Testing and Understanding Error Recovery Code in Java Applications

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Abstract. Server applications are expected to handle lower level faults and keep them from bringing down the whole system. Java provides a program-level exception handling mechanism in response to error conditions (that are translated into *exceptions* by Java VM). However, exception handling code is often widely scattered throughout an application and untested. This paper presents a program visualization tool *ExTest* that shows precisely all the handlers for exceptions triggered by certain kinds of operations, and for each of these handlers all the witness paths of how the operation would be triggered. Thus *ExTest* helps programmers understand the exception handling behavior of Java programs and also facilitates testing exception handling code.

1 Introduction

The Java programming language provides a program level exception handling mechanism in response to error conditions that happen during program execution. Subsystem faults (e.g. disk failure, network congestion) are translated into exceptions (e.g. `java.io.IOException`, `java.net.SocketException`) by the Java Virtual Machine [1]. Proper handling of these exceptions in program code is extremely important for reliability and fault-tolerance in server applications built in Java.

An exception handling mechanism helps separate exception handling code from code that implements functionalities during normal execution. However, exception handling code that deals with certain kinds of faults is still widely scattered over the whole program and mixed with other exception handling code, or even irrelevant code, making it hard to understand the behavior of the program under certain system fault conditions.

Moreover, exception handling blocks, especially those corresponding to system faults, are often left untested, for the reason that they can not be triggered by just tuning input data of the program. In our previous work [2], we proposed a white box testing metric for the exception handling behavior of the program. Supporting program analysis algorithms together with a testing framework using fault injection [3] were presented. Although very precise analysis is used in identifying exception def-uses, false positives can not be fully eliminated. It is a tedious and dif cult job to identify the real false positives when they can not be exercised during the test.

In this paper we present *ExTest* a program visualization tool built on top of Eclipse[4]. Based on program analysis introduced in [2], it groups together handlers

that handle exceptions triggered by a set of fault-sensitive operations[1]. Thus it facilitates navigation of the program code that relates to exceptions triggered by certain operations of interest. It also shows all program paths via which these operations can be reached from a call site in a try block, helping a user to understand the exception handling structure and to identify spurious exception def-uses.

The rest of this paper is organized as following: In Sec. 2 we give a brief overview of exception def-use analysis that was introduced in [2]. Section 3 shows the structure and the functionality of *ExTest* in detail. In Sec. 4 we discuss the related work in the area of understanding and improving exception handling code in Java programs. Our future research work is discussed in Sec. 5.

2 Background

In [2], we proposed a def-use testing methodology for exception handling code, which is analogous to the *all-uses* criteria of traditional def-use testing [5]. We repeat some of the key concepts here: In a given program execution, each fault-sensitive operation may produce exceptions that reaches some subset of the program's `catch` blocks. We can treat fault-sensitive operations as the definition points of exceptions, and `catch` blocks as uses of exceptions. We define *exception-catch (e-c) links*:

Definition ***e-c link*** *Given a set P of fault-sensitive operations that may produce exceptions, and a set C of* `catch` *blocks in a program, we say there is an e-c link([ ] between and if could possibly trigger ; we say that a given e-c link is* **executed** *in a set of test runs T, if actually transfers control to by throwing exception during a test in .*

Currently in the experiments conducted, we select to contain all the native methods in JDK library that do network or disk I/O. In the rest of this paper we make this assumption unless explicitly stated otherwise[2].

Figure shows the organization of our exception def-use testing system, which composed of two kinds of program analysis: static (compile time) and dynamic (run time) analysis. The static analysis calculates the possible *e-c links* for a program, which will be introduced shortly. The dynamic analysis monitors program execution, calles for fault injection to trigger an exception at an appropriate time, and records test coverage: The compiler uses the set of *e-c links* to identify where to place instrumentation that will communicate with the fault injection engine during execution. This communication will trigger injection of a particular fault when execution reaches the `try-catch` block of an *e-c link*. The injected fault will cause an exception to be thrown upon execution of a fault-sensitive operation of the *e-c link*. The compiler also instruments the code to record the execution of the corresponding `catch` block. The tester runs the program and gathers the *observed e-c links* from each run. The testing goal is to drive the program into different part of the code so that fault injection can help exercise all the *e-c links* found in the program. Finally, the test harness calculates the overall coverage information for this test suite: the *observed e-c links* vs. the possible *e-c links*.

[1] Either a `throw` statement or a native method that may be affected by some fault a hardware or OS failure and produce some exception.

