Automated Deobfuscation of Android Native Binary Code

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ABSTRACT
With the popularity of Android apps, different techniques have been proposed to enhance app protection. As an effective approach to prevent reverse engineering, obfuscation can be used to serve both benign and malicious purposes. In recent years, more and more sensitive logic or data have been implemented as obfuscated native code because of the limitations of Java bytecode. As a result, native code obfuscation becomes a great obstacle for security analysis to understand the complicated logic. In this paper, we propose DiANA, an automated system to facilitate the deobfuscation of native binary code in Android apps. Specifically, given a binary obfuscated by Obfuscator-LLVM (the most popular native code obfuscator), DiANA is capable of recovering the original Control Flow Graph. To the best of our knowledge, DiANA is the first system that aims to tackle the problem of Android native binary deobfuscation. We have applied DiANA in different scenarios, and the experimental results demonstrate the effectiveness of DiANA based on generic similarity comparison metrics.

1 INTRODUCTION
Android apps have received widespread adoption recently [24]. Besides the standard Android programming model in Java, Android NDK [9] was introduced to allow developers to include native code binaries (write in C/C++) in their apps.

Recent work suggested that native code had been widely used [21, 22, 47] in Android apps, which severely complicates the process of static analysis. As Java bytecode can be easily decompiled, malware developers usually hide the malicious payload and core functionalities in the native code to evade detection [6, 7, 18, 21]. Even worse, native code can also be obfuscated, which further increases the difficulty of security analysis. For example, the towelroot exploit (CVE-2014-3153) [1, 4], one of the biggest Root Exploits family in Android, was found obfuscated at the native code level by O-LLVM. It took a lot of efforts for security researchers to dive into the technical details of the code due to obfuscation. Figure 1 shows the control flow graph of an obfuscated function “search_goodnum”, which is one of the key components of a Proof-of-Concept (PoC) implementation of the towelroot exploit. Apparently, the obfuscated control flow becomes too complex to understand the real logic.

Although several attempts [26, 27] have discussed the deobfuscation of Android apps, all of them have been focused on Java-level deobfuscation. For example, DeGuard [27] was proposed to reverse layout obfuscation (naming obfuscation) generated by ProGuard. Their key idea is to learn a probabilistic model over a large number of non-obfuscated apps and to use this model to deobfuscate new APKs. Layout obfuscation is the easiest one in Android app obfuscation, which does not alter the program logic (e.g., control flow) of the apps. To the best of our knowledge, no previous studies have attempted to tackle native code deobfuscation for Android yet.

Motivation. The focus of this paper is deobfuscating the native code in Android apps. To be specific, we focus on the deobfuscation of native code that was protected by Obfuscator-LLVM (O-LLVM), which is the most popular native code obfuscator. O-LLVM is a set of obfuscating code transformations suite, which is implemented as middle-end passes in the LLVM compilation flow. O-LLVM offers three obfuscating methods: Instruction Substitution (InsSub), Bogus Control Flow (BCF) and Control Flow Flattening (CFF). Many popular packing tools, e.g., Baidu Jiagu [11] and Bancle [12], are implemented based on O-LLVM.

Challenges. Binary code deobfuscation is not a new task introduced in Android, as many studies have already been proposed for PC platforms (e.g., x86). Udupa et al. [49] use static techniques to remove the dead edges added by the obfuscator. Yadegari et al. [57] proposed a deobfuscating approach based on the execution trace of the executable code. However, it is non-trivial to deobfuscate Android native binary code because there are no existing deobfuscation tools that can deal with full O-LLVM obfuscation, especially in the scenario of Android apps and for the ARM platform. Specifically, we face the following main challenges in this work:

• Complexity due to instruction optimization on ARM. Due to the specific optimizations on the ARM platform, some obfuscated operations may not be independent. It may be interleaved with normal instructions and operations. Thus it becomes a challenge to comprehensively and accurately pinpoint the obfuscated instructions.

• Difficulty in control flow recovery due to basic block splitting. Control Flow Flattening in O-LLVM obfuscation...
can completely destroy the original control flow. At the same time, original basic blocks can also be split or partially merged, which may cause the separation of original semantic information. It becomes difficult to properly recover control flow in this kind of situations.

- **Challenges in symbolic execution due to unknown path constraints.** We will apply symbolic execution as one of the key steps in deobfuscation for the purpose of systematically exploring multiple program paths, similar as in previous work [35, 36, 55]. However, since the recovering process of O-LLVM obfuscated binary is flow-sensitive, incomplete context information may lead to incomplete or wrong path exploration, while performing symbolic execution directly will cause the path explosion problem. Thus we need to find a way to retain the context information as much as possible, while avoiding path explosion during symbolic execution.

**Approach** In this paper, we propose DiANA (Deobfuscation of Android Native Binary Code), a new approach for automated deobfuscation of Android native binary code. Technically, DiANA works by combining static taint analysis and symbolic execution to remove the obfuscation introduced by different obfuscating techniques in O-LLVM. One key feature of DiANA is that we introduce taint analysis to perform semantic level deobfuscation, while considering both general and compiler optimization situation. We also exploit flow-sensitive symbolic execution to rebuild the seriously obfuscated control flow. To overcome the challenge of basic block splitting, we chop the original control flow, select analysis targets through static features, and dynamically adjust the analysis target sequence to maximize context inheritance.

Experiments on multiple benchmarks and real-world cases suggest that our approach can accurately deobfuscate native code obfuscated by O-LLVM. We believe DiANA can be used by security analysts to make it easier to inspect native code, even if it was heavily obfuscated. This paper makes the following major contributions:

- To the best of our knowledge, this is the first work to tackle native code deobfuscation in Android apps. Our approach is able to handle different obfuscations provided by O-LLVM, the most popular obfuscator for Android.
- We design and implement DiANA, a system that can successfully deobfuscate native code in Android apps. DiANA leverages taint analysis to overcome the complication due to ARM-specific optimizations. It also deploys flow-sensitive symbolic execution to tackle Control Flow Flattening obfuscation in O-LLVM.
- Our evaluation on a set of Android apps demonstrates that DiANA is effective in native code deobfuscation and could become a valuable tool for tasks including program analysis and malware detection. We will release our system and the benchmarks to the research community at: [Link removed due to double-blind requirement.]

