Software Distribution Transparency and Auditability

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Abstract

A large user base relies on software updates provided through package managers. This provides a unique lever for improving the security of the software update process. We propose a transparency system for software updates and implement it for a widely deployed Linux package manager, namely APT. Our system is capable of detecting targeted backdoors without producing overhead for maintainers. In addition, in our system, the availability of source code is ensured, the binding between source and binary code is verified using reproducible builds, and the maintainer responsible for distributing a specific package can be identified. We describe a novel “hidden version” attack against current software transparency systems and propose as well as integrate a suitable defense. To address equivocation attacks by the transparency log server, we introduce tree root cross logging, where the log’s Merkle tree root is submitted into a separately operated log server. This significantly relaxes the inter-operator cooperation requirements compared to other systems. Our implementation is evaluated by replaying over 3000 updates of the Debian operating system over the course of two years, demonstrating its viability and identifying numerous irregularities.

1 Introduction

Software systems require regular updates. The protection of software distribution from manipulation is therefore an integral part of computer security [1, 3, 4, 5, 13, 17, 18, 28, 30]. The attractiveness of using software updates to distribute malware is evidenced by several recent attacks piggybacking on legitimate software to target large enterprises with backdoors [14, 16, 19].

Many systems rely on package-based software updaters to provide updates, such as installations of Linux distributions. These distributions offer a central and collectivized point of security updates. Many organizations, unable to provide their own security support for software, depend on the distributions for important updates. Due to their central position, distributions consequently provide an important lever for improving the security of software dissemination. This distribution process poses a number of challenges.

Package managers generally use cryptographic signatures to protect the distribution of software packages, if they provide any security at all [7]. Systems based on signatures are vulnerable to targeted backdoors, where an attacker is able to correctly sign a manipulated version of the code. The manipulated version is only offered selectively to the victim [13].

To prepare software for redistribution, modifications and additions are often required as integration glue. The attribution of these changes is important, because authorizing a software for distribution constitutes a statement of confidence into its benevolence.

Providing assurance of the mapping between source code and binary code is being addressed in the Reproducible Builds efforts [24]. Building on this property, a secure software distribution can assure that for any binary the corresponding source code is guaranteed to be available to assist audit and forensic activities.

In this paper, we develop and evaluate a system to address these challenges for package managers. We propose that the software package meta data and source code are submitted into an untrusted append-only Merkle tree log. The design of the log allows third parties to efficiently verify its honest operation. In detail, our contributions are:

- Protection against targeted backdoors, including a novel “hidden version” attack against existing software transparency systems (Section 4).

- Auditability, providing the inspectable source code corresponding to any installed binary and identifying the authorizing maintainer (Section 5).
We discuss Background in Section 2 and outline Related Work in Section 3.

2 Background

In order to effectively secure the distribution process of software it is necessary to understand how code is commonly redistributed. In this section we therefore describe the architecture of the APT package manager.

2.1 Software distribution models

For many software projects, a dissemination model along the following lines applies. Programmers, referred to as “upstream” in our context, provide their software for reuse. They upload the code to code hosting platforms, such as Github, or programming language specific package managers. From there, software is downloaded by distribution maintainers for packaging and integration. This dissemination model is shown in Figure 1. Steps marked with boxes regularly include transformations or modifications, such as packaging or adding meta data. The parts relevant to the distribution package manager are shown below the dashed line.

Linux distributions, as an outcome of non-commercial or commercial collaboration, have an important role in the distribution of software. The core task of a distribution is the integration work of making up to tens of thousands of individual software projects co-installable and standardizing interfaces for administration. After integrating a package, distributions regularly provide security support for it. Other tasks of the distribution include license vetting and quality assurance.

Distributions are therefore important parts of software dissemination. Viewing the process of software distribution as a series of transformations, we can observe that it would ideally be possible for the user to determine the provenance of each piece of code in reverse direction of the arrows in Figure 1. Each of the transformations should be inspectable, by offering a machine readable description allowing to reproduce the transformation.

2.2 Debian

Debian is one of the oldest Linux distributions, and constitutes the basis for many derivative distributions [11]. In the following, we provide a simplified overview on how packages are distributed with the APT package manager in Debian.

On a Debian machine, additional software can be installed by downloading and installing packages containing the libraries, executables and additional artifacts using the Advanced Package Tool (APT) package manager. These packages are created by the maintainers of the Debian distribution, who upload the signed packages to a central server, the archive. This server coordinates the building of binary packages for the supported CPU architectures. It serves the authoritative copy of the package archive to the repository mirrors.

To decide no acceptance of a submitted package, the archive verifies that its signature was created by an authorized uploader key. This list of keys has the role of an ACL, where some people may upload only specific packages, while others may be allowed to upload any package. There are other issues that may prevent acceptance of the package, for example the license under which the software is distributed. The package is then built for all supported architectures. Information about the build environment, captured in “buildinfo” files, is recorded by the build servers [6, 25]. If building is successful, the package may be included into the upcoming release.

