A practical approach for updating an integrity-enforced operating system

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Abstract

Trusted computing defines how to securely measure, store, and verify the integrity of software controlling a computer. One of the major challenges that make them hard to be applied in practice is the issue with software updates. Specifically, an operating system update causes the integrity violation because it changes the well-known initial state trusted by remote verifiers, such as integrity monitoring systems. Consequently, the integrity monitoring of remote computers becomes unreliable due to the high amount of false positives.

We address this problem by adding an extra level of indirection between the operating system and software repositories. We propose a trusted software repository (TSR), a secure proxy that overcomes the shortcomings of previous approaches by sanitizing software packages. Sanitization consists of modifying unsafe installation scripts and adding digital signatures in a way software packages can be installed in the operating system without violating its integrity. TSR leverages shielded execution, i.e., Intel SGX, to achieve confidentiality and integrity guarantees of the sanitization process.

TSR is transparent to package managers, and requires no changes in the software packages building and distributing processes. Our evaluation shows that running TSR inside SGX is practical: since it induces only ~1.18× performance overhead during package sanitization compared to the native execution without SGX. TSR supports 99.76% of packages available in the main and community repositories of Alpine Linux while increasing the total repository size by 3.6%.

Keywords: trusted computing, software updates, integrity measurement architecture (IMA), Intel software guard extensions

1 Introduction

In the last years, trusted computing (TC) technologies, such as Intel trusted execution technology (TXT) [28], integrity measurement architecture (IMA) [61, 69], and trusted platform module (TPM) [32, 67], have received much attention both in industry and academia because of their capacities for measuring integrity, remote attestation, and sealing. While promising at first glance, the approach of leveraging TC technologies suffers from technical issues. One of the major problems of applying them in production systems is the lack of support for operating system (OS) updates. Specifically, the security patches, which might be released frequently and installed automatically, break system integrity. We refer to integrity
of creating packages for every OS distribution. Second, software packages contain not only files that are extracted to the filesystem but also configuration scripts that might alter OS configuration, thus breaking the integrity.

Instead of modifying the well-established process of package generation (which requires approval from the entire open-source community), an alternative approach consists of creating a standalone repository with modified packages containing digital signatures [10]. The approach requires a trusted organization which owns a signing key and re-creates packages after injecting digital signatures. Such an organization must put additional efforts to protect the signing key and must have a good reputation to convince users to trust it. We argue that it might be difficult to achieve, considering incidents from the past, when signing keys of major Linux distribution were leaked affecting millions of users [25, 59].

Another problem is that an adversary controlling a repository can provide the OS with outdated packages containing known vulnerabilities (replay attack), or even prevent the OS from seeing the update (freeze attack) [12, 13]. The secure choice is to rely only on the original repository, which is a repository managed by a trusted organization, such as an official software repository of the OS distribution. But, this approach does not tolerate the original repository failure, thus the OS must also accept mirrors. Mirrors store a copy of the original repository, and, in the case of open-source distributions, are hosted voluntarily. As reported by previous studies [12], it is not difficult to create a custom mirror that becomes accepted as an official mirror. Therefore, we must tolerate that some of the available mirrors are controlled by an adversary, exposing operating systems to threats mentioned above. For example, it happened that a compromised mirror of a popular repository distributed a vulnerable version of the software, allowing an adversary to remotely access the system [63].

We present the trusted software repository (TSR), an intermediate layer between the OS and the software repository that provides sanitized software packages. The installation of sanitized packages causes deterministic changes to the OS configuration and filesystem. Because such changes are verifiable by monitoring systems, TSR eliminates the risk of false-positives. According to our measures, sanitization enables 99.76% of packages available in the Alpine main and community repositories to be safely installed in integrity-enforced operating systems.

TSR requires zero code changes to both monitoring systems as well as operating systems. Due to the shared nature of the software repositories, we designed TSR as a service that can be hosted on the third-party resources, i.e., in the cloud. TSR exploits trusted execution environment (TEE), i.e., Intel software guard extensions (SGX) [6, 18, 53], to protect the signing keys and TSR integrity. Our evaluation shows that running TSR inside SGX is practical; SGX induces in average 1.18× performance overhead during sanitization, up to 1.96× slowdown has no practical impact.

In summary, we make the following main contributions:

1. We propose a practical solution to support OS updates in integrity-enforced systems, with the following properties:
   (a) The software packages are safe to install in integrity-enforced operating systems (§4.2).
   (b) Our solution is transparent to the existing software update processes and infrastructure (§4.3).
   (c) A minority of mirrors exhibiting Byzantine behavior are tolerated (§4.5).

2. We realize the above-mentioned design by developing TSR—a secure proxy framework for supporting software updates in integrity-enforced operating systems (§5).

3. We have evaluated TSR using a series of micro-benchmarks, and a real-world use case—Alpine Linux package updates (§6).

2 Background

To better understand the decisions taken in designing TSR, we start by providing background information on software update processes and about existing technologies used to collect, report, and verify system integrity.

