GoLeash: Mitigating Golang Software Supply Chain Attacks with Runtime Policy Enforcement

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Abstract

Modern software supply chain attacks consist of introducing new, malicious capabilities into trusted third-party software components, in order to propagate to a victim through a package dependency chain. These attacks are especially concerning for the Go language ecosystem, which is extensively used in critical cloud infrastructures. We present GoLeash, a novel system that applies the principle of least privilege at the package-level granularity, by enforcing distinct security policies for each package in the supply chain. This finer granularity enables GoLeash to detect malicious packages more precisely than traditional sandboxing that handles security policies at process- or container-level. Moreover, GoLeash remains effective under obfuscation, can overcome the limitations of static analysis, and incurs acceptable runtime overhead.

Keywords

Software Supply Chain Security, Runtime Enforcement, Golang

1 Introduction

In recent years, software supply chain (SSC) attacks have jumped to the forefront of cybersecurity concerns. Rather than attacking end-users directly, adversaries now infiltrate the software development pipeline. Attackers have been injecting harmful code into widely-used software packages through social engineering, malicious commits, typosquatting, and hijacking unmaintained repositories [14, 16]. Once a compromised package is released, downstream projects are infected by malicious code through normal dependency resolution and build processes. Their users then become susceptible to credential theft, resource hijacking, and remote command execution [31].

These supply chain attacks are especially alarming for the Go language (Golang) ecosystem. This language has been heavily used for critical cloud software [73], including Kubernetes [43], Docker [22], Terraform [39], Etcd [24], and several others mission-critical infrastructure [20]. Injecting malicious code into these Golang software projects would enable unauthorized control over cloud infrastructures, with potentially devastating consequences. We are already

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witnessing supply chain attacks against the Golang ecosystem, including the recent typosquatting attacks to the BoltDB database [7] and Hypert testing library [8], and the huge number of Go packages found on GitHub that are vulnerable to repojacking [5]. In this paper, we aim to improve the state of the art of mitigating software supply chain attacks on Golang critical applications.

We present *GoLeash*, a novel approach and its research prototype for mitigating malicious behavior of Go packages once they have been compromised. GoLeash is inspired by the "principle of least privilege", that is, the idea that accesses should be limited to the minimal set that is feasible and practical [61, 65]. GoLeash has two modes: 1) an analysis mode to automatically infer the policies of Go packages; an enforcement mode that restricts the behavior of Go packages at run-time, by checking that Go packages comply with the package policy. Go packages in the supply chain are forbidden to perform operations with *capabilities* that they are not supposed to have (for example, opening a network connection in a package for local data processing).

GoLeash monitors Go programs at run-time, using the eBPF framework [23], to collect information about capabilities accessed by Go packages and automatically build a security policy (analysis). Thus, it enforces Go packages to have the minimal set of capabilities required to perform their intended purpose (enforcement).

GoLeash is a novel approach for policy enforcement. Existing approaches for monitoring and sandboxing of system calls for Go [38, 69] only apply to entire processes and containers, which makes enforcement too coarse-grained to mitigate supply chain attacks. If a package in the program is allowed to use a capability (e.g., a privileged system call), the entire process or container needs to be assigned that capability. GoLeash works at a finer grain, since it is able to trace back which Go package is using a capability at a given moment, thus it can enforce separate policies across different Go packages. As we will demonstrate, this ability makes GoLeash more precise and less prone to omissions.

To evaluate GoLeash, we systematically inject malicious behaviors (e.g., exfiltrate or infiltrate files) into the software supply chain of real-world, complex applications such as kubernetes. Our evaluation shows that GoLeash is able to successfully identify malicious packages in 98% of cases, compared to 32% in the case of coarse-grained monitoring. Moreover, our approach is effective even when obfuscation techniques are used for hiding the malicious code. GoLeash has an acceptable overhead, by introducing an average system call latency of 3.17 ms and an average overhead of 9.34%.

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In summary, the main contributions of this work are:

- A new approach for run-time capability enforcement of Go programs. It works at the fine-grain level of Go dependencies, tracing and enforcing specific capabilities by individual Go packages in a software supply chain.
- GoLeash, an efficient implementation of the approach, based on the eBPF observability framework, available as open-source for future research [10]. GoLeash is able to both learn and enforce package-level dependency policies.
- An evaluation of GoLeash on five real-world, complex Go projects, incl. Kubernetes, in terms of software supply chain attack mitigation and performance overhead.

The paper is structured as follows. In Section 2, we provide technical background and motivation for the paper. In Section 3, we present the threat model and assumptions. Section 4 presents the design of GoLeash. Section 5 evaluates the approach. Section 6 analyzes related work. Section 7 discusses use cases and limitations of GoLeash. Section 8 concludes the paper.

2 Background

2.1 Motivating Example of a Real-world Go Supply Chain Attack

A concrete real-world example of the pressing supply chain threats in Go is the recent compromise of the popular boltdb/bolt module [7]. An adversary published a typosquatted module impersonating the original library. While appearing entirely benign and preserving its normal database functionality, the malicious module stealthily introduced remote code execution (RCE) capabilities at run-time. Specifically, the compromised package established a persistent, obfuscated network connection to a command-and-control (C2) server using Go's standard net.Dial function. Once connected, the package awaited commands from attackers and executed arbitrary shell instructions through the os/exec.Command API, effectively enabling unrestricted file manipulation, process control, and network access, which are capabilities never intended by the original BoltDB library. After the malicious package was cached by the Go Module Mirror, the attacker rewrote the Git tag to point to a clean commit, concealing the backdoor in the public repository. However, the proxy had already cached the malicious pseudo-version, which downstream applications continued to fetch long after the repository appeared clean. This allowed the backdoor to persist in the Go ecosystem for years.

Software supply chain attacks are powerful. Attackers increasingly leverage sophisticated obfuscation techniques, ranging from encryption of malicious payloads to more subtle strategies. Go's runtime provides uniquely powerful features such as CGO (integration of C code into Go binaries), inline assembly, dynamically loaded plugins, external binary execution, and reflection-based dynamic function invocation, which can all be used for malicious purposes. These techniques bypass traditional static analysis [47], and are best addressed through run-time solutions [41]. However, as also discussed in Section 6, there is no run-time solution to address software supply chain attacks for Go.

2.2 The Go Module System

Modern software development heavily relies on third-party code reuse, and the Go ecosystem is no exception. GitHub hosts over 1.8 million Golang modules [30]. This vast ecosystem highlights the scale at which open-source third-party code is made available and actively consumed in Go development. Large-scale, industrial Go applications often depend on hundreds of external packages. A notable example is Kubernetes, which currently pulls hundreds direct and indirect Go dependencies to build [53]. The Go module system [9] provides comprehensive support for dependency management, with semantic versioning, reproducible builds, and compatibility guarantees.

In Go, a module is a collection of packages that are released, versioned, and distributed together. Modules may be downloaded directly from version control repositories (commonly Git repositories), or from module proxy servers. Modules are downloaded and built using the standard go command-line tool. A package refers to a directory containing one or more Go source files in the same namespace and represents the fundamental unit of compilation and encapsulation. A module may consist of one or many packages. A project is a library or an application hosted in a repository with one or several modules.

When a Go project is built, all required modules and packages are bundled into a single statically-linked binary. The binary contains the Go runtime [33], which manages initialization, garbage collection, and concurrency. In order to achieve high performance, the Go runtime is designed to be simple and lightweight.

The Go module system introduces unique technical challenges. In particular, the activity of packages inside a Go program is opaque from the point of view of monitoring tools. Since the compiled Go program is a flat binary, the OS has no visibility on which Go package is invoking a system call. Moreover, the Go runtime does not provide security features to analyze and manage accesses to platform features and APIs, such as in the Security Manager for the Java language. This lack of observability makes it easier for attackers to slip malicious code into Go programs.

2.3 The eBPF Runtime Monitoring System

The Extended Berkeley Packet Filter (eBPF) [23] is a Linux kernel technology that executes small, sandboxed programs in kernel space. eBPF offers a versatile framework for dynamic tracing and performance analysis. By attaching eBPF programs to kernel hooks, one can analyze kernel events at runtime with minimal overhead. This includes capturing information on system call IDs and arguments, and the current stack trace, a feature we will extensively use in GoLeash. eBPF is an excellent tool for security. It has been used to implement fine-grained policies and analyses on systemwide and application-specific behavior [13, 26, 40, 67]. Since eBPF is embedded in the kernel, it ensures that telemetry data collection remains efficient and isolated. To sum up, eBPF is a mature solution to detect runtime anomalies and enforce run-time constraints based on security policies.

Existing security solutions fall short to counter sophisticated supply chain attacks in Go. On the one hand, static analysis struggles against advanced forms of obfuscation [47]. On the other hand, current runtime monitoring solutions enforce coarse-grain policies at the process- or container-level [41]. Finegrain, package-level policies are required to detect and mitigate modern software supply chain attacks.

3 Threat Model

GoLeash is designed to mitigate software supply chain attacks targeting third-party Go dependencies. Our threat model assumes attackers compromise initially trusted dependencies through malicious updates, typically via compromised developer credentials or repository hijacking [64]. The primary attacker objective is to inject malicious code into legitimate-looking packages to perform unauthorized operations at runtime, such as accessing and manipulating the filesystem, establishing network communications, and executing arbitrary commands.

