String Test Data Generation for Java Programs

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Overview

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  - String Test Data Generation
  - Existing Work
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  - String API Usage
  - Motivating Example
- Our Approach
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  - String API Invocation Sequence Extraction
  - Regex Generation
- Evaluation
  - DataSets and Experimental Results
  - Case Study
- Conclusion

1.1 String Test Data Generation

- String operations in Java programs are mostly performed by calling string APIs.
- We need to understand the semantics of the API to generate suitable test data.

```
1    // str is a method parameter
2    String[] splitArray = str.split("#");
3    String splitStr = splitArray[2];
4    String subStr = splitStr.substring(3, 8);
5    if (subStr.equals("class")) {
6       ... //True branch: omitted
7    } else { ... //False branch: omitted }
```

complex semantics for single API

multiple string API combination

1.2 Existing Work

- **SMT Solvers**([1]-[8]):
  - SMT-LIB[9] cannot support the split(...) method and the lastIndexOf(...) method
  - The automatic conversion from the string API combinations to SMT formats is not supported.

- **test case generation**
  - EvoSuite[10]
    - Seeding Strategy [11] : It supports single and simple string APIs to seed data and mutate
  - Randoop[12]
    - feedback-directed random test generation
    - It does not intentionally generate string-related data.

[1] Norn: An SMT Solver for String Constraints
[2] String constraints with concatenation and transducers solved efficiently
[3] Towards Constraint Logic Programming over Strings for Test Data Generation
[4] On Solving Word Equations Using SAT.
[5] Z3str4: A Solver for Theories over Strings
[6] cvc5: A Versatile and Industrial-Strength SMT Solver
[7] A decision procedure for path feasibility of string manipulating programs with integer data type
[8] Solving string constraints with regex-dependent functions through transducers with priorities and variables
[9] https://smtlib.cs.uiowa.edu/theories-UnicodeStrings.shtml
[10] Evosuite: automatic test suite generation for object-oriented software
[11] Seeding strategies in search-based unit test generation
[12] Randoop: feedback-directed random testing for java

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2.1 String API Usage

TABLE II
STRING API USAGE

API	NO.	In Path		In Branch	
		ct.(Total)	ct.(Dedup)	ct.(Total)	ct.(Dedup)
Single	1	11,536	29	8,304	25
Combination	2	**873**	**84**	**753**	**75**
	3	159	58	132	49
	4	32	7	27	6
	5	4	2	3	1
Sum		12,604	180	9,219	156

`Single`: a single string API invocation.
`Combination`: combination of multiple API invocations.
`NO`: the number of API combinations, a single API involves only one API.
`ct.(Total)`: the usage the API combination is used.
`ct.(Dedup)`: the count the API combination is used after deduplication.

- The combinations of string APIs make up 8.5% (1068/12604).
- 73.1% (9219/12604) of string API invocations or their combinations have affected the branches in the programs.

2.2 Motivating Example

Listing 1. A Motivating Example

```
1  // str is a method parameter
2  String[] splitArray = str.split("#");
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6     ... //True branch: omitted
7  } else { ... //False branch: omitted }
```

ArrayIndexOutOfBoundsException

StringIndexOutOfBoundsException

- **SMT solvers, EvoSuite and Randoop** can not generate suitable test data to cover the true branch.
- The purpose of this paper is to generate regular expressions:
  - cover the branches
  - trigger the potential exception proactively

