Abstract

We introduce TIMELOOPS, a novel technique for automatically learning system call filtering policies for containerized microservices applications. At run-time, TIMELOOPS automatically learns which system calls a program should be allowed to invoke, while rejecting attempts to call spurious system calls. Further, TIMELOOPS addresses many of the shortcomings of state-of-the-art static analysis-based techniques, such as the ability to generate tight filters for programs written in interpreted languages such as PHP, Python, and JavaScript. TIMELOOPS has a simple and robust implementation because it is mainly built out of commodity, and proven, technologies such as seccomp-BPF, systemd, and Podman containers. We demonstrate the utility of TIMELOOPS by learning system calls for individual services and two microservices benchmark applications, which utilize popular technologies like Python Flask, Nginx (with PHP and Lua modules), Apache Thrift, Memcached, Redis, and MongoDB. Further, the amortized performance of TIMELOOPS is similar to that of an unhardened system, while producing a smaller system call filter than state-of-the-art static analysis-based techniques.

1 Introduction

Microservices have become prominent due to shifts from monolithic to modularized and distributed architectures. While monoliths are complex and large services running on a single host, microservices are lightweight, loosely-coupled services running in a distributed fashion. Inter-service network communication allows these small components, which are typically containerized, to collaborate and complete actions that would previously be completed by a single monolith. Microservices have become a popular choice due to their modularity, which simplifies the development of large applications, allows for elastic scaling, and supports language and framework heterogeneity. More importantly, microservice deployments are quickly rising in popularity: surveys conducted by O’Reilly in 2020 concluded that 77% of tech companies have adopted this model for computing [46].

Microservice deployments, however, introduce two main complexities that make security challenging: (1) Dynamism: graphs of microservices architectures evolve rapidly due to new application features [28], making it difficult to keep security policies up to date; (2) Heterogeneity: each service in an application can be developed by different teams in dissimilar programming languages, and hosted on completely different platforms, sometimes across data centers, increasing the attack surface. These challenges are also compounded to a degree by the need to provide low end-to-end latency. In the absence of good security protection for microservices, there is risk not only of application compromises but also a risk to other tenants via container escape attacks [41].

State-of-the-art efforts for securing a microservice in industry and academia focus on two main techniques for protecting microservices: (a) Rootless containers: increasingly containers offer rootless deployment options that permit containers to be run as unprivileged users—this raises the bar to gain privileged execution on a system via a compromised microservice; (b) System call filtering: even with rootless containers, compromised microservices can be used to gain privileges via the system call API. As such, system call filtering is used to confine the process’ ability to make arbitrary system calls, or invoke buggy ones [42], thus mitigating this risk [9, 30, 37, 55]. An added benefit of system call filtering is that it does not significantly impact the latency of the microservice.

In this paper, we propose a new method for securing microservices called TIMELOOPS. We designed TIMELOOPS with microservices’ strengths and weaknesses in mind. For each service in a microservices application, the TIMELOOPS technique relies on three components for learning legitimate system calls: (1) a production service, (2) an oracle service, and (3) a TIMELOOPS controller. The production service is an unhardened service that is tuned for low latency, while the oracle service is a hardened service that is tuned for security. An example of an oracle service could be a microservice running with compiler-inserted, runtime checks to protect against memory safety errors. The high level idea is to sparingly use the oracle service to decide if a system call should be added to
the allow list. This provides the security guarantees of a hardened microservice without constantly incurring the overheads associated with hardening.

Compared to state-of-the-art microservice security techniques, our solution has two unique advantages: (i) TIMELOOPS is language agnostic, since microservice deployments tend to be heterogeneous with services written in different languages. Traditional system call filtering approaches that use static analysis to create filters [17, 31] require writing custom tools for each language. This increases the difficulty of applying these methodologies to modern cloud microservices—TIMELOOPS avoids this problem completely. (ii) TIMELOOPS offers a tighter set of system call constraints that is customized to each service. Unlike static analysis systems, TIMELOOPS learns the system calls required per service using runtime workloads and therefore produces a much tighter set.

Using these components we measure both the security and performance of our TIMELOOPS system. We observe that the amortized performance of a TIMELOOPS-protected system is similar to that of an unhardened, insecure system, and our approach nearly eliminates all the performance overheads associated with hardening. In terms of the tightness of the system call filtering set, we show that a state-of-the-art static analysis tool generated system call sets that were 32.7% larger than the ones generated by TIMELOOPS. Additionally, we demonstrate that TIMELOOPS succeeds in creating system call filters for interpreted languages with very little effort, which is a challenge for existing static analysis-based techniques. Finally, as a side effect, we show that we can easily detect memory corruption-based exploits while taking place.

The remainder of this paper is organized as follows. In Section 2, we provide the necessary background information and present our threat model. In Section 4, we introduce TIMELOOPS, a novel approach for learning new security policies, which leverages runtime exploit detection techniques, while providing amortized runtime performance overhead. We consider the security architecture of TIMELOOPS in Section 6, and evaluate our prototype’s runtime performance and filter learning correctness in Section 7. We discuss related work in Section 8, and conclude our work in Section 10.

2 Background and Threat Model

2.1 Microservices Overview

Microservices Microservices have become a de facto standard for building and deploying web-based services. Building software as a set of communicating lightweight processes allows multiple teams to work independently on small individual units of code—i.e., microservices—that can then be combined together using only API calls exposed by the service [27]. For example, if we consider the set of services running in Figure 1, a team may be responsible for maintaining Service 1, independently, while another team may manage Services 3 and 4 without needing to understand the implementation details of the other services. The development of microservice-based applications has been made easier by the use of popular languages and libraries, like Python, Thrift, and Node.js. Microservice environment management has become configurable and reproducible through container technologies, like Docker and Podman. Cloud platforms like Amazon EC2, Google Cloud Platform, and Microsoft Azure have made deployments easy to schedule and dynamically scale.

Since microservices are typically deployed in multitenant cloud environments, they have to be written in a manner that makes them resilient to crashes and long-latency inducing events such as network congestion. A very common design pattern is to write these microservices in a stateless manner with retry semantics i.e., in a manner that does not preserve state across requests and that produces correct results even when multiple repeated queries are issued by a client. In fact, most cloud deployments today isolate the stateless frontend, routing, or computation services from the stateful database or caching services, where service crashes and restarts do not affect the correct behavior of the (composite) system. To ensure successful execution of their requests despite frequent restarts and long-latency events, clients will often resend identical, idempotent requests until the requests are satisfied.

While the modularity of microservices has enabled many desirable software engineering practices, like rapid feature development, and continuous integration/delivery (CI/CD), it has also created some serious security challenges. It is not uncommon today to have deployed applications with hundreds or even thousands of microservices [23], written in many different languages, such as Python, PHP, Javascript,
The system call (syscall) interface enables user-space applications to request privileged services from the OS kernel. This interface is quite large: for example, the Linux kernel (v5.x) provides ≈350 syscalls to user-space applications [25]. Like most programs, microservices only need a subset of these syscalls for proper execution [17, 18, 25, 30, 31, 37]. An attacker, however, who is able to leverage a vulnerability in a microservice to gain arbitrary code execution can use any of the available syscalls, effectively (1) violating the principle of least privilege and (2) further (ab)using vulnerabilities in less-stressed kernel code paths to escalate privilege [42]. By restricting the system calls available to a microservice, an attacker is constrained to only performing actions that fall within the benign behavior(s) of the victim program.

Determining which system calls should be allowed for a microservice is challenging. Policies can be created manually, but with significant developer effort [26]. Therefore, attempts to synthesize policies automatically have become more prevalent [17, 25, 30, 31, 37]. Current approaches for automatically generating system call policies oftentimes use either static or dynamic analyses (or a combination thereof).

Static analyses attempt to reason about the system calls that a target program should be allowed to execute without executing the program [25, 30, 31]. These approaches are generally over-approximate in their analyses because they explore all possible code paths a program may execute. Dynamic analyses typically execute the target program with some set of known-safe training inputs, like developer-written tests, in order to record all executed system calls and to populate an allow-list from them [17, 37]. These approaches are generally under-approximate, because they are only able to identify system calls that are observed during execution of training data, and fail when a new legitimate system call is executed.