That is, third-party dependencies are considered untrusted and potentially compromised, as they can embed arbitrary code execution capabilities.

Attackers can add malicious capabilities in pure Go code, either using obfuscation or not. Attackers in our model may also employ sophisticated techniques beyond Go code [11], using mechanisms such as CGO integration (C binding), inline assembly, dynamically loaded plugins, and execution of external binaries. Such advanced methods evade detection from static analysis tools, as malicious behaviors only become observable during actual program execution.

The Go run-time environment is assumed to be trusted and uncompromised. This implies that a threat actor cannot manipulate the context of system calls or compromise the integrity of the runtime's stack traces, and that control flow proceeds as intended (i.e., no external interference or tampering affects how Go dispatches function calls, manages stack traces, or schedules goroutines).

We do not cover attacks executed during earlier phases of software development, such as attacks triggered by test functions, Go generate scripts, Makefiles, or other build and deployment tooling. These attacks primarily compromise developer machines rather than production systems.

In this paper, our threat model is unauthorized runtime behavior in production, introduced via third-party Go dependencies compromised with malicious code.

4 Design of GoLeash

In this section, we present the design requirements, key design choices, and implementation details of GoLeash.

4.1 Requirements

GoLeash is designed to meet the following requirements, which are essential for the practical adoption of the approach:

- Infer package-level security policies without developer manual work.
- Enforce security policies without changes to source code, build pipelines, and the Go runtime.
- Handle real-world, complex applications, including ones involving multiple processes and binaries.
- Detect malicious dependencies even when the malicious behavior is obfuscated.



Figure 1: GoLeash Architecture

4.2 Architecture

Figure 1 illustrates the high-level architecture of GoLeash. The system consists of a kernel-space tracing component and a user-space analysis engine.

The workflow includes the following stages. (1) GoLeash inserts tracing probes in the kernel to capture system call (syscall) events. (2) These events are pushed into a ring buffer, and asynchronously collected in user space, where (3) the stack trace is resolved. (4) GoLeash maps the stack trace to the originating Go packages, and (5) classifies the syscall into a capability. Finally, (6) GoLeash either uses the event to build a policy (*analysis mode*), or it checks whether the event matches against a policy to detect violations (*enforcement mode*). In the first case, the allowlist is saved for later use. In the second case, enforcement actions are triggered.

This architecture allows GoLeash to enforce least-privilege boundaries across dependencies, as opposed to coarse-grain process-based privileges. The system is designed to operate with no changes to build and deployment pipelines, it does not require recompilation or dedicated instrumentation of the protected application.

4.3 System Call Tracing

At the core of GoLeash lies a low-level monitoring infrastructure built on top of the eBPF framework. GoLeash attaches eBPF programs to syscall-related tracepoints, allowing it to intercept every system call made by the target application in real time. A Linux tracepoint provides a static hook point to call a function provided at runtime. Specifically, eBPF programs are attached to Linux kernel tracepoints to capture syscall invocations [68].

Each captured syscall event includes two key pieces of information: the *syscall identifier* and a *stack trace identifier*, which references the user-space call stack that led to the syscall.

To reduce noise and ensure that only relevant syscalls are captured, GoLeash filters events based on the *command name* of the traced binary, and tracks all associated PIDs. This design supports real-world scenarios, such as multi-process Go applications, and horizontally-scaled replicas in containerized environments.



Figure 2: On the left: example stack trace with highlighted frames that are part of the call path responsible for the write syscall. On the right: dependency graph of the corresponding application being traced.

4.4 Dependency Attribution

After system call events are captured in kernel space, GoLeash's user-space component analyzes these events, to attribute each syscall to the specific Go package responsible for triggering it. This attribution is critical for building precise capability profiles and precise policy enforcement at the package level.

Each syscall event delivered from the kernel includes a stack trace identifier, which corresponds to a snapshot of the user-space call stack captured at the time of invocation. In user space, GoLeash resolves this identifier into a full stack trace by referencing the stack_id and its associated memory snapshots. To interpret the raw return addresses in the stack trace, GoLeash maps each address to the corresponding function name and Go package import path. This symbol resolution process begins by parsing the target binary's ELF symbol table, which provides a mapping from memory addresses to symbol names in unstripped binaries.

Once the stack trace is resolved, GoLeash traverses it from the most recent frame backwards to identify the Go package from which the syscall originates. In Go programs, system calls often pass through multiple layers of abstraction, including standard library functions (e.g., from net/http, os, and io [32]) and runtime helpers, before reaching the kernel. These intermediate layers are part of Go's trusted infrastructure and are not considered responsible for the syscall. GoLeash should not misattribute behavior to trusted components. Hence, GoLeash does not assign the syscall to the topmost stack frame. Instead, it scans the full trace to find the first frame originating from an application-defined or thirdparty package function, and considers that frame as the initiator of the syscall. For instance, in the trace shown in Figure 2 (on the left), where os.Write and other standard packages wrap the syscall, GoLeash skips them and correctly attributes the syscall to the frame of third-party package fatedier/frp/server. In addition to identifying the responsible frame, GoLeash also saves the full chain of Go packages that led to the syscall, for call path analysis discussed later in subsection 4.7.

4.5 Capability Mapping

GoLeash defines a capability taxonomy (Table 1) that maps low-level syscalls to semantically meaningful categories of system functionality. The taxonomy aggregates syscalls that operates on the same resource and that serve the same function, and yet differentiates between operations that have different security implications. For instance, filesystem-related syscalls are split into read and write capabilities, allowing developers to grant read access without permitting file modifications. Likewise, networking is broken down into socket creation, connection establishment, and packet transmission. This granularity enables expressive yet narrowly scoped policies, significantly reducing the risk of unintended or malicious behavior. The syscall-to-capability mapping is manually curated and verified against official Linux syscall documentation [70] to ensure accuracy. The detailed mapping is provided within our implementation of GoLeash [10]. During both analysis and enforcement, GoLeash uses this mapping to translate raw syscall activity into high-level capability usage.

4.6 Analysis Mode

Once system calls are attributed to specific capabilities and the invoking package is identified through stack trace resolution, GoLeash aggregates this information to build a capabilities *allowlist* for each package. These allowlists are constructed in the *analysis mode*, where the application is executed in a trusted environment, using integration tests or representative workloads to exercise the intended behavior of the application. This allowlist acts as a behavioral contract: any future execution is expected to conform to these observed patterns. Once reviewed and approved, the allowlist becomes the *policy* used for enforcement.

For each traced package exercised during the execution, the allowlist records the set of capabilities it invoked, as well as all observed call paths that led to each capability. These call paths capture the broader execution context: they consist of the ordered sequence of Go packages extracted from the stack trace, with the traced package acting as the terminal caller responsible for the capability.

Formally, the allowlist \mathcal{A} is defined as:

$$\mathcal{A} = \{ (P_i, \{ (C_{ij}, \mathcal{T}_{ij}) \}) \}$$

where:

- *P_i* is a traced package,
- C_{ij} is a capability invoked by P_i ,
- $\mathcal{T}_{ij} = \{T_{ijk}\}$ is the set of call paths observed for capability C_{ij} ,
- each call path T_{ijk} is an ordered list of Go packages:

$$T_{iik} = [Q_1, Q_2, \dots, Q_n, P_i]$$

with Q_k denoting intermediary packages and P_i as the terminal traced package.

To optimize for performance and memory efficiency, GoLeash stores each observed call path as a hash of the array \mathcal{T}_{ij} . This compact representation allows for fast lookups at run-time while preserving the ability to verify complete calling contexts. Recalling the example in Figure 2, during analysis, GoLeash saves the entire

Category	GoLeash Capability	Description	Example Syscalls
File Capabilities	CAP_FILE	Manage file descriptors	close, poll
	CAP_READ_FILE	Read data from files	read, open, stat
	CAP_WRITE_FILE	Write or append data to files	write, writev
	CAP_CREATE_FILE	Create new files or directories	mkdir, creat
	CAP_DELETE_FILE	Remove existing files or directories	unlink
	CAP_FILE_METADATA	Modify file metadata (permissions or ownership)	chmod, chown
Network Capabilities	CAP_CONNECT_REMOTE	Initiate outbound connections to remote endpoints	socket, connect
	CAP_LISTEN_LOCAL	Bind to local ports to accept incoming connections	bind, listen
	CAP_SEND_DATA	Transmit data over established network connections	sendto, sendmsg
	CAP_RECEIVE_DATA	Receive data from network connections	recvfrom, recvmsg
Execution Capabilities	CAP_EXEC	Launch new processes or threads	clone, execve
	CAP_TERMINATE_PROCESS	Terminate running processes or threads	exit, kill
System State and Configuration	CAP_READ_SYSTEM_STATE CAP_WRITE_SYSTEM_STATE CAP_RESOURCE_LIMITS	Access system configuration or status information Modify environment variables or system settings Adjust process or system resource limits	getpid,getitimer setuid,setgid setrlimit
Memory Operations	CAP_MEMORY_MANIPULATION	Alter memory regions or mappings at runtime	munmap,mmap
	CAP_DIRECT_IO	Perform low-level I/O operations on devices or memory	ioctl

sequence of legitimate call paths executed, such as [cobra \rightarrow golib \rightarrow write].

