Balloon: A Forward-Secure Append-Only Persistent Authenticated Data Structure

Tobias Pulls[1] and Roel Peeters[2]

[1] Karlstad University, Dept. of Mathematics and Computer Science, Sweden
tobias.pulls@kau.se,
[2] KU Leuven, ESAT/COSIC & iMinds, Belgium
roel.peeters@esat.kuleuven.be

Abstract. We present Balloon, a forward-secure append-only persistent authenticated data structure. Balloon is designed for an initially trusted author that generates events to be stored in a data structure (the Balloon) kept by an untrusted server, and clients that query this server for events intended for them based on keys and snapshots. The data structure is persistent such that clients can query keys for the current or past versions of the data structure based upon snapshots, which are generated by the author as new events are inserted. The data structure is authenticated in the sense that the server can prove all operations with respect to snapshots created by the author. No event inserted into the data structure prior to the compromise of the author can be modified or deleted without detection due to Balloon being publicly verifiable. Balloon supports efficient (non-)membership proofs and verifiable inserts by the author, enabling the author to verify the correctness of inserts without having to store a copy of the Balloon. We formally define and prove that Balloon is a secure authenticated data structure.

1 Introduction

This paper is motivated by the lack of an appropriate data structure that would enable to relax the trust assumptions needed for privacy-preserving transparency logging. In the setting of transparency logging, an *author* logs messages intended for *clients* through a *server*: the author sends messages to the server, and clients poll the server for messages intended for it. Previous work [19] assumes a *forward security* model: *both* the author and the server are assumed to be initially trusted and may be compromised at some point in time. Any messages logged *before* this compromise remain secure and private. One can reduce the trust assumptions at the server by introducing a secure hardware extension at the server as in [23].

This paper proposes a novel *append-only authenticated data structure* that allows the server to be untrusted without the need for trusted hardware. Our data structure, which is called Balloon, allows for efficient proofs of both membership and non-membership. As such, the server is forced to provide a verifiable reply to all queries. Balloon also provides efficient (non-)membership proofs for past versions of the data structure (making it *persistent*), which is a key property for providing proofs of time, when only some versions of the Balloon have

been time-stamped. Since Balloon is append-only, we can greatly improve the efficiency in comparison with other authenticated data structures, such as persistent authenticated dictionaries [1].

As already discussed, Balloon is a key building block for privacy-preserving transparency logging to make data processing by service providers transparent to data subjects whose personal data are being processed. Balloon can also be used as part of a secure logging system, similar to the history tree system by Crosby and Wallach [5]. Another closely related application is as an extension to Certificate Transparency (CT) [11], where Balloon can be used to provide efficient non-membership proofs, which are highly relevant in relation to certificate revocation for CT [10,11,17].

We take a similar approach as Papamanthou *et al.* [18] for formally defining and proving the security of Balloon. We view Balloon in the model of *authenticated data structures* (ADS), using the *three-party* setting [22]. The three party setting for ADS consists of the *source* (corresponding to our author), one or more *servers*, and one or more *clients*. The source is a trusted party that authors a data structure (the Balloon) that is copied to the untrusted servers together with some additional data that authenticates the data structure. The servers answer queries made by clients. The goal for an ADS is for clients to be able to verify the correctness of the queries based only on public information. The public information takes the form of a verification key, for verifying signatures made by the source, and some *digest* produced by the source to authenticate the data structure. The source can update the ADS, in the process producing new digests. In our case, we refer to the digests as *snapshots*. The query we want to enable clients to verify is a *membership query*, that proves *membership* or *non-membership* of an event with a provided key for a provided snapshot.

After we show that Balloon is a secure ADS in the three party setting, we extend Balloon to enable the author to discard the data structure and still perform verifiable inserts of new events to update the Balloon. Finally, we describe how *monitors* and a *gossiping mechanism* would prevent the an author from undetectably modifying or deleting events once inserted into the Balloon, which lays the foundation for the forward-secure author setting.

We make the following contributions:

- A novel append-only authenticated data structure called Balloon that allows for both efficient membership and non-membership proofs, also for past versions of the Balloon, while keeping the storage and memory requirements minimal (Section 3).
- We formally prove that Balloon is a secure authenticated data structure (Section 4) according to the definition by Papamanthou *et al.* [18].
- Efficient verifiable inserts into our append-only authenticated data structure that enable the author to ensure consistency of the data structure without storing a copy of the entire (authenticated) data structure (Section 5).
- We define publicly verifiable consistency for an ADS scheme and show how it enables a forward-secure source (Section 6). Verifiable inserts can also have applications for monitors in, e.g., [3,9,10,11,20,25].

– In Section 7, we show that Balloon is applicable in practice, providing performance results for a proof-of-concept implementation.

The rest of the paper is structured as follows. Section 2 introduces the background of our idea. Section 8 presents related work and compares Balloon to prior work. Section 9 concludes the paper. Of independent interest, Appendix B shows why probabilistic proofs are insufficient for ensuring consistency of a Balloon without greatly increasing the burden on the prover.

2 Preliminaries

First, we introduce the used formalisation of an authenticated data structure scheme. Next, we give some background on the two data structures that make up Balloon: a history tree, for efficient membership proofs for any snapshot, and a hash treap, for efficient non-membership proofs. Finally we present our cryptographic building blocks.

2.1 An Authenticated Data Structure Scheme

Papamanthou *et al.* [18] define an authenticated data structure and its two main properties: correctness and security. We make use of these definitions and therefore present them here, be it with slight modifications to fit our terminology.

Definition 1 (ADS scheme). *Let D be any data structure that supports queries q and updates u. Let $\mathit{auth}(D)$ denote the resulting authenticated data structure and $\mathtt{s}$ the snapshot of the authenticated data structure, i.e., a constant-size description of D. An ADS scheme $\mathcal{A}$ is a collection of the following six probabilistic polynomial-time algorithms:*

1. $\{\mathtt{pk}, \mathtt{sk}\} \leftarrow \mathit{genkey}(1^\lambda)$*: On input the security parameter λ, it outputs a secret key* $\mathtt{sk}$ *and public key* $\mathtt{pk}$*;*
2. $\{\mathit{auth}(D_0), \mathtt{s}_0\} \leftarrow \mathit{setup}(D_0, \mathtt{sk}, \mathtt{pk})$*: On input a (plain) data structure D_0, the secret key, and the public key, it computes the authenticated data structure $\mathit{auth}(D_0)$ and the corresponding snapshot $\mathtt{s}_0$;*
3. $\{D_{h+1}, \mathit{auth}(D_{h+1}), \mathtt{s}_{h+1}, upd\} \leftarrow \mathit{update}(u, D_h, \mathit{auth}(D_h), \mathtt{s}_h, \mathtt{sk}, \mathtt{pk})$*: On input an update u on the data structure D_h, the authenticated data structure $\mathit{auth}(D_h)$, the snapshot $\mathtt{s}_h$, the secret key, and the public key, it outputs the updated data structure D_{h+1} along with the updated authenticated data structure $\mathit{auth}(D_{h+1})$, the updated snapshot $\mathtt{s}_{h+1}$ and some relative information upd;*
4. $\{D_{h+1}, \mathit{auth}(D_{h+1}), \mathtt{s}_{h+1}\} \leftarrow \mathit{refresh}(u, D_h, \mathit{auth}(D_h), \mathtt{s}_h, upd, \mathtt{pk})$*: On input an update u on the data structure D_h, the authenticated data structure $\mathit{auth}(D_h)$, the snapshot $\mathtt{s}_h$, relative information upd and the public key, it outputs the updated data structure D_{h+1} along with the updated authenticated data structure $\mathit{auth}(D_{h+1})$ and the updated snapshot $\mathtt{s}_{h+1}$;*

5. $\{\Pi(q), \alpha(q)\} \leftarrow$ ***query***$(q, D_h,$ ***auth***$(D_h), \mathtt{pk})$*: On input a query q on data structure D_h, the authenticated data structure* ***auth***(D_h) *and the public key, it returns the answer $\alpha(q)$ to the query, along with proof $\Pi(q)$;*
6. $\{$***accept***$,$ ***reject***$\} \leftarrow$ ***verify***$(q, \alpha, \Pi, \mathtt{s}_h, \mathtt{pk})$*: On input query q, an answer α, a proof Π, a snapshot $\mathtt{s}_h$ and the public key, it outputs either* ***accept*** *or* ***reject****.*

Next to the definition of the ADS scheme, another algorithm was defined for deciding whether or not an answer α to query q on data structure D_h is correct: $\{\mathtt{accept}, \mathtt{reject}\} \leftarrow \mathtt{check}(q, \alpha, D_h)$.

