Effective and Efficient API Misuse Detection via Exception Propagation and Search-Based Testing

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ABSTRACT

Application Programming Interfaces (APIs) typically come with implicit usage constraints. The violations of these constraints (API misuses) can lead to software crashes. Even though there are several tools that can detect API misuses, most of them suffer from a very high rate of false positives. We introduce Catcher, a novel API misuse detection approach that combines static exception propagation analysis with automatic search-based test case generation to effectively and efficiently pinpoint crash-prone API misuses in client applications. We validate Catcher against 21 Java applications, targeting misuses of the Java platform’s API. Our results indicate that Catcher is able to generate test cases that uncover 243 (unique) API misuses that result in crashes. Our empirical evaluation shows that Catcher can detect a large number of misuses (77 cases) that would remain undetected by the traditional coverage-based test case generator EvoSuite. Additionally, on average, Catcher is eight times faster than EvoSuite in generating test cases for the identified misuses. Finally, we find that the majority of the exceptions triggered by Catcher are unexpected to developers, i.e., not only unhandled in the source code but also not listed in the documentation of the client applications.

CCS CONCEPTS

• Software and its engineering → Software libraries and repositories; Error handling and recovery; Software testing and debugging; Search-based software engineering.

KEYWORDS

API misuse, software crash, static exception propagation, search-based software testing.

∗This work was done and completed at the Delft University of Technology.

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1 INTRODUCTION

Developers use external libraries to increase the velocity and reduce the production cost of software projects [38]. While increasing productivity, this form of software reuse comes with several challenges: dependencies need to be kept up to date [15], developers must learn the intricacies of each imported Application Programming Interface (API), and resulting client programs should be robust, efficient, and responsive. Correctly using third-party APIs is not an easy task; many APIs are millions of lines of code large, interact with various external systems and, importantly, they use stacks of software that offer increasing levels of abstraction at the expense of observability of the workings of the underlying layers.

The fact that APIs are opaque to developers is known to lead to incorrect uses (or API misuses [3, 4]) since client applications can violate the (implicit) usage constraints (often referred to as contract) of those APIs. For example, a violation occurs when a client application calls a method that expects a non-null constrained formal parameter without validating (i.e., via null checks or error handling) the references used as arguments. API misuses can cause software reliability problems, originating from issues such as poor handling of user input and resource misuses [3], or even increasing the attack surface of client applications [18, 40]. Documentation is not adequate, as it is usually either outdated [10], defective [64], or just ignored by the developers of client applications [50].

While static API misuse detectors can successfully identify specific types of API misuses, they suffer from various limitations [4]. In particular, these approaches have a high rate of false positives, requiring developers to manually inspect (via cross-checking [4] or writing test cases [57]) and review large lists of candidate API misuses produced by static analysis. In fact, according to a recent empirical study of Johnson et al. [28], who interviewed developers, false positives and developer overload are the main sources of dissatisfaction with static analysis tools.
Dynamic analysis tools [21, 34, 35] can pinpoint crash-related bugs in the source code without any false positives. However, these approaches have to compromise between the exploration of the vast search space of possible execution paths of the application under test and the time budget allowed for the discovery of the bugs. If an API misuse requires an additional effort to get exposed (i.e., if only a few execution paths contain it), the analysis may fail to detect it. To overcome this, we can either set a larger search-time budget or reduce the search space by including only potentially interesting parts of the application under test.

The main idea of this paper is to restrict the search space of automatic test case generators to crash-prone API-call locations (candidate misuses), i.e., method calls that might throw exceptions at runtime. To this end, we define a novel approach, CATCHER, that combines static exception propagation analysis and test case generation to effectively and efficiently discover candidate misuses in a software under test. CATCHER can help developers by automating (i) the detection of misuses of the Java platform’s API that can cause client application crashes and (ii) the generation of test cases triggering such crashes.

CATCHER works as follows. First, static exception propagation [25, 51] (based on Soot [59]) identifies call paths that propagate runtime exceptions raised by API methods but remained unhandled, in the application call sites, potentially causing application crashes [19, 31]. The call sites to each one of those API methods represent candidate misuses, defining the search space for the test case generation. Then, traditional code coverage heuristics and the previously identified candidate misuses are used for focusing the automatic test suite generator EvoSuite [20, 21] towards the generation of test cases that trigger the candidates’ (propagated) exceptions.

To evaluate our approach, we initially examine whether existing state-of-the-art test coverage-based approaches (here we consider EvoSuite) are effective and efficient in discovering API misuses (RQ1). Then, we assess whether the performance of automatic test suite generators, such as EvoSuite, on detecting crash-prone API misuses can be improved by CATCHER (RQ2). Finally, we cross-check whether the exceptions that CATCHER triggers are listed in the documentation (i.e., are expected) of the Java platform’s API and client projects or not (RQ3).

We evaluate CATCHER by using 21 Java client applications and targeting API misuses of the Java’s JDK v. 1.8.0_181. We find that CATCHER can automatically uncover 243 (unique) misuses of the Java platform’s API in 21 client applications. The collected results show that CATCHER revealed more API misuses (77 cases) that remained undetected by plain EvoSuite, while requiring less than 20% of the time.

In summary, we make the following contributions: (i) an investigation of state-of-the-art search-based test case generator (EvoSuite) for evaluating its efficiency and effectiveness on identifying API misuses in client projects; (ii) a novel technique (CATCHER) that combines static exception propagation analysis and search-based software testing to maximize the number of found crash-prone API misuses in a software under test and minimize the time needed for discovering those misuses; (iii) an empirical evaluation involving 21 Java projects that shows the effectiveness and efficiency of the proposed solution. Finally, we provide the data of our study as well as the source code of CATCHER and the scripts for the postprocessing of our results.

