

# Automatic Generation of Oracles for Exceptional Behaviors

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## ABSTRACT

Test suites should test exceptional behavior to detect faults in error-handling code. However, manually-written test suites tend to neglect exceptional behavior. Automatically-generated test suites, on the other hand, lack test oracles that verify whether runtime exceptions are the expected behavior of the code under test.

This paper proposes a technique that automatically creates test oracles for exceptional behaviors from Javadoc comments. The technique uses a combination of natural language processing and bytecode instrumentation. Our implementation, Toradocu, can be combined with a test input generation tool. Our experimental evaluation shows that Toradocu improves the fault-finding effectiveness of automatically-generated test suites, while at the same time reducing the number of false positive alarms they report.

The experimental results show that Toradocu improves the fault-finding effectiveness of EvoSuite and Randoop test suites by 8% and 16% respectively, and reduces the amount of false positives by 32% with respect to EvoSuite.

## CCS Concepts

•Software and its engineering → Software testing and debugging;

## Keywords

Testing, oracle problem, automatic test oracle, oracle generation

## 1. INTRODUCTION

This paper addresses the oracle problem: the creation of assertions that indicate the expected behavior of a software system. A test case consists of two parts: an input that triggers the behavior of the unit under test and an oracle that indicates whether the behavior was correct. Oracles are an essential part of a test case, since they determine whether a test execution should pass or fail. Oracles encode the *intended* behavior of the software system, so they must be provided by a human or generated from human-provided information such as a formal specification. However, developers

often fail to write oracles, and they even more rarely write formal specifications.

This work automatically generates oracles from information that developers do commonly write: natural language documentation. It is considered standard practice to write semi-structured natural-language documentation. For example, Java programmers write Javadoc comments to document their Java code. Our approach is to *convert such natural-language documentation into test oracles*, and use them in combination with a test input generator to automatically create complete test cases that expose defects.

Our technique uses natural language processing (NLP) techniques to parse the documentation into grammatical relations between words in a sentence. Next, it matches parsed subjects and predicates to source code elements, thus creating conditional expressions that describe the programmer-intended behavior. The technique then converts these conditional expressions into test oracles. We integrated our oracle-generation technique with existing test input generation tools, yielding a system that can automatically create complete tests from scratch, without any human involvement.

This paper focuses on exceptional behavior — situations in which a procedure should raise an exception. Our approach parses Javadoc comments to determine which exceptions a Java method should throw, and under what conditions. Exceptional behavior is particularly interesting because it is a significant cause of failures, and because it tends to be poorly covered by both manual and automatically-generated test suites.

Exceptional behavior is a frequent cause of field failures [47] because developers usually have the common case in mind when writing code, because recovering from failures is inherently challenging, and because developers often forget to account for failures that occur during exception processing.

Exceptional behavior is poorly covered in manually-written test suites, as confirmed by the experimental data reported in Section 4.1. The reasons are similar to those above, and also because it can be difficult to force software into the unusual situations that involve exceptions and exception processing.

Exceptional behavior is poorly covered in automatically-generated test suites for some of the same reasons, but primarily because, in the absence of a human-written specification, a test generation tool cannot determine whether a thrown exception is legal or illegal behavior. If a test throws an exception, then there are four main possibilities: (i) the exception might be specified behavior, given the inputs, (ii) the exception might reveal an error in the software under test, (iii) the exception might be legal but unspecified behavior caused by incorrect usage of the software, such as when the test supplies an invalid input, or (iv) the exception might be due to a system failure such as out-of-memory, timeout, or hardware failure.

If there is no specification of exceptional behavior, then when a tool generates a test that throws an exception, the tool has to use heuristics to classify the test into the four categories listed above. (Section 5.1 gives examples of such heuristics.) Use of heuristics makes the generated tests suffer false alarms and/or missed alarms, and a poor choice of heuristics can make test generation tools practically unusable [13, 14, 41]. Our goal is to *automatically generate oracles from human-written documentation, such as Javadoc comments, which is a reliable and commonly-available source of information.*

We have implemented our oracle generation technique in a tool called Toradocu, and we used it in combination with the EvoSuite and Randoop test input generation tools to generate complete test cases that expose exception-related errors in Java programs.

The contributions of this paper include:

- An empirical study showing that developers tend to neglect exceptional behavior when they test their code. The results of this study motivate our work.
- A technique that combines natural-language processing and bytecode instrumentation to create executable oracles that can be used during testing.
- A publicly-available implementation of the technique, Toradocu.<sup>1</sup>
- An experimental evaluation of the technique showing that it can reduce the number of false positive reports from popular automatic test case generation tools.
- An experimental study. Toradocu’s oracles revealed 4 previously unknown defects in Google Guava, and also defects in reimplementations of parts of Apache Commons.

The remainder of the paper is structured as follows. Section 2 presents a motivating example, Section 3 describes the main ingredients of our technique, Section 4 reports on our experimental evaluation, and Section 5 describes related work.

## 2. MOTIVATING EXAMPLE

Automatically-generated test cases tend to perform poorly with respect to exceptional behaviors of a system under test (SUT). This is because automatically-generated test oracles have to guess at the specification of the SUT — that is, they have to guess at the SUT’s expected behavior. When a test input generator creates a test input whose execution throws an exception, the tool must guess whether the execution is a failure and the test case reveals a defect in the SUT.

As an example, consider the Java class `FixedOrderComparator` from the Apache Commons Collections library.<sup>2</sup> This comparator allows a developer to specify a comparison order among a set of objects. A `FixedOrderComparator` instance cannot be modified, i.e., it is *locked*, once it has performed a comparison. Method `checkLocked` is specified to raise an `UnsupportedOperationException` if the comparator is locked:

```

1 | /**
2 |  * Checks to see whether the comparator is now locked
3 |  * against further changes.
4 |  *
5 |  * @throws UnsupportedOperationException if the
6 |  * comparator is locked
7 |  */
8 | protected void checkLocked() {...}

```

State-of-the-art test case generators do not produce test cases that effectively test this code. Some test case generators, such as

JCrasher [13] and Check ’n’ Crash (CnC) [14], assume that a method should not raise any exception unless the method signature explicitly declares it. Such a test generator would produce a failing test case such as the following and wrongly indicate that it reveals a fault in the code under test:

```

1 | void test() {
2 |     FixedOrderComparator c = new FixedOrderComparator(...);
3 |     ...
4 |     c.compare(...);
5 |     ...
6 |     c.checkLocked();
7 | }

```

This would be a *false alarm*: method `checkLocked` correctly throws an exception because `c` is locked, given that it has been used already for a comparison.

