The Emerging Field of Test Amplification: A Survey

Benjamin Danglot  Oscar Vera-Perez  Zhongxing Yu
Martin Monperrus  Benoit Baudry
Inria and University of Lille

Abstract

Context: The increasing adoption of test-driven development results in software projects with strong test suites. These suites include a large number of test cases, in which developers embed knowledge about meaningful input data and expected properties in the form of oracles.

Objective: This article surveys various works that aim at exploiting this knowledge in order to enhance these manually written tests with respect to an engineering goal (e.g., improve coverage of changes or increase the accuracy of fault localization). While these works rely on various techniques and address various goals, we believe they form an emerging and coherent field of research, and which we call “test amplification”.

Method: We devised a first set of papers based on our knowledge of the literature (we have been working in software testing for years). Then, we systematically followed the citation graph.

Results: This survey is the first that draws a comprehensive picture of the different engineering goals proposed in the literature for test amplification. In particular, we note that the goal of test amplification goes far beyond maximizing coverage only.

Conclusion: We believe that this survey will help researchers and practitioners entering this new field to understand more quickly and more deeply the intuitions, concepts and techniques used for test amplification.

1 Introduction

Software testing is the art of analyzing and exercising software in order to assess its dependability. Automatic test generation is a traditional area in software testing: the goal is to generate tests according to a specific test criterion. Traditionally, test generation assumes that no test exists at all, or that they are either too few or of too low quality for being considered useful in the generation process.

However, with the progress of agile development methodologies, which advocate test-driven development, it is now the state-of-the-art to have programs accompanied with a strong test suite. This test suite is large, and has been written on top of a lot of human intelligence and domain knowledge. Developers spend a lot of time in writing the tests, so that those tests exercise interesting cases (including corner cases), and so that a good oracle verifies as much as possible the program behavior.

The wide presence of strong manually written tests has triggered a new thread of research that consists of leveraging the value of existing tests to achieve a specific engineering goal. This is what we call in this paper “test amplification”. This paper presents a survey of this emerging and novel field in software testing, the goal of this survey being to strengthen the foundations of test amplifications and foster further work in this promising research direction.

We note that the literature uses not only the term “amplification” but also other expressions such as “augmentation”. There is no consensus on the differences between all terms. To our opinion, it is natural for a new field, it is normal that the community tinkers a bit before converging to a specific expression. We use the term “amplification”, because it well conveys the idea that a machine or an algorithm improves an existing thing coming from humans, as a sound amplifier amplifies the voice of pop singer Shakira.

1.1 Novelty

There are a number of notable surveys in software testing. However none of them is dedicated to test amplification. For instance, we refer to Edvardsson’s et al’s and McMinn et al’s articles for a survey on test generation. Yoo and Harman have structured the work on test minimization, selection and prioritization. In the prolific literature on symbolic execution for testing, we refer the reader to the survey of Pasareanu and Visser. In general, test optimization, test selection, test prioritization,
test minimization, test reduction is out of the scope of this paper.

Similarly, the work on test refactoring is related, however, as meant by Van Deursen et al. [39], it is different in nature from test amplification as considered in this paper, because classical test refactoring is not fully automated. On the contrary, test amplification is meant to be fully automated, as other technical amplification such as as sound amplification.

Harrold et al. [18] discusses the problem of “retesting software”, where there is a section related to amplification. However, it is only a light account on the topic which is now outdated. To our knowledge, this survey is the first survey ever dedicated to test amplification.

1.2 Methodology

Before starting the survey, we scope test amplification as follows. This scope naturally defines an inclusion criterion, and we will discuss all notable papers that fit into this scope.

In this paper, test amplification means improving the efficiency of a test suite with respect to an engineering goal.

The most commonly considered engineering goals are:

- maximize a test criterion (mostly coverage);
- improve observability;
- assess properties of the test suite under study;
- assess properties of the application under study;
- improve the applicability of the test suite wrt a usage;

To survey the literature, we followed the systematic methodology as follows. We devised a first set of papers based on our knowledge of the literature (we have been working in software testing for years). Then, we systematically followed the citation graph: backwards for finding the first papers mentioning this idea (such as [17]) and forwards in order to find the most recent contributions in this area. Our goal is to be inclusive, we do not only include papers from specific conferences and journals, we include papers based on the novelty and significance of the idea it contains.

Finally we classified and ordered the considered papers in categories. This categorization is not exclusive, and other categorization may be found as well. However, it well conveys the main threads of research in test amplification. Section 2 presents techniques that synthesize new tests from existing ones. Section 3 focuses on the works that synthesize new tests dedicated to a specific change in the application code (in particular a specific commit). Section 4 discusses the less researched yet powerful idea of modifying the execution of tests for amplifying. Section 5 is about the modification of existing tests. Section 6 recapitulates the main techniques and goals that we have found in the literature. Section 7 concludes this paper.

2 Amplification by Adding New Tests as Variants of Existing Ones

Here we address the most intuitive form of test amplification: considering an existing test suite, automatically generate variants of the existing test cases, and add these variants into the test suite. This is one kind of test amplification, that we call \( \text{AMP}_{\text{add}} \).

**Definition:** Test amplification technique \( \text{AMP}_{\text{add}} \) consists of creating new tests from existing ones so as to improve an engineering goal. The most commonly used engineering goal is to improve coverage according to a coverage criterion.

Here we survey the works that investigate \( \text{AMP}_{\text{add}} \) for different engineering goals.

2.1 Coverage or Mutation Score Improvement

Baudry *et al.* [3, 4] improve the mutation score of an existing test suite by generating variants of existing test cases through the application of specific transformations (e.g., modify literal values in method calls). They iteratively run these transformations, and propose an adaptation of genetic algorithms (GA), called a bacteriological algorithm (BA), to guide the search for test cases that kill more mutants. The results demonstrate the ability of search-based amplification to significantly increase the mutation score of a test suite.

Tillmann and Schulte [38] describe a technique that can generalize existing unit tests into parametrized unit tests. The basic idea behind this technique is to refactor the unit test by replacing the concrete values that appear in the body of the test with parameters, which is achieved through symbolic execution. The problem of generalizing unit tests into parametrized
unit tests is also studied by Thummala et al. [21]. Their empirical study shows that unit test generalization can be achieved with feasible effort, and can bring the benefits of additional code coverage.