2 BACKGROUND

API misuses occur when a developer of a client application violates an implicit (or explicit) usage constraint of an API [4]. Figure 1 presents a misuse of the Java StringTokenizer API in Joda-time:\footnote{Available at https://github.com/mkechagia/Catcher.} the nextToken method might throw a NoSuchElementException if the condition on the current position in the input string is not satisfied (line 348). This post-condition is documented but not handled by the constructor of the Rule class in Joda-time. The client (Figure 1(b)) neither performs any validation check for the input (input sanitization) before calling the API nor uses any exception handling mechanism for that API call. As a result, this API misuse propagates an exception from the Java platform’s API to the caller, the Rule constructor, if the input parameter contains less than three tokens (line 696).

In their recent work, Amann et al. [4] proposed a classification of API misuses by identifying four missing and redundant API-usage elements: (i) missing (resp. redundant) method calls that should (resp. should not) be called before (resp. after) calling an API method; (ii) missing (resp. redundant) conditions that should (resp. should not) be checked before (resp. after) calling an API method; (iii) missing iterations for methods that should be called in a loop, checking a particular condition after each call, and redundant iterations for methods that should never be called in a loop; and (iv) missing (resp. redundant) exception handling that should (resp. should not) catch exceptions after calling an API method. According to this classification, the misuse in Figure 1(a) is both a missing condition misuse and a redundant condition misuse.

\label{fig:tokenizer}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{tokenizer.png}
\caption{JDK API misuse in joda-time, issue #319}
\end{figure}
when the input string to tokenize is exhausted, the client neither
respects this implicit contract nor handle the thrown exception.

In this work, we look at crash-related misuses that can trigger
exceptions propagated to the client, as they represent the vast
majority of misuses [4]. Various static analysis methods are able
to detect such kind of misuses, but they suffer from multiple
limitations, including a high number of false positives, preventing
their adoption in practice [4]. Moreover, even though some misuses
can be effectively prevented through static analysis (e.g., by checking
the presence of try–catch constructs to properly handle declared
exceptions), other misuses, such as those related to input sanitization,
require dynamic analysis (e.g., by using search-based testing)
to cover the input and output domains of a method.

Various search-based test case generation approaches and tools
have been proposed [20, 21, 35, 36] and shown effective in
discovering real faults [2, 47, 54]. Those approaches rely on various
kinds of criteria (like line and branch coverage [53], or input and
output value domains coverage [52]) and algorithms (like genetic
algorithms [22] or multi-objective algorithms [44, 45]) to explore a
(large) search space, i.e., all the possible test cases that one could
write for a given system under test. Furthermore, other approaches
related to ours include C’n’C [16], which combines static checking
and concrete test generation, and MutApi [37], which identifies
API misuses based on mutation analysis. To the best of our knowl-
edge, this work is the first that studies the relationship between
search-based test case generation and crash-related API misuses.

3 THE CATCHER APPROACH

CATCHER combines static exception propagation analysis [25, 51]
with search-based test case generation [20, 21] to provide evidence
of API misuses as a set of test cases. To achieve this, we use the
approach described in Figure 2: (i) the static exception propagation
analysis builds a call graph of the API under test with information
about exceptions that might be thrown at runtime; (ii) using this
graph, candidate misuses are identified by applying exception-flow
analysis to API calls in the client, where such exceptions may be
propagated; (iii) a rule set is then used to filter out propagated excep-
tions that are directly handled by the client (i.e., using try–catch
constructs or throws clauses in method signatures); (iv) the remain-
ing candidate misuses become coverage targets for the search-based
test case generation. The test suite generated, in the latest step, will
contain test cases that cover the target API calls in the client applica-
tion and trigger the propagated exceptions.

The implementation of CATCHER relies on Soot [59] for the
call-graph construction and the exception-flow analysis, and on
EvoSuite [20] for the search-based test case generation. We choose
Soot for the following reasons: first, Soot is a well-known static
analysis tool used in several research studies [8, 12, 25]; second,
Soot’s soundness and precision have been evaluated by researchers
[49]; third, Soot can be easily used to analyze a Java program,
by receiving only the application’s .jar file as input; finally, the
produced output can be easily used in exception-flow analysis [12,
25, 42]. After filtering the candidate misuses, CATCHER relies on
EvoSuite to focus the search-based test case generation process. We
detail hereafter the configuration of EvoSuite, the modifications
made on the standard implementation of the DynaMOSA algorithm,
and the heuristics used for the test case generation.

3.1 Static Exception Propagation

3.1.1 Call-Graph Construction. The first step of our approach
refers to the analysis of the source code of a software platform’s
API for spotting runtime (i.e., unchecked) exceptions that may be
propagated to the callers of the API. This is done by building an
annotated call graph, whose nodes represent the methods in the
API and the edges denote the call dependency between each caller
(outgoing edge) and callee (ingoing edge). The nodes are annotated
with the list of runtime exceptions that might be thrown by the
corresponding methods. Then, we build the annotated call graph
for the client application under analysis and we connect it to the
call graph of the API based on the method calls between the client
and the API. On the resulting global call graph, we identify the first
set of candidate misuses, which are the client nodes that have out-
going edges to the API nodes with annotated exceptions. Additional
misuses are detected through the exception propagation analysis
(see the next subsection 3.1.2).

For instance, the global call graph for the example in Figure 1
would contain two nodes: one is the method nextToken() from the
API and the other one is the constructor Rule from the client.
The two nodes are connected by an edge outgoing for the latter
and ingoing for the former. Based on our analysis, the constructor
Rule is a candidate misuse because it directly calls an API method
that can throw an exception at runtime.

3.1.2 Exception-flow Analysis. To enlarge the set of candidate mis-
uses, we use reachability analysis to propagate the exceptions from
the API to the client. Specifically, for every node \( N_{api} \) of the API, its
annotated exceptions are propagated backwards to all its adjacent
nodes \( N_j \) (depth 1). Then the propagation is done for each node
\( N_j \) recursively. The propagation path ends when the first client
node in the global graph is encountered (depth \( k \)). All client nodes
with exceptions propagated from API nodes are candidate misuses
because they may expose exceptions thrown by the API.

