

Obfuscation with Turing Machine

Yan Wang¹, Dinghao Wu,² Shuai Wang, and Pei Wang

Pennsylvania State University, State College, PA 16801, USA,
ybw5084@ist.psu.edu,

WWW home page: <http://users/~iekeland/web/welcome.html>

Abstract. Software security is a fundamental research domain in this threat emerging technology world. Leveraging system vulnerabilities is one of the common ways to hack into computer system. Hackers have to understand the program control flow in order to figure out the hacking logic and technique. In this way, concealing important branch trigger condition logics are crucial for protecting softwares from being hacked. In this paper we propose a novel control flow obfuscation method with Turing machine. By entwining the original software programs with Turing machine execution, software control flow graphs could be significantly obfuscated which means it is much more harder or even impossible for hackers to embed malicious execution codes into Turing machine obfuscated programs. We implemented a obfuscation tool to generate obfuscated binaries using LLVM. Evaluation results demonstrate that software programs become much more complicated after Turing machine obfuscation. At current stage, we only obfuscated the integer operand instructions which are vital to the whole program.

Key words: software security, control flow obfuscation, Turing machine, LLVM

1 Introduction

Obfuscation derives from intellectual property protection. Internet brings us unprecedented convenience and threat of idea plagiarism and copyright infringement at the same time. Concealing the algorithm of a software means a lot for the society especially for high-tech industry. Reverse engineering is often used by to recover source code from binaries to analyze software vulnerabilities or to steal software ideas or algorithms. Obfuscation is a technique to block or harden the process of reverse engineering.

Recently, Software security has become a bigger and bigger concern in research community because of infamous ransomware attack and severe vulnerability such as the recent “Wannacry” incident and the openssl heartbleeding bug. These incidences challenge the computer world greatly. Hackers endeavor to figure out vulnerabilities inside a software program. Knowing the software architecture and program logic like control flow graph is an indispensable prerequisite for hackers to analyze the original codes. With the help of some monitoring techniques hackers could even iterate all possible paths to try to restore all important branch

information along the execution paths. *Concolic testing* is an example which exploits symbolic execution given a certain input while it keeps changing input data until the code coverage proceed a threshold[1] as shown in Figure 1. It has been proved to work in restoring the branch information in the original source codes. Hence, a lot of research focus on preventing bad guys from figuring out the essential logic. Concealing important “crossroad” in a source program. Control flow obfuscation is one of these techniques. Control flow obfuscation aims at hiding conditional transfers and complicating the execution path within a source program. Through replacing or inserting extra control flow graph edges, the original software logic become harder or even impossible to trace. Previous research[2] have prove the effectiveness of control flow obfuscation.

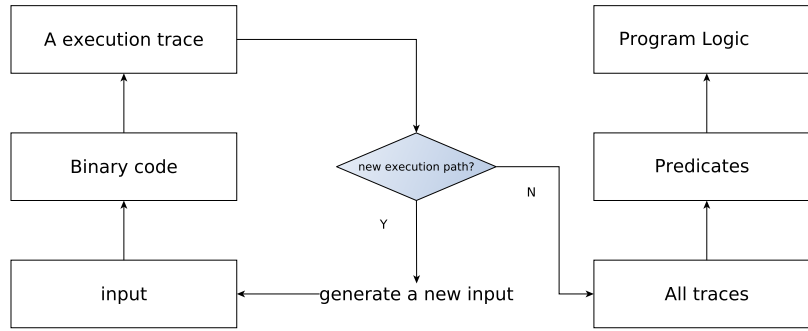


Fig. 1. Reverse engineering with concolic testing

In this paper, we propose a novel control flow obfuscation method with Turing machine embedded in the original program source codes. Turing machine is the essence of computation so it could calculate accurately all kinds of computer operation. In this way, important branch conditions in original source code could be replaced by a Turing machine execution which yields the very identical conditional value. Besides, a Turing machine behaves like a state machine so it contains a lot of branch condition checks in Turing machine transition table. In this whole process, sensitive branch information could be successfully hidden in Turing machine call graphs. In the mean time, Turing machine execution greatly introduces computational complexity to the target program so it is almost impossible to read the obfuscated programs to do reverse engineering.