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Our Approach

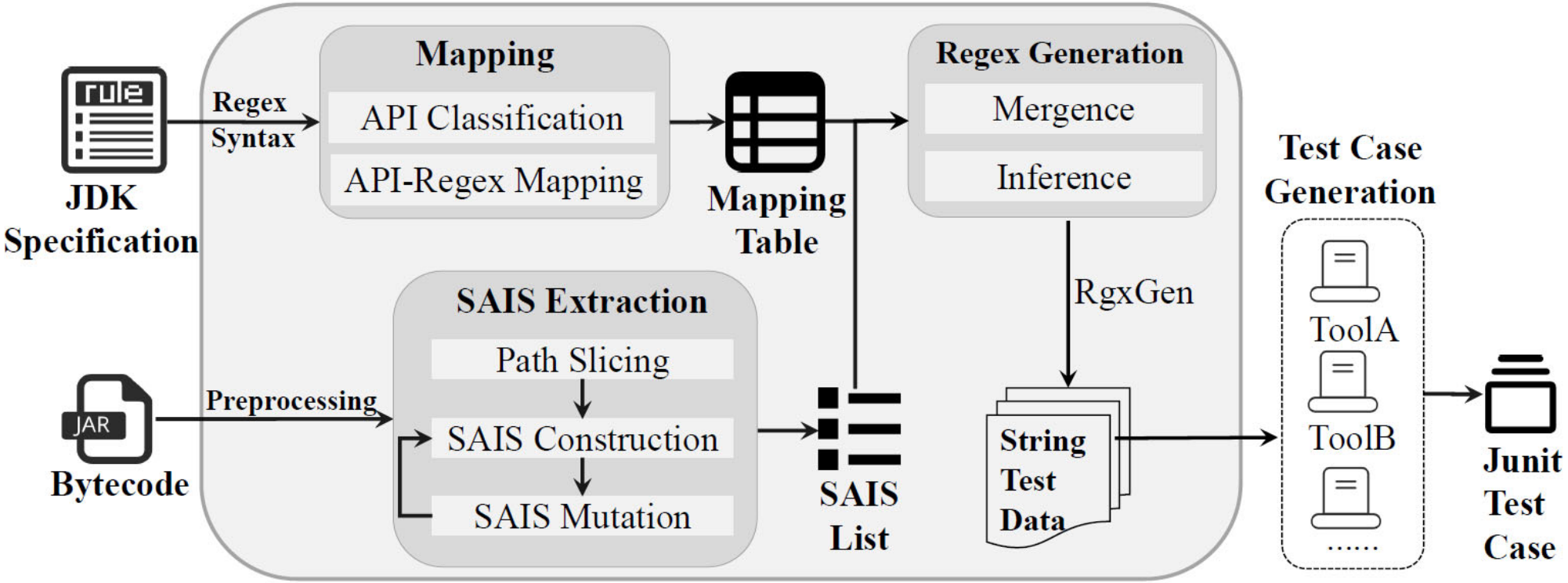


Fig. 1. Overview of Our Approach.

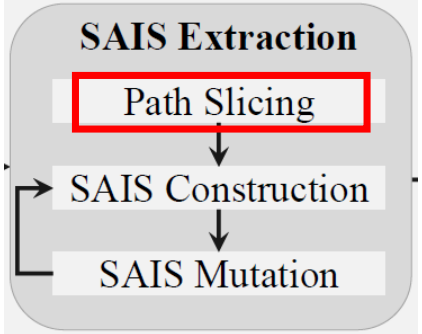
3.1 SAIS Extraction

Algorithm 1: Slice

```
Input: StrPP, condExpr
Output: snippet
containsStringParameter = False;
snippet = {};
variableSet = {};
stmt = condExpr;
snippet.insertAtFirst(stmt);
variableSet.addAll(getVariables(stmt));
while stmt != NULL do
    for each v ∈ variableSet do
        if stmt.isAssignStatementOf(v) then
            variableSet.remove(v);
            snippet.insertAtFirst(stmt);
            variables = getVariables(stmt);
            variableSet.addAll(variables);
            if isStringParaLocalization(stmt) then
                containsStringParameter = true;
            break;
    if variableSet.isEmpty() then
        break;
    stmt = StrPP.getPredecessorOf(stmt);
if containsStringParameter == False then
    snippet = NULL;
return snippet
```

Definition III-A1. (StringParaPath)

A ***StringParaPath*** is the path in a method which contains at least one string API invocation statement on the local variable of the string parameter.



