JHYDE - THE JAVA HYBRID DEBUGGER

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Keywords: Java, Debugging, Hybrid, Declarative, Omniscient, Coverage Criteria, Divide and Query.

Abstract: We present a hybrid debugger for the Java programming language which integrates declarative and omniscient debugging techniques. Omniscient debugging is an extension of trace debugging which is the most common debugging method for Java programs. Declarative debugging is a technique mostly used in the area of functional and logic approaches. By combining both techniques our debugger benefits from the advantages of both techniques. We demonstrate how to use our debugger and mention important aspects of its implementation. Furthermore, we develop a declarative debugging strategy to reduce the number of questions and give empirical evidence of its usefulness.

1 INTRODUCTION

Debugging is a complex and time-consuming task of the software development process. Software developers spend a considerable amount of time debugging, trying to locate bugs in software programs. Reducing the time and effort required to detect a bug can greatly increases the efficiency and productivity of software development (Hailpern and Santhanam, 2002).

No matter what debugging method or tools are used to locate a bug, the general debugging process looks as follows (cf. (Zeller, 2005)). At first the user notices a *failure*, i.e. an externally observable error in the program behavior. The failure is caused by an *infection*, that is a deviation of the actual program state from the intended program state. The task of the user is to locate the *bug*, i.e. the defect statement(s) in the debuggee program which caused the *initial* infection. In many cases the initial infection does not directly result in an observable program failure. Instead, it is propagated into later program states causing further infections which eventually cause a program failure. As a consequence, the user has to reason backwards in the execution history from the failure to the bug.

Until today, the most common debuggers used for object-oriented programming languages like Java are program tracers which track the execution of a debuggee program in a step-by-step manner. A trace debugger works on a low level of abstraction. Starting at a breaking point which predates the bug in the execution history the user has to inspect the sequence of statements executed by the debuggee program. The debugging process ends when the user encounters a buggy statement, i.e. bug, which produces the initial infection. While this method works well for a narrow search space, it can be very annoying and time-consuming if there aren't any clues about the position of the bug.

To minimize debugging effort the starting point should be as close to the bug as possible. However, the defect as well as its position in the execution history are unknown. When selecting a starting point for program tracing, we risk to select a point which lies chronologically either far before or even after the bug. In the first case we will have to inspect a lot of instructions and in the second case we will have to restart debugging with an earlier starting point.

Another severe drawback of trace debuggers is the fact that they are only capable of executing the debuggee program forward in time, while the reasoning from the program failure to the program defect naturally happens backwards in time. *Omniscient debugging* (Lewis, 2003), an extension of the trace debugging technique, addresses these shortcomings. The idea is to record the entire execution history of a debuggee program, making it possible to inspect the execution history back and forth in time. Nevertheless, even omniscient debugging takes place on a relatively low level of abstractions where the user still has to check single statements for validity.

A debugging method which abstracts from the details of implementation is declarative debugging. The method was developed by E. Y. Shapiro (Shapiro, 1983) for the Logic Programming paradigm. It was later applied to other declarative programming paradigms such as functional (Nilsson, 2001) and

Hermanns C. and Kuchen H..
JHYDE - THE JAVA HYBRID DEBUGGER.
DOI: 10.5220/0003441200250035
In *Proceedings of the 6th International Conference on Software and Database Technologies* (ICSOFT-2011), pages 25-35
ISBN: 978-989-8425-77-5

functional logic (Caballero and Rodríguez-Artalejo, 2002) programming. A declarative debugger asks the user questions about the validity of the program execution and infers the location of the bug from the user's answers. The precision by which the location of a bug can be detected depends on the level of abstraction of the declarative debugger. The more abstract the questions, the less precise the location of the bug can be determined. For example, a declarative debugger asking questions about the validity of method calls is able to detect a method containing a defect, but it cannot tell which statement inside the method is defect.

In this paper we present JHyde (Java Hybrid Debugger), a debugger which implements a hybrid debugging method for the object-oriented language Java. JHyde combines omniscient and declarative debugging into one debugging tool. In general, our hybrid debugging method looks as follows. At first the declarative debugging method is used to locate the method call causing the initial infection. After that omniscient debugging functionality is used to find the buggy statement inside the method. Thus, the user can at first, during the declarative debugging process, concentrate on "what" the method calls do and can ignore "how" the calls work internally. Afterwards, the identified call causing the initial infection provides a narrow search space for the omniscient debugging method. That way, our hybrid debugging technique abstracts from the implementation details during declarative debugging but is yet capable of identifying the exact buggy statement by means of omniscient debugging.

JHyde is based on a declarative debugger for the Java programming language which we developed in former work (Caballero et al., 2007). The main contribution of this paper is to show how omniscient and declarative debugging can be combined. We present JHyde which is available for download (Hermanns, 2010) and show important aspects of implementation. Furthermore, we have developed a declarative debugging strategy based on coverage information which reduces the number of method calls a user has to inspect. Tests show that this strategy saves up to 40 percent of the debugging effort.

The rest of the paper is organized as follows: In the next section we present our hybrid debugging technique for Java programs. Section 3 describes the user interface of JHyde, a prototypical plugin for the Eclipse IDE (Eclipse Foundation, 2010) which implements the hybrid debugging technique. To show how our debugger behaves in practice, we debug a sample program using JHyde in Section 4. In Section 5 we provide some implementation details. Section 6 presents some test results which proof the usefulness of the coverage-based search strategy. In section 7 we discuss how our paper is related to other works in this field. This paper ends with section 8, where we conclude and point out future work.

2 HYBRID DEBUGGING TECHNIQUE

2.1 Overview

As indicated before the general idea of our hybrid debugging technique is to combine elements of omniscient debugging and declarative debugging. Declarative debugging has the benefit that it works on a higher level of abstraction relieving the user from the task to inspect implementation details. Nevertheless, it is somewhat imprecise. For example, a declarative debugger for Java Programs is only able to identify the method containing the bug, but not the buggy statements inside the method.

