Drndalo: Lightweight Control Flow Obfuscation Through Minimal Processor/Compiler Co-Design

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Abstract

Binary analysis is traditionally used in the realm of malware detection. However, the same technique may be employed by an attacker to analyze the original binaries in order to reverse engineer them and extract exploitable weaknesses. When a binary is distributed to end users, it becomes a common remotely exploitable attack point. Code obfuscation is used to hinder reverse engineering of executable programs. In this paper, we focus on securing binary distribution, where attackers gain access to binaries distributed to end devices, in order to reverse engineer them and find potential vulnerabilities. Attackers do not however have means to monitor the execution of said devices. In particular, we focus on the control flow obfuscation — a technique that prevents an attacker from restoring the correct reachability conditions for the basic blocks of a program. By doing so, we thwart attackers in their effort to infer the inputs that cause the program to enter a vulnerable state (e.g., buffer overrun). We propose a compiler extension for obfuscation and a minimal hardware modification for dynamic deobfuscation that takes advantage of a secret key stored in hardware. We evaluate our experiments on the LLVM compiler toolchain and the BRISC-V open source processor. On PARSEC benchmarks, our deobfuscation technique incurs only a 5% runtime overhead. We evaluate the security of Drndalo by training classifiers on pairs of obfuscated and unobfuscated binaries. Our results shine light on the difficulty of producing obfuscated binaries of arbitrary programs in such a way that they are statistically indistinguishable from plain binaries.

1. Introduction

There is a multitude of software vulnerabilities that allow an attacker to gain unauthorized access to the critical parts of a multi-user system. For example, in modern server environments, an attacker logged in as a regular user is interested in running a malicious program as the privileged user. One of the techniques to achieve their goal is privilege escalation through exploiting buffer overflows. To mount a buffer overflow, the attacker looks for an appropriate location in the targeted binary. If the plain version of the binary that runs in privileged mode is available to the attacker, the job of hunting for the mount points becomes easier. For example, the attacker may undertake the reverse engineering of the original software or can only explore the input space to find the malicious inputs. To prevent reverse engineering, software vendors resort to software obfuscation — a technique generally applicable to a wide range of problems as we discuss in Section 8.

One of the most effective obfuscation targets is the program’s control flow (CF). CF obfuscation is a technique in which a dedicated program called the obfuscator performs semantic-preserving transformations on the original program in order to hide the original CF. This kind of obfuscation traditionally heavily relies on opaque predicates. A predicate is opaque if its resolution is hard or ambiguous for the attacker. The technique of opaque predicates is used in obfuscation tools such as Obfuscator-LLVM [10]. The construction of an opaque predicate is done by tailoring a computationally intensive challenge for the underlying concolic execution engine such as present in Mayhem [6], Angr [24] or Triton [19]. Some of the challenges proposed by Xu et. al. [31] are: symbolic memory, floating-point algebra, covert symbolic propagation and parallel programming. This approach provides the mechanism for constructing multiple different concrete challenges from the same basic templates. Despite a certain amount of generality, an attacker can expose the constructed challenges by observing similar patterns in the critical sections of the binary. Upon successful detection of such patterns, an attacker can unfold them to restore the original semantics. This is possible because the majority of the challenges that are constructed for this purpose have completely deterministic behavior. That is, for the particular input they always produce the same output. But the power of a versatile attacker goes far beyond that. New advances in concolic execution engines allow them to solve more of computationally intensive tasks generated by opaque predicates. The state-of-the-art techniques for binary analysis of real world software are becoming practical and mature [1, 24, 6, 22, 9, 15, 27, 25, 19]. For example, Angr [24] is powerful enough to automatically translate low level disassembler information to an abstract level in which it can do unified analysis for a variety of different platforms. It can also perform symbolic analysis of the program’s control flow to infer reachability conditions for the basic blocks of interest. Furthermore, it can simulate the processor execution and even the interaction with the operating system. When symbolic analysis falls short, Angr supports different fuzzing techniques [25] to help symbolic analysis. We discuss the function of Angr in more details in Section 5.
The advances in flexibility of hardware design promoted by the initiatives such as RISC-V and OpenRISC create fertile soil for hardware-software co-designs. However, RISC-V binaries pose easier targets for reverse engineering than, e.g., x86 binaries. As opposed to x86 binaries, RISC-V binaries have fixed-size instruction lengths and clearly separate code from data, which is one of the challenges for reverse engineering of x86 binaries. Thus, we rethink the CF obfuscation in the context of hardware-software co-design and propose Drndalo — a lightweight hardware-assisted control flow obfuscation technique. Our approach does not rely on the lack of obfuscation-specific features of the binary analysis frameworks nor their theoretical limitations, but on a safely distributed hardware-software shared secret.