Policy Management in the Development Process. The construction of allowlists is designed to be iterative and non-disruptive. As new functionality is added to the application, GoLeash can be rerun to observe and record additional capability and call paths, and incorporate them into the existing policy. This makes it possible to start with a conservative baseline and refine the policy over time without requiring a complete re-generation. Additionally, developers can manually audit the allowlist and append entries when necessary, such as when preparing for production deployment after a review of expected system behavior. For example, developers can review which Go packages run external executables or establish outbound network connections, and freeze the allowlist after the review, so that no other package will be able in the future to stealthly introduce such operations for malicious purposes.

In typical development workflows, developers would often modify allowlists for major version updates of a dependency. Minor version updates usually involve bug fixes or refactoring, and by default do not call for updating policies. To sum up, GoLeash policies should be updated and re-audited whenever a dependency publishes a major version, or when new privileged operations are explicitly added in Changelogs.

4.7 Enforcement Mode

Once a policy has been constructed and approved during development, GoLeash can be used in the enforcement mode to protect the running application from unauthorized behaviors. The same eBPF-based tracing infrastructure is reused to intercept system calls; however, instead of gathering these observations for analysis, GoLeash now checks each syscall in real-time against the policy. Enforcement is made at runtime by validating both the origin of the syscall and the capability being exercised.

For every intercepted syscall, GoLeash resolves its associated capability and identifies the terminal package responsible, using the same attribution and classification logic from analysis. The syscall is then validated against the policy: if the (package, capability) pair is present, and the corresponding call path matches one of the approved sequences stored for that capability, the syscall is allowed to proceed uninterrupted. Otherwise, GoLeash flags the event as a policy violation and triggers a configurable enforcement action.

By validating not only the invoking package but also the full call path in the stack trace, GoLeash supports context-aware enforcement. This defends against confused deputy attacks [46], when a restricted dependency may attempt to trigger a privileged capability indirectly by invoking a more permissive package within the same application. In such cases, even if the terminal package is authorized for a capability, the unapproved calling context causes the request to be denied. This ensures that both the origin and the execution context of every syscall align with the previously observed and trusted policy. In the example of Figure 2, an attacker could compromise spf13/cobra to import a function from xtaci/kcp, triggering a SEND_DATA, which was not part of cobra's original capability set (see also Appendix A). GoLeash prevents the invocation path between cobra and kcp, since it is not part of the policy.

GoLeash supports multiple enforcement strategies, allowing it to be used for forensics and response purposes. In forensics use cases, violations are logged for postmortem analysis, enabling developers to assess suspicious behaviors without disrupting application functionality. In response use cases, GoLeash can terminate the offending process entirely, preventing potential exploitation in real time. These strategies can be configured per environment, supporting progressive hardening.

4.8 Advanced Support

Support for Trusted Go Internals. It is important to consider that the Go runtime itself can initiate system calls, independently from application logic, such as, for scheduling, I/O polling, and garbage collection. GoLeash distinguishes between system calls originating from the Go runtime from those issued by packages of the application and modules. These runtime-initiated events are excluded from enforcement, by examining the stack trace associated with each system call. If the entire call stack contains only frames from Go's runtime and does not include any package of the application or modules, the system call is treated as coming from trusted infrastructure and excluded from analysis. This design ensures that only behavior explicitly caused by the application or its dependencies is subject to capability enforcement, reducing the overhead and avoiding false positives.

Support for Evasion Techniques. The syscall attribution mechanism implemented in GoLeash is robust even in the presence of advanced attack vectors that use defense evasion techniques, including obfuscation. Techniques such as encoded Go code, CGO bindings, inline assembly, and dynamically loaded plugins may attempt to execute malicious operations. However, all such operations ultimately result in syscalls that pass through the kernel. Since the stack includes the originating Go package, GoLeash can identify the dependency involved in the syscall. Moreover, GoLeash is able to handle malicious code that hides its behavior by executing existing binaries on the target system (*living-off-the-land* attacks), as in MITRE ATT&CK *T1036 (Masquerading)*, as well as through obfuscation and control flow manipulation strategies commonly seen in *T1574 (Hijack Execution Flow*), as described later.

Support for Exec-based Control Transfer. Go applications commonly invoke external binaries to delegate tasks, such as running system utilities, interacting with non-Go components, and launching helper tools. This pattern is supported directly by the Go standard library via wrappers around exec(). However, this behavior introduces challenges for security monitoring. The exec() syscall replaces the current process image with a new binary while retaining the same PID, effectively shifting execution to code that may not be vetted or trusted. Attackers can exploit this to bypass runtime controls from within a compromised package. This tactic aligns with MITRE ATT&CK techniques T1055 (Process Injection) and T1543 (Create or Modify System Process). To handle this safely, GoLeash analyzes both sys_enter and sys_exit events for the same exec() syscall. A pending "external binary execution" event is recorded at the syscall entry, and only committed if the syscall completes successfully. This avoids recording syscalls from failed or aborted transitions. It must be noted that the external binary is not necessarily a Go program. Thus, after a successful exec, GoLeash tracks syscalls using a flat (i.e., dependency-unaware) allowlist for the process as a whole, indexed by the new executable's name. During this transition, residual syscalls, such as those issued by the Go runtime or by parallel threads active at the moment of the exec(), are filtered out.

Support for Multi-process and Multi-Binaries. GoLeash handles runtime behaviors that complicate syscall attribution in Go, such as process forking and multi-binary applications. Supporting these

behaviors is essential, as they are common in modern Go systems. Forking is used to spawn workers, isolate tasks, and handle concurrent requests, while multi-binary applications assign distinct responsibilities to separate executables. This design is especially prevalent in distributed systems. For example, Kubernetes runs several binaries within a single node, and often deploys multiple replicas of the same binary for redundancy and load balancing. These behaviors are also security-relevant. Attackers may fork subprocesses to evade runtime monitoring or enforce stealth, aligning with MITRE ATT&CK techniques such as *T1059 (Command and Scripting Interpreter)*. GoLeash counters this by dynamically tracking all processes spawned across all binaries in the target application, including those created via fork(), ensuring that syscall attribution and policy enforcement remain consistent across the entire process tree.

4.9 Implementation Details

We implemented GoLeash using the C and Go languages. The codebase includes 1, 190 lines of code, split between the eBPF tracing component (kernel-space) and the Go-based analysis and enforcement engine (user-space).

The kernel component uses the cilium/bpf2go library [12] to attach probes that capture syscall events. Each event includes a hashbased ID derived from the user-space stack trace, enabling efficient, deduplicated lookup for execution paths. Events are relayed to user space via a ring buffer to ensure low-overhead, non-blocking communication. The user-space component resolves stack traces, maps instruction addresses to Go symbols and Go package paths, and enforces capability policies. This process leverages symbol information embedded in Go binaries, which includes fully qualified package paths, allowing for accurate attribution without source code access. GoLeash targets x86-64 Linux systems and requires a kernel version 5.7 or later for full eBPF tracing support.

5 Experimental Analysis

We conduct a systematic, large-scale experimental evaluation of GoLeash, structured around the following research questions.

- **RQ1:** How effectively does GoLeash detect malicious code in third-party dependencies? We investigate GoLeash's ability to identify unauthorized use of system capabilities as part of software supply chain attacks. The experimental protocol consists in simulating realistic supply chain attacks, by injecting malicious behaviors into benign Go projects, and measuring GoLeash's detection rate.
- **RQ2: How robust is GoLeash in detecting obfuscated malicious behavior?** Typically, malicious software is hidden through obfuscation techniques, to make it more difficult to detect by malware detectors. Thus, we assess whether obfuscation techniques can evade GoLeash's enforcement mechanism.
- **RQ3: What is the performance overhead introduced by GoLeash?** We measure the overhead introduced by GoLeash in terms of system call latency and overall execution time of traced applications.

RQ4: How does GoLeash compare with static capability analysis? GoLeash leverages dynamic analysis for capability attribution, complementing static approaches. Therefore, we quantify the overlap and differences between GoLeash and a state-of-the-art static capability analysis tool.

Experimental Targets. We evaluate GoLeash on real-world, complex Go software projects. We select projects that meet the following criteria: 1) they have more than 10000 stars, 2) they are actively maintained, 3) they come a test suite or a workload to exercise their core functionalities, 4) they are security sensitive Applying this strict criteria result in the following five projects: *kubernetes* (k8s) [43] for container orchestration, *etcd* [24] for key-value storage), *coredns* [15] and *frp* (fast reverse proxy) [27] for networking, and *go-ethereum* (geth) [25] for blockchain infrastructure.

Those applications are complex and some contain multiple binaries. We include all binaries in our evaluation. For example, in the case of Kubernetes, we analyzed the five main control plane binaries:*kube-apiserver*, *kube-controller-manager*, *kube-scheduler*, *kube-proxy*, *kubelet*.

Malicious Code Injection. Malicious behaviors in supply chain attacks typically abuse system-level capabilities, such as establishing outbound network connections to exfiltrate data, accessing the file system to steal information, and executing system commands to further compromise the system.

To the best of our knowledge, there is no existing dataset of malicious Go packages. We tried to access the few malicious ones reported in blog posts, by did not succeeding in obtaining the code. For our evaluation, we tackle this lack of data by building synthetic malicious packages according to the following sound methodology.

