SWORD: A Scalable Whole Program Race Detector for Java

Yanze Li
Texas A&M University
yanzeli@tamu.edu

Bozhen Liu
Texas A&M University
april1989@tamu.edu

Jeff Huang
Texas A&M University
jeff@cse.tamu.edu

***Abstract*—We present the design and implementation of SWORD, a scalable and fully automated static data race detector for Java, implemented as a plugin in the Eclipse IDE. SWORD is the first whole program race detector that can scale to millions of lines of code in a few minutes while achieving good precision in practice. The cornerstone of SWORD is a new algorithm that judiciously combines points-to analysis and happens-before analysis efficiently, without losing precision. We have evaluated SWORD on an extensive collection of large-scale open source Java projects. Our results show that SWORD detects more races and reports fewer false positives than the state-of-art race detector, RacerD. Moreover, SWORD requires no human effort to annotate code regions as required by RacerD. SWORD also displays comprehensive bug traces and racing pair information on the GUI, which make debugging the races easier. A demo video is available at https://youtu.be/XQ0CBy7mMaY.**

***Index Terms*—Data Race Detection, Whole Program Analysis, Static Analysis, IDE**

I. Introduction

Concurrency bugs, especially data races, can be easily introduced but hard to detect and fix, yet the demand for multi-threaded programs is ever increasing with the development of multi-core hardware. Developers need fast and reliable tools to detect concurrency bugs. Most existing techniques, however, are designed for the late phases of software development, e.g., testing and production. This often renders it more expensive to fix a bug compared to detecting and fixing the bug in the programming phase, because the developers' memory of the context for a bug may decrease with time.

We present SWORD, a **S**tatic **W**hole pr**O**gram **R**ace **D**etector in the form of an Eclipse plugin. SWORD is inspired by our prior work ECHO [1] and D4 [2], in which an incremental pointer analysis and a static happens-before (SHB) graph are proposed to detect data races incrementally. SWORD focuses on detecting data races at the whole program scale, thus it trims off the incremental analysis, and simplifies the structure of the SHB graph based on typical race patterns. As a result, SWORD detects data races in the IDE in a batch mode and provides a more detailed display, e.g., showing complete race traces in the GUI.

To make SWORD scalable and useful, we have solved following the engineering challenges:

1) We implement a flexible parallel design for SHB construction and race detection.
2) We avoid redundant storage and computation for the whole detection by optimizing the SHB design and leveraging typical race patterns.
3) We provide a user-friendly GUI with comprehensive traces for developers to utilize.

Despite the enormous body of existing race detection research, there is a surprising lack of out-of-box static race detectors open-sourced for developers in real-world projects. For Java programs, we have known **Chord** [3] and **RacerD** [4]. Chord is a project dated back to 2006 and is no longer maintained. It is hard to compile and run it on current Java projects. RacerD is a compositional race detector that relies on developer annotations to detect bugs in code segments. We evaluated both SWORD and RacerD, and found that SWORD has comparable performance with RacerD for most benchmarks but it provides more precise detection results at the whole program level and requires no human effort. This makes SWORD competitive for a whole program analysis at the code review phase.

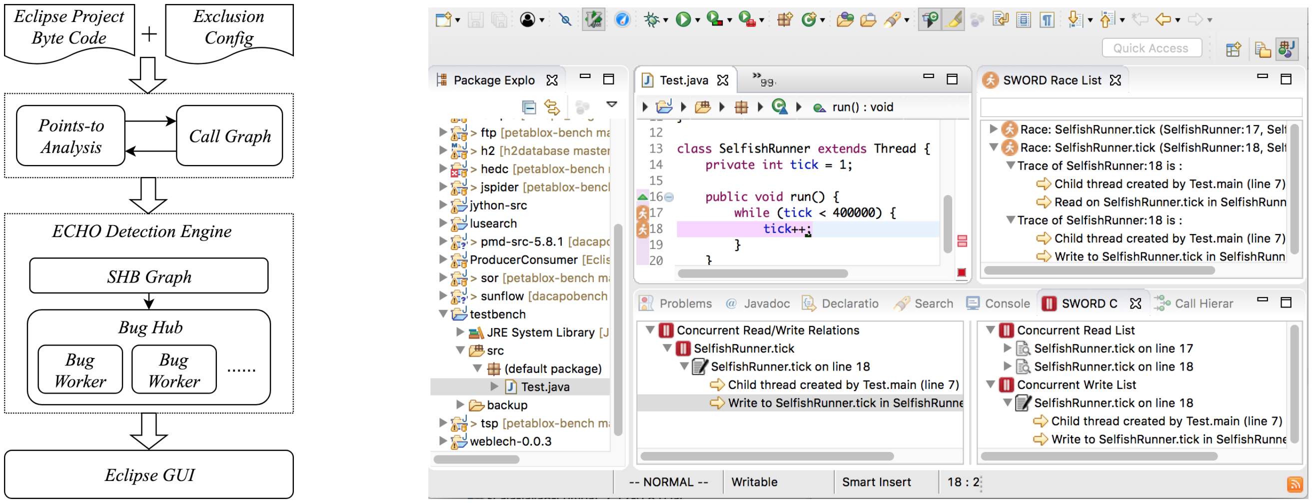
The source code of SWORD is publicly available at https://github.com/parasol-aser/SWORD

