Cage4Deno: A Fine-Grained Sandbox for Deno Subprocesses

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ABSTRACT

Deno is a runtime for JavaScript and TypeScript that is receiving great interest by developers, and is increasingly used for the construction of back-ends of web applications. A primary goal of Deno is to provide a secure and isolated environment for the execution of JavaScript programs. It also supports the execution of subprocesses, unfortunately without providing security guarantees.

In this work we propose *Cage4Deno*, a set of modifications to Deno enabling the creation of fine-grained sandboxes for the execution of subprocesses. The design of Cage4Deno satisfies the compatibility, transparency, flexibility, usability, security, and performance needs of a modern sandbox. The realization of these requirements partially stems from the use of Landlock and eBPF, two robust and efficient security technologies. Significant attention has been paid to the design of a flexible and compact policy model consisting of `RWX` permissions, which can be automatically created, and deny rules to declare exceptions. The sandbox effectiveness is demonstrated by successfully blocking a number of exploits for recent CVEs, while runtime experiments prove its efficiency. The proposal is associated with an open-source implementation.

CCS CONCEPTS

• **Security and privacy** → **Software and application security**; **Access control**; **File system security**; **Usability in security and privacy**.

KEYWORDS

Sandboxing, Access control, JavaScript runtime, Deno, Subprocess

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1 INTRODUCTION

JavaScript is currently one of the most popular programming languages [68]. One of its strengths is versatility, indeed, it can be used both in the front-end and in the back-end to write fully fledged web applications. JavaScript was originally meant for the browser, and its porting on the back-end by *Node.js* is not without security risks. As highlighted in previous studies [24, 69, 74, 75, 78], vulnerabilities affecting the language or the toolchain can lead to severe breaches.

A recent initiative aiming to reduce the risk coming from the execution of vulnerable or untrusted JavaScript code on the back-end is *Deno* [44], a modern, secure, open-source, cross-platform JavaScript runtime. Contrary to its well-known predecessor (i.e., Node.js), Deno was designed with security as one of its primary goals [17]. This aspect partly stems from the programming language used to implement it (i.e., Rust instead of C++), but mostly originates from its default behavior of executing JavaScript code in a completely isolated sandbox. Unless otherwise stated by the developer, Deno prevents any program from accessing the filesystem, network, environment variables, and even high-resolution time measurements. Unfortunately, although its permission model allows developers to grant fine-grained authorizations (read/write/execute privilege on a single file, permissions to connect to a known hostname, etc.), dynamic libraries and subprocesses can access system resources regardless of the permissions granted to the Deno program that spawned them, essentially invalidating the security sandbox [19].

Research has shown that third-party code accounts for a great portion of a JavaScript application codebase [74]. The 2022 State of Open Source Security [66] shows that on average open-source JavaScript projects rely on 174 third-party dependencies. The practice of reusing third-party libraries is so widespread that it led the authors of Deno to implement the *Node compatibility mode* [21], which enables the execution of Node packages in Deno. Third-party modules often depend on subprocesses [23, 32, 69]. There is a broad spectrum of programs that fall into this category, ranging from Linux utilities to handle files [56], to programs that process media (e.g., image/video conversions [55], metadata removal [54]), and many more. Since these programs *(i)* are executed outside of a sandbox, *(ii)* are potentially exposed to unsanitized input, and *(iii)* are often written with unsafe languages, the risk of security violations is concrete. The 2022 State of Open Source Security reports that, on average, JavaScript projects are affected by 40 vulnerabilities when dependencies are taken into account. We focused on the records of the last 5 years, and have identified a sample of 15 high-severity

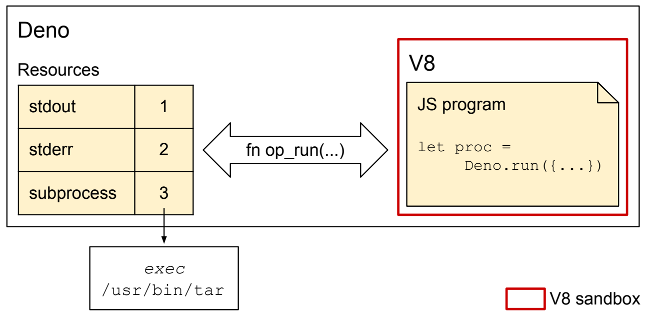


Figure 1: High level view of the Deno architecture

CVEs that affect third-party software used by popular packages (averaging more than 1M downloads/week), and allow an attacker to perform privilege escalation on the host, open reverse shells, perform local file inclusion, and corrupt the filesystem.

Our contribution. In this work we propose *Cage4Deno*: an extension of the Deno security functions aimed at mitigating vulnerabilities that may be introduced when subprocesses are used. Specifically, we design and implement[1] a solution targeting Linux systems, which leverages the recent *Landlock* Linux Security Module and the *Extended Berkeley Packet Filter* (eBPF), to transparently sandbox processes currently executed outside of the sandbox by Deno. The primary goal of the proposed protection mechanism is to preserve the integrity of the filesystem, and preventing access to confidential resources. While designing Cage4Deno, we paid great attention to the usability by developers: *(i)* no understanding of the kernel security features leveraged by our solution is required to use it, and *(ii)* although developers should be knowledgeable about the functionalities of the program they want to use, we do not expect them to be fully aware of its functioning under the hood. To this end, we first design a flexible and compact policy model. It consists of rules granting `read` (`R`), `write` (`W`) or `exec` (`X`) permissions on a filesystem node, which propagate towards its descendants, and `deny` rules (`D`) to block the propagation, thus reducing the number of rules and the effort of the developer. Then, we implement an auxiliary open-source tool named `dmng` to generate the least-privileged `RWX` rules required by each program. The tool can be invoked interactively by the developer via CLI, or integrated into CI/CD pipelines and run against a set of use cases, as best practice suggests. We also highlight that Cage4Deno preserves backward compatibility, meaning sandboxing of existing code, including direct or transient dependencies, can be achieved without code changes.

We demonstrate the security benefits of our solution showing how it mitigates a number of real-world vulnerabilities, which have been exploited against popular services (e.g., GitLab [14] and TikTok [36]). Finally, we perform an experimental evaluation comparing our solution to scenarios with no sandboxing, and sandboxing with state-of-the-art proposals, showing substantial performance improvements with respect to the available alternatives.

2 BACKGROUND

This section overviews the frameworks used in our proposal.

[1]https://github.com/unibg-seclab/cage4deno

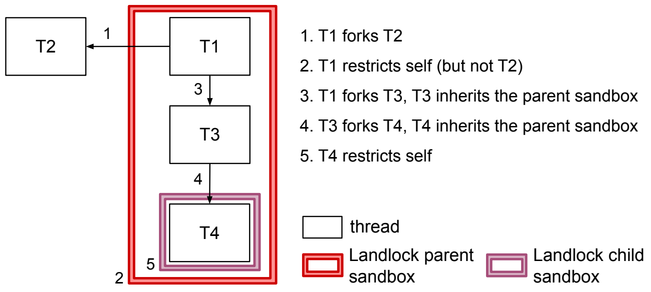

T2
1
T1
3
T3
4
T4
5
2
1. T1 forks T2
2. T1 restricts self (but not T2)
3. T1 forks T3, T3 inherits the parent sandbox
4. T3 forks T4, T4 inherits the parent sandbox
5. T4 restricts self
thread
Landlock parent sandbox
Landlock child sandbox

Figure 2: Creation and inheritance of a Landlock sandbox

2.1 Deno

Deno [44] is a runtime for JavaScript and TypeScript embedding *V8* [72], an open-source high-performance JavaScript and WebAssembly engine by Google. As already mentioned, Deno can be seen as an alternative to Node.js, with some key security features that derive from its design. In detail, it has a modular architecture organized into three main components: *(i) rusty_v8*, which defines the set of bindings to the V8's API; *(ii) deno_core*, a package built on top of *rusty_v8* implementing the abstractions required to run JavaScript (i.e., the *JsRuntime*); and *(iii) deno*, a package providing the Deno executable and the user-facing API.

