Detection and Mitigation of JIT-Induced Side Channels*

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1 SIDE CHANNELS IN SOFTWARE

Cyber-attacks stealing confidential information are becoming increasingly frequent and devastating as modern software systems store and manipulate greater amounts of sensitive data. Leaking information about private user data, such as the financial and medical records of individuals, trade secrets of companies and military secrets of states can have drastic consequences. Confidentiality of such private data is critical for users of these systems. Many software development practices, such as the encryption of packages sent over a network, aim to protect the confidentiality of private data by ensuring that an observer is unable to learn anything meaningful about a program's secret input from its public output. Under these protections, the software system's main communication channels, such as the content of the network packets it sends, or the output it writes to a public file, should not leak information about the private data. However, many software systems still contain serious security vulnerabilities. Side channels are an important class of information leaks where secret information can be captured through the observation of non-functional side effects of software systems. Potential side channels include those in execution time, memory usage, size and timings of network packets, and power consumption. Although side-channel vulnerabilities due to hardware (such as vulnerabilities that exploit the cache behavior) have been extensively studied [1, 2, 10, 13, 15–17, 19, 23], software side channels have only recently become an active area of research, including recent results on software side-channel detection [4, 8, 11, 12, 18, 22, 24] and quantification [5, 20, 21], and

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```
public static boolean pwd_safe(String g, String p) {
    bool flag = true;
    bool fakeFlag = true;
    for (int i = 0; i < g.length(); i++) {
        if (g.charAt(i) != s.charAt(i))
            flag = false;
        else
            fakeFlag = false;
    }
    return flag;
}
```

Figure 1: A seemingly timing-channel-free password checking function.

Figure 2: Execution time distributions for the password checking function with and without JIT-enabled.

my own work on a static analysis framework for detection of software side-channels called CoCo-CHANNEL [8]) and a constraint caching framework to accelerate side-channel quantification called CASHEW [9].

2 JIT-INDUCED SIDE CHANNELS

An underlying assumption common in existing software side-channel analysis techniques [4, 8, 12, 18] is that the source code is the only determiner of the side-channel observable. This is not the case. As I have shown in my research, just-in-time (JIT) compilation, which is crucial to the performance of modern programming languages such as Java and JavaScript, can introduce timing side channels into deceptively secure-looking code fragments when it attempts to optimize paths it deems “hot” [6]. For example, the Java Virtual Machine tracks how often each branch of a conditional branch instruction is taken, and uses this profiling data when optimizing a method to generate native code favoring the more common branch. As a result, JIT compilation can introduce timing side channels in cases where the input distribution to the program is non-uniform.

Consider a simple password checking function that compares two strings character by character. If a programmer is concerned with timing vulnerabilities, they would avoid coding a function that returns as soon as there is a mismatch between characters but instead does the same amount of work per loop iteration regardless

Figure 3: Automated JIT-Induced Side-Channel Detection

of whether the characters match. Figure 1 is such a function. At a static level, this function is devoid of timing side channels. However, once the behavior of the runtime is considered, this is no longer the case. Figure 2a shows two violin plots – the timing distribution of this password checking function when the first characters do not match and the timing distribution when they do. No timing channel is observed – because JIT is disabled. Figure 2b shows the analogous violin plots with JIT enabled. A side channel has arisen! This occurs because it is much more likely that the first character of a randomly chosen input does not match that of the password, causing JIT to optimize one path over the other.

JIT-induced side channels could potentially allow an attacker to prime an application in such a way that another user’s private data or actions are leaked. I am the first researcher to investigate this class of side-channel vulnerabilities, and my work is the first scientific demonstration of JIT-induced side channels. I have developed three different attack scenarios under which JIT-induced side channels might be leveraged by an attacker and five vulnerability templates to detect susceptible code fragments [6]. Using these templates and attack scenarios, I evaluated three classes from the Java standard library and three JavaScript built-in objects for their vulnerability to JIT-induced side channels, finding many functions vulnerable. I have also induced JIT-based side-channels in the Apache Shiro security framework and the GraphHopper route planning server that are large enough in magnitude to be observable over the public internet [6].

3 AUTOMATIC DETECTION OF JIT-INDUCED SIDE CHANNELS

The side channels discussed above [6] were induced manually, through intelligent choices of priming input and scenarios. The set of potential priming scenarios for a runtime is extensive, yet not all priming scenarios (or even most) result in observable timing side channels. Therefore, I recently developed an automated process to efficiently and automatically explore the possibility of a timing side channel being induced by the runtime of a program [7].

My automated process consists of two stages, given in Figure 3. First, an *Input Generation* stage takes a program with some subset of input marked as secret. This phase produces two results. The first is a set of pairs of partitions of the secret domain. Intuitively, these partitions divide the secret domain in disjoint partitions that are most likely to be separable due to a timing side channel. These partitions will be used in the second stage to evaluate if a timing side channel has arisen. The second goal of the input generation phase is to produce a set of priming input. The program under test

Figure 4: Differential Privacy for Timing Channels

will be primed (i.e. run repeatedly) on these input in an attempt to produce a timing side channel.

The second stage is the *JVM Fuzzing* stage. The goal of this stage is to answer the question: is there a priming input such that priming in favor of that input results in a timing side channel by which two partitions of the secret domain are distinguishable. The priming input generated in the Input Generation stage are each considered in turn when priming the runtime. Likewise, each pair of partitions of the secret domain generated in the Input Generation are evaluated for separability due to their timing distributions.

Details on the implementation of this process can be found in [7]. I evaluated this technique on three widely used datasets – the BLAZER dataset, the THEMIS dataset, and the DIFFFUZZ dataset. These datasets have been used in the evaluation of four state-of-the-art program analysis tools for side-channel detection [4, 8, 12, 18]. Ultimately, I found that many code variants labeled “safe” are in fact vulnerable to JIT-induced timing side channels. My results show that inducing JIT-based side channels can be effectively automated, and also directly contradict the conclusions of four separate side-channel analysis tools. The failure of other program analysis tools in detecting this kind of side channel further motivates the importance of my automated technique.

4 MITIGATION OF JIT-INDUCED SIDE CHANNELS

JIT-induced side channels can produce devastating information leaks. It is crucial that the computer science community is not only aware of these vulnerabilities but develops strategies to mitigate their impact. I plan to work towards this end by developing mitigation techniques at the runtime level and leveraging tools from differential privacy to ensure that sensitive user data remains private. Differential privacy allows for the public sharing of aggregate information about a dataset while ensuring that information about any single member of that dataset remains private [14]. I will extend this concept to runtime engines: the runtime state should leverage aggregate information about past input but no one input should be identifiable based on timing information. I will modify the Jikes Research Virtual Machine [3] so that its dynamic compilation mechanism satisfies this constraint. This will defend against the type of JIT-induced side channel present in the Apache Shiro framework and the Graphhopper routing algorithm. However, this mitigation technique will have no chance of being adopted if it introduces significant performance loss. Therefore, I also plan to experimentally evaluate how much execution speed is lost when dynamic compilation is forced to adhere to this differentially private constraint. The extension of differential privacy to the new area of JIT-induced side channels is given in Figure 4.

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