Dynamic Detection of Atomic-Set-Serializability Violations

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ABSTRACT

Previously we presented *atomic sets*, memory locations that share some consistency property, and *units of work*, code fragments that preserve consistency of atomic sets on which they are declared. We also proposed *atomic-set serializability* as a correctness criterion for concurrent programs, stating that units of work must be serializable for each atomic set. We showed that a set of problematic data access patterns characterize executions that are not atomic-set serializable. Our criterion subsumes data races (single-location atomic sets) and serializability (all locations in one set).

In this paper, we present a dynamic analysis for detecting violations of atomic-set serializability. The analysis can be implemented efficiently, and does not depend on any specific synchronization mechanism. We implemented the analysis and evaluated it on a suite of real programs and benchmarks. We found a number of known errors as well as several problems not previously reported.

Categories and Subject Descriptors

D.1.3 [**Programming Techniques**]: Concurrent Programming—*Parallel Programming*; D.2.5 [**Software Engineering**]: Testing and Debugging—*Tracing*; D.2.4 [**Software Engineering**]: Software/Program Verification—*Reliability*; F.3.2 [**Logics and Meaning of Programs**]: Semantics of Programming Languages—*Program Analysis*

General Terms

Algorithms, Experimentation, Measurement, Reliability

Keywords

Concurrent Object-Oriented Programming, Data Races, Atomicity, Serializability, Dynamic Analysis

1. INTRODUCTION

As multi-core systems are coming into general use, concurrency-related bugs are a more significant problem for mainstream programmers. The traditional correctness criterion for concurrent programs is the absence of data races, which occur when two threads access the same shared variable, one of the accesses is a write, and there is no synchronization between them. In general, data-race freedom does not guarantee the absence of concurrency-related bugs. Therefore, different types of errors and correctness criteria have been proposed, such as high-level data races [3], stale-value errors [4,9], and several definitions of serializability (or atomicity) [16,17,35,14,34,2,15,30,22,37,36]. According to these definitions of serializability, an execution of read and write events performed by a collection of threads is *serializable* if it is equivalent to a serial execution, in which each thread's transactions (or atomic sections) are executed in some serial order. These correctness criteria ignore relationships that may exist between shared memory locations, such as invariants and consistency properties, and therefore may not accurately reflect the intentions of the programmer for correct behavior, resulting in missed errors and false positives.

In previous work [32] we presented a correctness criterion for concurrent systems that takes such relationships into account, and developed an automated inference technique for placing synchronization correctly. The criterion is based on *atomic sets* of memory locations that must be updated atomically, and *units of work*, fragments of code that, when executed sequentially, preserve the consistency of the atomic sets that they are declared on. *Atomic-set serializability*, our correctness criterion, states that units of work must be serializable for each atomic set they operate on. Executions that are not atomic-set serializable can be characterized by a set of problematic data access patterns [32].

In this paper, we present a dynamic analysis for detecting violations of atomic-set serializability in executions of existing Java applications, by checking for the presence of the problematic data access patterns that we previously identified. Our approach provides the following benefits: First, atomic-set serializability is more flexible than existing correctness criteria because it can be used to check for traditional data races [27] (single-location atomic sets), standard notions of serializability (all locations in one atomic set), and a range of options in between. In particular, concurrency bugs such as stale-value errors [4,9] and inconsistent views [3] can be viewed as violations of atomic-set serializability. A second benefit of atomic-set serializability is that it permits certain non-problematic interleaving scenarios that are

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rejected by standard notions of serializability. Third, the problematic data access patterns we check [32] do not depend on specific synchronization constructs such as locks. Our analysis can therefore be used in settings where many existing approaches cannot, such as classes from the Java 5 `java.util.concurrent` library (e.g., `ArrayBlockingQueue` and `ConcurrentHashMap`) and lock-free algorithms. Fourth, since the analysis checks for problematic data access patterns, it only needs to consider fragments of the execution at a time. The entire execution is not needed to detect atomic-set serializability violations.

Key steps of our technique include:

- Using a simple static escape analysis [5] to detect fields of objects that may be accessed by multiple threads,
- For each shared field, maintaining a set of state machines that determine to what extent each problematic interleaving pattern has been matched during execution, and
- Instrumenting the code with yields to encourage problematic interleavings, a technique also known as *noise making* [6] (this last step is optional).

We implemented the analysis using the *Shrike* bytecode instrumentation component of the WALA program analysis infrastructure [1]. Our tool instruments the bytecodes of an application in order to: (i) intercept accesses to shared data, (ii) update the state machines accordingly, and (iii) maintain a dynamic call graph to determine the units of work to which these accesses belong. We show how the state machines can be represented efficiently, minimizing the perturbation caused by executing instrumentation code. For our prototype, we made the heuristic assumptions that method boundaries delineate units of work, and that there is one atomic set for (each instance of) each class, containing all the instance fields of that class.

We evaluated the tool on a number of benchmarks, including classes from the Java Collections Framework, and applications from the ConTest suite [12]. We found a significant number of violations, including known problems [12, 16], as well as problems not previously reported. Our tool may report false positives for a number of reasons, in particular when the determined units of work are too large, but we found that a significant percentage of the serializability violations (89%) reported by the tool are indeed harmful. On average over all benchmarks, the instrumentation inserted by our tool slows down program execution by a factor of 14, which is similar to, or better than the performance overhead incurred by other dynamic serializability violation detection tools [14, 36, 37, 38, 22]

In summary, the contributions of this paper are as follows:

- We present a dynamic analysis for detecting atomic-set serializability violations.
- We implemented the technique using the WALA infrastructure, and demonstrated its effectiveness on a number of Java benchmarks. We found both known bugs and problems not previously reported.
- Our approach is independent of the synchronization constructs employed, and can be applied in situations where many previous techniques cannot (e.g., lock-free algorithms and classes from `java.util.concurrent`).

2. BACKGROUND

In this section, we present our notion of atomic-set serializability and compare it to several existing notions of serializability and atomicity. Figure 1(a) shows a class `Account` that declares fields `checking` and `savings`, as well as a method `transfer()` that models the transfer of money from one to the other. Also shown is a class `Global` that declares a field `opCounter` that counts the number of transactions that have taken place. For the purposes of this example, we assume that the programmer intends the following behavior:

(1) Intermediate states in which the deposit to `checking` has taken place without the accompanying withdrawal from `savings` cannot be observed.

(2) Concurrent executions of `inc()` are allowed provided that variable `opCounter` is updated atomically.