The binary and source packages are included into a package index. These indices (“Packages” and “Sources”) cover all package contents by their cryptographic hash. They also contain meta data such as dependencies. All indices are covered, again by hash, by a release file which is signed. The release file is signed by the publishing archive, constituting the main security feature of plain APT. Indices, release file, and the packages themselves can now be released by the archive and distributed to the global mirror network, which acts as content distribution network. An APT client can retrieve a package from a repository mirror server and verify its authenticity by confirming its inclusion into the signed release file. A release file has a wall clock validity time
of two weeks.

3 Related work

We consider research on the security of package managers and on Merkle tree-based log systems.

Security of package managers. Cappos et al. analyze the security of popular package managers, among those APT. They define a threat model focused mainly on adversarial control of a package mirror. Expanding on this threat model, Samuel et al. consider compromise of signing keys in the design of The Update Framework (TUF), a secure application updater [30]. To guard against key compromise, TUF introduces a number of different roles in the update release process, each of which operates cryptographic signing keys.

The following three properties are protected by TUF. The content of updates is secured, meaning its integrity is preserved. Securing the availability of updates protects against freeze attacks, where an outdated version with known vulnerabilities is served in place of a security update. The goal of maintaining the correct combination of updates implies the security of meta data.

An attack is deemed successful under the TUF threat model in either of the following two cases. The client installs a different software than the most current version of the software to be updated. An attack is also successful, if the client does not install the most current version, but perhaps leaves an older version installed, without causing an alert.

Later works focus on role separation and adoption to domain specific threat models [17,18].

Formal analysis of transparency logs. Dowling et al. as well as Chase and Meiklejohn formally analyze transparency logs. The model of Chase and Meiklejohn, the transparency overlay, includes equivocation. They prove several cryptographic security properties for this transparency, which can be instantiated to represent Certificate Transparency as well as Bitcoin.

In a transparency overlay, the dynamic list commitment (DLC) is defined as a commitment to a list of elements that can represent exactly one list e.g., a Merkle tree root. The list of elements can only be updated by appending elements, producing a new commitment for the new list. The commitments allows to efficiently prove that the list has been operated append-only, and that an element is part of the list. Notable properties include the security of cryptographic evidence. For any kind of violation, there exists evidence provably identifying the culpable party. This evidence is infeasible to fabricate.

The overlay extends an abstract system with the roles of log, auditor, and monitor. The log stores the events produced by the system, its DLC can be instantiated with a Merkle tree. The auditor verifies consistency and inclusion of events without having to store the entire list maintained by the log. The monitor retrieves elements from the log, verifies log consistency, and analyses the new events in order to flag any entries that are considered problematic. By exchanging observed commitments, the auditor and monitor can detect equivocation by the log.

Securing package updates with co-signing. Nikitin et al. develop CHAINIAC, a system for software update transparency [28]. Software developers create a Merkle tree over a software package and the corresponding binaries. This tree is then signed by the developer, constituting release approval. The signed trees are submitted to co-signing witness servers.

The witnesses require a threshold of valid developer signatures to accept a package for release. Additionally, the mapping between source and binary is verified by some of the witnesses. If these two checks succeed, the release is accepted and collectively signed by the witnesses.

The system allows to rotate developer keys and witness keys, while the root of trust is an offline key. It also functions as a timestamping service, allowing for verification of update timeliness.

Additionally to individual packages, releases of multiple packages are also supported. These “snapshots” are created by aggregating individual package skipchains. Over the most recent versions of these, a Merkle tree can be constructed and signed by the witnesses.

Transparency systems. Certificate transparency (CT) uses Merkle tree logs to provide a public view on all certificates used in HTTPS [20,21,22,23,27]. Site operators can observe certificates issued for their domains and detect misissuances. CT is widely deployed and its use continues to expand. Basin et al. develop ARPKI, an alternative public key infrastructure for server certificates [5]. Domain owners choose two certification authorities and an integrity log server. The system assumes that a number of public integrity log servers exist. These are used to provide a globally consistent view on all the certificates in existence. Fahl et al. suggest a transparency model for Android applications, providing “Application Transparency” [13]. In order to secure application updates, the hashes of these are submitted into a transparency log system. Melara et al. apply Merkle tree-based auditing to secure mobile messaging in the Continuous identity and key management system (CONIKS) [26]. The central premise of the approach is that users are changing their keys frequently, and this process must provide a smooth and secure user experience. Keys are bound to identities by submitting them into the audit log, which also serves as a public key directory.
4 Design

We propose to extend the signature based APT by a transparency system, adding on top of the existing security mechanisms. This system is modeled after the transparency overlay, where a log server maintains a Merkle tree over a list of submitted items. The honest operation of the log is verified by auditors and monitors. In our case, the auditor is integrated into the APT client and the monitor is a new standalone component.

