# Moving Target Techniques: Leveraging Uncertainty for Cyber Defense

**Hamed Okhravi, William W. Streilein, and Kevin S. Bauer**

Cyber moving target techniques involve randomizing cyber system components to reduce the likelihood of successful attacks, adding dynamics to a system to shorten attack lifetime, and diversifying otherwise homogeneous collections of systems to limit attack damage. A review of five dominant categories of cyber moving target techniques assesses their benefits and weaknesses.

» **Securing critical computer systems** against cyber attacks is a continual struggle for system managers. Attackers often need only find one vulnerability (a flaw or bug that an attacker can exploit to penetrate or disrupt a system) to successfully compromise systems. Defenders, however, have the technically difficult task of discovering and fixing every vulnerability in a complex system, which usually comprises an operating system, device drivers, numerous software applications, and hardware components. Within cyberspace, this imbalance between a simple, one-vulnerability attack tactic and a complicated, multipart defense strategy favors attackers. While defensive applications have grown significantly in complexity and size over many years, malicious software, i.e., malware, has remained relatively simple, computationally small, and still effective in bypassing defensive applications [1].

A major contributing factor to the imbalanced security of cyberspace is the static nature of systems and defenses. The same copy of a popular software application with the same internals developed by a major software vendor may run on millions of machines. As a result, an attack designed to infect that software application is likely to compromise millions of machines. Similarly, many defensive applications are static; they discover suspicious inputs by applying a set of rules and checks commonly used by software built to detect attacks. Therefore, clever cyber invaders can craft attacks to bypass existing defenses by analyzing local copies of readily available defensive applications and then exploiting the weaknesses within those applications.

A promising approach to defense that attempts to rebalance the cyber landscape is known as cyber moving target (MT) defense (or just moving target). Moving target techniques change the static nature of computer systems to increase both the difficulty and the cost (in effort, time, and resources) of mounting attacks. Simply put, these techniques turn systems into moving targets that will be hard for cyber villains to hit. Defenders using MT techniques pursue any or all of the following goals: make computer systems more dynamic by changing their properties over time, make internals of computer systems more random and nondeterministic, and make computer systems more diverse.

Although numerous techniques categorized as MT have been offered in the academic literature, we are limiting our overview of dynamic MT techniques to those in five computer domains—platforms, runtime environment, software, data, and network. Readers can find a more detailed discussion of these five categories of MT techniques in Okhravi et al. [2].

## Moving Target Overview

An overview of different components of a computer system is a good place to start to understand the domains of MT techniques. For ease of design and implementation, a computer system (e.g., a desktop or laptop machine, a mobile device, or a process control machine in an industrial control system) often consists of multiple layers of software and hardware. These layers are commonly referred to as the software stack although the stack includes the hardware elements as well. Each layer relies on other layers for its proper operation and function. Figure 1 presents one representation of such a layered design. At the very bottom of the software stack are the hardware components of the machine: the processor, the motherboard, the memory cards, and other peripheral devices and cards, such as the sound card and video card. Above this layer resides the operating system, which is responsible for controlling and managing the hardware components and providing an abstraction of them to the application. This abstraction is key to the interoperability and compatibility of the applications because the vast majority of the applications do not interact directly with the hardware components; rather, they use the operating system's abstraction. The abstraction layer, which is the interface that the operating system provides to the application, is sometimes referred to as the runtime environment. The hardware and operating system of a machine are collectively called the platform. Above the operating system reside the applications that are used to process and present data. The data themselves and their representation can be considered a layer atop the application. Finally, many systems do not operate as isolated devices but, in fact, are connected to other