II. Background

RacerD [4] is an industrial-strength static race detector for Java programs developed by Facebook, and can scale to millions of lines of code in a few minutes. Unlike most race detectors analyzing a whole program, RacerD only partially checks the source project. To achieve great scalability, developers of RacerD made the following design choices:

1) Do compositional analysis instead of whole program analysis
2) Replace points-to analysis with an aggressive *ownership analysis* [4].
3) Do not reason about the interleaving between threads.

The compositional design of RacerD also faces several challenges. Since RacerD does not reason about thread interleavings, it requires a lightweight annotation library to provide extra information. Otherwise, it can miss real data races. For projects without normative annotations, it requires extra human effort to annotate. In principle, RacerD is neither sound nor complete. Due to the lack of alias information, RacerD only checks syntactically identical access paths, which makes it unsound and may introduce many false negatives in the whole



(a) Achitecture Overview

(b) SWORD GUI Display

Fig. 1: Overview for SWORD's Architecture and GUI

program. Due to the lack of a precise call graph, RacerD may also report false positives containing infeasible memory accesses that can never be reached by the program. In practice false positives are especially distractive to developers from fixing real bugs.

III. Overview

An overview of SWORD's architecture design is shown in Figure 1a. After users import their projects, SWORD starts from an entry method (e.g., *main*). It traverses all the reachable methods in the call graph in order to record the events in the SHB graph. Then, SWORD checks all the shared memory accesses to find if there exists any race. Users are allowed to exclude certain libraries and define arbitrary entries to customize the analysis.

SWORD visualizes the detected races in the IDE in a well-organized way. Figure 1b shows two types of views provided by SWORD for developers to review the results. The bottom view shows the race relation between memory accesses. Its left column shows all memory writes in reported races. After clicking at each write access, the right column will display all the *read*s and *write*s racing with the *write* we click. The listed memory accesses can be expanded to view its full trace to help developers analyze the bug. The top right view lists all the data race pairs. In the source file editor, a bug icon is also attached to each racy statement.

IV. Implementation

The implementation of SWORD is based on the Eclipse IDE [5], WALA [6] and Akka [7]. SWORD takes the bytecode or Eclipse AST as inputs, and uses WALA to transform the inputs into the SSA form IR. The analysis contains three main components: points-to analysis, SHB graph construction, and race detection on the SHB graph.

TABLE I: SHB Graph Node Types

IR Statement	Node Type
$x = y.f$	$read(y.f)$
$x.f = y$	$write(x.f)$
$x = o.m(arg*)$	$\forall O_c \in pts(o) : call(O_c.m)$
$t.start()$	$\forall O_c \in pts(t) : fork(O_c) \rightarrow start(O_c)$
$t.join()$	$\forall O_c \in pts(t) : join(O_c) \rightarrow end(O_c)$
$synchronized(x)$	$\forall O_c \in pts(o) : lock(O_c), unlock(O_c)$

A. Points-to Analysis

In SWORD, we use *0-CFA* in WALA to perform a context-, flow-insensitive and field-sensitive on-the-fly points-to analysis (PTA), so that we can obtain both call graph and pointer-assignment graph (PAG) where each variable node associates with a points-to set. The reason of choosing context-insensitive analysis is that the PTA sometimes takes more time than race detection when analyzing large programs. Even changing the context to *1-call-site*, which is usually insufficient to filter out most false positives, makes the simplest test case 2X slower. Considering such a large performance cost, the accuracy improvement brought by context-sensitivity is relatively small.