Other test case generators, such as EvoSuite [19], either ignore test cases that throw exceptions, or assume any observed behavior is correct and create regression test suites that catch run-time exceptions. Such a test case generator would suffer *missed alarms* and possibly create misleading tests. This would happen if the SUT implementation throws an exception in violation of its specification, such as if the developer wrongly implemented method `checkLocked` to throw the exception under all circumstances.

Randoop [32] can be configured to behave in any of the above ways, but no heuristic or combination of them can reliably check that the behavior of `checkLocked` matches its specification, i.e., that the method should throw an exception only under specific circumstances.

On the other hand, the Javadoc comment of method `checkLocked` precisely describes its intended exceptional behavior. A human or tool that reads the Javadoc specification, and understands the semantics of natural-language sentences such as “if the comparator is locked”, could produce the following test case that embeds line 6 within an oracle:

```

1 | void test() {
2 |     FixedOrderComparator c = new FixedOrderComparator(...);
3 |     ...
4 |     c.compare(...);
5 |     ...
6 |     if (c.isLocked()) {
7 |         try {
8 |             c.checkLocked();
9 |             fail("Expected exception not thrown");
10 |         } catch (UnsupportedOperationException e) {
11 |             // Expected exception!
12 |         }
13 |     } else {
14 |         c.checkLocked();
15 |     }
16 | }

```

The test oracle in this test case correctly checks that `checkLocked` throws `UnsupportedOperationException` only when the comparator is locked, reducing both false and missed alarms. Our Toradocu tool produces a test case that is semantically equivalent to this one. The Toradocu-generated test case is textually different because it is implemented using aspects (see Section 3.3).

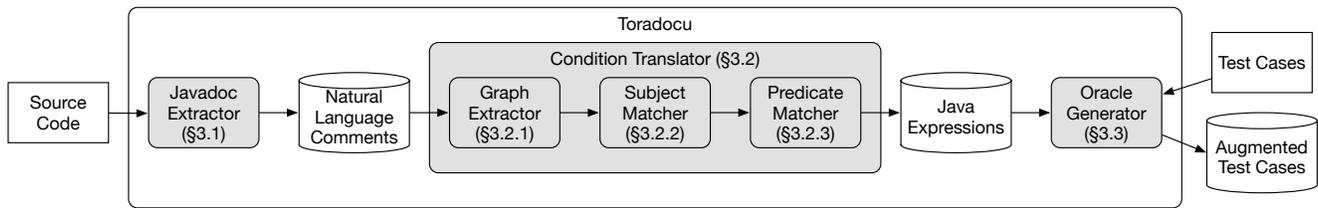
## 3. TORADOCU

This section explains how Toradocu converts Javadoc comments into test oracles. Toradocu works in three phases that correspond to the three components illustrated in Figure 1:

1. The *Javadoc extractor* (Section 3.1) identifies all the Javadoc comments that are related to exceptional behaviors. The

<sup>1</sup><https://github.com/albertogoffi/toradocu>

<sup>2</sup><http://commons.apache.org/proper/commons-collections>



**Figure 1: Architecture of Toradocu.** The three components of Toradocu are represented by gray rounded rectangles. The test cases may be human-written or automatically-generated.

Javadoc extractor outputs a list of the exceptions that each method of the class under test is specified to throw, together with a natural-language description of the conditions under which each exception is intended to be thrown. For instance, referring to the example of Section 2, the Javadoc extractor outputs that method `checkLocked` should throw an `UnsupportedOperationException` under the condition “the comparator is locked”.

2. The *condition translator* (Section 3.2) translates each natural-language condition into Java boolean expressions. In our example, the condition translator converts “the comparator is locked” into `target.isLocked()==true`. The variable `target` in the produced boolean expression is just a placeholder representing the receiver object of the method call.
3. The *oracle generator* (Section 3.3) produces test oracles in the form of assertions and embeds them in the provided test cases. The oracle generator also performs viewpoint adaptation, replacing the `target` placeholder with the proper variable name that the test case instantiates. For the example presented in Section 2 it replaces `target` with `c`.

### 3.1 Javadoc Extractor

Javadoc comments are semi-structured natural-language text blocks that specify a code element (a Java method, field, class, or package). Javadoc comments use tags (keywords starting with `@`) to structure the documentation. For example, the `@param` tag marks the specification of a formal parameter, `@return` marks the specification of the value returned by a method, and `@throws` and `@exception` mark a specification of exceptional behavior. An exceptional behavior specification is an exception type  $e$  plus some natural-language sentences describing when  $e$  should be thrown by the method.

Toradocu’s Javadoc extractor identifies all the comments related to exceptional behaviors for each method of a class under test (CUT). Given the example of Section 2, the Javadoc extractor produces the following information:

**method:** `checkLocked()`

**exception:** `UnsupportedOperationException`

**condition:** “if the comparator is locked”

We implemented this component as a Javadoc doclet. As a result, it also handles Javadoc comments that are inherited from a superclass and do not directly appear in the source code of the class under test. Our current prototype identifies descriptions tagged with `@throws` or `@exception`, and will miss untagged descriptions of exceptional behavior.

### 3.2 Condition Translator

The condition translator uses a mix of natural language processing techniques and pattern-matching to translate Javadoc conditions into Java boolean expressions. For example, the condition translator converts the condition “if the comparator is locked” to `c.isLocked()==true`, converts “if expectedKeys or expectedValuesPerKey

is negative” to `expectedKeys<0 || expectedValuesPerKey<0`, and converts “if both iterator and the element are null” to `iterator==null && element==null`. Algorithm 1 details the behavior of the condition translator. The algorithm takes as input a condition as extracted by the Javadoc extractor, and it outputs a list of Java boolean expressions. It works in three phases that are described in the following sections.

#### 3.2.1 Natural Language Parsing

The condition translator starts transforming a given Javadoc comment text by invoking function `GET-PROPOSITION-GRAPH` at line 4 of Algorithm 1. This function, defined at line 17, relies on the Stanford Parser library [25, 26] to process the natural language Javadoc comment transforming it into a forest of binary trees.

Given the Javadoc comment text, the condition translator uses the Stanford Parser to identify separate sentences (line 19), and to produce a semantic graph for each of the sentences (line 20). The semantic graph consists of a parse tree plus additional information, such as grammatical relations.<sup>3</sup>

Next, the condition translator identifies subjects (line 21) and related predicates (line 23). In the NLP community, this step is called *open information extraction* [1, 16]. A subject is a noun phrase that the sentence is about, and the predicate is the remainder of the sentence, which says something about the subject. Given the sentence “either the iterator or the element are null”, the identified subjects are “iterator” and “element”, while the predicate is “are null” for both of them. In that predicate, the object of the copular verb “are” is “null”. The function `IDENTIFY-SUBJECTS` (line 21) returns all the subjects of a parse tree. In the case of a compound noun, the function `IDENTIFY-SUBJECTS` returns the head noun plus the noun compound modifier.

