Exception-Driven Fault Localization for Automated Program Repair

Davide Ginelli, Oliviero Riganelli, Daniela Micucci, Leonardo Mariani University of Milano - Bicocca, Milan, Italy {davide.ginelli, oliviero.riganelli, daniela.micucci, leonardo.mariani}@unimib.it

Abstract—Automated Program Repair (APR) techniques typically exploit spectrum-based fault localization (SBFL) to identify the program locations that should be patched, making the effectiveness of APR techniques dependent on the effectiveness of fault localization. Indeed, results show that SBFL often does not localize faults accurately, hindering the effectiveness of APR.

In this paper, we propose EXCEPT, a technique that addresses the localization problem by focusing on the *semantics* of failures rather than on the correlation between the executed statements and the failed tests, as SBFL does. We focus on failures due to exceptions and we exploit their type and source to localize and guess the faults. Experiments with 43 exception-raising faults from the Defects4J benchmark show that EXCEPT can perform better than Ochiai and ssFix.

Index Terms—automatic program repair, fault localization, SBFL, exceptions

I. INTRODUCTION

Automated Program Repair (APR) techniques have been extensively studied as approaches that can assist developers during the debugging and bug fixing tasks [1], [2]. Although often limited to the simplest bugs, APR has already demonstrated its effectiveness with large-scale industrial systems [3].

APR techniques offer a range of strategies to repair code. For example, *generate-and-validate* techniques (e.g., Gen-Prog [4] and AE [5]) discover plausible fixes by exploring a space of potential patches, while *semantics-driven* techniques (e.g., SemFix [6] and NOPOL [7]) synthesize fixes from a representation of the repair problem directly derived from the faulty application.

APR techniques share the challenge of identifying the *fix locus*, that is, the program location(s) that should be modified to produce a fix. Indeed, it is *hard or even impossible* to repair a fault without selecting a good location for the fix [8].

The larger the program size, the more difficult it is to identify the correct location(s) in which to apply the fix. Focusing on the wrong locations may waste significant computational resources, since each location can be modified in many different ways in the attempt of obtaining a fix [9]. Even worse, choosing the wrong location multiple times can dramatically impact performance and even the feasibility of the repair process.

APR techniques address the problem of identifying the fix locus using Spectrum-Based Fault Localization (SBFL) [10], which can heuristically compute a suspiciousness score associated with each program location: the higher the score, the higher the probability that the program location is faulty. The suspiciousness scores of the statements is derived from the information about the number of passing and failing test cases that execute them. Intuitively, the more a statement is executed by failing executions only, the more suspicious it is.

The suspiciousness scores associated with the statements determine a ranking that is used by APR techniques to identify the targets of the repair process. For example, jGenProg [11], uses the ranking generated by the Ochiai SBFL technique [12] to select statements as modification points with a probability that depends on their suspiciousness, while NOPOL [7] follows the ranking generated by Ochiai to analyze each statement in the ranking one after the other. Unfortunately, experimental evidence shows that SBFL techniques are often unable to rank faulty statements at top positions [8], [13], [14].

In this paper, we propose to address the localization problem by primarily exploiting the *semantics of the failures* rather than the correlation between the executed statements and the failed tests, that has been proven to produce inaccurate results. To this end, we focus on *failures caused by exceptions*, which represent a large portion of the failures that can be observed [15]–[17].

Exceptions carry extensive information about the occurred failures, such as the location that raised the exception, which can represent a good starting point for fault localization, and the type of the exception, which provides useful semantic information about the possible nature of the problem. For instance, a failure caused by a Java ArrayIndexOutOfBoundsException suggests the statement that raised the exception as a possible location for the fix, but the statement where the array has been initialized, and the statements that assigned a value to the variables used to access a location of the array are good locations as well. The type of the exception can thus be used to guide the analysis in the selection of the suspicious locations according to the semantics of the failure.

Since locations are identified based on a guessed cause of the failure (e.g., the value of an index might be wrong), a suspicious location can be enriched with information about the program elements that are likely responsible for the failure (e.g., a variable in an index expression) and the likely fault (e.g., wrong variable used), which can in turn be exploited to identify the change that should be operated to correct the program (e.g., replace the variable).

Although some approaches addressed the localization and repair of failures caused by exceptions, NullPointerExceptions in particular [18], [19], they cannot generate ranked lists of statements that can be used by APR techniques, neither they considered enriching the localization with debugging information that can be useful to developers. The localization used in ssFix [20] can exploit stack traces to improve rankings, but this is not sufficient to correctly localize several faults, as reported in our evaluation.

This paper presents EXCEPT, an exception-driven fault localization technique that can be used to support APR techniques. EXCEPT analyzes failures caused by exceptions and localizes faults by following the semantics of exceptions and their causes. In addition to producing an *ordered list of statements* that are reported as high-priority elements on top of ranked lists returned by SBFL techniques, EXCEPT enriches the identified items with information about the *individual expressions* that are likely faulty (e.g., a specific variable in an expression) and the *guessed faults* (e.g., wrong variable used), which can be used by APR techniques and developers to determine how to patch programs (e.g., replacing the variable).

In our empirical evaluation, EXCEPT outperformed both Ochiai [12] and the localization used in ssFix [20] for 43 exception-raising fault locations selected from the Defects4J benchmark [21]. Further, EXCEPT could correctly guess faults for multiple exception types.

In a nutshell, the main contributions of this paper are:

- EXCEPT, a fault localization technique that considers the semantics of exceptions to localize faults for APR, enriching the localization with information about the *expressions* likely responsible for the failures and the *guessed faults*,
- Empirical evidence of the effectiveness of the proposed strategy in comparison to Ochiai and ssFix.

This paper is organized as follows. Sections II presents EXCEPT. Section III describes the supported exceptions. Section IV presents the empirical evaluation. Section V discusses the related approaches. Section VI provides final remarks.

II. EXCEPT

As exemplified in Figure 1, EXCEPT returns a ranked list of *repair targets* starting from three inputs: a faulty program p, a test t that fails with an uncaught exception, and a list of suspicious statements *rankingSBFL* identified with an SBFL technique. A repair target reports the following information:

- a program *location*, which is a likely faulty program statement,
- an *expression* in the location, which represents a specific program element likely responsible of the fault,
- guessed faults, which associate the expression with specific guessed faults that may affect the expression,
- a *suspiciousness value*, which is a positive number that can be used to rank repair targets from the most likely to the least likely to be relevant for fixing the fault.

For example, a repair target may refer to an array variable (expression) in a statement with an array access (program location) as a likely faulty element, while suggesting that the array name is wrong (guessed fault), with a given suspiciousness

Algorithm 1 Description of EXCEPT.

1: **procedure** EXCEPT (p, t, rankingSBFL)

1:	procedure EXCEPT	(p, t, rankingSBFL)
2:	Input	
3:	p	The faulty program
4:	î	A test case that fails raising an exception
5:	rankingSBFL	The list of suspicious statements identified with a SBFL technique
6:	Output	-
7:	•	List: a list of repair target or null
8:	// Step 1: Stack	Trace Analysis
9:		ExceptionStackTrace(p, t);
10:		getExceptionType(stackTrace);
11:		<pre>itsList = getRelevantStatementsList(stackTrace);</pre>
12:	// Step 2: Rankin	ng Generation
13:	repairTargetsList	$t = \emptyset;$
14:	relevantStmsAna	lyzed = 0;
15:	// Sub-step 2.1:	Selection of suspicious locations
16:	for each relevant	$tStatement \in relevantStatementsList do$
17:	if relevantStr	msAnalyzed <
	exe	ceptionType.maxRelevantStatementsToConsider then
18:	relevantS	tmsAnalyzed = relevantStmsAnalyzed + 1;
19:	suspiciou	sLocations = selectSuspiciousLocations(p, relevantStatement, exceptionType);
20:	// Sub-ste	ep 2.2: Generation of repair targets
21:		suspLoc \in suspiciousLocations do
22:		= computeSuspValue();
23:	1	rTarget = generateRepairTarget (suspLoc, exceptionType, susp);
24:	renai	rTargetsList.add(repairTarget);
25:	end for	·····8··········
26:	end if	
20. 27:	end for	
28:	*	Merging of the rankings
29:	1 0	t.addTargetsFrom(rankingSBFL);
20	4 · · · · · · · · · · · · · · · · · · ·	

30: return repairTargetsList;31: end procedure

value. Or, it may identify the variable used as index of the array (expression) as the faulty element, suggesting that the value of the variable is wrong (guessed fault), with a given suspiciousness value.

EXCEPT adds the repair targets that derive from the knowledge of the exception raised by the failing test as high priority items in the initial ranked list produced by a SBFL technique. Repair targets and SBFL locations are merged together to obtain a comprehensive ranked list that can benefit from the joint contributions of two complemental approaches. Since the information about the faulty expression and the guessed fault derives from the knowledge of the exceptions, they are available only for the high priority targets added by EXCEPT, and are not available for the elements in the initial ranked list produced by SBFL.

EXCEPT works in two main steps:

- *Stack Trace Analysis*, which analyzes the stack trace of the exception to identify the *type of the exception* and the *relevant statements* that occur in the stack trace;
- *Ranking Generation*, which identifies the *relevant expressions* that may have caused the exception, traces them back

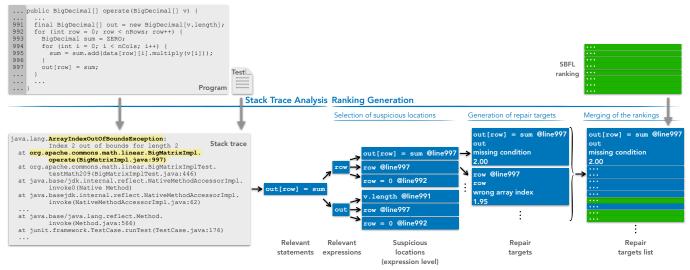


Fig. 1: Except applied to the program in Listing 1.

to the suspicious locations that might have affected the values of the relevant expressions, and creates a ranked list of repair targets from the suspicious locations and the input SBFL ranking.

