

Towards Cross-Build Differential Testing

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Abstract—Recent concerns about software supply chain security have led to the emergence of different binaries built from the same source code. This will sometimes result in binaries that are not identical and therefore have different cryptographic hashes. The question arises whether those binaries are still equivalent, i.e., whether they have the same behaviour. We explore whether differential testing can be used to provide evidence for non-equivalence.

We study this for 3,541 pairs of binaries built for the same Maven artifact version, distributed on Maven Central, Google Assured Open Source Software and/or Oracle Build-From-Source. We use EVOSUITE to generate tests for the baseline binary from Maven Central, run these tests against this baseline binary and any available alternately built binaries, and compare the results for consistency. We argue that any differences may indicate variations in program behaviour and could, therefore, be used to detect compromised binaries or failures at runtime.

Although our preliminary experiments did not reveal any compromised builds, our approach successfully identified two build configuration errors that caused changes in runtime behavior. These findings underscore the potential of our method to uncover subtle build differences, highlighting opportunities for improvement.

Index Terms—test generation, differential testing, reproducible builds, software supply chain security, java, evosuite

I. INTRODUCTION

Software supply chain security has attracted increasing attention recently after a number of high impact attacks such as equifax, log4shell, solarwinds and xz [3], [9], [10], [18]. In general, these fall into two categories – compromising components (such as equifax and log4shell), and compromising processes (such as solarwinds and xz). When build processes are compromised, attackers can inject malicious code into a program, resulting in a vulnerable program built from clean source code. The classic approach to achieve this is to compromise the compiler [24].

Reproducible builds [1], [17] are a common countermeasure. The idea is to perform a second build leading to the same binary. As an adversary is very unlikely to compromise two build environments, this can confirm the integrity of the binary with high certainty. Establishing that the binaries are identical is usually done by means of bitwise comparison, often using cryptographic hashes as proxies. Several organisations have started to provide infrastructure and services to provide such secondary builds at scale, often meeting additional security-related requirements, such as SLSA compliance [2]. Two such products that include support to build Java / Maven artifacts are Google’s *Assured Open Source Software (gaoss)*¹, and Oracle’s *Build-From-Source (obfs)*².

However, there are several challenges with the reproducibility of builds: (i) build environments are difficult to replicate, (ii) locating the source code version (commit, tag or release) associated with a binary release version is not always straightforward and (iii) builds may be non-deterministic [7], [12], [15], [27]. In particular, different versions of compilers may employ different compilation strategies, resulting in different, yet functionally equivalent binaries [7], [21], [27]. In order to address this, bytecode normalisation techniques have recently been proposed [4], [21], [27].

From a security analysis point of view, the comparison of binaries from alternative builds is used to detect vulnerabilities: two different binaries may suggest that one has been compromised, for instance, by a backdoor being added during the build. A comparison based on strict binary equality is likely to result in poor precision as differences between binaries can be explained by the variability of compilers and other tools used in the build toolchain. Low precision is known to have a serious impact on the acceptance of program analysis tools by engineers [8], [20]. Using bytecode normalisation techniques such as *jnorm* [21] can help to reduce the false positive rate by identifying *equivalent* binaries. The question arises whether binaries built from the same sources that are not equivalent actually have behavioural differences. A good way to check this is to find or construct test cases to demonstrate such differences.

This is the question we set out to study. We use test case generation with EVOSUITE [11] to synthesise regression tests for a baseline build, and then assess whether these tests behave in the same way on programs that are the result of an alternative build from the same sources.

The paper is organised as follows: in Section II we describe the methodology used in our study. Results are discussed in Section III, followed by a brief overview of related work in Section IV and the conclusion (Section VI). Details on how to access the dataset used and the generated tests are provided in Section V.

II. METHODOLOGY

A. Overview

An overview of our methodology is depicted in Figure 1. As a baseline build we use the artifacts distributed on Maven Central³ as this is the default deployment repository for most open source developers. From there we obtain the binary (jar file containing Java bytecode) *mvnc jar* and the pom *mvnc pom*. From this pom we extract the *dependencies* using the Maven

¹<https://cloud.google.com/security/products/assured-open-source-software>

²<https://maven.oracle.com/public/>

³<https://central.sonatype.com/>

dependency plugin ⁴. The *mvnc jar* and the *dependencies* can then be used as input to generate *tests-sources* with EVOSUITE, which are then compiled into test binaries *tests-bin*. Finally, those tests can then be executed against the original jar *mvnc jar* and some alternative jar (from a different build) *alt jar*, and the resulting test reports can be compared.