Whole-executable encryption may pose a plausible alternative to CF obfuscation. The device running the encrypted code can either decrypt the executable in bulk, or just-in-time [5]. While this secures the binary against distribution-time attacks, in order to maintain similar performance compared to a device running unencrypted code, the device may need to have hardware decryption modules and enough memory to store the decrypted code. For small embedded devices, this may be prohibitive due to hardware area (potentially increasing the device cost), and power (both from the cryptographic accelerator and additional memory). We therefore propose a lightweight alternative to binary encryption, both in terms of area and power.

The main contributions of this paper are:

• We introduce a new hardware-assisted CF obfuscation technique utilizing a minimal extension to BRISC-V processor core, LLVM compiler and a secret key stored in hardware,

• We evaluate the security of our method against automated attacks based on different classifiers and analyze their success rates,

• We highlight and discuss the family of scenarios in which our obfuscation technique exhibits imperfections and propose possible enhancements.

The rest of the paper is organized as follows. In Section 2 we model our attack scenario and explain the means that an attacker has at its disposal. In Section 3 we describe the details of the obfuscation process that happens in the compiler. In Section 4 we explain the deobfuscation phase that takes place in hardware and describe the needed extensions to underlying processor core. In Section 5 we describe the internals of Angr [24] that empower the attacker from our attack model. In Section 6 we evaluate the overhead of our Drndalo method through a comparison of different deobfuscation phase designs. In Section 7 we evaluate the security of our method against the classifiers that have access to obfuscated and plain binaries. In Section 8 we give an overview of the literature that tackles the problem of program obfuscation. Finally, in Section 9 we discuss the possible extensions of our work to maximize its security against the classification based attacks and conclude our paper in Section 10.

2. Attack Model

In our scenario, an organization developing software needs to deploy the software to client machines, but wants to prevent attackers from gaining access to the program’s original behavior. The organization does that by obfuscating reachability conditions for the basic blocks in the compiled binaries. The organization performs the obfuscation and sends the obfuscated version of the binary to clients. The organization can (1) obfuscate binaries in a client-agnostic fashion, or (2) can separately obfuscate the binaries for each individual client. In either case, the binary is deobfuscated using some secret value, e.g., a key or a physical unclonable function (PUF) [26] challenge-response pair. Both obfuscation and deobfuscation procedures are public and described in Section 3 and Section 4, respectively. The obfuscation hinges on the security of the secret value.

The attackers are able to steal any number of (possibly differently) obfuscated binaries once they have left the organization, but are unable to steal the deobfuscation keys. If the deobfuscation hinges on a specific piece of hardware (as in the case of PUFs), the attackers do not have access to the actual chip that can deobfuscate the code. The attackers steal the obfuscated binaries by either intercepting network traffic to the client or by stealing the binaries from the drives of infected clients. The attackers can also perform obfuscation of their own programs with their own keys arbitrarily many times. In our scenario, the attackers cannot however monitor the execution of the original binary on the target machines, i.e., the binary theft and the binary execution occur at different times.

In our obfuscation and deobfuscation procedures that we discuss in Sections 3 and 4 we use a cryptographic hash function. In fact, the security of the hash function is orthogonal to the Drndalo technique that we propose. In our experimental settings we use a parametrizable Linear Feedback Shift Register (LFSR) due to its minimal hardware cost. However, a defender with higher security requirements may want to use a cryptographically secure hash function (e.g., SHA) with higher hardware and performance costs.

3. Obfuscation Procedure

The essence of our approach relies on potentially inverting all the conditional branches in the original program. For each branch, the obfuscator decides whether to invert that branch by evaluating a function that takes two inputs: (1) a unique identifier of the branch (e.g., the address of the instruction), and (2) a program key, and produces a 1-bit output. If the function returns a 1, the branch condition is inverted, otherwise it is not. In our implementation, we use a cryptographic hash function with a binary output. Hence, the only secret information is the deobfuscation key.

Table 1 summarizes the translations that are used for obfuscation and deobfuscation if the hash function answers with the value 1 for the conditional branch under consideration.
Figure 1 shows a segment of the original code of an example C program while Figure 2 shows its assembly. Assuming that the hash function returns the value 1 for both conditional branches marked in gray, the obfuscated RISC-V assembly is shown in Figure 3.

Table 1: Basic table of translations used if the hash function returns a 1. IF_THEN labels the basic block that is not executed when the branch with the condition from the first column is taken, IF_END labels the basic block that is executed if the branch is taken.

| Condition | Original branch | Obfuscated branch |
|-----------|-----------------|-------------------|
| x1 == x2  | bne x1, x2, IF_END | beq x1, x2, IF_END |
| x1 != x2  | beq x1, x2, IF_END | bne x1, x2, IF_END |
| x1 < x2   | bge x1, x2, IF_END | j_IF_THEN |
| x1 > x2   | bge x2, x1, IF_END | j_IF_THEN |
| x1 <= x2  | blt x2, x1, IF_END | j_IF_THEN |
| x1 >= x2  | blt x1, x2, IF_END | j_IF_THEN |

Figure 1: Segment of the example C program before obfuscation.

```c
if (atoi(args[1]) > atoi(args[2]))
    printf("Basic Block A\n");
else if (atoi(args[2]) < atoi(args[3]))
    printf("Basic Block B\n");
```

Figure 3: Obfuscated code

Figure 4: Example program assembly code before and after obfuscation.

