X10: New opportunities for Compiler-Driven Performance via a new Programming Model

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Compiler-Driven Performance Workshop

CASCON 2004

Oct 6, 2004

Acknowledgments

- **IBM PERCS Team members**
  - **Research**
  - **Systems & Technology Group**
  - **Software Group**
  - **PI: Mootaz Elnozahy**
- **University partners:**
  - **Cornell**
  - **LANL**
  - **MIT**
  - **Purdue University**
  - **RPI**
  - **UC Berkeley**
  - **U. Delaware**
  - **U. Illinois**
  - **U. New Mexico**
  - **U. Pittsburgh**
  - **UT Austin**
  - **Vanderbilt University**
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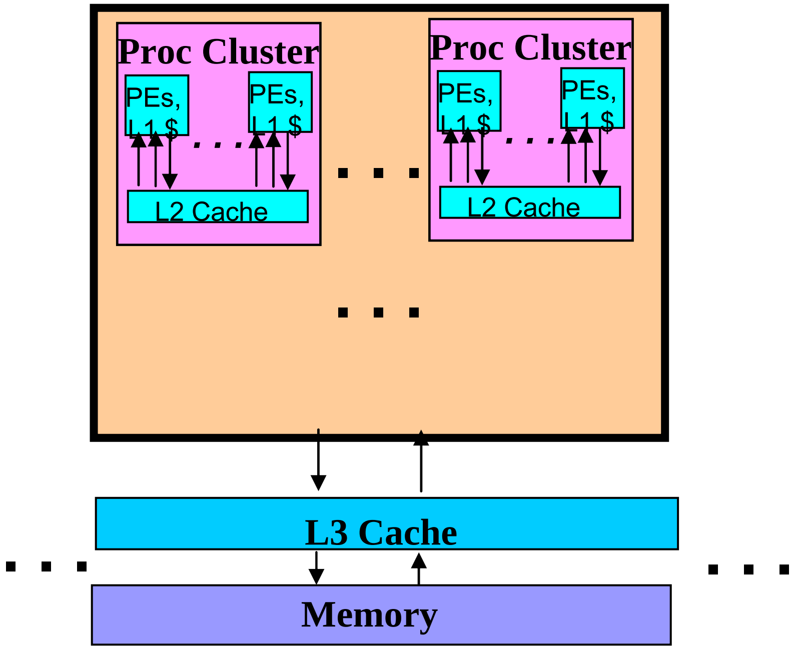
  - Robert O'Callahan
  - Filip Pizlo (Purdue)
  - Christoph von Praun
  - V.T.Rajan
  - Lawrence Rauchwerger (Texas A&M)
  - Vijay Saraswat (contact for lang. spec.)
  - Vivek Sarkar
  - Mandana Vaziri
  - Jan Vitek (Purdue)

Performance and Productivity Challenges facing Future Large-Scale Systems

1) <u>Memory wall:</u> Severe *non-uniformities* in bandwidth & latency in memory hierarchy



2) <u>Frequency wall:</u> Multiple layers of *hierarchical heterogeneous parallelism* to compensate for slowdown in frequency scaling

Clusters (scale-out)
SMP
Multiple cores on a chip
Coprocessors (SPUs)
SMTs
SIMD
ILP

3) <u>Scalability wall:</u> Software will need to deliver ~ *10^5-way parallelism* to utilize large-scale parallel systems

IBM PERCS Project (Productive Easy-to-use Reliable Computing Systems)

Increase overall productivity

Increase number of applications written

Increase development productivity

Increase performance of applications

Increase execution productivity

PERCS Programming Tools
performance-guided parallelization and transformation, static & dynamic checking, separation of concerns --- all integrated into a single development environment (Eclipse)

PERCS Programming Model | **OpenMP** | **MPI**

Static and Dynamic Compilers for base language w/ programming model extensions
Mature languages: C/C++, Fortran, Java
Experimental languages: X10, UPC, StreamIt, HTA/Matlab

Language Runtime + Dynamic Compilation + Continuous Optimization

PERCS System Software (K42)

PERCS System Hardware

Limitations in exploiting Compiler-Driven Performance in Current Parallel Programming Models

- MPI: Local memories + message-passing
  - Parallelism, locality, and “global view” are completely managed by programmer
  - Communication, synchronization, consistency operations specified at low level of abstraction

  ➔ Limited *opportunities* for compiler optimizations
- Java threads, OpenMP: shared-memory parallel programming model
  - Uniform symmetric view of all shared data
  - Non-transparent performance --- programmer cannot manage data locality and thread affinity at different hierarchy levels (cluster, SMT, …)

