The Unsafety in Java Regression Test Selection and its Occurrence in the Wild

Lukas Döllerer

Seminar: Software Quality
Technical University of Munich
lukas.doellerer@tum.de

Abstract. Regression testing is used by developers to ensure that new revisions of a program do not negatively impact existing features. Regression Test Selection (RTS) excludes test cases from the regression test set. An RTS-tool that correctly selects all tests affected by introduced changes is called *safe*. Prior research has shown that this safety is hard to achieve. Undetected unsafety can be caused by a faulty implementation or imperfect methodology of an RTS-tool. In this study, we collected known and discovered new unsafety in the popular open source RTS-tools *Ekstazi*, *GIBstazi*, *OpenClover*, *STARTS* and *HyRTS*. We compared the tools with each other, based on reference projects that simulate sources of unsafety. To confirm the relevance of the discovered unsafety, we performed a broad analysis of its occurrence on a selection of the 100 most popular Java repositories on the GitHub platform. We were able to document 10 hypothetical scenarios that cause unsafe behavior of the examined RTS-tools. These scenarios include reflections, dependency injection, problems with runtime instrumentation and external files. All examined tools acted unsafe. Sources of unsafety were found in 88 out of the 100 scanned repositories. This leads us to the conclusion that none of the examined tools are currently ready to be safely used in production environments. Further research must combine existing knowledge and tools to develop and maintain an up-to-date implementation of RTS for Java.

Keywords: Regression Test Selection · Unsafety · Java

1 Introduction

With agile and iterative software development processes, project owners need to ensure that every new revision of their program's source code still complies with the project's specification. They need to make sure that no new bugs were introduced. Ensuring the project's ongoing compliance is increasingly complicated due to large, distributed code bases, the involvement of multiple developers and complex program structures. Regression testing is widely used to detect such regression faults by re-running existing tests to ensure that the new code changes have no negative impact on the code base.[**?**,**?**]

Executing all tests from a project's regression test suite is a time consuming task that also goes with an economical cost. Even for companies with enormous computing resources, rerunning all regression tests does not scale well. Google's Test Automation Platform (TAP) deals with an average program delivery frequency of one commit per second, resulting in 150 million test runs a day [**?**].

Regression Test Minimization, Regression Test Prioritization and Regression Test Selection (RTS) are the three major approaches identified by Yoo and Harman (2012) to reduce the computational cost of regression testing [**?**].

RTS aims to reduce the amount of unnecessarily executed tests, i.e. it excludes tests from the test suite whose outcome should not be affected by the changes. This selection process is based on information about changes in the program files and source code dependencies of tests cases. Only tests running changed code paths are selected for execution. Other test cases should not change their behavior with the new code base.

RTS-tools exist in many variations. Though, one common goal of all examined tools is to be *safe*. An RTS system which does not exclude tests that can be affected by the applied changes is called *safe* [**?**]. Any undetected changes to dependencies of tests makes the RTS-tool *unsafe*, as they open the possibility for regression faults to be overlooked by not running the corresponding test cases [**?**].

Safety is hard to proof. Although many RTS-tools claim to be safe in most cases, this safety is often only shown in experimental evidence [**?**,**?**] or in comparison to other RTS-tools [**?**,**?**,**?**]. Unsafety can be caused by methodological limitations, errors in the implementation of the tool or outdated RTS software that is no longer compatible with up-to-date library or language versions.[**?**] Even if the RTS-tool's methodology and implementation is proven to be safe in theory, unsafety can still occur through third party language extensions such as the Spring Framework.

With this seminar paper, we provide further insights into the unsafety of the following open source RTS-tools for the Java programming language: The dynamic tools *Ekstazi* [**?**,**?**], *GIBstazi* [**?**,**?**], *OpenClover* [**?**] and *HyRTS* [**?**,**?**], and the static tool *STARTS* [**?**,**?**].

The last years show a shift in the open source software community away from the examined RTS-tools, leading to an abandonment of their code bases. Even the often showcased [**?**,**?**,**?**] projects Apache CXF [**?**], Commons Math [**?**] and Camel [**?**] stop integrating *Ekstazi* into their testing process.[1]

We show the potential and problems of the examined RTS-tools to help project owners mitigate the risks and advantages of using RTS in their quality control procedures.

We were able to identify 10 hypothetical scenarios that provoke unsafe behavior of at least one of the examined RTS-tools. They include problems with reflections, dependency injection frameworks, runtime instrumentation and external files. These scenarios were not just explained and executed in laboratory conditions, but were also examined in the last 100 commits of a selection of 100 of the most popular open source GitHub repositories.

[1] The plugin was removed from Apache Camel with commit eb60743f22c2. Apache CXF and Commons Math do not document a process that involves Ekstazi and did not update the plugin since its introduction in 2014.

2 Related Work

Broad reviews and surveys of RTS techniques [?,?] evaluated theoretical approaches and combined the knowledge of existing research papers in great detail. However, they did not specify or supply an implementation and did not focus specifically on the Java programming language. This opens the possibility for discrepancies between theoretical safety and the safety of the resulting RTS-tool.

While the study behind the *Ekstazi* RTS-tool claimed to provide a safe implementation because of the proven safety of their approach, they lack a formal proof of this inference. Additionally, unsafety might be introduced by their implementation, as stated in their internal threats to validity. [?]

The *HyRTS* software paper provided a formal proof that their approach of hybrid code change transformations does not add to the unsafety of dynamic RTS. They did not evaluate the existing sources of unsafety.[?]

The papers published about the *STARTS* RTS-tool [?,?] discussed the possible safety issues of static RTS in combination with reflections and changes between compile-time and runtime dependencies. However, when experimentally evaluating the unsafety of the predecessor tools of *STARTS*, they used the *Ekstazi* RTS-tool as a reference for a safe RTS technique [?]. This assumption could lead to imprecisions in the detection of unsafety when both, *Ekstazi* and *STARTS*, acted in an unsafe manner.

Zhu and others (2019) built a framework for checking RTS-tools. They evaluated the safety, precision and generality issues of *Ekstazi*, *STARTS* and *OpenClover*. However, they focused on building a framework that automatically detects defects in the evaluated catagories. This leads to very specific findings that do not transfer to general problems with the examined RTS-tools. An exception to this observation is their discovery that none of the evaluated tools detect changes to non-Java files.[?]