→ **StringParaPath**

3.1 SAIS Extraction

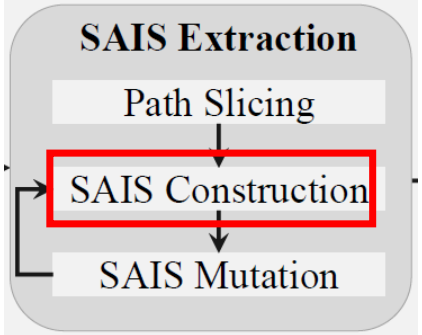
Definition III-A2. (String API Invocation Sequence (SAIS))
A ***SAIS*** is a 2-tuple

SAIS = <CondExpr, Trajectory>

where the ***CondExpr*** is a conditional expression in the ***StringParaPath***, and the Trajectory is a k-length list of ordered pairs

$<(stmt_1, map_1), (stmt_2, map_2), ..., (stmt_k, map_k)>$

where the $stmt_i$ in each pair is a string API invocation statement related to the conditional expression and the map_i maps the variables in the $stmt_i$ to their values.




```
1  // str is a method parameter
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5  if (subStr.equals("class")) {
6     ... //True branch: omitted
7  } else { ... //False branch: omitted }
```

SAIS	CondExpr:	eq==True	
	Trajectory:	$splitStr$=str.split(v_4)[i_1]	{v_4:"#", i_1:2}
		$substr$=$splitStr$.substring(v_2,v_3)	{v_2:3,v_3:8}
		eq=$subStr$.equals(v_1),	{v_1:"class"}