For both static and dynamic system call policy extraction, current approaches for syscall extraction and enforcement create immutable policies that cannot be later refined. In an immutable system, when the target program attempts to execute a non-allowed system call, the enforcing mechanism will terminate the program in order to prevent potential exploitation. This occurs at the risk of the system call being the result of a safe input that was incorrectly omitted from the training data—i.e., a false positive. In order for it to be flexible enough to update its policy once deployed, the system must be able to distinguish the execution of syscalls that result from benign and offending inputs at runtime.

Once a system call policy is created in the form of an allow- or deny-list, it must be enforced. The Linux kernel provides the `SECure COMPuting` (seccomp) mode that allows users to restrict the system calls that a process is allowed to make [44]. With custom BSD Packet Filters (BPF) [49], seccomp-BPF allows a user to configure the behavior of the kernel when the user-space process makes a non-allowed system call; for example, the kernel can be configured to send a SIGKILL or SIGSYS signal to the process, depending on the arguments provided via the seccomp-BPF interface, log the event to an audit log, etc. [68].
2.3 Threat Model

In this work, we consider an attacker who is able to gain remote code execution in victim network applications. That is, the attacker can provide inputs to a program over a network connection to exploit vulnerabilities in the program and introduce new, unintended code or behavior in the victim process. Our model assumes that the attacker does not have physical access to the host machine and considers side-channel [39,45] and fault [50,66] attacks out-of-scope.

In our model, the victim application executes in a container environment that is isolated from the host system resources, so we consider that the attacker is motivated to “escape” from the container by using remote code execution to remove the isolation between the victim application and the host resources. The attacker is able to exploit some vulnerability or misconfiguration to execute code in the container process [65], and may desire to escape the container environment or compromise the container application for malicious purposes via executing arbitrary system calls [11,19,42]. Our threat model is in parallel with prior work in the area [17,18,25,31].

3 Approach Overview

For a system to be able to learn a security policy at runtime, it must be able to determine whether a violation of the current policy is the result of a benign input that was previously unseen or the result of an offending input that should be prevented by the policy. In this section, we describe a novel approach for learning software security policies by introducing an oracle to assist with determinations of safe inputs.

Our policy learning approach provides a mechanism to learn from policy violations. When a violation occurs after the program executes a specific input, we consult the oracle service by providing it with the current policy and input, and re-execute the program under the oracle’s observation. The oracle makes a determination that the security policy violation occurred either because of a benign input to the program or because of offending input to the program. If the oracle determines that the policy violation was due to a benign input, then the policy is updated to allow the event that was observed, and the program can be restarted with the updated policy. If the oracle determines that the policy violation was due to offending input, then an exploit attempt was prevented and an alert is raised accordingly.

For this approach to succeed, the program must be resilient to repeated re-executions from a known state, whether from the program start or from some checkpoint location. We observe that network services, and in particular, microservices, are often designed to be stateless and support the re-execution of idempotent request operations. Because of this, we can take advantage of retry semantics or we can record and replay requests without affecting the correctness of the entire application’s state. For engineering simplicity, we assume that retry semantics exist and our application’s clients resend requests until they succeed. These types of services can be re-executed and are thus good candidates for a timelooping security policy learning approach.

4 Design and Implementation

In this section, we describe the design and implementation of the TIMELOOPS system, which learns systems call policies on-the-fly, as the programs execute, thereby including only system calls that are actually observed and detecting malicious behavior when a new system call is introduced. The sequence of events that occur when a service running in TIMELOOPS receives an input that causes a system call violation is illustrated in Figure 2.

4.1 System Call Policy Learning

The TIMELOOPS system is designed as three main components: (1) the service, (2) the oracle, and (3) the controller. Both the service and oracle are deployed in their own isolated container environments, while the controller is responsible for managing the execution of the service and oracle containers and for applying policy changes as information is learned.

The TIMELOOPS controller begins execution by starting the service container with some default policy of allowed syscalls (which may be initialized as an empty list). If, given some input, the service container attempts to execute a syscall that is not in the allow-list, the service is forced to exit and the controller is notified. The controller then starts the oracle
container, which, in turn, starts the same service but with additional runtime exploit mitigations deployed; for example, the service can be compiled with ASan to act as an oracle for some types of memory corruption-based exploits. Importantly, the controller starts the oracle service with the same allow-list of system calls that was applied to the service. Given the same input, the oracle should either (1) exit due to the same system call violation, or (2) exit due to an ASan abort. Case (1) indicates that the code path taken to reach the system call did not result in memory corruption, and so the offending system call may safely be added to the allow-list—in this case, the controller updates the policy and starts the original service with the new policy. Case (2) indicates that prior to reaching the new system call, a memory corruption violation occurred, and that the input is unsafe.

To summarize, TIMELOOPS identifies when a new system call violates an existing policy, queries an oracle to determine whether the input that caused the system call execution is “safe” according to the runtime exploit detection features of the oracle, and makes policy update decisions based on the determination. An additional benefit is that the runtime performance overhead of executing a program with exploit detection and mitigations applied occurs lazily, i.e., only when a system call policy violation occurs. This means that in the critical path of the program execution, the overall system executes with the amortized runtime of the service, while still providing the benefits of executing exploit detection checks opportunistically. We study and analyze the runtime performance of TIMELOOPS in Section 5.

4.2 System Call Policy Enforcement

The service and oracle programs are isolated in their own container environments, as we would see in typical microservices deployments. This provides separation from system resources and from the controller service that manages the security policy. We use Podman containers [7] in the TIMELOOPS implementation, which is an alternative to Docker, the most popular container engine. Podman’s security advantage is its daemonless architecture—unlike Docker, which uses a single daemon executing with administrative privileges to manage containers, Podman can create containers as non-root child processes. Podman is compliant with the Open-Container Initiative (OCI) standard, which makes it easy to use and compatible with existing Docker images. The TIMELOOPS controller leverages these features to start and stop the service, and oracle containers as systemd services.

Both Podman and other container runtimes provide support for applying a seccomp-BPF filter to a container on start-up. This functionality is enabled by the default filter [10] and removes access to at least 44 system calls that can be abused for container escape exploits, but which still leaves over 300 system calls available. We use the Podman feature to apply a custom seccomp-BPF filter every time the TIMELOOPS con-
troller starts the service and oracle containers. In between executions of the containers, the controller updates the filter, but once a container is started with a given filter, the set of syscalls that the container is allowed to execute is immutable until the container exits (by the seccomp-BPF design).

4.3 System Calls Introduced by the Oracle

It is possible for the oracle container to execute system calls that the original service did not. This occurs when the oracle’s exploit detection mechanism introduces new system calls or non-deterministic behavior takes place. To handle this, we instruct our TIMELOOPS controller to add any system call that the oracle encounters during execution to the allow-list, assuming that the oracle does not detect exploitation prior to the system call being executed. These system calls can be trusted because the oracle is the determinant of safe inputs. However, introducing these syscalls potentially causes our allow-list to be looser than necessary and requires extra iterations of TIMELOOPS learning, so ideally we want to choose a hardening technique that provides strong security guarantees without introducing many new system calls.

4.4 Retry-request Expectations

In the current TIMELOOPS implementation, the service may receive an input that results in a system call violation, causing the service to exit without handling the request. TIMELOOPS then restarts the service container in the oracle and awaits the next request. We expect the client to use retry semantics, meaning that the client retries the request until successful. These expectations also align with the behavior of clients interacting with idempotent microservices often expect retry semantics until a response confirms success for robustness and fault tolerance [24]. Additionally, the expectation that identical messages are repeated does not introduce security vulnerabilities in the TIMELOOPS system when the expectation is not met—it only makes the system inefficient. The security implications of this are discussed further in Section 6.

4.5 Limitations of Policy Learning

In our implementation, we use ASan as the runtime exploit detection technique for the oracle since it provides instrumentation for detecting runtime memory safety violations. To create an oracle container for a given service, we use Clang to compile the service’s code and dependencies with ASan. Our flexible design allows users to create oracle containers hardened with other exploit detection techniques, customized to their threat landscape. We opt for ASan since ≈70% of CVEs each year are attributed to memory safety issues [67].