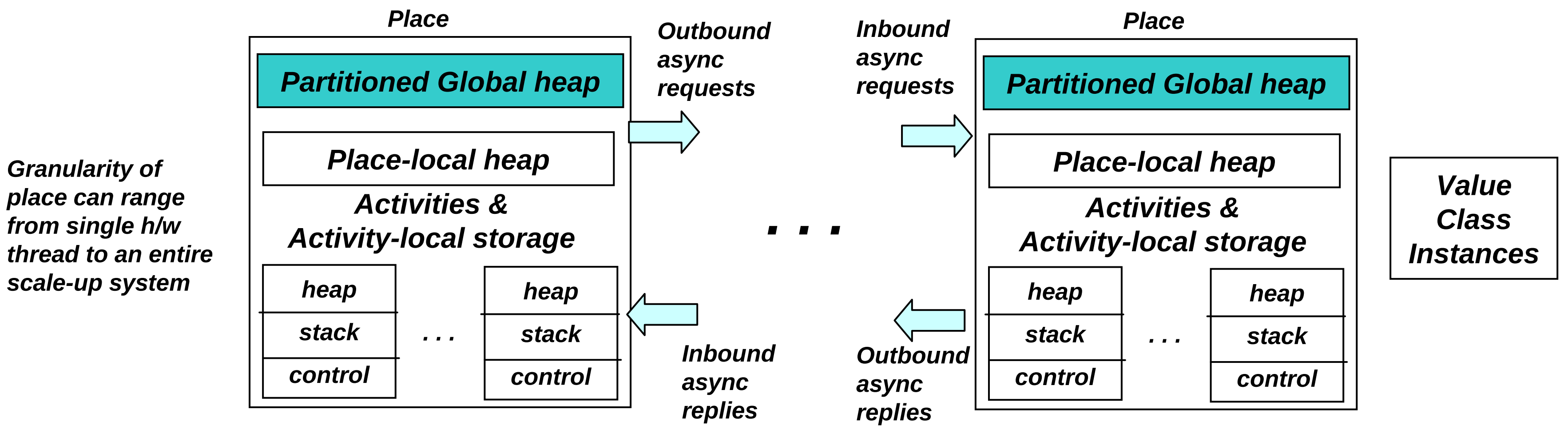
  ➔ Limited *effectiveness* of compiler optimizations
- HPF, UPC: partitioned global address space + SPMD execution model
  - User specifies data distribution & parallelism, compiler generates communications using owner-computes rule
  - Large overheads in accessing shared data; compiler optimizations can help applications with simple data access patterns

  ➔ Limited *applicability* of compiler optimizations

X10 Design Guidelines: Design for Productivity & Compiler/Runtime-driven Performance

- **Start with state-of-the-art OO language primitives as foundation**
  - No gratuitous changes
  - Build on existing skills
- **Raise level of abstraction for constructs that should be amenable to optimized implementation**
  - Monitors → atomic sections
  - Threads → async activities
  - Barriers → clocks
- **Introduce new constructs to model hierarchical parallelism and non-uniform data access**
  - Places
  - Distributions
- **Support common parallel programming idioms**
  - Data parallelism
  - Control parallelism
  - Divide-and-conquer
  - Producer-consumer / streaming
  - Message-passing
- **Ensure that every program has a well-defined semantics**
  - Independent of implementation
  - Simple concurrency model & memory model
- **Defer fault tolerance and reliability issues to lower levels of system**
  - Assume tightly-coupled system with dedicated interconnect

Logical View of X10 Programming Model (Work in progress)



- *Place* = collection of resident activities and data
  - Maps to a data-coherent unit in a large scale system
- Four storage classes:
  - Partitioned global
  - Place-local
  - Activity-local
  - Value class instances
    - Can be copied/migrated freely

- Activities can be created by
  - *async statements* (one-way msgs)
  - *future expressions*
  - *foreach & ateach constructs*
- Activities are coordinated by
  - *Unconditional atomic sections*
  - *Conditional atomic sections*
  - *Clocks* (generalization of barriers)
  - *Force* (for result of future)

Async activities: abstraction of threads

- **Async statement**
  - `async(P){S}:` run S at place P
  - `async(D){S}:` run S at place containing datum **D**
  - S may contain local atomic operations or additional async activities for same/different places.
- *Example: percolate process to data.*

```
public void put(K key, V value) {
   int hash = key.hashCode()% D.size;
  async (D[hash]) {
         for (_ b = buckets[hash]; b != null; b = b.next) {
            if (b.k.equals(key)) {
               b.v = value;
              return;
            }
         }
         buckets[hash] =
            new Bucket<K,V>(key, value, buckets[hash]);
   };
}
```

- **Async expression (future)**
  - `F = future(P){E}:` Return the value of expression E, evaluated in the place containing datum D.
  - `force F` **or** `!F :` suspend until value is known
- *Example: percolate data to process*.

```
public ^V get(K key) {
     int hash = key.hashCode()% D.size;
     return future (D[hash]) {
        for (_ b = buckets[hash]; b != null; b = b.next) {
           if (b.k.equals(key)) {
              return b.v;
           }
        }
       return new V();
     }
  }
```