For each identified subject, the function `IDENTIFY-PREDICATE` (line 23) searches the parse tree for matches to patterns that commonly appear in Javadoc documentation. Our prototype supports sentences structured as in Table 1. Notice that Toradocu identifies as the predicate only some words of the sentence. Furthermore, the predicate includes a negation modifier when present. This pattern-matching approach is not complete, in the sense that it will not extract meaning from the predicate in every possible English sentence. However, it is effective, and it was adequate in our experiments. Future work could devise a more comprehensive and general approach for interpreting the predicate.

Line 24 shows what the function `GET-PROPOSITION-GRAPH` produces: a forest of binary trees where each tree represents a single sentence of the original natural language comment. The leaves of each binary tree represent propositions (i.e., pairs of subject and predicate), and the internal nodes connecting such leaves represent either *and* or *or* conjunctions. As an example, the Javadoc comment “either the iterator or the element are null” would become a tree where the root node represents the conjunction “or”, the left leaf

<sup>3</sup>[http://nlp.stanford.edu/software/dependencies\\_manual.pdf](http://nlp.stanford.edu/software/dependencies_manual.pdf)

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**Algorithm 1** Condition Translator

---

```
1: Translates the English condition extracted by the Javadoc extractor into
  a list of Java boolean expressions (one per sentence).
2: INPUT: t (English text describing a condition), m (method commented
  by t)
3: function TRANSLATE-CONDITION(t, m)
4:   propositionGraph := GET-PROPOSITION-GRAPH(t)
5:   for each proposition p = (subj, pred) in propositionGraph do
6:     jExpr := ""
7:     jSubjs := MATCH-SUBJECT(subj, m, m.getClass())
8:     for each subject jSubj in jSubjs do
9:       jPred := MATCH-PREDICATE(pred, jSubj)
10:      jExpr := CREATE-JAVA-EXPR(jSubj, jPred, jExpr, pred)
11:    end for
12:    p.jExpression := jExpr
13:  end for
14:  return IN-ORDER-TRAVERSE(propositionGraph)
15: end function
16: Translates English text into logical formulas, as a forest of binary trees
  (one per sentence). Internal nodes represent “and” and “or”.
17: function GET-PROPOSITION-GRAPH(t)
18:   graph := {}
19:   for each sentence s in t do
20:     semGraph := GET-SEMANTIC-GRAPH(s) // Stanford Parser
21:     subjectList := IDENTIFY-SUBJECTS(semGraph)
22:     for each subject subj in subjectList do
23:       proposition := (subj, IDENTIFY-PREDICATE(subj, semGraph))
24:       graph := graph.add(proposition)
25:     end for
26:   end for
27:   return graph
28: end function
29: Tries to match a string subj, representing a subject, to the most likely
  Java element.
30: function MATCH-SUBJECT(subj, m, cut)
31:   jElements := GET-JAVA-ELEMENTS-FOR-SUBJECT(m, cut)
32:   return GET-MOST-SIMILAR-ELEMENTS(subj, jElements)
33: end function
34: Returns Java elements that a subject can potentially match: m’s param-
  eter names and parameter types, and cut’s name, public field names, and
  public nullary method names.
35: function GET-JAVA-ELEMENTS-FOR-SUBJECT(m, cut)
36: Returns the elements whose names have minimum Levenshtein edit
  distance from s. Returns multiple elements if there is a tie. Does not
  return any element whose edit distance is greater than 8.
37: function GET-MOST-SIMILAR-ELEMENTS(s, elements)
38: Tries to match a string pred, representing a predicate, to the most likely
  Java element.
39: function MATCH-PREDICATE(pred, jSubj)
40:   match := PATTERN-MATCHING(pred) // see Section 3.2.3
41:   if match ≠ empty then
42:     return match
43:   else
44:     jElements := GET-JAVA-ELEMENTS-FOR-PREDICATE(jSubj)
45:     return GET-MOST-SIMILAR-ELEMENTS(pred, jElements)[0]
46:   end if
47: end function
48: Returns Java elements that a predicate can potentially match: the field
  and method names of jSubj.
49: function GET-JAVA-ELEMENTS-FOR-PREDICATE(jSubj)
50: Returns a new Java expression that is the combination of the existing
  Java expression jExpr and a new expression composed of subject jSubj
  and predicate jPred. This function handles cases where a single subject is
  actually referring to multiple Java elements. Also, this function decides
  whether a condition should be evaluated to either true or false. See
  Section 3.2.4.
51: function CREATE-JAVA-EXPR(jSubj, jPred, jExpr, pred)
```

---

**Table 1: List of sentence structures from which Toradocu can correctly extract the predicate.**

Sentence Form	Predicate comprises
Copula	Negation modifier, copular verb, complement
Active Form	Verb, complement
Passive Form	Negation modifier, verb, passive auxiliary

is the proposition with subject “*iterator*”, and the right leaf is the proposition with subject “*element*”. As we explained before, both subjects would be bound to the same predicate “*are null*”.

### 3.2.2 Matching a Subject to a Java Element

Having parsed English text into propositions, where each proposition consists of a subject and a predicate, Toradocu now tries to match each subject and predicate to a Java element in the code, as explained in this section and the next one.

The function MATCH-SUBJECT, called on line 7, tries to match the subject to *identifiers* and *types* that appear in the code (lines 30–33). In particular, a subject can be matched with (i) one or more of the formal parameters of the documented method, (ii) one of the methods of the CUT, or (iii) the target object. Javadoc comments often refer to parameter types, as in the case of “*the collection is empty*”, which refers to a parameter of type `java.lang.Collection`. For this reason the algorithm considers type names, in addition to identifiers, for subject matching.

The algorithm also considers matches with CUT’s nullary methods—that is, those that take no arguments. Matching the subject with such methods handles cases in which the subject refers to a non-public field of the CUT for which a getter method exists; the test oracle can access the getter method. For instance, a sentence such as “*the capacity of the container*” refers to `capacity`, which is a private field of the CUT. This field cannot be accessed directly, but only by means of the getter method `getCapacity()`.

Moreover, the algorithm looks for a match with the name of the CUT itself and with the name of any interface it implements. The example introduced in Section 2 falls in this category, since in the sentence “if the comparator is locked” the subject (i.e., the comparator) refers to the instance of the CUT itself (i.e., `FixedOrderComparator`), which implements the `Comparator` interface.

Among all the possible matching candidates, the algorithm picks the Java element with the smallest Levenshtein edit distance (number of character insertions, deletions, and replacements). It returns no candidate if the edit distance is greater than 8; we determined this value experimentally.