Using two open source programs as the study subjects, Smith and Williams [39] empirically evaluate the usefulness of mutation analysis in improving an existing test suite. They execute the existing test cases against a set of generated mutants. Then, for each of mutant that is not killed, a new test case is written with a single intention: kill this mutant and only this one. Their results reveal that a majority of mutation operators is useful for producing new tests, and the focused effort on increasing mutation score leads to increase in line and branch coverage. The same authors later conduct another study [37] that confirms this finding. It also emphasizes the importance of choosing the appropriate mutation tool and operators to guide the production of new test cases.

To improve the cost efficiency of the test generation process, Yoo and Harman [52] propose a technique for augmenting the input space coverage of the existing tests with new tests. The technique is based on four transformations on numerical values in test cases, i.e., shifting \((\lambda x.x + 1 \text{ and } \lambda x.x - 1 )\) and data scaling (multiply or divide the value by 2). In addition, they employ a hill-climbing algorithm based on the number of fitness function evaluations, where a fitness is the computation of the euclidean distance between two input points in a numerical space. The empirical evaluation shows that the technique can achieve better coverage than some test generation methods which generate tests from scratch.

To maximize code coverage, Bloem et al. [6] propose an approach that alters existing tests to get new tests that enter new terrain. The approach first analyzes the coverage of existing tests, and then selects all test cases that pass a yet uncovered branch in the target function. Finally, the approach investigates the path conditions of the selected test cases one by one to get a new test that covers a previously uncovered branch. To vary path conditions of existing tests, the approach uses symbolic execution and model checking techniques. A case study has shown that the approach can achieve 100% branch coverage fully automatically.

2.2 Fault Detection Capability Improvement

Starting with a source of test cases, Harder et al. [17] propose an approach that dynamically generates new test cases with good fault detection ability. A generated test case is kept only if it adds new information to the specification. They define “new information” as adding new data for mining invariants with Daikon, hence producing new or modified invariants. What is unique in the paper is the augmentation criterion: helping an invariant inference technique.

Pezze et al. [31] observe that method calls are used as the atoms to construct test cases for both unit and integration testing, and that most of the code in integration test cases appears in the same or similar form in unit test cases. Based on this observation, they propose an approach which uses the information provided in unit test cases about object creation and initialization to build composite cases that focus on testing the interactions between objects. The evaluation results show that the approach can reveal new interaction faults even in well tested applications.

Writing web tests manually is time consuming, but has the advantage of gaining domain knowledge of the developers. Instead, most web test generation techniques are automated and systematic, but lack the domain knowledge required to be as effective. In light of this, Milani et al. [23] propose an approach which combines the advantages of the two. The approach first extracts knowledge such as event sequences and assertions from the human-written tests, and then combines the knowledge with the power of automated crawling. It has been shown that the approach can effectively improve the fault detection rate of the original test suite.

2.3 Oracle Improvement

Pacheco and Ernst implement a tool called Eclat [27], which aims to help the tester with the difficult task of creating effective new test inputs with constructed oracles. Eclat first uses the execution of some available correct runs to infer an operational model of the software’s operation. By making use of the established operational model, Eclat then employs a classification-guided technique to generate new test inputs. Next, Eclat reduces the number of generated inputs by selecting only those ones that are most likely to reveal faults. Finally, Eclat adds an oracle for each remaining test input from the operational model automatically. It has been shown that Eclat can generate inputs that reveal real errors in Java classes.

Given that some test generation techniques just generate sequences of method calls but do not contain oracles for these method calls, Fraser and Zeller [16] propose an approach to generate parametrized unit tests containing symbolic pre- and post-conditions.
Taking concrete inputs and results as inputs, the technique uses test generation and mutation to systematically generalize pre- and post-conditions. Evaluation results on five open source libraries show that the approach can successfully generalize a concrete test to a parameterized unit test, which is more general and expressive, needs fewer computation steps, and achieves a higher code coverage than the original concrete test.

2.4 Debugging Effectiveness Improvement

Baudry et al. [5] propose the test-for-diagnosis criterion (TFD) to evaluate the fault localization power of a test suite, and identify an attribute called Dynamic Basic Block (DBB) to characterize this criterion. A Dynamic Basic Block (DBB) contains the set of statements that are executed by the same test cases, which implies all statements in the same DBB are indistinguishable. Using an existing test suite as a starting point, they apply a search-based algorithm to optimize the test suite with new tests so that test-for-diagnosis criterion can be satisfied.

Rößer et al. [33] propose BugEx, which leverages test case generation to systematically isolate failure causes. The approach takes a single failing test as input and starts generating additional passing or failing tests that are similar to the failing test. Then, the approach runs these tests and captures the differences between these runs in terms of the observed facts that are likely related with the pass/fail outcome. Finally, these differences are statistically ranked and a ranked list of facts is produced. In addition, more test cases are further generated to confirm or refute the relevance of a fact. It has been shown that for six out of seven real-life bugs, the approach can accurately pinpoint important failure explaining facts.

Yu et al. [54] aim at enhancing fault localization under the scenario where no appropriate test suite is available to localize the encountered fault. They propose a mutation-oriented test data augmentation technique that is capable of generating test suites with excellent fault localization capabilities. The technique uses some mutation operators to iteratively mutate some existing failing tests to derive new test cases potentially useful to localize the specific encountered fault. Similarly, to increase the chance of executing the specific path during crash reproduction, Xuan et al. [50] propose an approach based on test case mutation. The approach first selects relevant test cases based on the stack trace in the crash, followed by eliminating assertions in the selected test cases, and finally uses a set of predefined mutation operators to produce new test cases that can help to reproduce crash.

Instead of operating at the granularity of complete test cases, Yoshida et al. [53] propose a novel technique for automated and fine-grained incremental generation of unit tests through minimal augmentation of an existing test suite. Their tool, FSX, treats each part of existing cases, including the test driver, test input data, and oracles, as “test intelligence”, and attempts to create tests for uncovered test targets by copying and minimally modifying existing tests wherever possible. To achieve this, the technique uses iterative, incremental refinement of test-drivers and symbolic execution.