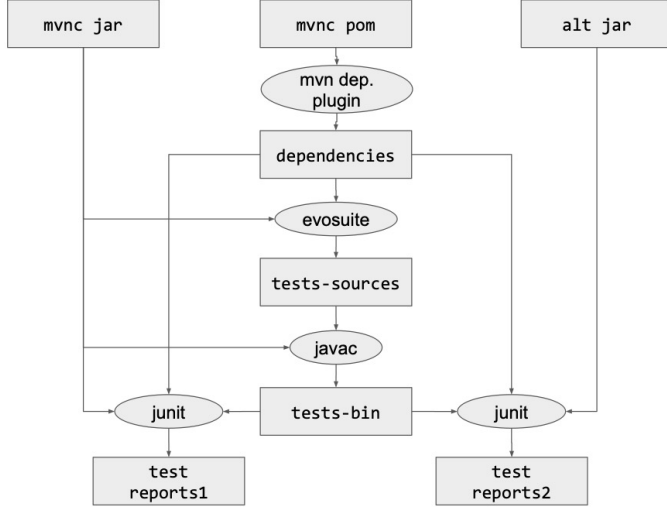


Fig. 1. Methodology Overview

B. Project Selection

We started with the dataset from [4] that contains jars corresponding to the same artifact identified by the same group id, artifact id and version (i.e., GAV coordinates) built by different parties. This dataset contains the results of builds from Maven Central (*mvnc*), Google (*gaoss*), Oracle (*obfs*) and RedHat. We ignored jars built by RedHat as they have an additional patch id that suggests behavioural differences. We only considered pairs where one of the jars was sourced from Maven Central, i.e., built by the developer(s). There are 3,541 such pairs.

C. Static Pre-analysis

We then ran a static pre-analysis to eliminate pairs that are probably equivalent. We first applied *jnorm* [21] ⁵, and compared jars by comparing the result of the transformation applied to each class; we eliminated pairs with equal *jnorm* output, resulting in 226 pairs of jars. We then added a custom comparison based on a change in the Java 18 compiler ⁶ not yet supported by *jnorm*. Applying this additional filtering resulted in 166 pairs of jars, 31 of those pairs with an alternatively built jar from *gaoss*, 135 with such a jar from *obfs*. In total there are 1,248 classes that differ between *mvnc* and one of the other two providers, which reduces to 802 after condensing classes to top-level classes.

D. Test Generation

We opted to generate tests for these experiments. The reason is that existing tests that are part of the project are usually executed during builds, i.e., alternative builds would ensure that those tests succeed.

We used EVOSUITE ⁷ to generate regression tests. While there are several alternatives available for test generation for Java programs, recent benchmarks have shown the superior performance of EVOSUITE [13] in achieving higher code coverage and mutation scores.

EVOSUITE automatically generates test cases for a given object-oriented class under test (CUT). A test case consists of (i) a method call sequence that instantiates and modifies the state of objects of the CUT through method invocations and (ii) one or more assertions that predicate on the values returned by the method invocations. The state of objects often dictates program behaviour, so manipulating these states is crucial for achieving high coverage. It is worth noting that EVOSUITE may need to create and modify objects that do not instantiate the CUT, as the methods of the CUT might require non-primitive parameters. For primitive parameters, EVOSUITE uses randomized values guided by heuristics. The tool implements an evolutionary algorithm that evolves populations of test cases to maximize code coverage, typically targeting branch coverage.

EVOSUITE and similar automated testing tools are most effective when running in regression mode due to the oracle problem. In fact, they are predominantly evaluated in this mode [13], [22]. While the oracle problem is one of the greatest challenges in test automation, it is mitigated in the context of regression testing, where we assume that one version is correct. In regression mode, EVOSUITE adds assertions to the generated test cases that capture the “implemented” behaviour of the given version. These assertions are based on the actual values returned by method call invocations during execution, without regard for the “intended” behaviour of the CUT. This approach can effectively expose behavioural differences between two implementations: if a test generated for one version fails on another version, it indicates a behavioural difference.