[2] The analysis and the testing framework are not dependent on the P selected.

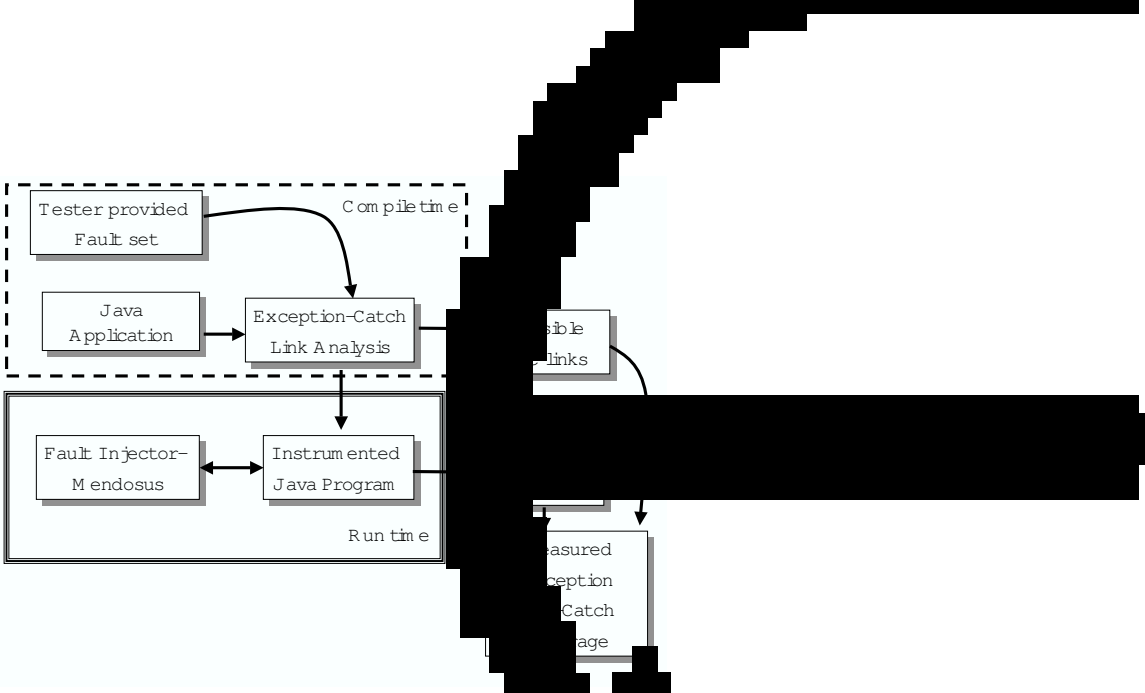


Fig. 1. Exception def-use Testing Frame

Next we introduce the static analysis that nds the possible Java program. Two algorithms are developed: ***Exception- o w*** and ***DataRe*** [2].

Exception- o w is a data o w analysis, similar to Reaching De nit runs on call graphs instead of control o w graphs. Each p is prop call edges in the reverse direction until some `try-catch` block c is m the call site and catches the exception thrown by ; thus an *e-c link* (rec Moreover, during the propagation process, in each method (i.e. call gra node) to which propagates, we can record the immediately *previous* method, thus indicating where comes from. The exception propagation path can be collected *on d mand* after the analysis nishes.

It is obvious that using a more precise analysis for call graph const ction such as points-to analysis [7, 8] helps to reduce the number of infeasible *e-c links* found by exception- o w analysis. However, in practice even a very precise cal aph building algorithm introduces many infeasible *e-c links*. Figure 2 is an exam e of typical uses of the Java I/O packages. Figure 3 illustrates how infeasible *e-c l s* are introduced even given a fairly precise call graph. As we can see, the `catch` `readFile` only handles exceptions result from disk failure and the `catch` in `rea et` only handles those triggered by network faults. But exception- o w informati s merged in `BufferedInputStream.read1()` and propagated to both `readFile` nd `readNet`.

