X10: Concurrent Object-Oriented Programming for Modern Architectures

OOPSLA 2006 Tutorial

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Recent Publications

Tutorials
- TiC 2006, PACT 2006
Tutorial outline

1) X10 in a Nutshell

2) Sequential X10
   - Type system
   - Standard library
   - extern

3) Concurrency in X10
   - activities
   - atomic blocks
   - clocks, clocked variables

4) X10 Arrays
   - Points
   - Regions

5) Distributed X10
   - places
   - distributions and distributed arrays

6) Comparison with other Concurrent Languages
   - Java
   - OpenMP
   - MPI
   - UPC

7) Current Status and Future Work
X10 in a Nutshell
A new era of mainstream parallel processing

The Challenge
Parallelism scaling replaces frequency scaling as foundation for increased performance \(\Rightarrow\) Profound impact on future software

Multi-core chips  Heterogeneous Parallelism  Cluster Parallelism

Our response:
Use X10 as a new language for parallel hardware that builds on existing tools, compilers, runtimes, virtual machines and libraries
Server Trends: Concurrency, Distribution, Heterogeneity at all levels

- Workload
- Apps
- Servers
- Network

Shared Administrative Domain

HPC Scale Out

Appliance

Commercial Scale Out

Blade

Multi-Core Chip
The X10 programming model

Support for productivity

- Axiom: Exploit proven OO benefits (productivity, maintenance, portability benefits).
- Axiom: Rule out large classes of errors by design (Type safe, Memory safe, Pointer safe, Lock safe, Clock safe ...)
- Axiom: Support incremental introduction of explicit place types/remote operations.
- Axiom: Integrate with static tools (Eclipse) -- flag performance problems, refactor code, detect races.
- Axiom: Support automatic static and dynamic optimization (CPO).

Support for scalability

- Axiom: Provide constructs to deal with non-uniformity of access.
- Axiom: Build on asynchrony. (To support efficient overlap of computation and communication.)
- Axiom: Use scalable synchronization constructs.
- Axiom: Permit programmer to specify aggregate operations.
Our philosophy

- Be conservative strategically, aggressive tactically.
- Build on sound foundations, but design for the programmer.
  - Not the theoretician, not the language designer.
- Use Occam’s Razor.
  - Avoid a variety of linguistic mechanisms for the same programming idiom.
- Steal.
- Focus on a few things, do them well.
- Keep the language small.
- Keep the language orthogonal.
- Ensure the language “grows on you.”
- Exploit structure in concurrency.
- Make easy things easy, hard things possible.
X10 Programming Model

- Dynamic parallelism with a Partitioned Global Address Space
- Places encapsulate binding of activities and globally addressable data
  - Number of places currently fixed at launch time
  - All concurrency is expressed as asynchronous activities – subsumes threads, structured parallelism, messaging, DMA transfers, etc.
- Atomic sections enforce mutual exclusion of co-located data
  - No place-remote accesses permitted in atomic section
- Immutable data offers opportunity for single-assignment parallelism

Storage classes:
- Activity-local
- Place-local
- Partitioned global
- Immutable
X10 v0.41 Cheat sheet

**Stm:**
- async [ ( Place ) ] [clocked ClockList ] Stm
- when ( SimpleExpr ) Stm
- finish Stm
- next; c.resume() c.drop()
- for( i : Region ) Stm
- foreach ( i : Region ) Stm
- ateach ( i : Distribution ) Stm

**Expr:**
- ArrayExpr

**DataType:**
- ClassName | InterfaceName | ArrayType
- nullable DataType
- future DataType

**Kind:**
- value | reference

**ClassModifier:** Kind
**MethodModifier:** atomic

---

x10.lang has the following classes (among others)
- point, range, region, distribution, clock, array

Some of these are supported by special syntax.

Forthcoming support: closures, generics, dependent types, place types, implicit syntax, array literals.
X10 v0.41 Cheat sheet: Array support

ArrayExpr:

new ArrayType ( Formal ) { Stm }

Distribution Expr -- Lifting
ArrayExpr [ Region ] -- Section
ArrayExpr / Distribution -- Restriction
ArrayExpr // ArrayExpr -- Union
ArrayExpr.overlay(ArrayExpr) -- Update
ArrayExpr. scan( [fun [, ArgList]])
ArrayExpr. reduce( [fun [, ArgList]])
ArrayExpr.lift( [fun [, ArgList]])

ArrayType:

Type [Kind] [ ]
Type [Kind] [ region(N) ]
Type [Kind] [ Region ]
Type [Kind] [ Distribution ]

Region:

Expr : Expr -- 1-D region
[ Range, ..., Range ] -- Multidimensional Region
Region && Region -- Intersection
Region || Region -- Union
Region – Region -- Set difference
BuiltinRegion

Dist:

Region -> Place -- Constant distribution
Distribution | Place -- Restriction
Distribution | Region -- Restriction
Distribution || Distribution -- Union
Distribution – Distribution -- Set difference
Distribution.overlay ( Distribution )
BuiltinDistribution

Language supports type safety, memory safety, place safety, clock safety.
Comparison with Java, JUC, RMI
Comparison with Java, JUC, RMI

X10 language builds on the Java language

*Shared underlying philosophy: shared syntactic and semantic tradition, simple, small, easy to use, efficient to implement, machine independent*

X10 does not have:
- Dynamic class loading
- Java’s concurrency features
  - thread library, volatile, synchronized, wait, notify

X10 restricts:
- Class variables and static initialization

X10 adds to Java:
- value types, nullable
- Array language
  - Multi-dimensional arrays, aggregate operations
- New concurrency features
  - activities (async, future), atomic blocks, clocks
- Distribution
  - places
  - distributed arrays
Messaging and Cluster Parallelism: RMI and X10

- **Storage model**
  - Java: independent JVM’s communicating via RMI
    - Some support for distributed garbage collection.
  - X10: global address space partitioned into *places*
    - One node may have many places
    - Supports distributed collections and other distributed data structures
    - Distributed GC still being designed.

- **Remote method invocation**
  - Java supports serialization of arbitrary object reference subgraph, communication to remote object.
  - X10: reference objects stay fixed, activities may be spawned remotely.
    - Value data is copied.

- **Distribution infrastructure**
  - RMI: nodes may intermittently fail
    - Application code has to handle RemoteException
  - X10 – nodes part of a single distributed VM instance.
  - RMI: support for long-lived processes, registries, service discovery.
  - X10 – not intended for globally distributed computation
Comparison with Java, JUC, RMI

- X10 as a Java successor for concurrency and distribution
- Compatible with JUC
- Multiple places
- Block-structured concurrency (finish/async) w/ integrated exception model
- Atomic blocks
- Phased computation
- Static guarantees
- Richer annotations

Coming soon!
- Generics
  - Over an integrated type system
  - That work for arrays
  - No ‘?’
- Closures
- Dependent types, place types, implicit syntax
- Formal memory model
- FP support
- Relaxed exception model
- Precise specification of XVM
- Support for determinate cancellation?

Future work
X10 project landscape

- Array language design
  V1 → V2

- Core concurrency and distribution design.
  - Extern interface
  - JVM implementation
  - X10DT

- Place types
- Applications
- Dependent types
- Implicit syntax
- Memory model
- Tiled regions
- Generics
- X10lib
- XVM spec
- FP semantics
- Relaxed exceptions
- Annotations

- 02/04 07/04 02/05 07/05 02/06 07/06
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8) Current Status and Future Work
Sequential X10

- Overview
- value types
- nullable types
- Safety properties
Sequential X10

```
public class HelloWorld {
    public static void main(String[] args) {
        System.out.println("Hello, world!");
    }
}
```
Sequential X10

- Classes and interfaces
  - Fields, methods, Constructors
  - Encapsulated state
  - Single inheritance
  - Multiple interfaces
  - Nested/Inner/Anon classes
- Static typing
- Objects, GC
- Statements
  - Conditionals, assignment, ...
  - Exceptions (but relaxed)

- Not included
  - Dynamic linking
  - User-definable class loaders

- Changes
  - Value types
  - Points, regions, dist ...
  - Aggregate data/operations
  - Space: Distribution
  - Time: Concurrency

- Changes planned
  - Generics
  - Type system
  - FP support
Value types: immutable instances

**value class**
- Can only extend value class or `x10.lang.Object`.
- All fields are implicitly **final**
- Can only be extended by value classes.
- May contain fields with reference type.
- May be implemented by reference or copy.

```
public value complex {
    double im, re;
    public complex(double im, double re) {
        this.im = im;
        this.re = re;
    }
    public complex add(complex a) {
        return new complex(im+a.im, re+a.re);
    }
} ...
```

Values are equal (==) if their fields are equal, recursively.
Memory safety

Runtime invariants

- An object may only access memory within its representation, and other objects it has a reference to.
  - X10 supports no pointer arithmetic.
  - Array access is bounds-checked dynamically (if necessary).

- No “ill mem ref”
  - No object can have a reference to an object who’s memory has been freed.
  - X10 uses garbage collection.