The number of candidate misuses grows exponentially with the
depth \( k \) that we consider. Buse and Weimer showed that exceptions
with propagation depths larger than three are rarely listed in the
documentation [12]. This possibly happens because it is not efficient
for developers to consider these exceptions for debugging. For the
sake of our study, focusing on the Java platform’s API, we
consider calls with depth $k \leq 4$ to balance scalability and usability of Catcher.

### 3.2 Filtering

The previous step identifies all API calls annotated with propagated exceptions. However, not all the identified calls are necessarily API misuses. In fact, API usage constraints can be satisfied at the client side through a combination of **programming language elements** [3]. A `try`–`catch` construct can be used to handle an exception propagated from the API to recover the client from the corresponding error state. Furthermore, the client application may include the propagated exception in the `throws` clause in the method signature of the caller. This postpones the exception handling to occur in other client methods and classes that exist later in the stack. These two types of programming language elements (i.e., `try`–`catch` constructs and `throws` clause in method signatures) can be easily identified via static analysis rules. To this aim, **CATCHER** uses a rule set to filter out API calls with propagated exceptions that are correct API usages: (i) calls made by the client to the API within a `try`–`catch` construct catching the propagated exception. Moreover, (ii) calls made by the client to the API within a method itself declaring a propagation of the exception using a `throws` clause. Besides, the rule set takes the Java `Exception` hierarchy into account. For instance, if an API method throws an `IOException` and the client has a `catch` clause for `IOException`, our rule set filters out the related candidate misuse. The list of the remaining candidate misuses is the input of the **CATCHER**’s search-based test case generation.

### 3.3 Focused Search-based Test Generation

Given the list of candidate misuses identified in the previous steps, the generation of a test suite can be formulated as a search problem:

**Problem 1.** Let $M = \{m_1, \ldots, m_n\}$ be a set of candidate misuses (test targets) for a client class $C$. Our problem is to find a test suite $T = \{t_1, \ldots, t_n\}$ for $C$ that identifies as many API misuses in $M$ as possible by triggering the corresponding propagated exceptions.

A candidate misuse $m_i \in M$ is successfully identified by a test case $t_j \in T$ if the following conditions hold: (1) $t_j$ covers the candidate API call in the client class $C$ (the call site), (2) $t_j$ triggers the propagated exception, and (3) the last stack trace element in the crash stack trace is the (misused) API method. To solve the aforementioned problem, we need an adequate **heuristic** to guide a search algorithm toward covering the candidate misuses in $M$.

#### 3.3.1 Heuristic

We consider three state-of-the-art search heuristics. First, we use **line coverage**, which is defined as the sum of the approach level (a1) and the normalized branch distance (bd) [36]: $bc_{m_i} = a(t_j, b_k) + \text{norm}(bd(t_j, b_k))$ for test case $t_j$ and branch $b_k$. Such a heuristic is widely applied in white-box testing and, in our case, it measures how far a test case $t_j$ is to cover the API call site.

Additionally, we also consider **input coverage** $ic_{m_i}(t_j, b_k)$ and **output coverage** $oc_{m_i}(t_j, b_k)$ for the client method (caller) containing the potential API misuse. These two heuristics are black-box and aim to increase the input and the output data diversity during the test generation process. More diverse input/output can increase the likelihood of triggering unexpected behaviors [52], such as triggering the propagated exceptions.

For $M$, we have the following set of objectives to optimize:

$$\begin{align*}
\min_{f(m)}(bc_{m_i}) & , \max_{f(m)}(ic_{m_i}) , \max_{f(m)}(oc_{m_i}) \\
\vdots \\
\min_{f(m_n)}(bc_{m_n}) & , \max_{f(m_n)}(ic_{m_n}) , \max_{f(m_n)}(oc_{m_n})
\end{align*}$$

#### 3.3.2 Search Algorithm

As in other search-based test case generation problems, covering as many candidate misuses as possible with **CATCHER** is a multi-target problem since a client class can contain multiple candidate misuses (targets) to be covered. Therefore, as a search algorithm, we choose the **Dynamic Many-Objective Sorting Algorithm** (Dynamosa) [44], a state-of-the-art many-objective algorithm that optimizes multiple coverage targets, simultaneously. We opted for Dynamosa since recent studies [13, 47] showed its better effectiveness and efficiency compared to other multi-target approaches, such as the whole-suite approach, random search, evolution strategies, and other many-objective algorithms.

In Dynamosa, coverage targets (e.g., branches) correspond to search objectives, which are prioritized based on their structural dependencies in the control dependency graph of the class under test. The search starts by optimizing coverage targets positioned higher in the hierarchy; the other targets are incrementally reinserted in the search when their parent targets are satisfied (for instance, reach branch $n$ before trying to reach branch $n + 1$). Using our heuristic, the algorithm executes as follows:

**Initialization.** The search starts by identifying a pool of client call sites (containing the candidate misuses) from $M$. Next, it generates a set of random test cases to produce an **initial population**.

**Selection.** To form the next generation, Dynamosa applies **elitism** by using a preference sorting function [44]. For each candidate misuse $m_i$, the preference sorting function takes the test cases with the best individual objective scores and inserts them into the next population. The remaining test cases are then sorted and selected by the non-dominated sorting algorithm proposed in NSGA-II [17].

**Reproduction.** In each generation, parents are selected using the **tournament selection** and new test cases (offspring) are created by applying crossover and mutation operators [20].

**Objective update.** Once a test case reaches the API call site, the exception in $m_i$ has to be thrown and propagated through the same methods. Thus, we ensure that the test $t_j$ is archived to be part of the final test suite only if $t_j$ triggers and propagates the exception through the same methods as $m_i$. When $m_i$ is successfully detected, the list of objectives is (dynamically) updated by removing the corresponding objectives $bc_{m_i}, ic_{m_i}$, and $oc_{m_i}$.