Among the abstractions implemented in *deno_core* there are *ops*, native functions directly called from JavaScript that expose services not directly available in V8. These include primitives to open files, create network sockets, spawn child processes, access environment variables, etc. From a security perspective, each of the requests issued by the program running inside the V8 sandbox (i.e., the *op* calls) can be monitored by Deno and explicitly blocked or authorized based on a set of permissions. By default apps run without any permission, that is why Deno claims to be secure by default. The permission system categorizes the resources based on their type (filesystem, environment variables, network, etc.). There are two granularity levels: access to the whole resource category (e.g., all the files on the filesystem), and access to a single resource in the category (e.g., a single file). The resources accessible through *ops* are stored by *deno_core* in a resource table, and are uniquely identified by integers, similarly to the Unix concept of file descriptor.

The *ops* and resources interface abstraction gives Deno the ability to control the information flow between the system and the sandboxed app. This is a big step forward compared to Node.js in terms of security. Unfortunately, this level of protection applies only to the components written in JavaScript. When the app executes a program on the host leveraging for example the `Deno.run()` function, the request is handled by Deno spawning a new subprocess. As depicted in the high level view of the Deno architecture shown in Figure 1, this process runs unconstrained on the host (without sandboxing). This is a limitation of the current security model as, in case of a vulnerability, the host can be compromised [17].

2.2 Landlock LSM

The *Landlock* Linux Security Module (LSM) aims to provide developers with an unprivileged solution to implement application sandboxing. The availability of Landlock is expected to help mit-

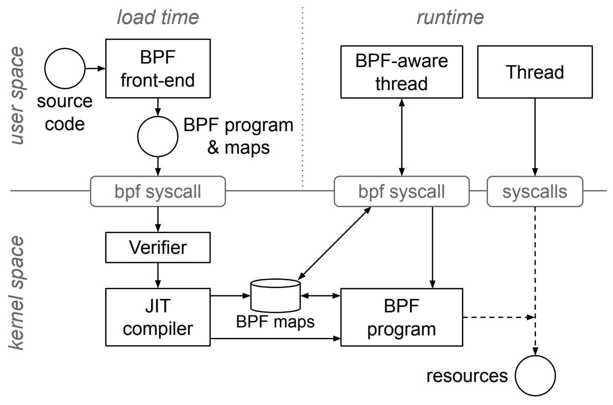


Figure 3: Overview of the BPF architecture

igate the security impact of bugs and unintended or malicious behavior of user-space applications. Also, it is fully composable with other LSMs like SELinux, AppArmor and Yama.

Currently, Landlock focuses on the protection of the filesystem. In detail, Landlock classifies kernel resources as *objects*, permitting *actions* over them based on *rulesets*. As an example, a ruleset can grant the thread `read` and `exec` access to objects stored under `/tmp`. Rulesets are created using the `landlock_create_ruleset()` and `landlock_add_rule()` system calls, and subsequently activated with `landlock_restrict_self()`. Rules are *inherited* by the children created after sandbox activation, and the actions available can only be further restricted. The process is detailed in Figure 2.

Although Landlock permits to sandbox a thread ensuring low performance overhead, there are a few limitations. The most relevant to this paper are: *(i)* it is not possible to perform any filesystem topology modification (i.e., arbitrary mounts), and *(ii)* there is no support for a deny listing approach during policy creation.

2.3 eBPF

The *Extended Berkeley Packet Filter* (eBPF, henceforth referred to as BPF) [33, 41] enables the execution of programs within the operating system kernel. The programs, which are loaded at runtime, extend the kernel capabilities, without requiring the developer to change the kernel source code, nor loading new kernel modules.

BPF programs are non-preemptable event-driven programs that are run when a certain user- or kernel-space hook point is reached. Pre-defined hooks include system calls, tracepoints, network events, function entry/exit, etc. BPF programs are usually written using a BPF front-end, which provides an abstraction to write programs in a high-level language, specify attachment points, declare data structures, and compile the source code into BPF bytecode. A few BPF front-ends exist; we use *libbpf* [47, 51] as it elegantly addresses portability following a Compile Once – Run Everywhere approach [51]. After a BPF program is compiled to bytecode, it can be loaded into the Linux kernel via the `bpf()` system call. This is a privileged operation that requires the `CAP_BPF` Linux capability, and optionally `CAP_PERFMON` (to load tracing-related programs) and `CAP_NET_ADMIN` (to load networking-related programs) [1]. As the program is loaded into the kernel, it is subject to the *verification* and *JIT compilation* phases. The verification phase ensures the program is safe and does not introduce reliability issues (e.g., termination is guaranteed, memory requirements are satisfied), while the Just-In-Time (JIT) compilation translates the generic bytecode to architecture-specific optimized code. Once completed, the program is loaded into the kernel and attached to the selected hook. The architecture of BPF and the loading process are shown in Figure 3.

BPF programs cannot call arbitrary kernel functions and cannot freely share the information collected with user space. Instead, they rely on *helper functions*, a stable API implemented by the kernel that is used for tasks like manipulating network packets, inspecting kernel data structures, etc. Among the most frequently used helpers, there are functions to read and write *maps*. Basically, maps are data structures that permit to keep a state between different invocations of BPF programs, and share data with user-space applications.

BPF's capabilities have been further extended in 2020 with the addition of the Kernel Runtime Security Instrumentation (KRSI) [13], also known as BPF LSM. This feature permits to attach BPF programs to LSM hooks, and thus enforce access control.

3 CAGE4DENO

This Section gives an overview of *Cage4Deno*, clarifying the threat model. We also introduce our design objectives (Section 3.3).

3.1 Overview

Cage4Deno aims to provide a set of sandboxing functions to strengthen the Deno security model. The proposal arises from the need to provide isolation for subprocesses spawned with the `Deno.run()` and `Deno.Command.spawn()` functions. As mentioned in Section 1, the practice of executing subprocesses is heavily used by developers. Unfortunately, any subprocess that executes this way falls outside of the Deno security model, essentially invalidating the sandbox (see Section 2.1). Indeed, an attacker that successfully exploits a security flaw affecting the utility run by a subprocess can perform privilege escalation on the host, open reverse shells, perform local file inclusion, corrupt the filesystem, etc.

Cage4Deno extends Deno giving developers the ability to constrain the execution of subprocesses. To do that, the developer associates each subprocess with a policy file, listing a set of rules. Rules are straightforward, each of them granting `read` (`R`), `write` (`W`) or `exec` (`X`) permissions on a filesystem node. To reduce the number of rules in the policy, the set of `RWX` permissions is extended with `deny` (`D`). This enables permissions granted on a filesystem node to propagate towards its descendants, and to block the propagation with the use of deny rules. The permissions granted by the developer are then automatically assigned to the subprocess at runtime. This is achieved by the *sandboxer*, a new module we added to Deno that leverages the Landlock LSM and the BPF framework (operating in stacking mode [79]) to implement the sandbox at kernel level. This ensures security checks are not bypassable, however it implies that our solution only works on Linux-based systems with these features enabled. Nowadays, Landlock LSM is already available in most systems, BPF LSM not yet. However, bleeding edge distributions, like Arch Linux, are starting to release with it enabled by default.[2] Compared to other well-known general-purpose

[2]Enabling BPF LSM on systems not supporting it by default requires replacing the system kernel with the same release of the kernel, but with BPF LSM available.

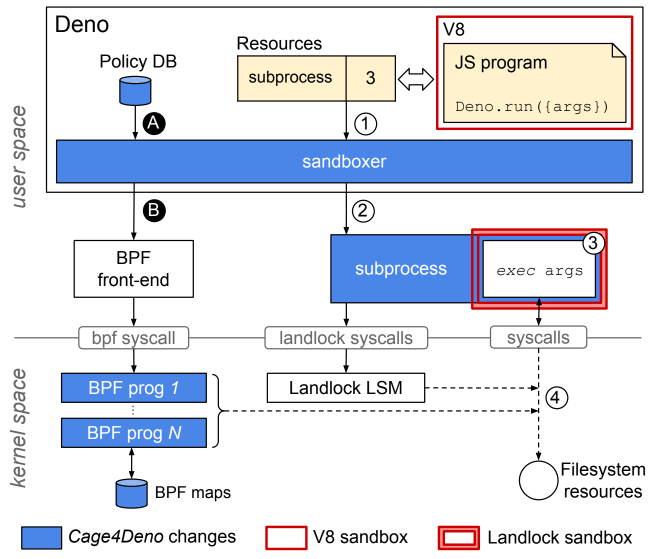


Figure 4: Overview of Cage4Deno implementation. Initial setup: *(A)* read the policy and *(B)* load BPF programs and write maps according to it. On subprocess request: *(1)* intercept subprocess creation, *(2)* create a Landlock-sandboxed subprocess with BPF deny, and *(3)* execute the utility. All the requests issued by the subprocess are restricted according to the policy *(4)*

sandboxing solutions like Minijail [30], and Google Sandbox2 [31], Cage4Deno does not require the developer to know anything about the advanced security features offered by the kernel to confine a process. All the developer has to understand is the straightforward `RWX+D` permission model. Moreover, Cage4Deno does not require the developer to understand the internal logic of the utility executed by the subprocess, all she needs to know are its input and output (provided by either absolute or relative path). An overview of our proposal is shown in Figure 4.

