

# Building a Probabilistic Model of Statement Replacements for Automatic Bug Fixing based on an Empirical Study of Real Java Bug Fixes

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## ABSTRACT

With the rise of automated program repair in the last few years, there are a lot of questions that remain unanswered. We performed a study on 100 open source projects, in which we analyzed the 20 most recent bug fixing commits of this dataset, and found all the replacements made in these 62,470 commits from real life projects in Github.

We found very valuable information to guide automatic software repair, such as the most common and least common replacements made by human developers in order to build a successful patch; we analyzed the most and least common statement to replace others, and the most and least likely statement to get replaced by other. We also analyzed, once you have a statement that you want to replace (a faulty statement), what are the most likely statements to replace it for. These information will help automatic program repair tools to be more maintainable and user friendly, taking it one step closer to what humans developers do to repair their code. We performed an evaluation for our model, that shows via 10-fold cross validation that our model can predict replacements in a 78.52% of the times in the first 3 guesses. Finally we also performed a study to validate the accuracy of the regular expression being normally use to find bug fixing commits.

## Keywords

Automatic error repair; Maintainability; Replacements

## 1. INTRODUCTION

Automatic bug repair is the branch of software engineering that deals with automated ways to repair errors in software without requiring human intervention [4, 5, 6, 8]. There have been several approaches taken towards improving the different methodologies to repair bugs in software automatically [4, 5, 9, 12]. One of the more successful approaches so far has been GenProg [5, 12], a tool which combines stochastic search methods like genetic programming with lightweight program analyses to find patches for real bugs in software. Based on evolutionary computation, GenProg applies four different kinds of possible changes to code in order to find a patch for a given bug. These changes are: (1) delete, (2) replace, (4) swap, and (4) append.

Our research aims to provide guidelines to improve one of these possible changes. The one which remains to be unstudied since it is probably the hardest of them: Replace. It will provide the data necessary for this tool and other approaches to have a guide on what is the way in which

human programmers change their code when coding a fix for a bug. This way it will make it more likely for automatic error repair approaches to succeed in finding a patch for a particular error, and also, to provide automatic error repair software with heuristics to make the patches more human-like and therefore more readable and maintainable by human developers.

In this article we perform an empirical study that consists of mining 100 open source projects, and determining the frequency with which human programmers replace different statements to their source code in order to fix a bug.

In this paper, we study bug-fixing commits to Java programs, taken from several thousand human-made bug fixes from Github. We make observations to directly guide future research in automatic repair of Java programs, to increase the success rate of such techniques and the degree to which the patches are human-like and therefore more readable and maintainable by human developers. This is important, because patch quality is an important concern in this area [10].

**Related work.** Zhong and Su [13] ask some of the same questions we do, on 6 projects. We study a mutation operation that these researchers left out due to its complexity, which is the operator Replace, and we also look at more statement types than the previous work.. Similar to our study in Section 5, researchers have studied AST-level [7] and line-level changes [1] across bug fixing commits. Although it is worth notice that so far none of these approaches have studied in depth the Replace operator. An important study was done in this subject by Soto et al [11] in which they count the number of statements in the before-fix and after-fix versions of the code and try to infer a correlation between the two number of statements. This study avoids this assumption, and instead creates a direct comparison between the two abstract syntax trees to be able to infer more accurately when replacements are being made and create the model with this data.

## 2. DATASET AND CHARACTERISTICS

For the dataset of this project we picked the 100 Java projects in Github with the most stars. In Github when a user stars a project it means that the user is:

- Creating a bookmark for easier access
- Showing appreciation to the repository maintainer for their work

Therefore, by picking the projects with more stars we are taking the Java projects more liked and supported by the

community and developers of Github, which may have a correlation with having a lot of followers, contributors and activity; and this diversity benefits our study since having a larger diversity of bug fixes, makes the model being built from this data more reliable and more diverse.

From each of these 100 projects we picked the last 20 bug fixing commits for two reasons. First, we had time restrictions, and making it with more than 20 commits became very time consuming. As a sample of this, for the first project, we tried getting all the bug fixing commits and cloning the before-fix and after-fix versions of each of the commits. We had to stop this process when the commits were taking 65 gigs of space just for the first project. Therefore we considered that taking the last 20 commits would be a good balance between depth of each project and would also allow us to get the breadth we were looking by in analyzing 100 different projects.