**Termination.** The iteration process continues until $M$ is covered or the search time is over.

### 4 EVALUATION PROTOCOL

#### 4.1 Study Context

The context of our study consists of Java client applications and the third-party APIs they use. We selected the latest version of 21 open-source Java projects, whose names and characteristics are reported in Table 1. We chose these projects because they are well-known, regularly maintained, and have been already used in the related literature to assess the performance of testing tools (e.g., [44, 45]) or to build datasets of known bugs (e.g., [29]). Also, they have different sizes, development teams, and application domains (e.g., byte code...
We investigate the following research questions:

**RQ1**: How do existing unit level coverage-based test generation tools perform in discovering API misuses?

With this first research question, we aim to examine the effectiveness and efficiency of existing state-of-the-art automatic test suite generators regarding their capability to generate test cases able to expose API misuses. We are interested in investigating this research question because API calls are statements in the source code of the client applications and they can be covered by traditional unit-test generation tools (such as EvoSuite) tailored to maximize coverage-based criteria (e.g., branch coverage). However, covering API call sites does not necessarily imply that the corresponding tests can trigger the exceptions propagated from the APIs, exposing the misuses. To the best of our knowledge, we are the first to apply and evaluate such tools to study how they help to expose API misuses.

**RQ2**: Does Catcher improve the performance of existing test coverage-based approaches on detecting API misuses?

With this second research question, we investigate the impact of reducing the search space in test case generation by using information from the static exception propagation. Namely, we examine whether we can get test cases that expose more API misuses, and in less time, by considering only particular paths with candidate misuses identified by Catcher during the search. To this extent, we compare the effectiveness and efficiency of Catcher and EvoSuite for API misuses detection.

**RQ3**: What types of API misuses does Catcher expose?

Using Catcher, we can argue about particular API misuses (related to constraint misuses and exception handling misuses) at the code level. APIs also come with their reference documentation, which can significantly affect the robustness of client applications [12, 14, 31]. If an exception that might throw at runtime is not listed in the documentation (i.e., it is unexpected), developers stay unaware of the possible manifestation of that exception at runtime. Then, developers usually leave these exceptions unhandled decreasing the robustness of their programs. Based on that, we want to examine whether the exceptions triggered by Catcher are documented (and therefore expected) or not.

### 4.3 Baseline Selection and Parameter Setting

To answer RQ1, we select EvoSuite [20, 21] as our baseline. EvoSuite is a state-of-the-art testing framework for generating unit test suites for Java classes. It won the latest two editions of the sbst tool context [59, 48], which showed its ability to produce tests with higher code coverage and better fault detection capability compared to alternative tools (e.g., RandooP [43]). EvoSuite implements various search algorithms for test case generation. In our study, we use the Dynamic Many-objective Sorting Algorithm (DynaMOSA) proposed by Panichella at al. [44], which is the same many-objective genetic algorithm used in Catcher. We select DynaMOSA because it outperforms other multi-target and single-target approaches as demonstrated by recent studies [13, 44, 45, 47] that compare different algorithms in test case generation.

EvoSuite optimizes eight test criteria simultaneously as they are described by Rojas et al. [52]: branch, line, weak mutation, input, output, method, and exception coverage. In this study, we consider all these criteria as recent studies showed that their combination increases the fault detection capability of the generated test suites [27, 46]. Suites with higher fault detection capability are likely able to detect more crash-related API misuses. When enabled with exception coverage, EvoSuite archives all test cases that (i) trigger an exception and (ii) are created when trying to maximize the other aforementioned coverage criteria. The archived test cases are included in the final test suite, which contains test cases that allow reaching high code coverage plus all test cases generated during the search that trigger an exception. Some of these crashes might be related to propagated exceptions due to API misuses.

To answer RQ2, we compare EvoSuite and Catcher. Both EvoSuite and Catcher share the same search algorithm (i.e., DynaMOSA) and the same test case generation engine (e.g., genetic operators, chromosome representation). The differences between the DynaMOSA algorithm in EvoSuite and Catcher regard the objectives they optimize. The former targets all source code elements (e.g., branches, lines) for code coverage optimization. Instead,
as explained in Section 3.3, the latter targets only candidate APIs misuses (that are specific lines in the source code) as well as input and output coverage for the client methods (callers) containing candidate misuses.

Parameter Setting. Search algorithms have various parameters to set, which may potentially impact the results of our study. However, Arcuri and Fraser [7] showed that parameter tuning in search-based software engineering is extremely expensive and does not provide substantial improvements compared to default parameter values. We use the default parameter values suggested in the literature [7, 21, 45]: EvoSuite and Cacher were configured with a population size of 50 test cases; test cases are selected using the tournament selection, with tournament size $s=10$. Each newly generated test $t$ is mutated through a uniform mutation with the probability $p_m=1/n$, where $n$ is the number of statements in $t$. EvoSuite and Cacher were configured with a search budget of three minutes per each class under test. We use this setting because it represents a reasonable compromise between running time and coverage as reported in the related literature [22, 47].

4.4 Experimental Protocol

The number of candidate misuses for each project in our benchmark is reported in the rightmost column of Table 1. Then, test cases are generated only for classes that, according to the first two steps in Cacher, contain candidate API misuses. Therefore, classes with no candidate misuses are not targeted by Cacher during the test case generation phase. Instead, EvoSuite does not identify candidate API misuses before starting the test case generation process.

