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DynaMoth: Dynamic Code Synthesis for Automatic Program Repair

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ABSTRACT
Automatic software repair is the process of automatically fixing bugs. The Nopol repair system [4] repairs Java code using code synthesis. We have designed a new code synthesis engine for Nopol based on dynamic exploration, it is called DynaMoth. The main design goal is to be able to generate patches with method calls. We evaluate DynaMoth over 224 of the Defects4J dataset. The evaluation shows that Nopol with DynaMoth is capable of synthesizing patches and enables Nopol to repair new bugs of the dataset.

1. INTRODUCTION
Automatic software repair is the process of automatically fixing bugs. Test-suite based repair, notably introduced by GenProg [8], consists in synthesizing a patch that passes a given test suite with at least one failing test case. Test-suite based repair may use or not program synthesis to create parts of the patch. For instance, Semfix [9] uses oracle-guided component-based program synthesis [6] to synthesize patches. On the contrary, other techniques do not use synthesis, as in the case of GenProg which repairs by moving and copying existing code in the program to repair the bug, which is not synthesis per se.

The Nopol repair system [4] repairs Java code using code synthesis. It repairs bugs in conditionals: buggy if conditions and missing preconditions. Nopol uses a synthesis technique based on Satisfiability Modulo Theory (SMT), derived from oracle-guided component-based program synthesis [6]. This synthesis technique enables the system to generate a patch that contains arithmetic and first order logic operators, as well as simple unary method calls (with no parameters). This is an important limitation for automatic repair. Indeed, many real-world Java patches contain complex method calls. The motivation of the work presented here is to replace the SMT-based synthesis component of Nopol by a new synthesizer that is able to generate richer patches.

We have designed a new code synthesis engine for Nopol based on dynamic exploration. The main design goal is to be able to generate patches with method calls. The engine is called DynaMoth and works as follows. At runtime, the synthesis engine stops the execution of the program under repair and explores the space of all possible expressions at a given suspicious statement. Since a buggy statement can be executed by several different test cases, the synthesis engine collects those expressions over many runs, and then infers offline the valid boolean expressions.

We evaluate DynaMoth over 224 of the Defects4J dataset. The evaluation shows that Nopol with DynaMoth is capable of repairing 27 bugs. DynaMoth is able to repair bugs that have never been repaired so far. It is capable to synthesize patches with complex operators and involving method calls with parameters.

To sum up, this paper makes the following contributions:

- DynaMoth, a dynamic synthesis algorithm for automatic repair of conditional bugs
- A publicly available implementation in Java of DynaMoth
- An evaluation of DynaMoth of 224 real bugs of open-source Java programs.

This paper is organized as follows. Section 2 discusses the context of this work. Section 3 describes the main contribution of this work: a dynamic code synthesis engine for repair. Section 4 contains the evaluation of DynaMoth based on 224 real-world bugs from Defects4J. We present our conclusions in Section 6.

2. BACKGROUND
We first briefly describe test-suite-based automatic software repair and the two classes of bugs we address.

2.1 Test-suite-based Repair
Test suite based repair uses a test suite as the specification of the correct behavior of the program. The test suite has to contain at least one failing test case which characterizes the bug to be repaired. Test-suite-based repair aims at automatically generating a patch that fixes it. Nopol [4] is an automatic repair system that is able to repair two classes of bugs: buggy if conditions and missing preconditions.

2.2 Fault Classes

Buggy if Conditions.
The first kind of bugs that Nopol targets are buggy conditions in if-then-else statements. Figure 1 gives an example of such a repair.

Missing Preconditions.
The second class of bugs addressed by Nopol are preconditions. A precondition is a check consisting in the evaluation of a boolean predicate guarding the execution of a statement or a block.
2.3 Overview of Nopol

Figure 3 describes the general algorithm of Nopol. This algorithm is composed of four main steps. The first step is the localization of suspicious statements. It uses standard spectrum based fault localization using Ochiai [1]. The second step is angelic value mining, that consists in trying to identify an arbitrary value required somewhere during the execution to pass the failing test(s). As third step, input-output based code synthesis is used to generate a new Java expression which is the patch. Since Nopol repairs conditions, the synthesized expressions are boolean expressions. Finally, for patch validation, Nopol re-executes the whole test suite on the patched program.

