Technological Report: A Toolkit for Runtime Detection of Userspace Implants

J. Aaron Pendergrass† Nathan Hull† John Clemens† Sarah Helble†
Mark Thober† Kathleen McGill‡ Machon Gregory‡ Peter Loscocco‡
† Johns Hopkins Applied Physics Laboratory ‡ National Security Agency
May 1, 2019

Abstract

This paper presents the Userspace Integrity Measurement Toolkit (USIM Toolkit), a set of integrity measurement collection tools capable of detecting advanced malware threats, such as memory-only implants, that evade many traditional detection tools. Userspace integrity measurement validates that a platform is free from subversion by validating that the current state of the platform is consistent with a set of invariants. The invariants enforced by the USIM Toolkit are carefully chosen based on the expected behavior of userspace, and key behaviors of advanced malware. Userspace integrity measurement may be combined with existing filesystem and kernel integrity measurement approaches to provide stronger guarantees that a platform is executing the expected software and that the software is in an expected state.

1 Introduction

Modern malware often relies on subtle subversions of the runtime environment of userspace processes to maintain an adversary’s foothold on victim systems. These implants elude most traditional detection mechanisms while providing a range of features such as execution of arbitrary programs, bulk data transfers, victim monitoring, network discovery, persistent storage, proxied communications, and command and control. In particular, memory-only implants are able to avoid many popular defensive technologies based on filesystem scanning. The primary contribution of this paper is the introduction of userspace integrity measurement, an approach to filling this gap in malware defense, and the USIM Toolkit, an initial implementation of userspace integrity measurement with a demonstrated ability to detect core techniques of advanced implants. Userspace integrity measurement is based on a principled evaluation of the userspace abstractions provided by an operating system and the violations of these abstractions that allow implants to operate outside the visibility of traditional system monitoring tools.

1.1 Motivation

The motivation for this work is the conviction that memory-only implants are active in the wild and often undetected. Memory-only attacks in general are becoming prevalent [8,45,46] and go by many names: advanced volatile threat, fileless, living off the land, malware-free, memory-only, and non-malware. While detection and reporting of such attacks is increasing, the most notable report of a memory-only implant may be Georg Wicherski’s talk at SyScan 2014 about Procedure Linkage Table (PLT) infections and Evanescent Bat [44].

Evanescent Bat was an intrusion into a large European IT company in mid-2013 in which many Linux
servers were compromised. The adversary injected a memory-only implant into running processes from the post-exploitation shell that infected the PLT of those processes. The implant was highly sophisticated: it used gcc plugins to scrub local variables as they went out of scope and to encrypt global and heap variables, in addition to handling many different PLT implementations and corner cases. The intrusion went undetected until the adversarial operators mistakenly revealed their presence and the implant.

1.2 Approach

Userspace integrity measurement and appraisal is the process of collecting evidence of the current state of the basic abstractions provided by an operating system, and evaluating this evidence for violations of invariants that indicate deviations from expected runtime behavior. The primary abstractions we consider are namespaces, filesystems, networking and inter-process communication channels, environment variables, virtual memory management, and runtime linker/loaders. Implants take advantage of subtle divergences between application developers’ understandings of these abstractions and the actual behavior of the operating system. These divergences may be caused by errors in the operating system implementation, ambiguities in the specification, or misunderstandings by the application developers. The premise of userspace measurement is that these implant behaviors create observable effects in the point-in-time state of an infected system that are unlikely to be caused by benign software.

This paper introduces and evaluates the USIM Toolkit as a proof-of-concept implementation for userspace integrity measurement targeting the GNU/Linux operating system. Section 2 defines userspace and describes our heuristics for including data as part of userspace integrity measurement. Section 3 describes the adversary model considered directly by userspace integrity measurement, and how the USIM Toolkit can be combined with other measurements to protect against more powerful adversaries. Section 4 describes a range of known implant techniques and how they are likely to impact userspace. Section 5 describes the specific measurement and appraisal capabilities currently implemented in the USIM Toolkit. Section 6 evaluates the USIM Toolkit’s ability to detect proof-of-concept implementations illustrating the techniques of Section 4, and gives initial performance benchmarks for the USIM Toolkit. Section 7 considers our approach in the context of the large body of existing work combating malware. Section 8 describes the primary limitations and areas for future work in the current USIM Toolkit implementation. Section 9 summarizes our approach to userspace measurement and the primary contributions of this paper.

2 What Is Userspace

Userspace is everything, aside from the executing kernel, that is needed for the system to run, persist across reboots, and correctly perform operations on behalf of the user. A complete userspace integrity measurement should reflect the security relevant state of all aspects of a system other than the kernel itself. Rather than attempt to produce such a measurement, we focus on providing a core set of measurement tools aimed at bootstrapping trust from a kernel measurement to the underlying runtime provided for all processes on a system.

Userspace refers to those aspects of a computer system that are built using abstractions provided by an operating system’s kernel. The exact features and mechanisms of userspace may vary from system to system. From an attacker’s perspective, userspace provides a rich set of opportunities to cause the system to diverge from correct operation without requiring direct modification of the kernel. An expansive approach to userspace measurement would reveal this variety of compromises by examining all elements of userspace, recording their attributes and interrelationships, and appraising these measurements against expected values for the system. Such a measurement would reflect

- The complete memory state of every executing process, including application specific data and common process runtime structures
- Inter-process communication mechanisms in-
including network state, shared memory regions, files opened by processes, and pipes

- The complete state of the file system including all subtrees, executable images, system libraries, data files, and program configurations
- Configuration data needed for system administration, including user accounts and application specific configuration semantics such as a webserver’s configuration file
- The set of configured devices and how they are exposed (e.g., via the /dev virtual filesystem)
- Policy configurations used for access control, network management, boot-time process execution, or other system services
- The state of kernel-level data reflecting the current configuration of the system such as date and time information, process privileges, memory maps, namespaces

Such a measurement would be extremely challenging both to collect and to verify. It would likely be extremely large and depend on significant application-specific knowledge to reflect the internal data of the processes that happen to be running on a given system. Thus, our definition of userspace integrity measurement is narrower than this. Rather than reflect all aspects of userspace in a single measurement, we focus on capturing the dynamic state of the common runtime environment. Which data we include in the userspace integrity measurement is based on the following heuristics:

- **Include:** Well-formedness conditions that apply to all processes executing on a system should be verifiable based on userspace measurement.
- **Include:** The current relationships between executing processes should be reflected in userspace measurement.
- **Include:** The values of kernel-level data structures that directly govern how processes interact with system resources should be reflected in userspace measurement.
- **Include:** Cryptographic hashes of critical system files that must maintain bit-for-bit equality with a trusted baseline for correct system operation should be included in userspace measurement. This includes system executables, shared libraries, and some configuration files.
- **Exclude:** Well-formedness of kernel-level data structures should not be reflected in userspace integrity measurement.
- **Exclude:** Application-specific semantics are best verified by application-specific measurements and thus should not be included in the generic userspace integrity measurement.

