X10 Programming:
Towards High Productivity
High Performance Systems
in the post-Moore’s Law Era

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Outline

1. X10 Execution Model
   • Integration of multiple levels of concurrency and asynchronous data transfer

2. X10 Language and Environment
   • Extended subset of the Java™ language
   • X10 environment is integrated into Eclipse ecosystem
   • Synergies between HPC VM technologies (X10) and real-time VM technologies (Metronome)
Future System Trends

Parallelism scaling replaces frequency scaling as foundation for increased performance

Scale-up Parallelism

| SMP | Multi-core | SMT’s | SIMD | ILP |

Heterogeneous Parallelism (Co-processors, accelerators)

Scale-out Parallelism

Implications to software:
1) Exploit intra-process parallelism with non-uniform data affinities
2) Exploit inter-process parallelism in tightly coupled clusters of distributed nodes
Overview of X10 Execution Model

- **Asynchronous activities**
  - Unification of task parallelism and asynchronous data transfers
  - Ultra-lightweight “async” threads, augmented with (optional) loop-level constructs (“foreach”, “ateach”)

- **Coordination of parallel control flow**
  - “finish” and “clock” constructs

- **Coordination of data accesses**
  - “atomic” blocks, “future” and “force” constructs

- **Places**
  - Extension of Partitioned Global Address Space (PGAS) to Threaded Partitioned Global Address Space (T-PGAS)
  - Place = collection of non-migrating activities and mutable data
  - An activity can create a new activity at a local or remote place
Locality Rule in X10 Execution Model

- Any access to a shared mutable datum must be performed by an activity at the same place as the datum
  - Immutable data can be freely access from any place
- A BadPlaceException is thrown when the Locality Rule is violated

(Threaded Partitioned Global Address Space model (T-PGAS))
X10 Execution Model: Examples

1) \textbf{finish} \\
   \hspace{1em} \texttt{async (A[R]) A[R] = 99; // Initiate remote put} \\
   \hspace{1em} \texttt{// Do other work in parallel} \\
   \\
2) \hspace{1em} // Combine remote get and remote put, A[L] = A[R] \\
   \hspace{1em} \texttt{async (A[R])\{ final int v = A[R];} \\
   \hspace{2em} \texttt{async (A[L]) A[L] = v; \}} \\
   \\
3) \texttt{async (T[j]) atomic T[j] ^= k; // Asynchronous atomic block} \\
   \\
4) \texttt{ateach ( point[j] : A.distribution)} \\
   \hspace{1em} \texttt{A[j] = f(j); // Equivalent to async(A[j]) A[j] = f(j)}
X10 Execution Model: Examples

1) \textbf{finish} {
   \begin{verbatim}
   async (A[R]) A[R] = 99; // Initiate remote put
   // Do other work in parallel
   \end{verbatim}
}

   \begin{verbatim}
   async (A[R]) {
   final int v = A[R];
   }
   \end{verbatim}

3) \textbf{async (T[j]) atomic T[j]^=k; // Asynchronous atomic block}

4) \textbf{ateach (point[j] : A.distribution)}
   \begin{verbatim}
   A[j] = f(j); // Equivalent to \textbf{async(A[i]) A[i] = f(i)}
   \end{verbatim}

\textbf{Any local variable accessed by a child activity must be declared as final}

\textbf{Activity body is in-line --- need not be extracted into a separate method or class}
X10 Dynamic Activity Invocation Tree

Activity A0 (Part 1)
    async
    Activity A1
        async
        Activity A2

Activity A0 (Part 2)
    async
    Activity A3

Activity A0 (Part 3)
    async
    Activity A4

finish

Local variables are passed by value from parent to child activity --- no need for a cactus stack

Child activity A2 can out-live parent activity A1
X10 Dynamic Activity Invocation Tree

Finish serves as root for both normal and exceptional termination (for designated subset of activities)

IndexOutOfBoundsException exception
Summary of X10 Execution model

Advantages:

• Any program written with atomic, async, finish, foreach, ateach, and clock parallel constructs will never deadlock

• Inter-node and intra-node parallelism integrated in a single model

• Remote activity invocation subsumes one-sided data transfer, remote atomic operations, active messages, . . .