To this end, `transfer()` and `inc()` are protected by separate locks, which is accomplished by making each of these methods `synchronized`. Figure 1(a) also shows a class `Test` that creates two threads `T1` and `T2` that execute `Account.transfer()` and `Global.inc()` concurrently.

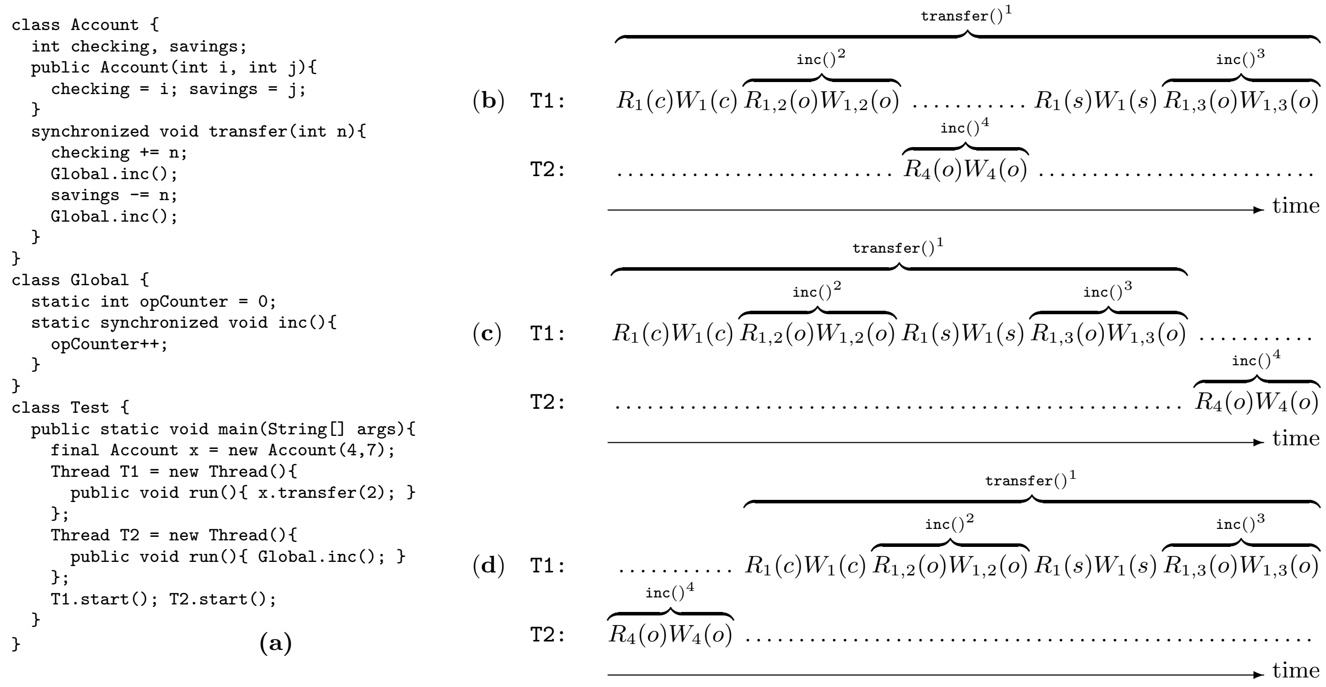
Figure 1(b) depicts an execution in which two threads, `T1` and `T2`, concurrently execute the `transfer()` and `inc()` methods, respectively. In particular, we show the various read (R) and write (W) events performed on fields `checking` (c), `savings` (s), and `opCounter` (o). For convenience, each method execution is labeled with a distinct number (1 through 4) in Figure 1(b), and each read/write event is labeled with a sequence of numbers corresponding to the methods on the call stack during its execution. For example, $R_1(c)$ indicates the read of field `checking` during the execution of `transfer()`, and $W_{1,2}(o)$ denotes the write to field `opCounter` during the first execution of `inc()` that was invoked from `transfer()`. Observe that, in Figure 1(b), the execution of `inc()` by `T2` occurs interleaved between that of the two calls to `inc()` by `T1`.

2.1 Atomicity/Serializability

We now discuss several notions of atomicity and serializability that have been defined previously.

Atomicity. Atomicity is a non-interference property in which a method or code block is classified as being *atomic* if its execution is not affected by and does not interfere with that of other threads. In this setting, the idea is to show that `checking` and `savings` are updated atomically by demonstrating that the `transfer()` method is an atomic section or a transaction.

Lipton's theory of reduction [21] is defined in terms of right-movers and left-movers. An action b is a *right-mover* if, for any execution where the action b performed by one thread is immediately followed by an action c performed by a concurrent thread, the actions b and c can be swapped without changing the resulting state [14]. *Left-movers* and *both-movers* are defined analogously. In this theory, lock acquires are right-movers, and lock releases are left-movers. Accesses to shared variables that are consistently protected by some lock are both-movers, and accesses to variables that are not consistently protected by some lock are non-movers. The pattern consisting of a sequence of right movers, followed by at most one non-mover, followed by a sequence of left movers, can be reduced to an equivalent serial execution. However, method `transfer()` corresponds to the



```
class Account {
  int checking, savings;
  public Account(int i, int j){
    checking = i; savings = j;
  }
  synchronized void transfer(int n){
    checking += n;
    Global.inc();
    savings -= n;
    Global.inc();
  }
}
class Global {
  static int opCounter = 0;
  static synchronized void inc(){
    opCounter++;
  }
}
class Test {
  public static void main(String[] args){
    final Account x = new Account(4,7);
    Thread T1 = new Thread(){
      public void run(){ x.transfer(2); }
    };
    Thread T2 = new Thread(){
      public void run(){ Global.inc(); }
    };
    T1.start(); T2.start();
  }
}
```

(a)
(b)
T1: $\overbrace{R_1(c)W_1(c)\,\overbrace{R_{1,2}(o)W_{1,2}(o)}^{\texttt{inc()}^2}\,\ldots\ldots\ldots\,R_1(s)W_1(s)\,\overbrace{R_{1,3}(o)W_{1,3}(o)}^{\texttt{inc()}^3}}^{\texttt{transfer()}^1}$
T2: $\ldots\ldots\ldots\,\overbrace{R_4(o)W_4(o)}^{\texttt{inc()}^4}\,\ldots\ldots\ldots$
time
(c)
T1: $\overbrace{R_1(c)W_1(c)\,\overbrace{R_{1,2}(o)W_{1,2}(o)}^{\texttt{inc()}^2}\,R_1(s)W_1(s)\,\overbrace{R_{1,3}(o)W_{1,3}(o)}^{\texttt{inc()}^3}}^{\texttt{transfer()}^1}\,\ldots\ldots\ldots$
T2: $\ldots\ldots\ldots\,\overbrace{R_4(o)W_4(o)}^{\texttt{inc()}^4}$
time
(d)
T1: $\ldots\ldots\ldots\,\overbrace{R_1(c)W_1(c)\,\overbrace{R_{1,2}(o)W_{1,2}(o)}^{\texttt{inc()}^2}\,R_1(s)W_1(s)\,\overbrace{R_{1,3}(o)W_{1,3}(o)}^{\texttt{inc()}^3}}^{\texttt{transfer()}^1}$
T2: $\overbrace{R_4(o)W_4(o)}^{\texttt{inc()}^4}\,\ldots\ldots\ldots$
time