For example, we include measurements of the PLTs of running processes as part of userspace integrity measurement, but exclude the content of data structures within a process’s runtime heap. The correctness of the PLT is core to what it means to be a well-formed process, while the semantics of the data held inside the process heap is application specific and excluded from our measurement. Similarly, data maintained by the kernel that define the privileges of processes, such as the user id associated with each process, should be included in userspace measurement, but the details of how these data are stored in the kernel, e.g., the tree of `struct task_struct` instances maintained by the Linux kernel, should not.

This approach leads to a model for userspace integrity that supports the detection the kinds of advanced malware threats described in Section 1.1, but does not present the technical and administrative challenges of representing the allowable internal states of all programs that may be present on a system.

### 3 Adversary Model

Userspace measurement targets an adversary that is able to arbitrarily modify the memory of any normal system process but is unable to modify the USIM Toolkit or its trusted computing base. In particular, the adversary is unable to corrupt the operating system kernel hosting both the measurement tools and
the victim processes. In existing systems, most adversaries capable of modifying arbitrary processes are likely to be able to also modify the measurement tools or operating system kernel. To protect against realistic adversaries our approach relies on the concept of nested measurements and isolated execution environments provided by a measurement and attestation system such as Maat [25].

Conversely, the adversaries considered by the USIM Toolkit could employ application-specific implants to meet their goals. For example, an implant could modify function pointers defined by a particular network service daemon in order to maintain a presence on a system. Such an implant would not be detected by the USIM Toolkit, because the USIM Toolkit does not inspect application specific data. Detection of such an attack would require application-specific measurement in addition to userspace, kernel, and lower-level measurements. While we believe there is ample opportunity for developing measurement strategies capable of verifying application-specific properties, (a) these measurements would rely on the guarantees provided by a system like the USIM Toolkit, and (b) mitigating the more general attack classes should be higher priority as they tend to provide greater robustness and portability for the adversary.

The key to generalizing userspace integrity measurement to more interesting classes of adversaries is the ability of one measurement to provide evidence that another measurement was correctly performed. For example, a measurement capability built into the OS kernel can provide evidence that the USIM Toolkit is correctly installed and executed. Similarly, a measurement capability such as the Linux Kernel Integrity Measurer (LKIM) [21] may use virtual machine introspection to provide evidence that the kernel-level measurement capability is reliable. Each measurement in the chain supports trust in the measurements above it. Ultimately, this chain of measurements should be rooted in low-level cryptographic guarantees such as those provided by the trusted boot process and trusted platform module [10,22]. The formalization of protocols for specifying appropriate chains of measurements for a given use case is an area of ongoing research [27] which could also be leveraged by implementations of the USIM Toolkit to guarantee integrity.

4 Implant Techniques

All implants have the fundamental goal of providing an adversary stealthy access to a victim system. Inherent in achieving this goal is the requirement for execution. An implant that cannot execute cannot serve its purpose. Implants may satisfy this requirement using various techniques that we divide into two categories: simple and sophisticated.

Simple techniques rely on “hiding in plain sight” to evade detection. They use system interfaces in a generally expected way to a nefarious end and succeed when users and administrators fail to carefully examine the primary state of the system (e.g., processes running and files on the file system). Such techniques include replacing system binaries with malicious binaries, file infections, and more generally file modifications, and they fall under Joanna Rutkowska’s type 0 malware classification [28]. These techniques are uninteresting in this context because they have been well studied [5] and may be detected by file integrity checkers (e.g., IMA and Tripwire) or other security and system auditing tools, including antivirus software.

Sophisticated techniques use system interfaces in unusual ways to evade detection. These techniques go undetected without deeper examination of the primary state of the system and fall under Rutkowska’s type I and type II malware classifications [28]. It is impossible to anticipate all conceivable techniques in this category, but we have identified some common techniques implants may use to achieve execution. We also chose to examine a relatively new technique for concealment and a privileged resource acquisition technique that may facilitate communication. The techniques are

- Process Text Segment Modification
- Global Offset Table/Procedure Linkage Table Hooking
- Shared Object Injection
• Thread Injection
• Namespace Manipulation
• File Descriptor Passing

These techniques cover a core set of userspace effects the USIM Toolkit needs to be able to detect and distinguish from benign system behavior in order to detect an implant. The first three are common userland rootkit techniques that abuse existing processes [41, Chapter 25] to achieve execution. Thread injection has some overlap with those techniques (i.e., it may be achieved using any of the previous three), but has a distinct effect on userspace. Namespace manipulation is a relatively new means of achieving stealth that may become increasingly relevant as containers become more common [11]. File descriptor passing is a long-standing feature of UNIX domain sockets that may enable an implant to acquire or transfer privileged resource access. Our understanding of these techniques directly informed the prioritization of measurements included in the initial implementation of the USIM Toolkit.

4.1 Process Text Segment Modification

Text segment modification is one of the simplest approaches an implant can take to maintaining execution within a legitimate process. For most programs, executable code is mapped directly into the process memory space from the “.text” sections of the program binary and supporting shared libraries. Notable counter-examples to this rule are the Procedure Linkage Tables (PLTs) of dynamically linked processes that are generated by the runtime linker/loader (discussed below in Section 4.2), and just-in-time compiled code that is generated by many interpreters in dynamically allocated heap buffers. Modifying executable code in place gives the implant all the permissions of the host process, allows the implant to intercept communications intended for the host process, and evades some basic detection approaches by not creating new executable memory regions.

By default most programs’ load segments are marked as executable/non-writeable. This causes the runtime loader to request that the operating system map these regions without the writable bit set in the corresponding page table entries, which will prevent an implant from naively attempting to overwrite a process’s code. Many implants overcome this limitation by employing a code-reuse attack, such as Return-oriented Programming (ROP) [31], to remap part of the text segment then inject and jump to the implant payload. For consistency, the payload should then remap the region as non-writable before entering its main program (although not all implants are this careful).

This approach is observable, even after the fact, because it modifies memory pages that should be identical to the on-disk representation in the program binary. Given the on-disk binaries of the program and all of its shared object dependencies, a simple comparison with process memory reveals any modifications [41, Chapter 25].

