IMUnit: Improved Multithreaded Unit Testing

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Multicore World

Shared Memory Multithreaded

Parallel

Performance!
Difficult to Develop Multithreaded Code

- Non-deterministic scheduling
- Data races
- Deadlocks
- Atomicity violations
- ...

Correct

Shared Memory Multithreaded

Parallel
Difficult to Test Multithreaded Code

- Failures triggered by specific schedules
- Most research focuses on exploring schedules for given manually written tests on one given code version
Challenges in Unit Testing MT Code

1. How to write multithreaded unit tests?
   – Developers often want to test specific schedules
   – How to express schedules in unit tests?

2. How to explore multithreaded unit tests?
   – Current techniques focus on one code version
   – Code evolves, need efficient regression testing

3. How to generate multithreaded unit tests?
   – How to automatically generate test code?
   – How to automatically generate schedules?
Our Work on All Three Topics

1. Writing multithreaded unit tests (this talk)
   – **IMUnit**: Illinois/improved multithreaded unit testing [ESEC/FSE’11]
     • Read “immunity”: isolate code from bugs

2. Regression testing
   – Prioritizing exploration of change-impacted schedules [ISSTA’11]
   – Selecting schedules under changes [ICST’10, STVR’12?]

3. Generating tests
   – Generating schedules [ICSE’08]
   – Generating code [ICSE’12]
Example: ConcurrentHashMultiSet

- Thread-safe Multiset aka Bag implementation
- Provided by Guava (Google Collections)
- Consider testing these three methods

```java
package com.google.common.collect;
public class ConcurrentHashMultiSet<E> {
    boolean add(E element) ...
    boolean remove(Object element) ...
    int count(Object element) ...
    ...
}
```
Testing Adds and Remove

```
add(42)
add(42)
remove(42)
```

`count(42)` is schedule dependent

```
multiset
```
Testing Remove Before Adds

multiset

add(42)
add(42)

remove(42)
count(42) == 2
Sleep-Based Test: Remove Before Adds

```java
@Test
public void testRemoveBeforeAdds() {
    Multiset<Integer> multiset = ConcurrentHashMultiset.create();
    Thread addThread = new Thread(new Runnable()
    {
        @Test
        public void testRemoveBeforeAdds() {
            multiset = ConcurrentHashMultiset.create();
            Thread addThread = new Thread(new Runnable()
            {
                public void run()
                {
                    Thread.sleep(60);
                    multiset.add(42);
                    multiset.add(42);
                }
            });
            addThread.start();
            multiset.remove(42);
            addThread.join();
            assertEquals(2, multiset.count(42));
        }
    });
    addThread.start();
    multiset.remove(42);
    addThread.join();
    assertEquals(2, multiset.count(42));
}
```
Testing Remove Between Adds

multiset

add(42) -> remove(42) -> count(42) == 1
Sleep-Based Test: Remove Between Adds

```java
@Test
public void testRemoveBetweenAdds() {
    multiset = ConcurrentHashMultiset.create();
    Thread addThread = new Thread(new Runnable() {
        public void run() {
            multiset.add(42);
            Thread.sleep(80);
            multiset.add(42);
        }
    });
    addThread.start();
    Thread.sleep(40);
    multiset.remove(42);
    addThread.join();
    assertEquals(1, multiset.count(42));
}
```

Sleeps used to express and enforce schedule.
Sleep-Based Tests: Issues

@Test
public void testRemoveBetweenAdds() {
    
    multiset = ConcurrentHashMultiset.create();
    Thread addThread = new Thread(new Runnable() {
        public void run() {
            multiset.add(42);
            Thread.sleep(80);
            multiset.add(42);
        }
    });
    addThread.start();
    Thread.sleep(40);
    multiset.remove(42);
    addThread.join();
    assertEquals(1, multiset.count(42));
}

---

- **Fragile**
- **Inefficient**
- **Non modular**
- **Implicit schedule**

<table>
<thead>
<tr>
<th></th>
<th>Not buggy</th>
<th>Buggy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pass</td>
<td>True Negative</td>
<td>False Positive</td>
</tr>
<tr>
<td>Fail</td>
<td>False Negative</td>
<td>True Positive</td>
</tr>
</tbody>
</table>
Others have also recognized issues...

