Programmable System Call Security with eBPF

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Abstract

System call filtering is a widely used security mechanism for protecting a shared OS kernel against untrusted user applications. However, existing system call filtering techniques either are too expensive due to the context switch overhead imposed by userspace agents, or lack sufficient programmability to express advanced policies. Seccomp, Linux's system call filtering module, is widely used by modern container technologies, mobile apps, and system management services. Despite the adoption of the *classic* BPF language (cBPF), security policies in Seccomp are mostly limited to *static* allow lists, primarily because cBPF does not support *stateful* policies. Consequently, many essential security features cannot be expressed precisely and/or require kernel modifications.

In this paper, we present a programmable system call filtering mechanism, which enables more advanced security policies to be expressed by leveraging the *extended* BPF language (eBPF). More specifically, we create a new *Seccomp eBPF* program type, exposing, modifying or creating new eBPF helper functions to safely manage filter state, access kernel and user state, and utilize synchronization primitives. Importantly, our system integrates with existing kernel privilege and capability mechanisms, enabling unprivileged users to install advanced filters safely. Our evaluation shows that our eBPF-based filtering can enhance existing policies (e.g., reducing the attack surface of early execution phase by up to 55.4% for temporal specialization), mitigate real-world vulnerabilities, and accelerate filters.

1 Introduction

Modern computer systems run a large variety of untrusted applications on a trusted operating system (OS) kernel. These applications interact with the OS kernel through the system call interface. Hence, system call security is a cornerstone for protecting a shared kernel against untrusted user processes. System call filtering is a widely used system call security mechanism. The basic idea is to restrict the system calls a given process can invoke based on predefined security policies, thereby reducing the attack surface. The filtering is done at the entry point of every system call to decide whether to allow or deny each system call.

Early system call filtering techniques such as Janus [94] and Ostia [50] employ trusted userspace agents to implement system call security policies. However, userspace agents incur significant context switch overheads to system call filtering, because every system call needs to switch to user space for policy checking and then switch back. Furthermore, the implementations are prone to many common traps and pitfalls, such as time-of-check-to-time-of-use (TOCTTOU) based race conditions of argument values [22, 49, 84].

Modern system call filter techniques such as Linux's Seccomp (SECure COMPuting) run entirely inside the OS kernel, without the overhead of additional context switches. This brings significant performance advantages over userspace agents and some resistance to TOCTTOU-based argument races. Today, Seccomp is widely used to provide "*the most important security isolation boundary* [18]." For example, every Android app is isolated using Seccomp [83]; `systemd` uses Seccomp for user process sandboxing [29]; Google's Sandboxed API project [14] uses Seccomp for sandboxing C/C++ libraries; Lightweight virtualization technologies such as Docker [15], Google gVisor [7], Amazon Firecraker [6, 18], LXC/LXD [9], Rkt [88], and Kubernetes [73] all use Seccomp.

However, a major limitation of Seccomp is the lack of sufficient programmability to express advanced security policies. From an initial mode (known as strict mode) that blocked all system calls except `read()`, `write()`, `_exit()`, and `sigreturn()`, Seccomp now (since Linux v3.5) allows custom security policies to be written in the *classic* BPF language (cBPF) [30] in the filter mode. Filter mode enables application-specific security policies and results in the wide adoptions of Seccomp by different applications.

Unfortunately, the programmability of cBPF is overly limited—security policies in Seccomp are mostly limited to *static* allow lists. This is primarily because cBPF provides no mechanism to store states and hence cBPF filters have to be *stateless*. Furthermore, cBPF provides no interface to invoke any other kernel utilities or other BPF programs. As a result, many desirable and/or essential system call filtering features cannot

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be directly implemented based on Seccomp-cBPF, instead requiring significant kernel modifications (a major deployment obstacle). Section 3 discusses these features in details. Recognizing the need for more expressive policies, Seccomp recently added a new feature known as Notifier [23], to support the old idea of userspace agents, which unfortunately shares their limitations (performance overhead, TOCTTOU issues, etc.).

In this paper, we present a programmable system call filtering mechanism by leveraging the *extended* BPF language (eBPF). Our goal is to enable advanced system call security policies to better protect the shared OS kernel, without impairing the system call performance or reducing OS security.

Our choice of eBPF is a result of practicality considerations: 1) eBPF offers basic building blocks for the target programmability, including maps for statefulness and helper functions for interfacing with the kernel; 2) like cBPF, eBPF is verified to be safe by the kernel; and 3) we can largely reuse existing implementation code in Linux.

Note that naïvely opening the eBPF interface in Seccomp, as early Linux patches [36, 65, 102], is not a solution, because: 1) basic support is missing (e.g., synchronization primitives for serialization); 2) existing utilities (e.g., task storage) may not fit the Seccomp model because they target privileged contexts only; and 3) existing features are not safe for Seccomp use cases, e.g., the current user memory access feature cannot address TOCTTOU issues.

To this end, we create a new Seccomp-eBPF program type which is highly programmable for users to express advanced system call security policies in eBPF filter programs. Specifically, we expose, modify, and create new eBPF helper functions to safely manage filter state, access kernel and user state, as well as utilize synchronization primitives. Importantly, our system integrates with existing kernel privilege and capability mechanisms, enabling unprivileged users to install advanced filters safely and preventing privilege escalation. The security of Seccomp-eBPF is equivalent to the two existing kernel components: Seccomp and eBPF.

We implement the new Seccomp-eBPF program type on top of Seccomp in the Linux kernel. We maintain the existing Seccomp interface with tamper protection. We implement many features required by real-world use cases, such as checkpoint/restore in userspace (CRIU), sleepable filter, and deployment configuration to make Seccomp-eBPF a privileged feature. We also modified an existing container runtime (crun) to support Seccomp-eBPF-based system call filtering.

We use Seccomp-eBPF to implement various new security use cases, including system call count/rate limiting, flow-integrity protection (SFIP), and serialization. We show how these features can prevent real-world vulnerabilities that cannot be safely prevented by cBPF filters. We also use eBPF filters to enhance temporal specialization, which achieves up to 55.4% reduction of the system call interface of the early execution phases, compared to existing cBPF implementations.

Lastly, we use eBPF filters to implement validation caching which can improve application performance by up to 10%.

The paper makes the following main contributions:

- We discuss several essential use cases of system call filtering, which reveal limitations of the state-of-the-art filtering mechanism exemplified by Seccomp.
- We present the design and implementation of Seccomp-eBPF that enhances programmability of system call security and integrates well with the kernel, without affecting performance or security.
- We implement and evaluate the advanced system call security features using Seccomp-eBPF filters for real-world applications against real-world vulnerabilities.

The code of our implementation of Seccomp-BPF on Linux can be found at,

https://github.com/xlab-uiuc/seccomp-ebpf-upstream

2 Background

In this section, we briefly discuss the necessary background for understanding the limitation of Seccomp as the state-of-the-practice system call filtering mechanism.

2.1 Seccomp-cBPF

Seccomp currently relies on the *classic* BPF (cBPF) language for users to express system call filters as programs [39, 71]. cBPF has a very simple register-based instruction set, making the filter programs easy to verify. Due to the limited programmability, cBPF filters in Seccomp mostly implement an allow list—the filter only allows a system call if the system call ID is specified. Occasionally, a cBPF filter will further check arguments of primitive data types and prevent a system call if the argument check fails. Pointer-typed arguments, however, cannot be dereferenced.

cBPF filters are *stateless*—the output of a Seccomp-cBPF filter execution depends only on the specified system call ID and argument values (in the allow list), because cBPF does not provide any utility of state management.

A cBPF filter is size-limited by 4096 instructions; therefore, complex security policies have to be implemented by a chain of multiple filters. All installed filters in the chain are executed for every system call, and the action with the highest precedence is returned. The chaining behavior, however, comes with a performance overhead mainly due to security mitigations (e.g., Spectre) against indirect jumps [74].

Under the cover, Seccomp chooses to transform cBPF filters into eBPF code internally to take the advantage of extensively optimized eBPF toolchains, which produce code that runs up to 4X faster on x86-64 over using cBPF directly [91]. Note: this does not mean system call filters can be implemented in eBPF—the language exposed is still cBPF and eBPF features (e.g., maps and helpers) are not available.

2.2 Seccomp Notifier

The limited expressiveness of cBPF makes it hard to implement complex security policies. Therefore, Seccomp recently incorporated support for a userspace agent (called Notifier [23]) to complement cBPF filters. Similar to early system call interposition frameworks [49, 50, 58, 94], it defers the decision to a trusted user agent. Specifically, when Seccomp captures a system call, it blocks the calling task and redirects the system call context (e.g., calling PID, system call ID, and argument values) to the agent.

A major disadvantage of Seccomp Notifier is its significant performance overhead due to the additional context switches introduced by switching to the user space back and forth. Furthermore, to examine the contents of system call arguments that are user-space pointers, Seccomp Notifier must use ptrace to access the memory of the monitored process. In addition to its performance implications, such inspection is subject to time-of-check-to-time-of-use (TOCTTOU) race conditions where a thread in the monitored program may change memory contents (and thus argument values) after the check has been completed by Seccomp Notifier. Finally, the need to run a userspace agent in a trusted domain makes it challenging to be used in some deployment environments, e.g., for daemonless container runtimes [12]. For all of these reasons, Seccomp Notifier is inadequate for complex system call filtering policies.

3 Essential System Call Filtering Features

We highlight four features, none of which can be implemented using Seccomp-cBPF, that will lead to a more effective, efficient, and robust system call filtering framework: statefulness, expressiveness, synchronization, and safe user memory access. We motivate the need for each feature with concrete examples.

3.1 Statefulness

System call filtering with the existing Seccomp-cBPF framework is fundamentally stateless: an invocation of the system call filter cannot carry state to subsequent invocations. As a result, policies are overly loose. Here we describe three practical, tight policies that require state passing: system call count limiting, system call sequences checking, and enhanced temporal specialization.