2 BACKGROUND AND RELATED WORK

To the best of our knowledge, this is the first work that tackles Android native code deobfuscation in our community. Nevertheless, there are already many studies on code obfuscation and deobfuscation for applications on both mobile and PC platforms.

2.1 Android App Obfuscation

To increase the bar for reverse engineering and hinder cracking, and prevent theft of intellectual property, code obfuscation techniques have been widely used in Android apps [32], for both legitimate apps and malware. Many tools allow developers to obfuscate their apps [8, 10, 14, 19, 20, 38]. For example, ProGuard is a popular obfuscation tool integrated in the Android build system. These tools may operate at different levels, e.g., Java code level, Dex bytecode level and native code level.

Native code level protection is much stronger than Java-level protection, thus state-of-the-art commercial packers utilize native code obfuscation to increase the complexity of reverse engineering [33]. As a side effect, Android malware also take advantage of native code obfuscation to evade detection.

**Obfuscator-LLVM (O-LLVM)** is one of the most widely used code obfuscator for both x86 and ARM platforms [38]. It is implemented as middle-end passes in the LLVM compilation process, which offers guaranteed compatibility with LLVM. It offers the following three obfuscation techniques:

1. **Instruction Substitution (InsSub).** InsSub is the simplest obfuscation technique in O-LLVM. It replaces the standard binary operations, e.g., arithmetic (ADD, SUB) or boolean ones (AND, OR and XOR), by functionally equivalent but more complicated sequences of instructions. For each kind of operations, there are multiple ways to perform obfuscation. InsSub chooses one at random to increase code diversification in the resulting obfuscated code.

2. **Bogus Control Flow (BCF).** BCF modifies the CFG by adding a conditional jump to randomly selected basic blocks, which either points to the original basic block or to a fake basic block looping back to the conditional jump block[38]. In order to evade detection and optimization by the optimizers, an opaque predicate [50] (i.e., a mathematical expression which always evaluating to the same value) is used to ensure that only the original basic block is executed during run-time.

3. **Control Flow Flattening (CFF).** This is the most effective, and the most difficult to deobfuscate, pass in O-LLVM. The basic idea is to remove all easily identifiable conditional jumps (e.g., IF-ELSE) and looping structures (e.g., WHILE, FOR), and use a big switch construct to route the code control flow through the proper basic blocks. The flow dispatcher chooses the next block using a routing variable, which resets in each basic block and leads the flow to the next correct basic block. Besides, there is a compilation flag that enables further breaking the code structure by artificially increasing the number of basic blocks in a function.

In general, InsSub and BCF are both semantic obfuscations that work at the instruction level, while CFF is an overall remodeling of the control flow in a function.

2.2 Mobile App Deobfuscation

Although several attempts have been focused on the deobfuscation of Android apps, all of them deal with Java-level deobfuscation. DeGuard [27] was proposed to deal with layout obfuscation introduced by ProGuard [20]. The key idea is to summarize a probabilistic model by learning unobfuscated apps on a large scale and then use the model to recover the obfuscated code. Also, Baumann et al. [26] use a similar approach to perform ProGuard deobfuscation by code
2.3 General Code Deobfuscation

Binary code deobfuscation has been widely studied for the PC platforms [31, 35, 36, 39, 41, 42, 49, 56, 57]. The closest work related to ours might be the one proposed by Gabriel [35], which attempted to recover O-LLVM obfuscated code on the x86 platform. The work is based on the Miasm [17] framework to reverse the obfuscated function to a control flow graph. Similarly, El-Faramawy et al. [15] used a similar approach based on the Binary Ninja framework [13]. However, they did not tackle the challenges introduced by basic block splitting and instruction optimization, which pose a great challenge for both x86 and ARM platforms. Besides, they did not provide an effective method to identify the obfuscation techniques used in a binary. Finally, context inheritance and sub-function calls are not considered in their work, which is more likely to fail when analyzing large programs. Yadegari et al. [57] proposed a generic approach to automatically deobfuscate binary code on x86. They use the execution trace extracted from a specific dynamic analysis environment as the input of their system. As a result, their work is not suitable on analyzing shared libraries in Android projects because most shared libraries lack of main functions or entry points [53].

3 APPROACH OVERVIEW

Goal. We use the term deobfuscation to refer to the process of removing the effects of obfuscation from the native binary, and ideally recover the original code and control flow before obfuscation. For a given APK input, DiANa first extracts the native binary and determines whether it is obfuscated, then analyzes and transforms the code to obtain a functionally equivalent form that is simpler and easier to understand. For non-trivial code, the deobfuscation results is rarely the same as the original code, however, it is close to the original and much easier to understand compared to the obfuscated version.

Key Techniques. To address the aforementioned challenges, we rely on taint analysis and enhanced symbolic execution to recover O-LLVM obfuscated code. Taint analysis is used to address the challenge introduced by instruction optimization, which performs global feature matching to comprehensively detect all obfuscations introduced by O-LLVM and identify instructions needed to be rewritten by tracking tainted registers. Symbolic execution is used to reconstruct the control flow ruined by CFF. We first identify basic blocks that maintain original operations based on an ARM-specific basic block classification approach. Then we perform chopped symbolic execution [48] to address the path explosion challenge. To perform flow-sensitive symbolic execution, we use dynamic queue scheduling to maximize the context inheritance and rebuild the original control flow.

Overall Architecture. Fig. 2 illustrates the system architecture of DiANa that is mainly composed of four parts. During the pre-processing stage, DiANa first determines what kinds of obfuscation techniques are used in the input binary. Then it performs semantic level deobfuscation for InsSub and BCF based on mainly taint analysis. For the binaries protected by CFF, DiANa will perform chopped flow-sensitive symbolic execution to rebuild the control flow. Then the recovered control flow will be optimized in consideration of basic block splitting. All the deobfuscation results will be integrated and rewritten to the binary(or control flow graph) in the end.

Next, we will elaborate on the details of DiANa and how it works on each obfuscation technique in O-LLVM.

4 INSTRUCTION SUBSTITUTION DEOBFUSCATION

The basic idea of InsSub is to replace standard binary operations by functionally equivalent but more complicated sequences of instructions. Note that in order to avoid the interference of constant folding [51], we set all variable as unknown numbers in our analysis, e.g. a variable waiting for user’s input, in order to keep InsSub activated. Table 1 summarizes 13 kinds of instruction substitution in 5 different categories, which are all the transformations we can find in O-LLVM. Among these transformations, three cases (which are highlighted in the table) are new and not specified in previous work [38].