Figure 1: **(a)** Example program. **(b)**–**(d)** Three different thread executions.

sequence: a right-mover (lock acquire at the beginning of `transfer()`^{1}), 2 both-movers (read/write to field `checking`), a right mover (lock acquire at the beginning of `inc()`^{2}), 2 both-movers (read/write to `opCounter`), a left mover (lock release at the end of `inc()`^{2}), 2 both-movers (read/write to `savings`), a right mover (lock acquire at the beginning of `inc()`^{3}), 2 both-movers (read/write to `opCounter`), a left mover (lock release at the end of `inc()`^{3}), and a left-mover (lock release at the end of `transfer()`^{1}). Hence, according to Lipton's theory, the method `transfer()` of Figure 1 is not atomic. In other words, the theory cannot show that the transfer from `checking` to `savings` is performed without exposing intermediate states to other threads.

Conflict-serializability. Two events that are executed by different threads are a *conflicting pair* if they operate on the same location and one of them is a write. Two executions are *conflict-equivalent* [7,36] if and only if they contain the same events, and for each pair of conflicting events, the two events appear in the same order. An execution is *conflict-serializable* if and only if it is conflict-equivalent to a serial execution. For the threads `T1` and `T2` in our example, two serial executions exist, as shown in Figure 1(c) and (d). The execution of Figure 1(b) is not conflict-equivalent to either of these and thus not conflict-serializable, because:

- The pairs of conflicting events include: $(R_{1,2}(o)$,$W_4(o))$, $(R_{1,3}(o)$,$W_4(o))$, $(W_{1,2}(o)$,$R_4(o))$, and $(W_{1,3}(o)$,$R_4(o))$.
- In order for execution (b) to be conflict-equivalent to serial execution (c), both $R_{1,2}(o)$ and $R_{1,3}(o)$ must occur before $W_4(o)$, and both $W_{1,2}(o)$ and $W_{1,3}(o)$ must occur before $R_4(o)$. This is not the case.
- In order for execution (b) to be conflict-equivalent to serial execution (d), both $R_{1,2}(o)$ and $R_{1,3}(o)$ must occur after $W_4(o)$, and both $W_{1,2}(o)$ and $W_{1,3}(o)$ must occur after $R_4(o)$. This is not the case either.

View-serializability. Two executions are *view-equivalent* [7, 36] if they contain the same events, if each read operation reads the result of the same write operation in both executions, and both executions must have the same final write for any location. An execution is *view-serializable* if it is view-equivalent to a serial execution. It is easy to see that execution (b) is not view-equivalent to serial execution (c), because there, $R_4(o)$ reads from $W_{1,3}(o)$, whereas in execution (b), it reads from $W_{1,2}(o)$. Likewise, execution (b) is not view-equivalent to serial execution (d) because there, $R_{1,3}(o)$ reads from $W_{1,2}(o)$, whereas in execution (b), it reads from $W_4(o)$. Hence, execution (b) is not view-serializable. View- and conflict-serializability differ only on how they treat *blind writes*, i.e., when a write performed by one thread is interleaved between writes to the same location by another thread. Conflict-serializability implies view-serializability [7, 36].

2.2 Atomic-set serializability

The existing notions of atomicity, conflict-serializability and view-serializability reject the non-problematic execution of Figure 1(b) because these notions do not take into account the relationships that exist between memory locations. Atomic-set serializability assumes the existence of programmer-specified *atomic sets* of locations that must be updated atomically, and *units of work* on an atomic set, code fragments that, when executed sequentially, preserve consistency of the atomic set. Given assumption (1) stated above, we assume that `checking` and `savings` form an atomic set S_1, and that `transfer()`^{1} is a unit of work on S_1. Moreover, from assumption (2) stated above, we infer that `opCounter` is another atomic set S_2 and `Global.inc()`^{2}, `Global.inc()`^{3}, and `Global.inc()`^{4} are units of work on S_2. Atomic-set serializability is equivalent to conflict serializability *after projecting the original execution onto each atomic set*, i.e., only events from one atomic set are included when determining conflicts.

The projection of execution (b) onto atomic set S_1 contains the following sequence of events:

$$R_1(c)\ W_1(c)\ R_1(s)\ W_1(s)$$

This is trivially serial, because the events from only one thread are included. Furthermore, the projection of execution (b) onto atomic set S_2 is:

$$R_{1,2}(o)\ W_{1,2}(o)\ R_4(o)\ W_4(o)\ R_{1,3}(o)\ W_{1,3}(o)$$

which is also serial because the events of units of work `Global.inc()`^{2}, `Global.inc()`^{3}, and `Global.inc()`^{4} are not interleaved. Therefore, execution (b) is atomic-set serializable.

In conclusion, by taking the relationships between shared memory locations (atomic sets) into account, atomic-set serializability provides a more fine-grained correctness criterion for concurrent systems than the traditional notions of Lipton-style atomicity, conflict-serializability, and view-serializability. In practice, conflict- or view-serializability and atomicity would classify execution (b) as having a bug, but atomic-set serializability correctly reveals that there is none. On the other hand, if a coarser granularity of data is desired or available, all three locations can be placed in a single atomic set, in which case our method would revert to the traditional notion of conflict-serializability.

3. ALGORITHM

Let $\mathcal{L}$ be the set of all memory locations. A subset $L \subseteq \mathcal{L}$ is an *atomic set*, indicating that there *exists* a consistency property between those locations. For two locations l and l', we write *sameSet*(l, l') to indicate that l and l' are in the same atomic set. An *event* is a read $R(l)$ or a write $W(l)$ to a memory location $l \in L$, for some atomic set L. We assume that each access to a single memory location is uninterrupted. Given an event e, the notation *loc*(e) denotes the location accessed by e.