- Every value read from a location has been previously written into the location.
  - No uninitialized variables.
Pointer safety

X10 supports the nullable type constructor.
- For any datatype $T$, the datatype nullable<$T$> contains all the value of $T$ and null.
- If a method is invoked or a field is accessed on the value null, a NullPointerException (NPE) is thrown.

Runtime invariant
No operation on a value of type $T$, which is not of the form nullable $S$, can throw an NPE.

```java
public interface Table {
    void put(Object o);
    nullable<Object> get(Object o);
}

public class Foo {
    boolean check (Table h) {
        return h.get(this) != null;
    }
}
```

May return null

Cannot throw NPE.
x10.lang standard library

Java package with “built in” classes that provide support for selected X10 constructs

- Standard types
  - boolean, byte, char, double, float, int, long, short, String
- x10.lang.Object -- root class for all instances of X10 objects
- x10.lang.clock --- clock instances & clock operations
- x10.lang.dist --- distribution instances & distribution operations
- x10.lang.place --- place instances & place operations
- x10.lang.point --- point instances & point operations
- x10.lang.region --- region instances & region operations

All X10 programs implicitly import the x10.lang.* package, so the x10.lang prefix can be omitted when referring to members of x10.lang.* classes

- e.g., place.MAX_PLACES, dist.factory.block([0:100,0:100]), …

Similarly, all X10 programs also implicitly import the java.lang.* package

- e.g., X10 programs can use Math.min() and Math.max() from java.lang
Programmer’s eye view
Single Node SMP X10 Implementation

X10 source

X10 Grammar

X10 Parser

AST

Analysis passes

DOMO Static Analyzer

Annotated AST

Java code emitter

Java compiler

Target Java

X10 Front End

Common components w/ SAFARI

X10 classfiles

(X10 classfiles with special annotations for X10 analysis info)

JCU thread pool

Place

Completed Activities

Executing Activities

Blocked Activities

Atomic sections do not have blocking semantics

Activity can only access its stack, place-local mutable data, or global immutable data

Inbound activities

Outbound activities

Clock

Future

Inbound replies

Outbound replies

Place 0

Place 1

X10 Inspired Interface

JCU thread pool

Java Concurrency Utilities (JCU)

STM library

Ensure utility

Java Library

Portable Standard Java 5 Runtime Environment (Runs on multiple Platforms)
X10 prototype implementation

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

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

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

X10 Program Output

X10 Abstract Performance Metrics (event counts, critical path)
Examples of X10 compiler error messages

1) x10c TutError1.x10
   TutError1.x10:8: Could not find field or local variable "evenSum".
   for (int i = 2 ; i <= n ; i += 2 ) evenSum += i;
   ^^^^^

2) x10c TutError2.x10
   x10c: TutError2.x10:4:27:4:27: unexpected token(s) ignored

3) x10c TutError3.x10
   x10c: C:\vivek\eclipse\workspace\x10\examples\Tutorial\TutError3.java:49:
   local variable n is accessed from within inner class; needs to be declared
   final

Case 1: Error message identifies source file and line number
Case 2: Error message identifies source file, line number, and column range
Case 3: Error message reported by Java compiler – look for #line comment in .java file to identify X10 source location

Case 1: Carats indicate column range
Eclipse demo
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Concurrency in X10

- async, finish
- future, force
- foreach
- Global vs. local termination
- Exception handling
- Behavioral annotations
- Atomic
- clocks
Memory Model

- X10 v 0.41 specifies sequential consistency per place.
  - Not workable.
- We are considering a weaker memory model.
- Built on the notion of atomic: identify a step as the basic building block.
  - A step is a partial write function.
- Use links for non hb-reads.

- A process is a pomset of steps closed under certain transformations:
  - Composition
  - Decomposition
  - Augmentation
  - Linking
  - Propagation

- There may be opportunity for a weak notion of atomic: decouple atomicity from ordering.

Correctly synchronized programs behave as SC.

Correctly synchronized programs= programs whose SC executions have no races.

Please see: http://www.saraswat.org/rao.html
async

Stmt ::= async PlaceExpSingleListopt Stmt

cf Cilk’s spawn

async (P) S

- Creates a new child activity at place P, that executes statement S
- Returns immediately
- S may reference final variables in enclosing blocks
- Activities cannot be named
- Activity cannot be aborted or cancelled

// global dist. array
final double a[D] = ...;
final int k = ...;

async ( a.distribution[99] ) {
    // executed at A[99]'s place
    atomic a[99] = k;
}

- Memory model: hb edge between stm before async and start of async.
finish

**finish S**
- Execute S, but wait until all (transitively) spawned asyncs have terminated.

**Rooted exception model**
- Trap all exceptions thrown by spawned activities.
- Throw an (aggregate) exception if any spawned async terminates abruptly.
- implicit `finish` at main activity

`finish` is useful for expressing “synchronous” operations on (local or) remote data.

```plaintext
Stmt ::= finish Stmt

cf Cilk’s sync

```

```plaintext
finish ateach(point \[i\]: A)
A[i] = i;

finish async
(A.distribution \[j\])
A[j] = 2;

// all A[i]=i will complete
// before A[j]=2;

```

- Memory model: hb edge between last stm of each async and stm after `finish S`. 
Termination

**Local termination:**
Statement \( s \) terminates locally when activity has completed all its computation with respect to \( s \).

**Global termination:**
Local termination + activities that have been spawned by \( s \) terminated globally (recursive definition)

→ main function is **root activity**
→ program terminates iff root activity terminates.
  (implicit finish at root activity)
→ ‘daemon threads’ (child outlives root activity) not allowed in X10
Termination (Example)

```java
public void main (String[] args) {
    ...
    finish {
        async {
            for () {
                async {
                    ...
                }
            }
            finish async {
                ...
            }
        }
        ...}
    } // finish
}
```

Rooted computation X10

```java
public void main (String[] args) {
    ...
    finish {
        async {
            for () {
                async {...
            }
        }
    } // finish
}```
Rooted exception model

```java
public void main (String[] args) {
    ...
    finish {
        async {
            for () {
                async {...
            }
            finish async {...
        }
    ...
} // finish
```

Propagation along the **lexical scoping**: Exceptions that are not caught inside an activity are propagated to the nearest suspended ancestor in the root-of relation.
Example: rooted exception model (async)

```java
int result = 0;
try {
    finish {
        ateach (point [i]:dist.factory.unique()) {
            throw new Exception ("Exception from " + here.id)
        }
        result = 42;
    } // finish
} catch (x10.lang.MultipleExceptions me) {
    System.out.print(me);
}
assert (result == 42); // always true
```

- no exceptions are ‘thrown on the floor’
- exceptions are propagated across activity and place boundaries
Behavioral annotations

nonblocking
On any input store, a nonblocking method can continue execution or terminate. (dual: blocking, default: nonblocking)

recursively nonblocking
Nonblocking, and every spawned activity is recursively nonblocking.

local
A local method guarantees that its execution will only access variables that are local to the place of the current activity. (dual: remote, default: local)

sequential
Method does not create concurrent activities. In other words, method does not use async, foreach, ateach. (dual: parallel, default: parallel)

Sequential and nonblocking imply recursively nonblocking.
Static semantics

- Behavioral annotations are checked with a conservative intra-procedural data-flow analysis.

- Inheritance rule: Annotations must be preserved or strengthened by overriding methods.

- Multiple behavioral annotations must be mutually consistent.
foreach

foreach (FormalParam: Expr) Stmt

defined as

foreach (point p: R) S

- Creates |R| async statements in parallel at current place.

- Termination of all (recursively created) activities can be ensured with finish.

- finish foreach is a convenient way to achieve master-slave fork/join parallelism (OpenMP programming model)
atomic

- Atomic blocks are conceptually executed in a single step while other activities are suspended: isolation and atomicity.

- An atomic block ...
  - must be nonblocking
  - must not create concurrent activities (sequential)
  - must not access remote data (local)

- Memory model: end of tx hb start of next tx in the same place.

