Exploiting Synergy Between Testing and Inferred Partial Specifications

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Technical Report UW-CSE-03-04-02
April 2003

Abstract

The specifications of a program can be dynamically inferred from its executions, or equivalently, from the program plus a test suite. A deficient test suite or a subset of a sufficient test suite may not help to infer generalizable program properties. But the partial specifications inferred from the test suite constitute a summary proxy for the test execution history. When a new test is executed on the program, a violation of a previously inferred specification indicates the need for a potential test augmentation. Developers can inspect the test and the violated specification to make a decision whether to add the new test to the existing test suite after equipping the test with an oracle. By selectively augmenting the existing test suite, the quality of the inferred specifications in the next cycle can be improved while avoiding noisy data such as illegal inputs. To experiment with this approach, we integrated the use of Daikon (a dynamic invariant detection tool) and Jtest (a commercial Java unit testing tool). This paper presents several techniques to exploit the synergy between testing and inferred partial specifications in unit test data selection.

1. Introduction

Given that specifications play an important role in a variety of software engineering tasks and that the specifications are often absent from a program, dynamically inferring program specifications from its executions is a useful technique [3]. The output of the dynamic specification inference has been used to aid program evolution in general [3] and program refactoring in particular [7]. Most of the applications can achieve better results if the inferred specifications are closer to the oracle specifications. Like other dynamic analysis techniques, the dynamic specification inference is also constrained by the quality of the test suite for the program. Usually it is unlikely that the inferred properties are true over all possible executions. When properly applied, static verification tools can filter out false positives in the inferred specifications [8].

Different from previous applications that use the final inferred specifications from all the available tests, two recent approaches have begun to use the intermediate partial specifications inferred from a subset. Both are based on the fact that the inferred specifications may change when new tests are added to the existing test suite. The first, called the operational difference (OD) technique, makes use of the differences in inferred specifications between test executions to generate, augment, and minimize the test suites [5]. The second, as implemented in the tool DIDUCE, can continuously check a program's behavior against the incrementally inferred partial specifications during the run(s), and produce a report of all violations detected along the way [4]. This can help detect bugs and track down the root causes. It is noteworthy that "partial specification" also carries the denotation that the specification is not complete or accurate in terms of an oracle specification. Thus there is a convergence of the two meanings when the specifications inferred from the whole test suite are used to approximate the oracle specification.

In this research, we further exploit the synergy between testing and inferred partial specifications. All available tests in this context are a small size of the existing unit test suite plus a large size of the automatically generated unit tests. The purpose is to tackle the problem of selecting automatically generated tests to augment the existing unit test suite. Violations of the inferred partial specifications from the existing unit test suite can help this unit test data selection. Moreover, selectively augmenting the existing test suite can prevent introducing noisy data, e.g. illegal inputs, from negatively affecting the specification inference.

The next section presents background materials on unit test selection and two third-party tools that are integrated in our approach. Section 3 illustrates our specification violation approach through a motivating example. Section 4 explains the effects of inferred specifications on test generation. Section 5 describes our experimental results

for the motivating example. Section 6 discusses related work. Section 7 makes conclusions.

2. Background

The "test first" principle, as advocated by Extreme Programming (XP) development process [1], requires unit tests to be constructed and maintained before, during, and after the source code is written. Developers need to manually generate the test inputs and oracles based on the requirements in mind or in documentation. They need to decide whether enough test cases have been written to cover the features in their code thoroughly. Some commercial tools for Java unit testing, e.g. ParaSoft Jtest [10], attempt to fill the "holes" left by the execution of the manually generated unit tests. These tools can automatically generate a large number of unit tests to exercise the program. However, there are two main issues in automatic unit test generation. First, there are no test oracles for these automatically generated tests unless developers write down some formal specifications or runtime assertions [2]. Second, only a relatively small size of automatically generated tests can be added to the existing unit test suite. This is because the unit test suite needs to be maintainable, as is advocated by the XP approach [1].

Two main unit test selection methods are available. In white box testing (e.g., the residual structural coverage [11]), users select tests that provide new structural coverage unachieved by the existing test suite. In black box testing, the operational difference (OD) technique is applicable in augmenting a test suite [5]. However, the OD technique for this unit test augmentation problem might select a relatively large set of tests because the specification generator's statistical tests usually require multiple executions before outputting a specification clause. Additionally, OD requires frequent generation of specifications, and the existing dynamic specification generation is computationally expensive. Therefore, instead of using OD in the unit test selection, we adopt a specification violation approach similar to DIDUCE [4].