Distributed hash-table code

RandomAccess (GUPS) example

```
public void run(int a[] blocked, int seed[] cyclic,
            int value smallTable[]) {
    ateach (ran : seed) {
       for (int count : 1.. N_UPDATES/place.MAX_PLACES) {
           ran = Math.random(ran);
           int j = F(ran);
           int k = smallTable[g(ran)];
           async (a[j]) atomic {a[j]^=k;}
       } // for
    } // ateach
}
```

Regions and Distributions

- **Regions**
  - The domain of some array; a collection of array indices
  - region R = [0..99];
  - region R2 = [0..99,0..199];
- **Region operators**
  - region Intersect = R3 && R4;
  - region Union = R3 || R4;
  - Etc.
- **Distributions**
  - Map region elements to places
    - distribution D = cyclic(R);
  - Domain and range restriction:
    - distribution D2 = D | R;
    - distribution D3 = D | P;
- Regions/Distributions can be used like type and place parameters
  - <region R, distribution D> void m(...)

ArrayCopy example: example of high-level optimizations of async activities

Version 1 (orginal):

```
<value T, D, E>  public static void
    arrayCopy( T[D] a, T[E] b) {
        // Spawn an activity for each index to
        // fetch and copy the value
       ateach (i : D.region)
           a[i] = async b[i];
       next c; // Advance clock
    }
```

Version 2 (optimized):

```
<value T, D, E>  public static void
    arrayCopy( T[D] a, T[E] b) {
       // Spawn one activity per place
       ateach ( D.places )
           for ( j : D | here )
               a[i] = async b[i];
       next c; // Advance clock
    }
```

Version 3 (further optimized):

```
<value T, D, E>  public static void
    arrayCopy( T[D] a, T[E] b) {
    // Spawn one activity per D-place and one
    // future per place p to which E maps an
    // index in (D | here).
       ateach ( D.places ) {
           region LocalD = (D | here).region;
           ateach ( p : E[LocalD] ) {
               region RemoteE = (E | p).region;
               region Common =
                                  LocalD && RemoteE;
               a[Common] = async  b[Common];
           }
       }
       next c; // Advance clock
    }
```

Uniform treatment of Arrays & Loops and Collections & Iterators

- **Arrays**
  - Map region elements to values (therefore multidimensional)
  - Declared with a given distribution
  - int[D] array;
- **Loops**
  - ateach (D[R]) { ... }
  - ateach (array) { ... }
  - foreach (i : R) { ... }
  - foreach (i : D) { ... }
  - foreach (i : array) { ... }
  - sequential variants of foreach are available as for loops
- **Distributed Collections**
  - Map collection elements to places
  - Collection<D,E> identifies a collection with distribution D and element type E
- **Parallel iterators**
  - foreach (e : C) { … }
  - ateach (C) { … here … }
- **Sequential iterator**
  - for (e : C)

Clocks: abstraction of barriers

- **Operations:**
  `clock c = new clock();`
  `now(c){S}`
    - Require S to terminate before clock can progress.

  `continue c;`
    - Signals completion of work by activity in this clock phase.

  `next` $c_1,\ldots,c_n$ `;`
    - Suspend until clocks can advance. Implicitly continues all clocks. $c_1,\ldots,c_n$ names all clocks for activity.

  `drop c;`
    - No further operations on c..

- **Semantics**
  - Clock c can advance only when all activities registered with the clock have executed continue c..
- **Clocked final**
  - clocked(c) final int l = r;
  - Variables is "final" (immutable) until next phase

Unstructured Mesh Transport Example (UMT2K)

- 3D, deterministic, multi-group, photon transport code
- Solves 1st order form of steady-state Boltzman equation
- Represented by an unstructured mesh
  - Partitioning strives to maintain load balance, reduce communicate/compute ratio

