A Systematic Comparison of Two Refactoring-aware Merging Techniques

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Abstract—Dealing with merge conflicts in version control systems is a challenging task for software developers. Resolving merge conflicts is a time-consuming and error-prone process, which distracts developers from important tasks. Recent work shows that refactorings are often involved in merge conflicts and that refactoring-related conflicts tend to be larger, making them harder to resolve. In the literature, there are two refactoring-aware merging techniques that claim to automatically resolve refactoring-related conflicts; however, these two techniques have never been empirically compared. In this paper, we present RefMerge, a Java re-implementation of the first technique, which is an operation-based refactoring-aware merging algorithm. We compare RefMerge to Git and the state-of-the-art graph-based refactoring-aware merging tool, IntelliMerge, on 2,001 merge scenarios with refactoring-related conflicts from 20 open-source projects. We find that RefMerge completely resolves 143 (7%) merge scenarios while IntelliMerge resolves only 78 (4%). We additionally conduct a qualitative analysis of the differences between the three merging algorithms and provide insights of the strengths and weaknesses of each tool.

Index Terms—conflict resolution, refactoring, software merging, revision control systems

1 INTRODUCTION

Version control systems (VCS) play a crucial role in enabling software developers to collaborate on large projects. Whether developers are working on the same branch \[1\], using branch-based development \[2\], or using pull requests to contribute changes from their external forks \[3\], integration issues can arise when they push their changes to the repository. When two developers try to contribute different changes to the same part of the code, a VCS reports a merge conflict. Developers then need to spend time and effort understanding and resolving the reported conflict. Previous work found that merge conflicts occurred more than 34% of the time and could sometimes take several days to resolve \[4\]. Even worse, existing merge tools cannot detect every merge conflict; such conflicts might not be discovered until building or testing and may even be released in software products, causing unexpected behavior \[5\].

Most modern version control systems, such as Git \[6\], Mercurial \[7\], or SVN \[8\], treat all stored artifacts as plain text and merge files line by line. When two different changes happen to the same line of code, a textual line-based merging tool (often referred to as an unstructured merge tool \[9\]) will report a conflict since it cannot automatically decide which change to choose. However, depending on the semantics of these code changes, automated resolution may still be possible if a tool understands the nature of the code change that occurred \[10\], \[11\].

Refactorings are code changes that modify the structure of the code to improve its readability or maintainability without altering its observable behavior \[12\]. Refactorings are one example of a code change with well-defined semantics that an automated merge-conflict resolution tool can understand and resolve \[10\], \[13\], \[14\], \[15\]. For example, if on one branch, Bob refactors method foo by moving it from one class to another while Alice, on another branch, adds a line of code to foo’s body, an unstructured merging tool will report a merge conflict because Bob and Alice changed the same line of code. However, a merge tool that is aware of the semantics behind these refactoring changes could add the line of code to foo and then move foo to the other class. Thus, understanding the semantics of refactorings could result in more precise merging results, avoiding unnecessary merge conflicts. A recent study found that 15 of more than 70 known refactorings are involved in 22% of merge conflicts and tend to result in larger conflicts \[13\]. The considerable portion of merge conflicts that refactorings complicate motivates the need for automated merging tools that can handle refactorings.

While there are several research efforts that work on understanding the structure of the underlying code to automate more merge-conflict resolutions \[11\], \[16\], \[17\], \[18\], \[19\], \[20\], \[21\], there are mainly two efforts that specifically focus on refactorings. The first is by Dig et al. \[15\] that proposes an operation-based refactoring-aware merging technique. The premise of their technique is that if the version-control history records operations (i.e., the types of code changes that occur instead of simple textual changes), then we can leverage these refactoring operations in the history to resolve conflicts. To that end, their technique relies on developers using their operation-based version control system, MolhadoRef. At a high level, given two branches to be merged, the technique would first invert refactorings on both branches, textually merge the refactoring-free version of the code, and then replay the refactorings on the merged code. Their evaluation, based on one project, shows a 97% reduction of merge conflicts. However, recently, Shen et al. \[14\] argued that such an operation-based technique has its limitations, because certain complex refactoring types, such as extract method, cannot easily be inverted. Instead,
they propose IntelliMerge, a graph-based refactoring-aware approach. IntelliMerge converts code on both branches to graphs, and does a graph-based three-way merge (i.e., considering the common ancestor of both branches too) where it tries to match nodes across the three versions. This node matching is based on a set of predefined rules that are meant to capture refactoring semantics along with a similarity score threshold. The authors evaluate IntelliMerge on 10 projects and report 88% and 90% precision and recall, respectively, when compared to the resolution committed by developers. While the results reported by both these techniques in their respective publications is promising, they have never been directly compared to each other. Given the merit of solving merge conflicts when refactorings are involved, we believe a direct comparison will shed light on the strengths and weaknesses of these techniques. Such insights can help push the state of the art of refactoring-aware merging techniques further.

In this paper, our goal is to compare these two techniques on real-world projects that use Git as their version control system, since it is the most popular version control system used by practitioners [22]. However, while IntelliMerge has a publicly available implementation, Dig et al.’s approach [15] does not. Even if such an implementation is available, the reliance on MolhadoRef is a major deterrent to the application of this merging technique in practice. Thus, we first develop and present RefMerge, an operation-based refactoring-aware merging tool that works with Git history. RefMerge is a re-imagined design and implementation of Dig et al.’s work [15]. RefMerge follows the same approach of reverting and replaying refactorings, but has the following key novelties to enable a practical evaluation: (1) RefMerge directly works on top of Git and does not rely on the version control system already storing operations in its history, (2) to detect refactorings, RefMerge uses the state-of-the-art refactoring detection tool, RefactoringMiner [23] which does not rely on similarity thresholds, (3) RefMerge supports merging changes with the most complex types of refactorings that challenge the idea of operation-based merging, specifically ExtractMethod and InlineMethod, and finally (4) we evaluate RefMerge on a large scale. In summary, this paper makes the following contributions:

- An open-source design and implementation [24] of operation-based refactoring-aware merging, RefMerge, built on top of Git and which covers 8 refactoring types, including two complex refactorings that complicate conflicts [13], Extract Method and Inline Method.
- A large-scale quantitative comparison of the effectiveness of operation-based refactoring implemented in RefMerge versus graph-based based refactoring implemented in IntelliMerge. Our evaluation includes 2,001 merge scenarios from 20 open-source projects.
- A systematic qualitative comparison of the strengths and weaknesses of both techniques through a manual analysis of their results across a sample of 50 merge scenarios.
- A discussion of how refactoring-aware merging can be improved based on the identified strengths and weaknesses of the two techniques.

Overall, our evaluation results show that while IntelliMerge reduces the number of refactoring conflicts a developer needs to deal with, graph node matching errors and the reliance on a similarity score cause IntelliMerge to highly increase the number of false positives and false negatives. On the other hand, RefMerge is able to handle its supported refactorings well while reporting only a couple false negatives. However, RefMerge sometimes introduces conflicts while inverting refactorings due to move-related refactorings. Our findings shed light on how both refactoring-aware approaches can be improved and we recommend adding support for more refactorings with operation-based merging. Our complete replication package is available online [24]

2 BACKGROUND AND MOTIVATING EXAMPLE

To introduce the terms we use, we briefly describe how merging works in Git. We also provide an example to motivate the need for refactoring-aware merging techniques.

2.1 Software Merging in Git

A merge scenario occurs when developers using Git need to integrate changes they separately worked on in different branches. The merge tools that are commonly utilized by VCs such as Git use three-way merging techniques [25]. In three-way merging, two versions of the software are merged by making use of these versions’ common ancestor, which is the common version of the code the two versions originated from before they started diverging. When merging two branches, Git attempts to merge the most recent commit on each branch, which we refer to as the parent commits, using the common ancestor of these commits, which we refer to as the base commit. The result of the merge is stored in a merge commit. An example of a commit history leading to a merge commit is shown at the top left corner of Figure 2.

A conflicting merge scenario is one where a merge tool is not able to automatically merge the changes from the two versions being integrated. Git reports the conflicting locations by annotating them with <<<, ===, and >>> markers. We call these regions conflict blocks. When a file contains at least one conflict block, we refer to the file as a conflicting file. We refer to the lines within the conflict block as conflicting lines of code, or conflicting LOC. For example, Figure 2b shows two conflicting files, Scanner.java and Reader.java. Each file has one conflict block. The first conflict block in Scanner.java has 5 conflicting LOC while the second conflict block in Reader.java has 3 conflicting LOC (Assuming we treat the whole body of the Read class as one line here for better visualization).