EVOSUITE can be set up to generate targeted tests for certain classes. Since the static pre-analysis compares *jar* files by comparing the *.class* files they contain, we can use targeted test generation for those classes only.

EVOSUITE was applied to generate regression tests for the *mvnc* version of each of these 802 differing top-level classes, resulting in 476 generated test classes comprising in total 20,437 JUnit4 tests, or 25.5 tests per differing class on average.

We ran EVOSUITE test generation per-class with all settings at their defaults, in particular with *search_budget* (generation time) set to 1 minute. ⁸ All computation was performed using a JDK 8 toolchain on an 8-core Linux Mint 21.2 VM

⁴<https://maven.apache.org/plugins/maven-dependency-plugin/>

⁵We used *jnorm* version 1.0.0, downloaded from <https://github.com/stschott/jnorm-tool/releases/tag/v1.0.0>, with the arguments `-o -n -s -a -p`.

⁶<https://github.com/openjdk/jdk/pull/5165>

⁷We used EVOSUITE version 1.2.0, downloaded from <https://github.com/EvoSuite/evosuite/releases/tag/v1.2.0>.

⁸Extending generation time to 10 minutes on a subset of classes did not generate any additional tests.

with 50GB RAM.⁹ Resource settings were informed by [13].

III. RESULTS

A. Overview

Table I shows the number of differing test outcomes for each artifact where one or more tests produced a different outcome on an alternate builds than on *mvnc*. Note that this excludes 55 test failures that occurred on *mvnc* itself.

We now discuss the found inconsistencies in detail.

B. Incorrect Build Configurations

The first kind of test outcome difference, corresponding to rows 4–11 of Table I, occurs 48 times across 7 versions of *io.undertow:undertow-servlet*, and twice “in the other direction” in *io.netty.netty-codec-http:4.1.102.Final*. We first describe the *undertow-servlet* cases.

For each of the 7 versions of the *undertow-servlet* artifact shown in Table I, there are two binaries available: the jar from *mvnc*, and an alternatively built jar from *gaoss*. In each case, when the *gaoss* jar is tested using the *io.undertow.servlet-spec.UpgradeServletInputStream_ESTest*¹⁰ test class generated from the *mvnc* jar, test failures occur, while these tests all succeed against the original *mvnc* jar.

All 48 *gaoss* test failures result from a *java.lang.NoSuchMethodError*, caused by an attempt to invoke *java.nio.ByteBuffer.flip()Ljava/nio/ByteBuffer;*. Failure counts vary across versions only because of random variation in the number of test methods that (indirectly) attempt to call this method. Concretely, for version 2.2.23.Final, the 5 failing tests are *test00*, *test01*, *test12*, *test15* and *test16*.

The errors occur during linking, and are related to binary compatibility [25]. I.e., there are call sites for this method in two *undertow* methods (*UpgradeServletInputStream.readIntoBufferNonBlocking* and *UpgradeServletInputStream.readIntoBuffer*, respectively), however, the method is missing. A closer inspection reveals that the *gaoss* version was built with Java 11¹¹. In Java 11, *java.nio.ByteBuffer.flip()Ljava/nio/ByteBuffer;* exists¹², and the respective call site is added. The *mvnc* jar was built against Java 8, where this method did not exist, causing the compiler to instead add a call site to invoke *java.nio.ByteBuffer.flip():()Ljava/nio/Buffer;*¹³.

Therefore, this issue is caused by the different JDK versions used during the build. This is surprising, as reproducing builds usually try to replicate the build environment in order to maximise the chances of the build to succeed and the resulting

binary to be identical to the binary from the build to be reproduced. In this case the engineers seem to have attempted this somehow by setting the compiler target level to bytecode version 52, which is associated with Java 8 [25, Sect. 4.1] instead of using version 55 associated with Java 11. However, they did not account for the fact that there are changes in the standard library that have an impact on how bytecode is compiled. Since Java 9 (JEP247 [16]), there is a *-release* compiler flag that can be used to avoid issues like this. It is likely that engineers used only *-target* instead. The generated tests reveal those changes.