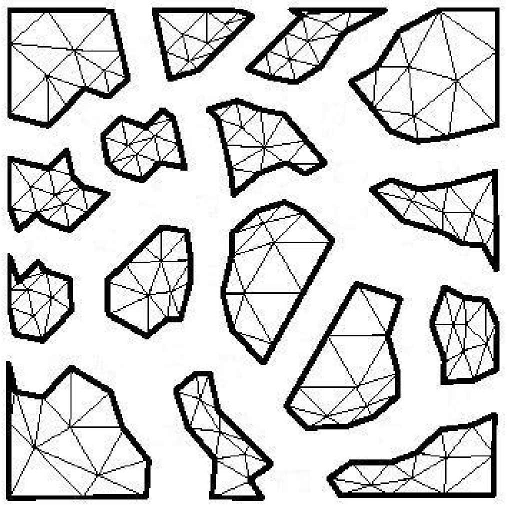
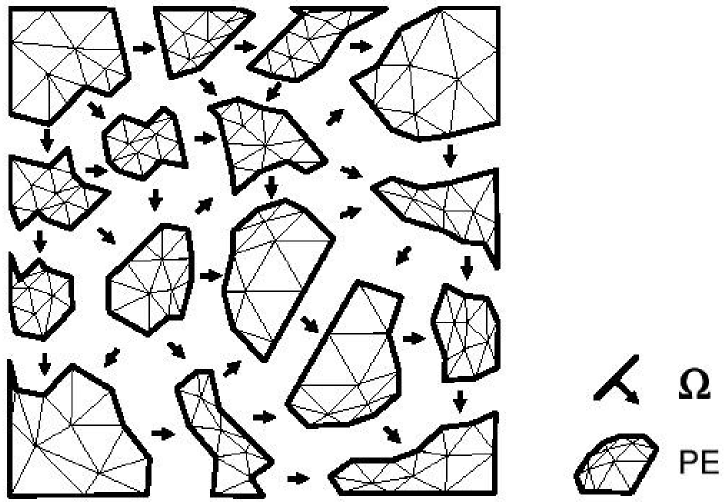


Figure source: Modified from Mathis and Kerbyson, IPDPS 2004

Communication Structure

- Nearest neighbor communication in graph domain
- Communication can be minimized via judicious mapping of graph to system nodes



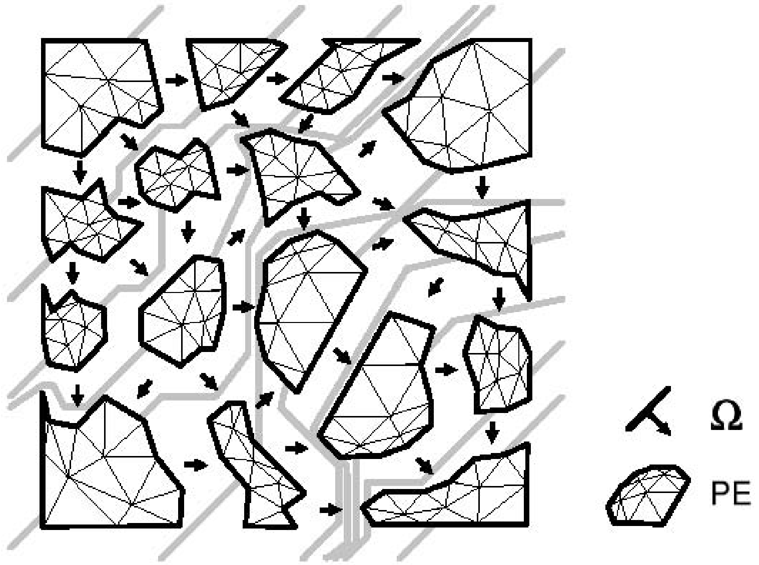


Figure source: Modified from Mathis and Kerbyson, IPDPS 2004

UMT2k in X10: example of hierarchical heterogeneous parallelism

```
do {
  now ( c ) {
    ateach ( n : nodes ) {  // Cluster-level parallelism
        foreach ( s : Sweeps ) { // SMP parallelism
              // receive inputs
              flows = new Flux[R] (k) { // SMT parallelism
                  async (…) inputs[s][k].receive();
              }
              // Choice of using clock or force to synchronize on flows[*]
              // Thread-local with vector & co-processor parallelism
              flux = compute(s, flows);
              // send outputs
               . . .
        } // foreach
    } // ateach
  } // now
  // use clock c to wait for all sweeps to complete
  next c;
  . . .
} while ( err > MAX_ERROR ) ;
```

Clusters (scale-out)
SMP
Multiple cores on a chip
Coprocessors (SPUs)
SMTs
Vector (VMX)
ILP