```
Stmt ::= atomic Statement
MethodModifier ::= atomic

// target defined in lexically
// enclosing scope.
atomic boolean CAS( Object old,
                     Object new) {
    if (target.equals(old)) {
        target = new;
        return true;
    }
    return false;
}

// push data onto concurrent
// list-stack
Node node = new Node(data);
atomic {
    node.next = head;
    head = node;
}
```
Static semantics of atomic blocks

An atomic block must...be local, sequential, nonblocking:

- ...not include blocking operations
  - no await, no when, no calls to blocking methods
- ... not include access to data at remote places
  - no ateach, no future, only calls to local methods
- ... not spawn other activities
  - no async, no foreach, only calls to sequential methods
Exceptions in atomic blocks

- Atomicity guarantee only for successful execution.
- Exceptions should be caught inside atomic block
- Explicit undo in the catch handler

```java
boolean move(Collection s, Collection d, Object o) {
    atomic {
        if (!s.remove(o)) {
            return false; // object not found
        } else {
            try {
                d.add(o);
            } catch (RuntimeException e) {
                s.add(o); // explicit undo
                throw e; // exception
            }
        }
    }
    return true; // move succeeded
}
```

- (Uncaught) exceptions propagate across the atomic block boundary; atomic terminates on normal or abrupt termination of its block.

cf. [Harris CSJP'04]
Data races with async / foreach

final double arr[R] = ...; // global array

class ReduceOp {
    double accu = 0.0;
    double sum ( double[] arr ) {
        finish foreach (point p: arr) {
            // concurrent conflicting access to shared variable: data race
            atomic accu += arr[p];
        }
        return accu;
    }
}

X10 guideline for avoiding data races:
- access shared variables inside an atomic block
- combine ateach and foreach with finish
- declare data to be read-only where possible (final or value type)
Concurrency Control: Clocks

- clock
- Clocks safety
- Clocked variables
Clocks: Motivation

- Activity coordination using `finish` and `force()` is accomplished by checking for activity termination.
- However, there are many cases in which a producer-consumer relationship exists among the activities, and a “barrier”-like coordination is needed without waiting for activity termination.
  - The activities involved may be in the same place or in different places.

```
Phase 0

Phase 1

Activity 0      Activity 1      Activity 2
```

- Activity 0
- Activity 1
- Activity 2

...
**Clocks (1/2)**

```
clock c = clock.factory.clock();
  Allocate a clock, register current activity with it. Phase 0 of c starts.
  
async(...) clocked (c1,c2,...) S
ateach(...) clocked (c1,c2,...) S
foreach(...) clocked (c1,c2,...) S
  Create async activities registered on clocks c1, c2, ...

  c.resume();
  Nonblocking operation that signals completion of work by current activity for this phase of clock c

next;
  Barrier --- suspend until all clocks that the current activity is registered with can advance. c.resume() is first performed for each such clock, if needed.
  Next can be viewed like a “finish” of all computations under way in the current phase of the clock
```
Clocks (2/2)

c.drop();
- Unregister with c. A terminating activity will implicitly drop all clocks that it is registered on.

c.registered()
- Return true iff current activity is registered on clock c
- c.dropped() returns the opposite of c.registered()

ClockUseException
- Thrown if an activity attempts to transmit or operate on a clock that it is not registered on
- Or if an activity attempts to transmit a clock in the scope of a finish
Semantics

**Static semantics**
- An activity may operate only on those clocks it is registered with.
- In finish S,S may not contain any (top-level) clocked asyncs.

**Dynamic semantics**
- A clock c can advance only when all its registered activities have executed c.resume().
- An activity may not pass-on clocks on which it is not live to sub-activities.
- An activity is deregistered from a clock when it terminates

- Memory model: hb edge between next stm of all registered activities on c, and their subsequent stm

Supports over-sampling, hierarchical nesting.

No explicit operation to register a clock.
Behavioral annotations for clocks

clocked (c0,..., ck).

- A method $m$ that spawns an `async clocked(c0,...,ck)` must declare {c0,...,ck} (or a superset) in its annotation: `clocked (c0,..., ck)`.
- {c0,...,ck} are fields of type clock declared in the calss that declares $m$. 
Example (TutClock1.x10)

```java
finish async {
    final clock c = clock.factory.clock();
    foreach (point[i]: [1:N]) clocked (c) {
        while (true) {
            int old_A_i = A[i];
            int new_A_i = Math.min(A[i], B[i]);
            if (i > 1)
                new_A_i = Math.min(new_A_i, B[i-1]);
            if (i < N)
                new_A_i = Math.min(new_A_i, B[i+1]);
            A[i] = new_A_i;
            next;
            int old_B_i = B[i];
            int new_B_i = Math.min(B[i], A[i]);
            if (i > 1)
                new_B_i = Math.min(new_B_i, A[i-1]);
            if (i < N)
                new_B_i = Math.min(new_B_i, A[i+1]);
            B[i] = new_B_i;
            next;
            if (old_A_i == new_A_i && old_B_i == new_B_i)
                break;
        } // while
    } // foreach
} // finish async
```

parent transmits clock to child

exiting from while loop terminates activity for iteration i, and automatically deregisters activity from clock
Clock safety

- An activity may be registered on one or more clocks
- Clock \( c \) can advance only when all activities registered with the clock have executed \( c\text{.resume()} \) and all posted activities have terminated globally.

**Runtime invariant:** Clock operations are guaranteed to be deadlock-free.
Deadlock freedom

- **Central theorem of X10:**
  - Arbitrary programs with async, atomic, finish (and clocks) are deadlock-free.

- **Key intuition:**
  - atomic is deadlock-free.
  - finish has a tree-like structure.
  - clocks are made to satisfy conditions which ensure tree-like structure.
  - Hence no cycles in wait-for graph.

- **Where is this useful?**
  - Whenever synchronization pattern of a program is independent of the data read by the program
  - True for a large majority of HPC codes.
  - (Usually not true of reactive programs.)
Clock example: SPECjbb

```java
finish async {
    final clock c = new clock();
    final Company company =
    createCompany(...);
    for (int w : [0:wh_num]) {
        async clocked(c) { // a warehouse
            int mode;
            atomic { mode = company.mode; }
            initialize;
            next; // 1.
            while (mode != STOP) {
                select a transaction;
                think;
                process the transaction;
                if (mode == RECORDING)
                    record data;
                if (mode == RAMP_DOWN)
                    next; // 2.
                atomic { mode = company.mode; }
            } // while
        } // a warehouse
    } // for
    // ------ continued next column -->
    // master activity
    next; // 1.
    atomic { company.mode = RAMP_UP; }
    sleep rampuptime;
    atomic { company.mode = RECORDING; }
    sleep recordingtime;
    atomic { company.mode = RAMP_DOWN; }
    next; // 2.
    // all clients in RAMP_DOWN
    company.mode = STOP;
} // finish async

// simulation completed.
print results.
```

![Diagram of clock example: SPECjbb](image-url)
Cellular Automata Simulation: Game of Life

Acknowledgment:

“Barriers”, Chapter 5.5.4, Java Concurrency in Practice, Brian Goetz et al
Game of Life – Java version (1 of 2)

`java.util.concurrent` version (Listing 5.15, p102, JCiP)

```java
public class CellularAutomata {
    private final Board mainBoard;
    private final CyclicBarrier barrier;
    private final Worker[] workers;

    public CellularAutomata(Board board) {
        this.mainBoard = board;
        int count = Runtime.getRuntime().availableProcessors();
        this.barrier = new CyclicBarrier(count,
                new Runnable() { // barrier action
            public void run(){mainBoard.commitNewValues();}});
        this.workers = new Worker[count];
        for (int i = 0; i < count; i++)
            workers[i] = new Worker(mainBoard.getSubBoard(count, i));
    } // constructor

    public void start() {
        for (int i = 0; i < workers.length; i++)
            new Thread(workers[i]).start();
        mainBoard.waitForConvergence();
    } // start()
} // CellularAutomata
```
private class Worker implements Runnable {
    private final Board board;
    public Worker(Board board) { this.board = board; }

    public void run() {
        while (!board.hasConverged()) {
            for (int x = 0; x < board.getMaxX(); x++)
                for (int y = 0; y < board.getMaxY(); y++)
                    board.setNewValue(x, y, computeValue(x, y));
            try { barrier.await(); } catch (InterruptedException ex) { return; } catch (BrokenBarrierException ex) { return; }
        } // while
    } // run()

    private int computeValue(int x, int y) {
        // Compute the new value that goes in (x,y)
        
    } // Worker
public class CellularAutomata {
    private final Cell[.] mainBoard1, mainBoard2;
    public CellularAutomata(Cell[.] board) {
        mainBoard1 = board; mainBoard2 = null;
    } // constructor

    public void start() {
        finish async {
            final clock barrier = clock.factory.clock();
            foreach ( point[i] : dist.unique() ) clocked(barrier) {
                boolean red = true;
                while ( !subBoardHasConverged(mainBoard1,mainBoard2,red) ) {
                    for ( point[x,y] : mainBoard1 | here ) {
                        if ( red ) mainBoard2[x,y] = computeValue(mainBoard1, x, y);
                        else mainBoard1[x,y] = computeValue(mainBoard2, x, y);
                    } // for
                    red = ! red;
                } // while
            } // foreach
            if ( ! red) mainBoard1 = mainBoard2; // answer is now in mainBoard1
        } // finish async
        // All boards have now converged
    } // start()
} // CellularAutomata
Game of Life – X10 version