A unit of work u is a sequence of events, and is *declared on* a set of atomic sets. Let $\mathcal{U}$ be the set of all units of work. We write *sets*(u) for the set of atomic sets corresponding to u. We say that $\bigcup_{L \in sets(u)} L$ is the *dynamic atomic set* of u. Units of work may be nested, and we write $u \leftarrow u'$ to indicate that u' is nested in u. Units of work form a forest via the $\leftarrow$ relation.

An access to a location $l \in L$ appearing in unit of work u *belongs* to the top-most (with respect to the $\leftarrow$ forest) unit of work u' within u such that $L \in sets(u')$. The notation $R_u(l)$ denotes a read belonging to u, and similarly for writes. So if a method `foo` calls another method `bar`, where both are declared units of work for the atomic set L_1 and `bar` reads a location $l \in L_1$ in `bar`, then this read belongs to `foo`, as `foo` $\leftarrow$ `bar`. Given an event e, the notation *unit*(e) denotes the unit of work of e.

A *thread* is a sequence of units of work. The notation *thread*(u) denotes the thread corresponding to u. An *execution* is a sequence of events from one or more threads. Given an execution E and an atomic set L, the *projection of E on L* is an execution that has all events on L in E in the same order, and only those events.

A *data access pattern* is a sequence of events that originate from two or more threads. For example, $R_u(l)\ W_{u'}(l)\ W_u(l)$ is a data access pattern where unit of work u first reads l, then another unit of work u' performs a write, followed by a write by u. An execution *is in accordance with* a data access pattern if it contains the events in the data access pattern, and these appear in the same order.

	Data Access Pattern	Description
1.	$R_u(l)\ W_{u'}(l)\ W_u(l)$	Value read is stale by the time an update is made in u.
2.	$R_u(l)\ W_{u'}(l)\ R_u(l)$	Two reads of the same location yield different values in u.
3.	$W_u(l)\ R_{u'}(l)\ W_u(l)$	An intermediate state is observed by u'.
4.	$W_u(l)\ W_{u'}(l)\ R_u(l)$	Value read is not the same as the one written last in u.
5.	$W_u(l)\ W_{u'}(l)\ W_u(l)$	Value written by u' is lost.
6.	$W_u(l_1)\ W_{u'}(l_1)\ W_{u'}(l_2)\ W_u(l_2)$	Memory is left in an inconsistent state.
7.	$W_u(l_1)\ W_{u'}(l_2)\ W_{u'}(l_1)\ W_u(l_2)$	same as above.
8.	$W_u(l_1)\ W_{u'}(l_2)\ W_u(l_2)\ W_{u'}(l_1)$	same as above.
9.	$W_u(l_1)\ R_{u'}(l_1)\ R_{u'}(l_2)\ W_u(l_2)$	State observed is inconsistent.
10.	$W_u(l_1)\ R_{u'}(l_2)\ R_{u'}(l_1)\ W_u(l_2)$	same as above.
11.	$R_u(l_1)\ W_{u'}(l_1)\ W_{u'}(l_2)\ R_u(l_2)$	same as above.
12.	$R_u(l_1)\ W_{u'}(l_2)\ W_{u'}(l_1)\ R_u(l_2)$	same as above.
13.	$R_u(l_1)\ W_{u'}(l_2)\ R_u(l_2)\ W_{u'}(l_1)$	same as above.
14.	$W_u(l_1)\ R_{u'}(l_2)\ W_u(l_2)\ R_{u'}(l_1)$	same as above.

Figure 2: Problematic Data Access Patterns.

Figure 2 shows a number of problematic data access patterns (taken from [32] where 3 patterns were pairwise symmetric) in which data may be read or written inconsistently. Definition 1 below defines a data race in terms of the problematic data access patterns of Figure 2.

Definition 1 (data race). *Let L be an atomic set, $l_1, l_2 \in L$, l one of l_1 or l_2, and u and u' two units of work for L, such that* thread$(u) \neq$ thread(u')*. An execution has a data race if it is in accordance with one of the data access patterns of Figure 2.*

As an example, consider Figure 3(a) which shows two threads T_1 and T_2 with associated units of work $u1$ and $u2$, respectively, which operate on two shared locations, x and y. Figure 3(b) shows an execution in which the following sequence of operations occurs: First (i) T_1 executes its conditional expression, then (ii) T_2 executes its conditional expression, then (iii) T_2 executes the body of its if-statement, and finally (iv) T_1 executes the body of its if-statement. An occurrence of problematic interleaving pattern 11 is highlighted in Figure 3(b) using underlining.

3.1 Race Automata

Our approach for detecting atomic-set serializability violations relies on the construction of a set of *race automata* that are used to match the problematic data access patterns

```
                            x=3; y=2;
                            fork;
//Unit of Work u1 (T1):                         //Unit of Work u2 (T2):
if (x+y+3<10){                                  if (x+y+4<10){
  x+=3                                            y+=4
  y=2;                                            x=1;
}                                               }
```

(a)

$R_{u1}(x), \underline{R_{u1}(y)}, R_{u2}(x), R_{u2}(y), R_{u2}(y), \underline{W_{u2}(y), W_{u2}(x), R_{u1}(x)},$
$W_{u1}(x), W_{u1}(y)$

(b)

Figure 3: **(a)** Example threads. **(b)** An execution that exhibits an occurrence of problematic data access pattern 11 (shown underlined). The variables u, u', l_1, and l_2 in the pattern are bound to $u1$, $u2$, y, and x, respectively.

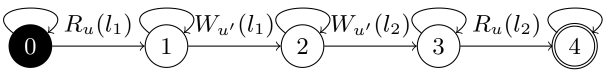


Figure 4: Automaton to detect pattern 11.

of Figure 2 during program execution. Each race automaton has an initial state in which no event of the pattern has been matched yet, an accept state in which the entire pattern has been matched, and a number of intermediate states. Transitions between states are labeled with the events of the pattern under consideration, and each state has a self-transition for all other events. Reaching an accept state results in our tool issuing a warning. For example, the race automaton depicted in Figure 4 detects the problematic data access pattern corresponding to pattern 11 of Figure 2. To detect pattern 11 in the execution of Figure 3(b), $u1$ and $u2$ in the execution are bound to u and u' in the pattern, and locations y and x are bound to pattern variables l_1 and l_2, respectively. The automaton stays in state 0 after the first event $R_{u1}(x)$ in the execution of Figure 3(b), which does not match the first event in the pattern, and transitions to state 1 when it observes the second event, $R_{u1}(y)$. The next three events do not change the state, but then $W_{u2}(y)$ causes a transition to state 2. The next two events, $W_{u2}(x)$ and $R_{u1}(x)$ cause transitions to states 3 and 4, respectively, at which point the pattern is fully recognized, and a warning is issued.