This is where the omniscient debugging functionality of our debugger comes into play. Once the method call causing the initial infection is found using declarative debugging, the user can resort to the omniscient debugging. By tracking the execution of the method call in a step-by-step manner back and forth in time, the user can exactly determine the buggy statement(s).

2.2 Declarative Debugging

Declarative debugging requires the execution of the debuggee program to be represented by a computation tree (CT). To enable the declarative debugging of Java programs we have defined a suitable CT data structure in (Caballero et al., 2007). In our data structure each node of the CT will contain information about a particular method call of the computation. Let a be a node of the CT containing information about a call of method m_a. Child nodes of a correspond to calls that have been executed during the computation of the result of a.

During the declarative debugging process the user will be asked to classify nodes of the CT. A node has to be classified as *valid* if the represented method call produced a valid result, i.e. the return value including all side effects and as *invalid* if the represented method call produced an invalid result. Furthermore, a method can be classified as *trusted* if we know that it does not contain any defects. In this case every node representing a call of the trusted method is automatically trusted. A trusted node will not cause an infection, but it can have untrusted subnodes which could infect the program state.

The classification of the nodes is used to reduce the set of suspicious nodes, i.e. the set of nodes that can be buggy. We define N as the set of all nodes of the CT and $A_i \subseteq N$ as the set of suspicious nodes after the i-th user answer. At the beginning A_0 contains all nodes of the CT, i.e. $A_0 = N$. Furthermore, let $S_a \subseteq N$ be the set of all nodes of the subtree rooted at node a in the CT. If node $a \in A_{i-1}$ is classified, the suspicious set A_{i-1} can be reduced by the following rules. If node a is classified as valid, all its subnodes are automatically valid, i.e. $A_i = A_{i-1} \setminus S_a$. If a method call is classified as invalid either the call itself or any of its sub calls must be the buggy method call we are looking for. Hence, the debugger will continue the search in the subtree of this method call and we get $A_i = S_a$. If a method call is classified as trusted, then all calls of the same method will also become trusted. JHyde will not ask any questions about trusted method calls. However, a trusted method call can have unclassified child calls. These calls must be considered in the further debugging process. Thus, $A_i = A_{i-1} \setminus \{b \in A_{i-1} | m_b = m_a\}$. A method call's state can be set to unclassified if the user is not sure about the classification and wants to categorize it later.

If at least one method call has been classified as invalid, the size of the suspicious set is eventually reduced to 1, i.e. $\exists z \in \mathbb{N} : |A_z| = 1$. The only node n remaining in A_z is an invalid node with no invalid children. The call represented by the buggy node produced an invalid result while its inputs, i.e. the arguments provided by the parent call and the return values of the child calls, are all valid. We call this node the *buggy node*. The method call associated to the buggy node must contain a bug we are looking for.

A method call in an object-oriented language can produce side effects which are considered to be part of its result. These side effects must be taken into account during classification of a method call. Hence, the data presented to the user at each node of our CT will be:

- The fully qualified name of the method being called.
- All local variables of the method call, i.e. the arguments of the call and all locally defined variables. In case of a call to a non-static method the "this" reference to the object whose method is being called is also considered as an argument. For each local variable an entry and an exit value will be stored. The entry value is the variable's value at the beginning of the method call and can be regarded as part of the method's input. The exit value is the value at the end of the call and belongs to the method's result.
- The fields of referenced objects. For any object directly or indirectly referenced by a local variable we need to know the entry and exit values of its fields w.r.t. the considered method call. An array is considered as a special type of object with all its fields of the same type. Note that the fields of referenced objects can in turn reference further objects, spanning a *graph of referenced objects*. We call this graph the state space which is accessible by the respective method call. The accessible state spaces spanned by the entry and exit values are part of the method's input and the method's result, respectively.
- Additionally, the entry and exit values of static class fields should be available because they can be part of the methods input and output as well.
- Finally, we need the return value.

The usability of the debugger will depend on a compact and clear representation of the relevant (changed) information.

2.3 Omniscient Debugging

Omniscient debugging is an extension of trace debugging. During trace debugging the user directly observes the effects of executed statements on the program state. To find a defect the first statement in the execution history which changed the program state from valid to infected must be identified.

A severe drawback of trace debugging is that we have to trace statements executed *before* the defect, while a defect effects the program states which occur *after* its execution. Before the defect is executed the program state is sane which is why we do not have facts we can use to reason about the location of the bug. Hence, the odds are that we miss the the defect and have to start over again.

Omniscient debugging addresses these drawbacks as it allows to track the execution of a program back and forth in time. If we miss the execution of a defect, we can now simply step back in the execution history and do not have to restart our debugger. More importantly, we can now reason backwards from the program failure to the initial infection, following the infected program states to the bug. This is a great improvement over ordinary trace debugging.

It is obvious that these benefits come with costs. Omniscient debugging requires us to record the entire execution history of the debuggee program. The amount of data we have to record can be huge, especially for large and complex programs. But we have to record most of the execution information anyway for declarative debugging. Therefore, in the case of our hybrid debugger we get the benefits of omniscient debugging almost for free.

2.4 Coverage based Navigation Strategy

How do the individual debugging efforts develop if the size of the recorded execution history grows? On average, we expect the omniscient debugging effort to remain almost constant as we are looking for the defect in a single method call, while we expect the declarative debugging effort to grow as we are facing a growing size of the CT. Especially when debugging complex programs the number of executed method calls can become huge. Thus, an efficient strategy for the declarative debugging process can greatly reduce the overall debugging effort.

