One-to-One or One-to-many? What function inlining brings to binary2source similarity analysis

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ABSTRACT
Binary2source code matching is critical to many code-reuse-related tasks, including code clone detection, software license violation detection, and reverse engineering assistance. Existing binary2source works always apply a “1-to-1” (one-to-one) mechanism, i.e., one function in a binary file is matched against one function in a source file. However, we assume that such mapping is usually a more complex problem of “1-to-n” (one-to-many) due to the existence of function inlining. To the best of our knowledge, few existing works have systematically studied the effect of function inlining on binary2source matching tasks. This paper will address this issue. To support our study, we first construct two datasets containing 61,179 binaries and 19,976,067 functions. We also propose an automated approach to label the dataset with line-level and function-level mapping. Based on our labeled dataset, we then investigate the extent of function inlining, the factors affecting function inlining, and the impact of function inlining on existing binary2source similarity methods. Finally, we discuss the interesting findings and give suggestions for designing more effective methodologies.

KEYWORDS
Binary2source Matching, Function Inlining, One-to-many

1 INTRODUCTION
With the flourishing growth of open-source software [14], nothing is more common than using ready-to-use code snippets to assist software development. Although proper use of open-source code helps reduce the development cost, improper use of open-source code may bring legal and security risks. Developers may unintentionally violate Open-source licenses, consequently, even causing great financial loss to software companies. For example, Cisco and VMware were exposed to serious legal issues because they did not adhere to the licensing terms of Linux kernel [1, 2]. Moreover, vulnerabilities are easy to emerge in open-source software since its code is accessible which makes it easy to be explored. Software systems that use the vulnerable code and don’t patch in time will suffer from security risks [63].

A fundamental task for detecting the above issues is to get a match between binary and source code. Given the queried binary code, finding its original source code is called binary2source code matching. Binary2source code matching [35, 39, 40, 42, 46, 47, 51, 56, 62] is critical to many code-reuse-related tasks, including code clone detection [42], software license violation detection [35, 40], and reverse engineering assistance [62]. Due to the huge semantic gap between source code and binary, existing works mostly rely on immutable features such as strings and integers to carry out binary2source matching, and the matching granularity is mostly file-level or function-level. Same with the most binary level similarity detection methods [32, 41, 50, 53, 65], the mechanism of binary2source matching is always considered as “1-to-1” (one-to-one) in existing work, i.e., one function in a binary file is matched against one function in a source file. However, we assume that such mapping is usually a more complex problem of “1-to-n” (one-to-many) due to the existence of function inlining [12], which is a common optimization during the compilation from source code to binaries.

We will use a real-world example to illustrate our motivation. Figure 1 (a) shows the vulnerable version and patched version of function scm_send in the project Linux [26] for CVE-2020-165931. As there may exist code reuses of this vulnerable function, vulnerability would be propagated to disparate binaries. To detect the influenced binaries, it requires searching whether there is a function in the target binary that is similar to the vulnerable function in the source code. To support this process, Figure 1 (c) depicts the complete CFG (control flow graph) of a binary function netlink_sendmsg that will be checked, with a partial CFG shown in Figure 1 (b). Each node represents a basic block and the array represents the control flow between them.

We originally followed the “1-to-1” mechanism adopted by existing works during the above search process. After inspecting all functions in binaries, we cannot find an individual binary function that is produced merely by source function scm_send. As a result, we only found a binary function named netlink_sendmsg (c) that contains the binary code of the risky scm_send (b). When computing the similarity between source function scm_send and the target binary function netlink_sendmsg, it returned a low score, indicating they are unmatched and thus leading to a failure of detecting function binaries which reuse vulnerable function scm_send.

We found that this detection failure in the above example is due to function inlining, that is, function scm_send is inlined by netlink_sendmsg as shown in Figure 1 (d). Apart from scm_send, netlink_sendmsg also inlines other functions such as scm_destroy shown in Figure 1 (d). When a function inlining occurs, it replaces the call-site statement inside a callee with the function body of the callee. As a result, the produced binary function will contain more than one source functions. Even more, the function inlining can

1https://github.com/torvalds/linux/commit/e0e3cea46d31d23de40dfba49a7a2ce04ef8edfe

...
be nested, meaning that an inlined function may further inline another function. As shown in Figure 1 (d), the `scm_send`, inlined by `netlink_sendmsg`, inlines `scm_set_cred`. We can observe that the mapping between binary function `netlink_sendmsg` and its original source functions is no longer a “1-to-1” mapping but a “1-to-n” issue—one binary function maps multiple source functions, sometimes even in a nested inlining manner.

“1-to-n” issues bring a great challenge to existing binary2source matching works, as we have shown. However, to the best of our knowledge, few existing works have systematically studied the effect of function inlining on binary2source matching tasks. It is still unclear about the extent of function inlining and its impact on binary2source matching works. This paper will address this problem, and concretely we will investigate the three research questions.

**RQ1:** To what extent inlining will happen during compilation? The answer to this question will evaluate the frequency and extent of function inlining. The severity of function inlining will demonstrate the necessity for a consideration of function inline in source2binary matching tasks.

**RQ2:** What factors will affect function inlining? Revealing these factors will be helpful for better understanding the inlining potential of functions, facilitating the design of mapping strategies from source to binary functions.

**RQ3:** What is the effect of function inlining on the performance of existing binary2source matching works? This question will evaluate the performance loss without considering function inlining, which indicates the direction for method improvement.

