Path Projection for User-Centered Static Analysis Tools

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ABSTRACT

The research and industrial communities have made great strides in developing sophisticated defect detection tools based on static analysis. However, to date most of the work in this area has focused on developing novel static analysis *algorithms*, and neglected study of other aspects of static analysis *tools*, in particular user interfaces. In this work, we present a novel user interface toolkit called Path Projection that helps users visualize, navigate, and understand program paths, a common component of many static analysis tools' error reports. We performed a controlled user study to measure the benefit of Path Projection in triaging error reports from Locksmith, a data race detection tool for C. We found that Path Projection improved participants' time to complete this task, without affecting accuracy, and that participants felt Path Projection was useful.

1. INTRODUCTION

The research and industrial communities have made great strides in recent years developing sophisticated *defect detection* tools based on static analysis. Such tools have been used to find tens of thousands of bugs in real-world systems, including Linux [16, 15, 13], Microsoft productivity software [23, 28], and Java software [29], and in some cases have been used to verify the correctness of mission critical systems [5, 12]. Large companies such as Microsoft, Google, eBay, and Goldman-Sachs are now integrating tools into their regular development processes [9, 25, 36], and companies like Coverity [7] and Fortify [18], which provide defect detection tools and services, have hundreds of customers.

Most research on defect detection tools has focused on designing new static analysis *algorithms*. We believe it is equally important to study the other aspects of static analysis *tools*. Indeed, Pincus states that *"Actual analysis is only a small part of any program analysis tool [used at Microsoft]. In PREfix, [it is] less than 10% of the 'code mass'."* [31].

Generally speaking, static analysis tool users must perform two tasks: *triage*, deciding whether a report is a true or false positive, and *remediation*, fixing a true bug. An effective tool will assist the engineer in performing these tasks. However, while many tools provide support for categorizing and managing error reports, most provide little assistance for determining whether a report is true or false, and if true, how to fix it.

To address this problem, we present a new user interface toolkit called *Path Projection* that helps users visualize, navigate, and understand *program paths*—call stacks, control flow paths, or data flow paths—which are a common component of many static analysis tools' error reports. Our toolkit accepts a set of paths, each consisting of a sequence of program statements, and produces a concise view of them in conjunction with the source code. Path Projection aims to help engineers understand error reports more easily, to improve the speed and accuracy of triage and remediation.

An underlying principle of Path Projection's design is to keep the path display as close to the original source code layout as possible, since that is what the programmer is most familiar with. To follow this principle, we use three main techniques. We show multiple paths *side-by-side* for easy comparison. We perform *function call inlining* to textually insert the bodies of called functions just below the call site, which rearranges the source code in the order of the path. Finally, we perform *code folding* to automatically hide potentially-irrelevant statements that are not involved in the path. While other interfaces incorporate some of these features, we believe Path Projection's combination and design of features is novel.

We evaluated Path Projection's utility by performing a controlled experiment in which users triaged reports produced by Locksmith [33], a static data race detection tool for C. When Locksmith finds a potential data race, it produces an error report that includes a set of call stacks (the paths). Each call stack describes a concurrently-executing thread that contains an access involved in the potential race. For Locksmith, the triaging task requires examining each reported call stack to decide whether it is actually *realizable* at run time, and then deciding whether there are at least two realizable accesses that can execute in parallel.

We would like to emphasize that, to our knowledge, ours is the first work to empirically study a user interface for sophisticated static analysis. While commercial vendors may study the utility of their interfaces internally, no results of such studies are publicly available. Independent evaluation of commercial tools is also difficult because of the tools' licensing, which often forbids disclosure of information.

In our study, we measured users' completion time and ac-

curacy in triaging Locksmith reports, comparing Path Projection to a "standard" viewer that we designed to include the textual error report along with commonly-used IDE features. Both interfaces included a *checklist* specialized to each error report that enumerates the sub-tasks needed to triage the report correctly. We did not require that users propose actual fixes to the code, since even when a bug is clear its proper fix may be hard to determine.

In our within-subjects study, each user participated in one session with one interface, and one session with the other interface. Half the participants started with Path Projection, and the other half began with the standard viewer, to help factor out learning effects. In each session, after some introductory material, the user was asked to triage three error reports. At the end of the experiment, we asked users to qualitatively evaluate the interface and compare both.

We found that Path Projection improved the time it takes to triage a bug, and participants using it made about the same number of mistakes as with the standard viewer. Moreover, in Path Projection users spent little time looking at the error report itself. This suggests that Path Projection succeeds in making paths easy to see and understand in the source code view. Users clearly preferred Path Projection over the standard viewer, and generally rated all the features of Path Projection as somewhat or very useful. We also observed that the checklist dramatically reduced the overall triaging times for users of both interfaces, compared to an earlier pilot study. Though this result is not scientifically rigorous (several other features changed between the pilot and the current study), we believe it suggests checklists would be a useful addition to many static analysis interfaces, and merit further study.

In summary, this paper makes two main contributions:

1. We present *Path Projection*, a novel toolkit for visualizing program paths (Section 3). While mature static analysis tools can have sophisticated graphical user interfaces (Section 6), these interfaces are designed for particular tools and cannot easily be used in other contexts. Moreover, we believe Path Projection's combination and design of features is novel.

2. We present quantitative and qualitative evidence of Path Projection's benefits in triaging Locksmith error reports (Sections 4 and 5). To our knowledge, ours is the first study to consider the task of triaging defect detection tool error reports, and the first to consider the user interface in this context. Our study results provide some scientific understanding of which features are most important for making users more effective when using static analysis tools.

We believe Path Projection is a valuable new toolkit that can benefit a wide range of static analyses.

2. BACKGROUND: LOCKSMITH

Locksmith [33], our target static analysis, works by enforcing the *guarded-by pattern* [37]: for each memory location shared among threads, there must exist a lock that is consistently acquired at every access to that location.[1] Locksmith initially performs an *alias analysis* to conservatively model the pointers and locks in the program. It then uses a *sharing analysis* to determine what locations are thread-shared, and a *lock state analysis* to compute the set of locks held at each program point. After putting the information from these last two phases together, Locksmith issues an error report for any shared location that is inconsistently guarded.