Figure 1 shows the elements that are incrementally identified by EXCEPT to finally generate the ranking, when applied to the faulty program in Listing 1, which throws an ArrayIndexOutOfBoundsException. Algorithm 1 and Algorithm 2 detail how EXCEPT works with pseudocode. The blue constant and the blue functions depend on the type of the exception and are described in details in Section III for the supported exceptions.

A. Stack Trace Analysis

Stack trace analysis (lines 9-11 of Algorithm 1) extracts two key data from the stack trace associated with an exception: the exception type and the relevant statements.

The exception type is explicitly reported in the stack trace and can be trivially retrieved.

EXCEPT identifies as relevant statements that might have contributed to the exception every program statement explicitly reported in the exception stack trace, that is, every location that appears in the context of the statement that raised the exception. Since the fault is assumed to be in the program, EXCEPT discards the statements that do not refer to the program under analysis, but rather refer to external libraries, JDK classes, test frameworks (e.g., JUnit [22] or Mockito [23]), and test cases. For each unfiltered statement, EXCEPT creates a relevant statement which includes the line number of the statement, the Java class to which it belongs to, the method that executes it, and the *file name* containing the statement. This is done by function getRelevantStatementsList invoked at line 11 of Algorithm 1.

The list of relevant statements is ordered according to their position in the stack trace, starting from the one closest to the statement that generates the exception under analysis.

Algorithm 2 Description of selectSuspiciousLocations.

1: procedure selectSuspiciousLocations(p, stp, et)

- 2: Input 3:
- The faulty program р 4:
- stp A Stack Trace Poi 5:
 - The type of the exception et

6: Output

7.

- suspiciousLocations: a set of suspicious locations
- 8: relevantExpressions = selectRelevantExpressions(p, stp, et);

```
Q٠
        suspiciousLocations = \emptyset;
```

- 10: for each $re \in relevantExpressions$ do 11:
 - suspiciousLocationsForRe = findSuspiciousLocations(p, re, et);
- 12: suspiciousLocations.add(suspiciousLocationsForRe);
- 13: end for
- 14: return suspiciousLocations;
- 15: end procedure

B. Ranking Generation

The generation of the ranking (lines 13-29 in Algorithm 1) implies 1) analyzing the relevant statements to identify the suspicious program locations that might have caused the exception, 2) generating the repair targets, and 3) merging the identified repair targets with the initial SBFL ranking.

Selection of Suspicious Locations (lines 16-19 in Algorithm 1 and Algorithm 2). The number of the analyzed relevant statements is bound to prevent that too many repair targets can be generated (line 17 in Algorithm 1). In fact, adding many targets to the initial ranking generated by SBFL may hinder the effectiveness of APR techniques, since they would have to consider too many highly suspicious program locations. On the contrary, EXCEPT aims to add a small and focused set of high-priority repair targets that may help in directing repair algorithms on the right statements for the right reason.

In practice, the number of relevant statements to be con-

sidered might be different based on the exception type. The bound could be small (e.g., 1) for some exceptions. For instance, in the case of ArrayIndexOfOutBoundsException, the statement that raises the exception includes the array variable and the index value that causes the exception and the analysis can be effectively driven by their values. The bound could be higher for other exceptions, such as the IllegalArgumentException, since the raised exception may strongly depend on the execution context, and considering multiple points derived from the stack trace of the exception might be beneficial (e.g., also considering the calling method).

The selection of the suspicious locations from a relevant statement is described in the selectSuspiciousLocations function presented in Algorithm 2. The selection is driven by two key logical steps: the *selection of the relevant expressions* (line 8 in Algorithm 2) and the *identification of the suspicious locations* (line 11 in Algorithm 2).

When a relevant statement is analyzed, EXCEPT first narrows down the analysis to the specific expressions that might be responsible for the exception, ignoring the rest of the statement. For example, if a statement raises an ArrayIndexOutOfBoundsException, EXCEPT would select the expression used to access the array and the expression that identifies the array as relevant expressions for the analysis, as shown in Figure 1. Since this step of the analysis depends on the semantics of the exception, it is described in details for each supported exception in Section III.

Each expression relevant to the exception is used to identify the statements that might have caused the exceptional situation that finally resulted in the failure. For instance, if the relevant expressions are the array name and the array index, EXCEPT would select the code that defines the array and the code that defines the index as suspicious locations. This is done with a local data-flow analysis that depends on the relevant expression and the type of exception. The specific analysis for the supported exceptions is described in Section III.

Generation of Repair Targets (lines 21-24 of Algorithm 1). Every suspicious location is turned into a repair target by adding the guessed faults and a suspiciousness value. The guessed faults are annotations that specify why the expression could be faulty. For example, if the exception is ArrayIndexOutOfBoundsException and the selected expression defines the value of the size used to initialize the array, a guessed fault may assume the initial size of the array is wrong. Developers and APR techniques can exploit this annotation to change the program accordingly. Since the annotation depends on the type of the exception, we describe how faults are guessed for each exception type in Section III.

The suspiciousness value assigned to the repair targets considers the fact that these targets must have higher priority compared to the top ranked items in the input SBFL ranking. Since the maximum suspiciousness in the input SBFL ranking is 1, EXCEPT assigns suspicious values that start from 2 to the identified repair targets. Since repair targets are generated by following the order of occurrence of the relevant statements, which are ordered based on their distance from the statement that raises the exception, EXCEPT prioritizes the repair targets accordingly, decreasing the suspiciousness value by 0.05 every time a target is added to the ranking. This gap is chosen to accomodate up to 20 high-priority repair targets before potentially reaching the elements in the input ranking.

Merging of the rankings (line 29 of Algorithm 1). The last step requires merging the identified repair targets with the input ranked list. This is performed with two simple steps. First, the locations that are present both in the SBFL ranking and in the repair targets are removed, keeping only the location with the highest suspiciousness score. The additional information produced by EXCEPT (the expression and the guessed fault) are also preserved. Second, all the items are ordered according to their suspiciousness.

III. SUPPORTED EXCEPTIONS

To demonstrate EXCEPT, we defined the analysis for four types of exceptions: ArrayIndexOfOutBoundsException, StringIndexOutOfBoundsException, NullPointer-Exception, and IllegalArgumentException. We focused on some of the most popular types of exceptions based on faults contained in public benchmarks, such as Defect4J [21], Bears [24], and Repairnator [17]. Similar analyses can be added to support additional exceptions.

EXCEPT is equipped with simple and fast analyses based on data flow and bounded in scope to identify the likely fault locations. In particular, the analysis to determine the suspicious locations is bounded to the method that includes the relevant expression. Note that multiple relevant expressions in multiple methods can be selected, thus the analysis is not generally limited to the method that raises the exception. Moreover, the scope of the analysis always includes the definition of class variables, which may initialize variables with wrong values. Bounding the analysis is useful to generate a limited number of repair targets and complete the analysis quickly (in our experiments every case could be processed in few seconds).

In the following, we discuss and exemplify the elements that depend on the exceptions for the four supported exception types: maxRelevantStatementsToConsider specifies the number of relevant statements to consider, selectRelevantExpressions describes how the relevant expressions are determined, findSuspiciousLocations describes the analysis that selects the suspicious code locations, and generateRepairTarget indicates the guessed faults that are associated with the suspicious locations. The guessed fault consists of a label with known semantics (e.g., "wrong variable name") that is included in the repair target and that can be exploited by developers or APR techniques.

A. ArrayIndexOfOutBoundsException

maxRelevantStatementsToConsider. The analysis only considers the statement that raises the exception.

selectRelevantExpressions. EXCEPT looks for instances of the expression refArray[exprIndex] in the relevant statement, to select the occurrences of refArray and exprIndex as relevant expressions that might be wrong

TABLE I: Analysis of ArrayIndexOutOfBoundsException.

Suspicious locations	Guessed faults		
statement with refArray	array variable is wrong missing conditional statement		
allocation of refArray	wrong array initialization		
definitions of the variables that deter- mine the size of refArray	wrong variables values		
statement with exprIndex	exprIndex is wrong		
<i>definitions of variables used in</i> exprIndex	wrong variables values		

and thus cause the exception. In fact, the access to the array might fail because the wrong array is used or the wrong array location is selected.

findSuspiciousLocations and generateRepair-**Target**. When refArray is considered, EXCEPT runs a recursive backward bounded data-flow analysis to identify the locations in which refArray is allocated. If the array initialization statement uses other variables, the analysis process is iterated to determine the locations that assign a value to these variables. Also the location itself, where refArray is used, is returned as a suspicious location.

When exprIndex is considered, EXCEPT runs a backward bounded data-flow analysis to identify the locations that define the variables that occur in exprIndex. Also the location itself where exprIndex is used is returned as a suspicious location. Table I lists the identified locations and the corresponding guessed faults.