To support our study, we first construct two datasets containing 61,179 binaries and 19,976,067 functions. We also propose an automated approach to label the dataset with line-level and function-level mapping. Based on our labeled dataset, we then investigate the extent of function inlining, the factors affecting function inlining, and the impact of function inlining on existing binary2source similarity methods. Finally, we discuss the interesting findings and give our suggestions for designing more effective methodologies.

Our main contributions are listed below:

- To the best of our knowledge, our work is the first to comprehensively evaluate the effect of function inlining on binary2source matching tasks.
- We create the first function inlining dataset by designing an approach that automatically labels the dataset with a mapping between source and binary code. (Section 3)
- We conduct three studies to understand the effect of function inlining on binary2source matching tasks (Section 4, 5, 6) and further point out potential improvements of existing binary2source matching tasks (Section 7).

To facilitate further research, we have made the source code and dataset publicly available.

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2 RELATED WORK

This section will introduce binary2source code matching methods and the work about function inlining.

### 2.1 Binary2source Code Matching

Existing binary2source code matching works can be classified into feature-based methods, learning-based methods, and compilation-based methods.

Feature-based methods [35, 39, 40, 42, 47, 51, 56] are commonly used by early works. BAT [42] considers textual strings as features to match source and binary code. BinPro [51] extracts similar features but utilizes machine learning algorithms to compute optimal code features for the matching. B2SFinder [40], a state-of-art feature-based method, considers three types of features including string, integer, and control-flow features. Although feature-based methods are easy to carry out and scalable to large datasets, they require

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https://github.com/island255/source2binary_dataset_construction
a successful syntax and semantic analysis of source code. Besides, most feature-based methods employ file-level similarity analyses. Since some functions may have insufficient string and integer features, feature-based methods are unable to detect function-level similarities precisely.

CodeCMR [62] is a learning-based method for binary2source matching. CodeCMR models binary2source matching as a cross-modal retrieval task, with the source code and binary code as two inputs of the neural network. The model output is the similarities between source and binaries. CodeCMR also extracts string and integer features to supply the inputs. By developing a deep learning method, CodeCMR has achieved a fast and precise matching.

Buggraph [46] is a compilation-based method. Different from feature-based and learning-based methods which detect the similarity between binary and source directly, this approach translates binary2source task into a binary2binary task by compiling the source code to binary. Buggraph first identifies the compilation provenance of the target binary, i.e., optimization level, architecture, compiler family, and compiler version. It then compiles the source code under the same configurations. After that, Buggraph constructs a neural network to calculate the similarity between two binaries by leveraging existing binary2binary similarity detection methods. However, the method is ineffective if the source code compilation fails. Moreover, it is usually unfeasible to accurately infer the compilation configurations since there are hundreds of combinations of compiler options.

All existing binary2source matching works rarely take the function inlining into consideration, which may lead to a significant performance loss in function inlining scenarios.

2.2 Function Inlining

Function inlining [44] conducts function expansion, replacing a function call with the callee body. Besides that function inlining benefits decreasing the cost of method calls, its major purpose is to enable additional compilation optimizations [55]. As a few passes can be used for inter-procedural optimizations, inlining the callee function can convert inter-procedural optimizations into intra-procedural optimizations, which have more options than inter-procedural ones.

On the other hand, function inlining can cause an increase of binary code size and compilation time. It is a trade-off to determine when to inline for a balance between these benefits and costs. Prior researches have proposed lots of inlining strategies [28, 31, 33, 34, 37, 43, 45, 64] from different aspects. We will introduce inlining strategies adopted in GCC [13] and LLVM [25], the two most popular compilers.

GCC and LLVM follow a similar workflow for function inlining, including inlining decision heuristics and inlining conduction. To decide which call-sites should be inlined, they consider user-forced inlining, user-suggested inlining, and normal inlining candidates. User-forced inlining, such as "__attribute__((always_inline))", will first be considered to be inlined, as long as the call-site of this function does not violate fundamental requirements. User-suggested inlining is specified by users using the keyword "inline" to decorate function definitions. Such decorated functions will be possible candidates to be inlined, but the inline occurrence still depends on the strategy of the compiler. Normal inlining candidates will be identified and determined according to the strategies used in GCC and LLVM themselves.

GCC uses a priority-guided inlining algorithm to decide which call-sites should be inlined. They first define the inline priority of a function call by pre-estimating the benefit of this inline. At the same time, the cost of inlining also increases with this potential inlining. Once the total cost of inlined methods reaches a maximal threshold as configured, inlining process will stop. Apart from the inlining strategy for normal function calls, GCC-10 also implements specific settings for small-size functions and functions that are called only once. For example, when compiling a program with the option of "-O1", GCC-10 applies "-finline-functions-called-once" to conduct inlining. This command will inline all static functions that are called only once no matter whether they are marked with "inline" or not. And if a function called once is inlined, then the function will be not compiled as an individual function in the binary. [20].

Instead, LLVM uses a prediction-driven inlining method to determine function inlining. This inliner first classifies functions into hot and cold ones according to the times they are called. Then each call-site will be assigned with the measurements of inlining benefit and inlining cost [3]. If the cost value is lower than the benefit value, this call-site would be inlined [18].

Besides, there are binary-level similarity analysis works taking function inlining into consideration, such as Bingo [30]. However, Bingo targets binary-level similarity analysis and doesn’t provide a systematic analysis of function inlining, which provides fewer insights for binary2source code matching works.