Malicious packages are constructed by selecting a package from the dependency graph of the application under study, and by injecting a piece of malicious code into this target package. The selection of packages to consider is uniformly random, ensuring the absence of bias.

First, we surveyed malicious code patterns from established datasets in npm and PyPi [19, 50]. Next, we adapt those patterns to the Go language through five different malicious behavior injectors, spanning data exfiltration, remote file infiltration, information stealing, code injection and execution. Our malware implementations adopt the same Go packages also adopted by known campaigns against Go projects (see Section 2.1), as reported by technical blogs [7, 8, 58]. Table 2 summarizes these behaviors, and maps them to the relevant entries of the MITRE ATT&CK knowledge base.

We automate the injection of malicious code through rewriting the source code of the target package. We developed a tool to analyze the abstract syntax tree of the target package, and to weave malicious code snippets within an existing function of the package, without disrupting the existing functionality and structure of the target package. During experiments, we injected each malware type into every exercised package (targeting a randomly selected exercised functions). Our malicious code injector is made open source for future research. All malicious packages generated during experiments are publicly available in our replication package [10].

System Configuration. All experiments are conducted on a machine with an Intel Core i7-1260P CPU, 16GB of RAM, running Ubuntu 22.04, with Linux kernel version 6.7, and Go version 1.24.1.

Table 2: Injected malicious behaviors.

ID	Behavior	MITRE ATT&CK
M1	Base64-encoded command execution for reverse shell access	T1059, T1140
M2	Exfiltrate and transmit system configuration data to a remote server	T1552, T1082, T1041
M3	Information stealing from user applications	T1115
M4	Inject a shared library into current process	T1055.001
M5	Infiltrate malicious files	T1105

5.1 RQ1: Effectiveness Against Malicious Behavior in Dependepencies

Objective. The goal of this experiment is to evaluate GoLeash's effectiveness in mitigating supply chain attacks by detecting unauthorized system capability usage introduced through compromised third-party packages. We aim to show that GoLeash's per-package enforcement can accurately flag malicious behaviors, even when injected into deep transitive dependencies. As a baseline, we compare against the state-of-the-art process-level enforcement model, such as Seccomp [69], which handles the entire application as a monolith. A detection is considered successful when GoLeash successfully detects that a malicious package exercises a malicious capability absent from the policy.

Methodology. We first use GoLeash in *analysis mode* to generate per-package policies. This is done by executing each target application with its end-to-end workload while GoLeash traces all invoked packages. These workloads are designed to reflect the application's intended, benign behavior.

To compare GoLeash's per-package enforcement with traditional sandboxing models, we implement a *process-level enforcement baseline*. This baseline aggregates all observed capabilities into a flat, application-wide policy, without attributing them to individual packages.

After policy generation, we construct a dataset of malicious variants of the target applications. For each variant, we rebuild the application with exactly one malicious code snippet at a time, injected into a single target package. The injection point is randomly selected from functions that are actually executed, which are profiled using our tracing infrastructure. It is worth noting that not all packages in the dependency graph are actually reachable by the workload. For example, the net Go package may import crypto for encrypted communication, but the application using net might not use encryption features. Therefore, we limit injections to packages that are actually active during execution. This ensures that the malicious code is reachable and that it represents a realistic attack. We leverage the injection approach described in Section 5. In total, we produced *3,265* unique malicious application variants.

The effectiveness of GoLeash is measured using the *detection rate*, defined as the percentage of malicious packages flagged by

Table 3: Detection Rate of GoLeash vs Baseline. Malware IDs are defined in Table 2. The *"inj."* column indicates the number malicious application variants.

Project	Malw.	Inj. (#)	Baseline (%)	GoLeash (%)
	M1	441	100	100
	M2	441	0	99.77
k8s [43]	M3	441	100	100
	M4	441	0	99.32
	M5	441	0	99.55
	M1	62	100	100
	M2	62	0	98.39
etcd [24]	M3	62	0	100
	M4	62	0	91.94
	M5	62	0	98.39
	M1	20	100	100
	M2	20	0	100
coredns [15]	M3	20	100	100
	M4	20	0	95
	M5	20	0	100
	M1	47	100	100
	M2	47	0	97.87
frp [27]	M3	47	100	100
	M4	47	0	87.23
	M5	47	0	95.74
	M1	83	100	100
	M2	83	0	97.59
geth [25]	M3	83	0	100
	M4	83	0	91.57
	M5	83	0	97.59
Aggregate		3,265	32%	98%

GoLeash out of the total number of created malicious packages for a given application. For comparison, the same metric is applied to the process-level baseline. Under this coarse-grained model, a variant is only detected if the injected code uses capabilities not observed anywhere in the application during baseline execution.

Malware IDs used in the evaluation are defined in Table ??, and the *inj.* column indicates the number of application packages individually injected with each malware for testing.

Results. Table 3 summarizes the results of this experiment. As previously discussed, we profile which packages are actually executed (e.g., 441 in the case of k8s), and inject five types of malicious code into each target package. In total, we obtain 3, 265 malware injections.

GoLeash successfully detects malicious behavior with high accuracy. The average detection rate across all projects is 98%. This is much higher than the 32% detection rate achieved by the application-wide baseline approach. GoLeash achieves a perfect 100% detection rate on two different malware categories: M1 and M3. Importantly, the detection rate never dropped below 87%.

GoLeash effectively identifies deviations from normal execution, by detecting when the injected malicious code uses capabilities that are not part of the policy generated with benign executions. Our results indicate that certain sensitive capabilities, such as initiating outbound network connections or spawning external commands, used by malware, are particularly effective indicators.

In contrast, the coarse-grained, process-level baseline model was significantly less effective. By aggregating all capabilities into a single policy, process-level enforcement often allows stealthy malware to go undetected. This happens when the malicious code uses capabilities that are also legitimately used by the target package. The baseline is able to detect malware M1 and M3, which leverages the rarely-used capability RESOURCE_LIMITS capability, which is absent in the original applications.

Finally, we observe that GoLeash enforcement incurs *zero false positives* in our experiments. However, it is important to note that, in general, dynamic analysis can be affected by false positives if the security policy is trained with a workload that is not representative of the operational stage. We further discuss this aspect in Section 7.

We have performed a large-scale experiment with 3265 malicious packages injected in five real-world Go projects. GoLeash stops 98% of the simulated software supply chain attacks. GoLeash's per-package enforcement offers precise and robust defense against software supply chain attacks.

5.2 RQ2: Effectiveness Against Obfuscated Attacks

Objective. Malicious actors often attempt to hide dangerous logic via obfuscation techniques, making it harder for security tools to detect unauthorized actions [52, 76]. This experiment evaluates whether obfuscation techniques impact the ability of GoLeash to perform per-package capability enforcement.

Methodology. As in RQ1, we begin by running each target application with its normal workload in GoLeash analysis mode, generating a per-package policy that captures legitimate capabilities. Then, we inject obfuscated malicious code, using four Go-specific obfuscation strategies [11]:

- **Plugin**: we compile the malicious functionality as a Go plugin, and load it at runtime.
- **Reflection**: we wrap malicious functions with reflection calls, with dynamic resolution to invoke them.
- External Binary: we embed the payload in a separate binary, and invoke it at runtime via exec syscall.
- CGO: we write the malicious code as C code, and invoke it through Go's foreign function interface (CGO).

Each of these obfuscation techniques conceals the malicious injected capabilities behind more convoluted, indirect execution paths.

We reuse the same injection framework described in Section 5, but apply the above four evasion strategies to the malicious snippets before injecting them into each exercised package. In this second experiment, we focus on two malicious behaviors (i.e., M2 data exfiltration and M5 remote file infiltration) from the original set, for the sake of brevity. Similar results were obtained for the other types of malware. Each obfuscation variant is injected one at a time into each exercised package across the five Go projects. We then switch GoLeash to enforcement mode and rerun the applications with their workload to measure if GoLeash detects these obfuscated attacks.

Table 4: Detection Rate of GoLeash against obfuscated attacks

(a) Malware M2 (data exfiltration)

Project	w/o(%)	plug.(%)	refl.(%)	bin.(%)	cgo(%)
k8s	99.77	99.77	99.77	100	99.09
etcd	98.39	98.39	98.39	100	98.39
coredns	100	100	100	100	90
frp	97.87	93.62	93.62	100	76.60
geth	97.59	97.59	97.59	100	96.39
avg.	98.72	97.87	97.87	100.00	92.09
(b) Malware M5 (remote file infiltration)					
Project	w/o(%)	plug.(%)	refl.(%)	bin.(%)	cgo(%)
k8s	99.55	99.55	99.55	100	99.32
etcd	98.39	98.39	98.39	100	98.39
coredns	100	100	100	100	95
frp	95.74	95.74	95.74	100	85.11
geth	97.59	97.59	100	96.39	96.39
avg.	98.25	98.25	98.33	99.28	94.44

Results. Tables 4a and 4b report GoLeash's detection rates of GoLeash for both unobfuscated malware as in RQ1 (column w/o), and their obfuscated counterparts. For each exercised package in the target applications, we generate eight malicious injections (two malware variants and four evasion techniques), resulting in a total of 5, 224 injections across all five applications.