Challenges. For each kind of operation, there are multiple ways to replace it with functionality equivalent instructions. To achieve code diversification in the final results, the InsSub obfuscator randomly chooses one way to do the obfuscation. Besides, the obfuscated instructions are often interleaved with normal instructions (unobfuscated ones) at the assembly level, which is hard to separate. As a result, it is not enough by simply searching for specific opcode combinations during InsSub deobfuscation. Instead, we introduce static taint analysis to address this challenge.

Method. We apply taint analysis to determine the combination of obfuscating instructions and locate instructions needed to be rewritten. We use the following example to illustrate how to use taint analysis to deobfuscate InsSub.

As shown in Fig. 3(a), assuming line 4 does not exist, the operations from line 3 to line 6 will lead to $R_7 = R_7 + R_5 + 1 - R_5 = R_7 + 1$. After matching the opcode sequence ADD, ADD, SUB and identifying the relationship between these operands, DiANa will directly.

![Figure 2: Overall architecture of DiANa.](image-url)
Table 1: Semantic features used in InsSub.

| Obfuscated Expression | Origin Expression |
|-----------------------|-------------------|
| a = b - (c)           | a = b + c         |
| a = -(b + (c))        | a = b + c         |
| a = b + r; a + = c; a = r | a = b + c         |
| a = b - r; a + = c; a += r | a = b + c         |
| a = b + (c)           | a = b + c         |
| a = -(b + (c))        | a = b - c         |
| a = b + r; a - = c; a -= r | a = b - c         |
| a = b - r; a -= c; a -- r | a = b - c         |
| a = (b ⊕ 1) & b      | a = b & c         |
| a = (b & 1)c & (r | 1)r | a = b & c         |
| a = (b ⊕ c) | (b ⊕ c) | a = b | c |
| a = (b & c) | (b & c) | a = b | c |

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Figure 4: An example of BCF deobfuscation.

![Figure 4](image_url)

**Figure 4:** An example of BCF deobfuscation.

obfuscation. As a result, the challenge we encountered is similar to InsSub. However, BCF is significantly more complicated because the obfuscated instructions are often across basic blocks. To address this challenge, we also rely on taint analysis to perform global opaque predicate matching in order to remove dead branches efficiently.

**Method.** We rely on assembly features to detect whether a binary is obfuscated by BCF. For the given opaque predicate, we have summarized multiple assembly features. Note that InsSub may change the assembly features of BCF (e.g., sub operation may be obfuscated), thus we also manually summarized BCF features when InsSub is involved.

BCF introduces two branches to the original block using 'CMP Rx, 0xA' \((y < 10)\). One successor block containing the 'SUB MUL ANDS' combination (maybe different implementations of the same expression \((x(x-1) \mod 2)\)) is used to direct the control flow back to the original block. Another branch of this successor is always headed to a dead branch. All basic blocks that take opaque predicates as jump conditions are designated as predicate blocks. We use Fig. 4 as an example to show how DiAnA works on this obfuscating pass.

As shown in Fig. 4 (1), the 'SUB MUL ANDS' sequence first appears in Block B. When the opaque predicate operation is detected, taint analysis first sets Block B as a predicate block and sets R2 as a tainted register. Then it will force the conditional jump in the parent block reaching the predicate block Block B. After that, because only one condition jump of the predicate block can actually be accessed, taint analysis will head to Block D and label jump instruction at the end of Block B as to be modified.

Due to the optimization on ARM instructions during compilation, sometimes BCF obfuscation can occur as shown in Block E. If a conditional jump occurs and the constraint is a tainted register compared to zero (there are some cases that compare with 1), DiAnA will automatically set it as a predicate block. In this case, because register R2 is tainted, when system traverses the child blocks of Block D, the block Block E will be set as the predicate block too. The tainted register will be freed when modified by normal instructions.

After taint analysis, all deobfuscated information about instructions that need to be modified will be passed to the rebuilding process. When the binary is not obfuscated with CFF at the same time, the deobfuscated result (as shown in Fig. 4 (2)) will be rewritten to the binary.
6 CONTROL FLOW FLATTENING DEOBfuscATION

The CFF obfuscation rebuilds the control flow to a SWiTCH construct. To deobfuscate the control flow, we need to identify basic blocks that maintain original operations and rebuild the control flow. Symbolic execution is a means of using symbolic input to analyze a program to determine what inputs cause each part of a program to execute [54]. Since the analysis of CFF obfuscated code is flow sensitive, and symbolic execution has been proved as an effective program analysis technique that can systematically explore multiple program paths [23, 28, 29], we combine automatic static analysis and symbolic execution to deobfuscate the binary code. However, we still need to address the following Challenges:

1. Due to the instruction optimizations introduced by the ARM compiler and obfuscator, original blocks are often split and reused. It is a challenge to identify the blocks that contain original operations from a super complicated control flow.
2. As the original control flow has been destroyed by CFF, most basic blocks use direct jumps to reach successors after obfuscation. Before rebuilding the original control flow, we need to know what kind of blocks have multiple successors in the original flow.
3. The recovery work on CFF-obfuscated code is flow-sensitive (e.g. the switch structure relies on the routing variable, which affects the control flow), thus we need to know how to maximize context inheritance and avoid path explosion.

DiANA first determines whether the code is obfuscated by CFF during preprocessing, and then conduct static analysis to identify basic blocks that contain original operations (OO Blocks for short). After that, it performs flow-sensitive symbolic execution on these blocks to reconstruct the original control flow. After optimization, the final deobfuscation result will be written to the output.

6.1 Feature Extraction

Since the flow between basic blocks is directed by a big switch construct, which is led by a routing variable, we use this switch construct and routing variable as two fingerprints to identify CFF-based obfuscation.

The switch construct is actually a nested set of conditional jumps. As shown in Fig. 5, each block ending with a conditional jump mainly consists of three instructions. We call these blocks Dispatchers. Also, the second operand of the compare instruction, which is different from other compare operations, is determined by both the value of the ARM R15 register (Program Counter Register) and an immediate number \( \alpha \). DiANA calculates the value of routing variable as follows:

\[
V_{routing} = \alpha + \text{ins.address} + 8 \tag{1}
\]

Here, ins.address is the address of the current instruction, which will be added by 8 (add 4 in Thumb mode), and becomes the value of Register R15 in the ARM mode. All values of \( V_{routing} \) are saved into a dispatcher dictionary.