Definition 2 (Correctness). *Let Balloon be an ADS scheme* {***genkey***,***setup***, ***update***,***refresh***,***query***,***verify***}*. We say that the ADS scheme Balloon is correct if, for all $\lambda \in \mathbb{N}$, for all* $\{\mathtt{sk}, \mathtt{pk}\}$ *output by algorithm* ***genkey****, for all D_h,* ***auth***(D_h)*, $\mathtt{s}_h$ output by one invocation of* ***setup*** *followed by polynomially-many invocations of* ***refresh****, where $h \geq 0$, for all queries q and for all $\Pi(q), \alpha(q)$ output by* ***query***$(q, D_h,$ ***auth***$(D_h), \mathtt{pk})$ *with all but negligible probability, whenever algorithm* ***check***$(q, \alpha(q), D_h)$ *outputs* ***accept****, so does* ***verify***$(q, \Pi(q), \alpha(q), \mathtt{s}_h, \mathtt{pk})$*.*

Definition 3 (Security). *Let Balloon be an ADS scheme* {***genkey***,***setup***, ***update***,***refresh***,***query***,***verify***}*, λ be the security parameter, $\epsilon(\lambda)$ be a negligible function and* $\{\mathtt{sk}, \mathtt{pk}\} \leftarrow$ ***genkey***(1^λ)*. Let also* **Adv** *be a probabilistic polynomial-time adversary that is only given* $\mathtt{pk}$*. The adversary has unlimited access to all algorithms of Balloon, except for algorithms* ***setup*** *and* ***update*** *to which he has only oracle access. The adversary picks an initial state of the data structure D_0 and computes $D_0,$* ***auth***$(D_0), \mathtt{s}_0$ *through oracle access to algorithm* ***setup****. Then, for $i = 0, ..., h =$* ***poly***(λ)*,* **Adv** *issues an update u_i in the data structure D_i and computes $D_{i+1},$* ***auth***(D_{i+1}) *and $\mathtt{s}_{i+1}$ through oracle access to algorithm* ***update****. Finally the adversary picks an index $0 \leq t \leq h+1$, and computes a query q, answer α and a proof Π. We say that the ADS scheme Balloon is secure if for all $\lambda \in \mathbb{N}$, for all* $\{\mathtt{sk}, \mathtt{pk}\}$ *output by algorithm* ***genkey****, and for any probabilistic polynomial-time adversary* **Adv** *it holds that*

$$Pr\left[\begin{array}{l}\{q, \Pi, \alpha, t\} \leftarrow \mathbf{Adv}(1^\lambda, \mathtt{pk});\ \textit{accept} \leftarrow \textit{verify}(q, \alpha, \Pi, \mathtt{s}_t, \mathtt{pk}) \\ \qquad\qquad\qquad\qquad\qquad\qquad \textit{reject} \leftarrow \textit{check}(q, \alpha, D_t).\end{array}\right] \leq \epsilon(\lambda) \quad (1)$$

2.2 History Tree

A tamper-evident history system, as defined by Crosby and Wallach [5], consists of a *history tree* data structure and five algorithms. A history tree is in essence a *versioned* Merkle tree [14] (hash tree). Each leaf node in the tree is the hash of an event, while interior nodes are labeled with the hash of its children nodes in the subtree rooted at that node. The root of the tree fixes the content of the entire tree. Different versions of history trees, produced as events are added, can be proven to make consistent claims about the past. The five algorithms, adjusted to our terminology, were defined as follows:

- $c_i \leftarrow$ `H.Add`(e): Given an event e the system appends it to the history tree H as the i:th event and then outputs a commitment[3] c_i.
- $\{P, e_i\} \leftarrow$`H.MembershipGen`(i, c_j): Generates a membership proof P for the i:th event with respect to commitment c_j, where $i \leq j$, from the history tree H. The algorithm outputs P and the event e_i.
- $P \leftarrow$ `H.IncGen`(c_i, c_j): Generates an incremental proof P between c_i and c_j, where $i \leq j$, from the history tree H. Outputs P.
- $\{$`accept`, `reject`$\} \leftarrow$ `P.MembershipVerify`(i, c_j, e'_i): Verifies that P proves that e'_i is the i:th event in the history defined by c_j (where $i \leq j$). Outputs `accept` if true, otherwise `reject`.
- $\{$`accept`, `reject`$\} \leftarrow$ `P.IncVerify`(c'_i, c_j): Verifies that P proves that c_j fixes every event fixed by c'_i (where $i \leq j$). Outputs `accept` if true, otherwise `reject`.

2.3 Hash Treap

A treap is a type of randomised binary search tree [2], where the binary search tree is balanced using heap priorities. Each node in a treap has a key, value, priority, and a left and a right child. A treap has three important properties:

1. Traversing the treap in order gives the sorted order of the keys;
2. Treaps are structured according to the nodes' priorities, where each node's children have lower priorities;
3. Given a deterministic attribution of priorities to nodes, a treap is *set unique* and *history independent*, i.e., its structure is unique for a given set of nodes, regardless of the order in which nodes were inserted, and the structure does not leak any information about the order in which nodes were inserted.

When a node is inserted in a treap, its position in the treap is first determined by a binary search. Once the position is found, the node is inserted in place, and then rotated upwards towards the root until its priority is consistent with the heap priority. When the priorities are assigned to nodes using a cryptographic hash function, the tree becomes probabilistically balanced with an expected depth of $\log n$, where n is the number of nodes in the treap. Inserting a node takes expected $\mathcal{O}(\log n)$ operations and results in expected $\mathcal{O}(1)$ rotations to preserve the properties of the treap [8]. Given a treap, it is straightforward to build a hash treap: have each node calculate the hash of its own attributes[4] together with the hash of its children. Since the hash treap is a Merkle tree, its root fixes the entire hash treap. The concept of turning treaps into Merkle trees for authenticating the treap has been used for example in the context of persistent authenticated dictionaries [6] and authentication of certificate revocation lists [17].

We define the following algorithms on our hash treap, for which we assume that keys k are unique and of predefined constant size cst:

[3] A commitment c_i is the root of the history tree for the i:th event, signed by the system. For the purpose of this paper, we omit the signature from the commitments.

[4] The priority can safely be discarded since it is derived solely from the key and implicit in the structure of the treap.

- $r \leftarrow$`T.Add`(k, v): Given a unique key k and value v, where $|k| = cst$ and $|v| > 0$, the system inserts them into the hash treap T and then outputs the updated hash of the root r. The add is done with priority `Hash`(k), which results in a deterministic treap. After the new node is in place, the hash of each node along the path from the root has its internal hash updated. The hash of a node is `Hash`$\big(k||v||$left.hash$||$right.hash$\big)$. In case there is no right (left) child node, the right.hash (left.hash) is set to a string of consecutive zeros of size equal to the output of the used hash function $0^{|\texttt{Hash}(\cdot)|}$.
- $\{P^T, v\} \leftarrow$ `T.AuthPath`(k): Generates an authenticated path P^T from the root of the treap T to the key k where $|k| = cst$. The algorithm outputs P^T and, in case of when a node with key k was found, the associated value v. For each node i in P^T, k_i and v_i need to be provided to verify the hash in the authenticated path.
- $\{$`accept`$,$ `reject`$\} \leftarrow \mathrm{P}^T$`.AuthPathVerify`$(k, v)$: Verifies that P^T proves that k is a non-member if $v \stackrel{?}{=}$ `null` or otherwise a member. Verification checks that $|k| = cst$ and $|v| > 0$ (if $\neq$ `null`), calculates and compares the authenticator for each node in P^T, and checks that each node in P^T adheres to the sorted order of keys and heap priority.