Figure 2 shows that there are 14 patterns that need to be matched simultaneously. In addition, for each pair of variables l and l', there are two ways of matching them against two program locations, and likewise, there are two ways of matching the units of work u and u' against observed units of work in the execution. Therefore, we need to construct the 14 automata discussed above for each tuple $t \in \mathcal{U} \times \mathcal{U} \times \mathcal{L} \times \mathcal{L}$. The corresponding automata $(Q^i, \Sigma, \delta^i, S_0^i, F^i)$ are defined as follows: For each scenario i, Q^i contains states S_j^i representing that exactly j events of the scenario have already been detected, including the accept state F^i. The input alphabet Σ is the union of all traceable events

$$\Sigma = \bigcup_{u \in \mathcal{U}, l \in \mathcal{L}} \{R_u(l), W_u(l)\},$$

and the transition function $\delta^i : Q^i \times \Sigma \rightarrow Q^i$ is defined as follows:

$$\delta^i(S_j^i, e) = \begin{cases} S_{j+1}^i & \text{if } e \text{ is the } j^{\text{th}} \text{ event of scenario } i \\ S_j^i & \text{otherwise} \end{cases}$$

Conceptually, when we process an event e, all automata for all tuples $q \in \{(u1, u2, l1, l2) \mid \mathit{unit}(e) \in \{u1, u2\} \wedge \mathit{thread}(u1) \neq \mathit{thread}(u2) \wedge \mathit{loc}(e) \in \{l1, l2\}\}$ need to be updated. While this may require significant space and processing time in principle, the implementation techniques presented below make this approach quite feasible in practice.

3.2 Efficient Representation of Race Automata

For each tuple $t \in \mathcal{U} \times \mathcal{U} \times \mathcal{L} \times \mathcal{L}$, there are 14 race automata that need to be represented. Since each automaton has at most 5 states, we can represent the dynamic state of an automaton with 3 bits. For each tuple t, we use a `long` value to capture the state of all 14 corresponding automata (42 bits). Representing automata for all tuples in a program is prohibitive. So we only capture automata for the tuples that actually appear during the dynamic analysis and delete them when they are no longer needed.

We use the notation $(u, *, l, *)$ to represent the set of tuples $\bigcup_{u' \in \mathcal{U}, l' \in \mathcal{L}} (u, u', l, l')$. Likewise, the notation $(u, u', l, *)$ denotes the set of tuples $\bigcup_{l' \in \mathcal{L}} (u, u', l, l')$. We call such tuples *summary tuples*. We define a map *Bits* which takes a (summary) tuple and maps it to a bitset containing the dynamic state of all 14 corresponding race automata. We use the shorthand notation *Bits* to denote the range of the map.

Procedures for manipulating bitsets are the following. There are two ways of creating a new bitset. *createBits*$(u, *, l, *)$ creates a new bitset, initializes it to all zeroes, and associates it to tuple $(u, *, l, *)$ in map *Bits*. *copyBits*(u, u', l, l', b) creates a new bitset, copies the contents of the bitset b into it, and associates it to tuple (u, u', l, l') in map *Bits*. Procedure *deleteBits*(u, u', l, l') deletes the bitset corresponding to tuple (u, u', l, l') in *Bits*. Function *Bits*(u, u', l, l') returns the bitset, if any, associated with (u, u', l, l') in map *Bits*. Procedure *updateBits*(b, e) takes a bitset b and an event e and updates the states of the automata represented by b according to e. Finally, *reportBits*(u, u', l, l') checks if any of the automata associated with (u, u', l, l') have reached an accept state and reports them to the user.

Figure 5 shows pseudocode for our algorithm. The algorithm consists of intercepting events in the execution and for each event $e = (u, l)$: (i) creating automata if necessary (*Create*(e)); and (ii) updating existing automata (*Update*(e)). At the end of the updates, any automata that have reached an accept state are reported to the user. *GC*() runs regularly to clean up unnecessary bitsets.

Procedure *Create*(e) works as follows: If e is a first occurrence of an event in u on l, then a new bitset is created for tuple summary $(u, *, l, *)$. The rest of the body of *Create*(e) deals with refining tuple summaries and creating new bitsets based on their corresponding ones. For example, if $b =$ *Bits*$(u', *, l', *)$ such that u and u' are from different threads, and l and l' are different memory locations from the same atomic set, then event e causes the creation of a new bitset for tuple (u', u, l', l). The state of b is copied into this new bitset, which is then associated with tuple (u', u, l', l) in map *Bits*.

Procedure *Update*(e), where e is an event of u on l, goes through the set of bitsets and updates those having u as one of their units of work, and l as one of their memory locations. Finally, procedure *GC*() works as follows: The set $\mathcal{T}$ represents the set of units of work whose execution has terminated, and is initially empty. Upon termination of

```
Algorithm
    $\mathcal{T} := \varnothing$
    upon each event $e$
        Create($e$)
        Update($e$)
        GC($e$)

Create($e$)
    let $u = unit(e)$ and $l = loc(e)$
    if $e$ is a first occurrence of an event in $u$ on $l$
        $createBits(u, *, l, *)$
    for each $b$ in $Bits$
        if ($b = Bits(u', *, l', *)$ or $b = Bits(u', u, l', *)$
                s.t. $thread(u) \neq thread(u')$
                and $l \neq l'$ and $sameSet(l, l')$)
                    $copyBits(u', u, l', l, b)$
        if ($b = Bits(u', *, l', *)$ s.t. $thread(u) \neq thread(u')$
                and $l = l'$)
                    $copyBits(u', u, l, *, b)$
        if ($b = Bits(u, u', l', *)$ s.t. $l \neq l'$ and $sameSet(l, l')$)
                    $copyBits(u, u', l', l, b)$

Update($e$)
    let $u = unit(e)$ and $l = loc(e)$
    for each $b$ in $Bits$
        if ($b = Bits(u1, u2, l1, l2)$ s.t. $u \in \{u1, u2\}$, $l \in \{l1, l2\}$
            or $b = Bits(u, *, l, *)$
            or $b = Bits(u1, u2, l, *)$ s.t. $u \in \{u1, u2\}$)
                $updateBits(b, e)$

GC($e$)
    if ($e$ terminates unit of work $u$)
        $\mathcal{T} := \mathcal{T} \cup u$
        $deleteBits(u, *, l, *)$
        for each $b$ in $\mathcal{B}$ s.t. $b = Bits(u, u', l, *)$
                        or $b = Bits(u, u', l, l')$
            if ($\{u, u'\} \subseteq \mathcal{T}$)
                $reportBits(u, u', l, *)$
                $deleteBits(u, u', l, *)$
                $reportBits(u, u', l, l')$
                $deleteBits(u, u', l, l')$
```

Figure 5: Algorithm for detecting atomic-set serializability violations.

each unit of work u, the procedure adds u to $\mathcal{T}$, and deletes the bitset. It also goes through all bitsets to find those corresponding to tuples with both units of work terminated and deletes them as well, reporting any detected patterns. Note that the bitset corresponding to a summary tuple could reach a final state (detecting one of patterns 1 through 5).