System call count limiting. Many attacks rely on invoking specific system calls repeatedly to cause starvation (e.g., fork bomb) or overflows (§7.2.1). An effective defense is to limit the times a system call can be executed based on the demand of the application.

As a concrete example, a special case of system call count limiting is to restrict the use of a specific system call to a single invocation, which is a common goal for container runtimes. The goal is to prevent the launched containers from issuing exec() to replace the process image. Container runtimes take three common steps to launch a container: 1) installing Seccomp filters, 2) dropping privileges, and 3) launching containers using an exec system call. The three steps are exemplified by the following code from runc [13], a container runtime used by Docker and Kubernetes:

```
1  // Without NoNewPrivileges, seccomp is a
2  // privileged operation, so we need to do
3  // this before dropping capabilities
4  if l.cfg.Config.Seccomp != nil &&
5      !l.cfg.NoNewPrivileges {
6    seccomp.InitSeccomp(...)
7  }
8  // Drops the capabilities, sets the correct
9  // user and working dir, before executing the
10  // command inside the namespace
11  finalizeNamespace(...)
12  ...
13  pdeath.Restore()
14  ...
15  if unix.Getppid() != l.parentPid { ... }
16  ...
17  unix.Write(fd, []byte("0"))
18  ...
19  system.Exec(name, l.cfg.Args[0:], os.Env())
```

The snippet shows that the Seccomp filter needs to be installed *before* calling exec (L19). The desired policy is to only allow exec once at L19, but not later. However, it is hard to implement the policy using stateless filters. Note that the filter installation (L6) cannot be moved to a later point, because it requires the CAP_SYS_ADMIN capability, which is dropped within finalizeNamespace (L11).

As a result, with cBPF filters, the dangerous exec system call is commonly allowed for the entire duration of the container execution, even though it is not needed by the containerized applications [4, 8].

In fact, exec is not an exception. The container runtime has to allow many other security-sensitive system calls in the same way, such as prctl, capset, and write as shown in the code snippet. As with exec, these system calls cannot be blocked in a stateless filter, either.

If the system call filtering framework supported stateful policies, the filter could keep track of the number of invocations of a (potentially dangerous) system call and block further invocations.

Checking system call sequences and state machines. Recent work [24] shows that an application's system call behavior can be modeled by a "system call state machine", which can be used for security enforcement named SFIP (Syscall Flow Integrity Protection); the state machine can be automatically generated using static analysis [24]. Moreover, prior work on IDS (Intrusion Detection Systems) has showed that an attack can be modeled by a sequence of system calls [27, 44, 45, 57, 77, 78]. Support for stateful filters that maintain sequences and state machines would enable a

system call filtering framework to implement both SFIP and IDS enforcement.

Precise temporal specialization. Prior work [54, 63, 75] shows the benefits of fine-grained security policies for different execution phases of the target application which often need distinct sets of system calls.

Ghavamnia et al. [54] propose to apply cBPF Seccomp filters at different execution phases to achieve temporal system call specialization. However, this technique is fundamentally limited under the current Seccomp-cBPF security model. In Seccomp, a filter, once installed, cannot be uninstalled during the process lifetime. Filters installed in later phases are chained with the filters installed earlier; all the installed filters are executed for every system call and the most restrictive policy is applied. Hence, with cBPF Seccomp filters, a system call needed in Phase N has to be allowed in all earlier phases (Phases $1...N-1$), even though the system call is not needed in any of the $N-1$ phases. Figure 4 illustrates this point with a two-phase temporal specialization ($N = 2$), where P1 (Initialization) has to include system calls from P2 (Serving) with Seccomp-cBPF.

The limitation is rooted in the fact that cBPF filters cannot record states (i.e., the current execution phase). By recording the current phase in a state variable and applying the corresponding policy, a stateful system call filtering framework would enable precise temporal specialization and achieve tighter security policies for each phase.

3.2 Expressiveness

As with any user-supplied code or policy running in the kernel, system call filtering frameworks typically must trade off expressiveness and safety. The safety goals of cBPF have led it to a design prioritizing safety, with an overly restricted instruction set and runtime.

Performance optimizations. Given the cBPF instruction set, a cBPF filter is typically in the form of an allow list, implemented by a series of conditional jumps [39, 71]. Complex policies result in long lists of jumps and multiple filters (due to the size limit of a cBPF filter, see §2). Consequently, system call checking becomes expensive due to the need of iterating over long jump lists [60, 65, 66, 71, 90] and the overhead of indirect jumps caused by mitigations to speculative vulnerabilities (e.g., Retpoline) [74]. To reduce the overhead, multiple optimizations were proposed, such as dedicated Seccomp caches [90], skip-list search [35], and filter merging [74].

A more expressive system call filtering framework can optimize the filter performance. First, advanced data structures with constant lookup time (e.g., a hash map) can be used to eliminate long jump lists. Such an implementation is essentially equivalent to the dedicated Seccomp cache [90].

Moreover, cBPF filters are limited by 4096 instructions; allowing more instructions could eliminate the overhead of indirect jumps caused by chaining multiple filters, raised by Retpoline or other mitigations to speculative vulnerabilities. In a stateful system call filtering environment, one can further use map entries to sequence filters for more complex policies with low overhead. As we will see in §5, such enhancements to expressiveness can be achieved without sacrificing safety.

Rate limiting. Besides the performance aspects, the limited expressiveness of cBPF, due to the simple instruction sets and the program size constraints, also makes it hard to support advanced policies. One such example is rate limiting which only allows specified system calls to be issued under expected rates. Rate limiting relies on a timer. However, there is no timer utility in cBPF; in fact, cBPF cannot invoke any kernel functions or utilities. Furthermore, cBPF cannot record the last time in any state variable. A system call filtering framework with better expressiveness could be a solution; in particular, by exposing advanced and complex operations to the filters in a safe way. Such a framework could expose the current time information to the filter to facilitate the desired system call rate limiting.

3.3 Synchronization

System call filtering frameworks essentially provide a platform for mandating access into the kernel and can be used to implement application- or system-wide policies to prevent misuse of the kernel. Specifically, there has been increasing reports on kernel vulnerabilities that manifest via race conditions and are exploitable by two concurrently executing system calls [59, 68, 97, 98, 100]. Mitigating such attacks requires kernel developers to identify the race condition in the kernel, patch the vulnerable code, potentially backport the revisions to older kernel versions, and release a patched version. The above process is time-consuming; waiting for the kernel patches could open a long window of vulnerability. A system call filtering framework which can serialize specific system calls that are known to be exploitable by system call racing can immediately and effectively nullify race conditions without waiting for patches, backports, and releases.

3.4 Safe User Memory Access

Since a large number of system calls take pointers to user memory as arguments, deep argument inspection (DPI) is long desired [40, 42]. Seccomp-cBPF cannot support DPI because it only checks non-pointer argument values, i.e., if an argument is a pointer, it cannot be dereferenced by Seccomp-cBPF, which means that accepting or rejecting the system call cannot depend on values in structures that are passed to system calls via pointers. In fact, it means that Seccomp-cBPF cannot even address any string values (e.g., a file path in open()). To enable DPI, a system call filtering framework needs to provide a safe way to access user memory referred to by the pointer arguments. The main challenge (which is

also the reason that Seccomp does not dereference pointers) is to avoid the time-of-check-to-time-of-use (TOCTTOU) issue [22, 49, 84], where user space can change the value of what is being pointed to between the time the filter checks it and the time the value gets used.

4 Threat Model and Design Goals

4.1 Threat Model

We strictly adhere to the current threat model of Seccomp. The goal is to restrict how untrusted userspace applications interact with the shared OS kernel through system calls to protect the kernel from userspace exploits (e.g., shellcode or ROP payload). The kernel is trusted.

Seccomp requires the calling context to either be privileged (having CAP_SYS_ADMIN in its user namespace), or set NO_NEW_PRIVS [38] which ensures that an unprivileged process cannot apply a malicious filter and then invoke a set-user-ID or other privileged program using exec.

Once a filter is installed onto a process, it cannot be removed before the process termination. A filter cannot be tampered—a filter program and its states will be invisible to unprivileged processes once it is installed.

4.2 Design Goals

Given this threat model, we set the following goals:

- **Expressiveness and kernel support.** We aim to support all the essential system call filtering features discussed in §3. This not only requires a more programmable and expressive language, but also additional kernel support.
- **Maintain Seccomp usage model and interfaces.** In order to provide a practical, familiar and useful system call filtering framework, we must adhere to the same usage and threat model of Seccomp (§4.1). Further, to lower the barrier of adoption, we aim to maintain its interface.
- **No privilege escalation for unprivileged users.** As Seccomp supports the unprivileged use case (§4.1), our design must ensure no privilege escalation.

5 Design

5.1 Overview

We develop a programmable system call filtering mechanism on top of Seccomp, by leveraging the *extended* BPF language (eBPF), to enable advanced security policies (see §3). eBPF is a fundamental redesign of the BPF infrastructure within the Linux kernel [5]. It not only has a rich instruction set and flexible control flows (e.g., bounded loops and BPF-to-BPF calls), but also offers new features, such as *helper functions* to interface with kernel utilities and *maps* as efficient storage primitives to maintain states.

The choice of eBPF is a result of practicality considerations: 1) eBPF offers basic building blocks for the target
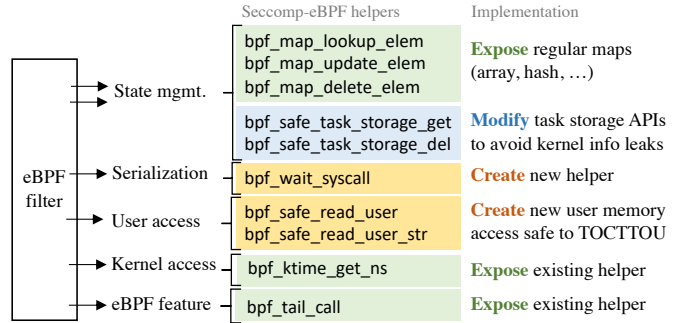

Figure 1. Features, helper interfaces, and their implementation of the Seccomp eBPF program type.

programmability, including maps for statefulness and helper functions for interfacing with the kernel; 2) eBPF is verified to be safe by the kernel; and 3) since Seccomp already converts cBPF code into eBPF internally (§2.1), we can largely reuse existing Seccomp implementation and workflow.

