ABSTRACT

Multithreaded code is notoriously hard to develop and test. A multithreaded test exercises the code under test with two or more threads. Each test execution follows some schedule/interleaving of the multiple threads, and different schedules can give different results. Developers often want to enforce a particular schedule for test execution, and to do so, they use time delays (Thread.sleep in Java). Unfortunately, this approach can produce false positives or negatives, and can result in unnecessarily long testing time.

This paper presents IMUnit, a novel approach to specifying and executing schedules for multithreaded tests. We introduce a new language that allows explicit specification of schedules as orderings on events encountered during test execution. We present a tool that automatically instruments the code to control test execution to follow the specified schedule, and a tool that helps developers migrate their legacy, sleep-based tests into event-based tests in IMUnit. The migration tool uses novel techniques for inferring events and schedules from the executions of sleep-based tests. We describe our experience in migrating over 200 tests. The inference techniques have high precision and recall of over 75%, and IMUnit reduces testing time compared to sleep-based tests on average 3.39x.

Categories and Subject Descriptors
D.2.5 [Software Engineering]: Testing and Debugging

General Terms
Verification, Reliability

Keywords
IMUnit, Unit Testing, Multithreaded Code

1. INTRODUCTION

Multicore processors are here to stay. To extract greater performance from multicore processors, developers need to write parallel code. The predominant paradigm for parallel code is that of shared memory where multiple threads of control communicate by reading and writing shared data objects. Shared-memory multithreaded code is often afflicted by concurrency bugs, which are hard to detect because multithreaded code can demonstrate different behavior based on the scheduling of threads, and the bugs may only be triggered by a small specific set of schedules.

To validate their multithreaded code, developers write multithreaded unit tests. A multithreaded test creates and executes two or more threads (and/or invokes code under test that itself creates and executes two or more threads). Each test execution follows some schedule/interleaving of the multiple threads, and different schedules can give different results. Developers often want to enforce a particular schedule for a test. For example, consider two threads, one executing a method m and the other executing a method m'. Developers may want to ensure in one test that m finishes before m' starts and in another test that m' finishes before m starts (and in more tests that m and m' interleave in certain ways). Without controlling the schedule, it is impossible to write precise assertions about the execution because the results can differ in the two scenarios, and it is impossible to guarantee which scenarios were covered during testing, even if multiple runs are performed.

To control the schedule of multithreaded tests, developers mostly use a combination of timed delays in the various test threads. In Java, the delay is performed with the Thread.sleep method, so we call this approach sleep-based. A sleep pauses a thread while other threads continue execution. Using a combination of sleeps, developers attempt to enforce the desired schedule during the execution of a multithreaded test, and then assert the intended result for the desired schedule. A sleep-based test can fail when an undesired schedule gets executed even if the code under test has no bug (false positive). Dually, a sleep-based test can pass when an unintended schedule gets executed even if the code under test has a bug (false negative). Indeed, sleeps are an unreliable and inefficient mechanism for enforcing schedules.

To use sleeps, one has to estimate the real-time duration for which to delay a thread while the other threads perform their work. This is usually estimated by trial and error, starting from a small duration and increasing it until the test passes consistently on the developer’s machine. The estimated duration depends on the execution environment (hardware/software configuration and the load on the machine). Therefore, when the same test is executed in a different environment, the intended schedule may not be en-
forced, leading to false positives/negatives. Moreover, sleep can be very costly to migrate the existing sleep-based tests.

Researchers have previously noted the numerous problems with using sleeps to specify schedules in multithreaded tests and have developed frameworks such as ConAn [22, 23], ConcJUnit [27], MultithreadedTC [26], and ThreadControl [13] to tackle some problems in specifying and enforcing schedules in multithreaded unit tests. However, despite these frameworks, multithreaded unit testing still has many issues that could be categorized as follows:

**Readability**: Most current frameworks force developers to reason about the execution of threads relative to a global clock. This is unintuitive since developers usually reason about the execution of their multithreaded code in terms of event relationships (such as m finishing before m' starts).

Some frameworks require users to write schedules in external scripts, which makes it even more difficult to reason about schedules. In other frameworks the schedule is implicit, as a part of the unit test code, and hence it is difficult to focus on the schedule and reason about it separately at a higher level.

**Modularity**: In some current frameworks, the intended schedule is intermixed with the test code and effectively hard-coded into a multithreaded unit test. This makes it difficult to specify multiple schedules for a particular unit test and/or to reuse test code among different tests.

**Reliability**: Some current frameworks, as well as the legacy sleep-based tests, rely on real time. As explained, this makes them very fragile, leading to false positives/negatives and/or slow testing time.

**Migration Costs**: Most current frameworks are very different from the traditional sleep-based tests. This makes it costly to migrate the existing sleep-based tests.