Despite attempts to conceal malicious capabilities, GoLeash still identifies unauthorized behavior that falls outside a package's generated policy, achieving average detection rates across all projects ranging from 92.09% to 100% for malware M2, and from 94.44% to 99.28% for malware M5, depending on the obfuscation technique. Our experiment shows that the evasion strategies poorly circumvent GoLeash's per-package policies. Malicious accesses are still flagged as suspicious calls whenever they deviate from a package's baseline profile. For example, malware based on CGO still needs to issue system calls for connecting to remote hosts, such as those mapped to the CONNECT_REMOTE capability, which remains detectable. Interestingly, in the scenario of external binary evasion, GoLeash's detection rate is slightly higher than in the unobfuscated variant, primarily because this approach introduces the EXEC capability, which is absent in most of the baseline profile and immediately triggers an alert.

GoLeash is highly robust against obfuscated software supply chain attacks, where the malicious code in obfuscated inside a dependency. Despite obfuscation, GoLeash detects the deviations from the security policy.

5.3 RQ3: Performance Overhead

Objective. The goal of this evaluation is to quantify the performance overhead introduced by GoLeash when used in enforcement

mode. Recall that the enforcement mode is meant to be used in production. In enforcement mode, GoLeash actively intercepts and potentially blocks system calls from the target application. Since runtime overhead can impact on real-world adoption, it is critical to measure how much additional cost is imposed by GoLeash.

Methodology. For this evaluation, we run the applications using benchmark workloads that offer consistent, high-volume execution, making them better suited for measuring performance metrics. These benchmarks replace the workloads used in RQ1, which were meant to perform end-to-end testing to exercise the several functionalities of the applications.

We consider the same five Go applications, with the following workloads. For etcd, we configure its official benchmarking tool [57] to send write requests to a running etcd cluster. For frp, we set up a tunnel to a web server through the frp proxy and generate HTTP traffic using the wrk benchmarking tool [55]. For geth, we deploy an Ethereum node and submit transaction requests using its benchmarking suite [56]. For CoreDNS, we issue DNS queries using DNSPerf [21]. For all of these applications, we measure the total *execution time* over 10 repetitions, configuring benchmark for executing 10,000 requests each.

For Kubernetes, we simulate typical API operations using the kube-burner benchmark [42]. In this case, rather than measuring request execution time, we use *pod latency*, that is the time it takes for a pod to reach the Ready state after being scheduled. This metric is widely used to benchmark the responsiveness and provisioning performance of Kubernetes clusters.

In addition, for all applications, we measure *syscall latencies* introduced by the kernel probes, averaging over 1,000 traced syscalls per project. Before each repetition, we reset the environment (e.g., by clearing application-generated caches) to ensure consistency.

Table 5: Execution Time overhead measurements.

Project	w/o (s)	GoLeash (s)	Overhead (%)
kubernetes	17.50 ± 0.56	19.00 ± 0.49	+8.57%
etcd	7.09 ± 0.13	7.48 ± 0.10	+5.5%
coredns	13.16 ± 0.24	13.74 ± 0.49	+4.4%
frp	0.64 ± 0.005	0.79 ± 0.004	+23.43%
geth	22.54 ± 1.08	23.63 ± 0.82	+4.83%

Results. Table 5 shows the mean and standard deviation of performance measurements, both without (w/o) and with GoLeash, along with the relative overhead as percentage. We observe an average overhead of 9.34% in *execution time*, primarily due to kernel-level probes on sys_enter and user-space operations such as syscall-capability mapping, dependency attribution, and allowlist inspection. These results align with previous studies on eBPF-based tracing [17]. In addition, we observe an average syscall latency of 3.53*ms* for Kubernetes, 3.09*ms* for etcd, 2.8*ms* for CoreDNS, 3.01*ms* for frp, and 3.44*ms* for geth, respectively.

Our measurements show that GoLeash's enforcement mode adds 4-25% execution overhead in production. This overhead is an acceptable cost for the security benefits provided by GoLeash against the state-of-the-art software supply chain attacks.

5.4 RQ4: Comparison with Static Analysis

Objective. Our goal in this experiment is to assess how GoLeash compares to *Capslock* [35]. Capslock is a state-of-the-art static capability analysis tool for Go, developed by Google. Capslock obtains the transitive dependency graph of the application under analysis. Then, for each package used by the application, it infers whether the package can manipulate files, open network connections, or perform certain system-level operations. It scans the source code by means of static analysis, by looking for calls to the Go standard library in the call graph. These capabilities are similar to those used by GoLeash (see Table 1), even if at a coarser level of granularity. We investigate whether Capslock's static analysis can effectively detect unobfuscated and obfuscated malicious code, and how it compares to GoLeash's runtime-based detection.

Methodology. Similarly to the previous RQ1 and RQ2, we evaluate Capslock in terms of detection rate. First, we apply Capslock on the original (benign) version of the five applications, and obtain the set of capabilities inferred by Capslock. Then, we apply Capslock on the malicious application variants. For each malicious variant, we get the set of capabilities, which includes the capabilities used by the injected malicious code. If the original and the malicious applications exhibit a different set of capabilities, we conclude that the malicious code has been detected by Capslock. For fair comparison, we compute the detection rate for both GoLeash and Capslock on the same datasets of injected packages from RQ1 and RQ2.

Table 6: Differences in Detection Rate of GoLeash against Capslock

(a) Malware M2 (Data Exfiltration)

Project	w/o(%)	plug.(%)	refl.(%)	bin.(%)	cgo(%)
k8s	+76.64	+67.12	+80.95	+64.85	+63.04
etcd	+62.91	+58.07	+69.36	+58.06	+56.45
coredns	+50.00	+50.00	+60.00	+45.00	+20.00
frp	+70.21	+29.79	+70.22	+36.17	+10.64
geth	+62.65	+32.53	+67.47	+33.73	+27.72
avg.	+64.88	+47.90	+69.20	+47.96	+35.97
	(b) Malwai	re M5 (Remo	ote File Inf	iltration)	
Project	w/o(%)	plug.(%)	refl.(%)	bin.(%)	cgo(%)
k8s	+74.38	+66.90	+80.73	+64.85	+63.27
etcd	+59.68	+58.07	+69.36	+58.06	+56.45
coredns	+45.00	+50.00	+60.00	+45.00	+25.00
frp	+53.19	+53.19	+72.34	+36.17	+19.15
geth	+56.63	+32.53	+67.47	+33.73	+27.72
avg.	+57.38	+52.54	+69.58	+47.96	+38.72

Results. For space limitations, we again focus on two malware types. Tables 6a and 6b report the absolute differences in detection rates between GoLeash and Capslock, respectively for the M2 and M5 malware types, across the five Go projects. We consider both the cases without (w/o) and with obfuscation. Each cell shows the percentage-point difference between GoLeash's dynamic detection results from RQ2 and Capslock's static analysis.

The results shows that GoLeash consistently and significantly outperforms Capslock across all five projects and obfuscation techniques. This performance gap stems from two main limitations of Capslock's analysis. First, Capslock operates at a coarser level of granularity than GoLeash, which causes overlap between broad capabilities attributed to trusted packages and those required by injected malware. As a result, it often fails to distinguish malicious behavior from benign behavior. For example, read and write operations fall in the same capability in Capslock, obscuring distinctions that GoLeash can capture at the syscall level. Second, Capslock's static analysis struggles to precisely reconstruct call graphs, especially in the presence of dynamic features such as plugin loading or reflection. Based on manual inspection of randomly sampled cases, we observed that Capslock occasionally misses even coarse-grained capabilities that are clearly exercised during runtime.

Interestingly, when CGO-based obfuscation is used, GoLeash still outperforms Capslock in every scenario, although the percentagepoint advantage is somewhat reduced. This is because CGO variants introduce additional calls to Go standard libraries and foreign function interfaces, which Capslock explicitly flags (e.g., via CGO_CAPABILITY). However, Capslock often raises alerts on the presence of these foreign interfaces rather than on the core malicious logic itself (e.g., actual file writes or exfiltration operations).

It is important to note that Capslock can still bring unique benefits to supply chain security. Our approach relies on the actual execution of the target application with a representative workload that triggers its capabilities, which is typically the case of production-grade software. Looking at actual executions enables our solutions to overcome obfuscation and other limitations of static analysis. However, if users cannot find or run such a workload, it is not possible to perform dynamic analysis. In these cases, static analysis can still be used to obtain an approximation of the capabilities used within the application.

GoLeash's dynamic analysis outperforms Capslock's static analysis. Yet, we note that they are complementary, and that practical defense-in-depth against software supply chain attacks require using both kinds of solution.

6 Related Work

We categorize related work along the five key dimensions from our design: need for code changes, support for fine-grained access control, automated policy generation, support for multi-process apps, and detection of obfuscated behavior. We summarize in Table 7 other systems that are most directly comparable to our one, and discuss at more length the others in the text (e.g., static analysis).

6.1 Application-Level Sandboxing

A number of solutions confine or restrict the system-level behavior through runtime sandboxing. NatiSand [2] and Cage4Deno [1] use Linux security features (e.g., Seccomp, eBPF, Landlock) to restrict native extension in JavaScript runtimes like Node.js and Deno. Natinad relies on manual JSON-based configuration to restrict operations such as file or network access. Cage4Deno adds support for isolating subprocesses, but treats each subprocess as a standalone application, lacking awareness of finer-grained entities like npm packages. Similarly, HODOR [72] shrinks the attack surface of Node.js applications by auto-generating syscall whitelists. While it achieves thread-level granularity, it cannot distinguish which dependency initiated a syscall, limiting its ability to isolate malicious libraries.