```java
public class CellularAutomata {
    private final Cell[] mainBoard1, mainBoard2;
    public CellularAutomata(Cell[] board) {
        mainBoard1 = board; mainBoard2 = null;
    } // constructor

    public void start() {
        finish async {
            final clock barrier = clock.factory.clock();
            ateach ( point[i] : dist.unique() ) clocked(barrier) {
                boolean red = true;
                while ( !subBoardHasConverged(mainBoard1,mainBoard2,red) ) {
                    for ( point[x,y] : mainBoard1 | here )
                        if ( red ) mainBoard2[x,y] = computeValue(mainBoard1, x, y);
                        else mainBoard1[x,y] = compute
                        next;
                    red = ! red;
                } // while
            } // foreach
            if (! red) mainBoard1 = mainBoard2; // answer is now in mainBoard1
        } // finish async
        // All boards have now converged
    } // start()
} // CellularAutomata
```

**Example of transmitting clock from parent to child**

**NOTE:** exiting from while loop terminates activity for iteration i, and automatically deregisters activity from clock
Futures
future

\[ \text{Expr ::= future PlaceExpSingleListopt \{Expr\}} \]

future (P) S
- Creates a new child activity at place P, that executes statement S;
- Returns immediately.
- S may reference final variables in enclosing blocks.

future vs. async
- Return result from asynchronous computation
- Tolerate latency of remote access.

Considering addition of a delayed future: needs run() to be called before it is activated

// global dist. array
final double a[D] = ...;
final int idx = ...;

future<double> fd =
future (a.distribution[idx])
{
    // executed at a[idx]'s
    // place
    a[idx];
};

future type
- no subtype relation between T and future<T>
future example

```java
public class TutFuture1 {
    static int fib (final int n) {
        if ( n <= 0 ) return 0;
        if ( n == 1 ) return 1;
        future<int> x = future { fib(n-1) };
        future<int> y = future { fib(n-2) };
        return x.force() + y.force();
    }

    public static void main(String[] args) {
        System.out.println("fib(10) = " + fib(10));
    }
}
```

- Divide and conquer: recursive calls execute concurrently.
Example: rooted exception model (future)

double div (final double divisor)
    future<double> f = future { return 42.0 / divisor; }
    double result;
    try {
        result = f.force();
    } catch (ArithmeticException e) {
        result = 0.0;
    }
    return result;

- Exception is propagated when the future is forced.
Futures can deadlock

```java
NullableFuture<Integer> f1 = null;
NullableFuture<Integer> f2 = null;

void main(String[] args) {
    f1 = future(here){a1()};
    f2 = future(here){a2()};
    f1.force();
}

int a1() {
    NullableFuture<Integer> tmp = null;
    do {
        tmp = f2;
    } while (tmp == null);
    return tmp.force();
}

int a2() {
    NullableFuture<Integer> tmp = null;
    do {
        tmp = f1;
    } while (tmp == null);
    return tmp.force();
}

cyclic wait condition

X10 guidelines to avoid deadlock:
- avoid futures as shared variables
- force called by same activity that created body of future, or a descendent.
```
Memoization

- Acknowledgment:
  - “Memoization”, Chapter 5.6, Java Concurrency in Practice, Brian Goetz et al
public class Memoizer<A, V> implements Computable<A, V> {
    private final ConcurrentHashMap<A, Future<V>> cache = new ConcurrentHashMap<A, Future<V>>() {
        private final Computable<A, V> c;
        public Memorizer(Computable<A, V> c) { this.c = c; }
        public V compute(final A arg) throws InterruptedException {
            while (true) {
                Future<V> f = cache.get(arg);
                if (f == null) {
                    Callable<V> eval = new Callable<V>() {
                        public V call() throws InterruptedException {
                            return c.compute(arg);
                        }
                    };
                    FutureTask<V> ft = new FutureTask<V>(eval);
                    f = cache.putIfAbsent(arg, ft);
                    if (f == null) { f = ft; ft.run(); }
                }
                try {
                    return f.get();
                } catch (CancellationException e) {
                    cache.remove(arg, f);
                } catch (ExecutionException e) {
                    throw launderThrowable(e.getCause());
                }
            }
        }
    }
}
Memoization

```java
public class Memoizer implements Computable {
    private final ConcurrentHashMap cache =
        new ConcurrentHashMap();
    private final Computable c;

    public Memoizer(Computable c) { this.c = c; }

    public Object compute (final Object arg) throws Exception {
        nullable<Future> f = (Future) cache.get(arg);
        if (f == null) {
            Future g = new Latch(c, arg);
            f = cache.putIfAbsent(arg, g);
            if (f==null) { f=g; f.run();}
        }
        return f.force();
    }
}
```
Memoization (with proposed generics)

```java
public class Memoizer<V,A> implements Computable<V,A> {
    private final ConcurrentHashMap<future<V>,A> cache =
        new ConcurrentHashMap<future<V>,A>();
    private final Computable<V,A> c;

    public Memoizer(Computable<V,A> c) { this.c = c; }

    public V compute (final A arg) throws Exception {
        nullable<future<V>> f = cache.get(arg);
        if (f == null) {
            future<V> g = new Latch(c, arg);
            f = cache.putIfAbsent(arg, g);
            if (f==null) { f=g; f.run();}
        }
        return f.force();
    }
}
```
Concurrency Control:
Conditional atomic blocks, when, await
when

Stmt ::= WhenStmt

WhenStmt ::= when ( Expr ) Stmt /
WhenStmt or (Expr) Stmt

- **when** (E) S
  - Activity suspends until a state in which the guard E is true.
  - In that state, S is executed atomically and in isolation.

- **Guard** E
  - boolean expression
  - must be nonblocking
  - must not create concurrent activities (sequential)
  - must not access remote data (local)
  - must not have side-effects (const)

- **await** (E)
  - syntactic shortcut for when (E) ;

```java
class OneBuffer {
    nullable<Object> datum = null;
    boolean filled = false;

    void send(Object v) {
        when ( ! filled ) {
            datum = v;
            filled = true;
        }
    }

    Object receive() {
        when ( filled ) {
            Object v = datum;
            datum = null;
            filled = false;
            return v;
        }
    }
}
```
Static semantics of guard for when / await

- boolean field
- boolean expression with field access or constant values

```java
class BufferBuffer {
    ... void send(Object v) {
        when (size() < MAX_SIZE)
        {
            datum = v;
            filled = true;
        }
    }
    ...
}
```

compile-time error
class Semaphore {
    private boolean taken;

    void p() {
        acquire semantics
        when (!taken)
            taken = true;
    }

    atomic void v() {
        release semantics
        taken = false;
    }
}
Atomic blocks: Simplifying barrier synchronization

**Original Java code**

```java
// Main thread (see spec.jbb.Company): ...
// Wait for all threads to start.
synchronized (company.initThreadsStateChange) {
    while (initThreadsCount != threadCount) {
        try {
            initThreadsStateChange.wait();
        } catch (InterruptedException e) {...}
    }
} ...
// Tell everybody it’s time for warmups.
mode = RAMP_UP;
synchronized (initThreadsCountMonitor) {
    initThreadsCountMonitor.notifyAll();
}

// Worker thread
// (see spec.jbb.TransactionManager): ...
synchronized (company.initThreadsCountMonitor) {
    synchronized (company.initThreadsStateChange) {
        company.initThreadsCount++;
        company.initThreadsStateChange.notify();
    }
    try {
        company.initThreadsCountMonitor.wait();
    } catch (InterruptedException e) {...}
```

**X10 atomic sections**

```java
// Main thread: ...
// Wait for all threads to start.
when(company.initThreadsCount == threadCount) {
    mode = RAMP_UP;
    initThreadsCountReached = true;
} ...

// Worker thread: ...
atomic {
    company.initThreadsCount++;
}

await (initThreadsCountReached);
//barrier synch.
...
```
Event Handling and Concurrency: GUI Applications as an Exemplar

Acknowledgment:

“GUI Applications”, Chapter 9, Java Concurrency in Practice, Brian Goetz et al
Scenario: Thread Hopping in a GUI Application (Java)

java.util.concurrent version (Listing 9.5, p196, JCiP)

```java
private void longRunningTaskWithFeedback() {
    button.addActionListener(new ActionListener() {
        public void actionPerformed(ActionEvent e) {
            button.setEnabled(false); label.setText("busy"); // 1) Dim button
            exec.execute( // 2) Submit long-running task for execution
            new Runnable() {
                public void run() {
                    try {
                        /* Do big computation */
                    } finally {
                        // 3) Submit task to run in GUI even thread executor
                        GuiExecutor.instance().execute(new Runnable() {
                            public void run() {
                                button.setEnabled(true); label.setText("idle");
                            }
                        });
                    } // run()
                }
            });
        }
    } // run()
}
```
Scenario: Thread Hopping in a GUI Application (X10)