We developed ***DataReach*** analysis to reduce the number of in sible *e-c links* produced. The intuition was to use data reachability, usually obtai d using points-to analysis, to con rm control- o w reachability. For example, continuing with Fig. 2, we can prove `SocketInputStream.read()` is **not** reachable from the call site `fsrc.read()` in method `readFile`, by showing that during the lifetime of the call `fsrc.read()`, no object of type `SocketInputStream` may be either loaded from any static/instance eld of some class/object, or created by a `new` statement. In this way we can show that all the control o w paths associated with this *e-c link* are not

```
void readFile(String s){
  byte[] buffer = new byte[256];
  try{
    InputStream f =new FileInputStream(s);
    InputStream fsrc=new BufferedInputStream(f);
    for (...)
      c = fsrc.read(buffer);
  }catch (IOException e){ ...}
}
void readNet(Socket s){
  byte[] buffer = new byte[256];
  try{
    InputStream n =s.getInputStream();
    InputStream ssrc=new BufferedInputStream(n);
    for (...)
      c = ssrc.read(buffer);
  }catch (IOException e){ ...}
}
```

Fig. 2. Code Example for Java I/O Usage

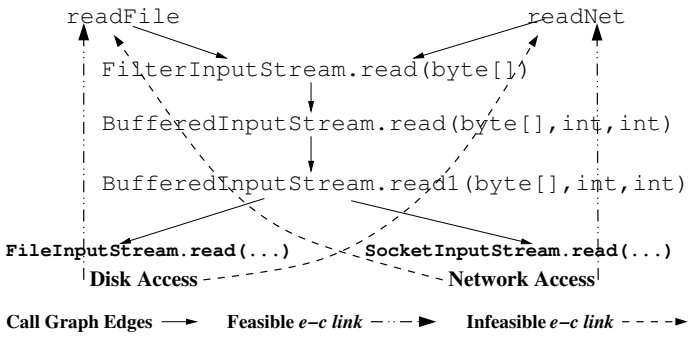


Fig. 3. Call Graph for Java I/O Usage

feasible, so that the infeasibility of the *e-c link* from `SocketInputStream.read()` to the `catch` block in `readFile` is proved. In general, *DataReach* tries to prove the infeasibility of each *e-c link* output by *Exception- ow* analysis, and only outputs those that it cannot prove to be infeasible. Our experiments showed that *DataReach* improved the precision of the system signi cantly; it reduced the number of possible *e-c links* by 41% on average in 6 benchmarks used in [2].

3 Visualization Tool ExTest

In addition to being used by the exception def-use testing system, the information produced by these analysis, if carefully organized and visually displayed in an integrated development environment (IDE), can greatly facilitate both testing and program understanding of the exception handling code. We developed an Eclipse plug-in *ExTest*, which invokes these analysis and organizes the output data into tree views to let users browse *e-c links* and trace exception propagation paths.

3.1 Motivation

When studying the exception handling [illegible]avior of [illegible] programs, we found that, as mentioned in Sec. 1, exception handle[illegible] deal [illegible] kinds of faults are often scattered in the program and mixed w[illegible] [illegible]ers [illegible]t ta[illegible]re of other kinds of error conditions.

```
void readString(String s){
 String buffer = s;
 try{
  InputStream n =new String[illegible]uffe[illegible]putStream[illegible];
  InputStream in=new Buffe[illegible]dIn[illegible]tream(n);
  for (...)
   c = in.read(buffer);
 }catch (IOException e){ . . }
}
```

Fig. 4. Unreach[illegible]catch Block

For instance, a `catch` clause that h[illegible]s an I/O e[illegible]n may appear at each program point where some I/O channel [illegible]tive. Each [illegible]se `catch` clauses may handle I/O exceptions triggered by differ[illegible]ult-sensitiv[illegible]ations (e.g. le write or socket creation), as shown in Fig. 2. Wor[illegible]ome of these[illegible]ch clauses never handle any I/O exception: Suppose in the progra[illegible]taining the[illegible] in Fig. 2, there is another method `readString`, shown in Fig. 4[3]. [illegible]catch bloc[illegible]his method handling I/O exception will **never** be triggered, beca[illegible]e code in [illegible]orresponding `try` block only reads from a string buffer in the m[illegible]ry no actu[illegible] operation involved. Yet the `try-catch` structure is necessary f[illegible]e program to [illegible]pile.

If a programmer wants to learn this p[illegible]am's behav[illegible]der disk failure, she needs to nd all the `catch` clauses that may [illegible]le exceptio[illegible]at result from disk faults. Suppose a powerful lexical search tool[illegible] Java lang[illegible]knowledge as well as program speci c information (e.g. type) [illegible]ailable. Th[illegible]e can easily locate all the `catch` clauses that handle `IOExcepti[illegible]` more ge[illegible] types of exceptions, but she still has to manually inspect at least a[illegible]ee `try-[illegible]ch` blocks in both Fig. 2 and Fig. 4, and sometimes code reachable [illegible]em too[illegible]ead of just the one in method `readFile` that actually handles the [illegible]n resu[illegible]m disk failure. The problem becomes much more severe in non-toy [illegible]ver[illegible]ications.