Currently, we are more interested in integer operation condition instructions. Utilizing LLVM, we could turn original program source codes into intermediate representation (IR). Turing machine obfuscator takes over from IR and selects interested instruction candidates which would be redirected to semantic equivalent Turing machine execution. After all paths finished in the Turing machine “blackbox”, the original call graph resumes from the obfuscator interrupt and the whole program control flow graph is greatly expanded and complicated. Since LLVM is the implementation foundation, currently our proposed obfus-

cator could only be applied to C/C++ source programs. Inspired by previous works[4], we evaluate our obfuscator from four dimensions which are potency, resilience, cost and stealth respectively. Results indicate that Turing machine obfuscator could effectively obfuscate target source codes with acceptable cost overhead.

This paper is organized as follows. Section 2 discusses related works on obfuscation, especially control flow obfuscation. Section 3 illustrates the idea and architecture of Turing machine obfuscator. Obfuscator implementation is discussed in section 4. Section 5 discusses the evaluation result of our proposed obfuscator. Finally, we conclude this paper in section 6.

2 Related Works

Generally speaking, reverse engineering is divided into static analysis such as and dynamic analysis. To compete static reverse engineering, researchers usually focus on hardening disassembling and decompiling process. To compete the dynamic reverse engineering techniques such as concolic testing, conditional transfer logic must be hidden from adversaries. Control flow obfuscation has been proved effective in previous works.

In [5], the authors identified conditions that could trigger malware execution then using hash function to transform the values which could launch malware. Afterwards, correspondent conditional codes which would be ran with satisfied value were encrypted with a key generated based on the instruction trigger value. By this means the obfuscation analyzer could never get a chance to get the expected “launching code” consequently planted malware could never be executed. This technology works on certain fixed trigger value but not in scenarios that trigger values are intervals such as $>$ and $<$. This limitation narrows the applicable conditions greatly since a large volume of branch conditions are comparison operations. In addition, the encryption and decryption process in this methodology also introduces inneglectable overhead.

In [6], the authors used signals(“traps”) to replace the control transfers unconditional instructions like “jmp” and “call” in order to confuse disassembly operation which is the first step of reverse engineering. Dummy control transfers and junk instructions were also inserted after signal replacements. This method seems to be effective in fooling disassemblers but it can’t be applied in scenarios that conditional instruction logic needs to be protected from being figured out.

In [7], the authors endeavor to conceal branch information leveraging a remote trusted third party environment. The idea seemed to work while it not only introduced a great network overhead, but also relies on trusted network accessibility which can’t be guaranteed in reality. This drawback means this idea can’t be applied in common obfuscation cases.

In [2], the authors took advantage of neural network to replace appropriate conditional instructions in source programs in order to achieve the goal of concealing conditional instruction logic thus dynamic analysis like concolic testing could never dig useful branch information. Although the idea looks promising

and the results indicates the effectiveness of this methodology to some degree, fundamentally we don't believe neural networks solution is suitable for such scenarios. To the best of our knowledge, neural networks works like a blackbox. It lacks the rigorous mathematical proof to illustrate a correct result must be generated given a input. Neural networks not only introduced complexity but also unpredictability to the original source programs. Trained models may behave very differently if given initial parameters with only some nuances, which means that it is also very hard to train a accurate enough model to simulate the conditional instruction. In addition, we noticed that neural networks consume too much memory in the evaluation experiments.

3 Turing machine obfuscation

In a computer program, conditional transfer instruction compare two operands and direct the following running path based on the comparison result. In theory, Turing machine has been proved to be able to simulate any algorithm and generate a corresponding correct answer. If a problem could be solved mathematically, it could definitely be solved by a Turing Machine. Taking advantage of Turing machine's powerful computational ability and mathematical correctness, we introduce Turing machine to the control flow obfuscation process. Through Turing machine computation, the identical comparison result could be produced to guide further execution direction and the conditional logic is protected from being discovered. The intuitive methodology of Turing machine conditional branch transformation is shown in Figure 2.

