LSTSIZE)];  } }
 NGA_Release_update(g_a, lo, hi);
```

UPC

- Characteristics
  - Provides illusion of shared one-dimensional arrays
  - Language features
    - Global pointers to cyclically distributed arrays
    - Explicit one-sided msgs (upc_memput(), upc_memget())
  - Compilers translate global pointers, generate communication
- Example

```
shared unsigned int table[TABSIZE];
for (i=0; i<NUM_UPDATES/THREADS; i++) {
        int ran = random();
        table[ (ran & (TABSIZE-1)) ] ^= stable[ (ran >> (64-LSTSIZE)) ];
}
barrier();
```

UPC

- Most flexible method for arbitrary remote references
- Supported by many vendors
- Can cast global pointers to local pointers
  - Efficiently access local portions of global array
- Can program using hybrid paradigm
  - Global pointers for fine-grain accesses
  - Use upc_memput(), upc_mempget() for coarse-grain accesses

Target Applications

- Parallel applications
  - Most standard benchmarks are easy
    - Coarse-grain parallelism
    - Regular memory access patterns
- Applications with irregular, fine-grain parallelism
  - Irregular table access
  - Irregular dynamic access
  - Integer sort

Options for Fine-grain Parallelism

- Implement fine-grain algorithm
  - Low user effort, inefficient
- Implement coarse-grain algorithm
  - High user effort, efficient
- Implement hybrid algorithm
  - Most code uses fine-grain remote accesses
  - Performance critical sections use coarse-grain algorithm
  - Reduce user effort at the cost of performance
    - How much performance is lost on clusters?

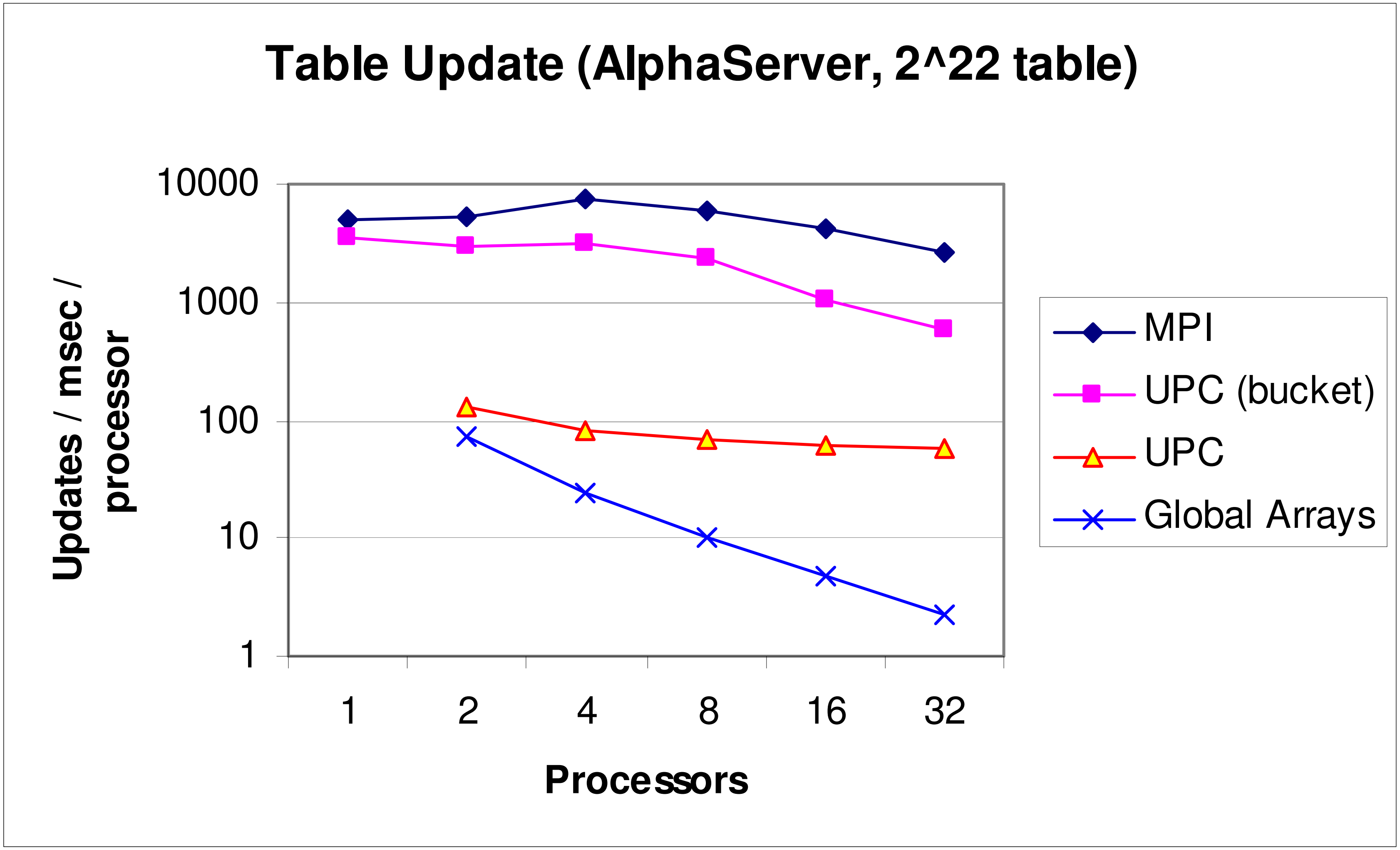
Experimental Evaluation

- Cluster : Compaq Alphaserver SC (ORNL)
  - 64 nodes, 4-way Alpha EV67 SMP, 2 GB memory each
  - Single Quadrics adapter per node
- SMP : SunFire 6800 (UMD)
  - 24 processors, UltraSparc III, 24 GB memory total
  - Crossbar interconnect

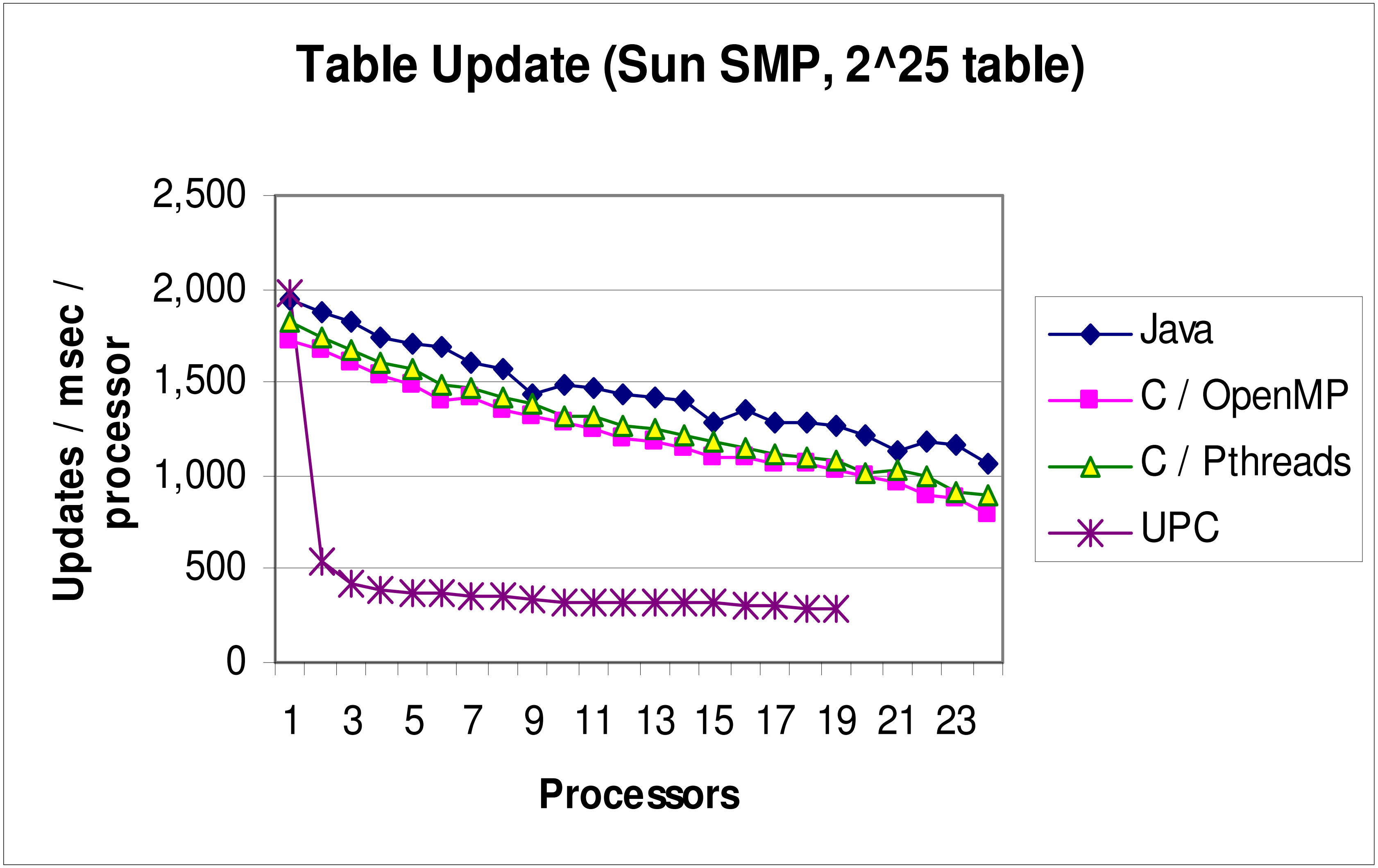
Irregular Table Update

- Applications
  - Parallel databases, giant histogram / hash table
- Characteristics
  - Irregular parallel accesses to large distributed table
  - Bucket version (aggregated non-local accesses) possible
- Example

```
for ( i=0; i<NUM_UPDATES; i++ ) {
    ran = random();
    table[ran & (TABSIZE-1)] ^= stable[ran >> (64-LSTSIZE)];