2.4 Angelic Value Mining

The angelic value mining step determines the required value of the buggy boolean expression to make the failing test cases to pass. For buggy if-conditions, angelic value mining is done by forcing at runtime the branch of the suspicious if statement. The condition expression is arbitrarily substituted for either true or false: the state of the program is artificially modified during its execution as it would have been by an omniscient oracle or angel. If all failing tests pass with the modified execution, the used value is called the angelic value and is stored for use in synthesis later.

For missing preconditions, suspiscious statements are forcefully skipped at runtime. When this makes the previously failing tests pass, a precondition has to be synthesized that returns with angelic value false for the failing test cases. For example, in Figure 2 let us assume that the code is specified by two tests. The first test checks the normal case when specific != null. The second test case, which fails, executes the buggy statement with specific == null. In this case, the angelic value of the precondition will be false: the boolean expression to be synthesized as precondition should return true when specific != null and false otherwise.

Once an angelic value is known for all test cases, we obtain an input-output synthesis problem. The input is the context of the statement under repair (all variables in the scope), the output is the angelic value. By default, Nopol uses an SMT-based code synthesis engine implementing oracle-based component guided synthesis, this engine is called SMTSynth. This paper presents a new engine for this input-output synthesis problem.

3. DYNAMIC CODE SYNTHESIS FOR AUTOMATIC REPAIR

We now present DynaMoth, a new code synthesis engine for Nopol, that is based on dynamic exploration of tentative expressions.

3.1 Code Synthesis

Thanks to angelic value mining, we know that for a set of locations and point in time during execution, a particular boolean value is expected. This boolean value is the expected result of the boolean condition to be synthesized.

As shown in Algorithm 1, the code synthesis of DynaMoth is composed of three steps: first, the collection of the runtime contexts $c$ of the suspicious condition (see Section 3.1.1) for which it exists an angelic value. The runtime context includes parameters, variables, fields and return values of method calls; second, the generation of new boolean expressions (see Section 3.1.2); third, the comparison of each new $EEXP$ to the expected values (see Section 3.1.3).

We now introduce two definitions, for runtime context and $EEXP$.

Definition (Runtime context) The runtime context of a statement is made of the values of all local variables, static variables, parameters, fields and method calls available in the scope of the statement. A runtime context also contains a reference to a test and an integer value representing the n-th times that the statement has been executed by the test.

Definition (EEXP) A Evaluated-Expression, denoted $EEXP (c)$, is a pair $e, v$ where $e$ is a valid Java expression and $v$ the value of the Java expression in a specific runtime context $c$.

An example of $EEXP$ is "$e.size()", 4" which means that for a given context, the result of the evaluation of "$e.size()" is 4.

3.1.1 Runtime Context Collection

Algorithm 2 presents our technique to collect the runtime context. It is achieved by stopping the execution of the program under repair at a specific location. In our case, we stop the execution only at the locations for which we have identified an angelic value. For buggy if-conditions, angelic value mining is done by forcing at runtime the branch of the suspicious if statement. The condition expression is arbitrarily substituted for either true or false: the state of the program is artificially modified during its execution as it would have been by an omniscient oracle or angel. If all failing tests pass with the modified execution, the used value is called the angelic value and is stored for use in synthesis later.

```java
if (u == 0 || v == 0) {
    return (Math.abs(u) + Math.abs(v));
}
```

Figure 1: Patch example for a buggy if condition. The original condition with a comparison operator == is replaced by a disjunction between two comparisons. An overflow could thus be avoided.

```java
if (specific != null) {
    sb.append(String.format("%c%s", c, sb)); //sb is a string builder in Java
}
```

