Technical Report CS15-02

An Eclipse-based Integrated and Automated Fault Localization System

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I hereby recognize and pledge to fulfill my responsibilities as defined in the Honor Code, and to maintain the integrity of both myself and the college community as a whole.

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Contents

List of Tables

List of Figures

Chapter 1

Introduction

The process of debugging can be complex and difficult. The first task associated with debugging is identifying the fault, and this step, *fault localization*, is the most expensive in terms of time cost [4]. In this chapter, we discuss current techniques for fault localization. In addition, we highlight the major goals of this research project.

1.1 Current State of the Art

At present, the process of fault localization is mostly manual, though several techniques exist that attempt to automate the process. A number of these techniques are described in detail below. Many of these automated fault localization techniques (AFLs) compare the flow of execution through a faulty program when executing passed and failed test cases. This type of approach employs *coverage monitoring*, the tracking of which statements are executed by test cases. Any statement that is executed is said to be *covered*. Tools such as Java Code Coverage (JaCoCo) [3] provide information regarding which statements are covered by a supplied test suite. By analyzing code coverage for different test cases, these AFLs seek to determine which statements are most likely to contain the fault.

Many Coverage tools exist, including those designed for integrated development environments such as Eclipse. For example, JaCoCo provides interactive coverage monitoring within Eclipse. However, JaCoCo only reports total coverage for a test suite; that is, the tool reports which statements were covered, partially covered, or not covered after execution of all of the test cases. This system does not report on coverage of individual test cases. Since *per-test coverage* is vital to the application of several fault localization techniques, the lack of such information leads to increased difficulty in applying those techniques.

As an alternative to the more popular JaCoCo, we will make use of a lesser known tool called CodeCover. Though a number of interfaces are provided, including command-line and Apache Ant, we will focus on the Eclipse plugin for the purpose of this project. Unlike JaCoCo, CodeCover is designed to produce coverage on a per-test basis. The system includes support for breaking coverage information for a JUnit test suite across test methods, automatically generating distinct coverage data

for each test method. This functionality makes CodeCover ideal to the goals of this project.

1.2 Goals of the Project

There are two significant goals for this project. The first is the empirical evaluation of existing risk evaluation functions to determine the most effective on average. This is a necessary step in the process toward completion of our second goal, because no study has made the specific comparison necessary.

The second goal of this project is the development of an Eclipse plugin which displays the per-test coverage from a test suite and per-statement suspiciousness analysis, through an interactive system, as well as to demonstrate its effectiveness. The plugin will allow a programmer to select individual or multiple test cases and view their coverage, or to select individual statements and view a list of covering test cases as well as suspiciousness rating and ranking.

We hypothesize that making per-test coverage (in addition to suspiciousness information), the basis for many fault localization techniques, readily available will allow programmers to more rapidly identify faults in programs. This hypothesis will be investigated through human study, employing experienced programmers, specifically undergraduate students, to compare the benefits of per-test coverage when compared to full suite coverage. To generate test cases for evaluating our plugin, we will introduce faults into programs using the MAJOR mutation analysis system [6].

1.3 Thesis Outline

This thesis consists or five chapters, which cover a wide variety of topics related to the project. In Chapter 2, we discuss past approaches to problems in the area of fault localization. In addition, we cover existing tools which we will incorporate into our final system or make use of to produce intermediate data. Chapter 3 features a thorough discussion of the method of approach used to achieve the results. Specifically, we relate the details of our test environment and setup for the empirical comparison of risk evaluation functions, including test programs, method of producing per-test coverage, and system for evaluating risk evaluation functions. In addition, Chapter 3 covers implementation details of the Eclipse plugin.

Chapter 4 provides the empirical results of the risk evaluation function comparison study. This includes various data visualization figures and a discussion of these data. We also discuss our conclusions as a result of this study, as well as the impact these results have on our plugin implementation. Chapter 5 discusses the human study used to evaluate our plugin, beginning with the format and setup details and including the results of the study. We also discuss our conclusions based on the results of the study. The final chapter reviews the project as whole, a annotates difficulties encountered, reiterates conclusions drawn in the previous chapters, and a discusses future work.

Chapter 2

Related Work

2.1 Automated Fault Localization Techniques

There are a wide variety of existing fault localization techniques [4]. Many of these methods make use of per-test coverage analysis, such as Set-union, Set-intersection, Nearest Neighbor, and Tarantula. There are other AFLs that do not use per-test coverage, such as Cause Transitions [1], but they are outside the scope of this project.

Set-union and Set-intersection compare the coverage of a single failed test case to the coverage of all of the passed test cases. Set-union defines the initial set of suspicious statements by the set of all test cases visited by the failed test case but not visited by any passed test cases. Conversely, Set-intersection defines the initial set as the set of all statements visited by every passed case but not by the failed test case. Nearest Neighbor works similarly to the previous techniques, but instead of considering all of the passed test cases, it only considers one. By some method, the passed test cases that is most similar to the failed test case is identified. Nearest Neighbor defines the initial set as the set of all statements visited by the failed case and not by the passed case.

Tarantula is notably different from the previously mentioned techniques. Instead of determining a set of suspicious statements, Tarantula ranks techniques in order of suspiciousness. However, Tarantula still utilizes per-test coverage reporting. In their paper, Jones and Harrold present an empirical analysis which indicates the superiority of Tarantula in both efficiency and effectiveness when compared to the other techniques described above, as shown in Figure 1 [4]. Since Tarantula uses per-test coverage, this provides substantial evidence for the importance of per-test coverage in the fault localization process.

Xie et al. present an alternative discussion of various risk evaluation functions focusing primarily on theoretical correctness [13]. They argue that many existing risk evaluation formulas are actually functionally equivalent. In addition, they provide theoretical analysis that shows the superiority of specific functions relative to one another both within functionally equivalent groups and between those groups. Through detailed theoretical proof they show that the equivalent sets ER1 and ER5 are maximal for accurately calculating suspiciousness. The ER1 set includes a pair

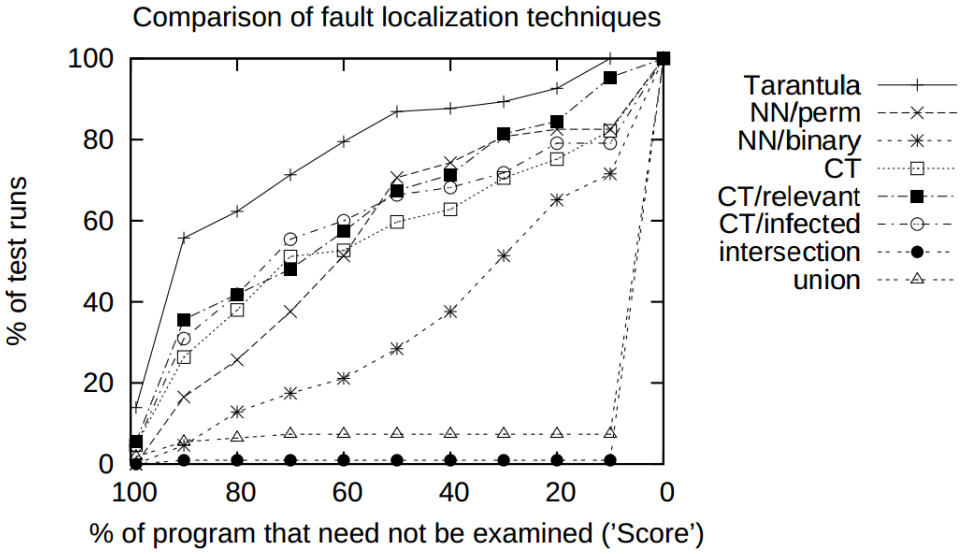

Figure 2.1: An empirical comparison of several fault localization techniques by percentage of code eliminated from consideration. The graph plots percentage eliminated (determined by the rank of the faulty statement) against frequency that the tool achieved that level of success. Tarantula is demonstrated to achieve better results more often than other techniques.(from [4])

of formulas studied in a paper by Naish et al. [7] The ER5 equivalent set includes three functions, two of which are also studied in the paper by Naish et al. The third is discussed in a paper by Wong et al. [12] It is important to note that all the above risk evaluations also require per-test coverage data.

As a followup to the paper by Xie et al. mentioned above, Qi et al. [9] performed a detailed empirical to study the practical effectiveness of the theoretically maximal functions as proven by Xi et al. This study includes a wide variety of risk evaluation functions, and compares them by applying them to practical, real-world programs and faults. The various formulas were inserting them into popular automated program repair system GenProg. GenProg uses genetic programming, applying a risk evaluation function to repeatedly alter a faulty program by mutating suspicious statements. In their study, Qi et al. modified GenProg to use several different formulas. By comparing the effectiveness of automated repair when using each different risk evaluation function, they were able to provide substantial empirical evidence regarding the superiority of certain formulas. Note that this method of comparison differs from that pursued by Jones and Harrold [4], discussed previously, which compared the relative suspiciousness ranking of faulty statements (referred to as EXAM score).

Surprisingly, Qi et al. did not confirm the results shown by Xie et al. Instead, they found that several functions, eliminated from consideration as maximal functions early in the proof provided by Xie et al., were actually better than expected. Specifically, Qi et al. show that in practice, the Jaccard risk evaluation function performed equally

as well or better than all other formulas considered. They conclude that, at least within the context of automated program repair, Jaccard should be favored when choosing a risk evaluation function. In addition, they further conclude that the EXAM score method of comparing these formulas does not accurately reflect their relative performance in the context of automated program repair.

In another paper [8], Parnin and Orso performed a human study about the real-world effectiveness of fault localization techniques. In that study, they asked participants, graduate students in computer science with varying levels of experience, to perform debugging tasks. Participants were asked to compare their experiences when using standard debugging practices with using an Eclipse plugin designed to display Tarantula suspiciousness ranking. This plugin was as simple as possible, to eliminate from consideration any other factors besides suspiciousness ranking. The only functionality provided was a list of suspicious statements which, when selected, navigated the environment to that line in the source code. When evaluating their hypotheses, he authors considered the relative average amount of time required for each task, with and without the plugin. They also considered the relative experience level of the participants, which they evaluated based on number of tasks completed. In addition, they also experimented with artificially raising and lowering the rank of the fault statement in the suspicious statement list. Finally, Parnin and Orso used their plugin to record the order in which users visited the suspicious statements, and asked the participants to complete a questionnaire about their experiences and use of the tool.

Parnin and Orso came to a number of conclusions regarding several different comparisons. First, they noticed that in general, the participants did not on average complete the tasks faster with statistical significance. However, they did notice a significant improvement in performance when using the tool if the subject in question was more experience. This suggests that, if the tool were more refined and participants more used to the tool, it might actually be significantly more helpful. They also found evidence that suggests that the exact rank of the statement does not significantly affect the difficulty of locating the fault when using the tool. In particular, participants often navigated the list of statements in a non-linear fashion: sometimes they skipped ahead or backwards. When skipping ahead, the authors suggest that participants may have been skipping over code blocks they had already deemed unlikely to contain the bug. Finally, they conclude that there is no such thing as perfect bug understanding in practice. That is, simply seeing a faulty statement out of context is not sufficient to identify and repair the bug.

We notice first that a large number of the negative results from Parnin and Orso's study, in regards to the effectiveness of automatic fault localization, may have stemmed from the simplicity of the Eclipse plugin tested. We therefore hypothesize that with a more sophisticated tool, programmers will have significantly improved performance over use of traditional debugging techniques. Since the goal of our tool is to provide per-test coverage as context for suspiciousness, we suggest that our tool is likely to outperform traditional debugging.

2.2 CodeCover Coverage Analysis

CodeCover produces coverage information for Java, and has built in functionality for generating coverage information on a per-test suite, per-test case, and even per-test method basis. In addition, CodeCover is designed to function within Eclipse. All parts of the coverage monitoring process can be done through the Eclipse development environment. Since the final goal of this project is to produce an integrated Eclipse tool for fault localization, using per test coverage and risk evaluation, CodeCover is ideally suited to our purposes.

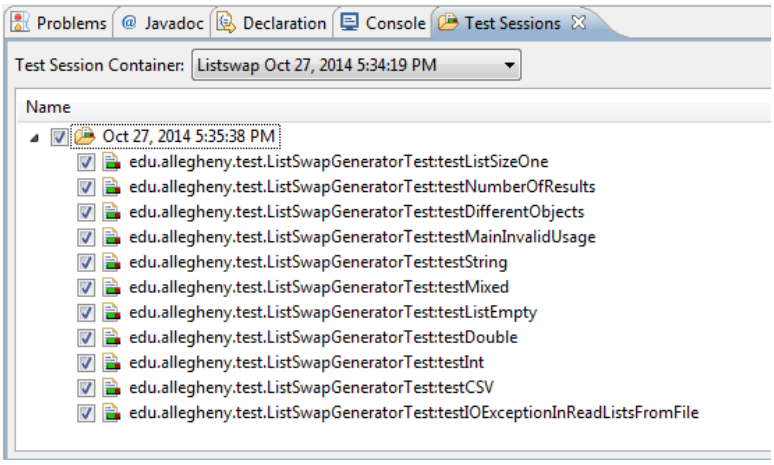

Figure 2.2: Screenshot of CodeCover Eclipse plugin displaying per-test coverage output from a single execution of a JUnit test suite.