6.2 Identification the OO Blocks

Though CFF ruined the original control flow, original operations still exist in part of the obfuscated basic blocks. To re-construct the control flow, we first need to identify the OO Blocks, i.e., the blocks containing the Original Operations. In reference to previous work on the x86 platform [35], and combined with the characteristics of CFF on ARM, we divided the obfuscated control flow structure into five categories, as shown in Fig. 5.

- **Prologue** is the entrance block that contains information about almost all the constants in the original function.
- **Dispatcher** is a conditional-jumping block whose constraint is determined by R15 and an immediate number.
- **Pre-dispatcher** is the Dispatcher block whose in-degree is larger than two. Note that an obfuscated function may have more than one Pre-dispatchers.
- **Return** is the basic block whose out-degree is 0. Note that an obfuscated function may have more than one Return blocks.
- **Relevant** is the basic block that maintains operations of the original function. DiANA does a reverse traversal from the Pre-dispatcher until it encounters a Dispatcher block. All basic blocks in this path between the Pre-dispatcher and Dispatcher are Relevant blocks because these blocks are all dispatched by the switch structure.

The original operations exist in Prologue, Return and Relevant Blocks, which forms the OO Blocks. Due to the introduced optimizations, Relevant blocks may be partly merged, as the bottom gray block shown in Fig. 5. In this case, the block will be duplicated and added to its two parent nodes.

**Determine the number of original successors.** Before the recovering process, we need to determine whether an OO Block has multiple successors when it was in the original control flow. The goal of this step is to prepare for subsequent analysis. Symbolic execution will be performed twice to explore each possible path if a basic block has two successors.

Different from previous work on the x86 platform [35], which just used the opcode ‘CMOV’ as the feature to detect the existence of multiple branches, and due to the simplicity of the ARM instruction set, we use elements in the previously mentioned dispatcher...
will set the conditional flag in Angr’s Intermediate Representation.

As a result, while performing symbolic execution on basic blocks, the deobfuscation system will dynamically save current execution state and adjust the position of the elements in block sequence to ensure the state inheritance.

Two pointers are used in the process of symbolic execution: the Execution Pointer pointing to the current analyzing block, and the Swap Pointer pointing to the front position that never being swapped. Initially, the Execution Pointer points to the Prologue and the Swap Pointer points to the first block in the block sequence. The returned successor block will be swapped to the position that the Swap Pointer points to. At the same time, the current symbolic state will be saved. When the analysis proceeds to this successor, the saved state will be restored. If the returned successor block is
We apply two optimization here. When using CFF to obfuscate the native code, there is a certain will be removed in the final output. In special cases when the two pointers coincide, DiANa will move the Swap Pointer forward one space.

The purpose of dynamically exchanging basic blocks in the sequence is to ensure that most of the basic blocks inherit the state from the previous analysis before execution, while not starting the analysis of a basic block from a blank state.

Algorithm 1 presents the top-level algorithm of our dynamic basic blocks scheduling approach. We also use Fig. 6 as an example to show how this algorithm work. ① After analyzing the True branch, the state before executing Block 5 is saved. ② Then Block 5 is exchanged to the first place of sequence and ③ the Swap Pointer is moved to the next. ④ Following the analysis of the False branch, ⑤ the successor Block 3 is swapped with the second block in sequence and ⑥ the Swap Pointer is moved to the third position. At the same time the state reaching Block 3 will be saved. After that, ⑦ the Execution Pointer points to the first block (Block 5) in the sequence and the previously saved state of Block 5 will be restored. The analysis of other blocks will continue like this successively.

Performing symbolic execution in this way not only guarantees the maximum state inheritance of each basic block, but also avoids path explosion and ensures the order of the entire analysis process.

6.4 Control Flow Reconstruction

When using CFF to obfuscate the native code, there is a certain degree of basic block splitting and merging due to ARM optimizations, no matter the basic block splitting pass is activated or not. As a result, it is necessary to optimize the recovered control flow. We apply two optimization here.

RULE i. As shown in Fig. 7 (1), for two nodes connected by a direct jump, if the in-degree of the parent node is not greater than one, DiANa merges these two nodes.

RULE ii. As shown in Fig. 7 (2), for multiple connected nodes, if their out-degree are all equal to two and the other branch of them points to a same node, once the contents of each node are alike (e.g. comparing operation with consecutive integers), DiANa will optimize this structure as a loop.

Note that when BCF and CFF are used together (with or without InsSub), the introduction of opaque predicates does not affect the recovery of original control flow. Because these blocks (previous mentioned blocks in dead branch) are always unreachable, they will be removed in the final output.

7 IMPLEMENTATION AND EVALUATION

Our experiment is based on O-LLVM 4.0, while our approach can be easily extented to code obfuscated by any OLLVM versions. We use Android NDK V16.1 to build shared libraries. The symbolic engine of DiANa is implemented based on Angr 7.8.2. The function addresses are exported by IDA Pro 7.0.

7.1 Dataset

To evaluate the effectiveness of DiANa, we first need to build a reliable open source dataset with high coverage. We have applied our system to the following three different datasets, respectively.

C/C++ Obfuscation Benchmark. We first evaluate our system on a widely used C/C++ obfuscation benchmark [5]. This dataset was created by a previous work [25] to evaluate different obfuscation algorithms. It includes common basic algorithms, hash functions, and small programs (mainly containing combinations of IF, WHILE, and FOR structures). We eliminated the benchmark programs that contain only one basic block, because it is hard to apply obfuscation techniques on these tiny programs. At last, we obtain 94 benchmark programs in total to evaluate the effectiveness of DiANa.

Open-Source Android Native Code. To evaluate our system on real-world Android apps, we have crawled 100 open source Android projects from F-Droid [16]. Among them, 24 projects use native code. Note that Android apps could use native code in two ways: reusing the existing native libraries by embedding the *.so in the project or implementing their own C/C++ code and then compiling it within the project. Finally, we have identified 5 real-world Android projects that contain open source C/C++ code, which can be used to evaluate our approach.

Real-world Android Root Exploits. We further apply DiANa to Android Root Exploits (aka REs), a binary tool used to obtain the root privilege by exploiting privilege escalation vulnerabilities. In this case, we could evaluate the effectiveness of DiANa on deobfuscating real threats in the wild.