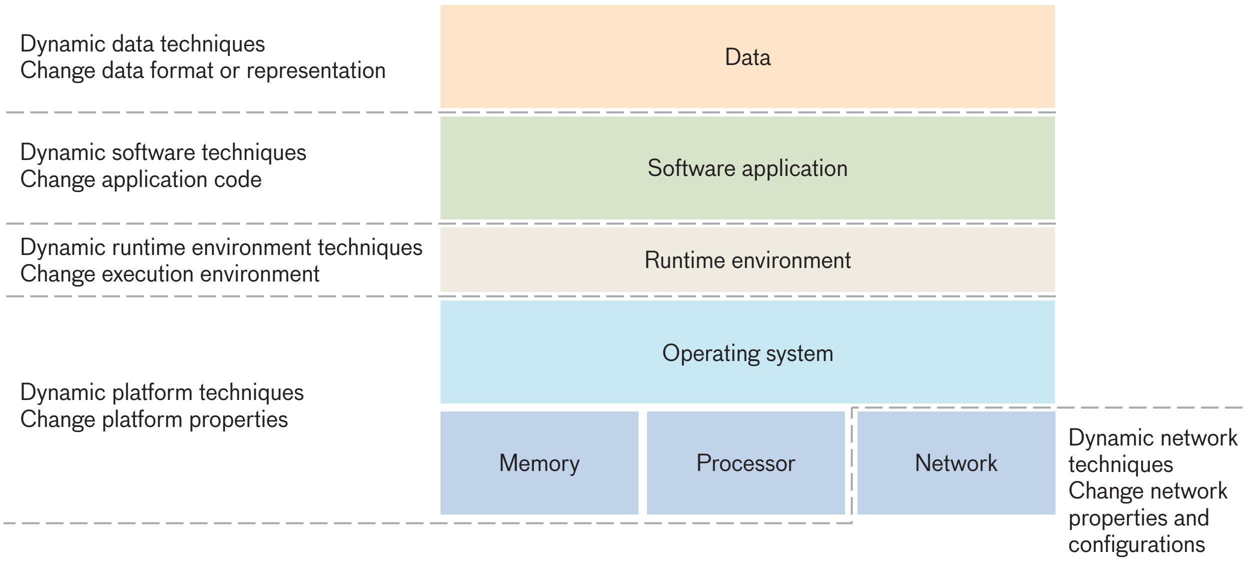
Dynamic data techniques
Change data format or representation
Data
Dynamic software techniques
Change application code
Software application
Dynamic runtime environment techniques
Change execution environment
Runtime environment
Operating system
Dynamic platform techniques
Change platform properties
Memory
Processor
Network
Dynamic network techniques
Change network properties and configurations

**FIGURE 1.** On the right side of the figure is a depiction of the software stack. The layers of the stack address the five different domains of cyber moving target techniques (explained in text at the figure edges) that are assessed in this article.

machines through a network. In general, five domains of MT techniques address dynamically changing the abovementioned software stack layers.

### Dynamic Platform

The dynamic platform domain consists of cyber defensive techniques that dynamically change the properties of the computing platform. Consider a system that runs a given application on top of multiple operating systems and hardware architectures. The application can run on top of a platform consisting of the Fedora operating system and x86 processor architecture or a platform consisting of the FreeBSD operating system and ARM processor architecture. Such a system can be implemented by compiling the application for different processor architectures and employing a platform-independent checkpointing mechanism to preserve the current state of the application during platform changes [3]. This type of system illustrates a dynamic platform MT technique. Other examples of dynamic platform techniques include a voting system that runs an application on top of different platforms, each platform voting on the output of the system [4], or a system that randomizes the operating system's internals that are unimportant for the correct functionality of the application.

The major benefit of a dynamic platform technique is that it can prevent platform-dependent attacks. Crafting a successful exploit against a system usually requires that an attacker consider the exact platform of that system. By varying the computing platform, an MT technique can mitigate attacks that are platform-dependent. An attacker can develop a strong attack by incorporating different exploits against different platforms, but this approach increases the cost (in time and/or computation complexity) of developing the attack. Note that dynamic platform techniques cannot mitigate attacks that target a higher-level application logic flaw and that do not depend on the platform. For example, SQL[1] injection attacks, which inject malicious commands into a database application by leveraging a flaw in the application's high-level logic, are typically not mitigated by dynamic platform techniques.

While dynamic platform MT techniques offer the potential to defeat platform-dependent attacks, these techniques can increase the complexity of the overall system, are generally difficult to effectively manage, and can actually be detrimental to security if used inappropriately [5]. Perhaps the greatest challenge from a system complexity and management perspective is the synchronization of application state across the set of diverse platforms. Examples of application states could include information about open data files, user input from a keyboard or mouse, or network traffic that needs to be correctly delivered to a specific running process (while correctly maintaining connection-specific state in the kernel). Synchronizing these resources among the dynamic platforms in real time requires a complex management infrastructure that can migrate state with speed and agility. Such a management infrastructure increases system complexity considerably.