CodeCover works in several stages. The first step to acquiring coverage information is instrumentation. During instrumentation, numerous statements are procedurally inserted into the Java source files which are to be included in the coverage analysis. In the context of Eclipse, these files are manually marked, since there may be source files for which coverage information is unnecessary. The statements that are inserted during instrumentation record various information as the code is executed, including which existing Java statements were executed, and which test case or method exeucted them. After instrumentation is complete, the newly instrumented source files, as well as any other source files, are compiled as normal.

CodeCover provides functionality for using existing JUnit test cases and test suites for coverage analysis. With an existing Eclipse project with a JUnit test class, CodeCover can simply be enabled and executed. By default, CodeCover produces output in the form of a several coverage reports. The output includes a full coverage report for every test method within the JUnit test; that is, per-test coverage data, as shown in Figure 2.2.

After executing a test process through the CodeCover Eclipse, per-test coverage can be viewed in several ways. First, coverage can be viewed on a per-test basis within Eclipse. As shown in Figure 2.3, selecting one or more test methods displays coverage

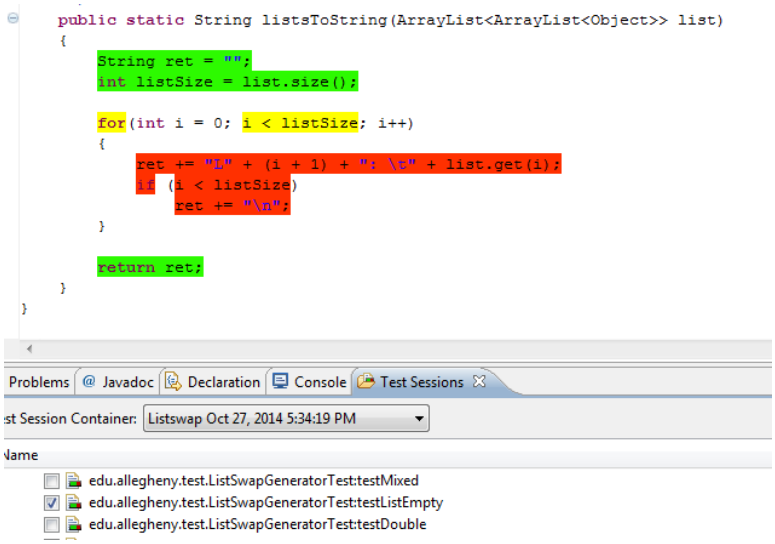

Figure 2.3: Screenshot of CodeCover Eclipse plugin displaying coverage highlighting for a single test method. Statements highlighted in green were covered by this test method, and those in red were not.

information for those test methods only. In addition to viewing coverage within Eclipse, CodeCover allows coverage information to be executed in a variety of formats. Using provided template XML (eXtensible Markup Language) files, coverage data can be exported, for example, as hierarchical HTML (HyperText Markup Language) documents or as CSV (Comma Separated Value) files.

2.3 MAJOR Mutation

MAJOR is a fault seeding and mutation analysis tool that integrates directly into the Java compiler [6]. *Mutation* is the process of intentionally introducing faults into a program for various purposes, including evaluation of test suite quality and testing for fault localization techniques. Mutants generated are either *killed* by the test suite or *live*. A mutant is killed if a test case fails; that is, the test suite was sufficient to identify the fault. Live mutants either indicate that the test suite is insufficient or that the introduced fault was in fact logically equivalent to the original code.

MAJOR can perform a number of conditional mutations, including replacing binary arithmetic, logical, relational, shift and unary operators with valid alternatives. Figure 4 shows an example of one possible mutation performed by MAJOR. The tool can also replace literal values with alternatives; these various mutation types can be selected with compiler operators. Along with the domain specific language provided by MAJOR, this allows for great flexibility and extensibility. Additionally, MAJOR has been shown to be relatively efficient, with only about 15% runtime overhead. It is also noteworthy that MAJOR utilizes coverage analysis to improve efficiency.

A recent paper by Just et al. [5] indicates a statistical correlation between mutant

```
public static Type classify(int a, int b, int c) {
    int trian;
    if (a <= 0 || b <= 0 || c <= 0)
      return Type.INVALID;
    trian = 0;
          ... (additional statements) ...
}
```

```
public static Type classify(int a, int b, int c) {
    int trian;
    if ((a <= 0 || b <= 0) != c <= 0)
      return Type.INVALID;
    trian = 0;
          ... (additional statements) ...
}
```

Figure 2.4: (top) Original program and (bottom) program after mutation.

detection and real world fault detection. Although they also note that as much as 20% of real world faults cannot be represented by mutants, this still suggests that mutants are a viable substitute for real world faults in the context of software testing and, similarly, fault localization.

Chapter 3

Method of Approach

In this chapter, we discuss the implementation details for our system. The implementation can be broken into four distinct sections:

1. XML parsing
2. Intermediate representation
3. Simplified representation
4. Risk evaluation

3.1 XML Parsing

When CodeCover produces per-test coverage information, it stores the results in a container. Though CodeCover features several coverage report export types, including hierarchical HTML, these reports do not include all information necessary for this project. Specifically, these export formals only include general per-test coverage information, displaying percent coverage for each test. They do not include information related to precisely which tests executed each statement, which is a requirement for suspiciousness analysis.

Due to the limitations in CodeCover export formats, we are forced to make use of the more complex XML container. Since the container is in XML format, we must first parse the file before we can perform analysis. To that end, we utilize DOM (document object model) parsing to store the entire container as a tree structure. We chose DOM over SAX(simple API for XML) due to the complexity of the container file. Since SAX does not store the document in memory in its entirety, multi-pass analysis is both more efficient and less complex when using DOM parsing.

3.2 Intermediate Representation

After DOM parsing is complete, provided no errors occurred, the document tree root is passed into the intermediate representation constructor. The IR (intermediate representation) for the container is designed to be simple to build while traversing a DOM

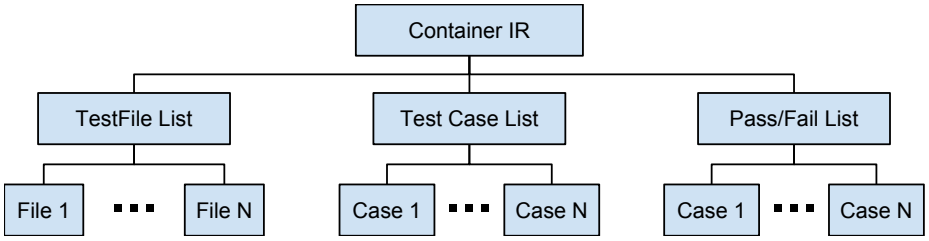

Figure 3.1: Diagram of data structure for IR.

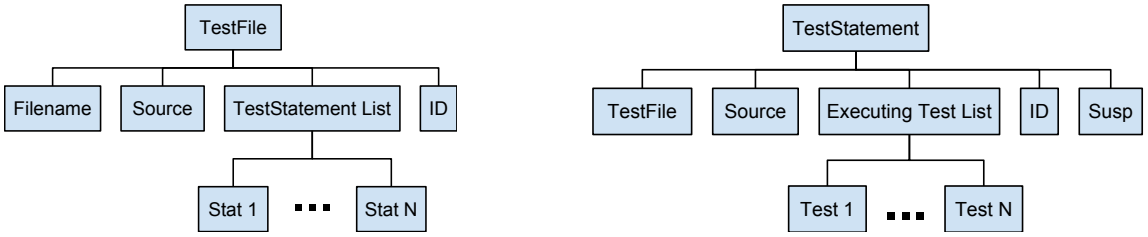

Figure 3.2: Diagram of data structures used within the IR to store files (left) and statements (right)

of a CodeCover container. The `ContainerIR` object contains a list of `TestFile`s, as well as a list of `String` names of test cases. The object also includes a boolean values, in which the i^{th} element indicates the pass/fail status of the i^{th} test case. A visualization of the container IR, as well as its internal data structures, can be found in Figures 3.1 and 3.2 respectively.

Each `TestFile` object contains the name and source code of the file as a `String`, the internal identification numberfor the file as an `int`, and a list of `TestStatement`s. A `TestStatement` includes an ID and source code for the statement, each stored as `String`s. In addition, the `TestStatement` object stores a `TestFile` parent object and the suspiciousness value associated with the statement. Finally, the statement includes a `boolean` list, where each element corresponds to a test case. These boolean values indicate whether the respective test case executed this statment. A `TestStatement` can be uniquely identified by the combination of its source file and ID.

CodeCover coverage containers include all required information, divided into three sections. First, the container lists all source files included in coverage analysis, including the entirety of their source code, the name of the file, and a unique internal identification value. Following the source files is a hierarchical list of all statements within those files. These statements are defined by by their category, source file, and character offset within the source file. For this project, we only consider basic statements (in Java, this essentially refers to executable statements terminated with semicolons).

The final section of a CodeCover container is the per-test coverage data itself. This is represented by a series of test cases, each of which contains a child for every file executed by that test. Under each file is a list of specific statements executed

```
<BasicStmnt CovItemId="S19"
  CovItemPrefix="net.sf.jniinchi.JniInchiStructure.java"
  Intrnl_Id="457">
    <LocList>
        <Loc EndOffset="3716" SrcFileId="4" StartOffset="3672"/>
    </LocList>
</BasicStmnt>
```

Figure 3.3: Excerpt of a container showing a single `BasicStmnt` element. This excerpt is taken from the CodeCover container produced from the JniInchi case application. The statement defined here has the ID `S19`, and consists of the source code from character position `3672` to `3716` within the file with name `net.sf.jniinchi.JniInchiStructure.java`.

by that test inside that file. These statements are identified by their alphanumeric identifier.

Our system processes these sections in the order they appear above. Using the DOM produced from parsing, we can easily traverse the relevant segments of the container. Traversal of the DOM tree consists of repeated iterations of sub-levels of the XML hierarchy, in order to locate a node with a specific name. Throughout this process, we make no assumptions about the sequence in which nodes appear. Rather than assume that, for example, a given node is always the first child, we always use a loop structure to make certain we identify the correct node.

In order to identify all source files defined by the XML container, we first locate the `SrcFileList` node. We then iterate through its children to locate all `SrcFile` nodes. For each `SrcFile` node found, we extract the attributes of that node and add a `TestFile` to the `ContainerIR` file list.

Once we have located the source files, we must next identify the statements. To do so, we first locate the hierarchical statement definition root. Beginning with that root node, we recursively traverse the entire sub-tree. Within a the hierarchical component of a CodeCover container, there exists a `BasicStmnt` node, demonstrated by the excerpt shown in Figure 3.3, for every basic statment in the source code. For each `BasicStmnt` node, we add a new statement to the correct `TestFile`. In order to do so, we must first identify the `LocList` child node, followed by its `Loc` child node. The attributes of the `Loc` node include the source code character offset for the basic statement in question. Between the attributes of the `BasicStmnt` node and those of the `Loc` node, we extract the information necessary to create a new `TestStatement` object. Once this recursive traversal of the statement hierarchy is complete, the `TestFile`s in the `ContainerIR` will contain all basic statements.

Since we now have a complete list of basic statements, we can process the coverage data section of the container to identify test cases and their coverage. To begin, we first iteratively locate the `TestSession` node, whose children include a `TestCase` node for each test case in the test suite. We add the name of each test case to the `ContainerIR` test case list, then process the children of the node to find coverage

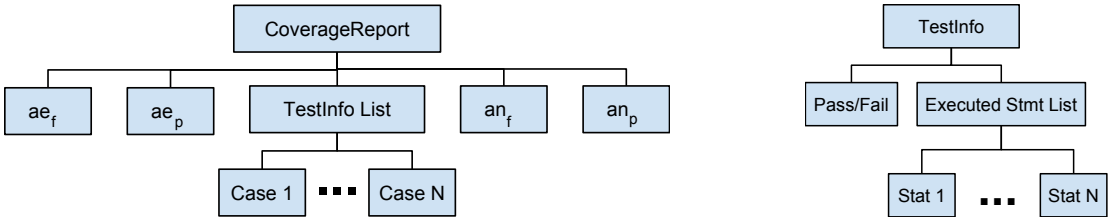

Figure 3.4: Diagram of data structures for simplified representation (left) and storing information about a single test case within the SR (right).

data. Each test case node contains a hierarchy of `CovList`, `CovPrefix`, and `Cov` nodes. We locate all `CovPrefix` nodes, which each correspond to a single file, then retrieve the `TestFile` corresponding to this node from the list of test files within the `ContainerIR`. Finally, we iterate through all `Cov` children of the `CovPrefix` to find all basic statements covered by a given test case within a given file. For each statement identified, we mark the corresponding `TestStatement` as covered.