The obfuscated code from Figure 3, observed in isolation, does not reveal that it is obfuscated even if our method is known to the attacker. It represents a valid program in its own right and it also does not contain obvious traces of obfuscation. That is, the obfuscation is stealthy. In Section 7 we use a classifier to quantitatively evaluate the stealth of our Drndalo obfuscation.

In contrast to our Drndalo method, some of the existing methods for control flow obfuscation [31] rely on the code snippets that increase computational complexity of the original program. However, those snippets, if known to the attacker, can be spotted in the obfuscated program.

The main property that differentiates obfuscated program from the plain program is the set of reachability conditions for the basic blocks behind conditional branches. The topology of the obfuscated CF graph and its original in the plain program are identical. When an attacker executes the obfuscated program by providing it with the inputs, the obfuscated program has significantly different behavior from its original. That is, the traces of execution affected by the reverted branches in the obfuscated program are different from the traces in the plain program. The mutated runtime behavior will give the attacker a wrong set of crashing inputs (see Section 5). Each conditional branch is either inverted or not with the same probability (provided that the hash function is secure). Given that the attacker does not apply semantic and symbolic analysis, the action of restoring the original program from the obfuscated program comes down to guessing the original branches from the obfuscated branches. If the attacker applies brute force only, its probability of success in restoring the original program from the obfuscated program is \( P = 0.5^n \), where \( n \) is the number of conditional branches.

The obfuscator itself is implemented as an LLVM Pass — the same technique that LLVM compiler infrastructure uses internally for its optimizations. The place of the obfuscator in the LLVM compilation chain is given in Figure 5. At the beginning, a high-level programming language is translated to LLVM intermediate representation (IR) using the corresponding compiler frontend. After the IR is obtained, LLVM’s optimizer performs the optimizations in the specified order. The obfuscator takes control over the process as the very last optimization and performs the obfuscation immediately before the RISC-V backend. Since the branch obfuscation is done at the level of LLVM IR, our technique supports all the programming languages with compilers that target LLVM IR. This group of programming languages includes C, C++, Rust, Apple Swift and others.

Another reason to build our obfuscation as an optimization on LLVM IR is our need to have a stealthy obfuscation. In other words, we are minimizing the number of properties that all obfuscated programs have in common even before considering conditional branches. By doing so, we aim at hindering adversarial queries of the form “is this binary even obfuscated or not”. A hypothetical obfuscation that would perform on the resulting platform-specific assembly code would risk to make the transformations that naturally cannot come from the given compiler. In a realistic scenario, an attacker could know the compiler that the victim software owner uses. From that information an attacker could infer that the given binary can-
not come from the known compiler. For example, an attacker might consider the registers utilization patterns in the obfuscated binary. The information on register utilization patterns can be obtained using an advanced reverse engineering tool as described in Section 5.

4. Deobfuscation Procedure

The obfuscated program correctly executes only on a trusted RISC-V core designed to support deobfuscation and supplied with the secret key. We outline four designs here: the baseline, stalled-hash, cached-hash and the mask-based design.

Baseline design: the baseline design is a 7-stage RISC-V CPU without any hardware modifications enabling obfuscation [2]. The processor uses synchronous block RAM (BRAM) for instruction and data memories, which requires 2 extra stages over a typical 5-stage processor. A simplified processor architecture is illustrated in Figure 6.

Stalled-hash design: here, the baseline CPU is equipped with a hardware hash function. When a branch instruction is in the decode stage, the hash function is fed with the branch instruction address and the program key. When the branch instruction reaches the execute stage, all the stages up to and including the execute stage are stalled until the hash function produces an output. Once a (single bit) output is produced, that value is XOR-ed with the branch signal. This way, branches that would be taken may not be, and vice-versa. For the hash function, we use a parametrizable Linear Feedback Shift Register (LFSR) with \( n \) registers, and let the LFSR run for \( k > n \) cycles. A cryptographically secure pseudo-random number generator may provide higher security at the cost of an increased latency, causing the processor to stall more. As only a single hash function is calculated at any given time, pipelining the hash function brings no benefit. Additionally, since the output of the hash is pseudo-random, a branch predictor may at best have a 50% chance of guessing the branch result. The modified architecture is illustrated in Figure 7.