It is worth noting that none of the papers published about the examined RTS-tools [?,?,?,?,?,?] evaluates the safety of their proposed tools in combination with Dependency Injection (DI) frameworks, although they are widely used in professional Java software development.[2]

3 Methodology

The examined study objects shown in Table 1 each represent a different approach to RTS. *Ekstazi* registers test case dependencies on a file-level while *GIBstazi* and HyRTS use hybrid approaches, on a module-/file-level and file-/method-level granularity. *OpenClover* performs intrusive, static code instrumentation by altering the program's source code [?,?]. The other dynamic RTS-tools perform dynamic bytecode instrumentation with an agent that intercepts and changes bytecode during the class loading process [?,?,?].

[2] Experimental evidence that supports this statement is shown in Section 4.2.

Table 1: **Study Objects:** Examined RTS-tools with their corresponding versions.

Name	Version
STARTS [?]	1.4-SNAPSHOT[3]
Ekstazi [?]	5.3.0
HyRTS [?]	1.0.1
GIBstazi [?]	3.5.7
OpenClover [?]	4.4.1

3.1 Research Questions (RQs)

The RQs for this seminar paper are the following:

- **RQ1** What sources of unsafety exist for the examined RTS-tools?
- **RQ2** What are the differences in safety of the examined tools, in the context of the previously identified sources of unsafety?
- **RQ3** How can potential for unsafety be automatically identified in code changes without dynamic program analysis?
- **RQ4** In which quantities do the identified sources of unsafety occur in real world software projects?

3.2 Identification and Documentation of Sources of Unsafety

Definition 1. *A source of unsafety consists of a combination of an existing code base S_0 and changes to the source code C. The application of the changes C to S_0 leads to the new program revision S_1. Every valid source of unsafety makes at least one of the examined RTS-tools behave in an unsafe manner. This means that either test cases whose behavior is affected by the changes C are excluded or the tool interferes with the testing process in another way that leads to unwanted deviations in the test results.*[4]

We built model Java projects for all scenarios that could be sources of unsafety.[5] We refer to these model projects as Proof of Concept (PoC) repositories. They were combined as modules in a Java project, managed by the Apache Maven software management tool. This enabled us to define a set of Maven profiles that activate the RTS-tools on a top level, reducing the configuration overhead for each submodule.

[3] This version was built from commit e1d29be2958ec27fac12e6c8611577fce5a73e40 from the tool's GitHub repository [?], because the newest version (edu.illinois:starts-maven-plugin:1.3) in the Maven Central Repository is not functional.

[4] The definition of a source of unsafety is based on the definition of safe RTS introduced by Rothermel and Harrold (1997) [?].

[5] Our supplementary material containing all model projects and experiment results can be found in [?].

All PoC repositories are executed and built using the Java Standard Edition (SE) Development Kit (JDK) version 8u291[6]. The examined tools either support this version or do not specify a supported JDK version. Besides Maven (version 3.8.3), we used the JUnit unit testing framework in version 4.12 for the dependency injection tests and in version 4.10 for all other tests. *Ekstazi* and *OpenClover* were combined with the Maven Surefire Plugin (version 3.0.0-M5) as instructed by their documentations.

The following subsections each describe potential sources of unsafety. The supplied implementation details describe the main structure of the PoC repositories that were used to test the corresponding hypotheses.

3.3 Dynamic Dispatch as a Source of Unsafety

The Java language's polymorphic type system allows the Java runtime to select a more specific implementation of a called method, if this implementation is available. This behavior was already identified to cause unsafety of the *OpenClover* tool, but was not evaluated on all examined RTS-tools [**?**].

Hypothesis H1 *Changes that lead to a different dynamic dispatch are not recognized as dependency changes. This means that changes to an object's implementation are undetected, as long as the static type of the variable storing the object is of a less specific superclass.*

Implementation 1 We created a PoC repository containing two classes. Class A that implements a method m and class B that inherits from A and does not implement the method m. A test case t initializes a variable b of type A with an instance of the class B. The test compares the return value of $b.m$ with the expected return value of $A.m$. They are equal because B does not implement m and thus no dynamic dispatch was performed. The changeset C adds the definition of a method m to class B, overwriting the inherited version from class A. This new method returns a different return value than $A.m$.

3.4 External Files as Sources of Unsafety

The examined RTS-tools concentrate on identifying code dependencies and perform test exclusion mostly based on source code changes. This however does not work with programs that have side effects and dependencies outside of their available source code. The examined tools *GIBstazi* and *Ekstazi* are, according to the their research papers, especially built for identifying such external file dependency changes [**?**,**?**].

Hypothesis H2 *Changing an external non-Java file is not correctly detected as a change of test case dependencies.*

[6]The Java SE is used by about 70% of all Java projects, with 79% of them using Version 8.

Implementation 2 We chose to test external files that are in the standard directory for program code dependency files. This directory is specified by the Maven management tool to be `src/main/resources`, while the source code should be in `src/main/java`. A test case t, directly or indirectly, reads the contents of a plain text file at `src/main/resources/test.txt` using an `InputStream` from the Java standard io library (`java.io`). The changeset C simply contains changes to the contents of the dependency text file.

3.5 Configuration Files as Sources of Unsafety

Java projects typically use `.xml` or `.property` files to configure the behavior of libraries and additional tools. Famous examples are the `pom.xml`, `gradle.properties` or `build.xml` files that configure the most popular open source Java dependency management tools Maven, Gradle and Ant [**?**]. We differentiate between external files and configuration files. The former are explicitly accessed through program code. The latter are used implicitly by external tools or libraries.

Hypothesis H3 *Changes in library versions and other changes introduced through external configuration files are not correctly recognized by the examined RTS-tools.*

Implementation 3 We simulated the update of a library dependency to a new minor version. For this example, we updated the jackson JSON parsing library [**?**] from version 2.11.4 to version 2.13.0. S_0 consists of a test case t that converts an instance of a `Thread` class' class loader to a string and asserts the outcome. To transition to S_1, we only updated the library version and did not change the source code. The new library version had introduced changes in the object to string mapping and should therefore cause the test t to fail. Though, the test case would not be executed by the RTS-tools, if H3 is true.