```java
private void longRunningTaskWithFeedback() {
    button.setEnabled(false); label.setText("busy"); // 1) Dim button
    async (ExecPlace) { // 2) Create long-running task at ExecPlace
        /* Do big computation */
        // 3) When done, create task at GuiExecutorPlace
        async (GuiExecutorPlace) {
            button.setEnabled(true);
            label.setText("idle");
        }
    }
}
```

<table>
<thead>
<tr>
<th>Swing utility</th>
<th>X10 idiom</th>
</tr>
</thead>
<tbody>
<tr>
<td>SwingUtilities.isEventDispatchThread()</td>
<td>here == GuiExecutorPlace</td>
</tr>
<tr>
<td>SwingUtilities.invokeLater()</td>
<td>async (GuiExecutorPlace)</td>
</tr>
<tr>
<td>SwingUtilities.invokeLaterAndWait()</td>
<td>finish async (GuiExecutorPlace)</td>
</tr>
</tbody>
</table>
Single-threaded vs. Multi-threaded GUI frameworks

1) **Java approach** -- *Single-threaded* GUI framework
   - GUI objects are kept consistent by thread confinement
   - Pro: Programmer does not have to worry about deadlock in GUI thread
   - Cons:
     - Cannot exploit parallelism to speed up GUI framework
     - Reasoning about data accesses across task boundaries can still be tricky due to nondeterminism of task scheduling

2) **X10 approach** – *Single-place Multi-threaded* GUI framework
   - All GUI tasks are scheduled at GuiExecutorPlace -- GUI objects are accessed only by activities in GuiExecutorPlace
   - Pro: Can easily exploit parallelism within GuiExecutorPlace
   - Con: atomic blocks necessary to ensure mutual exclusion among tasks (but making atomicity explicit should also make the code more maintainable?)
   - See next slide on how to address overhead of atomic blocks in a Single-place Multi-threaded GUI framework
Performance Implications (Discussion)

- Use of atomic blocks can introduce additional overhead in X10 implementation, compared to single-threaded Java version
  - For multi-core architectures, this additional overhead should be more than compensated for by performance improvements due to concurrency …

- … but if there is a real need for improving the performance of GuiExecutorPlace for execution on a single thread …
  - Restrict GuiExecutorPlace to be a local nonblocking place
    - only local nonblocking activities are permitted to run at such a place
    - nonblocking ➔ no static occurrence of when, force(), next() permitted (but finish is permitted)
    - local ➔ all data accessed is statically guaranteed to be place-local
  - X10 runtime can use a single active worker thread for GuiExecutorPlace and guarantee absence of interleaving among tasks at GuiExecutorPlace
    ➔ atomic-enter and atomic-exit can then be replaced by no-ops
Using X10 method annotations

A method declaration, foo(), can be annotated with:

- **nonblocking** ➞ no static occurrence in foo() of when, force(), next(); any method that foo() invokes must also be annotated as **nonblocking**
- **local** ➞ all data accessed in foo() is statically guaranteed to be **place-local**; any method that foo() invokes must also be annotated as **local**

To check if an activity (async, foreach, ateach, future) is **local nonblocking**

- Check local body of activity to ensure that it satisfies the conditions
- Check that all methods called in activity are also annotated (and checked) as local nonblocking
- NOTE: this also works in the presence of recursion
1) X10 in a Nutshell

2) Sequential X10
   - Type system
   - Standard library
   - extern

3) Concurrency in X10
   - activities
   - atomic blocks
   - clocks, clocked variables

4) X10 Arrays
   - Points
   - Regions

5) Distributed X10
   - places
   - distributions and distributed arrays

6) Comparison with other Concurrent Languages
   - Java
   - OpenMP
   - MPI
   - UPC

7) Current Status and Future Work
X10 Array Language

- point, region, distribution
- Syntax extensions
- Initialization
- Multi-dimensional arrays
- Aggregate operations
A **point** is an element of an n-dimensional Cartesian space (n>=1) with integer-valued coordinates e.g., [5], [1, 2], ...
  - Dimensions are numbered from 0 to n-1
  - n is also referred to as the **rank** of the point

A point variable can hold values of different ranks e.g.,
  - point p; p = [1]; ... p = [2,3]; ...

**Operations**
  - p1.rank
    - returns rank of point p1
  - p1.get(i)
    - returns element (i mod p1.rank) if i < 0 or i >= p1.rank
  - p1.lt(p2), p1.le(p2), p1.gt(p2), p1.ge(p2)
    - returns true iff p1 is **lexicographically** <, <=, >, or >= p2
    - only defined when p1.rank and p1.rank are equal
Syntax extensions for points

- Implicit syntax for points:
  \[
  \text{point } p = [1,2] \Rightarrow \text{point } p = \text{point.factory}(1,2)
  \]

- Exploded variable declarations for points:
  \[
  \text{point } p [i,j] \quad // \quad \text{final int } i, j
  \]

- Typical uses:
  - \text{for (point } p [i, j] : r) \{ \ldots \}
  - \text{for (point } [i, j] : r) \{ \ldots \}
  - \text{int sum (point } [i,j], \text{point } [k, l])
    \quad \{ \text{return } [i+k, j+1]; \}
  - \text{int } [] \text{ iarr } = \text{new int } [2] \text{ (point } [i,j]) \{ \text{return } i; \}
Example: point (TutPoint1)

```java
class TutPoint {
    public static void main(String[] args) {
        point p1 = [1, 2, 3, 4, 5];
p4oint p2 = [1, 2];
p4oint p3 = [2, 1];
        System.out.println("p1 = " + p1 +
            " ; p1.rank = " + p1.rank +
            " ; p1.get(2) = " + p1.get(2));
        System.out.println("p2 = " + p2 +
            " ; p3 = " + p3 + " ; p2.lt(p3) = " +
p2.lt(p3));
    }
}
```

**Console output:**

```
p1 = [1, 2, 3, 4, 5] ; p1.rank = 5 ; p1.get(2) = 3
p2 = [1, 2] ; p3 = [2, 1] ; p2.lt(p3) = true
```
Rectangular regions

A rectangular region is the set of points contained in a rectangular subspace

A region variable can hold values of different ranks e.g.,
- region R; R = [0:10]; ... R = [-100:100, -100:100]; ... R = [0:-1]; ...

Operations
- R.rank := # dimensions in region;
- R.size() := # points in region
- R.contains(P) := predicate if region R contains point P
- R.contains(S) := predicate if region R contains region S
- R.equal(S) := true if region R equals region S
- R.rank(i) := projection of region R on dimension i (a one-dimensional region)
- R.rank(i).low() := lower bound of i\textsuperscript{th} dimension of region R
- R.rank(i).high() := upper bound of i\textsuperscript{th} dimension of region R
- R.ordinal(P) := ordinal value of point P in region R
- R.coord(N) := point in region R with ordinal value = N
- R1 && R2 := region intersection (will be rectangular if R1 and R2 are rectangular)
- R1 || R2 := union of regions R1 and R2 (may not be rectangular)
- R1 – R2 := region difference (may not be rectangular)
Example: region (TutRegion1)

```java
public class TutRegion {
    public static void main(String[] args) {
        region R1 = [1:10, -100:100];
        System.out.println("R1 = " + R1 + " ; R1.rank = " + R1.rank + " ; R1.size() = " + R1.size() + " ;
                          R1.ordinal([10,100]) = " + R1.ordinal([10,100]) + " ;
                          R1.rank = 2 ; R1.size() = 2010 ;
                          R1.ordinal([10,100]) = 2009
        region R2 = [1:10,90:100];
        System.out.println("R2 = " + R2 + " ; R1.contains(R2) = " + R1.contains(R2) + " ; R2.rank(1).low() = " +
                          R2.rank(1).low() + " ; R2.coord(0) = " + R2.coord(0));
    }
}
```

**Console output:**

```
R1 = {1:10,-100:100} ; R1.rank = 2 ; R1.size() = 2010 ;
    R1.ordinal([10,100]) = 2009
R2 = {1:10,90:100} ; R1.contains(R2) = true ;
    R2.rank(1).low() = 90 ; R2.coord(0) = [1,90]
```
Syntax extensions for regions

Region constructors

```java
int hi, lo;
region r = hi;
    // region r = region.factory.region(0, hi)
region r = [low:hi]
    // region r = region.factory.region(lo, hi)

region r1, r2;  // 1-dim regions
region r = [r1, r2]
    // region r = region.factory.region(r1, r2);
    // 2-dim region
```
X10 arrays

- Java arrays are one-dimensional and local
  - e.g., array args in main(String[] args)
  - Multi-dimensional arrays are represented as “arrays of arrays” in Java
- X10 has true multi-dimensional arrays (as Fortran) that can be distributed (as in UPC, Co-Array Fortran, ZPL, Chapel, etc.)

**Array declaration**
- T [.] A declares an X10 array with element type T
- An array variable can refer to arrays with different rank

**Array allocation**
- new T [ R ] creates a local rectangular X10 array with rectangular region R as the index domain and T as the element (range) type
  - e.g., int[.] A = new int[ [0:N+1, 0:N+1] ];

**Array initialization**
- elaborate on a slide that follows...
Array declaration syntax: [] vs []

**General arrays: `<Type>[:]`**
- one or multidimensional arrays
- can be distributed
- arbitrary region

**Special case (“rail”): `<Type>[]`**
- 1 dimensional
- 0-based, rectangular array
- not distributed
- can be used in place of general arrays
- supports compile-time optimization

**Array of arrays (“jagged array”): `<Type>[:][:]`**
Simple array operations

- **A.rank** ::= # dimensions in array
- **A.region** ::= index region (domain) of array
- **A.distribution** ::= distribution of array A
- **A[P]** ::= element at point P, where P belongs to A.region
- **A | R** ::= restriction of array onto region R
  - Useful for extracting subarrays
Aggregate array operations

- **A.sum(), A.max()** := sum/max of elements in array
- **A1 <op> A2**
  - returns result of applying a pointwise op on array elements, when A1.region = A2. region
  - <op> can include +, -, *, and /
- **A1 || A2** := disjoint union of arrays A1 and A2
  (A1.region and A2.region must be disjoint)
- **A1.overlay(A2)**

Future work: framework for array operators
Example: arrays (TutArray1)