2.2 Motivating Example

To understand how refactorings complicate merge scenarios, consider the example inspired by multiple real conflicts in Figure 1. In the left branch (Figure 1c), the developer renames class Listen to Read in Reader.java and extracts the notNull and validate calls from addListener to a new method, validateObject. In the right branch (Figure 1d), the other developer: (1) moves class Listen from being an outer class in Reader.java into an inner class of class Reader in the same file, (2) renames method validateReader to...
validateObject, (3) renames method addReader to scanReader in Scanner.java, and (4) changes the code inside addListener.

As shown in Figure 1d, Git reports a conflict in file Reader.java because the developer rename Listen on one branch and move it into class Reader on the other. Although both branches change the same lines of code, a smart merge tool could automatically merge these changes by considering their semantics and renaming class Listen to Read, then moving it into Reader, as shown in the “ideal” merge result in Figure 1e. We refer to the Git conflict in Reader.java from Figure 1d as a false positive, because it is a conflict that can be automatically resolved. If the conflict cannot be automatically resolved and required manual intervention, we would refer to it as a true positive.

Git reports another conflict in file Scanner.java, where the developer on the left branch extracts code from the same region that the right branch edits the code within addListener. The developer now needs to compare the code inside of the extracted method with the conflict block, which may even be worse if the method was extracted to a distant location in the file, or another file altogether. However, a merge tool that considers the semantics of extract method would realize that the changes should be performed in the extracted method, rather than in addListener and that these changes can be merged, as shown in Figure 1e.

Figure 1e shows the ideal merge result for this scenario. This merge result avoids the unnecessary conflict in Reader.java by understanding the semantics of the rename and move operations. It also avoids the unnecessary conflict in Scanner.java by understanding the semantics of the extract method operation and playing the right branches changes in validateObject. Note, however, that the ideal merge result also reports a conflict in Reader.java and Scanner.java for validateObject. By renaming validateReader to validateObject on the right branch and extracting a method with the same name on the left branch, the developers introduce an accidental override, which could introduce bugs or critical errors that may not be discovered until their software is released. Git fails to report this because the developers did not change the same lines of code. Such a case illustrates Git reporting a false negative, where the merge tool should report a conflict because integrating these changes requires the developer’s
intervention, but the tool silently merges the changes.

3 RefMerge: Refactoring-Aware Operation-Based Merging

The high level idea of operation-based refactoring-aware merging is that if we invert refactorings before merging and then replay the refactorings, there will be no refactoring-related conflicts to complicate the merge. Figure 2 presents the following overview of our implementation of RefMerge, which consists of the following five steps.

1) Detect and Simplify Refactorings: We use RefactoringMiner, a state-of-the-art refactoring detection tool with 99.7% precision and 94.2% recall [23] to detect refactorings in each commit between the base commit and each parent respectively. We check if each detected refactoring can be simplified and simplify the refactorings accordingly.

2) Invert Refactorings: We use the corresponding refactoring list from Step 1 to invert each refactoring until all covered refactorings have been inverted.

3) Merge: We use Git to merge the left and right parents, \( P'_L \) and \( P'_R \), after all their refactorings have been inverted.

4) Detect Refactoring Conflicts: We compare the left and right refactoring lists for potential refactoring conflicts and commutative relationships and merge them into one list.

5) Replay Refactorings: We finally use the merged refactoring list to replay all non-conflicting refactorings.

In this section, we focus on our implementation of the operation-based approach to enable it to work on top of Git, which makes some of the details different from MolhadoRef.

3.1 Step 1: Detect and Simplify Refactorings

Refactoring Detection: We use RefactoringMiner to detect refactorings in each commit between the base commit and each parent commit respectively. We detect refactorings in each commit instead of only comparing the base and parent commits to ensure precise detection in longer histories. This is an important difference from MolhadoRef as the use of RefactoringMiner allows RefMerge to be implemented for Git, instead of relying on a research-based VCS.
it adds this second refactoring to the list and also updates the first refactoring to rename B.foo to B.bar. That way, when RefMerge processes the third refactoring rename B.bar to B.foobar, it can detect the transitive relationship and update it accordingly. Our artifact contains all our detailed logic for detecting transitive refactorings and refactoring chains [24].

Refactoring Order: When refactorings are detected, RefMerge creates a refactoring-free version of each parent commit by inverting the refactorings in the refactoring lists from Step 1. To invert a refactoring \( r \), RefMerge needs to create and apply the inverse refactoring \( \overline{r} \). \( \overline{r} \) is an inverse of \( r \) if \( \overline{r}(r(E)) = E \). For example, the inverse of a refactoring that renames method foo to bar is another refactoring that renames bar to foo.

RefMerge uses the information provided by RefactoringMiner to create each inverse refactoring. Each refactoring detected by RefactoringMiner is represented by a data structure that contains important information about the refactoring. Among others, the data structure contains information such as the refactoring type, information about the original program element, and information about the refactored program element. From the provided information, RefMerge obtains the corresponding elements and executes the refactoring through a refactoring engine. Importantly, executing the inverse refactoring does not only invert the refactored program element, but it also changes any references to the program element. This includes references added at any point after the refactoring was performed. In the case that the refactored program element is deleted in a future commit, the inverse refactoring cannot be performed and RefMerge moves on to the next refactoring.

3.3 Step 3: Merge

After all refactorings are inverted on both branches, only non-refactoring changes remain in the parent commits. We refer to this version of each parent as \( P' \) in Figure 2. In this step, we textually merge \( P_1' \) and \( P_2' \). Most same-line or same-block conflicts that would have been caused by refactorings are now eliminated through inverting the refactorings. However, some same-line and same-block conflicts may still exist because additional edits may have been performed to or beyond the refactored code.

For example, consider the conflict blocks in Scanner.addListener in Figure 1. If the developer adds several other lines of code to the extracted method, those lines will be inlined to the validateObject method invocation and reported in the conflict block. In this case, RefMerge will report more conflicting lines than Git because no matter how many lines of code are added to Scanner.validateObject, Git’s conflicting region will remain the same. While the extra conflicting lines that RefMerge reports could be considered to be disadvantageous, inlining the extracted code clearly indicates what code is part of the conflict in a single location.

3.4 Step 4: Detect Refactoring Conflicts

Generally speaking, a pair of refactorings that touch unrelated program elements do not have any interaction. However, a pair of refactorings that touch related program elements will have interactions, which can be conflicting or commutative. For each pair of refactorings, we have to predetermine the interactions that the refactorings can result in and then use that knowledge to detect conflicts and commutative refactorings. Refactoring operations that conflict cannot both be replayed, while refactoring operations that are commutative can be replayed in either order and will result in the same code. We make the assumption that two refactoring operations cannot both conflict and have a commutative relationship. We carefully compute and revise the conflict and commutative logic for each refactoring combination, which we explain below and can be found in our artifact [24]. RefMerge uses this knowledge to compare each refactoring in the left branch with each refactoring in the right branch and detect conflicting refactorings.

3.4.1 Detecting Conflicts

RefMerge first checks if the two refactoring operations are conflicting. There are a series of preconditions that must be met for two refactoring operations to conflict. To illustrate, we provide an example using the conflict logic for RenameMethod(\( m_1, m_2 \)) and RenameMethod(\( m_3, m_4 \)) in Figure 3. These two refactorings result in a conflict if (1) the source of both refactorings is the same program element (\( m_1 = m_3 \)) but their names differ (\( m_2 \neq m_4 \)) or (2) the sources of both renames are different program elements (\( m_1 \neq m_3 \)) but the renamed destinations are the same program element (\( m_2 = m_4 \)). In other words, if the same method is renamed to two separate names or if two different methods inside of the same class are renamed to the same name with the same signature, then the refactoring conflict.

In addition, two refactoring operations can conflict without changing the same program element. We refer to this as a semantic conflict. There are two examples of semantic conflicts for RenameMethod/RenameMethod: (1) an accidental overload and (2) an accidental override. In the case of
and it appears in testing, or worse in production. The branches. The developer might not realize the problem until Semantic conflicts will not be detected by a text-based merge which causes one of the methods to override the other. are renamed to the same name with the same signature, two methods within classes with an inheritance relationship different signatures. In the case of an accidental override, are renamed to the same name in the same class but have different signatures. In the case of an accidental override, two methods within classes with an inheritance relationship are renamed to the same name with the same signature, which causes one of the methods to override the other. Semantic conflicts will not be detected by a text-based merge tool such as Git because the same line is not changed by both branches. The developer might not realize the problem until it appears in testing, or worse in production. The Rename Method and Extract Method refactorings are an example of conflicting refactorings that can cause an accidental override, such as the motivating example in Figure 1.