A sample Locksmith error report is shown in the pane labeled (1) in Figure 1. We will come back to the rest of this figure later. This error report comes from aget, a multithreaded FTP client we examined previously [33]. The report begins at the top with the name and definition site of the shared variable involved in the race, in this case prev. Locksmith next lists a set of thread states identifying potential races: each state consists of the call stack at the time of the potential race, along with the set of locks held at each access. In this example, the first call stack indicates updateProgressBar() contains the offending access (simply called "dereference" whether it is a read or write), which is reachable from a thread created in main(). The second call stack reaches the same access, but in a different thread, created in resume_get(). In both cases, there are no locks held at the access.[2]

To triage this error report, the user must check three things: (a) that potentially-racing accesses refer to the same run-time memory, and were not conservatively conflated by Locksmith's alias analysis; (b) that Locksmith has not missed a lock that is actually held (something that could happen at join points in the control-flow graph); and (c) that the potentially-racing accesses can actually occur, and can occur simultaneously.

In our experience, (a) and (b) are rarely an issue—Locksmith's alias and lock state analyses are almost always good enough on the programs we looked at, and if they are too conservative, it is usually readily apparent. However, checking (c) can be quite challenging, because it involves examining the program logic along each path to decide whether the paths are simultaneously *realizable* at run time.

The focus of Path Projection and our empirical study is on improving user performance on task (c), and when we refer to *triaging* in the remainder of the paper, we will mean this task in particular. We leave as future work additional support for tasks (a) and (b). For example, aliasing information could be displayed using techniques from MrSpidey [17] or CQual [19].

Consider the problem of triaging the report shown in Figure 1. This figure shows a screenshot of our *standard viewer*, which displays the Locksmith error report (1) side-by-side with syntax-colored program source code (2). This interface is our baseline for comparing against Path Projection, and represents the assistance a typical editor or IDE gives users in understanding Locksmith error reports.

The first step in triaging is to examine the dereferences and look for pairs of accesses that are not guarded by the same lock. This is trivial given the error report, and in fact we can identify these pairs automatically. The checklist (3) in Figure 1 includes a tab "1–2" indicating that paths 1 and 2 are guarded inconsistently (in fact, not at all), and thus the user should compare both of those paths. We defer further discussion of the checklist to Section 4.4.

[1] Locksmith also includes logic to support thread-local and read-only variables (which need not be protected by locks), as well as initialization (prior to becoming shared, variables may be written to without holding a lock).

[2] Note that this report format, used in our experiments (Section 5), is slightly different than Locksmith's current output, but the differences are merely syntactic.

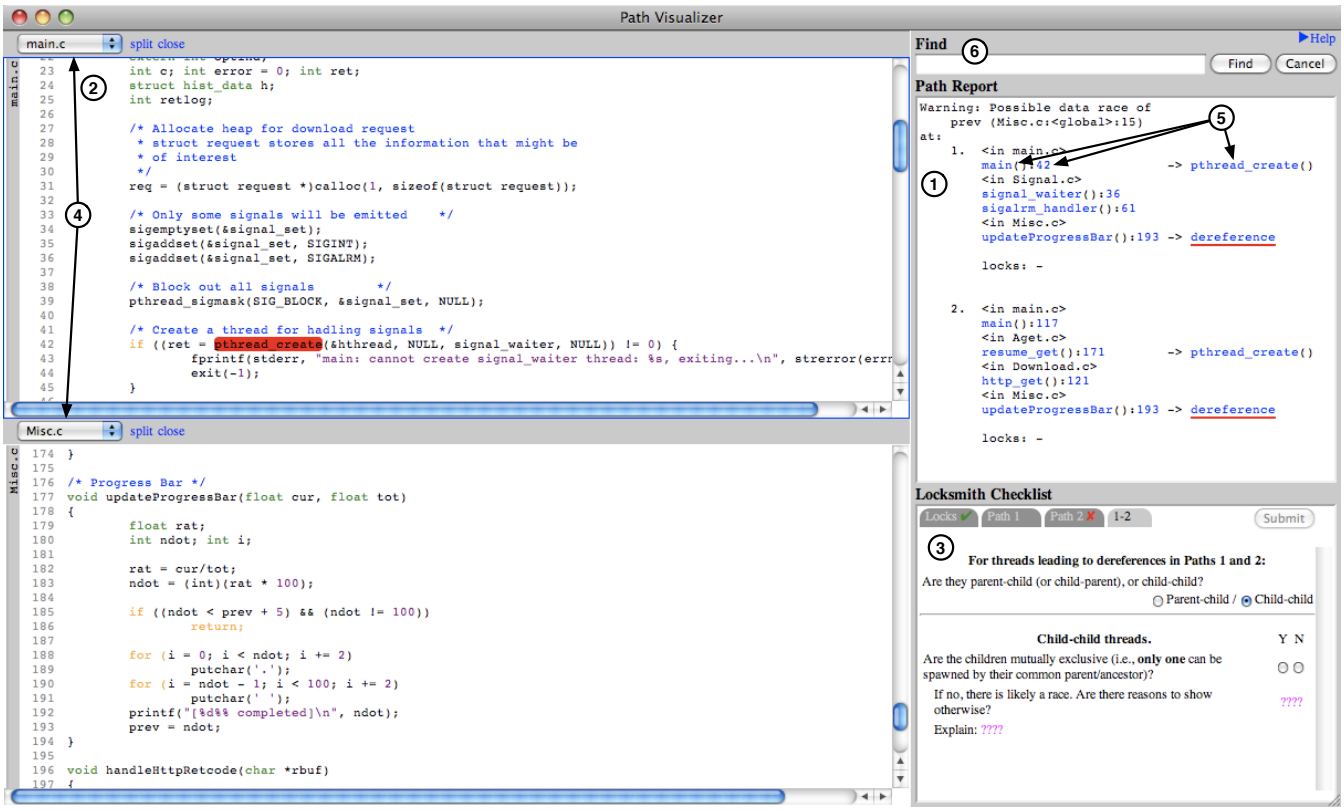


Figure 1: Standard viewer (picture in color; labels described in text)

Now that we have a candidate race, we need to trace through the control-flow of the program, to see under what conditions the two dereferences are reachable. The call stack paths in the error report show exactly what code to examine. In the screenshot in Figure 1, we are tracing path 1, and we have split the source code view horizontally to show multiple files at once (4). The bottom window displays the access at the end of the path, and the top window displays the thread creation site. In this case, the user has clicked on a hyperlink (5) in the error report. Each element in the report is linked to the corresponding position in the program (an access, function name, or line number). The interface also includes a search capability (6). Users can also jump to the definition of any identifier by command-clicking on the identifier name.