3 DATASET

As aforementioned in Section 1, an open-sourced binary2source dataset with a mapping between binary functions and source functions is lacking in the domain of binary2source matching. To fill the gap, this section will construct a dataset and propose a method for dataset labeling. As illustrated in Figure 2, we first collect source projects and compile them into binaries under diverse configurations (shown in Section 3.1). Based on the dataset, we design a data labeling approach to generate the mappings from source code to binaries, which are the ground-truth dataset for our study (shown in Section 3.2).

3.1 Dataset Collection

We focus on C/C++ programs and two popular compilers, GCC [13] and Clang [7]. We have collected two datasets (dataset I and dataset II) for binary2source matching by employing Binkit [23, 48], a binary code similarity analysis benchmark.

| Table 1: Projects and versions of dataset I |
|--------------------------------------------|
| package   | version      |
|------------|--------------|
| binutils   | 2.33.1, 2.34, 2.35, 2.36, 2.36.1 |
| coreutils  | 2.28, 8.29, 8.30, 8.31, 8.32 |
| findutils  | 4.4.1, 4.4.2, 4.6.0, 4.7.0, 4.8.0 |
| gzip       | 1.10, 1.16, 1.7, 1.8, 1.9 |

Dataset I. Table 1 shows the source projects with version information in the dataset I. coreutils [8] and gzip [16] have been extensively used in binary and binary2source similarity researches [30, 38, 49, 58, 60, 62]. binutils [6] and findutils [11] are popular
subjects studied by vulnerability detection and patch detection [57, 59, 61]. These four projects belong to GNU projects [24].

| Compilers | gcc-4.9.4, gcc-5.5.0, gcc-6.4.0, gcc-6.4.0, gcc-6.4.0, clang-4.0, clang-5.0, clang-6.0, clang-7.0 |
|-----------|--------------------------------------------------------------------------------------------------|
| Architectures | O0, O1, O2, O3, Os |

We compiled the source projects in Table 1 under compilation settings listed in Table 2. We used 9 versions of compilers, including 5 gcc versions and 4 clang versions. When applying each compiler, we adopted the default 5 optimization options (from O0 to Os) to compile source projects to the architecture of x86_32 and x86_64.

That is, for each version of each source project, the compiler settings will produce 90 compiled projects. Finally, we obtained 4 × 5 × 90 = 1800 compiled projects by compiling all 4 projects with 5 release versions.

In total, through compiling the four subjects with diverse versions and rich compilation settings, we produced 1800 compiled projects. This Dataset I includes 57,739 binaries and 19,868,341 functions.

**Dataset II.** Dataset II includes coreutils [8] v8.29 and v8.31 as source projects. We chose coreutils [8] due to its popularity in existing binary code similarity analyses [30, 38, 49, 58, 60]. We compiled the two source versions using four compilers, i.e., gcc-5, gcc-6, clang-3.6, clang-10 under four standard optimizations (-O0, -O1, -O2, -O3). When using clang compilers, we also switched on “-flto” option to enable inter-modular optimizations.

During the compilation process of coreutils, it will first clone a project named gnulib [15], which serves as the coreutils library. After cloning the source code of the project library, the produced binaries will have few mappings to the system library, making the mapping results less dependent on the system. Our Dataset II includes coreutils with the gnulib, which form the final binaries after compilation.

Table 3 shows the statistics of dataset II. For example, coreutils v8.29 contains 3947 source files including 6133 source functions, accounting for 799,494 lines. After compilation, it produced 4 × 4 × 107 = 1712 binaries including 107,726 binary functions. In summary, dataset II includes 3440 binaries and 224,341 functions.

**3.2 Dataset Labeling**

Based on the source projects and compiled binaries we collected in Section 3.1, we design an approach to label the datasets, outputting source to binary matching ground-truth.

Algorithm 1 formalizes our method for labeling the dataset at line-level and function-level. The method leverages the line mapping implied by the relation between binary address and source code line, which can be provided in the debug mode. By extending line mapping results, the method will generate a function-level mapping between binary functions and source functions. We will introduce the algorithm with an example in Figure 3.

Algorithm 1 Method for dataset labeling

**Input:** Source projects S, Binaries B

**Output:** Line mapping LM_{b2s}, Function mapping FM_{b2s}

1. function PREPROCESSING(B, S)
   2. LM_{b2s} = extract_line_mapping(B)
   3. SM_{l2f} = extract_source_line_to_function_mapping(S)
   4. BM_{a2f} = extract_binary_address_to_function_mapping(B)
   5. return LM_{b2s}, SM_{l2f}, BM_{a2f}
   6. end function

7. LM_{b2s}, SM_{l2f}, BM_{a2f} = PREPROCESSING(B, S)
8. F_{b2s} = []
9. for (line,address) in LM_{b2s} do
10. source_function = SM_{l2f}[line]
11. binary_function = BM_{a2f}[address]
12. if (binary_function, source_function) not in F_{b2s} then
13. F_{b2s}.append((binary_function, source_function))
14. end if
15. end for
16. return L_{b2s}, F_{b2s}

The method first compiles source code with "-g" option and leverages Dwarf [9] to produce the .debug_line section in binary. To extract the line-level mapping, it uses Readelf [21] to parse binaries (line 2). As shown in Figure 3, the line mapping contains the mapping between source file lines and binary addresses.