Additionally we define the following helper algorithm on our hash treap:

- `pruned`$(\mathrm{T}) \leftarrow$ `T.BuildPrunedTree`$(<\mathrm{P}_j^T>)$: Generates a pruned hash treap `pruned(T)` from the given authenticated paths P_j^T in the hash treap T. This algorithm removes any redundancy between the authenticated paths, resulting in a more compact representation as a pruned hash treap. Note that evaluating `pruned(T).AuthPathVerify`(k, v) is equivalent with evaluating P^T`.AuthPathVerify`(k, v) on the authenticated path P^T through k contained in the pruned hash treap.
- $r \leftarrow \mathrm{P}^T$`.root`$()$: Outputs the root of the authenticated path. Note that `pruned(T).root`$()$ and P^T`.root`$()$ are equivalent for any authenticated path P^T contained by the pruned tree.

2.4 Cryptographic Building Blocks

We assume idealised cryptographic building blocks in the form of a hash function `Hash`$(\cdot)$, and signature scheme that is used to sign a message m and verify the resulting signature: $\{$`accept`$,$ `reject`$\} \leftarrow$ `Verify`$_{\texttt{vk}}\big($`Sign`$_{\texttt{sk}}(m), m\big)$. The hash function should be collision and pre-image resistant. The signature scheme should be existentially unforgeable under known message attack. Furthermore, we rely on the following lemma for the correctness and security of a Balloon:

Lemma 1. *The security of an authenticated path in a Merkle (hash) tree reduces to the collision resistance of the underlying hash function.*

Proof. This follows from the work by Merkle [15] and Blum *et al.* [4]. □

3 Construction and Algorithms

Our data structure is an append-only key-value store that stores events e consisting of a key k and a value v. Each key k_i is assumed to be unique and of predefined constant size cst, where $cst \leftarrow |\texttt{Hash}(\cdot)|$. Additionally, our data structure encodes some extra information in order to identify in which set (epoch) events were added. We define the algorithm $k \leftarrow \texttt{key}(e)$ that returns the key k of the event e.

Our authenticated data structure combines a hash treap and a history tree when adding an event an event e as follows:

- First, the event is added to the history tree: $c_i \leftarrow H.add\big(\texttt{Hash}(k||v)\big)$. Let i be the index where the hashed event was inserted at into the history tree.
- Next, the hash of the event key $\texttt{Hash}(k)$ and the event position i are added to the hash treap: $r \leftarrow \texttt{T.Add}(\texttt{Hash}(k), i)$.

Figure 1 visualises a simplified Balloon with a hash treap and a history tree. For the sake of readability, we omit the hash values and priority, replace hashed keys with integers, and replace hashed events with place-holder labels. For example, the root in the hash treap has key 42 and value 1. The value 1 refers to the leaf node in the history tree with index 1, whose value is p42, the place-holder label for the hash of the event which key, once hashed, is represented by integer 42.

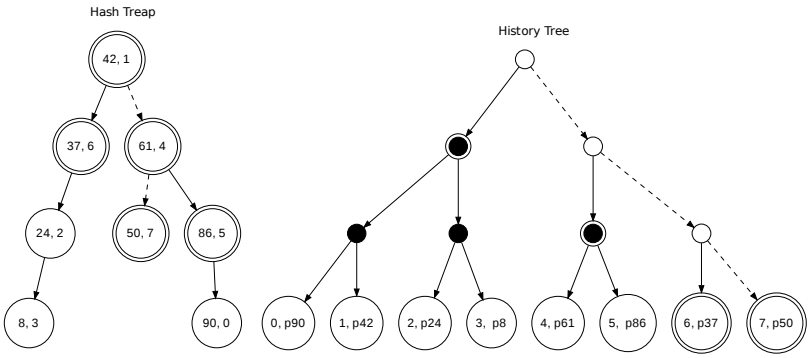


Fig. 1: An simplified example of a Balloon consisting of a hash treap and history tree. A membership proof for an event $e = (k, v)$ with $\texttt{Hash}(k) = 50$ and $\texttt{Hash}(e)$ denoted by p50 (place-holder label) consists of the circle nodes in both trees.

By putting the hash of the event key, $\texttt{Hash}(k)$, instead of the key into the hash treap, we avoid easy event enumeration by third parties: no valid event keys leak as part of authenticated paths in the treap for non-membership proofs. Note that when `H.MembershipGen` returns an event, as specified in Section 2.2, the actual event is retrieved from the data structure, not the hash of the event as stored in the history tree (authentication). We store the hash of the event in the history tree for sake of efficiency, since the event is already stored in the (non-authenticated) data structure.

3.1 Setup

Algorithm $\{\mathtt{pk}, \mathtt{sk}\} \leftarrow \mathtt{genkey}(1^\lambda)$: Generates a signature key-pair $\{\mathtt{vk}, \mathtt{sk}\}$ using the generation algorithm of a signature scheme with security level λ and picks a function Ω that deterministically orders events. Outputs the signing key as the private key $\mathtt{sk} = \mathtt{sk}$, and the verification key and the ordering function Ω as the public key $\mathtt{pk} = \{\mathtt{vk}, \Omega\}$.

Algorithm $\{\mathtt{auth}(D_0), \mathtt{s}_0\} \leftarrow \mathtt{setup}(D_0, \mathtt{sk}, \mathtt{pk})$: Let D_0 be the initial data structure, containing the initial set of events $< e_j >$. The authenticated data structure, $\mathtt{auth}(D_0)$, is then computed by adding each event from the set to the, yet empty, authenticated data structure in the order dictated by the function $\Omega \leftarrow \mathtt{pk}$. The snapshot is defined as the root of the hash treap r and commitment in the history tree c_i for the event that was added last together with a digital signature over those: $\mathtt{s}_0 = \{r, c_i, \sigma\}$, where $\sigma = \mathtt{Sign}_{\mathtt{sk}}(\{r, c_i\})$.

3.2 Update and Refresh

Algorithm $\{D_{h+1}, \mathtt{auth}(D_{h+1}), \mathtt{s}_{h+1}, upd\} \leftarrow \mathtt{update}(u, D_h, \mathtt{auth}(D_h), \mathtt{s}_h, \mathtt{sk}, \mathtt{pk})$: Let u be a set of events to insert into D_h. The updated data structure D_{h+1} is the result of appending the events in u to D_h and indicating that these belong the $(h+1)^{\text{th}}$ set. The updated authenticated data structure, $\mathtt{auth}(D_{h+1})$, is then computed by adding each event from the set to the authenticated data structure $\mathtt{auth}(D_h)$ in the order dictated by the function $\Omega \leftarrow \mathtt{pk}$. The updated snapshot is the root of the hash treap r and commitment in the history tree c_i for the event that was added last together with a digital signature over those: $\mathtt{s}_{h+1} = \{r, c_i, \sigma\}$, where $\sigma = \mathtt{Sign}_{\mathtt{sk}}(\{r, c_i\})$. The update information contains this snapshot $upd = \mathtt{s}_{h+1}$.

