A C++ Implementation of the Co-Array Programming Model

Maria Eleftheriou   Siddhartha Chatterjee   José E. Moreira
IBM Thomas J. Watson Research Center

POHLL-02 Workshop
New York, NY

Outline

- Background
- Co-Array C++ library motivation
- Implementation of Co-Array C++
- Performance of Co-Array C++
- Future work

Programming Models

- Research on programming models for the Blue Gene/L project
- Message passing model
  - MPI - will be implemented in BG/L
- Global address space model
  - Titanium
  - Unified Parallel C (UPC) - under way
  - Global Arrays
  - Co-Array Fortran

Co-Array Fortran

- Language extension to F95 [Numrich and Reid]
  - Based on earlier F-- work
- Global address space model
  - Shared memory semantics + locality
  - `integer A(10)[*]`
    - Each node has a one-dimensional array of ten integers named A
- Two-level addressing
  - `A(offset)[image]`
  - image is the rank of the node
  - offset is the position of the local data

Co-Array Fortran (*continued*)

- Program directly stores and loads local and remote data
  - `v(i) = A(offset)[image]`
  - `A(offset)[image] = v(i)`
- Significantly higher level semantics than MPI
  - Subscripting implies communication between images
  - Compiler/RTE responsible for synthesizing and managing communication

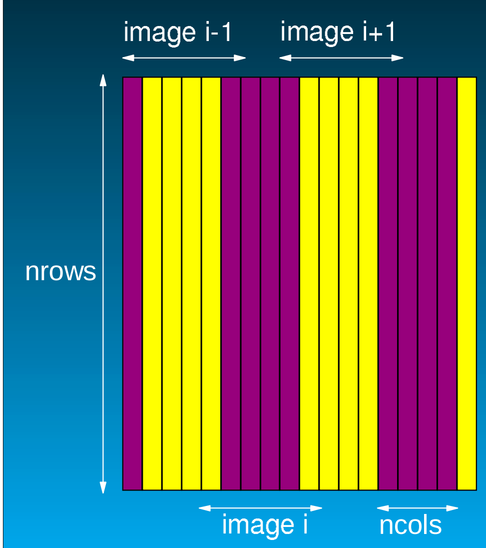
Relevant Features of BG/L

- 65,536 dual processor nodes interconnected in torus topology
  - Processors are symmetric in access to memory/devices
  - Non-coherent shared memory on node
- Interconnection network
  - High bandwidth, low latency
  - Nodes can send and receive at aggregate rate of 2GB/s
- Preferred programming model
  - Dedicate one processor to handle inter-node communication
  - Dedicate other processor to run user application
  - Other models are possible

C++ Library for Co-Array Model

- C++ features allow most of Co-Array notation to be implemented naturally
  - Operator overloading (for [] and () operators)
  - Generic programming (CoArray<T>)
- Library implementation is faster to prototype and faster to deploy
- Easier to motivate users to experiment with new library than new language
- Portable across variety of systems
- We wanted to have some fun with C++

Example: Relaxation Code



- Grid represented as one-dimensional CoArray
- The elements of the CoArray are vectors of size "nrows"
- Each image has (ncols+2) elements
  - It "owns the middle ncols
  - Left and right shadows
- Before relaxation step, image i has to update shadows of images i-1 and i+1
- Synchronize at the end of update
- After update, relaxation step is a strictly local operation