Next, the method extracts line-to-function mapping in the source code by employing Understand [22] and extracts address-to-function mapping in the binary code by employing IDA Pro [17]. Understand and IDA Pro are two state-of-art commercial tools and have been widely used in academia [36, 52, 54] and industry [4, 5, 27]. Understand is a static analysis tool to identify source entities (e.g., files, functions) and their dependencies. By exploring source entities, we can infer which entity the code line belongs to (line 3). IDA Pro recovers the function boundary [29] from binaries, outputting binary address to binary function (line 4). For example in Figure 3, source line 287 belongs to the source function usage, and binary address 0x40C181 belongs to binary function usage.

Finally, our method extends the above line-level mapping results to function-level mapping by combining these three mappings (lines 8-15). As shown in Figure 3, now we can get the function mapping between source usage and binary usage. Our method cannot only acquire the line mapping between binary and source but also generate the function-level mapping.
However, in some cases, Understand may fail to identify some code entities especially when a source file contains directives such as "#ifdef". Whether the code entities under conditional macro definitions will be compiled or not depends on environment variables. As a result, such entities may remain unresolved. For example, in coreutils v8.29, we found that 2544 lines in 117 files remain unresolved by Understand. To handle this issue, we first compiled the source files to LLVM IR in debug mode without optimization and extracted the debug information produced by Clang and LLVM. This process can reduce the unresolved lines from 2544 to 597 and unresolved files from 117 to 31. In the remaining 31 files, 16 files are project files and 15 files are other system library files. Our datasets involve system library functions although they only take about 1% in our analysis. Finally, we manually analyzed the rest of 31 unresolved source files.

Our dataset I and dataset II collected in Section 3.1 are labeled by our automatic method. For dataset II, we marked the unresolved entities and further analyzed them, which require extra manual effort. According to the mapping results between binary functions and source functions, we can easily identify the binary function produced by function inlining. The results of our data labeling method can support the study in our work. Besides, this method can also be applied to any binaries compiled in debug mode. Note that Understand and IDA Pro can be substituted with other tools with similar functionalities if available.

4 RQ1: EXTENT OF FUNCTION INLINEING

In this section, we will conduct a study on our dataset II to evaluate the frequency of function inlining, the inlining degree from a view of source code, and the inlining degree from a view of binary code. The quantification of the extent of function inlining will help understand the necessity and importance to take function inlining into consideration in binary2source tasks.

4.1 Study Results

As for the binary2source task, take coreutils as an example, the files of source project coreutils and its lib gnulib serve as the source side, and the binaries produced by the source serve as the binary side. As we have constructed the mapping between source functions and binary functions, we refer to binary functions that map more than one source function as the functions produced by function inlining.

Table 4 shows the statistics of binaries compiled by four compilers with four default optimization options from coreutils v8.29.

In the table, “Binary function” shows the number of binary functions produced, “Binary function inlining” shows the number of binary functions that have inlined other functions. “Inlining ratio” shows the ratio between them. For the binary functions that inline other functions, “one-to-many” ratio shows the average number of source functions that a binary function has inlined. For the source functions that have been inlined, “many-to-one” ratio shows the average number of binary functions that have inlined this source function. All statistics are associated with real mapping from binary to source, excluding binary functions that are produced by the compiler or from the library. Based on Table 4, we present our findings from the frequency of function inlining and inlining degrees from binary and source views.

Frequency of function inlining. As shown in Table 4, the inlining ratios are ranging from 0.02% when using clang-10 with -O0 to 79.22% when using clang-3.6 with -O1. The differences between different compilers and optimizations are caused by their inlining strategies, where clang-3.6 uses an aggressive inlining strategy for both O0 to O3 and clang-10 uses more separated inlining strategies between O0, O1 and O2, O3. Despite the huge difference between compilers and optimizations, when compilers apply high optimizations (such as O3), the inlining ratio has raised more than 60%. When we want to match a binary function with its source functions in this situation, more than half of the binaries should be considered to match more than one function.

Inlining degree from binary view. Figure 4 shows the distribution of the function inlining numbers when applying clang-10 with O3. For a total of 2262 binary functions, about half of them (1089 functions accounting for 48.14%) inline 1 to 3 functions, comprised of 2 to 4 source functions. Moreover, one-to-two mapping (one binary function is compiled from two source functions) is not even the most common case in this high optimization situation, and there are more binary functions comprised of 4 source functions. To complicate matters further, from Table 4, when using clang compiling in O2 and O3, functions are likely to inline more than 4 source functions on average. And in an extreme case, binary function “main” of binary “sort” even have inlined 82 source functions other than the main function “main” in “sort.c”.

![Figure 3: Example of labeling function-level mapping](image)

![Figure 4: Distribution of the source function numbers belonging to inlined binary functions](image)
are also some cases that one source function may be used hundreds of times to produce different binaries. In binaries compiled by clang-3.6, source function “xmalloc” in “gnumlib\lib\xmalloc.c” are reused more than 200 times with optimization O0 to O3. In binaries compiled by gcc-5 with O3, “__NTH” in the system library file “\usr\include\x86_64-linux-gnu\bits\string_fortified.h” are reused even for 3065 times.

4.2 Summary
Answering RQ1. Function inlining is a common optimization in binaries. Our results reveal that When applying “-O3” optimization, more than 60% of the functions will inline other functions. Moreover, the degree of function inlining is surprisingly high: on average, one binary function will inline 4 source functions and one source function can be inlined to more than 10 binary functions.

Insights. Our findings present strong evidence that binary2source matching is not a “1-to-1” issue but a more complicated “1-to-n” problem with a considerable extent of function inlining. We recommend that binary2source matching tasks should take function inlining into account.