Using the analysis mentioned in S[illegible], w[illegible]ompute all the potential *e-c links* of the program. Each *e-c link* (t[illegible]us t[illegible]ult-sensitive operation that triggers the exception and where it is handle[illegible]us, [illegible]an help solving the above problem by grouping *e-c links* according to t[illegible] value. Since the number of fault-sensitive operations that relate to disk I/O is s[illegible], one can just browse *e-c links* starting with

[3] This program a single Java class c[illegible]ning the `main` method calling all of these three methods (also de ned in this class) i[illegible]. 2 and 4 is used as a running example in the following discussion about *ExTest*.

these operations to to get a good estimate of all the `try-catch` blocks that are related to disk I/O.

Ours is a program analysis which computes a safe approximation of program behavior. False positives are unavoidable, which means for some of the *e-c links* (, the exception thrown at never reaches . It is up to the human programmer to decide whether an *e-c link* is actually spurious. This is especially important for exception def-use testing, because spurious *e-c links* can never be exercised during any test. Our program analysis provides exception propagation path data for all *e-c links*. Displaying these paths visually in Eclipse IDE helps to identify the spurious ones. In order for identifying spurious *e-c links*, all propagation paths for a given *e-c link* must be shown

3.2 Tool Structure

Our program analysis are implemented as modules in the Soot Java Analysis and Transformation Framework [8] version 2.0.1. Upon user request, *ExTest* (i) calculates environments of the current working program (e.g. class paths) using Eclipse service starts another process running Soot with our modules enabled, and (iii) reads the data of the Soot modules after the process nishes.

In the Eclipse IDE, we want the users to be able to explore the *e-c links* (e.g. being all the `catch` clauses and their relationships with the fault-sensitive operations) as well as the witness paths that demonstrate the feasibility of an *e-c link*. The data generated by the Soot modules are organized in an XML le, which contains all the *e-c links* found in the given program and information about the paths needed by *ExTest* to perform the intended functionality.

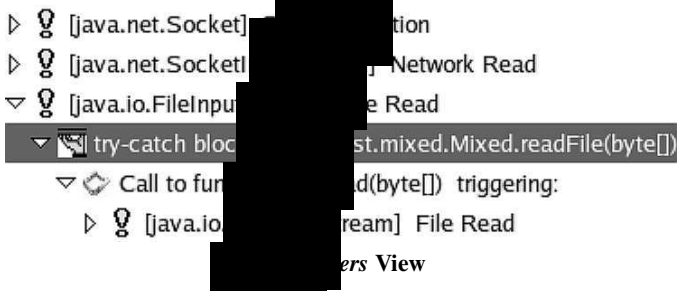
3.3 Browsing *e-c links*

Each record of an *e-c link* in the output data of our Soot modules contains the following information: the ID of , the position of in source code and the call site(s) in the corresponding `try` block which may lead to the execution of . These *e-c links* can be grouped in two ways: by or by . We implemented both of them by means of two different views in Eclipse: the *Handlers* view and the *Triggers* view.

Figure 5(a) shows the *Handlers* view: a tree-view in Eclipse where *e-c links* are grouped by the `try-catch` blocks. These `try-catch` blocks are further grouped by their de nition positions: the methods, classes, packages in which they are de ned. Each `try-catch` block can be expanded to show all the fault-sensitive operations that may trigger exceptions reaching the `catch`. The last `try-catch` block in the gure is highlighted and expanded. It is de ned in package `iotest.mixed`, class `Mixed` and method `readFile`. We can see that one method call in the `try` block reaches a fault-sensitive operation in the JDK: File Read .

Figure 5(b) shows the *Triggers* view, where the *e-c links* are grouped by the fault-sensitive operations. By expanding the File Read operation we can see that only one `try-catch` block in the program handles an exception thrown by read of a le. So if a user is interested in program behavior under a disk fault, she can just concentrate on this one `catch` block.