Our system determines when a new system call is the result of a memory corruption exploit that ASan detects. However, when a system call is introduced by an attacker via an exploit
or misconfiguration that does not leverage a memory corruption vulnerability, TIMELOOPS will update the system call policy to allow the new system call. Therefore, the scope of the security policies that TIMELOOPS can learn is limited by the abilities of the oracle. In Section 6.1, we discuss complimentary approaches for maintaining the security of the service container and the overall TIMELOOPS system in the context of exploits beyond what the oracle can detect. We also intend for the TIMELOOPS oracle model to be modular, such that multiple oracle containers with different forms of analyses can be deployed in parallel to alleviate some of the pressure of finding one perfect hardening mechanism.

5 Evaluation Testbed

We conduct our analyses by executing four different applications in TIMELOOPS. Two applications are statically served by Python Flask and Nginx, and two applications are the social network and media microservices benchmarks from the DeathStarBench suite [28].

5.1 Python Flask

Flask is a popular Python web development framework used in microservices. We developed a simple Flask application that serves a static website over HTTP(S) to evaluate our TIMELOOPS prototype. Flask applications are executed by the Python interpreter and provide multi-threaded functionality. Many web applications are developed using similar frameworks and interpreted languages, like PHP, Ruby, and JavaScript. Since Python and its modules facilitate developing web applications, or querying databases, easily, it is useful for the rapid development of microservices, and thus has become a popular choice for cloud developers and a suitable application to evaluate TIMELOOPS [36].

5.2 Nginx and PHP

Nginx is a free and open-source web server that is used by 32.9% of all websites, the largest of any available web server [69]. It is often used as a gateway or load-balancer to multi-tier microservices applications. We built a simple, static website hosted by an Nginx server with PHP-FPM integrations—PHP is used by 78.1% of websites where the server-side language is known [70]. Both Nginx and PHP-FPM use a forking server model that spawns worker processes to handle connections. We evaluate TIMELOOPS with this application to represent services that use multiple processes to provide web content. Additionally, the PHP modules used in this Nginx application rely on an interpreter which makes predicting its behavior difficult, but suitable for our application like the Python Flask application.

5.3 DeathStarBench Microservices

In order to evaluate TIMELOOPS in an environment representative of real-world microservices applications, we selected applications from the DeathStarBench benchmark suite of microservices [28]. We specifically evaluated against the media streaming benchmark, which models the structure of popular media streaming services like Netflix, and the social network benchmark, which models a social network site like Twitter. Both applications depend on technologies used in real microservice deployments such as Memcached, Redis, Thrift, MongoDB, and Nginx, and its services are written in a wide variety of programming languages.

To deploy these services, we ran each microservice from a benchmark on a different Amazon EC2 instance [8], similarly to how it might be deployed in practice. Each EC2 instance had its own TIMELOOPS controller setup and generated a unique filter for each service.

To evaluate the social media and media streaming applications, we use the workload generator provided by the benchmark suite. The workload generated for evaluation resulted in the creation of many requests within the tiers of the microservices application and required all services to undergo many iterations of TIMELOOPS policy learning. This way, we ensured that this workload is suitable for not only performance benchmarking, but also our TIMELOOPS security evaluation.

6 Security Evaluation

In this section, we consider the security features of TIMELOOPS, and present the argument that it provides protection to a container application given reasonable assumptions about the threat model considered.

6.1 Attacks Classification

Given the presence of a remote attacker, as described in our threat model (see Section 2.3), we classify attack scenarios by considering whether the attacker invokes new system calls and whether the attacker leverages oracle-detectable vulnerabilities. The security of TIMELOOPS hinges on detecting system call violations and detecting attacks with the oracle, which is why we chose these components to rigorously analyze. These four attack categories are shown in Table 1, and in this section we explain how the TIMELOOPS implementation provides varying security benefits in each attack scenario.

Category (1) attacks (oracle-detectable exploit that executes a policy-violation system call) are detected and prevented by the TIMELOOPS system, and TIMELOOPS provides the strongest security benefits against these attacks. When the application container violates the system call policy as a result of offending input, the oracle container will detect that the input is an exploit trigger, prevent any changes to the security policy, and alert an administrator.
Table 1: TIMEOOPS provides strong security benefits in comparison to previous works that rely on generating a static system call filter. Static system call filtering tools generate a filter prior to execution and only enforce that filter throughout application execution. Our tight and incremental filter building process results in a smaller attack surface and restricts attacker capabilities when a service is under attack.

Category (2) attacks (oracle-detectable exploit that does not execute a policy-violation system call) and category (3) attacks (oracle-undetectable exploit that does not execute a policy-violation system call) are handled in the same way by the TIMEOOPS. In these attack scenarios, TIMEOOPS’s security benefits are in line with the approach of enforcing the Principle of Least Privilege (PoPL) [59], the goal of previous work in system call filtering. Because the system call policy is never violated in Category (2) and (3) attacks, the oracle is never consulted, but an attacker is still severely limited in terms of its capabilities with respect to accessing the system call API. Due to the tight system call policy learned, the attacker is restricted to only invoking previously observed system calls, thereby limiting attempts to compromise the application or escape from the container. Unlike previous works that create immutable lists that include all system calls an application requires, TIMEOOPS is a significant improvement because system calls are conservatively added as they are observed. Hence, the TIMEOOPS allow-list can be much smaller than the set of all syscalls required by the application.

Category (4) attacks (oracle-undetectable exploit that executes a policy-violation system call) may seem the most dangerous to the TIMEOOPS system, but with relatively-simple modifications, TIMEOOPS is able to prevent the execution of arbitrary system calls. When an input from this attack category is received, the oracle service is consulted to make a determination on the input, but the oracle is unable to detect an exploit. This grants attackers the ability to add any system calls to the allow-list until a sufficient set are available to conduct an exploit. Therefore, to mitigate the chance of this occurring, we propose two best practices when deploying an application with TIMEOOPS. First, an oracle must be carefully chosen considering the application and the nature of its vulnerabilities. Second, we can specify a list of system calls that are known to be unnecessary and common in exploits and prevent them from ever being added to our system call policy. For example, an over-approximate static analysis tool or the system calls in the default Docker and Podman seccomp-BPF filter can be used to create this list. For stronger guarantees, a static analysis-based technique for generating system call filters can also be applied to create a list of system calls that may never be included in the TIMEOOPS filter [25]. With this mitigation, we see that TIMEOOPS security guarantees are equal to those of static-analysis based techniques, but in many most cases, much stronger.

### 6.2 System Call Policies

In addition to the qualitative analysis, we evaluated the quality of the system call policies created by TIMEOOPS. To determine the effectiveness of TIMEOOPS for generating correct and safe policies, we sought to determine the following:

1. How many fewer system calls does TIMEOOPS allow than over-approximate static analysis techniques (RQ1)?
2. Which system calls do static analysis techniques allow that are not allowed by TIMEOOPS (RQ2)?
3. Which system calls does TIMELOOPS allow that are not allowed by static analysis techniques (RQ3)?

4. Which system calls does TIMELOOPS allow that would not have otherwise be necessary for the application to execute safely in a non-TIMELOOPS system (RQ4)?

To evaluate the system call policies, we generated system call filters using static analysis, TIMELOOPS, and dynamic tracing. We chose sysfilter [25] to represent state-of-the-art static analysis techniques for system call policy creation. As a static analysis tool, sysfilter tends to be over-approximate in its determinations. We used sysfilter to generate syscall profiles for all our evaluated applications.

To generate our TIMELOOPS system call policies, we executed each program in a container with seccomp RET_LOG mode, which allows, but logs, each system call. We provided a set of sample inputs to the profiled service and monitored the system calls invoked. This technique can be considered elemental dynamic analysis for generating system call filters. This provided a baseline of system calls that the program executes for a given input without the introduction of new system calls from the TIMELOOPS system.

**RQ1** For all evaluated programs, sysfilter created policies that were at least as large as those created by TIMELOOPS. On average, the sysfilter generated system call sets that were 32.7% larger than those generated by TIMELOOPS, meaning that an attacker has access to approximately 32.7% more system calls when exploiting a system defended by sysfilter over one defended by TIMELOOPS, resulting in a larger attack surface and capability set. Static approaches ignore the fact that inputs modulate program behavior, at runtime, and estimate the system call behavior solely based on static program code, thus over-approximating the set of allowed system calls.

In contrast, our results demonstrate that TIMELOOPS is able to tailor the system call list to specific inputs, and the degree of difference shows the typical reduction in attack surface.