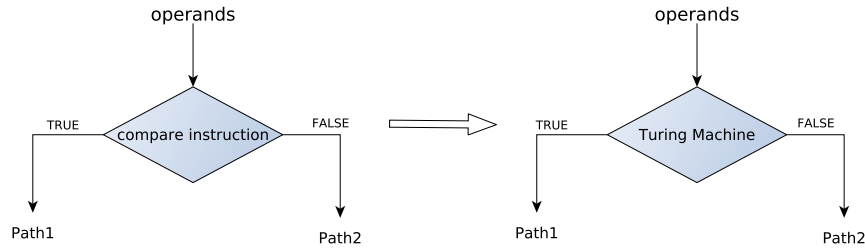


Fig. 2. Turing Machine Obfuscation Overview

3.1 Turing Machine

3.2 Universal Turing machine

4 Implementation

5 Evaluation

Inspired by previous work[4], we evaluated our obfuscation method based on four metrics which are *potency*, *resilience*, *stealth* and *cost* respectively. Potency indicates the complexity of a certain obfuscated program. It shows how complex or how unreadable obfuscated codes are. To measure how well an obfuscated program could withstand automatic deobfuscation techniques, metric resilience is introduced. Besides automated deobfuscators, a lot of reverse engineering works are conducted by hackers, obfuscated program should not be too different from the original one or it would be easy for experienced hackers to discern it. Stealth is used to measure to how well a obfuscated program resembles the original one. Cost is naturally used the measure running overhead of a obfuscated program. Obfuscation would inevitably induce more overhead while it should be constricted to an acceptable level.

We choose two popular open source programs as target programs to verify effectiveness of our Turing machien obfuscator: compress tool bzip2[8] and regular expression engine slre[9]. In Turing machine obfuscator, we select integer conditional transfer instruction as replacement candidates. Obfuscation level is a index which indicates the ratio between obfuscated instructions and all instruction candidates. In our experiments, we arbitrarily set it to 50% which means half of all conditional transfer candidates are randomly chosen and obfuscated.

5.1 Potency

Control flow graph(CFG) and call graph provide useful information about the general structure of a program so they are the traditional foundation for static software analysis. With the help of IDA Pro[11] which is a well known commercial disassembler and debuuger, CFG and call graph are generated from original and obfuscated binaries. Through analyzing both graphs, basic block number, call graph edge number and control graph edge number could be extracted. These static metrics are used to indicate complexity of a target program in [10]. Experiment results are shown in table 1. Comparing the metrics of source program and corresponding Turing machine obfuscated program, we found program complexity is strenthened in terms of every metric.

Program	# of CFG Edges	# of Basic Blocks	# of Function
bzip2	4283	2837	78
obfuscated bzip2	4195	2828	134
regexp	906	619	25
obfuscated regexp	1122	773	43

Besides the traditional static evaluation, we refer to [12] and [13] to further quantify Turing machine obfuscated programs. Cyclomatic number and knot number were introduced in these works. Cyclomatic metric is defined by as

$$\text{Cyclomatic} = E - N + 2$$

where E and N represent the number of edge and node in a CFG respectively. Knot number means the quantity of edge crossings in the CFG. These two metrics intuitively weigh how complicated a program is in terms of logic diversion number. Results in Table 2 show that both knot number and cyclomatic number increase after obfuscation. Potency of Turing machine obfuscator is proved.

Program	# of Cyclomatic	# of Knot
bzip2	1448	11982
obfuscated bzip2	1369	5682
regex	289	478
obfuscated regex	351	1068

We pick 50% as the obfuscation level to demonstrate the performance of Turing machine obfuscator while we also conducted experiments with other obfuscation levels as %30, %80 and %100. Figure 3 demonstrated that with more control transfer instruction candidates transformed to Turing machine execution, binary call graph edges increase which indicates obfuscated binaries become more and more complicated.