2.1 OS updates

Figure 2 shows a high-level overview of an OS update process: releasing, exposing, and installing new software versions. The process begins when software maintainers create a new software release that contains bug fixes or new features. The OS distribution community uses the source code of the new software release to create a software package. A software package is an archive containing software-specific files and meta-information required by the OS to install and manage the package. Packages are stored in a repository, from which
Figure 3. The internal structure of a software package, i.e., Alpine APK package format. The package authenticity and integrity can be verified by using the digital signature and the content hash. The digital signature is stored inside the header, and is issued over the package control. The hash of the package contents is stored inside the meta-attributes of the package control.

end-users download them. A repository stores also a metadata index that contains a digitally signed list of all packages. In this paper, we refer to a software repository controlled by an OS distribution community as an original repository. The original repository is a root of trust for software updates. The metadata file downloaded from the original repository provides information about the most recent versions of software available in the repository. As such, it can be used to verify that the OS is up-to-date.

Repository mirrors contain a copy of the original repository. They are used to distribute the load and to decrease the latency of downloading packages. The community has limited control over the mirrors, which are typically supported by volunteer organizations. Importantly, mirrors do not have access to the signing key. End-users verify that the metadata file and packages downloaded from mirrors originate from the original repository by verifying digital signatures using a public portion of the signing key provided by the OS distribution community.

2.2 Package managers

Operating systems use package managers to simplify installation, update, and removal of software. The majority of distributions ship with package managers that use pre-built packages (e.g., .rpm, .deb [19], .apk [5]), but some build software directly from sources [7, 26]. In this paper, we focus only on the pre-built packages, which we refer further as packages.

A package is an archive containing software-specific files, installation scripts, meta-information (such as dependency on other packages), and digital signatures. Figure 3 shows an example of a package in the Alpine Linux .apk format. The package header stores a digital signature issued by a developer with an offline signing key (a private key stored off the repository). The digital signature permits verifying the authenticity and the integrity of the package control, which contains installation scripts and meta-information describing package dependencies, software version, and a cryptographic hash of package contents. The hash permits verifying the integrity of executables, dynamic libraries, and configuration files stored inside the package.

To install the package, the package manager first downloads it from the repository, or from middlemen such as a content delivery network (CDN) or mirrors. After that, it verifies that a trusted entity created the package. Finally, it runs installation scripts and extracts software-specific files to the file system.

2.3 Integrity measurements

To bootstrap the computer, multiple low-level software components execute. They form a chain of trust by following the rule that every component calculates a cryptographic hash (an integrity measurement) of the next component before executing it. The measurements are stored in tamper-resistant memory of a hardware root of trust, e.g., TPM [68]. Eventually, one of the components measures the bootloader, which measures and loads the kernel. At the kernel level, the integrity measurements continue. The Linux kernel integrity measurement subsystem (Linux IMA [61, 69]) measures each file, executable, or library before loading it to the memory. The list of all measurements, certified by a hardware root of trust (e.g., TPM [68]), vouches for the system integrity [66]. Integrity monitoring systems use the measurements to verify if only expected software executed on the computer since its bootstrap.

3 Threats and challenges

3.1 Threat model

We assume an adversary whose goal is to install vulnerable software on a remote computer by exploiting the software update mechanism. A remote computer is configured to install updates from TSR, which itself relies on the original repository and official mirrors. An adversary has root access to the machine running TSR and to the minority of machines hosting mirrors. In more detail, she controls up to $f$ mirrors out of a total of $2f + 1$ mirrors available to TSR. The adversary has access to all outdated packages that contain vulnerabilities, including outdated signed metadata files. By having root access to machines hosting TSR and mirrors, she can prevent network connection to the original repository and arbitrary mirrors.

We assume that the OS distribution community, software maintainers, their internal processes (i.e., software development, packages build), and infrastructure are trusted. In particular, packages are build using legitimate compilers; signing keys are well protected; the original repository provides the most recent software versions. We do not consider attacks resulting from the incorrect design of package formats and metadata, i.e., the endless data attack and the extraneous dependencies attack [12]. The assumption is practical because main repositories hosted by the popular Linux distributions...
We exclude them from the threat model, assuming they can be addressed using dedicated tools [15, 56, 57], by updating microcode [34], or by excluding a particular type of hardware during the remote attestation protocol [37].

The TEEs are vulnerable to side-channel attacks [41, 70]. We exclude them from the threat model, assuming they can be addressed using dedicated tools [15, 56, 57], by updating microcode [34], or by excluding a particular type of hardware during the remote attestation protocol [37].

3.2 Problem statement

We now introduce the main challenges and problems that shaped the TSR design.

Problem 1: How to modify the package so that the changes made to the OS configuration and filesystem are verifiable by the monitoring system?

The monitoring systems regularly verify that remote computers run only expected software in the expected configuration. Machines that fail the attestation might be restarted or reinstalled to bring the system back into the correct state. Also, there exist mechanisms to enforce OS integrity locally. Such mechanisms are built into the kernel (e.g., IMA-appraisal [60]), allowing the kernel to authorize each file before loading it to the memory. They make the integrity attestation more robust, preventing accidental or malicious changes to the filesystem.

The main problem of applying trusted computing in production systems is, however, that software updates cannot be safely installed because they modify the OS configuration and change files in a way unknown to monitoring systems. Figure 4 shows why the package installation might move the OS into an untrusted state. After the package is downloaded (①), the package manager executes software-specific installation scripts that modify the OS configuration (②). Moreover, the package manager extracts software-specific files (③), which contents are not known to verifiers. The integrity of the OS configuration files and software-specific files is measured by trusted computing components (④). Eventually, a monitoring system uses remote attestation to read the measurements (⑤), thus detecting the OS integrity change. The OS is considered compromised.

