Optimizing Bandwidth Limited Problems Using One-Sided Communication and Overlap

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Conventional Wisdom

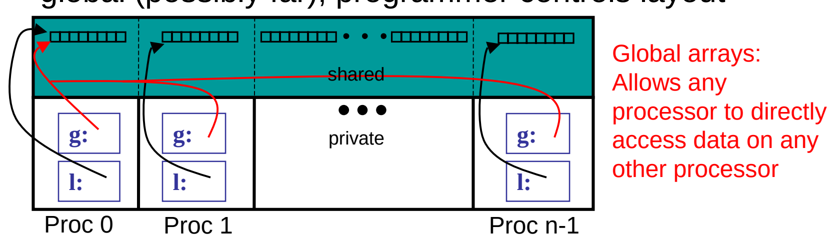
- Send few, large messages
  - Allows the network to deliver the most effective bandwidth
- Isolate computation and communication phases
  - Uses bulk-synchronous programming
  - Allows for packing to maximize message size
- Message passing is preferred paradigm for clusters
- Global Address Space (GAS) Languages are primarily useful for latency sensitive applications
- GAS Languages mainly help productivity
  - However, not well known for their performance advantages

Our Contributions

- Increasingly, cost of HPC machines is in the network
- One-sided communication model is a better match to modern networks
  – GAS Languages simplify programming for this model
- How to use these communication advantages
  – Case study with NAS Fourier Transform (FT)
  – Algorithms designed to relieve communication bottlenecks
    - Overlap communication *and* computation
    - Send messages early and often to maximize overlap

UPC Programming Model

- *Global address space:* any thread/process may directly read/write data allocated by another
- *Partitioned:* data is designated as local (near) or global (possibly far); programmer controls layout

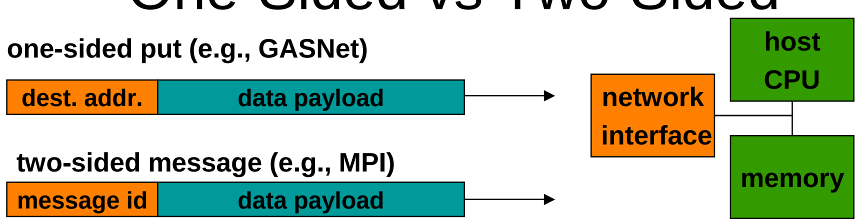


- *3 of the current languages:* UPC, CAF, and Titanium
  – Emphasis in this talk on UPC (based on C)
  – However programming paradigms presented in this work are not limited to UPC

Advantages of GAS Languages

- Productivity
  - GAS supports construction of complex shared data structures
  - High level constructs simplify parallel programming
  - Related work has already focused on these advantages
- Performance (the main focus of this talk)
  - GAS Languages can be faster than two-sided MPI
  - One-sided communication paradigm for GAS languages more natural fit to modern cluster networks
  - Enables novel algorithms to leverage the power of these networks
  - GASNet, the communication system in the Berkeley UPC Project, is designed to take advantage of this communication paradigm

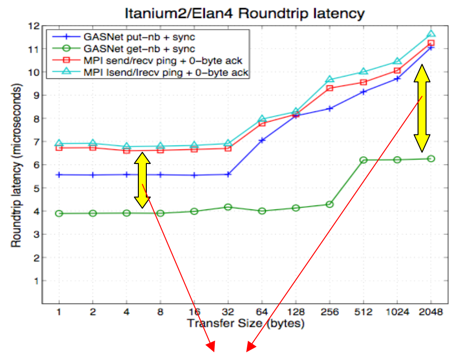
One-Sided vs Two-Sided



- A one-sided put/get can be entirely handled by network interface with RDMA support
  - CPU can dedicate more time to computation rather than handling communication
- A two-sided message can employ RDMA for only part of the communication
  - Each message requires the target to provide the destination address
  - Offloaded to network interface in networks like Quadrics
- RDMA makes it apparent that MPI has added costs associated with ordering to make it usable as a end-user programming model

Latency Advantages

- Comparison:
  - One-sided:
    - Initiator can always transmit remote address
    - Close semantic match to high bandwidth, zero-copy RDMA
  - Two-sided:
    - Receiver must provide destination address
- Latency measurement correlates to software overhead
  - Much of the small-message latency is due to time spent in software/firmware processing

