AADEBUG2003 225

Debugging Backwards in Time

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ABSTRACT

By recording every state change in the run of a program, it is possible to present the programmer every bit of information that might be desired. Essentially, it becomes possible to debug the program by going "backwards in time," vastly simplifying the process of debugging. An implementation of this idea, the "Omniscient Debugger," is used to demonstrate its viability and has been used successfully on a number of large programs. Integration with an event analysis engine for searching and control is presented. Several smallscale user studies provide encouraging results. Finally performance issues and implementation are discussed along with possible optimizations.

This paper makes three contributions of interest: the concept and technique of "going backwards in time," the GUI which presents a global view of the program state and has a formal notion of "navigation through time," and the integration with an event analyzer.

Introduction 1

Over the past forty years there has been little change in way commercial program debuggers work. In 1961 a debugger called "DDT" [MIT62] existed on Digital machines which allowed the programmer to examine, deposit, set break points, set trace points, single step, etc. In 2003 the primary debuggers for Java allows one to perform the identical functions with greater ease, but little more.

I believe that the reason for this is that the designers of debuggers have all concentrated on answering one question: "What information can we provide to the programmers while the program is running?" While this is not at all unreasonable, it's not the right question. The question they should have been asking is "What information will help the programmer most?" The answers are not the same.

Omniscient Debugging An omniscient debugger works by collecting events at every state change (every variable assignment of any type) and every method call in a program. After the program is finished, it brings up a debugger display and allows the programmer to look at the state of the program at any time desired. The programmer can select any variable and go "backwards in time" to see where it was set, or what its values were. It is possible to "single step" the program forwards or backwards, to step to any method call, follow any exception throw, any context switch, etc.

The objective of this paper is to introduce the concept of omniscient debugging and to illustrate by use of a specific implementation that it is effective. The details of implementation and performance

In M. Ronsse, K. De Bosschere (eds), proceedings of the Fifth International Workshop on Automated Debugging (AADE-BUG 2003), September 2003, Ghent. COmputer Research Repository (http://www.acm.org/corr/), cs.SE/yymmnnn; whole proceedings: cs.SE/0309027.

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are interesting only as they form a lower bound. If it proves to be effective, there are lots of ways of improving performance.

Omniscient Debugging is Interesting There are a number of things that make omniscient debugging worth the effort of exploring.

- First and foremost, (I claim) debugging is easier if you can go backwards. The most common question programmers have is "Who set this variable?"
- It eliminates the worst problems with breakpoint debuggers: no "guessing" where to put breakpoints, no "extra steps" to debugging, no "Whoops, I went too far", no non-deterministic problems. The programmer will never have to run the program twice.
- It gives the programmer a unique view of the program. Being able to see the traces of all the method calls for each of the threads is quite simply interesting. It makes looking at unknown code much easier.
- All the data is serializable. It can be analyzed remotely. It can be saved to a file. Several programmers can work with the exact same debugging session. Beta customers can e-mail a debugging session to developers even if they don't have the source.

Section 2 describes the appearence and functionality of the ODB (an implementation in Java). Section 3 tells how it is used on different types of bugs and discusses the results of user studies. Section 4 describes an implementation, its performance and limitations. Section 5 talks about its integration with event analyzers.

2 The ODB

For the rest of this paper, we are going to discuss the issues of Omniscient Debugging within the context of the "ODB", an implementation of this concept in Java. It's important to note that the general concept of Omniscient Debugging is independent of the implementation language and can equally well be done in C or C++.

The ODB is an implementation in pure Java which collects information by instrumenting the byte code of the target program as it's loaded. It uses a single high-level lock to order the events from different threads. It has been tested on MacOS, UNIX, and Windows on a large variety of programs. It is freely available for download from www.LambdaCS.com. It is a proof-of-concept and serves as an upper bound for the cost of collection and display. It is also a very effective debugger.

For a graphical debugger such as the ODB, there are two vitally important issues we need to address: presentation of information and "navigation." How does the programmer get the debugger to display the program state of interest and how does he recognize that state?