Another potential limitation of dynamic platform techniques is that the use of multiple distinct platforms can actually increase the system's attack surface, that is, the components of the system that are exposed to and could be targeted by a potential attacker. Suppose that a dynamic platform MT technique migrates an application between three platforms: Linux, Windows, and Mac. If the attacker has an exploit that works on the Windows host, the attacker simply needs to wait until the application migrates to the Window host to launch the exploit and compromise the application. Making the program migration less predictable can help, provided that the attacker cannot reliably guess which platform is running the application.

Dynamic platform techniques are only effective defenses when the attacker must compromise all platforms (i.e., an in-series configuration) not just one platform (i.e., an in-parallel configuration). If the attack requires a long time to succeed (a long-duration disruption of service), a dynamic platform approach can be helpful in thwarting the attack; for short-duration attacks, that approach can be detrimental to security because the attacker's goal may be accomplished on one platform.

### Dynamic Runtime Environment

Techniques in the dynamic runtime environment domain dynamically change or randomize the abstraction provided by the operating system to the applications, without hindering any important functions of the system. One of the most important abstractions in a computer system is how memory is presented to the applications. For various reasons, including isolation of different applications, compatibility, and interoperability, a memory location that is

[1] SQL stands for Structured Query Language, a standardized programming language for requesting information from a database.

presented to an application in most modern computer systems is not a direct representation of the actual physical memory. Rather, a redirection is applied by the operating system, i.e., an abstraction known as the virtual memory. A well-known dynamic runtime environment MT technique randomizes what addresses in the virtual memory are used by the application. The technique is typically referred to as address space layout randomization (ASLR) [6] and is implemented in most modern operating systems, including Linux, Windows, Mac OS X, Android, and iOS. By randomizing the addresses, ASLR makes exploit development significantly more difficult for attackers because they do not know where to place their malicious code on the system. Other dynamic runtime environment techniques include those that change the processor instruction encoding (also called instruction set randomization) or finer-grained variants of ASLR in which smaller regions of memory are randomized.

Dynamic runtime environments are among the most practical and widely deployed MT techniques. Despite the success of this MT domain, two important weaknesses can allow an attacker to circumvent the defense. First, ASLR requires memory secrecy. If the contents of memory are disclosed or leaked to an attacker, the attacker may be able to use this information to defeat ASLR. Such memory disclosures are possible via separate vulnerabilities, known as buffer over-read vulnerabilities, in which the contents of memory are read beyond the allowed boundary, disclosing how memory has been randomized. Without strict memory secrecy, an attacker can circumvent the ASLR protections to launch code injection or code reuse attacks. Second, the low granularity of randomization in many ASLR implementations reduces the overall protection provided by the technique. For example, in Linux, only the start location of certain memory regions (e.g., dynamically linked libraries) is randomized by default, and the executable program code itself is often not compiled with ASLR support. As such, this section of the program's memory is not protected and can be a vector for exploitation.

### Dynamic Software

In the dynamic software domain, MT techniques randomize or diversify the internals of the software application. One technique, the multicompiler [7], creates different versions of software executables (binaries) from the same source code (e.g., written in C) that perform the same function. Variations in the versions can arise from the use of different but equivalent processor instructions utilized during the compilation process or from the use of the same instructions utilized in different locations inside the executable. Note that a given copy of the executable with a given set of internals may never change, but various machines in an enterprise may run different executables. In other words, this technique can create spatial diversity (i.e., diversity among many machines) as opposed to temporal diversity (i.e., diversity in one machine over time). The major benefit of dynamic software techniques is that they mitigate the impact of large-scale attacks. If an exploit is designed against a given variant of the executable, that exploit will have a small chance of working against other variants of the executable. Hence, an attacker cannot compromise many machines at once. This situation is contrary to the current one in which an attacker develops malware that can successfully compromise many machines running the same target application. In recent sophisticated breaches, attackers reuse parts of the benign code of the target application itself to achieve malicious behavior. Known as code reuse attacks, or return-oriented programming attacks [8], these attacks can successfully circumvent existing defenses that detect and stop foreign pieces of code. By varying the benign application code, dynamic software techniques can effectively stop code reuse attacks.