A strawman approach consists of providing the monitoring system with a list of valid measurements before installing a new package. In practice, constructing such a list a priori is a difficult problem because of the complex nature of software dependencies, the OS configuration depending on the order in which software has been installed, and unpredictable schedules of security updates.

Problem 2: How to modify packages without changing the well-established package creation requiring community approval?

Previous studies proposed changing the package creation process operated by different Linux communities to include digital signatures that vouch for individual file integrity [9]. Although different approaches have been proposed [51, 64], they have not gained enough community approval and have not been merged into upstream repositories. Therefore, a practical solution should not require changes to the existing package creation processes, thus be transparent to the existing update infrastructure and processes.

Problem 3: How to protect the signing key and to guarantee the correct generation of signatures in the presence of a powerful adversary with administrative access to TSR?

If we assume that we know how to modify the package (problem 1), the OS would reject the modified package because its digital signature would not match the package contents. This is expected behavior because it prevents operating systems from installing packages tampered by an adversary. Therefore, a new package content must be certified again. However, without community support, it is impossible to issue the signature because the community would restrict access to the signing key (problem 2).

An alternative approach is to let TSR generate a custom signing key, so it uses it to sign all modified packages. However, an adversary with access to the machine on which the
signing keys are used might extract the signing key by simply reading the process memory using administrative rights or by exploiting memory corruption techniques [49]. Consequently, the adversary might sign arbitrary packages compromising all operating systems that trust the signing key.

**Problem 4:** How to ensure access to the most up-to-date packages despite having no connection to the main software repository?

Software repositories are maintained by the OS distributions and provide public access to packages and updates. We refer to such repositories as *original repositories* because new versions of packages and software updates are published directly there. Although the secure choice would be to always rely on the original repository controlled by a trusted organization, such a decision would introduce a single point of failure. For this reason, original repositories propagate software updates to mirrors, which expose them to the wide range of end client machines.

As reported by previous studies, an adversary controlling the mirror can serve outdated, vulnerable packages, decreasing the security of operating systems relying on that mirror [12, 13]. Figure 5 shows that an adversary might prevent OS from accessing the original repository, and forcing the OS to use mirrors under her control.

## 4 Approach: Trusted Software Repository

Our objective is to provide an architecture that:

- provides software updates which can be safely installed in an integrity-enforced OS,
- requires no changes to the process of how communities create and distribute software packages,
- tolerates threats defined in §3.

### 4.1 Design

Figure 6 shows a high-level overview of the TSR design. It consists of four components: (A) an integrity-enforced OS measured by trusted computing components, (B) a monitoring system which remotely verifies OS integrity, (C) mirrors, copies of the original repository, containing OS-dependent software packages, (D) TSR, an intermediate layer that provides the OS with access to software packages that are safe to install in an integrity-enforced OS.

Now, we present how TSR integrates with the software update process. First, TSR fetches the most up-to-date packages from mirrors (➊) and modifies them in a way they are safe to install (➋). Next, the package manager queries TSR to collect information about the latest versions of packages. After selecting packages to update, it downloads them from TSR (➌). Then, the package manager installs them (➍), causing partial update of the existing OS configuration, replacement of existing files (*e.g.*, dynamic libraries), and extraction of new files into the filesystem. Trusted computing components regularly measure these changes, and the corresponding integrity measurements are stored inside a TPM chip (➎). The monitoring system collects the attestation report (➏), which next to integrity measurements, contains the corresponding digital signatures. After verifying the digital signatures and the integrity measurements, the monitoring system accepts a new state of the updated OS.

### 4.2 Solution to Problem 1: Sanitization

To enable support for software updates, we must solve two problems. First, convince a monitoring system that the integrity measurements of files extracted from the software package to the OS are valid. Second, make sure that the execution of a software package installation script does not cause the transition of the OS into an untrusted state.

To address these problems, we introduce the concept of package sanitization (Figure 6 (➏)). It consists of verifying Table 1. Number of packages with and without custom configuration scripts in Alpine Linux main and community repositories. Some packages (*Safe=X*) contain scripts that break OS integrity.

| Alpine repository | No. packages in | Main | Community |
|-------------------|----------------|------|-----------|
|                   |                |      |           |
|                   | Total          | 5665 | 5916      |
|                   | Safe           | ✓    | ✓         |
|                   | Without scripts| ✔    |           |
|                   | With safe scripts| ✔ |           |
|                   | With unsafe scripts| X |           |
we propose that for each file stored inside a package, a corresponding digital signature certifying its integrity is also stored inside the package. The package manager would extract digital signatures from the filesystem, allowing the IMA to include digital signatures inside the attestation report. Consequently, the verifiers could recognize that the new integrity measurements are valid because they correspond to installation scripts and package-specific files.

### Installation scripts

Software packages might contain scripts that are executed with administrative rights during the package installation. Developers or package creators provide such scripts, and there are no limitations on what kind of OS configuration changes scripts can do. Therefore it is possible that, due to a misconfiguration, a script reconfigures OS, allowing remote access to the machine. We designed TSR to modify packages in such a way the installation scripts change OS configuration deterministically. The packages which scripts cannot be sanitized are rejected from TSR, and thus not available for installation.