Cached-hash design: since the hash function output is only dependent on the address of each branch, the hash of a given branch is constant. This allows us to cache the hashes of previously evaluated branches. In this design, we add a cache to the stalled-hash design. When a branch is in the decode stage, the architecture starts calculating the hash function and in parallel checks the cache for whether that branch’s hash has previously been calculated. If not, when the hash function finishes, it both feeds the value to the XOR gate, and saves the result to the cache. If the value is found in the cache, it is sent to the XOR, just in time as the branch enters the execute stage, causing no stall. In our experiments we used a simple 256-line, one branch per line, direct-mapped cache.

Mask-based design: here, the baseline CPU is modified so that the instruction memory is extended with a single ‘mask’ bit. The mask bit specifies whether a branch should be reversed or not. The mask bit follows the instruction through the stages, and is consumed in the execute stage if the instruction is a branch. Having an independent mask bit per each branch removes the possibility of an attacker predicting future branches based on the existing ones. However, widening the instruction word width complicates the design of L2 caches and memory controllers. Furthermore, depending on the attack model, the masks may need to be kept encrypted in memory and decrypted on-the-fly.

5. Reverse Engineering of Obfuscated Code

Offensive binary analysis is a mixture of static and dynamic techniques that discover crashing inputs. Besides the trivial usage in compromising system’s availability, this family of techniques can be used in attack surface exploration. Some of the discovered crashes (overwritten function pointers, buffer overflows, etc.) can be used by attackers to take control of a program’s execution. One of the possible attacks applicable to the results of offensive binary analysis is return-oriented programming [18]. This particular technique draws much attention because it does not require any code injection. Instead, it constructs malicious actions from the instructions already present in the address space of the executed program.

To show the behavior of the obfuscated binary under offensive analysis we use Angr [24]. Its core binary analysis features rely on concolic execution. This technique combines symbolic and concrete execution to construct the inputs that spot the vulnerabilities and eventually exploit them. Further, we briefly discuss the structure and function of Angr without claiming credit for its design or implementation.

Angr can analyze the binaries packed without the symbol table and relocation information — stripped binaries. When
Angr can analyze binaries targeting multiple architectures. From the functional perspective, certain architectures are similar to each other enough to be handled by a single abstraction. General analysis algorithms are then applied to the abstraction instead of each platform separately. For this purpose, Angr reuses the Valgrind VEX [17] intermediate representation. Roughly speaking, VEX abstraction consists of 1) establishing a unique register naming for all the platforms, 2) removing the differences in memory accesses and segmentation, and 3) unfolding the instructions with side effects to make them transparent.

The binary is given, the analysis process flows as shown in Figure 9.

**Binary loading.** A universal loader creates an address space in which it organizes all the needed binaries. The abstraction of the address space is returned to the system. Besides ELF binary format, Angr also supports others such as Microsoft Windows PE. When the binary format is recognized, its header is used to fetch the architecture information.

**Lifting.** Angr can analyze binaries targeting multiple architectures. From the functional perspective, certain architectures are similar to each other enough to be handled by a single abstraction. General analysis algorithms are then applied to the abstraction instead of each platform separately. For this purpose, Angr reuses the Valgrind VEX [17] intermediate representation. Roughly speaking, VEX abstraction consists of 1) establishing a unique register naming for all the platforms, 2) removing the differences in memory accesses and segmentation, and 3) unfolding the instructions with side effects to make them transparent.

**Simulation.** In accordance with architecture information, the tool chooses the adequate simulation engine. Such an engine uses basic blocks as the portions of program’s execution. It further interprets the portions starting with an input state that comprises of the register snapshot, memory etc. The results of the simulation step are all the possible successor states. While the simulation explores the branches, it collects the branch conditions. Subsequently, each resulting successor state contains its reachability condition. This is the prerequisite for the cyber reasoning features in Angr. However, when the tool explores our obfuscated binary, it collects the branch conditions whose correctness depends on whether obfuscator performed the reversal or not. If the collected branch condition remained intact during obfuscation, the simulation engine will discover it correctly. Otherwise, if the simulation engine traverses at least one reversed branch on its way to the successor state, its reachability condition is rendered incorrect. Under the premise of safe key distribution, by no means can the simulation discover the correct branch conditions for all the branches in a non-trivial program.

**Constraint solving.** All the simulation steps that the simulator undertakes may be performed on concrete or symbolic values. Symbolic values can be complex expressions and the operations on them result in the new symbolic expressions. For example, if the value of the program counter depends on the input of the program, all the transitions will be represented by the symbolic expressions. The core of the constraint solver
deployed in Angr leans on Satisfiability Modulo Theories [4] carried by Microsoft’s Z3 solver [8]. This allows an attacker to efficiently explore the inputs that lead to vulnerabilities. However, our obfuscator eliminates the threat imposed thereof since it makes the simulator construct the wrong constraints. A quick and correct solution to the wrong constraints does not equip the attacker with a functional vulnerability-discovering input.