However, directly opening the eBPF interface in Seccomp is not a solution: 1) basic supports are missing (e.g., synchronization primitives for serialization); 2) existing utilities (e.g., task storage) may not fit the Seccomp model because they target privileged context only; and 3) existing features are not safe for Seccomp use cases, e.g., the current user memory access feature cannot address TOCTTOU issues.

We expose, modify, and create new eBPF helper functions to safely manage filter state, access kernel and user state, and utilize synchronization primitives. Figure 1 illustrates these helper functions. Importantly, our system integrates with existing kernel privilege and capability mechanisms, enabling unprivileged users to safely install advanced filters. Essentially, we create a new *Seccomp-eBPF* program type which is highly programmable to express advanced system call security policies in eBPF filter programs.

In terms of security, we reduce the security of Seccomp-eBPF to the security of Seccomp and eBPF.

5.2 Seccomp-eBPF Program Type

An eBPF program type defines what helper functions (helpers) a program of the type is allowed to invoke and the corresponding capabilities required for invoking them. In other words, a program type defines its interface to the kernel and the capability system to use the interface. For a given filter program, the eBPF verifier checks the helper invocation instructions in the filter program and the capabilities of the calling context at the load time, as shown in Figure 2.

Specifically, the eBPF verifier checks both eBPF language specifications and Seccomp-eBPF program type. We extend the eBPF verifier to check the new Seccomp-eBPF program type, BPF_PROG_TYPE_SECCOMP. Seccomp-eBPF restricts (1) the use of helper functions, (2) the access to Seccomp data structures. The eBPF verifier already provides hooks where we
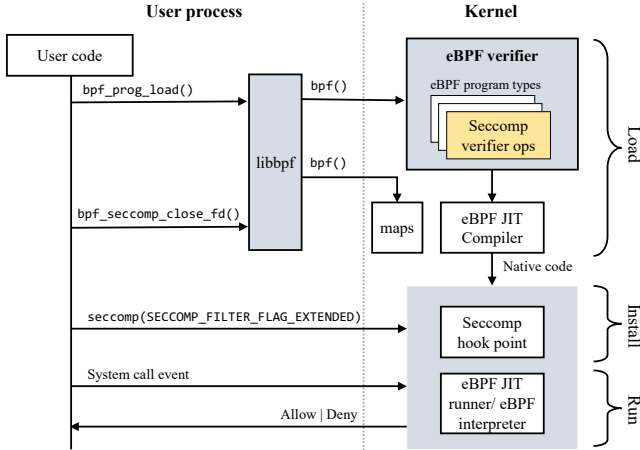
Figure 2. Workflow of a Seccomp-eBPF filter

directly add our verification code. For (1), we declare the helper functions that eBPF filters are permitted to use (§5.3). For (2), we verify that filters only access data within the boundary of Seccomp data structures with correct offset and size. We strictly follow the verification against eBPF language specifications.

Figure 2 depicts the workflow of loading, installing, and running a Seccomp-eBPF filter. The filter is first loaded into the kernel, where it is verified and optionally JIT-compiled, and then installed in Seccomp. After that, the installed eBPF filter will be invoked upon every subsequent system call.

5.3 Helper Functions

Figure 1 shows the helper functions of the Seccomp-eBPF program type (`BPF_PROG_TYPE_SECCOMP`). Overall, there are ten helpers in five categories: (1) *state management* based on helpers to access (lookup/update/delete) maps, (2) *serialization* which needs synchronization helpers, (3) *user access* for safely accessing user memory, (4) *kernel access* for invoking kernel utilities such as time, and (5) *eBPF program features* such as tail calls that allow more complex programs.

Five of them already exists in Linux and can be directly *exposed* to the Seccomp-eBPF program type. The others are not available. In this section, we discuss the *new* helpers that are created from scratch or by modifying existing ones.

5.3.1 Task Storage. Maps are the basic enabler to statefulness (§3.1). eBPF currently supports different types of maps, including array maps and hash maps.

One important map type is task storage, which provides primitives for policies that need to maintain separate states for different tasks executing the same eBPF filter (loaded by the same FD). eBPF already implements task storage map, which uses Linux tasks as keys to access the stored values. This guarantees that storage from different tasks does not collide. The task storage can be used through two helpers: (1) `bpf_task_storage_get` and (2) `bpf_task_storage_delete`.

However, both the two helpers require additional capabilities, `CAP_BPF` and `CAP_PERFMON`, and thus cannot be used in unprivileged contexts, which hinders Seccomp's use cases (an unprivileged user process can install a Seccomp filter as long as it sets `NO_NEW_PRIVS`, see §4.1). Our goal is to redesign the helpers for task storage maps to make them essential utilities of Seccomp-eBPF filters.

Why do the helpers for task storage maps need additional privileges, while the other map helpers do not (e.g., `bpf_map_lookup_elem` in Figure 1)? The reason is that the API design of the existing helpers for task storage maps makes them insecure to unprivileged Seccomp-eBPF filters: the existing helpers used to access the task storage require a `task_struct` pointer as input argument to find the corresponding map storage. While a privileged eBPF filter can call `bpf_get_current_task_btf` to retrieve the needed `task_struct` pointer, such operation is insecure in an unprivileged context because a `task_struct` contains a pointer to its parent `task_struct`. A malicious filter can dereference the parent pointer recursively to reach the init task (PID 0) from the current process, leaking sensitive kernel information.

To avoid this issue and provide unprivileged filters with secure task storage, we create a new set of task-storage helpers. Our new helpers do not require a `task_struct` as input. Instead, the helpers automatically find the current task's group leader. For a process, this is its own `task_struct`; for a thread, this is the group leader—the task that spawned it.

5.3.2 Safe User Memory Access. Safely accessing user memory is an important feature for checking pointer-typed argument values, as discussed in §3.4. We support such a feature and expose it through specialized helpers. Note that eBPF provides two helpers for accessing memory of user processes. However, these helpers cannot be used for deep argument inspection because they cannot address TOCTTOU-based argument racing [49, 97].

We follow the prior work on deep argument inspection [25, 40]. The key principle is to disallow user space to modify the argument values during and after the values are checked. This can be achieved by (1) copying the target user memory into a protected memory region that is only accessible by the kernel, (2) making the target user memory write-protected or inaccessible to user space, or (3) using protection-key functionalities in the kernel to prevent races from user space [32, 47, 61]. We implement the first two solutions, as they can be done on all commodity hardware, and expose them with user-memory access helpers.

Capability. The existing user-memory access helpers from eBPF require `CAP_BPF` and `CAP_PERFMON`. We reduce the security of Seccomp-eBPF to Seccomp Notifier [23] which allows the userspace agent to read and copy user memory if the agent is allowed to `ptrace` the process. i.e., the security of Seccomp Notifier is equal to `ptrace`. Therefore, we also reduce the capabilities of user-memory access helpers to `ptrace`.

Linux determines if one process (tracer) can `ptrace` another process (tracee) based on the following checks: 1) they are in the same thread group, 2) they are under the same user and group, or if the tracer has `CAP_SYS_PTRACE`, 3) the tracee cannot be traced without `CAP_SYS_PTRACE` if it has set itself to be non-dumpable, and 4) other LSM hooks.

How does `ptrace` apply to Seccomp? In Seccomp, the filter is regarded as the tracer, with the process that installs the filter being the tracee. Since unprivileged Seccomp requires the `NO_NEW_PRIVS` attribute to be set on the calling task, the UID/GID and capability set can not change after the filter installation. Hence, the in-kernel `ptrace` checks are largely covered by the `NO_NEW_PRIVS` attribute. Furthermore, the dumpable attribute is respected.

On Linux, the capability of `ptrace` also depends on a system-wide configuration, `ptrace_scope` [16]. To ensure that user-memory access helpers follow `ptrace` security, we define a new LSM hook that enforces the helpers to adhere to the policy set by `ptrace_scope`.

Protecting non-dumpable process. On Linux, a process (e.g., OpenSSH) handling sensitive information can set the "dumpable" attribute (via `PR_SET_DUMPABLE`) to prevent being coredumped or ptraced by another unprivileged process. Hence, an unprivileged Seccomp-eBPF filter should not be able to access memory of non-dumpable processes. To protect such processes, we apply a privilege requirement similar to ptrace. The helpers are modified to allow a filter to access non-dumpable memory only if the loader process has ptrace privileges (`CAP_SYS_PTRACE`).

Handling page faults. The original user-memory access helpers in Linux do not handle page faults when reading memory from userspace. The helpers use non-blocking functions (e.g., `copy_from_user_nofault`), which emit errors upon page faults. This is based on the dated assumption that a BPF program never sleeps, i.e., it cannot be blocked in the middle of execution [33]. This is inconvenient for Seccomp-eBPF filters—invoking a user-memory helper would fail if the memory access triggers a page fault. We support *sleepable* Seccomp-eBPF filters (§6). Therefore, our user-memory access helpers can handle page faults.

5.3.3 Serializing System Calls. The basic idea to serialize two racing system calls is to record the event of involved system calls. When a system call is invoked concurrently with another system call under execution which is known to have race vulnerabilities with it, the kernel stops the former system call until the latter finishes.

In this use case, the kernel records whether a particular system call (in terms of system call ID) is currently being executed and stores the information. For each system call, we add an integer atomic variable in the kernel to store whether there exists processes that are currently executing the system call. This atomic variable has an initial value of 0 and will be incremented by our new helper function. When a system

call exits, its atomic variable is decremented, but the value will have a minimum of 0.

