XcalableMP Implementation and Performance of NAS Parallel Benchmarks

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What’s XcalableMP?

- XcalableMP (XMP for short) is:
  - A programming model and language for distributed memory, proposed by XMP WG
  - http://www.xcalablemp.org

- XcalableMP Specification Working Group (XMP WG)
  - XMP WG is a special interest group, which organized to make a draft on “petascale” parallel language.
  - Started from December 2007, the meeting is held about once in every month.
    - Mainly active in Japan, but open for everybody.

- XMP WG Members (the list of initial members)
  - Academia: M. Sato, T. Boku (compiler and system, U. Tsukuba), K. Nakajima (app. and programming, U. Tokyo), Nanri (system, Kyusyu U.), Okabe (HPF, Kyoto U.)
  - Research Lab.: Watanabe and Yokokawa (RIKEN), Sakagami (app. and HPF, NIFS), Matsuo (app., JAXA), Uehara (app., JAMSTEC/ES)
  - Industries: Iwashita and Hotta (HPF and XPFortran, Fujitsu), Murai and Seo (HPF, NEC), Anzaki and Negishi (Hitachi), (many HPF developers!)

- Funding for development
  - e-science project: “Seamless and Highly-productive Parallel Programming Environment for High-performance computing” project funded by MEXT, Japan
    - Project PI: Yutaka Ishiakwa, co-PI: Sato and Nakashima(Kyoto), PO: Prof. Oyanagi
    - Project Period: 2008/Oct to 2012/Mar (3.5 years)
Agenda

- XcalableMP: directive-based language eXtension for Scalable and performance-aware Parallel Programming
  - Concept and model
  - directives
  - Some examples

- XMP implementation of Nas Parallel Benchmark
  - ES, IS, CG (1-D, 2-D)
  - Preliminary performance reports
XcalableMP : directive-based language eXtension for Scalable and performance-aware Parallel Programming

- **Directive-based language extensions** for familiar languages F90/C (C++)
  - To reduce code-rewriting and educational costs.

- **“Scalable” for Distributed Memory Programming**
  - SPMD as a basic execution model
  - A thread starts execution in each node independently (as in MPI).
  - Duplicated execution if no directive specified.
  - MIMD for Task parallelism

- **“performance-aware” for explicit communication and synchronization.**
  - Work-sharing and communication occurs when directives are encountered
  - All actions are taken by directives for being “easy-to-understand” in performance tuning (different from HPF)
Overview of XcalableMP

- XMP supports typical parallelization based on the **data parallel paradigm** and work sharing under "global view".
  - An original sequential code can be parallelized with **directives**, like OpenMP.
- XMP also includes CAF-like PGAS (Partitioned Global Address Space) feature as "**local view**" programming.

**User applications**
- **Global view Directives**
  - Support common pattern (communication and work-sharing) for data parallel programming
  - Reduction and scatter/gather
  - Communication of sleeve area
  - Like OpenMPD, HPF/JA, XFP
- **Local view Directives** (CAF/PGAS)
  - Array section in C/C++
- **Parallel execution model**
  - **XMP runtime libraries**
  - **Two-sided comm. (MPI)**
  - One-sided comm. (remote memory access)

**Parallel platform (hardware+OS)**
Code Example

```c
int array[YMAX][XMAX];

#pragma xmp nodes p(4)
#pragma xmp template t(YMAX)
#pragma xmp distribute t(block) on p
#pragma xmp align array[i][*] with t(i)

main(){
    int i, j, res;
    res = 0;

    #pragma xmp loop on t(i)  reduction(+:res)
    for(i = 0; i < 10; i++)
        for(j = 0; j < 10; j++){
            array[i][j] = func(i, j);
            res += array[i][j];
        }
}
```

add to the serial code: incremental parallelization

work sharing and data synchronization

data distribution
The same code written in MPI

```c
int array[YMAX][XMAX];

main(int argc, char**argv){
    int i,j,res,temp_res, dx,llimit,ulimit,size,rank;

    MPI_Init(argc, argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &rank);
    MPI_Comm_size(MPI_COMM_WORLD, &size);
    dx = YMAX/size;
    llimit = rank * dx;
    if(rank != (size - 1)) ulimit = llimit + dx;
    else ulimit = YMAX;

    temp_res = 0;
    for(i = llimit; i < ulimit; i++)
        for(j = 0; j < 10; j++){
            array[i][j] = func(i, j);
            temp_res += array[i][j];
        }

    MPI_Allreduce(&temp_res, &res, 1, MPI_INT, MPI_SUM, MPI_COMM_WORLD);
    MPI_Finalize();
}
```
Nodes, templates and data/loop distributions

- Idea inherited from HPF
- Node is an abstraction of processor and memory in distributed memory environment, declared by node directive.
  - #pragma xmp nodes p(32)
  - #pragma xmp nodes p(*)

- Template is used as a dummy array distributed on nodes
  - #pragma xmp template t(100)
  - #pragma distribute t(block) onto p

- A global data is aligned to the template
  - #pragma xmp align array[i][*] with t(i)

- Loop iteration must also be aligned to the template by on-clause.
  - #pragma xmp loop on t(i)
Array data distribution

- The following directives specify a data distribution among nodes
  - #pragma xmp nodes p(*)
  - #pragma xmp template T(0:15)
  - #pragma xmp distribute T(block) on p
  - #pragma xmp align array[i] with T(i)

Array data distribution:

```
array[]

node0

node1

node2

node3
```

Reference to assigned to other nodes may cause error!!