The two *gaoss* test failures on *io.netty.netty-codec-http:4.1.102.Final* are similar, but “in reverse”: Here, it is the *mvnc* jar that was built with a newer JDK version (19¹⁴), while *gaoss* was built with JDK 8¹⁵. This time, the generated tests *expect NoSuchMethodError* to be thrown, resulting in test failure on *gaoss* when the call to *java.nio.ByteBuffer.flip():()Ljava/nio/Buffer;* completes normally.¹⁶

Table II summarises our analysis. One might expect different behaviour not revealed by tests when tests are executed with Java 11, as the call sites in these two binaries refer to different methods in the standard libraries. However, this is not the case as the Java compiler does create a synthetic *bridge method* when compiling overriding methods with covariant return types. In this case, it creates the bridge method *java.nio.ByteBuffer.flip()Ljava/nio/Buffer;* that invokes *java.nio.ByteBuffer.flip()Ljava/nio/ByteBuffer;*. This bridge method is used during the runtime resolution of the virtual call for the binary from Maven Central.

C. EvoSuite Mock Generation

We have identified three generated test classes with inconsistent behaviour between the *obfs* and *mvnc* builds for *commons-io:commons-io:2.15.0*:

- 1) *org...io.monitor.FileAlterationObserver_ESTest*
- 2) *org...io.filefilter.NotFileFilter_ESTest*
- 3) *org...io.output.UncheckedAppendableImpl_ESTest*

All of these test inconsistencies are caused by the same pattern. The *obfs* binary was built with Java 8, while the *mvnc* binary was built with Java 21. The target level for both was set to 52 (compatible with Java 8). Table III summarises the situation.

In Java 18, a subtle change occurred regarding how methods implemented in the root class (*java.lang.Object*) such as *toString*, *equals*, *getClass* and *hashCode* are invoked for interfaces¹⁷. For instance, consider the code in the following listing:

```
1 Comparable comp = ... ;  
2 comp.toString();
```

¹⁴The jar manifest contains the entry *Build-Jdk-Spec: 19*.

¹⁵The jar manifest contains the entry *Build-Jdk-Spec: 1.8*.

¹⁶Interestingly, the code paths that trigger the *NoSuchMethodError* on *mvnc* seem to occur only as a result of buggy interference between test methods: See for details.

¹⁷<https://github.com/openjdk/jdk/pull/5165>

⁹JDK 8 was used in order to improve the reliability of EVOSUITE test generation. Although EVOSUITE could sometimes generate tests under JDK 11—including for 32 CUTs that refused to compile at JDK 8—doing so produced around one third as many tests overall due to widespread failures.

¹⁰The class under test by an EVOSUITE-generated test can easily be identified by removing the *_ESTest* suffix.

¹¹The jar manifest contains the entry *Build-Jdk-Spec: 11*

¹²Though its existence is not mentioned in the documentation at <https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/nio/ByteBuffer.html>.

¹³Unlike Java source code, Java byte code supports return type overloading, and changing the return types alters the descriptor, and therefore is a binary incompatible change causing linkage errors. [6], [25]

build	artifact	test class	tests
gaoss	commons-io:commons-io:2.15.0	org.apache.commons.io.filefilter.NotFileFilter_ESTest	2
gaoss	commons-io:commons-io:2.15.0	org.apache.commons.io.monitor.FileAlterationObserver_ESTest	2
gaoss	commons-io:commons-io:2.15.0	org.apache.commons.io.output.UncheckedAppendableImpl_ESTest	1
gaoss	io.netty:netty-codec-http:4.1.102.Final	io.netty.handler.codec.http.multipart.AbstractDiskHttpData_ESTest	2
gaoss	io.undertow:undertow-servlet:2.2.23.Final	io.undertow.servlet.spec.UpgradeServletInputStream_ESTest	5
gaoss	io.undertow:undertow-servlet:2.2.24.Final	io.undertow.servlet.spec.UpgradeServletInputStream_ESTest	17
gaoss	io.undertow:undertow-servlet:2.2.25.Final	io.undertow.servlet.spec.UpgradeServletInputStream_ESTest	5
gaoss	io.undertow:undertow-servlet:2.2.26.Final	io.undertow.servlet.spec.UpgradeServletInputStream_ESTest	6
gaoss	io.undertow:undertow-servlet:2.2.28.Final	io.undertow.servlet.spec.UpgradeServletInputStream_ESTest	5
gaoss	io.undertow:undertow-servlet:2.2.31.Final	io.undertow.servlet.spec.UpgradeServletInputStream_ESTest	5
gaoss	io.undertow:undertow-servlet:2.2.32.Final	io.undertow.servlet.spec.UpgradeServletInputStream_ESTest	5
obfs	commons-io:commons-io:2.15.0	org.apache.commons.io.filefilter.NotFileFilter_ESTest	2
obfs	commons-io:commons-io:2.15.0	org.apache.commons.io.monitor.FileAlterationObserver_ESTest	2
obfs	commons-io:commons-io:2.15.0	org.apache.commons.io.output.UncheckedAppendableImpl_ESTest	1