In addition to coverage data, a `TestCase` node also contains a `Comment` attribute. This content of this attribute is comprised of the entire text output produced when the test case was executed. When the test case passes, this attribute is empty; however, when a failure occurs, the description of the failure is stored in this node. As a result, we can observe this attribute to determine the pass/fail status of a given test. We ascertain this data by checking the `Comment` attribute for the starting string `"Failure"`. Since this word always heads the description of a failure, the `Comment` of a failed test will always begin with the same text. We also allow the text `"Error"` to indicate a failing test, since an unhandled error in a test case indicates that the test did not complete successfully. This pass/fail value is recorded in the boolean list stored in the `ContainerIR`, where true indicates a passed test and false indicates a one in which a failure occurred.

3.3 Simplified Representation

The intermediate representation discussed in section 3.2 is appropriate as a preliminary data structure. However, it is not conducive to suspiciousness analysis. All of the risk evaluation functions considered in this project require four pieces of information for each statement that must be evaluated: ae_f, ae_p, an_f, and an_p [13]. These variables represent the number of test cases that meet certain requirements for a given statement. Variables ae_f and ae_p denote the number of test cases that executed the given statement and failed or passed respectively. Similarly, an_f and an_p refer to the number of test cases that did not execute the statement and passed or failed, respectively. These four values become the input to each of the suspiciousness functions. Therefore, the simplified representation (SR) that best suits our needs is one that stores these values for each statement, with no extraneous information.

In order to convert the IR to the described simple representation, the first step

is to build a list of `TestInfo` objects, which represent individual test cases. Each `TestInfo` object includes a pass/fail boolean value, as well as a boolean list that describes, for each statement under test, whether that statement was executed by this test. A visualization of this data structure can be found in Figure 3.4. We extract this information from the IR by iterating through the list of test case names. For each test case, we check the execution status of that test case for each statement, storing this information in a list (where each element corresponds to a single statement, and true indicates the statement was executed by this test). Next, we cross check that test case index with the corresponding element in the pass/fail boolean list in the IR and set the pass/fail status of the new `TestInfo` object to reflect that value.

Iterating through the `TestInfo` list, we can determine the $ae_f, ae_p, an_f,$ and an_p of each statement. For each test case, we check whether the test passed then determine which statements it executed by iterating through the boolean list stored in the `TestInfo` object. For each statement, we increment the appropriate variable depending on its pass/fail and execution status. The result is a list, for each of the four variables, in which each element corresponds to its value for the corresponding statement. After completing this process, we have a `CoverageReport` object with all of the information necessary for risk evaluation. This data structure is demonstrated by the diagram in Figure 3.4.

3.4 Risk Evaluation

There are many different risk evaluation functions, but they are structurally similar. We internally represent risk evaluation functions using our `REFunction` interface. This interface provides abstract methods for returning the name of the function and for evaluating the function on provided $ae_f, ae_p, an_f,$ and an_p. Figure 3.5 provides an example implementation of the REFunction interface. For each function included, we create an implementation of `REFunction`. A complete list of `REFunctions` is stored in a static array of the same name in `CoverageReport` for ease of iteratively performing all evaluation functions.

When performing risk evaluation, we iterate through the specified functions. For each of these functions, we store the results of analysis in a `ResultsList` data structure. This structure allows for ease of sorting analyzed statements by suspiciousness rating. In addition, the suspiciousness values of the `ResultsList` are normalized to a zero-to-one scale according to

$$L_i = \frac{L_i - L_{min}}{L_{max} - L_{min}}.$$

In this equation, L_i refers to the i^{th} element of the `ResultsList`, and L_{max}, L_{min} refer to the maximum and minimum values in the list, respectively. Though normalizing the results does not change the ordering of the statements, it does make the actual suspiciousness values easier to compare across multiple different functions. The final result of analysis is a list of statements, ordered from most suspicious to least

```
public class Jaccard implements REFunction {
  public double analyze( int Iaef, int Iaep, int Ianf, int Ianp ) {
    double aef, aep, anf;

    aef = (double) Iaef;
    aep = (double) Iaep;
    anf = (double) Ianf;

    return ( aef / (aef + anf + aep ) );
  }

  public String toString() {
    return "Jaccard";
  }
}
```

Figure 3.5: Implementation of REFunction interface for Jaccard function.

suspicious, with values ranging from zero (not suspicious) to one (very suspicious). In the case of undefined results to risk evaluation functions (specifically, any time a risk evaluation function returns `NaN`), we treat the value as zero. This avoids problems such as completely uncovered statements always appearing as the most suspicious value.

3.5 Overview

When executing the system, the main class, `Test.java`, must be invoked with three additional parameters. The first parameter is the name of the CodeCover container to be analyzed. This parameter must be *only* the filename, and the file must be placed in the `containers` directory. The second parameter is the name for the output file—the output path is fixed to the (to be created) results directory within the present working directory. The final parameter is the source code for the inserted fault in the system represented by the supplied CodeCover container.

Execution begins with parsing the XML container. When the document has been stored as a DOM, it is passed forward to the `ContainerIR` constructor, which processes the document into an IR as described previously. The IR is then passed to the `CoverageReport` class, where the test class is executed and coverage information is collated into the simple representation. Suspiciousness evaluation is then completed using all risk evaluation functions specified.

After performing suspiciousness evaluation, the results are written to an output file in CSV (comma separated value) format. The attributes *Function, Statement ID, Filename, Suspiciousness, Rank, Statement Count, Case Application,* and *IsFault* serve to uniquely identify a statement while providing information on risk evaluation. The *IsFault* field is always either true or false, and is produced by comparing the source of each statement to the provided faulty statement. Only when these state-

ments match will true be written; otherwise, false is written. This format conforms to *tidy data* [11], a "standard way of mapping the meaning of a dataset to its structure", in that each variable forms a column and each observation forms a row. This organizational structure allows for reliably simple evaluation of data using statistical analysis tools. Though tidy data contains extensive redundancy, that redundancy simplifies the data analysis and visualization process.

Chapter 4

Experimental Results

In this chapter, we will discuss our method of verifying the accuracy of our system, a discussion of our case study, an analysis of the results produced by our system, and a listing of possible threats to the validity of our results.

4.1 Testing

Throughout the development process, we used several mechanisms to verify the accuracy of our system. Prior to starting implementation, we selected a very simple sample program to ensure that we could use CodeCover to produce per-test coverage data. The program we selected was a small system developed by Tristan Challener, Nathaniel Blake, and Eric Weyant as a course project at Allegheny College. The system consists of four source files and eleven JUnit test cases, and has functionality related to file input, list manipulation, and CSV output. We selected this application primarily for its simplicity, existing JUnit test suite, and our familiarity with the code. Its simplicity allowed us to easily import the system to Eclipse and set up the environment to successfully run all included tests. This process was aided by our familiarity with the code and tests; although we did not have to modify any executable code or the content of any tests, we were required to update certain aspects of the tests to behave correctly on a Windows operating system.

After importing our selected application into Eclipse, we installed the most recent version of the CodeCover Eclipse plugin. By following directions provided in the CodeCover documentation, we were able to execute the application through CodeCover and produce per-test coverage data. Because CodeCover containers are internal mechanisms for storing coverage data, and are not meant to be viewed directly, there is very little documentation available. As such, we were forced to examine the container output to determine its structure before developing parsing tools. See Section 3.2 for additional details about the content of CodeCover container files.

As we proceeded with the implementation described in Chapter 3, we cross-checked the data produced from our parse tool with that available through interacting with the CodeCover Eclipse plugin. For example, we were able to verify that our parsed coverage data was consistent with the data shown in Eclipse. Verifiable

data included as statement source code, execution counts for each statement, and test case pass/fail status. In addition, we verified the values generated for ae_p, ae_f, an_p, and an_f through manually totaling the number of appearances of each statement in the container coverage segment to the values of each of the aforementioned variables.

Through these processes we were able to establish a reasonable level of confidence in the correctness of our system. Automated testing was not a feasible option for this process due to the complex nature of the container being parsed, since any testing would require repeating the parsing process—thereby negating the benefits of the test. Automated testing was used, however, to verify the accuracy of the risk evaluation function implementations used in the system. We designed table-driven JUnit tests with multiple test inputs to ensure that all functions were correctly implemented, within a reasonable degree of confidence.

4.2 Case Study

In order to provide further evidence for the accuracy of our system, and to produce preliminary comparison data for our tested risk evaluation functions, we performed a case study with another selected application. Due to the simplicity of the test application described in 4.1, we chose a different case application for our study. The program we selected is Jni-InChi [**?**], which "enables Java software to generate IUPAC's International Chemical Identifiers (InChIs) by making Java Native Interface (JNI) calls to the InChI C library developed by IUPAC".

This application, along with several others, were prepared and executed through MAJOR by Sarojini Balasubramanian. The mutation data were provided as well. We selected this application from the several other applications available due to limitations of CodeCover that were not clear until we began testing various applications. Many tested applications had passing JUnit test suites after being important to Eclipse, but still produced the following (or similar) error when we attempted to run them through CodeCover:

```
[FATAL] An error occured when trying to compile the instrumented sources.
```

According a discussion post at the CodeCover `sourceforge` page, made by CodeCover developer Tilmann Scheller [**?**], there is not currently any means of producing more verbose output (including details on compiler errors) through Eclipse. Additional discussion at the same source indicated that CodeCover is able to "instrument a single source directory only." Since the majority of projects provided and executed with MAJOR feature several source directories, we were severely limited in choice of case study application. Fortunately, the Jni-InChi system incorporates only a single source directory, and we were able to generate CodeCover output for this system.

In order to produce meaningful results, the CodeCover execution of JUnit must complete and must feature at least one failure—otherwise, coverage data is not written to the container or no suspiciousness information can be generated, respectively. To

```
119:ROR:==(java.lang.Object,java.lang.Object):
  FALSE(java.lang.Object,java.lang.Object):
  net.sf.jniinchi.JniInchiAtom@<init>:117:el == null |==> false
137:STD:<CALL>:<NO-OP>:
  net.sf.jniinchi.JniInchiStructure@addBond:99:
  bondList.add(bond) |==> <NO-OP>
149:LVR:POS:NEG:
  net.sf.jniinchi.JniInchiStereo0D@<init>:79:3 |==> -3
194:COR:||(boolean,boolean):LHS(boolean,boolean):
  net.sf.jniinchi.JniInchiWrapper@checkOptions:183:
  op.startsWith("-") || op.startsWith("/") |==> op.startsWith("-")
197:STD:<CALL>:<NO-OP>:
  net.sf.jniinchi.JniInchiWrapper@checkOptions:189:
  sbOptions.append(flagChar + option.name()) |==> <NO-OP>
```

Figure 4.1: Mutants selected for use in case study.

achieve this, we repeatedly selected arbitrary *killed* mutants generated by MAJOR (their killed status guarantees at least failing test case).

There were various complications that forced us to reject mutants. First, any mutant that causes the Eclipse JUnit `TestRunner` to crash prematurely and not complete the entire test suite cannot be used. This is due to meaningless or incomplete coverage data, which is not useful for generating suspiciousness data. In many cases, if the `TestRunner` crashed prematurely, CodeCover would not write *any* coverage data to the test session container. Thus, we skipped and mutants with this property. We also passed over any mutants that modify non-executed code; for instance, static variable declarations, which, though statements, cannot be executed by test cases. This makes mutants of this type invalid for the purpose of suspiciousness analysis. Any remaining mutants were considered valid. From those not disqualified, we chose five arbitrary mutants to form the basis for this case study. These mutants can be seen in Figure 4.1.

Since we only consider basic statements when parsing the CodeCover container, inserted mutants must be formatted in such a way that they occur as a Java statement and get parsed by CodeCover as basic statements. For `<NO-OP>` mutants such mutant 137, we achieved this by replacing the listed line with a statement that does nothing. Specifically, we insert a local variable initialization an always-false `if` statement making use of that variable (if the variable is never referenced, CodeCover will not recognize the initialization as a basic statement). That variable initialization is treated as the faulty treatment, effectively simulating a no-operation statement. Mutants which modify the condition inside an `if` statement can be represented by moving the condition to a boolean variable declared and initialized directly before the `if` statement. That boolean variable initialization is treated as the faulty statement. The remaining mutant, number 149 as labeled in Figure 4.1, requires no additional modifications since it directly alters a basic statement.

When CodeCover processes source code and builds a test session container, it

copies the entire source code into the container, but removes all comments from the content. As such, line numbers and character offsets within CodeCover are not comparable to those within the original source code. Therefore, in order to locate the inserted fault within the container, we require the source code for the faulty statement to be included as an input to our system, as described in 3.5.