Other efforts focus on container-level hardening. Confine [60] statically generates restrictive Seccomp syscall policies for containers via whole-binary analysis, but lacks intra-container granularity or obfuscation resilience. μ PolicyCraft [6] synthesizes stateful syscall automata for microservices through symbolic execution and enforces them via a telemetry monitor, yet still operats at the microservice/container level rather than inside processes.

Finally, μ SCOPE [59] dynamically traces memory accesses and privilege operations in lage codebases (e.g., the Linux kernel) to identify overprivileged regions. While effective for analysis and privilege planning, it does not enforce runtime behavior and lacks syscall-level or per-package enforcement.

Overall, application-wide or "coarse-level" sandboxing solutions successfully confine large swaths of code, but they lack per-dependency distinctions, which means that malicious or compromised libraries cannot be individually restricted. In contrast, GoLeash operates at the package level within a single Go binary, with no reliance on manual configuration.

6.2 Permissions Systems for Packages

A second line of work provides package-level or library-level permission systems.

MIR [71] uses static analysis to assign read-write-execute capabilities to Node.js libraries, applying them at runtime. ZTD_{JAVA} [3] similarly enforces package-level permissions in Java via a combination of manual configuration and runtime monitoring. While both tools reduce risk from vulnerabilities within a dependency, their threat models do not account for maliciously added capabilities, and they lack support for native code or obfuscated behavior.

Other efforts depend on manually specified permissions or operate over high-level, language-specific API. Ferreira et al. [28] propose a Node.js permission system configured by developers to constrain packages at the JavaScript API level, with no syscall visibility. FLEXDROID [63] enforces privilege separation in Android apps by intercepting Dalvik calls, but relies on Android permission model and does not observe OS-level behavior.

Other work enforces stronger isolation at the library level using system call interposition. Codejail [74] transparently confines dynamically linked libraries in Linux via a dual-process model that mediates memory and syscall behavior with the main program. LibVM [36] builds virtualized execution environments for shared libraries, with hardware-assisted or ptrace-based syscall control. Enclosure [29] similarly isolates untrusted libraries by associating closures with restricted memory views and syscall filters, enforced via Intel VT-x. It supports package-level policies in Go and Python, but requires developers to annotate code explicitly and integrate language-level constructs. While all three systems support native code and intra-process isolation, they lack automated policy generation, and require developer effort or manual integration into host applications. Most systems either assume dependencies are benign, require developer effort to specify policies, or lack visibility into system-level behavior. None provide runtime enforcement against malicious capabilities introduced via supply chain compromise. In constrast, GoLeash dynamically enforces syscall-level capabilities at the package level, without requiring source changes or developer-defined manifests. Its threat model explicitly includes malicious dependencies and it operates independently of language-specific security models. This makes GoLeash uniquely applicable to Go binaries, which underpins mission critical software [20], such as Kubernetes.

6.3 Malicious Pattern Scanning

A significant body of research focuses on mitigating software supply chain attacks , via static code analysis. These studies encompass malicious package updates, installation-time attacks, and privilege escalations.

Latch [75] traces system calls during installation to generate permission manifests, preventing preventing packages from performing unexpected actions in install scripts. Ohm et al. [51] propose a differential capability analysis approach that compares new package versions against trusted baselines and restricts capabilities through a modified Node.js runtime. iHunter [44] performs static taint analysis on iOS SDKs to detect privacy violations such as cross-library data harvesting, using symbolic execution and NLP-assisted API modeling. While these approaches offer effective pre-deployment vetting, they operate entirely offline and during installation, and do not detect runtime behavior after deployment.

Other tools such as GuardDog and Amalfi [18, 62] scan for known malware patterns, suspicious, suspicious metadata, or typosquatting during package publication. These techniques help eliminate obviously malicious packages but are blind to capabilities that are invoked dynamically at runtime.

These methods are inherently limited to static or pre-deployment analysis and cannot respond to runtime malicious behavior. GoLeash instead operates at runtime and captures malicious behavior even if introduced post-installation or obfuscated via native code. Its runtime enforcement makes it resilient to evasion techniques that bypass static analysis.

7 Discussion

We here discuss key design choices and considerations that shape the applicability of GoLeash.

Workload Coverage. GoLeash uses dynamic analysis to generate fine-grained, per-package policies based on observed behavior. Its coverage is thus limited by the code exercised during analysis. If (1) rarely executed paths are missed, and (2) those paths use additional capabilities, GoLeash may flag them as violations at runtime (i.e., false positives). This is a known limitation of dynamic analysis [60], not unique to our system. In practice, since we propose using integration tests as workload for policy generation, this problem is mitigated in production-grade software with robust test suites, as is common in critical cloud systems. Moreover, GoLeash supports the incremental update of security policies, which enables users to conservatively limit capabilities as observed during testing, and later enable capabilities that trigger false positives after more careful scrutiny.

Approach	No Code Changes	Fine-Grained Control	Auto Policy Gen	Multi-Process Support	Detect Obfuscated Behavior
MIR [71]	×	\checkmark	\checkmark	×	×
	instrumentation at load-time	per-lib + field-level APIs	static + dynamic analysis	single-process JS	JS APIs only
NatiSand [2]	\checkmark	×	\checkmark	\checkmark	×
	external JSON policy only	coarse FS/IPC/NET	trace-based (eBPF/strace)	native libs + subprocesses	not syscall-level
Cage4Deno [1]	\checkmark	×	\checkmark	×	×
	CLI policy, no code mods	file-level RWX only	dynamic tracing tool	Deno subprocesses only	JS runtime only
HODOR [72]	\checkmark	×	\checkmark	×	\checkmark
	seccomp, no app mods	per-thread, not dep	call graph + tracing	threads only	syscall-level filters
ZTD _{JAVA} [3]	×	\checkmark	\checkmark	×	\checkmark
	Java agent + bytecode mod	per-dep + resource-level	runtime tracing	no proc tracking	native/resource-level
μ PolicyCraft [6]	\checkmark	×	\checkmark	\checkmark	×
	no code mods, trace-based monitor	microservice/container level	symbolic exec + telemetry	full service orchestration	not syscall-level
Confine [60]	\checkmark	×	\checkmark	\checkmark	\checkmark
	no code mods, binary-level	container-level only	static binary analysis	full container, incl. procs	syscall-level
GoLeash (ours)	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark
	eBPF, no code/build mods	per-package + syscall-level	call graph + trace	multi-proc + threads	syscall-level enforcement

Table 7: Comparison of Capability Enforcement Approaches Against GoLeash's Design Requirements

Capability Reuse. GoLeash enforces policies by detecting when packages invoke unauthorized capabilities. However, if malware is injected into a permissive module and reuses already-allowed capabilities, it may evade detection under our current model. Still, GoLeash significantly limits such opportunities, as most packages use a narrow set of capabilities, as shown in our experiments. Detecting residual attacks would require deeper inspection of syscall arguments and side effects (e.g., destination IPs, file paths), as explored in prior work [54, 60, 77]. Such analysis is orthogonal to our focus on per-package capability boundaries, and can be integrated into GoLeash.

Vulnerabilities in third-party software. This work focuses on detecting malicious code introduced via upstream dependencies, a major software supply chain risk. Benign packages may also contain vulnerabilities, exposing dependent applications to attacks. This is another area of interest, covered by tools such as Trivy and Snyk [4, 66], but outside our scope. GoLeash indirectly mitigates certain vulnerabilities, particularly those enabling remote code execution (RCE), such as command injection and deserialization flaws such as Log4Shell [48] and the recent Ingress-nginx RCE [49]. In such cases, the exploited package would invoke a capability outside its policy, which GoLeash would flag as a violation.

Portability Across Languages and Systems. GoLeash is designed for the Go language on Linux, leveraging eBPF tracing and Gospecific features (e.g., package management, symbol tables). However, its core design principles (e.g., stack-based syscall attribution, per-component capability policies), are conceptual and portable to other languages and systems. For instance, similar techniques could apply to Java and Rust, which also support package management and expose symbols and package information in runtime stack traces. Additionally, other operating systems, such as FreeBSD and Windows, also offer production-grade tracing frameworks, such as DTrace [45]. *Stripped Binaries.* GoLeash relies on Go symbol tables to map system calls to their originating packages via stack traces. This works reliably because Go binaries are typically not stripped in production environments [34]. In the rare case of stripped binaries, such as in performance-critical deployments, GoLeash can integrate with tools like redress [37] to heuristically recover function boundaries and naming information. While this may reduce attribution precision, enforcement remains effective through hashed stack traces and recovered labels. Therefore, stripped binaries are a deployment consideration, but not a fundamental obstacle for using GoLeash.

8 Conclusion

GoLeash is a novel solution for mitigating software supply chain attacks in Go. By enforcing runtime least-privilege boundaries at the level of individual Go packages, GoLeash can detect maliciously added capabilities introduced via compromised dependencies. These fine-grained enforcement mechanisms enable GoLeash to identify stealthy behaviors that process-level dynamic techniques or static analysis miss. Our evaluation shows that GoLeash achieves high detection accuracy, remains effective under obfuscation, and incurs acceptable overhead. As supply chain attacks continue to escalate in sophistication, GoLeash provides a foundation for hardening the runtime security of modern software.