Listing	1:	Example	e of	ArrayIndexOutOfBoundsException.
---------	----	---------	------	---------------------------------

```
1 public BigDecimal[] operate(BigDecimal[] v) {
2
   final BigDecimal[] out = new BigDecimal[v.length];
3
   for (int row = 0; row < nRows; row++) {
  BigDecimal sum = ZERO;</pre>
4
5
     for (int i = 0; i < nCols; i++) {</pre>
6
     sum = sum.add(data[row][i].multiply(v[i]));
7
8
     1
9
     out[row] = sum;
10
   }
11 } /*** Source: Math 98 - Defects4J ***/
```

Example. Listing 1 shows an excerpt of the Math 98 fault in Defects4J. The statement at line 9 is the relevant statement, since it generates the ArrayIndexOutOfBoundsException. The variables out and row are selected as *relevant expressions*, which in turn generate 6 *suspicious locations* with the corresponding guessed fault: out might be the wrong array variable used at line 9; row might be the wrong index used at line 9; there might be a missing condition (e.g., it is necessary to add an if-statement that influences the access to array out); row might be assigned with the wrong; the expression v.length used at line 3 might be wrong. In this case, the correct fix consists in modifying the initialization of the array at line 3 by replacing the expression v.length with nRows, which is one of the guessed faults.

TABLE II: Analysis of StringIndexOutOfBoundsException.

Suspicious locations	Guessed faults
<i>statement with</i> stringVar	String variable is wrong missing conditional statement
definition of stringVar	wrong value missing conditional statement
statement with exprIndex	exprIndex is wrong
definitions of vars used in exprIndex	wrong variables values missing conditional statement

B. StringIndexOutOfBoundsException

maxRelevantStatementsToConsider. The analysis only considers the statement that raises the exception.

selectRelevantExpressions. EXCEPT looks for instances of the expression string-Var.op(...exprIndex...) in the relevant statement, where stringVar is a String variable, op is a method that can return a StringIndexOutOfBoundsException, such as charAt(int index), and exprIndex is an Integer expression for accessing the string at a specific position.

EXCEPT selects the occurrences of stringVar, in case the wrong string is used, and exprIndex, in case the wrong index is used, as relevant expressions.

findSuspiciousLocations and generateRepair-Target. When either stringVar or exprIndex are considered, EXCEPT runs a backward data-flow analysis to identify the locations in which the variables included in these expressions are defined. Also the location where these variables are used is returned as a suspicious location. Table II lists the identified locations and the guessed faults.

Listing 2: Example of StringIndexOutOfBoundsException.

Example. Listing 2 shows an excerpt of the Lang 45 fault in Defects4J. The statement at line 9 relevant statement, generates is the since it the StringIndexOutOfBoundsException. The analysis selects the expressions str, 0 and upper as relevant expressions, which in turn generate 8 suspicious locations with the corresponding guessed fault. For sake of space, we do not list all of them, but they include the actual fix, which consists of a missing condition.

C. NullPointerException

maxRelevantStatementsToConsider. The analysis considers both the statement that raises the exception and the

TABLE III: Analysis of NullPointerException.

Suspicious locations	Guessed faults
statement with obj	variable is wrong missing conditional statement
definition of obj	wrong value missing conditional statement
calling site	wrong variables

calling method to address the case of null values erroneously passed as parameters.

selectRelevantExpressions. EXCEPT looks for instances of the expression obj.op() in the first relevant statement, where obj is a non-primitive variable. EXCEPT selects the occurrences of obj as relevant expressions that might be wrong and thus cause the exception. Finally, EXCEPT selects the non-primitive parameters used in the method call in the second relevant statement to account for null values generated by the caller.

findSuspiciousLocations and generateRepair-Target. When obj is considered, EXCEPT runs a backward bounded data-flow analysis to identify the locations where obj is defined. When the caller is analyzed, if the null variable is defined through the method call, the calling site is also identified as a suspicious location. The location itself where this variable is used is also returned as a suspicious location. Table III lists the identified locations and the corresponding guessed faults.

Listing 3: Example of NullPointerException.

1	public class XYPlot {
2	
3	<pre>public Range getDataRange(ValueAxis axis) {</pre>
4	
5	XYItemRenderer r = getRendererForDataset(d);
6	
7	Collection c = r.getAnnotations();
8	
9	}
10	} /*** Source: Chart 4 - Defects4J ***/

Example. Listing 3 shows an excerpt of the Chart 4 fault included in Defects4J. The statement at line 7, since it generates the NullPointerException, is a relevant statement. The analysis selects the expression r as relevant expression, which in turn generates 3 suspicious locations with the corresponding guessed fault: the variable r at line 7 might be wrong; the entire statement at line 7 might have to be accessed only within a conditional statement; and the method getRendererForDataset() used to assign a value to the variable r at line 5 might be wrong. The actual fix consists of adding the conditional statement.

D. IllegalArgumentException

maxRelevantStatementsToConsider. EXCEPT considers both the statement that raises the exception and the caller statement of the method that raises the exception as relevant statements for the analysis.

selectRelevantExpressions. EXCEPT looks for one or more instances of the expression op(...exprPar...)

TABLE IV: Analysis of IllegalArgumentException.

Suspicious locations	Guessed faults
exprPar used as parameter	wrong parameter wrong method invoked
definition of variables in exprPar	wrong value

in the relevant statements. The expression represents any method call with at least one parameter. If the invocation is found in the first relevant statement, the second relevant statement is skipped. Otherwise, (e.g., the first relevant statement throws the exception instead of invoking a method), the second relevant statement is also searched for the same pattern.

EXCEPT selects the occurrences of exprPar as relevant expressions that might be wrong, thus causing the exception.

findSuspiciousLocations and generateRepair-Target. When exprPar is considered, EXCEPT runs a backward bounded data-flow analysis to identify the locations where the variables used in exprPar are defined. Table IV lists the identified locations and the guessed faults.

Listing 4: Example of IllegalArgumentException.

1	<pre>public class TimeSeries {</pre>
2	
3	<pre>public Object clone() {</pre>
4	Object clone = createCopy(0, getItemCount() - 1);
5	return clone;
6	}
8	<pre>public TimeSeries createCopy(int start, int end)</pre>
	throws {
9	<pre>if (start < 0)</pre>
10	<pre>throw new IllegalArgumentException("");</pre>
11	<pre>if (end < start)</pre>
12	<pre>throw new IllegalArgumentException("");</pre>
13	
14	}
15	} /*** Source: Chart 17 - Defects4J ***/

Example. Listing 4 shows an excerpt of the Chart 17 fault in Defect4J. The statement at line 12 raises an IllegalArgumentException if the value of the second parameter of method createCopy is less than the first one. The corresponding relevant locations are the statements at lines 12 and 4. The former statement does not contribute to the analysis since it does not include the actual invocation, while the latter does. The suspicious locations derived from the latter statement are four: the invocation of method createCopy(int, int); the integer 0; the expression getItemCount() - 1; and the call to getItemCount(). The fix requires changing the expression getItemCount() - 1 at line 4.

IV. EMPIRICAL EVALUATION

The empirical evaluation aims to answer three research questions.

RQ1 What is the fault localization effectiveness of Except? This research question investigates the fault-localization effectiveness of EXCEPT for different types of exceptions in comparison to state of the art solutions.

RQ2 How does Except affect the capability of modifying the faulty statements of APR techniques that use SBFL?

This research question investigates how using the ranking produced by EXCEPT affects the capability of program repair techniques to modify the right statement every time the generation of a patched program is attempted.

RQ3 What is the accuracy of the guessed fault?

This research question investigates how accurately EXCEPT can guess the fault that generated an exception.

A. Empirical Setup

In the evaluation, we used faults from the Defects4J benchmark v1.5 [21], a dataset of real-world bugs and fixes from 5 open-source Java projects (JFreeChart, Closure Compiler, Commons Math, Joda-Time, and Commons Lang) commonly used in program repair studies [20], [25], [26].

We initially selected every bug that fails with a test that raises an uncaught exception. The four most frequent exception types raised by these bugs match with the classes of exceptions supported by EXCEPT: NullPointerException (17 faults), IllegalArgumentException (15 faults), ArrayIndexOutOfBoundsException (10 faults), String-IndexOutOfBoundsException (7 faults). Out of these 49 faults, we discarded the faults that require changing multiple non-contiguous code locations without having a same number of failing tests because they could not be properly addressed by localization techniques. For instance, we keep faults that require changing 2 locations if there are 2 failing tests that can be used to localize these changes, but we discard the same fault if only one failing test case is available. We ended up with 33 faults and 43 fault locations to be localized. Table V column Bug ID reports the id of the selected faults, organized by exception type. In case a fault requires changing multiple locations, the table reports multiple rows for the same Bug ID.

To answer RQ1 and RQ2, we considered two competing approaches: the Ochiai SBFL technique [12], which is the most used fault localization technique in program repair [8], and the localization strategy used in ssFix [20] (hereafter referred as ssFix), which exploits the entries in the stack trace as top items of the ranking. Differently from EXCEPT, ssFix does not analyze the target program to extract the relevant expressions, thus missing to select the suspicious program locations that are not in the stack trace.

To precisely measure the improvement that EXCEPT and ssFix can introduce over an existing ranking, we used the ranking generated by Ochiai as input ranking for both EXCEPT and ssFix. We used the test cases available with the programs to compute the ranking with Ochiai. Our tool, which uses Spoon [27] for static program analysis, and experimental material are available at https://gitlab.com/qrs2021/except.