C+MPI FixedPoint iteration (Simpler example than UMT2K)

```
int n;
double *A, *Tmp;
const double epsilon = 0.000001;
int main(int argc, char* argv[]) {
  int i, iters;
  double delta;
  int numprocs, rank, mysize;
  double sum;
   MPI_Init(&argc, &argv);
  MPI_Comm_size(MPI_COMM_WORLD, &numprocs);
  MPI_Comm_rank(MPI_COMM_WORLD, &rank);
  if (argc != 2) {
    printf("usage: fixedpt n\n");
    exit(1);
  }
  n = atoi(argv[1]);
  mysize  = n * (rank+1)/numprocs -  n *  rank / numprocs;
  A = malloc((mysize+2)*sizeof(double));
  for (i = 0; i <= mysize; i++)   A[i] = 0.0;
  if (rank == numprocs - 1)  A [mysize+1] = n + 1.0;
  Tmp = malloc((mysize+2)*sizeof(double));
  iters = 0;
do {
   iters++;
   if (rank < numprocs -1)
     MPI_Send(&(A[mysize]), 1, MPI_DOUBLE, rank+1, 1,
         MPI_COMM_WORLD);
   if (rank > 0)
     MPI_Recv(&(A[0]), 1, MPI_DOUBLE, rank-1, 1,
         MPI_COMM_WORLD, MPI_STATUS_IGNORE);
   if (rank > 0)
     MPI_Send(&(A[1]), 1, MPI_DOUBLE, rank-1, 1,
         MPI_COMM_WORLD);
   if (rank < numprocs-1)
     MPI_Recv(&(A[mysize+1]), 1, MPI_DOUBLE, rank+1, 1,
         MPI_COMM_WORLD, MPI_STATUS_IGNORE);
   for (i=1; i <=mysize; i++)  Tmp[i] = (A[i-1]+A[i+1])/2.0;
   delta = 0.0;
   for (i = 1; i <= mysize; i++)  delta +=fabs(A[i]-Tmp[i]);
   MPI_Allreduce(&delta, &sum, 1, MPI_DOUBLE, MPI_SUM,
       MPI_COMM_WORLD);
   delta = sum;
   for (i = 1; i <= mysize; i++)  A[i]=Tmp[i];
  } while (delta > epsilon);
  if (rank == 0)  printf("Iterations: %d\n", iters);
  MPI_Finalize();
}
```

Courtesy: Larry Snyder et al

API-based control flow, distribution is hard-coded in program

Reduction and Scan Operators

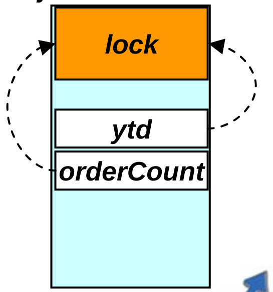
- Reduction operator over type T
  - Static method with signature: T(T,T)
  - Virtual method in class T with signature T(T)
  - Operator is expected to be associative and commutative
- Reduction operation: A >> foo() returns value of type T, where
  - A is an array over base type T
  - A>>foo() performs reductions over all elements of A to obtain a single result of type T
- Scan operation: A || foo() returns array, B, of base type T, where
  - B[i] = A[0..i]>>foo()

Example of Unconditional Atomic Sections SPECjbb2000: Java vs. X10 versions

Java version:

```
public class Stock extends Entity {…
private float  ytd;
private short orderCount; …
public synchronized void
  incrementYTD(short ol_quantity) { …
      ytd += ol_quantity; …}…
public synchronized void
  incrementOrderCount() { …
      ++orderCount; …} …
}
```

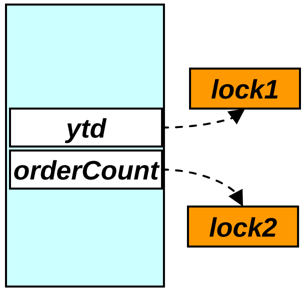
Layout of a "Stock" object



These two methods cannot be executed simultaneously because they use the same lock

X10 version (w/ atomic section):

```
public class Stock extends Entity {…
private float  ytd;
private short orderCount; …
public atomic void
  incrementYTD(short ol_quantity) { …
      ytd += ol_quantity; …}…
public atomic void
  incrementOrderCount() { …
      ++orderCount; …} …
}
```



With atomic sections, X10 implementation can choose to execute these two methods in parallel

Atomic Sections are deadlock-free!

Example of Conditional Atomic Section

- Conditional Atomic Sections are similar to Conditional Critical Regions (CCRs)
  - Powerful construct, misuse can lead to deadlock
  - Need to identify special cases that are most useful in practice

```
class OneBuffer<value T> {
    ?Box<T> datum = null;
    public void send(T v) {
         when (this.datum == null) {
             this.datum := new Box<T>(datum);
          }
    }
    public T receive() {
        when (this.datum !=null) {
           T v = datum.datum;
           value := null;
           return v;
        }
    }
}
```