3.4.2 Detecting Commutative Relationships

After RefMerge checks for refactoring conflicts, it checks for a commutative relationship between the two refactoring operations using the corresponding predetermined commutative logic. Two refactoring operations can only be commutative if they do not conflict and if they are different types of refactorings. If the pair of refactorings meets these conditions and they both refactor the same program element, then they are commutative. For example, Rename Method and Rename Method cannot be commutative because they are the same refactoring type and there is no way the same program element can be renamed on both branches to different names without conflicting. However, Move Method and Rename Method can be performed on the same program element commutatively. Similarly, the Move Class and Rename Class refactorings performed on class Listen in Figure 1 are an example of commutative refactorings.

We present the commutative logic for MoveMethod\(m_1, m_2\) and RenameMethod\(m_3, m_4\) in Figure 3 as an example. These two refactorings are commutative if the source of both refactorings is the same program element \(m_1 = m_3\) and their destinations are different \(m_2 \neq m_4\). The idea is that if a Move Method and Rename Method refactoring are performed on the same program element, then we can move the program element and then rename it, or rename it and then move it.

After all detected refactorings have been compared between branches for refactoring conflicts and commutative relationships, RefMerge combines the refactoring lists containing non-conflicting refactorings from each branch into one list. While RefMerge inverts the refactorings on each branch in a top-down order (after simplifying the refactoring lists to enable this), it orders the combined refactoring list in a bottom-up order for replaying refactorings. Multiple refactorings might touch the same program element, such as a Move Method and a Rename Class. By renaming the class before moving the method, RefMerge will not be able to find the method refactoring, because the class that the method is moved from will no longer exist. Since higher-level program elements do not depend on lower level program elements, replaying refactorings bottom-up allows RefMerge to replay the refactorings without any additional effort. The replay refactoring list for Figure 1 after detecting refactoring conflicts and commutative conflicts would contain Rename Method addListener to scanReader and Move And Rename Class Listen to inner class Reader.Read. The conflicting refactoring list would contain Extract Method validateObject from addLister and Rename Method validateReader to validateObject.

3.5 Step 5: Replay Refactorings

Finally, RefMerge replays the refactorings. For each inverted refactoring, RefMerge re-creates and performs the refactoring that was originally performed by the developer. Executing the refactoring includes updating all references in the program, including those added on the other branch.

3.6 Current Implementation

Technologies and Tools: We implement RefMerge as an IntelliJ plugin for merging Java programs. It consists of four key modules corresponding to the steps of the proposed technique. We use the state-of-the-art refactoring detection tool, RefactoringMiner [23] to detect the refactorings and we use the IntelliJ refactoring engine to programatically invert and replay the refactorings. Supported Refactorings: Even though the idea of operation-based refactoring-aware merging and our proposed implementation of it generally applies to all refactorings, there are more than 70 known refactoring types [12], it is a large engineering effort to implement every refactoring. Instead of implementing every refactoring, we use a subset of eight refactorings to show the feasibility of the approach and enable the empirical comparison.

We first choose refactorings that commonly appear in merge scenarios since these are refactorings developers will deal with. We find the top 10 occurring refactoring types from a recent large-scale empirical study of code changes in 450,000 commits [26]. Of these top 10 refactoring types, only Extract Method, Rename Method, and Move Class are involved frequently in merge scenarios with refactoring-related conflicts [13]. Thus, we include these three refactoring types in our implementation.

Next, we select refactorings that can conceptually challenge the idea of operation-based merging. The IntelliJMerge authors suggested that operation-based merging cannot handle Extract Method or Inline Method, because they do not have an inverse refactoring [14]. However, in theory, Extract Method can be inverted by performing an Inline Method refactoring, and vice versa. Thus, we select Extract Method and Inline Method as two refactorings that conceptually challenge operation-based merging.

2. https://www.jetbrains.com/idea
Finally, we select additional refactorings from the class and method level to cover refactorings that can result in larger conflicting regions and evaluate potential problems such as accidental override. We select Rename Class because it is at the class granularity and renames are the most universally used refactoring in the IntelliJ IDE [27]. We select Move Method and Move And Rename Method to evaluate potential inheritance problems, and we select Move And Rename Class to add full coverage of Move and Rename refactorings at the method and class granularity.

When a refactoring is performed that RefMerge does not support or RefMerge fails to invert, RefMerge results in the same merge as Git for the program element. Thus, RefMerge should improve on Git for supported refactorings, but should be no worse than Git for refactorings that are not currently supported. It is worth noting that our open-source implementation of RefMerge is designed in a modular way to easily allow for extension. Overall, the effort of adding a new refactoring amounts to adding 5 methods in 3 classes as well as $n + 1$ conflict handlers where $n$ is the current number of supported refactorings, with the full guidance of our documentation.

4 Evaluation Setup

We compare the effectiveness of RefMerge, Git, and the state-of-the-art refactoring-aware merge tool, IntelliJMerge [14] on 2,001 merge scenarios that contain refactoring-related conflicts from 20 open-source projects. These projects include the original 10 projects IntelliJMerge was evaluated on as well as an additional 10 projects with different distributions of conflicting merge scenarios. We answer the following research questions:

**RQ1** How many merge conflicts do the three merge tools report? A tool that automatically resolves more merge conflicts will reduce the time and effort developers have to spend resolving conflicts. We report conflicts at all granularity levels (scenarios, files, and conflict blocks).

**RQ2** What are the discrepancies between the merge conflicts that RefMerge and IntelliJMerge report? While either tools may report less conflicts, which seems better at face value, we need to investigate if they correctly resolve the conflicts or if they miss reporting real conflicts. We perform a qualitative analysis on the results reported by RefMerge and IntelliJMerge to understand the strengths and weaknesses of each tool.

4.1 Project & Merge Scenario Selection

We use the same 10 projects that the IntelliJMerge authors use in their evaluation [14]. To select these projects, the authors searched for the top 100 Java projects with high numbers of stargazers on Github, and then selected the projects with the most merge commits and contributors [14]. The authors then ran the analysis by Mahmoudi et al. [13] on these 10 projects to identify conflicting merge scenarios that have refactoring changes involved in the conflict. In a nutshell, this analysis replays merge scenarios in the Git history to find conflicting ones, uses RefactoringMiner [23] to find refactoring histories in the history of these conflicting merge scenarios, and then compares the location of the refactorings to the location of the conflict blocks to determine if a conflict has an involved refactoring. At the time of the IntelliJMerge publication, these 10 projects contained 1,070 conflicting merge scenarios with involved refactorings.

For generalizability, we expand our evaluation to cover an additional 10 projects. Mahmoudi et al. [13] shared a data set with the results of their analysis for 2,955 open-source GitHub projects. We use this data set to select the additional 10 projects for our evaluation. Our goal is to have a selection of projects with different distributions of (conflicting) merge scenarios to avoid any bias towards project-specific practices. Thus, we sort the 2,955 projects within the dataset based on the number of refactoring-related conflicts each project has. We randomly select three projects from the bottom 30% of the projects, four from the middle 40%, and three from the top 30%.

Given the 20 selected projects, we collect an up-to-date set of merge scenarios with involved refactorings by re-running Mahmoudi et al.'s analysis [13] on the latest history of each project as of September 26, 2021. Our artifact page [24] contains the exact version of each project that we consider. This means that for the 10 projects originally used by IntelliJMerge, our data set contains the original 1,070 merge scenarios as well as any additional ones that appear in the Git history since their publication date.

Table 1 shows the number of merge scenarios with refactoring-related conflicts in all 20 selected projects, with the projects used in the IntelliJMerge paper in bold. For additional context, we also show the number of stargazers of each project. Overall, we evaluate on 2,001 conflicting merge scenarios with involved refactorings.

| Project               | Stargazers | Merge Scenarios |
|-----------------------|------------|-----------------|
| cassandra             | 6,882      | 922             |
| elasticsearch         | 56,665     | 178             |
| gradle                | 12,410     | 117             |
| antlr4                | 10,738     | 100             |
| platform_framewirks_support | 1,609 | 96              |
| deeplearning4j        | 12,208     | 93              |
| realm-java            | 11,206     | 92              |
| jackson-core          | 1,984      | 81              |
| android               | 3,161      | 81              |
| comnetd               | 535        | 63              |
| storm                 | 6,278      | 33              |
| projectE              | 308        | 30              |
| javaparser            | 3,859      | 23              |
| druid                 | 24,576     | 17              |
| androidannotations   | 11,171     | 15              |
| junit4                | 8,198      | 14              |
| MinecraftForge        | 4,945      | 14              |
| iFixitAndroid         | 143        | 13              |
| MozStumbler           | 609        | 10              |
| error-prone           | 5,717      | 9               |
| Total                 |            | 2,001           |

Table 1: Number of conflicting merge scenarios with involved refactorings for the 20 projects we evaluate on. The 10 projects from the IntelliJMerge paper are in bold.