Our approach is implemented by integrating Daikon and Jtest. Daikon [3], a dynamic invariant detection tool, is used to infer specifications from program executions of test suites. The probability limit for justifying invariants is set by Daikon users. The probability is Daikon's estimate of how likely the invariant is to occur by chance. It ranges from 0 to 100% with a default value of 1%. Smaller values yield stronger filtering. Daikon includes a MergeESC tool, which inserts inferred specifications to the code as ESC/Java annotations [12]. ParaSoft Jtest [10], on the other hand, is a commercial Java unit testing tool, which automatically generates unit test data for a Java class. It instruments and compiles the code that contains Java Design-by-Contract (DbC) comments, then automatically checks at runtime whether the specified contracts are violated. We modified MergeESC to enable Daikon to insert the inferred specifications into the code as DbC comments. Since ESC/Java has better expressiveness than Jtest's DbC, a perl script is written to filter out the specifications whose annotations cannot be supported by Jtest's DbC. After being fed with a Java class annotated with DbC comments, Jtest uses them to automatically create and execute test cases and then verify whether a class behaves as expected. It suppresses any problems found for the test inputs that violate the preconditions of the class under test. But it still reports precondition violations for those methods called indirectly from outside the class. Note that DIDUCE tool reports all precondition violations [4]. By default, Jtest tests each method by generating arguments for them and calling them independently. In other words, Jtest basically tries the calling sequences of length 1 by default. Tool users can set the length of calling sequences in the range of 1 to 3. If a calling sequence of length 3 is specified, Jtest first tries all calling sequences of length 1 followed by all those of length 2 and 3 sequentially.

3. Specification Violation Approach

This section describes the specification violation approach. Section 3.1 introduces the motivating example we will use to illustrate our approach. Section 3.2 explains the basic technique of the approach. Section 3.3 presents the precondition guard removal technique to improve the effectiveness of the basic technique. Section 3.4 describes the iterative process of applying these techniques.

3.1. Motivating Example

The Java class in Figure 1 will be used as a running example to illustrate our approach. It implements a bounded stack of unique elements of integer type. Authors of [13] coded this Java implementation to experiment their algebraic-specification-based method for systematically creating complete and consistent test classes for JUnit. Its source code and associated test suites are available at a web link contained in their paper. Two unit test suites are designed for this class: a basic JUnit test suite (8 tests), in which one test-class method is generated for each method in the target class; a JAX test suite (16 tests), in which one test-class method is generated for each axiom in the ADT specification. The basic JUnit test suite does not expose any fault but the JAX test suite exposes one fault. The fault exposed by the JAX test suite is that the code is unable to handle a pop operation on an empty stack.

```
public class uniqueBoundedStack {
      private int[] elems;
      private int numberOfElements;
      private int max;

      uniqueBoundedStack(){…};
      void push(int k) {…};
      void pop() {…};
      int top() {…};
      boolean isEmpty() {…};
      int maxSize() {…};
      boolean isMember(int k) {…};
      boolean equals(uniqueBoundedStack s) {…}
      int[] getArray() {…};
      int getNumberOfElements() {…};
      public boolean isFull() {…};
};
```