Operating system simulation. To simulate program’s interaction with the operating system, Angr deploys the internal implementation of system calls. It supports multiple operating system kernels including Linux. The simulated system calls take effect on the simulated states that normally contain symbolic values.

6. Evaluation

To evaluate the performance of Drndalo we set up a series of experiments. The experiments are divided in two groups based on the implementation of the deobfuscation phase. First, we evaluate the performance and assess the security offered by experimental in-software deobfuscation procedures. Second, we measure the performance of various in-hardware deobfuscation implementations and discuss the security properties of each.

6.1. In-software Deobfuscation

Due to our attack model, a deobfuscation procedure must be capable of operating on the binary without debug symbols or other additional information — stripped binaries. To precisely define the space of possible designs, we impose three strict requirements to all in-software deobfuscation procedures: 1) knowing the correct key, a procedure must completely recreate the original program semantics, 2) deobfuscation must maximally avoid storing the plain version of the critical program so as to minimize the attack surface, and 3) in doing so, the procedure does not require any hardware modifications and runs on commodity hardware.

According to the mechanics used for restoring the original program from the obfuscated code and the secret key, we outline two families of in-software deobfuscation procedures:

JIT-based deobfuscation. This approach is based on traditional just-in-time compilation techniques. The JIT compiler implements the inverse transformation of the Table 1 and in-curs no other transformation. For example, given the code from the Figure 3, the compiler produces the code from the Figure 2. The compiled instructions are stored and only need to be deobfuscated once. Hence, the JIT penalty is proportional to code size, and not the program runtime.

Our experimental in-software deobfuscation procedure is implemented in Intel Pin dynamic binary instrumentation framework [13]. This implementation of JIT compiler operates on the basis of basic blocks and inspects all the conditional branches. The basic steps of the JIT compiler are as follows: 1) load the secret key, 2) instrument all the conditional branches, 3) apply the hash function to the conditional branch under consideration, 4) emit the branch instruction with the appropriate reversed condition (Table 1 obfuscated branch to original branch), 5) execute the next basic block. The simplest possible construct that can serve a similar purpose as a hash function is a bit mask of inversions generated by the obfuscator at compile time. In the absence of the key, we assume that the bit mask is kept secret. Since each branch has the same probability of being inverted, we assume that 50% of the inversion bits are set. Our experimental deobfuscation procedure caches the branches to assure that no branch inversion is checked twice. Thus, our procedure needs to: 1) load the corresponding inversion bit from the mask, 2) execute a compare instruction on the mask bit, and 3) execute the logic of reverting, if needed. There are many different ways for the JIT-compiler to perform the step 3 once it knows that it is needed. However, we will make an optimistic assumption that the logic of inversion will not take more than 10 instructions per execution. The optimistic estimates for both cached and non-cached JIT-compiler performance overheads are given in Figure 11. The main difference between JIT with and without caching is that when caching is disabled, the branch deobfuscation procedure is repeated for the repeating branches (e.g., branches in the loops). When caching is enabled, the result of the deobfuscation procedure is reused.

Runtime deobfuscation. Another in-software deobfuscation technique is to force the obfuscator to emit the code that contains the branch calculation in runtime. Here the code is obfuscated so as to load from the mask or calculate using the hash function whether each branch should be reverted at runtime. Given the original assembly in Figure 10, and opting to use the bit mask in obfuscation, the obfuscator outputs assembly as in Figure 12. When run, this code will find the appropriate mask bit, calculate the branch condition, and branch depending on the XOR-ed value of the two bits. Unlike in the case of the JIT implementation, the runtime penalty is proportional to the number of branches executed, and not code size (as in the case of a JIT implementation). As shown in Figure 12, runtime deobfuscation approach adds several instructions per each branch, leading to significant code bloat and a longer runtime. Figure 11 shows the overhead of the runtime obfuscation being significantly higher than its JIT-based counterpart. Hence, we opt for JIT-based deobfuscation as a more efficient in-software solution.

6.2. In-hardware Deobfuscation

We simulate the four architectures listed in Section 4. The baseline and the mask-based architectures have approximately the same performance, so we omit the second one. Further,
Baseline: a baseline 7-stage in-order RISC-V CPU, with BRAM-based instruction and data caches. The design is synthesized with 16KB of instruction and data memory, hence the BRAM utilization of the baseline design in Figure 14.

Stalled-hash: a modified design with a linear feedback shift register (LFSR)-based hash function that stalls the design for a parametrized number of cycles on every branch instruction. We choose an LFSR over a more cryptographically secure random number generator due to its small size and efficiency.

Cached-hash: an extended LFSR-based design with a cache used for storing the LFSR outputs of previously seen branches. Each cache stores a single bit hash value corresponding to an instruction address. The cache is accessed in the decode stage, and returns a match by the execute stage. If a match is found, the design does not stall at all. We test two configurations: a 256 and a 1024-line direct-mapped cache. In the current implementation, the cache is synthesized using registers, but can be stored in BRAM too.