B. What is the fault localization effectiveness of EXCEPT?

In this research question, we compare the fault localization effectiveness of Ochiai, ssFix, and ExcEPT. We considered the location modified by developers as the correct fault location to be identified. If new code is added, the location next to the added code is considered as the correct one. The metric that we used to compare the approaches is the *position* of

Position Probability (%) Additional Octiai Accept Except Additional Octiai Accept Info ArrayIndexVetBourdsxuetsvetsvetsvetsvetsvetsvetsvetsvetsvetsv								
Ochai ssrin EXCEPT Ochai EXCEPT Into ArrayIndexVutOBBUILSEX 47.50 6.50 6.61 5.57 None Lang 12 6.50 7.50 6.50 6.61 5.57 None Math 3 9.50 10.00 2.00 3.19 10.43 Both Math 98 10.00 10.50 2.00 3.19 10.43 Both Math 98 10.00 10.50 2.00 3.19 10.43 Both StringIndexVUTBUREX 51.00 1.00 0.54 7.15 Both Lang 44 90.50 94.00 0.81 0.65 None Lang 45 11.50 11.00 1.00 1.22 1.04 Only Guess Lang 51 - - 0.00 0.00 - Lang 51 - - 0.00 0.00 - Lang 45 11.50 1.00 1.00 1.66 2.18 Both Math 101 </td <td>Rug ID</td> <td></td> <td>Position</td> <td></td> <td>Probab</td> <td>ility (%)</td> <td>Additional</td>	Rug ID		Position		Probab	ility (%)	Additional	
Lang 126.50 6.507.50 7.506.50 6.506.61 6.615.57 5.57None NoneLang 6120.0021.0021.002.072.31NoneMath 39.5010.002.005.5817.65Only TargetMath 9810.0010.502.003.1910.43BothMockito 3452.0052.0053.000.300.26BothString Indextruct Flow the sector of the s	Dug ID	Ochiai	ssFix	EXCEPT	Ochiai	EXCEPT	Info	
Lang 6120.0021.0021.0020.002.572.31NoneMath 39.5010.002.005.5817.65Only TargetMath 9810.0010.502.003.1910.43BothMockito 3452.0052.0053.000.300.26BothStringTue=CutOBE=CutORE=CutORELang 6118.502.001.000.547.15BothLang 4490.5090.5094.000.810.65NoneLang 4511.5011.5013.001.221.04Only GuessLang 593.501.001.001.898.68BothMuth 1019.001.001.001.898.68BothNULPoint=rexception (NPE)Chart 453.002.3501.000.662.18BothClosure 26.005.001.000.332.63BothLang 334.501.001.003.4712.17BothLang 334.501.001.003.4712.17BothLang 573.501.001.003.4712.17BothLang 573.501.001.001.323.45BothLang 344.502.003.003.191.21BothLang 351.001.001.001.34BothLang 373.501.001.001.32S.14BothLang 573.	ArrayIndexOutOfBoundsException (AIOOBE)							
Math 3 9.50 10.00 2.00 5.58 17.65 Only Target Math 98 10.00 10.50 2.00 3.19 10.43 Both Mockito 34 52.00 52.00 53.00 0.20 0.26 Both StringIndexCutOfBoundexException SUOBE 0.54 7.15 Both Lang 6 118.50 2.00 1.00 0.54 7.15 Both Lang 41 90.50 90.50 94.00 1.81 0.65 None Lang 51 - - 0.00 0.00 - Lang 59 3.50 1.00 1.00 1.88 8.68 Both MullPoint=rexception<(NPE)	Lang 12	6.50 6.50	7.50 7.50	6.50 6.50	6.61 6.61	5.57 5.57	None None	
Math 98 10.00 10.00 10.50 10.50 2.00 2.00 3.19 3.19 10.43 10.43 Both Both Mockito 34 52.00 52.00 53.00 0.30 0.26 Both StringIndexCutOfBoundsException SUOBE Image 118.50 2.00 1.00 0.54 7.15 Both Lang 6 118.50 2.00 1.00 0.54 7.15 Both Lang 45 11.50 11.50 13.00 1.02 1.04 Only Guess Lang 59 3.50 1.00 1.00 1.89 8.68 Both MullPoint=rexception IP50 1.00 1.00 1.89 8.68 Both Chart 14 17.50 19.50 1.00 0.66 2.18 Both Lang 20 23.50 23.50 1.00 0.66 2.18 Both Lang 33 4.50 1.00 1.00 7.96 1.374 Both Lang 33 4.50 1.00 1.00 0.86 6.78 <td>Lang 61</td> <td>20.00</td> <td>21.00</td> <td>21.00</td> <td>2.57</td> <td>2.31</td> <td>None</td>	Lang 61	20.00	21.00	21.00	2.57	2.31	None	
Mockito 34 52.00 53.00 0.30 0.26 Both StringTudexUt9Escreption (SIOOBE) Lang 6 118.50 2.00 1.00 0.54 7.15 Both Lang 44 90.50 90.50 94.00 0.81 0.65 None Lang 45 11.50 11.50 13.00 1.22 1.04 Only Guess Lang 59 3.50 1.00 1.00 1.89 8.68 Both Math 101 9.00 1.00 1.00 1.89 8.68 Both Chart 4 53.00 2.50 1.00 0.66 2.18 Both Chart 14 17.50 19.50 1.00 0.66 2.18 Both Closure 2 6.00 5.00 1.00 0.33 2.63 Both Lang 33 4.50 1.00 1.00 2.43 9.86 Both Lang 33 4.50 1.00 1.00 0.76 6.78 Both La	Math 3	9.50	10.00	2.00	5.58	17.65	Only Target	
StringIndexUtOfBoundsException (SIOOBE) Lang 6 118.50 2.00 1.00 0.54 7.15 Both Lang 44 90.50 90.50 94.00 0.81 0.65 None Lang 45 11.50 11.50 13.00 1.22 1.04 Only Guess Lang 59 3.50 1.00 1.00 1.89 8.68 Both Math 101 9.00 1.00 1.00 1.89 8.68 Both NullPoint=Exception (NPE) 0.12 0.45 Both Both 0.666 2.18 Both Chart 14 17.50 19.50 1.00 0.66 2.18 Both Closure 2 6.00 5.00 1.00 0.33 2.63 Both Lang 33 4.50 1.00 1.00 7.96 13.74 Both Lang 37 3.50 1.00 1.00 7.96 6.78 Both Lang 57 3.50 1.00 1.00 0.82 3	Math 98		$10.50 \\ 10.50$	$2.00 \\ 2.00$	3.19 3.19	$10.43 \\ 10.43$		
Lang 6 118.50 2.00 1.00 0.54 7.15 Both Lang 44 90.50 90.50 94.00 0.81 0.65 None Lang 45 11.50 11.50 13.00 1.22 1.04 Only Guess Lang 51 - - 0.00 0.00 - Lang 59 3.50 1.00 1.00 1.89 8.68 Both Math 101 9.00 1.00 1.00 1.89 8.68 Both Chart 4 53.00 2.50 1.00 0.66 2.18 Both Closure 2 6.00 5.00 1.00 0.66 2.18 Both Lang 33 4.50 1.00 1.00 2.43 9.86 Both Lang 39 27.50 1.50 1.00 2.43 9.86 Both Lang 47 82.50 1.00 1.00 1.92 5.14 Both Lang 39 27.50 1.50 1.00 1.21 <td>Mockito 34</td> <td>52.00</td> <td>52.00</td> <td>53.00</td> <td>0.30</td> <td>0.26</td> <td>Both</td>	Mockito 34	52.00	52.00	53.00	0.30	0.26	Both	
Lang 44 90.50 90.50 94.00 0.81 0.65 None Lang 45 11.50 11.50 13.00 1.22 1.04 Only Guess Lang 51 - - 0.00 0.00 - Lang 59 3.50 1.00 1.00 1.89 8.68 Both Math 101 9.00 1.00 1.00 1.89 8.68 Both Chart 4 53.00 2.50 1.00 0.66 2.18 Both Chart 14 17.50 19.50 1.00 0.66 2.18 Both Closure 2 6.00 5.00 1.00 0.33 2.63 Both Lang 33 4.50 1.00 1.00 3.47 Both Lang 39 27.50 1.50 1.00 1.22 5.14 Both Lang 37 3.50 1.00 1.00 1.346 18.05 None Math 4 4.50 2.00 3.00 3.51 None </td <td>StringInd</td> <td>lexOutOfF</td> <td>BoundsEx</td> <td>ception</td> <td>(SIOOBE</td> <td>)</td> <td></td>	StringInd	lexOutOfF	BoundsEx	ception	(SIOOBE)		
Lang 4511.5011.5013.001.221.04Only GuessLang 510.000.00-Lang 593.501.001.001.898.68BothMath 1019.001.001.001.898.68BothNullPoint=rexception (NPE)Chart 453.002.501.000.662.18BothChart 1417.5019.501.000.662.18Both17.5019.501.000.662.18BothChart 1417.5019.501.000.662.18Both17.5019.501.000.662.18BothClosure 26.005.001.000.332.63BothLang 334.501.001.007.9613.74BothLang 3927.501.501.001.925.14BothLang 573.501.001.000.866.78BothLang 573.501.001.000.823.51NoneMath 44.502.003.003.000.310.31NoneMockito 351.001.001.000.830.83NoneMath 44.502.003.003.000.310.31NoneMockito 364.001.001.000.935.79BothMockito 381.501.501.21None <td< td=""><td>Lang 6</td><td>118.50</td><td>2.00</td><td>1.00</td><td>0.54</td><td>7.15</td><td>Both</td></td<>	Lang 6	118.50	2.00	1.00	0.54	7.15	Both	