We present a new framework, called IMUnit (pronounced “immunity”), which aims to address these issues with multithreaded unit testing. Specifically, we make the following contributions:

**Schedule Language**: IMUnit introduces a novel language that enables natural and explicit specification of schedules for multithreaded unit tests. Semantically, the basic entity in an IMUnit schedule is an event that an execution can produce at various points (e.g., a thread starting/finishing the execution of a method, or a thread getting blocked). We call the IMUnit approach event-based. An IMUnit schedule itself is a (monitorable) property [10, 24] on the sequence of events. More precisely, each schedule is expressed as a set of desirable event orderings, where each event ordering specifies the order between a pair of events (note that an IMUnit schedule need not specify a total order between all events but only the necessary partial order).

While the ideas of IMUnit can be embodied in any language, we have developed an implementation for Java. Syntactically, the IMUnit constructs are represented using Java annotations. A developer can use @Event and @Schedule annotations to describe the events and intended schedules, respectively, for a multithreaded unit test.

**Automated Migration**: We have developed two inference techniques and a tool to ease migration of legacy, sleep-based tests to IMUnit, event-based tests. Our inference techniques can automatically infer likely relevant events and schedules from the execution traces of existing sleep-based tests. We implemented our migration tool as an Eclipse plugin which uses the results of inference to automatically refactor a given multithreaded test into an IMUnit test.

**Execution and Checking**: We have implemented a tool for execution of IMUnit multithreaded unit tests. The tool can work in two modes. In the active mode, it controls the thread scheduler to enforce a given IMUnit schedule during test execution. In the passive mode, it checks whether an arbitrary test execution, controlled by the regular JVM thread scheduler, follows a given IMUnit schedule. To enforce/check the schedules, our tool uses the JavaMOP monitoring framework [10, 24]. We also include a new runner for the standard JUnit testing framework to enable execution of IMUnit tests with our enforcement/checking tool.

**Evaluation**: To guide and refine our design of the IMUnit language, we have been inspecting over 200 sleep-based tests from several open-source projects. We manually translated 198 of these tests into IMUnit, adding events and schedules, and removing sleeps. As a result, the current version of IMUnit is highly expressive, and we were able to remove all sleeps from all but 4 tests.

We evaluated our inference techniques by automatically inferring events/schedules for the original tests that we manually translated (the subprojects on manual translation and automatic inference were performed by different authors to reduce the direct bias of manual translation on automatic inference). Computing the precision and recall of the automatically inferred events/schedules with respect to the manually translated events/schedules, we find our techniques to be highly effective, with over 75% precision and recall.

We also compared the execution time of the original tests and our translated tests. Because the main goal of IMUnit is to make tests more readable, modular, and reliable, we did not expect IMUnit to run faster. However, IMUnit did reduce the testing time, on average 3.39x, compared to the sleep-based tests, with the sleep duration that the original tests had in the code. As mentioned earlier, these duration values are often over-estimated, especially in older tests that were written for slower machines. In summary, IMUnit not only makes multithreaded unit tests more readable, modular, and reliable than the traditional sleep-based approach, but IMUnit can also make test execution faster.

This paper makes progress on our vision for improving multithreaded unit testing; our position paper [15] proposed the idea of event-based specification of schedules, but the IMUnit language and algorithms/tools for inference and execution are completely new.

2. **EXAMPLE**

We now illustrate IMUnit with the help of an example multithreaded unit test for the ArrayBlockingQueue class in java.util.concurrent (JSR-166) [17]. ArrayBlockingQueue is an array-backed implementation of a bounded blocking queue. One operation provided by ArrayBlockingQueue is **add**, which performs a non-blocking insertion of the given element at the tail of the queue. If **add** is performed on an empty queue, it throws an exception. Another operation provided by ArrayBlockingQueue is **take**, which removes and returns the object at the head of the queue. If **take** is performed on an empty queue, it blocks until an element is inserted into the queue. These operations could have bugs that get triggered when the **add** and **take** operations execute on different threads. Consider testing some scenarios for these opera-
public class TestTakeWithAdd
extends MultithreadedTest {
    ArrayBlockingQueue<Integer> q;
    public void initialize() {
        q = new ArrayBlockingQueue<Integer>(1);
    }
    public void addThread() {
        q.add(1);
        waitForTick(2);
        expected("startingAdd2");
        @Event("startingAdd2")
        Integer taken = q.take();
        assertTrue(taken == 1 && q.isEmpty());
        @Event("startingTake1")
        q = new ArrayBlockingQueue<Integer>(1);
        Integer taken = q.take();
        assertTrue(taken == 2 && q.isEmpty());
        @Test
        @Schedule("finishedAdd1">startingTake1,
        [startingTake2]">startingAdd2")
    }
    public void testTakeWithAdd() {
        ArrayBlockingQueue<Integer> q;
        @Override
        public void realRun() {
            q.add(1);
        }
    }
    void addThread() {
        q.add(1);
        waitForTick(2);
    }
}