3.6 Reflections as Sources of Unsafety

Higher order class access through Java's meta class `Class` is often cited as a source of unsafety in regression test selection [**?**,**?**,**?**,**?**]. The STARTS RTS-tool's authors identify this reflective access as the only source of unsafety, when comparing their tool to *Ekstazi* [**?**]. The *HyRTS* tool is built, according to its authors, to overcome this weakness of static RTS by using a hybrid, dynamic approach [**?**]. Reflections are a powerful and commonly used technique. The factory pattern is an example of a common software engineering use case that often uses reflections.

Hypothesis H4 *The examined RTS-tools do not recognize reflective instantiation of a class. They do not create dependencies to objects that were created from their `Class` meta object, without explicitly importing the class.*

Implementation 4 We declared a class A that is not imported to the test case t's class file. Class A declares a method m which will later be tested. The test case t

acquires A's meta class instance via `Class.forName("A")` and stores it in a variable a. Tests are executed on a new instance of A, created either via `a.newInstance()` (deprecated since Java 9 [**?**]) or via A's constructor (`a.getDeclaredConstructor().newInstance()`). In S_1 we changed the implementation of the class A to fail test case t. The test should not be executed by the RTS-tool, though, if our hypothesis holds. It is important how we access the meta class object. Although we could also call `A.class`, this could create a solid dependency on class A, hiding any potential for unsafety.

To display a common use case of these reflective accesses, we also implemented a simple factory pattern using reflections.

3.7 Static Initializers as Sources of Unsafety

Java classes support the declaration of static initialization blocks. These are code segments that are executed once on class initialization. This process is either triggered by direct class access or by certain reflective access methods [**?**, 12.4.1].

Hypothesis H5 *RTS-tools do not monitor side effects that are caused by static initializers on class initialization. Classes initialized without a direct call to a constructor or static method can alter the program's behavior and test results without being detected.*

Implementation 5 Class A contains an uninitialized static public boolean field $A.b$. Class B declares a static initialization block that contains code that sets $A.b$ to equal $true$. The test case t triggers the initialization of B using the reflective access `Class.forName("B")`. t asserts that $A.b$ equals $true$. This is the base state S_0. For S_1, we changed the static initialization block in B to set $A.b$ to equal $false$. If H5 is true, this change of the dependencies of test case t is not recognized by the RTS-tool and t is not executed.

3.8 Dependency Injection as a Source of Unsafety

Many professional Java projects utilize the technique of DI. To reduce coupling between components of a program, an injector inserts initialized instances of required dependencies into methods, constructors and fields. This programming pattern is one possible realization of "inversion of control"[**?**]. [**?**]

DI in Java is commonly used through third party open source libraries such as Spring, Google's Guice or CDI [**?**] implementations. For the following study, we concentrate on the former two libraries, being the ones used in some of the repositories from the open source project selection, which is later introduced in Section 3.11.

Because of the strong static typing system of the Java programming language, parameters and attributes have to have a strict static type. Dependency injection libraries use Java interfaces to provide different implementation with equal signatures.

Dependencies are injected based on a mapping of implementations of interfaces to dependency identifiers. This mapping is either explicitly defined in program code or in external `.xml` configuration files. The Spring DI framework also offers automatic component scanning, automatically searching for dependency implementations in specified class paths. Methods and fields that require injection are marked using Java annotations.

Hypothesis H6 *Assume that the mapping of dependencies was explicitly defined in program code. Changes to the source code of injected dependencies can then not be tracked reliably by the examined RTS-tools.*

Implementation 6 The implementation for the Spring framework is the same as described in Section 3.8 with the difference that we do not introduce a new implementation for D in class C, but we change the source code of the implementation defined in class B.

For Guice dependency injection, no main application context is required, as dependencies are injected using an instance i of the `Injector` class. This means that it is sufficient to annotate the dependency interface D with the `@ImplementedBy (B.class)` annotation, referring to an implementation B of the interface D. Because dependency implementations need to be injected into objects, we define a helper class H that contains a Field of type D, annotated with the `@Inject` annotation. The test case t asserts the behavior of an instance of H, initialized using the `i.getInstance(H.class)` method. For S_1, we simply modify the source code of class B.

Hypothesis H7 *Assume that the mapping of dependencies was declared in an external configuration file. Then, changes to the source code and changes of the dependency mapping are not detected by the examined RTS-tools.*

Implementation 7 The hypothesis depends on the inability of the examined RTS-tools to detect changes of external files. A corresponding PoC repository was already implemented and described in Section 3.5 for hypothesis H3.

Hypothesis H8 *The RTS-tools do not track changes of injected collections of dependencies.*

Both DI libraries support automatic aggregation of multiple implementations of the same interface into a collection of implementations.

Implemenetation 8 Collection injection with the Spring framework can be achieved by choosing one of the approaches shown in Section 3.8. The type of the tested field f is changed from `D` to `Collection<D>`. The Spring framework now injects a collection of all available implementations for the dependency D into the field f. To transition to S_1, we perform the same actions as described in Section 3.8, but without annotating the new implementation with the `@Primary` annotation. The added implementation is automatically added to the injected collection, causing test case t to fail. If the hypothesis holds, this dependency change is not detected by the RTS tools.

The same principles apply to the implementation for the Guice library. Dependencies have to be explicitly bound to implementations, though. The Guice injector is configured from a subclass A of type `AbstractModule`. A possibility to add objects for the collection injection is to create multiple provider methods, returning different implementations of the injected interface D. These methods have to be annotated with the `@ProvidesIntoSet` annotation. We only declare one such provider method for the base state S_0. To transition to S_1, we just add another provider method, adding a new implementation to the injected set.

Hypothesis H9 *Dependencies collected using class path scanning without an explicit mapping are not tracked as test dependencies by the examined RTS-tools.*

Implementation 9 Automated class path scanning is only available in the Spring framework [**?**, 1.10][**?**].

