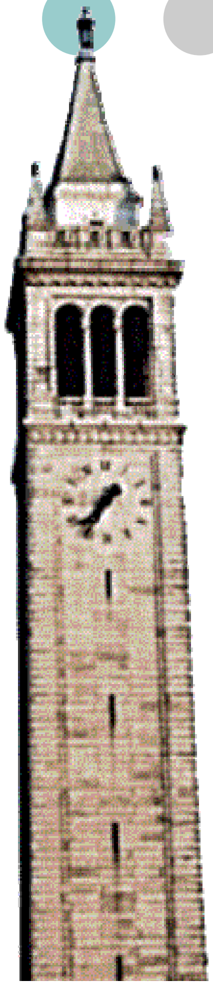


Incremental Checkpointing with Application to Distributed Discrete Event Simulation

Thomas Huining Feng and Edward A. Lee
{tfeng, eal}@eecs.berkeley.edu

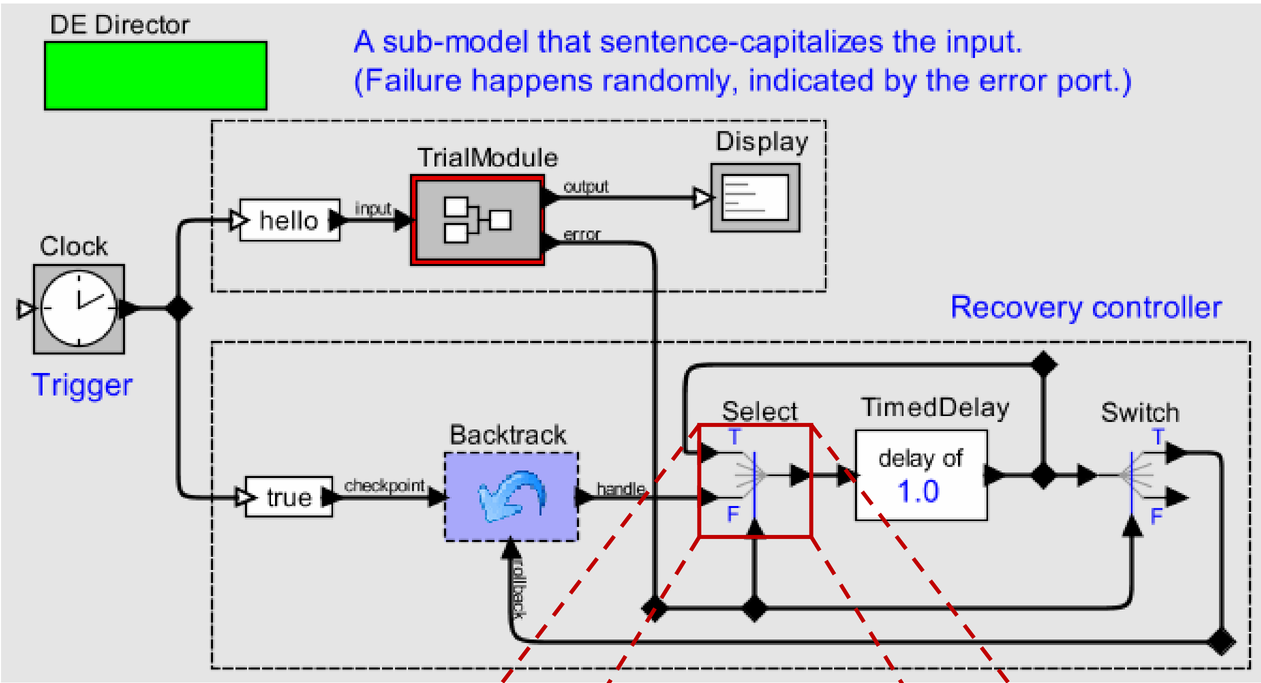
Center for **H**ybrid and **E**mbedded **S**oftware **S**ystems
EECS, UC Berkeley