Algorithm $\{D_{h+1}, \mathtt{auth}(D_{h+1}), \mathtt{s}_{h+1}\} \leftarrow \mathtt{refresh}(u, D_h, \mathtt{auth}(D_h), \mathtt{s}_h, upd, \mathtt{pk})$: Let u be a set of events to insert into D_h. The updated data structure D_{h+1} is the result of appending the events in u to D_h and indicating that these belong the $(h+1)^{\text{th}}$ set. The updated authenticated data structure, $\mathtt{auth}(D_{h+1})$, is then computed by adding each event from the set u to the authenticated data structure $\mathtt{auth}(D_h)$ in the order dictated by the function $\Omega \leftarrow \mathtt{pk}$. Finally, the new snapshot is set to $\mathtt{s}_{h+1} = upd$.

3.3 Query and Verify

Algorithm $\{\Pi(q), \alpha(q)\} \leftarrow \mathtt{query}(q, D_h, \mathtt{auth}(D_h), \mathtt{pk})$ (**Membership**): We consider the query q to be "a membership query for an event with key k in the data structure that is fixed by $\mathtt{s}_{queried}$", where $queried \leq h$. The query has two possible answers $\alpha(q)$: $\{\mathtt{true}, e\}$ in case an event e with key k exists in $D_{queried}$, otherwise $\mathtt{false}$. The proof of correctness $\Pi(q)$ consists of up to three parts:

1. An authenticated path P^T in the hash treap to $k' = \mathtt{Hash}(k)$;

2. The index i of the event in the history tree;
3. A membership proof P on index i in the history tree.

The algorithm generates an authenticated path in the hash treap, which is part of $\texttt{auth}(D_h)$, to k': $\{P^T, v\} \leftarrow \texttt{T.AuthPath}(k')$. If $v \stackrel{?}{=} \texttt{null}$, then there is no event with key k in D_h (and consequently in $D_{queried}$) and the algorithm outputs $\Pi(q) = P^T$ and $\alpha(q) = \texttt{false}$.

Otherwise, the value v in the hash treap indicates the index i in the history tree of the event. Now the algorithm checks whether or not the index i is contained in the history tree up till $\texttt{auth}(D_{queried})$. If not, the algorithm outputs $\alpha(q) = \texttt{false}$ and $\Pi(q) = \{P^T, i\}$. If it is, the algorithm outputs $\alpha(q) = \{\texttt{true}, e_i\}$ and $\Pi(q) = \{P^T, i, P\}$, where $\{P, e_i\} \leftarrow \texttt{H.MembershipGen}(i, c_{queried})$ and $c_{queried} \leftarrow \texttt{s}_{queried}$.

Algorithm $\{\texttt{accept}, \texttt{reject}\} \leftarrow \texttt{verify}(q, \alpha, \Pi, \texttt{s}_h, \texttt{pk})$ (**Membership**): First, the algorithm extracts $\{k, \texttt{s}_{queried}\}$ from the query q and $\{P^T, i, P\}$ from Π, where i and P can be $\texttt{null}$. From the snapshot it extracts $r \leftarrow \texttt{s}_h$. Then the algorithm computes $x \leftarrow \texttt{P}^T\texttt{.AuthPathVerify}(k, i)$. If $x \stackrel{?}{=} \texttt{false} \vee \texttt{P}^T\texttt{.root}() \neq r$, the algorithm outputs $\texttt{reject}$. The algorithm outputs $\texttt{accept}$ if any of the following three conditions hold, otherwise $\texttt{reject}$:

- $\alpha \stackrel{?}{=} \texttt{false} \wedge i \stackrel{?}{=} \texttt{null}$;
- $\alpha \stackrel{?}{=} \texttt{false} \wedge \mathit{queried}[-1]$[5] $\stackrel{?}{<} i$;
- $\alpha \stackrel{?}{=} \{\texttt{true}, e\} \wedge \texttt{key}(e) \stackrel{?}{=} k \wedge y \stackrel{?}{=} \texttt{true}$,
  for $y \leftarrow P\texttt{.MembershipVerify}(i, c_{queried}, e)$ and $c_{queried} \leftarrow \texttt{s}_{queried}$.

4 Security

Theorem 1. *Balloon* $\{\texttt{genkey}, \texttt{setup}, \texttt{update}, \texttt{refresh}, \texttt{query}, \texttt{verify}\}$ *is a correct ADS scheme for a data structure D, that contains a list of sets of events, according to Definition 2, assuming the collision-resistance of the underlying hash function.*

The proof of correctness can be found in Appendix A.1.

Theorem 2. *Balloon* $\{\texttt{genkey}, \texttt{setup}, \texttt{update}, \texttt{refresh}, \texttt{query}, \texttt{verify}\}$ *is a secure ADS scheme for a data structure D, that contains a list of sets of events, according to Definition 3, assuming the collision-resistance of the underlying hash function.*

Proof. The adversary initially outputs the authenticated data structure $\texttt{auth}(D_0)$ and the snapshot $\texttt{s}_0$ through an oracle call to algorithm $\texttt{setup}$. The adversary picks a polynomial number $i = 0, \ldots, h$ of updates with u_i insertions of

[5] $\mathit{queried}[-1]$ denotes the index of the last inserted event in version *queried* of the authenticated data structure.

unique events and outputs the data structure D_i, the authenticated data structure $\texttt{auth}(D_i)$, and the snapshot $\texttt{s}_i$ through oracle access to `update`. Then it picks a query $q =$ "a membership query for an event with key $k \in \{0,1\}^{|\texttt{Hash}(\cdot)|}$ in the data structure that is fixed by $\texttt{s}_j$, with $0 \leq j \leq h+1$", a proof $\Pi(q)$, and an answer $\alpha(q)$ which is rejected by $\texttt{check}(q, \alpha(q), D_j)$ as incorrect. An adversary breaks security if $\texttt{verify}(q, \alpha(q), \Pi(q), \texttt{s}_j, \texttt{pk})$ outputs `accept` with non-negligible probability.

Assume a probabilistic polynomial time adversary $\mathcal{A}$ that breaks security with non-negligible probability. Given that the different versions of the authenticated data structure and corresponding snapshots are generated through oracle access, these are correct, i.e., the authenticated data structure contains all elements of the data structure for each version, the root and commitment in each snapshot correspond to that version of the ADS and the signature in each snapshot verifies.

The tuple $(q, \alpha(q), D_j)$ is rejected by `check` in only three cases:

Case 1 $\alpha(q) = \texttt{false}$ and there exists an event with key k in D_j ;
Case 2 $\alpha(q) = \{\texttt{true}, e\}$ and there does not exists an event with key k in D_j ;
Case 3 $\alpha(q) = \{\texttt{true}, e\}$ and the event e^* with key k in D_j differs from e: $e = (k, v) \neq e^* = (k, v^*)$ or more specifically $v \neq v^*$;

For all three cases where the `check` algorithm outputs `reject`, $\mathcal{A}$ has to forge an authenticated path in the hash treap and/or history tree in order to get the `verify` algorithm to output `accept`:

Case 1 In the hash treap that is fixed by $\texttt{s}_{h+1}$, there is a node with key $k' = \texttt{Hash}(k)$ and the value $v' \leq j[-1]$. However for the `verify` algorithm to output `accept` for $\alpha(q)$=`false`, the authenticated path in the hash treap must go to either no node with key k' or a node with key k' for which the value v' is greater than the index of the last inserted event in the history tree that is fixed by $\texttt{s}_j$: $v' > j[-1]$.
Case 2 In the hash treap that is fixed by $\texttt{s}_{h+1}$, there is either no node with key $k' = \texttt{Hash}(k)$ or a node with key k' for which the value v' is greater than the index of the last inserted event in the history tree that is fixed by $\texttt{s}_j$: $v' > j[-1]$. However for the `verify` algorithm to output `accept` for $\alpha(q) = \{\texttt{true}, e\}$, the authenticated path in the hash treap must go to a node with key k', where the value $v' \leq j[-1]$. Note that, in this case, $\mathcal{A}$ also needs to forge an authenticated path in the history tree to succeed.
Case 3 In the hash treap that is fixed by $\texttt{s}_{h+1}$, there is a leaf with key $k' = \texttt{Hash}(k)$ and the value $v' \leq j[-1]$. In the history tree, the leaf with key v' has the value $\texttt{Hash}(e^*)$. However for the `verify` algorithm to output `accept` for $\alpha(q) = \{\texttt{true}, e\}$, the authenticated path in the hash treap must go to a leaf with key k', where the value $v' \leq j[-1]$, for which the authenticated path in the history tree must go to a leaf with key v' and the value $\texttt{Hash}(e)$.