References

- Marco Abbadini, Dario Facchinetti, Gianluca Oldani, Matthew Rossi, and Stefano Paraboschi. 2023. Cage4Deno: A fine-grained sandbox for Deno subprocesses. In ACM ASIA Conference on Computer and Communications Security (ASIACCS). 149–162.
- [2] Marco Abbadini, Dario Facchinetti, Gianluca Oldani, Matthew Rossi, and Stefano Paraboschi. 2023. NatiSand: Native code sandboxing for JavaScript runtimes. In 26th International Symposium on Research in Attacks, Intrusions and Defenses (RAID). 639–653.
- [3] Paschal C Amusuo, Kyle A Robinson, Tanmay Singla, Huiyun Peng, Aravind Machiry, Santiago Torres-Arias, Laurent Simon, and James C Davis. 2025.

ZTD_{JAVA}: Mitigating Software Supply Chain Vulnerabilities via Zero-Trust Dependencies. *IEEE/ACM 47th International Conference on Software Engineering* (ICSE) (2025).

- [4] Aqua Security. 2025. Trivy: Open Source Vulnerability and Misconfiguration Scanner. https://www.aquasec.com/products/trivy/ Accessed: 2025-04-12.
- [5] Jacob Baines. 2023. Hijackable Go Module Repositories. https://vulncheck.com/ blog/go-repojacking.
- [6] William Blair, Frederico Araujo, Teryl Taylor, and Jiyong Jang. 2024. Automated Synthesis of Effect Graph Policies for Microservice-Aware Stateful System Call Specialization. In 2024 IEEE Symposium on Security and Privacy (SP). IEEE, 4554– 4572.
- [7] Kirill Boychenko. 2025. Go Supply Chain Attack: Malicious Package Exploits Go Module Proxy Caching for Persistence. https://socket.dev/blog/maliciouspackage-exploits-go-module-proxy-caching-for-persistence.
- [8] Kirill Boychenko. 2025. Typosquatted Go Packages Deliver Malware Loader Targeting Linux and macOS Systems. https://socket.dev/blog/typosquatted-gopackages-deliver-malware-loader.
- [9] Tyler Bui. 2019. Using Go Modules The Go Programming Language. https: //blog.golang.org/using-go-modules Accessed: 2025-04-12.
- [10] Roberto Natella Carmine Cesarano, Martin Monperrus. 2025. Replication Package for "GoLeash: Mitigating GoLang Software Supply Chain Attack with Runtime Polocy Enforcement". https://figshare.com/s/ce9afb61cdc87936543a. Accessed: 2025-04-15.
- [11] Carmine Cesarano, Vivi Andersson, Roberto Natella, and Martin Monperrus. 2023. GoSurf: Identifying Software Supply Chain Attack Vectors in Go. In Proceedings of the 2024 Workshop on Software Supply Chain Offensive Research and Ecosystem Defenses. 33–42.
- [12] cilium. 2025. bpf2go. https://github.com/cilium/ebpf/tree/main/cmd/bpf2go Accessed: 2025-04-12.
- [13] Cilium. 2025. eBPF-based Networking, Observability, Security. https://cilium.io/ Accessed: 2025-04-12.
- [14] CISA and NSA. 2021. Defending Against Software Supply Chain Attacks. https://www.cisa.gov/sites/default/files/publications/defending_against_ software_supply_chain_attacks_508.pdf. Accessed: 2025-04-11.
- [15] CoreDNS Authors. 2025. CoreDNS: DNS Server That Chains Plugins. https: //github.com/coredns/coredns Accessed: 2025-04-12.
- [16] Russ Cox. 2025. Fifty Years of Open Source Software Supply Chain Security. ACM Queue 23, 1 (2025), 84–107.
- [17] Milo Craun, Khizar Hussain, Uddhav Gautam, Zhengjie Ji, Tanuj Rao, and Dan Williams. 2024. Eliminating eBPF Tracing Overhead on Untraced Processes. In Proceedings of the ACM SIGCOMM 2024 Workshop on eBPF and Kernel Extensions. 16–22.
- [18] Datadog. 2024. GuardDog: CLI Tool to Identify Malicious PyPI, npm Packages. https://github.com/DataDog/guarddog Accessed: 2025-04-12.
- [19] Datadog. 2025. Malicious Software Packages Dataset. https://github.com/ DataDog/malicious-software-packages-dataset Accessed: 2025-04-12.
- [20] Go Dev. 2025. Case Studies. https://go.dev/solutions/case-studies.
- [21] DNS-OARC. 2025. dnsperf: DNS Performance Testing Tools. https://github.com/ DNS-OARC/dnsperf Accessed: 2025-04-12.
- [22] Docker Inc. 2024. Docker: Empowering App Development for Developers. https: //www.docker.com. Accessed: 2025-04-11.
- [23] eBPF Foundation. 2024. What is eBPF? https://ebpf.io/what-is-ebpf/. Accessed: 2025-04-11.
- [24] etcd Authors. 2024. etcd: A Distributed, Reliable Key-Value Store for the Most Critical Data of a Distributed System. https://etcd.io. Accessed: 2025-04-11.
- [25] Ethereum Foundation. 2025. go-ethereum: Go Implementation of the Ethereum Protocol. https://github.com/ethereum/go-ethereum Accessed: 2025-04-12.
- [26] Falco. 2025. Detect security threats in real time. https://falco.org/ Accessed: 2025-04-12.
- [27] fatedier. 2025. frp: A Fast Reverse Proxy to Help You Expose a Local Server Behind a NAT or Firewall to the Internet. https://github.com/fatedier/frp Accessed: 2025-04-12.
- [28] Gabriel Ferreira, Limin Jia, Joshua Sunshine, and Christian Kästner. 2021. Containing Malicious Package Updates in npm with a Lightweight Permission System. In Proceedings of the 43rd International Conference on Software Engineering (ICSE '21). IEEE Press, 1334–1346. https://doi.org/10.1109/ICSE43902.2021.00121
- [29] Adrien Ghosn, Marios Kogias, Mathias Payer, James R Larus, and Edouard Bugnion. 2021. Enclosure: language-based restriction of untrusted libraries. In Proceedings of the 26th ACM International Conference on Architectural Support for Programming Languages and Operating Systems. 255–267.
- [30] GitHub. 2025. GitHub. https://github.com Accessed April 12, 2025.
- [31] GitHub Community. 2018. Malicious code found in npm package event-stream. https://github.com/dominictarr/event-stream/issues/116. Accessed: 2025-04-11.
 [32] Go Team. 2023. Go standard library - Go Packages. https://pkg.go.dev/std
- Accessed April 2025. [33] Go Team. 2025. Go standard library the runtime package. https://pkg.go.dev/
- [33] Go leam. 2023. Go standard library the runtime package. https://pkg.go.dev/ runtime Accessed April 2025.