• Finish subsumes point-to-point and team synchronization

• All remote data accesses are performed as activities ➔ rules for ordering of remote accesses follows simply from concurrency model

Applications:

• Can be easily mapped to multiple levels of parallel hardware (SIMD, SMT, coprocessors, cache prefetch, SMP, clusters, …)

• Can be used as target for multiple high level languages
  – X10 language serves as an exemplar
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PERCS Programming Model, Tools and Compilers
(PERCS = Productive Easy-to-use Reliable Computer Systems)

Productivity Measurements

Refactoring for Concurrency

Performance Exploration

Parallel Tools Platform (PTP)

X10 source code

Java™ source code (w/ threads & conc util)

C/C++ source code (w/ MPI, OpenMP, UPC)

Fortran source code (w/ MPI, OpenMP)

X10 Components

Java components

C/C++ components

Fortran components

X10 runtime

Java runtime

Fast extern interface

C/C++ runtime

Fortran runtime

Eclipse platform

Dynamic Compilation + Continuous Program Optimization

Integrated Parallel Runtime: MPI + LAPI + RDMA + OpenMP + threads
PERCS Programming Model: Position of X10 Language in Software Stack

Very High Level Languages (VHLL’s),
Domain Specific Languages (DSL’s)

Components

Libraries

X10 Language

Deployment

Managed Runtime

Implicit parallelism,
Implicit data distributions

Domain-specific frameworks

Collections, concurrency utils, …

**X10 places and activities**

Mapping of places & activities to nodes in HPC Platform

Safety guarantees + dynamic comp.

**Integrated Parallel Runtime: MPI + LAPI + RDMA + OpenMP + threads**
X10 vs. Java™ languages

- X10 is an extended subset of the Java language
  - Base language = Java 1.4 language
    - Java 5 features (generics, metadata, etc.) will be supported in the future
  - Notable features removed from Java language
    - Concurrency --- threads, synchronized, etc.
    - Java arrays – replaced by X10 arrays
  - Notable features added to Java language
    - Concurrency – async, finish, atomic, future, force, foreach, ateach, clocks
    - Distribution --- points, distributions
    - X10 arrays --- multidimensional distributed arrays, array reductions, array initializers,
    - Serial constructs --- nullable, const, extern, value types
- X10 supports both OO and non-OO programming paradigms
Sequence Comparison
Example: Local Alignment

- Goal: find the best matching subregions in a pair of sequences (e.g., DNA, RNA, sequence) so as to narrow down set of candidates for identifying biological relationships.

Each processor computes columns myLow..myHigh using columns overlapStart..myLow-1 as warm-up.
X10 Version of Sequence Alignment (Serial Version)

```plaintext
void computeMatrix(int[] A, value char[] c1, value char[] c2,
                  int firstCol, int lastCol) {
    // Dynamic programming algorithm
    for ( point[i,j] : [1:N,firstCol:lastCol] )
        M[i,j] = min4(0, a[i-1,j] + Gap, a[i,j-1] + Gap,
                        a[i-1,j-1] + (c1[i]==c2[j] ? Match : MisMatch)));
}

// Main program
const int N = c1.length, M = c2.length;
  ...
A = new int[[0:N,0:M]];
computeMatrix(A, c1, c2, 1, M);
  ...
```
X10 Version of Sequence Alignment
(Distributed Parallel Version)

// Allocate A with a [*,block] distribution
int[.] A = new int[dist.blockColumns([0:N,0:M])];
final int overlap = ceilFrac(N*(-Match),Gap) + N;
// SPMD computation at each place
finish ateach(point [i] : dist.unique()) {
    final dist myD = A.distribution | here; // sub-distribution for this place
    final int myLow = myD.region.rank(1).low();
    final int myHigh = myD.region.rank(1).high();
    final int overlapStart = max(0,myLow-overlap);
    final dist warmupD = [0:N,overlapStart:myLow]->here;
    final int[.] W = new int[warmupD]; // W = local warmup array
    computeMatrix(W, c1, c2, overlapStart+1, myLow);
    foreach (point[i]:[0:N]) A[i,myLow] = W[i,myLow]; // Copy col myLow
    // Compute my section of global array A
    computeMatrix(A, c1, c2, myLow+1, myHigh);
}
X10 Status