}
```



- UPC / Global Array fine-grain accesses inefficient (100x)
- Hybrid coarse-grain (bucket) version closer to MPI

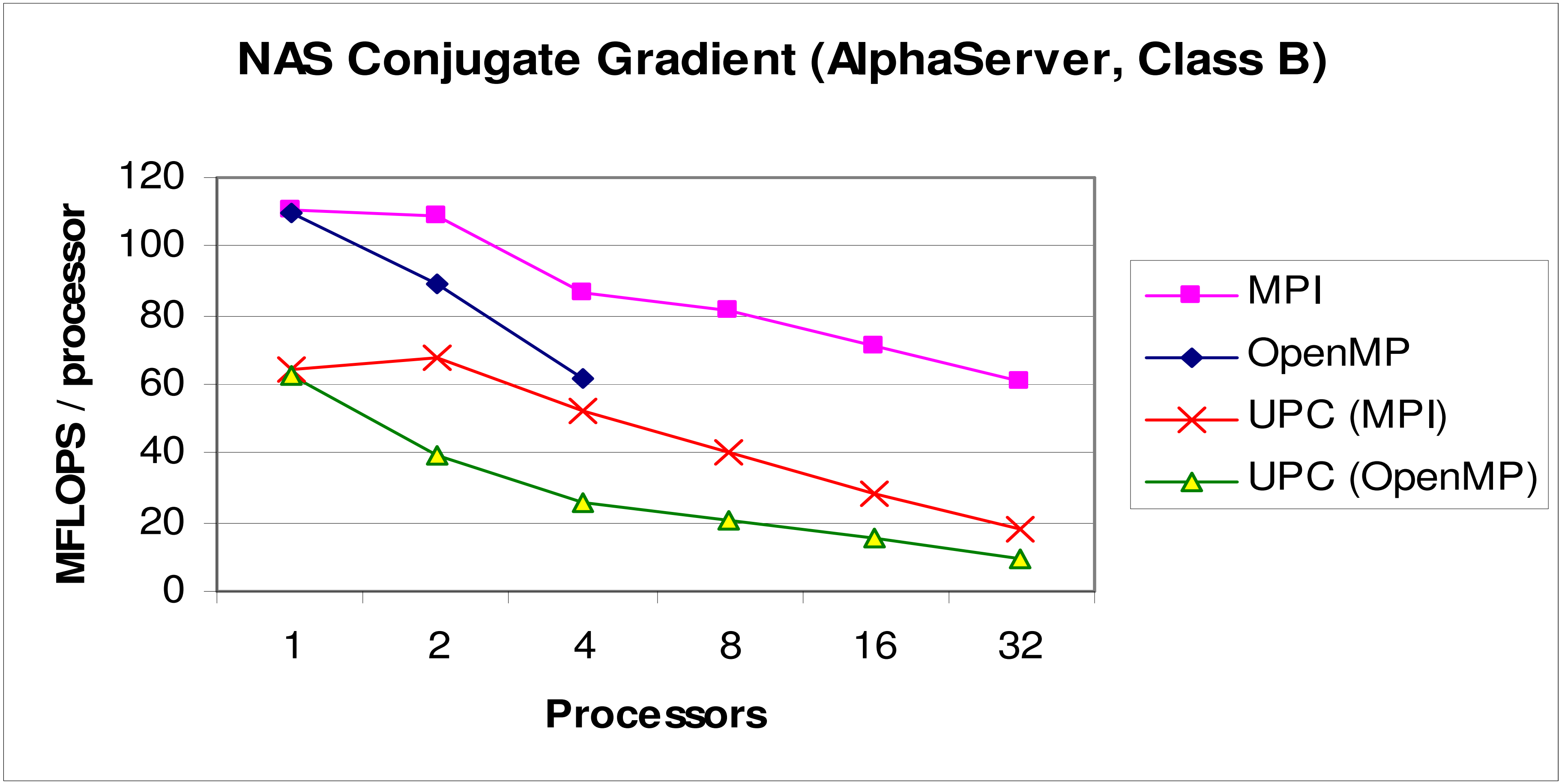


- UPC fine-grain accesses inefficient even on SMP

Irregular Dynamic Accesses

- Applications
  - NAS CG (sparse conjugate gradient)
- Characteristics
  - Irregular parallel accesses to sparse data structures
  - Limited aggregation of non-local accesses
- Example (NAS CG)

```
for (j = 0; j < n; j++) {
    sum = 0.0;
    for (k = rowstr[j]; k < rowstr[j+1]; k++)
        sum = sum + a[k] * v[colidx[k]];
    w[j] = sum;
}
```

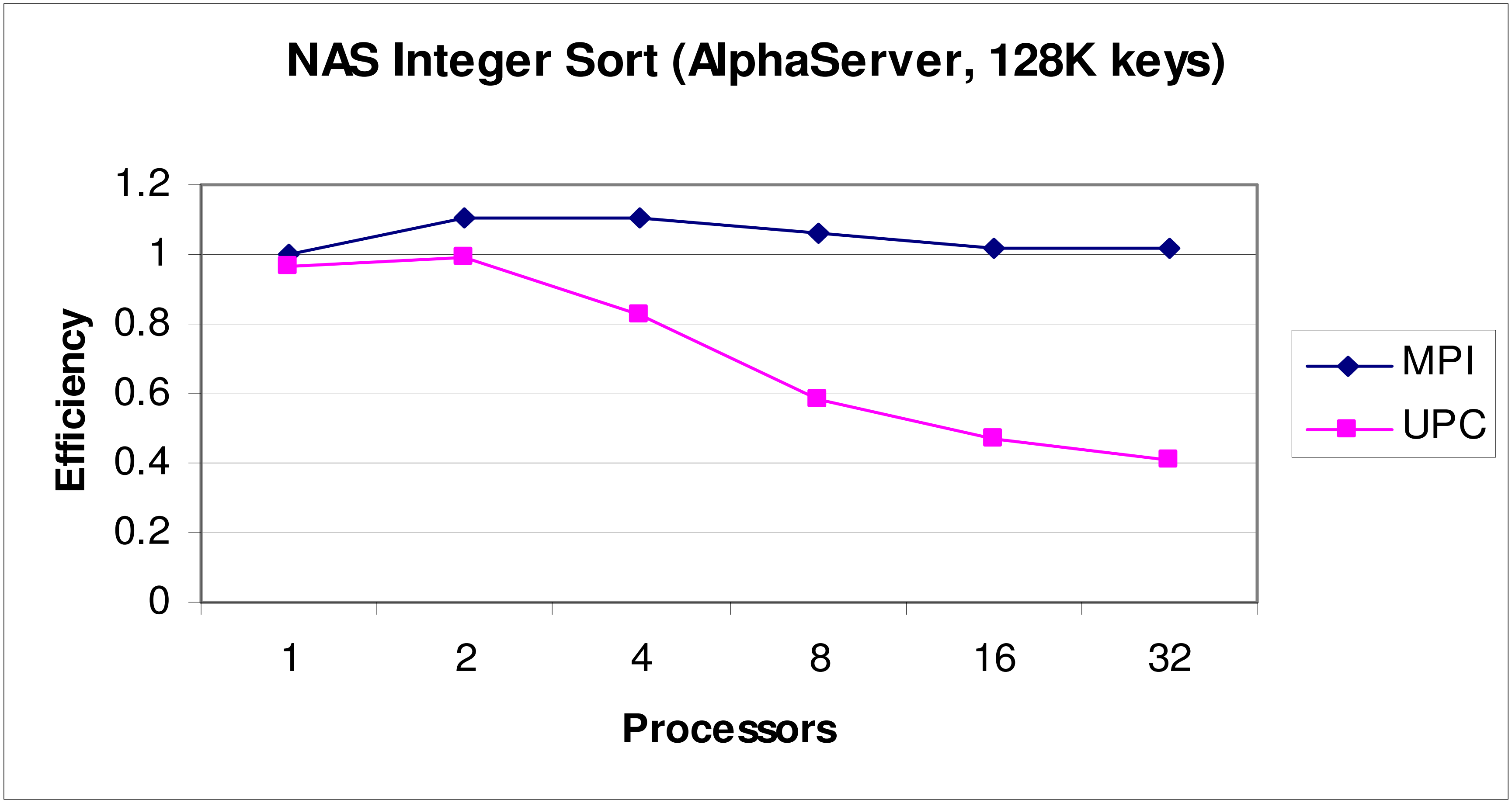


- UPC fine-grain accesses inefficient (4x)
- Hybrid coarse-grain version slightly closer to MPI

Integer Sort

- Applications
  - NAS IS (integer sort)
- Characteristics
  - Parallel sort of large list of integers
  - Non-local accesses can be aggregated
- Example (NAS IS)

```
for ( i=0; i<NUM_KEYS; i++ ) {    /* sort local keys into buckets */
   key = key_array[i];
   key_buff1[bucket_ptrs[key >> shift]++] = key; }