4.2 Reproducing IntelliJMerge

Before describing the evaluation metrics we use for comparing the merge tools, we need to ensure that we are correctly running IntelliJMerge. Thus, we first attempt to reproduce the results found in the corresponding publication [14] using their exact setup and data, as shared in their Github...
We share the exact steps we followed as well as the details of the results of reproducing IntelliMerge.

We run IntelliJMerge v1.0.7 on the same 1,070 merge scenarios used in the original publication, including their same post-processing steps such as removing all comments from the merged files. We use the same calculation proposed by IntelliJMerge's authors to measure precision and recall for IntelliJMerge and Git. They propose comparing auto-merged code with manually-merged code to measure precision and recall. They define *auto-merged code* as code that is not part of a conflict block in a tool's merge result and *manually-merged code* as the code that appears in the resolved merge commit. We use the same diff tool provided by Git that the IntelliJMerge authors used to calculate the number of different lines between the auto-merged and manually-merged code. Note that IntelliJMerge reports precision and recall based only on the conflicting files in each merge scenario, not on all changed files in the scenario.

We were not able to reproduce the exact numbers found in the IntelliJMerge paper. After emailing the authors, we verified that they perform post-processing steps to deal with some cases that are caused by the program elements being in a different order as well as format related diffs, such as textually moving, reordering, and cosmetic diffs. Because of these undocumented manual post-processing steps, it is impossible to reproduce the exact numbers in the IntelliJMerge paper. Although we were not able to get the exact numbers, the precision and recall we obtained were within 10% of the numbers in their paper. For further confirmation, we explicitly shared our setup with the IntelliJMerge authors and received confirmation that our setup is correct and that the differences in results we obtained do not misrepresent IntelliJMerge.

### 4.3 Tool Comparison Setup

After verifying with the IntelliJMerge authors that we are correctly running their tool, we could proceed with our evaluation. Given the 2,001 merge scenarios, we identify the base commit, left parent commit, and right parent commit of each scenario. We provide each tool (Git, IntelliJMerge, RefMerge) with these three commits in order to perform its three-way merge. We record the results of all changed files in the merge scenario, as opposed to only conflicting files (which is what the IntelliJMerge evaluation does). Considering the result of all changed files allows us to catch cases where one of the tools introduces a conflict in a file that Git did not originally report a conflict for. Additionally, while the IntelliJMerge authors removed comments in their evaluation, we do not post-process the results of any of the merge tools in any way to ensure that we see the same results a developer using the tool in practice would see. Overall, our goal in this evaluation is to minimize any manual pre and post processing steps such that we can compare the results of these tools in a practical setting. Note that IntelliJMerge supports 21 refactorings, including the 15 refactorings supported by Mahmoudi et al.’s analysis while RefMerge supports a subset of only 8 refactorings. While the scenarios we evaluate on may have refactorings that either tools do not support, we do not limit the evaluation to only supported refactorings so we can also understand how the tools handle unsupported refactorings.

We run our experiments on a quad-core computer with Intel (RJ) Core (TM) i7-7700HQ CPU @ 2.80GHz, 16 GB RAM and Ubuntu 20.04 OS. For feasibility of completing the evaluation, we use a 15 min timeout for each tool.

### 4.4 Used Metrics and Analysis Methods

(i.e., reporting a conflict when a conflict should not be reported) and false negatives. Consider the merge conflict in Scanner.java in Figure 14. If the developer merged the left changes but a merge tool failed to detect a conflict, causing the auto-merged code to contain both changes, then the auto-merged code will have 18 lines of code and the manually merged code will have 14 lines. Git diff will report 4 different lines since the auto-merged code also contains right changes, which are 4 lines that the manually merged file does not. In this case, the recall will be 1, because of the additional lines of code in the auto-merged code. Although the precision will suffer, it will also still be high (78%) and will not reflect the fact that the tool failed to detect the conflict. In their threats, the IntelliJMerge authors themselves recognize that using manually committed code as the ground truth is unreliable, because manually committed files often contain mistakes.

Instead, in RQ1, we report the number of conflicts each tool detects at various granularity levels (scenarios, files, and conflict regions). Additionally, we do not only report these numbers in isolation but instead report them at a scenario level to understand the proportion of scenarios in which each tool can improve the situation for a developer. Additionally, for RQ2, we manually sample merge conflicts that differ between the merge tools to understand the quality of the merge results and how the behavior of these tools differ in handling different types of merge scenarios. A similar analysis has been used in the past by Cavalcanti et al. to get a better understanding of merge results.

### 5 RQ1: Quantitative Tool Comparison

In this RQ, we compare the effectiveness of each tool in resolving merge conflicts at all granularity levels: complete merge scenarios, conflicting files, conflict blocks, and conflicting lines of code reported by each merge tool for the merge scenarios in our data set. We first focus on comparing the number of completely resolved conflicting scenarios. Completely resolving a conflicting scenario is the best case for any tool since this completely relieves the developer from looking at this scenario. While a tool may not be able to completely resolve a scenario, it may be able to reduce the number of conflicting files or conflict regions a developer needs to deal with, or it may also reduce the size of the reported conflicts in terms of lines of code (LOC). We report the cases in which such reduction happens. Alternatively, a tool may worsen the situation for a developer where it actually complicates the conflict by reporting more conflicting files, blocks, or lines of code.

#### 5.1 Completely Resolved Merge Scenarios

Table 2 shows the breakdown of the merge results for each project. The Total Scenarios column shows the number of
TABLE 2: Breakdown of merge scenario results for each tool, compare to Git. Number in parentheses shows the proportion from total scenarios in each project. For each project, the tool that was able to completely resolve more merge scenarios is shown in bold.

| Project Name     | Total Scenarios | IntelliMerge | RefMerge |
|------------------|-----------------|--------------|----------|
|                  | Resolved | Changed | Unchanged | Timeout | Resolved | Changed | Unchanged | Timeout |
| cassandra        | 922      | 41 (5%) | 88 (9%)  | 3 (0%)  | 790 (86%) | 84 (9%) | 49 (5%)  | 298 (33%) | 491 (53%) |
| elasticsearch    | 178      | 3 (2%)  | 99 (56%) | 5 (3%)  | 71 (40%)  | 8 (5%)  | 57 (32%) | 86 (54%)  | 17 (10%)  |
| gradle           | 118      | 1 (1%)  | 105 (89%)| 6 (5%)  | 6 (5%)    | 10 (8%) | 38 (32%) | 70 (59%)  | 0 (0%)    |
| antl4            | 100      | 1 (1%)  | 95 (95%) | 1 (1%)  | 3 (3%)    | 1 (1%)  | 28 (28%) | 71 (71%)  | 0 (0%)    |
| platform_fwk_supp| 95       | 5 (5%)  | 55 (58%) | 3 (3%)  | 32 (34%)  | 7 (7%)  | 25 (26%) | 63 (66%)  | 0 (0%)    |
| deeplearning4j   | 93       | 3 (3%)  | 83 (89%) | 6 (6%)  | 1 (1%)    | 5 (5%)  | 19 (20%) | 69 (74%)  | 0 (0%)    |
| realm-java       | 92       | 7 (8%)  | 69 (75%) | 14 (15%)| 2 (2%)    | 8 (9%)  | 20 (22%) | 64 (70%)  | 0 (0%)    |
| jackson-core     | 81       | 0 (0%)  | 80 (99%) | 1 (1%)  | 0 (0%)    | 3 (4%)  | 28 (35%) | 50 (62%)  | 0 (0%)    |
| android          | 81       | 3 (4%)  | 73 (90%) | 5 (6%)  | 0 (0%)    | 8 (10%) | 12 (15%) | 61 (75%)  | 0 (0%)    |
| cometl           | 63       | 2 (3%)  | 55 (87%) | 5 (8%)  | 1 (2%)    | 5 (8%)  | 11 (17%) | 47 (75%)  | 0 (0%)    |
| storm            | 33       | 1 (3%)  | 29 (88%) | 3 (9%)  | 0 (0%)    | 0 (0%)  | 5 (15%)  | 28 (85%)  | 0 (0%)    |
| ProjectE         | 30       | 1 (3%)  | 26 (87%) | 2 (7%)  | 1 (3%)    | 0 (0%)  | 12 (40%) | 18 (60%)  | 0 (0%)    |
| javaparser       | 23       | 3 (13%) | 13 (57%) | 7 (30%) | 0 (0%)    | 0 (0%)  | 9 (39%)  | 14 (61%)  | 0 (0%)    |
| druid            | 17       | 2 (12%) | 13 (76%) | 2 (12%) | 0 (0%)    | 1 (6%)  | 9 (53%)  | 7 (41%)   | 0 (0%)    |
| androidannnotations | 15   | 1 (7%)  | 14 (93%) | 0 (0%)  | 0 (0%)    | 0 (0%)  | 4 (27%)  | 11 (73%)  | 0 (0%)    |
| junit4           | 14       | 1 (7%)  | 12 (86%) | 1 (7%)  | 0 (0%)    | 1 (7%)  | 5 (36%)  | 8 (57%)   | 0 (0%)    |
| MinecraftForge   | 14       | 2 (14%) | 10 (71%) | 0 (0%)  | 2 (14%)   | 0 (0%)  | 6 (43%)  | 8 (57%)   | 0 (0%)    |
| iFixitAndroid    | 13       | 0 (0%)  | 13 (100%)| 0 (0%)  | 0 (0%)    | 1 (8%)  | 7 (54%)  | 5 (38%)   | 0 (0%)    |
| MozStumbler      | 10       | 0 (0%)  | 8 (80%)  | 2 (20%) | 0 (0%)    | 1 (10%) | 6 (60%)  | 3 (30%)   | 0 (0%)    |
| error-prone      | 9        | 1 (11%) | 7 (78%)  | 1 (11%) | 0 (0%)    | 0 (0%)  | 3 (33%)  | 6 (67%)   | 0 (0%)    |
| **Total**        | **2,001**| **78 (4%)** | **947 (46%)** | **67 (4%)** | **909 (46%)** | **143 (7%)** | **353 (18%)** | **997 (50%)** | **508 (25%)** |