To finish checking whether this path is realizable, we need to continue tracing the code from the thread creation site to the access. We can accomplish this by clicking on the hyperlinks, scrolling through the code, and possibly splitting the window further to keep more context on the screen. Notice that this is already quite challenging, and aget is not a large program. The problem is that we need to skim over many lines across many different files, checking control-flow constructs to understand how they behave. If paths are long or complicated, as they often are, it can be hard to keep track of the context of the path as we step through it.

Moreover, we need to trace through path 2 in the same way and decide whether both paths are simultaneously realizable. While this interface provides some help for this path tracing and comparison task, it places a significant cognitive burden on the user to extract and organize the relevant information from the source code and the error report. Juggling a lot of context at the same time is both difficult and distracting. In our experience, it is all too easy to get lost on a long path and have to retrace it many times.

3. PATH PROJECTION

3.1 Design Principles

The goal of Path Projection is to help the user quickly and easily examine a program path. We developed our interface with some of the key principles of information visualization in mind. We found three strategies described by Card et al [6] to be particularly applicable for our task:

1. *Increase users' memory and processing resources and reduce the search for information.* The Locksmith error report is compact, but examining the path in the actual source code may involve many different source code lines spread across many different files. We would ideally like to put all the necessary information for triaging an error report on one screen, so the user can see all the information at the same time. We would also like to allow the user to hide any unimportant information, to further reduce the cognitive burden.

2. *Use visual representation to enhance pattern detection.* We would like to visually distinguish the source code lines appearing in the Locksmith error report from the other lines in the program, since the lines in the error reports are presumably very important. We would

also like to bring important threading API calls, e.g., invocations of pthread_X() functions, to the user's attention.

3. *Encode information in a manipulable medium.* We need to give the user good mechanisms for searching and comparing the information we present to them.

Another key principle we would like to follow is that "code should look like code." We want the user to be able to relate any visualization back to the original source code. This is based on our experience as programmers: we spend a large fraction of time editing source code in standard textual form, and relatively little working with abstract visualizations. Understanding Locksmith error reports requires looking at source code in great detail. A visualization that looks like source code will be familiar, which should increase acceptance, and could increase comprehension.

3.2 Interface Features

Figure 2 shows the Path Projection interface for the same program shown in the standard viewer in Figure 1. Additional screenshots can be found at `http://www.cs.umd.edu/projects/PL/PP`. The core feature of Path Projection is that it makes multiple program paths manifest in the display of the source code. To achieve this, Path Projection uses three main techniques:

Side-by-side paths. This error report contains two paths, each of which is displayed side-by-side in its own column ((1), left side of Figure 2). This parallel display makes relationships between the paths easier to see than in the standard interface, which would require flipping between different views (Principle 1). Each column is capped at a maximum width, and users can horizontally scroll columns individually. This helps prevent files that are unusually wide from cluttering the display. In our experiments, participants used a wide-screen monitor, to make it easier to see multiple paths simultaneously. Since wide-screen displays are commonly available and popular, we think designing an interface with such displays in mind is reasonable.

Function call inlining. Path Projection inlines function calls along a path. In the left path in the example, we see that the bodies of signal_waiter() (called by pthread_create), sigalrm_handler(), and updateProgressBar() are displayed in a series of nested boxes immediately below the calling line (2). We color and indent each box to help visually group the lines from each function (Principle 2). This feature is where our interface name comes from—we are taking the path from the error report and "projecting" it directly onto the source code. Our motivation is to reduce the need for the programmer to look at the error report, since the path is apparent in the visualization. We also underline the racing access (innermost boxes) to make it easy to identify.

Notice that in Path Projection, we actually visually rearrange function bodies in the original source code to conform to the order they appear in the path. Moreover, we may pull in functions from multiple files (in our example, three separate files) and display them together. Together, these regroupings help keep relevant information close together to reduce search and free up cognitive resources (Principle 1).

In the standard viewer, the user could achieve a similar result by splitting the display into several pieces to show the functions along the path. However, this quickly becomes tedious if there are several functions to show at once, and it adds significant mechanical overhead to viewing and navigating a path. Moreover, without code folding, which we discuss next, it can be difficult to see all the relevant parts of the functions simultaneously.

Code folding. Finally, to keep as much relevant information on one screen as possible (Principle 1), we filter by default irrelevant statements from the displayed source code. For example, in the function updateProgressBar() in the left path, we have folded away all lines (3) except the implicated access (line 193) and the enclosing lexical elements (the function definition and open and close curly braces). The user can tell code has been folded by noticing non-consecutive line numbering.

Our code folding algorithm is a syntax-based heuristic that tags lines in the program as either *relevant* or *irrelevant*. Irrelevant lines are hidden when the code is folded. For each line l listed in the error report, we tag as relevant line l itself; the opening and closing statements of any lexical blocks that enclose l; and the beginning and end of the containing function. For lexical blocks that include a guard (i.e., if, for, while, or do), we include the guard itself, and for an if block, we show the line containing the else (though not the contents of the else block). For example, the call to sigalrm_handler() (4) is in the error path, and so we reveal it, the closing if and while blocks, and the beginning and end of the signal_waiter function.

Since our code folding algorithm is heuristic and may hide elements that the user actually needs to examine, we allow the user to click the expansion button in the upper-left corner of a box to reveal all code in the corresponding function. When unfolded, source lines tagged as irrelevant are colored gray to ensure the path continues to stand out. For example, we have unfolded the body of main (5) in Figure 2. Another approach would be to use program slicing [40] to determine relevant lines, although we suspect code folding would still be needed to hide unimportant parts of slices.

While code folding is common in many IDEs, most require the user manually perform folding on individual lexical blocks, which can be time consuming and tricky to get exactly right. In contrast, we use the path to automatically decide which lines of code to reveal or fold away, requiring no user effort. Furthermore, since we display each path in a separate column, we can apply our code folding algorithm to each path individually.

Additional interface features. Path Projection includes several other features to make it easier to use. We include a *multi-query* search facility (6) that allow users to locate multiple terms and keep them highlighted at the same time. Each term is distinguished by a different color in the source code, and the user can cancel the highlighting of any term individually. Any source line containing a match is automatically marked as relevant, as are any lexical blocks enclosing the match. For example, in the screenshot in Figure 2, calls to pthread_join, which are not included in the error report, have been marked as relevant due to the search (7). This facility follows Principle 3, since it allows the user to manipulate code folding in a natural way. In our experiments, we initialized multi-query to find the four pthread functions shown in the screenshot, since in our pilot study we found users almost always want to locate uses of these functions.