### 3.2.3 Matching a Predicate to a Java Element

Given a Java element that matches the subject of the sentence, the condition translator has to identify the Java element that the predicate refers to. Toradocu’s main strategy is to take advantage of the English text that the programmer has embedded in identifier names, and to look for similarities with the English text in the specification; this is the approach it takes for subjects (Section 3.2.2). This approach works when the predicate can be represented by a method call with a camelCase name. However, it does not work when the needed Java expression does not contain English text, as for arithmetic and null comparisons. Therefore, the function MATCH-PREDICATE (lines 39–47) implements two strategies:

- *Textual pattern matching* (lines 40–42): The function PATTERN-MATCHING looks for an exact match of the predicate with a set of predefined patterns that covers common cases (listed in Table 2). For instance, the pattern “*is positive*”, which can be applied to short, int, long, float, and double types, produces

**Table 2: List of predicate patterns that Toradocu directly translates.**

Predicate	Translates to
is/are positive	>0
is/are negative	<0
is/are true	==true
is/are false	==false
is/are null	==null
is/are < 1	<1
is/are <= 0	<=0

the Java predicate `subjectElement>0`. When the subject element’s type is reference type (a non-primitive type), the only relevant pattern is a check whether an object is null (i.e., is null  $\rightarrow$  == null). If pattern matching does not produce any result, MATCH-PREDICATE moves on to lexical matching.

- *Lexical matching* (lines 44–45): MATCH-PREDICATE looks for matching candidates among the public fields and methods of the subject instance. Thus, if the subject refers to the class itself, MATCH-PREDICATE looks at methods declared and inherited by the CUT. If the subject refers to a non-primitive variable (i.e., parameter or field), then the predicate matcher considers the methods in the subject’s declared type. For example, the “is locked” predicate would match the `isLocked()` method that `FixedOrderComparator` class declares. MATCH-PREDICATE limits its search to methods that return boolean values and take no parameters. Similarly to the logic of the function MATCH-SUBJECT, the matcher selects the method that has the lowest Levenshtein distance to the predicate less than eight.

### 3.2.4 Creating the Java Condition

The last step of Algorithm 1 is to produce the final Java “condition template” (line 10) that the oracle will instantiate, and it includes the decision on whether to produce a condition that should be evaluated to either true or false. If the predicate contains the substring “not” or “n’t”, as in the sentence “*the comparator is not locked*”, the predicate matcher produces a negative condition such as `(comparatorInstance.isLocked() == false)`.

CREATE-JAVA-EXPR also concatenates multiple Java expressions into a single one. Consider the comment “*either array is null*” where subject “*either array*” is referring to multiple Java elements (e.g., the formal parameters of the commented method). The function CREATE-JAVA-EXPR concatenates the expressions with a suitable conjunction: if the sentence starts with “*either*”, it would use the conjunction is “||” otherwise it would use “&&”.

## 3.3 Oracle Generator

At this point, a Javadoc `@throws` comment has been translated to a boolean expression by the condition translator. In particular, the output of the condition translator is a tuple (method *m*, expected exception type *e*, boolean Java condition *c*) for a given method *m* that is supposed to throw exception *e* when condition *c* holds.

The oracle generator converts the output of the condition translator into a test oracle and injects the oracle into any test case that invokes the method *m*. The oracle generator modifies the test case such that, right before each invocation of *m*, it checks whether *c* holds or not. If *c* holds, the oracle expects an exception *e* as the result of the invocation of *m*, and makes the test case fail if this does not happen.

Toradocu employs aspect oriented programming and AspectJ<sup>4</sup> to embed oracles in existing test suites.

Given the tuple (method *m*, exception *e*, condition *c*) Toradocu automatically generates a custom *aspect* for method *m*, and later uses this aspect to instrument the bytecode of a provided test suite. As an example, the custom aspect for method `FixedOrderComparator.checkLocked()` appears below.

```

1 @Around("call(protected void checkLocked())")
2 public Object advice(ProceedingJoinPoint jp) {
3     Object target = jp.getTarget();
4     Object[] args = jp.getArgs();
5     List<Class> expectedExceptions = getExpectedExceptions(target, args);
6     if (! expectedExceptions.isEmpty()) {
7         try {
8             jp.proceed(args); // checkLocked() is invoked here
9             fail("Expected exception not thrown");
10        } catch (Throwable e) {
11            if (! expectedExceptions.contains(e.getClass())) {
12                fail("Unexpected exception thrown");
13            } else {
14                return null; // success
15            }
16        }
17    }
18    return jp.proceed(args); // checkLocked() is invoked here
19 }

21 // Returns a list of all exceptions that the method is permitted to throw,
22 // based on run-time checks of conditions.
23 private List<Class> getExpectedExceptions(Object target, Object[] args) {
24     List<Class> expectedExceptions = new ArrayList<Class>();
25     if (target.isLocked()) { // condition is checked here
26         expectedExceptions.add(Class.forName("java.lang.
27             UnsupportedOperationException"));
28     }
29     return expectedExceptions;

```

The Toradocu-generated custom aspect checks whether method `checkLocked()` behaves correctly according to the described exceptional behavior. First of all, the aspect builds a list of *expectedExceptions* (lines 5, 23–29) by performing a run-time check of each boolean Java condition that was output by the condition translator, adding exceptions to the list whose condition currently holds (lines 25–26). In our example there is only one `@throws` clause and at most one element in the list. The list of expected exceptions may contain more than one element if multiple conditions hold at run time that lead to different exceptions. As an example, consider method `foo(Integer x, Integer y)` with Javadoc “*@throws NullPointerException if x is null*” and “*@throws IllegalArgumentException if y is negative*”. The invocation `foo(null, -10)` is permitted to raise either of the two exceptions, and the aspect accepts either one as correct behavior.

If Toradocu was not able to derive any information about the exceptional behavior of the method `checkLocked()`, the list of expected exceptions is empty (line 6). In such case, the method `checkLocked()` is invoked as if our oracles were not available (line 18). If a method that is not supposed to throw any exception throws an exception during its execution, and thus executes line 18, the test case fails, flagging a *likely* problem due to: (i) a missing `@throws` tag in the documentation documenting the thrown exception, or (ii) an error in the implementation that led to the exception. It is also possible that the thrown exception is a permitted behavior that is intentionally not documented.

When the list of expected exceptions is not empty (line 6), as in our example, the aspect invokes the method at line 8, catching any exception that its execution would generate. The test case fails if

- no exception is thrown (line 9), or
- the exception type differs from the list of expected exceptions (line 12).

<sup>4</sup><http://www.eclipse.org/aspectj>

It masks the exception if the method raised the expected exception, in which case the aspect returns null (line 14). Notice that a non-void aspect requires a return a value, and thus it returns null if the method under test *correctly* throws an exception.