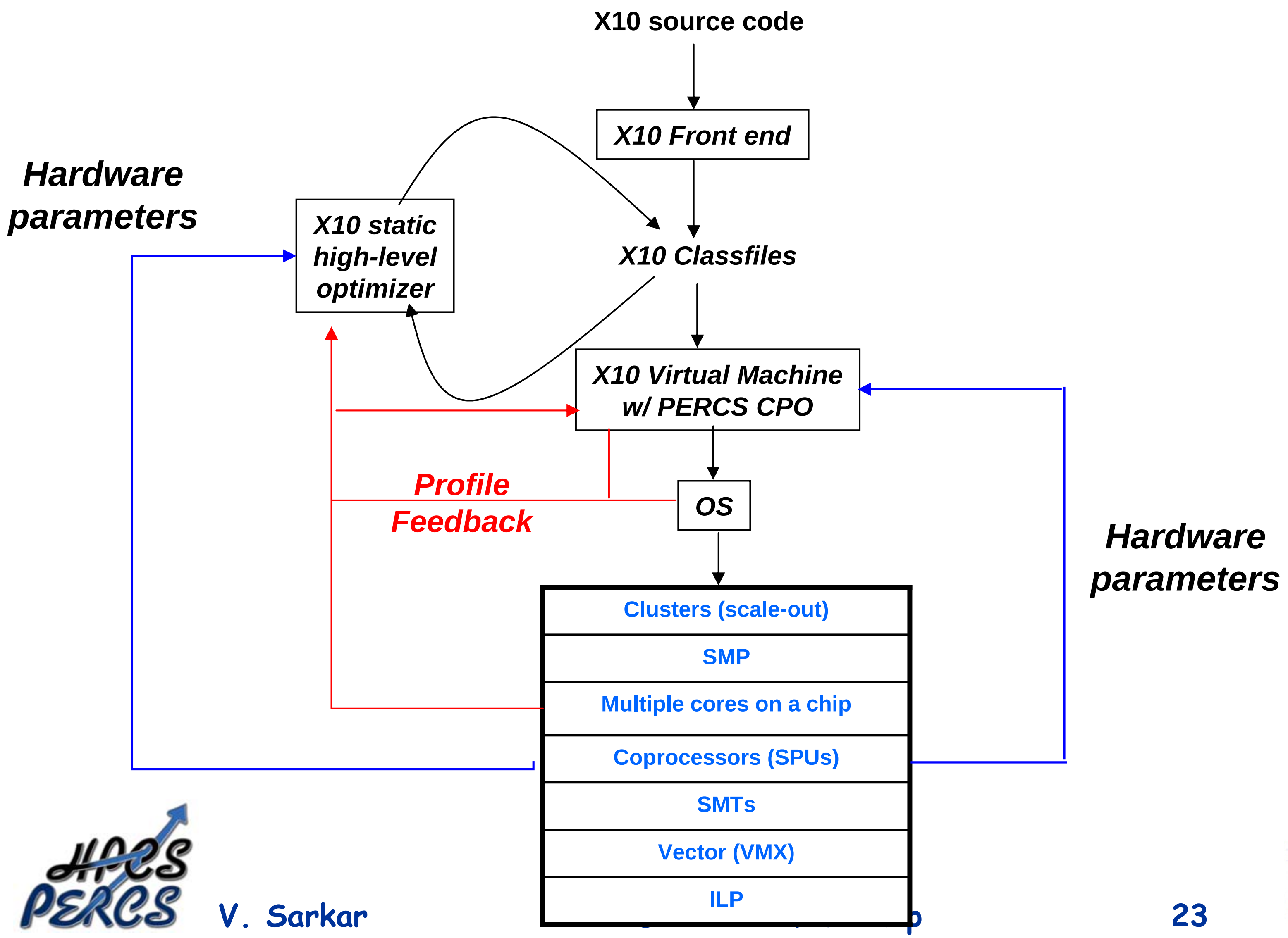
Memory Model

- X10 focus is on data-race-free applications
- Programmer uses atomic / clock / force operations to avoid data races
  - X10 programming environment also includes data race detection tool
- Weak memory model for defining consistency of unsynchronized accesses
  - Based on Location Consistency memory mode
  - Akin to weak ordering guarantees of messages in MPI

X10 Type System: Features relevant to Compiler Optimization

- Unified type system
  - All data items are objects
- Value classes and clocked final
  - Immutable --- no updatable fields
  - However, target of object reference in a field can be mutable (if it’s not itself a value class instance)
- Type parameters
  - Places, distributions,
- Nullable
  - All types are non-null by default, need to explicitly declare a variable as nullable
  - For any type T, the type ?T (read: “nullable T”) contains all the values of type T, and a special null value, unless T already contains null.
- Support for both rectangular multidimensional arrays (matrices) and nested arrays

X10 Compilation and Runtime Environment



Relating optimizations for past programming paradigms to X10 optimizations

Programming paradigm	Activities	Storage classes	Important optimizations
Message-passing e.g., MPI	Single activity per place	Place local	Message aggregation, optimization of barriers & reductions
Data parallel e.g., HPF	Single global program	Partitioned global	SPMDization, synchronization & communication optimizations
PGAS e.g., Titanium, UPC	Single activity per place	Partitioned global, place local	Localization, SPMDization, synchronization & communication optimizations
DSM e.g., TreadMarks	Multiple	Partitioned global, activity local	Data layout optimizations, page locality optimizations
NUMA	Single activity per place	Partitioned global, activity local	Data distribution, synchronization & communication optimizations
Co-processor e.g., STI Cell	Single activity per place	Partitioned-global, place-local	Data communication, consistency, & synchronization optimizations
Futures / active messages	Multiple	Place-local, activity local	Message aggregation, synchronization optimization
Full X10	Multiple activities in multiple places	Partitioned-global, place-local, activity-local	All of the above