To design the script sanitization algorithm, we started by analyzing existing scripts wrapped inside packages available in the Alpine Linux repositories\(^1\). Table 1 shows that 97.6% of packages do not contain any scripts. 81% of the remaining packages contain scripts that alter the OS configuration, breaking the system integrity.

We analyzed commands executed inside the scripts to understand how they interfere with the OS configuration. Table 2 shows that 45 packages modify the filesystem structure (\(i.e.,\) copying, moving, or removing files, directories, and symbolic links, also changing their permissions). From the OS integrity point of view, these actions are safe – they do not violate system integrity as defined by the IMA. Similarly, 36 packages execute text processing utilities (\(e.g.,\) parsing existing OS configuration), which do not alter any existing file; thus, they are safe. However, 230 packages contain scripts modifying the OS configuration, creating new users and groups, activating new shells, or creating empty files. These scripts are unsafe because they modify existing file contents in which integrity is certified using pre-generated signatures (as discussed in the previous section).

### Script sanitization

As we show next, the majority of the unsafe scripts provide a predictable output. Hence it is possible to predict the OS configuration before installing the package. The installation or update of 201 packages results in the creation of new users or groups. In the case of Linux-based operating systems, three files are affected, \(i.e.,\) `/etc/passwd`, `/etc/group`, `/etc/shadow`. Interestingly, these files change in a deterministic way. Adding a new user or group results in adding a new well-defined line in at least one of these files. However, the order in which users and groups are created determines final file contents. In particular, different package installation order results in a different order in which users and groups are defined inside of each file.

Our solution consists of scanning the entire repository to learn about all possible users and groups that might be added by any software package. Then, we change each installation script in each package in a way the script creates all possible users and groups in the same predefined order. Consequently, any selection of packages and their order always results in the same OS configuration – it contains all users and groups. Finally, TSR issues digital signatures over the predicted contents of the configuration files and modifies scripts to install the signatures in the target OS. Monitoring systems accept the new OS configuration because they read a measurement report containing the signatures, which vouch for the new configuration files contents.

Our TSR implementation detected and sanitized two packages that not only create a user but also set an empty password and shell. Installation of such packages might cause a security breach by allowing an adversary to remotely connect to the OS using a well-known username and password [55]. We reported our findings to the Alpine Linux community.

### Unsupported scripts

TSR does not support 28 packages (0.24%) out of all packages available in Alpine repositories. In particular, TSR does not support packages in which installation changes arbitrary configuration files. For example, a package `roundcube-mail` is not supported because it generates an unpredictable configuration file containing a random session key. Although TSR could support it by generating the session key during the sanitization, such a solution would contradict the script functionality that provides a unique key per OS.

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\(^1\) v3.11 of the Alpine Linux main [4] and community [3] repositories.

| № packages in | Type                  | Safe | TSR |
|---------------|-----------------------|------|-----|
| Main Community | Filesystem changes     | ✓    | ✓   |
| 30            | 15                    |      |     |
| 5             | 17                    | ✓    | ✓   |
| 17            | 19                    | ✓    | ✓   |
| 11            | 7                     | ✓    |     |
| 1             | 0                     | ✓    | ✓   |
| 97            | 104                   |      |     |
| 4             | 6                     | ✗    | ✗   |

| Operations performed by installation scripts located in software packages in Alpine Linux repositories. Some operations (Safe=✓) break OS integrity. The last column ("TSR") indicates which operations are safe after the sanitization. Filesystem changes - add/remove/modify folders, symbolic links, and their permissions. Empty scripts - conditional checks, display information.

| № packages in | Type                  | Safe | TSR |
|---------------|-----------------------|------|-----|
| Main Community | Empty scripts         |      | ✓   |
| 30            | 15                    |      | ✓   |
| 5             | 17                    | ✓    | ✓   |
| 17            | 19                    | ✓    | ✓   |
| 11            | 7                     | ✗    |     |
| 1             | 0                     | ✗    | ✓   |
| 97            | 104                   |      |     |
| 4             | 6                     | ✗    | ✗   |

| Operations performed by installation scripts located in software packages in Alpine Linux repositories. Some operations (Safe=✓) break OS integrity. The last column ("TSR") indicates which operations are safe after the sanitization. Filesystem changes - add/remove/modify folders, symbolic links, and their permissions. Empty scripts - conditional checks, display information.
On the other hand, TSR intentionally does not support software packages providing different shells (e.g., mksh, bash, tcsh). Their scripts modify the OS configuration by activating a newly installed shell using add-shell command. Although TSR might use the same technique as with adding users and groups, we argue that the installation of a custom shell should not occur during an OS update but should instead be part of the initial OS configuration.

4.3 Solution to Problem 2: Proxy

We designed TSR as a proxy between package managers and software repositories provided by the community. This design decision permits TSR to act as a separate software repository that serves sanitized packages signed directly by TSR. From the community point of view, no changes are required to the existing software package creation processes, software package formats, or the implementation of package managers. Package managers recognize TSR as a standard repository mirror. Hence, it is enough to adjust the OS configuration in a way the package manager uses only TSR as a mirror.