public void mainThread() {
    Thread addThread = new CheckedRunnable() {
        @Event("startingAdd1")
        public void realRun() {
            q.add(1);
            waitForTick(2);
            expected("startingAdd2");
            @Event("startingAdd2")
            Integer taken = q.take();
            assertTrue(taken == 2 && q.isEmpty());
            @Event("startingTake2")
            taken = q.take();
            addThread.join();
        }
    };
    addThread.start();
    Thread sleep = new Thread(() {
        public void run() {
            Thread.sleep(50);
            expected("startingTake2");
            @Event("startingTake2")
            @Schedule("finishedTake1")
            Integer taken = q.take();
            assertTrue(taken == 2 && q.isEmpty());
            @Event("startingTake3")
            taken = q.take();
            addThread.join();
        }
    });
    Thread take = new Thread(() {
        public void run() {
            expected("startingTake1");
            @Event("startingTake1")
            Integer taken = q.take();
            assertTrue(taken == 1 && q.isEmpty());
            @Event("startingAdd1")
            taken = q.take();
            addThread.join();
        }
    });
    take.start();
    sleep.start();
}

We now revisit, in the context of this example, the issues with multithreaded tests listed in the introduction. In terms of readability, we believe that making the schedules explicit, as in IMUnit, allows easier understanding and maintenance of schedules and code for both testing and debugging. In terms of modularity, IMUnit allows extracting the addThread as a helper thread (with its events) that can be reused in other tests. The intended schedule is specified with respect to a global, logical clock. Since this clock measures time in ticks, we call the approach tick-based. When a thread executes a waitForTick, it is blocked until the global clock reaches the required tick. The clock advances implicitly when all threads are blocked (and at least one thread is blocked in a waitForTick). While a MultithreadedTC test does not rely on real time, and is thus more reliable than a sleep-based test, the intended schedule is still not immediately clear upon reading the test code. It is especially not clear when waitForTick operations are blocked/unblocked, because ticks are advanced implicitly when all the threads are blocked.

Figure 1(c) shows the same test written using IMUnit. The interesting events encountered during test execution are marked with @Event annotations, and the intended schedule is specified with a @Schedule annotation that contains a comma-separated set of orderings among events. An ordering is specified using the operator ->, where the left event is intended to execute before the right event. An event specified within square brackets denotes that the thread executing that event is intended to block after that event. It should be clear from reading the schedule that the addThread should finish the first add before the main thread starts the first take, and that the main thread should block while performing the second take before the addThread starts the second add.

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event appears at most once in a trace. With PTLTL, this says that the following holds (\(\psi\) "previously"):
\[
\tau \models \neg \psi \land \varphi \land \varphi \\
\text{for any trace } \tau \text{ and any } a@t \text{ with } \alpha \notin \{\text{block, unblock}\}.
\]
The semantics of our logic is defined as follows:
\[
e_1 \ldots e_n \models \varphi \iff e = e_n \\
\tau \models \varphi \land \forall \psi \iff \tau \models \varphi \land \exists \psi \\
e_1 \ldots e_n \models \varphi \iff (\exists 1 \leq i \leq n) (e_i = \text{block}@t \land (\forall i < j \leq n) e_j \neq \text{unblock}@t) \\
\]
It is not hard to see that the two new operators \(t\) and \(\varphi \rightarrow \psi\) can be expressed in terms of PTLTL as
\[
[t] \equiv \neg \text{unblock}@t \land S \land \text{block}@t \\
\varphi \rightarrow \psi \equiv \exists t = \psi \lor (\psi \land \varphi)
\]
where \(S\) stands for "since" and \(\exists\) for "always in the past".

4. MIGRATION

We now describe the process of migrating legacy, sleep-based tests to IMUnit, event-based tests. First we present the steps that are typically performed during manual migration and then we describe the automated support that we have developed for key steps of the migration.

4.1 Manual Migration

Based on our experience of manually migrating over 200 tests, the migration process typically follows these steps:

**Step 1:** Optionally add explicit names for threads in the test code (by using a thread constructor with a name or by adding a call to `Thread::getName`). This step is required if events are tagged with their thread name (e.g. `finishedAdd100addThread`) in the schedule, because by default the JVM automatically assigns a name (e.g. `Thread-5`) for each thread created without an explicit name, and the automatic name may differ between JVMs or between different runs on the same JVM.

**Step 2:** Introduce `Event` annotations for the events relevant for the intended schedule. Some of these annotations will be used for block events and some for basic events.

**Step 3:** Introduce a `Schedule` annotation for the intended schedule. Steps 2 and 3 are the hardest to perform as they require understanding of the intended behavior of the sleep-based test. Note that a schedule with too few orderings can over-constraining the test execution. For example, `Block::call` is not collected for schedule inference. Also, the entries are buffered in memory during test execution, and they are converted to strings and logged to file only at the end of test execution.

**Step 4:** Check that the orderings in the introduced schedule are actually satisfied when running the test with sleeps (Section 5 describes the passive, checking mode).

**Step 5:** Remove sleeps.

**Step 6:** Optionally merge multiple tests with different schedules (but similar test code) into one test with multiple schedules, potentially adding schedule-specific code (Section 4.3).