Recapitulation

Main achievements: Compared with generating tests from scratch, using existing test cases as a start point to generate new test cases can make the test generation process more targeted and cost-effective. On the one hand, test generation process can be geared towards achieving a specific engineering goal better based on how existing tests perform with respect to the goal. For instance, new tests can be intentionally generated to cover those program elements that are not covered by existing tests. Indeed, it has been shown that tests generated in this way are effective in achieving multiple engineering goals, such as improving code coverage, fault detection ability, and debugging effectiveness. On the other hand, new test cases can be generated more cost-effectively by making use of the structure or components of the existing test cases. For instance, there exist several pieces of work that apply mutations to the existing tests and the generated tests have been shown to be especially effective for debugging.

Main Challenges: While existing tests provide a good starting point, there still exist some difficulties in how to better make use of the information contained in the existing tests. First, the number of new tests synthesized from existing ones can be large sometimes and hence an effective strategy should be used to select tests useful for the specific engineering goal. Second, the synthesized test can be invalid occasionally. For example, while it is relatively easy to synthesize new test inputs from the existing tests, it can be hard to add oracles for the synthesized new inputs sometimes. Finally, for some specific engineering goals, it is difficult to accurately measure how each test perform with respect to those goals.
3 Amplification by Synthesizing New Tests with Respect to Changes

Software applications are not tested at once. They are rather tested incrementally, along with the natural evolution of the code base: new tests are added together with a change or a commit, for instance to verify that a bug has been fixed or that a new feature is correctly implemented. In the context of test amplification, it directly translates to the idea of synthesizing new tests according to a change. This can be seen as a specialized form AMP\textsubscript{add}, which considers a specific change, in addition to the existing test suite, to guide the amplification. We call this form of test amplification AMP\textsubscript{change}.

**Definition:** Test amplification technique AMP\textsubscript{change} consists of adding new tests in the current test suite, by creating new tests that cover and/or observe the effects of a change in the application code.

We first present a series of works by Xu et al., who develop and compare two alternatives of test suite augmentation, one based on genetic algorithms and the other on concolic execution. A second subsection presents the work of a group of authors that center the attention in finding testing conditions to exercise the portions of code that exhibit changes. A third subsection relates other promising works in the same area.

**Search-based vs. Concolic Approaches**

In their work, Xu et al. [46] focus on the scenario where a program has evolved into a new version through code changes in development. They consider test augmentation techniques as (i) the identification of coverage requirements for this new version, given an existing test suite; and (ii) the creation of new test cases that exercise these requirements. Their approach first identifies the parts of the evolved program that are not covered by the test suite. In the same process they gather path conditions for every test case. Then, they exploit these path conditions with a concolic testing method to find new test cases for uncovered branches, analyzing one branch at a time. Targeting paths related to uncovered branches prevents a full concolic execution, which improves the performance of the augmentation process. They applied their technique to 22 versions of a small arithmetic program from the SIR [1] repository and achieved branch coverage rates between 95% and 100%. They also show that a full concolic testing is not able to obtain such high coverage rates and needs a significantly higher number of constraint solver calls.

In subsequent work, Xu et al. [42] address the same problem with a genetic algorithm. Each time the algorithm runs, it targets a branch of the new program that is not yet covered. The fitness function measures how far a test case falls from the target branch during its execution. The authors investigate if all test cases should be used as population, or only a subset related to the target branch or, if newly generated cases should be combined with existing ones in the population. Several variants are compared according to their efficacy and efficiency. The authors conclude that considering all tests achieve the best coverage but also requires more computational effort. They imply that the combination of new and existing test cases is an important factor to consider in practical applications.

Xu et al. then dedicate a paper to the comparison of concolic execution and genetic algorithms for test suite amplification [45]. They conclude that both techniques benefit from reusing existing test cases at a cost in efficiency. The authors also state that the concolic approach can generate test cases effectively in the absence of complex symbolic expressions. Nevertheless, the genetic algorithm is more effective in the general case but could be more costly in test case generation. Also, the genetic approach is more flexible in terms of scenarios where it can be used but the quality of the obtained results is heavily influenced by the definition of the fitness function, mutation test and crossover strategy.

The same authors propose a hybrid approach [44]. This new approach incrementally runs both the concolic and genetic methods. Each round applies first the concolic testing and the output is passed to the genetic algorithm as initial population. Their original intention was to get a more cost-effective approach. The authors conclude that this new proposal outperforms the other two in terms of branch coverage but in the end is not more efficient. They also theories about possible strategies for combining both individual approach to overcome their respective weaknesses and exploit their best features. A revised and extended version of the experiments performed to validate the proposals made by this group is given in [43].

**Finding Test Conditions in the Presence of Changes**

Another group of authors have worked under the premise that achieving only coverage may not be sufficient to adequately exercise changes in code.
Sometimes these changes manifest only in when particular conditions are met by the input. The following papers address the problem of finding concrete input conditions that not just can execute the changed code, but propagate the effects of this change to an observable point that could be the output of involved test cases. It is important to notice that they do not achieve test generation. Their goal is to provide guidance to generate new test cases independently of the selected generation method.

Apivattanapong et al. [2] target the problem of finding test conditions that could propagate the effects of a change in a program to a certain execution point. Their method takes as input two versions of the same program. First, an alignment of the statements in both versions is performed. Then, starting from the originally changed statement and its counterpart in the new version, all statements whose execution is affected by the change are gathered up to a certain distance. The distance is computed over the control and data dependency graph. A partial symbolic execution is performed over the affected instructions to retrieve the states of both program versions, which are in turn used to compute testing requirements that can propagate the effects of the original change to the given distance. As said before, the method does not deal with test case creation, it only finds new testing conditions that could be used in a separated generation process and is not able to handle changes to several statements unless the changed statements are unrelated.

Santelices et al. [34] continue and extend the previous work by addressing changes to multiple statements and considering the effects they could have on each other. In order to achieve this they do not compute state requirements for changes affected by others. Empirical evidence is provided regarding the capacity of this method over traditional coverage criteria to assess test conditions for program changes.

In a third paper [35] the authors address the problems in terms of efficiency of applying symbolic execution. They state that limiting the analysis of affected statements up to a certain distance from changes reduces the computational cost but scalability issues still exist. They also explain that their previous approach often produce test conditions which are unfeasible or difficult to satisfy within a reasonable resource budget. To overcome this, they perform a dynamic inspection of the program during test case execution over statically computed slices around changes. This approach also considers multiple program changes. Removing the need of symbolic execution leads to a less expensive method. They claim that propagation-based testing strategies are superior to coverage-based in the presence of evolving software.