5 RQ2: FACTORS AFFECTING INLINING
In section 4, we have witnessed the complexity of function inlining. If we can determine which compilation settings facilitate function inlining and which functions are likely to be inlined, these findings will help us to better handle function inlining. Thus, in this section, we will explore how external factors and internal factors influence function inlining.

5.1 External Factors
To explore the relationship between external factors and function inlining, we select dataset I which has more projects and compilation environment settings to conduct further analysis. In detail, we select four factors that may affect the occurrence of function inlining, including source projects, compilers, optimizations, and architectures. Here, we give our findings:

Projects. Inlining ratios are not related to the overall metrics of projects. Table 5 shows the inlining ratios of each project and the

| Table 4: Function inlining statistics for coreutils v8.29 |
|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| Compiler | Optimization | Binary function | Binary function inlining | Inlining ratio | One-to-Many ratio | Many-to-One ratio |
| clang-10 | O0 | 8505 | 2 | 0.02% | 22.00 | 10.00 |
| clang-10 | O1 | 9120 | 703 | 7.71% | 2.06 | 12.04 |
| clang-10 | O2 | 2267 | 1749 | 77.15% | 5.81 | 12.41 |
| clang-10 | O3 | 2231 | 1715 | 76.87% | 5.93 | 12.35 |
| clang-3.6 | O0 | 2638 | 1755 | 66.53% | 4.51 | 10.21 |
| clang-3.6 | O1 | 2180 | 1727 | 79.22% | 5.87 | 12.01 |
| clang-3.6 | O2 | 2165 | 1710 | 78.98% | 5.81 | 11.75 |
| clang-3.6 | O3 | 2108 | 1663 | 78.89% | 6.01 | 11.76 |
| gcc-6 | O0 | 14653 | 201 | 1.37% | 2.19 | 15.82 |
| gcc-6 | O1 | 8277 | 3050 | 36.85% | 3.04 | 20.49 |
| gcc-6 | O2 | 3861 | 2551 | 66.07% | 3.33 | 14.72 |
| gcc-6 | O3 | 6727 | 5706 | 84.82% | 4.02 | 30.04 |
| gcc-5 | O0 | 14673 | 201 | 1.37% | 2.19 | 15.78 |
| gcc-5 | O1 | 10379 | 3075 | 29.63% | 3.07 | 18.61 |
| gcc-5 | O2 | 8634 | 3215 | 37.24% | 3.13 | 17.21 |
| gcc-5 | O3 | 9308 | 6031 | 64.79% | 3.99 | 27.78 |

Inlining ratios are calculated by the average of different compiler settings. In these four projects, coreutils-8.28 has the highest inlining ratio as 24.50% and binutils-2.33.1 has the lowest inlining ratio as 14.79%. Compared with coreutils, findutils, and gzip, binutils has a smaller inlining ratio with about 3% to 10% lower. However, the inlining ratios are not related to the overall statistics of these projects. For example, we find that functions in binutils-2.33.1 call only 5.28 functions averagely while the number of the calls in coreutils-8.29 is 13.45. There may be a mislead that the difference of their function call results in the difference of inlining statistics. However, functions of gzip-1.6 averagely call 3.58 functions, which is lower than binutils-2.33.1 but with higher inlining ratios. Apart from the functions calls, these projects also differ greatly in their size, where gzip-1.6 has 216 files containing 325 functions accounting for 48,436 lines while binutils-2.33.1 has 2615 files containing 30,809 functions accounting for 2,190,733 lines. But the inlining ratios won’t increase with the project size. Thus, we cannot infer the happenings of function inlining merely by the overall metrics of the projects.

Compilers. Adjacent versions of a compiler may have similar inlining results for the same dataset, but distant versions of a compiler or different compiler families tend to have different inlining results. According to Figure 5, clang-4, clang-5, clang-6, and clang-7 seem to have a similar inlining statistic on the same dataset, which

| Table 5: Function inlining ratios of projects |
|-----------------------------|-----------------------------|-----------------------------|
| Dataset project | inlining ratio | Dataset project | inlining ratio |
| binutils-2.33.1 | 14.79% | findutils-4.4.1 | 22.85% |
| binutils-2.34 | 17.35% | findutils-4.4.2 | 22.85% |
| binutils-2.35 | 18.22% | findutils-4.6.0 | 22.26% |
| binutils-2.36 | 18.59% | findutils-4.7.0 | 21.50% |
| binutils-2.36.1 | 18.60% | findutils-4.8.0 | 21.43% |
| coreutils-8.28 | 24.50% | gzip-1.10 | 22.21% |
| coreutils-8.29 | 24.47% | gzip-1.6 | 20.86% |
| coreutils-8.30 | 23.72% | gzip-1.7 | 21.21% |
| coreutils-8.31 | 23.67% | gzip-1.8 | 21.23% |
| coreutils-8.32 | 23.79% | gzip-1.9 | 21.37% |
is also the case for gcc-4 to gcc-8. But when referring to statistics of clang-10 and clang-3.6 in Table 4, the inlining statistics differ largely especially when using low optimizations, which is due to inlining strategies they are using. As mentioned above, clang-3.6 uses an aggressive inlining decision for both O0 to O3, but clang-10 uses more separated inlining strategies between O0, O1, and O2, O3. And when comparing gcc-5 to gcc-8 with clang-4 to clang-7, the inlining ratios of gcc are a little higher than clang. We found that the difference mainly comes from the difference when using O1 options. As mentioned in section 2.2, when applying O1, gcc applies "-finline-functions-called-once" to inline functions called once, while clang only applies "AlwaysInliner" to process functions that are marked "inline". The difference in their inlining strategy causes the difference in their inlining results.