Through aspects, Toradocu automatically injects test oracles every time method `checkLocked()` is invoked in a test case. Thus, given a test case such as this one from Section 2:

```

1 void test() {
2     FixedOrderComparator c = new FixedOrderComparator(...);
3     c.compare(...);
4     c.checkLocked();
5 }

```

Toradocu would produce the following test case, which is semantically equivalent to the one we presented as the motivating example in Section 2:

```

1 void test() {
2     FixedOrderComparator c = new FixedOrderComparator(...);
3     c.compare(...);
4
5     List expectedExpects = getExpectedExpects(c, new Object[0]);
6     if (! expectedExpects.isEmpty()) {
7         try {
8             c.checkLocked();
9             fail("Expected exception not thrown");
10        } catch (Throwable e) {
11            if (! expectedExpects.contains(e.getClass())) {
12                fail("Unexpected exception thrown");
13            }
14        }
15    } else {
16        c.checkLocked();
17    }
18 }
19
20 private List getExpectedExpects(Object target, Object[] args) {
21     List expectedExpects = new ArrayList();
22     if (target.isLocked()) { // condition is checked here
23         expectedExpects.add(
24             Class.forName("java.lang.UnsupportedOperationException"));
25     }
26     return expectedExpects;
27 }

```

Toradocu does not explicitly output the source code of the resulting test cases. Rather, it outputs the source code of the aspects and uses AspectJ to instrument the bytecode of given test cases to add the oracles.

## 4. EXPERIMENTAL EVALUATION

The key contribution of Toradocu is the ability to automatically generate test oracles from Javadoc comments. Combined with test input generation tools such as EvoSuite and Randoop, Toradocu can automatically generate test cases with oracles that reveal faults in exceptional behaviors. Our experiments evaluate the effectiveness of our test oracles when integrated with automatically-generated test inputs. Thus, our experiments show the effectiveness of Toradocu combined with test generators as a uniquely powerful tool to automatically generate complete and accurate test suites for exceptional behavior.

Our evaluation addresses the following research questions:

**RQ1** Do developers test exceptional behavior less than normal behavior?

This research question assesses whether developers tend to overlook exceptional behaviors when testing their software. A positive answer to this question would make Toradocu relevant in practice. Section 4.1 reports the results.

**RQ2** To what extent does Toradocu reduce the number of false positives that test input generation tools produce?

Test input generation tools such as EvoSuite and Randoop do not produce test oracles or use simple heuristics to classify exceptional behaviors. Depending on the heuristic, they suffer false positives (reporting as a failure an intended behavior) and/or false negatives (considering correct a failing execution). Toradocu reduces the number of such errors. Section 4.2 reports the design and results of this experiment.

**RQ3** Does Toradocu reveal faults in the implementation of exceptional behavior?

Test input generation plus Toradocu has the potential to reveal bugs where developers do not correctly implement the expected exceptional behavior. Section 4.3 describes our experiment in which this approach found defects in student assignment submissions, and in which it found previously-unknown defects in Google Guava, which the developers have acknowledged and fixed.

### 4.1 RQ1: Exceptional Behavior Coverage

We selected 10 popular, well-tested open source libraries (nine Apache Commons projects and Google Guava) to evaluate whether Java developers pay equal attention to exceptional behavior and normal behavior when writing tests.

We ran the developer-written test suites for each project, and Figure 2 plots two coverage metrics:

- *all statement coverage*: The standard quality metric for test suites, this is the number of statements executed at least once by the test suite, divided by the total number of statements. It is a ratio between zero and one, inclusive. Higher numbers are better.
- *throw statement coverage*: This ratio is the number of throw statements executed at least once by the test suite, divided by the total number of throw statements. This metric represents the amount of exceptional behavior that test suites cover.

The test suites achieve high code coverage: always higher than 75%, and usually higher than 90%. Developers do not pay equal attention to testing exceptional behavior: the coverage of throw statements is never higher than of the overall coverage, and is usually significantly lower, in two cases below 50%.

Exceptional behavior is just as legal and expected as normal behavior, and it should be tested just as well. The results of our empirical study show that our Toradocu technique is needed to augment existing, high-quality manually written test suites too.

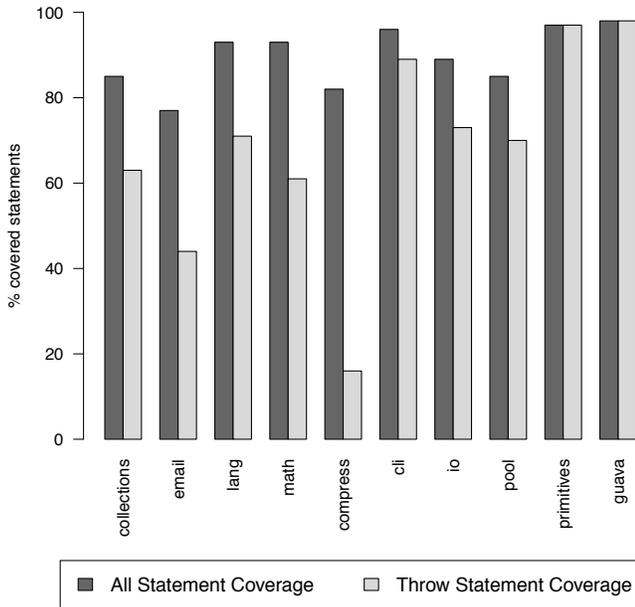
### 4.2 RQ2: Reducing False Positives in Test Executions

Test input generation tools such as EvoSuite and Randoop rely on heuristic oracles. For instance, one common heuristic is to consider any runtime exception as a failure without regard for the specification of the code under test. This heuristic results in many false alarms. Toradocu reduces the amount of false alarms in automatically-generated test suites by augmenting automatically-generated test cases with test oracles for exceptional behaviors. We evaluated how well it does so.

#### 4.2.1 Methodology

We selected nine subject classes from the packages `base`, `collections`, and `primitives` of the Google Guava project (Table 3). We chose these packages because of our familiarity with them, which reduces the effort to manually inspect the results.

We used EvoSuite to generate a test suite for each class under test. We configured EvoSuite to avoid false negatives, by producing test



**Figure 2: All statements coverage vs. exceptional statements coverage achieved by the test suites written by the Apache Commons and Google Guava developers.**

suites without regression oracles. (EvoSuite can generate regression oracles with test suites. It can treat every unchecked exception<sup>5</sup> as a failure and every other exception as expected behavior. These choices lead to both false positives and false negatives; we configured EvoSuite to avoid false negatives.) We directed EvoSuite to maximize all its search goals with a search budget of 60 seconds.

We then used Toradocu on each class to automatically generate oracles describing the exceptional behavior of each method.