7.2 Evaluation Metrics

We hereby define our evaluation metrics. We deployed Euclidean Distance (ED), Similarity of Control Flow Graph (Sim), and Input/Output equivalence (I/O) to evaluate the effectiveness and correctness of DiANa. Because InsSub works at the assembly instruction level and does not alter the control flow, we use ED to measure the deobfuscation effectiveness and I/O to ensure the correctness. For the BCF and CFF approaches, we deployed Sim.
to quantify the deobfuscation results, similar to previous work [57]. Most importantly, we also use I/O to ensure the deobfuscated function is semantically equivalent to the original one.

7.2.1 Euclidean Distance.
We use Euclidean Distance as a quantitative indicator of our work on Instruction Substitution. To evaluate InsSub deobfuscation, we first generate a feature vector for each function. Each dimension in the vector represents the frequency of certain opcode. We calculate the Euclidean distance [52] as in Formula 2.

\[ d(x, y) := \sqrt{\sum_{i=1}^{n} (x_i - y_i)^2} \]  

(2)

Here, \(x\) and \(y\) are the feature vectors of the obfuscated/deobfuscated function and the original one respectively, while \(n\) is the total number of types of opcode used in functions \(x\) and \(y\).

7.2.2 CFG Similarity Comparison.
From the perspective of reverse engineering, control flow analysis is an important procedure. Due to the difficulty of patching (rewriting) the CFG obfuscated native code at the assembly level, CFG analysis is a key technique in static analysis for Android apps. We adopted the algorithm of Hu [37] for computing the edit distance between two CFGs, which was suggested as one of the best CFG comparison algorithms in previous empirical study [30]. It has also been widely used in previous work [57][43][34].

The basic idea of this algorithm is to build a cost matrix that represents the costs of mapping different nodes in two graphs \(G_1\) and \(G_2\). Then the Hungarian algorithm [40] is used to find an optimal solution to the assignment problem in \(O(n^3)\) time. Note that when calculating the similarity, we perform content matching (e.g., key API-call operation, instruction operands, etc) for each node. Although it does not perfectly prove that the deobfuscated semantics and the original semantics are completely equivalent, we believe that matching node content can further enhance the original similarity comparison algorithm, thus ensuring that the similarity value can reflect the accuracy of deobfuscation results to a certain extent.

We use the formula below to calculate the CFG similarity:

\[ \text{Sim}(G_1, G_2) = 1 - \frac{\sigma(G_1, G_2)}{|N_1| + |N_2| + |E_1| + |E_2|} \]  

(3)

Here, \(\sigma(G_1, G_2)\) represents the edit distance between \(G_1\) and \(G_2\), \(|N_1|\) is the number of nodes in \(G_1\) and \(|E_1|\) is the number of edges in \(G_1\). The score given by Pearson correlation [44] is in the range of \([-1,1]\]. The closer the score is to 1, the more similar are the structures of these two graphs. A similarity score less than 0 means that two graphs are completely dissimilar [30].

7.2.3 Semantic Equivalence.
Though we adopt strict block matching in the calculation of CFG similarity, it is not convincing enough to prove that the deobfuscated function is semantically equivalent to the original one. Due to the change of the offset and function size, binary rewriting needs to be performed on each subsequent instruction and function from the *.so file, which may bring disturbances to the deobfuscation result. Also, to the best of our knowledge, there is no effective and accurate way to solve the problem of binary rewriting yet, even from the intermediate representation level. To minimize the introduction of bias caused by other tools, we choose to show our deobfuscation result of the CFF method on the disassembly instruction level, which is useful for reverse analysts to analyze malicious apps.

Regarding correctness, after applying deobfuscation, we use ANgr’s bit vector to generate 1,500 concrete value inputs (the 500 smallest integers, the 500 largest ones, 500 random others) and test whether the two corresponding outputs (origin and deobfuscated) are identical. If yes, we consider the deobfuscated code as semantically equivalent to the original one. We use I/O equivalence (Input/Output) to represent this evaluation process, which has also been widely used in previous work[45]. In order to visualize the experimental results, we use the percentage of the identical I/O in 1500 times of experiments as a quantitative indicator.

7.3 Evaluation on C/C++ Obfuscation Benchmarks
Because InsSub only works on computation-intensive programs, we select 5 programs with many computation-related instructions from the benchmark to evaluate the result of InsSub deobfuscation. For BCF and CFF, we apply them to all the 94 programs in the benchmark and use DiANa to deobfuscate them. We classified the benchmark programs into 5 categories based on their main functionalities: (1) sorting algorithm (Sort), (2) searching algorithm (Search), (3) mathematical calculation (Math), (4) string manipulation (String) and (5) conversion between number and string (Num2String). Furthermore, we also evaluated DiANa on cases when all three obfuscation techniques are applied.

7.3.1 Instruction Substitution.
The five programs used in the evaluation include: (1) Binary search, (2) Merge sort, (3) String splicing operation, (4) Quicksort and (5) a program with five arithmetical operations. For these programs, we first apply InsSub to obfuscate the samples and then use DiANa to deobfuscate them. Note that for the pass of instruction substitution, we could deobfuscate the results to the binary level.

Euclidean Distance. Column 2 and 3 in Table 2 list the Euclidean distance between the obfuscated function and the unobfuscated one (\(D_{ob}\)), and between the deobfuscated one and the unobfuscated one (\(D_{de}\)), respectively. As we can see, distances between obfuscated functions and unobfuscated ones are in the range of 14 to 44. After deobfuscation, the distances of the recovered functions are all below 10. Note that the gap between deobfuscated and unobfuscated binary (\(D_{de}\)) is mainly caused by the assignment of registers and memory addresses, e.g., move, load and store operations.

The number of obfuscated operations. We also manually checked the obfuscated and deobfuscated programs to measure the number of obfuscated operations (\(N_{ob}\)) introduced and the number of operations (\(N_{de}\)) successfully recovered, as listed in Column 4 and Column 5 in Table 2. All the obfuscated operations are successfully recovered to binary files in our experiment.