3.2 Threat model

Similarly to other research proposals [16, 70, 75], Cage4Deno focuses on the runtime compromise of possibly buggy or vulnerable utilities (i.e., binaries or libraries), and does not target actively malicious ones. Therefore, we do not regard the developers of the utilities as malicious actors, but nevertheless, they may inadvertently introduce vulnerabilities into their code. In this setting, attackers may control arguments of the utilities by passing malicious payloads through web interfaces or programmatic APIs. Prominent examples include utilities that offer manipulation capabilities of multimedia files (e.g., ExifTool, FFmpeg, GraphicsMagick, ImageMagick), or object de-compression (e.g., GNU Tar). These programs are usually written in memory-unsafe languages, such as C/C++, and due to their size and complexity are often the source of vulnerabilities [52]. The constant and extensive exposure to untrusted inputs in web applications may enable the attacker to trigger these vulnerabilities, leading to memory corruption issues. Arbitrary file reading or writing, local file inclusion and remote code execution are only a few of the possible risks associated with this kind of attack vector. In addition to that, package managers for languages commonly used in web development (e.g., `npm`, `pip`) do not enforce any kind of permission system. Thus, attackers can exploit vulnerabilities introduced by direct or indirect dependencies installed when 3rd party modules are imported by the application. Previous studies [15, 50, 80] have reported the risks associated with the propagation of vulnerabilities coming from dependencies in various software ecosystems. Usually, the exploitation of this kind of vulnerability leads to breaches that undermine confidentiality and integrity of data and code that reside outside the utility under attack. The goal of Cage4Deno is preventing a compromised utility running inside a Deno subprocess to violate access confidentiality and integrity of the filesystem. Notice that preventing integrity violation of the filesystem means, first and foremost, preserving the integrity of the web application code, configurations and data.

3.3 Design objectives

Several objectives need to be fulfilled by our proposal to ensure security, efficiency and ease of use.

O1. Integration with existing solutions (Compatibility): The proposal must be compatible with the current Deno architecture, and should be considered as an opt-in feature by the developer (i.e., backward compatible). Also, it has to be stackable with other security mechanisms already active on the host, like SELinux, AppArmor and Yama.

O2. Ease of use (Transparency): To be aligned with the needs of the web development scenario, the solution must be simple and easy to use. No specific understanding of the advanced security features leveraged by our solution, and of the underlying operating system, must be required to use it.

O3. Fine-grained access control (Flexibility): Unlike other security features that create a separated view of global resources (i.e., *Linux namespaces*), the solution must enable the developer to access the whole filesystem, granting access with file-level granularity rather than volume-level. Also, the developer must be able to flexibly switch between different policies, without requiring a host reboot when a new policy needs to be loaded.

O4. Automatic generation of policies (Usability): The proposal must provide tools to support zero-effort policy creation. With the exception of its input and output, no specific understanding of each utility should be required to run it successfully.

O5. Mitigation of vulnerabilities (Security): The proposal must prove effective in addressing the threat model described in Section 3.2 and mitigate CVEs affecting common Linux utilities.

O6. Low overhead (Performance): The overhead introduced with the additional security features must be compatible with the requirements of Web applications, which tend to prioritize short response time. It should be lower than the one introduced by state-of-the-art general-purpose sandboxing solutions, such as Minijail and Google Sandbox2.

4 DESIGN AND IMPLEMENTATION

This Section illustrates the design and implementation of Cage4Deno. We initially describe the interface used by the developer to input the policy, then we detail the changes introduced to support `read`, `write`, `exec` and `deny` permissions. A minimal program executing the `tar` utility in a subprocess is used as running example. The approach used to automatically generate the policy to confine `tar` is explained in Section 5, while additional BPF implementation details that focus on performance improvement are discussed in Appendix A.

4.1 Policy and interface

In the current Deno architecture, attributes and permissions associated with a program are always specified prior to execution. The developer provides this information through the Deno command line interface (CLI) using *runtime flags*. Runtime flags of the `deno run`, which precede the program name in the argument list, are immediately parsed and added to the global state before the JS program is executed. This design philosophy permits to directly address access requests issued by the application at runtime and, in case no permission is available, the program is promptly terminated. As an example, consider the program shown in Listing 1. Its purpose is simply to execute the `tar` utility to extract the compressed archive `input.tgz` to the `output` directory. Since to execute `tar` it leverages a subprocess, the argument `--allow-run=tar` must be provided, as the lack of such a permission would lead to the operation being prohibited.

As explained in the overview (Section 3.1), Cage4Deno relies on the ability to attach a policy to the program. To be compliant with the current design of Deno, we extended the global state adding the `--policy-file` runtime flag. As the name suggests, it receives as input a policy file. The policy file uses a JSON format, which is easy to edit and parse, and well-known by web developers. The file contains an array of policies identified by a `policy_name`. Each policy includes four arrays, `read`, `write`, `exec` and `deny`, listing a set of filesystem entries. As shown in Figure 4, the life cycle of Cage4Deno can be divided into two phases: load time and enforcing time. When Cage4Deno starts, the content of the policy file is read by the *sandboxer* (Ⓐ); to avoid repeating this step each time a new subprocess is spawned, the rule sets are stored in the permission state of Deno. Once all policies have been parsed, if any of them contains negative rules, the *sandboxer* loads the set of BPF programs needed to enforce deny, and a map for each policy containing the corresponding prohibited paths (Ⓑ). Due to this additional step, this is the only part of the execution in which Cage4Deno requires additional privileges compared to Deno. These privileges consist of the set of Linux capabilities necessary to load BPF components. To avoid any additional interaction the capabilities are configured as file capabilities. Once every BPF component has been loaded, we drop the capabilities, so to avoid running with higher privileges with respect to Deno at runtime.

After the initial setup, Cage4Deno is responsible of enforcing the policies provided by the developer. The *sandboxer* intercepts subprocess creation requests issued by the JS application at runtime (①) and, according to the policies available, it restricts the permissions associated with the subprocess (②) before the *exec* of the command provided to the `Deno.run()` is performed (③). During the subprocess (or any of its children) lifetime, file interactions are controlled by Landlock and our BPF programs to make sure access to the requested path is granted according to the policy definition

Listing 1: An example of child process in Deno

```
let a=Deno.run({cmd: ["tar", "xzf", "input.tgz
    ", "-C", "output"]});
await a.status();
```

Listing 2: Restricting a child process using `policyId`

```
let a=Deno.run({cmd: ["tar", "xzf","input.tgz"
    , "-C", "output"], policyId:"tarPolicy"});
await a.status();
```

provided by the developer (④). Two options are available to retrieve proper policy from the list: *(i)* automatically select the one with policy name matching the utility to be run in the subprocess (e.g., `tar` in Listing 1), and *(ii)* using the policy directly specified by the developer in the JS code using the newly introduced `policyId` option as shown in Listing 2. In both cases, if no policy is found, we fall back to the default Deno permission model. Option *(i)* allows the developer to run the subprocess without modifications to the JS program, while option *(ii)* gives more flexibility when multiple policy profiles for the same utility are available. This interface is straightforward and is perfectly aligned with the current Deno security model and architecture (Objective **O1**). Moreover, it does not require the developer to understand how the *sandboxer* leverages the kernel security features to add the restrictions, while granting the developer direct observability of the security boundaries put in place (Objective **O2**).