5.2 Internal Factors

In section 5.1, we have analyzed the external factors that influence the occurrence of function inlining. When we look into the characteristics of functions, there are also some internal factors. In this section, we select three internal factors including keywords in the function definition, size of functions, and function calls, to analyze their correlation with inlining. In Figure 7, 8 and 9, “in” means the inlined functions while “out” means the functions not inlined (outlined functions). Here, we present our findings:

Optimizations. There is an increasing tendency from O0 to O3 for inlining ratio. As shown in Figure 6, when applying optimizations from O0 to O3, the inline ratios increase gradually from 0.67% to 43.24%. Gcc and clang both have a higher inlining ratio when using O2 and O3 compared with O0 and O1, but the differences between O0 and O1 or O2 and O3 are coming from the inlining strategies of gcc but not clang. Figuratively speaking, the optimizations of gcc are more like a slope rising slowly while optimizations of clang are like two stairs of which the first stair is O0 and O1, and the second stair is O2 and O3. Besides, it may seem to be strange that although Os is based on some optimizations of O2, Os has a much lower inlining ratio than O2. This is because Os aims to reduce code size. As inlining a function called many times will increase the code size, Os will stop the function inlining and keep its occurrence at a relatively low level.

 Architectures. The inlining ratios have little difference between x86_32 and x86_64. As shown in Figure 6, the inlining ratio of x86_32 is 20.59%, 1.38% higher than x86_64, of which the inlining ratio is 19.21%. This mainly results from the compilation of some initialized functions. In x86_32, functions such as ".init_proc” and ".term_proc” are mapped to source functions by the description of .debug_line section provided by debugging info, while there is no mapping in x86_64. This is due to that our compilation is conducted in a 64-bit Ubuntu virtual machine. Once we get these functions removed, the inlining ratios of x86_32 and x86_64 are close to each other.
Size. Functions with smaller sizes are more likely to be inlined. Figure 8 shows the size of function in and out of the inlined functions set. We measure the function size by the length of characters and lines. In all compiler and optimizations, the size of inlined functions is nearly half of the size of not inlined functions. Actually, in both clang and gcc, the increased size caused by function inlining is the cost when considering whether to conduct it. And comprising to functions with large size, functions with small size are more likely to be inlined due to its low cost.

![Figure 9: Correlation between calls and function inlining](image)

**Calls.** Functions called more and calling less are more likely to be inlined. Figure 9 shows the frequency of the function calls in and out of the inlined functions. For all compilers and optimizations, inlined functions have a much smaller calling frequency and a less small called frequency. The fewer calls from other functions, the cost less for inlining this function. For example, if a function is called only once, there won’t be an increased size cost. The more calls to other functions mean this function is more likely to be a dispatcher. In this case, this function usually has large bodies, and inlining it may bring great cost. Besides, we also see an inlining preference for functions called more and calling less. Usually, these functions are behaving as individual functional modules, which have less dependence on other functions and usually have a small function size.

5.3 Summary

**Answering RQ2:** The happening of function inlining is influenced by compilers and optimizations. And functions with “static” or “inline” marked, functions with smaller size, and functions called more and calling less are more likely to be inlined.

**Insights:** Exploring when function inlining happens helps further developing binary2source matching methods. Combining the external factors and internal factors influencing the function inlining produces a more precise prediction for the inlining potential.

6 RQ3: EFFECT OF FUNCTION INLINING ON BINARY2SOURCE MATCHING WORKS

In section 4 and section 5, we have illustrated the extent of function inlining and factors that affect function inlining. The widely inlined functions and complexity of inlining potential pose a great challenge to existing binary2source matching works. In this section, we will evaluate some existing binary2source matching works on our dataset and present several findings based on the results.

6.1 Experiment Setting and Metrics

We select CodeCMR [62] and B2SFinder [40], two state-of-the-art methods for binary2source matching, to conduct evaluation for inlined functions. As CodeCMR aims to get function-level matched results and B2SFinder produces binary-level matched results, we provide our evaluation at function level and file level separately but with the same metrics.

Existing binary2source works [35, 39, 40, 42, 46, 47, 51, 56, 62] usually apply metrics to evaluate their returned results merely on the original source functions. But as shown in figure 1, the binary functions netlink_sendmsg not only contains its original function netlink_sendmsg, but also contains the inlined functions such as scm_send. Using existing metrics cannot reflect the ability in detecting inlined functions. Thus, we design an evaluation metric considering both the original function and inlined functions. In detail, we use rec@K to evaluate the results of the original function and use acc@K and recin@K for inlined functions. These metrics are defined as follows:

\[
rec@K = \begin{cases} 1, & \text{if original function in } K \text{ candidtes} \\ 0, & \text{else} \end{cases}
\]

\[
acc@K = \frac{|\text{inlined functions} \cap |K\text{ candidates}|}{\min(|\text{inlined functions}|, |K\text{ candidates} |)}
\]

\[
recin@K = \frac{|\text{inlined functions} \cap |K\text{ candidates}|}{|\text{inlined functions}|}
\]

In these formulas, |inlined functions| represent the set of source functions that the original function has inlined, and |K candidtes| represents the top K candidtes the method returned. We use min (|inlined functions|, |K candidtes|) to play as the denominator for formula (2) to avoid the case that the number of inlined functions is larger than the number of returned candidates.