conflicting Git scenarios evaluated for each project. We then show the results for IntelliMerge and RefMerge, respectively. For each tool, we show the number of completely resolved merge scenarios (columns Resolved), the number of merge scenarios where the conflict result changed from what Git reports (columns Changed), the number of merge scenarios where the merge conflict remains the same (columns Unchanged) and the number of merge scenarios where the tools times out (columns Timeout). Note that a change in the conflict result could mean either a decrease or increase in the number of the reported conflicts; we discuss the details of these changed scenarios in Section 5.2.

Note that RefMerge times out on 508 merge scenarios across two different projects and IntelliMerge times out on 909 merge scenarios across nine different projects.

As the table shows across all evaluated merge scenarios, IntelliMerge was able to completely resolve 78 merge scenarios out of the 2,001 total scenarios (i.e., 4%) while RefMerge was able to completely resolve 143 (7%) scenarios. At a project level, IntelliMerge and RefMerge are able to completely resolve at least one scenario in a total of 17 (85%) and 14 (70%) of projects respectively. However, there are seven projects where IntelliMerge resolves more scenarios than RefMerge, while there are 11 projects where RefMerge resolves more scenarios than IntelliMerge.

5.2 Merge Scenarios with Differences in Conflicts

We now look at the remaining scenarios that the tools are not able to completely resolve, for which the result of the conflict changed. We use Figures 5a to discuss these scenarios per project at the file, block, and lines of code levels respectively. There are two parts to each figure. On the left-hand side, we provide a box plot of the overall distribution of reported conflicts at that granularity level for all three tools across all evaluated scenarios. On the right-hand side, we provide a table that zooms in on the conflicting scenarios from the Changed column of Table 2. For each granularity level (conflicting files, conflict blocks, and conflict size in terms of LOC), we show the number of scenarios for which a tool increased or decreased the resulting number of conflicts. For example, for the last project error-prone in Figure 5c, we can see that there are four scenarios that IntelliMerge reduced the number of conflicting files for, while it increased the number of conflicting files for three scenarios. The percentage shown in parentheses is the median reduction/increase per merge scenario in that project (or over all scenarios in the last row of the table). For example, if Git reports 4 conflicting files while a tool reports 2 conflicting files, then this is a (4 - 2) / 4 = 50% reduction.
In the example of error-prone, the median reduction of the number of conflicting files for the corresponding four scenarios is 46%. The same interpretation of the numbers can be used for all granularity levels, which we discuss in detail below. Ideally, even if a tool cannot completely resolve a scenario, it would be able to partially resolve some of the reported conflicts. For each project, we show in bold which tool achieves the most reduction and the least increase.

**Conflicting files:** We first look at the conflicting file level in Figure 5. Figure 5a shows the distribution of the number of reported conflicting files per merge scenario. The figure shows that Git and RefMerge have a median number of two conflicting files while IntelliMerge has a median of eight. However, such a plot does not give us any indication about the developer experience on a scenario level, when it comes to what they currently experience with Git. To understand the tool’s behavior on a scenario level, we look at the table in Figure 5b, which shows the number of scenarios for which each tool results in an increase or decrease in the number of conflicting files. Overall, the table shows that IntelliMerge reduces the number of reported conflicting files in 81 scenarios (4% of all evaluated scenarios) by a median 38% reduction. On the other hand, RefMerge increases the number of reported conflicting files in 777 scenarios (39%) by a median 333% increase. In other words, on average, IntelliMerge increases the number of conflicting files by three-fold in these scenarios.

**Conflict Blocks:** We now look at the conflict block level in Figure 6a. The number of conflict blocks indicates the number of individual conflicting regions a developer needs to deal with. Figure 6a shows that Git and RefMerge have almost the same overall distribution of number of conflicting blocks per merge scenario (with a median of 4). However, IntelliMerge has a much higher median number of conflicting blocks at 16. Zooming in on the breakdown of increased and reduced conflict blocks in Figure 6b, we find that IntelliMerge reduces the number of reported conflict blocks for 137 scenarios (7%) by a median 50% reduction, while it increases the number of reported conflict blocks for 810 scenarios (40%) by a median of 367%. On the other hand, RefMerge reduces the number of reported conflicts in 140 scenarios (7%) by a median 25% reduction and increases the number of reported conflicts for 213 scenarios (11%) by a median of 25% increase.

**Conflicting Lines of Code:** Finally, we look at the conflicting lines of code (LOC) in Figure 7, which measures the total number of lines in all conflict blocks/regions of a merge scenario. From Figure 7a, we observe similar behavior of the tools as what we observed for the conflicting files in Figure 5a. More closely from the table in Figure 7b, we find that IntelliMerge reduces the number of conflicting LOC in 414 scenarios (21%) by a median 51% reduction, while it increases the conflicting LOC for 584 (29%) scenarios by a median 164% increase. RefMerge reduces the conflicting LOC in only 287 scenarios (14%) by a median 13% reduction and increases the conflicting LOC in 274 scenarios (14%) by a median 25% increase. Note that the discrepancy between IntelliMerge’s increase rate for conflicting regions and conflicting loc suggests that while IntelliMerge reports fewer conflicts in a lot more conflicting regions than Git, the size of these conflicting regions is small. To confirm this, we show the distribution of the reported conflicting loc per block (rather than over a whole scenario) in Figure 8. The plot confirms that the conflict regions that IntelliMerge reports are indeed quite small, even if they are much more frequent than the other tools.

**5.3 Interpretation of RQ1 Results**

The above results indicate that RefMerge completely resolves about twice as many merge scenarios as IntelliMerge (143 versus 78). While IntelliMerge is able to reduce conflicting LOC for a higher portion of scenarios than RefMerge (51% versus 13%), this comes at a cost of a high increase in the reported conflicts across all granularity levels for a large portion of the merge scenarios. Additionally, IntelliMerge times out on a higher number of merge scenarios than RefMerge. Thus, it seems
IntelliMerge works extremely well for a small proportion of scenarios where it is able to highly reduce the resulting conflicts in a scenario, but actually makes it much worse for other scenarios. Specifically, taking the total number of scenarios it can completely resolve (78 from Table 2) and the ones in which it can reduce the total number of conflicting LOC for (414 from Figure 7b), IntelliMerge can help the developer deal with less conflicts in 492 scenarios (25% of the overall scenarios). However, taking both timeouts (909 scenarios from Table 2) and worsened results in terms of overall conflicting LOC (584 scenarios from Figure 7b), IntelliMerge will not help the developer in the remaining 1,493 (75%) of the scenarios, and will in fact make it worse for them in almost a third of those.