4.2 GOT/PLT Hooking

The Global Offset Table (GOT) and Procedure Linkage Table (PLT) are structures created by the runtime linker/loader that can be manipulated by malware to provide execution in a victim process without modifying the text segment. Both the PLT and the GOT support dynamic library linking and position independent code (PIC) [38]. The GOT holds the runtime addresses of global data and functions that may not be known at compile time. The PLT holds executable code used to make external function calls via the GOT. Depending on how the program is linked, the GOT will be populated with the correct function addresses either at program load time or on the first invocation of each function. Figure 1 shows how the PLT and GOT are used for late binding of calls. (1) The program code calls into the PLT, (2) the PLT jumps to the address stored in the GOT. If the function’s address hasn’t been resolved yet, then (3) the address in the GOT is the next instruction in the PLT (after the instruction that just jumped into the GOT). (4) The PLT entry pushes information about the call target onto the stack, then (5) jumps to the zeroth entry in the PLT to invoke the dynamic linker. The dynamic linker resolves the ad-
dress of the desired function, stores it in the GOT, and executes the function.

Implants with the ability to modify a process’s GOT or PLT can easily redirect all invocations of a shared library function to trigger a function in an executable region controlled by the attacker.

These techniques are slightly harder to detect than direct modifications to a process’s text section because the PLT and GOT values may be unique per execution of a program. On the Intel architecture PLTs reside in a shared text segment [38], so detecting a PLT hook is equivalent to detecting a text segment modification. The GOT, however, is populated at load or run time, but its contents are predictable given the base load addresses of the process’s segments. A procedure for detecting some GOT overwrites has already been established for memory forensics [41, Chapter 25].

### 4.3 Shared Object Injection

Programs that support a plugin API often include the ability to load arbitrary shared object files to extend their built-in functionality. This can be directly exploited by implant authors to introduce malicious functionality into a process. Shared object injection is not strictly memory-only; it generally requires creation of a file in the filesystem. Thus, implants based on shared object injections can be detected by hashing the images of files as they are mapped (as Linux’s Integrity Measurement Architecture (IMA) does). In the unlikely event that shared objection injection attacks are possible without modifying the filesystem in a detectable way, these attacks are also detectable by validating the set of files mapped by each process.

*Pre-loading implants* are a common special case of shared object injection. The runtime linker/loader supports specification of extra shared libraries that should be mapped into every process based on the `LD_PRELOAD` environment variable or the contents of `/etc/ld.so.preload`. By setting this variable, an attacker can cause their implant to be mapped into arbitrary processes.

### 4.4 Thread Injection

Given the ability to run arbitrary code in a process, it’s trivial for an attacker to spawn a new thread via the `clone` system call. This provides stealthy execution and gives the implant ongoing access to the victim process’s resources.

A maliciously injected thread of this nature is difficult to detect because multi-threaded programs are common and threads don’t carry state explaining their genesis. However the code used to spawn the thread may reside in a suspicious memory mapping (e.g., one with both writeable and executable permissions or one that is anonymous and executable) or the thread may execute code in a suspicious memory mapping.

### 4.5 Namespace Manipulation

Namespaces provide isolation between processes with respect to a global system resource. If two processes are in different namespaces, they are invisible to each other with respect to the associated resource. This feature is commonly used as a form of lightweight virtualization called containers [32]. An adversary can achieve stealthy execution by running an implant in different namespaces from the rest of the system. The Horse Pill rootkit [20] implements this namespace isolation by installing a custom initial RAM disk (`initrd`) image that executes the rootkit functionality in the default namespaces and creates separate namespaces for the normal system boot process [37].
A namespace is identified by its type and inode number. These inode numbers begin at hard-coded default values that are distinct for each namespace type. If the init or systemd process has non-default namespace inode numbers, then there may be processes operating in different namespaces, outside the purview of most of the userspace processes.

4.6 File Descriptor Passing

File descriptors can be passed between processes using UNIX domain sockets via ancillary data [34, Chapter 17]. As such, an attacker could inject into a process and copy or send file descriptors to other processes. This could be used to bypass a firewall or port binding restrictions (e.g., requiring superuser privileges to bind well-known ports) or more generally to bypass access controls on any kernel abstraction with a file interface.

As with thread injection there is nothing inherent to file descriptors that could indicate malicious origins, but peripheral artifacts may enable detection. For example if a file has attributes indicating only the root user can access it, we do not expect a non-root process to possess a file descriptor for that file. Similarly, we might not expect a process without superuser privileges to have a TCP or UDP socket bound to a well-known port. More generally a process should not have file descriptors for objects unless the process meets the access requirements for those objects. Any deviation from this expectation is suspect. Additionally, the code that passed the file descriptor may reside in a suspicious memory mapping in either the sending or receiving process or in both.

5 Implementation

The USIM Toolkit consists of two components that work together to evaluate the integrity of userspace. The first component is a collection agent which gathers point-in-time information on both global and per-process system state. Specifically it collects

- System information: operating system, architecture, network name, and software inventory as reported by the native package manager
- Hashes of various important files on the system
- Meta-data for each process on the system
- Memory mappings, including permissions, addresses, and backing files and offsets for root-owned processes
- Namespaces in use on the system, and a map of which processes belong to which namespace
- The number, type, and owning process of each open file descriptor in all root-owned processes
- Per-process relocations (i.e. GOT/PLT entries) for each root-owned process
- Hashes of each executable memory segment currently mapped in a root-owned process

The choice to focus on root-owned processes is intended to limit the performance impact of the USIM Toolkit while providing adequate detection capabilities. This is a configuration option that can be trivially changed to include measurement of all, or an expanded subset of, processes. The USIM Toolkit is designed to be extensible, we expect to incorporate additional tools for measuring new aspects of system state.

The collected information is gathered into a single graph-based data structure which captures the complex relationship between the individual data. A graph also allows for multiple collection agents to collect different sets of data in parallel, optionally with different permissions. The collection agent then bundles this “measurement graph” into a portable format for evaluation. An example subgraph showing memory-mapped regions of a process is shown in Figure 2.

The second USIM Toolkit component, called the appraiser, evaluates the measurement graph to appraise the integrity of userspace. The appraiser extracts data and relations and evaluates the measurement based on a set of rules in a policy defined by an administrator. The number and complexity of these rules is limited only by the resources and data available to appraise. For this evaluation, our implementation defines the following set of rules.
1. Only a defined subset of programs can have memory mappings that are both writable and executable (a whitelist).

2. Only a defined subset of programs can arbitrarily have file-backed executable memory mappings that do not correspond to a direct or transitive dependency of the binary (a whitelist).

3. Only a defined subset of programs can have anonymous executable memory mappings (a whitelist).

4. The original executable for a process must be in the file-backed mappings for the process.

5. Read-only executable memory mappings for processes should hash to the same values as the respective sections of the associated on-disk files.

6. The `init` or `systemd` process that is the ultimate parent of all other processes should be in the default PID namespace.

7. Resolved GOT entries should not change (e.g., the resolved address of `printf` should not change across snapshots once it has been resolved).

