CLEAR & RETURN: Stopping Run-time Countermeasures in Cryptographic Primitives

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SUMMARY White-box cryptographic implementations often use masking and shuffling as countermeasures against key extraction attacks. To counter these defenses, higher-order Differential Computation Analysis (HO-DCA) and its variants have been developed. These methods aim to breach these countermeasures without needing reverse engineering. However, these non-invasive attacks are expensive and can be thwarted by updating the masking and shuffling techniques. This paper introduces a simple binary injection attack, aptly named clear & return, designed to bypass advanced masking and shuffling defenses employed in white-box cryptography. The attack involves injecting a small amount of assembly code, which effectively disables run-time random sources. This loss of randomness exposes the unprotected lookup value within white-box implementations, making them vulnerable to simple statistical analysis. In experiments targeting open-source white-box cryptographic implementations, the attack strategy of hijacking entries in the Global Offset Table (GOT) or function calls shows effectiveness in circumventing run-time countermeasures.

key words: White-box cryptography, Masking, Shuffling, Binary injection attack.

1. Introduction

The primary goal of white-box cryptography is to protect secret keys from invasive attacks, particularly in environments where adversaries can control the software implementation. In 2002, Chow et al. introduced white-box implementations of AES and DES [1, 2]. Their security was accomplished by converting the full-round operations into key-specific lookup tables, incorporating secret linear and nonlinear transformations. Because of the encoded lookup tables, it has become challenging for an adversary to extract the secret key solely by observing intermediate values in memory. Despite these advancements, these white-box implementations were later found to be susceptible to cryptanalysis attacks, as demonstrated by Billet et al [3]. An alternative attack method, Differential Computation Analysis (DCA) [4], has been developed to exploit vulnerabilities in white-box cryptography. It employs statistical analysis of computational traces to deduce the secret key, eliminating the need for reverse engineering. Contrasting with the noise-impacted power traces in Correlation Power Analysis (CPA) [5], computational traces are extracted directly from memory. They offer noise-free data on the read and write operations during encryption, significantly enhancing the precision of both analysis and key recovery.

To counteract DCA, various countermeasures have been implemented, notably run-time masking and shuffling techniques derived from the gray-box model. Masking, as a strategy, splits sensitive variables into several shares. This approach, coupled with advanced masking and shuffling defenses, makes it more resistant to these higher-order attacks. However, these obfuscation methods have been found vulnerable to advanced forms of DCA, such as higher-order DCA (HO-DCA) and even more sophisticated variants like higher-degree HO-DCA (HDHO-DCA) [8, 9]. Despite these vulnerabilities, it is important to note that the effectiveness of higher-order attacks, like HO-DCA and HDHO-DCA, diminishes with increasing complexity. As the dimensionality of the computational traces grows, the time complexity for these higher-order attacks escalates significantly. Consequently, some implementations of masked and shuffled cryptographic systems are likely to be more resistant to these types of non-invasive attacks.

This study underscores that run-time masking and shuffling techniques in white-box cryptography are heavily reliant on random sources, such as random number generators and deterministic cryptographic algorithms. This reliance potentially exposes them to invasive attacks. For white-box cryptography to be truly effective, it needs to prove its robustness against white-box attacks. Aligned with this perspective, this paper introduces straightforward binary injection attacks, aptly named clear & return†, aimed at these existing countermeasures that depend on run-time random sources. The demonstrations reveal the vulnerabilities of these countermeasures when faced with white-box attackers. To the best of our knowledge, it provides the first successful demonstration of a white-box attack targeting open-source white-box cryptographic implementations that employ masking and shuffling techniques.

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In addition to masking, operation shuffling is another technique employed to enhance security in cryptographic systems. Shuffling involves rearranging the order of operations or the execution sequence of a cryptographic algorithm. By randomly permuting these operations, shuffling makes it more challenging for an attacker to predict or analyze the data flow and intermediate states of the algorithm, thus further obfuscating side-channel signals. This randomized rearrangement is particularly effective in mitigating time-based side-channel attacks, as it disrupts the consistent timing patterns that such attacks often rely on.