To address the random nature of EvoSuite and Cacher, we ran each tool 25 times on each class under test. For EvoSuite, the classes under test are all the classes in the benchmark projects. For Cacher, the classes under test are only those classes identified as having candidate API misuses. In total, for Cacher, we performed 905 (classes) $\times$ 25 (repetitions) = 22,625 search executions, with three minutes of search budget per each execution. For EvoSuite, the number of classes increases to 8,409 corresponding to $\approx 210,225$ search executions, with three minutes of search budget per each execution. All executions were performed on a two node cluster. Each cluster node ran a GNU/Linux system (Ubuntu 16.04 LTS) with Linux kernel 4.4.0, on a dual 8-core 2.4GHz Intel E5-2630v3 CPU with 64GB of RAM. We used Oracle’s Java VM (JVM) version 1.8.0_181, allocating up to 12GB for the JVM.

In each run, we collected the generated test suite and the total running time needed for completing the search. We use the collected data to answer RQ1 and RQ2. In particular, we re-executed the generated test suites (by Cacher and EvoSuite) at the end of each search, to identify test cases that triggered an exception. Then, we compared the corresponding crash stack traces with the list of candidate API misuses identified with the exception propagation analysis. Cacher and EvoSuite expose a target misuse $m_i$ if they generate a test case $t_j$ that triggers an exception propagating from the API to the client in the same way as $m_i$. In other words, the detection requires that the following two conditions hold: (i) the name of the exception triggered by $t_j$ and the name of the propagated exception $m_i$ coincide; (ii) the chain of call sites of $m_i$ appears in the stack trace of the exception triggered by $t_j$.

To evaluate the effectiveness in RQ1 and RQ2, we compute the number of misuses exposed by Cacher and EvoSuite in each independent run. To measure the efficiency, we compute the total execution time taken by Cacher and EvoSuite for each project in each independent run. The running time for Cacher is measured by taking into account (1) the time required by the static exception propagation analysis (for all steps in Section 3.1) to identify potential API misuses, (2) the test case generation time (i.e., up to three minutes) and (3) the post-processing. For EvoSuite, the running time includes (1) the search budget (up to three minutes) and (2) the post-processing. More specifically, we post-processed the test suites generated by the two tools to remove statements in the test cases that do not contribute to coverage or trigger the exceptions (test suite minimization); furthermore, assertions are automatically generated using mutation analysis [24]. Notice that Cacher uses the post-processing engine of EvoSuite.

We compare both approaches (Cacher and EvoSuite) by considering the median and the interquartile range (IQR) of the number of exposed API misuses and the running time over 25 independent repetitions. Due to space limitation, the results are reported at the project level. We use the non-parametric Wilcoxon Rank Sum test with a confidence level $\alpha = 0.05$ to assess the statistical significance of the differences (if any). Besides, we use the Vargha-Delaney $A_{12}$ statistic [60] to measure the effect size of such differences.

To address RQ3, we inspect the API misuses detected by Cacher by analyzing and re-executing the generated tests, and inspecting the source code and the documentation (Javadoc) of both the API callers in the client applications and the misused APIs themselves. To reduce biases, we partially automated the analysis using a script which checks whether the propagated exceptions were adequately documented (e.g., reported in the Javadoc with the @throws or @exception tags) (i) in the APIs of the Java JDK and (ii) in the documentation or the source code comments of the callers (call sites) in client applications. The output of this analysis resulted in a classification of three types of API misuses that are discussed at the end of Section 5.

5 RESULTS

Results of RQ1. Table 2 reports, for each project, the median, the interquartile range (IQR), and the total number of unique API misuses detected by EvoSuite across 25 runs. EvoSuite can detect, on average, 123 crash-related API misuses in the 21 benchmark projects. If we consider all API misuses that are detected at least once across 25 runs, the total number of detected misuses is 166. While EvoSuite can detect some misuses by maximizing code coverage, the variability of the results is very high for some projects. For example, if we consider the project Gson, we notice that EvoSuite detects on average two misuses. However, if we run EvoSuite multiple times, the total number of unique misuses being detected is eight. Therefore, the set of discovered misuses differs substantially between two independent runs. To have more reliable results, we would need to run EvoSuite multiple times, with a corresponding increment of the overall running time. A similar observation can be done for other projects, such as apache-commons-compress (COMP), jackson-databind (JACK), JFreeChart (JFCH), and joda-time (JODA).
Table 2: Statistics on the comparison between the number of crash-related API misuses exposed by Catcher and EvoSuite.

<table>
<thead>
<tr>
<th>Project</th>
<th>Catcher Median</th>
<th>IQR Total</th>
<th>Mann–Whitney U</th>
<th>Catcher is % faster</th>
</tr>
</thead>
<tbody>
<tr>
<td>JACK 5 1 6</td>
<td>2 - 5</td>
<td>0.0001 (L)</td>
<td>95%</td>
<td></td>
</tr>
<tr>
<td>JAVS 4 - 4</td>
<td>2 - 2</td>
<td>0.0001 (L)</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>JCOM 1 - 2</td>
<td>1 - 1</td>
<td>0.0001 (L)</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>JFCH 25</td>
<td>14 3</td>
<td>0.0001 (L)</td>
<td>95%</td>
<td></td>
</tr>
<tr>
<td>JODA 20</td>
<td>10 1</td>
<td>0.0001 (L)</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>JOPT 3</td>
<td>- 3</td>
<td>0.0000 (L)</td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td>NATT 4</td>
<td>- 3</td>
<td>0.0000 (L)</td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td>NEO4 14 17</td>
<td>8 8</td>
<td>0.0000 (L)</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>SERIO 7</td>
<td>- 6</td>
<td>0.0000 (L)</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>XJOB 10 0.75</td>
<td>10 7</td>
<td>0.0000 (L)</td>
<td>96%</td>
<td></td>
</tr>
<tr>
<td>XTEXT 0 - 0</td>
<td>0 - 0</td>
<td>0.0000 (L)</td>
<td>100.00%</td>
<td></td>
</tr>
</tbody>
</table>

Total 207 243 123 166

Table 3: Execution time (in s) for Catcher and EvoSuite.