• Previous solutions:
  – ConAn: Long, Hoffman and Strooper
  – ConcJUnit: Ricken and Cartwright
  – ThreadControl: Dantas, Brasileiro and Cirne

• Latest solution:
  – MultithreadedTC: Pugh and Ayewah
  – Tick-based tests
    + Robust, Efficient
    – But Non modular, Implicit schedule
    – Different from traditional tests

• IMUnit: Event-based tests
@Test
@Schedule("finishRemove->startingAdd1")
public void testRemoveBeforeAdds() {
    ...
    multiset = ConcurrentHashMapMultiset.create();
    Thread addThread = new Thread(new Runnable() {
        public void run() {
            @Event("startingAdd1");
            multiset.add(42);
            multiset.add(42);
        }
    });
    addThread.start();
    multiset.remove(42);
    @Event("finishRemove");
    addThread.join();
    assertEquals(2, multiset.count(42));
}
@Test
@Schedule("finishRemove->startingAdd1")
public void testRemoveBeforeAdds() {
  ...
  multiset = ConcurrentHashMultiset.create();
  Thread addThread = new Thread(new Runnable() {
      public void run() {
        @Event("startingAdd1");
        multiset.add(42);
        multiset.add(42);
      }
  });
  addThread.start();
  multiset.remove(42);
  @Event("finishRemove");
  addThread.join();
  assertEquals(2, multiset.count(42));
}
@Test
@Schedule("finishRemove-&gt;startingAdd1")
public void testRemoveBeforeAdds() { ...
IMUnit Test: Remove Between Adds

@Test
@Schedule("finishAdd1->startingRemove, finishRemove->startingAdd2")
public void testRemoveBetweenAdds() {

    ...
    multiset = ConcurrentHashMultiset.create();
    Thread addThread = new Thread(new Runnable() {
        public void run() {
            multiset.add(42);
            @Event("finishAdd1");
            @Event("startingAdd2");
            multiset.add(42);
        }
    });
    addThread.start();
    @Event("startingRemove");
    multiset.remove(42);
    @Event("finishRemove");
    addThread.join();
    assertEquals(1, multiset.count(42));
}
IMUnit Test: Both Schedules

@Test
@Schedule("finishRemove->startingAdd1")
@Schedule("finishAdd1->startingRemove, finishRemove->startingAdd2")
public void testAddRemove() ... {

    multiset = ConcurrentHashMapMultiset.create();
    Thread addThread = new Thread(new Runnable() {
        public void run() {
            @Event("startingAdd1");
            multiset.add(42);
            @Event("finishAdd1");
            @Event("startingAdd2");
            multiset.add(42);
        }
    });
    addThread.start();
    @Event("startingRemove");
    multiset.remove(42);
    @Event("finishRemove");
    addThread.join();

    ...}
Schedule Language

\[
\text{<Schedule>} ::= \{ \text{<Ordering>} \"\}," \} \text{<Ordering>}
\]

\[
\text{<Ordering>} ::= \text{<Condition>} \"\rightarrow\" \text{<Basic Event>}
\]

\[
\text{<Condition>} ::= \text{<Basic Event>} \mid \text{<Block Event>} \mid \text{<Condition>} \"\mid\" \text{<Condition>} \\
\quad\mid \text{<Condition>} \"\&\&\" \text{<Condition>} \mid \"(" \text{<Condition>} \")\"
\]

\[
\text{<Block Event>} ::= \"[\" \text{<Basic Event>} \"]\"
\]

\[
\text{<Basic Event>} ::= \text{<Event Name>} \text{["@" <Thread Name>]}
\quad\mid \text{"start" }\text{["@" <Thread Name>]}
\quad\mid \text{"end" }\text{["@" <Thread Name>]}
\]

\[
\text{<Event Name>} ::= \{ \text{<Id> }\text{."} \} \text{<Id>}
\]

\[
\text{<Thread Name>} ::= \text{<Id>}
\]