Lang 51 - - 0.00 0.00 - Lang 59 3.50 1.00 1.00 1.89 8.68 Both Math 101 9.00 1.00 1.00 1.89 8.68 Both NullPoint=resception (NPE) - - 0.12 0.45 Both Chart 4 53.00 2.50 1.00 0.66 2.18 Both Chart 14 17.50 19.50 1.00 0.66 2.18 Both Closure 2 6.00 5.00 1.00 0.33 2.63 Both Lang 33 4.50 1.00 1.00 7.96 13.74 Both Lang 39 27.50 1.50 1.00 1.02 5.14 Both Lang 47 82.50 1.00 1.00 0.74 6.78 Both Lang 57 3.50 1.00 1.00 0.82 3.51 None Math 4 4.50 2.00 3.00 0.31 0.83<	Lang 44	90.50	90.50	94.00	0.81	0.65	None	
Lang 59 3.50 1.00 1.00 1.4.61 14.85 Both Math 101 9.00 1.00 1.00 1.89 8.68 Both NullPoint=Exception (NPE) 0.12 0.45 Both Chart 4 53.00 2.50 1.00 0.66 2.18 Both Chart 14 17.50 19.50 1.00 0.666 2.18 Both Closure 2 6.00 5.00 1.00 0.66 2.18 Both Lang 33 4.50 1.00 1.00 0.33 2.63 Both Lang 39 27.50 1.50 1.00 1.347 Both Lang 47 82.50 1.00 1.00 1.92 5.14 Both Lang 57 3.50 1.00 1.00 1.46 18.05 Both Lang 57 3.50 1.00 1.00 1.46 18.05 Both Lang 57 3.50 1.00 1.00 1.00 0.74	Lang 45	11.50	11.50	13.00	1.22	1.04	Only Guess	
Math 101 9.00 1.00 1.00 1.89 8.68 Both NullPoint=rException (NPE) - <	Lang 51	-	-	-	0.00	0.00	-	
NullPoint=rexception (NPE) Chart 4 53.00 2.50 1.00 0.12 0.45 Both Chart 14 17.50 19.50 1.00 0.66 2.18 Both Chart 14 17.50 19.50 1.00 0.66 2.18 Both Closure 2 6.00 5.00 1.00 0.33 2.63 Both Lang 20 23.50 23.50 1.00 1.00 3.47 12.17 Both Lang 33 4.50 1.00 1.00 1.40 1.92 5.14 Both Lang 37 3.50 1.00 1.00 1.92 5.14 Both Lang 57 3.50 1.00 1.00 1.46 18.05 Both Math 4 4.50 2.00 3.00 3.00 0.82 3.248 Only Target Mockito 18 644.00 644.00 644.00 0.31 0.31 0.31 0.31 0.31 0.31 0.31 0.31 No	Lang 59	3.50	1.00	1.00	14.61	14.85	Both	
Chart 4 53.00 2.50 1.00 0.12 0.45 BothChart 14 17.50 19.50 1.00 0.66 2.18 Both 17.50 19.50 1.00 0.33 2.63 Both $Lang 20$ 23.50 23.50 1.00 2.43 9.86 BothLang 33 4.50 1.00 1.00 7.96 13.74 BothLang 39 27.50 1.50 1.00 1.92 5.14 BothLang 57 3.50 1.00 1.00 0.86 6.78 BothLang 57 3.50 1.00 1.00 0.86 6.78 BothMath 4 4.50 2.00 3.00 0.82 32.48 Only TargetMockito 35 1.00 1.00 1.00 0.81 0.81 NoneMockito 36 4.00 1.00 1.00 0.31 0.31 0.31 Mockito 38 1.50 1.50 1.00 0.30 0.86 5.87 Math 70 1.00 2.00 3.00 0.74 1.46 BothMath 70 1.00 2.00 3.00 0.31 0.31 NoneMockito 38 1.50 1.50 1.21 NoneChart 9 13.50 14.50	Math 101	9.00	1.00	1.00	1.89	8.68	Both	
Chart 14 17.50 17.50 19.50 19.50 1.00 10.00 0.666 2.18 0.666 2.18 2.18 0.666 Both 0.666 Closure 2 6.00 5.00 1.00 0.666 2.18 0.666 Both 0.666 Lang 20 23.50 8.00 23.50 11.00 1.00 0.33 2.63 Both 0.666 Lang 33 4.50 1.00 1.00 3.47 9.86 12.17 Both 0.666 Lang 33 4.50 1.00 1.00 7.96 13.74 0.74 BothLang 33 4.50 1.00 1.00 1.92 5.14 0.74 BothLang 39 27.50 1.50 1.00 1.92 5.14 0.74 BothLang 57 3.50 1.00 1.00 1.46 18.05 BothMath 4 4.50 3.300 2.00 3.00 3.00 0.31 0.82 $0.32.48$ 0.91 0.31 $None$ Mockito 35 1.00 1.00 1.00 0.83 0.31 0.83 0.31 $None$ Mockito 36 4.00 1.00 1.00 0.30 0.31 0.31 0.31 0.31 Mockito 36 1.50 1.50 1.50 1.21 0.31 $None$ Mockito 36 1.50 1.50 1.21 0.31 $None$ Mockito 36 1.50 1.50 1.21 0.31 $None$ Mockito 38 1.50 1.50 1.21 0.31 $None$ Chart 9 13.50 14.50	NullPoint	erExcept	ion (NPE	E)				
Closure 2 6.00 5.00 1.00 0.33 2.63 Both Lang 20 23.50 23.50 1.00 1.00 3.47 12.17 Both Lang 33 4.50 1.00 1.00 7.96 13.74 Both Lang 33 4.50 1.00 1.00 1.92 5.14 Both Lang 37 82.50 1.00 1.00 1.92 5.14 Both Lang 57 3.50 1.00 1.00 1.00 7.76 Both Math 4 4.50 2.00 3.00 8.50 0.82 3.248 Only Target Mockito 18 644.00 644.00 644.00 0.11 0.11 None Mockito 35 1.00 1.00 1.00 0.30 0.31 0.31 0.31 None Mockito 36 4.00 1.00 1.00 0.00 0.30 0.31 0.31 None Mockito 38 1.50 1.50 1.00 0.00 <td>Chart 4</td> <td>53.00</td> <td>2.50</td> <td>1.00</td> <td>0.12</td> <td>0.45</td> <td>Both</td>	Chart 4	53.00	2.50	1.00	0.12	0.45	Both	
Closure 2 6.00 5.00 1.00 0.33 2.63 Both Lang 20 23.50 23.50 1.00 1.00 3.47 12.17 Both Lang 33 4.50 1.00 1.00 7.96 13.74 Both Lang 33 4.50 1.00 1.00 1.92 5.14 Both Lang 37 82.50 1.00 1.00 1.92 5.14 Both Lang 57 3.50 1.00 1.00 1.00 7.76 Both Math 4 4.50 2.00 3.00 8.50 0.82 3.248 Only Target Mockito 18 644.00 644.00 644.00 0.11 0.11 None Mockito 35 1.00 1.00 1.00 0.30 0.31 0.31 0.31 None Mockito 36 4.00 1.00 1.00 0.00 0.30 0.31 0.31 None Mockito 38 1.50 1.50 1.00 0.00 <td>Chart 14</td> <td>17.50 17.50 17.50 17.50</td> <td>19.50 19.50 19.50 19.50</td> <td>$1.00 \\ 1.00$</td> <td>0.66 0.66</td> <td>2.18 2.18 2.18 2.18 2.18</td> <td>Both Both</td>	Chart 14	17.50 17.50 17.50 17.50	19.50 19.50 19.50 19.50	$1.00 \\ 1.00$	0.66 0.66	2.18 2.18 2.18 2.18 2.18	Both Both	
Lang 208.0011.001.003.4712.17BothLang 334.501.001.007.9613.74BothLang 3927.501.501.001.925.14BothLang 47 82.50 1.001.001.000.866.78BothLang 573.501.001.0013.4618.05BothMath 44.501.508.500.823.248Only TargetMockito 18644.00644.00644.000.110.11NoneMockito 351.001.001.000.830.83NoneMockito 364.001.001.000.31NoneMockito 364.001.001.000.935.79BothMockito 381.501.501.000.865.87BothMath 701.002.003.0014.049.03NoneT11egalArgumentException (IAE)1.501.501.501.501.21Chart 913.501.45016.501.501.21NoneChart 175.001.501.002.387.59Only TargetChart 245.506.005.507.367.36NoneClosure 190.000.00-Lang 5482.5082.5082.5082.5082.5082.50	Closure 2			1.00	0.33	2.63	Both	
Lang 3927.501.501.001.925.14BothLang 47 82.50 1.001.001.000.746.78BothLang 573.501.001.0013.4618.05BothMath 44.502.003.000.8232.48Only TargetMockito 18644.00644.00644.000.110.11NoneMockito 35 1.00 1.001.000.830.83NoneMockito 364.001.001.000.935.79BothMockito 381.501.501.000.865.87BothMath 701.002.003.0014.049.03NoneMath 701.002.003.0014.049.03NoneT1legalArgumentException (IAE)1.501.21NoneChart 913.501.501.002.387.59Only TargetChart 175.003.505.005.005.001.21NoneChart 175.003.501.002.387.59Only TargetChart 245.506.005.507.367.36NoneClosure 190.000.00-Lang 538.0038.0038.0038.001.221.22NoneLang 5482.5082.5082.5082.5082.5082.5082.50	Lang 20	23.50 8.00	23.50 11.00	$1.00 \\ 1.00$	2.43 3.47	9.86 12.17	Both Both	