Figure 2: Patch example: a missing precondition is added to avoid a null reference. The patch is specific to the object-orientation of Java.

```java
if (u * v == 0) {
    return (Math.abs(u) * Math.abs(v));
}
```

Figure 3: Overview of the Nopol repair system.
Algorithm 1 Top-level algorithm of DynaMoth

**Input:** A: a set ofangelic values for specific statements

**Output:** P: a set of patches

1. \(P \leftarrow \emptyset\)
2. for all angelic value at statement \(s\) in \(A\) do
3. collect simple EExp at runtime at \(s\) [Algorithm 2]
4. combine simple EExp as compound EExp (Algorithm 3)
5. compare all EExp against the expected angelic value (Algorithm 4)
6. if valid EExp found then
7. add patch to \(P\)
8. end if
9. end for
10. return \(P\)

Algorithm 2 Collecting the set of runtime contexts for a statement \(S\) during test execution. Legend: \(<\) means “add to set”

**Input:** Statement \(S\), \(T\): set of tests

**Output:** R: set of runtime contexts

1. add breakpoint at \(S\)
2. for all \(t\) in \(T\) do
3. run \(t\)
4. if is stopped at breakpoint then
5. \(\text{eExpList} \leftarrow \emptyset\)
6. \(\text{eExpList} \leftarrow \text{variables} \cup \text{fields}\)
7. \(\text{eExpList} \leftarrow \text{(all method calls on this)}\)
8. for \(1\) to \(\text{max\_depth}\) do
9. for all \(\text{eExp in eExpList}\) do
10. \(\text{eExpList} \leftarrow (\text{fields eExp})\)
11. \(\text{eExpList} \leftarrow (\text{all method calls on eExp})\)
12. end for
13. end for
14. \(R_t \leftarrow \text{iteration number for this test}\)
15. \(R_t \leftarrow \text{execute test}\)
16. proceed test execution
17. end if
18. end for
19. return \(R\)

Algorithm 3 Combining EExp’s with a operators.

**Input:** eExpList: a list of EExp, O: a set of operators

**Output:** eExpList: EExp enriched with compound EExp

1. for \(1\) to \(\text{max\_depth}\) do
2. for all operator \(o\) in \(O\) do
3. \(n \leftarrow \text{number of required operators for } o\)
4. for all \(t\): tuple of size \(n\) in eExpList do
5. if types of \(t\) values compatible with \(o\) then
6. eExpList \leftarrow combine \((t\text{, operator})\)
7. end if
8. end for
9. end for
10. end for

For each execution of a suspicious statement, DynaMoth collects a set of simple EExp representing an expression and the result of its evaluation in the current runtime context. Those basic EExp will be used to form the actual patch.

### 3.1.2 Compound EExp Synthesis

After the collection of simple EExp (described in Section 3.1.1), DynaMoth combines them with operators.

The first kind of compound EExp are expression containing null checks. For example, let us consider two runtime contexts: the first contains a variable \(v\) which is an array and the second runtime context contains the same variable \(v\) but this time equal to \(null\). With the first context, DynaMoth can access the field: \(\text{length}\) of the array but in the second context, \(v\) does not have fields. In this case, DynaMoth can generates compound EExp of the form: \(v != \text{null} \&\& v.\text{length} == 0\) evaluating to true in the first context and false in the second.

The second phase consist of generating compound expressions with binary logic and arithmetic operators. This is done by generating new expressions combining all EExp collected so far with compatible logic/arithmetic operators: \(+\), \(-\), \(*\), \(/\), ||, &&, ==, !=, <, <=. A combination creates a new EExp and its value is compared to the expected value (this comparison is described in Section 3.1.2). This phase is executed recursively to create more and more complex expressions until the configuration parameter depth is reached. For example, DynaMoth can produce this type of expression: \((\text{matrix} := \text{null} \&\& 0 == \text{matrix.multiply}(\text{this}).\text{getReal}()) \&\& (\text{array} == \text{null} || \text{list}.\text{getSize}() < \text{array.\text{length}})\).