4.2 Automated Migration

We have developed automated tool support to enable easier migration of sleep-based tests to IMUnit. In particular, we have developed inference techniques that can compute likely relevant events and schedules for sleep-based tests by inspecting the execution logs obtained from test runs. We next describe the common infrastructure for logging the test runs. We then present the techniques for inferring events and schedules.

4.2.1 Lightweight Logging

Our inference of events and schedules from sleep-based tests is dynamic: it first instruments the test code (using AspectJ [19]) to emit entries potentially relevant for inference, then runs the instrumented code (several times, as explained below) to collect logs of entries from the test executions, and finally analyzes the logs to perform the inference.

Figure 3 shows the generic representation for log entries, although event and schedule inference require slightly different representations. Each log entry has a type, name/ID of the thread that emits the entry, potential info/parameters for the entry, and the ID of the statement that creates the entry (which is used only for event inference). The types of log entries and their corresponding info are as follows:

- **SLEEP_CALL:** Invocation of `Thread.sleep` method. (Only used for inferring events.)
- **SLEEP_RETURN:** Return from `Thread.sleep` method.
- **BLOCK_CALL:** Invocation of a thread blocking method (LockSupport.park or `Object.wait`).
- **BLOCK_RETURN:** Return from a thread blocking method.
- **OTHER_CALL:** Invocation of a method (other than those listed above) in the test case. The info is the method name. (Only used for inferring events.)
- **OTHER_RETURN:** Return from a method executed from the test class.
- **TH_START:** Invocation of `Thread.start`. The info is the ID of the started thread. (Only used for inferring schedules.)
- **TH_END:** End of thread execution.
- **EVENT:** Execution of an IMUnit event. The info is the name of the event. (Only available while inferring schedules.)

Note that any logging can affect timing of test execution. Because sleep-based tests are especially sensitive to timing, care must be taken to avoid false positives. We address this in three ways. First, our logging is lightweight. The instrumented code only collects log entries (and their parameters) relevant to the inference. For example, `OTHER_CALL` is not collected for schedule inference. Also, the entries are buffered in memory during test execution, and they are converted to strings and logged to file only at the end of test execution. While keeping entries in memory would not work well for very long logs, it works quite well for the relatively short logs produced by test executions. Second, our instrumentation automatically scales the duration of sleeps by a given constant \(N\) to compensate for the logging overhead. For example, for \(N = 3\) it increases all sleep times 3x. Increasing all the durations almost never makes a passing test fail, but it does make the test run slower. Third, we perform multiple
presents the algorithm for inferring IMUnit events and only collect logs for passing runs. This increases the confidence that the logs indeed correspond to the intended schedules specified with sleeps.

4.2.2 Inferring Events

Figure 4 presents the algorithm for inferring IMUnit events from a sleep-based test. The input to the algorithm consists of a set of logs (as described in Section 4.2.1) and a confidenceThreshold. The output is a set of inferred events. Each event includes the code location where the event annotation should be added and the name of the event. The intuition behind the algorithm is that SLEEP_CALL log entries are indicative of code locations for events. More precisely, a thread t calls sleep to wait for one or more events to happen on other threads (those will be “finished”) before an event happens on t (that will be a “starting” event). Recall our example from Section 2. When the main thread calls sleep, it waits for add to finish before take starts, and thus FinishedAdd executes before startingTake.

For each log, the algorithm first computes a set of regions, each of which is a sequence of log entries between SLEEP_CALL and the matching SLEEP_RETURN executed by the same thread. The log entries executed by other threads within a region are potential points for the “finished” events. Regions from different threads can be partially or completely overlapping, but regions from the same thread are disjoint (i.e., each SLEEP_CALL is followed directly by SLEEP_RETURN before any other statement is executed by the thread). Figure 5 shows two regions for a simplified log produced by our running example. In pseudo-code, each region is represented as a pair of ints that point to the beginning and end of the region in the list of log entries. For each region, the algorithm first calls addFinishedEvents to potentially add some “finished” events for threads other than the region’s thread. If an event is added, the algorithm calls addStartingEvent to add the matching “starting” event.

The procedure addFinishedEvents potentially adds an inferred event for each thread that executes at least one statement in the region. For each such thread, the procedure first discovers a relevant statement, which is one of SLEEP_CALL, BLOCK_CALL, and TH_END. Only threads that have exactly one relevant statement in the region are considered. The intuition is that sleep usually wait for exactly one event in each other thread. If a thread executes none or multiple relevant statements, it is most likely independent of the thread that started the region and therefore can be ignored. Figure 5 shows the relevant statements for each region. The procedure then finds the OTHER_RETURN statement immediately before the relevant statement for each thread. This statement determines the name for the new “finished” StaticEvent, whereas the relevant statement determines the location. Note that logging only method calls would not be enough to properly determine the previous statement since the call can come from a helper method in the test class. For our example, these before log entries are OTHER_RETURN(add), addThread, 326 and OTHER_RETURN(take), main, 336 (Fig. 5).