Lang 47 82.50 86.50 1.00 1.00 1.00 1.00 0.86 0.74 6.78 6.78 Both BothLang 57 3.50 1.00 1.00 1.346 18.05 BothMath 4 4.50 4.50 2.00 1.50 3.00 8.50 0.82 0.82 32.48 3.51 Only Target NoneMockito 18 644.00 644.00 644.00 0.11 0.11 NoneMockito 35 3.00 3.00 5.00 3.00 5.00 3.00 5.00 3.00 5.00 0.83 0.69 0.83 0.69 0.83 NoneMockito 36 4.00 1.00 1.00 0.93 5.79 0.69 BothMockito 38 1.50 1.50 1.00 0.86 5.87 0.69 BothMath 70 1.00 2.00 3.00 14.04 9.03 0.69 NoneT11egalArgumentException (IAE) 1.50 1.21 2.38 NoneChart 13 52.50 3.50 1.00 2.38 7.59 0.121 Chart 17 5.00 1.50 1.00 2.38 7.59 0.019 NoneClosure 19 0.00 0.00 -Lang 5 38.00 38.00 38.00 38.00 38.00 38.00 Lang 54 82.50 82.50 82.50 82.50 82.50 82.50	Lang 33	4.50	1.00	1.00	7.96	13.74	Both	
Lang 57 3.50 1.00 1.00 13.46 18.05 Both Math 4 4.50 2.00 3.00 3.00 0.82 32.48 Only Target None Mockito 18 644.00 644.00 644.00 0.11 0.11 None Mockito 35 1.00 1.00 1.00 0.00 0.83 0.83 None Mockito 36 4.00 1.00 1.00 0.01 0.31 0.31 None Mockito 36 4.00 1.00 1.00 0.69 0.69 None Mockito 38 1.50 1.50 1.00 0.86 5.87 Both Math 70 1.00 2.00 3.00 14.04 9.03 None Chart 9 13.50 14.50 16.50 1.50 1.21 None Chart 17 5.00 1.50 1.00 2.38 7.59 Only Target Chart 17 5.00 6.00 5.50 7.36 7.36 None	Lang 39	27.50	1.50	1.00	1.92	5.14	Both	
Nath 4 4.50 4.50 2.00 1.50 3.00 8.50 0.82 0.82 32.48 0.82 Only Target NoneMockito 18 644.00 644.00 644.00 0.11 0.11 0.11 NoneMockito 35 1.00 3.00 1.00 5.00 1.00 5.00 0.69 0.83 0.69 0.86 0.83 0.89 $None$ Math 70 1.00 2.00 3.00 14.04 9.03 $None$ 111 16.50 1.50 1.21 $None$ Chart 9 13.50 14.50 1.00 2.38 7.59 7.59 0.91 7.59 0.91 7.59 Chart 17 5.00 1.50 1.00 2.38 7.59 7.36 $None$ 0.22 1.22 $None$	Lang 47	82.50 86.50			0.86 0.74	6.78 6.78		
Math 4 4.50 1.50 8.50 0.82 3.51 None Mockito 18 644.00 644.00 644.00 0.11 0.11 None Mockito 35 1.00 3.00 1.00 5.00 1.00 5.00 1.00 5.00 1.00 5.00 0.83 5.00 0.83 0.31 0.83 0.31 0.83 0.69 0.69 None Mockito 36 4.00 1.00 1.00 0.00 0.93 5.79 Both Mockito 38 1.50 1.50 1.00 0.86 5.87 Both Math 70 1.00 2.00 3.00 14.04 9.03 None Chart 9 13.50 14.50 16.50 1.50 1.21 None Chart 17 5.00 1.50 1.00 2.38 7.59 Only Target Chart 24 5.50 6.00 5.50 7.36 7.36 None Closure 19 - - - 0.00 0.00 - Lang 54 82.50 82.50	Lang 57	3.50	1.00	1.00	13.46	18.05	Both	
Mockito 35 1.00 33.00 1.00 33.00 1.00 33.00 1.00 33.00 1.00 33.00 1.00 33.00 1.00 0.69 None 0.69 None 0.69 None 0.69 None None Mockito 36 4.00 1.00 1.00 0.00 0.31 0.31 None Mockito 36 4.00 1.00 1.00 0.93 5.79 Both Mockito 38 1.50 1.50 1.00 0.86 5.87 Both Math 70 1.00 2.00 3.00 14.04 9.03 None 111egalArgumentException (IAE) 1.50 1.50 1.50 1.21 None Chart 9 13.50 14.50 16.50 1.50 1.21 None Chart 17 5.00 1.50 1.00 2.38 7.59 Only Target Chart 24 5.50 6.00 5.50 7.36 None 0.00 - Lang 5 38.00 38.00 38.00 1.22 1.22 None Lang 54	Math 4						Only Target None	
Mockito 36 4.00 1.00 1.00 0.93 5.79 Both Mockito 38 1.50 1.50 1.00 0.86 5.87 Both Math 70 1.00 2.00 3.00 14.04 9.03 None IllegalArgumentException (IAE) Chart 9 13.50 14.50 16.50 1.50 1.21 None Chart 13 52.50 3.50 1.00 0.74 1.46 Both Chart 17 5.00 1.50 1.00 2.38 7.59 Only Target Chart 24 5.50 6.00 5.50 7.36 7.36 None Closure 19 - - - 0.00 0.00 - Lang 5 38.00 38.00 38.00 38.00 1.22 None Lang 54 82.50 82.50 82.50 0.86 0.86 None	Mockito 18	644.00	644.00	644.00	0.11	0.11	None	
Mockito 36 4.00 1.00 1.00 0.93 5.79 Both Mockito 38 1.50 1.50 1.00 0.86 5.87 Both Math 70 1.00 2.00 3.00 14.04 9.03 None IllegalArgumentException (IAE) Chart 9 13.50 14.50 16.50 1.50 1.21 None Chart 13 52.50 3.50 1.00 0.74 1.46 Both Chart 17 5.00 1.50 1.00 2.38 7.59 Only Target Chart 24 5.50 6.00 5.50 7.36 7.36 None Closure 19 - - - 0.00 0.00 - Lang 5 38.00 38.00 38.00 38.00 1.22 None Lang 54 82.50 82.50 82.50 0.86 0.86 None	Mockito 35	$1.00 \\ 33.00 \\ 5.00$	$1.00 \\ 33.00 \\ 5.00$	$1.00 \\ 33.00 \\ 5.00$	$0.83 \\ 0.31 \\ 0.69$	0.83 0.31 0.69	None	
Math 70 1.00 2.00 3.00 14.04 9.03 None IllegalArgumentException (IAE) Chart 9 13.50 14.50 16.50 1.50 1.21 None Chart 9 13.50 1.4.50 1.650 1.50 1.21 None Chart 13 52.50 3.50 1.00 0.74 1.46 Both Chart 17 5.00 1.50 1.00 2.38 7.59 Only Target Chart 24 5.50 6.00 5.50 7.36 7.36 None Closure 19 - - - 0.00 0.00 - Lang 5 38.00 38.00 38.00 1.22 None - Lang 54 82.50 82.50 82.50 0.86 0.86 None	Mockito 36		1.00		0.93	5.79	Both	
IllegalArgumentException (IAE) Chart 9 13.50 14.50 16.50 Chart 9 13.50 14.50 1.50 1.21 None Chart 13 52.50 3.50 1.00 0.74 1.46 Both Chart 17 5.00 1.00 2.38 7.59 Only Target Chart 24 5.50 6.00 5.50 7.36 7.36 None Closure 19 - - 0.00 0.00 - Lang 5 38.00 38.250 82.50 0.86 0.86 None Lang 54 82.50 82.50 0.86 None	Mockito 38	1.50	1.50	1.00	0.86	5.87	Both	
Chart 9 13.50 14.50 16.50 1.50 1.21 None Chart 13 52.50 3.50 1.00 0.74 1.46 Both Chart 17 5.00 1.50 1.00 2.38 7.59 Only Target Chart 24 5.50 6.00 5.50 7.36 7.36 None Closure 19 - - - 0.00 0.00 - Lang 5 38.00 38.00 38.00 1.22 1.22 None Lang 54 82.50 82.50 82.50 0.86 0.86 None	Math 70	1.00	2.00	3.00	14.04	9.03	None	
Chart 13 52.50 3.50 1.00 0.74 1.46 Both Chart 17 5.00 1.50 1.00 2.38 7.59 Only Target Chart 24 5.50 6.00 5.50 7.36 7.36 None Closure 19 - - 0.00 0.00 - Lang 5 38.00 38.00 38.00 1.22 1.22 None Lang 54 82.50 82.50 82.50 0.86 0.86 None								
Chart 17 5.00 1.50 1.00 2.38 7.59 Only Target Chart 24 5.50 6.00 5.50 7.36 7.36 None Closure 19 - - 0.00 0.00 - Lang 5 38.00 38.00 38.00 1.22 1.22 None Lang 54 82.50 82.50 0.86 0.86 None	Chart 9	13.50	14.50	16.50	1.50	1.21	None	
Chart 24 5.50 6.00 5.50 7.36 7.36 None Closure 19 - - - 0.00 0.00 - Lang 5 38.00 38.00 38.00 1.22 1.22 None Lang 54 82.50 82.50 82.50 0.86 0.86 None	Chart 13	52.50	3.50	1.00	0.74	1.46	Both	
Closure 19 - - 0.00 0.00 - Lang 5 38.00 38.00 38.00 1.22 1.22 None Lang 54 82.50 82.50 0.86 0.86 None	Chart 17	5.00	1.50	1.00	2.38	7.59	Only Target	
Lang 5 38.00 38.00 38.00 1.22 1.22 None Lang 54 82.50 82.50 82.50 0.86 0.86 None	Chart 24	5.50	6.00	5.50	7.36	7.36	None	
Lang 54 82.50 82.50 82.50 0.86 None	Closure 19	-	-	-	0.00	0.00	-	
	Lang 5	38.00	38.00	38.00	1.22	1.22	None	
Time 27 2,636.00 2,638.00 2,636.00 0.0037 0.0036 None	Lang 54	82.50	82.50	82.50	0.86	0.86	None	
	Time 27	2,636.00	2,638.00	2,636.00	0.0037	0.0036	None	