Some Challenges in Optimization of X10 programs

- **Analysis and optimization of explicitly parallel programs**
  - Proposed approach: use Parallel Program Graph (PPG) representation
- **Analysis and optimization of remote data accesses**
  - Proposed approach: perform data access aggregation and elimination using Array SSA framework
- **Optimized implementation of Atomic Sections**
  - Simple cases that can be supported by hardware e.g., reductions
  - Analyzable atomic sections
  - General case
- **Load-balancing**
  - Dynamic, adaptive migration of place s
- **Continuous optimization**
  - Efficient implementation of scan/reduce
- **Efficient invocation of components in foreign languages**
  - C, Fortran
- **Garbage collection across multiple places**

Traditional SSA Form: Issue with Preserving Definitions

Original Program

```
X[1:n] = . . .
. . .
X[k] = . . .
… = X[j]
```

“Traditional” SSA Form

$X_1[1{:}n] = . . .$

$. . .$

$X_2[k] = . . .$

$… = X[j]$

Q: What name should this use of X get?

Traditional SSA Form: Issue with Preserving Definitions

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```

"Traditional" SSA Form

X_1`[1:n] = . . .`

`. . .`

X_2`[k] = . . .`

`… = X[j]`

Q: What name should this use of X get?

A: It depends on the values of j and k!

Array SSA form approach: introduce a new ϕ function for aliased definitions

Original Program

```
X[1:n] = . . .
. . .
X[k] = . . .
… = X[j]
```

Array SSA Form

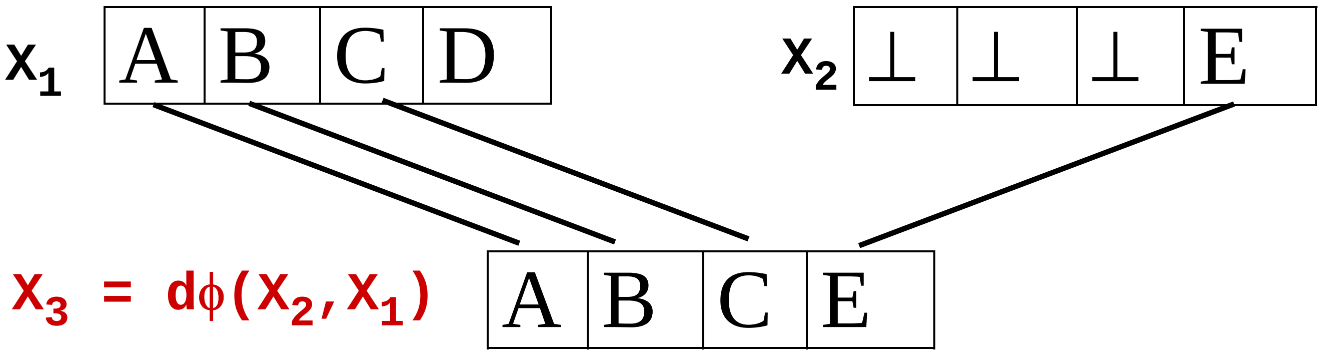
$X_1[1:n]$ = . . .

. . .

$X_2[k]$ = . . .

$X_3 = d\phi(X_2, X_1)$

… = $X_3[j]$



$X_3 = d\phi(X_2, X_1)$

$$X_3[j] = \begin{cases} X_2[j] & \text{if } j = k \\ X_1[j] & \text{otherwise} \end{cases}$$

"Array SSA form and its use in Parallelization.", K.Knobe, V.Sarkar, POPL 1998.

Array SSA form approach: introduce a new dϕ function for aliased definitions

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X[1:n] = . . .
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Array SSA Form

$X_1[1:n]$ = . . .

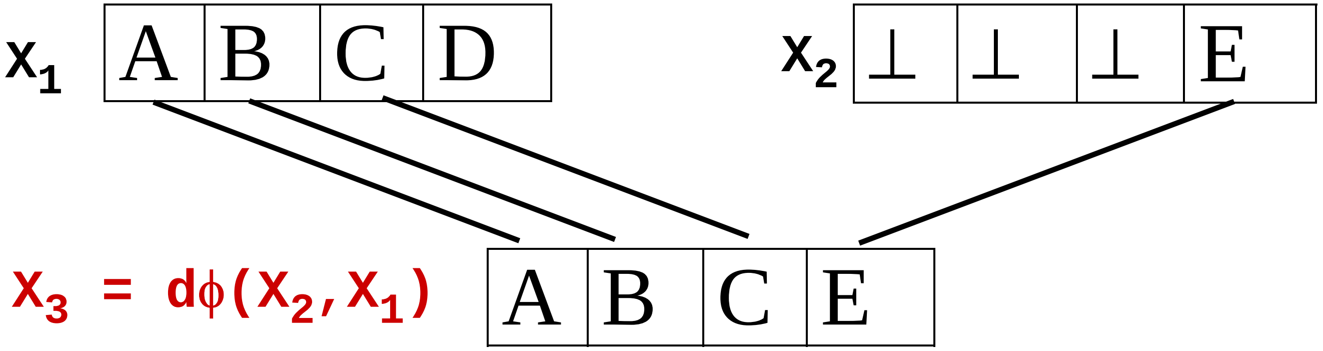
. . .