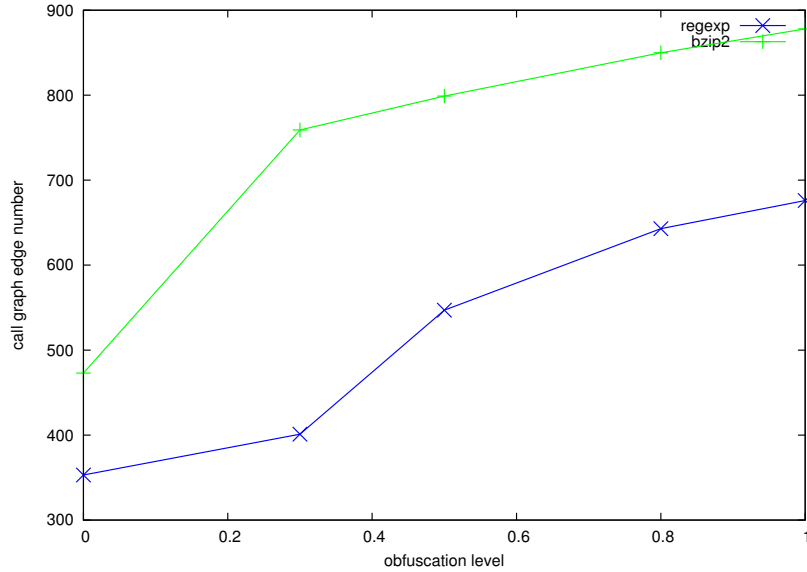


Fig. 3. Call graph Edge Number versus obfuscation level

5.2 Stealth

As mentioned in previous section, software obfuscation technique should not only combat automated deobfuscation tools, but also manual deobfuscation methods. In the evaluation of stealth, authors of [3] calculated the statistics of instruction distribution of both regular and obfuscated programs to draw a comparison. If instruction distribution statistics of a obfuscated program is distinct from normal programs(e.g call instruction proportion is abnormally high), it would be easy for reverse engineer to discern the program has been instrumented. We employed this same metric to evaluate our Turing obfuscator. Obfuscation level for stealth evaluation is set to 50%.

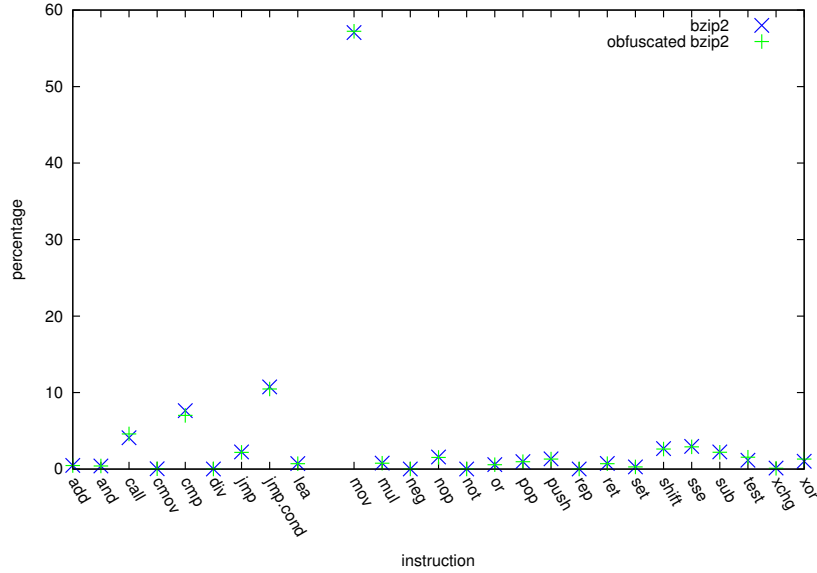


Fig. 4. bzip2 instruction distribution

References

1. Sen, Koushik, Darko Marinov, and Gul Agha. "CUTE: a concolic unit testing engine for C." ACM SIGSOFT Software Engineering Notes. Vol. 30. No. 5. ACM, 2005.
2. Ma, Haoyu, et al. "Control flow obfuscation using neural network to fight concolic testing." International Conference on Security and Privacy in Communication Systems. Springer International Publishing, 2014.
3. Wang, Pei, et al. "Translingual obfuscation." Security and Privacy (EuroS&P), 2016 IEEE European Symposium on. IEEE, 2016.
4. Collberg, Christian, Clark Thomborson, and Douglas Low. "Manufacturing cheap, resilient, and stealthy opaque constructs." Proceedings of the 25th ACM SIGPLAN-SIGACT symposium on Principles of programming languages. ACM, 1998.

5. Sharif, Monirul I., et al. "Impeding Malware Analysis Using Conditional Code Obfuscation." NDSS. 2008.
6. Popov, Igor V., Saumya K. Debray, and Gregory R. Andrews. "Binary Obfuscation Using Signals." Usenix Security. 2007.
7. Wang, Zhi, et al. "Branch obfuscation using code mobility and signal." Computer Software and Applications Conference Workshops (COMPSACW), 2012 IEEE 36th Annual. IEEE, 2012.
8. <http://www.bzip.org/>
9. <https://github.com/cesanta/slre>
10. Chen, Haibo, et al. "Control flow obfuscation with information flow tracking." Proceedings of the 42nd Annual IEEE/ACM International Symposium on Microarchitecture. ACM, 2009.
11. <https://www.hex-rays.com/products/ida/>
12. McCabe, Thomas J. "A complexity measure." IEEE Transactions on software Engineering 4 (1976): 308-320.
13. Woodward, Martin R., Michael A. Hennell, and David Hedley. "A measure of control flow complexity in program text." IEEE Transactions on Software Engineering 1 (1979): 45-50.