4.4 Solution to Problem 3: Shielded execution

TSR requires a signing key to certify changes made to packages during the sanitization process. To protect the signing key from an adversary with root access to the machine, we propose to use TEE. In particular, we propose to leverage SGX, which is Intel’s central processing unit (CPU) extension providing confidentiality and integrity guarantees to applications running in environments in which OS, hypervisor, or basic input/output system (BIOS) might have been compromised. Other studies [29] demonstrated that applications running inside an enclave (a trusted execution environment provided by SGX) can generate, store, and use cryptographic keys that are only known to the specific application – not even a human being can read them. TSR’s design relies on that concept. By running TSR inside an enclave, TSR generates a signing key that is used later to sign all modified software packages. The public portion of the signing key is exposed to both operating systems and monitoring systems that use it to verify that software packages were created by TSR.

4.5 Solution to Problem 4: Quorum

An adversary might leverage administrative privileges to drop network traffic to certain hosts. In particular, she might prevent TSR from accessing the original repository, forcing TSR to rely on a mirror serving outdated software packages.

As specified in §3, we assume that the majority of repository mirrors are available and provide the latest snapshot of the original repository. TSR does not trust any individual mirror. Instead, it reads 2f+1 mirrors and only relies on the information that matches responses of at least f+1 mirrors. Importantly, TSR requires a quorum only when reading the metadata index. The packages can be downloaded from a single mirror because their integrity is verifiable using the metadata index.

To allow different organizations to specify individual security requirements (i.e., which mirrors to use, which package creators to trust) and to provide custom initial OS configuration (i.e., initial users, groups, and passwords), TSR accepts security policies. Listing 1 shows an example of such a security policy. The format permits defining a list of mirrors (lines 1-16) and a list of trusted package signers (lines 17-25). The package signer is a developer or a build system (e.g., continuous integration and continuous deployment) that builds, signs, and deploys packages to the original repository.

TSR enforces the security policy by publishing only software packages in versions offered by the majority of available mirrors and only created by trusted entities. The policy could be extended to support a private/closed variant in which an OS owner can specify a subset of supported software packages by specifying whitelist/blacklist of packages.

Figure 7 shows how an organization can deploy a security policy to TSR. First, it establishes trust with TSR (➊) using SGX remote attestation protocol [37], which permits ensuring
We developed TSR in Rust, a programming language that triggered by the OS owner (Figure 7).

5 Implementation

We developed TSR in Rust, a programming language that ensures memory safety [50]. We rely on the external Rust libraries, i.e., Hyper [30], Rustls [38], to build the representation state transfer (REST) application programming interface (API) [21]. We use a Rust-based crypto library ring [11] to issue digital signatures. We use SCONE Rust cross-compilers [1] to execute TSR inside an SGX enclave. TSR is about 3.3k source lines of code, excluding external libraries.

We rely on SGX because it provides the following properties: confidentiality to protect the signing keys, integrity to protect the sanitization process, and attestation protocol to remotely ensure TSR integrity during the policy deployment. Alternative TEEs [20, 28, 47, 52] providing similar functionality might be considered but the threat model should be carefully adjusted, according to TEE-specific implementation. For example, TEEs relying on late-launch technologies [20, 28, 52] must assume trusted link between CPU and TPM [71, 72], while others, like Keystone [47], must assume trusted boot process.

5.1 Supported package formats

Our prototype implementation of TSR supports apk packages used by Alpine Linux. We selected Alpine Linux because it is a popular security-oriented Linux distribution that minimizes the amount of software required to run the OS. It is an important property for systems relying on trusted computing. In the future, we plan to add support for other formats (i.e., deb, rpm) used by other Linux distributions.

5.2 Repository initialization

TSR can be executed in the cloud and is operated by a cloud provider, who is responsible for correct hardware initialization, installation of the operating system, and TSR execution. The cloud provider exposes the hostname on which TSR API is accessible by his clients.

Multiple clients share a single TSR instance. Each client deploys a policy to create his individual, logically separated, software repository within the TSR instance. For each new repository, TSR, which runs inside an SGX enclave, generates a unique repository identifier and a unique signing key. The identifier and the public portion of the signing key are returned to the client as a response to the policy deployment request issued via https. Each client accesses his repository via the REST API after providing the identifier. By verifying the digital signature of the package, the client ensures that the package conforms to his requirements defined inside the policy.

5.3 Package sanitization

We define package sanitization as an operation consisting of the following steps: verifying package integrity and authenticity, extracting files from the package archive, modifying the installation scripts (see §4.2), issuing digital signatures to all files inside the package, updating the metafile, and recreating the package. TSR issues digital signatures using the signing key generated during the policy deployment.

The digital signatures are stored inside portable archive exchange (PAX) headers [33] of the tar archive [23], which is logically equivalent to the package. The modern versions of tar extractors (e.g., GNU tar [24]) transparently copy the specific PAX headers’ value into the extended attributes in the filesystem. Before opening a file, Linux IMA scans extended attributes and includes the digital signature inside a dedicated file (IMA log). Consequently, the monitoring systems read the measurement report and the IMA log. They check the integrity of every file measured by the IMA by verifying its digital signature included inside the IMA log.

5.4 OS configuration

Software repositories include information about software packages sizes and hashes inside the repository metadata index to mitigate the endless data attack and the extraneous...
dependencies attack [12]. Operating systems read the package size and its hash from the metadata index to ensure they download the file of the expected size and contents. Because of that, when an OS requests TSR to return the metadata index for the first time, TSR downloads and sanitizes all packages listed in the upstream metadata index. Then, TSR generates a new metadata index that matches the sanitized packages and returns it. Although the first metadata index generation is time-consuming, subsequent requests require TSR to sanitize only packages that have changed on the upstream mirrors, since the previous read.