Dynamic software techniques often employ specialized compiler techniques to produce executable software variants with different and unpredictable memory layouts. These variants may use padding (adding meaningless bytes of data) to make the size of memory regions unpredictable. They also may contain within the executable code a no-operation (NOP) instruction that does not perform any operation but can make code reuse attacks hard to launch because the instruction changes the location of other instructions.

Dynamic software techniques suffer from a variety of weaknesses. Recompilation to produce a software variant requires access to a program's source code and is not possible with proprietary, third-party software for which source code is not made available. Furthermore, ensuring correct operation of the compiled variant can be challenging because one cannot simply verify a known integrity measurement of the executable file to guarantee that the code has not been (maliciously) modified.

Another drawback of dynamic software methods is that software is often compiled with special optimization flags that reduce the space and/or computational complexity of the compiled binary code. An MT technique that explicitly compiles the software to introduce randomness in the memory layout (by randomizing the size and/or location of objects) may not be compatible with the space saving or compute-time saving optimization passes performed by the compiler. Consequently, the dynamic software is unlikely to maintain the same performance properties as the ideally optimized compiled code.

In addition, dynamic software techniques that use execution monitors to instrument and compare multiple versions of an executable introduce significant performance costs. For example, if an MT technique compares execution for an application that has two variants, there is at least a twofold performance cost relative to native execution of the application (in terms of processor, memory, and input/output utilization). This cost may be reasonable for protecting one or two applications for which the highest degree of security is required, but the cost is likely to be unacceptable for the protection of all applications running on a host. Techniques in the dynamic software domain may also be subverted by information leakage attacks. If attackers can expose how an executable has been diversified, they can attack it as if it were not diversified at all.

### Dynamic Data

Moving target techniques under the dynamic data domain change the format, syntax, representation, or encoding of the application data to make attacks more difficult. In this domain, the diversity can be temporal or spatial. For example, to protect a Linux operating system, a defender could dynamically change the representation of the user identifier (UID) that determines what access rights a user has. This defense is effective against attempts that seek to increase a user's access rights; for example, an attacker may attempt to change the UID to that of a privileged administrator so that the attacker can exploit the expanded rights to access sensitive resources. This type of attack is one example of a larger class known as privilege escalation actions that can be mitigated by UID randomization.

Dynamic data techniques offer the promise of protecting data from theft or unauthorized modification, but these techniques suffer from two important weaknesses. First, the number of acceptable data encodings is limited. For example, for encoding binary data either the base64 or the hexadecimal encoding scheme would most likely be used because there are few other accepted standards for data encoding. Nonstandardized schemes are certainly possible, but these may increase the complexity of the interoperation among system components. Second, the use of additional data encodings may also increase the attack surface of the software. For each encoding type, the software must have the proper parsing code to encode and decode the data. This additional parsing code itself could have security-relevant software bugs.

### Dynamic Network

Techniques in the dynamic network domain change the properties of the network to complicate network-based attacks. One such technique frequently changes the Internet protocol (IP) addresses of the machines in an enterprise network [9]. This IP rotation technique can thwart rapidly propagating worms that use a fixed hit list of IP addresses to infect a network. Another technique, known as an overlay network, creates dynamically changing encrypted tunnels (i.e., encrypted communication connections over public networks).

Dynamic networks is an appealing class of techniques to reduce an adversary's ability to conduct reconnaissance on a network, map a defended network, or select specific hosts for a targeted attack. However, these techniques face two important obstacles to deployment. First, because many dynamic network techniques lack a well-articulated threat model, it may be unclear to network defenders what threat needs to be mitigated and thus how best to deploy the defensive technique. Consider a technique that isolates a small group of machines from the larger network (or Internet). If hosts within the isolated network can still communicate to hosts beyond the isolated network, protected hosts may be vulnerable to any number of client-side attacks that exploit vulnerabilities within the unprotected hosts' web browsers or document viewers. For example, targeted spear phishing (fraudulent email messages that try to elicit information such as passwords to Internet accounts) could penetrate a protected network through the network's connections to unprotected hosts. Dynamic network–based MT techniques do not address these types of attacks.

Second, many dynamic network techniques introduce randomization into the fundamental protocols that are used on the Internet. However, the effectiveness of this randomization at stopping attacks is unclear. Suppose an MT technique randomizes network identifiers (such as an IP address). If service discovery protocols such as the domain name service (DNS) are used to convert human-readable domain names to machine-readable IP addresses, these services may undo any potential security benefit obtained through the MT technique itself, provided that the attacker can issue DNS queries.