Semantic Equivalence. We then applied the aforementioned approach (Section 7.2.3) to evaluate the semantic equivalence of deobfuscated binaries and the original ones. As shown in the “SE” column of Table 2, for each program, we get identical outputs for
Table 2: InsSub deobfuscation result.

| Name                  | \(D_{ob}\) | \(D_{de}\) | \(N_{ob}\) | \(N_{de}\) | SE    |
|-----------------------|------------|------------|------------|------------|-------|
| binarysearch          | 17         | 9          | 5          | 5          | 100%  |
| mergesort             | 16         | 8          | 2          | 2          | 100%  |
| concatstrings         | 22         | 0          | 3          | 3          | 100%  |
| quicksort             | 14         | 3          | 2          | 2          | 100%  |
| basic_arithmetic_operators | 44     | 10         | 8          | 8          | 100%  |

all the 1500 generated inputs, suggesting that the deobfuscated binaries are semantically equivalent to the original ones.

7.3.2 Bogus Control Flow.

BCF offers two additional obfuscation options \(bcf\_loop\) and \(bcf\_prob\), which controls the obfuscation times (default 1) and obfuscation intense (default 30%). To evaluate the effectiveness of DiANa on BCF deobfuscation, we applied two different levels of obfuscation intense: the default obfuscation (bcf\_prob=30%), and enhanced obfuscation (bcf\_prob=50%). We are also able to recover the deobfuscated code to the binary level.

**Result.** Table 3 shows the overall result. Column “BCF” and Column “BCF\_re” shows the result at the default obfuscation level, and Column “BCF\_50%” and Column “BCF\_50\_%\_re” shows the result of the enhanced one. At the default level, the CFG similarity between the original program and the obfuscated program is 0.453 on average, while the CFG similarity could reach up to an average of 0.870 after the deobfuscation process. For the enhanced obfuscation, CFG similarity score of most obfuscated functions has a significant decrease, with an average score of 0.296. Nevertheless, our system could achieve similar good results at different obfuscation level, with an average CFG similarity score of 0.855.

**Semantic Equivalence.** As shown in Table 3 (cf. Column “SE”), all deobfuscation results are equivalent to the original ones, for the two levels of BCF obfuscation. We further manually checked the deobfuscation results of the 16 functions shown in Table 3 by analyzing the instructions in each block of the CFGs, and found that their semantics are indeed equivalent to the original ones.

7.3.3 Control Flow Flattening.

BCF offers an additional obfuscating option split\_num, which means to split the original basic block a specified number of times, to increase the complexity of obfuscated control flow. In the evaluation, we have applied two different obfuscation levels: the default CFF obfuscation\(^1\), and an enhanced obfuscation level with the basic block splitting option on split\_num=3.

**Result.** Table 3 shows the results. Column “CFF” and Column “CFF\_re” shows the results on default obfuscation of CFF, and Column “CFF-3” and Column “CFF-3\_re” shows the results of enhanced obfuscation, respectively. Obviously, with CFF obfuscation, the obfuscated code achieved significant differences compared to original ones considering the CFG similarity. At the default obfuscation level, the average CFG similarity score is only 0.206 after obfuscation, while our deobfuscation results could achieve a similarity score of 0.807 on average. After activating basic block splitting, similarity scores between the obfuscated and original function are almost all negative correlation (-0.185 on average), which indicates that the obfuscated CFG is completely different from the original one. The listed deobfuscation result of the enhanced CFF ranges from 0.72 to 1. The average value on all 90 functions(4 failures with O-LLVM compiling) is 0.722.

**Case Study.** Experimental results suggest that our approach could achieve promising results on most cases. However, for several cases, the CFG similarity of deobfuscated code with the original binary is roughly 0.7. By further analyzing these cases, we found that the main reason is the redistribution of semantics in the original basic blocks. We use the program 16b-1-0-0-0-dc-2-2-0 as an example to illustrate this situation. As shown in Fig. 8. This is a function that calculates twice the sum of the ASCII codes of the input string. The program got a recover result of 0.722 in both default and enhanced obfuscation. Block A in the original CFG (Fig. 8 (a)) is a transition block, and we assume that its parent and child node are directly connected. Also, the two self-loop basic blocks in the original CFG become the loop between two blocks in the recovered result. The key operation ‘ADD’ of the two self-loop structures in the original function are now implemented in the split-out blocks B and C, as shown in Fig. 8 (c). Thus operations on edges D and E can be merged to another branch of its starting node. This example suggests that CFF may separate constraints and operations during obfuscation, which will lead to re-matching of nodes and edges in the recovered result. However, this scenario will not affect the analyzing results, but instead simplifying the analysis process.

**Semantic Equivalence.** Here we also use the I/O approach to check whether our deobfuscation results are semantic equivalent to the original ones. As shown in Table 3 (cf. Column “SE”), for the default CFF obfuscation, our deobfuscation results are totally identical with the original semantics. However, for the enhanced CFF obfuscation, we found some cases shared different outputs with original ones, thus the overall semantic equivalent evaluation result is 90%. By analyzing these exceptional cases, we found that the main reason is introduced by function splitting (cf. Figure 9), as we skipped the BL and BLX instructions when we perform the semantic equivalence evaluation. For such exceptional cases, we manually compared the deobfuscated programs and the original ones, and found that their semantics should be identical if we consider the BL and BLX instructions (superimposing the recovered functions), which we will elaborate in both following subsection and Section 8.

7.3.4 Full Obfuscation (All 3 Techniques).
The aforementioned results suggest that DiANa can recover the
which converts decimal numbers to Roman characters, has more

ing CFGs of functions protected by one of the three obfuscating

framework. Specifically, his work only aimed to recover correspond-

ing LLVM obfuscated code on the X86 platform based on the Miasm [17]

7.3.5 Comparing with Existing Studies.

In previous studies, Francis Gabriel [35] attempted to recover O-

LLVM obfuscated code on the X86 platform based on the Masm [17]

framework. Specifically, his work only aimed to recover corresponding

CFGs of functions protected by one of the three obfuscating
techniques in O-LLVM. However, as we illustrated in Section 2, it
did not tackle multiple challenges introduced by ARM and Android.

In this subsection, we would like to compare his work (we use the
symbol \( \Delta \) to represent it) with ours. Because the Approach \( \Delta \)
could not be used to deobfuscate Android native functions directly, we
make the compromise to remove the context inheritance algorithm
and control flow reconstructing rules in DiANa and assume that
Approach \( \Delta \) could achieve the alike deobfuscation result with the
degraded DiANa. Obviously it is unfair to our approach considering
the adoption of numerous improvements and innovations beside
these two dominating ideas. However, if DiANa could produce
better results than Approach \( \Delta \) in this scenario, the deobfuscating
ability of DiANa will be convincing.