For both CodeCMR and B2SFinder, we use rec@1 and rec@10 to evaluate their results on original function, and accin@10 and recin@10 on inlined functions in dataset II. We conduct three experiments to see the **overall performance** on the whole dataset, the difference of performance on binary functions inlining and not inlining, and the difference of performance on binary functions inlining with different numbers. To stay consistent with released binaries, all binaries in dataset II are stripped off the symbols.

### 6.2 Evaluation Results

| Method     | Return Rate | Original files/funcs | Inlined files/funcs |
|------------|-------------|----------------------|---------------------|
|            |             | rec@1                | rec@10              |
|            |             | acc@10               | acc@10              |
| B2SFinder  | 32.83%      | 32.97%               | 44.74%              | 75.31%              | 2.86% | 62.92% |
| CodeCMR    | 89.15%      | 56.35%               | 65.17%              | 62.94%              | 2.86% |

Table 6 shows the overall evaluation of B2SFinder and CodeCMR. In Table 6, return rate means the probability that a submitted binary function query can be returned with a result. B2SFinder has a lower return rate due to its reliance on the success of parsing source code to extract features. However, a lot of files cannot pass the preprocessing stage due to the missing of system library, thus features cannot be extracted from them. CodeCMR also misses some binary
functions. Although CodeCMR doesn’t need to parse source code, it has a default filter to get rid of some binary functions that have small function bodies. Though it is designed to omit some library functions, it also misses some functions that are produced by the source project. The metrics in Table 6 are divided into “original files/funcs” and “inlined files/funcs”. Figure 10 and Figure 11 directly use the metrics. Here, we present our findings:

**Overall performance.** For binary functions that have returned source functions, we evaluate the result using the above metrics. As shown in the table, acc@10 and rec@10 in the inlined files or functions are the metrics measuring the ability to detect the inlined functions, which is the new task we set for function inlining scenario, where both B2SFinder and CodeCMR lacking such ability. For detecting the original function as the previous task for B2SFinder and CodeCMR, the performance of B2SFinder and CodeCMR also decreases. We attribute this decreasing performance to the neglect of inlined functions, as it not only causes the misses of inlined function but also loses part of the semantics of the binary function. In general, the results not only reflect their shortness in detecting the inlined files or functions but also present their declining ability in detecting the original function.

![Graph](image1)

**Figure 10: Evaluation of CodeCMR for binary functions inlining and not inlining**

**Binary functions inlining and not-inlining.** Figure 10 shows the performance of CodeCMR on binary functions that inlining happened and did not happen. There is a huge decline in rec_o@1 and rec_o@10 when comparing the performance on normal functions to functions inlining. The return rate of functions inlining is a little higher because functions inlining tend to have a bigger size that can pass the filter of CodeCMR. And the acc_in@10 and rec_in@10 of functions not inlining are 100% due to that they don’t have inlined functions. Generally, existing binary2source matching works lose more than 50% of performance when detecting functions inlining compared to functions not inlining. The mapping relation between binary and source which changes from “1-to-1” to “1-to-n” when function inlining happens, directly brings challenges to existing matching mechanisms, making the performance of existing work suffering from inaccuracy.

**Binary functions inlining with different numbers.** Figure 11 shows the detection results of CodeCMR for functions inlining at different degrees. We set three intervals to see the changes between them. In general, there is a decreasing trend when the number of inlined functions increases. As a function inlines more functions, more code will come to comprise the final binary function, which brings more difficulties to detect the origin function. However, there is also an increase for inlined functions from 4-6 to 7-10 in accin@10 and recin@10. The increase can be attributed to the increased number of inlined functions, which makes it easy to return correlated functions. In general, when the function inlines more functions, it becomes harder to find its original function.

![Graph](image2)

**Figure 11: Evaluation of CodeCMR for functions inlining at different degrees**

### 6.3 Case Study

Figure 12 shows the mapping relation for function usage in binary base64 of the project coreutils v8.29. When compiling coreutils v8.29 with clang-10 using “-O3” option, source function usage inlines three other functions and finally are compiled to binary function usage. For this inlined binary function, we use CodeCMR[62] to search its matched functions in the source project coreutils. In its returned ranked 10 results, the most similar and related function is emit_ancillary_info, which has a score of 0.58 and ranks second. However, the function usage only ranks 7th and the other two inlined functions don’t appear in this list.

When we look into the composition of this binary function, we found it is comprised by 40 lines from emit_ancillary_info, 35 lines from usage, 16 lines from emit_stdin_note and 16 lines from emit_mandatory_arg_note. The main part of binary function usage is no longer the source function usage but emit_ancillary_info. And the “1-to-1” matching mechanism suffers from the neglect of the inlined functions.

![Graph](image3)

**Figure 12: Function inlining example: usage in base64**

### 6.4 Summary

**Answering RQ3.** The results not only reflect the shortness of existing binary2source matching works in detecting the inlined functions but also show the decrease of their ability in detecting the original function. Especially, existing binary2source matching works lose more than 50% of performance when detecting functions inlining compared to functions not inlining. And the more functions a function has inlined, the harder it is to detect it.
Insights: Function inlining has changed the mapping relation between binary functions and source functions, which brought great challenges to the existing “1-to-1” matching mechanism. To solve the matching for inlined functions, we need to either develop a “1-to-n” matching mechanism or find a new level suitable to conduct “1-to-1” matching. There requires a change for existing binary2source matching works.