Each integrity-enforced OS must be reconfigured to use the TSR repository instead of mirrors. Moreover, the OS must trust the packages signed by TSR; thus, the public portion of the signing key must be added to the list of trusted signers. This reconfiguration can be done automatically using configuration management systems such as Puppet [58] or Chef [16].

5.5 Package caching
A slow read of software updates increases the vulnerability window for the time of check to time of use (TOCTOU) attack, where an adversary exploits the existing vulnerabilities until the security patches become available in the repository. In the case of TSR, this time is increased by the sanitization process (see §4.2) and the time required to read the majority of available mirrors (see §4.5).

To minimize the vulnerability window for the TOCTOU attack, TSR uses a local file system to cache the already sanitized packages, including the metadata index. TSR detects the outdated software packages each time TSR reads the new metadata index from the upstream mirrors. Consequently, TSR invalidates the metadata index, downloads the new version of the package, sanitizes it, and stores the new version inside the cache.

An adversary might tamper with the cache by reverting software packages and the metadata index to the outdated versions. To mitigate the attack, TSR stores metadata indexes (the latest one read from upstream mirrors and the one reflecting the already sanitized packages) inside its memory, which integrity and freshness are guaranteed by SGX. TSR uses the first metadata index to check which software packages changed in the upstream mirrors. It uses the second metadata index to verify that the package read from the cache (untrusted disk) has not been roll-backed, before returning it to the OS.

However, the data stored inside TSR memory is lost as soon as TSR is shutdown, for example, due to the OS restart. To preserve the metadata indexes across TSR restarts, we extended TSR implementation with support for TPM monotonic counter (MC) [68]. After generating the metafile, TSR increases the MC value and uses SGX sealing [6] to store the metadata indexes together with the MC value on the disk. The SGX sealing, and its revert operation unsealing, uses a CPU-

Table 3. Time required to initialize a repository. We assume two scenarios. In the optimistic one, TSR has access to a copy of packages stored in a cache. In the pessimistic one, during the policy deployment, TSR must download all packages from the original repository.

| Operation       | pessimistic | optimistic |
|-----------------|-------------|------------|
| Download packages | 17 min      | 0 min      |
| Policy deployment | < 1 min     | < 1 min    |
| Sanitize packages | 13 min      | 13 min     |
| Total            | 30 min      | 13 min     |

and enclave-specific key. Hence, only the same enclave running on the same CPU can unseal the previously sealed file. After the restart, TSR unseals the metadata indexes from the disk together with the MC value and verifies that the unsealed MC value matches the current MC value.

6 Evaluation
In this section, we evaluate TSR to answer the following questions:

- What is the overhead related to the package sanitization?
- What are the performance limitations incurred by running TSR inside an SGX enclave?
- What is the cost of tolerating compromised mirrors?

Testbed. Experiments execute on a rack-based cluster of Dell PowerEdge R330 servers equipped with an Intel Xeon E3-1280 v6 CPU, 64 GiB of RAM, Samsung SSD 850 EVO 1TB. All machines have a 10 Gb Ethernet network interface card (NIC) connected to a 20 Gb/s switched network. The support for SGX is turned on; the hyper-threading is switched off. We statically configured SGX to reserve 128 MB of RAM for the enclave page cache (EPC) [18]. The CPUs are on the microcode patch level 0x5e. We run Alpine Linux 3.10 with enabled Linux IMA.

6.1 Package sanitization overhead
The sanitization process directly influences the software update process, i.e., time after which software updates are visible by the OS and the latency taken by the OS to download the update. For that reason, we run experiments in which we instrumented the sanitization process to measure its impact on packages from the main and community repositories of Alpine Linux. The results are based on a 20% trimmed mean from six independent experiment executions.

How much time does it take to sanitize all packages?

From the OS perspective, low repository initialization time results in faster delivery of software updates. Therefore, we calculated the time requires to create a new repository, i.e., to download and to sanitize all packages. In the case of packages update, this time is expected to be significantly lower because
TSR would have to download and to sanitize just a small amount of packages.

Table 3 shows the time taken to establish a new repository, assuming two scenarios. In the optimistic scenario, which takes about 13 min, TSR has access to pre-fetched packages, which are available, for example, pre-fetched by a service provider. In the pessimistic one, which takes about 30 min, TSR additionally downloads original packages (about 3 GB of data) from upstream repositories. We argue that the download time can be greatly reduced by enabling parallel downloading. This performance improvement is left as part of future work.

What are the main factors driving the sanitization time?

TSR sanitizes all packages provided with a software update, thus introducing a delay in how fast the OS receives the update. Therefore, it is important to understand the main drivers controlling the sanitization time.

Table 4 shows the correlations between package-specific properties (i.e., number of files inside a package, package size) and the proportional time contribution of certain components of the sanitization time. We observe a strong positive correlation ($\rho = 0.61$) between the archive processing time and package size, which indicates that the archive, compression and decompression algorithms take more time to process bigger archives. Also, we observe a strong correlation ($\rho = 0.69$) between signatures generation and the number of files inside a package. It confirms the intuitive expectation that in packages containing many files, the signature generation becomes a dominant factor of the sanitization time. Furthermore, we explain that a strong negative correlation ($\rho = -0.93$) between checking the package integrity and package size shows that the time required to check the package integrity becomes negligible for bigger packages because other operations (i.e., signature generation, archive, compression and decompression) become the dominant factors. All in all, we anticipate that the sanitization time is mainly driven by 1) extracting files from a package and compressing them again into a package, 2) issuing digital signatures.