upc_reduced_sum(…) ;               /* get bucket size totals */
for ( i = 0; i < THREADS; i++ ) {   /* get my bucket from every proc */
   upc_memget(…); }
```



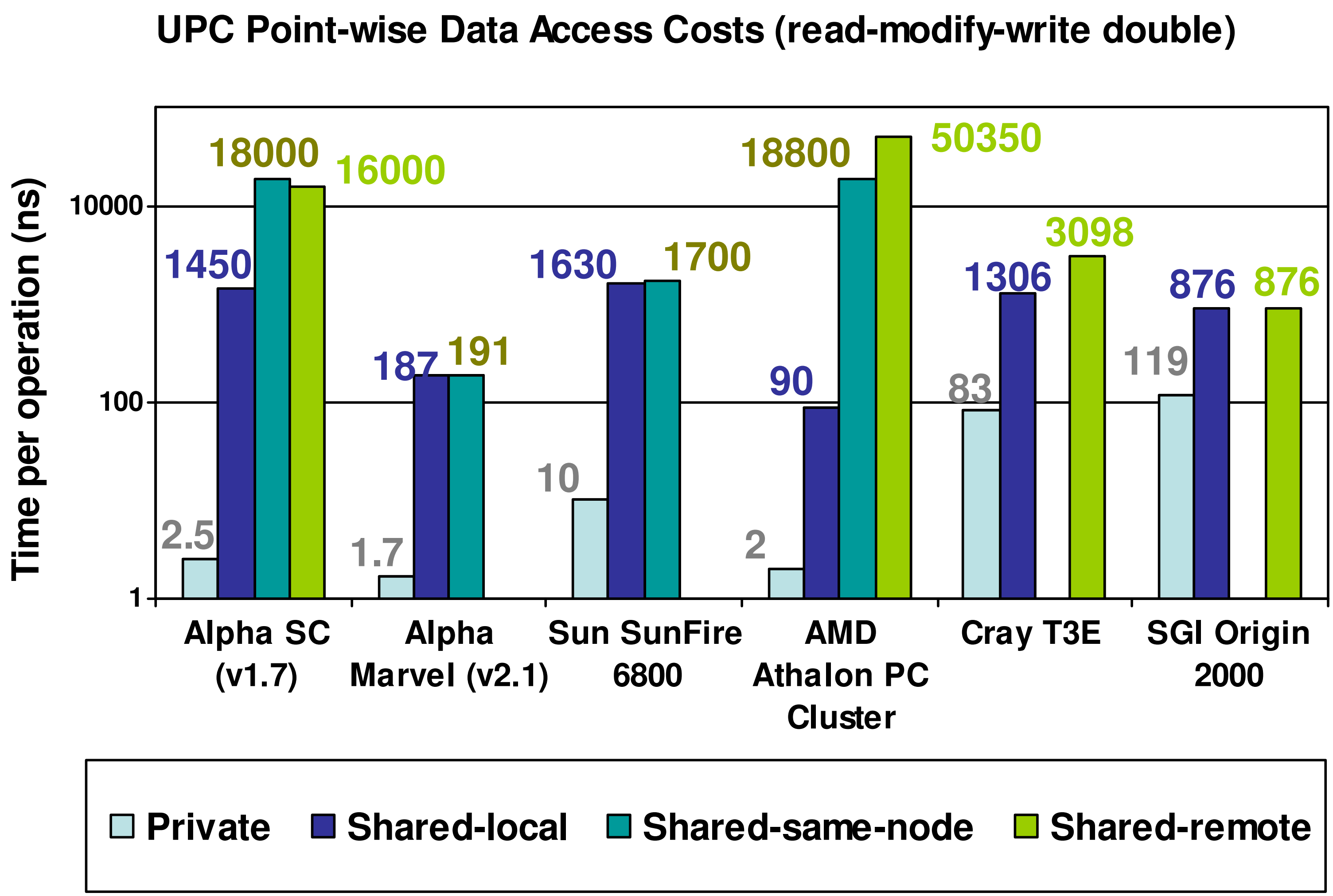
- UPC fine-grain accesses inefficient
- Coarse-grain version closer to MPI (2-3x)

UPC Microbenchmarks

- Compare memory access costs
  - Quantify software overhead
- Private
  - Local memory, local pointer
- Shared-local
  - Local memory, global pointer
- Shared-same-node
  - Non-local memory (but on same SMP node)
- Shared-remote
  - Non-local memory

UPC Microbenchmarks

- Architectures
  - Compaq AlphaServer SC, v1.7 compiler (ORNL)
  - Compaq AlphaServer Marvel, v2.1 compiler (Florida)
  - Sun SunFire 8600 (UMD)
  - AMD Athlon PC cluster (OSU)
  - Cray T3E (MTU)
  - SGI Origin 2000 (UNC)



- Global pointers significantly slower
- Improvement with newer UPC compilers

Observations

- Fine-grain programming model is seductive
  - Fine-grain access to shared data
  - Simple, clean, easy to program
- Not a good reflection of clusters
  - Efficient fine-grain communication not supported in hardware