4.3 Results Analysis

In order to process the data produced by our system for the case application, we made use of the R functional language for statistical computing [**?**]. Since our data already conforms to tidy data standards [11], and is formatted as CSV, it was relatively simple to import the data directly into R. We begin our analysis by reading each CSV results file into a single `data.frame`. We then vertically merge all of the resulting tables into a single table with the same variables, but including all observations rather than only those for a single case application (mutation). After merging the tables, we add the EXAM score for each statement to the table as a new variable, calculated according to

$$EXAM = \frac{Rank}{StatementCount} \times 100.$$

Before making any further use of the data, we create a new table consisting only of the statements which correspond to the fault. This is accomplished by selecting only observations from the table in which the `IsFault` attribute is true. We then break this table down into five smaller tables according to the risk evaluation function. For each of the resulting tables, we extract the `Exam` attribute vector and calculate its mean (the average EXAM value for a given function across all case applications). Using these average values, we construct a new table consisting only of the attributes `Function` and `Exam`, made up of five observations—one for each function and its corresponding average EXAM value. The final step before visualization is to recreate the original five tables, with EXAM values added, by splitting the large table according to case application.

For each of the five case application tables, as well as the average EXAM value table, we produce a single bar graph. To do so, we utilize the `qplot` function from the `ggplot2` library [**?**]. The bar graphs plot EXAM score against risk evaluation function, each displaying the performance of every risk evaluation function for a different case application. The final graph plots the average performance of each function across all mutations. The code used to generate one of the graphs can be seen in Figure 4.2.

Figure 4.3 displays the bar graph visualizations of our results. For nearly every case, we notice that every risk evaluation function performed nearly or exactly the same. Though the graph for Jni-InChi mutant 137 appears to be wildly skewed, it is important to note that the range of the graph only covers five percent. Even in the worst case, none of the risk evaluation functions achieved worse than a score of 3.5%. Recall from Section 2.1 that EXAM score is a lower-is-better metric indicating the

```
library( ggplot2 )
attach( jniinchi_119_fault )
graph_119 <- qplot( Function, Exam, data=jniinchi_119_fault, geom="
   bar",
          ylab="EXAM Score (%)", xlab="Risk Evaulation Function",
        stat="identity", ylim=c( 0,5 ),
        main="EXAM Score Per Risk Evaluation Function (JniInChi
           Mutant 119)",
        sub="JniInChi Mutant 119" )
graph_119 <- graph_119 + theme( axis.title=element_text( face="bold.
   italic" ) )
detach( jniinchi_119_fault )
```

Figure 4.2: Example code for generating visualization of results.

percent of statements that need to be visited, when proceeding sequentially through a list of suspicious statements, before encountering the actual faulty statement.

4.4 Threats to Validity

Due to complications related to the use of CodeCover to generate per-test coverage, we were only able to produce results for a single case application. As such, we can only provide a certain degree of confidence in the correctness and versatility of our system for processing CodeCover containers. However, after testing and developing the system with a very simple application, no modifications were necessary to process the far more extensive output generated when running CodeCover on our case application. This allows us to conclude that we can be reasonably confident that our system will likely work for any coverage container. The difficultly, then, lies in the limited capacity of CodeCover to produce output for a wide variety of source applications.

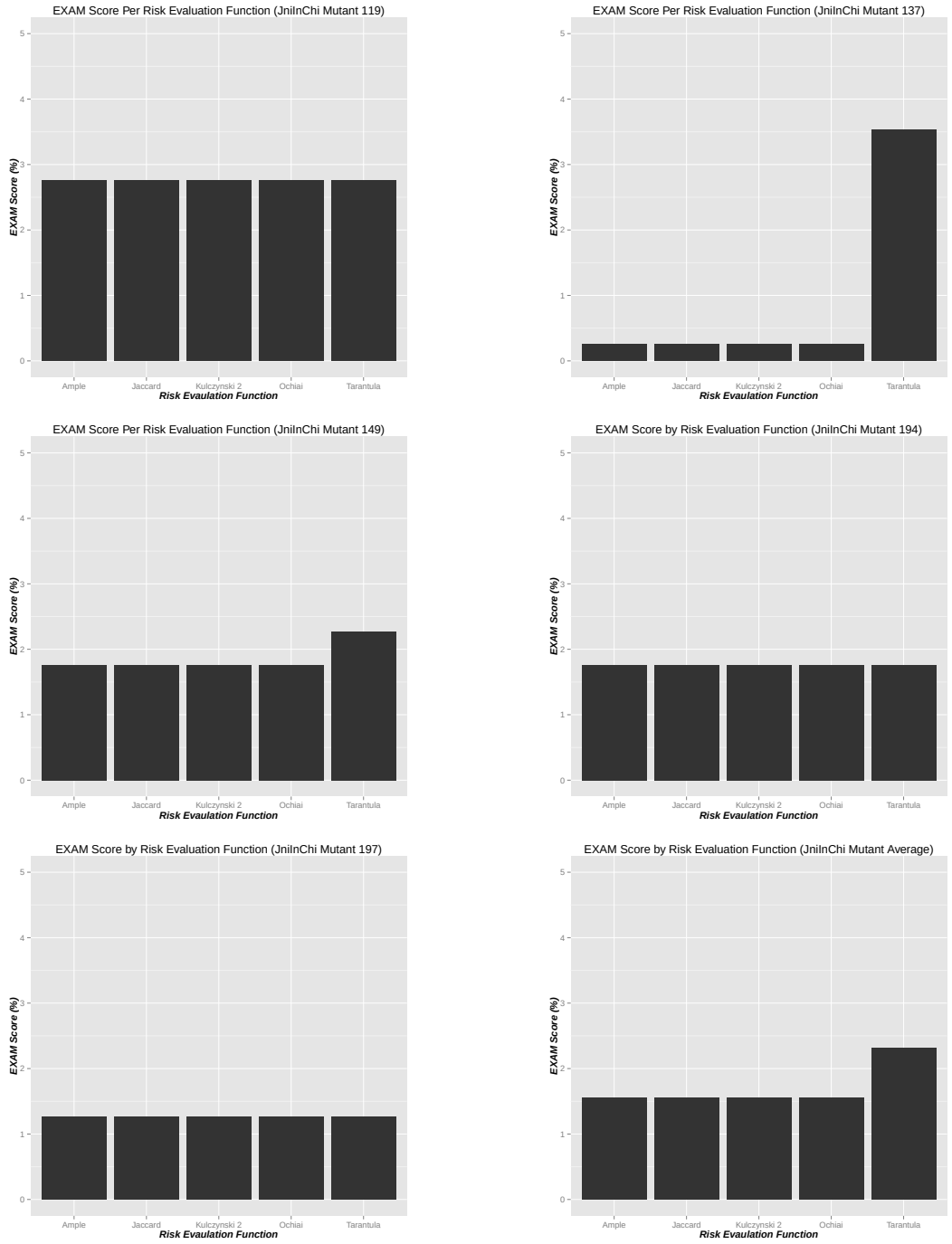

Figure 4.3: Graphs produced through R showing the results of running the system on each selected mutation on our case study. Each graph shows the EXAM score achieved by each risk evaluation function for a different mutant, with the exception of the last (lower right) which shows average EXAM score overall for the case application. All graphs are fixed to the same EXAM range from 0% to 5%.

Chapter 5

Discussion and Future Work

In this chapter we discuss the significance of our results and review important underlying assumptions that may affect the relevance of results. In addition, we discuss future work that may follow directly from the results and conclusion to this project. Finally, we summarize the important points presented throughout this thesis.

5.1 Summary of Results

5.2 Future Work

5.3 Conclusion

Appendix A

Source Code

This appendix contains all source code for our system. Source code is included in alphabetic order by class name.