## Summary

One way to understand the benefits of MT techniques is to look at the steps of a cyber attack that these techniques are trying to mitigate. To successfully compromise a system, an attacker must progress through the several phases depicted in Table 1. The first phase is conducting reconnaissance; an attacker collects information about the target. The second phase is accessing the victim; the attacker collects enough information about the configurations, applications, and software versions that are running on the target machine to develop an attack against it. During the third phase, the attacker develops an exploit against a vulnerability in the target machine. Next is the launch of the attack, which may include, for example, sending a malicious network packet to the target machine, luring the user to click on a maliciously crafted link, or using a malicious thumb drive. After the attack is launched and verified, the attacker may take additional steps to maintain a foothold on the target machine (i.e., persistence). These phases, together referred to as the cyber kill chain, are correlated in Table 1 with the MT technique domain that is aimed at mitigating the effectiveness of each step.

## Evaluating MT Techniques

Because attackers need only exploit the weakest link in any MT technique to bypass it or render it ineffective, it is difficult for researchers to evaluate the fundamental effectiveness of the technique. Lincoln Laboratory researchers have been developing MT evaluation and assessment capabilities to further their understanding of the techniques' efficacy.

### Quantifying Information Leakage Attacks

Although a variety of classes of attacks have been used against MT techniques, for the sake of brevity in our discussion, we describe a class of cyber attacks known as information leakage to illustrate our evaluation capabilities. Information leakage attacks are a crucial class to consider when one is measuring the effectiveness of MT techniques because these attacks are widely employed.

Information leakage attacks, through which an attacker can discover how a system has been randomized or diversified, can be achieved in two ways: (1) by exploiting a vulnerability that forces a system to include its randomized internals directly in its output, thereby allowing the attacker to observe those internals (this type of attack is also referred to as a memory disclosure attack) or (2) by using remote side-channel attacks, i.e.,

**Table 1. Primary Attack Phases Disrupted by Techniques in the Five MT Domains**

| MT DOMAINS | ATTACK PHASES | | | | |
|---|---|---|---|---|---|
| | RECONNAISSANCE | ACCESS | DEVELOPMENT | LAUNCH | PERSISTENCE |
| Dynamic networks | ✓ | | | ✓ | |
| Dynamic platforms | | ✓ | ✓ | | ✓ |
| Dynamic runtime environments | | | ✓ | ✓ | |
| Dynamic software | | | ✓ | ✓ | |
| Dynamic data | | | ✓ | ✓ | |

ones in which the randomized internals of a system are not leaked directly through the output but through an indirect property of the output, such as its timing.

Lincoln Laboratory researchers have discovered various new classes of side-channel attacks, including remote timing and fault-analysis attacks (which will be discussed in the following paragraphs), and have performed in-depth evaluations of their impact and how much information they can reveal to an attacker [10]. These attacks are particularly important in the context of dynamic software and runtime environment MT techniques.

Consider the code snippet below:

```
i = 0;
while (i < ptr->value)
       i++;
```

Attackers can redirect the pointer **ptr** to a chosen location in the memory. In such cyber attacks, the timing of the loop (a sequence of instructions repeated until the desired result is achieved) will depend on the byte value at that memory location. If the byte value is high, the loop takes a long time to terminate; if it is low, the loop terminates rapidly. By remotely observing these timing differences, an attacker can infer byte values in memory, thus undoing the impact of software randomization or diversification.

We have evaluated the effectiveness of a remote timing side-channel attack against Apache, the most popular web server on the Internet. As the results of the assessment of this attack illustrate (Figure 2), the cumulative delay in a webpage request that can be observed by an attacker correlates well with the sensitive byte values from the diversified software of Apache stored in memory.

Figure 3 illustrates a more general result for the amount of information leaked to an attacker via timing for Linux's main system library, libc. Here the $x$-axis indicates a metric called uncertainty set size (USS), which measures the uncertainty in attackers' knowledge of the target system if they are able to observe the timing information. The $y$-axis denotes the fraction of the diversified software's functions from which attackers can infer information through timing attacks. The different lines indicate the number of timing values observable by attackers.