4.1 Threat model

Additionally to existing Debian mechanisms, we introduce a log server that maintains a Merkle tree as part of a transparency overlay. The system consists of the following components. Individual maintainers upload signed source packages to the archive. The archive compiles and distributes binary packages, submitting releases into the log.

Compromise of components and collusion of participants must not result in a violation of the following security goals remaining undetected. A goal of our system is to make it infeasible for the attacker to deliver targeted backdoors. For every binary, the system can produce the corresponding source code and the authorizing maintainer. Defined irregularities, such as a failure to correctly increment version numbers, also can be detected by the system.

4.2 Release log

The APT release file identifies, by cryptographic hash, the packages, sources, and meta data which includes dependencies. This release file, meta data, and source packages are submitted to a log server operating an append-only Merkle tree, as shown in Figure 2. The log adds a new leaf for each file.

We assume maintainers may only upload signed source packages to the archive, not binary packages. The archive submits source packages to one or more log servers. We further assume that the buildinfo files capturing the build environment are signed and are made public, e.g. by them being covered by the release file, together with other meta data.

In order to make the maintainers uploading a package accountable, a source package containing all maintainer keys is created and submitted into the archive. This constitutes the declaration by the archive, that these keys were authorized to upload for this release. The key ring is required to be append-only, where keys are marked with an expiry date instead of being removed. This allows verification of source packages submitted long ago, using the keys valid at the respective point in time.

At release time, meta data and release file are submitted into the log as well. The log server produces a commitment for each submission, which constitutes its promise to include the submitted item into a future version of the tree. The log only accepts authenticated submissions from the archive. The commitment includes a timestamp, hash of the release file, log identifier and the log’s signature over these. The archive should then verify that the log has produced a signed tree root that resolves the commitment. To complete the release, the archive publishes the commitments together with the updates. Clients can then proceed with the verification of the release file.

The log regularly produces signed Merkle tree roots after receiving a valid inclusion request. The signed tree root produced by the log includes the Merkle tree hash, tree size, timestamp, log identifier, and the log’s signature.

On the client side, the release file will be retrieved as usual. Given the release file and inclusion commitment, the client can verify by hashing that the commitment belongs to this release file and also verify the signature. The client can now query the log, demanding a current tree root and an inclusion proof for this release file. Per standard Merkle tree proofs [8, 10, 20], the inclusion proof consists of a list of hashes to recompute the received root hash. For the received tree root, a consistency proof is demanded to a previous known tree root. The consistency proof is again a list of hashes. For the two given tree roots, it shows that the log only added items between them. Clients store the signed tree root for the largest tree they have seen, to be used in any later consistency proofs.

Set aside split view attacks, which will be discussed later, clients verifying the log inclusion of the release file will detect targeted modifications of the release.

The procedures described do not add any tasks for an ordinary user of APT, or for a maintainer. One further consideration is the availability of the log. To improve log availability, elements can be submitted into multiple logs. Clients would then contact all of these to validate a release, and require a quorum.
4.3 Removal of elements

Source packages sometimes must be removed from the archive. The reason is usually that the distribution license for a particular file in the package is not acceptable under the project’s guidelines. The offending packages are then removed from the archive, and a new version of the package is prepared, fixing the issues.

Since the log must be append-only, and also provide the source code for all packages, this legal requirement cannot be fulfilled directly. In order to perform the removal, a removal notice is submitted to the log. It consists of a statement signed by the archive, specifying which source package was removed, the time and reason of removal. It will be returned in response to requests for the original source.

4.4 Hidden versions

The hidden version attack attempts to hide a targeted backdoor by following correct signing and log submission procedures. It may require collusion by the archive and an authorized maintainer. The attacker prepares targeted malicious update to a package, say version v1.2.1, and a clean update v1.3.0. The archive presents the malicious package only to the victim when it wishes to update. The clean version v1.3.0 will be presented to everybody immediately afterwards.

A non-targeted user is unlikely to ever observe the backdoored version, thereby drawing a minimal amount of attention to it. The attack however leaves an audit trail in the log, so the update itself can be detected by auditing.

A package maintainer monitoring uploads for their packages using the log would notice an additional version being published. A malicious package maintainer would however not alert the public when this happens. This could be construed as a targeted backdoor in violation of the stated security goals.

To mitigate this problem a minimum time between package updates can be introduced. This can be achieved by a fixing the issuance of release files and their log submission to a static frequency, or by alerting on quick subsequent updates to one package.

In the hidden version attack, the attacker increases a version number in order to get the victim to update a package. The victim will install this backdoored update. The monitor detects the hidden version attack due to the irregular release file publication. There are now two cases to be considered. The backdoor may be in the binary package, or it may be in the source package.