**RQ2** When comparing system call policies, we can quantify the size of the attack surface with the number of system calls in a policy, but not all system calls are created equally. Attackers do not need to access to *every* system call to be successful; they frequently require only a specific subset of system calls that is unique to the post-exploitation behavior that they desire. This is difficult to characterize, but in attempt to do so, we will analyze the policies generated for two of the services that we evaluated: Nginx and the ComposePost service from the Social Network application.

For both the Nginx and ComposePost services, TIMELOOPS created smaller system call policies than sysfilter. The TIMELOOPS filter for Nginx and Compose Post were 40 and 37 system calls smaller than the sysfilter filter respectively. Many of these extraneous system calls were benign, like *exit*. Others, however, may provide opportunities to compromise the container isolation from the host system, with numerous previous CVEs reported with associated system calls in the Linux kernel. For example, sysfilter allowed both Nginx and ComposePost to have access to *mremap* (associated with CVE-2020-10757), *sendmsg* (CVE-2011-4594), and *ftruncate* (CVE-2018-18281), while TIMELOOPS did not. sysfilter also allowed Nginx to execute shared memory operations *shmget* (CVE-2017-5669), and allowed ComposePost to execute *clock_settime*, while TIMELOOPS did not allow these. *clock_settime* not allowed by the default Podman container filter due to its effects on the host system settings outside of the container. Note that the presence of previous CVEs associated with a system call is not enough to classify a system call as dangerous when executed inside a container by an attacker; the CVEs simply show that there has been some previous risk with allowing unrestricted access to the system call but do not mean that the system call is still a risk, nor that a system call with no associated CVE is *not* a risk. We provide a full table of system calls allowed by each system, along with a best-effort attempt to map the system calls to associated Linux kernel CVEs, in Appendix A.

**RQ3** Some system calls are allowed by TIMELOOPS that are not allowed by sysfilter, in part due to the ASan instrumentation applied to create the oracle services. The Nginx TIMELOOPS policy contained seven system calls that were not present in the sysfilter policy, and the ComposePost TIMELOOPS policy contained 13 system calls that were not present in the sysfilter. Some of these, like *open* (CVE-2020-8428 [4]) and *pipe* (CVE-2015-1805) do have history of being abused in prior vulnerabilities, but overall this remains a smaller attacker surface.

**RQ4** In order to determine which system calls were specifically introduced by the TIMELOOPS system, we compare the Nginx and ComposePost policies generated by TIMELOOPS to the system calls observed when executing the target program in a container outside of the TIMELOOPS system while profiling all system calls. The TIMELOOPS policies contain a superset of system calls compared to the system calls observed in the baseline profile, meaning that all system calls executed by the program outside of TIMELOOPS were also in the TIMELOOPS policies. The TIMELOOPS policies included six additional system calls in the Nginx policy (*clock_gettime*, *kill*, *madvise*, *open*, *readlink*, *sigaltstack*) and seven additional system calls in the ComposePost policy (*getpid*, *gettid*, *readlink*, *sched_getaffinity*, *sched_yield*, *setrlimit*, *sigaltstack*). These system calls were likely introduced by either ASan, as our oracle hardening technique, or by our modifications to ensure that forking services properly exit when anomalous activity is detected.

We conclude that TIMELOOPS is effective at generating tight system call policies when compared to current state-of-
6.3 Real-world Exploits

We evaluate the effectiveness of TIMELOOPS in the detection and prevention of real-world exploits. Long-running web services are often subject to memory errors that enable attackers to gain remote code execution abilities [47]. Buffer overflows, for example, account for many software vulnerabilities and memory unsafe code remains the foundation for many web services. We created a web server (written in C) to illustrate TIMELOOPS’s ability to detect and prevent attacks that perform memory corruption and strive to execute arbitrary code.

The web service contains a stack-based buffer overflow vulnerability modeled after CVEs sampled throughout the last decade [6] [5] [1] [3]. The vulnerable web service serves a simple HTML page in response to an HTTP GET request. Attackers can determine the addresses necessary to successfully exploit the service and put together a payload, using a state-of-the-practice or state-of-the-art code-reuse technique [12–14,21,29,32–34,48,58,60,62,63], which executes a TCP reverse shell. When the exploit is run on an unprotected service, an attacker is able to successfully coerce the service to “connect back” with a remote shell. However, when the attack is executed in a system defended by TIMELOOPS, the vulnerable buffer is overwritten, but the attacker is unable to cause the service to connect back (with a remote shell), because when the new system calls (e.g., dup2, connect) are executed to achieve this we switch to our oracle service and detect the corresponding memory corruption. While this simple example can be defended or patched in other ways, TIMELOOPS’s ability to mitigate attacker’s damage to the host machine can be extended to defending against the entire class of remote code execution attacks.

Additionally, we evaluated the effectiveness of TIMELOOPS on an Nginx vulnerability CVE-2013-2028 [2]. This vulnerability allows an attacker to abuse and integer signedness error and stack-based buffer to execute arbitrary code. Similar to our exploit with the HTTP server, the exploit succeeded on an undefended system, but was caught and prevented when TIMELOOPS system call filtering was enabled.

6.4 Violating Retry-request Expectations

The analysis conducted in Section 6.1 expected that identical requests are repeated until a valid response is sent from the application. However, we must also consider the case where an attacker violates this expectation or sends a different, malicious request instead of resending the original input. If this happens, then the oracle and the production services process different inputs, but this does not introduce any opportunities to violate security properties of the system.

The oracle is tasked with determining whether a given input is safe or not. Even if it is making the classification on an input different from the one that the production service handled, it will still be able to make the determination and update the security policy accordingly. If we supply a malicious request to the production and a benign one to the oracle, the oracle will not add the new malicious system calls to the filter and the malicious request will remain incomplete. If we supply a benign request to the production that triggers the oracle and a malicious one to the oracle, then the oracle will detect the exploit and quit execution. If we supply two different malicious inputs to the production and oracle services, the oracle will still be able to detect the exploit from the second malicious request and the first one will remain incomplete. There is no scenario where we can fool the oracle into adding a system call to the allow-list with an exploit that the oracle is capable of detecting.

This scenario still allows an attacker to abuse the system architecture to cause targeted increased runtime overheads. Attackers can induce repeated switches from application container to oracle by providing an input that results in a new system call, but by then providing inputs that do not cause system call violations, the oracle container handles all new requests but with the higher performance overhead that comes from the exploit detection instrumentation in the oracle. To prevent this from occurring (even accidentally), we add a watchdog timer to the oracle container that causes it to exit after some configurable amount of time, causing a switch back to the more performant application container. Besides, this behavior is trivially detectable using classic anomaly detection and/or prevention techniques [20].

6.5 Application Container Compromise

If an attacker achieves remote code execution in the application container, the TIMELOOPS system is engineered to prevent full-system compromise.

First, TIMELOOPS leverages container abstractions provided by Podman to isolate the application and oracle container resources. The containers are restricted from accessing the full set of system calls by the container seccomp-BPF policy that is set by TIMELOOPS. The file representing the system call policy is maintained entirely outside of the executing container environments, and is only passed as an argument to Podman at container startup. Therefore, an attacker with code execution inside either container is unable to directly manipulate the policy file. Additionally, since seccomp-BPF is handled in kernel space, all system call violations result in delivering SIGSYS signals to the offending container’s thread and recording the violation in the system’s audit log. It is possible for an attacker to manipulate the userspace handling of the SIGSYS signals, given code execution in the context of an application process. While this would prevent TIMELOOPS from functioning correctly, it would not allow the attacker to loosen the
existing syscall policy which is immutable (kernel-enforced).

We further mitigate the danger of a successful remote attacker by running all containers without administrative privileges. This ensures that any container escapes result in an attacker having the same permissions as the TEMLOOPS user, and no more. These limited permissions do not allow attackers to dismantle the system call filter or alter running processes on the host. We believe that due to the series of security benefits provided by our approach, from exploit detection and tight system call filtering to container isolation, TEMLOOPS sufficiently raises the bar for successful system compromise.