As shown in Table 3, not surprisingly, the average similarities
of the obfuscated functions in these three cases (CFF, CFF-3 and
ALL) are exactly the same. However, the average deobfuscated
result on \( \text{romannumerals} \) is 0.340, which is the lowest. The deobfuscating result on \( \text{romannumerals} \) is 0.807,
showing that DiANa is resilient to complicated code obfuscation.

Semantic Equivalence. We further perform semantic equivalence
evaluation. As shown in the last column of Table 3, besides
several exceptional cases (e.g., \( \text{bkdrhash} \)), we could get identical
outputs for most cases, and thus the final average result is 94%.
Note that we further manually analyzed the extreme cases, and
found the leading reason is the same with the cases we identified
in CFF deobfuscation, i.e., function splitting (cf. Section 8).

| Name          | BCF | BCF_re | SE | BCF_50% | BCF_50%_re | SE | CFF | CFF_re | SE | CFF-3 | CFF-3_re | SE | ALL | ALL_re | SE |
|---------------|-----|--------|----|---------|-----------|----|-----|--------|----|-------|----------|----|-----|--------|----|
| selectionsort | 0.904 | 0.938 | 100 | 0.398   | 0.938    | 100 | 0.151 | 0.919  | 100 | -0.160 | 0.875    | 100 | -0.128 | 0.747 | 100 |
| bubblesort    | 0.709 | 0.852 | 100 | 0.469   | 0.970    | 100 | 0.200 | 0.818  | 100 | -0.160 | 0.726    | 100 | -0.230 | 0.821 | 100 |
| binarysearch  | 0.759 | 0.897 | 100 | 0.372   | 0.923    | 100 | 0.137 | 0.868  | 100 | -0.192 | 0.886    | 100 | 0.025  | 0.816 | 100 |
| binarysearchc | 0.597 | 0.750 | 100 | 0.326   | 0.750    | 100 | 0.318 | 0.843  | 100 | -0.130 | 0.816    | 100 | 0.023  | 0.816 | 100 |
| gcd           | 0.660 | 0.872 | 100 | 0.388   | 0.872    | 100 | 0.075 | 0.776  | 100 | -0.211 | 0.776    | 100 | -0.294 | 0.776 | 100 |
| lcm           | 0.152 | 0.912 | 100 | 0.365   | 1.000    | 100 | 0.172 | 0.857  | 100 | -0.218 | 0.912    | 100 | -0.218 | 0.912 | 100 |
| concatenstrings | 0.213 | 0.769 | 100 | 0.133   | 0.795    | 100 | 0.213 | 0.778  | 100 | -0.261 | 0.872    | 100 | -0.124 | 0.872 | 100 |
| reverse       | 0.280 | 1.000 | 100 | 0.370   | 0.908    | 100 | 0.292 | 0.926  | 100 | -0.252 | 0.828    | 100 | -0.114 | 0.828 | 100 |
| romannumerals | 0.234 | 0.797 | 100 | 0.321   | 0.816    | 100 | 0.164 | 0.797  | 100 | -0.250 | 0.869    | 100 | -0.340 | 0.807 | 81  |
| decimalobinary| 0.184 | 0.906 | 100 | 0.253   | 0.783    | 100 | 0.310 | 0.854  | 100 | -0.174 | 0.854    | 100 | 0.016  | 0.854 | 100 |
| bkdrhash      | 0.175 | 0.828 | 100 | 0.155   | 0.822    | 100 | 0.294 | 0.926  | 100 | -0.165 | 0.828    | 100 | -0.070 | 0.926 | 67  |
| djbhash       | 0.378 | 0.828 | 100 | 0.409   | 0.813    | 100 | 0.264 | 0.926  | 100 | -0.173 | 0.926    | 100 | -0.198 | 0.742 | 100 |
| 1b-1-2-2-1-1g127-0-0-0 | 0.618 | 1.000 | 100 | -0.029 | 1.000    | 100 | 0.304 | 1.000  | 100 | -0.135 | 1.000    | 100 | -0.126 | 1.000 | 100 |
| 1b-1-2-1-1-gts127-dep1-0-1 | 0.618 | 0.893 | 100 | 0.083  | 0.737    | 100 | 0.143 | 0.821  | 100 | -0.224 | 0.750    | 100 | -0.223 | 0.821 | 100 |
| 16b-1-1-0-0-dec2-2-0 | 0.382 | 0.900 | 100 | 0.534   | 0.821    | 100 | 0.475 | 0.722  | 100 | -0.161 | 0.722    | 100 | -0.052 | 0.788 | 100 |
| 1b-4-2-0-0-dec2-2-0 | 0.618 | 1.000 | 100 | 0.196   | 0.742    | 100 | 0.216 | 0.821  | 100 | -0.149 | 0.821    | 100 | -0.242 | 0.821 | 100 |
| Overall similarity of Approach \( \Delta \) | -     | -     | -    | -       | -       | -   | 0.206 | 0.674  | -    | -0.185 | 0.393    | -   | -0.132 | 0.450 | -   |
| Overall similarity of DiANa      | 0.453 | 0.870 | 100 | 0.296   | 0.855    | 100 | 0.206 | 0.807  | 100 | -0.185 | 0.722    | 90  | -0.132 | 0.734 | 94  |
### 7.4 Evaluation on Open-Source Android Apps

The five open source Android apps used in our evaluation are: (1) Practice Hub (com.proch.practicehub.src), a tool for musicians; (2) Overchan (bus.chio.wishmaster), an app for browsing different kinds of imageboards; (3) AsciiCam (com.dozing.catsoftware.asciiCam), a photography app that generates ASCII images in real time, with more than 100K downloads in Google Play; (4) Agram (us.acromatic.metaphor.agram), a tool to list single-word and multi-word anagrams in English; (5) NicoWnnG (net.gorry.android.input.nicoWnnG), a keyboard IME with more than 50K downloads in Google Play.

**Result.** For each open-source app, we first extract its native source code. Then we use O-LLVM to perform obfuscation when building *.so according to Application.mk and Android.mk in the original Android projects. In the deobfuscation process, we filtered the functions that contain only one basic block. At last, we analyzed 56 functions in total.