We re-ran each test suite, this time with our oracles embedded, and we manually analyzed the 69 failing test cases.

#### 4.2.2 Results

Table 3 reports the results of our study. Toradocu generates aspects only for those methods that contain or inherit Javadoc comments using the `@throws` or `@exception` tags. When a method can throw different exceptions, Toradocu generates one single aspect checking multiple exceptional behaviors of the method.

Out of 290 EvoSuite-generated test executions, 101, or 35%, fail because the test inputs trigger exceptional behaviors that throw unchecked exceptions. For classes `ArrayListMultimap`, `Strings`, and `Verify`, EvoSuite generated more failing tests than passing tests. This is because these classes have a large amount of exceptional behaviors and EvoSuite strives to avoid redundant tests. When Toradocu’s oracles are embedded in the same test suites, the number of failing test cases is reduced from 101 to 69, which is an absolute decrease of 11% or a relative decrease of 32%.

We manually examined every test failure. There are three possibilities:

**True positive that reveals a defect in the CUT.** Three test failures are true positives due to missing `@throws` comments about

<sup>5</sup>In Java, an “unchecked exception” is one that a client is not required to catch and handle: `RuntimeException`, `Error`, and their subclasses.

unchecked exceptions that the code throws. Based on careful reading of the code and documentation, including comparing these methods with other similar methods, we judged that the developers had probably intended that these exceptions should be documented with a `@throws` comment.

Two examples are that method `removeExactly` throws `IllegalArgumentException` if its `occurrences` parameter is negative, and that method `verify` throws `VerifyException` if its argument expression is false.

We reported the three new documentation errors to the Guava developers.<sup>6</sup> The Guava developers acknowledged the problems and accepted our fixes to the documentation. The fact that all of these bug reports and fixes were accepted indicates that our categorization of tests was accurate.

One further test, in class `Verify`, is also a true positive due to an incorrect specification. The test failed Toradocu’s oracle due to a null pointer exception thrown by the test code `verifyNotNull(null, "dstk", null)`. Toradocu’s oracle expected the invocation to throw a `VerifyException` instead, because the documentation indicates that if the first parameter is null, the method throws a `VerifyException`:

```

139 /**
152  * @throws VerifyException if reference is null
153  */
155 public static <T> T verifyNotNull(
156     @Nullable T reference,
157     @Nullable String errorMessageTemplate,
158     @Nullable Object... errorMessageArgs) {

```

The erroneous `NullPointerException` is due to the fact that `errorMessageArgs` is null, which the specification permits via the `@Nullable` annotation on that formal parameter.

Although we were not previously aware of this defect in Guava, it had been independently reported.<sup>7</sup> This independent report shows that documentation errors do cause problems and confusion. The Google developers confirmed the documentation bug. We speculate that they have not yet fixed it because of limitations of the FindBugs `@Nullable` annotation that they are using. Their confirmation of the bug indicated that the intended specification was that `errorMessageArgs` should be non-null but that its elements may be null. Use of a more expressive tool for specifying and checking nullness [17, 34] would resolve the problem.

**False positive due to a limitation of Toradocu.** The Javadoc comment correctly documents the expected exceptional behavior, but Toradocu could not parse the sentence correctly to generate a Java expression and an aspect.

This caused eight test failures in Toradocu test suites. In class `ConcurrentHashMultiset`, the method `toArray(T[])` throws an exception when “*the runtime type of the specified array is not a supertype of the runtime type of every element in this collection*”. Toradocu failed to create the right assertion for this method. Similarly, in classes `Floats` and `Doubles` it failed to correctly generate a correct *and complete* aspect from four Javadoc comments that look like “*if collection or any of its elements is null*”. Toradocu correctly processed the information that when the collection is null the method should throw an exception. However, it failed to generate a complete

<sup>6</sup><https://github.com/google/guava/pull/2099> and <https://github.com/google/guava/pull/2106>

<sup>7</sup><https://github.com/google/guava/issues/1701>

**Table 3: Toradocu’s effectiveness in avoiding false positives for selected classes in Google Guava. Specification size is reported as the number of @throws tags in the method and the number of those tags that Toradocu was able to convert into an oracle (number of correct and complete oracles + number of correct but incomplete oracles). The EvoSuite-generated test suites are classified as passing, or failing due to an exception being thrown. Failures in the Toradocu-enhanced suites are classified as true positives (defects in the code or the documentation) or false positives (Toradocu weaknesses or illegal inputs generated by EvoSuite).**

Subject class	Spec size		EvoSuite		EvoSuite + Toradocu			
	@throws	Toradocu	Pass	Fail	Pass	True Pos.	False Pos.	Input
ArrayListMultimap	1	1+0	3	6	4	0	0	5
AtomicDoubleArray	1	1+0	20	10	21	0	0	9
ConcurrentHashMultiset	12	8+1	32	15	40	0	1	6
Doubles	4	3+1	42	12	47	0	2	5
Floats	4	3+1	43	18	47	0	2	12
MoreObjects	1	1+0	17	4	18	0	0	3
Shorts	6	3+1	22	22	30	0	3	11
Strings	1	1+0	6	9	9	0	0	6
Verify	4	4+0	4	5	5	4	0	0
Total	34	25+4	189	101	221	4	8	57

oracle because it did not check that the method throws an exception also when an element of the collection is null.

#### False positive due to an unexpected input generated by EvoSuite.

The remaining 57 failing test cases are exceptions that the code under test is allowed, but not required, to throw, given the non-typical inputs that EvoSuite generated.

The Javadoc documentation does not mention any expected exception because the specification is intentionally incomplete. A common reason for this is that the method has precondition contracts that forbid clients from passing a particular parameter value. In such a case, the documentation should *not* specify what exception is thrown if the precondition is violated. For example, a binary search routine requires that its array input is sorted, but does not promise any particular behavior if the array input is not sorted. As an example, EvoSuite generated a test containing the method invocation `Doubles.tryParse(null)`. This invocation threw `NullPointerException` as expected. As another example, an EvoSuite-generated test passed a very large value to the `ArrayListMultimap` static constructor `create(int, int)`, then invoked the method `createCollection()`, which threw `OutOfMemoryException`.

As above, we used our best judgment in determining whether the specification was intentionally incomplete. Our results are conservative, since this category might contain some cases where the developers truly intended to write a complete specification.

This study shows that Toradocu can reduce the number of false positive failures in a test suite, thus making the suite more fruitful for people to examine. Furthermore, Toradocu identified four defects in the Google Guava project, three of which were previously unknown and have now been fixed in response to our bug reports.

While these initial results are extremely encouraging, we caution that they have been performed on only 9 classes taken from one project. We cannot know whether the results will generalize.