4.2 Support to `RWX` rules

Deno permits to set filesystem-related permissions through the `allow-read`, `allow-write` and `allow-run` runtime flags. As explained in the background (Section 2.1), the flags can be used to configure access to the whole filesystem, or can be refined specifying a list of comma separated filesystem entries. Similarly, we expect the developer to detail the `read`, `write` and `exec` permissions inside the JSON policy file. Listing 3 exemplifies the `RWX` permissions associated with the `tar` example.

The support for `RWX` permissions was introduced to Deno changing the implementation of *deno_core*. Internally, when a program performs a call to the `Deno.run()` and `Deno.Command.spawn()` functions, the bindings defined in *rusty_v8* are used to translate the request into an *op_run*. The operation is subsequently sent to the JS runtime, which is responsible to manage the request. In the case of a subprocess creation, this is done leveraging the asynchronous Tokio [22] runtime to configure an instance of `Command`, a process builder providing fine-grained control over how the process should be spawned. To apply the correct policy, we modified process creation, scheduling a closure (Rust equivalent of a C++ lambda expression) to be run just before the `exec` function is invoked. The closure leverages our *sandboxer* to create a new Landlock ruleset consisting of the `RWX` permissions found in the policy, and then invokes the `landlock_restrict_self()` syscall to apply it. Thanks to the policy inheritance property of Landlock, the policy attached to the process also restricts its children (as explained in Section 2.2). Should any of them try to access a filesystem location not listed in the policy, the request is denied.

Listing 3: `RWX+D` permissions associated with `tar`

```
{
  "policies": [
    {
      "policy_name": "tarPolicy",
      "read": [
        "/usr/bin/tar",
        "/home/user/input.tgz"
      ],
      "write": ["/home/user/output"],
      "exec":  ["/usr/bin/tar"],
      "deny":  ["/home/user/output/misc"]
    }
  ]
}
```

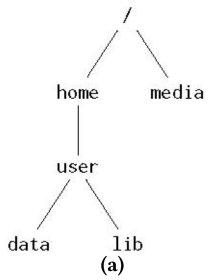
From a software development perspective, RWX permission rules are easy to understand and immediate to write. Contrary to the use of other frameworks such as the combination of Linux Namespaces [8] and Control Groups [28], RWX rules also permit to grant access with file-level granularity on the whole filesystem, and not only on single volumes (Objective **O3**).

4.3 Support to deny rules

Deny rules ensure a process has no access privileges over a file or a directory. Its introduction significantly reduces the overhead of the developer writing the policy. Unfortunately, the current *inode-based* design of Landlock does not provide support for it [64]. Given the low overhead associated with BPF (Objective **O6**), its fine-grained access control capabilities (Objective **O3**) and its compatibility with other LSM security mechanisms including Landlock (Objective **O1**), we identified BPF as the ideal candidate to implement the support to deny rules. However, loading BPF programs and maps is a privileged operation, so Cage4Deno needs to execute a preliminary initialization phase with additional permissions (as highlighted in Section 4.1).

This Section details the work we did to support deny rules. First, we present the problem of efficiently supporting access control decisions given a sequence of deny rules, then we explain how to translate the approach into BPF programs, making clear how the *sandboxer* enforces access control at runtime.

4.3.1 Deny listing approach. Similarly to what happens for RWX rules, we expect the developer to list the deny rules into the JSON policy file (see Listing 3). Based on the list provided, the *sandboxer* instruments the kernel so that, upon receiving an access request from a sandboxed process, the kernel is able to allow or deny it. For instance, assume the developer lists in the policy the deny rules `/home/user/data`, `/home/user/lib` and `/media`. When the sandboxed process issues an `open` to `/home/user/file` the request is allowed, but when the process tries to access `/home/user/data` (or any of its content) the request is denied. So, given a path request issued by the user, whether it matches exactly one of the rules in the deny list, or a deny rule is a prefix of the requested path, the access request is blocked. A classic solution to solve this problem efficiently can be implemented using a prefix tree (or trie). The idea is to split each path into a sequence of substrings using / as delimiter, treating the substrings as single character prefixes. The prefixes are then used to build a prefix tree as shown in Table 1a. At runtime, access requests are simply evaluated traversing the trie. If a leaf node is visited, we can conclude that a deny rule was hit, and the access request must be denied. The time complexity of a trie traversal depends on its maximum height. Given N the length of the longest deny rule D_{r_i} in the policy,[3] the maximum depth of the trie is $N/2$ (in the case of a path structured as $[/c]^{+}$). When a hashmap is used to implement the trie, each lookup (used to jump from the parent to the child) takes $O(1)$ time, thus traversing the trie takes $O(N)$ time (worst case upper bound).



(a)

		BPF Map	
r	**Trie prefix p_i**	**Hash**	**isLeaf**
1	/	$hash(p_1)$	0
2	/home	$hash(p_2)$	0
3	/home/user	$hash(p_3)$	0
4	/home/user/data	$hash(p_4)$	1
5	/home/user/lib	$hash(p_5)$	1
6	/media	$hash(p_6)$	1

(b)

Table 1: Deny prefix tree (a) and BPF Map_{policy} (b)

4.3.2 Implementation using BPF maps. The trie-based approach presented above cannot be translated directly to a BPF program. Indeed, there are some constraints a BPF program must satisfy to be executed by the kernel (see Section 2.3). The most important, in our case, is related to the use of memory. The current implementation of BPF does not provide support for multi-level map-in-map [48] structures required to implement the trie. Hence, we decided to translate the trie into a single-level hashmap Map_{policy} storing all the prefixes represented in the trie, as shown in Table 1b. The hash of each prefix is used as lookup key, while the value is a boolean to indicate whether the prefix is a leaf node in the trie. This representation permits to answer access queries with the same efficiency of the high-level approach. In fact, the trie traversal is easily replaced by a sequence of $O(N)$ lookups, each taking $O(1)$ time when a hash function is used to process the string representing the access path. Storing in the map also the prefixes that are not leaves in the trie increases the size of the map up to $O(M \cdot N)$ given a list of M deny rules, yet, it permits to reduce the query time for all the path prefixes that are not contained in the trie, as the lookup sequence terminates when a key error (i.e., a *miss*) occurs.

This design strategy relies on the ability to convert strings to integers using a cryptographic hash function. Unfortunately, such function is not currently available in BPF. In Appendix A we present this aspect in detail, explaining how we adapted the design to achieve the best trade-off between query response time and map size using an incremental hash function. Other details, such as explicit collision handling, are also discussed there, as they complement the design of our proposal.

4.3.3 BPF policy attachment. To enforce access control at runtime, the *sandboxer* must be able to retrieve the Map_{policy} according to

[3]The maximum path length is bounded to 4096 chars in `linux/limits.h`

Thread lifecycle hooks
uprobe/attach_policy
lsm/task_alloc
tp_btf/sched_process_fork
tp_btf/sched_process_exit

(a)

Access control hooks
lsm/path_mknod
lsm/path_mkdir
lsm/path_link
lsm/path_symlink
lsm/file_open
lsm/path_rename
lsm/path_rmdir
lsm/path_unlink

(b)

Table 2: Hooks and tracepoints monitored by Cage4Deno

the argument provided by the developer to the `Deno.run()`, and then to *attach* it to the sandboxed process. The attachment of the proper policy to the sandboxed process is delicate, and requires a set of programs to be loaded by Cage4Deno into the kernel alongside the maps. To reduce the runtime overhead, BPF programs, together with the BPF policy maps associated with all the policies listed in the JSON policy file, are loaded from user space to kernel space by Cage4Deno at startup time. These operations are carried out using *libbpf* [47]. The programs are separated in two categories: *(i)* programs that are needed to trace the lifecycle of a sandboxed process, and *(ii)* programs to evaluate the access queries it performs (according to the strategy described in Section 4.3.2).

The first group of BPF programs, namely the ones used to trace the process lifecycle, are responsible for maintaining in memory the map Map_{task} of processes running on the system that are subject to the restrictions imposed by Cage4Deno. Specifically, Map_{task} associates each thread identifier to the proper Map_{policy}. The entries in Map_{task} are updated when one of the hooks listed in Table 2a is reached. For instance, when a traced process issues the `clone` syscall, the tracepoint `tp_btf/sched_process_fork` is reached, the related BPF tracing program executed, and the new child process, inheriting the policy of the parent, is added to Map_{task}.