3.1 SAIS Extraction

```
1    // str is a method parameter
2    String[] splitArray = str.split("#");
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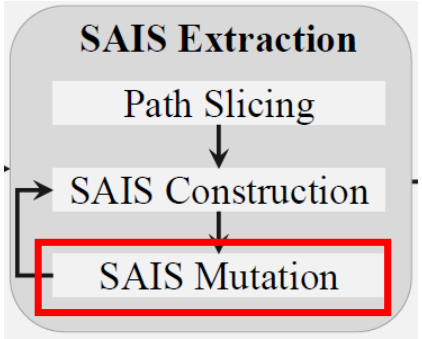


TABLE III
A SAIS AND ITS VARIANT

SAIS	CondExpr:	eq==True	
	Trajectory:	$splitStr$=str.split(v_4)[i_1]	{v_4:"#", i_1:2}
		$substr$=$splitStr$.substring(v_2,v_3)	{v_2:3,v_3:8}
		eq=$subStr$.equals(v_1),	{v_1:"class"}
SAIS$_N$	+CondExpr:	$length$<3	
	Trajectory:	$splitStr$=str.split(v_4)[i_1]	{v_4:"#", i_1:2}
		+ $length$=str.split(v_4).length	{v_4:"#"}

3.2 API-Regex Mapping

- **Terminated API.**
  - The API whose return type is char, int, boolean, char[] or byte[], that is, primitive type or its array type, is considered as a terminated API (Total: 15). In general, its return value is used directly in the conditional expression

- **Non-terminated API.**
  - The API whose return type is String, CharSequence or String[] is considered as a non-terminated API (Total: 33). Their return values cannot appear directly in conditional expressions.

3.2 API-Regex Mapping

Definition (RegexWrapper)

A ***RegexWrapper*** is a 4-tuple

- R is the regular expression according to the string API and the expression on its return value;
- L is the length of the string that the R allows to merge and –1 indicates that there is no limit for the length;
- S is the a special regular expression with which to replace during inference if the any character regular expression is in the suffix of the R;
- L_{min} is the minimum length of a string corresponding to the R;

Definition (API-Regex Mapping)

A ***API-Regex Mapping*** is a 2-tuple

$$\mathcal{M} = \langle APIPair, RegexWrapper \rangle$$

where ***APIPair*** is a pair including the string API invocation and its related conditional expression, and ***RegexWrapper*** is defined before.

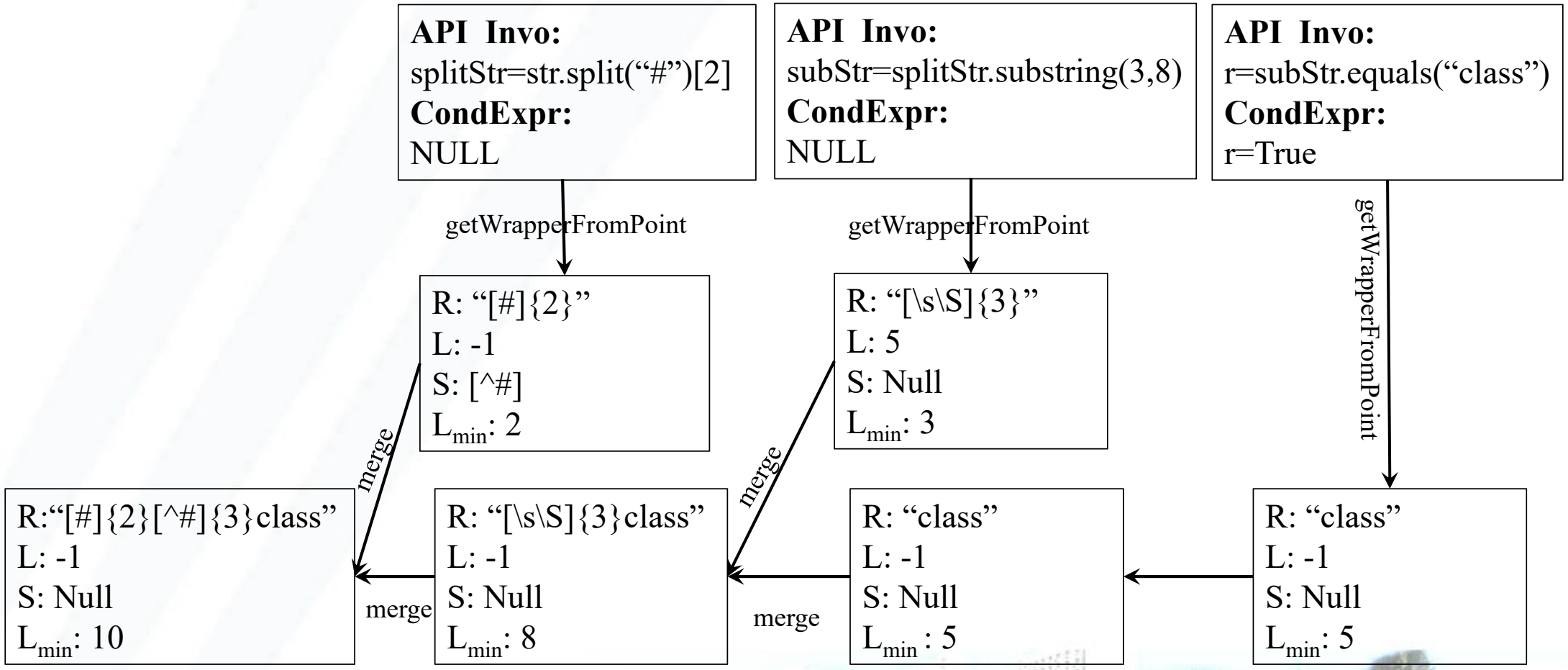
3.2 API-Regex Mapping

TABLE IV
PARTIAL API-REGEX MAPPING

APIPair		RegexWrapper			
API Invo. (caller: *str* | *arr*)	CondExpr	R	L	S	L_{min}
r=str.startswith(v)	r==T	v[\s\S]*	–1	NULL	Len(v)
r=str.length()	r==l	[\s\S]{l}	–1	NULL	l
r=str.substring(i_1,i_2)	NULL	[\s\S]{i_1}	i_2-i_1	NULL	i_1
r=str.split(v)[i]	NULL	[v]{i}	–1	[^v]	i
r=arr.length	r >i	[\s\S]{i+1,}	–1	NULL	i+1

https://github.com/suoyi123wang/JustinStr

3.3 Regex Generation



3.3 Regex Generation

TABLE I
COMPARISON ON JAVA TOOLS GENERATING STRING DATA

Tool	E-prone Regular Expression			
	[\s\S]{1,4}	[^a]{1,3}	(?i)AbC	[\Q*\E]{1,3}
xeger [4]	✗	✓	✗	✗
Generex [39]	✓	✓	✗	E
MutRex [41]	✓	✓	✗	✗
bfgex [22]	✗	✗	E	✗
RgxGen [19]	✓	✓	✗	✓
random-string [9]	E	E	✗	E

✓: the generated string matches the regex; ✗: not matching; *E*: an exception occurs during generation.

[#]{2}[^#]{3}class

RgxGen: "##abcclass"

Cover the true branch (line 6)