Winter Simulation Conference 2006
Monterey, CA
December 3-6, 2006

Outline

- Background: heterogeneous model simulation with Ptolemy II
- Problem: state recovery for backtracking
- Approach: automatic state recovery with incremental checkpointing
- Application: optimistic Time Warp simulation
- Conclusion

Ptolemy II Background

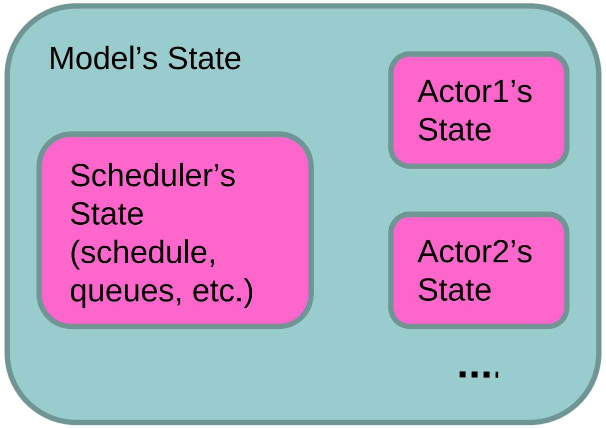



```
class Select extends Actor {
  public boolean prefire() {…}
  public void fire() {…}
  public boolean postfire() {…}
}
```

- Hierarchical composition of actors.
- Ports connected with relations.
- The scheduler determines the semantics.
- Users may define actors in Java.

Model State

- Situations requiring state recovery:
  e.g., optimistic Time Warp simulation (Jefferson 1985).
- A model's run-time state:



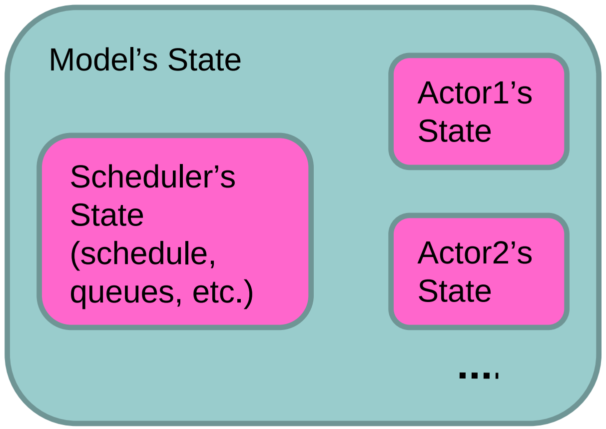

```
class Accumulator extends Actor {
  private int sum;
  Port input, output;
  ...
  void fire() {
    int value = input.get();
    sum = sum + value;
    output.send(0, sum);
  }
}
```

Problems of State Recovery (1)

- We could recover the sceduler’s state with a careful design of the simulation environment.
- But how to recover actors’ states?
  - Provide programmers with a library of state saving/recovery functions.

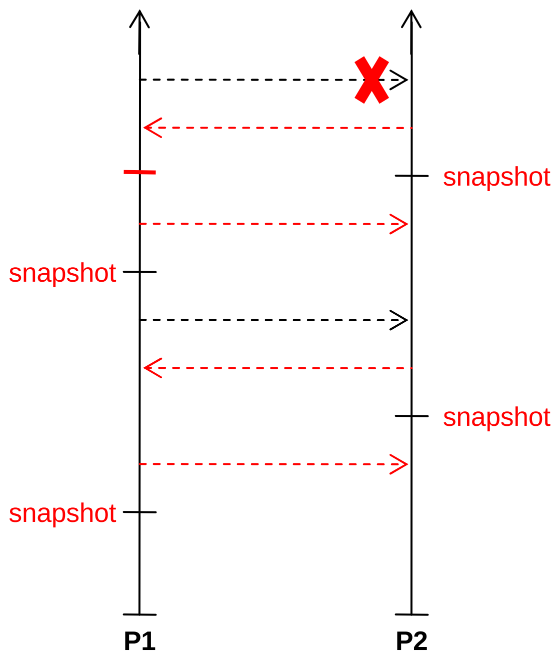
    Complicated user interaction.
  - Make assumptions on the states, and provide automatic recovery.