B. SHB Graph Construction

The SHB graph is critical in SWORD. It augments the call graph and points-to information in previous steps with directed edges to indicate the happens-before relation between nodes.

The SHB graph is constructed by traversing each IR statement sequentially following the call graph flows. Each IR is converted to a node as listed in Table I. Nodes in the same method are sequentially labeled with a unique id to show the intra-method happens-before relations. In addition, since new threads may be introduced by loops, we unroll loops twice to fully consider all possible data races.

Theoretically, the SHB graph only contains subgraphs representing the abstract threads. Subgraphs are connected by edges indicating the inter-thread happens-before relations. However, repeated method calls can introduce duplicate nodes from the same methods into subgraphs and make the SHB graph large. This will significantly increase the storage overhead and make our detection inefficient. To mitigate this issue, we represent both methods and threads as subgraphs. Any call to a method is translated to a happens-before edge from the invoke node to its subgraph, and the subgraph is associated with a list of *tid*s to record the threads that has invoked this method. Moreover, since the threads generated in a loop always have the same structure in the SHB graph, we do not unroll those loop but simply label them as threads created by loops. This further simplifies the SHB graph and avoids some redundant computations during the detection phase.

We refer our readers to [1] for a detailed description of the SHB graph construction. The construction process is further parallelized to speed up the tool.

C. Race Detection Engine

SWORD detects races in three steps: 1) Find shared abstract objects; 2) Find all reads/writes that access the shared abstract objects; 3) Detect data races by checking the lockset and happens-before relation in the SHB graph.

To scale SWORD, we leverage a parallel design based on *Akka* framework [7], which supports efficient message passing and asynchronous communication. With *Akka*, we can utilize the multi-core on single computer, or deploy the tool on remote clusters. In our implementation, we construct a *BugHub* that uses *BalancingPool* to dispatch tasks and manage the status of all *BugWorker*s. *BugWorker*s then carry out each step to detect data races.

V. Evaluation

We evaluated the accuracy and performance of SWORD by comparing with RacerD. Since RacerD only performs a partial analysis by default, we ran two sets of tests for it. First, we ran RacerD and SWORD directly on all benchmarks and collected all classes traversed by SWORD. Then we annotated all recorded classes using the *@ThreadSafe* annotation, and re-ran RacerD on all annotated benchmarks. After annotating, we made sure both tools achieve the exact same code coverage. The testing environment is a 4-core 2.5 GHz Intel x64 Macbook Pro with 16GB RAM. All standard and external libraries are excluded, because RacerD does not consider libraries. The number of *BugWorker*s in SWORD was set to 8. The benchmarks we use are collected from *Dacapo* [8] and *Petablox* [9], which cover different sizes of real-world Java programs.

Accuracy. The *Alarms* columns in Table II show the reported race number of SWORD and RacerD. The soundness of SWORD is guaranteed by PTA and SHB graph design. In order to verify the accuracy for all benchmarks, we compared SWORD's reports with RacerD's reports on annotated benchmarks, because they had the same code coverage. we manually checked all reported races in the first 4 benchmarks and confirmed all extra alarms reported by RacerD were false positives. The rest 3 large benchmarks all contain more than a thousand alarms, therefore we checked them by sampling. We categorized all reported races by their classes. For each class, we randomly pick three alarms to check:

1) The alarm is reported by RacerD but not by SWORD;
2) The alarm is reported by SWORD but not by RacerD;
3) The alarm is reported by both tools.

After checking all the sample alarms, we conclude that, for the first type of alarms, all of them are false positives. For the second type, there exist some real races, which means RacerD has false negatives. The last type of alarms consists of both false positives and real races.