```java
public class TutArray1 {
    public static void main(String[] args) {
        int[] A = new int[1:10,1:10]
            (point [i,j]) { return i+j; };
        System.out.println("A.rank = " + A.rank +
            " ; A.region = " + A.region);
        int[] B = A | [1:5,1:5];
        System.out.println("B.max() = " + B.max());
    }
}
```

Console output:

A.rank = 2 ; A.region = {1:10,1:10}
B.max() = 10
Initialization of mutable arrays

Mutable array with nullable references to mutable’ objects:

```java
RefType nullable [] farr = new RefType[N]; // init with null value
```

Mutable array with references to mutable objects:

```java
RefType [] farr = new RefType [N]; // compile-time error, init required

dist d = dist.factory.block(N);
RefType [] farr = new RefType [d] (point[i]) { return RefType(here, i); }
```

Execution of initializer is implicitly parallel / distributed (pointwise operation):

That hold ‘reference to value objects’ (value object can be inlined)

```java
int [] iarr = new int[N] ; // init with default value, 0
int [] iarr = new int[] {1, 2, 3, 4}; // Java style
int [] iarr = new int[N] (point[i])
    {return i}; // explicit init
```
Initialization of value arrays

Initialization of value arrays requires an initializer.

Value array of reference to mutable objects:

```java
RefType value [] farr = new value RefType [N];
    // compile-time error, init required
RefType value [] farr = new value RefType [N] (point[i])
    { return new Foo(); }
```

Value array of ‘reference to value objects’ (value object can be inlined)

```java
int value [] iarr = new value int[] {1, 2, 3, 4};
    // Java style init
int value [] iarr = new value int[N] (point[i])
    { return i };
    // explicit init
```
Tutorial outline

1) X10 in a Nutshell

2) Sequential X10
   – Type system
   – Standard library
   – extern

3) Concurrency in X10
   – activities
   – atomic blocks
   – clocks, clocked variables

4) X10 Arrays
   – Points
   – Regions

5) Distributed X10
   – places
   – distributions and distributed arrays

6) Comparison with other Concurrent Languages
   – Java
   – OpenMP
   – MPI
   – UPC

7) Current Status and Future Work
Distributed X10

- Places
- Locality rule
- Distributions
- async, futures
- ateach
- Distributed arrays
Places in X10

- place.MAX_PLACES = total number of places (runtime constant)
- place.places = value array of all places in an X10
- place.factory.place(i) = place corresponding to index i
- here = place in which current activity is executing
- <place-expr>.toString() returns a string of the form “place(id=99)”
- <place-expr>.id returns the id of the place

X10 language defines mapping from X10 objects to X10 places, and abstract performance metrics on places

Future X10 deployment system will define mapping from X10 places to system nodes; not supported in current implementation
Locality rule

Any access to a mutable (shared heap) datum must be performed by an activity located at the place as the datum.

→ direct access via a remote heap reference is not permitted.
→ Inter-place data accesses can only be performed by creating remote activities (with weaker ordering guarantees than intra-place data accesses)
→ **BadPlaceException** is thrown if the locality rule is violated.
async and future with explicit place specifier

**async (P) S**
- Creates new activity to execute statement S at place P
- async S is equivalent to async (here) S

**future (P) { E }**
- Create new activity to evaluate expression E at place P
- future { E } is equivalent to future (here) { E }

Note that **here** in a child activity for an async/future computation will refer to the place P at which the child activity is executing, not the place where the parent activity is executing.

Specify the destination place for async/future activities so as to obey the Locality rule e.g.,

```cpp
async (O.location) O.x = 1;
future<int> F = future (A.distribution[i]) { A[i] };
```
Implicit syntax

- Use conventional syntax for operations on values of remote type:

  - \( x.f = e \) \( \text{//write } x.f \text{ of type } T \)
    \[ \Rightarrow \text{final } T \ v = e; \]
    \[ \text{finish async}(x.loc) \ \{ \]
    \[ x.f = v; \]
    \[ \} \]
  
  - \( \_ = \_x.f \) \( \text{//read } x.f \text{ of type } T \)
    \[ \Rightarrow \text{future}<T>(x.loc)\{x.f\}.force() \]
  
- Similarly for array reads and writes.

- Invoke a method synchronously on values of remote type

  - \( e.m(e1, ..., en); \)
    \[ \Rightarrow \text{final } T \ v = e; \]
    \[ \text{final } T1 \ v1 = e1; \]
    \[ ... \]
    \[ \text{final } Tn \ vn = en; \]
    \[ \text{finish async}(v.loc) \ \{ \]
    \[ v.m(v1, ..., vn); \]
    \[ \} \]
  
- Similarly for methods returning values.
Inter-place communication using async and future

Question: how to assign $A[i] = B[j]$, when $A[i]$ and $B[j]$ may be in different places?

Answer #1: Use nested async:

```java
finish async ( B.distribution[j] ) {
    final int bb = B[j];
}
```

Answer #2: Use future-force and an async:

```java
final int b = future (B.distribution[j])
    { B[j] }.force();
finish async ( A.distribution[i] ) A[i] = b;
```
ateach (distributed parallel iteration)

ateach (point p:D) S

- Creates |D| async statements in parallel at place specified by distribution.

\[
\text{ateach (point p:D) S for (point p:D.region)}
\]
\[
\text{async (D[p]) \{ S \}}
\]

- Termination of all (recursively created) activities with finish.
- ateach is a convenient construct for writing parallel matrix code that is independent of the underlying distribution, e.g.,

\[
\text{ateach (point p : A.distribution )}
\]
\[
A[p] = f(B[p], C[p], D[p])
\]

- SPMD computation:

\[
\text{finish ateach( point[i] : dist.factory.unique() ) S}
\]
public class TutAteach1 {
    public static void main(String args[]) {
        finish ateach (point p: dist.factory.unique()) {
            System.out.println("Hello from " + here.id);
        }
        // main()
    }
}

unique distribution: maps point i in region [0 : place.MAX_PLACES-1] to place place.factory.place(i).

Console output:
Hello from 1
Hello from 0
Hello from 3
Hello from 4
Distributions in X10

A distribution maps every point in a region to a place.

Creating distributions (x10.lang.dist):
- `dist D1 = dist.factory.constant(R, here);` // local distribution
  - maps region R to here
- `dist D2 = dist.factory.block(R);` // blocked distribution
- `dist D3 = dist.factory.cyclic(R);` // cyclic distribution
- `dist D4 = dist.factory.unique();` // identity map on [0:MAX_PLACES-1]
Distributed Containers

- **DistributedHashMap**

- **Adaptation of ConcurrentHashMap by Doug Lea for X10.**
DistributedHashMap

- **Keys**
  - immutable objects (instances of value classes)
  - hashing of entries according to keys across places
- **Values**
  - references to mutable objects

**Design goals**
- Distribution of Key-Value pairs
- Thread-safety
- Operations are linearizable
- Internal concurrency for optimization
DistributedHashMap - design

DistributedHashMap  Segment  Entry

place 1

place 2

Object
DistributedHashMap - data structures

class DistributedHashMap {
    Segment[] segments; // references to segments in different places (unique distribution)
    Segment segmentFor(final int hash) { ... }
    int hash(final Object x) { ... }
}

class Segment {
    final int index; // index in Segments[]
    int count;
    int modCount;
    Entry[] table;
    public final Semaphore sem; // for consistency among concurrent readers and writers to detect ABA violation

    ...}

class Entry {
    final value key; // key is an instance of a value type
    final int hash;
    Object value;
    final nullable<Entry> next;
}
Selected operations

- `boolean containsValue(final value key)`
  - must not suffer from aba problem
  - optimization: internal concurrency across places
  - reader concurrency

- `nullable<Object> put(final value key, final Object value)`
  - concurrent across places, sequential in each place

- `nullable<Object> get(final value key)`
  - concurrent intra and inter-place read access

- others that we do not discuss here
DistributedHashMap – aba problem

**Linearizability** requires that ABA problem cannot occur:

```java
// initially {k1, v} is in the table

// thread 1                                  // thread2
table.put(k2, v);                           r = table.containsValue(v);
table.remove(k1, v);
```

- **ABA problem**: thread 2 must not observe `r == false`;
  (could happen if `k1, k2` target different segments and operations in both thread occur concurrently)

- Problem can occur whenever HasTable is traversed
  (operations isEmpty, size, containsValue)

→ Prevention of ABA complicates implementation significantly
→ Modification counters
DistributedHashMap – get

class DistributedHashMap ...

    nullable<

    final int hash = hash(key); // throws NullPointerException if key null
    final Segment segmentfor = segmentFor(hash);
    return segmentfor.get(key, hash);
    }

class Segment ...

    nullable<

    atomic if (count==0) return
    int hashIndex = indexFor(hash, index);
    nullable<Entry> first = table[hashIndex];
    nullable<Entry> e = first;
    for (e = first; e !=null; e =e.next)
        if (e.hash == hash &

    Object value = e.value;
    if (value !=null) return value;
    break;
    }

    // Recheck under synch if key apparently not there or interference
    Segment seg = segments[hash & SEGMENT_MASK];
    sem.p();
    try{
        Entry newFirst = table[index];
        if (e != null || first != newFirst) {
            for (e = newFirst; e != null; e = e.next) {
                if (e.hash == hash &

                return e.value;
            }
        }
        return null;
    } finally { sem.v();}
}
DistributedHashMap – put

class DistributedHashMap {

    nullable<Object> put(final Object key, final Object value) {
        int hash = hash(key);
        Segment segmentFor = segmentFor(hash);
        return segmentFor.put(key, hash, value);
    }
}

class Segment {

    nullable<Object> put(final Object key, final int hash, final Object value) {
        nullable<Object> oldval = null;
        sem.p();
        try {
            nullable<Entry> first = table[indexFor(hash, index)];
            nullable<Entry> e = first;
            while (e != null) {
                if (e.hash == hash && key == e.key)
                    break;
                e = e.next;
            }
            if (e != null) {
                oldval = e.value;
                atomic { e.value = value; }
            } else {
                modCount ++;
                table[index] = new Entry(key, hash, value, first);
                atomic { count ++; }
            }
        } finally { sem.v(); }
        return oldval;
    } release lock, sync with concurrent put.
}

acquire lock – exclusive put per segment, sync with concurrent put.

comparison of values with operator ==
aquivalent put means release (sync with concurrent get)

atomic write means release (sync with concurrent get)

atomic read + write means acquire-release sync with concurrent get
DistributedHashMap – containsValue (1/2)

class Segment...
  boolean containsValue(final Object value) {

    final int[] mc = new int[segments.distribution];
    final boolean[] vals = new boolean[segments.distribution];

    // try without locking
    finish at each (point p: segments) {
      atomic {
        mc[p] = segments[p].modCount;
        vals[p] = segments[p].containsValue(value);
      }
    }

    if (vals.or())
      reduction
    return true;

    finish at each (point p: segments) {
      mc[p] -= segments[p].modCount;
    }

    if (mc.sum() == 0)
      reduction
    return false;

    // resort to locking all segments ....
    acquire all locks in order

    for (point p: segments)
      finish async (segments.distribution[p]) { segments[p].sem.p(); }

    finish at each (point p: segments) {
      vals[p] = segments[p].containsValue(value);
      segments[p].sem.v();
    }

    return vals.or();
  }

non-blocking

reduction

blocking

search in parallel across segments
release locks in any order
class DistributedHashMap ...
    boolean containsValue(final Object value) {
        final int[] mc = new int[segments.distribution];
        final boolean[] vals = new boolean[segments.distribution];

        // try without locking
        finish ateach (point p:segments) {
            atomic {
                mc[p] = segments[p].modCount;
                vals[p] = segments[p].containsValue(value);
            }
        }
        if (vals.or()) {
            reduction
            return true;
        }
        finish ateach (point p:segments) {
            mc[p] -= segments[p].modCount;
        }
        if (mc.sum() == 0) {
            reduction
            return false;
        }

        // resort to locking all segments ....
        for (point p:segments)
            finish async (segments.distribution[p]) { segments[p].sem.p(); }

        finish ateach (point p:segments) {
            vals[p] = segments[p].containsValue(value);
            segments[p].sem.v();
        }
        return vals.or();
    }
class Segment ...

    boolean containsValue(final Object value) {
        atomic if (count == 0) return;
        for (point [p]: table) {
            nullable<Entry> e = table[p];
            while (e != null) {
                if (e.value.equals(value))
                    return true;
                e = e.next;
            }
        }
        return false;
    }

    atomic read means acquire sync with concurrent put.
1) X10 in a Nutshell

2) Sequential X10
   – Type system
   – Standard library
   – extern

3) Concurrency in X10
   – activities
   – atomic blocks
   – clocks, clocked variables

4) X10 Arrays
   – Points
   – Regions

5) Distributed X10
   – places
   – distributions and distributed arrays

6) Comparison with other Concurrent Languages
   – Java
   – OpenMP
   – MPI
   – UPC

7) Current Status and Future Work
X10 in Comparison

- MPI + OpenMP
- UPC
- Exemplary stencil computations in
  - C/MPI
  - Titanium
  - UPC
  - X10
  - C++ / htalib
X10, in comparison with MPI+OpenMP …

**MPI / OpenMP**
- Processes
- Programmer-managed global data structures
- Message passing w/ programmer-managed marshalling
  - Includes reductions
- Low-level message envelopes
  - <source, destination, tag, communicator>
- Barriers
- Fix number of OpenMP threads
- Locks, critical sections
- Affinity directives
- INDEPENDENT directive

**X10**
- Places
- Partitioned Global Address Space
- Asynchronous activities w/ objects and futures
  - Includes reductions
- Strongly-typed invocations and return values (futures)
- Clocks
- Asynchronous activities
- Atomic sections
- Placetype system (@-clauses)
- foreach, ateach statements
X10 in comparison with UPC

- Simple syntax for remote memory accesses: `rval, write is lval`
- Block cyclic distribution of 1D arrays
- SPMD model with standard synchronizations (barriers, locks), inquiry functions, etc.
- `split barriers w/ notify & wait`
- Work sharing supported by `upc_forall`
- Type system identifies private vs. shared data. Four classes of pointers (SP & SS pointer operations are expensive):
  - PP: Private space pointed by Private pointer e.g., `int *p1`
  - SP: Shared space pointed by Private pointer e.g., `shared int *p2`
  - PS: Private space pointed by Shared pointer e.g., `int *shared p3` (not recommended!)
  - SS: Shared space pointed by Shared pointer e.g., `shared int *shared p4`;
- Memory consistency can be controlled by user (relaxed vs. strict)
- Portable (to the extent that ANSI C is portable)

- Same in X10
- More general distributions in X10
- X10 supports both fork-join and SPMD models
- `Clock now & next ops`
- X10 has `foreach` and `ateach`
- (X10 may have @activity annotations.)
- X10 has type-safe object references, not pointers
- X10 has two different memory consistency models: within and across places
- X10 has stronger portability (like Java)
#include "mpi.h"

int main( argc, argv )
{
    int rank, value, size, errcnt, toterr, i, j, itcnt;
    int i_first, i_last;
    MPI_Status status;
    double xlocal[(12/4)+2][12];
    double xnew[(12/3)+2][12];
    MPI_Init( &argc, &argv );
    MPI_Comm_rank( MPI_COMM_WORLD, &rank );
    MPI_Comm_size( MPI_COMM_WORLD, &size );
    if (size != 4) MPI_Abort( MPI_COMM_WORLD, 1 );
    /* xlocal[][0] is lower ghostpoints,
       xlocal[][maxn+2] is upper */

    /* Note that top and bottom processes have one less
       row of interior points */
    i_first = 1;
    i_last = maxn/size;
    if (rank == 0) i_first++;
    if (rank == size - 1) i_last--;

    /* Fill the data as specified */
    for (i=1; i<=maxn/size; i++)
        for (j=0; j<maxn; j++)
            xlocal[i][j] = rank;
    for (j=0; j<maxn; j++)
        xlocal[i_first-1][j] = -1;
    xlocal[i_last+1][j] = -1;

    /* Send left unless I am s I'm at the top, then
       receive from below */
    /* Note the use of xlocal[i] for &xlocal[i][0] */
    if (rank < size - 1)
        MPI_Send( xlocal[maxn/size], maxn, MPI_DOUBLE,
                   rank + 1, 0,
                   MPI_COMM_WORLD );
    if (rank > 0)
        MPI_Recv( xlocal[0], maxn, MPI_DOUBLE, rank - 1,
                   0,
                   MPI_COMM_WORLD, &status );

    /* Send down unless I'm at the bottom */
    if (rank > 0)
        MPI_Send( xlocal[1], maxn, MPI_DOUBLE, rank - 1,
                   1,
                   MPI_COMM_WORLD );
    if (rank < size - 1)
        MPI_Recv( xlocal[maxn/size+1], maxn, MPI_DOUBLE,
                   rank + 1, 1,
                   MPI_COMM_WORLD, &status );

    itcnt ++;
    for (i=i_first; i<=i_last; i++)
        for (j=1; j<maxn-1; j++)
            xnew[i][j] = (xlocal[i][j+1] + xlocal[i][j-1] +
                          xlocal[i+1][j] + xlocal[i-1][j]) / 4.0;

    MPI_Finalize( );
    return 0;
}
2D-stencil in Titanium

code is rank-independent

data declaration

initialization

communication

computation