How much time does it take to sanitize a package?

To better estimate time which TSR requires to expose an update, we examine the time it takes to sanitize individual

Table 4. Spearman rank correlation coefficients ($\rho$) relating the package-specific properties and sanitization-specific operations. The corresponding $p$ values are indicated by regular font in grey fields ($p < 0.05$), bold font in grey fields ($p < 0.001$); fields with regular font indicate $p > 0.05$.

|                      | Number of Files | Package Size |
|----------------------|-----------------|--------------|
| archive, compress    | .46             | .61          |
| check integrity      | -.62            | -.93         |
| generate signatures  | .69             | .03          |
| modify scripts       | -.27            | -.33         |

Figure 8. Time required to sanitize a package, depending on the number of files and size. Color represents package size after decompression. Packages which size exceeds the EPC are marked as ▲. Boxplots indicate 5th, 25th, 50th, 75th, and 95th percentile.

What is the impact of sanitization on the repository size?

Repository size is the sum of all packages served by the repository. The higher the size, the more resources (i.e., disk space, bandwidth) are utilized. It not only increases the maintenance costs but also increases the latency because the OS requires more time to download packages.

Figure 9 shows that the package sizes increase when compared to the original package size and the number of files located inside the package. In particular, the sanitization process increases package size by 12%, 27%, and 76% in 50th, 75th, and 95th percentile, respectively. Packages with many small files suffer most from sanitization because the sizes of file signatures (each signature is 256 bytes) constitute a dominant part of the total package size. However, the total repository size increases only by 3.6%, from 3000 MB to 3110 MB.

Does the caching decreases the latency of package download?

TSR implements caching to decrease the latency of accessing sanitized packages; it stores on the disk the original version of the package (the one fetched from upstream and not yet sanitized) and the sanitized one. We run an experiment in which we measured how much time does TSR require to respond to a download request, assuming three scenarios: (i) only the original packages are cached, (Original), (ii) both original and sanitized packages are cached (Sanitized), and (iii) packages are not available in the cache (None).
In the first scenario, TSR downloads packages from an official Alpine mirror located on the same continent (an average network latency 26.4 ms). In the last two scenarios, TSR reads packages from the local disk. In each scenario, we requested TSR to return every package available in the upstream Alpine repository sequentially. We calculated the latency of downloading each package as a 20% trimmed average from five repeated downloads.

Figure 10 shows distributions of package download latencies for the scenarios mentioned above. Caching the sanitization results decreases the average download latency 129× when compared to the scenario where TSR runs without cache. We anticipate that the latency variation (0.37 ms) is mainly caused by accessing the cache (i.e., reading packages of different sizes) and verifying packages integrity after reading them from untrusted storage.

Similarly, caching the original packages decreases the average download latency 2.7× when compared to the scenario where TSR runs without cache. This is mostly the result of faster read of a package from the local disk than from a remote mirror accessed by the network.

What is the end-to-end latency of installing an update sanitized by TSR?

Installation of a software update takes a considerable amount of time because a package manager must download and verify the update, prepare the system for the new package version (check dependencies, lock installed packages database), unpack the new software package, launch installation scripts, copy files, set permissions, and finally clean the filesystem from no longer necessary files. In this experiment, we check the end-to-end latency of installing an update, which consists of sanitized packages or native Alpine packages. We measure the update installation latency for more than 5000 packages cached in a repository, i.e., TSR serves sanitized packages from the cache. Before launching the experiment for each single package, we install the package, and then we tamper with the OS configuration to pretend the installed package is outdated. We do it by modifying the package version number and its integrity hash stored in the file-based database used by the Alpine Linux to store information about installed packages. Before measuring the next package, we uninstall the previously measured package from the OS.

Figure 11 shows the experiment results in which we use two repositories, TSR and Alpine mirror, located in the same data center. We assume differences between network latency in both setups to be negligible. An average update installation latency is 141 ms and 110 ms for TSR and Alpine mirror, respectively. The higher latency observed when installing sanitized packages is caused by installing digital signatures in the filesystem.

6.2 SGX limitations

The current version of the SGX has a limited memory, up to 128 MB for SGXv1. Applications exceeding this amount...
cause SGX to swap the memory leading to performance degradation. Hence, we address the question of:

What is the performance overhead of running TSR inside an SGX enclave?

To answer this question, we observe that the package sanitization is the most memory consuming operation because TSR extracts and manipulates the package completely in the memory. For that reason, we executed TSR without SGX to measure the processing time of all available packages.

Figure 12 shows the comparison of packages sanitization times executed inside and outside an SGX enclave. We observe a minor overhead of executing inside SGX: 1.18× at 50th percentile, 1.12× at 75th percentile, and 1.16× at 95th percentile. However, at the top 5 percentiles that represent packages with sizes exceeding EPC, the SGX overhead increases to 1.96× because of EPC paging. The total sanitization time required to process all packages in the repository increases from 9.5 min to 13.6 min (1.43×) when running TSR inside an SGX enclave.