TABLE I

NUMBER OF TESTS WITH DIFFERENT RESULTS BETWEEN *mvnc* AND ALTERNATIVE BUILDS

build	bytecode version	JDK version used to build	test results (Java 8)	test results (Java 11)
mvnc	52	8	pass	pass
gaoss	52	11	error	pass

TABLE II

TEST RESULTS FOR *UpgradeServletInputStream_ESTest* TESTS FOR *io.undertow:undertow-servlet:2.2.23*, RUNNING TESTS ON THE ORIGINAL MAVEN CENTRAL ARTIFACT AND THE ALTERNATIVE BUILD FROM *gaoss*

build	bytecode version	JDK version used to build	test results (Java 8)
Maven Central	52	21	pass
obfs	52	8	fail

TABLE III

TEST RESULTS FOR SELECTED TESTS GENERATED FOR *commons-io:commons-io:2.15.0*, RUNNING TESTS ON THE ORIGINAL MAVEN CENTRAL ARTIFACT AND THE ALTERNATIVE BUILD FROM *obfs*

Up to Java 17, this call was compiled to *invokevirtual Object::toString*¹⁸. Starting with Java 18, this call is now compiled to *invokeinterface Comparable::toString*.

This results in changes to runtime behaviour when using the EVOSUITE runtime, as EVOSUITE replaces these calls with calls to its own mocks, such as *org.evosuite.runtime.System::toString*. But this only replaces the older call pattern, not the new one.

An example of such inconsistent behaviour we have encountered is when a *toString* implementation is recursive. Then EVOSUITE generates a test with a self-referential data structure that expects a *StackOverflowError* to occur when *toString* is invoked on this data structure. However, when the mock substitution is performed by EVOSUITE, this error does not occur as the mock *toString* method is not recursive, and the test fails. I.e., the test outcome now depends on whether EVOSUITE performs the substitution or not, and this depends on the compiler that had been used.

In this case we think the misconfiguration is on the Maven Central side, where a very recent Java version has been used to create a binary compatible with Java 8, but this hasn't been configured correctly.

IV. RELATED WORK

Differential Testing [19] is an automated approach that identifies various errors by comparing the behaviour of two or more comparable systems [14], [23], [26]. In the context of object-oriented (OO) programming, notable techniques include DIFFUT [26], BERT [14], and DIFFGEN [23]. Similar to our approach, these techniques leverage the differences between two software versions to generate test cases that reveal behavioural discrepancies. However, our approach focuses on comparing binaries, which required us to design and implement specialized ad-hoc analyses.

Although the implementation details may differ, all differential testing techniques share the core idea of generating and executing the same test cases on the versions being compared to reveal behavioural differences. While differential testing has been effective in detecting semantic errors in various domains (e.g., C compilers [28] and JVM implementations [5]), to the best of our knowledge, it has not yet been applied to identify differences between alternative builds of the same program version.

V. DATA ACCESS

The pairs of jars used as input, the generated tests and raw test run reports can be found here .

VI. CONCLUSION

In this paper we have explored a novel use case for differential testing: to assess the behavioural equivalence of binaries built independently from the same source code. Our research was motivated by software supply chain security. While we did not find any evidence that components in our dataset had been compromised during the build, we did find two interesting cases of build misconfiguration.

A possible avenue for future research is to analyse other signals from test executions, namely coverage. This could still reveal differences in program behaviour not captured by the assertions in generated tests.

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tba after review

¹⁸Package names and descriptors are omitted for brevity

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