The procedure addStartingEvent adds an event for the thread that starts the region. The event is placed just before the first statement that follows the end of the region. The type of the statement can be any, including OTHER_CALL. The same statement is used for naming the event. In Figure 5, OTHER_CALL(take), main, 336 and OTHER_CALL(add), addThread, 330 are found following the algorithm.

```java
1 // Input
2 Set(List(LogEntry)) logs;
3 float confidenceThreshold;
4 // Output
5 class StaticEvent { StmtID sid; String name; }
6 Set(StaticEvent) events;
7 // State
8 Flag(StaticEvent) inferred := false;
9
class Region { int start; int end; }
12 void inferEvents() {
13 foreach (List(LogEntry) log in logs) {
14 foreach (Region r in computeRegions(log)) {
15 boolean addedFinished := addFinishedEvents(r, log);
16 if (addedFinished) { addStartingEvent(r, log); }
17 }
18 }
19 filterOutLowConfidence(confidenceThreshold);
20 events := inferred.toSet();
21 }
22 Set(Region) computeRegions(List(LogEntry) log) {
23 return { new Region(j), j | log(j).type = SLEEP_CALL ∧
24 j := min[k | log(i).tid = log(k).tid ∧
25 log(k).type = SLEEP_RETURN ] }
26 }
27 boolean addFinishedEvents(Region r, List(LogEntry) log) {
28 boolean result := false;
29 foreach (ThreadID t in { log(j).tid | i ∈ r } - { log(r.start).tid }) {
30 Set(int) relevant := { i ∈ r | log(i).tid = t ∧
31 log(i).type ∈ { SLEEP_CALL, BLOCK_CALL, TH_END } ∧
32 ¬(∃ j ∈ r | log(j).tid = t ∧
33 log(j).type ∈ { SLEEP RETURN, BLOCK RETURN } )
34 if (relevant.size() > 1) continue;
35 int starting := max[j | j < relevant | log(j).tid = t ∧
36 log(j).type = OTHER_RETURN ]
37 addEvent(relevant, "finished", starting);
38 result := true;
39 }
40 return result;
42 void addStartingEvent(Region r, List(LogEntry) log) {
43 int finished := min[j | j > r.start | log(j).tid = log(r.start).tid ∧
44 log(j).type ∈ { OTHER_RETURN, TH_END } ]
45 addEvent(finished, "starting");
46 }
47 void addEvent(int location, String namePrefix, int suffixIndex) {
48 StmtID sid = log(location).sid;
49 events := new StaticEvent(sid, namePrefix +
50 log(suffixIndex).info + sid);
51 }
```

Figure 4: Events-Inference Algorithm

Figure 5: Snippet from a Log for Inferring Events
4.2.3 Inferring Schedules

Figure 6 presents the algorithm to infer an IMUnit schedule for a sleep-based multithreaded unit test that already contains IMUnit event annotations. These annotations can be automatically produced by our event inference or manually provided by the user. The input to the algorithm is a set of logs obtained from the passing executions of the sleep-based test. Figure 7 shows a snippet from one such log for our running example sleep-based test shown in Figure 1(a). The input also contains a confidenceThreshold which will be described later. The output is an inferred schedule, i.e., a set of orderings that encodes the intended schedule for the test.

The main part of the algorithm is the addSleepInducedOrderings procedure. It captures the intuition that a thread normally executes a sleep to wait for the other active threads to perform events. Recall line 13 from our example in Figure 1(a) where the main thread sleeps to wait for the thread addThread to perform an add operation, and line 9 where addThread sleeps to wait for the main thread to first perform one take operation and then block while performing the second take operation.

For each log, the procedure scans for SLEEP RETURN entries (line 31). As shown in Figure 7, the log for our example contains two SLEEP RETURN entries, one each in the main thread and addThread. For each SLEEP RETURN that is found, the procedure does the following:

1) Retrieves the next EVENT entry for the same thread (line 33). This event will be used as the after event in Orderings induced by the SLEEP RETURN. In the example log, the two after events are startingTake1 for the first SLEEP RETURN and startingAdd2 for the second SLEEP RETURN.

2) Computes the other threads that were active between the SLEEP RETURN and the after event (line 34). In the example, for the first SLEEP RETURN, the only other active thread is addThread and for the second SLEEP RETURN, the only other active thread is main.

3) Finds for each active thread the last EVENT entry that is before the after event. This event will be the before event in the Ordering induced by the SLEEP RETURN with the corresponding active thread (line 38). Note that this before event on another thread can be even before the SLEEP RETURN. Effectively, this event is the current last entry and not the last entry at the time of the sleep. In the example, the two before events are finishedAdd1 and startingTake2 for the first and second SLEEP RETURNs, respectively.

4) Creates an Ordering for each before and after event pair and inserts it into the inferred bag. If a before event is followed immediately by a BLOCK CALL (within entries for the same thread), a BlockingOrdering is created; otherwise, a NonBlockingOrdering is created (line 41). In the example, since startingTake2 is followed by a BLOCK CALL, the ordering between startingTake2 and startingAdd2 will be a BlockingOrdering, while the other ordering between finishedAdd1 and startingTake1 will be a NonBlockingOrdering.