    Not flexible.



Problems of State Recovery (2)

- The extra cost usually prevents us from creating as many checkpoints as we want.
- Domino effect:



Our Approach to State Recovery

- Correctness can be proved easily.
- Incremental.
- Small constant cost for checkpoint creation.
  - Allow to create checkpoint whenever it may be needed.
- The program is slowed down gracefully.
  - Real-time property can be proved.

Java Analysis and Transformation

1. Use an analyzer to identify the states in the Java code.

state

update

```
class Accumulator extends Actor {
  private int sum;
  Port input, output;
  ...
  void fire() {
    int value = input.get();
    sum = sum + value;
    output.send(0, sum);
  }
}
```

2. Use a transformer to modify the program.

```
class Accumulator extends Actor {
  private int sum;
  Port input, output;
  ...
  void fire() {
    int value = input.get();
    $ASSIGN$sum(sum + value);
    output.send(0, sum);
  }
}
```

Simple Assignment Transformation

- For each Java class:

```
class Accumulator extends Actor {
  private int sum;
  Port input, output;
  ...
  void fire() {
    int value = input.get();
    sum = sum + value;
    output.send(0, sum);
  }
}
```

⇨

```
class Accumulator extends Actor {
  private int sum;
  Port input, output;
  ...
  void fire() {
    int value = input.get();
    $ASSIGN$sum(sum + value);
    output.send(0, sum);
  }
  int $ASSIGN$sum(int v) {
    ... // save current sum
    return sum = v;
  }
}
```

- `$ASSIGN$sum` first saves sum's current value, and then performs the Java assignment.

Simulating Assignment with Function

- Assignments are expressions.

```
class Accumulator extends Actor {
  private int sum;
  Port input, output;
  ...
  void fire() {
    int value = input.get();
    output.send(0,
      sum = sum + value);
  }
}
```

⇨

```
class Accumulator extends Actor {
  private int sum;
  Port input, output;
  ...
  void fire() {
    int value = input.get();
    output.send(0,
      $ASSIGN$sum(sum + value));
  }
  int $ASSIGN$sum(int v) {
    ... // record sum
    return sum = v;
  }
}
```

- Function call precisely simulates assignment.
- Inlining as a compiler optimization.

Operators that Update Operands

```
class Accumulator extends Actor {
  private int sum;
  Port input, output;
  ...
  void fire() {
    value = input.get();
    output.send(0, sum += value);
  }
}
```

```
class Accumulator extends Actor {
  private int sum;
  Port input, output;
  ...
  void fire() {
    value = input.get();
    output.send(0, $UPDATE$sum(0, value));
  }

  /* Simulate Java operators.
  int $UPDATE$sum(int type, int v) {
    ... // record sum
    switch (type) {
    case 0: return sum += v;
    case 1: return sum -= v;
    case 2: return sum ++; // v ignored
    case 3: return sum --;
    case 4: return ++ sum;
    case 5: return -- sum;
    ...
    default: return error();
    }
  }
}
```

`$update$sum` handles all the Java operators, including +=, -=, ++, - -, etc.

Array Operations

```
class StringStack {
  private String[] array;
  private int index;
  ...
  void push(String s) {
    array[index++] = s;
  }
  String pop() {
    return array[index--];
  }
  void clean() {
    index = 0;
    array = new String[MAX];
  }
  void copy(StringStack stack) {
    stack.array =
      (String[]) array.clone();
    stack.index = index;
  }
}
```

```
class StringStack {
  private String[] array;
  private int index;
  ...
  void push(String s) {
    $ASSIGN$array($UPDATE$index(2, 0), s);
  }
  String pop() {
    return array[$UPDATE$index(3, 0)];
  }
  void clean() {
    $ASSIGN$index(0);
    $ASSIGN$array(new String[MAX]);
  }
  void copy(StringStack stack) {
      stack.$ASSIGN$array(
        (String[]) array.clone());
      stack.$ASSIGN$index(index);
  }
  ...
}
```