A.1 System Code

```
package edu.allegheny.cov;

public class Ample implements REFunction {
  public double analyze( int Iaef, int Iaep, int Ianf, int Ianp ) {
    double aef, aep, anf, anp;

    aef = (double) Iaef;
    aep = (double) Iaep;
    anf = (double) Ianf;
    anp = (double) Ianp;

    return (  aef / ( aef + anf ) ) - (  aep / ( aep + anp ) );
  }

  public String toString() {
    return "Ample";
  }
}
;
```

```
package edu.allegheny.cov;

import java.util.ArrayList;
import org.w3c.dom.Document;
import org.w3c.dom.NamedNodeMap;
import org.w3c.dom.Node;

/**
 * Intermediate representation for a CodeCover container.
 * Processes a DOM basic representation of the XML container,
 * locating source file and coverage information necessary for
```

```
 * suspiciousness evaluation.
 *
 * @author Tristan Challener
 *
 */
public class ContainerIR {
    private ArrayList< TestFile > files;
    private ArrayList< String > testCases;
    private ArrayList< Boolean > passFail;

    /**
     * Process DOM provided to locate all source file, basic
        statement,
     * and coverage information relevant for suspiciousness
        evaluation.
     *
     * @param doc DOM root object for the XML container
     */
    public ContainerIR( Document doc ) {
        files = new ArrayList< TestFile >();
        testCases = new ArrayList< String >();
        passFail = new ArrayList< Boolean >();

        // Build IR from DOM
        Node cont = doc.getFirstChild();  // This should be "
            TestSessionContainer" node

        // First find SrcFileList node
        Node srcList = null;
        for ( Node child = cont.getFirstChild(); child != null;
            child = child.getNextSibling() ) {
            if( child.getNodeName() == "SrcFileList" ) {
                srcList = child;
                break;
            }
        }
        if( srcList == null ) {
            System.out.println( "No source files found!" );
            return;
        }

        // Locate all source files and add to list
        String source = "EMPTY";
        String filename = "NOFILE";
        int id = 0;
        for( Node srcFile = srcList.getFirstChild(); srcFile != null
            ; srcFile = srcFile.getNextSibling() ) {
            if( srcFile.getNodeName() == "SrcFile" ) {
                NamedNodeMap attributes = srcFile.getAttributes();
                source = attributes.getNamedItem( "Content" ).
                    getNodeValue();
```

```
                filename = attributes.getNamedItem( "Filename" ).
                    getNodeValue();
                id = Integer.parseInt( attributes.getNamedItem( "
                    Intrnl_Id" ).getNodeValue() );
                files.add( new TestFile( source, filename, id ) );
            }
        }

        // Get hierarchy root
        Node root = null;
        for( Node child = cont.getFirstChild(); child != null; child
            = child.getNextSibling() ) {
            if( child.getNodeName() == "MASTRoot" ) {
                root = child;
                break;
            }
        }

        // Find statements
        findStatements( root );

        // Find coverage for all statements found
        checkCoverage( cont );
    }

    /**
     * Process DOM from root to locate all basic statements, adding
     * each identified statement to its source file in the IR.
     *
     * @param root Root of DOM tree from which to begin searching.
     */
    private void findStatements( Node root ) {
        if( root == null ) {
            return;
        }

        // Find all basic statements
        for( Node stmt = root.getFirstChild(); stmt != null; stmt =
            stmt.getNextSibling() ) {
            if( stmt.getNodeName() == "BasicStmnt" ) {
                NamedNodeMap attributes = stmt.getAttributes();
                String id = attributes.getNamedItem( "CovItemId" ).
                    getNodeValue();
                String sourceFileFullName = attributes.getNamedItem(
                    "CovItemPrefix" ).getNodeValue();
                Node location = null;
                for( Node locList = stmt.getFirstChild(); locList !=
                    null; locList = locList.getNextSibling() ) {
                    if( locList.getNodeName() == "LocList" ) {
                        for( Node loc = locList.getFirstChild(); loc
                            != null; loc = loc.getNextSibling() ) {
                            if( loc.getNodeName() == "Loc" ) {
```

```
                            location = loc;
                            break;
                        }
                    }
                    break;
                }
            }
            NamedNodeMap locAttributes = location.getAttributes
                ();
            int start = Integer.parseInt( locAttributes.
                getNamedItem( "StartOffset" ).getNodeValue() );
            int end = Integer.parseInt( locAttributes.
                getNamedItem( "EndOffset" ).getNodeValue() );
            int sourceId = Integer.parseInt( locAttributes.
                getNamedItem( "SrcFileId" ).getNodeValue() );
            TestFile file = findFile( sourceId );
            file.setFilename( sourceFileFullName );
            String source = file.getSourceOffset( start, end );
            TestStatement tStmt = new TestStatement( id, file,
                source );
            file.addStatement( tStmt );
        }
        else {
            findStatements( stmt );
        }
    }
}

/**
 * Process DOM from root to identify which statements
 * were executed by which test case.  Store test case
 * names in IR.
 *
 * @param root Root of DOM tree from which to begin searching.
 */
private void checkCoverage( Node root ) {
    Node testSession = null;
    for( Node child = root.getFirstChild(); child != null; child
        = child.getNextSibling() ) {
        if( child.getNodeName() == "TestSession" ) {
            testSession = child;
            break;
        }
    }

    int testCaseIndex = 0;
    for( Node testCase = testSession.getFirstChild(); testCase
       != null; testCase = testCase.getNextSibling() ) {
        if( testCase.getNodeName() == "TestCase" ) {
            NamedNodeMap attributes = testCase.getAttributes();
            testCases.add( attributes.getNamedItem( "Name" ).
                getNodeValue() );
```

```
            if( attributes.getNamedItem( "Comment" ).
               getNodeValue().startsWith( "Failure" )
             || attributes.getNamedItem( "Comment" ).
                getNodeValue().startsWith( "Error" ) ) {
              passFail.add( false );
            }
            else {
              passFail.add( true );
            }
            for( Node covList = testCase.getFirstChild();
               covList != null; covList = covList.getNextSibling
               () ) {
                if( covList.getNodeName() == "CovList" ) {
                    for( Node covPre = covList.getFirstChild();
                       covPre != null; covPre = covPre.
                       getNextSibling() ) {
                        if( covPre.getNodeName() == "CovPrefix"
                           ) {
                            NamedNodeMap covPreAttributes =
                               covPre.getAttributes();
                            String filename = covPreAttributes.
                               getNamedItem( "CovItemPrefix" ).
                               getNodeValue();
                            TestFile file = findFile( filename )
                               ;
                            for( Node cov = covPre.getFirstChild
                               (); cov != null; cov = cov.
                               getNextSibling() ) {
                                if( cov.getNodeName() == "Cov" )
                                    {
                                    NamedNodeMap covAttributes =
                                        cov.getAttributes();
                                    String id = covAttributes.
                                       getNamedItem( "CovItemId"
                                        ).getNodeValue();
                                    TestStatement ts = file.
                                       getStatement( id );
                                    if( ts != null ) {
                                        ts.markCovered(
                                           testCaseIndex );
                                    }
                                }
                            }
                        }
                    }
                }
            }
            testCaseIndex++;
        }
    }
```

```
        // Normalize size of coverage lists by adding false to the
           end (must not be covered)
        for( TestFile tf : files ) {
            for( TestStatement ts : tf.stmts() ) {
                while( ts.numTestCases() < testCaseIndex ) {
                    ts.getCoverage().add( false );
                }
            }
        }
    }

    /**
     * Find TestFile in list of files with the provided Internal ID.
     *
     * @param id ID to search for.
     * @return TestFile that matches requested ID.  Null if not
        found.
     */
    public TestFile findFile( int id ) {
        for( TestFile t : files ) {
            if( t.getId() == id ) {
                return t;
            }
        }
        return null;
    }

    /**
     * Find TestFile in list of files with the specified name.
     *
     * @param file Name of file to search for.
     * @return TestFile that matches requested name.  Null if not
        found.
     */
    public TestFile findFile( String file ) {
        for( TestFile f : files ) {
            if( f.getFilename().equals( file ) ) {
                return f;
            }
        }
        return null;
    }

    /**
     * Number of files in the IR.
     *
     * @return Number of files.
     */
    public int numFiles() {
        return files.size();
    }
```

```
    /**
     * Return file list.
     *
     * @return List of files found.
     */
    public ArrayList< TestFile > files() {
        return files;
    }

    /**
     * Simple string format of file list.  Format is:
     *
     *    Files: [ Filename1 ][ Filename2 ]...[ FilenameN ]
     */
    public String toString() {
        String ret = "Files: ";
        for( TestFile f : files ) {
            ret += "[ " + f.getFilename() + " ]";
        }
        return ret;
    }

    /**
     * Return test case list.
     *
     * @return List of test cases.
     */
    public ArrayList< String > getTestCases() {
        return testCases;
    }

    /**
     * Return pass fail list.
     *
     * @return List of pass/fail statuses for test cases
     */
    public ArrayList< Boolean > getPassFail() {
      return passFail;
    }
}
```

```
package edu.allegheny.cov;

import java.io.File;
import java.io.FileWriter;
import java.io.IOException;
import java.text.DecimalFormat;
import java.util.ArrayList;

import au.com.bytecode.opencsv.CSVWriter;

/**
```

```
 * Converts intermediate container representation into
 * a simplified data format for easy evaluation of
 * suspiciousness.
 *
 * @author Tristan Challener
 *
 */
public class CoverageReport {
  private ArrayList< Integer > aef;
  private ArrayList< Integer > aep;
  private ArrayList< Integer > anf;
  private ArrayList< Integer > anp;
    private ArrayList< TestStatement > stmts;
    private String fault;
  public static final REFunction[] REFUNCTIONS =
    { new Jaccard(), new Tarantula(), new Kulczynski2(),
      new Ample(), new Ochiai() };

  /**
   * Construct a new CoverageReport from the provided intermediate
   * container representation.
   *
   * @param con Container IR object.
   */
    public CoverageReport( ContainerIR con, String fault ) {
        ArrayList< String > testCaseList = con.getTestCases();
        ArrayList< Boolean > passFailList = con.getPassFail();

        this.fault = fault;

        stmts = new ArrayList< TestStatement >();
        for( TestFile file : con.files() ) {
            for( TestStatement stat : file.stmts() ) {
                stmts.add( stat );
            }
        }


        // Iterate through test cases and check coverage information
        ArrayList< TestInfo > l = new ArrayList< TestInfo >(
           testCaseList.size() );
        for( int i = 0; i < testCaseList.size(); i++ ) {
            ArrayList< Boolean > exec = new ArrayList< Boolean >();
            for( TestStatement stmt : stmts ) {
                exec.add( stmt.getCoverage().get( i ) );
            }

            boolean pass = passFailList.get( i );
            l.add( new TestInfo( pass, exec ) );
        }
```

```
        TestList info = new TestList( l );

        aef = new ArrayList< Integer >( info.size() );
    aep = new ArrayList< Integer >( info.size() );
    anf = new ArrayList< Integer >( info.size() );
    anp = new ArrayList< Integer >( info.size() );

    for( int i = 0; i < info.size(); i++ ) {
      aef.add( 0 );
      aep.add( 0 );
      anf.add( 0 );
      anp.add( 0 );
    }

    for( TestInfo test : info.list() ) {
      int i = 0;
      if( test.passed() ) {
        for( Boolean exec : test.statsExec() ) {
          if( exec ) {
            aep.set( i, aep.get( i ) + 1 );
          }
          else {
            anp.set( i, anp.get( i ) + 1 );
          }
          i++;
        }
      }
      else {
        for( Boolean exec : test.statsExec() ) {
          if( exec ) {
            aef.set( i, aef.get( i ) + 1 );
          }
          else {
            anf.set( i, anf.get( i ) + 1 );
          }
          i++;
        }
      }
    }
  }


    /**
   * Return the number of tests that executed the
   * statement with a specific index and failed.
   *
   * @param idx Index of statement.
   * @return Number of failing executing tests.
   */
  public int aef( int idx ) {
    return aef.get( idx );
  }
```

```
/**
 * Return the number of tests that executed the
 * statement with a specific index and passed.
 *
 * @param idx Index of statement.
 * @return Number of passing executing tests.
 */
public int aep( int idx ) {
  return aep.get( idx );
}

/**
 * Return the number of tests that did not execute the
 * statement with a specific index and failed.
 *
 * @param idx Index of statement.
 * @return Number of failing non-executing tests.
 */
public int anf( int idx ) {
  return anf.get( idx );
}

/**
 * Return the number of tests that did not execute the
 * statement with a specific index and passed.
 *
 * @param idx Index of statement.
 * @return Number of passing non-executing tests.
 */
public int anp( int idx ) {
  return anp.get( idx );
}

/**
 * Print the coverage report to standard output.
 */
public void print() {
      String currentFile = "";
  System.out.printf("    A < aef  aep  anf  anp >\n");
  for( int i = 0; i < aef.size(); i++ ) {
          TestStatement stmt = stmts.get( i );
          if( !stmt.getFile().getFilename().equals( currentFile )
             )
          {
              currentFile = stmt.getFile().getFilename();
              if( i > 0 ) {
                  System.out.printf( "
                     '--------------------'\n" );
              }
              System.out.printf( ">%s\n", currentFile );
```

```
                System.out.printf( "      .--------------------.\n"
                    );
            }
        System.out.printf( "%5s |%4d %4d %4d %4d |\n", stmt.getId(),
            aef.get( i ), aep.get( i ), anf.get( i ), anp.get( i ) );
    }
        System.out.printf( "      '--------------------'\n" );
}

/**
 * Analyze the coverage report according to the provided risk
    evaluation
 * function, optionally normalizing the results.
 *
 * @param re Risk evaluation to evaluate with.
 * @param norm Normalize results to zero to one scale if true.
 * @return ResultsList containing the suspiciousness value of each
     statement.
 */
public ResultsList analyze( REFunction re, boolean norm ) {
  ResultsList ret = new ResultsList( aef.size(), re );
  for( int i = 0; i < aef.size(); i++ ) {
          TestStatement ts = stmts.get( i );
          double analysis = re.analyze( aef.get( i ), aep.get( i )
              , anf.get( i ), anp.get( i ) );
          ts.setSusp( analysis );
    ret.add( ts );
  }
  if( norm )
  {
    ret.normalize();
  }
  return ret;
}

/**
 * Perform analysis on the coverage report using each risk
    evaluation function,
 * then write the results with the provided filename in CSV format
    .
 *
 * @param caseApp Name of the file to be written.  File will be
    written in
 * the results directory.  Also forms the CaseApplication
    attribute.
 */
public void printAnalysis( String caseApp ) {
  try {
    File file = new File("results");
    if (!file.exists()) {
      if (file.mkdir()) {
      }
```

```
      }
      CSVWriter writer = new CSVWriter( new FileWriter( "results/" +
          caseApp + ".csv" ) );
      ArrayList< TestStatement > spL;
      String[] row = new String[ 8 ];
      row[ 0 ] = "Function";
      row[ 1 ] = "StatementID";
      row[ 2 ] = "Filename";
      row[ 3 ] = "Suspiciousness";
      row[ 4 ] = "Rank";
      row[ 5 ] = "StatementCount";
      row[ 6 ] = "CaseApplication";
      row[ 7 ] = "IsFault";
      writer.writeNext( row );
      DecimalFormat fmt = new DecimalFormat( "0.####" );
      for( REFunction re : REFUNCTIONS ) {
        spL = this.analyze( re, true ).sort().list();
        for( int i = 0; i < spL.size(); i++ ) {
          TestStatement ts = spL.get( i );
          row[ 0 ] = re.toString();
          row[ 1 ] = ts.getId();
          row[ 2 ] = ts.getFile().getFilename();
          row[ 3 ] = fmt.format( ts.getSusp() );
          row[ 4 ] = "" + ( i + 1 );
          row[ 5 ] = "" + spL.size();
          row[ 6 ] = caseApp;
          row[ 7 ] = ts.getSource().contains( fault )? "true" : "
             false";
          writer.writeNext( row );
        }
      }
      writer.close();
    } catch (IOException e) {
      e.printStackTrace();
    }
  }
}
```

```
package edu.allegheny.cov;

public class Jaccard implements REFunction {
  public double analyze( int Iaef, int Iaep, int Ianf, int Ianp ) {
    double aef, aep, anf;

    aef = (double) Iaef;
    aep = (double) Iaep;
    anf = (double) Ianf;

    return ( aef / (aef + anf + aep ) );
  }

  public String toString() {
```

```
    return "Jaccard";
  }
}
```

```
package edu.allegheny.cov;

public class Kulczynski2 implements REFunction {
  public double analyze( int Iaef, int Iaep, int Ianf, int Ianp ) {
    double aef, aep, anf, anp;

    aef = (double) Iaef;
    aep = (double) Iaep;
    anf = (double) Ianf;
    anp = (double) Ianp;

    return 0.5d * ( (  aef / ( aef + anf ) ) + ( aef / ( aef + aep )
        ) );
  }

  public String toString() {
    return "Kulczynski 2";
  }
}
```

```
package edu.allegheny.cov;

public class Ochiai implements REFunction {
  public double analyze( int Iaef, int Iaep, int Ianf, int Ianp ) {
    double aef, aep, anf, anp;

    aef = (double) Iaef;
    aep = (double) Iaep;
    anf = (double) Ianf;
    anp = (double) Ianp;

    return ( aef / Math.sqrt( ( aef + anf ) * ( aef + aep ) ) );
  }

  public String toString() {
    return "Ochiai";
  }
}
```

```
package edu.allegheny.cov;

import javax.xml.parsers.DocumentBuilder;
import javax.xml.parsers.DocumentBuilderFactory;
import org.xml.sax.ErrorHandler;
import org.xml.sax.SAXException;
import org.xml.sax.SAXParseException;
import java.io.File;
import java.io.OutputStreamWriter;
```

```
import java.io.PrintWriter;
import org.w3c.dom.Document;

/**
 * Provides static functionality for parsing a CodeCover XML
    container
 * and returning intermediate representation for suspiciousness
 * processing.
 *
 * @author Tristan Challener
 *
 */
public class ParseContainer {
    static final String outputEncoding = "UTF-8";

    /**
     * Parse CodeCover XML container into an intermediate
        representation
     * with DOM XML parsing.
     *
     * @param filename Fully qualified path for XML container.
     * @return Intermediate representation object.
     * @throws Exception Throws an exception when any problem occurs
        in
     * parsing, including format errors.  Most likely indicates that
        either
     * the filename was not specified correctly or the file
        specified was not
     * a CodeCover XML container.
     */
    public static ContainerIR parse( String filename ) throws
       Exception
    {
        DocumentBuilderFactory dbf = DocumentBuilderFactory.
           newInstance();
        dbf.setIgnoringComments( true );
        dbf.setIgnoringElementContentWhitespace( true );
        DocumentBuilder db = dbf.newDocumentBuilder();
        OutputStreamWriter errorWriter = new OutputStreamWriter(
           System.err, outputEncoding );
        db.setErrorHandler( new MyErrorHandler( new PrintWriter(
           errorWriter, true ) ) );
        Document doc = db.parse(new File(filename));
        ContainerIR ir = new ContainerIR( doc );
        return ir;
    }

    /**
     * Copyright (c) 2014, Oracle America, Inc.
   * All rights reserved.
     *
```

```
     * @author Oracle DOM online tutorial.  This tutorial can be
        found
     * at http://docs.oracle.com/javase/tutorial/jaxp/dom/readingXML
        .html.
     *
     * This simple error handler prints relevant information about
        problems
     * that occur while parsing an XML document.
     */
    private static class MyErrorHandler implements ErrorHandler {

        private PrintWriter out;

        MyErrorHandler(PrintWriter out) {
            this.out = out;
        }

        private String getParseExceptionInfo(SAXParseException spe)
           {
            String systemId = spe.getSystemId();
            if (systemId == null) {
                systemId = "null";
            }

            String info = "URI=" + systemId + " Line=" + spe.
               getLineNumber() +
                ": " + spe.getMessage();
            return info;
        }

        public void warning(SAXParseException spe) throws
           SAXException {
            out.println("Warning: " + getParseExceptionInfo(spe));
        }

        public void error(SAXParseException spe) throws SAXException
            {
            String message = "Error: " + getParseExceptionInfo(spe);
            throw new SAXException(message);
        }

        public void fatalError(SAXParseException spe) throws
           SAXException {
            String message = "Fatal Error: " + getParseExceptionInfo
               (spe);
            throw new SAXException(message);
        }
    }
}
```

```
package edu.allegheny.cov;
```

```
/**
 * Risk evaluation function interface for suspiciousness evaluation.
 *
 * @author Tristan Challener
 *
 */
public interface REFunction {
  /**
   * Determine the suspiciousness of a statement according to
   * the specific function.  Takes as input the number of
   * passing and failing tests that executed and did not execute
   * the statement.
   *
   * @param aef Number of tests that executed the statement and
      failed.
   * @param aep Number of tests that executed the statement and
      passed.
   * @param anf Number of tests that did not execute the statement
      and failed.
   * @param anp Number of tests that did not execute the statement
      and passed.
   * @return Suspiciousness value.
   */
  public double analyze( int aef, int aep, int anf, int anp );

  /**
   *
   * @return Name of the REFunction.
   */
  public String toString();
}
```

```
package edu.allegheny.cov;

import java.util.ArrayList;
import java.util.Arrays;

/**
 * Helper list class with functionality for normalizing and sorting
 * to simplify suspiciousness evaluation.
 *
 * @author Tristan Challener
 *
 */
public class ResultsList {
  ArrayList< TestStatement > list;
  REFunction re;

  /**
   * General constructor, sets size of list and risk evaluation
      function.
   *
```

```
 * @param size Initial list size.
 * @param re Risk evaluation function for use in analysis.
 */
public ResultsList( int size, REFunction re ) {
  list = new ArrayList< TestStatement >( size );
  this.re = re;
}

/**
 * Add TestStatement to list.
 *
 * @param ts TestStatement to add.
 */
public void add( TestStatement ts ) {
  list.add( ts );
}

/**
 * Retrieve suspiciousness of selected index in list.
 *
 * @param idx Index to retrieve.
 * @return Suspiciousness value of TestStatement at index.
 */
public double get( int idx ) {
  return list.get( idx ).getSusp();
}

/**
 * Return the internal list.
 *
 * @return Internal list of TestStatements
 */
public ArrayList< TestStatement > list() {
  return list;
}

/**
 * Normalize suspiciousness values of the statement list
 * between zero and one.
 */
public void normalize() {
  double max = Double.MIN_VALUE, min = Double.MAX_VALUE;

  for( TestStatement temp : list ) {
    if( temp.getSusp() > max ) {
      max = temp.getSusp();
    }
    if( temp.getSusp() < min ) {
      min = temp.getSusp();
    }
  }
```

```
    for( int i = 0; i < list.size(); i++ ) {
      list.get( i ).setSusp( ( list.get( i ).getSusp() - min ) / (
          max - min ) );
    }

    // Remove NaNs and replace with zero
    for( int i = 0; i < list.size(); i++ ) {
      double susp = list.get( i ).getSusp();
      list.get( i ).setSusp( Double.isNaN( susp )? 0.0 : susp );
    }
  }

  /**
   * Return a string representation of the suspiciousness values
   * in the list. Format is:
   *
   *    REFunciton { Susp string 1, Susp string 2, ..., Susp string
      n }
   */
  public String toString() {
    String ret = re.toString() + " { ";
    for( int i = 0; i < list.size() - 1; i++ ) {
      ret += list.get( i ).suspToString() + ", ";
    }
    ret += list.get( list.size() - 1 ).suspToString() + " }";
    return ret;
  }

  /**
   * Sort the TestStatments in the list according to suspiciousness
   * value, with the first elements in the list having the highest
   * suspiciousness value.  Return the instance.
   *
   * @return This instance, after sorting.
   */
  public ResultsList sort() {
    TestStatement[] listTemp = new TestStatement[ list.size() ];
    for( int i = 0; i < list.size(); i++ ) {
      listTemp[ i ] = list.get( i );
    }
    Arrays.sort( listTemp );
    list = new ArrayList< TestStatement >( listTemp.length );
    for( int i = 0; i < listTemp.length; i++ ) {
      list.add( listTemp[ i ] );
    }
    return this;
  }
}
```

```
package edu.allegheny.cov;

public class Tarantula implements REFunction {
```

```
  public double analyze( int Iaef, int Iaep, int Ianf, int Ianp ) {
    double aef, aep, anf, anp;

    aef = (double) Iaef;
    aep = (double) Iaep;
    anf = (double) Ianf;
    anp = (double) Ianp;

    return ( aef / ( aef + anf ) )
         / ( aef / ( aef + anf )
           + aep / ( aep + anp ) );
  }

  public String toString() {
    return "Tarantula";
  }
}
```

```
package edu.allegheny.cov;

/**
 * Main class.  Processes a CodeCover container, executing the
 * specified test class, and outputs to the provided file.
 *
 * @author Tristan Challener
 *
 */
public class Test {

  /**
   * Processes CodeCover container and output to specified file.
   *
   * @param args Fully qualified test class name, fully qualified
      container
   * path, and output file name ( output path is fixed ).
   */
  public static void main( String[] args ) {
        ContainerIR ir = null;
        if( args.length < 2 ) {
            System.out.println( "Please provide CodeCover container,
                case application name, and faulty statement." );
            System.exit( 0 );
        }
        try {
            ir = ParseContainer.parse( "containers/" + args[ 0 ] );
        }
        catch( Exception e ) {
            e.printStackTrace();
        }

        CoverageReport cov = new CoverageReport( ir, args[ 2 ] );
        cov.printAnalysis( args[ 1 ] );
```

```
  }
}
```

```
package edu.allegheny.cov;

import java.util.ArrayList;

/**
 * Data representation of a file.  Includes source code,
 * file name, list of statements in the file, and an ID.
 *
 * @author Tristan Challener
 *
 */
public class TestFile {
    private String source;
    private String filename;
    private ArrayList< TestStatement > statementList;
    private int id;

    /**
     * Create a new instance with specified source code, filename,
     * and ID.
     *
     * @param s
     * @param f
     * @param i
     */
    public TestFile( String s, String f, int i ) {
        source = s;
        filename = f;
        id = i;
        statementList = new ArrayList< TestStatement >();
    }

    /**
     * Getter for source code.
     *
     * @return Source code.
     */
    public String getSource() {
        return source;
    }

    /**
     * Getter for file name.
     *
     * @return File name.
     */
    public String getFilename() {
        return filename;
    }
```

```
 /**
  * Setter for file name.
  *
  * @param f File name.
  */
public void setFilename( String f )  {
     filename = f;
 }

/**
 * Getter for ID.
 *
 * @return ID.
 */
public int getId()  {
     return id;
 }

/**
 * Add the specified statement to the file.
 *
 * @param tStmt TestStatement to add.
 */
public void addStatement( TestStatement tStmt ) {
     statementList.add( tStmt );
 }

/**
 * Retrieve the segment of the source that begins and
 * ends at the specified character offsets.
 *
 * @param start Start index.
 * @param end End index.
 * @return String containing the specified segment of
 * the file source code.
 */
 public String getSourceOffset( int start, int end ) {
     return source.substring( start, end + 1 );
 }

 /**
  * Getter for the list of statements in the file.
  *
  * @return Statement list.
  */
 public ArrayList< TestStatement > stmts() {
     return statementList;
 }

 /**
  * Retrieve the statement in this file with the given
```

```
     * statement ID.
     *
     * @param id ID to search for.
     * @return Statement that matches specified ID, or null if
     * the ID was not found.
     */
    public TestStatement getStatement( String id ) {
        for( TestStatement ts : statementList ) {
            if( ts.getId().equals( id ) ) {
                return ts;
            }
        }
        return null;
    }
}
```

```
package edu.allegheny.cov;

import java.util.ArrayList;

/**
 * Data representation of a single test case.  Stores pass/fail
    information,
 * as well as listing whether each statement was executed by this
    test.
 *
 * @author Tristan
 *
 */
public class TestInfo {
  private boolean pass;
  private ArrayList< Boolean > exec;

  /**
   * Create an instance with the specified pass or fail status, as
      well
   * as a list describing which statements were executed by this
      test.
   *
   * @param p Pass/fail status.
   * @param e List of statement execution status.
   */
  public TestInfo( boolean p, ArrayList< Boolean > e ) {
    pass = p;
    exec = new ArrayList< Boolean >( e );
  }

  /**
   * Getter for pass/fail status.
   *
   * @return True if the test passed, false otherwise.
   */
```

```
  public boolean passed() {
    return pass;
  }

  /**
   * Getter for statement execution status list.
   *
   * @return Statement execution status list.
   */
  public ArrayList< Boolean > statsExec() {
    return new ArrayList< Boolean >( exec );
  }
}
```

```
package edu.allegheny.cov;

import java.util.ArrayList;

/**
 * Helper list class with functionality for storing a different
 * size value, which represents the number of statements per test
 * rather than the number of tests.
 *
 * @author Tristan Challener
 *
 */
public class TestList {
  private ArrayList< TestInfo > list;
  private int stats;

  /**
   * Create an instance, copying the specified list values as the
      initial
   * values for the TestList
   *
   * @param l List to copy from
   */
  public TestList( ArrayList< TestInfo> l ) {
    list = new ArrayList< TestInfo >( l.size() );
    list.addAll( l );
    if( l.size() > 0 ) {
      stats = l.get( 0 ).statsExec().size();
    }
  }

  /**
   * Add the specified test to the list.
   *
   * @param t Test to add.
   */
  public void addTest( TestInfo t ) {
    list.add( t );
```

```
  }

  /**
   * Getter for size.
   *
   * @return Number of statements per test.
   */
  public int size() {
    return stats;
  }

  /**
   * Getter for internal list of tests.
   *
   * @return Internal list of tests.
   */
  public ArrayList< TestInfo > list() {
    return list;
  }

  /**
   * Retrieve the specified element in the list.
   *
   * @param idx Index of element to return.
   * @return Specified element of the list.
   */
  public TestInfo get( int idx ) {
    return list.get( idx );
  }
}
```

```
package edu.allegheny.cov;

import java.util.ArrayList;
import java.text.DecimalFormat;

/**
 * Data representation of a statement.  Includes ID, source code,
 * source file, suspiciousness value, and a list indicating which
 * tests executed or did not execute the statement.
 *
 * @author Tristan Challener
 *
 */
public class TestStatement implements Comparable< TestStatement > {
    private String id;
    private String source;
    private TestFile file;
    private double susp;
    private ArrayList< Boolean > testsExecuting;

    /**
```

```
     * Create a new instance with specified ID, source file, and
        source code.
     * Suspiciousness is initialized to zero, and no tests are
        listed.
     *
     * @param i ID.
     * @param f Source file.
     * @param s Source code.
     */
    public TestStatement( String i, TestFile f, String s ) {
        id = i;
        file = f;
        source = s;
        susp = 0;
        testsExecuting = new ArrayList< Boolean >();
    }

    /**
     * Getter for source code.
     *
     * @return Source code.
     */
    public String getSource() {
        return source;
    }

    /**
     * Getter for source file.
     *
     * @return Source file.
     */
    public TestFile getFile() {
        return file;
    }

    /**
     * Getter for ID.
     *
     * @return ID.
     */
    public String getId() {
        return id;
    }

    /**
     * Setter for suspiciousness.
     *
     * @param sp Suspiciousness
     */
    public void setSusp( double sp ) {
        susp = sp;
    }
```

```
/**
 * Getter for suspiciousness
 *
 * @return Suspiciousness.
 */
public double getSusp( ) {
    return susp;
}

/**
 * Getter for executed test list.
 *
 * @return Boolean list indicating, for each test case, whether
 * this statement was executed.
 */
public ArrayList< Boolean > getCoverage() {
    return testsExecuting;
}

/**
 * Mark the indicated test as covering this statement. Fill in
    gaps
 * in coverage list with false (if a test is not marked covering
    ,
 * it is assumed to not cover the statement).
 *
 * @param idx Index of test to mark as covering.
 */
public void markCovered( int idx ) {
    while( testsExecuting.size() < idx ) {
        testsExecuting.add( false );
    }
    testsExecuting.add( true );
}

/**
 * Returns the total number of tests consider for coverage on
    this
 * statement.
 *
 * @return Size of executing test list.
 */
public int numTestCases() {
    return testsExecuting.size();
}

/**
 * Format suspiciousness to a minimum of one decimal place
 * and a maximum of 4 decimal places, with a leading zero,
 * and return the string representation.
 *
```

```
     * @return Formatted string representation of suspiciousness
        value.
     */
    public String suspToString() {
        DecimalFormat fmt = new DecimalFormat( "0.0###" );
        return "(" + id + ", " + fmt.format( susp ) + ")";
    }

    /**
     * {@link Comparable} override method.  Smaller suspiciousness
     * values are considered higher for comparison (so, for example,
     * a sorted list of TestStatements from lowest to highest will
     * actually be order in descending order of suspiciousness).
     */
    public int compareTo( TestStatement st ) {
    Double thisSp = new Double( susp );
    Double thatSp = new Double( st.getSusp() );
    return thatSp.compareTo( thisSp );
  }
}
```

```
package edu.allegheny.cov.test;

import org.junit.Test;
import static org.junit.Assert.*;

import edu.allegheny.cov.Ample;
import edu.allegheny.cov.Kulczynski2;
import edu.allegheny.cov.Ochiai;
import edu.allegheny.cov.REFunction;
import edu.allegheny.cov.Jaccard;
import edu.allegheny.cov.Tarantula;

public class TestREFunctions {
  static final int[] AEP = { 5, 1, 1, 1 };
  static final int[] AEF = { 1, 5, 1, 1 };
  static final int[] ANP = { 1, 1, 5, 1 };
  static final int[] ANF = { 1, 1, 1, 5 };

  @Test
  public void TestJaccard() {
    REFunction re = new Jaccard();
    double analysis = re.analyze( AEF[ 0 ], AEP[ 0 ], ANF[ 0 ], ANP[
        0 ] );
    assertEquals( 0.1429d, analysis, 0.0001d );

    analysis = re.analyze( AEF[ 1 ], AEP[ 1 ], ANF[ 1 ], ANP[ 1 ] );
    assertEquals( 0.7143d, analysis, 0.0001d );

    analysis = re.analyze( AEF[ 2 ], AEP[ 2 ], ANF[ 2 ], ANP[ 2 ] );
    assertEquals( 0.3333d, analysis, 0.0001d );
```

```
    analysis = re.analyze( AEF[ 3 ], AEP[ 3 ], ANF[ 3 ], ANP[ 3 ] );
    assertEquals( 0.1429d, analysis, 0.0001d );

    assertEquals( re.toString(), "Jaccard" );
  }

  @Test
  public void TestTarantula() {
    REFunction re = new Tarantula();
    double analysis = re.analyze( AEF[ 0 ], AEP[ 0 ], ANF[ 0 ], ANP[
        0 ] );
    assertEquals( 0.375d, analysis, 0.0001d );

    analysis = re.analyze( AEF[ 1 ], AEP[ 1 ], ANF[ 1 ], ANP[ 1 ] );
    assertEquals( 0.625d, analysis, 0.0001d );

    analysis = re.analyze( AEF[ 2 ], AEP[ 2 ], ANF[ 2 ], ANP[ 2 ] );
    assertEquals( 0.75d, analysis, 0.0001d );

    analysis = re.analyze( AEF[ 3 ], AEP[ 3 ], ANF[ 3 ], ANP[ 3 ] );
    assertEquals( 0.25d, analysis, 0.0001d );

    assertEquals( re.toString(), "Tarantula" );
  }

  @Test
  public void TestKulczynski2() {
    REFunction re = new Kulczynski2();
    double analysis = re.analyze( AEF[ 0 ], AEP[ 0 ], ANF[ 0 ], ANP[
        0 ] );
    assertEquals( 0.3333, analysis, 0.0001d );

    analysis = re.analyze( AEF[ 1 ], AEP[ 1 ], ANF[ 1 ], ANP[ 1 ] );
    assertEquals( 0.8333d, analysis, 0.0001d );

    analysis = re.analyze( AEF[ 2 ], AEP[ 2 ], ANF[ 2 ], ANP[ 2 ] );
    assertEquals( 0.5d, analysis, 0.0001d );

    analysis = re.analyze( AEF[ 3 ], AEP[ 3 ], ANF[ 3 ], ANP[ 3 ] );
    assertEquals( 0.3333d, analysis, 0.0001d );

    assertEquals( re.toString(), "Kulczynski 2" );
  }

  @Test
  public void TestOchiai() {
    REFunction re = new Ochiai();
    double analysis = re.analyze( AEF[ 0 ], AEP[ 0 ], ANF[ 0 ], ANP[
        0 ] );
    assertEquals( 0.2887, analysis, 0.0001d );

    analysis = re.analyze( AEF[ 1 ], AEP[ 1 ], ANF[ 1 ], ANP[ 1 ] );
```

```
    assertEquals( 0.8333d, analysis, 0.0001d );

    analysis = re.analyze( AEF[ 2 ], AEP[ 2 ], ANF[ 2 ], ANP[ 2 ] );
    assertEquals( 0.5d, analysis, 0.0001d );

    analysis = re.analyze( AEF[ 3 ], AEP[ 3 ], ANF[ 3 ], ANP[ 3 ] );
    assertEquals( 0.2887d, analysis, 0.0001d );

    assertEquals( re.toString(), "Ochiai" );
  }

  @Test
  public void TestAmple() {
    REFunction re = new Ample();
    double analysis = re.analyze( AEF[ 0 ], AEP[ 0 ], ANF[ 0 ], ANP[
        0 ] );
    assertEquals( -0.3333, analysis, 0.0001d );

    analysis = re.analyze( AEF[ 1 ], AEP[ 1 ], ANF[ 1 ], ANP[ 1 ] );
    assertEquals( 0.3333d, analysis, 0.0001d );

    analysis = re.analyze( AEF[ 2 ], AEP[ 2 ], ANF[ 2 ], ANP[ 2 ] );
    assertEquals( 0.3333d, analysis, 0.0001d );

    analysis = re.analyze( AEF[ 3 ], AEP[ 3 ], ANF[ 3 ], ANP[ 3 ] );
    assertEquals( -0.3333d, analysis, 0.0001d );

    assertEquals( re.toString(), "Ample" );
  }
}
```