Helper API. We expose a new helper function,

`void bpf_wait_syscall(int curr_nr, int target_nr)`

for system call serialization. The helper function holds the execution of the current task until the execution of the target system call finishes. To achieve this, it increments the atomic variable of the current system call and perform busy waiting via a schedule loop until the atomic variable of the other system call is decremented to 0, which means no processes are executing the other system call. The helper is unprivileged, because it only affects the processes that attach the filter.

Enforcement. The eBPF filter that implements serialization uses a map to store system calls that have race vulnerabilities as key-value pairs. The map can be updated by a trusted userspace process after filter installation, when new race vulnerabilities need to be patched (§3.3). The filter implements a logic that, for each incoming system call, it checks whether the system call has a potential race condition based on the map. If so, the filter will invoke the `bpf_wait_syscall` helper to serialize the current system call.

To enforce system-wide serialization policies, we install the filter onto the `init` process. In Seccomp, a process inherits the filter of its parent process. Since `init` is the ancestor of all subsequent processes, the installed filter is inherited by all processes on the system, hence implementing a global policy. Since the kernel requires the root privilege when retrieving map file descriptor, only trusted, privileged processes can update the map.

5.4 Usage

The user loads a Seccomp-eBPF filter into the kernel via the `bpf()` system call and installs it using the `seccomp()` system call. Different from cBPF filters which are implemented using BPF instructions, the kernel expects eBPF filters to be loaded as bytecode. This allows eBPF filters to be written in high-level languages, such as C and Rust, and compiled using LLVM/Clang. In fact, eBPF has more mature and actively developing tool chains than cBPF (cBPF "*is frozen* [93].").

We add a new flag, `SECCOMP_FILTER_FLAG_EXTENDED`, to the `seccomp()` system call; if it is set, the filter is interpreted in eBPF; otherwise, it is in cBPF. Note that, different from cBPF filters, before installing an eBPF filter, one needs to load it using `bpf()`. Figure 3 shows the code snippets of loading and installing a Seccomp-eBPF filter, compared with installing a Seccomp-cBPF filter.

Note that cBPF does not have a separate load step (despite its name, the `bpf()` system call is specific to eBPF). A cBPF filter is installed in one step through the `seccomp()` system call, where the verification is done at the installation time. We choose to minimize changes to the existing `seccomp()` and `bpf()` interfaces, mainly for reducing adoption obstacles.

```
1  struct sock_fprog prog = ...;
2  prctl(PR_SET_NO_NEW_PRIVS, 1, 0, 0, 0);
3  // Load and install the filter program in Seccomp
4  seccomp(SECCOMP_SET_MODE_FILTER, 0, &prog);
```

(a) cBPF: load and install in one step

```
1  // Load the eBPF filter in bytecode
2  bpf_prog_load(filter_path,
3      BPF_PROG_TYPE_SECCOMP, &obj, &fd);
4  prctl(PR_SET_NO_NEW_PRIVS, 1, 0, 0, 0);
5  bpf_seccomp_close_fd(obj);
6  // Install eBPF filter in Seccomp
7  seccomp(SECCOMP_SET_MODE_FILTER,
8      SECCOMP_FILTER_FLAG_EXTENDED, &fd);
```

(b) eBPF: load and install in two steps; verification invoked on load

Figure 3. Code snippet for installing Seccomp filters in (a) cBPF and (b) eBPF. `bpf_prog_load` is the libbpf function that wraps the `bpf()` system call; `bpf_seccomp_close_fd` closes all file descriptors (FDs) except the eBPF program FD (which is needed as a parameter for `seccomp()` and gets closed inside).

However, the separation requires additional efforts to protect filters and maps against tampering (§5.5).

5.5 Tamper Protection

As a Seccomp-eBPF filter is verified and installed in two steps (§5.4), we develop the following two tamper protections.

Protecting filter program and maps. For eBPF filters, `seccomp()` automatically closes the file descriptor (FD) of the eBPF program before returning to the user space. The user space is responsible for closing all FDs of maps before issuing the `seccomp` system call. This is to prevent leaks of the FDs, as anyone with access to the maps can potentially manipulate filter's behavior. Our new function in libbpf, `bpf_seccomp_close_fd`, closes all these FDs except the eBPF program FD, which is closed by `seccomp` itself. The maps themselves are ref-counted by the eBPF filter program after eBPF verification; therefore, closing the map FDs does not remove the maps [92].

Namespace tracking. Currently, none of the helper functions we expose to Seccomp-eBPF filters requires additional privileges. If there is a need to expose helpers that require `CAP_BPF` and/or `CAP_PERFMON` (like many existing helpers), we need to enforce that an eBPF filter is loaded and installed in the same user namespace. Otherwise, an unprivileged attacker in the current user namespace can create a new user namespace (which has all capabilities by default [11]) to bypass the capability checks in the verifier, and then sends the filter FD back to its restricted parent namespace). We develop the enforcement by recording a reference to the load-time user namespace with the filter. When installing a filter, the

kernel checks whether the current user namespace matches the recorded load-time user namespace.

6 Implementation

For practical uses in a variety of deployment environments (such as container environments), we addressed a number of implementation challenges.

Sleepable Seccomp filters. Sleepable filters are needed for Seccomp-eBPF (cBPF programs do not need to sleep), e.g., for page fault handling when accessing user memory (§5.3.2). To support sleepable filters, we create new BPF section names (`seccomp` and `seccomp-sleepable`). The BPF section is an ELF section that is used by libbpf to determine the sleepable attribute of the BPF program and set the flag when calling `bpf()`. This allows us to maintain the same `bpf()` interface without additional flags or other tooling support.

Checkpoint/restore in userspace (CRIU). CRIU is widely used by container engines to checkpoint the state of a running container to disk and restore it later. It facilitates features such as live migrations or snapshots. Seccomp currently supports CRIU only for cBPF filters. To support eBPF filters, we add two new utilities for (1) returning a file descriptor (FD) associated with an eBPF filter and (2) checkpointing map states by returning the FD of the n-th map.

Note that CRIU is only possible for privileged applications, such as container engines, as it requires `CAP_SYS_ADMIN`. Hence, an attacker taking control of an unprivileged application cannot retrieve the FD associated with a filter and modify them. Additionally, this mirrors the behavior of Seccomp-cBPF, where CRIU is considered secure.

Container runtime integration. Seccomp is an essential building block for modern container frameworks [48, 60]. It has been mentioned that Seccomp-eBPF filters are desired [70]. Integrating Seccomp-eBPF with existing container frameworks is straightforward, as our implementation maintains the same Seccomp interface.

To demonstrate this, we have integrated Seccomp-eBPF filter support in crun [89], a fast OCI-compliant container runtime and the default container runtime of Podman [12]. The code can be found at [89]. Attaching an eBPF filter to a Podman container can be done with the following command:

```
1  podman --runtime /usr/local/bin/crun run
2      --annotation run.oci.seccomp_ebpf_file
3          =ebpf_filter.o
```

Contrary to cBPF filters, which are generated from JSON-based profiles in existing container runtimes, eBPF filters are directly loaded into the kernel during the container initialization. Adding such support to other container runtimes, such as runc and CRI-O, can be done in a similar way.

Seccomp-eBPF filters as a privileged feature. For deployments that do not enable unprivileged eBPF, we provide a sysctl configuration to make Seccomp-eBPF a privileged

feature. With it set, Seccomp-eBPF can only be used by processes with the `CAP_SYS_ADMIN` capability. Even with the configuration set, Seccomp-eBPF is still very useful for container runtimes and other management contexts (e.g., `init`) that run under the root privilege. For example, most of the container frameworks are not rootless.

7 Evaluation

We evaluate the usefulness and performance of Seccomp-eBPF. For usefulness, we use Seccomp-eBPF filters to enhance temporal system call specialization over existing cBPF filter implementations (§7.1). Moreover, we use eBPF filters to implement advanced security features that cannot be supported by cBPF filters. We evaluate them with real-world vulnerabilities listed in Table 2. We then evaluate the performance of eBPF filters with both micro and macro benchmarks. We also use eBPF filters to accelerate stateless checks (§7.3).

All experiments were run on an Intel i7-9700k with 8 cores, 3.60 GHz, and 32GB RAM. The machine runs Ubuntu 20.04 with Linux kernel v5.15.0-rc3, patched with our implementation of Seccomp-eBPF.