One possible declarative debugging strategy is based on the divide and query (D&Q) strategy developed by Shapiro (Shapiro, 1983). The idea of D&Q is to halve the set of suspicious nodes A_i with every user answer. Let $w_i : N \to \mathbb{N}, w_i(a) = |S_a \cap A_i|$ return the weight of a node a in the suspicious set after i user answers and let $W_i = |A_i|$ be the weight of the suspicious set.

D&Q will select the node a whose weight $w_i(a)$ is closest to half of the weight of the suspicious set, i.e. $W_i/2$, for classification. After the user answer, the weight of the remaining suspicious set W_{i+1} will be $W_i - w_i(a)$ or $w_i(a)$ if the answer was "valid" or "invalid", respectively. Especially for big and unbalanced CTs D&Q performs better than a top-down strategy. In the worst case only $O(\log n), n = |N|$ user answers are required.

D&Q assumes that every node of the CT has the same probability to contain a bug. In real applications this is rarely the case as method calls can have different complexities which result in different probabilities to contain a bug. We can improve the performance of D&Q if we take take varying error probabilities into account. For this, we define a coverage entity to be either a control-flow or data-flow element whose coverage is monitored during program execution. To estimate the complexity of a method call we assume that the complexity of a method call increases with the number of entities that are covered.

Let E be the set of all entities covered during the debuggee execution, $E_a \subseteq E$ the covered entities of node a, and $V_i \subset N$ the subset of nodes classified as valid after i user answers. Furthermore, the function $v_i : E \to \mathbb{N}_{\not 0}$ returns the number of valid classifications of a coverage entity after i user answers, i.e. $v_i(e) = |\{a \in V_i : e \in E_a\}|$. We compute the coverage-based weight of a node after i answers by $cbw_i : N \to \mathbb{R}^+$ as follows:

$$cbw_i(a) = \sum_{b \in (S_a \cap A_i)} \sum_{e \in E_b} g(v_i(e)).$$

Where the function $g : \mathbb{N}_0 \to \mathbb{R}^+$ returns the weight of a single entity e based on the number of valid classifications of e. Thus, the weight of a node a is the weight of all covered entities of all nodes which are element of the subtree rooted at a and the suspicious set A_i. In order to reduce the contribution of entities which have been classified as valid, the function g should be monotonically decreasing.

One possible definition of g is: $g(x) = p^x$, with $p \in [0,1]$. In this case the contribution to the coverage-based weight of an entity e which has not been classified as valid yet, i.e. $v_i(e) = 0$, is $p^0 = 1$. The contribution of e is exponentially reduced as the number of valid classification of e increases. For example, if $p = 1/2$ the contribution is halved for any additional valid classification.

Let $CBW_i = \sum_{b \in A_i} \sum_{e \in E_b} g(v_i(e))$ be the coverage-based weight of the suspicious set A_i. Similar to D&Q, our coverage-based D&Q will select the node a from A_i whose coverage-based weight $cbw_i(a)$ is nearest to half of the weight of the suspicious set, $CBW_i/2$, for the next classification. This way we try to halve the coverage-based weight of the suspicious set, CBW_i, with every user answer. We have implemented coverage-based D&Q using coverage of the edges of the control flow graph (CFG) and def-use chain coverage.

In a CFG each edge represents the flow of control between two nodes, i.e. basic blocks. A basic block is a sequence of code which has only one entry (no code within the sequence is destination of a jump) and one exit point (no jump statements within the sequence).

A def-use chain is a triple of a variable, a statement where the variable's value is computed, i.e. defined, and a statement where the variable's value is used. Moreover, the variable's value must not change between the definition and the use.

Both metrics, edge coverage of the CFG and def-use chain coverage, are common in the area of glass-box testing (Pressman, 2001), where they are used to measure the coverage of test cases. The goal is to generate a minimal set of test cases which completely covers a tested component w.r.t. to a certain coverage criterion. It is assumed that the probability of a component containing a defect is almost zero, if all test cases pass and their coverage is complete. Similarly, we employ coverage information during the debugging process to determine which parts of the program have the highest probability to contain a defect.

Please note, that we have employed edge and def-use chain coverage to reduce the number of questions during the declarative debugging process before (Caballero et al., 2007). In our earlier works we *avoid* questions about method calls whose covered entities are completely covered by method calls which are classified as valid. In other words, if $E_a \subseteq \bigcup_{b \in V_i} E_b$ holds, a will be automatically assumed to be valid. This approach significantly reduces the debugging effort, but it has a major drawback: if our debugger infers a wrong classification, this strategy might identify a wrong buggy method call. Our new approach does not have this shortcomings because we do not infer any answers but simply change the order of questions. Thus, our method always returns the correct result.

3 USER INTERFACE

The task of the JHyde front-end is to present the execution data of a program run in a structured and accessible way. The interface must be easy to use and understand to find bugs quickly. The JHyde front-end is an Eclipse (Eclipse Foundation, 2010) plugin. The plugin enables the user to conduct the hybrid debugging process for Java programs. When started JHyde executes the selected program and records its entire execution history. The search for the bug starts when the debuggee's execution is finished. The execution data is presented to the user in four different views shown in Figure 1. Each view is designed to present a different aspect of the execution data.