Our interface also includes a *reveal definition* facility that

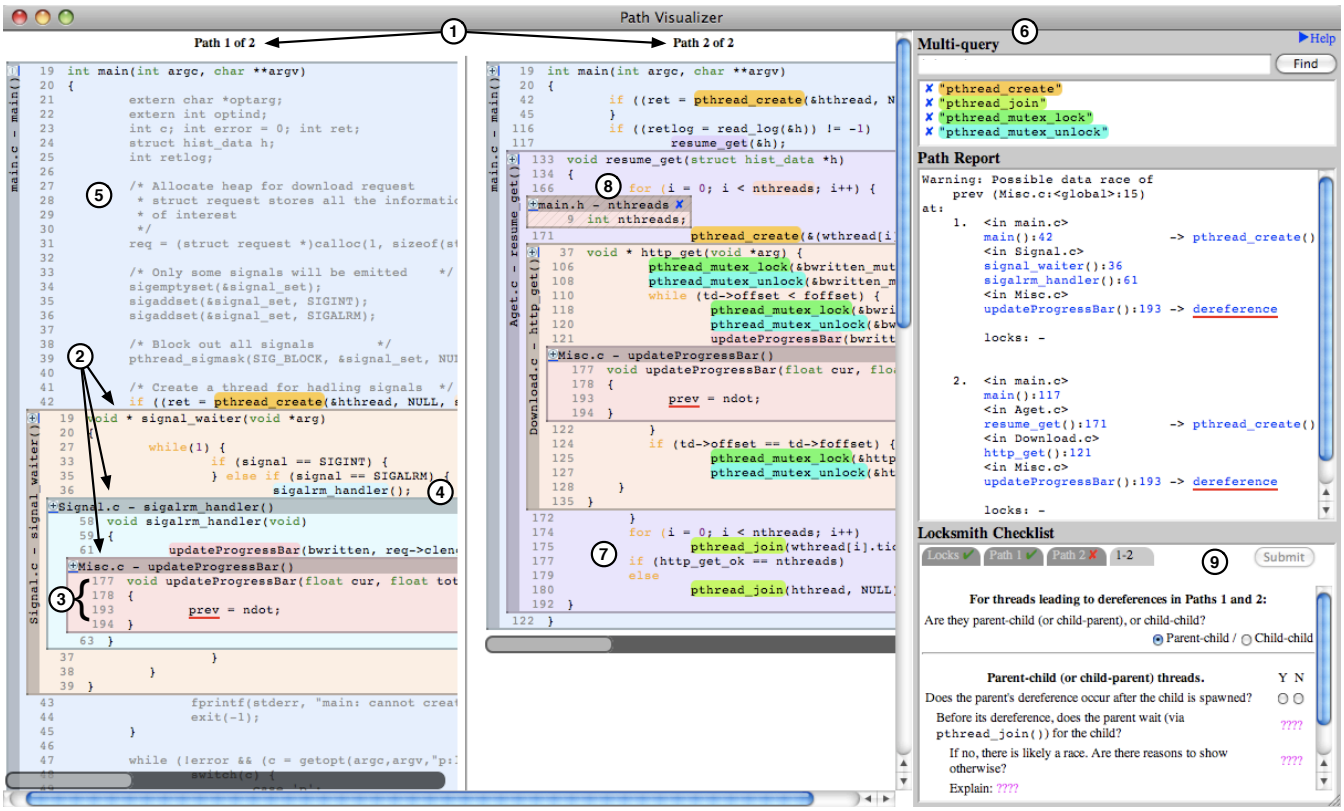


Figure 2: Path Projection (picture in color; labels described in text)

uses inlining to show the definition of a function or variable. In the screenshot, the user has clicked on nthreads, and its definition has been inlined below the use (8). While this feature seems potentially handy, we found it was rarely used by participants in our experiments.

Lastly, Path Projection still includes the original error report from which the visualization was generated, to act as a back-up and to provide consistency with the standard view. As with the standard view, the report is hyperlinked to the source display.

4. EXPERIMENTAL EVALUATION

We evaluated Path Projection's utility in a controlled user study. In our experiment, participants are asked to perform a series of triaging tasks, using either Path Projection (PP), described in Section 3, or the standard viewer (SV), described in Section 2. We implemented our own standard viewer instead of using an existing editor to eliminate bias due to participants' prior experience in any editor.

For each task, the participant is presented with a Locksmith error report for a program selected from a test corpus of open source programs. The participant's goal is to determine whether the error report constitutes an actual data race, or whether it is a false positive. In this task, PP provides an advantage over SV in triaging if it is faster, easier, and/or more accurate.

4.1 Participants

We recruited a total of eight participants (3 undergraduate, 5 graduate) for this experiment via e-mail and word-of-mouth advertising in the UMD Computer Science Department. We required the participants to have prior experience with C and with multithreaded programming (though not necessarily in C). All participants had taken at least one college-level class that involved multithreaded programming. On a scale of 1 (no experience) to 5 (very experienced), participants rated themselves between 3 and 4 when describing their ability to debug data races. Two participants had previous experience in using a race detection tool (Locksmith and Eraser [37]).

	Session 1			Session 2		
1	PP/1.1	PP/1.2	PP/1.3	SV/2.1	SV/2.2	SV/2.3
2	SV/1.1	SV/1.2	SV/1.3	PP/2.1	PP/2.2	PP/2.3

Figure 3: User interface/problem number schedules

4.2 Design

Each participant was asked to perform the triaging task in two sessions, first with one interface and then with the other. Thus, our experiment is a within-subjects design consisting of two conditions, using PP and using SV. Since participants experienced both interfaces, we were able to measure comparative performance, and we could ask participants to qualitatively compare the two interfaces.

A within-subjects design potentially suffers from order effects, since participants may be biased towards the interface given first. To compensate, we perform counterbalancing on the interface order: participants are randomly placed into one of the two schedules shown in Figure 3.

Participants in the first schedule use PP in the first session and SV in the second, whereas participants in the second schedule use SV first and PP second. However, all participants receive the same set of problems, numbered 1.1–2.3, in the same order, which allows us to directly compare our observations of each problem without the need to account for order effects.

4.3 Procedure

At the beginning of each session, we ask participants to review a short tutorial and quiz on pthreads and data races, as well as a tutorial on Locksmith with emphasis on the items in the triaging checklist (below, Section 4.4). Then we introduce the user interface (PP or SV) with another tutorial. We make sure that participants are familiar with each interface by encouraging them to try every feature and to triage a simple data race problem using the interface.