Before the addSleepInducedOrderings procedure is invoked, each log is modified by the preprocessLogs procedure. This procedure looks for SLEEP RETURN entries followed immediately by TH START entries for the same thread. For every such instance, it swaps the SLEEP RETURN and TH START entries and sets the tid of the SLEEP RETURN entry to be the ID of the thread that is started by the TH START event. The intuition is that a SLEEP RETURN followed by a TH START signifies that the started thread, rather than the starting thread perform-

Figure 6: Schedule-Inference Algorithm

Figure 7: Snippet from a Log for Inferring Schedules
shows the active-mode monitoring of sleep-based tests would be almost identical (with the sleep at line 9 moved to before line 16), they cannot share the common code without using additional conditional statements to enable the appropriate sleep during execution. In contrast, after both tests are migrated to IMUnit tests, they can be easily replaced by just one new test. This new test would have the same code as in Figure 1(a), with two added annotations: (1) \texttt{@Event("finishedAdd2")} added after the add(2) call, and (2) \texttt{@Schedule("finishedAdd2->startingTake2")} added before the test method.

5. ENFORCING & CHECKING

We now describe the IMUnit Runner, our tool for enforcing/checking schedules for IMUnit tests. It is implemented as a custom test runner for the JUnit testing framework. It executes each test for each IMUnit schedule and has two operation modes. In the active mode, it controls the thread scheduler to enforce an execution of the test to satisfy the given schedule. Note that this mode avoids the main problem of sleep-based tests, that of false positives and negatives due to the execution of unintended schedules. In the passive mode, our tool observes and checks the execution provided by the JVM against the given schedule.

Our runner is implemented using JavaMOP \cite{10, 24}, a high-performance runtime monitoring framework for Java. JavaMOP is generic in the property specification formalism and provides several such formalisms as logic plugins, including past-time linear temporal logic (PTLTL). Although our schedule language is a semantic fragment of PTLTL (Section 3), enforcing PTLTL specifications in their full generality on multithreaded programs is rather expensive.

Instead, we have developed a custom JavaMOP logic plugin for our current IMUnit schedule language from Figure 2. Since JavaMOP takes care of all the low-level instrumentation and monitor integration details (after a straightforward mapping of IMUnit events into JavaMOP events), we here only briefly discuss our new JavaMOP logic plugin. It takes as input an IMUnit schedule and generates as output a monitor written in pseudo-code; a Java shell for this language then turns the monitor into AspectJ code \cite{19}, which is further woven into the test program. In the active mode, the resulting monitor enforces the schedule by blocking the violating thread until all the conditions from the schedule are satisfied. In the passive mode, it simply prints an error when its corresponding schedule is violated.

A generated monitor for an IMUnit schedule observes the defined events. When an event \(e\) occurs, the monitor checks all the conditions that the event should satisfy according to the schedule, i.e., a Boolean combination of basic and block events (Figure 2). The status of each basic event is maintained by a Boolean variable which is true if the event occurred in the past. The status of a block event is checked as a conjunction of this variable and its thread’s blocked state. In the active mode, the thread of \(e\) will be blocked until this Boolean expression becomes true. If the condition contains any block event, periodic polling is used for checking thread states. Thus, IMUnit pauses threads only if their events are getting out of order for the schedule. Note that the user may have specified an infeasible schedule, which can cause a deadlock where all threads are paused. Our runner includes a low-overhead runtime deadlock detection that detects and reports deadlocks.

As an example, Figure 8 shows the active-mode monitor generated for the schedule in Figure 1(e). When events finishedAdd1 and startingTake2 occur, the monitor just sets the corresponding Boolean variables, as there is no condition for these events. For event startingTake1, it checks if there was an event finishedAdd1 in the past by checking the vari-
able `occurred_finishedAdd1`; if not, the thread will be blocked until `finishedAdd1` occurs. For event `startingAdd2`, in addition to checking the Boolean variable for `startingTake2`, it also checks whether the thread of the event `startingTake2` is blocked; if not, the thread of the event `startingAdd2` will be blocked until both conditions are satisfied.

### 6. EVALUATION

To evaluate the IMUnit contributions—schedule language, automated migration, and schedule execution—we analyzed over 200 sleep-based tests from several open-source projects. Table 1 lists the projects and the number of sleep-based tests that we manually migrated to IMUnit. We first describe our experience with the IMUnit language. We then present results of our inference techniques for migration. We finally discuss the test running time.

#### 6.1 Schedule Language

It is hard to quantitatively evaluate and compare languages, be it implementation or specification languages, including languages for specifying schedules. One metric we use is how *expressive* the language is, i.e., how many sleep-based tests can be expressed in IMUnit such that `sleeps can be removed altogether`. Note that IMUnit conceptually subsumes sleeps: sleeps and IMUnit events/schedules can coexist in the same test, and developers just need to make sleeps long enough to account for the IMUnit schedule enforcement. While every sleep-based test is trivially an IMUnit test, we are interested only in those tests where IMUnit allows removing sleeps altogether.