(a) **ew**



***ers* View**

F iews of *e-c links*

Thanks to the environmen by Eclipse IDE, these two n be interactively explored. The block, the statements in ck that may lead to the fault-sensi ed in the Java source le editors, up the view. For example, in both views, v he actual code for the `try` block #0 by double clicking on the lin

3.4 Displaying All Pa *-c link*

We also want to displa that show how p in an *e-c link* (n be reached from the `try` block tha ds to . Selecting and displaying only ne (the shortest) path for each *e-c l* ough, especially with the presence of ne false positives. In order for a pr to decide that an *e-c link* is spurious, s has to make sure that **all** the con s from the corresponding `try` to are ctually infeasible. So it is necess *est* to display **all** these paths to be practic ly useful. But the total number of e exponential to the size of the program]! Clearly, the approach of gather mping all these paths into an output le r the analysis nish

A *w* analysis records the pro gation paths of each $\in$ by annotating nodes on the call graph. These annotation can be trivially changed into annotations on call edges. Since the set of fault-sensiti operations is pre-selected according to the kind of faults that are of interest to the u (not depending

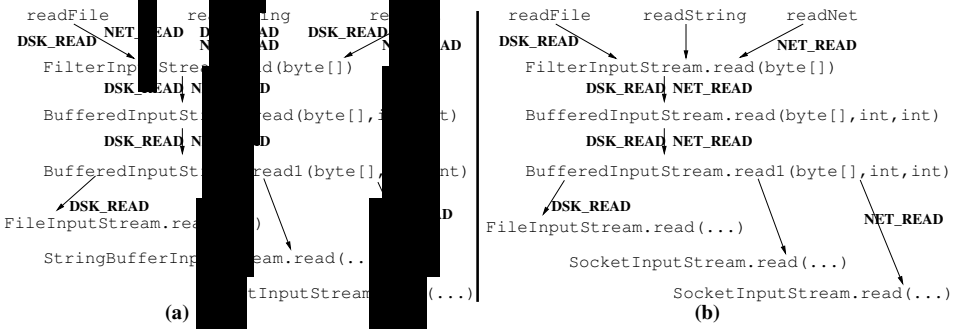


Fig. notated Call Graph

on the program b analyzed), ze of the annotated call graph is at most linear in the size of the inal call gra gure 6(a) shows the annotated call graph for the example in Figs 4. Edges call graph are annotated with IDs of the fault-sensitive operati ccording to esult of *Exception- ow* analysis.

The problem h this appr is that the results of *DataReach* are ignored. As stated before, *E ion- ow* an s alone would leave too many false positives in the graph; with thi , the user st manually explore many unnecessary call edges to decide that ain *e-c l* s infeasible. So we need to take the advantage of *DataReach* to r his wor .

Recall that *ch* p s that some of the *e-c links* are infeasible by showing the infeasibility ll t ntrol o w paths of these *e-c links*. To be able to incorporate its result th ted call graph, we modi ed *DataReach* so that for each *e-c link* (, nno ns of on all the call edges associated with are *con- rmed* only if *anno* ve the infeasibility of (i.e. survives *DataReach* test). During t tput of the call graph, only the *con rmed* annotations are written with the graph s many spurious annotations can be removed. Figure 6(b) shows the annotated call h with the uncon rmed annotations removed.

With the ated call graph, the paths can be generated on demand in *ExTest*. Suppose one u hooses to trace the paths of some *e-c link* . *ExTest* can retrieve from the grap the outgoing edges departing from the `try` block that are annotated with , and th get methods can be displayed to the user. Then the user can choose to trace one of t methods, *ExTest* can retrieve all the outgoing edges from that method that are anno with and display the target methods of these edges. This process can be repea ntil the fault-sensitive operation itself is reached.

Fig. 7. Exception Propagation Path

Figure 7 is the expanded view of the last *e-c link* shown in Fig. 5(b). Only one witness path was discovered by the analysis, which precisely re ects the analysis result shown in Fig. 6.

However, we are not always so lucky in bigger programs; paths in these programs can get very complicated, especially inside the JDK library classes that make heavy use of polymorphism. Figure 8 shows part of the *Triggers* view displayed when browsing *e-c links* in one of the testing benchmarks used in [2] a FTP server written in Java [10]. Witness paths of one *e-c link* are partly expanded in the gure, with the fault-sensitive operation `SocketInputStream.read()` highlighted.

As can be seen from the gure, the fan out of some of the nodes along the paths is large (e.g., `InputStreamReader.close()`). Furthermore, many of the methods appear more than once, which indicates the possibility of recursion introducing a path with unbounded length. Since these paths are extracted out of a call graph, expanding the second appearance of a method on a path brings exactly the same set of children in the tree view. This is wasteful and introduces unnecessary complexity into the view. Manually identifying the recursion in a complex view like this is not trivial. Therefore we have automated recursion detection in *ExTest*. As shown in Fig. 8, many methods are annotated with ... and they are **not** expandable, which shows that the method has been called recursively and further expansion is not necessary.