Co-Array Relaxation Code

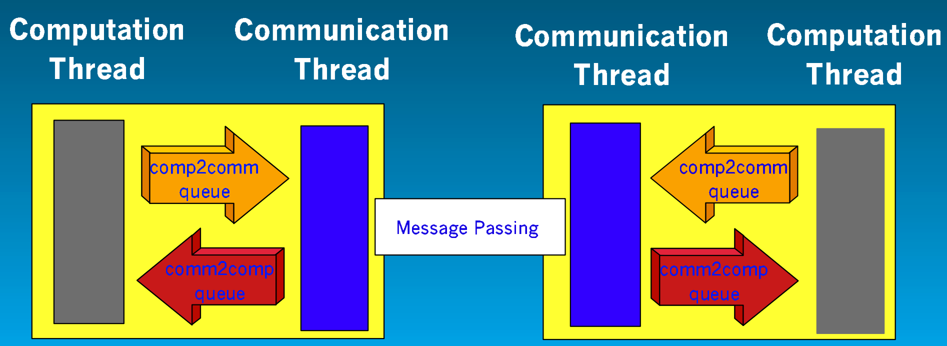
```
typedef double vector_t[VECTOR_SIZE];
void laplace(int nrow, int ncol, CoArray<vector_t>& u)
{
  int me = this_image();
  int images = num_images();
  Array<vector_t> new_u(ncol+2);
  int left  = me == 0 ? images-1 : me-1;
  int right = me == images-1 ? 0 : me+1;
  int list[2] = { left, right };
  u[left](ncol+1) = u(1);      // communication (put)
  u[right](0)     = u(ncol);   // communication (put)
  sync_all(list,2);
  for (int j = 1; j < ncol+1; j++) {
    new_u(j)[0] = u(j)[nrow-1] + u(j)[1] + u(j-1)[0] + u(j+1)[0];
    for (int i = 0; i < nrow-2; i++)
      new_u(j)[i+1] = u(j)[i] + u(j)[i+2] + u(j-1)[i+1] + u(j+1)[i+1];
    new_u(j)[nrow-1] = u(j)[0] + u(j)[nrow-2] + u(j-1)[nrow-1] +
                       u(j+1)[nrow-1];
  }
  for (int j = 1; j < ncol+1; j++)
    for (int i = 0; i< nrow; i++)
      u(j)[i] = new_u(j)[i] - 4.0 * u(j)[i];
}
```

Co-Array C++ Implementation

- Computation and communication agents
- Co-Array declaration and operations
- Point-to-point communication
- Group synchronization

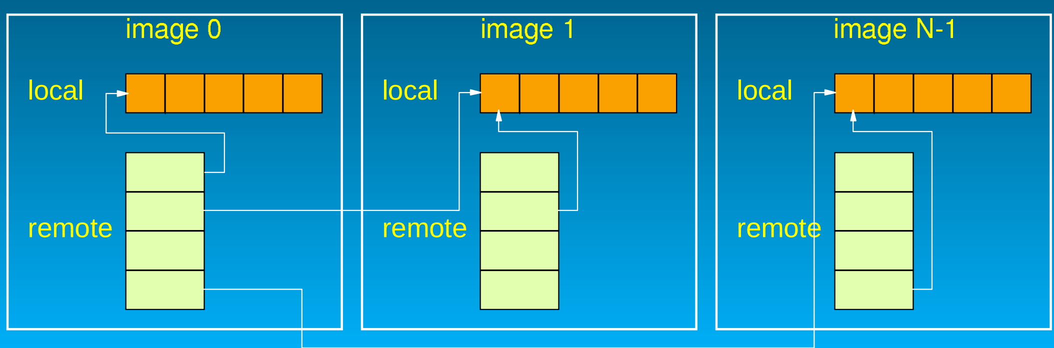
Implementing Computation and Communication Agents

- multithreading within a node
- MPI between nodes (prototype)



Implementing Co-Arrays

- Declare as a C++ object
  - `CoArray<double> A(100);`
- Collective operation



Implementing Co-Arrays

- `CoArray<T>::operator()` implements access to elements of the local portion of Co-Array
  - `u = A(i);`
- `CoArray<T>::operator[]` implements access to elements of remote portions of Co-Array
  - `A[node]` is a `RemoteArray<T>`
  - `A[node](i)` is a `RemotePtr<T>`
- `RemotePtr<T>::operator=` handles inter-image communication for put operation
  - `A[node](i) = u;`
- `RemotePtr<T>::operator T()` handles inter-image communication for get operation
  - `u = A[node](i);`

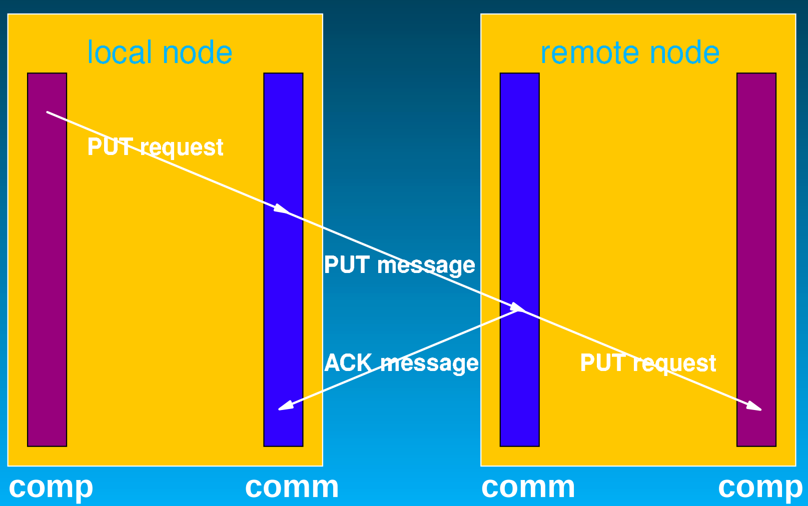
Implementing Point-to-Point Communication