2.1 Maintaining State

We want to be able to "revert" the program to any previous state. Effectively this means that every change in every accessible object or local variable constitutes a separate state and must be recorded. We'll need to record each assignment in each thread and define an ordering on them.

The time stamp (an integer) will be the sole referent to program state. Usually it will not be directly evident. The programmer will select a trace line to look at, switch to a different thread, move up on down the stack, or even step through the code. Most of the time he won't even notice the time stamp, but all display panes will be updated to reflect it.

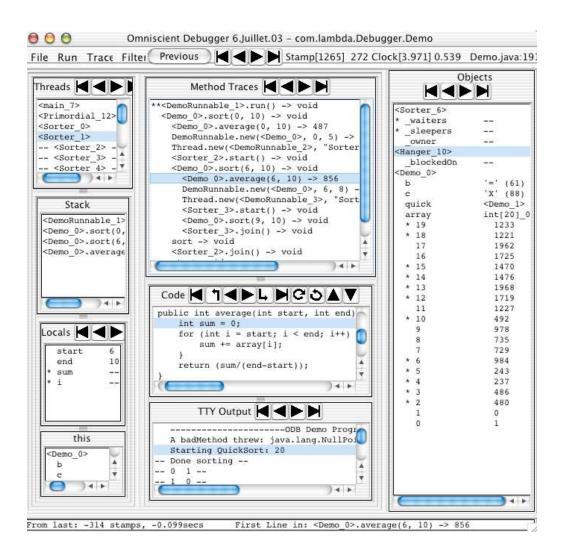


Figure 1: Main Debugger Window

2.2 Presentation

Every object, variable, I/O stream, etc. will have a known value at each time stamp. When we change the currently displayed time stamp (we will hence forth refer to this as "reverting the debugger" to a given time) all of the data displays will be updated to reflect the values at that time. The line of code which generated the event will be highlighted, the method trace that it happened in too. The panes for the current thread, the current stack, the variable values, etc. will all reflect the selected time stamp.

Things that don't change their value between the previously selected time stamp and the current one, shouldn't change either. They shouldn't change their appearance, their position, or their highlighting. Things that do change should do so obviously. New variable values should be marked, code lines should be highlighted, etc. The programmer should never wonder "Did this change?" or "Where am I?"

2.3 Recognizing State

It is essential be able to recognize state. This basically means the programmer should be able to look at an object and know which object it is and what values its instance variables have. The ODB supplies a print format showing the class name and an index number: <MyObject_75>, chopping off the package. Class objects are displayed as just the class name (e.g., Person), strings and primitives as expected (1, true, "A string").

This representation can be easily displayed in a JList, or stored in an editor. It can be printed out and it can even be typed back in to the debugger at a later date to reference that object. The object <Demo_0> in figure 1 shows its four instance variables, the last of which (array) is open recursively. In the locals pane the dashes (--) indicate that a variable hasn't been set yet.

There are a few cases where a different print format is more "intuitive" for the programmer. A blocked thread will acquire a "pseudo variable" to show the object it's waiting for (_blockedOn) as will objects whose locks are used.

The collection classes constitute another special case. In reality, a Vector comprises an array of type Object, an internal index, and some additional bookkeeping variables which are not of any interest to anyone other than the implementer. So the ODB displays vectors and hashtables in formats more consistent with the way they are used. For example, the keys for a hashtable won't disappear or move.

Large objects are problematic and remain an open issue. What is the best way to display a 1000x1000x1000 array? Or even just a 10000 element array? Or a large bitmap? Or a tree?

2.4 Displaying Method Traces

Every method call that is recorded will be displayed in a "method trace" pane. The format of the trace line will be:

<Object>.methodName(arg0, arg1) -> returnValue.

Each line will be indented according to depth and a matching "return line" will be added when it returns. Return lines which directly follow their trace line will be elided.