6.6 Timeloops vs. Permanent Hardening

We compare the security guarantees that TEMLOOPS provides with a permanently hardened system, or in our case, a service that is always running with ASan. In the TEMLOOPS design, we only check inputs with ASan when they trigger new system calls. In the case that a malicious input does not invoke a new system call, but induces memory corruption, our TEMLOOPS production service will be corrupted, but an ASan-hardened service will catch the exploit and quit. We only offer protection equal to an ASan-hardened service when new system calls are invoked, but we make the key observation that malicious payloads tend to invoke new system calls. By design, our hardened oracle service will inspect those inputs with greater scrutiny. Since it is impractical to deploy ASan-hardened services due to their great performance overheads, our approach provides the security benefits of ASan-hardening without incurring the costs. TEMLOOPS enables heavyweight security techniques to be practical in performance-critical deployments.

7 Performance Evaluation

To evaluate the performance of TEMLOOPS, we consider the end-to-end latency of network requests sent to a service application that is running under our TEMLOOPS prototype. We measure latency as the elapsed time between a client making the first request to the service and the client receiving a response, regardless of the number of times the client may have retried the request.

We compare the latency of the application running under TEMLOOPS to the latency of the same application running with no additional exploit mitigations applied (i.e., outside of TEMLOOPS). We additionally compare the latency of the TEMLOOPS-hardened application to that of the same application executing with ASan-hardening, outside of TEMLOOPS. This represents a system that is instrumented to maximally determine when an input causes a security violation. Our evaluation aims to show that TEMLOOPS can monitor for violations of security boundaries while also providing amortized performance benefits that are comparable to that of an unhardened (and hence unprotected) system.

All experiments began by executing the test application service in TEMLOOPS with an empty system call allow-list. We used an HTTP client program to send each request to the application repeatedly until it was successfully processed. Some system calls are iteratively learned even before the application is able to receive its first input.

In all experiments, the very first request sent to the TEMLOOPS application resulted in very slow response times since it typically required learning many new system calls. Following requests tended not to invoke many new system calls and were therefore quickly processed. Figure 4 shows the latency of each request sent, and how the application running in TEMLOOPS always has a slower start than the other services. However, the average latency, shown in Figure 5, of ensuing requests processed by the TEMLOOPS application was close to that of the completely unhardened service. In all trials the average TEMLOOPS request outperformed the average hardened service request.

The high latency of the first few requests led to another observation: by pre-training TEMLOOPS on known-safe inputs to the application, we can create an initial allow-list prior to deployment. However, unlike in traditional dynamic system call learning systems, these initial inputs do not need to exhaustively include every system call that should be learned—in this case, the TEMLOOPS system can still learn new system calls from future inputs. By training on the most performance-critical inputs ahead of time, an operator of the TEMLOOPS system can further amortize system call learning costs on the critical path.

8 Related Work

8.1 Static System Call Filtering

Static system call filtering approaches attempt to determine a correct system call policy without executing the program, and then apply the policy via some enforcement mechanism. sysfilter [25] is a binary analysis-based framework that synthesizes syscall filters and applies them to applications. Like our approach, sysfilter determines developer-intended program behavior and enforces only that behavior via seccomp-BPF filters. However, sysfilter determines this behavior statically and analyzes call graphs to generate their system call filters. While the authors use many techniques to prune this call graph to avoid adding unreachable syscalls to their filter, it still may be too large. Abhaya [53], like sysfilter, uses static code analysis to generate system call policies, but analyzes program source code, rather than compiled binaries, and targets both seccomp-BPF and Pledge policies for enforcement.

Temporal syscall filtering [31] relies on static analysis to create syscall filters for applications. It differs from sysfilter because it makes the observation that many system calls that are used for the initialization of an application

10
Figure 4: Comparison of cumulative time for processing repeated requests sent to an unhardened service, a TIMELOOPS service, and a hardened service. Figures 4a and 4b show the end-to-end latency of sending requests to the media microservices (MM) and social network microservices (SN) benchmark. Figures 4c and 4d show the end-to-end latency of sending requests to each of the stand-alone applications that process web requests. In every case, the TIMELOOPS service starts with a longer response time while system calls are learned, but eventually overtakes the hardened service (intercept is plotted).

Figure 5: Comparison of request latency distribution per request sent to an unhardened service, a TIMELOOPS service, and a hardened service. The average request latencies of the TIMELOOPS services are similar to that of the unhardened service and lower than the hardened service, despite the maximum value of the TIMELOOPS service being a significant outlier. The maximum value comes from the large delay in servicing the first requests as system calls are learned.
are no longer required during the application’s steady state. The authors create two filters: one that includes all of the initialization syscalls, applied during the “init” execution phase, while the other is applied during the “main loop” phase.

Saphire [15] presents an approach for creating system call policies for interpreted languages. Specifically, Saphire creates sandboxes for PHP applications by analyzing PHP source code rather than attempting to analyze the entire interpreter.

8.2 Dynamic System Call Filtering

Dynamic syscall filtering tools execute the target program various inputs to observe which system calls are required by an application. Like TIMELOOPS, dynamic approaches execute the program to derive policies based on observations of program behavior. However, they tend to execute in distinct phases of training and deployment, while TIMELOOPS conducts its learning while able to service production workloads. ZenIDS [35] is able to learn system call policies for PHP applications with an online training period to then monitor for anomalies. Systrace [54] also uses dynamic tracing to learn policies, but enforces the policies by implementing a userspace daemon.

8.3 Cloud and Container Security

As cloud and container environments have proliferated, new approaches have been proposed to secure them. Confine [30] is a static system call filtering technique specifically for analyzing the contents of containers to determine allowed system calls exposed to the container. Dynamic approaches have also been applied to containers [71] to profile the syscalls invoked by the container during the execution of automated test inputs, and to enforce a policy restricted by the profile. Work has been done to analyze and categorize [43] privilege escalation container exploits that break the resource isolation provided by container abstractions. AUTOARMOR [41] is a proposal to automatically generate policies for securing microservices by analyzing the interactions between them.

9 Future Work

9.1 Optimizations

9.1.1 Performance Optimizations

In our evaluation, we saw that most of the additional overheads that timeloops applications have in comparison to the unhardened services come from processing the first few requests. The rest of the execution after this “warmup phase” is similar to that of the unhardened services. To avoid incurring this warmup cost, we can save filters and reuse them in the future if we are confident of their correctness and can validate that they have not been compromised between uses.

Figure 6: With additional hardware checkpointing and replaying support, when a new syscall is encountered we will (1) save the state of the production service and pause execution, (2) execute the request in the oracle and update the policy, and (3) restore the production service state from the checkpoint and resume execution.

Additionally, we see that it is quite costly to stop and restart containers, but this step is necessary since Seccomp filters are immutable once installed. This is a feature of Seccomp since we do not want attackers to be able to modify the Seccomp filters that are installed on a running program. This could lead to uninstalling the Seccomp filter entirely or adding system calls necessary for an attack. If we had a custom eBPF program that allowed our trusted timeloops infrastructure to modify the system call filter, then we could avoid incurring this cost every time we encounter a new system call.

9.1.2 Security Optimizations

Our current implementation of TIMELOOPS involves iteratively writing a security policy by creating an allow-list of behaviors. However, over time, the intended behavior of an application may change depending on the phase of execution, the set of inputs, the time of day or some other factor. When application behavior changes, we do not want attackers to be able to modify the Seccomp filters that are installed on a running program. This could lead to uninstalling the Seccomp filter entirely or adding system calls necessary for an attack. Future instantiations of TIMELOOPS could use different or even multiple hardening techniques for the oracle.

Another assumption we make in our timeloops design is that malicious behavior is always introduced via a vulnerability that our oracle can detect. This is not always the case. Future instantiations of TIMELOOPS could use different or even multiple hardening techniques for the oracle.

Another optimization for our system call learning case study is to keep track of system call arguments. This will enforce a finer-grained security policy. Even though common system calls are used during attacks, they are often invoked with different arguments than the ones used in normal program execution.
9.1.3 Hardware Support

Introducing hardware support in our TIMELoops design may allow us to incorporate some of these optimizations with ease. For example, hardware checkpointing techniques [38] offer the ability to simply pause execution in one instance of a service and resume execution later. Instead of resending a request to the production service again, we can simply resume execution. Hardware checkpointing in conjunction with hardware support for replaying execution could save us the overheads of stopping services each time we need to consult the oracle. This support could potentially allow us to implement timeloops on services that are not stateless as well.