TABLE II: Performance and accuracy for SWORD and RacerD on different benchmarks

Program	LOC	RacerD Alarms*	RacerD Runtime†	SWORD Alarms	SWORD Runtime
tsp	454	6/44	1.2s	46	1s
elevator	1088	1/52	2.8s	45	1s
weblech	1322	10/53	2s	13	1.4s
sor	7176	44/64	3.3s	8	1.1s
sunflow	24713	59/1632	10.3s	1150	135s
lusearch	48128	222/2786	25s	1420	13s
avrora	70057	79/4788	30s	27	74s

* *# of alarms without annotations / # of alarms with annotations*
† *RacerD has similar performance with or without annotations*

```
TextSpider.java
main(String[] args){
  ...
  Spider spider = new Spider();
  spider.readCheckpoint();
  ...
  spider.start();
}

Spider.java
Class Spider extend Runnable {
  private queue;
  readCheckpoint(){
    //write queue
  }
  run(){
    synchronized(queue){...}}}
```

Fig. 2: A false positive reported by RacerD in the *weblech* benchmark, due to not reasoning the thread interleaving.

```
Sor.java
Class Sor {
  static black = new float[M][N];
  static red = new float[M][N];
  ...
  main(String[] args) {
    for (i=0;i<proc;i++)
      sor_first_row(s,e);
  }}

Class sor_first_row extend Thread {
  float[][] black_ = Sor.black;
  float[][] red_ = Sor.red;
  ...
  run() {
    black_[j][k] = red_[j-1][k] + red_[j+1][k];
    red_[j][k] = black[j-1][k] + black_[j+1][k];
  }}
```

Fig. 3: A false negative reported by RacerD in the *sor* benchmark, due to the lack of points-to analysis.

We use two examples to explain the imprecision of RacerD. Figure 2 is a code segment of *weblech*. *Spider* is a class implementing *Runnable*, and assign itself to multiple threads in the constructor. However, the *readCheckpoint()* will only be called once in *main* before *spider.start()*, therefore there is no concurrent access with the *queue* in this method. Since RacerD does not reason about happens-before relation, *readCheckpoint()* is reported to be in a race.

Figure 3 is a simplified code piece from *sor*. Class *sor_first_row* extends *Thread*. The Parameters s and e are consecutive ranges (e.g., 1 to 5; 6 to 10). The static arrays *black* and *red* in class *Sor* are assigned to local variables *black_* and *red_* in *sor_first_row*. All threads perform array accesses on *black_* and *red_*, therefore manipulating static arrays *black* and *red* concurrently. The indexes of these array accesses will overlap at $j-1$ and $j+1$. However, RacerD treats *black_* and *red_* as thread local variables due to the missing of precise pointer analysis. As a result, RacerD fail to detect the real races on *black_* on line 16 and *red_* on line 17, no matter it runs with or without annotations.

We can see that without annotation, RacerD can detect only a very limited number of races, and it misses some known real races due to its unsoundness. When fully annotated, RacerD detects many more false positives than SWORD. For benchmarks *sor* and *avrora*, a large portion of their source code cannot be reached during execution, but RacerD still reported many races in unreachable parts. SWORD is more precise than RacerD because it traverses call graphs starting from the program entry points only.

Performance. For small benchmarks, both tools manifest a fast detection speed. When the programs grow large, RacerD tends to have a better performance on average, because it utilizes a cheap *ownership analysis* to replace PTA. This design makes the performance of RacerD mainly depends on program sizes and is not affected by complexity. In contrast, SWORD performs a context-insensitive PTA, which is more precise but relatively more expensive. Nevertheless, SWORD can complete the detection within 3 minutes for all the benchmarks. The performance of SWORD is disproportionate to the program size. For example, *sunflow* has smaller program size than *lusearch*, but it contains more abstract threads and shared memory accesses, which require significantly more computation (135s vs 13s) to determine the happes-before relations and locksets.

Discussion. In general, both RacerD and SWORD are fast. When targeting at some specific code segments, RacerD is fairly handy, but SWORD is much more precise on whole program scale. Moreover, SWORD provides a comprehensive IDE integration for developers to debug the races. To understand false positives in SWORD, we carefully studied the *weblech* benchmark, and confirmed that 3 out of the 13 alarms are false positives. The main cause of false positives is context-insensitivity. This can be mitigated by applying a context-sensitive PTA or performing additional analysis based on SWORD to further filter out those false alarms.

VI. Related Work

Data races can be detected both statically and dynamically. Dynamic analysis [10]–[13] can detect real bugs in the program, but it is hard to reason about all possible interleaving between threads. Static tools [3], [4], [14] usually provide high code coverage along with many false positives.