Other Approaches

Other authors have also explored test suite augmentation for evolving programs with propagation-based approaches. Qui et al. [32] propose a method to add new test cases to an existing test suite ensuring that effects of changes in the new program version are observed in the test output. The technique consists in a two step symbolic execution. First, they explore the paths towards the program change guided by a notion of distance over the control dependency graph. This exploration produces an input able to reach the change. In a second moment they analyze the conditions under which this input may affect the output and make changes to the input accordingly.

Wang et al. [40] exploit existing test cases to generate new ones, which execute the change in the program. These new test cases should produce a new program state, in terms of variable values, that can be propagated to the test output. An existing test case is analyzed to check if it can reach the change in an evolved program. The test is also checked to see if it produces a different program state at some point and if the test output is affected by the change. If some of this conditions does not hold then the path condition of the test is used to generate a new path condition to achieve the three goals. Further path exploration is guided and narrowed using a notion of the probability for the path condition to reach the change. This probability is computed using the distance between statements over the control dependency graph. Practical results of test cases generation in 3 Java programs are exhibited. The method is compared to eXpress and JPF-SE two state of the art tools and is shown to reduce the number of symbolic executions by 45.6% and 60.1% respectively. As drawback, the technique is not able to deal with changes on more than one statement.

In a different direction, Bohme et al. [7] explain that changes in a program should not be treated in isolation. Their proposal focuses on potential interaction errors between software changes. They propose to build a graph containing the relationship between changed statements in two different versions of a program and potential interaction locations according to data and control dependency. This graph is used to guide a symbolic execution method and find path conditions for exercising changes and their potential interactions and use a Satisfiability Modulo Solver to generate a concrete test input. They provide
practical results on the GNU Coreutils toolset. They were able to find 5 unknown errors in addition to previously reported issues.

Marinescu and Cadar [20] target the coverage of the code included in a patch that is not covered by the tests from the existing test suite. Instead of dealing with one change to one statement, as most of the previous works, this approach first determines the differences of a program and its previous version, after a commit, in the form of a code patch. Lines included in the patch are filtered by removing those that contain non-executable code (i.e., comments, declarations). If several lines belong to the same basic program block, only one is kept, as they all will be executed together. From the filtered set of lines, those not covered by the existing test suite are considered as targets. The approach then selects the closest input to each target from existing tests using the static minimum distance over the control flow graph. Edges on this graph that renders the target unreachable are removed by inspecting the data flow and gathering preconditions to the execution of basic blocks. To generate new test inputs, they combine symbolic execution with heuristics that select branches by their distance to the target, regenerate a path by going back to the point where the condition became unfeasible or changing the definition of variables involved in the condition. The proposal is evaluated using the GNU findutils, diffutils and binutils which are distributed with most Unix-based distributions. They examine patches from a period of 3 years. In average, they automatically increase coverage from 35% to 52% with respect to the manually written test suite.

A posterior work of the same group [28] targets also patches of code, focusing on finding test inputs that execute different behavior in two program versions. They consider two versions of the same program, or the old version with the patch of changed code, and a test suite. The code should be annotated in places where changes occur in order to unify both versions of the program for the next steps. Then they select from the test suite those test cases that cover the changed code. If there is no such test case it can be generated using KATCH. The unified program is used in a two stage dynamic symbolic execution guided by the selected test cases: look for branch points where two semantically different conditions are evaluated in both program versions; bounded symbolic execution for each point previously detected. At those points all possible alternatives in which program versions execute the same or different branch blocks are considered and used to make the constraint solver generate new test inputs for divergent scenarios. The program versions are then normally executed with the generated inputs and the result is validated to check the presence of a bug or an intended difference. In their experiments this validation is mostly automatic but in general should be performed by developers. The evaluation of the proposed method is based on the CoREBench [8] data set that contains documented bugs and patches of the GNU Coreutils program suite. The authors discuss successful and unsuccessful results but in general the tool is able to produce test inputs that reveal changes in program behaviour.

Recapitulation

Main achievements:

AMP change techniques rely on symbolic and concolic. Both have been successfully combined with other techniques in order to generate test cases that reach changed or evolved parts of a program. Those hybrid approaches produce new test inputs that increase the coverage of the new program version. Data and control dependency has been used in several approaches to guide symbolic execution and reduce its computational cost. The notion of distance from statements to observed changes has been also used for this matter.

Main challenges: Despite the progress made in the area, a number of challenges remain open. The main challenge relates to the size of the changes considered for test amplification: most of the works in this area consider a single change in a single statement. While this is relevant and important to establish the foundations for AMP change, this cannot fit current development practices where a change, usually a commit, modifies the code at multiple places at once. A few papers have started investigating multi-statement changes for test suite amplification. Yet, the evolution of AMP change techniques and algorithms in order to consider a commit as the unit of change, remains the main challenge here.

Another challenge relates to scalability. The use of symbolic and concolic execution has proven to be effective in test input generation targeting program changes, but these two techniques are expensive in terms of computation resources. New and more efficient ways for exploring input requirements that could exercise program changes or new uncovered parts are needed. One of the previously cited papers removes the use symbolic execution by observing the program behavior during test execution but they don't generate test cases.
4 Amplification by Modify Test Execution

In order to explore new program states and behavior, it is possible to interfere with the execution at runtime so as to modify the execution of the program under test. This is one original kind of test amplification.

Definition: Test amplification technique AMP\textsubscript{exec} consists of modifying the test execution process or the test harness in order to maximize the knowledge gained from the testing process.

Zhang and Elbaum \[56\] describe a technique to validate exception handling in programs making use of APIs to access external resources such as databases, GPS or bluetooth. The method mocks the accessed resources and amplify the test suite by triggering unexpected exceptions in sequences of API calls. Issues are detected when there is an abnormal termination of the program or abnormal execution time while running the tests. The approach is shown to be cost-effective and able to detect real-life problems in 5 Android applications.

Cornu et al. \[10\] work in the same line of evaluating exception handling. They propose a method to complement a test suite in order to check the behaviour of a program in the presence of unanticipated scenarios. The original code of the program is modified with the insertion of throw instructions inside try blocks. The test suite is considered as a formal specification and therefore used as an oracle in order to compare the program execution before and after the modification. Under certain conditions, issues can be automatically repaired by catch-stretching. The approach is evaluated in 9 Java real-life open source projects.