The first case will be detected by monitors verifying the reproducible builds property. A monitor can rebuild all changed source packages on every update and check if the resulting binary matches. If not, the blame falls clearly on the archive, because the source does not correspond to the binary, which can be demonstrated by exploiting reproducible builds.

The second case requires investigation of the packages modified by the update. The source code modifications can be investigated for the changed packages, because all source code is logged. The fact that source code can be analyzed, and no analysis on binaries is required, makes the investigation of the hidden version alert simpler. The blame for this case falls on the maintainer, who can be identified by their signature on the source package. If the upload was signed by a key not in the allowed set, the blame falls on the archive for failing to authorize correctly.

If the package version numbers in the meta data are inconsistent, this constitutes a misbehavior by the submitting archive. It can easily be detected by a monitor. Using the release file the monitor can also easily ensure, by demanding inclusion proofs, that all required files have been logged.

5 Log validation

Monitors are a required component to ensure the log operates correctly as well as a building block against equivocation. Monitors communicate with the log, verifying consistency. In case of misbehavior, a monitor would raise an alert and provide the cryptographic proof that comes with it. Many monitors can observe one log.

Monitors retrieve all additions into the log, allowing them to execute custom investigation functions on the logged items. The consistency of the log is always checked before the items are processed for flagging. Each monitor can have different investigation rules, or none at all, in which case it only monitors the append-only operation of the log.

5.1 Log monitoring functions

The primary function of a monitor is to ensure the log operates correctly as well as a building block against equivocation. Monitors communicate with the log, verifying consistency. In case of misbehavior, a monitor would raise an alert and provide the cryptographic proof that comes with it. Many monitors can observe one log.

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5.1 Log monitoring functions

The primary function of a monitor is to ensure the log server maintains its list of items by only appending items. The monitor initializes by retrieving all items from the log server, as well as the signed tree root. The monitor verifies the correctness of the tree root by recomputing the hash tree and verifying the signature.

It will now continuously poll the log server if a new tree root is available. Should a new tree root be published, the monitor retrieves the tree root and all items that were added since the previous tree root the monitor had observed. The monitor can now recompute the new hash tree in order to verify the tree root signed by the log.

In this approach, the monitor stores all the items in the list maintained by the log. It will also observe any new
items. It is therefore possible for the log to investigate all items and raise alerts based on the findings.

5.2 Monitor examination of events

Additionally to their fundamental task in keeping the log honest, the monitors can fulfill additional roles by investigating the items kept in the log. In the following, several such functions are described.

For each of these, we will assume that the monitor continuously updates its view of the log by retrieving any new items the log has added. Before calling the investigating functions, the list of new items is filtered. In general, we are only interested in release files. The signature on the release file is verified. The functions are then called for each of the items remaining after filtering and verification. We will also assume that the investigating functions have access to the log content. They need to be able to determine if an element is part of the log, identify the preceding release file and parse it.

5.2.1 Release file consistency

A basic check that requires a monitor is to verify the consistency of the release file. This check ensures that the archive submitted a consistent meta data state into the log.

Completeness(releaseFile):

1. if not verifySignature(releaseFile):
   2. alert releaseFile
   // indices (Packages, Sources) logged
3. for indexFile in releaseFile:
   4. if not isInLog(indexFile):
      5. alert indexFile
      // source packages logged
6. for sourcesFile in releaseFile.sourcesFiles:
   7. for sourcePkg in sourcesFile:
      8. if not isInLog(sourcePkg):
         9. alert sourcePkg
10. return

Algorithm 1: Verify elements covered by a release file are logged.

The first process is Algorithm 1. The following verifications are executed for each new release file added to the log. For each Sources and Packages file, their presence in the log, with matching hash, must be ensured. For every Sources file, all listed source packages must be in the log with a matching hash.

Each binary package, as enforced by Algorithm 2, must come with a corresponding source package. This is necessary in itself and also for later checks such as reproducibility.

We enforce version bumps for modified packages by comparing the meta data fields of all source and binary packages. The meta data contains in particular the hash, version number, and dependencies. If this is not enforced, a client might see and install a new package with different meta data than others.

For this purpose, the monitor maintains several data items associated with the package name. Out of the Packages and Sources files, the package versions and meta data block are extracted. The meta data contains in particular the package hash and its dependencies.

For the given package names, the entire entry with meta data and hash of the package is compared for equality to the stored one. In case of changes, the local package entry is updated and the configured notification actions

SourceAvailable(releaseFile):

1. sourcesFiles ← releaseFile.sourcesFiles
2. for packagesFile in releaseFile.packagesFiles:
   3. for package in PackagesFile:
      // no source available
      4. if not sourcePresent(package, sourcesFiles):
         5. alert package, sourcesFiles
3. return

Algorithm 2: Verify that all sources are available.