Class path scanning with Spring can be achieved in two ways. For the first PoC repository, we use implicit configuration scanning. Class A in package P is the main application class, the entrypoint of a Spring application. It is annotated with the `@EnableAutoConfiguration` annotation, which is also included in the commonly used `@SpringBootApplication` annotation. Package P contains a configuration package p with a configuration class B that is annotated with the `@Configuration` annotation. The test class T is annotated with `@RunWith(SpringRunner.class)` and `@SpringBootTest(classes = A.class)` annotations to enable dependency injection. Test case t asserts the behavior of a field f. This field is annotated with the `@Autowired` annotation. Spring automatically injects the dependency D whose implementation is defined in class B. To transition to S_1, we declare another configuration class C in package p. This class defines an alternative implementation of D and markes it with the `@Primary` annotation. This way, it is prioritized over other alternatives. This new implementation C of D should make t fail on execution.

Another option for class path scanning with Spring is to replace the `@EnableAutoConfiguration` annotation of class A with a `@Configuration` and `@ComponentScan("P.p")` annotation. This avoids the overhead produced by a full Spring Boot application. The test class T does not need any annotations any longer, because we use the `AnnotationConfigApplicationContext(A.class).getBean(d.class)` function in t to retrieve implementations for dependencies. The transition to S_1 stays the same, with the same expected test outcome.

3.9 Runtime Instrumentation as a Source of Unsafety

The examined dynamic RTS-tools need to collect their dependency information during execution. They use different instrumentation mechanisms to capture call trees and resource accesses. *Ekstazi* and *HyRTS* both perform dynamic runtime instrumentation by augmenting java bytecode during class loading [**?**,**?**,**?**]. *OpenClover* on the other hand performs static runtime instrumentation by inserting additional instrumentation code into the java source files [**?**,**?**].

Hypothesis H10 *Runtime instrumentation leads to differences in test results when executing the code with or without the dynamic RTS-tools. Although this does not concern dependency collection, every undesired deviation of test results is treated as unsafe behavior, according to the definition 1.*

Implementation 10 To showcase the problems with runtime instrumentation, we combined already discovered problems of *OpenClover* [**?**] with additional problems caused by its alterations to the compiled class files. We also found incompatibilities of the used *Ekstazi* version with the new methods introduced in the `Class` meta class with Java 8. The problems are caused by a monitoring class that *Ekstazi* injects during class loading for method calls on the `Class` meta class. We call the set of method calls that are affected M_{CL} (documented in table 4). For testing the hypothesis on the identified methods, we create a test case for every method $m \in M_{CL}$.

3.10 Evaluation of Proof of Concept Repositories

The process of RTS depends on a set of changes of the program code. Therefore, we run every model project's tests twice. Once with the base state S_0 and once with the changed version S_1 to simulate creating a new revision. We started by running each PoC repository's tests before (S_0) and after (S_1) the simulated changes were applied without any activated RTS-tools. This dry run yields two test reports that were later used to identify deviations from the expected outcome when testing with activated RTS-tools.

Using the earlier mentioned Maven profiles, we executed both revisions' tests (S_0 and S_1) of every PoC repository with every RTS-tool. The test runs supplied all data required to filter out the valid sources of unsafe behavior. A repository implements such a valid source if at least one of the examined tools caused a test result that differs from the dry run result.[7]

With the filtered PoC repositories, we had a solid overview of the most important cases that induce unsafe behavior of the examined RTS-tools. This however does not yet show the impact of this unsafety in practical software engineering projects as we could have identified purely hypothetical sources of unsafety that do not occur in everyday programs.

3.11 Search for Unsafety in Open Source Projects

Project Selection In order to estimate the impact of the discovered sources of unsafety on real world software engineering, we performed a broad automated search over the most popular open source Java projects on GitHub. The base set of projects was acquired with the Python library PyGithub which uses the GitHub REST API as a data backend [**?**]. The result was then further filtered.

To be included in the final set of the 100 examined projects, a repository has to meet the following criteria:

---

[7] Apart from the difference caused by the test cases that were intended to be excluded by the tools.

- Over 50% of the repository's content has to be Java program code.
- The last code changing activity was after or on the 06/01/2020.
- The repository is not forked from another repository.
- The repository has at least 100 stars[8].
- The repository contains a branch called "main" or "master"[9], having a history of least 101 commits. This branch is considered to be the default branch.
- The repository is not archived.
- The repository is publicly accessible and readable.
- The description of the repository does not contain the words "tutorial", "example" or "sample".
- The repository contains a Maven configuration file ("pom.xml") in its root folder.

In addition to these criteria, we also excluded repositories that contained too few JUnit test cases, as these repositories do not represent serious software development projects. This criterion for project selection is common in research and was also used for evaluating the Ekstazi RTS-tool [?]. We therefore examined the state of the repository at 100 commits before the current default branch's latest commit and counted all appearances of the keywords `@Test` for JUnit 4 and 5 test cases and `extends TestCase` for JUnit 3 test cases. We are aware that we might underestimate the amount of JUnit 3 test cases with this method. However, other means of counting would make this filter unnecessarily complicated and 100 test cases are already an arbitrarily chosen, lower limit which should be easily exceeded.

The remaining set of software projects was sorted by the amount of stars, which users attributed to the projects. We included the top 100 projects of the resulting list in the further study.

Commit Selection We searched for the previously identified patterns for sources of unsafety in a filtered subset of the latest commits in the selected projects. Only the latest 100 commits on the default branch of the repository (which introduce new changes) have been selected.

Automated Repository Scanning Not all identified sources of unsafety are detectable using a simple and efficient scanning technique, without performing a dynamic analysis of the projects. We opted not to perform such a dynamic, in depth analysis. Most of the previously collected scanning candidates are not executable without individual configuration. Sorting out projects that do not work with dynamic analysis tools artificially filters the pool of examined projects, distorting the study's results.

We also did not scan for changes of configuration files, as these must occur at some point in every selected repository, making an in-depth analysis unnecessary.

[8] Stars are a measure of popularity on the GitHub platform. Users can attribute stars to repositories to show their appreciation or to store the project in their list of starred projects for later reference.

[9] GitHub, together with many other software projects [?], decided in 2020 to revise offensive or inappropriate technical terms. The hosting provider changed its default git repository branch name from "master" to "main" [?].