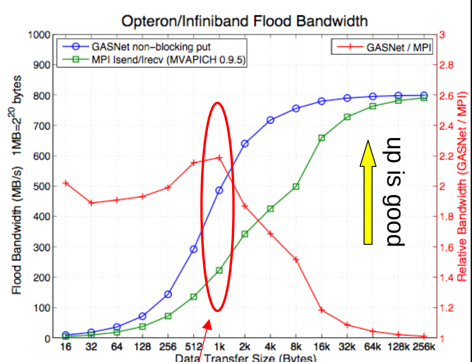


down is good

One-sided implementation consistently outperforms 2-sided counterpart

Bandwidth Advantages

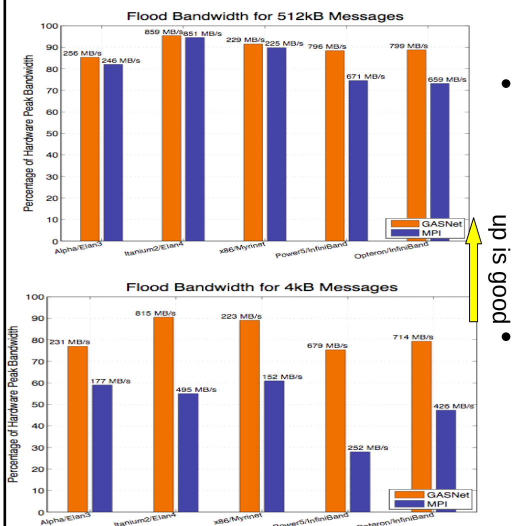
- One-sided semantics better match to RDMA supported networks
  - Relaxing point-to-point ordering constraint can allow for higher performance on some networks
  - GASNet saturates to hardware peak at lower message sizes
  - Synchronization decoupled from data transfer
- MPI semantics designed for end user
  - Comparison against good MPI implementation
  - Semantic requirements hinder MPI performance
  - Synchronization and data transferred coupled together in message passing



up is good

Over a factor of 2 improvement for 1kB messages

Bandwidth Advantages (cont)



- GASNet and MPI saturate to roughly the same bandwidth for “large” messages
- GASNet consistently outperforms MPI for “mid-range” message sizes

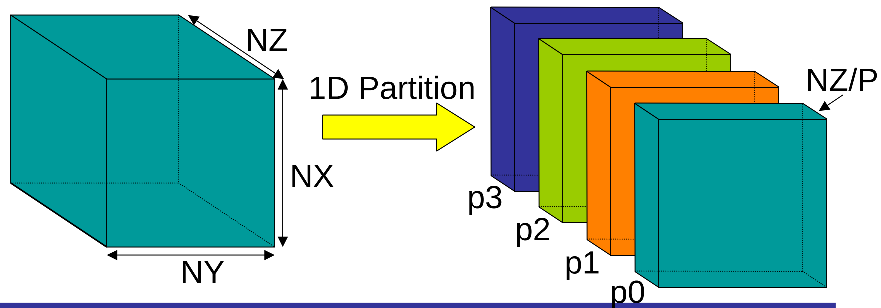
A Case Study: NAS FT

- How to use the potential that the microbenchmarks reveal?
- Perform a large 3 dimensional Fourier Transform
  - Used in many areas of computational sciences
    - Molecular dynamics, computational fluid dynamics, image processing, signal processing, nanoscience, astrophysics, etc.
- Representative of a class of communication intensive algorithms
  - Sorting algorithms rely on a similar intensive communication pattern
  - Requires every processor to communicate with every other processor
  - Limited by bandwidth

Performing a 3D FFT

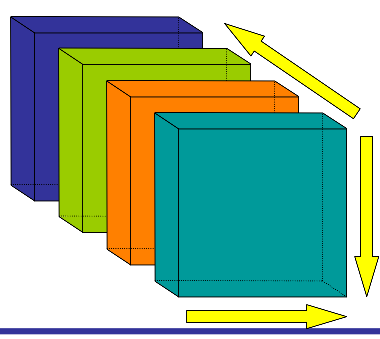
- NX x NY x NZ elements spread across P processors
- Will Use 1-Dimensional Layout in Z dimension
  - Each processor gets NZ / P “planes” of NX x NY elements per plane