7.1 Precise Temporal Specialization

We explained how eBPF filters could enhance the security of temporal system call specialization (§3). This section quantifies the security benefits of implementing temporal specialization in eBPF filters and comparing them with existing cBPF filter implementations [54]. We evaluate temporal specialization for two distinct phases—P1 (initialization) and P2 (Serving), as illustrated in Figure 4.

cBPF filter. With cBPF filters, we install two filters: the first filter, installed at process startup, allows $S_{init} + S_{serv}$; the second filter only allows S_{serv} and is installed at the program location that marks the start of the serving phase (the location is provided by the application developer). Hence, cBPF filters cannot precisely implement temporal specialization, i.e., only allowing S_{init} for the initialization phase. As discussed in §3, this problem becomes worse with more phases—a system call that is needed in the last phase has to be allowed in all the earlier phases.

eBPF filters. We implement temporal specialization in a single eBPF filter, installed at application startup, in which a global variable is used to record the phase. The eBPF filter strictly applies different policies based on the phase—it allows only S_{init} for the initialization phase and only S_{serv} for the serving phase. Hence, it addresses the limitations of cBPF filters. The following snippet sketches this filter:

```
1  unsigned int phase;
2  SEC("seccomp")
3  int bpf_prog_ts(struct seccomp_data *ctx) {
4    if (!phase && ctx->nr == -1) {
5      phase = 1; // phase change
6      return SECCOMP_RET_ALLOW;
```
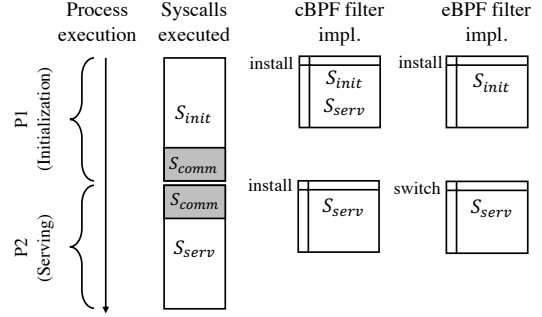

Figure 4. Two-phase temporal specialization implemented with cBPF and eBPF filters. S_{init} and S_{serv} refer to the set of system calls required by the initialization and serving phase, respectively; $S_{comm} = S_{init} \cap S_{serv}$

Application	$|S_{init}|$	$|S_{serv}|$	$|S_{comm}|$	Total	Init. Reduction
HTTPD	71	83	47	107	33.6%
NGINX	52	93	36	109	52.3%
Lighttpd	46	78	25	99	53.5%
Memcached	45	83	27	101	55.4%
Redis	42	84	33	93	54.8%
Bind	75	113	53	135	44.4%

Table 1. The numbers of unique system calls in different phases of the evaluated applications

```
7    }
8    if (!phase) { // only allow S_init
9      switch (ctx->nr) {
10       case SYS_alarm:
11         return SECCOMP_RET_ALLOW;
12       ...
13       default: break;
14     }
15   } else { // only allow S_serv
16     switch (ctx->nr) {
17       case SYS_accept:
18         return SECCOMP_RET_ALLOW;
19       ...
20       default: break;
21     }
22   }
23   return SECCOMP_RET_ERRNO | EPERM;
24 }
```

Different from cBPF filters, where the second filter needs to be installed at the phase-changing location, we insert a dummy system call that marks the phase change.

Attack surface reduction. We use the six server applications in the temporal specialization work [54]. We use S_{init} and S_{serv} of each application, provided by the research artifact [54], from which we derive S_{comm}. Table 1 shows the attack surface reduction of the initialization phase achieved by eBPF filters over the cBPF filters. The eBPF filters reduce

Vulnerabilities	Pattern	Involved System Call(s)	eBPF Filter as Defenses
CVE-2016-0728	Repeated system calls	`keyctl`	Counter limiting
CVE-2019-11487	Repeated system calls	`io_submit`	Counter limiting
CVE-2017-5123	Repeated system calls	`waitid`	Counter limiting
BusyBox Bug #9071	System call sequences	(socket → exec) or (socket → mprotect)	Flow-integrity protection
CVE-2018-18281	Raced system calls	`mremap, ftruncate`	Serialization
CVE-2016-5195	Raced system calls	(`write, madvice`) or (`ptrace, madvice`)	Serialization
CVE-2017-7533	Raced system calls	`fsnotify, rename`	Serialization

Table 2. Evaluated vulnerabilities and their patterns that can be effectively defended by Seccomp-eBPF filters.

the attack surface of the initialization phase by 33.6%–55.4% across the evaluated applications.

7.2 New Security Features

We present new security features enabled by Seccomp-eBPF filters and show that they can effectively mitigate real-world vulnerabilities (Table 2).

7.2.1 Count and rate limiting.
We implement eBPF filters for count limiting which only allows a system call to be invoked a limited number of times (§3). The filter keeps the count of the target system call using a global variable and increments the count when the system call is invoked. Once the count reaches a predefined value N, all subsequent invocations of the specific system call are denied.

The following code shows an eBPF filter that only allows an application to call the `keyctl` system call with the argument `KEYCTL_JOIN_SESSION_KEYRING` up to a max allowed count—most applications (e.g., `e4crypt`) only need to call `keyctl` once or twice.

```
1  unsigned int count;
2  SEC("seccomp")
3  int bpf_prog_cnt(struct seccomp_data *ctx) {
4    if (ctx->nr == SYS_keyctl &&
5        ctx->args[0] ==
              KEYCTL_JOIN_SESSION_KEYRING) {
6      if (count >= MAX_ALLOWED_CNT)
7        return SECCOMP_RET_ERRNO | EPERM;
8      count += 1;
9    }
10   return SECCOMP_RET_ALLOW;
11 }
```

The eBPF filter can mitigate vulnerabilities like CVE-2016-0728 which is exploited by repeatedly calling `keyctl` with `KEYCTL_JOIN_SESSION_KEYRING` to create invalid keyring objects. This would trigger buggy error handling code that omits to decrement the refcount and thus cause the refcount to overflow. We also evaluate count limiting with CVE-2019-11487 and CVE-2017-5123 shown in Table 2.

Also, we implement *rate* limiting for frequency of specific system calls, using timer helpers (Figure 1).

7.2.2 Flow integrity protection.
We use Seccomp-eBPF filters to implement the kernel enforcement of system call

flow-integrity protection (SFIP) [24] which otherwise requires kernel revisions and a new system call. SFIP checks both system call sequences and origins (code address that issues a system call). For the sequence check, we store the system call state machine in a two-level eBPF map, by encoding the state machine as a $N \times N$ matrix where N is the number of system calls an application uses. We maintain the previous system call ID s' in a global variable. Given a system call s, we check whether $s' \rightarrow s$ is valid. For the origin check, we store the system call origin mapping in another two-level map where the first-level map indexes the system call ID and the second-level stores the valid code addresses. For a system call s, we check whether s's origin is included in the second-level map after indexing the first-level map with s's ID (Seccomp already provides the calling address of a system call in its data structure).

We evaluate Seccomp-eBPF filter-based SFIP using the same buffer overflow vulnerability in BusyBox [2] in the evaluation of the original SFIP work [24]. The exploits require a system call sequence of either socket → execve to execute shellcode, or socket → mprotect to mark the memory protection of the shellcode as executable. Neither of the transitions is allowed by the eBPF filter based on the in-map system call state machines. Furthermore, the code addresses are checked as per the origin map.

7.2.3 Serialization.
We implement the eBPF based serializer (see §5.3.3) to mitigate the race-based vulnerabilities in Table 2. We write applications that issue the system calls of the race vulnerabilities concurrently. Take CVE-2018-18281 as an example, the filter serializes `mremap` and `ftruncate` when the applications issue both.

7.3 Performance

We compare the performance of eBPF filters with cBPF filters and Notifier that implement the same security policy. For fair comparison, we use policies that can be implemented by cBPF filters. We expect the performance of eBPF filters and cBPF filters to be similar, since Seccomp internally converts cBPF filters into eBPF code. On the other hand, eBPF filters and cBPF filters go through different toolchains and thus are optimized differently.

	getppid (cycles)	filter (cycles)
No filter	244.18	0
cBPF filter (default)	493.06	214.19
cBPF filter (optimized)	329.47	68.68
eBPF filter	331.73	60.18
Constant-action bitmap [31]	297.60	0
Seccomp notifier	15045.05	59.29

Table 3. Execution time of system calls with different types of filters and filter execution time.

| Application	Description	Benchmark
HTTPD	Web server	ab [1] (40 clients)
NGINX	Web server	ab [1] (40 clients)
Lighttpd	Web server	ab [1] (40 clients)
Memcached	In-memory cache	memtier [10] (10 threads)
Redis	Key-value store	memtier [10] (10 threads)
Bind	DNS server	dnseval [3]

Table 4. Applications and benchmarks used in evaluation

7.3.1 Microbenchmark.
Table 3 shows our microbenchmark results of different Seccomp filters, including the execution time (cycles) of the getppid system call and the filter programs. We use a policy that denies 245 system calls and allows the rest (getppid is allowed). To obtain reliable results, we fix the CPU frequency and disable Turbo boost.

We generate the two cBPF filters using libseccomp (v2.5.2), with the default option and with binary-tree optimization [66]. The latter generates a filter that sorts the system call ID in a binary tree. We implement the eBPF filter in C and use Clang (-O2) to compile the C code into eBPF bytecode. Clang optimizes switch-case statements into a binary tree so that reaching each case only takes $O(log(N))$ time, where N is the number of system calls. We also experiment with Seccomp constant-action bitmap [31], an optimization that skips the filter execution if the system call ID is known to be allowed. For Seccomp Notifier, we implement a userspace agent in C with the same logic as the eBPF filter.

Our results show that the eBPF filter outperforms the unoptimized cBPF filter. It has roughly the same performance as the cBPF filter optimized by libseccomp. Both Clang and libseccomp optimize the filter code using binary search to avoid walking over a long jump list. Constant-action bitmap achieves the highest performance, but it cannot help policies on argument values. With Seccomp Notifier, getppid runs 45.4 times slower than with the eBPF filter.

7.3.2 Application Performance.
We measure the application performance with different types of Seccomp filters. We use temporal specialization as the security policy. The implementations of the cBPF filters and eBPF filters are explained in §7.1. Seccomp Notifier can also support precise temporal specialization like eBPF filters. We implement a version that defers all decisions on system calls to a user agent. The handler keeps a phase-changing flag, which is
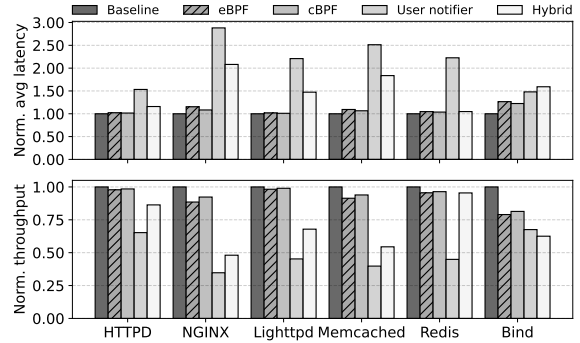
Figure 5. Avg. latency and throughput of the applications with different filters that implement temporal specialization (normalized to the baseline that disables Seccomp).

set when the application enters the serving phase. We also evaluate an optimization that combines cBPF filter and the agent, denoted as *hybrid*. The hybrid version installs a cBPF filter at the process startup, allowing S_{init}. For every system call outside of S_{init}, the filter defers the decision to the user space. An additional filter is installed at the beginning of the serving phase to block $S_{init} - S_{comm}$. The handler then only allows $S_{serv} - S_{comm}$ after the phase change.