The second group of BPF programs, the ones that are associated with the evaluation of the access query, are executed when any of the hooks listed in Table 2b is reached. The role of these programs is to check whether the current process (i.e., the process issuing the access request) belongs to the Map_{task}, and accordingly to perform the sequence of lookups in Map_{policy} to allow or deny the request.

5 POLICY GENERATION

A key aspect of our proposal is usability by developers. The straightforward `RWX+D` permission model is functional to achieve ease of use (Objective **O2**), however, we believe that it is also important to offer to the developers tools to support the generation of policies (Objective **O4**). Indeed, each policy can be seen as a template comprising the dependencies to run a program that can be further extended with information related to the input, the output, and the restrictions the program may be subject to. This section details the work we did to support the process, explaining how our solution can be leveraged to generate the `RWX` rules shown in Listing 3.

The retrieval of the dependencies used by a program is a recurring problem. Just to mention a few, it occurs in the Google Sandboxed API project, where the Sandbox2 sandboxing utility [31]

Listing 4: Semi-automatic generation of `tar` policy (Listing 3)

```
# Set the active policy_name for a program
dmng -c tar --setcontext tarPolicy
# Add the dependencies of tar to the template
dmng -c tar -t -s
# Add the input to the template
dmng -c tar -a input.tgz -p r--
# Add the output to the template
dmng -c tar -a output -p -w-
# Add the denials
dmng -c tar -a output/misc -d
# Serialize the entries into a JSON file
dmng --serialize tar_policy_file
```

leverages `ldd` (acronym for *List Dynamic Dependencies*) to retrieve the dependencies used by programs available on the host as *Executable and Linkable Format* (ELF) files; or in SlimToolkit [61], where a containerized service is run against a test suite to automatically create Seccomp [9] and AppArmor [10] security profiles matching the least-privilege principle. In Cage4Deno, we adopt a similar approach, which retrieves the files a program should be able to read, write, or execute to work as intended. Moreover, we need to provide the developer with functions to manage multiple policies simultaneously (updating the lists of dependencies and denials), and to serialize them into the JSON format as shown in Listing 3.

The solution we adopted was to develop `dmng`, a CLI tool written in Go (~3.5k lines of code), which ships within Cage4Deno, allowing the developer to automatically generate `RWX rules`, and interactively refine, the policy. The utility supports the retrieval of program dependencies that are available on the host as ELF files, and those that are spawned by dedicated POSIX or shell wrappers. It can also be used with programs loading dynamic modules at runtime (e.g., media processors loading custom encoders), or programs executing several binaries. To support these use cases, `dmng` relies on both `ldd` and `strace`. The former was preferred to `objdump` and `readelf` since it can be used to recover the so called *transient* dependencies of programs available as ELF files; while the latter is a diagnostic, debugging and instructional user-space utility for Linux that is used to trace programs at runtime.

Similarly to the approach presented in SandTrap [3], the developer can use `dmng` to run a test suite against a program (or a script). This apparoach allows the developer to reuse existing tests to generate `RWX` rules that satisfy multiple execution paths of the binary. By using `strace`, `dmng` monitors the interactions between the threads spawned by the tested utility and the kernel for a certain amount of time (usually less than 2*s*). In this time frame, the file-related syscalls issued by the set of threads, along with their arguments, are captured and saved to a log file. The log is then used by `dmng` to generate the `RWX` rules accordingly. The list of syscalls monitored comprises the ones wrapped by the standard system functions `execve()`, `open()`, `create()`, `link()`, `mkdir()`. The `dmng` tool exposes to the developer many functions to inspect, add, update or remove the entries associated with the policy template. Specifically, it allows to add deny rules, which generation cannot be automated. It also implements heuristics to reduce the number of `RWX` rules, thus improving their readability, and facilitating policy auditing, when explicitly requested by the developer. This inherently comes with the downside of producing coarser permissions. The process is called *permission pruning* and it is based on common security practices, like the identification of write-or-exec (`W^X`) memory regions, but also contextual information about the specific region of the filesystem being considered (e.g., there are no practical advantages in assigning fine-grained permissions under `/usr/share/fonts/`, while it is certainly useful to do so under `/home/user/Documents`). For this, the paths are arranged into a Trie, and then the above heuristics are used to incrementally prune leaf nodes untill the developer's target number of rules is met.

For each of the programs to be restricted, a sequence of commands may be input by the developer to synthesize the final policy (state is persisted between tests using a SQLite database). Since the developer can work with distinct programs and many policies simultaneously, a cache is used to store the active context (i.e., the current policy) of each program (line 2 in Listing 4). Then, each context is customized adding the dependencies as previously described. For instance, in line 4 `dmng` collects all the dependencies required by `tar` using dynamic tracing, and in line 10 the developer manually adds the deny rule. After all the policy contexts have been configured, the policy is serialized into the JSON format as expected by Cage4Deno (line 12). Appendix B reports the complete `tar` policy produced following the instructions in Listing 4.

In this paper we employ dynamic analysis for the automatic generation of policies, however this is widely known for producing results whose completeness depends on the test suite coverage [77]. To address this limitation, the current approach could be complemented by either source or binary code analysis. Relevant works (e.g., [16]) use static analysis to pinpoint the system calls, however they do not keep track of parameter values. On the other hand, *AutoArmor* [45] uses static taint analysis to perform semantics-aided program slicing from network API invocations, and then uses these slices to extract access control attributes. The approach also looks promising for the generation of file system policies.

6 EXPERIMENTS

In this Section we present the experimental evaluation of Cage4Deno. The evaluation considers two aspects of our solution: exploit mitigation (Section 6.1), and performance overhead (Section 6.2). To perform our evaluation we used the following test environment: an Ubuntu 22.04 LTS server powered by an AMD Ryzen 3900X CPU with 12 cores (24 threads), 64 GB RAM, 2 TB SSD. Then, we replaced the pre-installed Linux Kernel v5.15 with the same release of the kernel, but with BPF LSM available (Landlock LSM is enabled by default).

6.1 Exploit mitigation

The primary goal of this Section is to demonstrate the capability of Cage4Deno to mitigate real CVEs (Objective **O5**). Focusing on the records of the last 5 years, we selected a sample of 15 vulnerabilities affecting common web application utilities, such as ExifTool, FFmpeg, Git, GNU Tar, GraphicsMagick, Ghostscript, ImageMagick, OpenSSL, Pip, UnRAR, and Unzip. The CVEs we considered are classified into Remote Code Execution (RCE), Local File Read (LFR), and Arbitrary File Overwrite (AFO). Their details are reported in Table 3.

CVE ID	Utility	Use case
	Local File Read (LFR)	
CVE-2016-1897	FFmpeg v3.2.5	Video processing
CVE-2016-1898	FFmpeg v3.2.5	Video processing
CVE-2019-12921	GraphicsMagick v1.3.31	Image processing
	Arbitrary File Overwrite (AFO)	
CVE-2016-6321	GNU Tar v1.29	Archive decompression
CVE-2019-20916	Pip v19.0.3	Dependency fetch
CVE-2022-30333	UnRAR v6.11	Archive decompression
	Remote Code Execution (RCE)	
CVE-2016–3714	ImageMagick v6.9.2-10	Image processing
CVE-2020-29599	ImageMagick v7.0.10-36	Image processing
CVE-2021-3781	Ghostscript v9.54.0	PDF processing
CVE-2021-21300	Git v2.30.0	Clone repository
CVE-2021-22204	ExifTool v12.23	Image processing
CVE-2022-0529	Unzip v6.0-25	Archive decompression
CVE-2022-0530	Unzip v6.0-25	Archive decompression
CVE-2022-1292	OpenSSL v3.0.2	Certificate verification
CVE-2022-2566	FFmpeg v5.1	Image processing

Table 3: Sample of CVEs mitigated by Cage4Deno. Despite being discovered in 2016, CVEs 1897, 1898, and 6321 have seen recent exploitation in 2018 [67] and 2021 [36]

These vulnerabilities have been selected as they represent examples of 0-click exploits, they can lead to severe security breaches, and they target utilities extensively used by web applications. In general, similar considerations extend to a broader set of CVEs.