Table 4 shows the overall deobfuscation results. For binaries obfuscated with BCF (with average CFG similarity score ranging from 0.311 to 0.542), our approach could achieve a CFG similarity score in the range from 0.753 to 0.795 on average after deobfuscation. For binaries obfuscated with CFF (with average CFG similarity score ranging from 0.108 to 0.365), our approach could achieve a CFG similarity score around 0.75 on average after deobfuscation. Although the overall result is acceptable, for a few cases, our approach did not achieve good results as other cases. We further manually analyzed these cases.

We found that the main reason leading to the CFG inconsistency is function splitting. We use function "Anagrams_uninit" in "Agram" to illustrate it. Sometimes an operation in the original *.so can be implemented by one function, while in the obfuscated binary, part of this operation may be split out and used as a sub-function due to optimizations. As shown in Fig. 9 (2), the CFG of deobfuscated function only contains 4 basic blocks. In the first block, this recovered function calls "sub_5F24", which is also obfuscated by O-LLVM. The deobfuscation of "sub_5F24" is shown in Fig. 9 (3). After superimposing these two recovered functions’ CFG, it can be seen that the similarity between original and recovered CFG is very high. The deobfuscation results are 0.875 for CFF and 0.810 for BCF, compare to 0.333 and 0.16 respectively. This result suggests that function splitting could greatly affect the result. Thus, in our implementation, we take the function splitting into consideration, which is not carefully considered in previous studies [15, 35, 57].

**Semantic Equivalence.** As shown in the Column "SE" of Table 4, except for app "Overchan", all the recovered functions of the rest apps get 100% identical outputs in our I/O approach. We further manually analyzed such cases, and found that their semantics are completely equivalent to the original semantics, while this result is introduce by the limitation of our I/O approach (cf. Section 8).

### 7.5 Evaluation on Real-world Exploits

CVE-2014-3153 [1] is a well-known generic vulnerabilities in the Linux kernel, i.e., the Fast User space mtuEX (futex) subsystem, which is the basis of several mutual exclusion mechanisms. Its exploitation (e.g., towelroot [3] and different variants) had been widely spread around world. The original towelroot was protected by O-LLVM, which took researchers a long time to understand the technical details by performing laborious reverse engineering. As shown in the motivating example (Fig. 1), it is quite difficult, if not impossible, for researchers (even experienced experts) to figure out the details from the obfuscated CFG directly.

**Result.** As of this writing, the source code of the original towelroot is still unavailable. Fortunately, some researchers have published their results, which can be regarded as the identical PoCs of the original one. We will then demonstrate the capability of
our system based on one of them [2], and the results are summarized in Table 5. For simplicity, we focus on two key functions, i.e., “search_goodnum” and “send_magicmsg”, to illustrate our work.

The deobfuscation results of “send_magicmsg” and “search_goodnum” in “CFF” situation are 0.963 and 0.939 respectively, which means that the deobfuscated CFGs are almost the same as the original ones. In “ALL” obfuscation situation, these two value are 0.962 and 0.900 respectively. Fig. 10 shows the comparison between the two CFGs of “search_goodnum”. Compared to the obfuscated CFG shown in Fig. 1, it is obviously much easier to understand the logic of the exploitation, especially the system call sequences and key operands, from the deobfuscated CFG.

Semantic Equivalence. We also use the I/O approach to prove the deobfuscation results are semantic equivalent to the original function. As shown in Table 5, for all cases, all the outputs of deobfuscated functions are identical to the outputs of ones, considering the same 1,500 inputs.

8 THREATS TO VALIDITY AND DISCUSSION

Although the experimental results suggest that DiAna achieves good performance in recovering O-LLVM obfuscated functions, our study, however, carries a few threats to validity.

Inherent Limitations of IDA Pro and Angr. Since parts of our system build upon several state-of-the-art tools, which might introduce inherent limitations. As we perform function-level deobfuscation in this work, it is important to recognize the initial address and the basic blocks in each function. However, it is possible that IDA Pro cannot identify the address of a function accurately, which may lead to inaccuracy of our evaluation. In addition, we rely on Angr to perform symbolic execution, while the instructions that cannot be accurately recognized by Angr will likely cause inaccuracies. These are the limitations inherited from IDA Pro and Angr, although they rarely occur during our experiments.

Semantic Equivalence. Our experiment suggested that, for a small number of cases, there exist inconsistencies in evaluating the semantic equivalence of deobfuscated binaries and the original ones. We further manually explored these cases and pinpoint the following two reasons.

First, as we use symbolic execution to run the function at the IR level, the BL and BLX instructions sometimes may affect the proper execution of the symbolic execution engine. As shown in Fig. 9, the semantics of function sub_5F24 is split from the original function. At the very beginning, we try to enter the callee but unfortunately, the execution engine crashed there for quite a few times. Thus, when evaluating semantic equivalence, instead of entering the callee function, we skip them due to the uncertainty of the callee’s space. Based on the manual analysis of such samples, we observe that the semantics of them are completely recovered by DiAna. It is worth mentioning that we also skip callee functions in the deobfuscation process, but it will not affect the recovered control flow, as the flow is routed by Vrouting, which will not be modified cross function or through a callee function. Second, we saved the symbolic state after each time of symbolic execution in Algorithm 1. Actually, the chopped process of symbolic execution of a block may produce multiple different states before a successor. In the evaluation, DiAna only saves one single state, and the state will be updated in the following analysis if it is found to be a non-blank state. It makes our evaluation to be quite effective. However, in some exceptional cases, very few paths may not be found due to the loss of necessary states. In our work, we make the number of saved states of one single block configurable, i.e., users could increase the number of states to save. Increasing the number of saved states will improve our analysis results, as the saved variables are all inherited from the pre-executions.

Although our semantic evaluation approach does not report 100% identical for several cases, our manually efforts confirmed that all such cases were introduced by the aforementioned reasons, and the recovered programs keep the same semantics actually.

9 CONCLUSION

We have presented a novel approach for deobfuscating Android native code. It uses taint analysis to make semantic-level deobfuscation, and leverages an enhanced flow-sensitive symbolic execution to rebuild the seriously obfuscated control flow. We have implemented our approach in a system called DiANA, and demonstrated that DiANA could successfully reverse obfuscations performed by O-LLVM with high accuracy. To the best of our knowledge, this is the first work that tackles the problem of Android native code deobfuscation. We believe that our system could become a useful tool for security analysts and researchers to conduct studies including malware detection and program analysis.