From Lemma 1 it follows that we can construct a probabilistic polynomial time adversary $\mathcal{B}$, by using $\mathcal{A}$, that outputs a collision of the underlying hash function with non-negligible probability. □

5 Verifiable Insert

In practical three-party settings, the source typically has less storage capabilities than servers. As such, it would be desirable that the source does not need to keep a copy of the entire (authenticated) data structure for `update`, but instead can rely on its own (constant) storage combined with verifiable information from a server. We define new query and verify algorithms that enable the construction of a *pruned* authenticated data structure, containing only the events to be inserted with a modified update algorithm. The pruned authenticated data structure is denoted by $\texttt{pruned}\big(\texttt{auth}(D_h), u\big)$, where $\texttt{auth}(D_h)$ denotes the version of the ADS being pruned, and u the set of events where this ADS is pruned for.

Algorithm $\{\Pi(q), \alpha(q)\} \leftarrow \texttt{query}(q, D_h, \texttt{auth}(D_h), \texttt{pk})$ (**Prune**): We consider the query q to be "a prune query for if a set of events u can be inserted into D_h". The query has two possible answers: $\alpha(q)$: `true` in case no key for the events in u already exist in D_h, otherwise `false`. The proof of correctness $\Pi(q)$ either proves that there already is an event with a key from an event in u, or provides proofs that enable the construction of a pruned $\texttt{auth}(D_h)$, depending on the answer. For every $k_j \leftarrow \texttt{key}(e_j)$ in the set u, the algorithm uses as a sub-algorithm $\{\Pi'_j(q), \alpha'_j(q)\} \leftarrow \texttt{query}(q'_j, D_h, \texttt{auth}(D_h), \texttt{pk})$ (**Membership**) with $q' = \{k_j, \texttt{s}_h\}$, where $\texttt{s}_h$ fixes $\texttt{auth}(D_h)$. If any $\alpha'_j(q) \stackrel{?}{=} \texttt{true}$, the algorithm outputs $\alpha(q) = \texttt{false}$ and $\Pi(q) = \{\Pi'_j(q), k_j\}$ and stops. If not, the algorithm takes P_j^T from each $\Pi'_j(q)$ and creates the set $<\mathrm{P}_j^T>$. Next, the algorithm extracts the latest event e_i inserted into the history tree from $\texttt{auth}(D_h)$ and uses as a sub-algorithm $\{\Pi'(q), \alpha'(q)\} \leftarrow \texttt{query}(q', D_h, \texttt{auth}(D_h), \texttt{pk})$ (**Membership**) with $q' = \{\texttt{key}(e_i), \texttt{s}_h\}$. Finally, the algorithm outputs $\alpha(q) = \texttt{true}$ and $\Pi(q) = \{<\mathrm{P}_j^T>, \Pi'(q)\}$.

Algorithm $\{\texttt{accept}, \texttt{reject}\} \leftarrow \texttt{verify}(q, \alpha, \Pi, \texttt{s}_h, \texttt{pk})$ (**Prune**): The algorithm starts by extracting $< e_j > \leftarrow u$ from the query q. If $\alpha \stackrel{?}{=} \texttt{false}$, it gets $\{\Pi'_j(q), k_j\}$ from Π and uses as a sub-algorithm $\texttt{valid} \leftarrow \texttt{verify}(q', \alpha', \Pi', \texttt{s}_h, \texttt{pk})$ (**Membership**), with $q' = \{k, \texttt{s}_h\}$, $\alpha' = \texttt{true}$ and $\Pi' = \Pi'_j(q)$, where $k \leftarrow k_j$. If $\texttt{valid} \stackrel{?}{=} \texttt{accept}$ and there exists an event with key k in u, the algorithm outputs `accept`, otherwise `reject`.

If $\alpha \stackrel{?}{=} \texttt{true}$, extract $\{<\mathrm{P}_j^T>, \Pi'(q)\}$ from Π. For each event e_j in u, the algorithm gets $k_j \leftarrow \texttt{key}(e_j)$, finds the corresponding P_j^T for $k'_j = \texttt{Hash}(k_j)$, and uses as a sub-algorithm $\texttt{valid} \leftarrow \texttt{verify}(q', \alpha', \Pi', \texttt{s}_h, \texttt{pk})$ (**Membership**), with $q' = \{k_j, \texttt{s}_h\}$, $\alpha' = \texttt{false}$ and $\Pi' = \mathrm{P}_j^T$. If no corresponding P_j^T to k'_j is found in $<\mathrm{P}_j^T>$ or $\texttt{valid} \stackrel{?}{=} \texttt{reject}$, then the algorithm outputs `reject` and stops. Next, the algorithm uses as a sub-algorithm $\texttt{valid} \leftarrow \texttt{verify}(q', \alpha, \Pi', \texttt{s}_h, \texttt{pk})$ (**Membership**), with $q' = \{\texttt{key}(e_i), \texttt{s}_h\}$ and $\Pi' = \Pi'(q)$, where $e_i \in \Pi'(q)$. If $\texttt{valid} \stackrel{?}{=} \texttt{accept}$ and $i \stackrel{?}{=} h[-1]$ the algorithm outputs `accept`, otherwise `reject`.

Algorithm $\{\mathtt{s}_{h+1}, upd\} \leftarrow \mathtt{update*}(u, \Pi, \mathtt{s}_h, \mathtt{sk}, \mathtt{pk})$: Let u be a set of events to insert into D_h and Π a proof that the sub-algorithm $\mathtt{verify}(q, \alpha, \Pi, \mathtt{s}_h, \mathtt{pk})$ (**Prune**) outputs `accept` for, where $q = u$ and $\alpha = \mathtt{true}$. The algorithm extracts $\{<\mathrm{P}_j^T>, \Pi'(q)\}$ from Π and builds a pruned hash treap $\mathtt{pruned}(\mathrm{T}) \leftarrow \mathtt{T.BuildPrunedTree}(<\mathrm{P}_j^T>)$. Next, it extracts P from $\Pi'(q)$ and constructs the pruned Balloon $\mathtt{pruned}\big(\mathtt{auth}(D_h), u\big) \leftarrow \{\mathtt{pruned}(\mathrm{T}), P\}$. Finally, the algorithm adds each event in u to the pruned Balloon $\mathtt{pruned}\big(\mathtt{auth}(D_h), u\big)$ in the order dictated by $\Omega \leftarrow \mathtt{pk}$. The updated snapshot is the digital signature over the root of the updated pruned hash treap r and commitment in the updated pruned history tree c_i for the event that was added last: $\mathtt{s}_{h+1} = \{r, c_i\}, \mathtt{Sign}_{\mathtt{sk}}(\{r, c_i\})$. The update information contains this snapshot $upd = \mathtt{s}_{h+1}$.

Lemma 2. *The output of* `update` *and* `update*` *is identical with respect to the root of the hash treap and the latests commitment in the history tree of* $\mathtt{s}_{h+1}$ *and* upd[6].

The proof of Lemma 2 can be found in Appendix A.2. As a result of Lemma 2, the `update` algorithm in Balloon can be replaced by `update*` without breaking the correctness and security of the Balloon as in Theorems 1 and 2. This means that the server can keep and refresh the (authenticated) data structure while the author only needs to store the last snapshot s_h to be able to produce updates, resulting in a small constant size storage requirement for the author.