$X_2[k]$ = . . .

$X_3 = d\phi(X_2, X_1)$

… = $X_3[j]$

This approach can also be applied to array sections and collections



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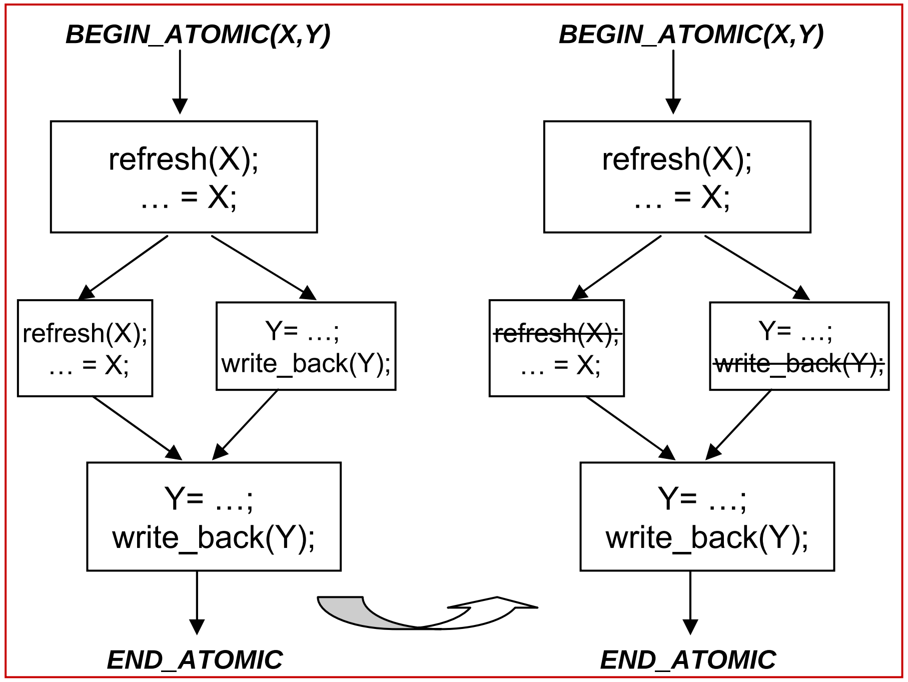
Analyzable Atomic Sections

- Definition: An atomic section is fully analyzable if the addresses of all shared locations that it accesses are computable on entry to the section
- Lock assignment problem: assign a set of locks to each atomic section so as to guarantee mutual exclusion and avoid deadlock
- Consistency optimization problem: PRE of consistency operations (refresh, writeback) necessary to support memory consistency of data accesses in an atomic section



"Analyzable Atomic Sections: Integrating Fine Grained Synchronization and Weak Consistency Models for Scalable Parallelism", V.Sarkar, G.Gao, U. Delaware CAPSL Technical Memo 52, Feb 2004.

X10 Status and Plans

- Draft Language Design Report available internally w/ set of sample programs
- Implementation begun on Prototype #1 for 1/2005
  - Functional reference implementation of language subset, not optimized for performance
  - Support for calls to single-threaded native code (C, Fortran)
- Productivity experiments planned for 7/2005
  - Use prototype #1 to compare X10 w/ MPI, UPC
  - Revise language based on feedback from productivity experiments
- Prototype #2 planned for 12/2005
  - Includes design & prototype implementation of selected optimizations for parallelism, synchronization and locality in X10 programs
  - Revise language based on feedback from design evaluation
- Next phase of PERCS project planned for 7/2006 – 6/2010 timeframe

Conclusions and Future Work

- Future Large-scale Parallel Systems will be accompanied by severe productivity and performance challenges
- Summarized X10 language approach in PERCS project, with a focus on next steps:
  - Use applications and productivity studies to refine design decisions in X10
  - Prototype solutions to address implementation challenges
- Future work (beyond 2005)
  - Explore integration of X10 with other language efforts in IBM
    - XML (XJ), BPEL, …
  - Community effort to build consensus on standardized "high productivity" languages for HPC systems in the 2010 timeframe