VersionConsistency(releaseFile):

1. sourcesFiles ← releaseFile.sourcesFiles
2. for packagesFile in releaseFile.packagesFiles:
   3. for package in PackagesFile:
      // compare with previous release file
      4. if not metaChanged(package):
         continue
      5. if not versionIncremented(package):
         alert package
      6. source ← getSource(package, sourcesFiles)
      7. if not metaChanged(source) and
      8. not buildinfoChanged(package):
         alert package, source
      9. for sourcesFile in sourcesFiles:
         10. for source in sourcesFile:
            11. if not metaChanged(source):
               continue
            12. if not versionIncremented(source):
               alert source
13. return

Algorithm 3: Verify version consistency of the release file.
taken. If a change in meta data is detected in Algorithm\[3\] the version number must be incremented as well.

Monitors may provide analysis functions additional to those discussed so far. In such a case, the monitor should meet the checks of Algorithms\[1\][2] and\[3\] These ensure that the meta data covered and provided by the release file is in a sane state and fit for further analysis.

5.2.2 Frequency

Another monitor function is to observe the frequency in which release files are produced and made available. The monitor needs to closely follow the log and know the expected release schedules. The monitor will produce an alert when an irregular release interval occurs.

This mechanism enables investigators to focus attention on possible misbehavior. There should also be an alert, if the archive stops publishing releases unexpectedly. This process is asynchronous and runs continuously.

If an alert occurs, the monitor also has the necessary tools to help investigation. As it has all source packages available, it can produce the difference in source code compared to the last release. The signatures on the source packages identify the maintainers involved. If the signature was produced by a valid key, the maintainer is responsible for any issues the source code exhibits. In case the signature is invalid, the archive has allowed violation of the submission access control.

5.2.3 Package maintainers

To verify the adherence of the archive to the package upload ACL, all source packages that were changed in a release file are investigated. A package is also investigated if its meta data or buildinfo files changed.

For the updated packages, if any of the signatures cannot be verified as having been created by a valid maintainer key, an alarm is raised. Not all uploaders may update every package. In the policy map of signing keys acceptable for each package, keys of full members are added to every package, other uploader keys are added to their respective packages.

Additionally to this generic check, individual maintainers of packages might want to see which of their packages were updated, and by whom. After submission, maintainers keep track if their package was published. They should also observe if a new upload signing key is published under their name. The maintainers of the upload ACL should also keep track of the keys published by the archive.

5.2.4 Reproducible builds

For every package that changes, a monitor can verify the reproducible build property. This check is important to make sure that the archive publishes the software intended by the maintainer, shown in Algorithm\[4\] If the relationship between source and binary is not verified, the archive could build backdoors into binaries, where the backdoors are not reflected in the source code.

Reproducible(releaseFile):
1 for package in releaseFile.allpackages:
2 if metaChanged(package):
3 // rebuild for all architectures and compare
4 correct ← isRepro(package, releaseFile)
5 if not correct:
6 alert package

Algorithm 4: Verify transformation from source to binary.

Given a new release file, the monitor would determine all modified source packages by comparing the new Sources file to the previous one. All changed packages are now rebuilt. The hashes of the binary packages must match the hashes provided in the Packages files. If any mismatches occur, an alarm is raised. The blame falls on the archive, which has published a non-reproducible package, possibly including a backdoor.

6 Equivocation

The most significant attack by the log or with the collusion of the log is equivocation. In a split-view or equivocation attack, a malicious log presents different versions of the Merkle tree to the victim and to everybody else. Each tree version is kept consistent in itself. The tree presented to the victim will include a leaf that is malicious in some way, such as an update with a backdoor. It might also omit a leaf in order to hide an update. This is a powerful attack within the threat model that violates the security goals and must therefore be defended. A defense against this attack requires the client to learn if they are served from the same tree as the others.

In some log systems equivocation is addressed with gossiping, or with monitors and auditors\[8\][9][10][29]. The auditor, as a functionality embedded with the client, exchanges tree roots with the monitor. They request consistency proofs between their own observed tree root and the tree root of the other party. Both are then able to notice if the log presents a different view to the other party, detecting equivocation. Because the tree roots are signed, the log can be attributed as the malicious party.
To some extent, we envision that monitors are run much like package mirrors are today. Some organizations may donate their resources for the public good, others may opt to just improve their own operations. To provide clients with a monitor after a new installation, a list of trustworthy monitors would need to exist. For the distribution to be confident in their reliability, it ultimately would need to run them. This runs contrary to the monitor’s task of holding the distribution accountable. It begs the question how a meaningful trust boundary can be drawn through the distribution infrastructure. We conclude that auditor-monitor communication is not sufficient to address equivocation in our case.

Log operations can be done on multiple logs e.g., by submitting everything into two logs. While this does help with equivocation in principle, the logs are in our scenario operated by the same group. It is therefore prudent to assume that if one of these is compromised, the second one would also be.