4. IMPLEMENTATION

In this section, we present details of our implementation of the algorithm presented in Section 3.1. We first present our choice of defaults for atomic sets and units of work (Section 4.1). We then discuss how we perform instrumentation to capture events (Section 4.2).

4.1 Defaults for Atomic Sets and Units of Work

We assume that all non-`final`, non-`volatile` instance fields of a class (including inherited instance members) are members of a single per-instance atomic set. All accessible non-`static` `public` and `protected` methods in that class, and its superclasses are considered initial units of work declared on these atomic sets. All its non-`final`, non-`volatile` `static` fields form another per-class atomic set with all non-private methods of the class as initial units of work.

Our previous work states a crucial condition: We assume that each access to a member of an atomic set is done within a unit of work declared on that atomic set [32, Section 4.1]. In order to fulfill this requirement, we assume that a method containing a direct access to a field is an additional unit of work for the atomic set the field belongs to.

4.2 Program Instrumentation

We instrument the program to intercept data accesses and to determine what unit of work each access belongs to. To this end, we use the Shrike bytecode instrumentor of the WALA program analysis infrastructure [1].

Before instrumentation, our tool performs a simple static escape analysis [5] to determine possibly shared fields. This analysis determines a conservative set of possibly-escaping fields by computing the set of all types that are transitively reachable from a `static` field or are passed to a thread constructor[1]. We instrument all non-`final` and non-`volatile` fields of such types. In addition, we instrument accesses to arrays, treating each array element as a separate location.

Our tool uses a concurrent, non-blocking queue similar to [19, Section 15.4.2] to store the events of different threads, which guarantees that no user-thread has to wait because of trace collection. Furthermore it timestamps the events in a sequential order which is a prerequisite for detecting the problematic interleaving scenarios. We chose a non-blocking queue to keep the *probe effect* [18] (i.e., changes to the system's behavior due to observation) as low as possible, and since, under contention, a blocking queue will show degraded performance due to context-switching overhead and scheduling delays.

Since a field access itself and the recording of that access do not happen atomically, the scheduler could activate another thread between the actual field access and its interception. Nevertheless, the execution obtained is always a valid execution of the program, i.e., it might happen with a possible scheduling. This is because the recording of an event takes place in the same thread as the access itself, and there is no synchronization between them. Hence, any synchronization that applies to the access also applies to the recording. Thus, the intercepted execution must be consistent with the program's synchronization scheme, so it is a feasible execution.

To determine what unit of work each access belongs to, we keep track of a *dynamic call graph*, which is essentially the stack trace for each called method. An access to a location in an atomic set belongs to the top-most unit of work declared on that atomic set. To maintain the dynamic call graph, we instrument method entry and exit points. To detect library callbacks, we also instrument invocation points in the program and compare the invocation's target to the invoked method at the entry. If the target and the called method do not match, a callback has been detected, in which case we start a new unit of work in the called method.

As an option, our instrumentation adds yields at certain points in the program to achieve more interleavings, a tech-

[1] This case covers both explicit constructor parameters and uses within thread or runnable methods of state defined in an enclosing scope.

nique is called *noise making*. Ben-Asher et al. found that, with a more elaborate noise strategy, the probability of producing a bug increases considerably [6].

5. EVALUATION

We evaluated our analysis on a suite of benchmarks: programs from the ConTest suite [12, 11], the W3C's Java-based Web server Jigsaw (version 2.2.5), and classes from the Java Collections Framework. The ConTest benchmark suite [12, 11] consists of short programs of up to 420 lines of code created by students of a class on concurrency. They contain a variety of known non-trivial concurrency-related bugs. Jigsaw is a large program and we analyzed all 939 classes of the main package, omitting other loaded libraries. For the Java Collections Framework, we chose representatives of different synchronization patterns: `java.util.Vector`, a fully synchronized class containing known bugs; `java.util.ArrayList` wrapped in a synchronization wrapper[2]; and classes containing new Java 5 synchronization primitives such as atomic variables and explicit locks like `java.util.concurrent.ArrayBlockingQueue`. For each collection class analyzed, we generated a test harness that randomly calls its methods 10000 times with appropriate parameters in each of ten threads. Noise making was crucial when executing on a single core processor, but with multicores our exhaustive noise insertion exposed about the same number of races as without (which is consistent with [6]).

Table 1 shows the results of our analysis, where each benchmark was at most executed twice. We evaluated each error report from our tool manually to determine benign (Table 2) and malign violations. For evaluation purposes, we followed the strict semantics of the new Java memory model (JMM) as described in [20]. We classified all access to shared data (in non-`volatile` variables) without proper synchronization as a malign bug. We also classified the double-checked-locking anti-pattern as broken when we found it on non-`volatile` variables. There are, however, executions that exhibit a problematic data access pattern where the code does not exhibit erroneous behavior, largely due to our heuristic choice for units of work. These violations were classified as benign. Note that bugs in the program may manifest themselves as several problematic data access patterns, so there are fewer bugs than serializability violations.

Nr	1	2	3	4	5	6	7	8	9	10	11	12	13	14
6	7	7	7	7	7	4	4	4	2	2	2	2	2	2
12	0	3	2	0	0	0	0	0	0	0	1	1	1	0
18	2	2	0	0	0	0	0	0	0	0	0	0	0	0

Table 2: Number of benign violations for each data access pattern, other programs displayed no benign patterns

The column "Specified bug found" in Table 1 applies to the documented bugs in the ConTest suite only. It indicates whether the (intended) bug of that program was found by our tool. The column "SF" in Table 1 shows the slowdown factor of our analysis compared to non-instrumented execution. The instrumentation itself imposes a slowdown of about 2-4x. Our slowdown factors are comparable with other dynamic analyses [14, 36, 37, 38, 22]. Indeed, our average slowdown of 14x is faster than these works, which report average slowdown factors from 25x [22] to more than 200x [36, block-based]. Regarding our false positive rate of about 11%, our tool improves significantly over previous approaches: With Atomizer [14] 93% of all found serializability violations were no actual bugs, while the best rate was achieved by algorithms in Wang's work [36] with about 67% false positives. The column "$|\mathcal{B}|$" shows the maximum number of quadruples in the algorithm of Figure 5 before each call to $GC()$, and the column "Stack depth" shows the average call stack depth of intercepted events. No direct correlation between these two numbers and the program size or slowdown factor is evident.