Applications and benchmarks. We use the same six server applications as in §7.1. We use official benchmark tools for each application (Table 4). All experiments are run 10 times and the average numbers are reported. Figure 5 shows the average latency and throughput of each application with cBPF, eBPF, Notifier, and Hybrid. We normalized all results to the *baseline*, a version that does not use Seccomp. The results show two consistent characteristics. First, Seccomp-eBPF has similar performance impacts as Seccomp-cBPF, while providing higher security for the initialization phase. Second, userspace agents incur significant performance overhead. Applications with pure user notifiers have additional 48%−188% average latency and 32%−65% lower throughput. Even for Hybrid, there is an additional 5%−108% average latency and 5%−52% lower throughput. NGINX suffers from the highest degradation, with latency increasing by a factor of 1.88 and throughput decreasing by 65%. Only Hybrid for Redis has a performance comparable to BPF filters, because in the serving phase of Redis, most system calls are from S_{comm}, which are filtered by cBPF filters.

7.3.3 Accelerating stateless security checks.
Lastly, we use eBPF filters to implement the Draco Seccomp cache [90] and repeat the Draco evaluation using the applications and benchmarks in Table 4. The key idea of Draco is to cache the ID and the corresponding argument values of a system call that has recently been validated by stateless security checks. If an incoming system call hits the cache, Draco saves the computation of running the stateless checks. Draco is effective when the stateless checks are expensive and the system

calls of an application have high locality. The eBPF filter implements Draco using an array map which maps a system call to its corresponding check filter through an eBPF tail-call. The check filter uses a hash map to store recently validated argument values in a 48-byte blob.

We use the profile which only allows a system call if its ID and argument values are recorded by strace in a dry run. Our results show that eBPF-based Draco increases the throughput of three web servers by 10% on average. We do not observe significant improvement for the other applications.

8 Discussion

System call filtering with LSM. Linux Security Modules (LSMs) provide enforcement for system-wide security policies. Therefore, it is commonly discussed together with Seccomp, often as an alternative to implement system call filtering, especially with LSM-eBPF [41]. In fact, Seccomp(-eBPF) and LSM(-eBPF) are fundamentally different.

Seccomp restricts the system call entry point, while LSMs provide access control on kernel objects deeply on the path of system call handling. Hence, LSMs cannot prevent vulnerabilities before reaching LSM hooks. Moreover, Seccomp can provide fine-grained per-process system call filtering, while LSMs are system-wide. Lastly, LSM requires privileged use cases (only sysadmins can apply LSM policies); Seccomp-eBPF supports unprivileged use cases where an unprivileged process can install a Seccomp-eBPF filter.

Seccomp and LSM have different principles. Seccomp requires no new kernel code; hence, it stays future-proof for new sysem calls; LSMs would need new code when new system calls are added. So, code in a Seccomp-eBPF filter takes a "microkernel" style. LSM uses a "monolithic kernel" style to implement custom checks for different system calls.

Automatic Seccomp-eBPF filter generation. Many tools have been developed to *automatically* generate application-specific Seccomp-cBPF filters. The basic idea is to profile the system calls of the target application with static code analysis [26, 53, 54, 82], binary analysis [26, 35], or dynamic tracking [87, 95]. The identified system calls are included in a static allow list.

How to automatically generate Seccomp-eBPF filters is an open question. Recent work like SFIP [24] shows promises of generating system call state machines. We believe that eBPF filters for count/rate limiting and temporal specialization can also be automatically generated. Moreover, many ideas from system call based intrusion detection using data modeling and machine learning can potentially be applied to generate advanced eBPF filters [27, 44, 45, 57, 77–79].

Risks of unprivileged eBPF. With bugs in Linux eBPF verifier and JIT compiler [81], Seccomp-eBPF may potentially allow unprivileged attackers to craft malicious eBPF filters to exploit vulnerabilities. Seccomp-cBPF shares the same risk; however, since it is simpler it likely has fewer bugs.

We believe that in the long term unprivileged eBPF will be safe, as evidenced by recent work on formally-verified eBPF verifiers and compilers [51, 52, 81, 96, 99], and more broadly, safe and correct kernel code [21, 43, 76, 80].

Note that Seccomp-eBPF can be configured as a privileged feature at deployment (§6), if unprivileged eBPF is a concern. The privileged configuration can be used by many container runtimes and management services (e.g., init).

9 Related Work

System call filtering. Prior work has studied system call filtering (aka interposition) techniques for protecting the shared OS kernel against untrusted applications [17, 19, 34, 37, 46, 50, 56, 58, 67, 72, 77, 85, 86, 94]. Early techniques rely on userspace agents (e.g., based on ptrace) that check user-specified policies to decide which system calls to allow or deny, in the same vein as Seccomp Notifier (see §2.2). However, the context switch overhead could be unaffordable to applications that require high performance. Seccomp provides a solution that allows user-specified policies to be implemented in cBPF and executed as kernel extensions. Compared with userspace agents, Seccomp filters have significant performance advantages, which is one main reason that makes it a widely-used building block for modern sandbox and container technologies. Our work builds on the success of Seccomp and rethinks the programmability of system call security in the Seccomp context.

Discussions on eBPF Seccomp filters in the Linux community. There were a few other proposals on supporting eBPF filters for Seccomp, with patches [36, 65]. However, our discussions with the community both on the kernel mailing list [102] and at the Linux Plumbers Conference [69] tell that it is still very controversial.

One common concern is lacking concrete use cases, as exemplified by the maintainer's response—"*What's the reason for adding eBPF support? Seccomp shouldn't need it... I'd rather stick with cBPF until we have an overwhelmingly good reason to use eBPF...*" [28]. One reason is that early patches [36, 65] do not support maps and thus still have no statefulness. We hope that our work addresses this concern. Our design is driven by an analysis of desired system call filtering features, which reveals the limitations of Seccomp (§3). We also show that existing eBPF utilities are insufficient; therefore, simply opening the eBPF interface cannot solve the problem.

There are other concerns on eBPF security, including (1) exposure of kernel data and functions to untrusted user space via maps and helpers, and (2) potential vulnerabilities in the eBPF subsystem. In our design, the security of Seccomp-eBPF can be systematically reduced to that of Seccomp and eBPF. We discuss the risk of unprivileged eBPF in §8. We believe that vulnerabilities in the eBPF subsystem implementation is a temporal (but challenging) problem that will be addressed

in the longer term. Our implementation also provides a configuration option to turn Seccomp-eBPF into a root-only feature (§6) which is useful for container environments.

Other eBPF use cases. Recently, eBPF has been actively used to build innovative tools and systems, ranging from networking [64] to tracing [62] to storage [55, 101] to virtualization [20]. Different from most of the eBPF use cases, Seccomp needs to support unprivileged use cases (§4.1). Therefore, security is a first-class design principle of Seccomp-eBPF.

10 Concluding Remarks

Our work makes one step towards empowering advanced system call security policies by enhancing the programmability of system call security mechanisms, namely Seccomp in Linux. We present our design and implementation of the Seccomp-eBPF program type and show that it can enable many useful features, without impairing system call performance or reducing system security. Our work is imperfect, but we hope that it could lay the foundation and motivate strong programmability for system call security.

Acknowledgement

References

[1] ab - Apache HTTP server benchmarking tool. https://httpd.apache.org/docs/2.4/programs/ab.html.

[2] Bug 9071 - busybox - (local) cmdline stack buffer overwrite. https://bugs.busybox.net/show_bug.cgi?id=9071.

[3] DNS Measurement, Troubleshooting and Security Auditing Toolset. https://dnsdiag.org/.

[4] Docker's default Seccomp profile. https://github.com/moby/moby/blob/master/profiles/seccomp/default.json.

[5] eBPF – Introduction, Tutorials & Community Resources. https://ebpf.io/.

[6] Firecracker Design. https://github.com/firecracker-microvm/firecracker/blob/master/docs/design.md.

[7] gVisor: Container Runtime Sandbox. https://github.com/google/gvisor/blob/master/runsc/boot/filter/config.go.

[8] Kubernetes's default crun profile. https://github.com/kubernetes-sigs/security-profiles-operator/blob/master/examples/baseprofile-crun.yaml.

[9] LXD. https://help.ubuntu.com/lts/serverguide/lxd.html#lxd-seccomp.

[10] memtier_benchmark: A High-Throughput Benchmarking Tool for Redis & Memcached. https://github.com/RedisLabs/memtier_benchmark.

[11] Namespaces in operation, part 1: namespaces overview [lwn.net]. https://lwn.net/Articles/531114/.

[12] Podman: A tool for managing OCI containers and pods. https://podman.io/.

[13] runc standard_init_linux.go. https://github.com/opencontainers/runc/blob/master/libcontainer/standard_init_linux.go#L161-L230.

[14] Sandboxed API. https://github.com/google/sandboxed-api.

[15] Seccomp security profiles for Docker. https://docs.docker.com/engine/security/seccomp/.

[16] Yama ptrace_scope - the linux kernel archives. https://www.kernel.org/doc/Documentation/security/Yama.txt.

[17] Anurag Acharya and Mandar Raje. MAPbox: Using Parameterized Behavior Classes to Confine Untrusted Applications. In *Proceedings of the 9th USENIX Security Symposium (USENIX Security '00)*, Denver, Colorado, USA, August 2000.

[18] Alexandru Agache, Marc Brooker, Alexandra Iordache, Anthony Liguori, Rolf Neugebauer, Phil Piwonka, and Diana-Maria Popa. Firecracker: Lightweight Virtualization for Serverless Applications. In *Proceedings of the 17th USENIX Symposium on Networked Systems Design and Implementation (NSDI'20)*, February 2020.