For the efficient scan of the open source projects, we built a modular Python application. Scanner modules are classes that receive a commit and decide whether this commit should be treated as a source of unsafety. The main application iterates over the set of projects and their commits. Using the PyDriller library [?], we clone every project's repository. To recreate the project state after each commit, we use the PyDriller git integration to programmatically check out each commit. Then, we call each scanner module to test for its source of unsafety in the program files. This process is repeated for the latest 100 commits of the previously selected 100 projects. The results are collected as `Dataframes` and stored in `.csv`-files via the pandas data manipulation library [?].

We created the following scanner modules to automatically detect sources of unsafety:

- **External Files:**
  This scanner reports a source of unsafety if a file was changed in the commit and its file path lies in either a resources or filter directory. These directories' paths were chosen according to the directory layout recommended by the Maven software management tool [?].

- **Dependency Injection:**
  The dependency injection scanner holds a set of regular expressions. They identify keywords that are required for unsafe behavior with either the Spring or the Guice framework (Table 3). We search for these expressions in the changed lines of Java source code of each commit. Every match is a potential source of unsafety, as it may not be recognized by one of our examined RTS-tools.

- **Runtime Instrumentation:**
  We perform a search for problematic methods which were found in the evaluation of Section 3.9 (Table 4). With the program state right after the commit checked out, we read every Java code file in the project's directory and test if it contains one of the affected methods. This gives an overview over the commits that are not able to run with the problematic tools enabled.

- **Reflections:**
  Although reflections are especially problematic, changes to reflectively accessed source code are hard to automatically detect. The class paths for reflective accesses are often only evaluated at runtime, e.g. with the factory pattern. That is why we focused on detecting whether a project contains reflective accesses at all. This was done using a regular expression that detects `Class.forName` method calls. In a second step, we attempted to detect changes to classes that are actually accessed using reflections. As explained, this is not a trivial task. Our solution only supports hard coded class paths, leading to rather conservative estimations and incomplete evaluation results.

4 Evaluation

4.1 RQ1 & RQ2: Sources of Unsafety for the Examined RTS-Tools

Using the PoC repository approach described in Section 3.2, we were able to test all proposed sources of unsafety with the examined RTS-tools. The results are shown in Table 2. We evaluated the Spring and Guice DI frameworks separately, because their different implementations lead to different test results. Hypothesis H7 was not tested separately, because the PoC repository for hypothesis H2 and its tests already cover external file changes as sources of unsafety. This superset of unsafety already includes unsafety from changed external configuration files for dependency injection.

While executing the testing procedure described in Section 3.2, we came across more problems with some of the examined tools that prevented us from collecting all test results. [10] [11] [12] These problems have the potential of leading to sources of unsafety themselves and should therefore be the subject of further studies.

Most of the presented sources of unsafety are undocumented for the examined tools. The *STARTS* tool documented problems with reflections [**?**] as their only known source of unsafety in comparison to the *Ekstazi* tool. That is the reason why especially unsafety occurring with the *Ekstazi* RTS-tool poses a great risk. Studies about newly developed RTS-tools often use it for comparisons of their selected test sets to determine their tool's safety and precision.[**?**,**?**,**?**,**?**].

In contrast to the paper published about the *Ekstazi* tool [**?**], our research shows that even the latest version of the RTS-tool is not able to track changes in external files and configuration files. The tool's published source code contains a disabled `FileRecorder` class that could be used to replace Java's default `SecurityManager` class. However, when we manually activated and tested[13] this supposedly linux-specific feature, Ekstazi was still not able to detect file access via `java.io` or `java.nio` functions. This file recording feature is disabled by default and not shipped with the RTS-tool.

GIBstazi, being a wrapper that mainly combines the GIB tool with RTS performed by *Ekstazi*, inherits most problems that occur with *Ekstazi*. External files however are detected, because *GIBstazi* executes all tests from a module if an external file was modified [**?**]. Besides that, the included, outdated version of *Ekstazi* leads to additional problems with modern test runners.

[10] The version of *Ekstazi* that is used by *GIBstazi* does not support method calls to `Class.getTypeName(...)`. *GIBstazi* therefore cannot run tests using the JUnit test runner `SpringRunner` required for testing Spring framework functionality.

[11] *OpenClover* cannot detect tests run with the `SpringRunner`.

[12] The latest version of *Ekstazi* (version 5.3.0) is incompatible with the latest version of Guice (version 5.0.1). This problem with *Ekstazi* is evaluated separately in Section 3.9. All tests with *Ekstazi* and the Guice framework therefore use Guice version 4.2.3, which is currently the latest version that is supported by *Ekstazi*.

[13] These specific tests were executed with the Java SE JDK Version 8, running on an Ubuntu 21.10 operating system with the 5.13.0 Linux Kernel.

Table 2: Test results of PoC repository tests, uncovering sources of unsafety in examined RTS-tools.

Hypothesis	*Ekstazi*	*GIBstazi*	*OpenClover*	*STARTS*	*HyRTS*
H1: Dynamic Dispatch	×	×	✓	×	×
H2: External Files	✓	×	✓	✓	✓
H3: Configuration Files	✓	×	✓	×	✓
H4: Reflections	×	×	×	✓	✓
H5: Static Initializers	✓	✓	✓	✓	✓
H6: Dependency Injection (Spring)	×	⚠[10]	⚠[11]	✓	×
H6: Dependency Injection (Guice)	×[12]	×[12]	×	✓	×
H8: Collection Injection (Spring)	✓	⚠[10]	⚠[11]	✓	✓
H8: Collection Injection (Guice)	×[12]	×[12]	×	×	✓
H9: Spring AutoConfiguration	✓	⚠[10]	⚠[11]	✓	✓
H9: Spring ComponentScan	✓	✓	✓	✓	✓
H10: Runtime Instrumentation	✓	✓	✓	×	×

Legend:
×: The hypothesis does not hold, the tool is not susceptible to this source of unsafety;
✓: The hypothesis does hold, this tool is unsafe;
⚠: No usable result was produced.