We were able to remove sleeps from 198 tests, in fact all sleeps from all but 4 tests. While the current version of IMUnit is highly expressive, we have to point out that we refined the IMUnit language based on the experience with migrating the sleep-based tests. When we encountered a case that could not be expressed in IMUnit, we considered how frequent the case is, and how much IMUnit would need to change to support it. For example, blocking events are very frequent, and supporting them required a minimal syntactic extension (adding events with square brackets) to the initial version of our language. However, some cases would require bigger changes but are not frequent enough to justify them. The primary example is events in a loop. IMUnit currently does not support the occurrence of an event more than once in a trace. We did find 4 tests that would require multiple event occurrences, but changing the language to support them (e.g., adding event counters or loop indices to events) would add a layer of complexity that is not justified by the small number of cases. However, as we apply IMUnit to more projects, and gain more experience, we expect that the language could grow in the future.

#### 6.2 Inference of Events and Schedules

To measure the effectiveness of our migration tool in inferring events/schedules, we calculated precision and recall of automatically inferred events/schedules with respect to the manually written events/schedules (i.e., the manual translations from sleep-based schedules). Calculating precision and recall requires comparing the automatically inferred and manually written events/schedules. For event inference, the input is a sleep-based test, and the output is a set of events. Our current comparison uses only the source-code location (line number) of the static events and not their name. For schedule inference, the input is a sleep-based test with *manually written* (not automatically inferred) events, and the output is a schedule. Our comparison considers all orderings from the automatically inferred and manually written schedules; two orderings match only if they have exactly the same both before and after events (including their name and type that can be basic or block). We performed the comparisons for all but 14 (discussed below) of our 198 tests. Table 2 shows for each project precision and recall values, averaged over the tests from that project.

Columns two and three show the results for event inference. In most cases, precision and recall are fairly high. We inspected the cases with lower precision and identified two causes for it. The first cause is due to our evaluation setup and not the algorithm itself. Namely, our current comparison requires the exact match of source-code locations. If the locations differ, the inferred event counts as a false negative, even if it was only a few lines from the manually written event, and even if those locations are equivalent with respect to the code. In the future, we plan to improve the setup by analyzing the code around the automatically inferred and manually written events to determine if their locations are equivalent. The second reason is that some tests use sleeps that are not relevant for the thread schedule (e.g., JBoss-Cache has such sleeps in the helper threads shared among tests, and Lucene has similar sleeps while interacting with the I/O library). These extra sleeps mislead our inference, which assumes that every sleep is relevant for the schedule and infers events for every sleep.

Columns four and five show the results for schedule inference. The results are even more impressive than for event inference, with precision and recall of over 75% in all cases. We identified two causes for misses. The first cause is that some threads can be independent. The algorithm always forms edges from all threads to the thread that invokes sleep method, but this should not be done for independent threads. In the future, we plan to consider an abstraction similar to regions (Figure 4) as a mechanism to detect inde-

---

### Table 1: Subject Programs Statistics

<table>
<thead>
<tr>
<th>Subject</th>
<th>Tests</th>
<th>Events</th>
<th>Orderings</th>
</tr>
</thead>
<tbody>
<tr>
<td>JBoss-Cache [18]</td>
<td>27</td>
<td>105</td>
<td>47</td>
</tr>
<tr>
<td>Lucene [6]</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Mina [7]</td>
<td>4</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Fost [5]</td>
<td>7</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>JSR-166 TCK [17]</td>
<td>149</td>
<td>977</td>
<td>277</td>
</tr>
<tr>
<td>Σ</td>
<td>198</td>
<td>774</td>
<td>585</td>
</tr>
</tbody>
</table>

---

Figure 8: Monitor for the schedule in Figure 1(c)
Table 2: Precision and Recall for Inference

<table>
<thead>
<tr>
<th>Subject</th>
<th>Original</th>
<th>CR</th>
<th>TR</th>
<th>LC</th>
<th>GeometricMean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collections</td>
<td>0.80</td>
<td>0.78</td>
<td>1.00</td>
<td>1.00</td>
<td>0.77</td>
</tr>
<tr>
<td>JBoss-Cache</td>
<td>0.76</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>0.76</td>
</tr>
<tr>
<td>Lucene</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Mina</td>
<td>0.82</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.82</td>
</tr>
<tr>
<td>Pool</td>
<td>0.90</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.90</td>
</tr>
<tr>
<td>Sysunit</td>
<td>0.76</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
<td>0.76</td>
</tr>
<tr>
<td>JSR-166 TCK</td>
<td>0.74</td>
<td>0.74</td>
<td>0.98</td>
<td>0.98</td>
<td>0.74</td>
</tr>
<tr>
<td>Overall</td>
<td>0.75</td>
<td>0.71</td>
<td>0.96</td>
<td>0.94</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Table 3: Numbers of Removed Orderings