### 4.3 RQ3: Revealing Implementation Errors

Our last experiment evaluated whether Toradocu effectively reveals buggy code: defects in the implementation of exceptional behavior. This study assumes a *complete* and *correct* natural-language Javadoc specification. In such a scenario, Toradocu should produce

**Table 4: Subjects of the evaluation of revealing implementation errors. Column *Methods* includes both methods and constructors.**

Class	Methods	Implementation snapshots
<code>collections.map.FilterIterator</code>	10	401
<code>collections.comparators.FixedOrderComparator</code>	9	391
<code>math.genetics.ListPopulation</code>	13	269
<code>collections.map.PredicatedMap</code>	7	283

failing test cases when developers do not correctly implement the expected exceptional behavior.

#### 4.3.1 Methodology

Rojas et al. [37] studied how developers use the EvoSuite test input generation tool when developing new software. They asked 41 developers to implement four different Java classes (Table 4) starting from their Javadoc documentation. The four classes were selected from the Apache Commons Collections and Apache Commons Math libraries. Rojas et al. recorded a snapshot of the implementation whenever the developers chose to run EvoSuite to test their implementation.

For each subject class, we used Toradocu to generate the aspects describing its exceptional behavior. We then used EvoSuite and Randoop to generate test suites for each implementation snapshot of each class.<sup>8</sup>

For Randoop, we used its default heuristic for oracles. Randoop outputs two distinct test suites: a suite of passing tests (the Randoop manual calls these the “regression tests”) and a suite of failing tests (the Randoop manual calls these the “error-revealing tests”). Since Randoop uses heuristics to classify tests as passing or failing, the regression tests may contain false negatives (missed alarms), and the error-revealing tests may contain false positive alarms. For EvoSuite, we used the heuristic that any thrown exception is expected behavior. This avoids false positive alarms but is prone to false negatives (missed alarms).

We ran each test suite with and without Toradocu oracles, and we evaluated the fault-finding effectiveness of the test suites. We measured the fault-finding effectiveness in terms of number of test

<sup>8</sup>We included Randoop because a recent study found that “debugging was significantly more efficient when Randoop test cases are used [compared to manual test cases]”, but “debugging was equally effective with manual and EvoSuite test cases” [9].

**Table 5: Toradocu effectiveness with developers’ implementations of a Javadoc specification. Specification size is as in Table 3. Tests are classified as passing, failing due to an exception being thrown (FE), or failing due to a test assertion (FA). Randoop generates two test suites: one containing only passing tests (RandoopR) and one containing only failing tests (RandoopE). The bottom row shows false negative rates for the “Pass” column, and false positive rates for the “FE” and “FA” columns; in both cases, smaller numbers are better.**

Subject Class	Spec size		EvoSuite			EvoSuite+Toradocu			RandoopR			RandoopR+Toradocu			RandoopE			RandoopE+Toradocu		
	@throws	Toradocu	Pass	FE	FA	Pass	FE	FA	Pass	FE	FA	Pass	FE	FA	Pass	FE	FA	Pass	FE	FA
FilterIterator	4	2	2748	3	0	2325	3	423	17440	0	0	8927	0	8513	0	12435	0	1423	7998	3032
FixedOrderComparator	9	5	4045	0	0	3980	0	65	12910	0	0	12670	0	240	0	23670	0	26	23382	262
ListPopulation	10	2	3536	2	0	3421	2	115	11614	28	0	11543	21	78	0	12693	0	97	12434	162
PredicatedMap	4	2	1968	4	0	1548	4	420	6186	0	0	6076	0	110	0	24257	0	136	24084	37
False pos./neg. rate			45%	78%	n/a	40%	78%	0%	35%	43%	n/a	20%	24%	0%	n/a	90%	n/a	0%	90%	0%

cases that fail, thus revealing an exception-related error in the implementation.

Similarly to the previous study, we manually analyzed the test executions. Given the large amount of data, we sampled 20 executions for each kind of test outcome (passing, failing because of a runtime exception, and failing because of a failing assertion).

### 4.3.2 Evaluation Results

Table 5 presents the results of our study. All of the aspects generated by Toradocu were correct and complete.

The results show that, as expected, automatic test case generator tools are rather weak in revealing implementation errors due to a lack of proper test oracles. For instance, EvoSuite generates test cases that fail nine times, all of them because of a run-time exception. Out of these nine failures, only two of them are true positives (two `NullPointerException` due to implementation errors for `ListPopulation`). The other seven are due to malformed test input (five `ClassCastException` and two `InitializationError`).

When we augment the EvoSuite test suites with Toradocu’s oracles the number of test cases failing for a run-time exception remains unchanged, while the number of test cases failing due to an assertion dramatically increases (from 0 to 1023). This is the direct effect of the test oracles we injected in the test suites. We manually inspected 20 randomly sampled tests leading to failures and we confirmed that all of them are true positives: they fail because of a bug in the implementation or because the implementation is entirely missing.

We confirm the same results with the Randoop test suites (from 0 to 8941 failed assertions and from 0 to 3493, all true positives among the inspected ones).

The last row of Table 5 reports the percentage of *incorrect* test results produced by the different test suites. The percentage is computed on the sample we manually analyzed. The table shows that when applied to Randoop test suites, Toradocu’s oracles can *significantly decrease the number of false positives* (from 43% to 24%).

Our results also show that 45% of the inspected passing test cases generated by EvoSuite are actually false negatives, as well as 35% of Randoop test cases. Toradocu *reduces the number of false negatives* reported by EvoSuite and Randoop by 5% and 15% respectively.

The results of this study show that Toradocu improves the effectiveness of a test input generation tool: it can both reduce the number of false negative test results — thus revealing more true faults — and reduce the number of false positives, thus saving developers’ time in inspecting test results.

## 5. RELATED WORK

Our work uses NLP to automatically extract conditional expressions regarding exceptional behavior from Javadoc comments. We see our work as particularly beneficial for test input generation techniques, since they typically lack a means to determine on the success (or failure) of a test execution.

Section 5.1 describes how test input generation tools treat exceptional behaviors. Section 5.2 surveys the related techniques that automatically generate test oracles from sources of information other than natural language documents. Section 5.3 concludes by presenting other techniques that infer specifications, which can sometimes be used as test oracles, from natural-language documents.

### 5.1 Treatment of Exceptions by Test Generation Tools

The state of the art in automated test generation uses heuristics to create oracles for exceptional behavior.