In figure 1 we can see that current time stamp is no. 272 (out of 1265) and is the first event in a method. It is a call to average(6, 10), which returned 856. This occurred in thread <Sorter_1>. From both the "stack" pane and the "trace" pane it's evident that sort(6, 10) is calling average(), and that it, in turn, is called recursively from sort(0, 10). The this object is <Demo_0>, which the programmer has copied to the "objects" pane and then expanded the array instance variable, which happens to be an array of 20 integers.

In multithreaded programs, each thread will have its own set of trace lines which will only be displayed when the debugger is reverted to a time stamp in that thread.

Although interesting in itself, the primary purpose of the trace window is not for debugging directly, but rather as a convenient index into the time sequence of the program. In other words, the programmer is going to use the traces to find interesting points in the program. The programmer will then revert to the time when that method call was executed and start looking at state.

The "objects" pane shows whatever objects the user has copied here via double-clicking on objects in other windows (any object in any pane may be copied here). Double-clicking on an instance variable will expand the value of that instance variable in-place (like the array int [20]_0).

Variables which changed values from the previously selected time stamp will be displayed with a leading '*' (e.g., start and end).

2.5 Navigation

Simple navigation through the program's history is accomplished through selecting lines in a pane or pushing the buttons above them. Selecting a line in the "threads" pane reverts the debugger to the

nearest event in that thread. Selecting a line in the stack frame will display that stack frame. Selecting a trace line, a code line, or an output line will revert to the time when that line executed (was printed).

The buttons work as uniformly as possible for the different panes. The four most common buttons revert to the first, previous, next, and last time stamp for the selected object in that pane. In the "threads" pane, these execute first/last time stamp for the thread, but previous/next context switch. In the "code" pane, they are first/last line in current method, and "step into forwards" and "step out of backwards." The other buttons execute "step over", "return from", and "next iteration on current line."

In addition to first/last/previous/next, it is possible to bring up a list of all the values a variable ever had and select one of them. The ODB will revert to the time when that variable was assigned that value.

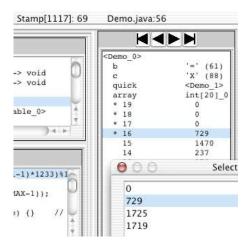


Figure 2: Selecting a Value

In figure 2 we see a selection from among the four values that array element 16 took on during the run of quick sort.

Modeled after EMACS, the ODB has a minibuffer which is used to present messages and to execute extended commands (such as *Evaluate Expression* or *Search*). The programmer may do an incremental text search through the "trace" pane, or an event-analysis search through all events, forwards or backwards.

2.6 Evaluating Expressions Interactively

Arbitrary method calls may be made at any time. The programmer may revert the debugger to any time and then evaluate a method call using the then-current values of the recorded objects. These methods will be executed in a different "timeline" and won't affect the original data. In the secondary timeline it is possible to change the value of instance variables before executing a method.

3 The Nature of Bugs under the ODB

The ODB divides bugs along two dimensions: Do all the events recorded for the bug fit in memory? Does the bug output wrong data or does it fail to output correct data?

3.1 The Snake in the Grass

This second is "the snake in the grass" metaphor. If the program prints out something wrong ("the answer is 41" instead of 42), then we have a handle on the bug. We can see the snake in the grass and we can grab its tail. Now if the program simply fails to output the correct answer, then we don't have a direct handle to the bug. This is the snake in the grass we can't see.

For programs that fit and we can see the snake, then the ODB is absolutely wonderful. It is possible to start on the faulty output and step backwards, finding the improper value at each point, and follow that value back to its cause. (If you've got a snake's tail and you pull on it long enough, you will get to its head.) It is not unusual to start the debugger, select the faulty output, and navigate to its source in 60 seconds. With perfect confidence.

A good example of this is when I downloaded the JUSTICE java class verifier. I found that it disallowed a legal instruction in a place I needed it. Starting with the output "Illegal register store", it was possible to navigate through a dozen levels to the code that disallowed my instruction. I changed that code, recompiled, and confirmed success. This took 15 minutes (most of which was spent confirming the lack of side-effects) in a complex code base of 100 files I had never seen before.