  - Architectural trend towards clusters, away from Cray T3E

Observations

- Programming model encourages poor performance
  - Easy to write simple fine-grain parallel programs
  - Poor performance on clusters
  - Can code around this, often at the cost of complicating your model or changing your algorithm
- Dubious that compiler techniques will solve this problem
  - Parallel algorithms with block data movement needed for clusters
  - Compilers cannot robustly transform fine-grained code into efficient block parallel algorithms

Observations

- Hybrid programming model is easy to use
  - Fine-grained shared data access easy to program
  - Use coarse-grain message passing for performance
  - Faster code development, prototyping
  - Resulting code cleaner, more maintainable
- Must avoid degrading local computations
  - Allow compiler to fully optimize code
  - Usually not achieved in fine-grain programming
  - Strength of using explicit messages (MPI)

Recommendations

- Irregular coarse-grain algorithms
  - For peak cluster performance, use message passing
  - For quicker development, use hybrid paradigm
    - Use fine-grain remote accesses sparingly
  - Exploit existing code / libraries where possible
- Irregular fine-grain algorithms
  - Execute smaller problems on large SMPs
  - Must develop coarse-grain alternatives for clusters
- Fine-grain programming on clusters still just a dream
  - Though compilers can help for regular access patterns

Impact of Architecture Trends

- Trends
  - Faster cluster interconnects (Quadrics, InfiniBand)
  - Larger memories
  - Processor / memory integration
  - Multithreading
- Raw performance improving
  - Faster networks (lower latency, higher bandwidth)
  - Absolute performance will improve
- But same performance limitations!
  - Avoid small messages
  - Avoid software communication overhead
  - Avoid penalizing local computation

Related Work

- Parallel paradigms
  - Many studies
  - PMODELs (DOE / NSF) project

- UPC benchmarking
  - T. El-Ghazawi et al. (GWU)
    - Good performance on NAS benchmarks
    - Mostly relies on upc_memput(), upc_memget()
  - K. Yelick et al. (Berkeley)
    - UPC compiler targeting GASNET
    - Compiler attempts to aggregate remote accesses

End of Talk