A.2 Test System (ListSwap)

```
package edu.allegheny.listswap;

public class Bear
{
    int weight, age;
    char gender;

    public Bear(int w, int a, char g)
    {
        weight = w;
        age = a;
        gender = g;
    }

    public String toString()
    {
        return "Bear: " + weight + ", " + age + ", " + gender;
```

```
    }
}
```

```
package edu.allegheny.listswap;

import au.com.bytecode.opencsv.*;
import edu.allegheny.listswap.ListSwapGenerator;
import java.util.ArrayList;
import java.util.Arrays;
import java.util.List;
import java.io.FileReader;
import java.io.FileWriter;
import java.io.IOException;

public class CSVListIO
{
    public static void main(String[] args)
  {
    if (args.length == 1)
    {
        writeListsToFiles(readListsFromFile(args[0], ','), ',');
    }
        else if (args.length == 3 && args[0].equals("-d"))
        {
        writeListsToFiles(readListsFromFile(args[2], args[1].charAt
           (0)), args[1].charAt(0));
        }
        else
        {
            System.out.println("Invalid usage.\nExample usage: java
               CSVListIO [-d DELIMITER] FILENAME");
        }
  }

    /**
     * Given a file path and delimiter, returns a list of string
        arrays representing the input csv,
     * where each array is one line from the csv and each individual
         string is a single element
     * @param filePath The relative path to the input csv file
     * @param delimiter The delimiter to be used to parse the input
        csv file
     */
  public static List<String[]> readListsFromFile(String filePath,
     char delimiter)
    {
      try
      {
      CSVReader reader = new CSVReader(new FileReader(filePath),
         delimiter);

      return reader.readAll();
```

```
}
catch (IOException e)
{
  System.out.println("Failed to open file: " + filePath);
}

return null;
}

/**
 * Takes a list of arrays of strings and outputs one csv file
    for each array which includes
 * all of the possible swaps for that array.
 * @param lists List of string arrays, where each array is one
    row in the input csv
 * @param delimiter The delimiter to use for the output csv
    files
 */
public static void writeListsToFiles(List<String[]> lists, char
   delimiter)
{
    int listNum = 0;
for (String[] listItems : lists)
{
        try
  {
    ArrayList<Object> entries = new ArrayList<Object>(listItems.
       length);

    entries.addAll(Arrays.asList(listItems));

    ArrayList<ArrayList<Object>> results = ListSwapGenerator.
       swapList(entries);

    CSVWriter writer = new CSVWriter(new FileWriter("
       swapped_lists_row" + listNum + ".csv"), delimiter);

    for (ArrayList<Object> list : results)
    {
      String[] strings = new String[list.size()];

      for (int i = 0; i < list.size(); i++)
        strings[i] = list.get(i).toString();

      writer.writeNext(strings);
    }

    writer.close();

    listNum++;
  }
  catch (IOException e)
```

```
      {
          System.out.println("Failed writing to file:
             swapped_lists_row" + listNum + ".csv");

        System.exit(1);
      }
        }
    }
}
```

```
package edu.allegheny.listswap;

public class Fish
{
    int weight, age;
    char gender;

    public Fish(int w, int a, char g)
    {
        weight = w;
        age = a;
        gender = g;
    }

    public String toString()
    {
        return "Fish: " + weight + ", " + age + ", " + gender;
    }
}
```

```
package edu.allegheny.listswap;

import java.util.ArrayList;

public class ListSwapGenerator
{
  /**
   * This method takes a list of objects and returns all lists that
      can be obtained
   * by swapping two items in the list.
   *
   * @param list The list to generate additional lists from.
   * @return A list of all lists obtained by swapping two element in
      the input list.
   */
    public static ArrayList<ArrayList<Object>> swapList(ArrayList<
       Object> list)
    {
        ArrayList<Object> temp;
        ArrayList<ArrayList<Object>> newList = new ArrayList<
           ArrayList<Object>>();
        for(int i = 0; i < list.size(); i++)
```

```
        {
            for(int j = i + 1; j < list.size(); j++)
            {
                temp = new ArrayList<Object>(list.size());
                temp.addAll(list);
                temp.set(i, list.get(j));
                temp.set(j, list.get(i));
        newList.add(temp);
            }
        }
        return newList;
    }

  /**
   * Prints a list of lists in the format provided in the
      Requirements Document.
   *
   * For example, the result of running swapList() with L = {1, 2,
      3} would
   * result in the string:
   *  L1 = {2, 1, 3}
   *  L2 = {3, 2, 1}
   *  L3 = {1, 3, 2}
   *
   * @param list A list of lists to print in the specified format.
   * @return A string description of the lists.
   */
    public static String listsToString(ArrayList<ArrayList<Object>>
       list)
    {
        String ret = "";
        int listSize = list.size();

        for(int i = 0; i < listSize; i++)
    {
            ret += "L" + (i + 1) + ": \t" + list.get(i);
            if (i <= listSize-1)
              ret += "\n";
    }

        return ret;
    }
}
```