On the other hand, RefMerge can completely resolve or reduce the number of conflicting LOC for only 430 scenarios (22%). However, RefMerge worsens the situation at a much lower rate than IntelliMerge in only 782 (39%). Additionally, the median percentage increase for RefMerge in terms of conflicting LOC is much lower at 23% as opposed to 164% for IntelliMerge. Thus, RefMerge makes the situation worse for the developer both in a smaller proportion of merge scenarios and by a lower percentage increase. Note that the number of unchanged merge scenarios for RefMerge is also much higher than IntelliMerge, because by construction, RefMerge resorts to a regular Git merge when there are no supported refactorings for it to work with. Overall, our quantitative results show that each tool has its pros and cons, and it is obvious that the characteristics or difficulty of a merge scenario impact the results in some way. This is why we perform a qualitative analysis of these discrepancies in RQ2 to understand the strengths and weaknesses of each tool, as well as the characteristics of merge scenarios that cause them to fail.

**RQ1 Summary:** IntelliMerge completely resolves 78 (4%) of the merge scenarios while RefMerge completely resolves 143 (7%). For scenarios the tools cannot completely resolve, IntelliMerge reduces the overall conflicting LOC in 414 scenarios (21%) by a median 51% reduction while it increases it in 584 scenarios (29%) by a median 164% increase. RefMerge reduces the conflicting LOC in 287 scenarios (14%) by a median 13% reduction and increases it for 274 scenarios (14%) by only 23% increase.

### 6 RQ2: DISCREPANCIES BETWEEN THE TOOLS

The quantitative numbers described in RQ1 are valuable for determining if a merge tool reports less conflicts. However, these numbers do not provide us information about the quality of the resolutions the tools provide. For example, a merge tool could report no merge conflicts in a merge scenario where conflicts should be reported. Similarly, we do not know if the reported conflicts are real conflicts or not. Thus, we perform a qualitative study for RQ2 to dig deeper into the reported results.

#### 6.1 Research Method

**Sampling Criteria:** We manually analyze a sample of 50 merge scenarios to shed light on the strengths and weaknesses of each tool. We randomly sample the 50 merge scenarios across the following criteria: (1) IntelliMerge and RefMerge produce similar results, in terms of completely resolving the merge scenario, or equally increasing/reducing the number of Git conflicts. (2) IntelliMerge outperforms RefMerge in terms of completely resolving the scenario or reporting a lower number of conflicts at any granularity level and (3) RefMerge outperforms IntelliMerge. When sampling the merge scenarios, we also try to evenly sample across projects.

**Analysis Method:** The goal of our manual analysis is to analyze the conflicts reported by all three tools across the sampled scenarios. To investigate if a merge conflict is a true positive or false positive, we look at the code region in the base commit, left commit, and right commit. We determine whether integrating the changes from both parents should result in a merge conflict, based on the semantics of the changes. If a merge conflict is expected, we label this conflict region as a true positive. If it should not result in a merge conflict, we label it as a false positive. If the other merge tools do not report the same merge conflict, we investigate the result of their merge and decide if it is a true negative (i.e., conflict should not be reported) or false negative (i.e., the tool missed the conflict). Additionally, we investigate and categorize the reasons behind false positives and false negatives for each tool. This process takes an average of 69 minutes per merge scenario.

#### 6.2 Results

Table 3 shows the total number of conflict blocks that we analyze across the 50 sampled scenarios, as well as the number of false positives and false negatives that we find for each tool. As shown, Git reports 243 false positives and 12 false negatives, IntelliMerge reports 923 false positives and 178 false negatives. Meanwhile, RefMerge reports 231 false positives and two false negatives. When compared to Git, RefMerge reduces the number of false positives and false negatives by 5% and 83% respectively, while IntelliMerge increases the number of false positives and false negatives by 279% and 1,383%. We also show the number of true positives reported by each tool. While Git and RefMerge report a total of 198 and 199 true positives respectively, IntelliMerge reports only 142 true positives.

**False Positives/Negatives Git Results:** Table 4 shows the reasons behind the false positives and false negatives for Git. There were generally three main reasons for false positives.
TABLE 3: Comparing the false positives and false negatives reported by each tool, across the 50 sampled scenarios.

| False Positives | False Negatives | Total |
|-----------------|-----------------|-------|
| RefMerge        | 199             | 211   |
| Git             | 218             | 239   |
| IntelliMerge    | 224             | 246   |

TABLE 4: The reason for each false positive and false negative reported by Git, as well as the frequency for each reason.

| Git Reasons                     | Type       | Frequency |
|---------------------------------|------------|-----------|
| No Refactoring Handling         | False Positive | 157       |
| Ordering Conflict                | False Positive | 190       |
| Formatting Conflict              | False Positive | 21         |
| No Refactoring Handling         | False Negative | 11        |
| Total                            |             | 257       |

TABLE 5: The reason and frequency for false positives and false negatives reported by RefMerge.

| RefMerge Reasons                  | Type       | Frequency |
|-----------------------------------|------------|-----------|
| Unsupported Refactoring           | False Positive | 100       |
| Ordering Conflict                 | False Positive | 25        |
| Refactoring-related Ordering Conflict | False Positive | 42       |
| Refactoring-related Formatting Conflict | False Positive | 20       |
| Formatting Conflict               | False Positive | 15        |
| IntelliJ Optimization            | False Positive | 5         |
| Undetected Refactoring           | False Positive | 2         |
| Fails to Invert Refactoring      | False Positive | 2         |
| Fails to Replay Refactoring      | False Negative | 1         |
| Total                            |             | 233       |

is not being able to handle refactorings, and thus reporting conflicts that could be resolved automatically. There are 157 (65%) false positive conflicts that Git reports which involve refactorings. Given the selection of merge scenarios we use in our evaluation, it is natural to find that many of the conflicts Git reports are related to refactorings. Table 1 also shows that 75 (31%) of Git’s reported false positives are due to ordering conflicts. An ordering conflict is a conflict caused by adding two program elements to the same location and the merge tool not knowing which order to put them in, when the order does not matter [11]. For example, if Bob and Alice add two new Java methods to the same location, Git will report a conflict when both methods can be added in either order. Finally, the remaining 11 (5%) of Git’s false positives are formatting conflicts that are caused by different formatting between branches. This could be an additional white space or a new line on one branch that does not exist on the other.

Not being able to handle refactorings also causes Git to miss reporting 12 conflicts (false negatives). Rename Class refactorings performed on each branch cause Git to think that changes are being made to the same file, which results in several syntax errors caused by two files being merge which should not be merged. Another false negative is caused by an Extract Method refactoring where Git only reports part of the conflicting region while the last false negative is caused by a Move Method refactoring.

False positive/negative RefMerge Results: Table 5 shows the reasons behind the false positives and negatives for RefMerge. Similar to Git, RefMerge also suffers from being unable to resolve ordering and formatting conflicts, reporting the same 75 ordering conflicts and 11 formatting false positives as Git. RefMerge reports an additional 26 ordering conflicts and 21 formatting conflicts that arise from its refactoring handling, totalling 101 (44%) ordering conflicts and 32 (14%) formatting conflicts. The majority of these additional ordering conflicts are caused by Move Method or Move Inner Class refactorings being moved to the correct class but not being moved to the correct location within the file. Instead of reporting the original move-related refactoring conflict, RefMerge reports a much larger ordering conflict containing several methods and classes. The additional formatting conflicts are caused by formatting differences from inverting refactorings, also typically Move Method and Move Inner Class refactorings. In these conflicts, RefMerge resolves the refactoring conflict but leaves behind a small conflict that usually consists of different amounts of white space.

In 88 (38%) of the false positives that RefMerge reports, the underlying issue is a refactoring that is not supported in the current implementation. For example, merge scenario ea42d642 within gradle has an Add Parameter refactoring that is involved in one of the reported conflicts.

There are five (2%) false positives caused by IntelliJ optimizations, which are automatic optimizations done to the code after using the refactoring engine. All five of the IntelliJ optimizations were caused by inverting refactorings that were not involved in the original refactoring conflicts reported by Git. An example of this is replacing several import statements with import package.*, which then cause Git to detect a conflict in the merging step.

There are three (1%) false positives that are due to undetected refactorings that RefactoringMiner did not detect. There are several similar methods, both in structure and naming, in the classes where RefactoringMiner misses a refactoring, which likely made it difficult for RefactoringMiner to detect the refactoring. We reported the issue to the RefactoringMiner developers.