Example: P = 4



Performing a 3D FFT (part 2)

- Perform an FFT in all three dimensions
- With 1D layout, 2 out of the 3 dimensions are local while the last Z dimension is distributed



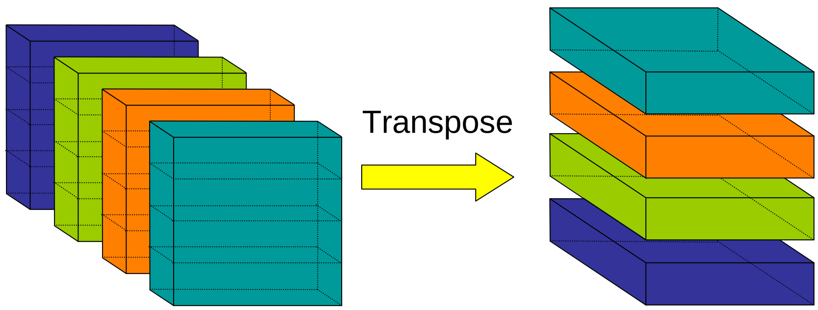
Step 1: FFTs on the columns
(all elements local)

Step 2: FFTs on the rows
(all elements local)

Step 3: FFTs in the Z-dimension
(requires communication)

Performing the 3D FFT (part 3)

- Can perform Steps 1 and 2 since all the data is available without communication
- Perform a Global Transpose of the cube
  - Allows step 3 to continue



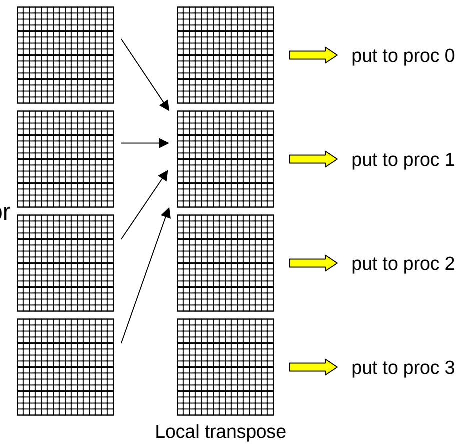
The Transpose

- Each processor has to scatter input domain to other processors
  - Every processor divides its portion of the domain into P pieces
  - Send each of the P pieces to a different processor
- Three different ways to break it up the messages
  1. Packed Slabs (i.e. single packed “Alltoall” in MPI parlance)
  2. Slabs
  3. Pencils
- An order of magnitude increase in the number of messages
- An order of magnitude decrease in the size of each message
- “Slabs” and “Pencils” allow overlapping communication and computation and leverage RDMA support in modern networks

Algorithm 1: Packed Slabs

Example with P=4, NX=NY=NZ=16

1. Perform all row and column FFTs
2. Perform local transpose
   – data destined to a remote processor are grouped together
3. Perform P puts of the data



- For 512^3 grid across 64 processors
  – Send 64 messages of 512kB each

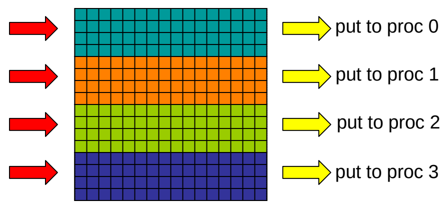
Bandwidth Utilization

- NAS FT (Class D) with 256 processors on Opteron/InfiniBand
  – Each processor sends 256 messages of 512kBytes
  – Global Transpose (i.e. all to all exchange) only achieves 67% of peak point-to-point bidirectional bandwidth
  – Many factors could cause this slowdown
    - Network contention
    - Number of processors that each processor communicates with
- Can we do better?