Figure 1. uniqueBoundedStack program

3.2. Basic Technique

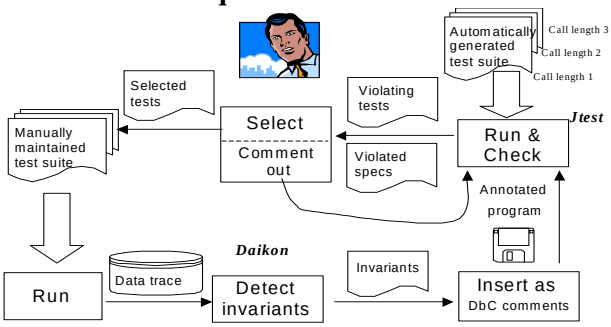

Figure 2. An overview of the basic technique

In our approach, partial specifications are inferred from program executions of the existing unit test suite by using Daikon (Figure 2). The partial specifications are inserted into the code as DbC comments. The resulting code is fed to Jtest. Initially, Jtest's calling sequence length is set to 1 and Jtest is run to automatically generate and execute test data. When a certain number of specification violations have occurred before Jtest exhausts its testing repository, it stops generating test data and reports specification violations. For each reported specification violation, i.e., the violated specification and the violating test, developers inspect them to decide whether to equip the test with an oracle and add it to the existing test suite. Then developers disable each violated specification by commenting them out and rerun Jtest repeating the above procedure until no specification violations are reported. The whole process is iteratively applied by setting the length of calling sequences as 2 and subsequently 3.

The rationale behind the basic technique is that if a new test violates an inferred partial specification, it is likely that this test exercises a new feature of the program uncovered by the existing test suite. This technique guarantees that the new test does not overlap with any others from the existing test suite in terms of the violated specification. In addition, the violating tests have a relatively high probability of exposing faults in the code if there are any. It is because that running the existing test suite on the code exhibits the normal behavior reflected by the inferred specifications and the violating tests might make the code exhibit the abnormal behavior.

The symptoms of specification violations can be that the boolean value of a specification predicate is false or exceptions are thrown. In order for the inferred specifications to be violated, we set the probability limit to be 100%.

Two examples of specification violations are shown in Figure 3. The example in the upper part indicates a deficiency of the JAX test suite. The example starts with method *isMember*'s two violated postconditions each of which is prefixed with a "*@post*". They are followed by the violating test inputs. Below the separator line, the implementation of the method *isMember* is shown. In the postconditions, *$pre* is used to refer to the value of an expression immediately before calling the method. The syntax to use it is *$pre (ExpressionType, Expression).* In addition, *$result* is used to represent the return value of the method.

Replacing the implementation of isMember method with "*if (k==3) return true else return false;*" can make all existing unit tests pass. This violating test is preferable to add to the existing test suite to fill this "hole". The example in the lower part shows a deficiency of the basic JUnit test suite. The existing test suite for the stack implementation only pushes the integer element of 2 or 3 into the stack, which is queried with method *top*. Thus one of the inferred postconditions for method *top* is that the return value is 2 or 3. The automatically generated tests that push the element of 1 into the stack and then query the stack with method *top* violate this specification. However, since the element of 1 is not so different than 2 or 3 for the purpose of testing this stack implementation, developers might not select the violating test to the existing test suite.

```
isMember: @post: [($pre(int , k) == 3) == ($result == true)]
isMember: @post: [($pre(int , k) == 3) == (this.numberOfElements == 1)]
For input:
 uniqueBoundedStack THIS = new uniqueBoundedStack ();
 boolean RETVAL = THIS.isMember (3);
---------------------------------------------------------------
boolean isMember(int k) {
   for( int index=0; index<numberOfElements; index++)
          if( k==elems[index])
                return true;
  return false;
}

$top: @post: [$result == 2 || $result == 3]
For input:
 uniqueBoundedStack THIS = new uniqueBoundedStack ();
 THIS.push (1);
 int RETVAL = THIS.top ();
---------------------------------------------------------------
void top()   {
       if ( numberOfElements < 1) {
                System.out.println("Empty Stack");
                return -1;
       } else
                return elems[numberOfElements-1];
}
```

Figure 3. Examples of specification violations

3.3. Precondition Guard Removal

In our basic technique, when the existing test suite is deficient, the inferred preconditions might be so restrictive as to filter out those legal test data inputs in Jtest test data generation and execution. This over-restrictiveness of preconditions also makes static verification of inferred specifications less effective [8]. Even if a static verifier could confirm an inferred post-condition specification given some over-restrictive preconditions, it is hard to tell whether it is generalizable to the actual preconditions.

To assure better quality of the unit under test, we need to exercise the unit under more circumstances than what is constrained by the inferred preconditions. Before the code that is annotated with DbC comments is fed to Jtest, all precondition comments are removed. In the preliminary experiment, we observed that precondition guard removal techniques reported more violations and exposed more faults than the basic technique (Section 3.1). Indeed, removing precondition guards produces more false positives by allowing some illegal inputs. Yet the tool only reports those illegal inputs that cause postcondition or invariant violations.