10 Conclusion

Creating security policies for microservices is a difficult and tedious process: it requires a thorough understanding of each service and must flexibly adapt to changes in the deployment. This paper takes the first steps towards automatically crafting security policies for containerized microservices. We aim to learn policies for system call filtering, a technology that is becoming increasingly necessary for maintaining isolation in cloud settings.

To learn policies automatically, we introduced the concept of timelooping. The key idea is to: (i) re-execute a program among two variants of an application, one hardened for security, and another one optimized for performance; (ii) learn execution properties from the hardened version; and (iii) use the results of the previous step to craft policies that can be enforced on the performance-optimized version. Our solution takes a pragmatic stance in the trade-off(s) between security and performance.

We demonstrated the merit and applicability of our TIMELoops learning scheme in three significant ways: (1) we showed that the system call allow-lists created by TIMELoops for our applications are significantly better than statically- and dynamically-generated policies, (2) we showed that the idea is compatible-with, and well-suited to, modern software engineering practices, such the use of containerized microservices crafted using popular interpreted languages. These use cases have been the Achilles’ heel of several security studies in our community, and (3) we showed that the idea can be easily implemented by combining existing technologies.

In our community there has been significant amount of work on hardening applications. As is to be expected, these hardening services come with performance and energy overheads. In an ideal world, these overheads should not matter. In reality, however, users care about performance, forcing them to make a hard choice between performance and security. In our TIMELoops system we use the oracle version as needed to learn security properties, and then enforce these security properties on the production version using lightweight enforcement techniques. Thus, TIMELoops obviates the need to make this performance-security choice. With time, we expect properties and policies beyond system call filtering to use our TIMELoops technique.

11 Acknowledgements and Disclosures

This work was partially supported by N00014-20-1-2746, a NSF Graduate Research Fellowship, and a gift from Bloomberg. Any opinions, findings, conclusions and recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the US government or commercial entities. Simha Sethumadhavan has a significant financial interest in Chip Scan Inc. Patent Pending.

References

[1] Cve-2009-0187. National Vulnerability Database.
[2] Cve-2013-2028. National Vulnerability Database.
[3] Cve-2014-2206. National Vulnerability Database.
[4] Cve-2020-8428. National Vulnerability Database.
[5] Cve-2021-46393. National Vulnerability Database.
[6] Cve-2022-22274. National Vulnerability Database.
[7] Pod manager tool (podman). podman website.
[8] What is amazon ec2? AWS User Guide for Linux Instances.
[9] Improving host security with system call policies. In 12th USENIX Security Symposium (USENIX Security 03), Washington, D.C., August 2003. USENIX Association.
[10] Seccomp security profiles for docker, Dec 2021.
[11] Muhammad Abubakar, Adil Ahmad, Pedro Fonseca, and Dongyan Xu. {SHARD}: Fine-grained kernel specialization with context-aware hardening. In 30th {USENIX} Security Symposium ({USENIX} Security 21), 2021.
[12] Andrea Bittau, Adam Belay, Ali Mashtizadeh, David Mazières, and Dan Boneh. Hacking Blind. In IEEE Symposium on Security and Privacy (S&P), pages 227–242, 2014.
[13] Tyler Bletsch, Xuxian Jiang, Vince W Freeh, and Zhenkai Liang. Jump-Oriented Programming: A New Class of Code-Reuse Attack. In ACM Asia Symposium on Information, Computer and Communications Security (ASIACCS), pages 30–40, 2011.
[14] Erik Bosman and Herbert Bos. Framing Signals—A Return to Portable Shellcode. In *IEEE Symposium on Security and Privacy (S&P)*, pages 243–258, 2014.

[15] Alexander Bulekov, Rasoul Jahanbashi, and Manuel Egele. Saphire: Sandboxing [PHP] applications with tailored system call allowlists. In *30th {USENIX} Security Symposium ({USENIX} Security 21)*, 2021.

[16] Nathan Burow, Xinping Zhang, and Mathias Payer. Sok: Shining light on shadow stacks. In *2019 IEEE Symposium on Security and Privacy (SP)*, pages 985–999. IEEE, 2019.

[17] Claudio Canella, Mario Werner, Daniel Gruss, and Michael Schwarz. Automating seccomp filter generation for linux applications. In *Proceedings of the 2021 on Cloud Computing Security Workshop*, pages 139–151, 2021.

[18] Claudio Canella, Mario Werner, Daniel Gruss, and Michael Schwarz. Automating seccomp filter generation for linux applications. *CCSW ’21*, page 139–151, New York, NY, USA, 2021. Association for Computing Machinery.

[19] Canister. Container escapes: An exercise in practical container escapology, Mar 2019.

[20] Varun Chandola, Arindam Banerjee, and Vipin Kumar. Anomaly detection: A survey. *ACM computing surveys (CSUR)*, 41(3):1–58, 2009.

[21] Stephen Checkoway, Lucas Davi, Alexandra Dmitrienko, Ahmad-Reza Sadeghi, Hovav Shacham, and Marcel Winandy. Return-Oriented Programming without Returns. In *ACM Conference on Computer and Communications Security (CCS)*, pages 559–572, 2010.

[22] Stefano Chierici. Cve-2022-0492: Privilege escalation vulnerability causing container escape, Mar 2022.

[23] Adrian Cockcroft. Evolution of microservices - craft conference, Apr 2016.

[24] Jeffrey Dean and Luiz André Barroso. The tail at scale. *Commun. ACM*, 56(2):74–80, Feb 2013.

[25] Nicholas DeMarinis, Kent Williams-King, Di Jin, Rodrigo Fonseca, and Vasileios P. Kemerlis. sysfilter: Automated system call filtering for commodity software. In *23rd International Symposium on Research in Attacks, Intrusions and Defenses (RAID 2020)*, pages 459–474, San Sebastian, October 2020. USENIX Association.

[26] Docker Documentation. Seccomp security profiles for docker.

[27] EdPrice-MSFT. N-tier architecture style - azure architecture center.

[28] Yu Gan, Yanqi Zhang, Dailun Cheng, Ankitha Shetty, Priyalskhi, Nayan Katarki, Ariana Bruno, Justin Hu, Brian Ritchken, Brendon Jackson, Kelvin Hu, Meghan Pancholi, Yuan He, Brett Clancy, Chris Cole, Fukanf Wen, Catherine Leung, Siyuan Wang, Leon Zaruminsky, Mateo Espinosa, Rick Lin, Zhongliang Liu, Jake Padilla, and Christina Delimitrou. An open-source benchmark suite for microservices and their hardware-software implications for cloud & edge systems. In *Proceedings of the Twenty-Fourth International Conference on Architectural Support for Programming Languages and Operating Systems, ASPLOS ’19*, page 3–18, New York, NY, USA, 2019. Association for Computing Machinery.

[29] Robert Gawlik, Benjamin Kollenda, Philipp Koppe, Behrad Garmany, and Thorsten Holz. Enabling Client-Side Crash-Resistance to Overcome Diversification and Information Hiding. In *Network and Distributed System Symposium (NDSS)*, 2016.

[30] Seyedhamed Ghavamnia, Tapti Palit, Azzedine Be nameur, and Michalis Polychronakis. Confine: Automated system call policy generation for container attack surface reduction. In *23rd International Symposium on Research in Attacks, Intrusions and Defenses ({RAID} 2020)*, pages 443–458, 2020.

[31] Seyedhamed Ghavamnia, Tapti Palit, Shachee Mishra, and Michalis Polychronakis. Temporal system call specialization for attack surface reduction. In *29th USENIX Security Symposium (USENIX Security 20)*, pages 1749–1766. USENIX Association, August 2020.

[32] Enes Göktas, Elias Athanasopoulos, Herbert Bos, and Georgios Portokalidis. Out Of Control: Overcoming Control-Flow Integrity. In *IEEE Symposium on Security and Privacy (S&P)*, pages 575–589, 2014.

[33] Enes Göktas, Benjamin Kollenda, Philipp Koppe, Erik Bosman, Georgios Portokalidis, Thorsten Holz, Herbert Bos, and Cristiano Giuffrida. Position-independent Code Reuse: On the Effectiveness of ASLR in the Absence of Information Disclosure. In *IEEE European Symposium on Security and Privacy (EuroS&P)*, pages 227–242, 2018.