Note that, in order to save on transmission bandwidth, `verify` (**Prune**) could output the pruned authenticated data structure directly. Given that $\mathtt{pruned(T).AuthPathVerify}(k, v)$ and $\mathrm{P}^T\mathtt{.AuthPathVerify}(k, v)$ are equivalent, the correctness and security of `verify` (**Prune**) reduce to `verify`. Section 7 shows how much bandwidth can be saved.

6 Publicly Verifiable Consistency

While the server is untrusted, the author is trusted. A stronger adversarial model assumes forward security for the author: the author is only trusted up to a certain point in time, i.e., the time of compromise, and afterwards cannot change the past. In this stronger adversarial model, Balloon should still provide correctness and security for all events inserted by the author up till the time of author compromise.

Efficient incremental proofs, realised by the `IncGen` and `IncVerify` algorithms, are a key feature of history trees [8]. Anyone can challenge the server to provide a proof that one commitment as part of a snapshot is *consistent* with all previous commitments as part of snapshots. However, it appears to be an open problem to have an efficient algorithm for showing consistency between roots of different versions of a treap (or any lexicographically sorted data structure) [7]. In appendix B, we show why one cannot efficiently use probabilistic proofs of consistency for a Balloon. In absence of efficient (both for the server and verifier

[6] Note that the signatures may differ since the signature scheme can be probabilistic.

in terms of computation and size) incremental proofs in hash treaps, we rely on a concept from Certificate Transparency [11]: monitors.

We assume that a subset of clients, or any third party, will take on a role referred to as a "monitor", "auditor", or "validator" in ,e.g., [3,9,10,11,20,25]. A monitor continuously monitors all data stored at a server and ensures that all snapshots issued by an author are consistent. We assume that clients and monitors receive the snapshots through gossiping.

Definition 4 (Publicly Verifiable Consistency). *An ADS scheme is publicly verifiable consistent if anyone can verify that a set of events u has been correctly inserted in D_h and $\texttt{auth}(D_h)$, fixed by $\texttt{s}_h$ to form D_{h+1} and $\texttt{auth}(D_{h+1})$ fixed by $\texttt{s}_{h+1}$.*

Algorithm $\{\alpha, D_{h+1}, \texttt{auth}(D_{h+1}), \texttt{s}_{h+1}\} \leftarrow \texttt{refreshVerify}(u, D_h, \texttt{auth}(D_h), \texttt{s}_h, upd, \texttt{pk})$: First, the algorithm runs $\{D_{h+1}, \texttt{auth}(D_{h+1}), \texttt{s}_{h+1}\} \leftarrow \texttt{refresh}(u, D_h, \texttt{auth}(D_h), \texttt{s}_h, upd, \texttt{pk})$ as a sub-algorithm. Then, the algorithm verifies the updated snapshot $\{r, c_i, \sigma\} \leftarrow \texttt{s}_{h+1} \leftarrow upd$:

- verify the signature: $\texttt{true} \stackrel{?}{=} \texttt{verify}_{\texttt{pk}}(\sigma, \{r, c_i\})$; and
- match the root of the updated hash treap $r' \stackrel{?}{=} r$; and
- match the last commitment in the updated history tree $c'_i \stackrel{?}{=} c_i$.

If the verify succeeds, the algorithm outputs $\{\alpha = \texttt{true}, D_{h+1}, \texttt{auth}(D_{h+1}), \texttt{s}_{h+1}\}$. Otherwise, the algorithm outputs $\alpha = \texttt{false}$.

Theorem 3. *With `refreshVerify`, Balloon is publicly verifiable consistent according to Definition 4, assuming perfect gossiping of the snapshots and the collision-resistance of the underlying hash function.*

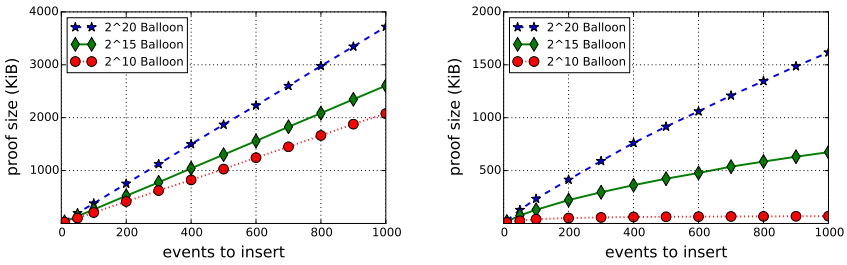
The proof of publicly verifiable consistency can be found in Appendix A.3. Note that for the purpose of verifying consistency between snapshots, it is not necessary to keep the data structure D. Moreover, the storage requirement for monitors can be further reduced by making use of pruned versions of the authenticated data structure, i.e., by using a $\texttt{refresh}^*$ sub-algorithm, similar to the $\texttt{update}^*$ algorithm. Finally, to preserve event privacy towards monitors, one can provide the monitors with $\tilde{u} =< \tilde{e_j} >$, where $\tilde{e_j} = \big(\texttt{Hash}(k_j), \texttt{Hash}(e_j)\big)$, and not the actual set of events. However, in this case, one must ensure that the ordering function $\Omega \leftarrow \texttt{pk}$ provides the same output for u and $\tilde{u}$.

7 Performance

We implemented Balloon in the Go[7] programming language using SHA-512 as the hash function. The output of SHA-512 is truncated to 256-bits, with the goal of reaching a 128-bits security level. Our performance evaluation focuses on

[7] golang.org, accessed 2015-04-10.

verifiable inserts, that is composed of performing and verifying $|u| + 1$ membership queries, since these algorithms presumably are the most common. Figure 2 shows the size of the proof from `query` (**Prune**) in KiB based on the number of events to insert ranging from 1–1000 for three different sizes of Balloon: 2^{10}, 2^{15}, and 2^{20} events. Figure 2a includes redundant nodes in the membership query proofs, and shows that the proof size is linear with the number of events to insert. Figure 2b excludes redundant nodes between proofs, showing that excluding redundant nodes roughly halves the proof size with bigger gains the more events are inserted. For large Balloons the probability that any two authenticated paths in the hash treap share nodes goes down, resulting in bigger proofs, until the number of events get closer to the total size of the Balloon, when eventually all nodes in the hash treap are included in the proof as for the 2^{10} Balloon.



(a) Including redundant nodes.

(b) Excluding redundant nodes.

Fig. 2: The size of the proof from `query` (**Prune**) in KiB based on the number of events to insert $|u|$ for different sizes of Balloon.

Table 1 shows a micro-benchmark of the three algorithms that enable verifiable inserts: `query`(**Prune**), `verify`(**Prune**), and `update*`. The table shows the average insert time (ms) calculated by Go's built-in benchmarking tool that performed between 30–30000 samples per measurement. The `update*` algorithm performs the bulk of the work, with little difference between the different Balloon sizes, and linear scaling for all three algorithms based on the number of events to insert.

Table 1: A micro-benchmark on Debian 7.8 (x64) using an Intel i5-3320M quad core 2.6GHz CPU and 7.7 GB DDR3 RAM.

Average time (ms)	Balloon 2^{10}			Balloon 2^{15}			Balloon 2^{20}		
	# Events $\|u\|$			# Events $\|u\|$			# Events $\|u\|$		
	10	100	1000	10	100	1000	10	100	1000
`query` (**Prune**)	0.04	0.37	3.64	0.04	0.37	3.64	0.06	0.37	3.62
`verify` (**Prune**)	0.07	0.72	6.83	0.07	0.73	6.84	0.07	0.72	6.85
`update*`	0.56	4.45	41.16	0.78	5.76	50.25	0.90	6.35	52.71

8 Related Work

Balloon is closely related to authenticated dictionaries [17] and persistent authenticated dictionaries (PADs) [1,6,7]. Balloon is not a PAD because it does not allow for the author to remove or update keys from the data structure, i.e., it is append only. By allowing the removal of keys, the server needs to be able to construct past versions of the PAD to calculate proofs, which is relatively costly. In Table 2, Balloon is compared to the most efficient tree-based PAD construction according to Crosby & Wallach [7]: a red-black tree using Sarnak-Tarjan versioned nodes with a cache-everywhere strategy for calculated hash values. The table shows expected complexity. Note that red-black trees are more efficient than treaps due to their worst-case instead of expected logarithmic bounds on several important operations. We opted for using a treap due to its relative simplicity. For Balloon, the storage at the author is constant due to using verifiable inserts, while the PAD maintains a copy of the entire data structure. To query past versions, the PAD has to construct past versions of the data structure, while Balloon does not. When inserting new events, the PAD has to store a copy of the modified authenticated path in the red-black tree, while the storage for Balloon is constant. However, Balloon is less efficient when inserting new events with regard to the proof size due to verifiable inserts.