• **Events**
  • Two types: non-blocking-event and [blocking-event]
  • Can be parameterized by thread-name: event@threadName
  • Can also be combined into conditions using “| |” and “&&”

• **Ordering** specifies order between a condition and event
  • “->” is the ordering operator
  • before-condition -> after-event

• **Schedule** is a comma-separated list of orderings
Schedule Logic

- **Fragment of PTLTL**
  - Over finite well formed multithreaded unit test execution traces
  - Two temporal operators
    - Block
    - Ordering
- **Guided by practical requirements**
  - Over 200 existing multithreaded unit tests
- **Details in paper**

**Logic Syntax:**

\[
\begin{align*}
a & ::= \text{start} \mid \text{end} \mid \text{block} \mid \text{unblock} \mid \text{event names} \\
t & ::= \text{thread names} \\
e & ::= a @ t \\
\varphi & ::= [t] \mid \varphi \rightarrow \varphi \mid \text{usual propositional connectives}
\end{align*}
\]

**Logic Semantics:**

The semantics of our logic is defined as follows:

\[
\begin{align*}
e_1 e_2 \ldots e_n & \models e \quad \text{iff} \quad e = e_n \\
\tau & \models \varphi \land/\lor \psi \quad \text{iff} \quad \tau \models \varphi \quad \text{and/or} \quad \tau \models \psi \\
e_1 e_2 \ldots e_n & \models [t] \quad \text{iff} \quad (\exists 1 \leq i \leq n) \ (e_i = \text{block} @ t \quad \text{and} \quad (\forall i < j \leq n) \ e_j \neq \text{unblock} @ t) \\
e_1 e_2 \ldots e_n & \models \varphi \rightarrow \psi \quad \text{iff} \quad (\forall 1 \leq i \leq n) \ e_1 e_2 \ldots e_i \neq \psi \quad \text{or} \quad (\exists 1 \leq i \leq n) \ (e_1 e_2 \ldots e_i \models \psi \quad \text{and} \quad (\exists 1 \leq j \leq i) \ e_1 e_2 \ldots e_j \models \varphi)
\end{align*}
\]

It is not hard to see that the two new operators \([t]\) and \(\varphi \rightarrow \psi\) can be expressed in terms of PTLTL as

\[
\begin{align*}
[t] & \equiv \neg \text{unblock} @ t \ S \ \text{block} @ t \\
\varphi \rightarrow \psi & \equiv \square \neg \psi \lor \Diamond (\psi \land \Diamond \varphi)
\end{align*}
\]

where \(S\) stands for “since” and \(\square\) for “always in the past”.
Schedule Enforcement

- Two implementations: original and light
- Original implemented using JavaMOP
- Schedule logic implemented as JavaMOP logic plugin
- Takes as input a schedule and outputs a monitor
- Monitor aspects are weaved into test code
- Different monitor for each test, schedule pair
- Monitor can work in two modes:
  - Active mode enforces schedules
  - Passive mode prints error if execution deviates from schedule
IMUnit Light

• Original implementation:
  – Preprocessing for @Event
  – Instrumentation to weave in monitor
  – Dependency on AspectJ etc

• IMUnit light
  – Just need imunit.jar on classpath
  – fireEvent ("eventName") instead of @Event
  – Centralized monitor provided by library
  – Even more efficient
IMUnit Event-Based Tests: Features

@Test
@Schedule("finishRemove->startingAdd1")
@Schedule("finishAdd1->startingRemove, finishRemove->startingAdd2")
public void testAddRemove() ... {

    multiset = ConcurrentHashMultiset.create();
    Thread addThread = new Thread(new Runnable() {
        public void run() {
            @Event("startingAdd1");
            multiset.add(42);
            @Event("finishAdd1");
            @Event("startingAdd2");
            multiset.add(42);
        }
    });
    addThread.start();
    @Event("startingRemove");
    multiset.remove(42);
    @Event("finishRemove");
    addThread.join();

    ...  

    multiset = ConcurrentHashMultiset.create();
    Thread addThread = new Thread(new Runnable() {
        public void run() {
            @Event("startingAdd1");
            multiset.add(42);
            @Event("finishAdd1");
            @Event("startingAdd2");
            multiset.add(42);
        }
    });
    addThread.start();
    @Event("startingRemove");
    multiset.remove(42);
    @Event("finishRemove");
    addThread.join();

    ...