[34] Enes Göktas, Kaveh Razavi, Georgios Portokalidis, Herbert Bos, and Cristiano Giuffrida. Speculative Probing: Hacking Blind in the Spectre Era. In *ACM Conference on Computer and Communications Security (CCS)*, pages 1871–1885, 2020.

[35] Byron Hawkins and Brian Demsky. Zenids: Introspective intrusion detection for php applications. In *2017
[36] Matt Hedges and Joseph Keating. Deploying python flask microservices to aws using open source tools, Apr 2021.

[37] Sungjin Kim, Byung Joon Kim, and Dong Hoon Lee. Prof-gen: Practical study on system call whitelist generation for container attack surface reduction. In 2021 IEEE 14th International Conference on Cloud Computing (CLOUD), pages 278–287. IEEE, 2021.

[38] Dirk Koch, Christian Haubelt, and Jürgen Teich. Efficient hardware checkpointing: Concepts, overhead analysis, and implementation. In Proceedings of the 2007 ACM/SIGDA 15th International Symposium on Field Programmable Gate Arrays, FPGA ’07, page 188–196, New York, NY, USA, 2007. Association for Computing Machinery.

[39] Paul Kocher, Jann Horn, Anders Fogh, Daniel Genkin, Daniel Gruss, Werner Haas, Mike Hamburg, Moritz Lipp, Stefan Mangard, Thomas Prescher, et al. Spectre attacks: Exploiting speculative execution. Communications of the ACM, 63(7):93–101, 2020.

[40] Per Larsen, Andrei Homescu, Stefan Brunthaler, and Michael Franz. Sok: Automated software diversity. In 2014 IEEE Symposium on Security and Privacy, pages 276–291. IEEE, 2014.

[41] Xing Li, Yan Chen, Zhiquang Lin, Xiao Wang, and Jim Hao Chen. Automatic policy generation for inter-service access control of microservices. In 30th {USENIX} Security Symposium ({USENIX} Security 21), 2021.

[42] Yiwen Li, Brendan Dolan-Gavitt, Sam Weber, and Justin Cappos. Lock-in-pop: Securing privileged operating system kernels by keeping on the beaten path. In 2017 {USENIX} Annual Technical Conference ({USENIX} ATC ’17), pages 1–13, 2017.

[43] Xin Lin, Lingguang Lei, Yuewu Wang, Jiwu Jing, Kun Sun, and Quan Zhou. A measurement study on linux container security: Attacks and countermeasures. In Proceedings of the 34th Annual Computer Security Applications Conference, ACSAC ’18, page 418–429, New York, NY, USA, 2018. Association for Computing Machinery.

[44] Linux Programmer’s Manual. Seccomp(2).

[45] Moritz Lipp, Michael Schwarz, Daniel Gruss, Thomas Prescher, Werner Haas, Jann Horn, Stefan Mangard, Paul Kocher, Daniel Genkin, Yuval Yarom, et al. Meltdown: Reading kernel memory from user space. Communications of the ACM, 63(6):46–56, 2020.

[46] Mike Loukides and Steve Swayer. Microservices adoption in 2020, Jul 2020.

[47] Kylee Malkiewicz. This year (so far) in buffer overflows - dover microsystems, Mar 2021.

[48] Andrea Mambretti, Alexandra Sandulescu, Alessandro Sorniotti, William Robertson, Engin Kirda, and Anil Kurmus. Bypassing memory safety mechanisms through speculative control flow hijacks. In IEEE European Symposium on Security and Privacy (EuroS&amp;P), pages 633–649, 2021.

[49] Steven McCanne and Van Jacobson. The bsd packet filter: A new architecture for user-level packet capture. In USENIX winter, volume 46, 1993.

[50] Kit Murdock, David Oswald, Flavio D Garcia, Jo Van Bulcke, Daniel Gruss, and Frank Piessens. Plundervolt: Software-based fault injection attacks against intel sgx. In 2020 IEEE Symposium on Security and Privacy (SP), pages 1466–1482. IEEE, 2020.

[51] Santosh Nagarakatte, Jianzhou Zhao, Milo MK Martin, and Steve Zdancewic. SoftBound: Highly Compatible and Complete Spatial Memory Safety for C. In ACM Conference on Programming Language Design and Implementation (PLDI), pages 245–258, 2009.

[52] Santosh Nagarakatte, Jianzhou Zhao, Milo MK Martin, and Steve Zdancewic. CETS: Compiler Enforced Temporal Safety for C. In International Symposium on Memory Management (ISMM), pages 31–40, 2010.

[53] Shankara Pailoor, Xinyu Wang, Hovav Shacham, and Isil Dillig. Automated policy synthesis for system call sandboxing. Proc. ACM Program. Lang., 4(OOPSLA), November 2020.

[54] Niels Provos. Improving host security with system call policies. In Proceedings of the 12th Conference on USENIX Security Symposium - Volume 12, SSYM’03, page 18, USA, 2003. USENIX Association.

[55] Niels Provos, Markus Friedl, and Peter Honeyman. Preventing privilege escalation. In Proceedings of the 12th Conference on USENIX Security Symposium - Volume 12, SSYM’03, page 16, USA, 2003. USENIX Association.

[56] Yuxin Ren, Guyue Liu, Vlad Nitu, Wenyuan Shao, Riley Kennedy, Gabriel Parmer, Timothy Wood, and Alain Tchana. F2c: Enabling fair and fine-grained resource sharing in multi-tenant iaas clouds. IEEE Transactions on Parallel and Distributed Systems, 27(9):2589–2602, 2016.
A System Call Policy Comparison Table

As part of our evaluation of TIMELOOPS, we generated policies for multiple programs, as described in Section 6.2. In this section, we list all syscalls contained in the generated policies produced by TIMELOOPS and sysfilter for our Nginx web application and the ComposePost microservice of the Social Network service benchmark. We additionally compare these policies to system calls observed when executing the programs in a container without any system call filtering, as well to the default Podman system call filter. We additionally list the most recent Linux kernel CVE that we were able to identify that could be associated with each system call.
Table 2: Comparison of system calls allowed by various filtering policies. If a system call does not appear in this table, it was not contained in a policy generated by TIMELOOPS, sysfilter, or observed when the program executed. The CVE column lists one CVE, if any could be found, in the Linux kernel where the associated system call was used to trigger the vulnerability.