The remaining two (1%) of RefMerge’s false positives are refactoring conflicts that RefMerge fails to resolve because it could not invert a Move Method refactoring. After investigating, we found that an additional unsupported refactoring was performed on the method, causing RefMerge to be unable to provide the correct information to the refactoring engine.

Finally, there are two false negatives that are caused by successfully inverting the refactoring and resolving the conflict but failing to replay the refactoring, resulting in an unexpected merge. This happens for a Move Method refactoring and an Extract Method refactoring. Replaying the merges resulted in null pointer exceptions, which suggests this is caused by a bug in our implementation, which we will further investigate.

False positive/negative IntelliJMerge Results: Table 6 shows the reasons behind the false positives and negatives for IntelliJMerge. We start with some of the reasons we already observed for the other tools. IntelliJMerge reports 25 false positives due to ordering conflicts and also has 74 false positives because of undetected refactorings. There
are 12 refactoring types where IntelliMerge fails to detect a refactoring with the top three being Add Parameter (19), Rename Parameter (15), and Extract Method (8). The undetected refactorings can be split into two groups: (1) where there are several similar program elements and a refactoring drops the program element below the similarity threshold, and (2) where several changes to a program element cause IntelliJMerge to think that the refactored program element is an addition.

Note that, unlike Git and RefMerge, IntelliJMerge reports only one false positive related to formatting conflicts. However, 814 of IntelliJMerge's false positives (88%) are due to matching errors. We define a matching error as an error caused by IntelliJMerge's graph node matching process. This primarily happens with comments, annotations, and imports.

There are seven false positives that are due to missing refactoring references, where IntelliJMerge detects a refactored program element but fails to match added references on the other branch. Both branches added a new reference in the same location, causing IntelliJMerge to think that a program element was refactored while an addition was made to the same location which resulted in a conflict.

The last two false positives that IntelliJMerge reports are caused by incorrectly detecting a refactoring that was never performed. IntelliJMerge incorrectly performs an Add Parameter refactoring to a method causing merge conflicts whenever the method is called.

IntelliMerge results in 87 (49%) false negatives because it deletes conflict blocks, incorrectly completely deleting code that exists in conflict blocks reported by Git and RefMerge. This primarily happens when IntelliJMerge deletes the file containing a merge conflict. When a file or program element exists in the base commit and IntelliJMerge cannot find a match for it in either parent commit, IntelliJMerge seems to incorrectly delete it. Note that this is a lower bound for how many times IntelliJMerge results in a false negative. IntelliJMerge could have deleted other files or program elements that were not part of a conflict block and since we focused on the reported conflicts by each tool, we would have missed this happening in files where no merge tool reported a conflict.

We find that 75 (42%) of IntelliJMerge's false negatives are due to matching errors which lead to syntax errors. Most of the syntax errors seem to happen in classes that contain several method-level refactorings and several similar method declarations.

Finally, the 16 (9%) remaining false negatives are due to IntelliJMerge detecting refactorings that were not performed, leading to IntelliJMerge moving methods to classes that the developers never moved them to and causing additional syntax errors.

### 6.3 Interpretation of RQ2 Results

The above results indicate that RefMerge reports about the same amount of false positives as Git (231 versus 243) while IntelliJMerge increases the number of false positives by almost three-fold (923 versus 243). Unlike Git and RefMerge, IntelliJMerge does well with ordering and formatting conflicts due to its graph-based approach. While IntelliJMerge also decreases the number of refactoring conflicts a developer needs to deal with, this comes at the price of many more false positives: 814 of IntelliJMerge’s false positives are matching errors which are typically small in size. This explains the quantitative results of RQ1 where IntelliJMerge reports more conflicts but less conflicting LOC. Additionally, while IntelliJMerge does not detect refactorings in 74 conflict blocks reported by Git (struggling the most with parameter level refactorings), IntelliJMerge typically does well with the refactoring conflicts it does detect. However, IntelliJMerge also incorrectly detects 18 refactorings (two false positives and 16 false negatives from Table 6) and reports a total of 178 false negatives. Thus, while the results of RQ1 suggest that IntelliJMerge works extremely well for a small proportion of scenarios where it is able to highly reduce the resulting conflicts in a scenario, our qualitative results suggest that some of these may actually be false negatives.

On the other hand, RefMerge reports only two false negatives caused by not replaying refactorings and reduces the number of false positives reported by 5% when compared to Git. RefMerge worsens the situation at a much lower rate than IntelliJMerge, reporting 52 false positives that Git does not, and 21 of them are formatting conflicts left after resolving a refactoring conflict. In general, RefMerge struggles most with move-related refactorings.

**RQ2 Summary:**

RefMerge reduces the number of false positives and false negatives by 5% and 83% respectively, while IntelliJMerge increases them by 279% and 1,383%. RefMerge struggles most with Move Method whereas IntelliJMerge struggles most with Add Parameter, Rename Parameter.

### 7 Discussion

In our study, we compared two refactoring-aware merging approaches that have not been compared before. RQ1 results show that despite supporting less refactorings, RefMerge managed to resolve about twice as many conflicting merge scenarios as IntelliJMerge. We found that while IntelliJMerge reduced the number of conflicting LOC in more scenarios compared to RefMerge, IntelliJMerge also increased the number of conflicting LOC in more scenarios. On the other hand, RefMerge
makes the situation worse in a smaller proportion of merge scenarios and by a lower percentage increase. Additionally, our qualitative analysis shows that IntelliJMerge reported a much higher number of false negatives whereas RefMerge reported only two false negatives in all 50 merge scenarios. Thus, even considering unsupported refactorings, operation-based refactoring-aware merging shows promise to help improve the developers’ experience without the risk of increasing the number of false negatives. In other words, the results in this study are a lower bound of its potential.

**Strengths and Weaknesses of IntelliJMerge:** The nature of IntelliJMerge’s graph-based approach makes it avoid formatting and ordering conflicts. However, IntelliJMerge seems to struggle with correctly matching graph nodes across the two versions of the code. We believe that IntelliJMerge’s use of a similarity score for its refactoring detection is one of the main reasons for this. IntelliJMerge often failed to detect a refactoring because the refactored program element was too similar to other existing program elements. We also found cases where a non-refactoring change caused a program element to be within the similarity threshold of other program elements, causing IntelliJMerge to treat it as a refactoring. Although IntelliJMerge could potentially change the used similarity threshold, the use of a similarity score will always run into these problems. However, when IntelliJMerge successfully detects a refactoring, it handles it correctly and almost always resolves the conflict.

**Strengths and Weaknesses of RefMerge:** Whereas IntelliJMerge’s graph-based approach makes it avoid formatting and ordering conflicts, RefMerge’s operation-based approach is more prone to such conflicts. While formatting conflicts are a small price to pay considering they are typically easier to resolve than refactoring conflicts, move-related refactorings proved to be conceptually challenging when it comes to undoing/redoing them. Although RefMerge can move the program element to the correct class, it cannot guarantee that it is moved to the same location it was previously at. Despite this, overall, RefMerge resolves or simplifies more refactoring conflicts than the complications it creates, all while avoiding syntax errors.

**Moving Forward:** Driven by these findings, we propose a few paths moving forward in refactoring-aware merging. We believe that improvements in graph-based refactoring-aware merging requires addressing the matching algorithm. The current merging algorithm IntelliJMerge uses seems to work well, but the initial matching phase can be improved by avoiding the similarity score matching and instead using a refactoring detection algorithm such as that used in RefactoringMiner [29].

We believe that operation-based refactoring-aware merging showed very promising results, despite a small list of supported refactorings. Future work could go in three different directions: (1) adding support for more refactoring types, (2) treating add and delete edits as operations, and (3) handling move-related ordering conflicts using light-weight program analysis to determine where the program element was in the base commit.

Finally, it could make sense to combine the two refactoring-aware approaches in some way similar to how changing strategies/auto-tuning between semi-structured and structured merge was previously proposed [18]. As the nature of graph-based merging seems to do well with ordering conflicts and formatting conflicts, this would address the weaknesses of operation-based merging. However, addressing the weaknesses caused by IntelliJMerge’s matching algorithm would need to happen before this path could be considered further.

### 8 Threats to Validity

We explain the potential threats to the validity of our results.

**Construct Validity:** In our qualitative analysis, we manually compare the results of the three tools to identify false positives and false negatives. This means we may miss false negatives that all three tools fail to report. Additionally, the analysis was done by a single author and is thus subject to their understanding of the scenario. To alleviate this as much as possible, we compare the changes in the left parent, right parent, and base commit for each merge scenario to first try to understand the developer’s intentions and the expected merge result. We record a detailed description of our interpretation of the scenario and conflicts and share this in our artifact to allow further external validation. Further analysis involving investigating run time and compile time errors could also further shed further light on false negatives reported by the three approaches.