For the ConTest benchmarks, our tool found all the specified bugs for all but 4 programs. For 3 benchmarks, our tool missed the violations due to the heuristics for units of work: For `MergeSort`, `AllocationVector` and `Shop` the actual unit of work was in an unsynchronized method, that called two synchronized methods of another object. Our tool groups only calls to the same target object into one unit of work, unless the calling method accesses fields of the called method's target directly. To circumvent this problem, future work needs to offer an annotation mechanism for *unit-for* constructs as presented in our previous work [32]. Atomicity checkers like [36] would miss those three bugs, too, as the transaction boundaries are determined according to synchronized blocks, but the bug in these programs is the fact that synchronization in the caller is missing. Our heuristics miss the bug in `FileWriter` due to its curious data access pattern: units of work span multiple threads. Our heuristics assume that this is not the case.

In Jigsaw, we found a bug in `httpd`: its field `finishing` is updated in the synchronized method `shutdown` (invoked by some other thread of class `org.w3c.jigsaw.daemon.ServerShutdownHook`), but read in `run` without synchronization. To make this code safe, the new JMM requires that this field be `volatile`, or else the program might never terminate on a multi-core processor. In addition, we found violations that were due to a possible view inconsistency in a synchronized method containing a `wait()`. We did not find the bug described in [36] in the version we analyzed (2.2.5). When manually inspecting the source code we found that the corresponding code sections are synchronized.

Previous work on atomicity [36] reported a serializability violation in the 1.4 version of `Vector`: The constructor with a collection argument does not synchronize on the collection parameter. We found this bug still present in Java 5. In `java.util.concurrent.ArrayBlockingQueue` we discovered a similar bug in the `addAll(Collection)` method. The JavaDoc of `AbstractBlockingQueue`, which it inherits, states that the "behavior of this operation is undefined if the specified [parameter] collection is modified while the operation is in progress". We discovered this bug together with violations for the other "bulk" methods that take parameters of type `Collection`. Manual inspection found that if the parameter collection is properly synchronized, the other bulk methods' violations are benign.

We also instrumented `ArrayLists` in a synchronization wrapper (`Collections.synchronizedList(...)`). `ArrayList`'s constructors resemble the code of `Vector`, so

[2] This synchronization wrapper is an object of a class that implements the `List` interface. All `public` methods in this class, except those dealing with iterators, are `synchronized` and delegate to the corresponding methods in an encapsulated `ArrayList` object. See method `java.util.Collections.synchronizedList()`.

			Pattern														Specified	SF	$\lvert\mathcal{B}\rvert$	Stack
Nr	Program	LOC	1	2	3	4	5	6	7	8	9	10	11	12	13	14	bug found			depth
1	account	155	1	0	0	0	0	0	0	0	0	0	0	0	0	0	Y	3.1	4K	2.6
2	airlinesTckts	95	1	2	0	2	0	0	1	0	0	1	0	1	0	0	Y	6.2	20K	3.1
3	AllocationV	286	0	0	0	0	0	0	0	0	0	0	0	0	0	0	N	25	10K	2.61
4	bubbleSort	362	1	1	2	1	1	1	0	0	2	1	2	1	1	1	Y	2.1	4K	2.8
5	BubbleSort2	130	1	1	1	0	0	0	0	0	1	0	1	1	1	0	Y	14	1K	2.5
6	BufWriter	255	0	2	2	0	3	0	7	8	2	2	2	2	2	2	Y	1.3	357	2.0
7	Critical	68	0	0	1	1	1	0	0	0	0	0	0	0	0	0	Y	1.7	10	2.1
8	DCL	183	0	1	0	0	0	0	0	0	1	0	1	0	0	0	Y	26	275	2.2
9	FileWriter	325	0	0	0	0	0	0	0	0	0	0	0	0	0	0	N	1.3	2K	
10	LinkedList	416	1	0	0	0	0	0	0	0	0	0	0	0	0	0	Y	1.6	32	3.6
11	Lottery	359	0	2	0	3	0	0	0	0	0	0	0	0	0	0	Y	6.7	205K	2.2
12	Manager	188	1	1	0	1	1	1	1	1	3	3	1	1	1	2	Y	1.7	6	2.9
13	MergeSort	375	0	0	0	0	0	0	0	0	0	0	0	0	0	0	N	4.0	154	5.0
14	MergeSort2	257	1	1	0	1	0	0	0	0	0	0	0	0	0	0	Y	12	6k	4.8
15	PingPong	272	2	1	1	0	1	0	0	0	0	0	0	0	0	0	Y	3.1	221	4.0
16	Shop	273	0	2	0	0	0	0	0	0	0	0	0	0	0	0	N	7.0	2k	3.2
17	Sun's Accnt	144	1	0	0	0	0	0	0	0	0	0	0	0	0	0	Y	4.3	40k	3.5
18	Jigsaw	142K	0	1	0	0	0	0	0	0	0	0	0	0	0	0	N/A	7.5	11K	15.4
19	Vector	2636	0	4	0	0	0	0	0	0	0	0	8	1	0	0	N/A	43	1K	5.0
20	ArrayL. (syn)	2266	0	1	0	0	0	0	0	0	0	3	3	1	3	2	N/A	40	365	5.2
21	ArrayBlQ.	1576	0	1	8	0	2	1	2	0	1	5	6	9	1	0	N/A	39	406	5.6
22	LinkedBlQ.	1620	4	4	8	4	6	3	1	0	4	2	0	0	0	0	N/A	45	274	5.7
23	DelayQueue	1961	3	5	9	4	3	9	8	6	2	1	1	1	6	6	N/A	33	728	6.8

Table 1: For each benchmark, the table indicates the number of malign violations for each data access pattern, as well as whether the specified bug is found (ConTest suite only), the slowdown factor, max. number of tuples, avg. call stack depth.

our tool reported the same serializability problem as for the constructor of `Vector` with a collection parameter. Apart from that, we found all bulk methods (except for `addAll()`, which is redefined in `ArrayList`) unserializable when the parameter collection is modified concurrently. The reason for this is that the synchronization wrappers do not provide a synchronized version of the `iterator()` method[3] but returns an iterator to the backing (unsynchronized) collection.