A.3 R Script

```
# Read in raw data
jniinchi_119 <- read.csv( "C:/Users/Tristan/workspace/Comp/results/
   jniinchi-119.csv" )
```

```
jniinchi_137 <- read.csv( "C:/Users/Tristan/workspace/Comp/results/
    jniinchi-137.csv" )
jniinchi_149 <- read.csv( "C:/Users/Tristan/workspace/Comp/results/
    jniinchi-149.csv" )
jniinchi_194 <- read.csv( "C:/Users/Tristan/workspace/Comp/results/
    jniinchi-194.csv" )
jniinchi_197 <- read.csv( "C:/Users/Tristan/workspace/Comp/results/
    jniinchi-197.csv" )

# Merge data vertically
jniinchi_all <- rbind( jniinchi_119, jniinchi_137, jniinchi_149,
    jniinchi_194, jniinchi_197 )

# Add EXAM score to data frame
jniinchi_all$Exam <- jniinchi_all$Rank / jniinchi_all$StatementCount
     * 100

# Take subset of data set for only faulty statements
jniinchi_all_fault <- jniinchi_all[ which( jniinchi_all$IsFault == "
    true" ), ]

# Sort data by EXAM score
jniinchi_all_fault <- jniinchi_all_fault[ order(
    jniinchi_all_fault$Exam ), ]

# Split data back into case applications
jniinchi_119_fault <- jniinchi_all_fault[ which(
    jniinchi_all_fault$CaseApplication == "jniinchi-119" ), ]
jniinchi_137_fault <- jniinchi_all_fault[ which(
    jniinchi_all_fault$CaseApplication == "jniinchi-137" ), ]
jniinchi_149_fault <- jniinchi_all_fault[ which(
    jniinchi_all_fault$CaseApplication == "jniinchi-149" ), ]
jniinchi_194_fault <- jniinchi_all_fault[ which(
    jniinchi_all_fault$CaseApplication == "jniinchi-194" ), ]
jniinchi_197_fault <- jniinchi_all_fault[ which(
    jniinchi_all_fault$CaseApplication == "jniinchi-197" ), ]

# Calculate average EXAM score for each function
j = jniinchi_all_fault[ which( jniinchi_all_fault$Function == "
    Jaccard" ), ]
jm = mean( j$Exam )

a = jniinchi_all_fault[ which( jniinchi_all_fault$Function == "Ample
    " ), ]
am = mean( a$Exam )

k = jniinchi_all_fault[ which( jniinchi_all_fault$Function == "
    Kulczynski 2" ), ]
km = mean( k$Exam )

o = jniinchi_all_fault[ which( jniinchi_all_fault$Function == "
    Ochiai" ), ]
```

```
om = mean( o$Exam )

t = jniinchi_all_fault[ which( jniinchi_all_fault$Function == "
   Tarantula" ), ]
tm = mean( t$Exam )

# Build data frame for average values

jniinchi_avg_fault = data.frame( Function=c( "Jaccard", "Ample", "
   Kulczynski 2", "Ochiai", "Tarantula" ), Exam=c( jm, am, km, om,
   tm ) )

# Generate graphs
library( ggplot2 )
attach( jniinchi_119_fault )
graph_119 <- qplot( Function, Exam, data=jniinchi_119_fault, geom="
   bar",
          ylab="EXAM Score (%)", xlab="Risk Evaulation Function",
        stat="identity", ylim=c( 0,5 ),
        main="EXAM Score Per Risk Evaluation Function (JniInChi
           Mutant 119)",
        sub="JniInChi Mutant 119" )
graph_119 <- graph_119 + theme( axis.title=element_text( face="bold.
   italic" ) )
detach( jniinchi_119_fault )

attach( jniinchi_137_fault )
graph_137 <- qplot( Function, Exam, data=jniinchi_137_fault, geom="
   bar",
          ylab="EXAM Score (%)", xlab="Risk Evaulation Function",
        stat="identity", ylim=c( 0,5 ),
        main="EXAM Score Per Risk Evaluation Function (JniInChi
           Mutant 137)",
        sub="JniInChi Mutant 137" )
graph_137 <- graph_137 + theme( axis.title=element_text( face="bold.
   italic" ) )
detach( jniinchi_137_fault )

attach( jniinchi_149_fault )
graph_149 <- qplot( Function, Exam, data=jniinchi_149_fault, geom="
   bar",
          ylab="EXAM Score (%)", xlab="Risk Evaulation Function",
        stat="identity", ylim=c( 0,5 ),
        main="EXAM Score Per Risk Evaluation Function (JniInChi
           Mutant 149)",
        sub="JniInChi Mutant 149" )
graph_149 <- graph_149 + theme( axis.title=element_text( face="bold.
   italic" ) )
detach( jniinchi_149_fault )

attach( jniinchi_194_fault )
```

```
graph_194 <- qplot( Function, Exam, data=jniinchi_194_fault, geom="
   bar",
          ylab="EXAM Score (%)", xlab="Risk Evaulation Function",
        stat="identity", ylim=c( 0,5 ),
        main="EXAM Score by Risk Evaluation Function (JniInChi
           Mutant 194)",
        sub="JniInChi Mutant 194" )
graph_194 <- graph_194 + theme( axis.title=element_text( face="bold.
   italic" ) )
detach( jniinchi_194_fault )

attach( jniinchi_197_fault )
graph_197 <- qplot( Function, Exam, data=jniinchi_197_fault, geom="
   bar",
          ylab="EXAM Score (%)", xlab="Risk Evaulation Function",
        stat="identity", ylim=c( 0,5 ),
        main="EXAM Score by Risk Evaluation Function (JniInChi
           Mutant 197)",
        sub="JniInChi Mutant 197" )
graph_197 <- graph_197 + theme( axis.title=element_text( face="bold.
   italic" ) )
detach( jniinchi_197_fault )

attach( jniinchi_avg_fault )
graph_avg  <- qplot( Function, Exam, data=jniinchi_avg_fault, geom="
   bar",
          ylab="EXAM Score (%)", xlab="Risk Evaulation Function",
        stat="identity", ylim=c( 0,5 ),
        main="EXAM Score by Risk Evaluation Function (JniInChi
           Mutant Average)",
        sub="JniInChi Mutant Average" )
graph_avg <- graph_avg + theme( axis.title=element_text( face="bold.
   italic" ) )
detach( jniinchi_avg_fault )

# Save graphs to thesis/img directory
ggsave( filename="C:/Users/Tristan/workspace/Comp/rsrc/thesis/
   AllegThesis/img/graph_119.pdf", plot=graph_119 )
ggsave( filename="C:/Users/Tristan/workspace/Comp/rsrc/thesis/
   AllegThesis/img/graph_137.pdf", plot=graph_137 )
ggsave( filename="C:/Users/Tristan/workspace/Comp/rsrc/thesis/
   AllegThesis/img/graph_149.pdf", plot=graph_149 )
ggsave( filename="C:/Users/Tristan/workspace/Comp/rsrc/thesis/
   AllegThesis/img/graph_194.pdf", plot=graph_194 )
ggsave( filename="C:/Users/Tristan/workspace/Comp/rsrc/thesis/
   AllegThesis/img/graph_197.pdf", plot=graph_197 )
ggsave( filename="C:/Users/Tristan/workspace/Comp/rsrc/thesis/
   AllegThesis/img/graph_avg.pdf", plot=graph_avg )
```