This approach can be used for redundancy, where a quorum of logs are queried and must provide the expected answer. If one log fails or must be taken offline after misbehaving, the clients could still be satisfied with responses of the other logs.

6.1 Design for tree root cross logging

There is limited advantage to using multiple logs by the same operator. Defenses against equivocation are closely related to operator diversity. To extend the pool of eligible secondary log operators, interoperation between logs of different organizations or even domains is required. To make this interoperation realistic, the interface should be small and simple, which we will strive for in the following.

One approach for detecting equivocation is logging of tree roots between cooperating logs. This approach requires multiple log servers. We now assume different logs exist, run by different operators. These could be other Linux distributions, or possibly a Certificate Transparency log made compatible.

Consider one log accepting new list items, for now dubbed the committing log. This log regularly creates a new signed tree root on inclusion of list items. This log will now submit this tree root, when it is created in response to a new release file, into another log, the witnessing log. Additionally to performing its native tasks, the witnessing log accepts the submitted tree root as a new list element and includes it into its Merkle tree. The inclusion commitment retained from the witnessing log, as well as the submitted tree root, will be provided to the archive by the committing log.

This relationship is shown in Figure 3. The upper row shows one log of list size three adding a fourth element.

The lower row shows a different log. The log with three elements in situation 1a adds an element in step 1b, resulting in a new tree root. It then submits this tree root in step 2 as element for log inclusion to the lower log. The lower log accepts this new element into its list. By publishing the tree root into the witnessing log, the primary log publicly commits to a history of its tree. This commitment can be used to detect equivocation through monitoring of the witnessing log.

When the client now verifies a log entry with the committing log, it also has to verify that a tree root covering this entry was submitted into the witnessing log. Additionally, the client verifies the append-only property of the witnessing log.

The witnessing log introduces additional monitoring requirements. Next to the usual monitoring of the append-only operation, we need to check that no equivocating tree roots are included. To this end, a monitor follows all new log entries of the witnessing log that are tree roots of the committing log. The monitor verifies that they are all valid extensions of the committing log’s tree history.

By using tree roots as a generic interoperability layer between logs, cooperation between different operators and domains is enabled. Each log only needs to add one new leaf type in order to participate. This is easier to achieve than, for example, making a CT log compliant with all the requirements for software transparency logging.

6.2 Auditor

To contribute to the security provided by root cross logging, an auditor component needs to contact the second log. The auditor verifies that its own view on the log is committed to the witnessing log. It validates the correct operation of this second log with the established proof mechanisms.

The committing log, denoted as log A here, has submitted a tree root into the witnessing log, log B. The auditor is now assumed to be provisioned by the archive with this tree root and the corresponding inclusion promise
from log B. An element, in our case the release file, is verified by requesting an inclusion proof for it from log A. The inclusion proof is requested specifically for the tree size of the root given by the archive, ensuring that it actually covers this element. The auditor then requests a consistency proof from that tree root to a previous known tree root. After verifying the two proofs, we have now established that log A has submitted a tree root into log B and that this tree root is consistent with the auditor’s view on the tree.

We proceed to verify inclusion into the witnessing log. Using the knowledge of the committed tree root and the inclusion promise by the witnessing log, we can request an inclusion proof from the witnessing log. For the tree root returned with that inclusion proof and a previous known tree root, we request a consistency proof from the witnessing log.

The auditor has now established that log A has presented the same log view to the auditor and to log B. Crucially, the auditor can not be certain that its view is the only one that log A has committed into log B. To ensure that, every element in log B must be inspected. This task naturally falls to a monitor, which is discussed next.

6.3 Monitor

The task of the monitor in cross logging is to make sure that one log only commits to one view. This requires the monitor to keep track of both the committing and the witnessing log. It monitors the committing log, log A. For simplicity, we assume that the monitoring process consists of downloading and storing all new log elements, and verifying signed tree roots. The knowledge of log A fixes the monitor’s view on the log and enables it to generate tree roots for all tree sizes. This is the usual procedure for monitoring.

Extending this, the monitor will also monitor the witnessing log B. In the following, all list elements of log B are investigated. We are interested in all elements that are tree roots of log A, so we filter for these.

For each of these elements, first the signature is verified. In a second step, the Merkle tree root in this element is recomputed using the knowledge of the elements of log A. The computed tree root is compared to the element in log B. If these checks succeed, the element corresponds to the view on log A that the monitor has.

If the verification procedure succeeds for all elements that are signed tree roots of log A, then the monitor has established that log A has only ever committed one view to its witness log B. Should a tree root not correspond to the known list of elements of log A, equivocation has been detected.

If log B is dishonest, it cannot frame log A, because tree roots are signed. Log B also cannot omit elements. Log A has obtained inclusion promises from log B, enabling it to demonstrate that a given tree root was submitted into log B. If both logs collude in equivocation, no security can be achieved in this system.