Following the tutorial is a single practice trial and three actual trials, all of which follow the same procedure. In each trial, we first ask participants to triage a real Locksmith error report generated from Locksmith's test corpus (below, Section 4.5). We log participants' mouse movements during the trial and measure the total time to completion. Triaging ends when participants complete and submit the triaging checklist. Immediately after, we present participants with the same problem, and ask them to explain out loud the steps they took to verify the warning. This allows us to compare their descriptions with our expectations.

We do not tell participants whether their answers are correct, for several reasons. Firstly, it is difficult for the experimenter to quickly judge the correctness of the answer, since identifying a data race may involve understanding many subtle aspects in a program. Secondly, we do not want the participants to become reliant on receiving an answer or to guess at an answer. Finally, in a real triaging scenario, users will not have the benefit of an oracle to confirm their intuitions.

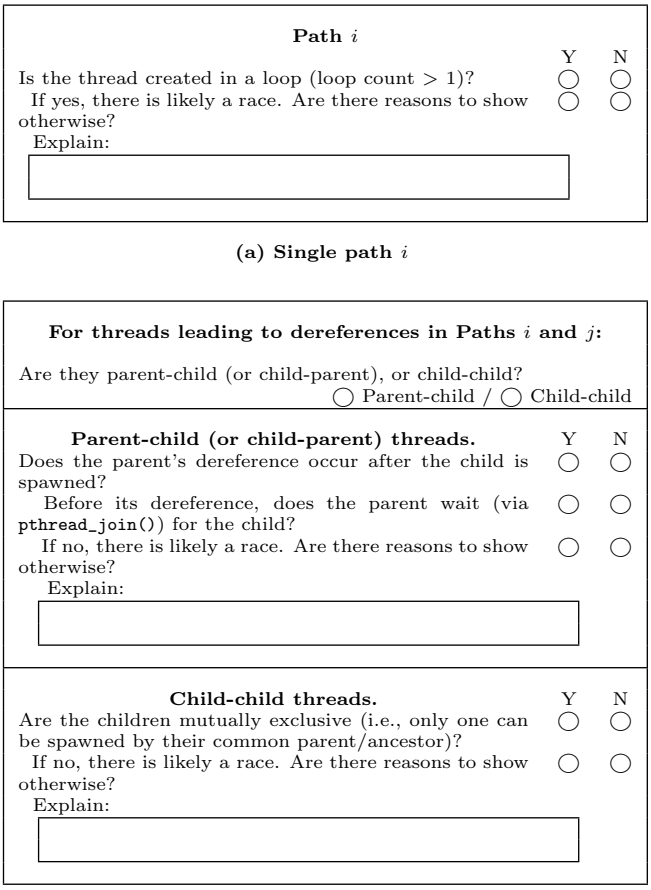
We have found this two-stage procedure to be very effective in our pilot studies. In particular, it allows us to ask about specific interesting behaviors observed without interrupting the participant during the task. The participants also benefit from a limited form of feedback. By recalling their work to the experimenter, they can confirm their initial understanding, or notice mistakes made. Furthermore, we have found that participants gain a better understanding of the user interface by demonstrating it to another person. This also helps mitigate the effects of what turned out to be a long learning curve in triaging error reports. The experimenter may also ask for clarification to certain points, which may reveal inconsistencies or mistakes.

After the experiment, participants complete a questionnaire and are interviewed to determine their opinion of the user interface. Users are asked to evaluate each tool based on ease-of-learning, ease-of-use, and effectiveness in supporting the triaging task.

We ran the experiment on Mac OS X 10.5.2. To avoid bias due to OS competency, all shortcuts are disabled except for cut, copy, paste, find, and find-next, and participants are informed of these shortcuts. We also display the interface on a 24-inch wide-screen 1920-by-1200 resolution LCD monitor.

4.4 Checklist

As discussed in Section 2, a Locksmith error report enumerates a series of thread states, each of which contains a call stack stack and the set of locks held. The thread states identify threads that could access the same memory location simultaneously. Assuming that (a) these states represent accesses to the same memory, and (b) that the set of held locks as determined by Locksmith is accurate, the participant's task is (c) to confirm that the thread states are realizable, i.e., that two such states could occur in parallel threads during an actual program execution. As discussed in Section 4.5, assumptions (a) and (b) do hold for all of the error reports we considered, so we instructed users to only perform task (c) in our experiment.



(a) Single path i

(b) Pair of paths i and j

Figure 4: Checklist tabs

In our pilot study we found that even with extensive pre-experiment tutorials, participants had trouble determining how to accomplish this task, and would often get distracted with irrelevant features, such as locating the definition of a global variable. This inconsistent behavior confounded our attempts to measure the benefits of the PP interface, since it varied significantly depending on the participant. To address this issue, we developed a tabbed *checklist* that breaks down task (c) into smaller sub-tasks, one per tab, that identify conditions under which reported thread states, if individually realizable, could execute in parallel and thus constitute a true race. A single error report could identify several races, so users must complete all tabs, at which point they may click *Submit* to complete the triage process.

A checklist is automatically generated for each Locksmith

error report, and is identical in both interfaces—(3) in Figure 1 and (9) in Figure 2. The first tab, labeled *Locks* (not shown), asks the users to document where the locks held at the end of each path were acquired. This tab is merely an experimental device: since users tend to examine the code before moving to the checklist, we insert this tab first to measure this initial startup period. The remaining tabs have two flavors, both illustrated in Figure 4.

The tab shown in Figure 4(a) is generated once for each path i that ends in an access with no locks held. The user is asked to check whether the access could occur in a thread created in a loop. If it could have, then the same access may occur in two different threads, constituting a race. For example, consider Path 2 in Figure 2. The write to prev (underlined in red) occurs in a thread created on line 171 of Aget.c. Notice that that line appears in a for loop that actually creates multiple threads. Thus, what Locksmith reports as Path 2 is actually a summary of nthreads total paths, all of which may reach the same access. Since no lock is held at the access, and it is a write, we have found a data race. The last part of this tab asks the user to look for any logic that would prevent the data race from occurring. For example, perhaps nthreads is always 1, so only one thread is spawned, or perhaps the given state is not realizable due to inconsistent assumptions about the branches taken on the path. While we could attempt to break this condition down into further subtasks, we chose this more open-ended question to reduce visual clutter and complexity.