The problem of categorizing which commits are actually bug fixing commits or not is an open problem in the literature. This is usually performed by applying a regular expression to the commit message, and this way inferring if a commit is a bug fixing commit or not depending on the words the commit message has. We used as inspiration the regular expression used by Boa [robert] to find bug fixing commits. We used a very similar regular expression to determine this, which is the following:

- "[Ff]ix(ed|es|ing)?(\\s)\*([Bb]ug|[Ii]ssue|[Pp]roblem)?(s)?"

To address the concern of knowing if this regular expression would get the commits that are actually bug fixing commits or not, we made the study in the following section.

## 2.1 Commit Validation

In order to build the probabilistic model for statement replacements, it is necessary to ensure that the commits selected using the regular expression specified above were truly bug-fixing commits. In particular, some of the commits whose commit messages matched the regular expression included changes to more than five Java source code files. But prior studies of bug fixes [13] have shown that programmers modify less than five files in order to fix a bug. So, it became necessary to check if these commits which involved modifications to five or more source code files were bug-fixing commits indeed.

We examined if commits that modified five or more Java files were bug-fixing commits or not by manually inspecting such commits. We selected the 50 most recent commits from the commit history of each of the 100 projects in our dataset. Some projects had less than 50 commits in total. We included all of the commits that were made to these projects. Among these commits, we then proceeded to select the ones that involved modification to five or more Java source files. We then manually inspected the commit messages of the selected commits to determine if the changes were being made in order to fix a bug. We included the commits which indicated that they were fixing issues such as a crash, NullPointerException or some other issue identified using a project-specific ID. We excluded the other commits. For example, if the commit message contains the words "prefix" or "suffix", it would match the regular expression that we have used, even though it is not fixing a bug. We excluded all such commits.

The 100 projects that we have used in our study have

Project	Bug-fixing commits	Other commits
platform_frameworks_base	18	1
kotlin	12	2
elasticsearch	23	6
netty	9	4
libgdx	8	3
spring-boot	15	9
spring-framework	12	22
presto	17	7
RxJava	22	10
titan	12	5

**Table 1: Distribution of bug-fixing commits in the 50 most recent commits for the top 10 projects with the highest number of commits**

a total of 62,470 commits. We selected 1,353 of them for performing commit validation. These commits are the ones among the 50 most recent commits for each of the 100 projects in which five or more source code files have been changed. We discovered that 847 out of these 1,353 commits were actually bug-fixing commits. The remaining 506 commits were made for other reasons. Majority of the commits that we have included for building the probabilistic model are indeed bug-fixing commits. Table 1 shows the distribution of bug-fixing commits in the 50 most recent commits for the top 10 projects in terms of the total number of commits.

## 3. STATEMENT REPLACEMENTS

As we have stated earlier, we build our probabilistic model at the granularity level of statements. So, for each pair of statement kinds, we count the number of times a statement of the first kind has been replaced with a statement of the second kind in the bug-fixing commits. In order to do this, we have used a tool named QACrashFix [3]. QACrashFix generates patches to bugs, particularly ones that result in crashes due to exceptions, by analyzing Q&A sites or programmer forums. It makes use of the fact that programmers working on projects using the same framework (e.g., Android, Hadoop, Spring, etc.) make similar kinds of mistakes related to the use of the framework. If a bug causes an exception, more often than not, programmers get the help of experts in fixing it by posting to Q&A sites. These posts usually include the exception message and stack trace as well. When another programmer encounters a similar exception, they can use QACrashFix which searches for posts made by other programmers on Q&A sites and constructs patches from the solutions posted on the page.

The construction of patches by QACrashFix involves four steps. First, a search query is constructed based on information about the exception. This search query is used to obtain a list of Q&A pages that contain possible fixes by performing a web search. The second step consists of extracting buggy and fixed code snippets from the Q&A pages in the search results. For each pair of buggy and fixed code snippets, QACrashFix generates an edit script that describes how the Abstract Syntax Tree (AST) of the buggy code may be transformed to that of the fixed code. In the third step, potential patches are constructed by customizing the edit script to the code the programmer is searching a fix for.