Mask-based: a mask-based design, with an additional BRAM-based cache storing one 1-bit hash value per each instruction. This value is only used in branch instructions, and is otherwise ignored.

The LUT, register, and block RAM counts of synthesized designs are shown in Figure 14. Note that we have implemented an separate hash cache from the instruction cache. The majority of memory used for this cache is spent on tags, not hash values. In future work we plan to explore an implementation that extends the L1 cache with the extra hash bit, removing the need for storing the tags twice.

7. Security Evaluation

The security of our obfuscation method relies on (1) the security of the hash function, and (2) the security of the branch obfuscator module. Assuming that the hash function is cryptographically safe, in this section we discuss the security of the obfuscation method.

We empirically evaluate the security of our obfuscation method by attempting to deobfuscate binaries using a classifier trained on both obfuscated and plain binaries from a dataset of known programs. This type of attack is plausible since the obfuscation method is published and the attacker can freely create a dataset of plain and obfuscated binaries. Hence, an attacker may be able to use an in-house trained classifier to reconstruct an original control flow of an obfuscated binary whose source they do not possess.

The classifier training pipeline is composed of:
1. **Dataset collection**: to create the dataset, we compile and obfuscate 98 programs from the LLVM test suite single source benchmarks.

2. **Feature extraction**: since the obfuscation is applied after the compiler front-end, both the plain and the obfuscated binaries will have the same topology, i.e., the control flow graph of a binary before and after obfuscation remains the same. This allows us to simply compare modified (obfuscated) and unmodified branching basic blocks (BBB1). We
use Angr to in-parallel parse plain and obfuscated binaries, detect which BBBI’s have been obfuscated, and store modified/unmodified BBBI’s into separate categories. We store several features of BBBI’s, shown in Table 2. As BBBI’s have different numbers of instructions, we only record a window of the last \( I \) instructions before (and including) the branch.

3. **Preprocessing:** we use cross-validation and create two datasets: a training and a test one. To prevent the classifier from learning binary-specific features, the test set is created with separate binaries from the training set (i.e., not just separate basic blocks). Since only the obfuscated binaries have obfuscated BBBI’s, and only 50% of those BBBI’s will be obfuscated, the ratio of plain to obfuscated BBBI’s is 3/1. To balance the two classes, we vary the training set to only include one third of plain branches. Next, since opcodes and register indexes are integers and it is meaningless to compare instructions by their opcode values, we convert all integers to one-hot vectors.

4. **Training:** we test several different classifiers. Each classifier is fed with a number of concatenated one-hot vectors, and is trained to predict the \( OBF \) bit, specifying whether the branch has been obfuscated.

### 7.1. Classifier Results

We test several classifiers, including: logistic regression, decision trees, random forest classifiers, and multi-layer perceptrons. All of the classifiers seem to achieve very similar results, with an average classification accuracy of 63%. We give the confusion matrices of different classifiers in Figure 15.

![Figure 15: Confusion matrices of 4 classifiers. TP, TO, PP, and PO labels stand for "true plain", "true obfuscated", "predicted plain" and "predicted obfuscated".](image)

In order to test whether the classifier only learns some statistical information (i.e., that certain branch instructions are more common in obfuscated binaries compared to plain ones) or if the classifiers found a pattern in the produced instructions, we vary the size of the instruction window \( I \). In Figure 16, we show the accuracy of classifiers trained on features with different windows sizes.

### 7.2. Analysis of Classifier Results

As our obfuscation method XORs branch predicates with random bits, we would expect that the outputted values are indistinguishable from randomness. Hence, any classifier should be unable to predict which branches were obfuscated with an accuracy higher than 50%, assuming that the number of obfuscated and plain branches is equal. However, Table 15
shows that all classifiers have some success in predicting which branch is obfuscated, with an average prediction accuracy of 63%. Interestingly, the majority of classifiers seem to be unable to distinguish whether a truly obfuscated branch is obfuscated or plain, but can consistently recognize truly plain branches as plain.

To understand why classifiers are able to reach accuracies higher than 50%, we train classifiers with varying window sizes, as seen in Figure 16. We see that the majority of the accuracy gains is achieved with a window size of 1, and that adding more instructions does not significantly improve performance. With only access to the branch instruction opcode \( OP_0 \), branch registers \( R10, R20, RW_0 \), and the \( BR_{up} \) bit specifying whether the branch instruction is branching to an address above or below it, the classifier is able to get an 11 percentage point increase over random guessing. Hence, the classifier is not learning any specific pattern of instructions that may reveal information about the original LLVM IR or the source code, but is instead relying on the distribution of different instructions in the dataset of plain and obfuscated binaries. As a simple example, consider a non-obfuscating compiler that outputs certain branch instructions, e.g., \( \text{BRLE} \) and \( \text{BRGT} \) with a 60% and 40% probability, respectively. The obfuscating compiler may shift these probabilities to 50% and 50%. Hence, whenever the attacker decodes a \( \text{BRGT} \) instruction, they can claim that the branch is obfuscated with 60% probability.