- Local computation thread initiates
  - remote write by enqueueing a PutRequest on its comp2comm queue
  - remote read by enqueueing a GetRequest on its comp2comm queue
- Local communication thread
  - dequeues the request
  - sends message to remote communication thread
    - Put message
    - Get message

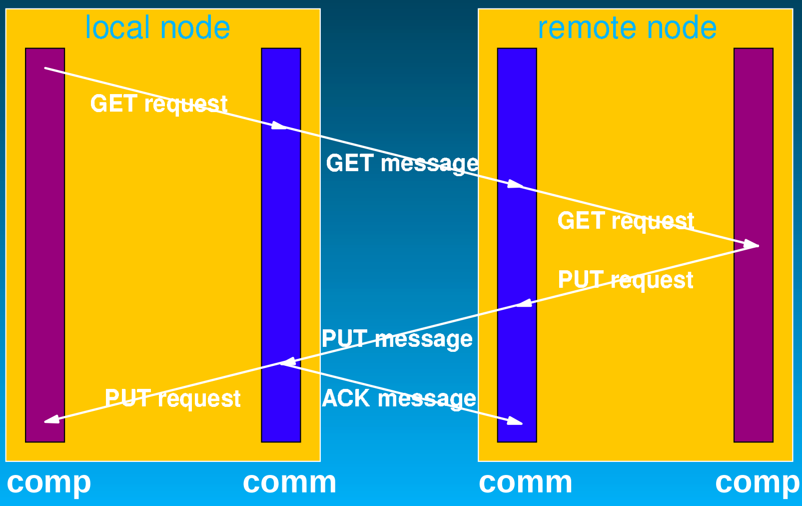
Implementing Point-to-Point Communication *(continued)*

- Remote communication thread takes the following actions on receiving a message
  - Put, enqueues a **PutRequest** on its comm2comp queue and sends **Ack** message back to local communication thread
  - Get, enqueues a **GetRequest** on its comm2comp queue
- Remote computation thread dequeues requests and takes the following actions
  - Put, completes remote write
  - Get, reads specified memory location and sends **Put** request