Checkpoint Control

- To create a checkpoint:

```
long handle = createCheckpoint();
```

- To recover state:

```
rollback(handle);
```

- To discard a checkpoint:

```
discard(handle);
```

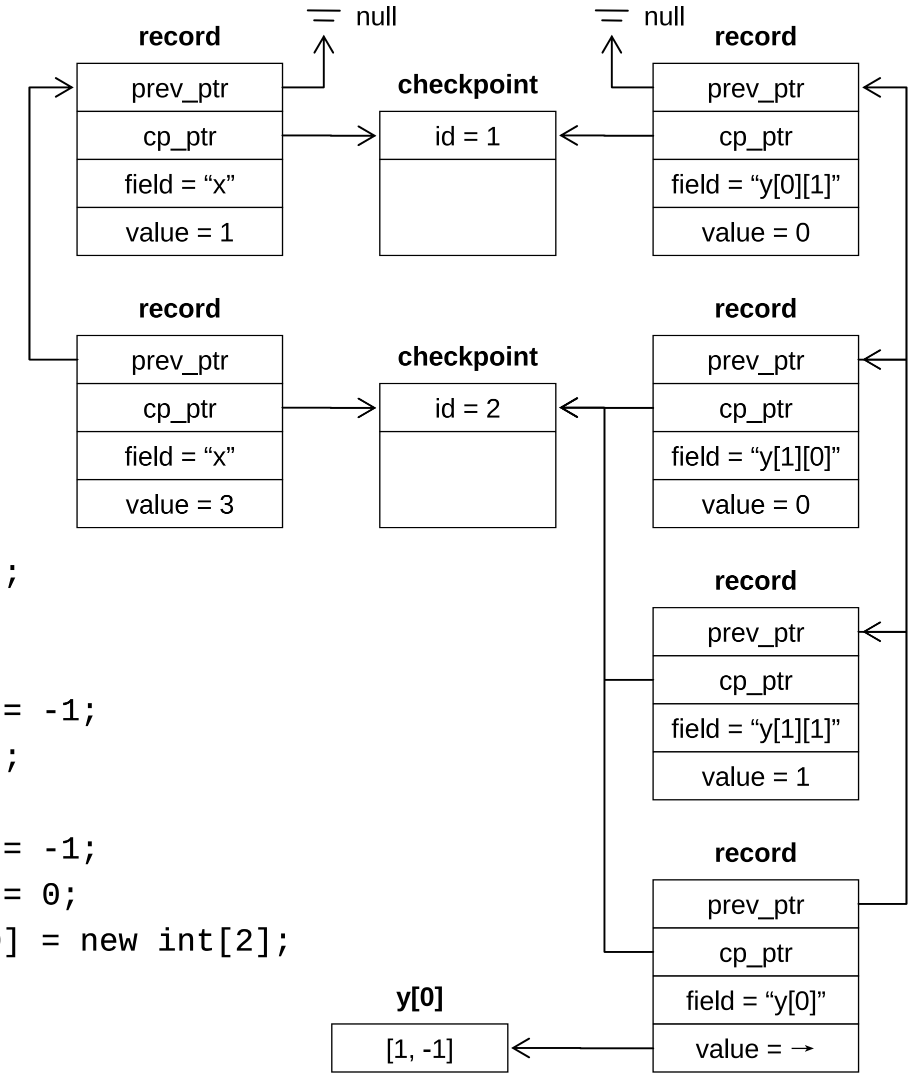
Application to threaded systems, e.g., Ptolemy II:

- Hierarchical composition of (sub-)models.
- An actor does not directly reference other actors.

Data Structure

$x = 1,\ y = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$

```
int handle1 = createCheckpoint();
$ASSIGN$x(2);        // x = 2;
$ASSIGN$x(3);        // x = 3;
$ASSIGN$y(0, 1, -1); // y[0][1] = -1;
int handle2 = createCheckpoint();
$UPDATE$x(2, 0);     // x++;
$ASSIGN$y(1, 0, -1); // y[1][0] = -1;
$ASSIGN$y(1, 1, 0);  // y[1][1] = 0;
$ASSIGN$y(0, new int[2]); // y[0] = new int[2];
rollback(handle1);
```



Stateful Java Classes

Hashtable, List, Random, Set, Stack, etc.