The tab in Figure 4(b) is generated once for each pair of paths i and j that end with inconsistent sets of locks held. First, the user selects whether the two threads are in a parent-child or other (child-child) relationship. In the first case, the user must check (a) that the access in the parent occurs after the child is created, and (b) that there is no parent-child synchronization with pthread_join. Case (a) is necessary for the parent and child to access a location in parallel. Case (b) is necessary because even if the parent accesses the location after creating its child, it might wait for the child to complete before performing the access, making parallel access impossible. If both (a) and (b) are true, then there is likely a race, and the user is asked to look for other program logic that would prevent a race.

In the second case, a child-child relationship, the user checks whether the two children are mutually exclusive. For example, they may be spawned in different branches of an if statement, only one of which can execute dynamically. Again, if they are not mutually exclusive, the user looks for other logic that would prevent a race.

The checklist proved to be quite useful as an experimental device. Though we did not carefully consider the benefits of the checklist experimentally, we observed anecdotally that participants' completion times for our current study were reduced in both variance and magnitude (by an average of 3:46 minutes, or 41%), compared to the pilot study. This improvement strongly suggests that a tool-specific checklist has independent value, and that tool builders might consider designing checklists for use with their tools. An interesting direction for future work would be to explicitly study the benefit of checklists in performing triaging.

4.5 Programs

Each trial's error report was drawn from one of four open source programs, all of which we have previously applied Locksmith to: engine, aget, pfscan, and knot. Reports from engine and pfscan are used during the tutorial and practice trials. Trials 1.1–1.3 use error reports from aget, and trials 2.1–2.3 use error reports from knot. By using different programs in each trial, we prevent participants from carrying over knowledge of the programs from the first interface to the second. The three selected reports within each program are significantly different from each other, e.g., they do not follow the same paths. This helps avoid bias that could arise if participants were given very similar triaging tasks for the same program. Overall, there were 23 (non-*Locks*) tabs to complete for the experiment, 8 of which are true positives, and 15 of which are false positives.

We chose reports in which imprecision in aliasing and lock state analysis do not contribute to the report's validity. The latter is trivially true for all our test programs, because locks are not acquired or released path-sensitively, and so Locksmith's estimation of lock state is always accurate. For these programs Locksmith does find potential races in which conflicting accesses are via aliases of the same memory. However, most reported conflicts are due to direct accesses of global variables, so we always chose reports of this flavor.

We also simplify the task slightly by making four small, semantics-preserving changes to the programs themselves. Doing so makes it simpler to ensure that our participants have a common knowledge base to work from, and reduces measurement variance due to individual differences. First, we made local static variables global. Second, we converted wait/signal synchronization to equivalent pthread_join synchronization when possible. We made both changes in response to confusion by some participants in our pilot study who were unfamiliar with these constructs. Third, we deleted lines of code disabled via #if 0 or other macros. Finally, in a few cases we converted gotos and switch statements to equivalent if statements. These last changes remove irrelevant complexity from the triaging task.

5. EXPERIMENTAL RESULTS

5.1 Quantitative Results

Completion time. We measured the time it took each participant to complete each trial, defined as the interval from loading the user interface until the participant submitted a completed checklist. The top part of Figure 5 lists the results, and the chart in the lower-left corner of the figure shows the mean completion times for each interface and session order combination. We found in general that PP results in shorter completion times than SV.

More precisely, the mean completion time is 4:56 minutes for PP, and 6:02 minutes for SV. A standard way to test the significance of this result is to run a user interface (within subjects) by presentation order (between subjects) mixed ANOVA on the mean of the three completion times for each participants in each session.[3] However, this test revealed a significant interaction effect between the interface and the presentation order ($F(1,6) = 6.046, p = 0.004$). (As is standard, we consider a p-value of less than 0.05 to indicate a statistically significant result.) We believe this is a learning effect—notice that for the SV-PP order (SV

[3]We run all statistical tests in R and SPSS. For ANOVA, we confirmed that all data sets satisfied normality using the Shapiro-Wilk test.

Completion times and accuracy for each trial

	Session 1				Session 2			
Trial	1.1	1.2	1.3	mean	2.1	2.2	2.3	mean
User	SV				PP			
1	8:36	14:14	9:44	10:51	7:07	4:48*	4:02	5:19
2	5:07*	3:10	5:50	4:42	4:16	2:29*	2:10*	2:58
5	7:46	2:34	5:38*	5:20	5:13	3:43*	1:18*	3:25
7	5:40	6:23	7:35	6:33	3:05	3:53*	2:32	3:10
				6:51				**3:43**
User	PP				SV			
0	6:27*	6:09	8:32*	7:03	9:42	5:16*	3:11*	6:03
3	6:38	7:18	8:35	7:30	11:18	6:21	3:39	7:06
4	8:21	2:11	4:43	5:05	5:26*	4:27*	2:46*	4:13
6	7:11	2:52	4:50**	4:57	4:33	4:06*	1:58*	3:32
				6:09				**5:14**
# Tabs	3	2	6		6	3	3	

* one incorrectly answered tab in the checklist

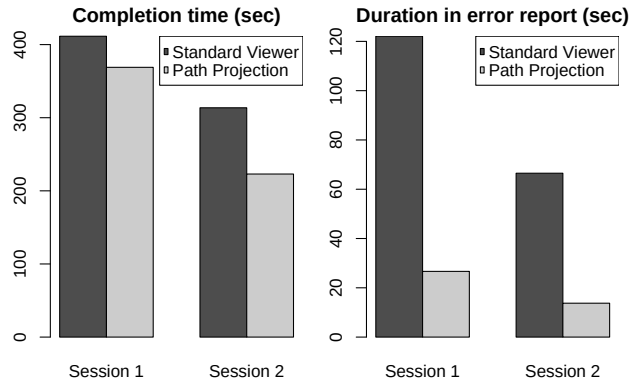


Figure 5: Quantitative data

first, PP second), the mean time improved 3:08 minutes from the first session to the second, and for the PP-SV order the mean time improved 55 seconds. We ran two one-way, within-subjects ANOVAs, analyzing each presentation order separately, and we found that both of these improvements were statistically significant ($F(1,3) = 12.78$, $p = 0.038$ and $F(1,3) = 19.33$, $p = 0.022$, respectively).

However, notice that the SV-PP improvement is much greater than the PP-SV improvement. We applied Cohen's d, a standard mean difference test, which showed that the SV-PP improvement was large ($d = 1.276$), and the PP-SV improvement was small-to-medium ($d = 0.375$). This provides evidence that while there is a learning effect, PP still improves user performance significantly.

Note that when analyzing completion times, we did not distinguish correct and incorrect answers. Indeed, it is unclear how this affects timings, especially since in many cases, only one tab out of several will contain an incorrect answer.