Fang et al. \[14\] develop a performance testing system named Perfblower, able to detect and diagnose memory issues by observing the execution of a set of test cases. The system includes a domain-specific language designed to describe memory usage symptoms. Based on the provided descriptions, the tool evaluates the presence of problems and amplifies them. The approach is evaluated in 13 Java real-life projects. The tool is able to find real memory issues and reduce the number of false positives reported by other similar tools.

Zhang et al. \[55\] devise a methodology to improve the capacity of the test suite to detect regression faults. Their approach is able to exercise uncovered branches without generating new test cases. They first look for identical code fragments between a program and its previous version. Then, new variants of both versions are generated by negating branch conditions that force the test suite to execute originally uncovered parts. The behaviours of version variants are compared through test outputs. An observed difference in the output could reveal an undetected fault. An implementation of the approach is compared with EvoSuite \[15\] in 10 real-life Java projects. In the experiments known faults are seeded by mutating the original program code. The results show that EvoSuite obtains better branch coverage while the proposed method is able to detect more faults. The implementation is available in the form of a tool named Isom.

Recapitulation

Main achievements: Proposals in this line of work provide cost-effective approaches to observe and modify a program execution to detect possible faults. This is done by instrumenting the original program code to place observations at certain points or mocking resources to monitor API calls to explore unexpected scenarios. It adds no prohibitive overhead to regular test execution and provide means to gather useful runtime information. Techniques in this section were used to analyze real-life projects of different sizes and they are shown to match other tools that pursue the same goal and obtain better results in some cases.

Main challenges: As shown by the relatively small number papers of this section, modifying test execution is an original area of research. The main challenge is to get this concept known so as to enlarge the research community working on this topic.

5 Amplification by Modifying Existing Test Code

In testing, it is up to the developer to macro- and micro-design the tests (size, etc). The main testing infrastructure such Junit in Java does not impose anything on the tests, such as the number of statements in a test, the cohesion of test assertions or the meaningfulness of test methods grouped in a test class. In the literature, there is interesting work on modifying existing tests with respect to a certain engineering goal.

Definition: Test amplifying technique AMP\textsubscript{mod} refers to modifying the body of existing test methods. Differently from AMP\textsubscript{add}, it is not about adding new test methods or new tests classes.
5.1 Input Space Exploration

Dallmeier et al. [11] automatically amplify test suites by adding and removing method calls in JUnit test cases. Their objective is to produce test cases that cover a wider set of executions than the original test suite in order to improve the quality of models reverse engineered from the code. They evaluate TAUTOKO on 7 java classes and show it able to produce richer typestates (a typestate is a finite state automaton which encodes legal usages of a class under test).

5.2 Oracle Improvement

Xie [11] amplifies object-oriented unit tests. The technique consists of adding assertions on the state of the receiver object, the returned value by the tested method (if it is a non-void return value method) and the state of parameters (if they are not primitive values). Those values depends of the behaviors of the given method, which depends on the state of the receiver and of arguments at the begin of the invocation. The approach, named Orstra, consists of the instrumentation of the bytecode, running the test suite to collect state of objects. Then, he uses instrumentation of the byte code to retrieve the state of the program with method calls sequence. Then it generates assertion, using observers (pure method with a non-void return type, e.g. toString()) and the collect values as oracle. He evaluated Orstra on 11 Java classes and their tests, and shows that it is able to increase the fault-detection capability of the test suite.

Carzaniga et al. [9] reason about generic oracles and propose a generic procedure to assert the behavior of a system under test. To do so, they exploit the redundancy of software. Redundancy of software happens when the system can perform the same action through different executions, either with different code or with the same code but with different input parameters or in different contexts. They devise the notion of “cross-checking oracles”, which compare the outcome of the execution of an original method call and an equivalent code. Such oracle use a generic equivalence check on the results and the state of the target object. If there is an inconsistency, the oracle reports it, otherwise, the checking continue. This oracles are added to an existing test suite with the aspect-oriented programming. They evaluate the approach on specific classes of 3 projects. They show that the approach can slightly increase (+6% overall) the mutation of score of a manual test suite.

Joshi et al. [19] try to amplify the effectiveness of testing by executing both concretely and symbolically the tests. Along this double execution, for every conditional statement executed by the concrete execution, the symbolic execution generates symbolic constraints over the input variables. At the execution of an assertion, the symbolic execute invokes a theorem prover to check the assertion is verified, according to the constraints encountered. If the assertion is not guaranteed, a violation of the behavior is reported. They evaluate their approach on 5 C programs. They are able to detect buffer overflow but it needs optimization because of the huge overhead that the instrumentation add.

Mouelhi et al. [20] enhance tests oracle for access control logic, also called Policy Decision Point (PDP). This is done in 3 steps: select test cases that execute PDPs, map each of test cases to specific PDPs and oracle enhancement. They add to the existing oracle checks that the access is granted or denied with respect to the rule and checks that that the PDP is correctly called. To do so, they force the Policy Enforcement Point, i.e. the point where the policy decision is setting in the system functionality, to raise an exception when the access is denied and they compare the produced logs with expected log. They evaluate the approach on 3 java projects. Compared to manual testing, automated oracle generation saves a lot of time (from 32 hours to 5 minutes).

5.3 Purification

Xuan et al. [17] propose a technique to split existing tests into smaller parts in order to “purify” test cases. For instance, an impure test case executes both branch then and else of the same if/then/else statement in code. The result of B-refactoring on this example is to have two different test cases that execute one branch only in isolation. They evaluate B-refactoring on 5 open-source projects, and show that it increases the purity of test cases: individual elements are purer after applying B-refactoring: 66% for if statement and 11% for try statement. They also improve the effectiveness of program repair (Nopol [18]) by applying B-refactoring.