1. Get the source (Hashtable, Map, …) from Sun (alternatively, GCJ):

```
package java.util;
class Hashtable implements Map {
  ...
}
```

2. Apply the same transformation:

   java.util.Hashtable → ptolemy.backtrack.java.util.Hashtable

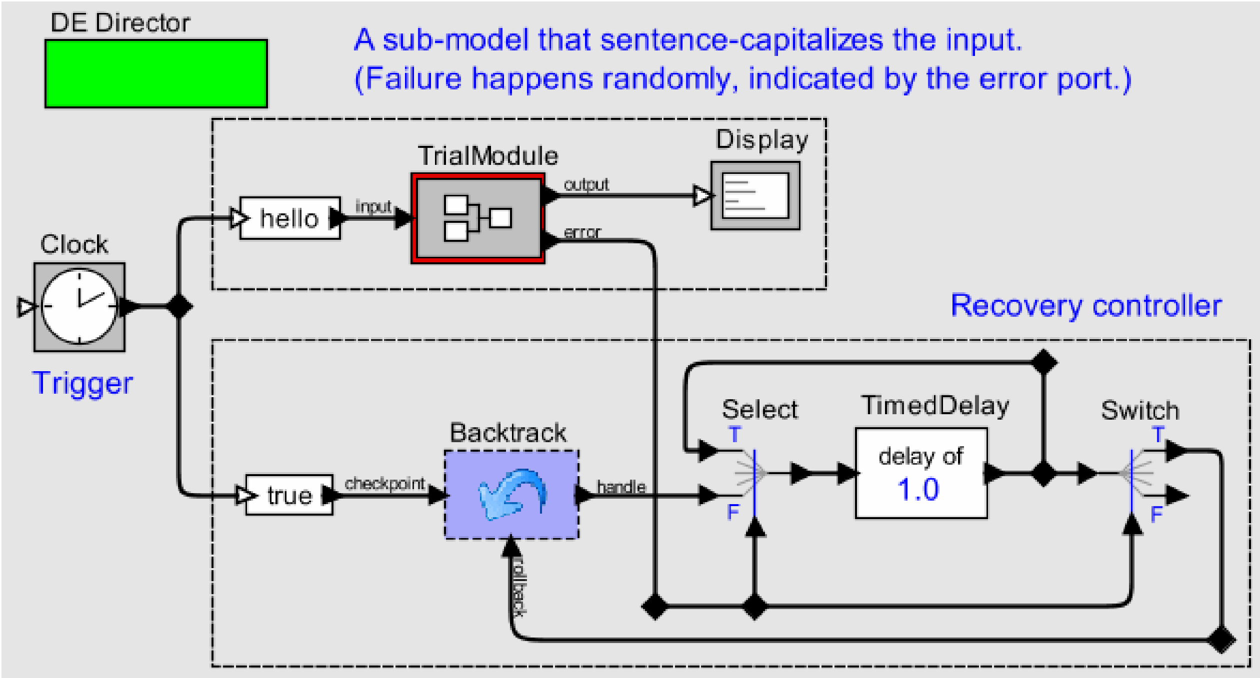
3. Fix references:

```
import java.util.Hashtable;
class A extends Actor {
  private Hashtable table;
  ...
}
```

→

```
import ptolemy.backtrack.java.util.Hashtable;
class A extends Actor {
  private Hashtable table;
  ...
}
```