Finally, patches which fail to compile are eliminated.

We count statement replacements by generating an edit script that transforms the version of a source code file prior to a commit to the version of the same file after the commit. We use the edit script generation component of QACrashFix for this purpose. This component is based on another tool named GumTree [2]. The edit scripts generated by GumTree contain four types of operations: (1) add, (2) delete, (3) update, and (4) move. QACrashFix extends GumTree to add two more operations: (1) replace, and (2) copy. The replace operation contains information about AST nodes which must be replaced with other AST nodes. We only consider replace operations in which both the AST node being replaced and the replacement AST node correspond to Java statements.

## 4. BUILDING THE MODEL

In order to build the probabilistic model we gather the data from the 100 projects. From each of these projects we took the 20 latest bug fixing commits, and each of these bug fixing commits consists of a variable number of files, which can vary between 1 to even a couple of hundreds. We ran the scripts to gather the data to build the model for 4 days straight on a laptop with an Intel i7 processor and 8 gigs of RAM. We added all the instances of replacements that we found in our dataset and with these, we modeled the distribution of replacements performed by human programmers when patching bugs.

According to The Eclipse Java development tools (JDT) <sup>1</sup>, the java language contains 22 different kinds of statements. We based our model and results on these 22 statement types. Since the names of the statement types are very long, we created abbreviations for all of them so that the table of the model is clearer. The abbreviations for the statement types are the following:

As: AssertStatement  
Bl: Block  
Br: BreakStatement  
CI: ConstructorInvocation  
Co: ContinueStatement  
Do: DoStatement  
Em: EmptyStatement  
EF: EnhancedForStatement  
Ex: ExpressionStatement  
Fo: ForStatement  
If: IfStatement  
La: LabeledStatement  
Re: ReturnStatement  
SC: SuperConstructorInvocation  
Ca: SwitchCase  
Sw: SwitchStatement  
Sy: SynchronizedStatement  
Th: ThrowStatement  
Tr: TryStatement  
TD: TypeDeclarationStatement  
VD: VariableDeclarationStatement  
Wh: WhileStatement

## 5. EVALUATION

<sup>1</sup><http://www.eclipse.org/jdt/>

For the evaluation section we wanted to know how likely is it that our model can predict the behavior of real bug fixes performed by humans. Therefore we decided to evaluate our model using 10-fold cross validation. By using this technique we randomly divided our 100 projects into 10 different groups (called folds), and then we make 10 runs, each run picking one of the folds as the testing data, and the rest of them being the training data.

For example, in the first run, we take the 10 projects in fold 1 and we are going to use those as the testing data. Meanwhile, we will build a pseudo probabilistic model from the remaining 9 folds, and then we will test how likely is it that the pseudo probabilistic model is capable of predicting the behavior of the testing data. We do this 10 times, each of them taking a different fold as the testing set.

Our interpretation of "predicting" for this study is the following: The model "predicts" an instance of a replacement in the testing dataset when given the statement to replace (replacee) it is able to guess with which statement it was replaced by (replacer) correctly within the first three guesses (the three highest percentages of probabilistic replacement for that statement type in the model).

As an example, consider the row "Re" (short for "Return") in the model shown in Table 1. As you may notice, the three highest probabilities of statements that can replace a Return statement are:

- Expression Statement (43%)
- If Statement (22%)
- Variable Declaration Statement (19%)

These would be the top three guesses of the model when trying to predict the testing dataset. So if, for example, the testing dataset would be

- Expression Statement: 4
- If Statement: 2
- Variable declaration Statement: 2
- Do Statement: 1
- Continue Statement: 1

In this example, we would get 8 instances of replacements correctly guessed by the model in the first 3 guesses, and 2 instances of replacements incorrectly guessed by the model in the first 3 guesses. Which means that the prediction of this model with this testing dataset had a success rate of 80%.

Following this approach, we performed a 10 fold cross validation in our model and the result of each of the runs taking a different fold as testing data is detailed in Table 2.