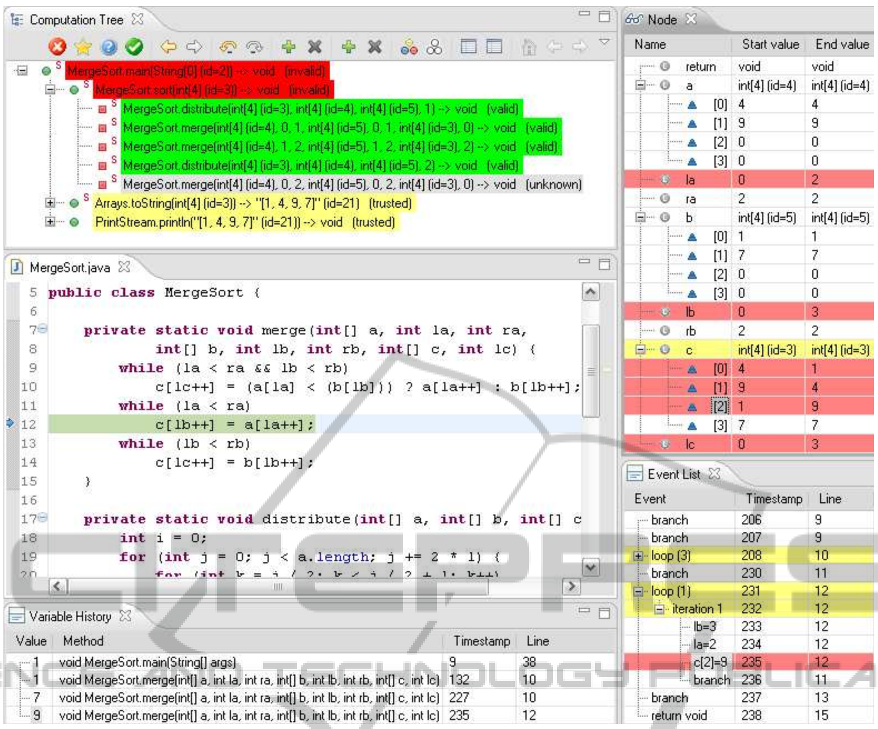
The Computation Tree View shows the CT of the debuggee program. Via the toolbar the user can classify the currently selected method call as valid, invalid, trusted or unclassified (unknown). According to its classification a method call is highlighted by green (valid), red (invalid), yellow (trusted), or white (unclassified) background color. After classification the debugger selects a new, yet unclassified method call. JHyde supports four different navigation strategies: top-down, D&Q, D&Q by edge coverage of the CFG, and D&Q by def-use chain coverage.

In order to classify a method call we need information about the inputs and outputs of a method call. This information is shown in the Node View of JHyde. As described in Section 2.2 we need all local variables, i.e. the arguments of the call, all locally defined variables, and the "this" reference to the object whose method is being called if the method is not static. Furthermore, we need all static variables. The Node View will always show these variables for the method call selected in the CT View. The Node View has a timestamp interval. The lower and the upper bound of the interval are set to the entry and exit timestamp of the method call selected in the Computation Tree View, respectively. For each variable its value at the lower bound (old value) and its value at the upper bound (new value) are shown. If the variable type is not a primitive but a reference type and at least one of the variable's values is not null then the fields of the referenced object will be shown in the variable's subtree.

To validate the selected method call a user can browse the old and new values of all relevant variables. If the method call's actual effect matches its intended effect the call is classified as valid. If actual and desired effect do not match, it must be classified as invalid. Validating the state change of the affected variables is a complex and time-consuming task. In the Node View every variable whose value changed during the selected method call is marked by a certain background color. A variable whose value changed is marked red, e.g. `la`, `lb`, `c[0]`...`c[2]`, and `lc`. A variable whose value did not change can reference an object whose variables, i.e. fields, have changed. These variables are marked yellow, e.g. `c`. The highlighting of the state changes makes it much easier to evaluate a method call. The user can directly navigate to the changes and check their correctness.

The Event List View and the Variable History View are used for omniscient debugging. The Event List View shows a chronological list of all events that occurred during the method call selected in the CT View. It is used to track the changes step-by-step, back and forth in time. If a user selects a specific event from the list, the source code line which produced this event is shown in the source code editor. Furthermore, the upper bound of the timestamp interval of the Node View is set to the timestamp of the selected event. This has the following effect: In the Node View the new value of each variable now shows the value the respective variable had right after the execution of the selected event. Hence, the Node View now shows all state changes which happened between the execution of the first event, i.e. the beginning of the method call, and the event selected in the Event List View. This gives the user a summary of all state changes performed by the events of the method call which precede the selected event. Thus, the user can conveniently check if the program state is still valid at the selected event.

If we want to lookup the event which changed a variable's value in the Event List View, we can select the desired variable in the Node View. Every event which changed the value of the selected variable will now be highlighted in the Event List View. For exam-



Computation Tree

```
⊟ ● S MergeSort.main(String[0] (id=2)) --> void   (invalid)
   ⊟ ● S MergeSort.sort(int[4] (id=3)) --> void   (invalid)
        ■ S MergeSort.distribute(int[4] (id=3), int[4] (id=4), int[4] (id=5), 1) --> void   (valid)
        ■ S MergeSort.merge(int[4] (id=4), 0, 1, int[4] (id=5), 0, 1, int[4] (id=3), 0) --> void   (valid)
        ■ S MergeSort.merge(int[4] (id=4), 1, 2, int[4] (id=5), 1, 2, int[4] (id=3), 2) --> void   (valid)
        ■ S MergeSort.distribute(int[4] (id=3), int[4] (id=4), int[4] (id=5), 2) --> void   (valid)
        ■ S MergeSort.merge(int[4] (id=4), 0, 2, int[4] (id=5), 0, 2, int[4] (id=3), 0) --> void   (unknown)
   ⊞ ● S Arrays.toString(int[4] (id=3)) --> "[1, 4, 9, 7]" (id=21)   (trusted)
   ⊞ ●   PrintStream.println("[1, 4, 9, 7]" (id=21)) --> void   (trusted)
```