Xuan et al. [19] aim at improving the fault localization capabilities by purifying test cases. By purifying, they mean to modify existing failing test cases into single assertion test case and remove all statements that are not related to the assertion. Then, they refine the rank of the pure test cases with an existing test cases. They evaluated the test purification on 6 open-source java project, over 1800 seeded bugs and compare their results with 6 mature techniques. They show that they improve the fault localization effectiveness on 18 to 43% of faults.
5.4 Test Case Repair

Daniel et al. [12] devise ReAssert to repair automatically test cases, i.e. to modify test cases that fail due to a change. ReAssert follows 5 steps: records the values of failing assertions, re-executes the test and catch the failure exception, i.e. the exception thrown by the failing assertion. From the exception, it extracts the stack trace to find the code to repair and choose the repair strategy depending the structure the code and the recorded value. Finally, ReAssert re-compiles the code changes and repeats all steps until no more assertion fail. They evaluated with controlled user study. ReAssert could repair 98% (131 of 135) of failures caused by the participants’ code changes.

Mirzaaghaei et al. [24] devise TCA, an automatic analysis tool for unit test cases. According to a modification in the source code, TCA supports 4 types of repairs (changes in test code) as follows. First, "signature changes" of test methods, i.e. change of parameters of a method and/or the returned type value. Second, with "Test class hierarchy", when a developers create and extend new classes in the source code, TCA is able to generate test cases for the new class, based on test of the extended class. TCA generates test cases for overloading and overriding of methods, reusing existing test cases. Their implementation support only the Signature changes and Test class hierarchy. They evaluate the former technique on 9 projects of the Apache foundation. On average, for each project, TCA can repair the compilation errors for 45% of the changes that lead to compilation errors. For the latter, TCA can generate test cases for 60% of classes of each of the 5 selected project.

6 Analysis

We now provide a recapitulation of all the dimensions considered in the survey.

6.1 Recapitulation on Engineering Goals

As we have defined in the introduction, test suite amplification always pursues a specific engineering goal. Table 1 shows the main goals we have identified and gathers the notable references for each category. Many papers describe techniques that try to maximize or increment the coverage that an original test suite gives. Those are shown in row "improve coverage". Another group of works aims to improve the observability of the test suite in the sense of providing additional information apart from the fact that a particular test case has failed or succeeded. This second group is listed in "improve observability". A few works directly target specific properties of the system under test such as robustness in exception handling or memory performance. Another set of papers do the same for the test suite. Those two groups are respectively shown as "asses properties of the application under study" and "asses properties of the test suite under study" respectively. A last group contains papers proposing ways to enhance the applicability of a test suite with respect to some usage: some of the techniques considered would aim to reproduce a runtime crash ("crash reproduction"), detect the presence of faults ("fault detection capability"), locate faults in the program under test ("fault localization") and even try to propose a fix that could be applied to some tests ("repair").

6.2 Recapitulation on Technical Approaches

There are several different techniques to achieve test amplification. We conduct an analysis of the underlying technique used in each reviewed paper and classify the used techniques into 6 main different categories. Table 2 shows this classification in detail, with the first column showing the category and the second column showing the notable references that fall into each category.

The first category of techniques is called test code analysis. Typically, this category of techniques uses the structure or components of the existing test code as a starting point. The second category of technique is called application code analysis, which contains most references in this review. Another category of
Table 1: Overview of the different goals of test suite amplification. Only most the notable references are given.

| Engineering goal                                      | Works |
|-------------------------------------------------------|-------|
| improve coverage                                      | 17[38][40][42][43][52][23][53][55] |
| improve observability                                 | 27[41][19][11][56][9][10][14][30] |
| assess properties of the test suite under study       | 36[37] |
| assess properties of the application under study      | 50[51][10] |
| crash reproduction                                     | 50    |
| fault detection capability                             | 4[55] |
| fault localization                                     | 5[49][54][47] |
| repair                                                 | 12[24][25] |

Since symbolic execution facilitates the identification of path conditions and program states, this category of techniques generally generally aim at improving coverage. Meanwhile, a variant of symbolic execution named concolic execution is also used by some works to further improve the efficiency of test amplification. Finally, there exists some works that make use of search based heuristics such as genetic programming to amplify existing tests. Basically, the aim of using search based heuristics is also making the test amplification process more cost-efficient.

6.3 Recapitulation on Scientific Reproducibility

Test case amplification requires heavy engineering of test code, test harnesses, and application code. In order to progress, the field requires that researchers can reproduce past results, and compare their new tools against existing ones. To this extent, we feel that open-science in the form of publicly-available and usable research prototypes is of utmost importance.

With this in mind, we have surveyed not only the articles but also the mentioned tools, if any. The protocol was as follows. First, we looked for a URL in the paper. If no URL were found, we contacted the authors directly. When a tool was available, with respect to usability, we checked that we were able to build and run the tool on a minimal and provided example. We granted for each tool 1 hour full time to retrieve, build and launch the example (the run can be longer, if it running, it is not consuming “active” time). If we could run it and observe a “similar” result as the one described in the paper, we considered the result as reproducible.

We regret to observe that most of the tools are not publicly available. Among the ones that are available, too many are hardly usable. Cross-checking oracles is one notable exception of a well-packaged and well-documented research prototype. To conclude, we call for more open-science and reproducible research in the field of test amplification.

7 Conclusion

We have presented a survey of works related to test amplification. This survey is the first that draws a comprehensive picture of the different engineering goals proposed in the literature for test amplification. In particular, we note that the goal of test amplification goes far beyond maximizing coverage only. It also gives an overview of the different techniques used, which span a wide spectrum, from symbolic execution to random search to execution modification.

We believe that this survey will help future PhD students and researchers entering this new field to understand more quickly and more deeply the intuitions, concepts and techniques used for test amplification. Finally, we note the absence of work that tries to compare “traditional” test generation (generating test cases from scratch), for which there is a myriad of papers, and test amplification (generating tests from existing tests). We think that sound and systematic experimental comparison of different test creation techniques would be a milestone for the nascent and emerging field of test amplification.

References

[1] Software-artifact infrastructure repository. http://sir.unl.edu Accessed: 2017-05-17.

[2] T. Apiwattanapong, R. Santelices, P. K. Chittimalli, A. Orso, and M. J. Harrold. Matrix: crosscheckingoracles/
Table 2: Overview of the different ways of performing test suite amplification.

| Category of techniques | Works |
|-------------------------|-------|
| test code analysis      | [12][24][31][54][50][52][41] |
| application code analysis| [35][47][36][37][17][16][14][27][30][1][5] |
| execution modification  | [56][10][55][49][11][12][24][25][29] |
| use of concolic execution| [46][44] |
| use of symbolic execution| [2][34][32][40][7][19][38][53] |
| use of search based heuristics | [42][44] |

Maintenance-oriented testing requirements identifier and examiner. In *Testing: Academic and Industrial Conference-Practice And Research Techniques, 2006. TAIC PART 2006. Proceedings*, pages 137–146. IEEE, 2006.