Some other techniques [15]–[18] exploit multicore CPU to speed up PTA using parallelism. These techniques can be integrated with SWORD to further improve the performance.

VII. Conclusion and Future Work

We have presented SWORD, a static whole program race detector for Java. We evaluated SWORD with RacerD on various open source projects, and found that SWORD can reveal more real races with fewer false positives and also have a comparable performance in most cases, therefore making SWORD a competitive out-of-box whole program race detector available. In the future, we plan to further consider common data race patterns and leverage techniques like selective context-sensitive PTA or a distributed system design to make SWORD more precise and scalable. The *Eclipse JDT language server* [19] is a Java language specific implementation of the Language Server Protocol [20]. This also makes it possible to deploy SWORD at remote servers to utilize more powerful computation resources and to work for different programming languages.

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References

[1] S. Zhan and J. Huang, "Echo: instantaneous in situ race detection in the ide," in *Proceedings of the 2016 24th ACM SIGSOFT International Symposium on Foundations of Software Engineering*. ACM, 2016, pp. 775–786.

[2] B. Liu and J. Huang, "D4: fast concurrency debugging with parallel differential analysis," in *Proceedings of the 39th ACM SIGPLAN Conference on Programming Language Design and Implementation*. ACM, 2018, pp. 359–373.

[3] M. Naik, A. Aiken, and J. Whaley, *Effective static race detection for Java*. ACM, 2006, vol. 41, no. 6.

[4] S. Blackshear, N. Gorogiannis, P. O'Hearn, and I. Sergey, "Racerd: compositional static race detection," *Proceedings of the ACM on Programming Languages*, 2018.

[5] "Eclipse plugin development environment," http://www.eclipse.org/pde/.

[6] "T. j. watson libraries for analysis (wala)," http://wala.sourceforge.net/.

[7] "Akka," https://akka.io/docs.

[8] "Dacapo benchmarks," http://www.dacapobench.org/.

[9] "Petablox," http://petablox-project.github.io/index.html.

[10] C. Flanagan and S. N. Freund, "Fasttrack: efficient and precise dynamic race detection," in *ACM Sigplan Notices*, vol. 44, no. 6. ACM, 2009, pp. 121–133.

[11] S. Savage, M. Burrows, G. Nelson, P. Sobalvarro, and T. Anderson, "Eraser: A dynamic data race detector for multithreaded programs," *ACM Transactions on Computer Systems (TOCS)*, vol. 15, no. 4, pp. 391–411, 1997.

[12] K. Sen, "Race directed random testing of concurrent programs," *ACM Sigplan Notices*, vol. 43, no. 6, pp. 11–21, 2008.

[13] K. Serebryany and T. Iskhodzhanov, "Threadsanitizer: data race detection in practice," in *Proceedings of the workshop on binary instrumentation and applications*. ACM, 2009, pp. 62–71.

[14] J. W. Voung, R. Jhala, and S. Lerner, "Relay: static race detection on millions of lines of code," in *Proceedings of the the 6th joint meeting of the European software engineering conference and the ACM SIGSOFT symposium on The foundations of software engineering*. ACM, 2007, pp. 205–214.

[15] M. Edvinsson, J. Lundberg, and W. Löwe, "Parallel points-to analysis for multi-core machines," in *Proceedings of the 6th International Conference on High Performance and Embedded Architectures and Compilers*. ACM, 2011, pp. 45–54.

[16] M. Méndez-Lojo, A. Mathew, and K. Pingali, "Parallel inclusion-based points-to analysis," in *ACM Sigplan Notices*, vol. 45, no. 10. ACM, 2010, pp. 428–443.

[17] S. Putta and R. Nasre, "Parallel replication-based points-to analysis," in *International Conference on Compiler Construction*. Springer, 2012, pp. 61–80.

[18] Y. Su, D. Ye, and J. Xue, "Parallel pointer analysis with cfl-reachability," in *2014 43nd International Conference on Parallel Processing (ICPP)*. IEEE, 2014, pp. 451–460.

[19] "Eclipse jdt language server," https://github.com/eclipse/eclipse.jdt.ls.

[20] "Language server protocol," https://microsoft.github.io/language-server-protocol/.