Use Case: Recoverable Model Execution

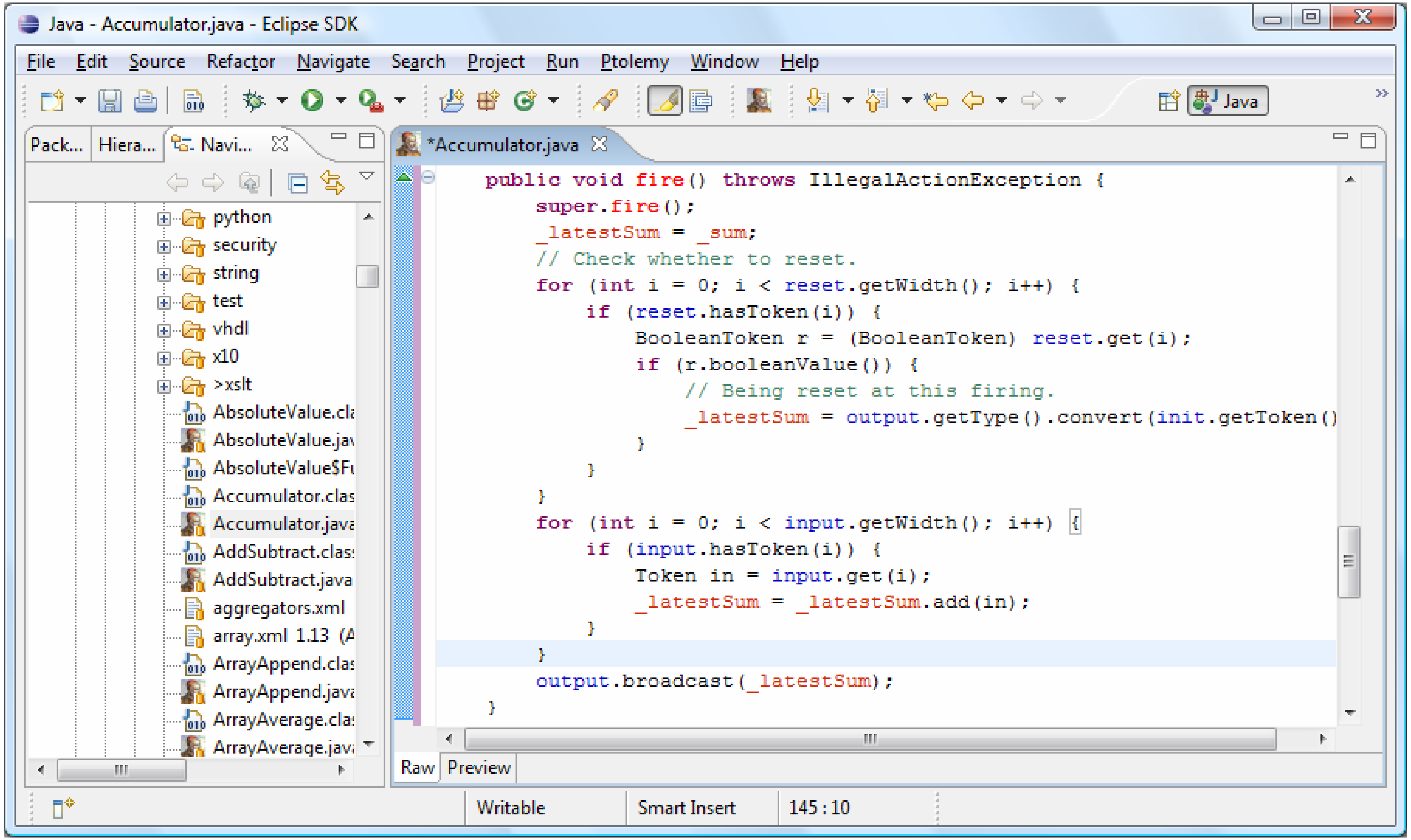


A DE model that autonomously recovers from error

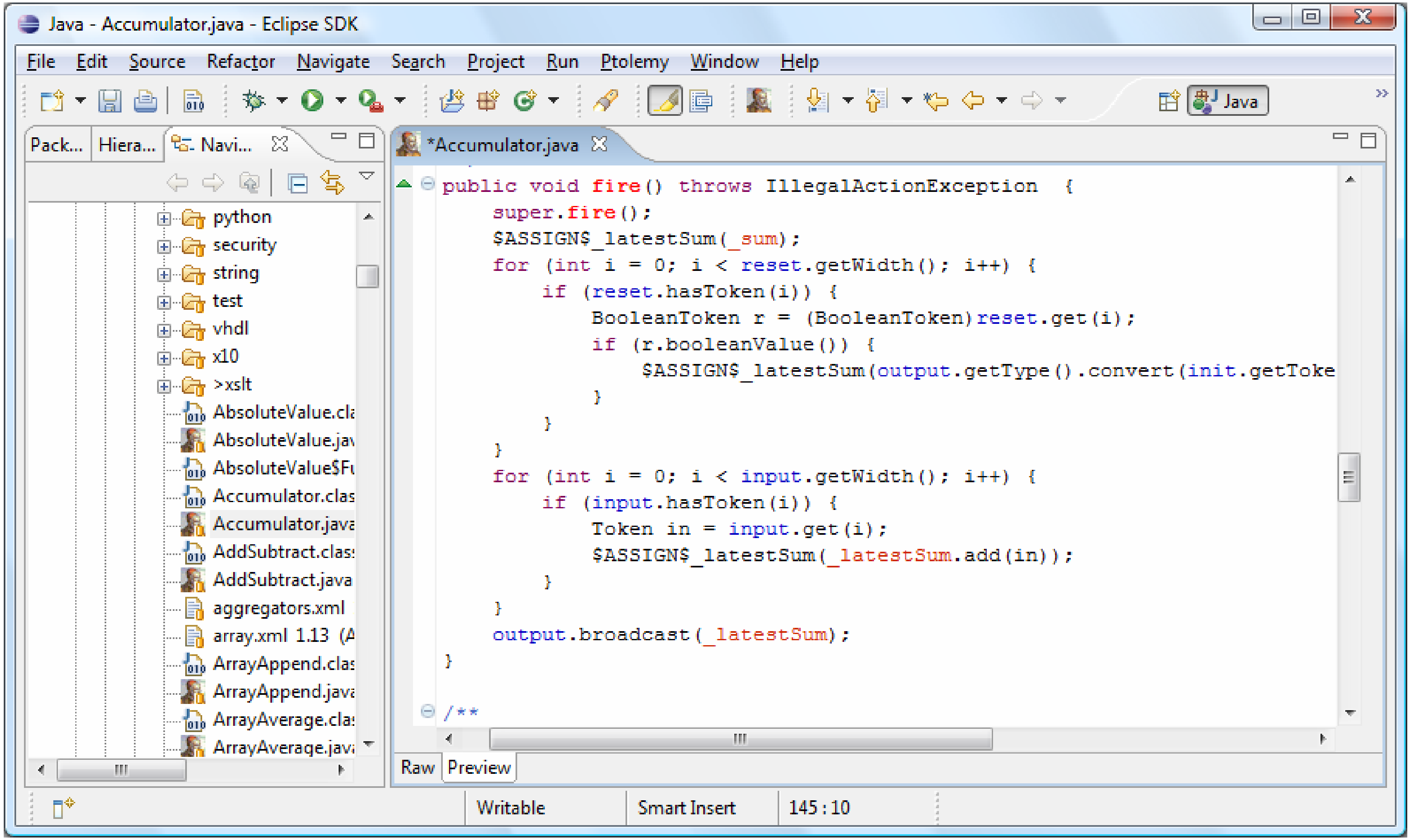
Application to Time Warp Simulation

- On receiving an event: create a checkpoint and record the handle.
- Process the event.
- When inconsistency happens:
  - Detect the event that caused this problem.
  - Recover the state *right before* the event was processed.
  - Re-process the events since that time in a *better* order.

Development Environment



Development Environment



Conclusion

- Easily proved correct using operational semantics of the Java language. (Refer to the paper.)
- High-performance backtracking mechanism.
  - Checkpoint creation incurs a small constant cost.
  - Rollback and discard operations are linear in the updates.
- Precisely roll back to any execution point (assuming enough memory).
- Applicable to real-time systems by slowing them down gracefully.
  - Proportional slowdown because of the constant extra cost per update.