[3] B. Baudry, F. Fleurey, J.-M. Jézéquel, and Y. Le Traon. Automatic test cases optimization: a bacteriologic algorithm. *IEEE Software*, 22(2):76–82, Mar. 2005.

[4] B. Baudry, F. Fleurey, J.-M. Jézéquel, and L. Yves. From genetic to bacteriological algorithms for mutation-based testing. *Software, Testing, Verification & Reliability journal (STVR)*, 15(2):73–96, June 2005.

[5] B. Baudry, F. Fleurey, and Y. Le Traon. Improving test suites for efficient fault localization. In *Proceedings of the 28th International Conference on Software Engineering, ICSE ’06*, pages 82–91, 2006.

[6] R. Bloem, R. Koenighofer, F. Röck, and M. Tautschnig. Automating test-suite augmentation. In *2014 14th International Conference on Quality Software*, pages 67–72, Oct 2014.

[7] M. Böhme, B. C. d. S. Oliveira, and A. Roychoudhury. Regression tests to expose change interaction errors. In *Proceedings of the 2013 9th Joint Meeting on Foundations of Software Engineering*, pages 334–344. ACM, 2013.

[8] M. Böhme and A. Roychoudhury. Corebench: Studying complexity of regression errors. In *Proceedings of the 2014 International Symposium on Software Testing and Analysis*, pages 105–115. ACM, 2014.

[9] A. Carzaniga, A. Goffi, A. Gorla, A. Mattavelli, and M. Pezzè. Cross-checking Oracles from Intrinsic Software Redundancy. In *Proceedings of the 36th International Conference on Software Engineering*, ICSE 2014, pages 931–942, 2014.

[10] B. Cornu, L. Seinturier, and M. Monperrus. Exception handling analysis and transformation using fault injection: Study of resilience against unanticipated exceptions. *Information and Software Technology, 57:66–76, 2015.*

[11] V. Dallmeier, N. Knopp, C. Mallon, S. Hack, and A. Zeller. Generating test cases for specification mining. In *Proceedings of the 19th International Symposium on Software Testing and Analysis, ISSTA ’10*, pages 85–96, New York, NY, USA, 2010. ACM.

[12] B. Daniel, V. Jagannath, D. Dig, and D. Marinov. Reassert: Suggesting repairs for broken unit tests. In *2009 IEEE/ACM International Conference on Automated Software Engineering*, pages 433–444, 2009.

[13] J. Edvardsson. A survey on automatic test data generation. In *Proceedings of the 2nd Conference on Computer Science and Engineering*, pages 21–28, 1999.

[14] L. Fang, L. Dou, and G. Xu. Perfblower: Quickly detecting memory-related performance problems via amplification. In *LIPics-Leibniz International Proceedings in Informatics*, volume 37. Schloss Dagstuhl-Leibniz-Zentrum fuer Informatik, 2015.

[15] G. Fraser and A. Arcuri. Evosuite: automatic test suite generation for object-oriented software. In *Proceedings of the 19th ACM SIGSOFT Symposium and the 13th European Conference on Foundations of Software Engineering*, pages 416–419. ACM, 2011.

[16] G. Fraser and A. Zeller. Generating parameterized unit tests. In *Proceedings of the 2011 International Symposium on Software Testing and Analysis*, pages 364–374. ACM, 2011.
[17] M. Harder, J. Mellen, and M. D. Ernst. Improving test suites via operational abstraction. In Proc. of the Int. Conf. on Software Engineering (ICSE), pages 60–71, 2003.

[18] M. J. Harrold and A. Orso. Retesting software during development and maintenance. In Frontiers of Software Maintenance, 2008. FoSM 2008., pages 99–108, 2008.

[19] P. Joshi, K. Sen, and M. Shlimovich. Predictive Testing: Amplifying the Effectiveness of Software Testing. In Proc. of the ESEC/FSE: Companion Papers, ESEC-FSE companion ’07, pages 561–564, New York, NY, USA, 2007. ACM.

[20] P. D. Marinescu and C. Cadar. KATCH: high-coverage testing of software patches. page 235. ACM Press, 2013.

[21] M. R. Marri, S. Thummalapenta, T. Xie, N. Tillmann, and J. de Halleux. Retrofitting unit tests for parameterized unit testing. Technical report, North Carolina State University, 2010.

[22] P. McMinn. Search-based software test data generation: A survey. Software Testing Verification and Reliability, 14(2):105–156, 2004.

[23] A. Milani Fard, M. Mirzaaghaei, and A. Mesbah. Leveraging existing tests in automated test generation for web applications. In Proceedings of the 29th ACM/IEEE international conference on Automated software engineering, pages 67–78. ACM, 2014.

[24] M. Mirzaaghaei, F. Pastore, and M. Pezze. Supporting Test Suite Evolution through Test Case Adaptation. In 2012 IEEE Fifth International Conference on Software Testing, Verification and Validation, pages 231–240, 2012.

[25] M. Mirzaaghaei, F. Pastore, and M. Pezze. Automatic test case evolution. Software Testing, Verification and Reliability, 2014.

[26] T. Mouelhi, Y. L. Traon, and B. Baudry. Transforming and selecting functional test cases for security policy testing. In 2009 International Conference on Software Testing Verification and Validation, pages 171–180, April 2009.

[27] C. Pacheco and M. D. Ernst. Eclat: Automatic Generation and Classification of Test Inputs, pages 504–527. Springer Berlin Heidelberg, Berlin, Heidelberg, 2005.

[28] H. Palikareva, T. Kuchta, and C. Cadar. Shadow of a doubt: testing for divergences between software versions. In Proceedings of the 38th International Conference on Software Engineering, pages 1181–1192. ACM, 2016.

[29] C. S. Păsăreanu and W. Visser. A survey of new trends in symbolic execution for software testing and analysis. International Journal on Software Tools for Technology Transfer (STTT), 11(4):339–353, 2009.