In our analysis we reproduced each of the vulnerabilities adapting public Proofs of Concepts. For each of them, we provide a single-click test showcasing the sandboxing capabilities added to Deno. In particular, we show that: *(i)* the attacker can successfully exploit the vulnerability when Deno is used (despite its permission model being in place), and *(ii)* the attack is unsuccessful when the sandboxing functions offered by Cage4Deno are used. The only difference between case *(i)* and *(ii)* is that a policy is provided with the `--policy-file` argument. This aspect testifies how simple it is to benefit from the sandboxing functions we have introduced (Objective **O2**). The policy files used to restrict each utility have been automatically generated with the `dmng` tool described in Section 5. Table 4 reports the number of rules generated for the selected list of utilities without applying any form of policy minimization (i.e., pruning). As shown in the table, the utilities require less than 115 permissions to work as intended, with `pip` requiring the largest set.

From a security standpoint, it is worth noting that Cage4Deno can block the attacks at multiple levels. For instance, in CVE-2020-29599, in which a crafted picture is sent to ImageMagick to execute a target command (e.g., `id`), Cage4Deno does not allow `RX` access to `/usr/bin`, blocking `/usr/bin/echo` first (which is used to inject `id` in a subshell), and then the target command itself (i.e., `usr/bin/id`). In this case, the denial is due to the Landlock sandbox allowing access solely to `/usr/bin/convert` (i.e., the ImageMagick binary). Instead, when we consider CVE-2016-6321, in which a decompression of an archive permits the attacker to overwrite a target file,

Utility	#rules	Deno [ms]	Cage4Deno [ms]
`cat`	9	3.05±0.23	3.81±0.25
GraphicsMagick	81	10.16±1.02	12.16±1.12
UnRAR	25	13.86±1.97	15.84±2.71
ImageMagick	17	17.49±2.14	18.74±2.26
Unzip	15	20.90±3.95	22.66±3.62
OpenSSL	17	27.80±4.93	30.10±7.50
Git	26	66.52±4.75	72.46±5.22
ExifTool	38	109.20±6.67	112.88±4.25
GNU Tar	14	114.52±7.21	125.48±6.89
FFmpeg	12	321.50±9.55	336.70±9.78
Ghostscript	20	449.96±18.19	455.66±21.37
Pip	115	3022.52±20.55	3203.32±20.84

Table 4: Preliminary test showing the execution time of utilities reported in Table 3 over 500 runs (as $\mu \pm \sigma$)

we show how deny rules can be used to prevent filesystem corruption. As a final note, we highlight the ability to simultaneously use distinct policies for a single utility. To give an example, in CVE-2021-21300 several distinct policies can be assigned to `pip`. By doing so, the developer can select a dedicated policy based on the Python virtual environment currently in use.

Popular packages affected by the aforementioned vulnerabilities can be found in both `deno.land/x` and `npm` package archives. Among them, we selected `astrodon` and `fast_forward` from the former, `fluent-ffmpeg` and `gm` from the latter (executed in Node compatibility mode). We confirmed that the vulnerable versions of the binaries are still exploitable through the mediation of third-party modules, and Cage4Deno proves to be effective in their mitigation without code modification to the application and its dependencies.

6.2 Performance evaluation

A requirement of our proposal is that it must not introduce a large runtime overhead compared to the scenario in which the developer relies solely on the basic functions offered by Deno (Objective **O6**). This is fundamental, as any additional delay could negatively affect the end-user experience or increase the cost to host the application. To investigate this aspect, we performed tests comparing the execution time of an application using vanilla Deno with respect to the same application subject to access restrictions with Cage4Deno. A second interesting aspect to consider in the evaluation is the overhead introduced by our proposal compared to general-purpose sandboxing solutions proposed by the industry. Finally, we evaluate how our solution scales with the numer of rules in the policy.

6.2.1 Runtime overhead. In our analysis we expected the runtime overhead to vary according to the size of the policy and the number of filesystem requests performed by the sandboxed utility. We therefore conducted a preliminary test involving the utilities affected by the CVEs detailed in Section 6.1. For each of them, we measured the execution time of vanilla Deno and Cage4Deno. The results of the test are reported in Table 4. The data clearly show that the largest overhead is associated with the larger policies and the shorter execution time. To further highlight this aspect, we imagined the worst case scenario in which a simple binary is used to perform a single access to the filesystem. As shown in row 1 of Table 4, printing the

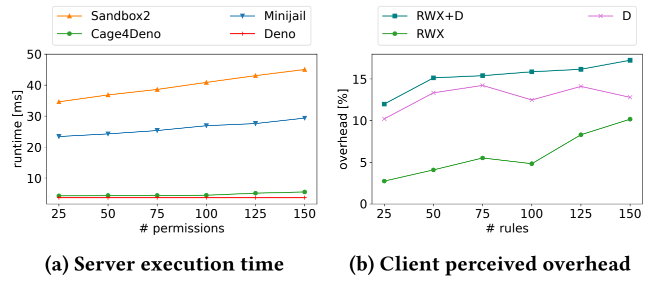


Figure 5: Deterioration of overhead varying the policy size

content of an empty file using the `cat` binary is associated with the greatest overhead, roughly 25% of the execution time. `cat` is characterized by a minimal execution time, and requires only 9 rules in the policy to work as intended, thus proving to be the best candidate to highlight the overhead introduced by Cage4Deno.

To evaluate how our solution scales with the increase of rules in the policy, we set up a second test. We again used `cat`, but this time we added to its minimum set of permissions a varying number of `RWX` rules, ranging from 25 to 150. To measure the execution time we relied on the benchmarking module provided by the Deno standard library [18], and to ensure the statistical value of the results we repeated the test 500 times. Initially, we compared the execution time of vanilla Deno and Cage4Deno. While Cage4Deno inevitably introduces an overhead, its performance degradation (compared to Deno's) ranges between 0.8 and 2.5 ms, which is a reasonable price for the additional security guarantees it provides.

To further inquire, we compared Cage4Deno with two general-purpose sandboxing solutions: *(i) Minijail* [30], and *(ii) Sandbox2*, a key component of the Sandboxed API [31] framework. As shown in Figure 5a, the execution time associated with the use of Minijail is 5.52 to 5.63 times slower compared to the one of Cage4Deno, and Sandbox2 exhibits even a worse degradation, which is never less than 8.15 times. To investigate the principal components causing the overhead, we profiled the execution of each tool with `perf`. Each of them presented two distinct phases: *(i)* sandbox setup, and *(ii)* restricted execution. For Minijail and Sandbox2 the first phase is dominated by creating the mount namespace, changing root directory, and performing a `bind-mount` for all the files needed to run the utility. For Cage4Deno, equivalent protection can be achieved with only the creation and enforcement of the Landlock rulesets. As for the execution phase, Minijail and Sandbox2 suffer slowdowns whenever performing filesystem operations due to the execution of kernel code paths related to the resolution of namespaces and bind mounts. In addition, Sandbox2 reference monitor architecture requires inter-process communication between the tracee and its tracer, which further degrades performance. On the other hand, Cage4Deno only pays the overhead of evaluating the Landlock security checks.[4] This validates our design choices, proving that our solution can provide significantly better performance with respect to industrial general-purpose sandboxing solutions. Moreover, Figure 5a depicts an interesting trend. Among the sandboxing alternatives, not only Cage4Deno delivers the best performance, but it

[4]The flame graphs used for the analysis are available in the repository of the project.

also exhibits the slowest linear growth with respect to the increase of the number of rules, making it the best option when a large number of policy rules is necessary.

6.2.2 *Overhead associated with deny rules.*

The previous tests do not take into account the deny rules. In fact, both Minijail and Sandbox2 do not support the presence of negative permissions. It is then important to measure the overhead introduced by them, as well as its degradation when the policy size increases. To better investigate the overhead experienced by end-users when Cage4Deno is used on the back-end, we evaluated the response time of a single HTTP endpoint that responds to incoming request with the content printed by the `cat` command. To generate the HTTP requests we relied on *JMeter* [5], a tool written in Java designed to load test and measure the performance of web applications. Specifically, we configured it to generate 100 warm up requests and measured the latency of the following 5000. To simulate the overhead experienced by end users of a web application, we also set up a network delay of 10±5 ms (with a normal distribution) using `tc` [4], a Linux utility to configure and shape the network traffic. The test is executed four times with the following policy configurations: *(i)* no policy (i.e., vanilla Deno), *(ii)* only positive rules (i.e., `RWX`), *(iii)* only deny rules, and finally *(iv)* a policy characterized by the same number of `RWX` and `D` rules. Again the number of rules in the policy ranges between 25 and 150.