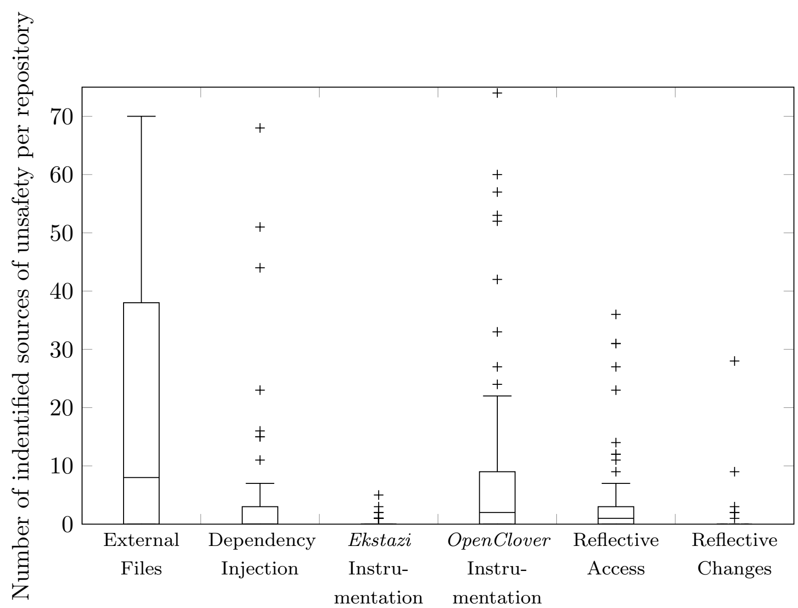
4.2 RQ3 & RQ4: Sources of Unsafety in the Wild

With the commit scanners defined in Section 3.11 we were able to detect several previously described sources of unsafety in open source projects in the wild. Out of the 100 examined projects, 88 included a source of unsafety in their 100 latest commits. 8 of these repositories even contained each of the searched sources of unsafety at least once. An overview of the number of sources of unsafety discovered in each project is shown in Figure 1.

Figure 2 visualizes the composition of sources of unsafety on a commit-level. Unsafety produced by runtime instrumentation is not included in the graphic. It is not caused by changes introduced in a commit, but by the underlying code base that contains the problematic method calls. We also only recorded all appearances of the `Class.forName(...)` method call for every commit without explicitly documenting the changes between commits. We used this data to infer changes between commits, which also means that we do not have change data for the first scanned commit of every repository.

External Files With this scanner, we identified a total of 989 commits that change an average of 11.85 external files in the searched paths. The commits change, on average, 1993.59 lines of text in the external files. This number only includes changes on external files whose content is versioned via git. Even though most of these file changes may not change the program's behavior, they all are sources of unsafety, because their changes are not detected by most of the examined RTS tools.

Fig. 1: Sources of unsafety per repository, discovered in repositories and commits collected in Section 3.11. (Removed outliers above 75 sources of unsafety. The full diagram is shown in Figure 3)

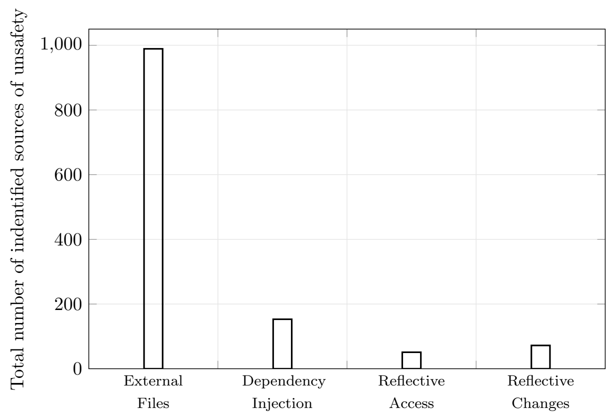


Dependency Injection (DI) Of the 100 examined projects, 53 depend on libraries from the Spring framework, 17 on Guice libraries, 5 on the CDI DI implementation and 3 on the Dagger DI framework. This shows that DI is an important factor in evaluating the unsafety of RTS-tools.

For in-depth scans, we concentrated on Spring and Guice DI features. We recorded 484 changes on Spring-related and 297 changes on Guice-related keywords (listed in Table 3). None of the examined repositories uses Guice in combination with the Netflix Governator library that allows for automatic classpath scanning.

Runtime Instrumentation This scanner identified 63 programs whose behavior changes due to the profiling and coverage approaches used by *Ekstazi* and *OpenClover*. 11 repositories contain code that cannot be executed with *Ekstazi*'s runtime instrumentation enabled. *OpenClover* changes the behavior of code in 49 repositories. 3 projects contain code that is affected by both tools. With, on average, 14.80 incompatible files per affected repository, this source of unsafety normally renders the corresponding tool unusable for the project. Though, if the repository still uses the tool, the resulting differences in test results can cause correctly failing tests to pass and vice versa.

Fig. 2: Absolute number of commits that contain the associated source of unsafety (over all projects).



Reflections We mainly scanned for appearances of the `Class.forName(...)` method call that is the main reason for most reflection-related unsafety. Other methods of reference to meta class instances require a static method call on the class that creates a solid dependency. 56 of the projects use this method at least once, but in general between 1 and 36 times. We counted 333 occurrences across all repositories. In addition to this search, we also tried to follow the loaded class paths and detect changes on these classes that loaded via reflections. The problems with this approach are described in Section 3.11. We were able to detect a total of 72 changes on classes that are loaded via reflections in 8 projects. These changes are undetected by *STARTS* and *HyRTS*. Their static initialization is also undetected by all examined tools, making them a major, so far undocumented source of unsafety.

5 Discussion

Maintenance Many of the problems and sources of unsafety introduced by the examined RTS-tools are caused by incompatibilities of the tools with modern language features. Especially *Ekstazi*, being one of the most promising examined tools, is outdated and cannot be used in projects in its current state. This abandonment of RTS-tools, such as *HyRTS*, *Ekstazi* and *GIBstazi*[14], leads to a market full of unusable RTS solutions. Research should focus more on updating and improving existing open source solutions than developing new projects from scratch that are not going to be maintained.