+ Robust
+ Efficient
+ Modular
+ Explicit schedule
Manual Migration

We manually migrated over 200 sleep-based tests to IMUnit

Migration typically involved the following steps:

1. Optionally name threads (default names non-deterministic)
2. Introduce events using @Event annotations
   – Need to identify interesting points
3. Introduce schedule using @Schedule annotation
   – Need to understand intended sleep-based schedule
   – Specify the orderings required by intended schedule
   – Also identify blocking vs. non-blocking events
4. Check that added schedule is the intended schedule
5. Remove sleeps
6. Optionally merge tests with different schedules but similar code
Automated Migration

• Introducing events and schedules most challenging

• Inferred using execution logs of sleep-based tests

• Two phase process:
  – Inferring likely events
    • Precision: 75%, Recall: 79%
  – Inferring likely schedules
    • Precision: 96%, Recall: 94%

• More details in paper
Evaluation

• Expressiveness of schedule language
• Efficiency of schedule enforcement
Expressiveness of Schedule Language

- Experience with migrating over 200 sleep-based unit tests
  - 7 different open source projects
- Evolved language using migration experience
  - Blocking events added because they were required by many tests
  - Events in loops were only required for 5 tests so not added yet
- Replaced sleeps with events and schedules in 198 tests

<table>
<thead>
<tr>
<th>Subject</th>
<th>Tests</th>
<th>Events</th>
<th>Orderings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commons Collections</td>
<td>18</td>
<td>51</td>
<td>32</td>
</tr>
<tr>
<td>JBoss-Cache</td>
<td>27</td>
<td>105</td>
<td>47</td>
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<tr>
<td>Lucene</td>
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<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Mina</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Pool</td>
<td>2</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>Sysunit</td>
<td>9</td>
<td>33</td>
<td>34</td>
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<tr>
<td>JSR-166 TCK</td>
<td>139</td>
<td>577</td>
<td>277</td>
</tr>
<tr>
<td><strong>Σ</strong></td>
<td><strong>198</strong></td>
<td><strong>779</strong></td>
<td><strong>398</strong></td>
</tr>
</tbody>
</table>
Efficiency of Schedule Enforcement

- IMUnit test execution vs. sleep-based test execution
- IMUnit test execution more than 3X faster
  - Schedule enforcement is efficient
- Also demonstrates the over estimation of sleep delays
  - Sleeps are inefficient

<table>
<thead>
<tr>
<th>Subject</th>
<th>Original [s]</th>
<th>IMUnit [s]</th>
<th>Speedup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commons Collections</td>
<td>4.96</td>
<td>1.06</td>
<td>4.68</td>
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<td>JBoss-Cache</td>
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<td>Lucene</td>
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<td>3.57</td>
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<tr>
<td>Mina</td>
<td>0.26</td>
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<td>Pool</td>
<td>1.43</td>
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<td>Sysunit</td>
<td>17.67</td>
<td>0.35</td>
<td>50.49</td>
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<tr>
<td>JSR-166 TCK</td>
<td>15.20</td>
<td>9.56</td>
<td>1.59</td>
</tr>
</tbody>
</table>

Geometric Mean     3.39
Writing Multithreaded Unit Tests...

• Dominant solution: sleep-based
  – Fragile, Inefficient, Non-Modular, Implicit

• IMUnit: event-based
  – Robust, Efficient, Modular, Explicit
  – Schedule language is expressive
  – Schedule enforcement is efficient
  – Automated migration
  – More details in paper

http://mir.cs.illinois.edu/imunit