Two examples of specification violations after removing precondition guards are shown in Figure 4. The example in the upper part indicates a deficiency of the basic JUnit test suite and the violating test exposes the fault that is detected by the JAX test suite. In the example, @invariant is used to denote class invariants, which are contracts that the objects of the class should always satisfy. They are checked for every non-static, non-private method entry and exit and for every non-private constructor exit. The example in the lower part shows a deficiency of the JAX test suite and exposes another potential fault. If this stack implementation can accommodate negative integer elements, this specification violation shows that using –1 as an exception indicator makes the *top* method work incorrectly when an integer element in top of the stack is –1. Using Java exception mechanisms can fix this problem. This is a typical value-sensitive fault and even full-path-coverage test suite cannot guarantee to expose this type of faults. However, this violation is not reported before the precondition guards are removed, since there are several inferred preconditions for method *top* to prevent –1 to be on the top of the stack, such as *@pre { for (int i = 0 ; i <= this.elems.length-1; i++) $assert ((this.elems[i] >= 0)); }*, where *@pre* is used to denote a precondition and *$assert* is used to represent an assertion.

```
pop: @post: [this.elems[this.numberOfElements] ==
                this.elems[$pre(int, this.numberOfElements)
pop: @post: [this.numberOfElements == 0 ||
                this.numberOfElements == 1]
pop: @invariant: [this.numberOfElements == 0 ||
    this.numberOfElements == 1 || this.numberOfElements == 2]
For input:
 uniqueBoundedStack THIS = new uniqueBoundedStack ();
 THIS.pop ();
-----------------------------------------
   void pop(){ numberOfElements --; }


top: @post: [($result == -1) == (this.numberOfElements == 0)]
For input:
 uniqueBoundedStack THIS = new uniqueBoundedStack ();
 THIS.push (-1);
 int RETVAL = THIS.top ();
```

Figure 4. Specification violations without precondition guards

3.4. Iterations

After the new test augmentations using the 3.2 and 3.3 techniques, all the violating tests with legal inputs, whether selected or unselected, can be further run together with the existing ones to infer new specifications. Although those unselected violating tests with legal inputs might not exercise any interesting new features, running them in the specification inference can relax the violated specifications to reduce the false positives in the next iteration. The same process described in Section 3.2 and 3.3 is repeated until there are no specification violations or no test data selected from the violating tests. In the preliminary experiment, most of the specification violations were observed in the first iteration, and all specification violations were observed before the third iteration.

Figure 5 shows two specification violations from the first and second iterations on the JAX test suite. After the first iteration, a violating test is added to the existing test suite to weaken the "==" predicate to the "*$implies*" predicate, where *a $implies b* is equivalent to *!a or b*. After the second iteration, another violating test further removes this "*$implies*" predicate since it is inferred just due to the deficiency of the tests. In our preliminary experiment on the motivating example, most of the specification violations are observed in the first iteration and all specification violations are observed before the third iteration.

```
(1st iteration)
isMember: @post: [($result == true) == (this.numberOfElements == 1)]
For input:
 uniqueBoundedStack THIS = new uniqueBoundedStack ();
 THIS.top ();
 THIS.push (2);
 boolean RETVAL = THIS.isMember (1);

(2nd iteration)
isMember: @post: [($result == true) $implies (this.numberOfElements == 1)]
For input:
 uniqueBoundedStack THIS = new uniqueBoundedStack ();
 THIS.push (2);
 THIS.push (0);
 boolean RETVAL = THIS.isMember (0);
```

Figure 5. Specification violations during iterations

4. Effect of Inferred Specifications on Test Generation

In previous sections, we showed that the inferred specifications can be used to select unit test data and improve the specification quality. Furthermore, we observed that the inferred specifications also had an effect on Jtest's automatic test generation. As is described in Jtest's manual [6], if the code has preconditions, Jtest tries to find inputs that satisfy all of them. If the code has postconditions, Jtest creates test cases that verify whether the code satisfies these conditions. If the code has invariants, Jtest creates test cases that try to make them fail. The preliminary experiment showed that preconditions have greater impacts on Jtest's test generation than either postconditions or invariants. Sometimes Jtest, equipped with specifications, could automatically generate tests that achieve better code coverage than the one without specifications. For the test length of two, the former Jtest automatically generated more tests for the stack implementation than the latter one. It suggests that inferred specifications are able to guide Jtest to generate better tests.