Table 2: Comparing Balloon and an efficient PAD construction [7]. The number of events in the data structure is n and the size of the version cache is v.

Expected Complexity	Total Storage Size (A)	Query Time (current)	Query Time (past)	Insert Storage Size (S)	Insert Time (A)	Insert Time (S)	Insert Proof Size
Balloon	$\mathcal{O}(1)$	$\mathcal{O}(\log n)$	$\mathcal{O}(\log n)$	$\mathcal{O}(1)$	$\mathcal{O}(\log n)$	$\mathcal{O}(\log n)$	$\mathcal{O}(\log n)$
Tree-based PAD	$\mathcal{O}(n)$	$\mathcal{O}(\log n)$	$\mathcal{O}(\log v \cdot \log n)$	$\mathcal{O}(\log n)$	$\mathcal{O}(\log n)$	$\mathcal{O}(\log n)$	$\mathcal{O}(1)$

Miller et al. [16] present a generic method for authenticating operations on any data structure that can be defined by standard type constructors. The prover provides the authenticated path in the data structure that are traversed by the prover when performing an operation. The verifier can then perform the same operation, only needing the authenticated paths provided in the proof. The verifier only has to store the latest correct digest that fixes the content of the data structure. Our verifiable insert is based on the same principle.

Secure logging schemes, like the work by Schneier and Kelsey [21], Ma and Tsudik [12], and Yavuz *et al.* [24] can provide deletion detection and forward-integrity in a forward secure model for append-only data. Some schemes, like that of Yavuz *et al.*, are publicly verifiable like Balloon. However, these schemes are insufficient in our setting, since clients cannot get efficient non-membership proofs, nor efficient membership-proofs for past versions of the data structure when only some versions (snapshots) are timestamped.

All the following related work operates in a setting that is fundamentally different to the one of Balloon. For Balloon, we assume a forward-secure author with an untrusted server, whereas the following related work assumes a (minimally) trusted server with untrusted authors.

Certificate Transparency [11] and the tamper-evident history system by Crosby & Wallach [5] use a nearly identical[8] data structure and operations. Even though in both Certificate Transparency and Crosby & Wallach's history system, a number *minimally trusted* authors insert data into a history tree kept by a server, clients query the server for data and can act as auditors or monitors to challenge the server to prove consistency between commitments. Non-membership proofs require the entire data structure to be sent to the verifier.

In Revocation Transparency, Laurie and Kasper [10] presents the use of a sparse Merkle tree for certificate revocation. Sparse Merkle trees create a Merkle tree with 2^N leafs, where N is the bit output length of a hash algorithm. A leaf is set to 1 if the certificate with the hash value fixed by the path to the leaf from the root of the tree is revoked, and 0 if not. While the tree in general is too big to store or compute on its own, the observation that most leafs are zero (i.e., the tree is sparse), means that only paths including non-zero leafs need to be computed and/or stored. At first glance, sparse Merkle trees could replace the hash treap in a Balloon with similar size/time complexity operations.

Enhanced Certificate Transparency (ECT) by Ryan [20] extends CT by using two data structures: one chronologically sorted and one lexicographically sorted. Distributed Transparent Key Infrastructure (DTKI) [25] builds upon the same data structures as ECT. The chronologically sorted data structure corresponds to a history tree (like CT). The lexicographically sorted data structure is similar to our hash treap. For checking consistency between the two data structures, ECT and DTKI uses probabilistic checks. The probabilistic checking verifies that a random operation recorded in the chronological data structure has been correctly performed in the lexicographical data structure. However, this requires the prover to generate past versions of the lexicographical data structure (or cache all proofs), with similar trade-offs as for PADs, which is relatively costly.

CONIKS [13] is a privacy-friendly key management system where minimally trusted clients manage their public keys in directories at untrusted key servers. A directory is built using an authenticated binary prefix tree, offering similar properties as our hash treap. In CONIKS, user identities are presumably easy to brute-force, so they go further than Balloon in providing event privacy in proofs by using verifiable unpredictable functions and commitments to hide keys (identities) and values (user data). CONIKS stores every version of their (authenticated) data structure, introducing significant overhead compared to Balloon. On the other hand, CONIKS supports modifying and removing keys, similar to a PAD. Towards consistency, CONIKS additionally links snapshots together into a snapshot chain, together with a specified gossiping mechanism that greatly increases the probability that an attacker creating inconsistent snapshots is caught. This reduces the reliance on perfect gossiping, and could be used in Balloon. If the author ever wants to create a fork of snapshots for a subset of clients and monitors, it needs to maintain this fork forever for this subset or risk detection. Like CONIKS, we do not prevent an adversary compromising a server, or author, or both, from performing attacks: we provide means of detection after the fact.

[8] The difference is in how non-full trees are handled, as noted in Section 2.1 of [11].

9 Conclusions

This paper presented Balloon, an authenticated data structure composed of a history tree and a hash treap, that is tailored for privacy-preserving transparency logging. Balloon is a provably secure authenticated data structure, using a similar approach as Papamanthou *et al.* [18], under the modest assumption of a collision-resistant hash function. Balloon also supports efficiently verifiable inserts of new events and publicly verifiable consistency. Verifiable inserts enable the author to discard its copy of the (authenticated) data structure, only keeping constant storage, at the cost of transmitting and verifying proofs of a pruned version of the authenticated data structure. Publicly verifiable consistency enable anyone to verify the consistency of snapshots, laying the foundation for a forward-secure author, under the additional assumption of a perfect gossiping mechanism of snapshots. Balloon is practical, as shown in Section 7, and a more efficient solution in our setting than using a PAD, as summarised by Table 2.

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A Proofs

A.1 Correctness

Theorem 1. *Balloon* {*genkey*,*setup*,*update*,*refresh*,*query*,*verify*} *is a correct ADS scheme for a data structure D, that contains a list of sets of events, according to Definition 2, assuming the collision-resistance of the underlying hash function.*

Proof. For every membership `query` q and for every answer $\alpha(q)$ that is accepted by the `check` algorithm and proof output by `query`, `verify` accepts with overwhelming probability. Let q be a membership query for a key k in the snapshot $\mathtt{s}_j$. Regardless of the queried snapshot, in the hash treap, the current root $r \in \mathtt{s}_h$ is used to construct the authenticated path verified by `verify`.