One way to present this is shown in Figure 17. Given an original high-level language program \( A \), the LLVM front-end produces LLVM IR, and the back-end produces the binary. If Dndalo is used to obfuscate the IR, the obfuscated IR is used to produce the binary. However, some obfuscated programs in the form of LLVM IR are unlikely to originate directly from a program expressed in a high-level language such as C. The classifier recognizes such unlikely program constructs and classifies them as obfuscated because they rarely appear in plain binaries.

To illustrate a scenario in which an unlikely LLVM IR is produced by the obfuscator, consider the top program of Figure 18 and assume that obfuscator inverts the loop’s branch. For the sake of clarity we will analyze the obfuscated program in its lifted version — the version in the C high-level language. If the lifted obfuscated program in the bottom of Figure 18 is now analyzed, it can be assessed as highly suspicious. Specifically, we see that the \( i \) starts with zero, and increases as long as it is larger than \( n \). As the variable \( n \) comes from a program input, we can detect two possible outcomes of this “for” loop: either the input \( n \) is zero or less and the loop executes infinitely many times, or \( n \) is larger than zero and the loop never executes. Thus, we can infer that this loop is either infinite or never executes. As such a loop is an uncommon construct, we can infer that the loop is obfuscated. The classifier can pick up such common and uncommon constructs and make predictions based on them.

The example in Figure 18 points out a weakness of Dndalo method that leaps beyond the scope of this work. The weakness roots in the fact that not all valid semantic constructs in high level programming languages are equally ubiquitous.

8. Related Work

Program obfuscation is a wide research subject and has historically been approached from significantly different viewpoints. Some of the research branches that tackle obfuscation are: 1) malware packing [23, 20], 2) intellectual property protection [29, 11, 21, 32], and 3) resistance to disassembly and reverse engineering [12, 31]. Normally, the approaches in literature serve one of the purposes extremely well while fall short to protect against other objectives. For example, the approach of Cousins et al. [7] obfuscates programs in a way that makes it completely unintelligible for an attacker. Con-
sequently, a program obfuscated in such a way is virtually resistant to IP thefts. However, if an input that leads to a vulnerable state is discovered by analyzing the obfuscated program it will not go away when the program is deployed. The attacker in the possession of the critical input will remain in the position to lead the system to a vulnerable state. The same is not true for our Drndalo method. In Drndalo, the inputs that lead to a vulnerable state discovered in the obfuscated version of the program normally do not lead the deobfuscated version of the program to a vulnerable state. Nonetheless, the approach of Cousins et al. is proved to be simulation-secure — the measure of security that we will describe later in this section — while Drndalo is not.

Not only that program obfuscation is historically developing to fulfill multiple purposes but it is also investigated by multiple research communities. For example, cryptographic research community gives us the definition of cryptographic obfuscation. We can utilize this definition to place our Drndalo method in a spectrum of security and usability of the existing obfuscation solutions.

Barak et al. [3], in their widely-known work on feasibility of obfuscation, define obfuscation and the obfuscator. They intuitively posit an obfuscator $O$ as an efficient probabilistic “compiler” that takes the plain program $P$ and produces the obfuscated program $O(P)$. The programs $O(P)$ and $P$ are guaranteed to have the same functionality and to be “unintelligible” from each other. In other words, there is nothing that an adversary can compute from $O(P)$ and cannot from only an oracle access to $P$. We refer to such an obfuscator as simulation-secure. However, the requirements of “unintelligibility” and “same functionality” allow for certain amount freedom in interpretation. Thus, Barak et al. define the requirements for an simulation-secure obfuscator by utilizing the concepts of Turing Machine(TM) and Probabilistic Polynomial-time Turing Machine(PPT) as are known in complexity-theory, and oracles as known in cryptography.

A TM $O$ is the obfuscator for the family of TMs $\mathcal{F}$ iff all the following are true:

1. **(functionality preservation)** For all TMs $M \in \mathcal{F}$, $O(M)$ denotes the obfuscated $M$ such that it computes the same function as $M$ itself.
2. **(polynomial slowdown)** There exists a polynomial $p$ such that for any $M \in \mathcal{F}$, $\|O(M)\| \leq p(|M|)$. Additionally, if $M$ halts within $t$ steps, $O(M)$ must halt in $p(t)$.
3. **(virtual black box)** For all PPT $\mathcal{A}$ and all TMs $M \in \mathcal{F}$, there exists a PPT $\mathcal{A}$ that has the oracle access to $M$, such that for a negligible function $\phi$

$$\Pr[\mathcal{A}(O(M)) = 1] - \Pr[\mathcal{A}(M)(t|M|) = 1] \leq \phi(|M|) \quad (1)$$