MergeSort.java

```java
 5 public class MergeSort {
 6
 7     private static void merge(int[] a, int la, int ra,
 8             int[] b, int lb, int rb, int[] c, int lc) {
 9         while (la < ra && lb < rb)
10             c[lc++] = (a[la] < (b[lb])) ? a[la++] : b[lb++];
11         while (la < ra)
12             c[lb++] = a[la++];
13         while (lb < rb)
14             c[lc++] = b[lb++];
15     }
16
17     private static void distribute(int[] a, int[] b, int[] c
18         int i = 0;
19         for (int j = 0; j < a.length; j += 2 * 1) {
```

Variable History

Value	Method	Timestamp	Line
1	void MergeSort.main(String[] args)	9	38
1	void MergeSort.merge(int[] a, int la, int ra, int[] b, int lb, int rb, int[] c, int lc)	132	10
7	void MergeSort.merge(int[] a, int la, int ra, int[] b, int lb, int rb, int[] c, int lc)	227	10
9	void MergeSort.merge(int[] a, int la, int ra, int[] b, int lb, int rb, int[] c, int lc)	235	12

Node

Name	Start value	End value
return	void	void
a	int[4] (id=4)	int[4] (id=4)
[0]	4	4
[1]	9	9
[2]	0	0
[3]	0	0
la	0	2
ra	2	2
b	int[4] (id=5)	int[4] (id=5)
[0]	1	1
[1]	7	7
[2]	0	0
[3]	0	0
lb	0	3
rb	2	2
c	int[4] (id=3)	int[4] (id=3)
[0]	4	1
[1]	9	4
[2]	1	9
[3]	7	7
lc	0	3

Event List

Event	Timestamp	Line
branch	206	9
branch	207	9
loop (3)	208	10
branch	230	11
loop (1)	231	12
iteration 1	232	12
lb=3	233	12
la=2	234	12
c[2]=9	235	12
branch	236	11
branch	237	13
return void	238	15

Figure 1: Screenshot of the JHyde plugin which consists of the Computation Tree View, the Node View, Event List View, and the Variable History View, which help to navigate the execution data of a debuggee program. The views represent the execution of the `MergeSort` program shown in Listing 1.

ple, the array field `c[2]` is selected in the Node View in Figure 1. Thus, the events which changed `c[2]` are highlighted in the Event List View. If a changing event is located in the subtree of an event it is marked with yellow (light gray) background color, e.g. timestamps 208, 231, and 232. If the event itself changed the value, it is marked red (dark gray), e.g. timestamp 235. The interaction between the Event List View and the Node View offers some nice and handy features which facilitate the search for a defect in the method call's execution history.

The second view which can be employed to search for the program bug is the Variable History View. It displays a chronological list of all events of the complete execution history that changed a specific variable. To assign a variable to the Event List View we can right click on any variable in the Node View and select "display in History View". For example, the History View in Figure 1 shows the value history of `c[2]`. With the help of the Variable History View we can check the value history of a Variable for invalid values. If we have identified an undesired value, we can select the corresponding event, e.g. the event with timestamp 235 which changed the value of `c[2]` to 9. Clicking an event in the History View will cause an update of the other views of JHyde. In the CT View the method call which executed the selected event is selected, the Event List View shows the events of the method call selected in the CT View. Furthermore, the examined event, i.e. the event with timestamp 235, is selected in the Event List View. The Node View will show the value changes of all variables of the corresponding method call from the beginning of the call to the timestamp of the selected event. Figure 1 shows the state of all JHyde views after the event with timestamp 235 has been selected in the History View. Hence, the Variable History View is a useful utility to navigate the execution data. By selecting an event in the History View we can directly jump to its location in the execution history. Thus, the History View allows us to reason backwards in the execution history. If we notice a program failure after the execution of the debuggee program, we can use the variable whose value caused the failure to trace back to the point in the execution history where a wrong value was assigned to the variable. If the wrong value was assigned due to a defect in the program, we have found the bug. Otherwise the wrong value must result from another variable which has a wrong value at the given time in the execution history. We can continue the backward reasoning process with this new variable. By this process we will eventually find the bug causing the program failure.

4 DEBUGGING SESSION EXAMPLE

To demonstrate how JHyde is used, we will show how to debug the Java implementation of the well-known merge sort algorithm (Cormen et al., 2001) presented in Listing 1. We assume that our debugger uses a top-down declarative debugging strategy.

```
 5 public class MergeSort {
 6
 7   private static void merge(int[] a, int la,
 8       int ra, int[] b, int lb, int rb, int[]
             c, int lc) {
 9     while (la < ra && lb < rb)
10       c[lc++] = (a[la] < b[lb]) ? a[la++] :
             b[lb++];
11     while (la < ra)
12       c[lb++] = a[la++]; // must be: c[lc++]
             =a[la++];
13     while (lb < rb)
14       c[lc++] = b[lb++];
15   }
16
17   private static void distribute(int[] a,
        int[] b, int[] c, int l) {
18     int i = 0;
19     for (int j = 0; j < a.length; j += 2 * l) {
20       for (int k = j / 2; k < j / 2 + l; k++)
21         b[k] = a[i++];
22       for (int k = j / 2; k < j / 2 + l; k++)
23         c[k] = a[i++];
24     }
25   }
26
27   public static void sort(int[] a) {
28     int[] b = new int[a.length];
29     int[] c = new int[a.length];
30     for (int size=1; size < a.length; size *=
           2) {
31       distribute(a, b, c, size);
32       for (int i = 0; i < a.length / 2; i +=
             size)
33         merge(b, i, i + size, c, i, i + size,
               a, 2 * i);
34     }
35   }
36
37   public static void main(String[] args) {
38     int[] a = new int[] {4,9,1,7};
39     MergeSort.sort(a);
40     System.out.println(Arrays.
41       toString(a));
42   }
```

Listing 1: Java implementation of the merge sort algorithm containing a defect in line 12. The line numbering starts at line 5 to match the numbering in the source code editor of Figure 1.