the faulty statement in the ranking. If the faulty statement has the same suspiciousness of other statements, we consider its average position, as done in other studies.

Table V column *Position* reports the ranking of the faulty statement for Ochiai, ssFix, and EXCEPT. When a technique outperforms another, we highlight the cell with light grey.

In the case of ArrayIndexOutOfBoundsException, EX-CEPT ranked the faulty statement better than competing approaches three times. Ochiai performed better than others once (Lang 61), while ssFix was never the best approach. Interestingly, while Ochiai introduced a marginal improvement for Lang 61, EXCEPT significantly improved the ranking, moving to the second position faulty statements that were below the ninth position in the initial ranking.

In the case of StringIndexOutOfBoundsException, EXCEPT ranked the faulty statement better than competing approaches once, while there was not a single winning approach in the rest of the cases. In two cases, Ochiai and ssFix performed better than EXCEPT, although with a marginal improvement on the raking. On the contrary, EXCEPT significantly improved the Ochiai ranking in two cases. For this class of exceptions, ssFix and EXCEPT performed similarly. In one case, (Lang 51), none of the approaches could locate the correct statement.

In the case of NullPointerException, EXCEPT performed significantly better than both Ochiai and ssFix both in the number of cases (10 cases) and the magnitude of the improvement. Vice versa, Ochiai and ssFix performed better than the other approaches in 1 and 2 cases, respectively, with marginal improvement in the ranking compared to EXCEPT.

Finally, in the case of IllegalArgumentException, EX-CEPT obtained the best result in 2 cases, while Ochiai obtained the best result in 1 case, and ssFix never obtained the best result. Again, EXCEPT obtained a significative relative improvement over Ochiai, while the improvement of Ochiai over EXCEPT was marginal. Also in this case, one fault related to the addition of new code was impossible to localize.

Overall, it is noticeable how EXCEPT managed to rank well a number of faults compared to Ochiai and ssFix, with ssFix performing better than Ochiai but worse than EXCEPT.

C. How does EXCEPT affect the capability of modifying the faulty statements of APR techniques that use SBFL?

To answer RQ2, we consider how APR techniques use the rankings returned by SBFL techniques. There are two main possible models: *probabilistic* and *one-by-one*.

In the probabilistic model, APR techniques assign to each statement a probability to be selected for mutation that is proportional to its suspiciousness and the suspiciousness of the rest of the statements in the ranking:

$$prob(s) = \frac{susp(s)}{\sum\limits_{s_i \in ranking} susp(s_i)}$$
(1)

where *s* is a statement in the ranking and *ranking* is the considered ranking. The higher the probability of selecting the faulty statement is, the more likely the APR technique shall modify the right code location to fix the fault. Examples of APR techniques that use this probabilistic schema to iteratively identify the statement to be modified are jGenProg [11], jMutRepair [28], DeepRepair [29], and Cardumen [30].

In the one-by-one model, APR techniques consider the statements in the same order they occur in the ranking from the most suspicious to the least suspicious. The lower the position value of the faulty statement in the ranking is, the sooner the APR technique will modify the right code location to fix the fault. Example of APR techniques that use this systematic

schema to iteratively identify the statement to be modified are NOPOL [7], AE [5], and jKali [28].

Statements selection: Probabilistic (Except vs Ochiai)

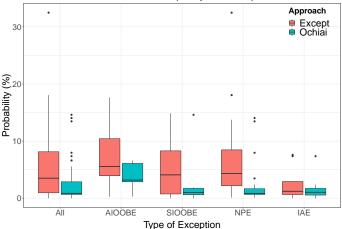


Fig. 2: Comparison between Except and Ochiai according to the *probabilistic* usage of the ranking.

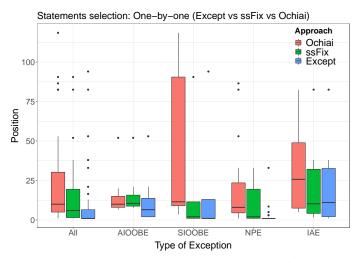


Fig. 3: Comparison between Except, ssFix, and Ochiai according to the *one-by-one* usage of the ranking.

To assess the impact of the rankings generated by EXCEPT, ssFix, and Ochiai in the context of APR, we computed the metrics prob(s) and position(s) for all the faulty statements s considered in our study. Since ssFix does not assign a probability to the statements moved at the top of the ranking, we could only assess the rankings produced by ssFix with the *position* metric. The analytical values of these metrics are reported in the columns *Position* and *Probability* of Table V.

Figure 2 visually shows the results obtained by considering the probabilistic selection schema, distinguishing per exception type and overall across all the exceptions. Probability values increase significantly with EXCEPT. In fact, the median, third quartile, and maximum obtained with EXCEPT are 3.51%, 8.14%, and 32.48% respectively, while the median, third quartile, and maximum obtained with Ochiai are 0.86%, 2.88%, and 14.61% respectively. The significant difference ($\alpha = 0.05$) between EXCEPT and Ochiai with all exceptions has been confirmed with a Wilcoxon rank sum test.

The better performance of EXCEPT is also observable at the level of the individual exception types, although with variable strength. In particular, while differences are remarkable for ArrayIndexOutOfBounds-Exception, StringIndexOutOfBoundsException and NullPointerException, the difference is smaller for IllegalArgumentException.

Figure 3 visually shows the results obtained considering the one-by-one selection schema, distinguishing per exception type and overall across all the exceptions. The relative performance of the three approaches was confirmed, with EXCEPT performing better than ssFix which performed better than Ochiai. The significant difference ($\alpha = 0.05$) between EXCEPT and both Ochiai and ssFix with all exceptions has been again confirmed with a Wilcoxon rank sum test.

At the level of the individual exceptions, we can observe that EXCEPT performed better than ssFix and Ochiai for both ArrayIndexOutOfBoundsException and NullPointerException, while it performed comparably to ssFix for StringIndexOutOfBoundsException and IllegalArgumentException.

In a nutshell, the outcome of this research question suggests that faults revealed by tests that generate uncaught exceptions should be addressed by APR techniques using the ranking produced by EXCEPT, regardless of the strategy used (probabilistic or one-by-one).

D. What is the accuracy of the guessed fault?

This research question evaluates the capability of EXCEPT to guess the fault that should be repaired. We assess the accuracy of the repair target distinguishing four cases: both the selected expression and the guessed faults associated with the faulty statement are correct (label Both), the faulty expression is correctly selected but the guessed fault is wrong (label Only Target), the fault is correctly guessed but the wrong expression is selected (label Only Guess), and both the selected expression and the guessed fault are wrong (label None). Table V column Additional Info shows the results.

EXCEPT both identified the expression to be changed and the fault to be fixed in 22 out of the 41 cases with a localization (54%). In three cases the faulty expression was identified but without correctly guessing the fault. In one case, EXCEPT guessed the right fault, but associated it with the wrong statement (EXCEPT guessed a missing condition, although not in the right place). In total, EXCEPT correctly enriched the localization with additional information in 26 out of 41 cases (63%). This result indicates that the additional information generated by EXCEPT frequently represents a meaningful suggestion about the fault.

E. Threats to validity

A threat to validity is about the limited set of exceptions supported by EXCEPT and the generalizability of the results. To mitigate this threat, we selected the exceptions by considering common types of problems reported in popular Java benchmarks, such as Defect4J [21], Bears [24], and Repairnator [17], that contain real-world faults from different projects raising different types of exceptions.

Another concern is about the correctness of the implementations that we used in the experiments. We relied on GZoltar [31], a widely used tool, for the implementation of Ochiai. We instead used our own implementation of ssFix [20]. To mitigate any implementation threat, we made our artefacts publicly available.

V. RELATED WORK

The classes of approaches closely related to EXCEPT are SBFL, slice-based, and stack trace-based techniques.

Spectrum-Based Fault Localization (SBFL) is probably the most widely used fault localization method [10]. It computes a suspiciousness score for the statements executed by a program, assigning an higher value to the statements mostly executed by failing test cases. Fault localization approaches based on SBFL are often unable to rank the faulty statements at the very top positions of the rankings [8], [13], [14] and they do not provide information about why a given location might be considered faulty, complicating their usage [32].

EXCEPT addresses these limitations for failures caused by uncaught exceptions. In particular, EXCEPT exploits the semantics of the failures to improve the ranking and enrich locations with information about the likely faulty expressions and the guessed faults.

Slice-based techniques use data and control-flow dependencies to focus the localization process on the slice of program locations that may affect the output of a test case [33]–[35]. The basic idea is that if a test case fails due to the incorrect value of a variable, the fault should be searched, either statically [35], [36] or dinamically [34], [37], in the slice of statements that may affect that variable.

Slicing techniques tend to select many locations, not significantly reducing the search space in practical situations. EXCEPT exploits static data-flow oriented slicing to identify the suspicious locations from the relevant expressions, but heavily bounds the scope of the analysis to select a small number of statements likely causing the exception.

Stack trace-based fault localization methods analyze the exception stack trace in order to improve fault localization. For example, Wong et al. [38] analyze the stack traces that occur in bug reports to increase the suspiciousness of files. Similarly, ssFix [20] prioritizes the statements that occur in the exception stack trace. However, as shown in our experimentation, using the statements that explicitly occur in stack traces is not always sufficient to effectively localize faults. CrashLocator [39] can localize faults from stack traces using static analysis, based on a large collection of stack traces, but it can be conveniently applied to a single failing execution.