If there is no event with key k in D_h, then there is no key with $k' \leftarrow \mathtt{Hash}(k)$ in the hash treap with overwhelming probability (a hash collision has negligible probability), and `verify` accepts only if $\alpha(q) = \mathtt{false}$. Conversely, if there is a node with key k' in the hash treap, then there is with overwhelming probability an event with key k in D_h and $\alpha(q)$ is either $\{\mathtt{true}, e\}$ or `false`. If $\alpha(q)$ is `false`, then the event with key k was inserted into D_h *after* $\mathtt{s}_j$. This means that the index i in the history tree, that is the value v' in the hash treap node for k', is $\mathtt{j}[-1] < i$ and hence the `verify` algorithm accepts. Finally, if $\alpha(q)$ is $\{\mathtt{true}, e\}$, then the proof contains a membership proof in the history tree for the key i and value $\mathtt{Hash}(e)$ and hence the `verify` algorithm accepts. □

A.2 Verifiable Insert

Lemma 2. *The output of* `update` *and* `update*` *is identical with respect to the root of the hash treap and the latests commitment in the history tree of* $\mathtt{s}_{h+1}$ *and upd.*

Proof. For `verify` (**Prune**), when $\alpha \stackrel{?}{=} \mathtt{true}$, the algorithm verifies $|u| + 1$ membership queries using as a sub-algorithm `verify` (**Membership**), which is correct and secure according to Theorems 1 and 2. Furthermore, `verify` (**Prune**) verifies that no event in u has already been inserted into the Balloon and that a membership query fixes the last event inserted into the history tree. This enables `update*` to verifiably create $\mathtt{pruned}\big(\mathtt{auth}(D_h), u\big) \leftarrow \{\mathtt{pruned}(\mathrm{T}), P\}$. Next we show that inserting events u into $\mathtt{pruned}\big(\mathtt{auth}(D_h), u\big)$ and $\mathtt{auth}(D_h)$ result in the same root r of the hash treap and commitment c_i on the history tree.

The pruned hash treap `pruned(T)` is the only part of the hash treap that is subject to change when inserting the events u. This follows from the fact that the position to insert each a new node in a treap is determined by a binary search (which path a membership query fixes and proves), and that balancing the treap using the heap priority only rotates nodes along the authenticated path. Since a treap is also set unique, i.e., independent of the insert order of events, all these authenticated paths can safely be combined into one pruned tree. As such the root of the hash treap after inserting the events will be identical when using the pruned and full hash treap.

To compute the new root of a Merkle tree after adding a leaf node, one needs the authenticated path of the last inserted leaf node to the root and the new leaf. Note that any new leaf will always be inserted to the right of the authenticated path. As such the roots (and by consequence the commitments) of the new history tree after adding all events in the order determined by $\Omega \leftarrow \mathtt{pk}$ will be identical for both cases. □

A.3 Publicly Verifable Consistency

Theorem 3. *With* `refreshVerify`*, Balloon is publicly verifiable consistent according to Definition 4, assuming perfect gossiping of the snapshots and the collision-resistance of the underlying hash function.*

Proof. By assuming perfect gossiping, one is assured that it receives all snapshots in the order they were generated and that these snapshots have not been altered afterwards.

First, one starts from the initial data structure D_0 and constructs the initial authenticated data structure $\texttt{auth}(D_0)$ by adding the events contained in D_0 to an empty Balloon. It then verifies the initial snapshot $\texttt{s}_0$ (received by gossip) as in `refreshVerify()`. If snapshot verifies, one now has $\{D_0, \texttt{auth}(D_0), \texttt{s}_0\}$ and is assured these values are consistent with the (authenticated) data structure as constructed by the author. Under the assumption that the underlying hash function is collision resistant, this follows directly from Lemma 1 and the fact that our authenticated data structure consists of two Merkle trees: a hash treap and a history tree.

Now, one keeps on building the authenticated data structure, snapshot by snapshot, until one finally ends up with the snapshots that one wants to check the consistency between. The authenticated data structure is built by running $\texttt{refreshVerify}(u,\ D_i, \texttt{auth}(D_i), \texttt{s}_i, \texttt{s}_{i+1}, \texttt{pk})$, where every time i is increased by one. A balloon is verifiably consistent, if for $i = h + 1$, this algorithm outputs $\{D_{h+1}, \texttt{auth}(D_{h+1}), \texttt{s}_{h+1}\}$. If the balloon is not consistent, then the output of the `refreshVerify`() algorithm is $\alpha = \texttt{false}$ for some $i \leq h$. □

B Negative Result on Probabilistic Consistency

Here we present a negative result from our attempt at ensuring consistency of a Balloon with probabilistic proofs. Probabilistic proofs are compelling, because they may enable more resource-constrained clients en-mass to verify consistency, removing the need for monitors that perform the relatively expensive role of downloading all events at a server. Assume the following pair of algorithms:

- $P \leftarrow \texttt{B.IncGen}(\texttt{s}_i, \texttt{s}_j, rand)$: Generates a probabilistic incremental proof P using randomness $rand$ between $\texttt{s}_i$ and $\texttt{s}_j$, where $i \leq j$, from the Balloon B. Outputs P.
- $\{\texttt{true}, \texttt{false}\} \leftarrow \texttt{P.IncVerify}(s_i, \texttt{s}_j, rand)$: Verifies that P probabilistically proves that $\texttt{s}_j$ fixes every event fixed by s_i, where $i \leq j$, using randomness $rand$.

Our attempt Our envisioned `B.IncGen` algorithm shows consistency in two steps. First, it uses the `H.IncGen` algorithm from the history tree. This ensures that the snapshots are consistent for the history tree. Second, it selects deterministically and uniformly at random based on $rand$, a number of events $E =< e_j >$ from the history tree. Which events to select from depends on the

two snapshots. For each selected event, the algorithm performs a `query()` for the event key $k_j \leftarrow key(e_j)$ to show that the event is part of the hash treap and points to the index of the event in the history tree.

The `P.IncVerify` algorithm checks the incremental proof in the history tree, $\texttt{verify()} \stackrel{?}{=} \texttt{true}$ for each output of `query()`, and that the events E were selected correctly based on *rand*. Next, we explain an attack, why it works, and possible lessons learned.

Attack Here we explain an attack on our attempt that allows an attacker to hide an arbitrary event that was inserted *before author compromise*. The attacker takes control over both the author and server just after snapshot s_t. Assume that the attacker wants to remove an event e_j from Balloon, where $j \leq t[-1]$. The attacker does the following:

1. Remove the event key $k'_j = \texttt{Hash}(k_j)$, where $k_j \leftarrow key(e_j)$ from the hash treap and insert a random key and rebalance the treap if needed. This results is a modified ADS $\texttt{auth}(D_t)^*$;
2. Generate a set of new events u and update the data structure: $\texttt{update}(u, D_t, \texttt{auth}(D_t)^*, \texttt{s}_t, \texttt{sk}, \texttt{pk})$, resulting in a new snapshot $\texttt{s}_{t+1}$.

It is clear that the snapshot $\texttt{s}_{t+1}$ is inconsistent with all other prior snapshots, $\texttt{s}_p$, where $p \leq t$.

Now, we show how the attacker can avoid being detected by `P.IncVerify` in the case that the verifier challenges the server (and therefore the attacker) to probabilistically prove the consistency between $\texttt{s}_p$ and $\texttt{s}_{t+1}$, AND that the randomness *rand* provided by the verifies selects the event e_j that was modified by the attacker. The attacker can provide a valid incremental proof in the history tree, using `H.IncGen`, since the history tree has not been modified. However, the attacker cannot create a valid membership proof for an event with key $k_j \leftarrow key(e_j)$ in the ADS, since this key was removed from the hash treap in $\texttt{auth}(D_{t+1})$. To avoid detection, the attacker puts back the event key k'_j in the hash treap and rebalances the treap if needed. Now by inserting a set of events using `update`, a *new snapshot* $\texttt{s}_{t+2}$ is generated, which is then used to perform the membership query against that will now output a valid membership proof.

Lessons learnt This attack succeeds because the attacker can, once having compromised the author and server, a) create snapshots at will; and b) membership queries are always performed on the current version of the hash treap.

In settings where snapshots are generated periodically, e.g., once a day, the probability of the attacker getting caught in this way is non-negligible given a sufficient number of queries. However, as long as the attacker can create snapshots at will, the probability that it will be detected with probabilistic incremental proofs is zero, as long as it cannot be challenged to generate past versions of the hash treap; and there are no monitors or another mechanism, that prevent the attacker from modifying or deleting events that were inserted into the ADS prior to compromise.