### 3.1.3 EExp Validation

Each time a boolean EExp is created, DynaMoth verifies that the EExp returns the expected value predicted by angelic value. If this is the case, it means that the EExp fixes the bug locally, for this particular runtime context. When this happens, DynaMoth validates the patch for all other runtime contexts. For example, we have the EExp\(\text{array} == \text{null} || \text{array.\text{length}} == 0\) and two runtime contexts: \(\text{array} == \text{null} \&\& \text{array.\text{length}} == 1\). The evaluation of the EExp with the first runtime context is equal to true because \(\text{array} == \text{null} \&\& \text{false}\) with the second runtime context because \(\text{array} == \text{null} \&\& \text{array.\text{length}} == 1\). If those are the two expected angelic values for a precondition, it means that a patch has been found.

### 3.2 Optimization Techniques

The search space of the synthesis is composed of all expressions

1The operators \(>\) and \(\geq\) are obtained by symmetry of \(<\) and \(<\).
Algorithm 4  Assessing whether a valid patch exists at a given statement S.

Input: eExp: a set of valued EE XP for all tests at statement s, A a set of angelic values for all tests, T a set of tests

Output: true if eExp is a valid patch

1: for all t in T do
2:   for all iteration i of S in t do
3:     eExpValue ← eExp,i
4:     angelic ← \textit{A}_{i,1}
5:     if eExpValue ≠ angelic then
6:       return false
7:   end if
8: end for
9: end for
10: return true

that can be generated from basic EE XP initially collected. In many cases, the search space is too large to be completely covered. Consequently, we have designed and implemented several optimizations that either reduce the size of search space or accelerate the discovery of a patch.

3.2.1 Exploration of Compound EE XP

During the synthesis of compound EE XP for a given runtime context, we only consider EE XP that have different values. For example, let us consider that DynaMoth is creating a binary expression and is looking for a boolean expression for the right operand. Furthermore, in the scope under consideration, there are two compatible variables that are both equal to true. In this case, DynaMoth will only consider the first variable because the value of the new EE XP will be exactly if it had considered the second variable. This greatly prunes the search space for a single runtime context. This optimization of the search space is similar to that of J. Galenson et al. in CodeHint [5]. This does not decrease the synthesis power: if two EE XP may evaluate to the same value in one runtime context c1 but to different value in another one c2, the synthesis of a patch using EE XP 1 would be discarded in c1 but explored in c2. If it works on c2 it would be validated on c1 afterwards.

3.2.2 Number of Collected Runtime Contexts

We need a threshold on the number of collected runtime contexts. We have found that a good threshold is that DynaMoth stop collecting after 100 runtime contexts of a given suspicious statement for a given test case. For instance, if the suspicious statement is in a loop, the runtime collection will start at each loop iteration. In order to limit the execution time of the collection, DynaMoth considers only the 100 first iterations and ignores the others. This optimization is sound because the synthesized patch is still validated on the real bug with all executions of the suspicious statement.

3.2.3 Method Calls Used in Synthesized Patch

The number of possible method calls yields of huge search space. Patches are unlikely to call methods that have never been used in the program. Consequently, DynaMoth only collects method calls which are used elsewhere in the program.

3.2.4 Ignore equivalent expressions

DynaMoth ignores equivalent expressions such as binary expressions with a commutative operator (example: \(x + y\) and \(y + x\)). DynaMoth ignores binary expressions which contain a neutral operand (example: \(0 + x\) or multiplication by 0). DynaMoth also ignores all trivially incorrect patches such as the comparison of two literals (example: \(1 == 2\)).

3.2.5 Method Invocation Time Timeout

During runtime context collection, we set a threshold on the execution time of method calls (2 seconds per default). This timeout creates an upper bound on the execution time of runtime context collection, and mitigates the problem of infinite loops caused by invalid method parameters.