Appendix B

Addendum

In this addendum we discuss in further detail the human study, including details regarding number of participation, pre-evaluation of participants, and study setup. In addition, we discuss our contingency plan if we encounter unexpected difficulty. The purpose of this addendum is to address concerns related to feasibility of the project and lack of exact details for the evaluation strategy.

B.1 Human Study

The evaluation strategy for the Eclipse plugin that will be the final product of this project will be evaluated using a human study. This human study will involve twenty undergraduate student participants. with varying experience in the areas of coverage analysis, automated testing, and development with Eclipse (or similar integrated development environment). The participants will be drawn from the Allegheny computer science department majors and minors, and will not accept those students who have not completed or are in the process of completing at least two computer science courses.

Since undergraduate students will have widely varying experience in the areas of coverage analysis, automated testing, and development with Eclipse (or similar integrated development environment), we will ask participants to self-evaluate these attributes of their computer science experience in order to allow us to better balance the groups in the study. This evaluation will take the form of simple scale values; each question will ask to the participant to rate his experience in that area on a scale from one to ten, with one representing complete unfamiliarity and ten representing high confidence. We will then divide the twenty participants into two groups with roughly even levels of experience. When evaluating overall level of experience, we will consider. In addition, we will ask students to list courses completed and to specify their industry experience (including jobs or internships) so that we may incorporate that information into our final results. This questionnaire will be provided to students well in advance of the actual study, so that we can make decisions on grouping before the start of the study.

Once students have been divided into groups, each group will be assigned two

faulty programs to debug (the students will work independently). For each of the two tasks, students will be allotted no more than 30 minutes to complete the debugging process. The purpose of this limitation is to avoid pushing the participants to exhaustion and thus affecting the results. Prior to beginning the tasks, we will instruct the students on the use of our plugin. We will allow 30 minutes for this instruction period, to ensure that participants are at least conversant in the use of the tool. This will eliminate the possibility that the tool was not helpful only because the students were not familiar with its functions.

We will use the same two programs, with the same fault, for each group of students. However, the first group of students will use our plugin to debug the first program, while they will use traditional debugging techniques to repair the fault in the second program. In contrast, the second group of participants will use our plugin for the second program and traditional debugging for the first program. This organization of tasks allows us to compare average completion times for each task when using or not using our plugin. Notice that this experiment setup is derived from that used by Parnin and Orso for their research paper in a similar area [8]. That study included 24 graduate students, two programs, and a similar division of students into groups; that is, where each group used or did not use the fault localization tool for opposite tasks, just as we have described.

After completion of the two tasks, or after each time limit has expired, we will ask students to complete a survey related to their experience when using the tool. Questions asked will include the following:

- In what ways did you find the plugin to be helpful for locating the fault?
- In what ways do you feel the plugin could be improved?
- Please briefly describe your debugging process when using the tool and when not using the tool.
- Did you find the tool to cause an overall benefit or detriment to your debugging process?
- In what situations would you consider using this tool again?
- In what situations would you prefer to use traditional debugging techniques?

Participants' answers to subjective question such as these will allow us to better gauge the strengths and weaknesses of the plugin, as well as evaluate the effectiveness of the tool from the perspective of the users. These answers will be particularly helpful if we find that the plugin does not result in a statistically significant increase in debugging performance, because it will allow us to determine in what ways the plugin could be improved. By considering these answers, we can further evaluate the reason for negative results. We can identify whether automatic fault localization is actually unhelpful, or if improvements to the plugin could give more positive results. The questions will also be helpful in the event of positive results, because we can

identify which features of the tool are most effective: per-test coverage, suspiciousness ranking, or absolute suspiciousness value.

B.2 Contingency Plan

Because this project is highly ambitious, especially considering the time constraints, any unforeseen difficulties could result in our inability to complete all of our goals. We will establish a contingency plan in the event that we discover at some point in the project that we will not be able to meet the deadline.

The first portion of the project deals with parsing CodeCover per-test coverage data from XML into a simplified intermediate representation, so that we may perform risk evaluation. This component will be very complex, and is in itself an ambitious project. It involves first designing a system to parse the highly complex XML test session containers produced by CodeCover, which will have to be tested for correctness. Then we must select a large number of test programs, which must have existing JUnit test suites for per-test coverage analysis. We will then need to import these programs into Eclipse, perform initial CodeCover setup, and execute the coverage monitoring tool on the existing test cases. We will then have to use or parsing system to extract the relevant data for every program tested and perform risk evaluation for every function we decide to study. Finally, we must correlate all of the resulting data inside R to produce effective visualizations, as well as analyze and discuss these results in writing.

Since any portion of this component of the project may prove to be too complex for the given time constraints, our contingency plan will involve completion of only this part of the project. We will leave development and evaluation of the Eclipse plugin as future work, and will discuss the difficulties that led to our use of this contingency. Since we will not have completed the Eclipse plugin, the implementation details will not be included in Chapter 3. In addition, we will omit Chapter 5 entirely, since its only purpose is discussion of the method and results of the human study. The revised thesis outline and project deadlines will be as follows:

Task	**Completion Deadline**
Chapters 1 and 2	December 15
Simplified Representation	February 3
Empirical Study	February 28
R Data Analysis	March 10
Chapter 4	March 24
Chapter 5	April 3
Oral Defense	April 6 - 24
Final Thesis	May 1

Table B.1: Proposed work schedule for contingency plan

1. Introduction
2. Related Work
3. Method of Approach
4. Empirical Results
5. Conclusion

Note that we will only follow this new schedule and outline if we determine that it will not be possible to achieve the original deadlines. The current plan is still to pursue the original schedule as defined in our project proposal. This is only a contingency plan, and we will not utilize it unless necessary. Regardless of difficulties, however, we will at least complete the first goal of the project: empirical comparison of risk evaluation functions (as described in Section 1.2).

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