Since TMs are intuitively harder to obfuscate than circuits, Barak et al. use $\exists \mathcal{T}_M \Rightarrow \exists \mathcal{O}_{\text{circuit}}$. By showing that a circuit obfuscator does not exist, they show that a TM obfuscator does not exist either. However, it is important to note that this well-accepted conclusion does not rule out the possibility of obfuscation for all programs. For example, Barak et al. do not rule out the obfuscators for finite automata or regular expressions. In fact, Lynn et al. [14] have shown that the provable obfuscation for point functions do exist under random oracle model and construct the provable obfuscations of complex access control functionalities. Later on, Wee [28] demonstrated that the random oracle is not necessary and replaced it with a probabilistic hash function based on a one-way permutation. Cousins et al. [7] have demonstrated the practicality of virtual black box obfuscation for the programs of the form $f(x_1, \ldots, x_L) = \bigwedge_{i \in [L]} y_i$, for $i \subseteq [L]$. This programs are referred to as conjunctions and can be used as approximations of classifiers in machine learning [30]. The approach from [7] achieves substantial performance overhead reduction when compared to other similar methods. However, it still does not answer the question of encoding arbitrary valid programs to conjunctions chosen from a distribution with enough entropy. The distribution entropy criteria affects the security of obfuscation. In fact, we are not aware of a cryptographic obfuscation approach that is suitable to arbitrary programs expressible in some high-level language such as C.

In contrast to cryptographic obfuscation approaches, our Drndalo method is not constrained to any subset of programs and accepts all the valid programs that are expressible in a language supported by the LLVM frontends. Additionally, the functionality preservation criteria from [3] is interpreted in a narrower sense. Specifically, the functionality is preserved only with respect to the trusted core. However, the security of our method is not derived from the computational hardness of a mathematical problem and therefore does not satisfy the virtual black box criteria as stated in Equation 1. Notwithstanding, the security of our method is evaluated against the attack model described earlier in Section 2.

To the best of our knowledge, the only obfuscation technique that guarantees simulation-secure obfuscation for an arbitrary program is proposed by Nayak et al. [16]. They propose a thorough architecture redesign encompassing scratchpad memories, ORAM (oblivious RAM), instruction scheduling and context switching. Nayak et al. do achieve a provably simulation-secure obfuscation for an arbitrary program through their hardware redesign but at a price of an overhead that spans from 8x to 76x. Our Drndalo, although not simulation-secure, achieves an overhead of only 5% on PARSEC benchmarks.

9. Future Work and Discussion

In previous sections we have demonstrated Drndalo obfuscation and deobfuscation procedures and discussed some of its weak points. The technique is shown to have a very low performance overhead in comparison to other similar methods. Our future work will thus seek improvements in two main directions: 1) improving security guarantees while keeping performance and hardware overheads low, 2) extending our attack model to allow the attacker to monitor the execution of
the obfuscated program.

To improve security guarantees we will perform cryptanalysis of our Drndalo obfuscation under the assumption of a cryptographically secure hash function. Additionally, we will strive to approach the ideal of simulation-secure obfuscation from Equation 1 with regards to our relaxed functionality preservation requirement as described in Section 8.

Our future work will also encompass additional hardening of the obfuscation phase. In the analysis of the classifier’s success rates we concluded that its accuracy comes from exploiting the compiler’s affinity to use some branch instructions more often than others. As an improvement to the Drndalo technique, we will refine the compiler’s code generation phase so as to utilize branch instructions more uniformly. In our investigation, we concluded that such a compiler code generation phase refinement is attainable. The refinement will not affect the program’s functionality. A uniform utilization of branch instructions will be achieved through a new register usage pattern.

10. Conclusion

In this work we explored the space of hardware-software co-designs for control flow obfuscation. We proposed a compile time obfuscation technique that relies on a cryptographic hash function with a secret key and inverts each conditional branch with the probability of 50%. Only a deobfuscator that holds the secret key can completely restore the control flow of the original program. Then, we evaluated both in-software and in-hardware deobfuscation techniques and demonstrated that in-software techniques incur an unacceptable performance overhead. Finally, we proposed multiple in-hardware implementations of deobfuscation phase as extensions to BRISC-V platform. The evaluation on the PARSEC benchmark singles out our 8-cycle and 16-cycle cached-hash implementations as the best in-hardware deobfuscation technique with an average performance penalty of around 2% and 5%, respectively. The added area of the hashed-cache implementation is dominated by the cache, requiring approximately 10% and 20% more hardware resources compared to the baseline processor. We evaluate the security of our obfuscation method by training a classifier to predict whether individual branches are obfuscated or not. We show that classifiers are able to spot some statistical regularities in the types of instructions used in plain and obfuscated binaries, and we propose a way of making Drndalo obfuscation stealthy for these ML classifiers.

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