<table>
<thead>
<tr>
<th>Project</th>
<th>Catcher Prop.</th>
<th>Search Median</th>
<th>IQR</th>
<th>Total</th>
<th>Mann–Whitney U</th>
</tr>
</thead>
<tbody>
<tr>
<td>JACK 5 1 6</td>
<td>2 - 5</td>
<td>0.0001 (L)</td>
<td>95%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>JAVS 4 - 4</td>
<td>2 - 2</td>
<td>0.0001 (L)</td>
<td>100%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>JCOM 1 - 2</td>
<td>1 - 1</td>
<td>0.0001 (L)</td>
<td>100%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>JFCH 25</td>
<td>14 3</td>
<td>0.0001 (L)</td>
<td>95%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>JODA 20</td>
<td>10 1</td>
<td>0.0001 (L)</td>
<td>100%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>JOPT 3</td>
<td>- 3</td>
<td>0.0000 (L)</td>
<td>0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NATT 4</td>
<td>- 3</td>
<td>0.0000 (L)</td>
<td>0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NEO4 14 17</td>
<td>8 8</td>
<td>0.0000 (L)</td>
<td>100%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SERIO 7</td>
<td>- 6</td>
<td>0.0000 (L)</td>
<td>100%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>XJOB 10 0.75</td>
<td>10 7</td>
<td>0.0000 (L)</td>
<td>96%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>XTEXT 0 - 0</td>
<td>0 - 0</td>
<td>0.0000 (L)</td>
<td>100.00%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Total 9,716 149,741 159,457 1,327,080 81%

XTEXT 299 362 - 661 862 0.33 24%

Concerning running time, EvoSuite requires on average 17 hours to complete the test generation for one project. The overall running time is proportional to the number and the complexity of classes in the project under test. Indeed, it varies from 14 minutes (xwikitext has three classes) to 1 day, 19 hours, and 38 minutes (for EasyMock) on average. This highlights the need for test case generation approaches that focus on API misuses.

Results of RQ2. Table 2 shows that Catcher detects on average 84 (+68%) API misuses compared to EvoSuite across the 25 runs. In total, the number of unique API misuses detected by Catcher in all runs is 243, i.e., +77 unique misuses over EvoSuite. These differences are also confirmed by the statistical analysis reported on the right side of Table 2: for 16 projects out of 21 (76%), Catcher identifies significantly more API misuses than EvoSuite. The effect size is always large (in 15 projects out of 16) and medium (in one project).

Let us consider the example in Figure 3 of an API misuse detected by Catcher but not by EvoSuite for the class KthSelector from the project apache-commons-math. The ArrayIndexOutOfBounds-Exception is thrown at line 120 of the API Arrays.rangeCheck and propagated back to the client application in the method select. An excerpt of the code of this method is reported in Figure 3-(a) while Figure 3-(c) reports the test case generated by Catcher. When executing the test case, the client method select invokes the method Arrays.sort using as parameters an array of size 17 and the variables begin=12 and end=19. The value of the variable end is larger than the size of the array and, thus, the exception is thrown in Arrays.rangeCheck, which is indirectly invoked. Notice that the value of these two variables is computed within the while loop in lines 84–113. This example is an API misuse because the client method select should validate the input data (e.g., the length of the array) before invoking the API.

Table 4 reports the number of API misuses detected by both approaches, Catcher and EvoSuite, as well as the number of misuses detected by one approach (e.g., Catcher) but not by the other one (e.g., EvoSuite). We observe that 163 unique API misuses are detected by both approaches; 80 unique API misuses are detected only by Catcher; two unique misuses are detected only by EvoSuite. Through manual investigation, we discovered that these two misuses are detected by EvoSuite thanks to the weak mutation coverage, which leads to generating input data able to weakly kill mutants (infection state). This input data might increase the likelihood of exposing misuses, although it happens for only two cases in our benchmark. Future work will be devoted to investigating other coverage criteria in Catcher, including the weak mutation coverage.

Finally, Table 3 reports the running time of Catcher and EvoSuite. Catcher requires less than 20% of the time spent by EvoSuite in total. On a per project basis, Catcher is on average 80% faster, with a maximum speedup of 96% for project natty. The smallest difference is observed in the case of xtext: a very small library comprising only 100 classes in the project under test. Indeed, it varies from 14 minutes (xwikitext has three classes) to 1 day, 19 hours, and 38 minutes (for EasyMock) on average. This highlights the need for test case generation approaches that focus on API misuses.
Table 4: Overlap between Catcher and EvoSuite regarding the unique crash-related API misuses detected across 25 repetitions.

<table>
<thead>
<tr>
<th>Project</th>
<th>Catcher</th>
<th>Catcher</th>
<th>Catcher</th>
<th>Catcher</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCEL</td>
<td>7</td>
<td>2</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>CODEC</td>
<td>9</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>COLL</td>
<td>9</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>COMP</td>
<td>16</td>
<td>18</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>LANG</td>
<td>23</td>
<td>9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>MATH</td>
<td>8</td>
<td>4</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>EASY</td>
<td>11</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>GSON</td>
<td>8</td>
<td>8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>JACK</td>
<td>5</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>JAVS</td>
<td>2</td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>JCOM</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>JFCH</td>
<td>23</td>
<td>4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>JODA</td>
<td>11</td>
<td>14</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>JOPT</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NATT</td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NEO4</td>
<td>8</td>
<td>9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SHIRO</td>
<td>6</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>XJOB</td>
<td>9</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>163</td>
<td>80</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

(a) Class KthSelector from apache-commons-math

```java
public double select(double[] work, final int[] pivotsHeap, final int k) {
    int end = work.length;
    int begin = 0;
    while (end - begin > MIN_SELECT_SIZE) {
        Arrays.sort(work, begin, end);
        int begin = pivotsHeap[begin];
        int end = pivotsHeap[end - 1];
        Arrays.sort(work, begin, end);
    }
    return work[k];
}
```

(b) ArrayIndexOutOfBoundsException occurs in the method select

```java
@Test
double[] doubleArray0 = new double[17];
```

(c) The test that is generated by Catcher

Figure 3: Example of API misuse detected by Catcher but not by EvoSuite.