[19] Albert Alexandrov, Paul Kmiec, and Klaus Schauser. Consh: Confined Execution Environment for Internet Computations. Technical report, The University of California, Santa Barbara, 1999.

[20] Nadav Amit and Michael Wei. The Design and Implementation of Hyperupcalls. In *Proceedings of the 2018 USENIX Annual Technical Conference (USENIX ATC'18)*, July 2018.

[21] Abhiram Balasubramanian, Marek S. Baranowski, Anton Burtsev, Aurojit Panda, Zvonimir Rakamarić, and Leonid Ryzhyk. System Programming in Rust: Beyond Safety. In *Proceedings of the 16th Workshop on Hot Topics in Operating Systems (HotOS'17)*, May 2017.

[22] Atri Bhattacharyya, Uros Tesic, and Mathias Payer. Midas: Systematic Kernel TOCTTOU Protection. In *Proceedings of the 31st USENIX Security Symposium (USENIX Security'22)*, August 2022.

[23] Christian Brauner. The Seccomp Notifier – New Frontiers in Unprivileged Container Development. https://brauner.github.io/2020/07/23/seccomp-notify.html, July 2020.

[24] Claudio Canella, Sebastian Dorn, Daniel Gruss, and Michael Schwarz. SFIP: Coarse-Grained Syscall-Flow-Integrity Protection in Modern Systems. *arXiv:2202.13716*, February 2022.

[25] Claudio Canella, Andreas Kogler, Lukas Giner, Daniel Gruss, and Michael Schwarz. Domain Page-Table Isolation. In *arXiv:2111.10876*, November 2021.

[26] Claudio Canella, Mario Werner, Daniel Gruss, and Michael Schwarz. Automating Seccomp Filter Generation for Linux Applications. In *Proceedings of the 2021 ACM Cloud Computing Security Workshop (CCSW'21)*, November 2021.

[27] Christina Warrender and Stephanie Forrest and Barak Pearlmutter. Detecting Intrusions Using System Calls: Alternative Data Models. In *Proceedings of the 1999 IEEE Symposium on Security and Privacy*, May 1999.

[28] Kees Cook. Re: [PATCH net-next 0/3] eBPF Seccomp filters. https://lore.kernel.org/netdev/CAGXu5jLiYh0rSRuJ_-2xLB03Wod5G07njpoESR4SnmsmiUnsEw@mail.gmail.com/, February 2018.

[29] Jonathan Corbet. Systemd gets seccomp filter support . https://lwn.net/Articles/507067/.

[30] Jonathan Corbet. BPF: the universal in-kernel virtual machine. https://lwn.net/Articles/599755/, May 2014.

[31] Jonathan Corbet. Constant-action bitmaps for seccomp(). https://lwn.net/Articles/834785/, October 2020.

[32] Jonathan Corbet. Memory protection keys for the kernel. https://lwn.net/Articles/756233/, July 2020.

[33] Jonathan Corbet. Sleepable BPF programs. https://lwn.net/Articles/825415/, July 2020.

[34] Asit Dan, Ajay Mohindra, Rajiv Ramaswami, and Dinkar Sitara. ChakraVyuha (CV): A Sandbox Operating System Environment for

Controlled Execution of Alien Code. Technical Report RC 20742 (2/20/97), IBM Research Division, T.J. Watson Research Center, February 1997.

[35] Nicholas DeMarinis, Kent Williams-King, Di Jin, Rodrigo Fonseca, and Vasileios P. Kemerlis. sysfilter: Automated System Call Filtering for Commodity Software. In *Proceedings of the 23rd International Symposium on Research in Attacks, Intrusions and Defenses (RAID'20)*, October 2020.

[36] Sargun Dhillon. eBPF Seccomp filters. https://lwn.net/Articles/747229/, February 2018.

[37] John R. Douceur, Jeremy Elson, Jon Howell, and Jacob R. Lorch. Leveraging Legacy Code to Deploy Desktop Applications on the Web. In *Proceedings of the 8th USENIX Symposium on Operating Systems Design and Implementation (OSDI'08)*, December 2008.

[38] Jake Edge. System call filtering and no_new_privs. https://lwn.net/Articles/475678/, January 2012.

[39] Jake Edge. A seccomp overview. https://lwn.net/Articles/656307/, September 2015.

[40] Jake Edge. Deep argument inspection for seccomp. https://lwn.net/Articles/799557/, September 2019.

[41] Jake Edge. Kernel runtime security instrumentation. https://lwn.net/Articles/798157/, September 2019.

[42] Jake Edge. Seccomp and deep argument inspection. https://lwn.net/Articles/822256/, June 2020.

[43] Nelson Elhage. Supporting Linux kernel development in Rust. https://lwn.net/Articles/829858/, August 2020.

[44] Henry Hanping Feng, Oleg M. Kolesnikov, Prahlad Fogla, Wenke Lee, and Weibo Gong. Anomaly Detection Using Call Stack Information. In *Proceedings of the 2003 IEEE Symposium on Security and Privacy*, May 2003.

[45] Stephanie Forrest, Steven A. Hofmeyr, Anil Somayaji, and Thomas A. Longstaff. A Sense of Self for Unix Processes. In *Proceedings of the 1996 IEEE Symposium on Security and Privacy*, May 1996.

[46] Timothy Fraser, Lee Badger, and Mark Feldman. Hardening COTS Software with Generic Software Wrappers. In *Proceedings of the 1999 IEEE Symposium on Security and Privacy*, May 1999.

[47] Tommaso Frassetto, Patrick Jauernig, Christopher Liebchen, and Ahmad-Reza Sadeghi. IMIX: In-Process Memory Isolation EXtension. In *Proceedings of the 27th USENIX Security Symposium (USENIX Security '18)*, August 2018.

[48] Jessie Frazelle. Security for the Modern Age. *Communications of the ACM*, 62(1):43–45, January 2019.

[49] Tal Garfinkel. Traps and Pitfalls: Practical Problems in System Call Interposition Based Security Tools. In *Proceedings of the 2004 Network and Distributed System Security Symposium (NDSS'04)*, February 2003.

[50] Tal Garfinkel, Ben Pfaff, and Mendel Rosenblum. Ostia: A Delegating Architecture for Secure System Call Interposition. In *Proceedings of the 2004 Network and Distributed System Security Symposium (NDSS'04)*, February 2004.

[51] Jacob Van Geffen, Luke Nelson, Isil Dillig, Xi Wang, and Emina Torlak. Synthesizing JIT Compilers for In-Kernel DSLs. In *Proceedings of the 32nd International Conference on Computer-Aided Verification (CAV'20)*, July 2020.

[52] Elazar Gershuni, Nadav Amit, Arie Gurfinkel, Nina Narodytska, Jorge A. Navas, Noam Rinetzky, Leonid Ryzhyk, and Mooly Sagiv. Simple and Precise Static Analysis of Untrusted Linux Kernel Extensions. In *Proceedings of the 40th ACM SIGPLAN Conference on Programming Language Design and Implementation (PLDI 2019)*, June 2019.

[53] Seyedhamed Ghavamnia, Tapti Palit, Shachee Mishra, and Michalis Polychronakis. Confine: Automated System Call Policy Generation for Container Attack Surface Reduction. In *Proceedings of the 23rd International Symposium on Research in Attacks, Intrusions and Defenses (RAID'20)*, October 2020.

[54] Seyedhamed Ghavamnia, Tapti Palit, Shachee Mishra, and Michalis Polychronakis. Temporal System Call Specialization for Attack Surface Reduction. In *Proceedings of the 29th USENIX Security Symposium (USENIX Security'20)*, August 2020.

[55] Yoann Ghigoff, Julien Sopena, Kahina Lazri, Antoine Blin, and Gilles Muller. BMC: Accelerating Memcached using Safe In-kernel Caching and Pre-stack Processing. In *Proceedings of the 18th USENIX Symposium on Networked Systems Design and Implementation (NSDI'21)*, April 2021.

[56] Douglas P. Ghormley, David Petrou, Steven H. Rodrigues, and Thomas E. Anderson. SLIC: An Extensibility System for Commodity Operating Systems. In *Proceedings of the Annual Conference on USENIX Annual Technical Conference (USENIX ATC'98)*, June 1998.

[57] Anup K. Ghosh and Aaron Schwartzbard. A Study in Using Neural Networks for Anomaly and Misuse Detection. In *Proceedings of the 8th USENIX Security Symposium (USENIX Security '99)*, August 1999.

[58] Ian Goldberg, David Wagner, Randi Thomas, and Eric A. Brewer. A Secure Environment for Untrusted Helper Applications (Confining the Wily Hacker). In *Proceedings of the 6th USENIX Security Symposium (USENIX Security '96)*, July 1996.

[59] Sishuai Gong, Deniz Altınbüken, Pedro Fonseca, and Petros Maniatis. Snowboard: Finding Kernel Concurrency Bugs through Systematic Inter-thread Communication Analysis. In *Proceedings of the 28th ACM Symposium on Operating Systems Principles (SOSP'21)*, October 2019.

[60] Aaron Grattafiori. Understanding and Hardening Linux Containers. Technical report, NCC Group, June 2016.

[61] Spyridoula Gravani, Mohammad Hedayati, John Criswell, and Michael L. Scott. Fast Intra-kernel Isolation and Security with IskiOS. In *Proceedings of the 24th International Symposium on Research in Attacks, Intrusions and Defenses (RAID'21)*, October 2021.

[62] Brendan Gregg. Linux Extended BPF (eBPF) Tracing Tools. https://www.brendangregg.com/ebpf.html.

[63] Zhongshu Gu, Brendan Saltaformaggio, Xiangyu Zhang, and Dongyan Xu. FACE-CHANGE: Application-Driven Dynamic Kernel View Switching in a Virtual Machine. In *Proceedings of the 44th Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN'14)*, June 2014.