3.2.6 Ordering of Runtime Contexts

All runtime contexts do not contain the same number of simple EE XP, before the combination step, as shown in Section 3.1.2. Consequently, the runtime context that contains more EE XP has more chance to produce a patch because more combinations of EE XP is possible. By considering first the runtime contexts that have more EE XP, we reduce the time spent searching the patch in a runtime context that cannot produce it.

3.2.7 Estimation of Usage Likelihood of Operators and Operands

DynaMoth collects the usage statistics of variables, operators and methods in the class that contains the suspicious statement. For instance, if we are repairing a statement in class Foo, DynaMoth extracts the information that operator “+” is used 10x in Foo, method “substring” is used 4x in Foo, etc. This usage statistics is used to drive the synthesis of compound EE XP: the composition operators that are most frequently used are prioritized during synthesis. This optimization is based on our intuition that patches are more likely to contain operators and methods that have previously been used in the class under consideration.

3.3 Implementation Details

DynaMoth uses the Java Debugging Interface as to set breakpoints and collect the runtime contexts. The Java Debugging Interface (JDI) is an API of the virtual machine that provides information for debuggers and systems needing access to the running state of a virtual machine.

For collecting the usage statistics (see Section 3.2.3 and Section 3.2.7) DynaMoth uses a library for analyzing Java source code: Spoon. Spoon is also used during the angelic value mining (Section 2.4) and during the final patch validation. The localization of suspicious statement is delegated to the library: GZoltar [3].

The source code of DynaMoth is part of the Nopol project [4] and is publicly available on GitHub at https://github.com/SpoonLabs/nopol.

4. EVALUATION

In order to evaluate the effectiveness of DynaMoth, we execute it on the Defects4J [7] dataset of 224 real-world bugs. The methodology of this evaluation is composed of the following dimensions: the bug-fixing ability, the patch readability and the execution performance. First, our evaluation protocol is described in Section 4.1. Second, our three research questions (RQ’s) are detailed in Section 4.2, and finally the responses to our research questions given in Section 4.3.

4.1 Protocol

We run DynaMoth to repair the bugs of the Defects4J dataset. Defects4J by Just et al. [7] is a database of 357 reproducible real bugs.
4.2 Research Questions

1. **RQ1.** Bug fixing ability: Which bugs of Defects4J can automatically be repaired with DynaMoth? In canonical test-suite based repair, a bug is considered as fixed when the whole test suite passes with the patched program. To answer this quantitative question, we run DynaMoth on each bug of the Defects4J dataset and count the number of fixed bugs.

2. **RQ2.** Patches Readability: Are the synthesized patches simpler than those generated by SMTSynth? The readability of the generated patches is an important factor when developers comprehend and validate them before including them in the code base. To answer this question, we look at the number of expressions (variable, literals, parameters), method calls and operators in each patch.

3. **RQ3.** Performance: How long is the execution of DynaMoth? For automatic repair to be applied in practice, it is important that it does not run too long. For instance, requiring one week to find a patch is not acceptable for developers. To answer this question, we analyze the execution time of DynaMoth when it finds a patch.

### 4.3 Empirical Results

We perform the experiment described in Section 4.1. The total execution time of this experiment is more than 11 days.

#### 4.3.1 Bug fixing Ability

**RQ1.** Which bugs of Defects4J can automatically be repaired with DynaMoth?

<table>
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<th>Bug Id</th>
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<th>DynaMoth</th>
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<td>43 (19.2%)</td>
<td>35 (15.6%)</td>
<td>27 (12%)</td>
</tr>
</tbody>
</table>

#### 4.3.2 Performance

**RQ2.** Patches Readability: Are the synthesized patches simpler than those generated by SMTSynth? The readability of the generated patches is an important factor when developers comprehend and validate them before including them in the code base. To answer this question, we look at the number of expressions (variable, literals, parameters), method calls and operators in each patch.