<table>
<thead>
<tr>
<th>Table 5: Categories of triggered crashes per project.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>BCEL</td>
</tr>
<tr>
<td>CODEC</td>
</tr>
<tr>
<td>COLL</td>
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<tr>
<td>COMP</td>
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<tr>
<td>LANG</td>
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<tr>
<td>MATH</td>
</tr>
<tr>
<td>EASY</td>
</tr>
<tr>
<td>GSON</td>
</tr>
<tr>
<td>JACK</td>
</tr>
<tr>
<td>JAVS</td>
</tr>
<tr>
<td>JCOM</td>
</tr>
<tr>
<td>JFCH</td>
</tr>
<tr>
<td>JODA</td>
</tr>
<tr>
<td>JOPT</td>
</tr>
<tr>
<td>NATT</td>
</tr>
<tr>
<td>NEO4</td>
</tr>
<tr>
<td>SHIRO</td>
</tr>
<tr>
<td>XJOB</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

6 DISCUSSION

Research implications. The findings of RQ2 indicate that focused testing of API uses is not equivalent to merely maximizing traditional coverage criteria, although candidate misuses are statements in the source code of the client applications. The better detection capability and performance of Catcher compared to plain EvoSuite is due to the heuristics (focusing the search-based test case

3https://github.com/neo4j/neo4j-java-driver/issues/520
generation) of Catcher. We hope that our study draws new research directions towards the evaluation of the benefits of focused search-based test case generation. New studies could possibly consider the detection of different types of API misuses, e.g., ones that are related to security and energy efficiency issues.

It is worth noting that EvoSuite combined with the static exception propagation analysis as implemented in Catcher is more effective and efficient than using only its default criteria. In particular, in Catcher, we run EvoSuite by targeting only the classes for which static analysis provided a list of filtered candidate misuses and considering only a subset of the coverage targets, i.e., API call sites, input, and output coverage for the caller methods. Furthermore, the exception propagation chains generated by the static analysis help us to automate the test oracle, i.e., to discover which generated tests can detect the misuses. In the traditional setting, plain EvoSuite should target all the classes of the examined projects, resulting in thousands of test suites (with multiple test cases each) that should be manually evaluated by developers [21] to identify those cases able to trigger the misuses. Therefore, we opt for more studies that combine the strengths of static analysis and automated search-based test case generation.

Practical implications. Catcher can identify API misuses in client programs. Both developers of client programs and developers of APIs can use this information to make their programs more robust.

Developers of client programs can use Catcher to correctly identify, handle and recover runtime errors caused by combinations of wrong inputs. The test cases that Catcher generates can be used as a safety net against regressions in both the client and the API code. The runtime cost of Catcher makes it suitable for use in release pipelines: Catcher could in less than 4 hours examine a 250k LOC program (for commons-math). As part of an automated release process, Catcher could be proven useful to identify last minute issues. Finally, Catcher could be further improved to examine changes on a per commit basis: this would allow it to run as part of continuous integration pipelines, in order to support interactive quality assurance processes, such as code review.

Moreover, the information that Catcher produces can be used upstream by developers of APIs, to help them improve the robustness of error-prone methods against wrong or adversary inputs. API developers can make their code less susceptible to runtime exceptions by guarding against inputs that Catcher identifies as erroneous. Catcher tests encode an implicit invocation protocol. API developers can inspect such tests to identify and fix initialization or ordering issues that may lead their APIs to fail. If corrective action is not possible, documentation can be used to make invocation protocols explicit to clients.

7 THEMES TO VALIDITY

Internal validity. State-of-the-art mining and static analysis detectors for API misuses suffer from low precision [4]. Instead, our results show that Catcher can precisely detect actual misuses and provide empirical evidence of such misuses through generated test cases. However, we acknowledge that we cannot make any claim about the completeness of Catcher because there is no ground truth for the projects in our benchmark. Further investigation in that regards is part of our future agenda. Furthermore, the automated analysis we performed to evaluate whether the exceptions triggered by Catcher are listed in the documentation of the Java platform’s API and the projects can also suffer from imprecision. Even though we have also manually inspected and confirmed the results, maybe a few exceptions found to be as undocumented could finally be listed in the documentation. Another potential threat to internal validity is the randomized nature of the genetic algorithms and the seed-based random search. To address this threat, we followed the guidelines from the related literature [6]: we launched each algorithm 25 times, and we used sound statistical tests, namely the Vargha-Delaney $A_{12}$ statistic and the Wilcoxon Rank Sum test, to draw any conclusion. Another threat is related to the parameter setting of the search algorithms. We used the parameter values suggested by the related literature [7, 45, 55].

External validity. We acknowledge that our results regard one particular API, i.e., the Java 8 platform’s API. Future work includes the analysis of other Java API versions, as well as additional third-party Java libraries used by client applications. Additionally, even though our results are related to specific client applications, we used a large benchmark of well-diversified and well-known software projects. Thus, we expect that our main conclusions can also apply to other benchmarks.

Reliability validity. For the reproducibility of our study, we have made the source code (Catcher), the processing scripts, and our data publicly available. Specifically, in the data, we include the examined projects and APIs (input), as well as the found test cases (output).

8 RELATED WORK

Static API misuse detection. To assist developers to detect API misuses, researchers have proposed tools that leverage techniques including mining of software repositories and static analysis [1, 33, 41, 57, 58, 61]. In general, these tools work as follows. Start by mining correct API usage patterns, from existing code bases, and continue by classifying infrequent patterns observed in target projects as candidate misuses. The produced candidates should be then manually reviewed by developers. The available techniques mainly differ on: (i) the representation (e.g., via graphs [41, 61], formal concepts [33]) of the method call usages and (ii) the mining algorithms (e.g., frequent-itemset mining [58], model checking [1], frequent-subgraph mining [41]) used to detect infrequent patterns (outliers)—based on thresholds defined a priori.