| syscall   | CVE      | Nginx | Compose Post |
|-----------|----------|-------|--------------|
| accept    | CVE-2017-8890 | x     | x     | x     | x     |
| accept4   |          | x     | x     | x     |         |
| access    |          | x     | x     | x     | x     | x     |
| alarm     |          | x     |       |       | x     |       |
| arch_prctl|          | x     | x     | x     | x     |       |
| bind      | CVE-2016-10200 | x     | x     | x     | x     |
| brk       | CVE-2020-9391 | x     | x     | x     | x     | x     |
| capset    |          | x     | x     | x     | x     |       |
| chdir     |          | x     |       |       | x     |       |
| chmod     |          | x     |       |       | x     |       |
| chown     |          |       |       |       | x     |       |
| clock_getres |          | x     | x     | x     | x     | x     |
| clock_gettime | CVE-2011-3209 | x     | x     | x     | x     | x     |
| clock_nanosleep | CVE-2009-2767 |     | x     |         | x     | x     |
| clock_settime |          | x     |       |       | x     |       |
| clone     | CVE-2019-11815 | x     | x     | x     | x     | x     |
| close     |          | x     | x     | x     | x     | x     |
| connect   |          | x     | x     | x     | x     | x     |
| dup       | CVE-2016-3750 | x     | x     | x     | x     |
| dup2      |          | x     | x     | x     |         |
| epoll_create | CVE-2011-1083 | x     | x     | x     | x     | x     |
| epoll_ctl | CVE-2013-7446 | x     | x     | x     | x     | x     |
| epoll_wait|          | x     | x     | x     | x     | x     |
| eventfd2  |          | x     | x     | x     | x     | x     |
| execve    | CVE-2018-14634 | x     | x     | x     | x     | x     |
| exit      |          | x     | x     | x     | x     | x     |
| exit_group|          | x     | x     | x     | x     | x     |
| fadvise64 |          |       |       |       | x     |       |
| fcntl     | CVE-2016-7118 | x     | x     | x     | x     | x     |
| fstat     |          | x     | x     | x     | x     | x     |
| ftruncate | CVE-2018-18281 |       |       |       | x     |       |
| futex     | CVE-2020-14381 | x     | x     | x     | x     | x     |
| getcwd    |          | x     | x     | x     | x     |
| getdents  | CVE-2011-1593 | x     | x     | x     | x     |
| getdents64|          | x     | x     | x     | x     |
| getegid   |          | x     | x     | x     | x     |
| geteuid   |          | x     | x     | x     | x     |
| getgid    |          | x     | x     | x     | x     |
| getpeername|          | x     | x     | x     | x     |
| getpgrp   |          | x     | x     | x     | x     |
| getrandom |          | x     | x     | x     | x     |
| getrlimit |          | x     | x     | x     | x     |
| getsockname | CVE-2021-38208 | x     | x     | x     | x     | x     |
| getsockopt| CVE-2021-20194 | x     | x     | x     | x     |
| getpid    |          | x     | x     | x     | x     |
| gettid    |          | x     | x     | x     | x     |
| gettimeofday |          | x     | x     | x     | x     |
| gettimeofday |          | x     | x     | x     | x     |
| ioctl     | numerous drivers | x     | x     | x     | x     |
| kill      |          | x     | x     | x     | x     |
| listen    | CVE-2013-3301 | x     | x     | x     | x     |
| lseek     |          | x     | x     | x     | x     |
| lstat     |          | x     | x     | x     | x     |
| madvise   | CVE-2016-5195 | x     | x     | x     | x     |
| mkdir     |          | x     | x     | x     | x     |
| mmap      | CVE-2018-7740 | x     | x     | x     | x     |
| mprotect  | CVE-2010-4169 | x     | x     | x     | x     |
| mremap    | CVE-2020-10757 | x     | x     | x     |
| munmap    | CVE-2020-29369 | x     | x     | x     | x     |
| nanosleep |          |       |       |       | x     |       |
| newfstatat |          | x     |       |       | x     |       |

17
Table 2: Comparison of system calls allowed by various filtering policies. If a system call does not appear in this table, it was not contained in a policy generated by TIMELOOPS, sysfilter, or observed when the program executed. The CVE column lists one CVE, if any could be found, in the Linux kernel where the associated system call was used to trigger the vulnerability.

| syscall        | CVE      | Baseline | Timeloops | Sysfilter | Baseline | Timeloops | Sysfilter | Podman |
|----------------|----------|----------|-----------|-----------|----------|-----------|-----------|--------|
| open           | CVE-2020-8428 | x        | x         | x         | x        | x         |           |        |
| openat         | CVE-2020-10768 | x        | x         | x         | x        |           |           |        |
| pause          | x         |           |           |           | x        |           |           |        |
| pipe           | CVE-2015-1805 | x         | x         |           |          |           |           |        |
| poll           | x         | x         |           | x         | x         | x         |           |        |
| prctl          | CVE-2020-10768 | x         | x         | x         | x         | x         |           |        |
| pread64        | x         | x         |           |           |           |           |           |        |
| prlimit64      | x         | x         |           | x         | x         |           |           |        |
| pselect6        | x         | x         |           | x         |           |           |           |        |
| pwrite64       | x         | x         |           |           |           |           |           |        |
| pwritev        | x         |           |           |           |           |           |           |        |
| read           | x         | x         | x         | x         | x         |           |           |        |
| readlink       | CVE-2011-4077 | x         |           | x         | x         |           |           |        |
| readv          | CVE-2008-3535 | x         | x         |           | x         |           |           |        |
| recvfrom       | CVE-2013-1979 | x         | x         | x         | x         | x         |           |        |
| recvmsg        | CVE-2013-1979 | x         | x         | x         | x         | x         |           |        |
| rename         | x         |           |           |           |           |           |           |        |
| restart_syscall | CVE-2014-3180 | x         |           |           |           |           |           |        |
| rmdir          | x         |           |           |           |           |           |           |        |
| rt_sigaction   | x         | x         | x         | x         | x         | x         |           |        |
| rt_sigprocmask | CVE-2017-15537 | x         | x         | x         |           |           |           |        |
| rt_sigtreturn  | x         | x         |           | x         |           |           |           |        |
| rt_sigsuspend  | x         | x         |           |           |           |           |           |        |
| sched_get_priority_max | x   | x         | x         | x         | x         |           |           |        |
| sched_get_priority_min | x   | x         | x         | x         | x         | x         |           |        |
| sched_getaffinity | x   | x         |           | x         |           |           |           |        |
| sched_getparam  | x         |           |           | x         |           |           |           |        |
| schedGetscheduler | x   |           |           | x         |           |           |           |        |
| sched_setaffinity | CVE-2021-26708 | x   |           |           |           |           |           |        |
| sched_setscheduler | x   |           |           | x         |           |           |           |        |
| sched_yield     | x         | x         |           | x         |           |           |           |        |
| select          | x         | x         |           |           |           |           |           |        |
| sendfile        | x         |           |           |           |           |           |           |        |
| sendmsg         | CVE-2011-4594 | x         |           | x         |           |           |           |        |
| sendmmsg        | CVE-2017-17712 | x   |           |           |           |           |           |        |
| sendto          | CVE-2017-17712 | x         | x         | x         |           |           |           |        |
| set_robust_list | x         | x         | x         | x         | x         | x         |           |        |
| set_tid_address | x         | x         |           | x         | x         | x         |           |        |
| setgid          | CVE-2021-32760 | x         | x         |           |           |           |           |        |
| setgroups       | CVE-2018-7169 | x         | x         |           |           |           |           |        |
| setitimer       | x         | x         |           |           |           |           |           |        |
| setpriority     | x         |           |           |           |           |           |           |        |
| setregid        | x         |           |           |           |           |           |           |        |
| setresgid       | x         | x         | x         | x         | x         |           |           |        |
| setresuid       | CVE-2019-18684 | x         | x         | x         | x         | x         |           |        |
| setreuid        | CVE-2011-3145 | x         |           | x         | x         |           |           |        |
| setrlimit       | x         |           |           |           |           |           |           |        |
| setuid          | CVE-2017-5669 | x         |           |           | x         |           |           |        |
| shmat           | x         |           |           |           |           |           |           |        |
| shmdt           | x         |           |           |           |           |           |           |        |
| shmmget         | CVE-2017-5669 | x         |           |           |           |           |           |        |
| shutdown        | x         | x         | x         | x         | x         |           |           |        |
| signalstack     | CVE-2009-2847 | x         |           |           |           |           |           |        |
| socket          | CVE-2017-9074 | x         | x         | x         | x         |           |           |        |
| socketpair      | CVE-2010-4249 | x         | x         | x         |           |           |           |        |
| stat            | x         | x         |           |           |           |           |           |        |
| statfs          | x         |           |           |           |           |           |           |        |
| sysinfo         | x         | x         |           |           |           |           |           |        |
| tgkill          | CVE-2013-2141 | x         |           |           |           |           |           |        |
Table 2: Comparison of system calls allowed by various filtering policies. If a system call does not appear in this table, it was not contained in a policy generated by TIMELOOPS, sysfilter, or observed when the program executed. The CVE column lists one CVE, if any could be found, in the Linux kernel where the associated system call was used to trigger the vulnerability.

| syscall | CVE     | Nginx | ComposePost |
|---------|---------|-------|-------------|
|         | CVE     | Baseline | Timeloops | Sysfilter | Baseline | Timeloops | Sysfilter | Podman |
| time    |         | x      | x          | x         | x      | x          | x          |         |
| times   |         | x      | x          | x         | x      | x          | x          | x       |
| umask   | CVE-2020-35513 | x      | x          | x         | x      | x          | x          | x       |
| uname   | CVE-2012-0957 | x      | x          | x         | x      | x          | x          | x       |
| unlink  | CVE-2016-6197 | x      | x          | x         | x      | x          | x          | x       |
| utimes  |         | x      | x          | x         | x      | x          | x          | x       |
| vfork   | CVE-2005-3106 | x      | x          | x         | x      | x          | x          | x       |
| wait4   |         | x      | x          | x         | x      | x          | x          | x       |
| writev  | CVE-2016-9755 | x      | x          | x         | x      | x          | x          | x       |