Algorithm 2: Slabs

- Waiting to send all data in one phase bunches up communication events
- Algorithm Sketch
  - for each of the NZ/P planes
    - Perform all column FFTs
    - for each of the P “slabs”
      (a slab is NX/P rows)
      - Perform FFTs on the rows in the slab
      - Initiate 1-sided put of the slab
  - Wait for all puts to finish
  - Barrier
- Non-blocking RDMA puts allow data movement to be overlapped with computation.
- Puts are spaced apart by the amount of time to perform FFTs on NX/P rows

plane 0



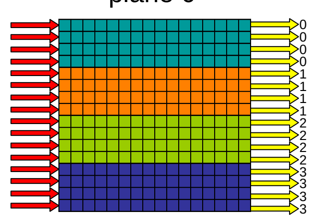
Start computation for next plane

- For 512^3 grid across 64 processors
  - Send 512 messages of 64kB each

Algorithm 3: Pencils

- Further reduce the granularity of communication
  - Send a row (*pencil*) as soon as it is ready
- Algorithm Sketch
  - For each of the NZ/P planes
    - Perform all 16 column FFTs
    - For r=0; r<NX/P; r++
      - For each slab s in the plane
        » Perform FFT on row r of slab s
        » Initiate 1-sided put of row r
  - Wait for all puts to finish
  - Barrier
- Large increase in message count
- Communication events finely diffused through computation
  - Maximum amount of overlap
  - Communication starts early

plane 0



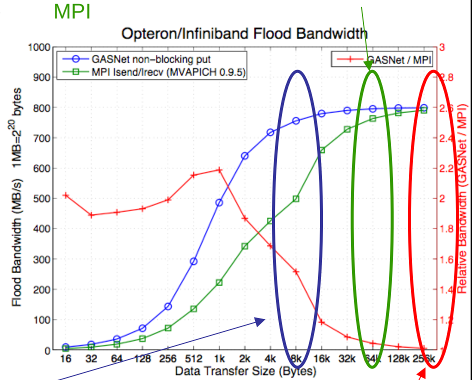
Start computation for next plane

- For 512^3 grid across 64 processors
  - Send 4096 messages of 8kB each

Communication Requirements

- 512^3 across 64 processors
  - Alg 1: Packed Slabs
    - Send 64 messages of 512kB
  - Alg 2: Slabs
    - Send 512 messages of 64kB
  - Alg 3: Pencils
    - Send 4096 messages of 8kB

With Slabs GASNet is slightly faster than MPI



GASNet achieves close to peak bandwidth with Pencils but MPI is about 50% less efficient at 8k

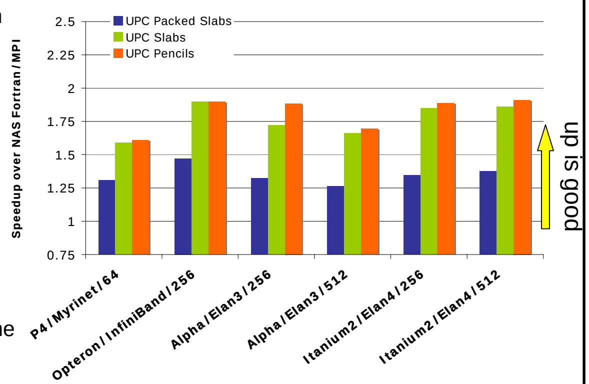
With the message sizes in Packed Slabs both comm systems reach the same peak bandwidth

Platforms

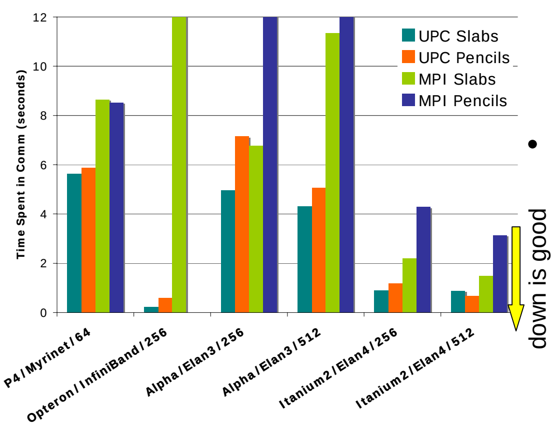
Name	Processor	Network	Software
Opteron/Infiniband “Jacquard” @ NERSC	Dual 2.2 GHz Opteron (320 nodes @ 4GB/node)	Mellanox Cougar InfiniBand 4x HCA	Linux 2.6.5, Mellanox VAPI, MVAPICH 0.9.5, Pathscale CC/F77 2.0
Alpha/Elan3 “Lemieux” @ PSC	Quad 1 GHz Alpha 21264 (750 nodes @ 4GB/node)	Quadrics QsNet1 Elan3 /w dual rail (one rail used)	Tru64 v5.1, Elan3 libelan 1.4.20, Compaq C V6.5-303, HP Fortra Compiler X5.5A-4085-48E1K
Itanium2/Elan4 “Thunder” @ LLNL	Quad 1.4 Ghz Itanium2 (1024 nodes @ 8GB/node)	Quadrics QsNet2 Elan4	Linux 2.4.21-chaos, Elan4 libelan 1.8.14, Intel ifort 8.1.025, icc 8. 1.029
P4/Myrinet “FSN” @ UC Berkeley Millennium Cluster	Dual 3.0 Ghz Pentium 4 Xeon (64 nodes @ 3GB/node)	Myricom Myrinet 2000 M3S-PCI64B	Linux 2.6.13, GM 2.0.19, Intel ifort 8.1-20050207Z, icc 8.1-20050207Z