Assign loop iteration as to compute own data

Communicate data between other nodes
Parallel Execution of “for” loop

- Execute for loop to compute on array

```plaintext
#pragma xmp loop on t(i)
for(i=2; i <=10; i++)
```

Data region to be computed by for loop

Execute “for” loop in parallel with affinity to array distribution by on-clause:

```plaintext
#pragma xmp loop on t(i)
```

XMP project
Data synchronization of array (shadow)

- Exchange data only on “shadow” (sleeve) region
  - If neighbor data is required to communicate, then only sleeve area can be considered.
  - Example: \( b[i] = array[i-1] + array[i+1] \)
    
    ```
    #pragma xmp align array[i] with t(i)
    ```

- Example:
  
  ```
  array[]
  0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
  ```

  ```
  #pragma xmp shadow array[1:1]
  ```

- Node distribution:
  
  - Node 0
  - Node 1
  - Node 2
  - Node 3

**Programmer specifies sleeve region explicitly**

**Directive:** `#pragma xmp reflect array`

XMP project
Data synchronization of array (full shadow)

- Full shadow specifies whole data replicated in all nodes
  - `#pragma xmp shadow array[*]`
- Reflect operation to distribute data to every nodes
  - `#pragma reflect array`
  - Execute communication to get data assigned to other nodes
  - Most easy way to synchronize → But, communication is expensive!

```
array[]
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
node0
node1
node2
node3
```

Now, we can access correct data by local access!!
The "gmove" construct copies data of distributed arrays in global-view.

- When no option is specified, the copy operation is performed collectively by all nodes in the executing node set.
- If an "in" or "out" clause is specified, the copy operation should be done by one-side communication ("get" and "put") for remote memory access.

```xmp
!$xmp nodes p(*)
!$xmp template t(N)
!$xmp distribute t(block) to p
real A(N,N), B(N,N), C(N,N)
!$xmp align A(i,*), B(i,*), C(*,i) with t(i)

A(1) = B(20)    // it may cause error
!$xmp gmove
    A(1:N-2,:) = B(2:N-1,:): // shift operation
!$xmp gmove
    C(:, :) = A(:, :)    // all-to-all
!$xmp gmove out
    X(1:10) = B(1:10,1)  // done by put operation
```

```
A
n o o o
n d d d
e e e e
1 2 3 4
```

```
B
n o o o
n d d d
e e e e
1 2 3 4
```

```
C
node1
node2
node3
node4
```
XcalableMP Global view directives

- Execution only master node
  - #pragma xmp block on master

- Broadcast from master node
  - #pragma xmp bcast (var)

- Barrier/Reduction
  - #pragma xmp reduction (op: var)
  - #pragma xmp barrier

- Task parallelism
  - #pragma xmp task on node-set
XcalableMP Local view directives

- XcalableMP also includes CAF-like PGAS (Partitioned Global Address Space) feature as "local view" programming.
  - The basic execution model of XcalableMP is SPMD
    - Each node executes the program independently on local data if no directive
  - We adopt Co-Array as our PGAS feature.

- In C language, we propose array section construct.
  - Can be useful to optimize the communication

- Support alias Global view to Local view

**Array section in C**

```c
int A[10];
int B[5];
A[5:9] = B[0:4];
```

**Co-array notation in C**

```c
int A[10], B[10];
#pragma xmp coarray [*]: A, B
...
A[:] = B[:][10]; // broadcast
```
Experience with NPB in XcalableMP

- The following three benchmarks are selected for the XMP benchmark
  - EP
  - IS
    - with a histogram (buckets)
    - without a histogram (buckets)
  - CG
    - one-dimensional parallelization
    - two-dimensional parallelization

- Check
  - Programmability/Expressiveness (How to write programs)
  - Performance (How fast the written programs run)
```c
#pragma xmp nodes p(*)
#pragma xmp template t(1:NN)
#pragma xmp distribute t(brock) onto p
...
#pragma xmp loop on t(k)
for(k=1; k<=NN; k++){
    /* pseudorandom number generation*/
}
```
NPB-IS without a histogram

Initialize array

Count the number of keys having the same value

Accumulate the counted number at each node and sum the accumulated number using the reduction operation
NPB-IS without a histogram

key_array[] is a distributed array.
Prv_buff1 is local

```
#pragma xmp loop on t(i)
for( i=0; i<NUM_KEYS; i++ ){
    key_buff2[i] = key_array[i];
    prv_buff1[key_buff2[i]]++;
}

for( i=0; i<MAX_KEY-1; i++ )
    prv_buff1[i+1] += prv_buff1[i];

#pragma xmp reduction(+:prv_buff1)
```