• Reference implementation
  − Used in PSC productivity study and university pilots
  − Nightly regression tests (~ 240 unit tests)
  − X10 application set starting to grow beyond unit tests
  − Plan for open source release at end of Phase 2

• Performance Prototype
  − Initial design for mapping X10 to LAPI using product J9 VM
  − Implementation has just begun
    • Bring-up of “hello world” X10 application on multiple nodes

• X10 Development Toolkit (X10DT)
  − Eclipse tools with basic language support (syntax highlighting, etc.)
  − Work started on X10-specific refactorings
    • Extract Async
    • Introduce atomic sections

• Static Analysis and Ahead-Of-Time Optimization (just starting)
  − Optimization of BadPlaceException checks
  − Use of static analysis to enhance Extract Async refactoring
X10 Reference Implementation

- **Foo.x10**
  - X10 source program --- must contain a class named Foo with a "public static void main(String[] args)" method
  - X10 compiler --- translates Foo.x10 to Foo.java, uses javac to generate Foo.class from Foo.java

- **Foo.java**
  - X10 program translated into Java --- // #line pseudocomment in Foo.java specifies source line mapping in Foo.x10

- **Foo.class**

- **x10c**

- **x10c Foo.x10**
  - X10 compiler --- translates Foo.x10 to Foo.java, uses javac to generate Foo.class from Foo.java

- **X10 Virtual Machine**
  - (JVM + J2SE libraries + X10 libraries + X10 Multithreaded Runtime)

- **External DLL’s**
  - X10 extern interface

- **X10 Program Output**
  - X10 Abstract Performance Metrics (event counts, distribution efficiency)
X10 Reference Implementation: Screen Shot
Future X10 Environment: Optimized X10 Deployment on a PERCS HPC system

Interconnect

Thin X10 VM

Thick X10 VM

Compute Node

I/O Node

Storage and I/O controllers

Other Storage Device

I/O Device
Towards Increased Productivity in High Performance Embedded Computing: Expanding the frontiers of Virtual Machine Technologies

HPC VM Enhancements --- IBM PERCS/X10 project

Real-time VM Enhancements --- IBM Metronome project

Commodity Virtual Machines

Reduced GC pause times improves HPC VM performance

Reduced overhead for asynchronous atomic operations times improves Real-time VM performance

IBM Metronome

IBM X10
IBM Metronome project: Real-time Garbage Collection

David Bacon, Perry Cheng, David Grove, V.T. Rajan, Martin Vechev

- **Garbage collection is fundamental to Java’s value proposition**
  - Safety, reliability, programmer productivity
  - But also causes the most non-determinism (100 ms – 10 s latencies)
  - RTSJ standard does not support use of garbage collection for real-time

- **Metronome is our hard real-time garbage collector**
  - Worst-case 2 ms latencies; high throughput and utilization
  - 100x better than competitors’ best garbage collection technology

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**Garbage Collection Pause Times**

(Customer application)

- Worst-case 1.7 ms
- Average 260 us
Summary

• X10 Execution Model is designed for productivity and scalability
  – X10 language is our preferred embodiment, but we are also plan to explore other manifestations

• X10 tools are integrated into a common development environment (Eclipse)
  – We expect that the Parallel Tools Platform (PTP) project will seed a new community ecosystem for parallel tools

• Where we are looking for collaboration on X10
  – Porting applications to X10 for evaluation
  – Volunteers productivity studies
  – Standardization of T-PGAS runtime
    • multithreading with asynchronous one-sided data transfers

• Did not have time to cover
  – Clocks, futures, array language details, …
  – Additional advances in Java technologies (and their use in non-Java langs)
  – Additional work on improving productivity & expertise gap in PERCS project