5. Quantitative Experimental Results

Table 1-3 show the results of our preliminary experiment on the bounded stack example. Table 1 shows the number of executed tests, inferred Jcontract DbC specifications and inferred ESC/Java specifications for three iterations. The second and the third columns are results for the basic JUnit test suite. The fourth and the fifth columns are those for the JAX test suite. In the second and the fourth columns, the numbers of the tests executed to infer specifications are shown. In the third and the fifth columns, the number of inferred Jcontract DbC specifications and the number of inferred ESC/Java specifications are separated by a "/". It is observed that executing violating tests in addition to the original test suite can reduce the number of inferred specifications. Most of these reduced specifications are inferred initially due to the deficiency of the test suite.

Table 2 shows the number of selected tests, violating tests, and violated specifications for the combination of test calling sequence lengths, iterations and specification types. The specification types comprise four categories: full specifications inferred by using the basic JUnit test suite (Basic Full); specifications with preconditions removed inferred by using the basic JUnit test suite (Basic No Pre); full specifications inferred by using the JAX test suite (JAX Full); specifications with precondition removed inferred by using the JAX test suite (JAX No Pre). In the second or the third iteration, the existing test suite in addition to all violating tests from previous iteration(s) is run to infer specifications. In the column 2 to 4, the results are showed in a form of "*a/b: c*" with *a* as the number of selected tests, *b* as the number of violating tests, and *c* as the violated specifications. In our experiment, the criteria for test data selection from candidates are subjective. However, we found that the violating specifications can be very helpful in the decision process. We usually do not select those violating tests similar to the second example in Figure 3. All entries that contain non-zero selected tests are marked in the bold font.

It is observed that using the inferred specifications with preconditions removed is more effective in assisting unit test data selection. The number of unit test data candidates for selection (violating tests) is not too large for developers to inspect. The number of selected unit test data is also not too large to enhance the existing test suite.

Table 3 shows the number of generated tests by Jtest and their achieved statement coverage for the combination of test calling sequence lengths, iterations, and specification types. The results are showed in a form of "*a (b%)*" with *a* as the number of generated tests and *b* as the achieved statement coverage. The first row shows the results for the original program without any inferred specifications. All entries that contain more generated tests than the ones generated without any inferred specifications. are marked in the bold font. It is observed that when the specifications with preconditions removed are fed to Jtest together with the code, Jtest generates the

same number of the tests and achieves the same statement coverage as the ones when the code without specifications is provided to Jtest. This lets us hypothesize that the postconditions and invariants have little impact on Jtest's test data generation. When the code with full specifications is fed to Jtest, Jtest can usually generate more tests with calling sequence length of 2 than the one without specifications or without precondition specifications. Moreover, when the code with full specifications is fed to Jtest, sometimes Jtest can generate tests with the calling sequence length of 3 achieving better statement coverage than the one without specifications or without precondition specifications. These let us hypothesize that precondition specifications can guide Jtest to better generate test data.

Table 1. The number of executed tests, inferred Jcontract DbC specifications and inferred ESC/Java specifications

Iteration	Basic Test Size	Basic Test Spec Size	JAX Test Size	JAX Test Spec Size
1(original)	8	81/100	16	131/159
2	34	34/43	47	48/55
3	36	31/40	51	42/49

Table 2. The number of selected tests, violating tests, and violated specifications

Iteration. Type	Test call length 1	Test call length 2	Test call length 3
1. Basic Full	0/1: 2	0/3: 3	0/0: 0
1. Basic No Pre	**5/7: 15**	**8/13: 15**	**1/2: 2**
1. JAX Full	**1/3: 3**	0/0: 0	**1/1: 1**
1. JAX No Pre	**1/3: 6**	**10/24: 41**	0/0: 0
2. Basic Full	0/0: 0	0/0: 0	0/0: 0
2. Basic No Pre	0/0: 0	0/1: 1	**1/1: 1**
2. JAX Full	0/0: 0	0/0: 0	**1/2: 2**
2. JAX No Pre	0/0: 0	0/1: 1	**1/1: 1**
3. Basic Full	0/0: 0	0/0: 0	0/0: 0
3. Basic No Pre	0/0: 0	0/0: 0	0/0: 0
3. JAX Full	0/0: 0	0/0: 0	0/0: 0
3. JAX No Pre	0/0: 0	0/0: 0	0/0: 0