For `LinkedBlockingQueue` we found a serializability violation when the inherited `addAll(Collection)` is executed concurrently with the `clear()` method. We also found several problematic data access patterns involving the `last` field. If the queue is cleared while `addAll()` is being executed the resulting state does not correspond to any serial execution of the two methods. The documentation for this class confirms that behavior is undefined in this case.

In summary, we found our analysis effective for determining atomic-set serializability problems. In Table 1, 89% of the reported violations are malign. We ran our analysis on a realistic web server implementation and on typical library code with inner classes and inheritance. All these features are naturally supported by our heuristics.

6. RELATED WORK

We discuss three broad classes of related work: traditional data race detection, high-level data race detection, and detection of violations of atomicity and serializability.

Traditional work on error detection for concurrent programs has been focused on data races. A data race occurs when there are two concurrent accesses to a shared memory location, at least one of which is a write, and there is no synchronization between them. Static approaches for detecting data races include type systems where the programmer indicates proper synchronization via type annotations [8, 13], model checking (see, e.g., [29]), and static analysis [25, 24].

Dynamic analyses for detecting data races include those based on the lockset algorithm [31, 33], on the happens-before relation [23], or on a combination of the two [28]. Savage et al. [31] present a practical implementation of the lockset algorithm in the *Eraser* tool. The basic idea is lockset refinement: associated with each variable v is the set of locks $C(v)$ that initially consists of all locks. At each access to v, $C(v)$ is intersected with the locks held by the current thread. If $C(v)$ becomes empty, no lock consistently protects v, and a race is reported. The happens-before approach checks whether conflicting accesses to shared data are ordered by explicit synchronization. O'Callahan et al. [28] combined lockset based and happens-before based detection to improve both the overhead and the accuracy of traditional data race detection.

Narayanasamy et al. [26] present a dynamic race detection tool and an automated technique for classifying the races found by the tool as benign or malign. This classification is based on replaying the execution of a piece of code that exhibits a race according to two different executions, and observing whether or not the resulting executions produce different results.

Both static and dynamic approaches to detecting races scale reasonably well for real applications and have detected a large number of bugs in real software [33, 28, 10, 34, 25, 24]. However, a data race is a heuristic indication that a concurrency bug may exist, and does not directly correspond to a notion of program correctness. In our approach, we consider serializability, and in particular atomic-set serializability as a correctness criterion, which captures the programmer's intentions for correct behavior directly. Moreover, our approach is independent of any synchronization mechanism unlike these techniques.

A program without data races may not be free of concurrency bugs as shown in [4, 9]. These *high-level data races* may take the form of *view inconsistency*, where memory is read inconsistently, as well as *stale-value errors* [9], where value read from a shared variable is used beyond the synchronization scope in which it was acquired. Our problematic data access patterns capture these forms of high-level data races, as well as several others, in one framework.

[3] This problem is documented in the JavaDoc of `Collections.synchronizedCollection(...)` as well.

In Section 2, we illustrated the differences between atomic-set serializability and atomicity and other forms of serializability. Flanagan and Freund [14] present *Atomizer*, a dynamic atomicity checker for multi-threaded Java programs, based on Lipton's theory of reduction [21]. Atomizer uses a variation on Eraser's LockSet algorithm [31] to determine which shared variables may be involved in data races, and inserts instrumentation code that issues warnings when atomicity violations are detected.

Wang and Stoller present a number of different algorithms for detecting atomicity violations [35,37,36]. The Multilockset algorithm [37] improves on the Eraser algorithm [31] by using dynamic escape analysis, happens-before information, and information about held locks. The Reduction-Based Algorithm for checking atomicity [37] resembles Flanagan and Freund's approach [14], but relies on the Multilockset algorithm for determining variables involved in data races [37]. The Block-Based Algorithm [35, 37] is based on non-serializable interleaving patterns that correspond to our patterns 1–4. Atomicity violations are detected by considering pairs of blocks from different transactions; warnings are issued for matches with one of the unserializable patterns. Wang and Stoller present an extension of this approach to non-serializable interleaving patterns that involve multiple variables. However, they view the heap as a single atomic set, whereas our approach is parameterized by a partitioning of the heap into multiple atomic sets. Wang and Stoller also [36] present two Commit-Node Algorithms for checking view serializability and conflict serializability (detailed comparison presented in Section 2).

Lu et al. [22] detect atomicity violations in C programs. They observe many correct "training" executions of a concurrent application and record nonserializable interleavings of accesses to shared variables. Then, nonserializable interleavings that *only* arise in incorrect executions are reported as atomicity violations. They only detect atomicity violations that involve a single shared variable, whereas our approach can handle multiple locations. The patterns of nonserializable interleavings in [22] correspond to our patterns 1–4. They view our pattern 5 (two writes interleaved by a write) as serializable, due to the use of a slightly different notion of serializability (view-serializability).

Another serializability violation detector was presented by Xu et al. [38]. It dynamically detects atomic regions (called Computation Units or CUs) using a *region hypothesis*, which proved useful in their experiments but is not sound in general. Thus, their analysis produces both false positives and negatives. Non-serializability checking is done using a heuristic based on strict two-phase locking. Like our work, it does not rely on the possibly buggy locking structure of the program.

7. CONCLUSIONS AND FUTURE WORK

In previous work [32], we proposed a correctness criterion for concurrent object-oriented programs. This criterion, referred to as *atomic-set-serializability* in this paper, is more flexible than existing notions of atomicity and serializability because it is parameterized by a programmer-specified partitioning of memory locations into atomic sets. Selecting a partitioning that matches the granularity of a concurrent data structure can help avoid some of the false positives and missed errors associated with existing notions of atomicity and serializability. Moreover, atomic-set-serializability is independent of a specific synchronization mechanism, and can therefore be applied in settings where most other approaches cannot (e.g., lock-free algorithms).

The contributions of this paper are threefold. First, we present a dynamic analysis technique to find violations of atomic-set serializability. Second, we implemented the dynamic analysis in a practical tool that can be applied in realistic scenarios with acceptable overhead. Third, we demonstrated that our tool is capable of detecting a high number of atomic-set serializability problems, including both known errors and problems not previously reported. To the best of our knowledge, we are the first to report concurrency-related problems in classes from the Java 5 concurrent collections framework in package `java.util.concurrent`.

Currently, our tool uses a fixed set of heuristics for partitioning memory locations into atomic sets. Our present results indicate that, in some cases, our tool fails to find errors when this partitioning is suboptimal. Longer term, we plan to extend our tool to allow users to specify atomic sets using annotations.

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