JCrasher [13] and CnC [14] use a heuristic for classifying whether a test that throws an exception should be reported as a possible bug. There are four cases. (1) Throws of `java.lang.Error` are always ignored, because they indicate a drastic problem. (2) Throws of declared exceptions are always ignored, because they might be part of the contract. (3) Throws of most undeclared exceptions are bugs only if they are thrown by the method under test; throws by transitively-called methods are ignored. (4) Throws of undeclared exceptions `IllegalArgumentException`, `IllegalStateException`, and `NullPointerException` are bugs if they are thrown by some public method that is (transitively) called by the method under test. They are ignored otherwise, including if they are thrown by the method under test itself or by a non-public method that is transitively called. These heuristics, however, suffer both false alarms and missed alarms. JCrasher and CnC also use a heuristic to group exceptions before presenting them to the user — if the backtrace is the same, the tool just shows one of them.

Randoop [36, 31, 32] also uses heuristics to classify each test as passing, failing, or invalid. Passing tests are output as regression tests, failing tests are output as indicating a likely bug in the software under test, and invalid tests are ignored and never shown to the user. When a test throws a: (1) checked exception except as noted below, the test is treated as passing, (2) unchecked exception except as noted below, the test is treated as passing, (3) `NullPointerException` and no null values were used in the test, the test is treated as failing, (4) `NullPointerException` and some null value was used in the test, the test is treated as invalid, (5) out-of-memory exception, the test is treated as invalid, or (6) different exception on different test executions, the test is treated as invalid. (7) Furthermore, a test that violates a contract stated in the JDK documentation (such as reflexivity, symmetry, and transitivity of `equals()`) is treated as failing. All of the above behaviors can be customized by the user. Randoop’s default settings are conservative, to avoid annoying the user by reporting too many possible errors in the program, when an exception may have been caused by incorrect usage of the software under test by the randomly-generated test. However, this means that Randoop fails to report some real errors that its test inputs have revealed.

The faults identified by JTest [35] “are usually ... illegal arguments or special object states” [51], where the latter probably means a violated precondition, such as calling `pop()` on an empty stack.

JTest suppresses warnings about any exception documented with the `@exception` comment tag; that tag does not indicate conditions, just the exception name.

EvoSuite [19, 21, 46] is intended to produce regression tests, not to detect errors. Thus, by default EvoSuite assumes any exception thrown is the correct, intended behavior.

Other test generators do not use any heuristic to treat exceptional behaviors. Differently from EvoSuite, however, they report every undeclared exception to the user, thus including many false alarms [5, 23, 40].

All the aforementioned tools and corresponding techniques are orthogonal to the contributions presented in this paper. The integration of Toradocu with any of these tools would improve them.

## 5.2 Automatic Generation of Test Oracles

Baresi et al. [6] and Barr et al. [7] wrote surveys on automatic test oracle generation techniques.

Many such techniques can automatically generate test oracles starting from formal specifications, which can be in the form of algebraic specifications [2, 22], assertions [3, 11, 28, 38, 45], Z specifications [27, 29], context-free grammars [15], JML annotations [12], and finite state machines [20], among others. However, formal specifications are seldom available, and this limits the applicability of these techniques in practice. By contrast, Toradocu relies on Javadoc comments, a form of specification that is frequently available in Java projects.

Recently many techniques explored the idea of metamorphic testing. In essence it is possible to generate oracles by comparing that two operations that are supposed to be equivalent, have the same behavior in practice [8, 10, 18, 24, 30]. The effectiveness of these oracles is limited to cases where such symmetric properties exist. Toradocu is currently limited to deal with exceptional behavior, but can potentially be extended to other cases. Moreover, Toradocu is likely to complement techniques that generate test oracles from other sources of information.

## 5.3 Using NLP to Extract Specifications

Toradocu uses NLP techniques and heuristics to extract test oracles from natural language comments. Other works use similar techniques for similar purposes.

A significant amount of works use NLP to extract specifications from natural language documents. Wu et al., for instance, parse Web services documentation to infer dependency constraints on service parameters [49]. Xiao et al. aim to extract security policies [50], while Wong et al. aim to extract input constraints from program documents to provide a better guidance during symbolic execution [48], and Zhong et al. designed Doc2Spec to analyze Javadoc comments to infer automata describing the resources-related behavior of Java programs [54]. Toradocu uses similar techniques to the ones that these works employ, but for a different purpose.

Pandita et al. proposed an approach to automatically extract function contracts from natural language documents [33]. Although this work extracts information that could be useful to generate test oracles, the technique is not meant for this purpose.

Natural language processing techniques have also been used to automatically detect inconsistencies between code and corresponding comments. For example, iComment [42] and aComment [43] derive rules about specific properties from code comments using both NLP and heuristics. Then they statically check the extracted rules to check whether there is any inconsistency between comments and code. DocRef combines NLP with island parsing to highlight inconsistencies between code and API documentation, thus revealing likely bugs in the documentation [53]. Rubio-González and

Liblit exploit static analysis to collect all the returning error codes of system calls in Linux. Then they compare this information with the documentation of the Linux manual to find undocumented error codes. Their analysis revealed over 1700 inconsistencies looking only at file-related system calls [39]. Although these techniques have similar goals as Toradocu, they do not aim to produce test oracles.

Bacherler et al. [4] designed a technique to automatically generate test cases out of natural language documents. However, their technique works under the assumption that the documents use a restricted, formalized English vocabulary. Toradocu is more flexible since it does not have this assumption.

Zhang et al. exploit NLP techniques to generate test inputs and a small set of related assertions from a set of test names provided by the developer [52]. Since Toradocu generates test oracle for a set of test inputs, the two techniques address complementary goals.

Tcomment by Tan et al. is the work that is most closely related to ours [44]. Just as Toradocu, they aim to generate test cases with oracles derived from the Javadoc comments of the class under test. Tcomment, however, resolves only exact pattern matchings between Java elements in the code and names in the documentation, and works only to check null values handling.

## 6. CONCLUSIONS

This paper presented Toradocu, a technique to automatically generate test oracles for exceptional behavior. It works from Javadoc comments, which are informal documentation that programmers are already accustomed to writing. Toradocu uses natural language processing techniques to identify subjects and predicates in comments, and then maps them to concepts in the source code, thus creating conditional expressions that describe the programmer-intended behavior. We have used Toradocu in combination with an automatic test input generation tool to create test suites with oracles that are able to detect errors in error-handling code in Java.

We performed an empirical study that shows that developers under-test exceptional behavior, motivating the need for a technique that can automatically generate test cases for exceptional cases, even when manually-written test suites already exist.

Our evaluation shows that Toradocu reduces the number of false alarms that automatically-generated test cases typically report, and at the same time it is effective at detecting real faults in implementations. Toradocu identified five defects in the Google Guava documentation, four of them previously unknown.

Toradocu is just a first prototype of what we envision as a powerful and general tool to generate test oracles. In the future we plan to improve the abilities of the NLP component to resolve more complex conditions. Moreover, we also plan to look at other parts of the Javadoc comments beside `@throws` tags.

## 7. ACKNOWLEDGMENTS

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