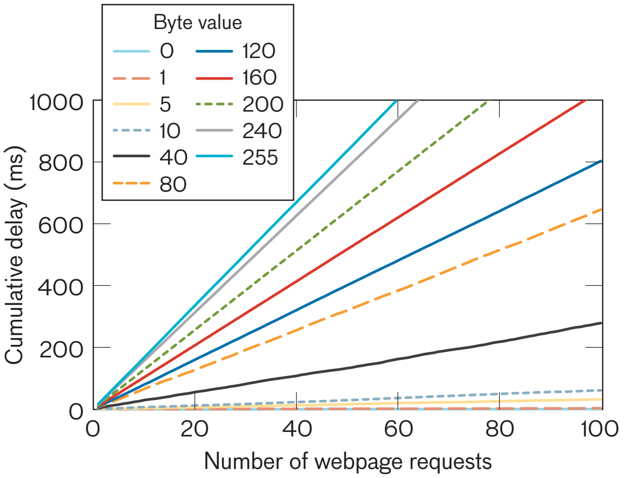

**FIGURE 2.** The data show the the correlation between cumulative delays in Apache webpage requests and the byte values stored in memory. By measuring the delay, an attacker can perform a remote timing attack and nullify the effectiveness of software diversification.

The figure shows that if attackers can observe just one timing value for the target server, they can narrow down 45% of all functions to a set of 10 or smaller (USS = 10). Note that a USS value of zero indicates the attackers made a correct identification of an exact function without any uncertainty. The figure also illustrates that by measuring a handful of timing samples, attackers can infer a lot of information from a diversified software application, thus negating the effect of randomization for the majority of functions.

Side-channel attacks can also be performed by using fault analysis, i.e., influencing a system to cause an error that the attacker can examine to gain insight into the system's internal operation. For example, the code snippet below indicates a side-channel attack in which the attacker can infer on the basis of the output of the application whether a byte value is zero or nonzero. If the output is "SUCCESS," **ptr** points to a byte value of nonzero; if the output is "ERROR," the byte value is zero.

```
recv(socket, buf, input);
if (ptr->value)
       rv = SUCCESS;
else
       rv = ERROR;
send(socket, &rv, length);
```

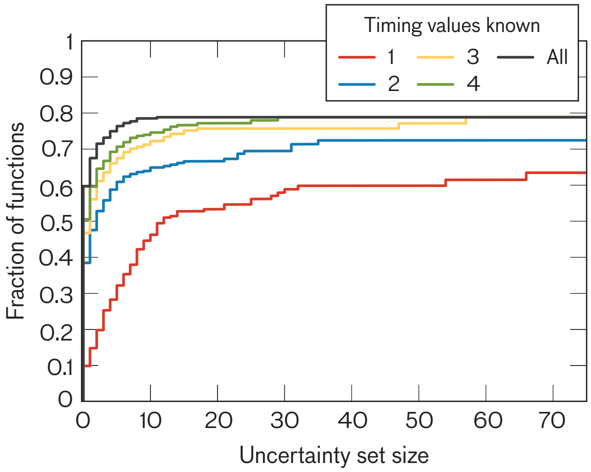

**FIGURE 3.** The plot shows the fraction of information on system functions ($y$-axis) leaked to an attacker from libc via timing side-channel attacks in which the indicated number of timing values is known. On the $x$-axis, the numbers represent measurements of the uncertainty in the attacker's knowledge of the target system.

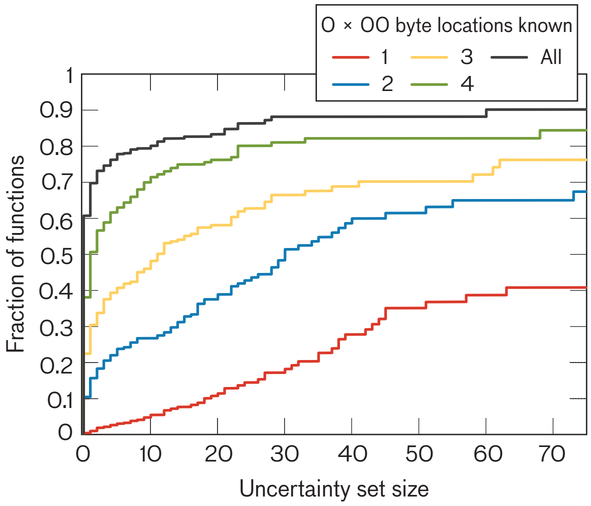

**FIGURE 4.** The plots show the amount of information (about functions) that is leaked to an attacker from libc via a fault-analysis side-channel attack when various byte locations are known. Again, the $x$-axis indicates the uncertainty of the attacker's knowledge of the system.