6.4 Security

The approach presented in this paper protects the clients directly that additionally check the witnessing log, if the logs do not collude. If the committing and witnessing logs do not collude, the committing log will be unable to observe that the client verifies its honesty by querying the witnessing log. It is therefore unable to distinguish between clients that do this additional check and those that do not. This results in herd immunity for clients that do not check the witnessing log, provided that a proportion of clients actually does this check. In any case, it is necessary that some of the clients of the committing log verify the witnessing log.

The more logs participate by including the tree roots of the other logs, the harder attacks become. One honest log is enough to detect equivocation. For package authentication, each distribution could run one or two logs, all of which cooperate by tree root logging. To mitigate the risk of collusion, multiple logs run by different operators are required.

7 Evaluation

In the following, we will informally analyze the security properties of the main design. We further implement the system and feed it two years worth of distribution updates, noting performance characteristics and detected irregularities.

7.1 Software transparency as a secure pledged transparency overlay

We claim that our log design described previously implements a secure transparency overlay as proposed and proven by Chase and Meiklejohn [8]. This constitutes our primary security argument, extended in separate arguments by monitoring functions and protection against equivocation.

In the following we show how a secure overlay is instantiated from the proposed software transparency mechanism. In the parlance of the secure overlay, the log, monitor, and auditor are part of the “overlay”. The “system” is an existing infrastructure to be secured with the transparency overlay. In our case, the system is the software distribution via the archive and the APT client.

**Theorem 1.** _Software transparency is a secure pledged transparency overlay._
Proof. We use the method of Chase and Meiklejohn to instantiate the secure pledged transparency overlay. Two parts need to be demonstrated. First, the function creating the system events (GenEventSet) needs to be instantiated. Second, we need to define for all transparency overlay protocols which parts of the software transparency system interact with them, namely for the Log and CheckEntry protocols. The Log protocol defines submission of events into the log. In the CheckEntry protocol, the system interacts with the auditor component of the transparency overlay. The auditor in turn verifies log inclusion and log consistency, given an event and a corresponding inclusion promise of the log.

GenEventSet. Elements are solely generated by the archive. They can be source package files, meta data files, and signed release files.

Log protocol. In the Log protocol, elements are submitted to the log. The archive is the sole originator of events and submits these to the log.

CheckEntry protocol. We designate this part of the system to be the APT client, making the auditor effectively part of the APT client.

We note that a release is now produced jointly by the archive and the log, not just the archive anymore. The client is now able to verify the transparency property on release files.

The functions of the log, the auditor and monitor are implemented as prescribed by the overlay. We conclude that the proposed software transparency mechanism constitutes a secure transparency overlay. This allows the system to build on proven security properties.

Detection of targeted backdoors. Using the secure overlay, we will demonstrate that our system detects targeted backdoors, achieved by tailored monitor services. Assume a malicious or compromised maintainer inserts a backdoor into a source package. In order to be accepted into the archive, it must be signed by their key. Should the archive not enforce this, a monitor verifying maintainer signatures would notice and alert. It can therefore be attributed to the maintainer and the source code is present for analysis. A maintainer cannot upload binary packages without help by the archive, because we assume only source uploads are allowed.

If the archive modifies a source package, this package lacks a valid maintainer signature. This is detected by a monitor validating the maintainer signatures and upload policy. If the archive modifies a binary package without modifying the corresponding source, this is detected by a monitor verifying the reproducible builds property. Modifications by the log are discovered, because the release file signed by the archive covers all other files.

7.2 Performance

Our system uses the Trillian generic Merkle tree implementation [15] which is also employed in some CT logs. We implement our log functionality using this hash tree. The log offers an HTTPS interface for JSON objects for element submission and the auditor and monitor functionality. The log is instantiated with the SHA256 hash function and the ECDSA-P256 signature scheme.

Starting at the inception of the Debian “stretch” release, we replay two years of Debian updates. The historic updates are retrieved from the snapshot.debian.org service before the experiment. This results in 3010 release files, starting on 2015-04-25 and ending on 2017-06-17. The “stretch” release is, at that point in time, a rolling release. As such it experiences much more updates than a final release that only gets updates for security support.

In our measurement setup, the log resides on a different machine than the submission component, auditor, and monitor. The network communication with the log consists of HTTPS requests. For each of the release files, we first submit the release meta data and source packages into the log and then run the auditor afterwards. Given the inclusion promise for the release file, the auditor validates the log operation. It retrieves an inclusion and a consistency proof with GET requests from the log and verifies these. After all releases are logged and validated, the monitor fetches the log elements using GET requests and executes its verification functions.