The semantics of the methods is straight forward. The method `merge` merges the values of array `a` from index `la` to index `ra` and `b` from index `lb` to `rb` into array `c`, starting at position `lc`. If `a` and `b` are sorted within the defined intervals, the result will be a sorted sequence of all elements of the intervals of `a` and `b` starting at `lc` in `c`.

The method `distribute` distributes the elements of `a` to `b` and `c`. Therefore, `a` is divided in subsequent chunks of size `l`. The chunks are copied to `b` and `c`, in turns.

The method `sort` uses `distribute` and `merge` to sort array `a`. Therefore, the contents of `a` are distributed to `b` and `c` and merged back into `a`. To get a completely sorted array $\log_2$`a.length`, distribute and `a.length`-1 merge operations must be performed. The sequence of chunk lengths after each distribute steps is $(2^0, \ldots, 2^{\log_2 n - 1})$. Please note that this simple implementation of merge sort does only sort arrays of length $2^i, i \in \mathbb{N}$. Finally, the method `main` calls the `sort` method to sort the array $[4, 9, 1, 7]$ and prints the result to the console output.

The implementation contains a defect in line 12, which should read "`c[lc++] = a[la++];`". When executing the `main` method of the `MergeSort` class, the output is the incorrectly sorted array "`[1,4,9,7]`". We will now show how JHyde can be used to detect the bug.

To debug the `MergeSort` program we first have to execute it using JHyde. After the execution is finished we can use the views of JHyde to explore the recorded execution data and find the bug. Figure 1 shows the state of the JHyde views at the end of the debugging session, when the defect has been detected.

The CT View shows the CT of the `MergeSort` execution. The call of the `main` and the `sort` method have been classified as invalid. The `main` method prints a wrong result array and the sort does not sort the elements of the argument array correctly. The two sibling calls of the `sort` call, `toString` and `println` are automatically marked as trusted because they are part of the Java API. The first 4 sub calls of `sort` are classified as valid as they return the expected result. The last call of the `merge` method is still unclassified. As this method is selected in the Computation Tree View, the Node View shows all local variables of this call. For each variable the start value and the end value are the variable's value at the beginning and the end of the selected method call, respectively. The variables whose values changed during the method call, e.g. `la`, `lb`, `c[0]`...`c[2]`, and `lc`, are marked red (dark grey). The local variable `c` is marked yellow (light grey) because the value of `c` did not change, but some fields of `c` changed.

Due to the intended semantics of the `merge` method, we would expect the chunks $[4, 9]$ and $[1, 7]$ stored in a and b, respectively, to get merged to $[1,4,7,9]$ in c. The Node View tells us that the actual result of the merge call stored in c is $[1,4,9,7]$. If we mark this method as invalid in the Computation Tree View the debugger informs us that the method merge must contain a bug because its inputs were all valid, while it produced a wrong result.

To find the exact location of the bug in the merge source code we switch to omniscient debugging. The field at index 2 of the array c is a promising entry point. The expected value of this field is 7, while its actual value is 9. We right click this variable in the Node View and select "Show in History View". The result is the value history shown in the History View of Figure 1. During the execution the value of the array field c[2] has changed 4 times. The History View shows the value, the full method signature, the timestamp, and the source code line of each value change. If we select the last entry in the list, where the value is changed to 9, the source code line which caused the value change is highlighted in the source code editor. Furthermore, the event with the timestamp 235 is selected in the Event List View. At this point all views of JHyde look exactly as shown in Figure 1. A further look at the History View tells us that the correct value was already assigned to the c[2] in line 10 by the same method call at timestamp 227. The value 9 should have been assigned to c[3]. Hence, line 12 must contain the defect.

Note that we could have used the Variable History View even at an earlier point in the debugging process to directly jump to the bug. For example, if we evaluate the result of the call sort, we notice the erroneous result $a = [1,4,9,7]$. Via the value history for c[2] we can directly jump from the method call sort to the buggy method call merge, skipping the previous children of sort. Thus, the value history is an excellent tool if we detect a variable with a wrong value. In this case we can easily track back to the origin of the infected program state.

Nevertheless, there are cases where the program state is infected but we do not have a wrong value which we can use to track back to the program bug. This is the case if the program state is not infected due to *wrong* values, but due to *missing* values. For example, consider a merge sort implementation with a defect merge method which misses lines 11-12. For the input [4,9,1,7] this implementation would return a=[1,4,7,7]. Although, the value of a[3], which must be 9, is not correct, we cannot use the value history of a[3] to track back to the origin of incorrect value. During the computation a[3] is assigned two values. The first value (7) is assigned during the initialization of a in the main method and the second value, which is also 7, is assigned during the second invocation of the merge method. As both value assignments are correct, the incorrect value of a[3] is a missing assignment and not a wrong assignment. We cannot track missing assignments with the Value History. In this cases we need the declarative debugger to identify the buggy method.

If we use a D&Q strategy based on edge coverage instead of the top-down strategy for declarative debugging, the debugger would compute the weight of each node in the CT w.r.t. edge coverage. At the beginning of the declarative debugging process the weight of the nodes shown in the CT View is: 46, 45, 7, 8, 8 ,7, 10, 0, and 0 (preorder traversal). Hence, the debugger would at first ask the user to classify the last call of merge, whose weight 10 is closest to $\frac{46}{2}$. In this case the buggy method call is found after the classification of only one method call, while 6 method calls can be skipped.

5 IMPLEMENTATION

Figure 2 shows the architecture of our declarative debugger. It consists of four basic components: the Instrumentation Engine, the Transmission Engine, the Recording Engine, and the Debugging Engine. The components are distributed over the Debugger JVM which conducts the debugging process and the Debuggee JVM which executes the debuggee program. The distribution over two separate JVMs decouples the execution process from the debugging process.