Table 3. The number of generated tests and achieved statement coverage

Iteration. Type	Test (cov) (length 1)	Test (cov) (length 2)	Test (cov) (length 3)
Original	14 (63%)	96 (86%)	1745 (86%)
1. Basic Full	10 (47%)	59 (65%)	339 (73%)
1. Basic No Pre	14 (63%)	96 (86%)	1745 (86%)
1. JAX Full	14 (63%)	**113 (80%)**	1010 (84%)
1. JAX No Pre	14 (63%)	96 (86%)	1745 (86%)
2. Basic Full	10 (63%)	**169 (86%)**	1623 (86%)
2. Basic No Pre	14 (63%)	96 (86%)	1745 (86%)
2. JAX Full	13 (63%)	**171 (86%)**	**1671 (91%)**
2. JAX No Pre	14 (63%)	96 (86%)	1745 (86%)
3. Basic Full	14 (63%)	**171 (86%)**	**1638 (91%)**
3. Basic No Pre	14 (63%)	96 (86%)	1745 (86%)
3. JAX Full	13 (63%)	**158 (86%)**	**1539 (91%)**
3. JAX No Pre	14 (63%)	96 (86%)	1745 (86%)

6. Related Work

As is described in Section 1 and 2, operational difference technique is used to generate, augment, and minimize test suites [5]. But its cost is more expensive than our approach since it requires *O(size_of_generated_tests)* times of specification inferences and it tends to select more tests than our approach, increasing the human inspection efforts.

DIDUCE checks a program's behavior continuously against the dynamically inferred specifications and finally reports all detected violations along the way [4]. Our approach is similar to theirs since both make use of specification violations. DIDUCE's main purpose is to track down the bugs but our apporach's main purpose is to select the tests to augment the existing test suite. Indeed, the selected tests are likely to detect the bugs.

Context-sensitive analysis provides a way to select predicates for implications during specification inference [14]. The invariants inferred for a method called from a unit test can indicate deficiencies in the unit test. Developers can inspect the inferred invariants to know the limitations of the unit test. In our approach, only violated invariants are reported together with a concrete violating test case.

Failed static verification attempts are used to indicate the deficiencies in the unit tests [15]. The unverifiable invariants indicate the unintended properties and developers can get hints on how to improve the tests. Our specification violation approach reports not only the violated invariants but also the executable counterexamples to them.

When specifications are provided for a unit a priori, specification coverage criteria are used to suggest a candidate set of test cases that exercise new aspects of the specification [16]. Like above other related work on inferred specifications, our approach does not require a specification a priori.

7. Concluding Remarks

In sum, selecting automatically generated tests to augment the existing unit test suite is an important step in the unit testing practice. Inferred partial specifications act as a proxy for the existing test execution history. A new

test that violates an inferred specification is a good candidate for developers to inspect for test data selection. The violating test also has a high probability to expose faults in the code. Instead of considering the test augmentation as a one-time phase, it should be considered as a frequent activity in software evolution, if not as frequent as regression unit testing. When a program is changed, the specifications inferred from the same unit test suite might change as well, giving rights to possible test violations. Tool-assisted unit test augmentation can be a means to evolving unit tests and assuring better unit quality. Moreover, augmenting unit test suite in a controlled way can lead to better quality of inferred specifications. In future work, we plan to apply the specification violation techniques in connecting system testing and unit testing. Specifications are to be inferred from system testing and specification violations by the generated unit tests are used to guide unit test data selection. Also, the partial specifications inferred from testing done by component providers are to be delivered as component metadata [9], which will aid component users to perform test augmentations. Finally, we plan to apply the specification violation techniques in other kinds of inferred specifications, e.g. sequencing constraints or protocols.

8. Acknowledgement

We thank Michael Ernst and the Daikon project members at MIT for their assistance in our installation and use of the Daikon tool. This work was supported in part by the National Science Foundation under grant ITR 0086003. The authors wish to acknowledge support through the High Dependability Computing Program from NASA Ames cooperative agreement NCC-2-1298.

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