A Study of Single Statement Bugs Involving Dynamic Language Features

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ABSTRACT
Dynamic language features are widely available in programming languages to implement functionality that can adapt to multiple usage contexts, enabling reuse. Functionality such as data binding, object-relational mapping and user interface builders can be heavily dependent on these features. However, their use has risks and downsides as they affect the soundness of static analyses and techniques that rely on such analyses (such as bug detection and automated program repair). They can also make software more error-prone due to potential difficulties in understanding reflective code, loss of compile-time safety and incorrect API usage. In this paper, we set out to quantify some of the effects of using dynamic language features in Java programs – that is, the error-proneness of using those features with respect to a particular type of bug known as a single statement bug. By mining 2,024 GitHub projects, we found 139 single statement bug instances (falling under 10 different bug patterns), with the highest number of bugs belonging to three specific patterns: Wrong Function Name, Same Function More Args and Change Identifier Used. These results can help practitioners to quantify the risk of using dynamic techniques over alternatives (such as code generation). We hope this classification raises attention on choosing dynamic APIs that are likely to be error-prone, and provides developers a better understanding when designing bug detection tools for such feature.

ACM Reference Format:
Li Sui, Shawn Rasheed, Amjed Tahir and Jens Dietrich. 2022. A Study of Single Statement Bugs Involving Dynamic Language Features. In 30th International Conference on Program Comprehension (ICPC ’22), May 16–17, 2022, Virtual Event, USA. ACM, New York, NY, USA, 5 pages. https://doi.org/10.1145/3524610.35277883

1 INTRODUCTION
Dynamic language features are widely available in modern programming languages and commonly used in code. In Java, features like reflection and dynamic proxies, are used to implement generic components that can be used in different contexts [3]. Landman et al. [8] report that 78% of Java projects they studied contain reflective calls. However, there are challenges in modelling and analysing programs and finding bugs that involve the use of dynamic language features [4, 9]. Recent studies on the analysis of dynamic features have focused on improving the recall of static analysers, whilst maintaining their precision [9, 12]. Challenges in analysing these features may affect software maintenance activities such as bug detection, automated refactoring and program repair.

The question is what the propensity is for the use of dynamic features to cause bugs. Dynamic features can be error-prone due to erroneous interpretation of APIs, difficulty in comprehending reflective code, loss of compile-time safety and incorrect API usage. However, to the best of our knowledge, no studies on bugs related to the use of these features in Java application code have been conducted. There was a recent study on bugs involving the use of dynamic features in Python [1] and some studies on reflection specific bugs in JVM code [10].

In this work, we attempt to answer the question: “how frequently are dynamic language features the cause of single statement bugs in Java programs?” Single statement bugs are the class of bugs which can be fixed with a change to a single statement. This simplicity allows easy identification whether bugs are related to the use of specific APIs (e.g., reflection). To answer this question, we extracted bug instances that involve references to dynamic language features from Java projects mined from GitHub. We used the ManySSubs4J dataset [6], which presents a classification of common single statement bug instances from 1000 Java projects on GitHub. We extended the original dataset by mining additional GitHub projects to identify even more bug instances from the newly added projects. The name of each classification is self-explanatory as it explains violations of certain rules that led to the bug, and in most cases, it also describes the fix of the potential bug. This includes patterns like Change Identifier Used and Same Function More Args.

As a result of our study, we found 139 dynamic language features-related bug instances from the mined projects. The majority of these bugs belong to three patterns: Wrong Function Name (34%), Same Function More Args (18%) and Change Identifier Used (15%). These findings can potentially provide guidance for automated program repair to detect and automatically patch dynamic language features related bugs.

2 RELATED WORK
Bugs related to underdetermined specifications in the reflection API are discussed in Pontes et al. [10]. These are bugs in JDK implementations, not applications or libraries. It seems unlikely that bugs of this nature (underdetermined API assumptions) in application code can be fixed with single statement changes. The study by Chen et al. [1] is an extensive study of Python bug fixes that have changes involving dynamic features. Zhang et al. [14] discuss a case where fixing a bug related to an underdetermined reflection API method (the order of the elements returned by getDeclaredFields) adds multiple lines to the code. Bug patterns involving Java streams are
discussed in Khatchadourian et al. [7]. Java exception handling bugs are explored in Ebert et al. [5].