Breakpoint debuggers suffer from the "lizard in the grass" problem. Even when they can see the lizard and grab its tail, the lizard will break off its tail and get away. And then they're back to the "lost lizard in the grass" problem.

For relatively small problems (say 10,000 events), it is easy just to scan the entire set of method traces. For larger problems, the "lost snake in the grass" problem becomes more problematic. We have a large data set and an uncertain idea of what we're looking for.

Happily, searching through large sets of method traces for uncertain situations is a well-studied problem. The ODB leverages directly off of this work and incorporates the get() function of Ducassé [Duc99b] as an minibuffer command. Of course now the get() can search backwards as well as forwards.

A good example of this is the quick sort demo that is part of the ODB jar file. It sorts everything perfectly, except for elements 0 and 1 sometimes. To search for this problem, we can issue a get() search to find all calls to sort() that include 0 and 1.

```
port = call & callMethodName = "sort" & arg0 = 0 & arg1 >= 1
```

There are four matches and sort(0, 2) is the obvious call to look at. Stepping through that method, it's quickly obvious that average() failed to include the high value, which is why sort usually worked.

3.2 Size

The other important dimension is that of size. In a 31-bit address space, there is room to store about 10 million events. A huge percentage of real bugs fit nicely into this space. A good percentage don't. There are a number of ways to attack this problem. We can:

- "garbage collect" old events and throw them away.
- instrument fewer methods.
- record for a shorter time.

3.2.1 Garbage Collection

Garbage collection is good because it requires no effort and effectively maintains a window of events surrounding the bug. It is bad because it's not throwing away garbage, but just older events which might be important. It is also bad because it allows the program to run long enough for performance to become an issue. It adds an extra 50% on top of the cost of the average event.

When the source of the bug is within 10 million events of the time when recording was turned off, then we are back to the well-known "snake in the grass problem." When it is further away, we've lost the source of the bug, and the garbage collector loses its value.

During the development of the GC, a bug occured sporadically after the second invocation of the GC. An index into the time stamp array was getting changed to account for a special situation during recording, but the GC didn't know it. It would write in a forwarding index, which would not be recognized as illegal until the second GC, by which time the original faulty object was long gone.

Attempts to debug this problem with breakpoints and print statements failed completely. Using the ODB on itself (which was tricky back then) revealed the problem in relatively short order.

3.2.2 Safe Code

It is quite normal for a large percentage of a program to consist of well-known, "safe" code. (These are either recomputable methods, or methods we just don't want to see the interiors of.) By requesting that these methods not be instrumented, a great deal of uninteresting events can be eliminated. The ODB allows the programmer to select arbitrary sets of methods, classes, or packages, which can then be instrumented or not.

The more work the program does in uninstrumented code, the lower the overhead. A good example of this is the following loops:

```
Code

for (int i=0; i<MAX; i++) sum+=smallArray[i]; 300x

for (int i=0; i<MAX; i++) x=x*x+x; 100x

for (int i=0; i<MAX; i++) sum+=bigArray[i]; 30x

for (int i=0; i<MAX; i++) s="Item"+i; 2x
```

These numbers are very sensitive to memory usage issues. The small array fits into cache, so the uninstrumented loop runs in three cycles. The large array (1,000,000 elements) doesn't fit, and the uninstrumented loop runs 10x slower.

3.2.3 Starting/Stopping Recording

If the programmer suspects that a certain known event always occurs before the bug (e.g., "When I push this button it crashes."), then recording could be turned on at that point and turned off after the bug. The ODB allows manual control (there's a "Start/Stop Recording" button). It also allows automatic control. Automatic control means that we're going to scan a large set of events for a particular pattern, which will turn on/off recording. Once again, this is precisely the problem event analyzers are intended for and the ODB uses the get() function of Ducassé for this purpose also. By using a very fast event comparison (as fast as 10ns to check for a given source line, object, or method), it is possible to run the ODB over a much wider range of programs.