We observe that the duration of the log submissions is dominated, by several orders of magnitude, the transfer duration incurred by submitting source packages. As the auditor runs on every client, its performance is most critical. In terms of computation, only some signature verifications and hash computations are added. Next, we measure the network layer PDU traffic between auditor and log, using the Linux net_c1s cgroups and netfilter. The data in Figure 4 shows the traffic caused by inclusion proofs and consistency proofs during auditor operation. The request for the inclusion proof requires sending 1.3 kB and receiving 2.9 kB on average. The consistency proof is requested for the tree size of the previous release file. The consistency proof requires receiv-
We conclude that the performance of all measured functions is sufficient for actual use. Even smaller projects should be capable of running a log server logging source packages.

7.3 Detected irregularities

The task of the monitor is to flag suspicious elements in the log and raise alerts. We now discuss anomalies discovered by our monitor functions when applied to the historic data.

As shown in Figure 7 there are continuously several hundred binary packages for which there is no corresponding source package in the release. Note that this function counts packages multiple times when the source is not identified for multiple architectures. Starting March 2017, there is a large number of sources missing, indicating an error which was fixed in May 2017.

Comparison of version numbers was implemented using the Python `apt_pkg` library, which implements the non-trivial versioning rules used in APT. For the comparison of package meta data to detect if a package was changed we filter non-critical fields such as tags. Note that the meta data includes a hash over the package contents. Whenever the meta data changes, we expect a version increase. All CPU architectures in the release are counted. We show a many version increments are missing in a release in Figure 8. There are 1717 releases without unexpected events. Some releases have a few inconsistencies in version increments, and a number of releases have thousands. The results for source and binary packages look similar in the plot, but differ slightly. There are a substantial number of changes in the package meta data without version increment, suggesting that meta data changes are regularly done without incrementing the version.

One source package that existed in the release meta data was missing in all releases, because it had been removed administratively from the snapshot.debian.org service. There were no files where the hash was indicated incorrectly by the meta data.

We discovered a considerable amount of anomalies in two years worth of updates. Our system would have discovered them automatically shortly after their release and raised an alarm. The result suggests that the release process must become more stringent in order to allow such
irregularities to be the cause of security alerts.

8 Comparison to related work

CHAINIAC [28] is a software update transparency system. Clients can verify they were presented with a recent software version using timestamping by the witnesses. The witnesses also serve the function of assuring global consistency by providing a collective signature. The release history is fixed as immutable by inclusion of historic hashes. In our proposed architecture, timeliness is assured by a wall clock validity period embedded in the release file. Global consistency and immutability is provided by submitting releases to the log server. The correct operation of the log is ensured by auditors and monitors.

The build verifiers in CHAINIAC can be compared to monitors running our reproducible builds verification algorithm. In contrast to the build verifier, the monitor operates asynchronously. This means that the build verifier will detect and effectively stop distribution of a non-reproducible package. It also results in the system having to wait for enough build verifiers to complete the build process for all supported instruction set architectures. The monitor does not delay an update because a package builds slowly, leading to a faster release compared to CHAINIAC.

In CHAINIAC, all code submissions must be confirmed by other developers through cryptographic signatures. The proposed architecture does not include a code review functionality, but rather supposes a mapping of expected developers to projects, verified by monitors. In particular, the maintainers of the distribution’s upload policy have an incentive to monitor this activity and alert the wider project in case of irregularities.

The collective authority consisting of independently operated witnesses provides collective signatures, where some of the witnesses may be compromised. The proposed architecture, on the other hand, relies on a single log or quorum of logs. This is justified by two reasons. First, the logs require substantial disk space to store all versions of all source packages ever submitted. A log therefore need not only resources to operate the tree, but also secondary storage, over time in the order of terabytes, which the generic witness servers might be unwilling to provide. Second, it is unclear who would operate the independent witness servers for Linux distributions. To achieve protection against equivocation, we advocate for the simple interface provided by tree root cross logging between different logs.

The CHAINIAC model does provide accountability, but does not offer the same forensic assurances. In our proposed architecture, investigators are guaranteed an audit trail of who made changes and the changes in source form. This guarantee is provided by the log, the operations of which are verified by monitors.

In conclusion, our proposed system follows an “untrusted but trustworthy” model, doing validity checks only after a release. This allows the system to reflect operational reality by exploiting the incentives of different roles in the project. Protection against equivocation is achieved by allowing independent organizations to interoperate easily to their mutual benefit.

Parts of the system were proposed previously by the authors [2]. In comparison, it is now extended with auditability, protection against equivocation, and evaluated on actual distribution updates.

9 Conclusion

We propose a software transparency system for the popular Linux package manager APT. The system detects targeted backdoors and offers several forensic guarantees, such as the availability of auditable source code for every installed binary.

To detect equivocation in log systems, we propose tree root cross logging. This allows logs of different operators and types to interoperate, requiring only a small interface.

An evaluation of the system on two years worth of actual distribution updates identifies numerous anomalies, for instance missing source code. Our system would have identified and allowed fixing these issues.

By tracking code and maintainer attribution, software transparency can offer a building block for future systems to securely track the provenance of code through various redistribution steps.

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