In general, the results reported in Figure 5b confirm the trend shown in Figure 5a, with an overhead increasing almost linearly with the number of rules in the policy. This is a positive aspect, since it applies to both `RWX` and `D` rules. The relative overhead perceived by clients, with respect to the default implementation of Deno, ranges from 2.74% to 10.21% for policies listing only `RWX` rules. This attests that the cost associated with Landlock is low, but it increases linearly with the number of rules (in accordance with the current inode-based implementation of the LSM). On the other hand, the use of BPF is distinguished by a higher initial cost, but the performance degradation introduced when the number of deny rules increases is smaller compared to the one measured with pure `RWX` policies, since it ranges between 10.17% and 12.79%. Moreover, policies composed of both rule types still exhibit a linear trend, with a client perceived overhead ranging from 11.99% to 17.24%. It is important to note that the presence of deny rules not only improves the readability and maintainability of the policy, but can also improve the performance as it permits to reduce the overall number of rules in the policy.

7 RELATED WORK

Several approaches to strengthen the security guarantees provided by JavaScript execution environments have been proposed by both industry and academia. While developing Cage4Deno we focused on solutions that target runtimes and are therefore applicable to the server-side scenario. Our proposal complements them providing effective isolation of subprocesses using recent technologies. In the following, we separate the related works into four main categories.

Secure JavaScript sandboxes. Several works have been proposed to strengthen the security guarantees offered by JavaScript runtimes before the advent of Deno [3, 20, 49, 57–59, 71, 74, 75, 78].

Secure EcmaScript (SES) [49] is a runtime library to execute third-party code safely in lightweight compartments. Essentially, SES implements a *frozen* execution environment in which scripts have no abilities to interfere with each other. An alternative for the safe execution of untrusted third-party JavaScript code is *vm2* [59]. Its peculiarity is that it overrides the built-in `require`, enabling the developer to restrict access to a pre-defined set of modules. SES and vm2 have been effective in mitigating the vulnerabilities coming from unverified or untrusted third-party JavaScript code, since they allow the developer to practically limit the APIs exposed to the sandboxed JavaScript program. However, when access to a dangerous API such as `Deno.run()` or `child_process.spawn()` is granted, no restriction on the subprocess is enforced.

Another interesting approach to reduce the security risks coming from the use of third-party modules is *BreakApp* [74]. The authors use module boundaries to automate compartmentalization of systems and enforce security policies. To this end, BreakApp spawns and executes modules in protected compartments, while preserving their original behavior. Compartments are characterized by three levels of isolation: sandbox, process, and container level. While the approach is powerful and ensures strong security properties when the container level is used, it is not straightforward to setup fine-grained filesystem permissions when the process level is selected.

Mir [75] is a relevant proposal to mitigate the security risks coming from third-party modules through the use of library-specialized contexts. Mir applies a fine-grained `RWX` permission model to every field of every free variable name in the context of an imported library, with permissions inferred through static and dynamic analysis. *SandTrap* [3] shares with Mir the idea of protecting read, write and call on entities (primitive values, functions, objects) and construct policies on cross-domain interaction. The goal again is to mitigate the security risk coming from the use of third-party modules, but in the Trigger-Action Platforms (TAPs) framework. While both the approaches can mitigate several JavaScript vulnerabilities, no restriction is applied on code executed outside of the runtime.

Wolf at the Door [78] is a recent proposal to reduce the risk coming from the installation of third-party modules. The authors propose to use the Apparmor LSM to detect install time anomalies such as connection to unknown hosts or read of confidential files. The security checks are enforced based on a policy typically written from the package maintainer. The approach protects the host against undesired behavior of third-party packages installed through `npm`, but the protection is enforced only at install time.

Isolation and sandboxing of unsafe libraries. The problem of isolating subprocesses addressed by Cage4Deno shares strong similarities with the isolation and sandboxing of third-party libraries. This area has received significant attention recently, and many proposals have been published [29, 37, 43, 52, 60, 62, 63, 65, 73, 76]. *Galeed* [62], *PKRU-Safe* [43], and *NoJITsu* [60] guarantee strong isolation of unsafe components with the use of Memory Protection Keys (MPK). Galeed and PKRU-Safe preserve the memory safety of Rust code when used in conjunction with unsafe code (e.g., C/C++). NoJITsu brings hardware-backed, fine-grained memory access protection to JavaScript engines, thus successfully hindering a wide range of memory corruption attacks. Differently from previous solutions, *RLBox* [52] achieves sandboxing of third-party libraries through software-based-fault isolation. RLBox facilitates the retrofitting of existing applications using a type-driven approach that significantly ease the burden of securely sandboxing libraries in existing code. These solutions are complementary to Cage4Deno, as they can be used in conjunction with it to enforce trust boundaries in the interaction between Deno and its subprocesses.

General-purpose sandboxers. To reduce the impact of potentially vulnerable processes, several approaches leveraging system call interposition have been proposed [7, 12, 16, 30, 31, 42, 53].

TRON [7] is a discretionary access control system. The authors designed a Unix based capability system to limit process access to files, directories and directory trees. Although the approach allows fine-granularity access control, it suffers from two major drawbacks: *(i)* it requires modifications on the kernel, and *(ii)* it requires programs changes to make them capability-aware.

Another interesting initiative to implement unprivileged sandboxes is *MBOX* [42]. MBOX executes a program in a sandbox, and prevents it from modifying the host filesystem by layering the sandbox filesystem on top of it. Only at the end of the execution the user can examine changes in the layered filesystem and commit them back to the host. To do so, MBOX interposes system calls using Seccomp filters, and relies on `ptrace` to enforce permissions. However, the use of `ptrace` is prone to TOCTOU attacks [39], and as experimented by the authors, it can lead to non-negligible overhead.

In practice, system call interposition is often used to limit the set of system calls available to a program [16, 61, 77]. This effectively limits the capabilities of an attacker expoiting the program, and reduces the attack surface of the kernel [46]. Nowadays, most solutions rely on Seccomp filtering, a Linux kernel feature that allow to filter system calls based on their identifiers and parameter *values*. While valid, Seccomp filters can neither dereference pointers to user memory, nor actionably use file descriptor numbers, thus they are not suitable to perform access control of filesytem resources. These solutions can be used in conjunction with Cage4Deno to reduce the attacker capabilities and the attack surface of the kernel.

In Section 6 we have already compared Cage4Deno to other general-purpose sandboxing solutions such as *Minijail* [30], and *Sandbox2* [31]. These tools support multiple types of containment techniques such as the introduction of new user ids, restriction of capabilities, policy-based Seccomp filtering, and namespace isolation. Both the tools are powerful and flexible, but they are not specifically aimed towards protecting web applications. Thus, they are not optimized for the execution of short-lived programs, and they target security experts, making them of difficult use to a wider audience. Specifically, to achieve comparable protection to our `RWX` rules, the developer needs to configure them to: *(i)* create a new mount namespace, *(ii)* change the root directory of the binary, and *(iii)* remount every part of the file hierarchy necessary for the functioning of the binary under the new root. On the other hand, Minijail and Sandbox2 use well enstablished kernel features available in every modern Linux kernel version, and can be used without additional privileges provided there is no need to bind-mount privileged resources. Similar considerations can be made about *Firejail* [53] and *Bubblewrap* [12]; sandboxing tools functionally comparable to Minijail and Sandbox2, but less mature.

BPF-based sandboxers. Other proposals have used BPF as the primary means to enforce access control policies [2, 6, 11, 25–27, 38].

BPFBox [27] and *BPFContain* [26] are runtime security frameworks focusing on the containment of processes and containers, respectively. Comparing Cage4Deno to both the proposals, *(i)* we do not require a privileged runtime daemon to keep track of the traced processes (single point of failure), *(ii)* we rely on Landlock to enforce `RWX` permissions so to guarantee low runtime overhead, and *(iii)* we provide a tool for the automatic generation of policies.

Snappy [6] strengthens the security of containers using namespaces and BPF policies. To support the programmable policies described, the authors introduced in the kernel a set of new *dynamic helpers*. Jia et al. [38] present a mechanism to define advanced syscall filtering policies with the *extended* BPF. This is currently achieved by hooking syscall tracepoints that cause system-wide performance degradation and are still subject to TOCTOU attacks. On the other hand, Jia et al. successfully address these limitations proposing changes to the Linux kernel. These proposals require to recompile the kernel with the addition of ad hoc functions not part of the kernel codebase, thus limiting their usability and portability.