During the class loading process of the Debuggee JVM the bytecode of the loaded class is manipulated by the Instrumentation Engine. After the instrumentation process, the bytecode of the loaded class contains additional instructions which invoke debugging event methods of the Transmission Engine. The instrumentation is done with the ASM (Object Web, 2009), a fast bytecode manipulation framework based on the visitor pattern (Gamma et al., 1995). The instrumentation process of ASM is controlled by user-defined visitors which inject additional bytecode into the visited class. As the instrumentation process is conducted during the dynamic class loading process at bytecode level, it is transparent from a programmers point of view. In a debugging session a programmer will always work with the original source code.

The Transmission Engine forwards the received events to the Recording Engine in the Debugger JVM. To transmit the events, they are converted to a byte stream in the Debuggee JVM and sent to the Debugger JVM via a socket connection. In the Debugger JVM the Transmission Engine reconstructs the de-

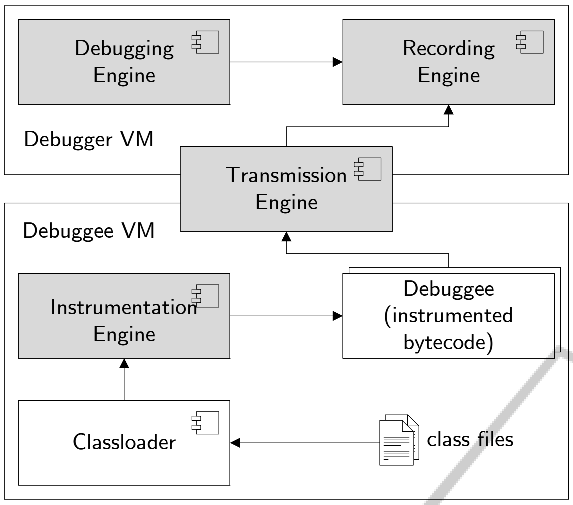


Figure 2: Architecture of the declarative debugger.

bugging events form the received byte stream and forwards them to the Recording Engine.

The Recording Engine stores the received events in an event file on the hard disk in chronological order. During the debugging process the execution data is lazily loaded from the event file and transferred to the Debugging Engine.

To reconstruct the program state of the debuggee program at an arbitrary time in the execution history the Recording Engine could theoretically reproduce the effect of all events from the beginning of the execution history to the desired point in the execution history. Especially for larger execution histories this would be much to slow to allow the user to navigate the execution history and the program state in real time. The debugging process would be unacceptably slow.

To speedup the reconstruction of the program states the Recording Engine constructs 3 additional data structures which are kept in the memory of the Debugger VM. The first data structure stores the static structure of the debuggee program, i.e. its classes, methods, fields, and local variables. The second structure is the CT of the debuggee program, i.e. a tree representing the method call history. The third structure stores data-flow information. It stores an array of timestamps for every variable of the debuggee execution. Each timestamp refers to the time in the execution history when the value of the associated variable changed. For each timestamp the Recording Engine can directly compute the position of the associated event in the event file.

Writing the whole execution data to the event file and keeping only three data structures in memory to speedup the navigation, is a trade off between memory usage and required effort to navigate the execution data.

The user interface of JHyde, i.e. the set of views as described in section 3, is implemented by the Debugging Engine. Hence, the Debugging Engine's task is to present the execution data to the user in a accessible way and conduct the interactive debugging process.

6 TEST RESULTS

To test the benefit of the coverage-based D&Q strategy, we have conducted the declarative debugging process with a set of selected test programs. For each of the programs which originally contained no errors we created several test samples. Each sample was generated from the original program by changing one distinct line of the source code such that the resulting test sample would contain a common programming error. This way we have created a set of 32 test samples out of 5 different programs. Using the declarative debugger component of JHyde we have determined the number of questions a user would have to answer, i.e. how many method calls he has to evaluate, before the erroneous method is found. The debugging process has been conducted four times for each error sample using top-down (TD), ordinary D&Q, D&Q by def-use chain coverage (DUC), and D&Q by edge coverage (Edge) strategies. DUC and Edge have been conducted with $p = 0.6$ and $p = 0.5$, respectively. These values minimize the number of questions w.r.t. the set of test cases. The number of questions we have to answer for each of strategy allows us to evaluate the efficiency of the different strategies.

Table 1 shows the test results. Column one indicates the name of the program which was subject to debugging. For each program we have manually constructed several test cases as described before. The number of test cases we created is shown in column two. The values in column 3 indicate the average size of the generated CT. Column 4 shows the average number of trusted method calls in the CT. Columns 5-8 contain the average number of answers necessary to find the buggy method. Each column corresponds to one of the above mentioned strategies. On average D&Q by edge coverage performs best, asking 7.66 questions, while the other strategies yield 8.25 (D&Q by def-use chain coverage), 10 (D&Q), and 12.84 (top-down). The ratio of classified method calls in columns 9-12 is calculated by dividing the average number of answers by the average number of untrusted method calls in the computation. On average we have to validate 23% of the CT using top-down, 18% using D&Q, 15% using D&Q by def-use chain coverage, and 14% using D&Q by edge cov-

Table 1: Results of test cases processed with the declarative debugger of JHyde.