```java
final static int DIM=2; //space dimension
final static Point<DIM> startPoint=Point<DIM>.all(0);
final static Point<DIM> endPoint=Point<DIM>.all(1)+Point<DIM>.direction(DIM,1);
public static single void main (String single [] single args)
{
final int single numThreads=Ti.numProcs();
final int threadID=Ti.thisProc();
final RectDomain<DIM> problemDomain=[startPoint:endPoint];
final int size=endPoint[DIM]-startPoint[DIM]+1;
if (numThreads*size) System.exit(-1);
final int localSize=size/numThreads;
final Point<DIM> startPoint0=startPoint-Point<DIM>.direction(DIM,threadID); //construct local domain
if (threadID==numThreads-1)
  localDomain=[startPoint0+Point<DIM>.direction(DIM,localSize*threadID):endPoint];
else
  localDomain=[startPoint0+Point<DIM>.direction(DIM,localSize*threadID):
   endPoint+Point<DIM>.direction(DIM,localSize*(threadID+1)-1)];
}
//construct a distributed array
double [1d] single local [DIM d] distArrayA=new double [0:numThreads-1] [DIM d];
double [DIM d] local localArrayA = new double [localDomain.accrete(1)]; //construct local subarray
distArrayA.exchange(localArrayA); //exchange references to local subarray
distArrayB=distArrayA; //construct local subarray
distArrayB.exchange(localArrayB); //exchange references to local subarray
//initialize the array
foreach (p in localDomain)
  localArrayA[p]=1;
//exchange ghost values for distArrayA. The boundary values are zeroes by default.
RectDomain<DIM> tempDomain;
if (threadID>0)
  tempDomain=distArrayA[threadID-1].domain().shrink(1);
  localArrayA.copy(distArrayA[threadID-1].restrict(tempDomain));
if (threadID<numThreads-1)
  tempDomain=distArrayA[threadID+1].domain().shrink(1);
  localArrayA.copy(distArrayA[threadID+1].restrict(tempDomain));
}
Ti.barrier();
//local stencil operation
Point<DIM> disp=Point<DIM>.direction(DIM,1);
foreach (p in localDomain)
  localArrayB[p]=(localArrayA[p-disp]+localArrayA[p+disp])*0.5;
}
```
2D-stencil in UPC

shared [N] double a[M][N];
shared [N] double b[M][N];

text

int main() {
    int i, j;

    // initialize a
    upc_forall(i = 0; i < M; i++; continue)
        upc_forall(j = 0; j < N; j++; &a[i][j]) {
            a[i][j] = rand();
        }
    }

    upc_barrier();
    // exchange ghosts
    upc_forall(i = 0; i < M; i++; &b[i][0]) {
        b[i][0] = a[(i-1)%M][N-1];
        b[i][N] = a[(i+1)%M][1];
    }

    upc_barrier();
    // compute b
    upc_forall(i = 0; i < M; i++; continue)
        upc_forall(j = 1; j < N-1; j++; &b[i][j]) {
            b[i][j] = (a[i][j+1] + a[i][j-1])*0.5;
        }
    }
}

data declaration

initialization

communication

computation
Additional material on distributions
Using distributions

\[ D[P] = \text{place to which point P is mapped by distribution D} \]
- if point p is in D.region
- otherwise \textit{ArrayOutOfBoundsException}

Allocate a distributed array e.g., \[ T[.] A = \text{new T[ D ]}; \]
- Allocates an array with index set = D.region, such that element A[P] is located at place D[P] for each point P in D.region
- NOTE: “new T[R]” for region R is equivalent to “new T[R->here]”

Iterating over a distribution – generalization of \texttt{foreach} to \texttt{ateach}
Operations on distributions

- **D.region** ::= source region of distribution
- **D.rank** ::= rank of D.region
- **D | R** ::= region restriction for distribution D and region R (returns a restricted distribution)
- **D | P** ::= place restriction for distribution D and place P (returns region mapped by D to place P)
- **D1 || D2** ::= union of distributions D1 and D2 (assumes that D1.region and D2.region are disjoint)
- **D1.overlay(D2)** ::= asymmetric union of D2 over D1
- **D.contains(p)** ::= true iff D.region contains point p
- **D1 – D2** ::= distribution difference: \( D1 | (D1.region – D2.region) \)
Syntax extensions for distributions

**Constant distributions**

```plaintext
class region r = [0:N];
dist d = r->here
   => dist d = dist.factory.constant(r, here);
dist d = 1000->here
   => dist d = dist.factory.constant([0,1000], here);
```

**Distributions are implicitly converted to regions**

```plaintext
for (point [i,j]: d) {...}
   => for (point [i,j]: d.region) {...}
```
Multidimensional arrays

double[] darr = new double[[0:N, 0:M]--here];
for (point [i,j]: darr.region)
    darr[i,j] = ..;

- initial values in darr are 0.0
- Iteration schema
  - ‘lexicographical order’ (standard, fix)
  - [0,0], [0,1], [0,2], ...
- Storage layout
  - row major (fix)
  - spatial access locality with standard iteration schema
Distributed multidimensional arrays

\[
\text{dist cyclic} = \text{dist.factory.cyclic}([0:4, 0:6])
\]
\[
\text{dist blockcyclic} = \text{dist.factory.blockCyclic}([0:4, 0:6], 6)
\]
\[
\text{double[.] darr = new double[XXX];}
\]

- **cyclic**
- **block cyclic**
- **tiled**

Future work: hierarchically tiled regions

for 1D arrays: cf. UPC

assuming 4 places
Example: RandomAccess (1/2)

```java
dist D = dist.factory.block(TABLE_SIZE);

(1) final long[] table = new long[D] (point [i]) { return i; }

(2) final long[] RanStarts = new long[dist.factory.unique()] (point [i]) { return starts(i); }

(3) final long value [] SmallTable = new long value[TABLE_SIZE] (point [i]) { return i*S_TABLE_INIT; }

(4) finish ateach (point [i] : RanStarts) {
    long ran = nextRandom(RanStarts[i]);
    for (int count: 1:N_UPDATES_PER_PLACE) {
        int J = f(ran);
        long K = SmallTable[g(ran)];
        async (table.distribution[J]) atomic table[J] ^= K;
        ran = nextRandom(ran);
    }
}

assert(table.sum() == EXPECTED_RESULT);
```
Example: RandomAccess (2/2)

1. Allocate and initialize table as a block-distributed array.
2. Allocate and initialize RanStarts with one random number seed for each place.
3. Allocate a small immutable table that can be copied to all places.
4. Everywhere in parallel, repeatedly generate random table indices and atomically read/modify/write table element.
JGF Monte Carlo benchmark -- Sequential

double[] expectedReturnRate = 
   new double[nRunsMC];
...
final ToInitAllTasks t = 
   (ToInitAllTasks) initAllTasks;
for 
   (point [i]: expectedReturnRate) {
      PriceStock ps = new PriceStock();
      ps.setInitAllTasks(t);
      ps.setTask(tasks[i]);
      ps.run();
      ToResult r = 
         (ToResult) ps.getResult();
      expectedReturnRate[i] = 
         r.get_expectedReturnRate();
      volatility[i] = 
         r.get_volatility();
   }

A task array (of size nRunsMC) is initialized with ToTask instances at each index.

Task:
- Simulate stock trajectory,
- Compute expected rate of return and volatility,
- Report average expected rate of return and volatility.
double[] expectedReturnRate =
    new double[nRunsMC];
...
final ToInitAllTasks t =
    (ToInitAllTasks) initAllTasks;
finish foreach
    (point [i]:expectedReturnRate) {
        PriceStock ps = new PriceStock();
        ps.setInitAllTasks(t);
        ps.setTask(tasks[i]);
        ps.run();
        ToResult r =
            (ToResult) ps.getResult();
        expectedReturnRate[i] =
            r.get_expectedReturnRate();
        volatility[i] =
            r.get_volatility();
    }
JGF Monte Carlo benchmark -- Distributed

```java
dist D = dist.factory.block([0:(nRunsMC-1)]);
double[,] expectedReturnRate = new double[D];

final ToInitAllTasks t =
    (ToInitAllTasks) initAllTasks;
finish ateach
    (point [i]:expectedReturnRate) {
        PriceStock ps = new PriceStock();
        ps.setInitAllTasks(t);
        ps.setTask(tasks[i]);
        ps.run();
        ToResult r =
            (ToResult) ps.getResult();
        expectedReturnRate[i] =
            r.get_expectedReturnRate();
        volatility[i] =
            r.get_volatility();
    }
```
The End!