```
1    // str is a method parameter
2    String[] splitArray = str.split("#");
3    String splitStr = splitArray[2];
4    String subStr = splitStr.substring(3, 8);
5    if (subStr.equals("class")) {
6      ... //True branch: omitted
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```

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4.1 DataSets

TABLE V
STATISTICS OF THREE DATASETS

Program	#Cls	#LOC	M_1	M_2	#RE
23 Assginments	406	9667	45	42	98
289 Solutions	289	4529	217	183	677
closure-compiler-20220202	8,162	218,939	194	153	475
commons-lang3-3.12.0	505	9,600	73	39	211
commons-io-2.11.0	240	5,544	21	17	81
mysql-connector-java-8.0.29	1,345	42,726	56	44	163
poi-ooxml-5.2.2	1,529	47,176	45	31	84
OpenJDK-8u292	25,574	697,752	1,513	1,250	6,697

4.2 Experimental Results

- **RQ1: How effectively does Justin-Str characterize the input string parameters?**

Length	Branch	Single (%)	Combination (%)			
			2	3	4	5
L=10,20 (30,40,50)	True	100.00	100.00	100.00	100.00	100.00
L=10	False	99.77	99.41	99.33	98.09	100.00
L=20	False	99.55	99.14	99.02	99.11	100.00
L=30	False	99.35	98.84	98.72	99.35	99.99
L=40	False	99.14	98.47	98.50	99.49	99.99
L=50	False	98.94	98.20	98.18	99.65	99.98

- **85x5 = 425 methods,**
  - **Each one ends with a branch (T/F)**

4.2 Experimental Results

- **RQ2: Improvement of the branch coverage**

Program	Seeds	$M_{Cov100\%}$	$M_{Cov}(\%)$	Max_{Cov}	Ave_{Cov}
closure-compiler	972	58	+18(19%)	+50%	+21%
commons-lang3	441	10	+10(34%)	+57%	+11%
commons-io	128	4	+5(38%)	+43%	+17%
mysql-connector-java	301	16	+5(18%)	+34%	+11%
poi-ooxml	125	10	+2(10%)	+50%	+28%

- **+22%(40/186) of the method**
- **up to +57%, and +17% on average**

4.2 Experimental Results

- **RQ3: Bug Finding**

TABLE VIII
COMPARISON OF BUGS FOUND BY JUSTINSTR AND EVOSUITE

Program	JustinStr	Common	Δ	Time (s)	
				JustinStr	EvoSuite
Assignments	38	27	11	339	1627
Solutions	72	60	12	14	12,453
closure-compiler	33	21	12	72	2,394
commons-io	11	1	10	16	80
commons-lang3	15	3	12	15	709
mysql-connector-java	7	3	4	23	306
poi-ooxml	3	0	3	40	-
OpenJDK	17	0	17	10,228	-
Total	196	115	81	-	-

TABLE IX
BUGS CONFIRMED OR FIXED BY THE JDK DEVELOPERS

Type:	ArrayIndexOutOfBoundsException (2)
Issue ID:	I4MWI1 (Commit ID), 8279422
Type:	StringIndexOutOfBoundsException (14)
Issue ID:	8278186, 8279128, 8279129, 8279198, 8279218, 8279336, 8279341, 8279342, 8279362, 8279423, **21212bd18(Commit ID), 8279424, **411a404a9(Commit ID), **8baba7d11(Commit ID)
Type:	Infinite Loop (1), **Issue ID**: 8278993