8. A socket in use by one processes should not later be used in a different, non-child process.

The USIM appraiser determines whether the collected data conforms to the defined policy and alerts the administrator with the result. Separating the collection component from the appraisal piece achieves two goals: 1) adherence to the principle of least privilege: while the collection agent(s) may require elevated privileges to collect data, the evaluation component often does not; and 2) flexibility: the two components can be executed on separate machines, and additional appraisal constraints can easily be added to more tightly confine the allowable states of the measured platform. Indeed, it is envisioned that in most scenarios the USIM evaluator component will be run on a remote appraisal server, with only the collection agent running on the client.

Although it should be possible to examine all of a process’s GOT entries and ascertain whether they point to reasonable locations, that was beyond the scope of this work. For our purposes it was sufficient to record GOT entries and manually detect changes across snapshots. This does limit the utility of our approach to catching a GOT infection as it happens rather than detecting any GOT infection, but this was reasonable for our needs. A more thorough dynamic linking integrity verification could simulate the dynamic linker’s load procedure, using the on-disk binary files, to verify that all observed entries match the expected value.

Several of our appraisal rules use whitelists to broaden applicability to a wider set of scenarios. For example interpreters, such as Python, Java, and web browsers, often have benign anonymous executable memory mappings or memory mappings that are both writable and executable. To accommodate these cases, we relax those rules and adopt a whitelist to provide flexibility. Additionally, some programs dynamically load plugins which are not explicitly listed as dependencies (e.g., `apache2`), and we address this by using another whitelist. For this work we naively whitelisted by binary executable name,
and the whitelists were not implemented in the USIM Toolkit. Rather the USIM Toolkit reports the suspicious observations and the onus is on the administrator to render the final appraisal decision.

We implemented both components of the USIM Toolkit using plain C99 language constructs with minimal external library dependencies. The collection agent is implemented as a collection of separate programs that are executed by a central control process. This allows each program to be run with a minimal set of privileges (e.g., the file hashing program does not require the ability to read arbitrary process’s memory). The USIM Toolkit targets the GNU/Linux operating system, but could likely be retargeted to other operating systems by porting the relevant collection subprograms.

Rules 7 and 8 also require access to previous measurements to identify changes over time. As of this writing, our implementation is not yet able to automatically compare current results to previous results, but the feature is in progress. Therefore, in this paper, we manually verify successive reports to verify those parts of policy. While not ideal, the fact that such verification can be done with the collected information is sufficient to evaluate the utility of the USIM Toolkit.

6 Evaluation

Security solutions must be capable of detecting malicious activities without imposing unacceptable performance overhead. This section presents a functional evaluation of the USIM Toolkit based on its ability to detect proof-of-concept implementations of the implant techniques described in Section 4, and initial benchmarks of the performance overhead of the USIM Toolkit.

6.1 Functional Evaluation

To evaluate the effectiveness of the USIM Toolkit in detecting common implant techniques, we implemented representative samples of the techniques described in Section 4 and observed the detection capability of the USIM Toolkit. Our original goal was to evaluate the USIM Toolkit against implant samples collected from the Internet. Unfortunately, running such an evaluation against real implants is extremely challenging because (a) implants may be highly tuned to a specific runtime environment and command and control system that is difficult to replicate in a lab environment, (b) running real implants even in a controlled environment risks an outbreak that could damage operational networks, and (c) individual implants may combine multiple known and unknown techniques which makes it difficult to test specific detection hypotheses. Based on these limitations, we opted to develop clean-room implementations of specific implant techniques and test detection of these samples instead. We used open-source implementations for any techniques where straightforward implementations with no additional functionality were readily available. Notably for process text segment modification and namespace manipulation we used Modern Userland Exec [12] and Horse Pill [20], respectively.

The USIM Toolkit is not intended to detect initial process exploitation. Accordingly, our implant samples do not include first stage exploit capabilities such as buffer overflows or ROP chains. The samples are simple C programs that each demonstrate a particular technique, excepting the two open-source samples. The narrow scope of each sample made it simple to isolate and test detection of the implant behavior under consideration. For similar reasons, we also disabled the built-in exploit mitigation functions such as address space layout randomization, stack canaries, W⊕X memory protections, and the SELinux mandatory access control system. These mechanisms are an important part of host defenses, but measurement systems like the USIM Toolkit provide an important fallback to detect when protections fail.

6.1.1 Process Text Segment Modification

To evaluate the effectiveness of the USIM Toolkit in detecting common implant techniques, we implemented representative samples of the techniques described in Section 4 and observed the detection capability of the USIM Toolkit. Our original goal was to evaluate the USIM Toolkit against implant samples collected from the Internet. Unfortunately, running such an evaluation against real implants is extremely challenging because (a) implants may be highly tuned to a specific runtime environment and command and control system that is difficult to replicate in a lab environment, (b) running real implants even in a controlled environment risks an outbreak that could damage operational networks, and (c) individual implants may combine multiple known and unknown techniques which makes it difficult to test specific detection hypotheses. Based on these limitations, we opted to develop clean-room implementations of specific implant techniques and test detection of these samples instead. We used open-source implementations for any techniques where straightforward implementations with no additional functionality were readily available. Notably for process text segment modification and namespace manipulation we used Modern Userland Exec [12] and Horse Pill [20], respectively.

The USIM Toolkit is not intended to detect initial process exploitation. Accordingly, our implant samples do not include first stage exploit capabilities such as buffer overflows or ROP chains. The samples are simple C programs that each demonstrate a particular technique, excepting the two open-source samples. The narrow scope of each sample made it simple to isolate and test detection of the implant behavior under consideration. For similar reasons, we also disabled the built-in exploit mitigation functions such as address space layout randomization, stack canaries, W⊕X memory protections, and the SELinux mandatory access control system. These mechanisms are an important part of host defenses, but measurement systems like the USIM Toolkit provide an important fallback to detect when protections fail.

6.1.1 Process Text Segment Modification

We used the open-source tool Modern Userland Exec [12] to evaluate text segment modification. This tool is especially interesting because instead of merely modifying part of the text segment, it mimics the `execve` system call and completely replaces the original process’s text segment with that of another bi-
Table 1: Summary of effectiveness against each class of implants, as well as whether other known techniques would catch the implant.

| Implant Class                  | Rules Triggered |
|--------------------------------|-----------------|
| Text Segment Mod               | 1, 4, 5         |
| GOT/PLT Hooking                | 7               |
| Shared Object Injection        | 2               |
| Thread Injection               | 1, 3, 4         |
| Namespace Manipulation         | 6               |
| FD Passing                     | 8               |

Table 1: Summary of effectiveness against each class of implants, as well as whether other known techniques would catch the implant.

binary. However, unlike `execve`, this is done with anonymous memory mappings and without causing changes to most of the kernel’s information about the process (e.g., `/proc/[pid]/exe`). This allows one program to masquerade as another.