Count the number of keys having the same value
accumulate
reduction
NPB-IS with a histogram

1 5 1 6 3 5
4 3 2 4 7 9 2

Initialize array

Create a histogram

Exchange the keys
(local view)

If the value of the key is small, the key is moved to left node.
NPB-1S with a histogram

key_array[] is distributed array.

```c
#pragma xmp coarray key_buff2
...
#pragma xmp loop on t(i)
for(i=0; i<NUM_KEYS; i++)
    bucket_size[key_array[i] >> shift]++;
...
for(i=0; i<NUM_PROCS; i++)
    key_buff2[a[i]:b[i]]:[i] = key_buff1[c[i]:d[i]];
```

Copy the range from c[i] to d[i] of key_buff2 to the range a[i] to b[i] of key_buff2 in proc [i] (equivalent to MPI_allgather_v)
Implementation of NPB-CG

How do arrays are distributed to each node?

Conjugate Gradient

- Two-dimensional parallelization: template(1:N, 1:N)
- One-dimensional parallelization: template(1:N)

Sparse matrix in array $a[]$
p[], q[], and w[] are distributed arrays.

```
#pragma xmp template t(0:N-1)
#pragma xmp distribute t(block) on proc
#pragma xmp align p[i],q[i],w[i] with t(i)
#pragma xmp shadow p[*]
...
for(....){
#pragma xmp reflect p
#pragma xmp loop on t(j)
for (j = 1; j <= lastrow-firstrow+1; j++) {
    sum = 0.0;
    for (k = rowstr[j]; k < rowstr[j+1]; k++) {
        sum = sum + a[k]*p[colidx[k]];
    }
    w[j] = sum;
}
#pragma xmp loop on t(j)
for (j = 1; j <= lastrow-firstrow+1; j++)
    q[j] = w[j];
... update p with q and w ....
```
- P[] is declared with full shadow
2D-Parallelization of NPB-CG (data distribution)

- Declaration of replicated Arrays

```c
#pragma xmp nodes on n(NPCOLS,NPROWS)
#pragma xmp template t(0:na-1,0:na-1)
#pragma xmp distribute t(BLOCK,BLOCK) on n

double x[na], z[na], p[na],
q[na], r[na], w[na];

#pragma xmp align [i] with t(i,*): x,z,p,q,r
#pragma xmp align [i] with t(*,i): w

w is replicated at the first dimension of t, and distributed for the second dimension in block distribution.

- Matrix data a[], rowstr[], colidx[]
  1. Declared as local arrays
  2. Arranged as to access each element locally.
#pragma xmp template t(0:N-1,0:N-1)
#pragma xmp distribute t(block, block) on p
#pragma xmp align A[j][i] to t(i,j)
#pragma xmp align p[i] to t(i,*)
#pragma xmp align w[j] to t(*,j)

p[], q[], and w[] are distributed arrays.

```
for(){
  ...

#pragma xmp loop on t(*, j)
for (j = 1; j <= lastrow-firstrow+1; j++) {
    sum = 0.0;
    for (k = rowstr[j]; k < rowstr[j+1]; k++) {
        sum = sum + a[k]*p[colidx[k]];
    }
    w[j] = sum;
}
#pragma xmp reduction(+:w) on p(*, :)
#pragma xmp gmove
q[] = w[];

Reduction operation on replicated array

..... Update p with q ....
```
\[ w[j] \text{ with } t(\ast,j) \]

\[ \text{reduction} \]

\[ \text{reduction}(+:w) \text{ on } p(\ast, :) \]

gmove \( q[:] = w[:] \);

transpose
Performance Evaluation

**T2K Tsukuba System**

- AMD Opteron Quad 2.3GHz
- Infiniband DDR 4rails (8GB/s)

**PC Cluster**

- Intel Core2 Quad 3GHz
- Gigabit Ethernet
The difference in performance at 1 node is because the performance of the C compiler is poor than that of Fortran.
The results indicate that the performance of XMP with a histogram is comparable to that of MPI.
Performance Results : NPB-CG

The results for CG indicate that the performance of 2D parallelization in XMP is comparable to that of MPI.
Short Summary

- Preliminary performance report  NPB results
  - We found XMP can be a good solution to describe these benchmarks.
  - Performance looks reasonable, but much performance tuning is required
  - More experience is needed in real apps.

- XcalableMP project: status and schedule
  - A draft of XcalableMP specification 0.7
    - http://www.xcalablemp.org/xmp-spec-0.7.pdf
  - 3Q/10 beta release, C language version compiler (at SC10)
  - Fortran version compiler after SC10

- Issues under discussion
  - Multicores (SMP) Cluster and Hybrid programming with OpenMP
  - Parallel IO
  - Extension to GPGPU, Manycore, Fault tolerant?, Others …
Thank you for your attention!!!

Q & A?

http://www.xcalablemp.org/

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We would like to thank XMP-WG members for Valuable discussions and comments