7 DISCUSSION

7.1 Suggestions

In general, there exists a great challenge for existing works when conducting binary2source matching for inlined functions. This challenge is not only limited to binary2source code similarity analysis but can also be extended to binary level similarity analysis tasks. To help resolve this challenge, we will give several suggestions based on our findings.

Consideration of inlining patterns. Section 4 and section 6 shows the “1-to-n” mapping relations of inlined functions and its effect on existing binary2source works. The challenge function inlining brings lies in the difference between the “1-to-1” function mapping and the “1-to-1” matching mechanism of existing works. One way without changing the matching mechanism is to find a more fine-grained level that is feasible to conduct “1-to-1” matching. Currently, there are some binary code similarity analysis works such as DeepBinDiff [36] which is based on the basic block level. Function inlining itself will not change the mapping of basic blocks and only the inter-procedural optimization the function inlining facilitates will cause block merge or split. After some preprocessing, basic blocks are feasible to be matched in binary-level code similarity analysis. This idea can also be extended to binary2source matching, but what should a basic block match in the source remains unknown. We recommend the construction of inter-procedural CFG augmented with entities, and the code blocks between control flow can serve as the merged basic blocks. And note that when conducting matching, a source “basic block” may be matched with many binary basic blocks due to the large reuse of source code. In general, convert function level “1-to-n” matching to basic block level “1-to-1” matching is a feasible idea to resolve the challenges brought by function inlining.

Consideration of affecting factors. Apart from developing a basic block level matching method, a “1-to-n” matching mechanism is also feasible with help of the inlining inference. In section 5, we analyze several factors affecting function inlining. Leveraging that, we can determine which functions are more likely to be inlined. And an idea coming into our mind is called “inline trial”. For the functions called by the original function, we can analyze each function for whether it will be inlined. If there is a high probability that inlining will happen, we combine this function with the original function. As the produced function is combined with the original function and other inlined functions, the comparison between source and binary is a “1-to-n” matching process. Moreover, if the similarity between the binary function and inlined source function is lower than the similarity before conducting inlining, we can cancel this inlining trial and try other functions. Finally, a precise mapping between binary function and source function can be obtained. Recovering the happening of function inlining and then conducting function inlining trial also facilitate the matching between binary function and source inlined functions.

Consideration of other inlining. During compilation, except for the source functions that may be inlined into the final binary functions, other entities such as macro, struct will also take part in the formation of the binary. In some cases, a macro or a global object may be defined with strings and constants. Most existing binary2source matching methods including CodeCMR and B2SFinder use strings to get a match. Thus, losing strings in the macro may cause a decrease in their precision. Macro functional is a macro containing a small function, which may contain control flow. When applying control-flow-based methods, control flow hidden in macro functional should be considered. We also found some macro functional may call other functions, which may contain function call relations. In summary, entities apart from functions still play an important role in identifying similar functions between binaries and sources. The binary2source matching method should take them into account to achieve better results. As our study focuses on function inlining, we leave the analysis of other inlining as future works.

7.2 Limitations

Influence of debug option on binary. As we construct the dataset using “-g” option, there may exist concerns that compilation in debug mode maybe produces different binaries compared to the custom setting. To remove such concerns, we conduct diff analyses between the stripped debugged binaries and stripped normal binaries. Take coreutils v8.29 as the example, 107 debugged binaries and 107 normal binaries are produced using clang-10 and “-O3” with and without “-g”. Then we stripped their symbol and disassemble these binaries for comparison. Among them, 15 binaries have different disassembly codes. After manual observation of the difference, 10 binaries have different contents due to change of address, reduced “jmp” instruction that won’t be executed, changed “nop” instruction, and added “xchg” instruction, which will not affect the semantics of the assembly. Another 5 binaries have some changes including instruction reorder and split of “jmp” instruction. However, these changes only account for a few lines of assembly, which we believe won’t bring non-negligible changes to the normal binaries.

Accuracy of dataset labeling. As our labeling method is mainly based on existing tools, the accuracy of dataset labeling depends on the accuracy of existing tools. In fact, we notice that there are difficulties for understand in parsing source entities, so we use a conservative approach to label the dataset. In detail, we run understand in its “strict” mode where it will accurately identify the entity, or add it to the unresolved list. And we manually analyze the unresolved entities to further complement them. We also tried other tools to label the dataset such as ctags [10], Readelf [21], Obidump [19] etc. But in our observation, understand and IDA Pro produce the most suitable results for binary2source matching tasks.

Selection of representative works. In this paper, we select B2SFinder and CodeCMR as the representative works to conduct analysis. There may be concerns that these two methods are not enough to represent all binary2source matching works. But, in our observation, B2SFinder is state-of-the-art in feature-based methods, which is feasible to represent the feature-based methods. CodeCMR is currently the most accurate and extensible work to conduct function level similarity detection, which is the reason why our
study mainly focuses on CodeCMR. There is another work named Buggraph, but it is more like a binary level matching method, which we didn’t include in our evaluation.

8 CONCLUSION

In this paper, we conduct an empirical study to analyze the effect of function inlining on binary2source matching researches. We first construct two datasets containing 61,179 binaries and 19,976,067 functions and propose an approach to automatically label the dataset with line-level and function-level mapping. Then we conduct several studies to investigate the extent of function inlining, the factors affecting function inlining, and the effect of function inlining on effectiveness of existing works. Finally, based on the findings of function inlining, we give our suggestions.

In the future, we will extend our evaluation to binary similarity researches including software plagiarism detection, vulnerability detection, and patch presence testing. We hope our study could provide new insights for researchers and help them develop more effective and scalable methods.

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