The USIM Toolkit appraiser alerted on this process for two reasons: 1) the process had anonymous executable memory mappings and the program is not on the whitelist of interpreters, and 2) the initial executable was missing from the file-backed mappings.

6.1.2 GOT/PLT Hooking

We evaluated GOT and PLT hooking by authoring a simple C program that prompts the user for a command. The user supplies either “got” or “plt” and then an address. For the “got” command, the address is the address of the GOT entry for `lxstat`, and the program overwrites that entry with the address of a malicious function. Then the program calls `stat` to demonstrate the hook.

For the “plt” command, the user-supplied address is the address of the PLT entry for `lxstat`, and the program uses `mprotect` to make that page of memory writable, overwrites the first instruction of that PLT entry with a call to a malicious function, and then uses `mprotect` to make the page read-only again. This solution is less portable than the GOT solution because it relies on the first instruction at that PLT address being a 6-byte jump and overwrites it with a 5-byte call to a malicious function and a 1-byte no-op. This also has the side effect of forcing the dynamic linker to resolve the address of `lxstat` every time `lstat` is called. The program then calls `lstat` to demonstrate the hook.

This program requires disabling RELocation Read-Only (RELRO) [17]. Otherwise the GOT would be unwritable, preventing our GOT hook, and the dynamic linker’s reserved GOT entries would be zeroed out, causing our PLT hook to crash the program. Our PLT hooking technique was to overwrite the jump instruction with a function call and a no-op in order to call our malicious function and then rely on the PLT’s symbol resolution to execute the intended function. This symbol resolution involves jumping to the address stored in the third entry of the GOT, which would normally be the address of the dynamic linker’s symbol resolution function. However on our Ubuntu 17.10 system, RELRO binaries are missing the `.got.plt` section and the second and third entries of the GOT are zeroed out. Thus, jumping to the address in the third GOT entry causes a segmentation fault. More sophisticated GOT and PLT hooks could easily bypass this defense mechanism by making the GOT writeable before writing to it (and then making it read-only again for stealth) and by using a PLT hook that preserves the PLT’s behavior (i.e. jumping to the address in the GOT and triggering symbol resolution if the symbol hasn’t been resolved yet).

The USIM Toolkit appraiser detected the GOT modification via resolving each relocation both before and after the infection, and noting the change. In our case, the GOT entry for `lxstat` pointed to the binary’s text segment mapping rather than a mapping to libc. Similarly, the appraiser detected the PLT modification because the hash of that memory mapping no longer matched its on-disk representation in the binary, as well as detecting that change in relocation value from before the infection.

6.1.3 Shared Object Injection

For shared object injection, we composed a simple C program that takes the path to a shared object and the name of its entry point symbol, calls `dlopen` to load the shared object, uses `dlsym` to find the entry point, and then calls the entry point.

The loaded shared object was not one of the bi-
nary’s dependencies, and was located outside of the normal library paths. The USIM Toolkit appraiser detected this, as this binary was not whitelisted to allow arbitrary loading of shared objects.

6.1.4 Thread Injection

We achieved thread injection via shellcode that uses the \texttt{clone} system call to create a new thread whose entry point is elsewhere in the shellcode. We fed the shellcode to a simple program that reads network data into a buffer, marks the buffer as executable, and calls into it. We wrote the shellcode in x86-64 assembly that we adapted from an open-source example [43].

While the USIM Toolkit appraiser had no way of knowing how many threads each process should have, it was able to notice that the parasite thread was executing code in an anonymous executable mapping, which our restrictive appraisal policy forbids for processes not in the whitelist, so the system failed appraisal.

6.1.5 Namespace Manipulation

We used Horse Pill [20], an open-source implementation of a custom initrd, to evaluate namespace manipulation. The custom initrd has a malicious \texttt{run-init} that compromises a system on boot. The modified \texttt{run-init} migrates most of the system to a new PID namespace, makes fake kernel thread processes in that namespace, and runs a backdoor outside the namespace.

Even running within Horse Pill’s infection namespace, the USIM Toolkit was able to gather sufficient evidence to cause the appraisal to fail because the init process’s namespace is not the expected default. Also, the total number of namespaces on the system differed from the expected value.

6.1.6 File Descriptor Passing

To evaluate file descriptor passing, we authored a simple C program that accepts a TCP connection and sends it to another process via UNIX domain socket. Two subsequent USIM Toolkit measurements showed the same socket file descriptor was open by one process in the first measurement, and another process in the second measurement. Manual inspection showed that the information was present to accurately identify and fail the second appraisal.

6.2 Performance Evaluation

We measured the performance overhead of the USIM Toolkit by performing complete measurements of (a) a freshly booted minimal CentOS 7 virtual machine, (b) a CentOS 7 VM under a synthetic load of benchmarking redis server performance while simultaneously compiling a Linux kernel, and (c) a typical Ubuntu 17.10 user desktop system after days of typical user activity (web browsing, email, etc). Systems (a) and (b) are virtual machines using the KVM hypervisor on system (c), with 4 virtual CPUs and 4 GB of memory assigned to them, while system (c) is a Dell Latitude E7450 laptop with 16GB of memory and an Intel i7-5600U CPU running at 2.6 Ghz. All appraisals were processed on the Dell E7450 laptop.

For each case we collected the total CPU time, peak CPU usage, peak memory usage, and network data transferred. Table 2 lists average values over 10 runs for these each of the three test scenarios.

We also measured the effect of measurement on the performance of a system under heavy load. We collected benchmark data from the \texttt{redis-benchmark} tool on an idle CentOS 7 VM with 4 vCPUs, the CentOS 7 VM while compiling the Linux kernel with \texttt{make -j4} with an \texttt{allyesconfig} configuration, and when taking a USIM measurement with the above load. This load ensured that the system was handling heavy disk, CPU, memory, and network load at the time of measurement. We repeated the benchmark 12 times for each condition and computed the averages by throwing away the max and minimum results and averaging the remaining 10 for each redis benchmark subtest. The results of this experiment are shown in Table 3.

These results show a significant impact of our unoptimized prototype on the Redis benchmark in isolation. Initial tests on an otherwise idle system show on average 28% less performance when taking
a measurement. However, when the system is under stress from another workload, the additional impact of USIM on the original benchmark is only 8%. The significantly lower impact on the loaded score suggests that much of the performance impact of measurement is related to running any task in addition to the benchmark suite.