**Internal Validity:** Any problems inherited from the tools used in RefMerge or in our evaluation setup may lead to inaccuracies in the results. To mitigate this, we carefully consider the role of each tool used in our study and analyze its results through manual verification. While not a bug with IntelliJ per se, our qualitative analysis showed that IntelliJ’s refactoring engine, which we use to invert and replay refactorings, performs optimizations that lead to unnecessary merge conflicts. This means that the reported number of conflicts in our results is an upper bound and with engineering effort and help from the IntelliJ developers to allow us to disable these optimizations, these limitations can be mitigated. Alternatively, a different refactoring engine that does not force these optimizations can be used. Any refactoring that RefactoringMiner misses will not be inverted and replayed, which will result in the same merge as Git. Any refactorings that RefactoringMiner detects which were not performed will result in RefMerge inverting and replaying a “fake” refactoring, which may lead to unnecessary merge conflicts. During our development, we came across some such occurrences and the RefactoringMiner author fixed these in the tool. In our qualitative analysis, we came across three refactorings that RefactoringMiner did not detect, which we recently reported. Overall, RefactoringMiner achieves a precision of 98% and 87% recall [23]. In general, it is important for RefMerge to rely on a tool with high precision to ensure we do not result in unnecessary conflicts. A lower recall simply means RefMerge will result in the same resolution as Git.

**External Validity:** By selecting sample projects with different sizes and refactoring histories, we try our best to have a representative evaluation. Our evaluation is limited to Java open-source projects since both tools are Java specific. That said, while our implementation of RefMerge is Java specific, an operation-based approach does not need to
be. Our qualitative analysis is based only on a sample of 50 merge scenarios due to the time consuming nature of the process (avg. 69min/scenario). However, the 50 merge scenarios we investigated have more than 1,300 unique merge conflicts. As far as we are aware, this is the most extensive qualitative analysis performed in terms of unique merge conflicts \[17\], \[18\], \[21\]. Naturally, investigating additional merge scenarios could reveal more for each tool.

9 RELATED WORK

Software Merging: The proposed software merging techniques in the literature can generally be categorized into unstructured, structured, and semi-structured merging techniques \[25\].

Unstructured merging techniques represent any software artifact as a sequence of text lines \[9\]. This gives unstructured merging techniques the strength of being able to process all textual artifacts, regardless of the programming language \[25\]. The downside to this technique is that unstructured merging cannot handle multiple changes to the same lines, since it cannot consider the syntactic and semantic meaning in software artifacts \[11\]. Due to its simplicity and versatility, modern version-control systems such as Git or mercurial still rely on such unstructured merging.

Structured merging tries to alleviate the problems of unstructured tools by leveraging the underlying structure of software artifacts, typically through operating on an Abstract Syntax Tree (AST) instead of textual lines \[16\]. Considering the structure of software artifacts allows structured merging techniques to handle syntactic and semantic conflicts \[30\], \[31\], \[32\]. This comes at the cost of generally being language specific and being too expensive to be used in practice. JDime is a structured merge tool that is capable of tuning the merging process by switching between unstructured merge and structured merge \[18\]. Zhu et al. \[21\] built on top of JDime by matching nodes based on an adjustable quality function. Leßnich et al. \[19\] proposed auto-tuning, an approach that switches between structured and unstructured merging, and implemented JDime to demonstrate their approach. Seibt et al. \[21\] recently performed a large-scale empirical study with unstructured, semi-structured, and structured merge algorithms and their findings suggest that combined strategies are promising moving forward.

Semi-structured techniques aim to create a middle ground by considering both the language independence of unstructured merging and the precision of structured merging \[11\]. jFSTMerge was proposed by Apel et al. \[11\] as one of the first semi-structured merging approaches. While jFSTMerge reduces the number of merge conflicts reported compared to unstructured merge, jFSTMerge struggles with renamings. Cavalcanti et al. \[17\] proposed jFSTMerge, building upon jFSTMerge by adding handlers for different types of conflicts such as renaming.

By representing software artifacts partly as text and partly as trees, semi-structured merging achieves a certain level of language-independence. Cavalcanti et al. \[33\] performed an empirical study to compare unstructured and semi-structured merging techniques. They found that semi-structured merge can reduce the number of merge conflicts by half. We compare only against IntelliJMerge because in their paper, they show that they outperform jFSTMerge \[14\]. Furthermore, we are focusing on techniques that specifically target refactoring in order to compare their strengths and weaknesses.

Proactive Conflict Detection & Prevention: The key idea behind this research line is that detecting conflicts as soon as they happen, even before a developer commits the changes, can lead to conflicts that are easier to resolve. Knowing what changes other developers are making is beneficial for team productivity and reducing the number of reported merge conflicts \[34\]. One such approach is speculative merging \[35\], \[36\], where all combinations of available branches are pulled and merged in the background. Owhadi-Kareshk et al. \[37\] designed a classifier for predicting merge conflicts with the aim of reducing the computational costs of speculative merging by filtering out merge scenarios that are unlikely to be conflicting.

Syde \[38\] and Palantic \[39\] are two tools that increase developer awareness by illustrating the code changes their team members are making. Cassandra \[40\] minimizes simultaneous edits to the same file by optimizing task scheduling. ConE \[41\] is an approach that proactively detects concurrent edits to help mitigate certain resulting problems, including merge conflicts. Silva et al. \[42\] proposed utilizing automated unit test creation to detect semantic conflicts that a merge tool could have missed. Fan et al. \[43\] proposed using dependency-based automatic locking to support fine-grained locking and avoid semantic conflicts. DeepMerge is a recent effort that defines merge conflict resolution as a machine learning problem \[44\]. The approach primarily leverages the fact that around 80% of merge conflict resolution only rearrange lines \[45\]. However, they do not explicitly consider refactoring semantics in their merge conflict resolution.

Refactoring Detection: Refactoring is a widespread practice that enables developers to improve the maintainability and readability of their code \[46\]. Refactoring has been extensively studied over the past few decades \[47\], with recent work focusing on the detection of refactoring changes and the relationship between refactoring and code quality \[48\], \[49\], \[50\], \[51\]. Multiple tools have been developed to detect different refactoring types, such as Ref-Finder \[52\] and RefDistiller \[53\]. We use the state-of-the-art refactoring detection tool, RefactoringMiner, which achieves a precision of 98% and a recall of 87% \[23\].

Operation-based & Refactoring-aware Merging: Operation-based merging is a semi-structured merging technique that models changes between versions as operations or transformations \[54\], \[55\], \[56\] which could be used to support refactoring-aware merging \[15\]. Nishimura et al. \[57\] proposed a tool that reduces the manual effort necessary to resolve merge conflicts by replaying fine-grained code changes related to conflicting class members. Their approach only considers edits and has problems with long edit histories and finer granularity of operations \[15\].

Ekmaan et al. \[58\] proposed a refactoring-aware versioning system designed for Eclipse IDE. Their approach keeps program elements in volatile memory, thus allowing for a short-lived history of refactored operations. However, their approach does not support software merging.

Dig et al. \[15\] proposed MolhadRef, an operation-based
refactoring-aware merging algorithm that treats refactorings as operations and considers their semantics, and Shen et al. [14] proposed IntelliMerge, a graph-based refactoring-aware algorithm. Since we discuss these two approaches in detail in the paper and in our empirical comparison, we do not discuss them again here.

10 Conclusion

In modern software development, version control systems play a crucial role in enabling developers to collaborate on large projects. Most modern version control systems use unstructured merging techniques that do not understand code-change semantics. In this paper, we focus on two merging techniques in the literature that promise to resolve refactoring-related conflicts: IntelliMerge, a graph-based refactoring-aware merging technique [14] and an operation-based refactoring-aware merging technique [15]. We create a Git-based implementation of the latter and compare the two refactoring-aware approaches for the first time. We perform a large-scale evaluation on 2,001 merge scenarios from 20 open-source projects and shed light on the strengths and weaknesses of each approach. We find that operation-based refactoring-aware merging is able to resolve more scenarios overall but is generally more conservative: it solves fewer individual conflicts overall than IntelliMerge but does not create as much extra work for the developers. We plan to explore two directions to further improve operation-based refactoring-aware merging: (1) add support for more refactoring types and (2) resolve refactoring-related ordering conflicts that our implementation of operation-based refactoring-aware merging causes.

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