Put Operation



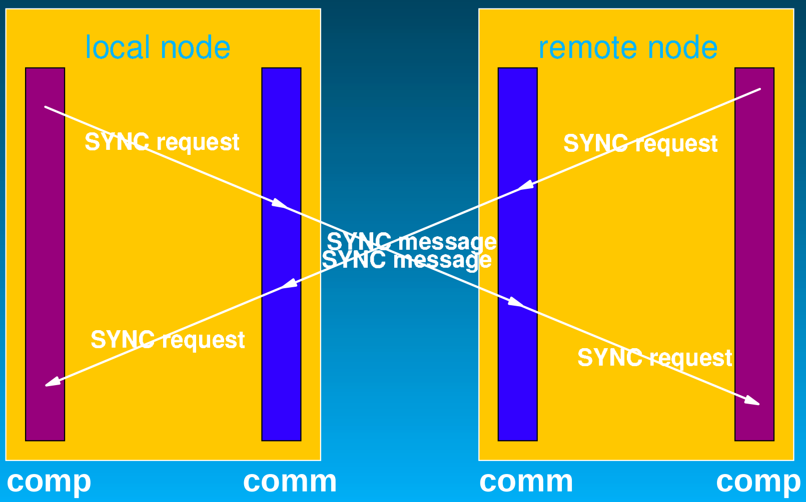
Get Operation



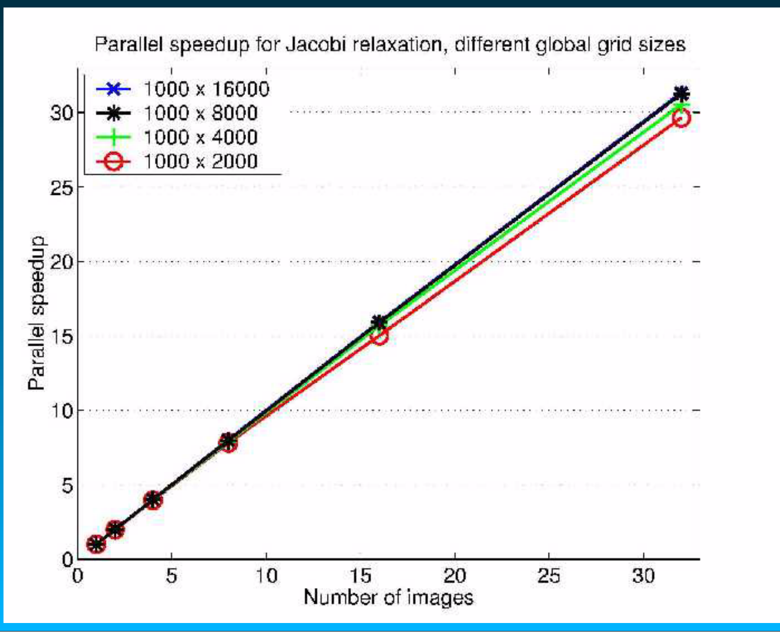
Group Synchronization

- `sync_all();`
  - barrier among all images
- `sync_all(list of images);`
  - barrier among all images
  - not all images need to wait for all others!
- Synchronization is implemented primarily by communication thread

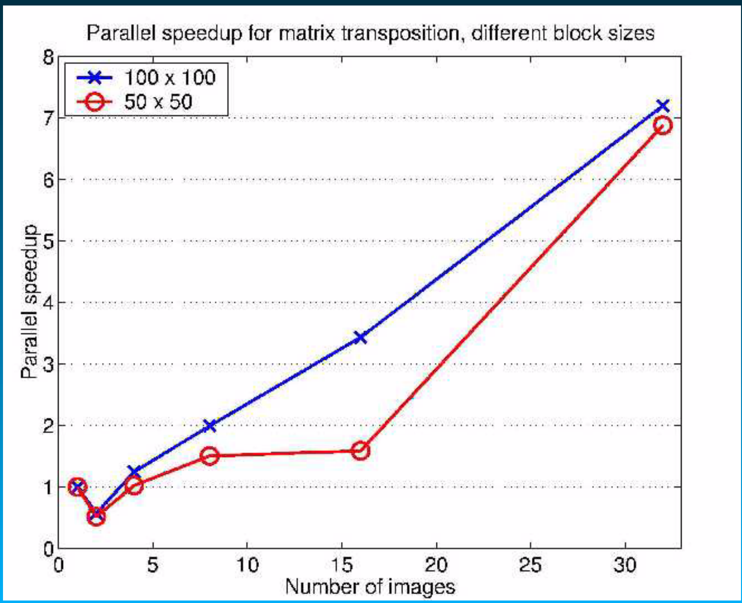
Synchronization Operation



Speedup of Jacobi Relaxation



Speedup of Matrix Transposition



Future Work

- Features
  - Array section operations
  - Multiple co-dimensions (process topologies)
- Program transformations with ROSE
- Scalability issues
  - Fill remote array information on demand
  - More scalable synchronization
- Improve performance
  - Eliminate copies (even with cache coherence problem)
  - Use basic packet operations in BG/L
- Better performance characterization
  - On BG/L simulator
  - Eventually on real hardware (2003)

Example: Matrix Transposition

```
typedef double block_t[BLOCK_SIZE][BLOCK_SIZE];
void MatrixTranspose(CoArray<block_t>&u, int nrow,int ncol){
  int me = u.this_image(),  comm_size = u.num_images();
  CoArray<block_t> b(nrow, ncol);
  block_t temp;
  CoArray<block_t>::sync_all();
  for (int I = 0; I < nrow; I++) {
    int i = (I+me*ncol) % nrow;
    for (int j = 0; j < ncol; j++) {
      transposeBlock(u(i,j),temp);  // transpose local block
      b[i/ncol](j+me*ncol, i%ncol) = temp;//comm (put)
    }
  }
  CoArray<block_t>::sync_all();
}
void transposeBlock(block_t& src, block_t& dst)
{
  for (int i = 0; i < BLOCK_SIZE; i++)
    for (int j = 0; j < BLOCK_SIZE; j++)
      dst[i][j] = src[j][i];
}
```