Accuracy. The chart at the top of Figure 5 also indicates, for each trial, how many of the checklist tabs were answered incorrectly. The total number of checklist tabs in each trial is listed at the bottom of the chart. We did not count the *Locks* tab in either of these numbers. User mistakes are evenly distributed across both interfaces. Participants made 10 mistakes (10.9%) under PP, compared to 9 mistakes (9.8%) under SV. For each participant, we summed the number of mistakes they made in each session, and we compared the sums for each interface using a Wilcoxon rank-sum test. This showed that the difference is not significant ($p = 0.770$), suggesting the distribution of errors is comparable for both interfaces.

Most of the participant mistakes occurred in trials 2.2 and 2.3, in which two potentially-racing paths actually contain a common unrealizable sub-path, making the data race report a false positive. In trial 1.3, one participant completed two tabs incorrectly, but there was only one underlying mistake: misidentifying the same child thread as a parent thread (and thus affecting the answers to two tabs).

Time spent in error report. We found that under PP, participants spend much less time with the mouse hovering over the error report compared to SV. The chart in the bottom right of Figure 5 shows the mean times for each session and interface. We found that on average, participants spend 20 seconds in the error report under PP, compared to 1:34 minutes under SV. This dramatic difference is highly significant ($F(1,3)=15.634$, $p < 0.001$) according to a user interface (within subjects) by presentation order (between subjects) mixed ANOVA.

We believe this difference is because PP makes the paths clearly visible in the source code display, whereas in SV, hyperlinks in the error report are heavily used to bring up relevant parts of the code. As additional evidence, participants themselves reported the same result: one noted that the error report is "necessary for the standard viewer, but just a convenience in [PP]."

Time spent in checklist. Finally, we found that participants spend 27 seconds more on average with the mouse hovering over the checklist in PP compared to SV. Since checklist times across different trial numbers are incomparable, we applied a user interface-by-trial between-subjects ANOVA, which indicated a statistically significant result ($p = 0.007$).

We were surprised by this result, because we expected roughly equal times for this in both interfaces. In retrospect, however, we realized that participants need not scroll or click on the error report very often under PP, and hence they may the mouse cursor idle over the checklist.

5.2 Qualitative Results

In addition to quantitative data, we also examined participants' answers to the questionnaires we administered. The questions are on a 5-point Likert scale, and we analyze them using either the Wilcoxon rank-sum test for paired comparisons, or the Wilcoxon signed-rank test otherwise.

Overall impressions. The upper chart in Figure 6 gives a box plot summarizing participants' opinions of the interfaces. Comparing the median responses for the first three questions, we see that participants felt PP took longer to learn, led to more confidence in answers, and made it easier to verify a race. However, none of these results is statistically significant ($p = 0.308$, 0.629, 0.152, respectively), perhaps due to the small sample size ($N = 8$). When asked to compare the interfaces head-to-head, all but one participant preferred PP ($p = 0.016$).

However, we should also note that several participants felt that they were unable to fairly assess PP due to the novelty of the interface and the limited amount of exposure to it in the experiment. One participant rated PP worse than SV in all metrics, yet stated he preferred PP due to its potential, saying, "once you get comfortable with seeing [only] pieces of your code, I feel it will be more efficient."

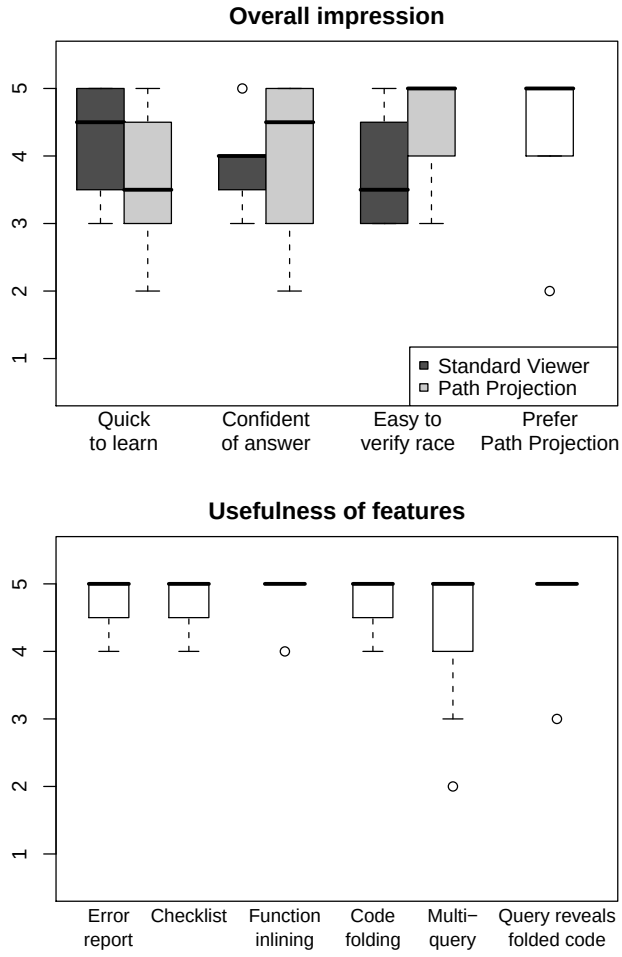


Figure 6: Participants' overall impression (1: disagree, 5: agree), and usefulness rating for particular features in Path Projection (1: not useful, 5: very useful)

Usefulness of features. Finally, participants generally rated all the features of PP as somewhat or very useful. The bottom chart in Figure 6 shows a box plot of participants' responses, and all answers are statistically significant in favor of PP compared to a neutral response of 3 ($p < 0.032$).

While participants felt that the error report was very useful, they also commented that it served mostly as an initial overview under PP, whereas it was critical under SV. This matches our quantitative result indicating participants spent much less time in the error report under PP.

The checklist was very well received overall. One participant said, "[It] saved me from having to memorize rules." Interestingly, two participants felt that, while the checklist reduces mistakes, verifying the data race takes longer. This conflicts with our own experience—as we mentioned earlier, participants in our pilot study, which did not include the checklist, took notably longer to triage error reports than participants in our current study.

We thought that participants would be wary about function inlining and code folding, since the former is an unfamiliar visualization and the latter hides away much code. However, participants rated both very highly, saying particularly that code folding was "the best feature," "my favorite feature," and "I love using this feature [code folding]."