Recently, Amann et al. [4] compared 12 state-of-the-art misuse detectors on a set of known APIs misuses collected from existing bug datasets. They found that all detectors suffer from a number of limitations. Initially, all detectors have low precision (below 12%) as they produce a large number of false positives. This means that, on average, the tools report less than 1.5 API misuses in the top-20 of their results. Yet these tools typically produce an extensive list of candidate APIs misuses, which developers have to manually check and approve. Also, most tools require large code bases to distinguish uncommon—but correct usages—from actual misuses.

\footnote{Available at https://github.com/mkruchagia/Catcher}
Contrary to previous approaches, CATCHER (i) effectively and efficiently identifies crash-related API misuses eliminating the need for the manual assessment of the candidate API misuses produced by the static analysis—it applies filtering and search-based test case generation to validate these candidates automatically; (ii) it does not need a code base for learning to distinguish good from bad API usage patterns—it uses exception propagation analysis to automatically pinpoint candidate API misuses. In essence, CATCHER sacrifices recall (it does not report all possible misuses) for achieving high precision (all reported misuses are indeed misuses).

Static exception propagation. Several tools exist for statically identifying possible exceptions that a method can throw at runtime [56]. Robillard and Murphy implemented Jex that applies inter-procedural analysis and finds all the exception types that a specific method of a Java program can generate at runtime [51]. Vallée-Rai et al. developed the SOOT Java byte code optimization framework that can identify might-thrown exceptions for API methods, using (in the first instance) intra-procedural static analysis [59]. Fu and Ryder presented an inter-procedural exception-flow analysis technique, based on SOOT, for the examination of the exception handling architecture of software systems [25]. Bravenboer and Smaragdakis combined inter-procedural exception-flow analysis and points-to analysis for better precision in call-graph construction [11]. Garcia and Cacho introduced an inter-procedural exception-flow analysis tool (eFlowMining) for .NET, which visualizes error handling constructions [26].

The exception propagation of CATCHER is inter-procedural and mainly differs from peer approaches in the filtering (Section 3.2) of the found API-misuse candidates coming from the initial stage of the static exception propagation analysis (Section 3.1). Our filtering approach helps us to keep in the candidate misuses’ list only the real API misuses that refer to: (i) uncaught exceptions and (ii) undeclared exceptions in the throws clause of the method signature of a caller.

Search-based software testing. Most of the research effort in search-based software testing (SBST) has been devoted to three main aspects: (i) evaluating fault detection capability of generated tests (e.g., [23, 27]), (ii) defining heuristics to guide the search process (e.g., [32, 62]), (iii) designing and evaluating different search algorithms (e.g., [5, 44, 45]). The goal of SBST tools consists in generating test cases/suites maximizing some coverage criteria (e.g., branch, line, and statement coverage) [21]. Recent studies [27, 52] empirically investigated the effect of combining multiple coverage criteria on the quality of the generated test suites and showed a positive impact on the fault detection capability. SBST techniques use heuristics that are specific to each coverage criterion and measure how far a candidate test case/suite is from covering each coverage target (e.g., branches). For example, common heuristics for branch coverage include the branch distance [32] and the approach level [62].

These heuristics are then used to guide search algorithms towards generating tests with higher coverage. The earliest search strategy is the single-target approach, which attempts to satisfy one coverage target (e.g., one branch) at a time through multiple re-executions of the search (e.g., genetic algorithms). More recent approaches [20, 21, 44, 45] handle all coverage targets (e.g., all branches) at once with one single execution of the search. Rojas at al. [53] showed that multi-target approaches are superior to the single-target ones, while Panichella et al. [44, 45] demonstrated the higher capability of many-objective search compared to alternative multi-target approaches in reaching higher code coverage.

Hybrid approaches. Several hybrid (static and dynamic) analysis approaches have been developed in the past for software verification. For instance, Babic et al. used static analysis to guide their symbolic-execution based automated test generation tool to identify vulnerabilities [9]. Additionally, Zhang et al. combined static and dynamic automated test generation approach to identify bugs related to the sequence of method calls among the classes of a Java project [63]. Also, Ma et al. developed a hybrid technique that uses static analysis to extract knowledge from a project under test to guide the run-time test generation [34]. Finally, Csallner and Smaragdakis developed C’n’C that automatically detects errors by combining static checking, based on theorem proving, and test generation [16].

To the best of our knowledge, CATCHER is the first that combines static exception propagation and search-based testing focusing on the identification of dependency-related bugs, in client programs, caused by misuses of the Java platform’s API.

9 CONCLUSIONS

We introduce a verification technique, CATCHER, that combines static exception propagation analysis and search-based testing to effectively and efficiently identify and expose API misuses in client programs. We validate CATCHER against 21 Java applications, targeting misuses of the Java platform’s API. Our results show that CATCHER is able to efficiently generate test cases that uncover 243 API misuses leading to crashes. The collected results indicate that CATCHER can reveal more API misuses (77 cases) that would remain undetected by plain EvoSuite, while also requiring less than 20% of the time spent by EvoSuite. Overall, static exception propagation analysis and search-based testing combined can significantly improve the detection capability of API misuses, thereby improving the robustness of applications.

In the future, we aim to extend CATCHER along the following dimensions: (i) introduce support for longer exception propagation chains to cover deeply nested API calls, (ii) consider third-party libraries in the analysis to cover the runtime exceptions they introduce, and (iii) extend CATCHER to cover other types of API misuses (e.g., API initialization violations).

ACKNOWLEDGMENTS

This research was partially funded by the EU Horizon 2020 ICT-10-2016-RIA “STAMP” project (No.731529) and the Dutch 4TU project “Big Software on the Run.”