VI. CONCLUSION

Fault localization is a key component of APR techniques, in fact a fault that is not localized cannot be repaired [8].

This paper presents EXCEPT, a technique that exploits the semantics of the exception and the related stack trace, to identify a small set of highly suspicious statements that are considered with high priority by APR techniques. The results obtained with our experiments show the effectiveness of EXCEPT, also in comparison with the other approaches.

Future work concerns with both experimenting EXCEPT with APR techniques and studying solutions that can exploit the semantics of failures also when no exception is raised.

REFERENCES

- L. Gazzola, D. Micucci, and L. Mariani, "Automatic software repair: A survey," *IEEE Transactions on Software Engineering (TSE)*, vol. 45, no. 1, pp. 34–67, 2019.
- [2] C. Le Goues, M. Pradel, and A. Roychoudhury, "Automated program repair," *Communications of the ACM*, vol. 62, no. 12, pp. 56–65, 2019.
- [3] A. Marginean, J. Bader, S. Chandra, M. Harman, Y. Jia, K. Mao, A. Mols, and A. Scott, "SapFix: automated end-to-end repair at scale," in *Proceedings of the International Conference on Software Engineering* (ICSE), 2019.
- [4] C. Le Goues, T. Nguyen, S. Forrest, and W. Weimer, "GenProg: A generic method for automatic software repair," *IEEE Transactions on Software Engineering (TSE)*, vol. 38, no. 1, pp. 54–72, 2012.
- [5] W. Weimer, Z. Fry, and S. Forrest, "Leveraging program equivalence for adaptive program repair: Models and first results," in *Proceedings of the International Conference on Automated Software Engineering (ASE)*, 2013.
- [6] H. Nguyen, D. Qi, A. Roychoudhury, and S. Chandra, "Semfix: Program repair via semantic analysis," in *Proceedings of the International Conference on Software Engineering (ICSE)*, 2013.
- [7] J. Xuan, M. Martinez, F. DeMarco, M. Clément, S. L. Marcote, T. Durieux, D. Le Berre, and M. Monperrus, "Nopol: Automatic repair of conditional statement bugs in Java programs," *IEEE Transactions on Software Engineering TSE*, vol. 43, no. 1, pp. 34–55, 2017.
- [8] K. Liu, A. Koyuncu, T. F. Bissyande, D. Kim, J. Klein, and Y. L. Traon, "You cannot fix what you cannot find! an investigation of fault localization bias in benchmarking automated program repair systems," in *Proceedings of the International Conference on Software Testing, Validation and Verification (ICST)*, 2019.
- [9] F. Long and M. C. Rinard, "An analysis of the search spaces for generate and validate patch generation systems," in *Proceedings of the International Conference on Software Engineering (ICSE)*, 2016.
- [10] W. E. Wong, R. Gao, Y. Li, R. Abreu, and F. Wotawa, "A survey on software fault localization," *IEEE Transactions on Software Engineering*, vol. 42, no. 8, pp. 707–740, 2016.
- [11] M. Martinez and M. Monperrus, "Astor: Exploring the design space of generate-and-validate program repair beyond genprog," *Journal of Systems and Software*, vol. 151, pp. 65 – 80, 2019.
- [12] R. Abreu, P. Zoeteweij, and A. J. C. van Gemund, "On the accuracy of spectrum-based fault localization," in *Proceedings of the Testing: Academic and Industrial Conference Practice and Research Techniques* - MUTATION (TAICPART-MUTATION), 2007.
- [13] F. Y. Assiri and J. M. Bieman, "Fault localization for automated program repair: effectiveness, performance, repair correctness," *Software Quality Journal (SQJ)*, vol. 25, pp. 171–199, 2016.
- [14] S. Pearson, J. Campos, R. Just, G. Fraser, R. Abreu, M. D. Ernst, D. Pang, and B. Keller, "Evaluating and improving fault localization," in *Proceedings of the International Conference on Software Engineering* (ICSE), 2017.
- [15] P. Sawadpong, E. B. Allen, and B. J. Williams, "Exception handling defects: An empirical study," in *Proceedings of the International Symposium on High-Assurance Systems Engineering (HASE)*, 2012.
- [16] D. Ginelli, M. Martinez, L. Mariani, and M. Monperrus, "A comprehensive study of code-removal patches in automated program repair," *arXiv* preprint arXiv:2012.06264, 2020.

- [17] S. Urli, Z. Yu, L. Seinturier, and M. Monperrus, "How to design a program repair bot? insights from the repairnator project," in *Proceedings* of the International Conference on Software Engineering (ICSE), 2018.
- [18] T. Durieux, B. Cornu, L. Seinturier, and M. Monperrus, "Dynamic patch generation for null pointer exceptions using metaprogramming," in *Proceedings of the International Conference on Software Analysis*, *Evolution and Reengineering (SANER)*, 2017.
- [19] S. Sinha, H. Shah, C. Görg, S. Jiang, M. Kim, and M. J. Harrold, "Fault localization and repair for java runtime exceptions," in *Proceedings* of the Eighteenth International Symposium on Software Testing and Analysis (ISSTA), 2009.
- [20] Q. Xin and S. P. Reiss, "Leveraging syntax-related code for automated program repair," in *Proceedings of the IEEE/ACM International Conference on Automated Software Engineering (ASE)*, 2017.
- [21] R. Just, D. Jalali, and M. D. Ernst, "Defects4j: A database of existing faults to enable controlled testing studies for java programs," in *Proceed*ings of the International Symposium on Software Testing and Analysis (ISSTA), 2014.
- [22] jUnit Team, "junit," https://junit.org/junit5/, 2021.
- [23] Szczepan Faber, "Mockito," https://site.mockito.org, 2021.
- [24] F. Madeiral, S. Urli, M. Maia, and M. Monperrus, "Bears: An Extensible Java Bug Benchmark for Automatic Program Repair Studies," in *Proceedings of the IEEE International Conference on Software Analysis, Evolution and Reengineering (SANER)*, 2019.
- [25] M. Martinez, T. Durieux, R. Sommerard, J. Xuan, and M. Monperrus, "Automatic repair of real bugs in java: A large-scale experiment on the defects4j dataset," *Empirical Software Engineering*, vol. 22, no. 4, pp. 1936 –1964, 2017.
- [26] K. Liu, A. Koyuncu, D. Kim, and T. F. Bissyandé, "Tbar: Revisiting template-based automated program repair," in *Proceedings of the ACM* SIGSOFT International Symposium on Software Testing and Analysis (ISSTA), 2019.
- [27] R. Pawlak, M. Monperrus, N. Petitprez, C. Noguera, and L. Seinturier, "Spoon: A Library for Implementing Analyses and Transformations of Java Source Code," *Software: Practice and Experience*, vol. 46, pp. 1155–1179, 2015.
- [28] M. Martinez and M. Monperrus, "Astor: A program repair library for java," in *Proceedings of the ACM SIGSOFT International Symposium* on Software Testing and Analysis (ISSTA), 2016.
- [29] M. White, M. Tufano, M. Martínez, M. Monperrus, and D. Poshyvanyk, "Sorting and transforming program repair ingredients via deep learning code similarities," in *Proceedings of the IEEE International Conference* on Software Analysis, Evolution and Reengineering (SANER), 2019.
- [30] M. Martinez and M. Monperrus, "Ultra-large repair search space with automatically mined templates: The cardumen mode of astor," in *Search-Based Software Engineering*, T. E. Colanzi and P. McMinn, Eds., 2018.
- [31] J. Campos, A. Riboira, A. Perez, and R. Abreu, "Gzoltar: an eclipse plug-in for testing and debugging," in *Proceedings of the International Conference on Automated Software Engineering (ASE)*, 2012.
- [32] C. Parnin and A. Orso, "Are automated debugging techniques actually helping programmers?" in *Proceedings of the international Symposium* on Software Testing and Analysis (ISTA), 2011.
- [33] Y. Lei, X. Mao, Z. Dai, and C. Wang, "Effective statistical fault localization using program slices," in *Proceedings of the IEEE Annual Computer Software and Applications Conference (COMPSAC)*, 2012.
- [34] X. Mao, Y. Lei, Z. Dai, Y. Qi, and C. Wang, "Slice-based statistical fault localization," *Journal of Systems and Software*, vol. 89, pp. 51 – 62, 2014.
- [35] M. Weiser and J. Lyle, "Experiments on slicing-based debugging aids," in *Proceedings of the Workshop on Empirical Studies of Programmers*, 1986.
- [36] T. Gyimóthy, Á. Beszédes, and I. Forgács, "An efficient relevant slicing method for debugging," in *Proceedings of the European Software Engineering Conference (ESEC)*, 1999.
- [37] H. Agrawal and J. R. Horgan, "Dynamic program slicing," in Proceedings of the ACM Conference on Programming Language Design and Implementation (PLDI), 1990.
- [38] C. Wong, Y. Xiong, H. Zhang, D. Hao, L. Zhang, and H. Mei, "Boosting bug-report-oriented fault localization with segmentation and stack-trace analysis," in *Proceedings of the International Conference on Software Maintenance and Evolution (ICSME)*, 2014.
- [39] R. Wu, H. Zhang, S.-C. Cheung, and S. Kim, "Crashlocator: Locating crashing faults based on crash stacks," in *Proceedings of the International Symposium on Software Testing and Analysis (ISSTA)*, 2014.