	# of	Avg. # of		Avg. number of				Classified				Savings [%]		
	Test	method calls		answers				method calls[%]						
Program	Cases	Total	Trusted	TD	D&Q	DUC	Edge	TD	D&Q	DUC	Edge	D&Q	DUC	Edge
Avl	10	132.80	65.30	13.90	9.10	7.70	6.60	0.21	0.13	0.11	0.10	0.35	0.45	0.53
Binary Tree	5	128.00	84.00	11.80	10.20	7.40	7.80	0.27	0.23	0.17	0.18	0.14	0.37	0.34
B Tree	7	195.86	118.86	15.57	13.43	8.57	9.43	0.20	0.17	0.11	0.12	0.14	0.45	0.39
Heap sort	5	68.00	25.80	9.60	7.20	9.00	9.00	0.23	0.17	0.21	0.21	0.25	0.06	0.06
Hash table	5	73.40	22.40	11.20	9.60	9.00	5.80	0.22	0.19	0.18	0.11	0.14	0.20	0.48
Total Avg.	32	119.61	63.27	12.84	10.00	8.25	7.66	0.23	0.18	0.15	0.14	0.22	0.36	0.40

erage. Columns 13-15 show the relative savings, i.e. the percentage of questions that is saved w.r.t. a top-down strategy. On average we save 22% with D&Q and 36% with D&Q by de-use chain coverage. D&Q by edge coverage performs best saving 40% percent of questions on average. The number of saved questions is nearly doubled w.r.t. ordinary D&Q.

7 RELATED WORK

The idea to apply declarative debugging outside the declarative programming paradigm is not new. In 1998 Shahmehri and Fritzson presented an approach for declarative debugging of the imperative language *Pascal* (Shahmehri and Fritzson, 1991) which was further developed by the same authors in (Fritzson et al., 1992). The main difference of our approach w.r.t. these earlier proposals is that Java is a language much more complex than Pascal. The declarative debugging of programs including objects and object states introduces new difficulties.

There are several approaches which use an execution history to locate bugs in Java programs. In a first step these methods trace and record the complete execution of the debuggee program. In a second step the recorded information is used to identify errors in the debuggee program. For example, JavaDD (Girgis and Jayaraman, 2006) follows a query-based approach, storing events occurring during the debuggee execution in a deductive database. The database can be queried to retrieve the states of different program entities (variables, threads, etc.) at different moments of the computation history to infer where the bug is located. Another approach is omniscient debugging (Lewis, 2003) which can trace the execution of the debuggee program back and forth in time. Our debugger does also record the entire execution of a debuggee program before the debugging process is started and it supports omniscient debugging as well. But in contrast to these approaches, our debugger does also support declarative debugging, which concentrates on the logic of method calls, storing them in a structured way, i.e. the CT. The declarative debugging component allows our debugger to guide the debugging process, deducing the wrong method from user answers.

Hoon-Joon Kouh et al. (Kouh et al., 2004) propose a debugging technique for Java which combines algorithmic and step-wise debugging. In contrast to our work they neither present a tool implementation nor do they present a solution to display side effects in an accessible form. Furthermore, they use slicing techniques to reduce the size of the CT, while our tool uses enhanced D&Q strategies.

JHyde is based on a declarative debugger we have developed for the Java programming language (Caballero et al., 2007). In this paper we extend our declarative debugger to a hybrid debugging tool which supports declarative and omniscient debugging. Furthermore, we have developed and tested new declarative debugging strategies which enhance the D&Q strategy by def-use chain and edge coverage information. These strategies improve our previous answer-inference based approach. First our new optimization is guaranteed to be correct and cannot infer any wrong answers, second the reduction of the debugging effort is slightly more efficient.

As described by Silva (Silva, 2007) a lot of different strategies have been developed to reduce the number of questions asked during declarative debugging. Like our approach some of the more advanced strategies estimate the error probability of CT nodes based on previous user answers. However, none of these approaches is based on coverage information. To the best of our knowledge, there exists no strategy which is based on data-flow and/or control-flow coverage to calculate the error probability of nodes of the CT.

8 CONCLUSIONS AND FUTURE WORK

We have presented a tool which enables the hybrid debugging of Java programs combining declarative and omniscient debugging methods. The major advantage of declarative debugging compared to conventional debugging is that it works on a higher level of abstraction. The tester is relieved from the task to inspect the state space after each instruction starting from some break point. By answering questions about the soundness of some method calls the user can concentrate on the semantics. A major drawback of declarative debugging is the fact, that we can only determine a buggy method call but not the buggy statements inside a method. This downside is cured by the fact that JHyde does also support omniscient debugging. With omniscient debugging the user can track the execution of a debuggee program statement-wise back and forth in time. The combination of both debugging techniques JHyde can profit from the advantages both methods, the abstraction of the declarative debugging method and the precision of the omniscient debugging method.

The JHyde user interface consists of four views which allow the user to inspect and navigate the execution history of a debuggee program effectively. At any point in the debugging process the user is free to choose the most suitable views and/or debugging method.

A particular novelty of our approach is the usage of code-coverage criteria such as def-use chain coverage and coverage of the edges of the control-flow graph to calculate the error probability of method calls. The error probability increases with the number of covered entities, i.e. def-use chains or edges of the CFG. Furthermore, our strategy takes previous user answers into account. The more often an entity is classified as valid the lesser its contribution to the error probability of a method call.

We have conducted a number of tests, using different declarative debugging strategies to debug a set of buggy Java programs. The results show that up to 40% of the questions asked can be saved with our coverage-based D&Q strategy w.r.t. the ordinary top-down strategy. Furthermore, our strategy is an efficient improvement to the ordinary D&Q strategy. In our test scenario the number of questions saved could be nearly doubled if D&Q is enhanced by coverage-based error probability. The improved reduction of the debugging effort makes our debugger more suitable for real-world applications where the debugging effort has great influences on the costs of the software development process.

In the future we plan to investigate how our hybrid debugging method can be extended to multi-threaded program executions. Although, our debugger is already capable of recording multi-threaded programs, there are still some problems to be tackled regarding a multi-threaded hybrid debugging method. For example, it is much harder to check the validity of method calls if their execution is interleaved.

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