6.3 Tolerating compromised mirrors

What is the overhead of mitigating compromised mirrors?

In this experiment, we measured the latency in which TSR (running in Europe) returns the metadata index depending on the number of mirrors defined in the policy and their geographical locations. We were increasing the number of mirrors from one (default setting currently used by operating systems) to ten instances. We divided the experiment into four scenarios. In each scenario, TSR uses official Alpine mirrors located on different continents, i.e., Asia, Europe, North America, and their combination (All). In each scenario, we calculated a 10% trimmed latency average from 20 consecutive requests.

Figure 13 shows that the latency of downloading the metadata index depends on the number and location of mirrors. TSR returns the metadata index in less than 400 ms for up to five mirrors on the same continent. In the case of 10 mirrors, TSR returns the metadata index in less than 1.2 seconds.

We observed higher latency when using mirrors located on different continents, mainly due to higher network latency.

The last scenario (All) shows that the latencies measured when mirrors are evenly distributed across three continents are similar to the latencies measured when using mirrors located only in North America. It is a result of TSR implementation; TSR contacts the fastest \( f + 1 \) mirrors, and, in case they present different metadata index, it contacts additional mirrors until reaching the quorum \( f + 1 \) responses are the same). Therefore, mirrors in Europe and North America were preferred, and TSR latency depends on the slowest selected mirror.

It is the responsibility of the TSR clients to decide on the tradeoff between security and performance. The experiment shows that even when specifying nine mirrors distributed across different continents, TSR returns the metadata index in about 2.2 seconds.

7 Related work

Given the importance of software updates, a plethora of works has been proposed to ensure the security of software update systems [22, 48, 54, 73]. Typically, they aim to protect the updates using cryptographic signatures and transfer them to targets via secure connections. The critical aspect of these approaches is how to protect the signing keys because their leakage compromises the update process.

The Update Framework (TUF) [22] addresses the problem by assigning different roles for accessing specific signing keys, raising the bar for an adversary to get in possession of all keys. Unfortunately, TUF requires an online project registration; thus it cannot protect a community repository against several attacks, such as delivering arbitrarily modified packages. Diplomat [44] overcomes the shortcoming of TUF by dividing signing keys into offline and online keys. The online keys are used to provide fast package signing, a feature required in community repositories. Only online keys are leaked in the case of a repository compromise, which
is a manageable problem since they can be easily revoked and the repository with new online keys can be regenerated using well-protected offline keys. CHAINIAC [54] provides mechanisms to secure the entire software supply chain. Developers create Merkle trees defining software packages with their corresponding binaries. To approve the package release, they sign and submit the trees to co-signing witness servers, which verify the signatures from developers as well as the mapping between the sources and the binaries. This mechanism relies on the blockchain technology, which permits the maintenance of the history of the releases but it increases the system’s complexity. With a similar goal but reduced complexity, in-toto [65] offers a mechanism to ensure the integrity of the software supply chain cryptographically. It enables users with the integrity verification of the whole software supply chain. However, CHAINIAC, in-toto, and TUF do not consider the case that the target systems are under the protection of trusted computing mechanisms. Thus, they do not protect against integrity violations caused by software updates. Recently, KShot [73] introduced a secure kernel live patching mechanism to fix security vulnerabilities. KShot makes use of system management mode and SGX to perform the patching process without trusting the underlying OS securely. Similarly, TSR leverages SGX to protect the software update patching mechanism (sanitization), but TSR also ensures that software updates do not break the OS integrity. We selected Intel SGX to implement TSR since it has become available in clouds [27, 39], ported many of confidential cloud native applications including analytics systems [45, 46], key management system [29], and performance monitoring [42].

TSR follows the idea introduced by Berger et al. [10] to maintain custom mirror with modified packages containing digital signatures. Unlike the previous work, TSR removes the mirror owner from trusted computing base by protecting the signing keys using TEE. Also, TSR introduces the sanitization mechanism to enable the installation of packages containing installation scripts.

Several previous studies also considered various security aspects of the mirrors in software update systems [12, 14, 40]. Knockel et al. [40] indicated that man-in-the-middle attacks on third-party software are possible for open infrastructures. Fortunately, this can be handled by securing connections using modern TLS instead of outdated SSL technology. The Stork package manager [14] provided mechanisms to handle various attacks from malicious mirrors by dedicating the selective trust to users, i.e., users specify which packages they trust to install. Mercury [43] addresses the rollback attacks on software packages [8, 12] by maintaining a separated signed metadata file at the package manager. However, Mercury did not address the problem of the first update in which a package manager cannot ensure the metadata index freshness. TSR tackles this problem by relying on the repository metadata index obtained from the majority of mirrors under the assumption that most mirrors are trustworthy.

8 Conclusion

In this paper, we presented TSR, a trusted software repository, to support secure software updates for integrity-enforced operating systems relying on trusted computing. TSR is transparent to the existing implementations of package managers and software repositories. Importantly, it does not require changes to well-established distribution-specific procedures of creating software packages.

Our implementation supports 99.76% of the packages available in Linux Alpine main and community repositories. It can be hosted on-premises, e.g., in the cloud, while maintaining strong security properties by running inside a trusted execution environment (TEE), enabling clients to define custom security policies, and permitting a minority of software repository mirrors to exhibit Byzantine behavior.

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