Most participants found multi-query useful, but two did not. When we asked them why, they replied that they felt that the code folding was already doing an adequate job without it. However, they had forgotten that the multi-query was in use by default with the four preset queries (shown in Figure 2). We believe that multi-query is actually extremely useful in combination with code folding.

5.3 Threats to Validity

There are a number of potential threats to the validity of our results. The core threat is whether our results generalize. We had a small number of participants, all of whom were students rather than expert programmers who had significant experience debugging data races. The set of programs ($N = 2$) and error reports ($N = 6$) in the experiment was small. Moreover, participants were asked to triage error reports for unfamiliar programs, rather than code bases they had developed themselves. Lastly, despite long tutorials before each experiment, we were unable to eliminate the learning effect across our trials.

However, even with these limitations, our experiment did produce statistically significant and anecdotally useful information for our population and sample trials. We leave carrying out a wider range of experiments to future work.

One minor threat is the small set of changes we made to the programs (Section 4.5) to avoid confusion in our participants. Using more expert programmers as test subjects would obviate the need for this. Also, the SV interface represents a typical IDE, but is not an actual, production-quality IDE. We chose this approach on purpose, so that familiarity with a particular IDE would not be a factor, but we may have omitted features that would be useful for our task.

6. RELATED WORK

A number of static analysis tools provide custom user interfaces [3, 28, 8, 24, 20, 1, 17, 7] or IDE plug-ins [26, 18, 38, 21], or even both [34]. Most of these tools apply static analysis to defect detection, searching for a variety of different errors. In all cases, the tools report the errors in part by using program paths, e.g., to illustrate a suspect data flow or an erroneous execution trace. We surveyed these tools based on publicly-available screenshots and literature, and compared their features with Path Projection.

As can be seen from Table 1, most interfaces share some features with Path Projection, though the implementation of these features is rarely the same. Code Sonar has many features in common with Path Projection, but we believe some of its interface choices could be improved. For example, several of Code Sonar's features insert additional colored lines of text into the source code. We find this results in a multitude of interleaving colored lines that make the source code hard to understand.

Several tools provide features not present in Path Projection, e.g., they insert summaries of the internal results of their analysis at corresponding lines in the source code. For example, SDV and Code Sonar visualize the state of an automaton-based specification at lines in the path. A few tools provide means to query an analysis' internal results at a given program line or expression. For example, MrSpidey allows the user to query possible run-time values

Tool	Features (legend below) HLR	HPC	CF	FCI	IAC	IAR	OV
Path Projection	×	×	×	×			
SDV [3]	×				×		
PREFix [28]		×			×	×	
PREFast [28]	×	×		n/a[1]			
Prevent [7]	×				×		
Code Sonar [20]	×	×	×	×	×		
MrSpidey [17]	×	×				×	×
Fortify SCA [18]	×		×				×
Klocwork [26]	×		×				
Fluid [38]	×		×				
FindBugs (GUI) [34]	×	×		n/a[1]			
FindBugs (Eclipse)	×		×	n/a[1]			
CQual [21]	×						

Feature legend

HLR : hyperlinked error report
HPC : highlighted path in code
CF : user-controllable code folding
FCI : function call inlining
IAC : internal analysis in code
IAR : internal analysis result queries
OV : other visualization (see text)

[1]PREFast and FindBugs are intraprocedural, so FCI does not apply.

Table 1: Summary of tool interface features

for a given expression, based on a value-flow analysis. Some tools provide more graphical visualizations of paths. Fortify SCA illustrates a path as UML-style interaction diagram, and MrSpidey overlays lines on the source code to illustrate value flows. Path Projection's multi-query, path-derived code-folding, and check-list seem to be unique among the tools we studied. Interestingly, the FindBugs standalone GUI has features that are disjoint from its Eclipse plugin, which show how these features can sometimes be beheld to the constraints of the IDE framework.

To our knowledge, Path Projection is the first static analysis visualization toolkit targetable by a wide variety of tools. Of the tools we considered, only MrSpidey, FindBugs, and CQual are open source, and their interfaces are not easily extracted. Moreover, we are not aware of any prior studies that measure the impact of the user interface on a tool's efficacy. Indeed, many proprietary tools have licenses that specifically prohibit publishing the results of studies about their tools. We hope that Path Projection will open the door to further research on how to build tools most effectively.

Triaging is a necessary first stage in identifying and fixing a software defect. In some organizations, there are programmers who are responsible solely for locating and documenting software defects into bug databases [36]. Work on bug triaging has been focused on detecting duplicate bug reports [35], assigning bug-fixing responsibility [2, 10], or visualizing the progress of bug reports [11]. Path Projection, and our study, differs from this work in exploring how triage can be performed more accurately and efficiently.

Error report triaging is essentially a program comprehension task. In our study, the particular task is to determine whether two dereferences could possibly execute simultaneously in two different threads. There is a substantial body of tools aimed at assisting in program comprehension tasks typically (but not exclusively) associated with code maintenance or re-engineering (e.g., SHriMP [39], and Code Surfer [1], to name just two more recent tools). As far as we are aware, none of these tools has been specifically designed to support users of static analysis for defect detection, nor has any tool focused on means to visualize program paths at the source-code level.

A number of proposals aim to improve the quality of error reporting by generating more intelligent error messages [14, 30, 4, 22, 41], or by prioritizing those messages [27]. This can be helpful, and our work complements these techniques by visualizing results in the context of code as much as possible.

7. CONCLUSIONS

We introduced Path Projection, a new program visualization toolkit that is specifically designed to help programmers navigate and understand program paths, a common output of many static analysis tools. Path Projection visualizes multiple paths side-by-side, using function call inlining and code folding to show those paths in a compact format. Our interface also includes a multi-query search facility to locate and reveal multiple terms simultaneously. To our knowledge, Path Projection is the first tool-independent framework for visualizing static analysis results in particular, and program paths in general.

We measured the performance of Path Projection for triaging error reports from Locksmith, a data race detection tool for C. For this experiment, we added a task-specific checklist that enumerates the sub-tasks needed to triage each error report. Our controlled user study showed that, compared to a standard viewer, Path Projection reduced completion times for triaging data races, with no adverse effect on accuracy, and that users felt that Path Projection was useful. We also found the checklist improved performance overall compared to a pilot study. To our knowledge, ours is the first study of the impact of the user interface on the efficiency and accuracy of triaging static analysis error reports.

We believe that Path Projection has many potential applications beyond bug triage. We intend to apply it to bug fixing and other programming tasks, such as interactive debugging. We also intend to study the use of checklists to complement static analysis tools.

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