If we only show only one witness path of the *e-c link* the natural selection would be to show the shortest one the view can be greatly simpli ed, but the real complexity of the problem would be hidden from the user. With only one path shown, the user is not helped in identifying infeasible paths; however, expanding and highlighting the shortest path automatically among all paths may help in understanding the overall program structure quickly. We are now working on implementing this feature in *ExTest*.

4 Related Work

This paper presents a tool to help understand and maintain the exception handling feature of Java programs, based on *exception-catch link* analysis. There is much previous research work in both exception handling analysis and its usage in various software engineering tools. Here we will discuss only the works that are most closely related to the tool discussed in this paper[4].

There are tools built to improve exception handling in programs, for example avoiding exception handling through subsumption, or nding unhandled exceptions for a given method. Jo et. al [11] presented an interprocedural set-based [12] exception- o w analysis for checked exceptions. A tool [13] was built based on this analysis which shows, for a selected method, uncaught exceptions and their propagation paths. It is unclear from the paper whether a certain path for each exception is selected and displayed, or if all of the paths are displayed. Experiments show that this is more accurate than an intraprocedural JDK-style analysis on a set of benchmarks ve of which contain more than 1000 methods. Robillard et. al [14] described a data o w analysis that propagates both checked and unchecked exception types interprocedurally. Their tool *Jex* illustrate

[4] More discussion about research results in fault injection, exception analysis and optimizations, infeasible paths detection and program testing can be found in the related work section of [2].

Fig. 8. Exception Propagation Path

exception handling structure in application code. It analyzes exception control o w and thus identi es exception subsumption. These analysis mentioned above are less precise than ours. Their call graph is constructed using class hierarchy analysis, which yields very imprecise results [15, 16]. Even if a fairly precise call graph[5] were provided for their analysis, the precision of the results would be resemble those of our *Exception-ow* analysis using the same call graph. So they are not capable of identifying that the `catch` clause in Fig. 4 can never be triggered.

Reimer and Srinivasan [17] introduced *SABER*, part of which targets at a wide range of exception usage issues in order to improve exception handling code in large J2EE applications and ultimately to increase robustness of the program. These issues include swallowed exceptions, single `catch` for multiple exceptions, a handler too far away from the source of the exception and costly handlers. Warnings are given to the programmer upon recognizing one of these problems. Unfortunately, analysis used to identify these potentially problematic code areas are not introduced. Their work, if combined with our analysis, might prune some of the warning messages to reduce the workload of user, and produce more valuable information at the same time. For instance, suppose the `catch` clause in Fig. 4 is empty, since our analysis shows that it can never be triggered, warnings relative to this `catch` clause can be suppressed. Moreover, when facing a `try` block with many call sites that potentially throw the same type of exception, our analysis can show whether these exceptions are of the same origin and with similar propagation paths, which in turn helps deciding whether the `try` block needs to be split.

5 Conclusions and Future Work

We present a program visualization tool that facilitates navigating code related to the exception handling feature of Java programs, based on the program analysis used in exception def-use analysis [2]. We want to reveal all information needed to the user, while carefully organizing the data to help human browsing and reasoning.

Despite of our current efforts, Fig. 8 shows us that exploring program code based on conservative static program analysis results can be dif cult. One way to alleviate the situation is to use more precise analysis (but possibly more expensive) to reduce the size of the result data.

The current implementation of *ExTest* only displays the results of the static analysis in [2]. Our next step is to display visually both the static and dynamic analysis results, because we believe that it will give user more intuition and hints when browsing. We are working on combining two kinds of dynamic information into the current views: testing coverage data of *e-c links* and dynamic call graphs/trees. Once we incorporate these data, we can highlight *e-c links* not covered during the test in the *e-c link* views (shown in Fig. 5) to draw the user's attention to these untested parts of the program. Furthermore, when a user chooses to explore the paths of a certain *e-c link*, with the dynamic call graph/tree, we can graphically show which of the edges are actually executed during the test. On this view, the users might want to concentrate on the fringe

[5] For example, a call graph constructed using *Spark*, a eld sensitive context insensitive points-to analysis module in Soot.

of the already executed edges, to see why the program is taking the wrong branch . Thus *Extest* can help the user either to compose another test case or decide that edge is actually infeasible.

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