- [35] Google Inc. 2025. Google Capslock. https://github.com/google/capslock.
- [36] Nuwan Goonasekera, William Caelli, and Colin Fidge. 2015. LibVM: an architecture for shared library sandboxing. Software: Practice and Experience 45, 12 (2015), 1597–1617.
- [37] goretk. 2025. Redress: A Tool for Analyzing Stripped Go Binaries. https://github. com/goretk/redress Accessed: 2025-04-12.
- [38] gVisor Team. 2024. gVisor: The Container Security Platform. https://gvisor.dev/. Accessed: 2025-04-11.
- [39] HashiCorp. 2024. Terraform by HashiCorp. https://www.terraform.io. Accessed: 2025-04-11.
- [40] Isovalent. 2025. eBPF-based networking, security, and observability. https: //isovalent.com/ Accessed: 2025-04-12.
- [41] Raphaël Khoury and Nadia Tawbi. 2012. Which security policies are enforceable by runtime monitors? a survey. *Computer Science Review* 6, 1 (2012), 27–45.
- [42] Kube-Burner Contributors. 2025. kube-burner: Kubernetes Performance and Scale Test Orchestration Framework. https://github.com/kube-burner/kube-burner Accessed: 2025-04-12.
- [43] Kubernetes Authors. 2024. Kubernetes: Production-Grade Container Orchestration. https://kubernetes.io. Accessed: 2025-04-11.
- [44] Dexin Liu, Yue Xiao, Chaoqi Zhang, Kaitao Xie, Xiaolong Bai, Shikun Zhang, and Luyi Xing. 2024. {iHunter}: Hunting Privacy Violations at Scale in the Software Supply Chain on {iOS}. In 33rd USENIX Security Symposium (USENIX Security 24). 5663–5680.
- [45] Microsoft. 2025. DTrace on Windows. https://github.com/microsoft/DTrace-on-Windows Accessed: 2025-04-12.
- [46] MITRE. 2025. CWE-441: Unintended Proxy or Intermediary ('Confused Deputy'). https://cwe.mitre.org/data/definitions/441.html Accessed: 2025-04-12.
- [47] Borja Molina-Coronado, Antonio Ruggia, Usue Mori, Alessio Merlo, Alexander Mendiburu, and Jose Miguel-Alonso. 2025. Light up that Droid! On the effectiveness of static analysis features against app obfuscation for Android malware detection. Journal of Network and Computer Applications 235 (2025), 104094.
- [48] National Institute of Standards and Technology (NIST). 2025. CVE-2021-44228: Apache Log4j2 Remote Code Execution Vulnerability. https://nvd.nist.gov/vuln/ detail/CVE-2021-44228 Accessed: 2025-04-12.
- [49] Nir OhfeldSasson. 2025. IngressNightmare: CVE-2025-1974 9.8 Critical Unauthenticated Remote Code Execution Vulnerabilities in Ingress NGINX. https: //www.wiz.io/blog/ingress-nginx-kubernetes-vulnerabilities Accessed: 2025-04-12.
- [50] Marc Ohm, Henrik Plate, Arnold Sykosch, and Michael Meier. 2020. Backstabber's knife collection: A review of open source software supply chain attacks. In Detection of Intrusions and Malware, and Vulnerability Assessment: 17th International Conference, DIMVA 2020, Lisbon, Portugal, June 24–26, 2020, Proceedings 17. Springer, 23–43.
- [51] Marc Ohm, Timo Pohl, and Felix Boes. 2023. You Can Run But You Can't Hide: Runtime Protection Against Malicious Package Updates For Node.js. arXiv preprint arXiv:2305.19760 (2023).
- [52] Philip O'Kane, Sakir Sezer, and Kieran McLaughlin. 2011. Obfuscation: The hidden malware. *IEEE Security & Privacy* 9, 5 (2011), 41–47.
- [53] Open Source Insights Team. 2025. Open Source Insights. https://deps.dev/ Accessed April 12, 2025.
- [54] Shankara Pailoor, Xinyu Wang, Hovav Shacham, and Isil Dillig. 2020. Automated policy synthesis for system call sandboxing. *Proceedings of the ACM on Programming Languages* 4, OOPSLA (2020), 1–26.
- [55] Github repo. 2015. wg/wrk: Modern HTTP Benchmarking tool. https://github. com/wg/wrk.
- [56] Github repo. 2019. Ethereum Benchmark. https://github.com/OBrezhniev/ ethereum-benchmark.
- [57] Github repo. 2024. etcd benchmark. https://github.com/etcd-io/etcd/blob/main/ tools/benchmark/README.md.
- [58] Michen Riksen. 2025. Finding Evil Go Packages. https://michenriksen.com/ archive/blog/finding-evil-go-packages/. Accessed: 2025-04-15.
- [59] Nick Roessler, Lucas Atayde, Imani Palmer, Derrick McKee, Jai Pandey, Vasileios P Kemerlis, Mathias Payer, Adam Bates, Jonathan M Smith, Andre DeHon, et al. 2021. Mscope: A methodology for analyzing least-privilege compartmentalization in large software artifacts. In Proceedings of the 24th International Symposium on Research in Attacks, Intrusions and Defenses. 296–311.
- [60] Maryam Rostamipoor, Seyedhamed Ghavamnia, and Michalis Polychronakis. 2023. Confine: Fine-grained system call filtering for container attack surface reduction. *Computers & Security* 132 (2023).
- [61] Jerome H Saltzer and Michael D Schroeder. 1975. The protection of information in computer systems. Proc. IEEE 63, 9 (1975), 1278-1308.
- [62] Adriana Sejfia and Max Schäfer. 2022. Practical automated detection of malicious npm packages. In Proceedings of the 44th International Conference on Software Engineering (ICSE '22). Association for Computing Machinery, 1681–1692. doi:10. 1145/3510003.3510104

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FLEXDROID: Enforcing In-App Privilege Separation in Android.. In NDSS.
[64] Hossein Siadati, Sima Jafarikhah, Elif Sahin, Terrence Hernandez, Elijah Tripp, Denis Khryashchev, and Amin Kharraz. 2024. DevPhish: Exploring Social Engineering in Software Supply Chain Attacks on Developers. In 2024 IEEE 15th Annual Ubiquitous Computing, Electronics & Mobile Communication Conference (UEMCON). IEEE, 517–523.

- [65] Richard E Smith. 2012. A contemporary look at Saltzer and Schroeder's 1975 design principles. *IEEE Security & Privacy* 10, 6 (2012), 20–25.
- [66] Snyk Ltd. 2025. Snyk CLI Documentation. https://docs.snyk.io/snyk-cli Accessed: 2025-04-12.
- [67] Tetragon. 2025. eBPF-based Security Observability and Runtime Enforcement. https://tetragon.io/ Accessed: 2025-04-12.
- [68] The Linux Kernel Archives. 2025. Using the Linux Kernel Tracepoints. https: //docs.kernel.org/trace/tracepoints.html.
- [69] The Linux Kernel Community. 2024. seccomp(2) Linux manual page. https: //man7.org/linux/man-pages/man2/seccomp.2.html. Accessed: 2025-04-11.
- [70] The Linux Kernel Community. 2025. x86_64 System Call Table (syscall_64.tbl). https://github.com/torvalds/linux/blob/v6.7/arch/x86/entry/syscalls/syscall_64. tbl Accessed: 2025-04-12.
- [71] Nikos Vasilakis, Cristian-Alexandru Staicu, Grigoris Ntousakis, Konstantinos Kallas, Ben Karel, André DeHon, and Michael Pradel. 2021. Preventing Dynamic Library Compromise on Node.js via RWX-Based Privilege Reduction. In ACM SIGSAC Conference on Computer and Communications Security (CCS). 1821–1838.
- [72] Wenya Wang, Xingwei Lin, Jingyi Wang, Wang Gao, Dawu Gu, Wei Lv, and Jiashui Wang. 2023. HODOR: Shrinking Attack Surface on Node js via System Call Limitation. In ACM SIGSAC Conference on Computer and Communications Security (CCS). 2800–2814.
- [73] Alex Williams. 2024. Giving Go a Go: Simplifying Cloud Infrastructure Development. https://cacm.acm.org/blogcacm/giving-go-a-go-simplifying-cloudinfrastructure-development/.
- [74] Yongzheng Wu, Sai Sathyanarayan, Roland HC Yap, and Zhenkai Liang. 2012. Codejail: Application-transparent isolation of libraries with tight program interactions. In Computer Security–ESORICS 2012: 17th European Symposium on Research in Computer Security, Pisa, Italy, September 10-12, 2012. Proceedings 17. Springer, 859–876.
- [75] Elizabeth Wyss, Alexander Wittman, Drew Davidson, and Lorenzo De Carli. 2022. Wolf at the door: Preventing install-time attacks in npm with latch. In ACM ASIA Conference on Computer and Communications Security (ASIACCS). 1139–1153.
- [76] Wei Xu, Fangfang Zhang, and Sencun Zhu. 2012. The power of obfuscation techniques in malicious JavaScript code: A measurement study. In 2012 7th International Conference on Malicious and Unwanted Software. IEEE, 9–16.
- [77] Zhaoqi Zhang, Panpan Qi, and Wei Wang. 2020. Dynamic malware analysis with feature engineering and feature learning. In *Proceedings of the AAAI conference* on artificial intelligence, Vol. 34. 1210–1217.

A Example Security Policy for frp

In the following we provide an excerpt from a real security policy generated by GoLeash for the frp application. The policy illustrates the granularity and structure of the analyzed capabilities across a selected subset of dependencies. We omit call paths hashes for brevity.

Listing 1: GoLeash Security Policy

```
{
     "github.com/fatedier/frp/client": {
       "type": "dep",
       "path": "github.com/fatedier/frp/client",
       "syscalls": [1, 35, 202, 281, 318],
       "capabilities": [
         "CAP_MEMORY_MANIPULATION",
         "CAP_MODIFY_SYSTEM_STATE",
         "CAP_READ_SYSTEM_STATE",
         "CAP_WRITE_FILE"
10
       ],
11
       "executed_binaries": [],
12
       "call_paths": {
13
14
```

}, "github.com/fatedier/golib/log": { "type": "dep", "path": "github.com/fatedier/golib/log", "syscalls": [1, 3, 9, 15, 39, 202, 234, 281], "capabilities": ["CAP_FILE", "CAP_MEMORY_MANIPULATION", "CAP_MODIFY_SYSTEM_STATE", "CAP_READ_FILE", "CAP_READ_SYSTEM_STATE", "CAP_TERMINATE_PROCESS", "CAP_WRITE_FILE"]. "executed_binaries": [], "call_paths": { . . . } }, "github.com/spf13/cobra": { "type": "dep", "path": "github.com/spf13/cobra", "syscalls": [1], "capabilities": ["CAP_WRITE_FILE"], "executed_binaries": [], "call_paths": { } }, "github.com/xtaci/kcp-go/v5": { "type": "dep", "path": "github.com/xtaci/kcp-go/v5", "syscalls": [0, 1, 9, 15, 24, 35, 41, 49, 51, 54, 202, 281, 299, 307, 318], "capabilities": ["CAP_CONNECT_REMOTE", "CAP_LISTEN_LOCAL", "CAP_MEMORY_MANIPULATION", "CAP_MODIFY_SYSTEM_STATE", "CAP_READ_FILE", "CAP_READ_SYSTEM_STATE", "CAP_RECEIVE_DATA", "CAP_SEND_DATA", "CAP_WRITE_FILE"], "executed_binaries": [], "syscalls_paths": {

, ,

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