There are also industrial solutions using BPF, for instance: *Cilium* [11] and *Falco* [25]. The former provides BPF-based networking, observability and security between container workloads, the latter is a threat detection engine for clusters. Both operate at the container granularity; hence, developers may find it difficult to set up fine-grained permissions with these frameworks.

These proposals demonstrate the value of BPF in securing different types of system resources. Extending our proposal to the protection of non-filesystem resources is promising for future work.

8 CONCLUSIONS

Web development is a fast-paced environment characterized by tight time constraints. In this vast ecosystem, we specifically considered the role of Deno, a modern and secure runtime for JavaScript and TypeScript. Our proposal presents a way to improve the Deno security model by sandboxing the invocation of subprocesses, which represent an important attack vector of web applications. As shown in the experimental evaluation, Cage4Deno effectively mitigates real CVEs affecting widely-used utilities in web applications. Moreover, it exhibits significantly better performance with respect to other general-purpose sandboxing solutions. We paid great attention to reduce the overhead of the developer willing to strengthen the security of its application. This is achieved not only by exposing a simple and clear interface to the developer (requiring no mandatory code changes), but also providing a command line tool to generate least-privileged, yet human-readable, access control policies. We believe the proposed approach is general enough to be applied to other runtimes, since they share the same design as Deno regarding the unconstrained execution of subprocesses (e.g., Node.js and Bun). This is a promising line of research we plan to explore in the future.

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A BPF DETAILS

In the following we detail, as a complement, some of the issues we found working with the current implementation of BPF, explaining how we solved them.

A.1 Hashing & collision handling

As anticipated in the design and implementation of deny rules (Section 4.3), the current implementation of the BPF framework does not provide support for map-in-map structures [48]. Moreover, support for using string keys in a map is still limited [35]. At the time of writing, a patch for providing this option, along with efficient ternary search support to lookup the map [34], are under active development on `bpf-next`, the branch dedicated to the features and improvements that should eventually land in BPF. Nonetheless, we had to cope with the temporary limitation of using an integer key to lookup the Map_{policy}, hence, we had to find a way to transform the string prefixes stored in the trie to fixed size integers. A typical approach to solve this problem is to use a hash function. Given the need to preserve the ability to search for prefixes efficiently, we opted for using an incremental hash function. Given S_r, the string representing the access path, an incremental hash function permits to compute $hash(S_r\ [i])$, the hash of the prefix terminating at character i, in constant time given the hash of the prefix terminating at $i-1$. In our case we relied on *djb2* [40], a non-cryptographic low-complexity incremental hash function proposed by D. J. Bernstein.

The use of a hashing function also required us to handle the collisions explicitly. Indeed, collisions may occur during map creation, and at runtime upon receiving an access request. Basically, this means that every time a key is found in the policy map Map_{policy}, a collision check has to be performed to determine whether a deny rule was hit. The best trade-off between query response time and size of the policy map has been achieved adapting the separate hash chaining approach, in which a fixed size array is used to store a sequence of colliding paths. To explain how it works we introduce the following example. Let us assume to have three deny rules in the policy: `/home/user/data`, `/home/user/lib` and `/media`. Also, let us assume that the djb2 hash of `/home/user/lib` and `/media` collide. Instead of using the deny rules to build a prefix tree, we can build the policy map Map_{policy} as shown in Table 5. Upon receiving an access request S_r, the verifier computes the incremental hash for each of its prefixes, and then performs a sequence of map lookups. In case no lookup is successful, the verifier concludes that no deny rule was hit, hence the access request is granted. Conversely, the verifier must check whether a deny rule was hit, or a collision was found. To do that, the verifier compares the access request S_r, and each of the colliding paths associated with the lookup key. Algorithm 1 details the procedure.

The time complexity of the proposed approach varies according to the presence of collisions. When none occurs, the worst case time complexity is given by the total hashing time $O(N)$, plus the total lookup time $O(N)$ (i.e., in the worst case S_r is structured as $[/c]^+$, hence $N/2$ lookups each taking $O(1)$ time are performed). Instead, each time a collision occurs (or a deny rule is hit), the verifier incurs in an $O(N \cdot L)$ extra time, where L is the length of the longest collision chain. Similarly to other research proposals [40], the results presented in our Experimental Evaluation showed a limited impact associated with the presence of collisions (see Section 6). It is worth mentioning that the number of collisions can be reduced using a cryptographic hash function, at the expense of a lower efficiency. With regard to the size of the policy map, given M the number of deny rules in the policy, a space of $O(M \cdot N)$ is required.

BPF Map	
Deny rule hash	**Array of colliding paths**
$djb2(D_{r1})$	`/home/user/data` $\longrightarrow \emptyset$
$djb2(D_{r2}, D_{r3})$	`/home/user/lib` $\longrightarrow$ `/media` $\longrightarrow \emptyset$

Table 5: Map_{policy} with separate hash chaining (assuming the hashes of `/home/user/lib` and `/media` colliding)

Algorithm 1 Modified deny rule verifier

```
1:  procedure DENY_VERIFIER($S_r$)
2:      $task \leftarrow bpf\_get\_current\_task\_btf()$
3:      if $\neg task \in Map_{task}$ then
4:          return 0                                        ▷ Grant request
5:      $Map_{policy} \leftarrow Map_{task}\ [task]$
6:      for each $prefix$ in $S_r$ do
7:          if $djb2(prefix) \in Map_{policy}$ then
8:              $collision\_chain \leftarrow Map_{policy}\ [djb2(prefix)]$
9:              for $D_r$ in $collision\_chain$ do
10:                 if $isPrefix(D_r, prefix)$ then
11:                     return -EPERM                       ▷ Deny request
12:     return 0                                            ▷ Grant request
```

A.2 Map types

BPF provides several map types to the developer. Each of them is characterized by distinct performance and functions. In Sections 4.3 and A.1 we illustrated our construction of the verifier, detailing the role of Map_{task} and Map_{policy}. The former permits to keep track of the processes subject to the control of Cage4Deno and to associate them with a policy map, while the latter stores the restrictions listed in a policy. Since the content and number of entries of Map_{task} varies at runtime, in the implementation we opted for the `TASK_STORAGE` map type, which permits to be modified calling the `bpf_task_storage_get()` and `bpf_task_storage_delete()` BPF helpers. With regard to Map_{policy}, no modification is permitted after the creation of the map. The only parameter to be minimized is the lookup time, hence we opted for the `HASH` map type.

A.3 Stack limitation

The maximum path length on a Linux system is bounded to 4096 characters (in `linux/limits.h`). Unfortunately, the stack size of a BPF program is limited to 512 bytes. To circumvent this limitation, we stored each access path outside of the BPF stack, in a dedicated `PERCPU_ARRAY` map. As the name suggests, each CPU core executing a BPF program has an instance of the `PERCPU` map, which can hold a different state. However, the content of an instance cannot be modified for the whole duration of the check performed by the verifier (except for the verifier itself), as BPF programs are non-preemptable. Therefore, the use of the PERCPU type bypasses the BPF stack limitation without requiring any additional concurrency primitive (e.g., spinlocks).

B GNU TAR POLICY FILE

Listing 5 reports the policy associated with GNU Tar. The policy has been generated using dmng according to the procedure described in Listing 4.

Listing 5: Example of policy associated with `tar`

```
  {
  "policies": [
    {
    "policy_name": "tarPolicy",
      "read": [
        "/usr/local/bin/tar",
        "/usr/lib/locale/locale-archive",
        "/usr/share/locale/locale.alias",
        "/usr/bin/gzip",
        "/lib/x86_64-linux-gnu/libc.so.6",
        "/lib64/ld-linux-x86-64.so.2",
        "/etc/ld.so.cache",
        "/home/user/input.tgz",
      ],
      "write": [
        "/home/user/output"
      ],
      "exec": [
        "/usr/local/bin/tar",
        "/usr/bin/gzip",
        "/lib/x86_64-linux-gnu/libc.so.6",
        "/lib64/ld-linux-x86-64.so.2"
      ],
      "deny": [
        "/home/user/output/output/misc"
      ]
    },
}
```