[64] Toke Høiland-Jørgensen, Jesper Dangaard Brouer, Daniel Borkmann, John Fastabend, Tom Herbert, David Ahern, and David Miller. The EXpress Data Path: Fast Programmable Packet Processing in the Operating System Kernel. In *Proceedings of the 14th International Conference on Emerging Networking EXperiments and Technologies (CoNEXT '18)*, December 2018.

[65] Tom Hromatka. [RFC PATCH] all: RFC - add support for ebpf. https://groups.google.com/g/libseccomp/c/pX6QkVF0F74/m/ZUJlwI5qAwAJ, February 2018.

[66] Tom Hromatka. Using a cBPF Binary Tree in Libseccomp to Improve Performance. In *Linux Plumbers Conference (LPC'18)*, November 2018.

[67] K. Jain and R. Sekar. User-Level Infrastructure for System Call Interposition: A Platform for Intrusion Detection and Confinement. In *Proceedings of the 2000 Network and Distributed System Security Symposium (NDSS'00)*, February 2000.

[68] Dae R. Jeong, Kyungtae Kim, Basavesh Shivakumar, Byoungyoung Lee, and Insik Shin. Razzer: Finding Kernel Race Bugs through Fuzzing. In *Proceedings of the 2019 IEEE Symposium on Security and Privacy*, May 2019.

[69] Jinghao Jia, YiFei Zhu, Andrea Arcangeli, Hubertus Franke, Tobin Feldman-Fitzthum, Claudio Canella, Dimitrios Skarlatos, Daniel Gruss, Dan Williams, and Tianyin Xu. Revisiting eBPF Seccomp Filters. In *Linux Plumbers Conference (LPC'22)*, September 2022.

[70] Sean Kerner. The future of Docker containers. https://lwn.net/Articles/788282/, May 2019.

[71] Michael Kerrisk. Using seccomp to Limit the Kernel Attack Surface. In *Linux Plumbers Conference (LPC'15)*, August 2015. https://man7.org/conf/lpc2015/limiting_kernel_attack_surface_with_seccomp-LPC_2015-Kerrisk.pdf.

[72] Taesoo Kim and Nickolai Zeldovich. Practical and Effective Sandboxing for Non-root Users. In *Proceedings of the 2013 USENIX Conference on Annual Technical Conference (USENIX ATC'13)*, June 2013.

[73] Kubernetes Documentation. Configure a Security Context for a Pod or Container. https://kubernetes.io/docs/tasks/configure-pod-container/security-context/, July 2019.

[74] Hsuan-Chi Kuo, Kai-Hsun Chen, Yicheng Lu, Dan Williams, Sibin Mohan, and Tianyin Xu. Verified Programs Can Party: Optimizing Kernel Extensions via Post-Verification Merging. In *Proceedings of the 17th European Conference on Computer Systems (EuroSys'22)*, April 2022.

[75] Lingguang Lei, Jianhua Sun, Kun Sun, Chris Shenefiel, Rui Ma, Yuewu Wang, and Qi Li. SPEAKER: Split-Phase Execution of Application Containers. In *Proceedings of the 14th Conference on Detection of Intrusions and Malware and Vulnerability Assessment (DIMVA'17)*, July 2017.

[76] Jialin Li, Samantha Miller, Danyang Zhuo, Ang Chen, Jon Howell, and Thomas Anderson. An Incremental Path towards a Safer OS Kernel. In *Proceedings of the 18th Workshop on Hot Topics in Operating Systems (HotOS'21)*, June 2021.

[77] C. M. Linn, M. Rajagopalan, S. Baker, C. Collberg, S. K. Debray, and J. H. Hartman. Protecting Against Unexpected System Calls. In *Proceedings of the 14th USENIX Security Symposium (USENIX Security '05)*, July 2005.

[78] Federico Maggi, Matteo Matteucci, and Stefano Zanero. Detecting Intrusions through System Call Sequence and Argument Analysis. *IEEE Transactions on Dependable and Secure Computing (TDSC)*, 7(4):381–395, October 2010.

[79] Darren Mutz, Fredrik Valeur, Giovanni Vigna, and Christopher Kruegel. Anomalous System Call Detection. *ACM Transactions on Information and System Security (TISSEC)*, 9(1):61–93, February 2006.

[80] Luke Nelson, James Bornholt, Ronghui Gu, Andrew Baumann, Emina Torlak, and Xi Wang. Scaling Symbolic Evaluation for Automated Verification of Systems Code with Serval. In *Proceedings of the 27th ACM Symposium on Operating Systems Principles (SOSP'19)*, October 2019.

[81] Luke Nelson, Jacob Van Geffen, Emina Torlak, and Xi Wang. Specification and verification in the field: Applying formal methods to BPF just-in-time compilers in the Linux kernel. In *Proceedings of the 14th USENIX Symposium on Operating Systems Design and Implementation (OSDI'20)*, November 2021.

[82] Shankara Pailoor, Xinyu Wang, Hovav Shacham, and Isil Dillig. Automated Policy Synthesis for System Call Sandboxing. *Proc. ACM Program. Lang.*, 4(OOPSLA), November 2020.

[83] Paul Lawrence. Seccomp filter in Android O. https://android-developers.googleblog.com/2017/07/seccomp-filter-in-android-o.html, July 2017.

[84] Mathias Payer and Thomas R. Gross. Protecting Applications Against TOCTTOU Races by User-Space Caching of File Metadata. In *Proceedings of the 8th Annual International Conference on Virtual Execution Environments (VEE'12)*, March 2012.

[85] David S. Peterson, Matt Bishop, and Raju Pandey. A Flexible Containment Mechanism for Executing Untrusted Code. In *Proceedings of the 11th USENIX Security Symposium (USENIX Security '02)*, August 2002.

[86] Niels Provos. Improving Host Security with System Call Policies. In *Proceedings of the 12th USENIX Security Symposium (USENIX Security '03)*, August 2003.

[87] Valentin Rothberg. Generate SECCOMP Profiles for Containers Using Podman and eBPF. https://podman.io/blogs/2019/10/15/generate-seccomp-profiles.html, October 2019.

[88] Rtk docs. Seccomp Isolators Guide. https://coreos.com/rkt/docs/latest/seccomp-guide.html.

[89] Giuseppe Scrivano. seccomp: add support for eBPF seccomp. https://github.com/giuseppe/crun/commit/3906b4fbcb671f8f188deef08c94ceae86a80120.

[90] Dimitrios Skarlatos, Qingrong Chen, Jianyan Chen, Tianyin Xu, and Josep Torrellas. Draco: Architectural and Operating System Support for System Call Security. In *Proceedings of the 53rd IEEE/ACM International Symposium on Microarchitecture (MICRO-53)*, October 2020.

[91] Alexei Starovoitov. rework/optimize internal BPF interpreter's instruction set. https://git.kernel.org/pub/scm/linux/kernel/git/torvalds/linux.git/commit/?id=bd4cf0ed331a275e9bf5a49e6d0fd55dffc551b8, March 2014.

[92] Alexei Starovoitov. Lifetime of BPF objects. https://facebookmicrosites.github.io/bpf/blog/2018/08/31/object-lifetime.html, August 2018.

[93] Alexei Starovoitov. Re: seccomp feature development. https://lwn.net/ml/linux-kernel/CAADnVQKRCCHRQrNy=V7ue38skb8nKCczScpph2WFv7U_jsS3KQ@mail.gmail.com/, May 2020.

[94] David A. Wagner. Janus: an Approach for Confinement of Untrusted Applications. Technical Report UCB/CSD-99-1056, EECS Department, University of California, Berkeley, 2016.

[95] Zhiyuan Wan, David Lo, Xin Xia, Liang Cai, and Shanping Li. Mining Sandboxes for Linux Containers. In *Proceedings of 2017 IEEE International Conference on Software Testing, Verification and Validation (ICST'17)*, Tokyo, Japan, March 2017.

[96] Xi Wang, David Lazar, Nickolai Zeldovich, Adam Chlipala, and Zachary Tatlock. Jitk: A trustworthy in-kernel interpreter infrastructure. In *Proceedings of the 11th USENIX Symposium on Operating Systems Design and Implementation (OSDI'14)*, October 2014.

[97] Robert N. M. Watson. Exploiting Concurrency Vulnerabilities in System Call Wrappers. In *Proceedings of the 1st USENIX Workshop on Offensive Technologies (WOOT'07)*, August 2007.

[98] Meng Xu, Sanidhya Kashyap, Hanqing Zhao, and Taesoo Kim. KRACE: Data Race Fuzzing for Kernel File Systems. In *Proceedings of the 41st IEEE Symposium on Security and Privacy*, May 2020.

[99] Qiongwen Xu, Michael D. Wong, Tanvi Wagle, Srinivas Narayana, and Anirudh Sivaraman. Synthesizing Safe and Efficient Kernel Extensions for Packet Processing. In *Proceedings of the 2021 ACM SIGCOMM Conference (SIGCOMM'21)*, August 2021.

[100] Shixiong Zhao, Rui Gu, Haoran Qiu, Tsz On Li, Yuexuan Wang, Heming Cui, and Junfeng Yang. OWL: Understanding and Detecting Concurrency Attacks. In *Proceedings of the 48th Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN'18)*, June 2018.

[101] Yuhong Zhong, Haoyu Li, Yu Jian Wu, Ioannis Zarkadas, Jeffrey Tao, Evan Mesterhazy, Michael Makris, Junfeng Yang, Amy Tai, Ryan Stutsman, and Asaf Cidon. XRP: In-Kernel storage functions with eBPF. In *Proceedings of 16th USENIX Symposium on Operating Systems Design and Implementation (OSDI'22)*, July 2022.

[102] YiFei Zhu. eBPF seccomp filters. https://lwn.net/Articles/855970/.