ManySStus4J [6] is a dataset of over 153k single statement bug fix changes mined from 1,000 popular open-source Java projects. We used this dataset to locate dynamic language feature bug fixes, but we extended the original dataset with 1,032 additional GitHub projects. Another similar dataset is CodeRep [2], which is a single-line changes dataset mined from different repositories, which has been used in program repair studies. Bugs2Fix [13] is a data set of simple bugs used in program repair and bug-related studies. Unlike these two datasets, ManySStus4J focuses on fix templates and fixes that are at the statement level.

3 METHODOLOGY

Figure 1: An overview of our mining and data extraction process

Figure 1 provides an overview of the data collection process that we followed in this paper. As a first step, we gathered project URLs from (1) the ManySStus4J [6], (2) additional projects from six organizations and communities hosted on GitHub (namely Google, Eclipse, JetBrains, Mozilla, Apache, and Spring.) We identified those organizations and communities based on the following criteria: Firstly, they contain projects that are known for heavy use of dynamic language features, such as Spring. Secondly, they have a number of well-known Java projects, indicated by GitHub star counts. Thirdly, the availability of an issue tracker, either hosted on GitHub or externally, such as on Bugzilla.

We first removed duplicate projects (i.e., projects that have already been included in the ManySStus4J dataset). We then cloned all remaining projects locally. To extract single statement bugs from each repository, we used the same script used in the original ManySStus4J study.

We developed a script to identify single statement bugs that are related to dynamic language features. The script searches for specific keywords at call sites in the parent commit of fix commits (where the bug occurs). These methods and keywords are based on a benchmark of dynamic feature usage patterns by Sui et al. [11] and a list of the Java Reflection APIs from Landman et al. [8]. We have excluded certain APIs from [8], such as logic operators (i.e., ==, !=) and call sites that can cause false positives, e.g., toString() set and get as those keywords can be too generic. There are a total of 106 call sites selected for keyword matching. We acknowledge that this is not an exhaustive list of dynamic language feature methods and keywords in Java. To the best of our knowledge, there are no studies that have comprehensively listed all the dynamic language feature methods and keywords in Java. Acquiring such a comprehensive list is outside the scope of this study.

The dataset includes bug data from 2,024 Java projects, with a total of 249,089 bug instances being identified. From those projects, we mined a total of 104,337 single statement bugs (i.e., bugs that match the patterns identified in Karampatsis and Sutton [6]) searching for the use of specific dynamic language features.

We provide the scripts used to extract the data together with our full results in a replication package.

4 RESULTS AND DISCUSSION

By filtering each bug instance using the dynamic features keywords, we identified 1,916 dynamic feature related bugs. To verify the results, we developed a script to perform source code analysis on a limited scope (at class-level) to reduce potential false positives (e.g., call sites that match any of the keywords, but are not actually dynamic features). This analysis reduces the total number to 398 dynamic feature related bugs. At the end, two other authors conducted a manual validation by inspecting each bug instance to further check whether those bugs actually represent dynamic language feature related bugs (limited scope source code analysis may also cause false positives), and also to identify possible duplicates (e.g., same changes/fix but appear in multiple commits). We ended up with 139 unique single statement bugs in the datasets.

We note that the number of bugs found, 139, is relatively low compared to the total number of bug instances in the dataset. There are some possible explanations for the low occurrence of fixes involving direct changes to the use of dynamic language features. Firstly, those features are primarily used in code written to be reused (i.e., in upstream artefacts that are likely to be well-tested) which might be the case for some projects. Secondly, while the use of these features is often not safeguarded by the compiler, it is safeguarded by the usage context or a framework. For instance, consider data binding, where Java objects are mapped to some structured data representation (JSON, XML, etc.). When data is read, object state is initialized by invoking setters. However, these setters are not controlled by the programmer, but extracted from classes on-the-fly.

Detailed statistics of the distribution of bugs across different dynamic language features (grouped by categories) is shown in Table 1. Note that the total number is not 139 as a single bug with multiple fixes can contain different dynamic call sites.

To determine how the changes (fix commit - the commit that fixes the bug) on dynamic language features changes relate to the program behaviours, we specified them into three relationships: strong, intermediate and weak. (1) A strong relationship implies the fix also involves using a dynamic language features - it could be the same call site (change from Method.invoke(this, null) to Method.invoke(this, “null”)) or different one (change from getClass() to getDeclaredClass()). (2) Intermediate indicates the changes are not directly on the dynamic language call site, but a dynamic language features still in used (e.g., type.equals(number . getClass()) or type . isAssignableFromFrom(number . getClass())). (3) A weak relationship indicates that there is a removal of dynamic

1All projects were cloned on 12 Nov 2021, so the mining process is accomplished on the latest commit available on that date.