Usability of the Examined Tools Looking at the discovered sources of unsafety and their occurrence in current Java software development, it is clear that none of the

[14] *STARTS* has recently been maintained and is therefore not considered abandoned.

examined tools should be used without in-depth knowledge of their downsides. Because of the continued maintenance on the *STARTS* program, we see high future potential in this static RTS-tool. However, the current latest official release (version 1.3) is not functional. The previously described state of dynamic RTS for Java is alarming. The examined tools are all poorly maintained. The most up-to-date tool is *OpenClover* with its last release in October 2019. The dynamic tools also act surprisingly unsafe, compared to the possibilities they have for monitoring changes.

5.1 Limitations

This paper does not claim to include all sources of unsafety that occur when using one of the examined tools. They may contain bugs that we did not find. Other external tools or libraries, for example other DI frameworks than Spring or Guice, could also cause undiscovered unsafety. We concentrated on evaluating the major causes of unsafety that are likely to occur in real world software projects.

The results of the repository scanning are limited by the number of scanner modules, our methodology and the selection of projects. We did not scan for all discovered sources of unsafety. Our scanning approach trades simplicity for accuracy, meaning the results are prone to including false positives and false negatives. Every line of text in a Java source code file was treated as runnable code, only plaintext files were analyzed. Many well known Java projects were excluded from this study, because we use the GitHub stars feature to determine the popularity of projects and they did not have enough stars to be included in the top 100 repositories.

We excluded all projects that do not use the Maven build system. This was necessary to enforce a uniform project structure for the external files scanner module. The Maven tool is used by approximately 60% of all Java projects [**?**], making it a viable prerequisite for scanned projects.

6 Threads to Validity

External The examined study objects are a selection of currently available RTS-tools for the Java programming language that may not fully represent the capabilities and problems of other existing tools. We chose this selection of promising static and dynamic RTS solutions based on their occurrence in other studies and software projects. The repository selection of the 100 projects that were scanned may also limit the generalizability of the results. For this reason, we have chosen the repositories base on their popularity and not based on other research papers or external sources, like it was done in previous research [**?**,**?**,**?**].

Internal PoC repositories and automatic scan scripts may contain bugs. To mitigate this risk, we performed tests on PoC repositories manually and multiple times to identify flaky and buggy behavior. The code for the evaluation of scan results was written twice in different ways to eliminate logical programming errors. We only used well maintained, popular open source libraries for the git integration and data manipulation to reduce the risk of hidden errors in third party code.

7 Conclusions

The presented evidence uncovers the alarming situation of safe RTS-tools for Java. Through a combination of incompatibilities with new language features, methodological limitations and implementation errors, the examined RTS solutions are prone to act in an unsafe manner. The latest versions of the examined tools are all not safely usable in software projects. Further research is required not to create new, supposedly safe RTS-tools that end up like our study objects, but to update the most promising solutions and eliminate existing bugs. An up-to-date open source implementation of safe RTS for Java will show that RTS is achievable and has great potential for saving time and processing resources, without compromising regression test safety.

A Appendix

Table 3: Keywords required for unsafety in dependency injection.

Spring Framework		Guice Framework	
Keyword	Regular expression	Keyword	Regular expression
`@Bean`	`@Bean`	`@AutoBindSingleton`	`@AutoBindSingleton`
`@Component`	`@Component`	`@Provides`	`@Provides`
		`@CheckedProvides`	`@CheckedProvides`
		`@ProvidesIntoSet`	`@ProvidesIntoSet`
		`@ProvidesIntoMap`	`@ProvidesIntoMap`
		`@ProvidesIntoOptional`	`@ProvidesIntoOptional`
		`bind(...)`	`bind\(.*\)`
		`LifecycleInjector`	`LifecycleInjector`

Table 4: Methods whose behavior changes with the corresponding RTS-tools runtime instrumentation. All methods are called on the meta class object of type `Class`.

Ekstazi	*OpenClover*
`getAnnotatedInterfaces()`	`getDeclaredClasses()`
`etAnnotatedSuperclass()`	`getDeclaredFields()`
`toGenericString()`	`getClasses()`
	`getFields()`

Fig. 3: Sources of unsafety per repository, discovered in repositories and commits collected in Section 3.11 (Including all outliers).

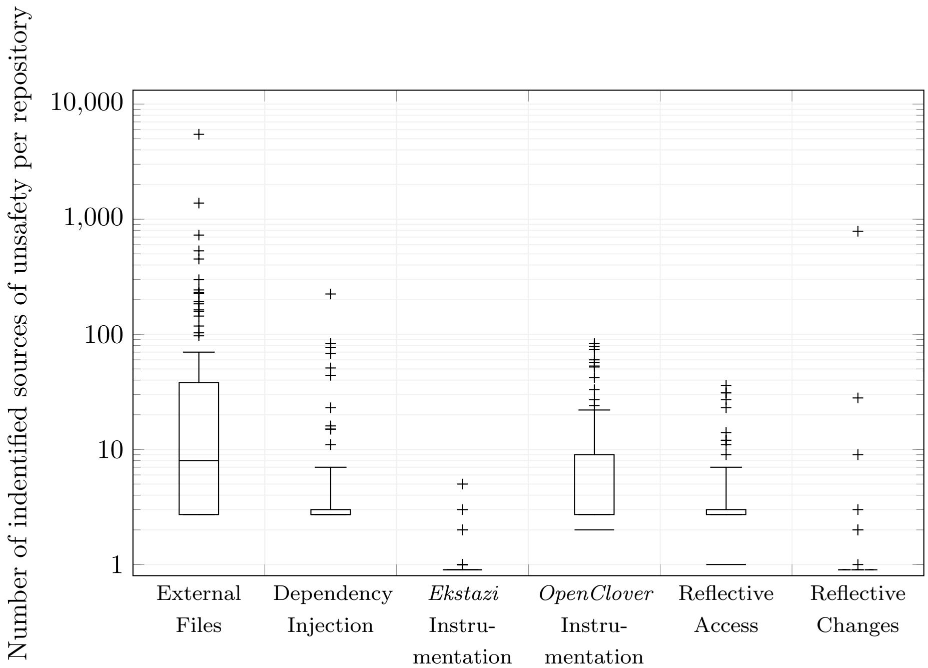


Table 5: List of selected open source projects. (Collected between 11/11/2021 and 11/13/2021)