4.2 Experimental Results

- **RQ3: Bug Finding (Order)**

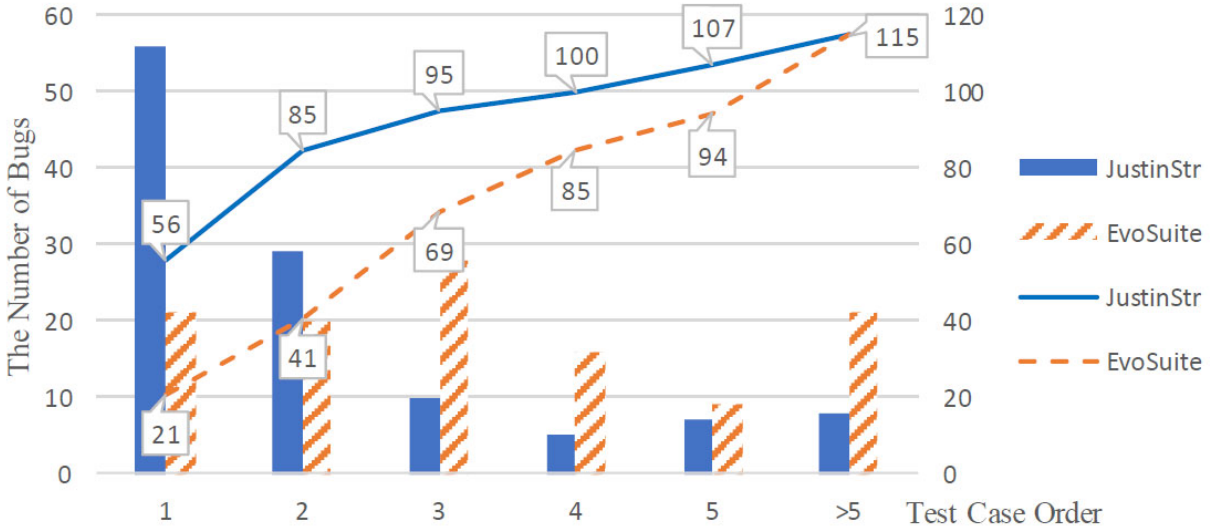

Fig. 3. Comparison on Number of Bugs Found by `JustinStr` and `EvoSuite` under Test Case Order. Bars represent the number of bugs triggered by the test case at current order and poly-lines represent the number of accumulated bugs triggered by the test cases before and within the order.

- The first two test cases in JustinStr can trigger 74% of the bugs, while EvoSuite only triggers 36%.

4.3 Case Study

Listing 2. Case Study in JDK

```
1  // Case 1: StringIndexOutOfBoundsException
2  public static String parseIdFromSameDocumentURI(String
       uri) {
3      if (uri.length() == 0) {
4          return null;
5      }
6      String id = uri.substring(1);
7      if (id != null && id.startsWith("xpointer(id(")) {
8          int i1 = id.indexOf('\'');
9          int i2 = id.indexOf('\'', i1+1);
10         id = id.substring(i1+1, i2);
11     }
12     return id;
13 }
14 //Case 2: Infinit Loop
15 static public String sansArrayInfo (String name) {
16     int index = name.indexOf ('[');
17     if (index >= 0) {
18         String array = name.substring (index);
19         name = name.substring (0, index);
20         while (!array.equals ("")) {
21             name = name + "[]";
22             array = array.substring(array.indexOf(']') + 1);
23         }
24     }
25     return name;
26 }
```

StringIndexOutOfBoundsException
Regex: "[\s\S]{1}xpointer\(id[\s\S]*
String: 0xpointer(id(G6

Infinite loop:
Regex: [[\s\S]*
String: [

https://bugs.java.com/bugdatabase/view_bug.do?bug_id=JDK-8278186
https://bugs.java.com/bugdatabase/view_bug.do?bug_id=JDK-8278993

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Conclusion

- **API-Regex Mapping**. We build a mapping from 48 string APIs to regular expressions based on their semantics, which are equivalent or approximate.
- **Inference Algorithm**: We design an inference algorithm that can characterize the string parameter with regular expressions under the combination of its string API invocations.
- **String Test Data Generation Tool**. We developed an automatic tool **JustinStr** to output the string test data for test cases generation.

Future work:

- Convert the string API with the symbolic value into regular expressions.
- Support for converting more string APIs to regular expressions.

Q & A