2https://git.io/fnS32

3https://github.com/lsui/miningSStus

4An example of keyword match that turns out not to be a dynamic feature is shown here https://git.io/fnDyz
language features or the changes has nothing to do with the dynamic language call site (e.g. a change on the logical operator). In summary, we identified 105 strong, 20 intermediate and 14 weak relationships.

The 139 single statement bugs are distributed across 79 projects. We also checked whether those bugs were reported in the issue tracker system of the project so that we could read through the issue/comments to better understand the cause of the bug. We found 80 of the 139 bugs to have related issues in the issue tracking system. In most cases, with issues created for those bugs, we observed that there are more details about the nature of the bug, how it occurred and how it was fixed. For those 80 bugs, we analysed the discussion in the issue trackers in order to classify those bugs.

We mapped each bug into the bug patterns that were defined in [6]. Table 2 shows the distribution of dynamic feature-related single statement bugs we found across the different bugs patterns. The results also show that the majority of bugs belong to two patterns: Wrong Function Name (34%) and Same Function More Args (18%). We discuss the top five bug patterns we found, with examples for each of these patterns below.

Table 2: Single statement bug patterns

| Pattern name                  | No. of bugs |
|-------------------------------|-------------|
| Wrong Function Name           | 47          |
| Same Function More Args       | 25          |
| Change Identifier Used        | 21          |
| Same Function Wrong Caller    | 19          |
| Same Function Less Args       | 6           |
| More Specific If              | 7           |
| Less Specific If              | 8           |
| Change Operand                | 4           |
| Change Boolean Literal        | 1           |
| Change Numeric Literal        | 1           |

4.1 Wrong Function Name

This bug pattern describes a case where the method caller and the method call arguments are the same, but the name of the method that is different. In the context of reflection, this can appear as a method that has been used in place of another similar method. We observed 37/47 bug instances in this category, before fix and after fix share similar method name, and have the same return type. This could be caused by a confusion over API usage. An example is shown below. java.lang.Class::getName returns the name entity, but getSimpleName returns the name with "[" appended.

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| Change Operand                | 4           |
| Change Boolean Literal        | 1           |
| Change Numeric Literal        | 1           |

4.2 Same Function More Args

The most common pattern we found is Same Function More Args, with 25 bug instances found in 14 projects. We show an example of this bug from the popular JUnit framework.

A bug describes an ExceptionInInitializerError that has been thrown when filtering tests by category, indicating there is an issue with class initialization. The solution is to add more arguments to the Class::forName method. The class java.lang.Class provides two overloaded methods to load a class: one providing the fully qualified name for a class (i.e., Class.forName("name")) and another that provides a detailed class loading scenario (i.e., Class.forName("name", false, getClassLoader())) by specifying on which class loader that the class will be loaded, and whether this class should be initialized or not. In this case, a full initialization of a class is not required, therefore the second argument should be flagged as false.

4.3 Change Identifier Used

This pattern describes a bug where the fix involves replacing an identifier with another one. In total, we found 21 instances of this bug. An example of this bug from Apache Tomcat is shown below:

A bug was reported for class org.apache.tomcat.jdbc.pool.JdbcInterceptor. This abstract class is responsible for implementing JDBC interceptor. The bug is the result of not using the correct identifier in the method call. To fix this, the identifier argument (the target instance that the method is invoked upon) was changed from this (the current object) to proxy (a proxy object).

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Another example of this category of bugs is shown in project M66B XPrivacy. The method getDeclaredField returns all declared fields within the class, whereas the method getClass returns public member fields of the class. To fix this, the call site was changed from getDeclaredField to getClass, without changing the arguments. The fix implies that the intention of the call was to access public fields via reflection.
We further investigated common usage patterns found in the de-
gument to be included. We found a total of 6 bug instances that
9https://git.io/JnS3H
an overview of a number of bugs for each call site and dynamic
reason for the bug. This was done by one of the authors, and all
the source code and the issue tracker to find out the cause and
commit message: fixed check, actually need to instantiate it if it exists.
issue link https://git.io/JnS36
The bug reported the use of a generic caller to a specific caller.
The caller java.lang.Class has been replaced by its own imple-
mentation: org.apache.el.util.ReflectionUtil. Another bug found in DBEaver indicates a change of caller from TIMESTAMP_READ_METHOD to TIMESTAMPTZ_READ_METHOD. The method name and the rest of the arguments remain unchanged.