<table>
<thead>
<tr>
<th>Subject</th>
<th>Number of Removed Orderings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collections</td>
<td>33</td>
</tr>
<tr>
<td>JBoss-Cache</td>
<td>19</td>
</tr>
<tr>
<td>Lucene</td>
<td>20</td>
</tr>
<tr>
<td>Mina</td>
<td>6</td>
</tr>
<tr>
<td>Pool</td>
<td>15</td>
</tr>
<tr>
<td>Sysunit</td>
<td>24</td>
</tr>
<tr>
<td>JSR-166 TCK</td>
<td>900</td>
</tr>
<tr>
<td>Overall</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 4: Test execution time. DDD - deadlock detection disabled; DDE - deadlock detection enabled
due to low confidence (LC). As it can be seen, the mini-
mization phase does not remove many orderings. However, it is important to remove the orderings it does remove. For example, without removing the cycle for JBoss-Cache, not only would inference have a lower precision but it would also produce a schedule that is unrealistic.

6.3 Performance

Table 4 shows the execution times of the 198 original, sleep-based tests and the corresponding IMUnit tests (for IMUnit, with deadlock detection both disabled and enabled). We ran the experiments on an Intel i7 2.67GHz laptop with 4GB memory, using Sun JVM 1.6.0_106. Our goal for IMU-

nit is to improve readability, modularity, and reliability of multithreaded unit tests, and we did not expect IMUnit ex-

ecution to be faster than sleep-based execution. In fact, one could expect IMUnit to be slower because of the addi-
tional code introduced by the instrumentation and the cost of controlling schedules. It came as a surprise that IMUnit is faster than sleep-based tests, on average 3.39x. Even with deadlock detection enabled, IMUnit was on average 2.76x faster. This result is with the sleep durations that the original tests had in the code.

We also compared the running time of IMUnit with Multi-

threadedTC on a common subset of JSR-166 TCK tests that the MultithreadedTC authors translated from sleep-based to tick-based [25]. For these 129 tests, MultithreadedTC was 1.30x faster than IMUnit. Although MultithreadedTC is somewhat faster, it has a higher migration cost and, in our view, produces test code that is harder to understand and modify than the IMUnit test code. Moreover, we were surprised to notice that running MultithreadedTC on these tests, translated by the MultithreadedTC authors, can result in some failures (albeit with a low probability), which means that these MultithreadedTC tests can be unreliable and lead to false positives in test runs.

7. RELATED WORK

Three areas of work are related to IMUnit: (1) unit test-
ing of multithreaded code, (2) enforcement of schedules, and (3) automated inference of specifications. We briefly discuss each of them. (1) ConAn [22, 23] and MultithreadedTC [26] introduce unit testing frameworks that allow developers to specify schedules to be used during the exe-
cution of multithreaded unit tests. However, the schedules in both frameworks are specified relative to a global clock (real time for ConAn and logic time for MultithreadedTC), which makes it difficult to reason about the schedules. Also, neither framework supports automated migration of sleep-
based tests. ConcJUnit [27] extends JUnit to propagate except-
ion assertion information from the main thread and also checks whether all child threads have finished at the end of a test method. ThreadControl [13] proposes a tool to ensure that assertions are performed without interference from other threads. (2) There has been some previous work on using formally specified sequencing constraints to verify multithreaded programs [28]. The specifications are over sync events with LTL-like constraints, and the verification ensures that the implementation is faithful to the specification. In contrast, IMUnit schedule specifications are used to enforce ordering between user-specified events while the system is tested. Carver and Tai [9] use deterministic replay for concurrent programs. LEAP [14] is a more recent system using a similar record-and-replay approach to reproduce bugs. In comparison, our enforcement and checking mechanism targets ensuring the user-specified schedule rather than replaying a previously observed execution. (3) Work on au-
tomated mining of specifications for programs [2, 3, 8, 21] is related to our automated inference of events and schedules. However, most existing work focuses on mining API usage patterns/rules in a single threaded scenario, while our tech-
niques mine the intention of sleep-based tests i.e. interesting events and event orderings across multiple threads.

8. CONCLUSIONS
Current approaches for unit testing of multithreaded code have issues with readability, modularity, reliability, and/or migration cost. We presented IMUnit, a novel approach that addresses these issues. IMUnit includes a new language that makes tests more readable and modular as it allows explicitly specifying schedules on the events during test execution. We described inference techniques and a tool to help in migrating sleep-based tests to IMUnit. We also described a tool that can reliably execute the specified schedule to avoid false positives/negatives. The promising results with IMUnit encourage us to further explore this approach, e.g., work on using formally specified sequencing constraints to verify concurrent programs. LEAP [14] is a more recent system using a similar record-and-replay approach to reproduce bugs. In comparison, our enforcement and checking mechanism targets ensuring the user-specified schedule rather than replaying a previously observed execution. (3) Work on au-
tomated mining of specifications for programs [2, 3, 8, 21] is related to our automated inference of events and schedules. However, most existing work focuses on mining API usage patterns/rules in a single threaded scenario, while our tech-
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pus Research Board Award, and by a Samsung SAIIT grant.

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