While some impact on the system is unavoidable, these benchmarks suggest that significant work is needed to reduce the performance impact of the USIM Toolkit. Implementing local evaluation checks to limit the amount of data that must be cached and sent to the appraiser will likely greatly reduce the peak memory usage and network IO of the USIM Toolkit. When implementing the USIM Toolkit, we paid little attention to performance optimization, so many implementation optimizations are likely available that would reduce the CPU time and memory required.

### 7 Related Work

Computer defense has long been a “cat and mouse game” in which attackers continually discover and deploy new mechanisms for exploiting and controlling their victims, and defenders respond by developing counter measures to prevent exploitation or detect the control mechanism. Defensive strategies include

---

**Table 2**: USIM measurement metrics in three test scenarios. Average of 10 measurements.

| Metric                  | CentOS 7 (VM, Idle) | CentOS 7 (VM, Load) | Ubuntu 17.10 (HW, Desktop) |
|-------------------------|---------------------|---------------------|----------------------------|
| Graph Nodes             | 6275                | 6750                | 14804                      |
| Graph Edges             | 27837               | 36275               | 14804                      |
| Total Size (MB)         | 12.5                | 13.3                | 30.3                       |
| Processes               | 123                 | 151                 | 341                        |
| Root-Owned Processes    | 27                  | 47                  | 54                         |
| Collection Time (s)     | 199                 | 606                 | 255                        |
| Per-Process Time (s)    | 7.5                 | 16                  | 4.6                        |
| Peak CPU Usage (%)      | 100                 | 100                 | 100                        |
| Peak Mem Usage (MB)     | 67                  | 67                  | 80                         |
| Appraisal Time (s)      | 649                 | 1575                | 1594                       |

**Table 3**: Redis benchmark performance degradation attributable to the USIM Toolkit relative to an idle system (larger is better)
active mitigations, runtime integrity measurement, and hardware-based trust mechanisms, as well as traditional antivirus and enterprise client management tools. Defenders use these tools to attempt to prevent adversaries from gaining access to systems, to detect when a system has been compromised, and to limit the effects a compromise might have on a single host or across a network.

7.1 Active Mitigations

Many defensive measures, such as $W \oplus X$ [9] and Address Space Layout Randomization (ASLR) [24], introduce challenges to initial exploitation, but experience has shown that adversaries are able to work around these mitigations, using techniques such as memory disclosures, information side-channels, and return-oriented programming [4, 6, 30, 31, 35], to install implants for long-term control. Operating system controls such as access-control based sandboxing [33, 40] and code signing attempt to mitigate implants by limiting what executables can be run from different security contexts, but various attacks have shown that these too are circumvented by adversaries [7,18,42].

7.2 Measurement Agents

Integrity measurement tools attempt to detect implants by attesting to the integrity of a system. A key advantage for implant detection tools is that implants intentionally have lasting effects on a victim platform such as providing a command and control channel for the adversary. Measurement tools, such as Linux’s Integrity Measurement Architecture (IMA) [29], the Linux Kernel Integrity Measurer (LKIM) [21], and Semantic Integrity [26], attempt to identify these effects on either the filesystem or the runtime behavior of processes. These existing integrity measurement solutions have focused on pre-boot environments, the operating system kernel, or file images. Userspace integrity measurement extends the concepts introduced in these works to support verification of the next abstraction level in a modern system, the userspace operating environment. Comprehensive system integrity measurement should include application-level measurements, and runtime measurements of lower platform levels such as the hypervisor or system management mode.

Dynamic Measurements LKIM [21] and Semantic Integrity [26] are dynamic measurement techniques that can measure kernel data structures at any time during a platform’s execution. Like the USIM Toolkit, these tools work by inspecting their target’s runtime state to identify violations of key invariants that may indicate compromise. Unlike the USIM Toolkit, these tools focus on implants that operate by modifying data structures in the kernel’s memory space. Combining these kernel integrity measurement solutions with userspace integrity measurement can significantly reduce the opportunities for an implant to hide in a modern system. Filling in the gaps, for example by adding measurement of the USIM Toolkit to a kernel-level solution, is an important area of future research.

Static Measurements Static measurement tools, such as IMA and Cb Protection, attempt to guarantee integrity by taking a cryptographic hash of files at loadtime. IMA is functionality built into the Linux kernel that performs cryptographic hashes of all, or a configured subset of, files accessed by a system. The log of these hashes can be reported to userspace along with a certification of the current value using a Trusted Platform Module (TPM). IMA builds on a long history of file-hashing based approaches to system integrity validation; TripWire [19] is the earliest notable ancestor of IMA. IMA improves on historic approaches primarily by (a) hashing files as they are accessed, (b) performing the hash from within the operating system kernel context, and (c) using a TPM to endorse the hash log. To detect implants using a system like IMA, a trusted system can compare the reported log with either a blacklist of known implants or a whitelist of approved files. Cb Protection from Carbon Black [2] also provides load-time checks on programs as they are launched in order to verify integrity at program start.

In environments, such as fixed-purpose embedded systems, where a complete whitelist of valid files is
tractable, static measurements can provide strong guarantees that no implants are loaded from a system’s filesystem. Unfortunately, most systems are not amenable to complete whitelists, and creation of a comprehensive blacklist of malware hashes is infeasible because new variants with new hashes are trivially created by attackers. Further, memory-only implants may not require loading any attacker-modified files from the filesystem. This paper complements these approaches by extending integrity from the filesystem to other key aspects of the userspace runtime environment such as environment variables, interprocess communication channels, and runtime linker-loader behavior.

**Root of Trust** Confidence in measurement tools requires a root of trust to guarantee that the measurements are correctly collected and reported. In their research, England et al. [13] describe an approach to integrity measurement in which measurements are cryptographic hashes of boot-time software. This approach is also used by the Trusted Computing Group (TCG) as part of the “Trusted Boot” technology [10]. SecureBoot [3] also aims to provide a chain of integrity checks beginning at system power-on. These checks are optimal for identifying persistent threats on the platform, but are largely ineffective against attacks that take place after startup. The work described in this paper aims to extend this trusted base to userspace software at runtime in order to more effectively guard against a wider range of attacks.

### 7.3 Antivirus

Integrity measurement attempts to enforce a set of invariants to which any well-behaved system should conform. Antivirus tools take the opposite approach, defining specific static or behavioral signatures that only malicious software should exhibit. The specific techniques used by antivirus products are generally proprietary, but most appear to be based on fingerprinting files and monitoring runtime process behavior such as system call tracing [16,36]. Fingerprinting files may be more resilient to variations than the precise cryptographic hashes used by IMA, but decades of experience has shown that implant authors are able to quickly adapt and deploy variants with previously unknown signatures [23,47].

Behavioral profiling is another powerful tool that has proven useful in recognizing many implants as they are executing. Behavioral approaches are enhanced by the ability of antivirus vendors to collect large scale data from across their customer base and correlate newly observed behavior with historical indicators of infections. This is most effective in detecting broadly distributed implants that may trigger other alerting systems such as network monitoring solutions.