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<td>Total</td>
<td>43 (19.2%)</td>
<td>35 (15.6%)</td>
<td>27 (12%)</td>
</tr>
</tbody>
</table>
4.3.2 Patch readability

**RQ2.** Are the synthesized patches simpler than those generated by SMTSynth?

We compare the readability of patches generated by SMTSynth and DynaMoth. Table 2 shows the number of expressions (E) which are variables and constants, method calls (M) and operators (O) in each patch. In 9/19 cases, DynaMoth generates patches that contain less elements, hence that are easier to read. In 7/19 cases, DynaMoth generates patches that contain equals number of elements. In 3/19 cases, DynaMoth generates patches that contain more elements. In average DynaMoth contains less expressions (2.6 vs 2.94), less operators (0.85 vs 2) but more method calls (0.44 vs 0.28).

This quantitative result is confirmed by the manual analysis. The manual analysis shows that 22/27 patches synthesized by DynaMoth are easy to read and 5/27 to medium. As expected, there is a clear relation between the small amount of expressions and method calls in the patches and the readability.

**Answer to RQ2.** DynaMoth synthesizes patches that are simpler and easier to read compared to SMTSynth.

### 4.3.3 Performance

**RQ3.** How long is the execution of DynaMoth on one bug?

The experiment in this paper is run on a grid where the nodes are machines such as Intel Xeon X3440 Quad-core processor and 15GB of RAM. Table 3 shows the total execution time of Nopol and DynaMoth for all bugs. Table 4 shows the execution time for the bugs which are repaired. The average execution time of all bugs are similar for DynaMoth and SMTSynth. For the repaired bugs, DynaMoth is slower than the SMT-based synthesis of Nopol.

**Answer to RQ3.** The execution time of DynaMoth is comparable to that of SMTSynth for all bugs but slower when we only consider the fixed bugs. However the average repair time remains acceptable for classical repair scenarios.

5. RELATED WORK

Test-suite-based repair approaches (described in Section 2.1) use a test suite as program specification to generate and validate a patch. We discuss them with respect to code synthesis.

Le Goues et al. [8] proposed GenProg, a test-suite-based repair approach using genetic programming in the C language. GenProg does no do any synthesis, it moves and copies existing code in the program. SemFix by Nguyen et al. [9] uses symbolic execution for fixing assignments and conditions, the synthesis engine is the...
same algorithm as SMTSynth, but DynaMoth is another completely different implementation.

The closest synthesis engine is CodeHint [5]. CodeHint [5] synthesizes Java code from runtime data inside the development environment. It uses the Java runtime Debug Interface to collect the runtime data and call methods. CodeHint uses optimizations in order to reduce the search space by ignoring expression that have a low score according to classical usage. The score of an expression is computed using with the type of operators in the expression, and the usage frequency of each method call in the expression. The goal of CodeHint (helping developers) is completely different from automatic repair. This implies a key technical difference: CodeHint has to synthesize an expression for a single runtime contexts, while DynaMoth has to generate an expression that is valid for a many different runtime contexts at the same time (the number of executions of the statement under repair summed over all test cases).

### 6. CONCLUSION

We have presented DynaMoth, a new patch synthesizer for Java, integrated into the Nopol toolchain. The synthesis algorithm starts by collecting the execution context of suspicious statements. The DynaMoth explores a rich search space of the combination of existing values. Several optimizations are necessary to tackle the large size of the search space.

The system has been evaluated on 224 bugs from the Defects4J dataset. DynaMoth synthesizes patches for 27 of them, incl. 8 which have never been repaired before. In total, DynaMoth fixes 27 bugs from the dataset. We consider those results are encouraging. In the future, we plan to implement additional optimizations, in particular to address the combinatorial explosion of the search space caused by methods accepting many arguments and the presence of many candidate EEXP to be used as parameters.

### 7. REFERENCES