Organisation / User	Repository Name	Stars	Last examined commit hash (truncated)
iluwatar	java-design-patterns	71106	2674cb9523a6
google	guava	42835	a2bbcc3bc2b4
apache	dubbo	36435	ae6c6a9a9ab1
zxing	zxing	28624	c25029d29ad2
eugenp	tutorials	28091	41c8af76d2c9
netty	netty	27936	3d6bed01cd07
alibaba	arthas	27624	3792ca308785
apolloconfig	apollo	25882	02fff624870a

Organisation / User	Repository Name	Stars	Last examined commit hash (truncated)
alibaba	druid	24749	3b4e77034a62
xkcoding	spring-boot-demo	23941	f10dc0a45be8
alibaba	fastjson	23926	869746101f6d
dbeaver	dbeaver	23148	2e1a4eda8b07
alibaba	easyexcel	21750	f8fd5f0427f0
alibaba	canal	21143	b54bea5e3337
seata	seata	21111	5ddfbc1f3cb7
alibaba	spring-cloud-alibaba	20593	8bd5a8d688d4
alibaba	nacos	20257	5a4d433970be
google	gson	20255	6e06bf0d89ad
apache	skywalking	18107	b63008c61e1f
jenkinsci	jenkins	18057	09f0269e8762
alibaba	Sentinel	17814	0a34fc4d1139
redisson	redisson	17747	fdcb943828c5
apache	flink	17519	1529b78ddc4a
mybatis	mybatis-3	16455	a2cdac6f7664
brettwooldridge	HikariCP	15981	8b4a6bbebb77
apache	rocketmq	15852	df4e98855d46
openzipkin	zipkin	14868	b6a5f76c4d13
apache	shardingsphere	14825	c2c51985437e
prestodb	presto	12808	70f8f59e0889
eclipse-vertx	vert.x	12482	3c494da0a4a8
YunaiV	SpringBoot-Labs	12249	85c7322b9d1a
eclipse	deeplearning4j	12244	a12d6eecbc61
apache	hadoop	12081	7bc78ab70790
pinpoint-apm	pinpoint	11801	15577df66448
apache	druid	11335	6f6e88e02ed0
pagehelper	Mybatis-PageHelper	10763	4b0484662bae
google	guice	10532	0ce94279a16d
keycloak	keycloak	10508	2f8c5dd05e74
thingsboard	thingsboard	10358	f2974532c607
codecentric	spring-boot-admin	10331	2076c6ac1d85
OpenAPITools	openapi-generator	10276	70737fb1e6b6
redis	jedis	10127	253664ff1eac
apache	zookeeper	9962	864b8a7c8044
apache	pulsar	9880	2c4d913c4b3f
square	javapoet	9255	88517888277e
perwendel	spark	9209	54079b0f95f0
MyCATApache	Mycat-Server	9140	92174cd734f1
jhy	jsoup	9122	46b0b9569a76
quarkusio	quarkus	8816	0f896210478b
TooTallNate	Java-WebSocket	8558	bcfc9675d611

Organisation / User	Repository Name	Stars	Last examined commit hash (truncated)
OpenRefine	OpenRefine	8481	8d06810af85a
stanfordnlp	CoreNLP	8219	0f7c464edc7c
junit-team	junit4	8213	7167b23b3ba7
Activiti	Activiti	8159	f9351cc5b978
dropwizard	dropwizard	8054	684c51ecbf43
square	moshi	7744	954ca46b9ed9
OpenFeign	feign	7607	f21d32a7d9d9
apache	shardingsphere-elasticjob	7320	49506b53cbfa
signalapp	Signal-Server	7210	aaa2a6eef17f
vipshop	vjtools	7182	4c1ee2a312b7
questdb	questdb	6915	883474bd7513
alibaba	otter	6893	7f80d17d74e5
apache	dolphinscheduler	6702	daf21b09dd94
abel533	Mapper	6658	84e33f7c9e11
NLPchina	elasticsearch-sql	6539	4b1c87eb1cfe
Angel-ML	angel	6437	0e60cddf5efa
checkstyle	checkstyle	6337	b6e54419d8bd
apache	storm	6297	f481eaf043db
NanoHttpd	nanohttpd	6118	efb2ebf85a2b
Graylog2	graylog2-server	5890	4ddbc427df79
AsyncHttpClient	async-http-client	5854	c959fa0483ad
google	error-prone	5749	f10bba5891d9
weibocom	motan	5746	f9c46071eafc
sohutv	cachecloud	5674	f9dfc98eadcf
debezium	debezium	5625	39ecc4e73248
joelittlejohn	jsonschema2pojo	5608	4d00331095a1
rest-assured	rest-assured	5584	4eeb3d82b1d4
lets-blade	blade	5563	118d856b53bd
languagetool-org	languagetool	5535	a76e5ab4938c
apache	zeppelin	5478	cd09f93b0d71
apache	incubator-shenyu	5463	2f5cc73fb7f5
karatelabs	karate	5383	14807dbf8d7c
pentaho	pentaho-kettle	5336	b79362de3e19
Alluxio	alluxio	5300	b9681d4ec598
scribejava	scribejava	5218	124745961e99
JodaOrg	joda-time	4723	e9337f0c0955
quartz-scheduler	quartz	4706	cbce9b6d0669
hazelcast	hazelcast	4611	d05be9ecf18d
raphw	byte-buddy	4601	7402e597870d
confluentinc	ksql	4598	0de5dda35ccc
mapstruct	mapstruct	4567	735a5bef6a36
flowable	flowable-engine	4562	f7323c2b0424

Organisation / User	Repository Name	Stars	Last examined commit hash (truncated)
gephi	gephi	4503	db454c59cc9d
spring-projects	spring-security-oauth	4484	2b58aafecac3
spring-cloud	spring-cloud-netflix	4483	dc45b7f580fa
sofastack	sofa-boot	4405	f65941f97fb9
orientechnologies	orientdb	4378	3a394ef87dc4
trinodb	trino	4368	a836e7c223b1
lettuce-io	lettuce-core	4262	b0a392f606d9
apache	hbase	4260	8458e44a1a7d