3. Proposed Method

3.1 Key Idea Behind and Assumption

To defeat aforementioned countermeasures, run-time random sources must be disabled so that key-dependent intermediate values are exploitable. Generally speaking, a random number generator can be implemented by using either shared libraries or user-defined functions. In this section, we introduce simple binary injection attacks, enforcing the random number generator to always output a fixed value.

One of the easy ways to produce a sequence of random numbers is to call a function, such as $\text{rand}()$, provided in shared libraries. Lazy binding in Linux ELF binaries resolves unknown references to functions located in shared libraries, using the Procedure Linkage Table (.plt) and the Global Offset Table (.got) sections. In other words, the address of $\text{rand}()$ can be found in its GOT entry once it is called. The steps 1 - 8 shown in Fig. 2 present the overall procedure of lazy binding to call $\text{rand}()$ for the first time.

In Unix-like systems, overwriting the GOT entries is a traditional control flow hijacking technique. Leveraging the dynamic symbol binding mechanism, this attack modifies a GOT entry to redirect the program’s execution flow to a chosen target address. Previously, it was commonly employed to tamper with the GOT entry of a shared library function, often substituting it with $\text{system}()$, thereby enabling the execution of $/bin/sh$ and spawning a shell [10]. In our attack scenario, by substituting the GOT entry with the address of injected code, the attacker can manipulate the behavior of the $\text{rand}()$ function within the context of side-channel analysis. Essentially, if the injected code consistently returns zero, the protection of sensitive variables is compromised.

Utilizing user-defined functions or static libraries for random number generation is independent of the GOT entry, rendering GOT entry hijacking ineffective. In such scenarios, an attacker would need to identify and modify the specific function calls, replacing them with manipulated calls to their injected code. It is noteworthy that numerous established countermeasures leverage cryptographic functions to produce a sequence of uniformly distributed random numbers. Standard block ciphers are frequently employed in these countermeasures to ensure a high entropy in the generated sequence.

In the following, we present clear & return, a binary in-

![Fig. 1: Fundamental design of typical white-box cryptographic implementations.](image)
To introduce our attack, we utilize two open-source white-box AES implementations: Mask-WB-AES and Shuff-WB-AES, respectively.

3.3 Discussion

Adding Randomness

To evaluate our attack, we encrypted 1,000 random plaintexts for both Mask-WB-AES and Shuff-WB-AES. To collect computational traces, we employed dynamic binary instrumentation (DBI) tool using Valgrind to capture data from memory write operations during the encryption process. Subsequent CPA attacks were executed, after intercepting the randnum() function calls, for both implementations. The specific register must be filled with a reference via an argument to stopping randomness capabilities. The return values are transmitted from the EAX register, which are conventionally stored in the EAX register. This is important to note that if a user-defined function modifies the EAX register, these functions are thus conventionally neutralized. The return values from these functions are transmitted as EAX register values. With this form of attack, we emphasize the comprehensive nature of our attack on the argument’s position. In accordance with the System V-style calling convention.
code injection and GOT overwriting take place before the binary is loaded, rendering run-time protection ineffective.

Indeed, our binary injection could be thwarted through various anti-tampering techniques, including obfuscation, integrity checks, and binary encryption. Among these methods, integrity checks on the binary stand out as the most straightforward and widely applicable approach. However, implementing such verification processes often involves resource-intensive cryptographic operations like hashing and signature algorithms. Consequently, cryptographic functions in low-cost devices such as IoT devices may still remain vulnerable to our attack, as these devices are typically not protected by integrity checks.

4. Conclusion & Future Work

This paper demonstrated the binary injection attack, capable of defeating the cryptographic countermeasures that are dependent on run-time random sources. We redirected the GOT entries and the calls to user-defined functions to our injected code, consistently producing zeros instead of random numbers. To protect the target binary from a binary injection attack, various binary anti-tampering techniques can be employed. For instance, integrity checks including hash-based checks, checksums, and digital signatures can be utilized to detect modifications to the binary code. Our future work includes several key initiatives. First, we aim to conduct a performance comparison detailing the number of computational traces necessary to recover a subkey and the time elapsed between HO-DCA, HDHO-DCA, and DCA using our injected code. Additionally, we plan to demonstrate the hijacking of calls to various cryptographic functions, each with distinct prototypes. Last but not least, we intend to develop an automation tool capable of detecting all random sources in binaries and customizing code injections based on the characteristics of each random source.

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References