Some antivirus tools, such as Cb Defense [1] have begun to use predictive modeling to identify when a process is behaving suspiciously. However, as is often the case in the arms race for cyber security, researchers are already inventing ways to hide their malicious behavior in the execution of benign processes [15].

**Enterprise Defense** Enterprise defense frameworks have similar goals to traditional antivirus tools, but at a larger scale. These include Trusted Network Connect (TNC) and SAMSON. Similar to the limitations with antivirus tools, these frameworks have a narrow focus and would generally not detect the attacks evaluated in this paper. Specifically, TNC is focused on attestation only within the scope of access control [39], while SAMSON is designed to do remote attestation of client systems using IMA logic to gauge the integrity of programs running on the system [14]. Neither of these frameworks introduces novel measurements capable of detecting the userspace attacks targeted by this paper.

More recent enterprise defense products are incorporating integrity measurement-like functionality. Forcepoint Threat Protection for Linux has claimed success in detecting Horse Pill [37]. Now known as Forcepoint Linux Security or Second Look, this tool uses memory forensics to identify malicious software on the system. The backend of this tool is proprietary; however, it seems to rely on comparing the captured kernel memory image to a reference kernel, and taking pagewise hashes of executables to compare to known-good versions. These abilities would
make it effective against some of the implant techniques listed in this paper.

8 Future Work

The USIM Toolkit includes measurements of process environments, runtime structures, and access to OS resources. We evaluated these measurements against proof-of-concept implementations of common implant techniques to demonstrate that they are able to reliably detect implants that may elude detection by traditional means. It is unlikely that these measurements are comprehensive; continued study of userspace invariants and how they are violated by advanced malware is an important area of continued research.

Performance evaluation of the USIM Toolkit showed a significant performance impact, a full measurement of an active system took over 200 seconds, required 80 MB or more of memory, and transferred 20+ MB of data to a remote appraiser. We believe that USIM Toolkit prototype implementation could be significantly optimized, the data collected for the same measurements could be reduced, and some local checks could be performed to minimize the data transmitted to the remote appraiser. Implementing these improvements in order to reduce the performance overhead is important to ensure these approaches are usable in practical contexts.

Userspace measurement is only one part of producing comprehensive integrity measurement of a modern platform. Prior work largely focuses on kernel-level measurements. Future work may introduce strategies for measurements of individual security-critical applications and measurement of lower-level components such as hypervisors. To fully benefit from these components, significant additional work must also be done to understand how measurements can be combined to ensure that the correct appraisal of a lower-level measurement justifies trust in higher-level measurements.

9 Conclusion

This paper introduced the USIM Toolkit, an extensible set of GNU/Linux measurement and appraisal tools for verifying the integrity of userspace. We have shown that this prototype is capable of detecting a variety of sophisticated implant techniques. Although work is needed to improve the toolkit’s completeness and performance, it is a general mechanism to detect a broad class of integrity violations with myriad security implications. Because the USIM Toolkit is based on invariants of well-behaved systems, it is part of a workable integrity strategy that requires no preknowledge of specific attacks. By combining the USIM Toolkit with other integrity verification techniques, trust could be extended from a root of trust to the application level to form a comprehensive verification solution. Even on its own the USIM Toolkit is a critical advancement in the detection of sophisticated in-memory userspace implants.

References

[1] Cb defense. https://www.carbonblack.com/products/cb-defense/, 2018. Accessed: 2018-03-07.

[2] Cb protection. https://www.carbonblack.com/products/cb-protection/, 2018. Accessed: 2018-03-07.

[3] W. A. Arbaugh, D. J. Farber, and J. M. Smith. A secure and reliable bootstrap architecture. In Security and Privacy, 1997. Proceedings., 1997 IEEE Symposium on, pages 65–71. IEEE, 1997.

[4] A. Bittau, A. Belay, A. Mashtizadeh, D. Mazieres, and D. Boneh. Hacking blind. In 2014 IEEE Symposium on Security and Privacy, pages 227–242, May 2014.

[5] A. Bunten. Unix and linux based rootkits techniques and countermeasures. In 16th Annual First Conference on Computer Security Incident Handling, Budapest, 2004.
[6] N. Carlini and D. Wagner. ROP is still dangerous: Breaking modern defenses. In 23rd USENIX Security Symposium (USENIX Security 14), pages 385–399, San Diego, CA, 2014. USENIX Association.

[7] A. Chuvakin. Using chroot securely. http://www.linuxsecurity.com/content/view/117632/49/, November 2007. [Online; accessed: 2018-02-28].

[8] CrowdStrike. Crowdstrike releases annual cyber intrusion services casebook. https://www.crowdstrike.com/resources/news/crowdstrike-releases-annual-cyber-intrusion-services-casebook/, December 2017. [Online; accessed: 2018-03-12].

[9] T. de Raadt. W®X - the mechanism. http://www.openbsd.org/papers/ven05-deraadt/mgp00009.html, May 2006. [Online; accessed: 2018-02-26].

[10] Dice. Trusted boot (tboot). http://tboot.sourceforge.net, 2015. Accessed: 2015-03-20.

[11] R. Dua, A. R. Raja, and D. Kakadia. Virtualization vs containerization to support paas. In 2014 IEEE International Conference on Cloud Engineering, pages 610–614, March 2014.

[12] B. Edinger. Modern userland exec. http://stratigery.com/userlandexec.html, 2014. [Online; accessed: 2018-01-29].

[13] P. England, B. Lampson, J. Manferdelli, M. Peinado, and B. Willman. A trusted open platform. Computer, 36(7):55–62, July 2003.

[14] C. Fisher, D. Bukovich, R. Bourquin, and R. Dobry. Samson - secure authentication modules. http://sourceforge.net/p/secureauthentic/wiki/Home/, 2015. Accessed: 2015-04-02.

[15] K. K. Ispoglou and M. Payer. malwash: Washing malware to evade dynamic analysis.

In 10th USENIX Workshop on Offensive Technologies (WOOT 16), Austin, TX, 2016. USENIX Association.

[16] G. Jacob, H. Debar, and E. Filiol. Behavioral detection of malware: From a survey towards an established taxonomy. Journal in Computer Virology, 4(3):251–266, Aug 2008.

[17] J. Jelinek. [rfc patch] little hardening dsos/executables against exploits. https://www.sourceware.org/ml/binutils/2004-01/msg00070.html, January 2004. [Online; accessed: 2018-01-11].

[18] D. Kim, B. J. Kwon, and T. Dumitraș. Certified malware: Measuring breaches of trust in the windows code-signing pki. In Proceedings of the 2017 ACM SIGSAC Conference on Computer and Communications Security, CCS ’17, pages 1435–1448, New York, NY, USA, 2017. ACM.