3.3 User Studies

Several small-scale studies involving 2 - 8 subjects were performed and gave encouraging results. An abstracted version of an actual bug was presented to the subjects with a brief explaination of the code and a half-hour introduction to the ODB. The bug was a classic "seen snake-in-the-grass" bug which took over an hour to find by the original programmer using conventional tools. All subjects were able to pin-point the source within fifteen minutes.

4 Performance and Memory Requirements

The important thing to recognize here is that the ODB represents a worst-case implementation—we can only do better. The ODB is completely naive, it does no optimization at all. With aggressive use of recomputation, collection can be reduced by orders of magnitude, leaving us with insignificent slowdown and near-infinite recording space. This allows us to focus on the main issue: Is this an effective way to debug a program?

On a 700MHz Apple 3G, the standard test method is one which takes two arguments and performs four assignments to local variables. It requires roughly 10μ s to record the method call and another 1μ s per each assignment and marker event, for a total of 10 events in 19μ s, and average of 2μ s/event.

Performance is not an issue for bugs which generate less than 10 million events. At a rate of 2μ s/event, it takes only 20 seconds to fill the entire 2GB address space.

For programs that depend on the GC, this is a issue. A couple typical programs are shown below.

Code	Slowdown
Debugging ODB back-end	300x
Debugging ODB display	10x
Debugging Ant	7x

Notice that the back-end of the ODB is a worst-case program. It uses no utility methods and manipulates few strings. Ant, by contrast, uses a lot of utilities and libraries. The ODB display uses Swing extensively, but still does a lot of array manipulations and JList construction.

A 64-bit address space changes things. It is then possible to collect billions of events, and performance for data sets that fit becomes an issue. This implies that using get() to start and stop recording will become more important.

In actual experience with the ODB, neither CPU overhead nor memory requirements have proven to be a major stumbling block. Debugging the debugger with itself is not a problem on a 110 MHz SS4 with 128 MB. On a 700 MHz iBook it's a pleasure. All bugs encountered while developing the ODB fit easily into the 500k event limit of the small machine.

4.1 Implementation

The ODB keeps a single array of time stamps. Each time stamp is a 32-bit int containing a thread index (8 bits), a source line index (20 bits), and a type index (4 bits). An event for changing an instance variable value requires three words: a time stamp, the variable being changed, and the new value. An event for a method call requires: a time stamp and a TraceLine object containing: the object, the method name, the arguments, and the return value (or exception), along with a small pile of housekeeping variables. This adds up to about 20 words. A matching ReturnLine will also be generated upon return, costing another 10 words.

Every variable has a HistoryList object associated with it which is just a list of time stamp/value pairs. When the ODB wants to know what the value of a variable was at time 102, it just grabs the value at the closest previous time. The HistoryLists for local variables and arguments hang off the TraceLine, those for instance variables hang off a "shadow" object which resides in a hashtable.

Every time an event occurs, it locks the entire debugger, a new time stamp is generated and inserted into the list, and associated structures are built. Return values and exceptions are backpatched into the appropriate TraceLines as they are generated.

The code insertion is very simple. The source byte code is scanned, and instrumentation code is inserted before every assignment and around every method call.

A typical insertion looks like this:

289 aload 4 // new value

```
291 astore_1 // Local var ie
292 ldc_w #404 <String "Micro4:Micro4.java:64">
295 ldc_w #416 <String "ie">
298 aload_1 // ie
299 aload_2 // parent Trace
300 invokestatic #14 <change(String, String, Object, Trace)>
```

where the original code was lines 289 and 291, assigning a value to the local variable ie. The instrumentation creates an event that records that on source line 64 of Micro. java (#292), the local variable ie (#295), whose HistoryList can be found on the TraceLine in register 2 (#299), was assigned the value in register 1 (#298). The other kinds of events are similar.

5 Integration with Event Analyzers

The get() is a function which will match a modestly complex pattern to an event. The pattern to be matched is based on prolog syntax and proves to be very expressive and convenient. Because a moderately complex query can be easily typed on a single line, it becomes possible to implement get() as an extended minibuffer command. And this is a very good thing.