Comparison of Algorithms

- Compare 3 algorithms against original NAS FT
  - All versions including Fortran use FFTW for local 1D FFTs
  - Largest class that fit in the memory (usually class D)
- All UPC flavors outperform original Fortran/MPI implantation by at least 20%
  - One-sided semantics allow even exchange based implementations to improve over MPI implementations
  - Overlap algorithms spread the messages out, easing the bottlenecks
  - ~1.9x speedup in the best case

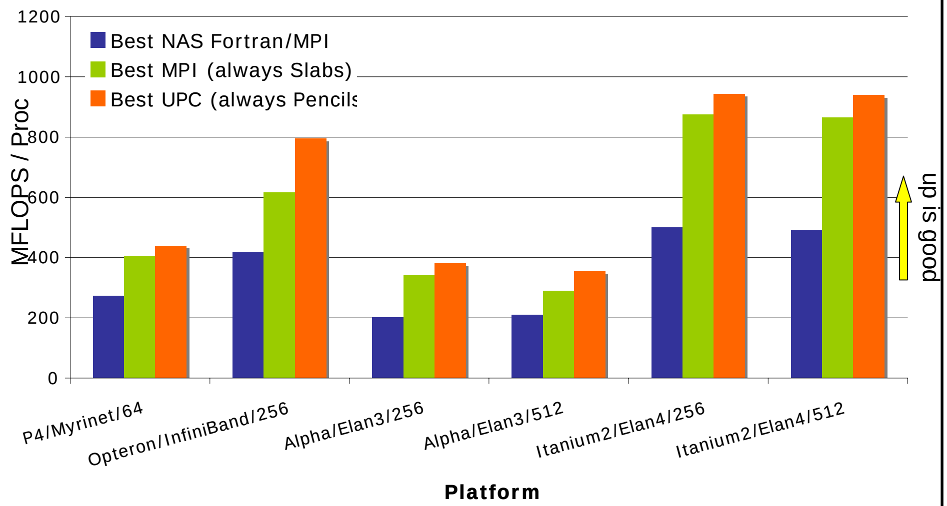


Time Spent in Communication



- Implemented the 3 algorithms in MPI using Irecvs and Isends
- Compare time spent initiating or waiting for communication to finish
  - UPC consistently spends less time in communication than its MPI counterpart
  - MPI unable to handle pencils algorithm in some cases

Performance Summary



Conclusions

- One-sided semantics used in GAS languages, such as UPC, provide a more natural fit to modern networks
  - Benchmarks demonstrate these advantages
- Use these advantages to alleviate communication bottlenecks in bandwidth limited applications
  - Paradoxically it helps to send more, smaller messages
- Both two-sided and one-sided implementations can see advantages of overlap
  - One-sided implementations consistently outperform two-sided counterparts because comm model more natural fit
- *Send early and often* to avoid communication bottlenecks

Try It!

- Berkeley UPC is open source
  - Download it from http://upc.lbl.gov
  - Install it with CDs that we have here

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- Associated Paper: IPDPS '06 Proceedings
- Berkeley UPC Website: http://upc.lbl.gov
- GASNet Website: http://gasnet.cs.berkeley.edu

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