[30] M. Patrick and Y. Jia. Kd-art: Should we intensify or diversify tests to kill mutants? Information and Software Technology, 81:36 – 51, 2017.

[31] M. Pezze, K. Rubinov, and J. Wuttke. Generating effective integration test cases from unit ones. In Software Testing, Verification and Validation (ICST), 2013 IEEE Sixth International Conference on, pages 11–20. IEEE, 2013.

[32] D. Qi, A. Roychoudhury, and Z. Liang. Test generation to expose changes in evolving programs. In Proceedings of the IEEE/ACM international conference on Automated software engineering, pages 397–406, 2010.

[33] J. Rößler, G. Fraser, A. Zeller, and A. Orso. Isolating failure causes through test case generation. In Proceedings of the 2012 International Symposium on Software Testing and Analysis, pages 309–319. ACM, 2012.

[34] R. Santelices, P. K. Chittimalli, T. Apiwattanapong, A. Orso, and M. J. Harrold. Test-suite augmentation for evolving software. In 23rd IEEE/ACM International Conference on, pages 218–227. IEEE, 2008.

[35] R. Santelices and M. J. Harrold. Applying aggressive propagation-based strategies for testing changes. In IEEE Fourth International Conference on Software Testing, Verification and Validation, pages 11–20. IEEE, 2011.

[36] B. H. Smith and L. Williams. On guiding the augmentation of an automated test suite via mutation analysis. Empirical Software Engineering, 14(3):341–369, 2009.

[37] B. H. Smith and L. Williams. Should software testers use mutation analysis to augment a test set? Journal of Systems and Software, 82(11):1819–1832, 2009.
[38] N. Tillmann and W. Schulte. Unit tests reloaded: Parameterized unit testing with symbolic execution. *IEEE Software*, 23(4):38–47, 2006.

[39] A. Van Deursen, L. Moonen, A. van den Bergh, and G. Kok. Refactoring test code. In *Proceedings of the 2nd international conference on extreme programming and flexible processes in software engineering (XP2001)*, pages 92–95, 2001.

[40] H. Wang, X. Guan, Q. Zheng, T. Liu, C. Shen, and Z. Yang. Directed test suite augmentation via exploiting program dependency. In *Proceedings of the 6th International Workshop on Constraints in Software Testing, Verification, and Analysis*, pages 1–6. ACM, 2014.

[41] T. Xie. Augmenting Automatically Generated Unit-test Suites with Regression Oracle Checking. In *Proceedings of the 20th European Conference on Object-Oriented Programming*, pages 380–403, 2006.

[42] Z. Xu, M. B. Cohen, and G. Rothermel. Factors affecting the use of genetic algorithms in test suite augmentation. In *Proceedings of the 12th annual conference on Genetic and evolutionary computation*, pages 1365–1372. ACM, 2010.

[43] Z. Xu, Y. Kim, M. Kim, M. B. Cohen, and G. Rothermel. Directed test suite augmentation: an empirical investigation. *Software Testing, Verification and Reliability*, 25(2):77–114, 2015.

[44] Z. Xu, Y. Kim, M. Kim, and G. Rothermel. A hybrid directed test suite augmentation technique. In *Software Reliability Engineering (ISSRE), 2011 IEEE 22nd International Symposium on*, pages 150–159. IEEE, 2011.

[45] Z. Xu, Y. Kim, M. Kim, G. Rothermel, and M. B. Cohen. Directed test suite augmentation: techniques and tradeoffs. In *Proceedings of the eighteenth ACM SIGSOFT international symposium on Foundations of software engineering*, pages 257–266. ACM, 2010.

[46] Z. Xu and G. Rothermel. Directed test suite augmentation. In *Software Engineering Conference, 2009. APSEC’09. Asia-Pacific*, pages 406–413. IEEE, 2009.

[47] J. Xuan, B. Cornu, M. Martinez, B. Baudry, L. Scinturier, and M. Monperrus. B-Refactoring: Automatic Test Code Refactoring to Improve Dynamic Analysis. *Information and Software Technology*, 76:65–80, 2016.

[48] J. Xuan, M. Martinez, F. DeMarco, M. Clément, S. L. Marcote, T. Durieux, D. L. Berre, and M. Monperrus. Nopol: Automatic repair of conditional statement bugs in java programs. *IEEE Transactions on Software Engineering*, 43(1):34–55, 2017.

[49] J. Xuan and M. Monperrus. Test case purification for improving fault localization. In *Proceedings of the 22nd ACM SIGSOFT International Symposium on Foundations of Software Engineering*, pages 52–63. ACM, 2014.

[50] J. Xuan, X. Xie, and M. Monperrus. Crash Reproduction via Test Case Mutation: Let Existing Test Cases Help. In *Proceedings of the 2015 10th Joint Meeting on Foundations of Software Engineering, ESEC/FSE 2015*, pages 910–913, New York, NY, USA, 2015. ACM.

[51] S. Yoo and M. Harman. Regression testing minimization, selection and prioritization: a survey. *Software Testing, Verification and Reliability*, 22(2):67–120, 2012.

[52] S. Yoo and M. Harman. Test data regeneration: generating new test data from existing test data. *Software Testing, Verification and Reliability*, 22(3):171–201, 2012.

[53] H. Yoshida, S. Tokumoto, M. R. Prasad, I. Ghosh, and T. Uehara. FSX: Fine-grained Incremental Unit Test Generation for C/C++ Programs. In *Proceedings of the 25th International Symposium on Software Testing and Analysis*, ISSTA 2016, 2016.

[54] Z. Yu, C. Bai, and K.-Y. Cai. Mutation-oriented Test Data Augmentation for GUI Software Fault Localization. *Inf. Softw. Technol.*, 55(12):2076–2098, Dec. 2013.

[55] J. Zhang, Y. Lou, L. Zhang, D. Hao, L. Zhang, and H. Mei. Isomorphic regression testing: Executing uncovered branches without test augmentation. In *Proceedings of the 2016 24th ACM SIGSOFT International Symposium on Foundations of Software Engineering, FSE 2016*, pages 883–894, New York, NY, USA, 2016. ACM.

[56] P. Zhang and S. Elbaum. Amplifying tests to validate exception handling code. In *Proceedings of the 34th International Conference on Software Engineering*, pages 595–605. IEEE Press, 2012.