The most common get () patterns will also map down to very efficient code. A simple search pattern such as this:

```
port=enter & methodName="sort" & parmNames=["start", "end"]
```

can run as fast as 10ns/test (7 cycles!). This pattern reads "Find the entry line in a method named "sort" which has two parameters, named "start" and "end"." Optimized code would require only six equality tests. The less-than-optimal ODB adds about 50ns to this. Thus an get() test currently runs about 40x faster than recording an event (50ns vs. 2us).

The conclusion is that using get() to start/stop recording can make a huge impact on a long-running program, contrasted to running that same program and relying on the garbage collector.

6 Related Work

There have been several previous attempts at doing something along these lines. The most significant distinctions of the ODB are not related to instrumentation and recording, but rather concern presentation and navigation. The ODB is based on presenting *state*, not events. The "debugger style" interface is central to the ODB and navigation is based on changing state ("What was the previous value of that variable?"), rather than on the stream of events. The integration of an event analyzer with a recording debugger is also unique.

In contrast, a number of projects have focused on "reversible execution" and "play back" which record much the same information, but don't allow the programmer the same view, nor the same navigation techniques. Checkpointing and deterministic re-execution provide the programmer the ability to use traditional breakpoints more quickly, but are otherwise unrelated.

Starting in 1969, the EXDAMS project [Bal69] was a TTY-based system which retained some amount of program state and allowed the programmer to examine it post-facto. It is difficult to ascertain just how much it was able to do. It was clearly hindered by the lack of a display.

Cohen and Carpenter [CC77] built a system that collected and stored trace information and allowed the user to make complex queries about it. The interface was a Algol-like programming language for making queries with TTY output.

"ZStep 95" [Lie97] is a visualization/debugging tool for Lisp which contains much of the same concept of retaining state and some of the "navigation" concepts. It has a significant emphasis on

graphical representations of call graphs and allows the programmer to "play back" the execution of a program, video-style.

Tolmach and Appel [TA93] describe a debugger for ML which is based on "reversible execution." It has a similar concept in that it allows the programmer to look at earlier state of a program based on direct commands. It also relies on a TTY interface.

"Deja Vu" [CS00] addresses the non-deterministic problems of multithreaded programs by recording synchronization information, thus allowing deterministic rerunning of the program. Ronsse et. al. [BdK00] also discuss the same problem. They do not attempt to use any of the information for debugging directly.

HERCULE [Ren00] is a tool which can record and replay distributed events, in particular, window events and appearence. It does for windows much of what ODB does for programs, and provides much of the functionality that the ODB lacks.

Trace analysis tools are generally designed as a sophisticated breakpoint mechanism, sometimes accompanied by a query language capable of deep program analysis [Duc99a], [HS03]. These tools address a different problem than Omniscient Debugging, and are relatively orthogonal. They are based on a knowledgeble programmer making intelligent queries about suspicious code. (The ODB allows the clueless programmer to wander around.) The ODB incorporates the get() function of Ducassé for recording control and dynamic queries.

7 Conclusion

For a large number of bugs, the ODB is highly effective. Problems that take hours with a breakpoint debugger can be solved in minutes. These are the "seen snake in the grass" problems. The "unseen snake in the grass" problems are more challenging because the programmer has no obvious place to start. Still, if the programmer has a reasonable idea of how the code works, it is possible to search through the history to find a suspect value. Once found, it is easy to verify.

For bugs that don't fit in the 10 million event limit of the 32-bit ODB, there are a variety of approaches to make them fit. Garbage collection can be effective for programs that generate an order of magnitude more events. Beyond that, the run time can become excessive. A sophisticated instrumentation tool, or a knowledgeble programmer, can specify methods that don't need to be instrumented, radically reducing the number of events recorded. An event analysis engine can select just the right moments for turning recording on and off, also reducing the number of events recorded.

In practice, it has proven to be quite easy to make bugs fit into 10 million events, and debugging even highly complex programs has not been a problem. In addition to finding the bug, the ODB allows the programmer to confirm exactly why it occured.

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