[19] G. H. Kim and E. H. Spafford. The design and implementation of tripwire: A file system integrity checker. In Proceedings of the 2Nd ACM Conference on Computer and Communications Security, CCS ’94, pages 18–29, New York, NY, USA, 1994. ACM.

[20] M. Leibowitz. Horse pill. https://github.com/r00tkillah/HORSEPILL, 2016. [Online; accessed: 2018-01-29].

[21] P. A. Loscocco, P. W. Wilson, J. A. Pendergrass, and C. D. McDonell. Linux kernel integrity measurement using contextual inspection. In Proceedings of the 2007 ACM workshop on Scalable trusted computing, pages 21–29. ACM, 2007.

[22] T. Morris. Trusted platform module. In Encyclopedia of Cryptography and Security, pages 1332–1335. Springer, 2011.

[23] P. OKane, S. Sezer, and K. McLaughlin. Obfuscation: The hidden malware. IEEE Security Privacy, 9(5):41–47, Sept 2011.
[24] PaX Team. Address space layout randomization. https://pax.grsecurity.net/docs/aslr.txt, March 2003. [Online; accessed: 2018-02-26].

[25] J. A. Pendergrass, S. Helble, J. Clemens, and P. Loscocco. Maat: A platform service for measurement and attestation. arXiv preprint arXiv:1709.10147, 2017.

[26] N. L. Petroni Jr, T. Fraser, A. Walters, and W. A. Arbaugh. An architecture for specification-based detection of semantic integrity violations in kernel dynamic data. In Usenix Security, 2006.

[27] P. D. Rowe. Bundling evidence for layered attestation. In M. Franz and P. Papadimitratos, editors, Trust and Trustworthy Computing, pages 119–139, Cham, 2016. Springer International Publishing.

[28] J. Rutkowska. Introducing stealth malware taxonomy. https://blog.invisiblethings.org/papers/2006/rutkowska_malware_taxonomy.pdf, November 2006. [Online; accessed: 2017-11-20].

[29] R. Sailer, X. Zhang, T. Jaeger, and L. van Doorn. Design and implementation of a tcg-based integrity measurement architecture. In Proceedings of the 13th Conference on USENIX Security Symposium - Volume 13, SSYM'04, pages 16–16, Berkeley, CA, USA, 2004. USENIX Association.

[30] J. Seibert, H. Okhravi, and E. Söderström. Information leaks without memory disclosures: Remote side channel attacks on diversified code. In Proceedings of the 2014 ACM SIGSAC Conference on Computer and Communications Security, CCS ’14, pages 54–65, New York, NY, USA, 2014. ACM.

[31] H. Shacham. The geometry of innocent flesh on the bone: Return-into-libc without function calls (on the x86). In Proceedings of the 14th ACM Conference on Computer and Communications Security, CCS ’07, pages 552–561, New York, NY, USA, 2007. ACM.

[32] S. Soltesz, H. Pötzl, M. E. Fiuczynski, A. Bavier, and L. Peterson. Container-based operating system virtualization: A scalable, high-performance alternative to hypervisors. In Proceedings of the 2Nd ACM SIGOPS/EuroSys European Conference on Computer Systems 2007, EuroSys ’07, pages 275–287, New York, NY, USA, 2007. ACM.

[33] R. Spencer, S. Smalley, P. Loscocco, M. Hibler, D. Andersen, and J. Lepreau. The flask security architecture: System support for diverse security policies. In Proceedings of the 8th Conference on USENIX Security Symposium - Volume 8, SSYM'99, pages 11–11, Berkeley, CA, USA, 1999. USENIX Association.

[34] W. R. Stevens and S. A. Rago. Advanced Programming in the UNIX Environment, Third Edition. Addison-Wesley Professional, 2013. [Online] Available: Safari e-book.

[35] R. Strackx, Y. Younan, P. Philippaerts, F. Piessens, S. Lachmund, and T. Walter. Breaking the memory secrecy assumption. In Proceedings of the Second European Workshop on System Security, EUROSEC ’09, pages 1–8, New York, NY, USA, 2009. ACM.

[36] O. Sukwong, H. Kim, and J. Hoe. Commercial antivirus software effectiveness: An empirical study. Computer, 44(3):63–70, March 2011.

[37] A. Tappert and T. O’Connor. The horse pill rootkit vs. forcepoint threat protection for linux. https://blogs.forcepoint.com/security-labs/horse-pill-rootkit-vs-forcepoint-threat-protection-linux, November 2016. [Online; accessed: 2018-01-11].

[38] TIS Committee. Tool Interface Standard (TIS) Executable and Linking Format (ELF) Specification Version 1.2, May 1995. [Online].

[39] T. TNC. Tnc architecture for interoperability version 1.5, revision 3. TCG specification, 1, 2012.
A. Viswanathan and B. Neuman. A survey of isolation techniques. Draft Copy, Information Sciences Institute, University of Southern California, 2009.

A. Walters, J. Levy, A. Case, and M. H. Ligh. *The Art of Memory Forensics: Detecting Malware and Threats in Windows, Linux, and Mac Memory*. John Wiley & Sons, Indianapolis, 2014. [Online] Available: Safari e-book.

R. N. Watson. Exploiting concurrency vulnerabilities in system call wrappers. In *Proceedings of the first USENIX Workshop On Offensive Technologies*, pages 2:1–2:8, Berkeley, CA, USA, 2007. USENIX Association.

C. Wellons. Pure linux threads demo. https://github.com/skeeto/pure-linux-threads-demo/blob/master/threads-x86_64.s, 2015. [Online; accessed: 2018-01-29].

G. Wicherski. Syscan’14 singapore: Linux memory forensics a real life case study by georg wicherski. https://www.youtube.com/watch?v=JpY88tnqPhw, May 2014. [Online; accessed: 2018-01-29].

T. Wilson. Move over, apts – the ram-based advanced volatile threat is spinning up fast. https://www.darkreading.com/vulnerabilities---threats/move-over-apts---the-ram-based-advanced-volatile-threat-is-spinning-up-fast/d/d-id/1139211?, February 2013. [Online; accessed: 2018-03-25].

C. Wueest and H. Anand. Internet security threat report: Living off the land and fileless attack techniques. an istr special report. https://www.symantec.com/content/dam/symantec/docs/security-center/whitepapers/istr-living-off-the-land-and-fileless-attack-techniques-en.pdf, July 2017. [Online; accessed: 2018-01-11].

I. You and K. Yim. Malware obfuscation techniques: A brief survey. In *2010 International Conference on Broadband, Wireless Computing, Communication and Applications*, pages 297–300, Nov 2010.