The mean of the 10 different success rates per each of the 10 folds gives us a mean success rate of 78.52% of success in predictability of the model being able to guess the correct statement by which each statement is being replaced. The authors of this paper think that if we analyze the how likely the model is to predict the 10 different folds using the first 5 guesses of the model instead of the first 3 guesses, then the success rate of the model would have been closer to a 95%. But this couldn't be done due to time restrictions, and it is advised to be done as future work.

	As	Bl	Br	CI	Co	Do	Em	EF	Ex	Fo	If	La	Re	SC	Ca	Sw	Sy	Th	Tr	TD	VD	Wh
As	0	0	0	0	0	0	0	0	25	0	25	0	25	0	0	0	0	0	0	0	25	0
Bl	0	0	0	1	0	0	0	0	33	0	15	0	31	0	0	0	0	0	0	0	19	0
Br	0	0	0	0	0	0	0	0	48	0	12	0	0	0	40	0	0	0	0	0	0	0
CI	0	10	0	0	0	0	0	0	0	0	0	0	10	80	0	0	0	0	0	0	0	0
Co	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0
Do	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0
Em	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EF	0	12	0	0	0	0	0	0	54	4	12	0	0	0	0	0	0	0	12	0	8	0
Ex	0	26	3	0	0	0	0	1	0	0	13	0	3	0	0	0	0	1	3	0	50	0
Fo	0	8	0	0	0	0	0	17	0	0	0	0	75	0	0	0	0	0	0	0	0	0
If	0	19	2	0	0	0	0	1	52	0	0	0	9	0	0	0	0	0	3	0	14	0
La	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Re	0	2	0	2	5	0	0	0	43	0	22	0	0	2	2	0	0	3	2	0	19	0
SC	0	8	0	54	0	0	0	0	23	0	0	0	0	0	0	0	0	0	0	0	15	0
Ca	0	0	30	0	0	0	0	0	20	0	10	0	30	0	0	0	0	0	0	0	10	0
Sw	0	33	0	0	0	0	0	0	0	0	67	0	0	0	0	0	0	0	0	0	0	0
Sy	0	0	0	0	0	0	0	0	10	0	20	0	0	0	0	0	0	0	70	0	0	0
Th	0	0	0	0	0	0	0	0	71	0	0	0	29	0	0	0	0	0	0	0	0	0
Tr	0	0	0	0	0	0	0	0	26	0	9	0	4	0	0	0	30	0	0	0	30	0
TD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VD	0	6	0	0	0	0	0	1	81	1	6	0	2	0	0	0	0	0	2	0	0	0
Wh	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 2: Likelihood of replacing a statement type (row) by a statement of another type (column), for Java.

Test Fold No.	Instances correctly predicted	Instances incorrectly predicted	Success rate
1	72	11	86.75%
2	82	43	65.60%
3	64	23	73.56%
4	752	423	64.00%
5	83	42	66.40%
6	81	18	81.82%
7	713	6	99.17%
8	186	25	88.15%
9	37	9	80.43%
10	23	6	79.31%

Table 3: 10 Fold cross validation of the probabilistic model

## 6. CONCLUSION AND FUTURE WORK

Our work is publicly available to be downloaded, extended and reproduced by anyone.<sup>2</sup> As some possible extensions of our work, the authors of this paper think that it would be valuable to create a model with a larger sample of data, both in depth and breadth, but the authors of this paper consider that in this case it is more valuable to give a major importance to breadth, since the model benefits more from diversity of different programmers and different projects, and not as much from a repeated pattern of bug fixing in a particular set of projects. This will also help to the fact that the model will be less likely to overfit the training data. As an extension of section 2.1, we would like to dig deeper into why is the number of actual bug fixing commits so low, and what can be done to mitigate this. Since this error is causing a lot of noise to be introduced to every study that deals with similar regular expressions and who are trying to caught bug fixing commits, and they are getting almost a 40% of their population to be not actual bug fixing commits. As a next step for this study, it would be interesting to insert this model into GenProg's code and compare its performance with previous runs and also to different approaches to see how well it works with our approach.

## 7. ACKNOWLEDGMENTS

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<sup>2</sup><https://github.com/mausotog/ReplacementsEmpiricalStudy>