4.5 Same Function Less Args
Unlike Same Function More Args, this pattern requires fewer ar-
uments to be included. We found a total of 6 bug instances that
followed this pattern. We show an example of this category for a bug that was reported in the Calligraphy project 9. The bug shown below is the opposite to the previous example, where a class should be fully initialized when calling Class::forName.

before fix:    Class.forName(this.owner);
after fix:     ReflectionUtil.forName(this.owner);
bug pattern:   Same Function Wrong Caller
fix commit:   461ab19dd8b2c8132e53f7e0fb1d7ad18c7adb
commit message: bug 41797: CNFE/NPE thrown from function mapper when externalizing.
issue link: none

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issue link: none

5 CONCLUSION AND FUTURE WORK
In this paper, we studied single statement bugs that are associated with the use of dynamic language features. We analysed data from 2,024 Java projects. From a total of 104,337 single statement bug instances, we identified only 139 unique bugs that relate to the use of dynamic language features. We attributed the relatively low number of bugs to how these features are used in practice (e.g., they are primarily used in code written to be reused). Still, analysing these bugs provide an insight into this class of bugs in real-world programs. With the identification of these bugs, we hope (1) this work helps practitioners to quantify the risk of using dynamic techniques over alternatives. (2) The work informs the developers of program analyses where to focus their efforts in order to produce tools with better recall. (3) The work informs the developers and maintainers of reflective APIs about which APIs are particularly error-prone and may need refactoring or additional documentation.

One of the limitations of this work is that we consider only a subset of dynamic language features, as we did not use a comprehensive list of all dynamic feature methods and keywords. To the best of our knowledge, such a list is not currently available. Expanding the list of methods and keywords would involve challenges in mining (e.g., * get can yield false positives with the string matching approach, and we will need to statically analyse the code for precision). We expect the manual effort required for these tasks to be beyond the scope for this preliminary study and hence, it has been left for future work.

There are a number of open issues that will need to be investi-
gated in the future, such as root cause analysis for these bugs and improving the precision/recall of mining.

4.4 Same Function Wrong Caller
In this bug, the function that is executed is the same, but it is being
called by a different caller. The fix is simple, and it involves changing the caller class in the call. An example of this bug from Apache Tomcat is shown below.

before fix: get_next().invoke(this,method, args);
after fix: get_next().invoke(proxy,method, args);
bug pattern: Change Identifier Used
fix commit: 746259923e3e1e0879271e389873df551ba4a73c
commit message: Fix BZ53615 JdbcInterceptor passes not 'this' but 'proxy' to get Next().invoke.
issue link https://bz.apache.org/bugzilla/show_bug.cgi?id=53015

4.6 Further investigation of common causes of these bugs
We further investigated common usage patterns found in the de-
tected bugs and reported the potential causes below. We present the reasons/causes for the top three patterns (i.e., Class::forName, Method::invoke, Class::getDeclared|Class|Field|Method|Constructor|Name). For each bug instance, we manually inspect the source code and the issue tracker to find out the cause and reason for the bug. This was done by one of the authors, and all instances were cross-validated by another co-author. Table 1 shows an overview of a number of bugs for each call site and dynamic feature category. As explained in Section 3, these categories were adopted from Landman et al. [8] and Sui et al. [11]. The raw results are available in our replication package10.

(1) Class::forName
• Passing an incorrect class name.
• Need to delay initialization of static blocks when initialization is not appropriate in the loading context but at the time of class use.
• Incorrect class loader specified.
• Using the wrong caller. Section 4.4 describes an example where a reflection wrapper is used.
(2) Method::invoke
• Using the wrong caller.
• Method invoked on wrong target object.
(3) Class::getDeclared|Class|Field|Method|Constructor|Name
• Trying to access a method/field that is inherited from superclasses.
• Trying to access a method/field that is declared as a public or private member.
• Using the wrong caller.
• Passing the incorrect arguments when accessing methods and constructors.
• Using the wrong method.e.g. Class::getName vs Class::
getSimpleName

| Name                | Cause                                                                 | Description                                                                 |
|---------------------|------------------------------------------------------------------------|----------------------------------------------------------------------------|
| Class::getName      | Incorrect class loader specified                                       | Passed the incorrect arguments when accessing methods and constructors.   |
| Class::getName      | Passing the incorrect arguments when accessing methods and constructors.|                                                                            |
| Class::getName      | Using the wrong caller.                                                |                                                                            |
| Class::getName      | Trying to access a method/field that is inherited from superclasses.  |                                                                            |
| Class::getName      | Trying to access a method/field that is declared as a public or private member. |                                                                            |

9https://git.io/JnS35
10https://github.com/lsiui/miningSStubs
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