Figure 4 illustrates the results for the fault-analysis attack for libc. Similar to timing side-channel attacks, fault side-channel attacks can leak valuable information to an attacker. For example, merely knowing the location of four zero bytes in the entire libc library allows an attacker to uniquely fingerprint 38% of functions (USS = 0) and narrow down 70% of the functions to a set of 10 or smaller (USS = 10), as shown in the figure by the green line on these points: ($x = 0$, $y = 0.38$) and ($x = 10$, $y = 0.7$).

To summarize, our findings indicate that MT techniques can be maliciously bypassed using side-channel attacks. Our evaluations indicate that even a small number of timing or fault-analysis samples can leak a significant amount of information to an attacker. These results suggest that MT techniques must rerandomize system internals periodically to be resilient against information leakage attacks [11].

### Practical Considerations

When deciding to deploy an MT technique, system defenders have many practical issues to consider. They should understand the potential impact of the MT technique on the system's performance. Many MT techniques offer security against strong adversaries, but incur performance penalties that for some applications could be prohibitively high. Recognizing the performance requirements of the system and the expected performance costs of the MT technique can help defenders make the right decision about deploying MT defenses.

Defenders should also understand the effectiveness of an MT technique against a relevant threat model before it is deployed. Techniques that have shown high effectiveness against realistic attack models should be selected before those that have uncertain benefits or those that protect against an unrealistic threat. Hence, it is important to have access to a well-defined attack model that describes the exact types of attacks that are of concern and that are relevant to the system being protected.

Finally, MT techniques do not necessarily solve all security problems; rather, they are best suited to defending against specific threats. Defenders, therefore, should understand the composability (i.e., combinatorial possibilities) of MT and non-MT techniques so that they can enhance protections against cyber security threats. For example, defenders may want to guard against code injection attacks by using ASLR. But to improve security even more, they might add signature-based network monitoring to examine network traffic in real time and drop all packets that appear to contain code injection payloads.

## Future Directions

Future research in MT techniques will take multiple directions. In designing new techniques or evaluating existing ones, researchers should analyze whether or not the additional complexity created by the randomization or diversification of the system's components is actually exposed to a potential attacker. Many MT techniques create complexity in a system component, but attackers can avoid or bypass the complexity through attacks that exploit information leakage or attacks that work regardless of the specific internals of a component (e.g., higher-level logic flaws in the application). The challenge for defenders, then, is to ensure that the complexity is not exposed to the system's operators and maintainers. Ease of deployment, operation, and maintenance is important for widespread deployment of cyber defensive techniques.

Additional work is needed in the area of evaluation and assessment of MT techniques. For cyber security to transition from a craft to a science, it is important for researchers to have concrete, meaningful, and repeatable evaluation methods. An imperative part of evaluation is the development of metrics that define measurement units of security and that can be used to evaluate the absolute security offered by an MT technique and to comparatively assess it against other techniques. Meaningful and objective evaluation of MT techniques can benefit from a variety of approaches, including abstract analysis, modeling and simulation, test bed experimentation, and real-world measurements in operational systems.

Finally, an important future direction for MT research is the examination, study, and evaluation of the composability of MT techniques with other MT and non-MT defenses. Cyber defenses in general, and MT techniques specifically, do not provide a "silver bullet," protecting against every known cyber attack. Therefore, in practice, multiple defenses should be combined to provide adequate protection of systems. Understanding the impact of these defenses on each other, as well as the composability challenges arising from these defenses, is an open research area. Other important areas for further study include determining if a defense will improve, co-exist, or conflict with another defense and investigating how a defense is influenced by second-order effects, such as an attacker's reactions to the presence of a new MT technique.

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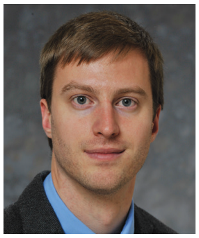

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