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Secure History Preservation through Timeline Entanglement

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Abstract

A *secure timeline* is a tamper-evident historic record of the states through which a system goes throughout its operational history. Secure timelines can help us reason about the temporal ordering of system states in a provable manner. We extend secure timelines to encompass multiple, mutually distrustful services, using *timeline entanglement*. Timeline entanglement associates disparate timelines maintained at independent systems, by linking undeniably the past of one timeline to the future of another. Timeline entanglement is a sound method to map a time step in the history of one service onto the timeline of another, and helps clients of entangled services to get persistent temporal proofs for services rendered that survive the demise or non-cooperation of the originating service. In this paper we present the design and implementation of *Timeweave*, our service development framework for timeline entanglement based on two novel disk-based authenticated data structures. We evaluate Timeweave's performance characteristics and show that it can be efficiently deployed in a loosely-coupled distributed system of several hundred nodes with overhead of roughly 2-8% of the processing resources of a PC-grade system.

1 Introduction

A large portion of the functionality offered by current commercial "secure" or "trusted" on-line services focuses on the here and now: certification authorities certify that a public signature verification key belongs to a named signer, secure file systems vouch that the file with which they answer a lookup query is the one originally stored, and trusted third parties guarantee that they do whatever they are trusted to do when they do it.

The concept of *history* has received considerably less attention in systems and security research. What did the certification authority certify a year ago, and which file did the secure file system return to a given query last week?

Interest in such questions is fueled by more than just curiosity. Consider a scenario where Alice, a certified accountant, consults confidential documents supplied by a business manager at client company Norne, Inc. so as to prepare a financial report on behalf of the company for the Securities and Exchange Commission (SEC). If, in the future, the SEC questions Alice's integrity, accusing her of having used old, obsolete financial information to prepare her report, Alice might have to prove to the SEC exactly what information she had received from Norne, Inc. before preparing her report. To do that, she would have to rely on authentic historic data about documents and communication exchanges between herself and Norne, on the authentic, relative and absolute timing of those exchanges, perhaps even on the contents of the business agreement between herself and the company at the time. Especially if the company maliciously chooses to tamper with or even erase its local records to repudiate potential transgressions, Alice would be able to redeem herself only by providing undeniable proof that at the time in question, Norne, Inc. did in fact present her with the documents it now denies.

Besides this basic problem, many other peripheral problems lurk: what if Norne, Inc. no longer exists when Alice has to account for her actions? What if Alice and the SEC belong to different trust domains, i.e., have different certification authorities or different secure time stamping services?

In this work we formulate the concept of secure timelines based on traditional time stamping [5, 11] and authenticated dictionaries [8, 10] (Section 3). Secure timelines allow the maintenance of a persistent, authenticated record of the sequence of states that an accountable service takes during its lifetime.

Furthermore, we describe a technique called *time-*

line entanglement for building a single, common tamper-evident history for multiple mutually distrustful entities (Section 4). First, timeline entanglement enables the temporal correlation of independent histories, thereby yielding a single timeline that encompasses events on independent systems. This correlation can be verified independently in the trust domain of each participant, albeit with some loss of temporal resolution. Second, it allows clients to preserve the provability of temporal relationships among system states, even when the systems whose states are in question no longer participate in the collective, or are no longer in existence.

We then present *Timeweave*, our prototype framework for the development of loosely-coupled distributed systems of accountable services that uses timeline entanglement to protect historic integrity (Section 5). We describe novel, scalable algorithms to maintain secure timelines for extended time periods and for very large data collections. Finally, we evaluate the performance characteristics of Timeweave in Section 6 and show that it efficiently supports large-sized groups of frequently entangled services—up to several hundred—with maintenance overhead that does not surpass 2-8% of the computational resources of a PC-grade server.

2 Background

In this work we draw on results from research on secure time stamping and authenticated dictionaries. The main inspiration behind our approach comes from Lamport's classic logical clock paradigm [14].

2.1 Secure Time Stamping

In secure time stamping, it is the responsibility of a centralized, trusted third party, the *Time Stamping Service* (TSS), to maintain a temporal ordering of submission among digital documents. As documents or document digests are submitted to it, the TSS links them in a tamper-evident chain of authenticators, using a one-way hash function, and distributes portions of the chain and of the authenticators to its clients. Given the last authenticator in the chain it is impossible for anyone, including the TSS, to insert a document previously unseen in the middle of the chain unobserved, without significant collusion, and without finding a second pre-image for the hash function used [11].

Benaloh and de Mare [5] describe synchronous, broadcast-based time stamping schemes where no central TSS is required, and introduce the concept of a time stamping *round*. All documents time stamped during a round are organized in a data structure, flat or hierarchical, and yield a collective digest that can be used to represent all the documents of the entire round, in a tamper-evident manner; given the digest, the existence of exactly the documents inside the data structure can be proved succinctly, and any document outside the data structure can be proved not to be there.

Buldas et al. [8] extend previous work by significantly diminishing the need to trust the TSS. They also introduce efficient schemes for maintaining relative temporal orderings of digital artifacts with logarithmic complexity in the total number of artifacts. A large, concurrent project towards the full specification of a time stamping service is described by Quisquater et al. [21].

Ansper et al. [2] discuss time stamping service availability, and suggest a scheme similar to consensus in a replicated system to allow for fault-tolerant time stamping.

Finally, Schneier and Kelsey propose a flexible scheme to protect access-controlled ordered logs on untrusted machines against tampering or unauthorized retroactive disclosure [23], based extensively on hash chaining. They address the problem in an application setting where historic integrity need be maintained only for the short-term, until the local history is uploaded to a trusted server for evaluation and storage, and where the entities enforcing historic integrity need not be themselves held accountable, as is the case in many corporate intranets.

2.2 Authenticated Dictionaries

Authenticated dictionaries are data structures that operate as tamper-evident indices for a dynamic data set. They help compute and maintain a one-way digest of the data set, such that using this digest and a succinct proof, the existence or non-existence of any element in the set can be proved, without considering the whole set.

The first such authenticated dictionary is Merkle's hash tree [17], originally proposed as a digital signature scheme. Hash trees are binary trees in whose leaves the data set elements are placed. Each leaf node is labeled with the hash of the contained data element and each interior node is labeled with a hash of the concatenated labels of its children. The label of the root node is a tamper-evident digest for the entire data set. The existence proof for an element in the tree consists of the necessary information to derive the root hash from the element in question; specifically, the proof consists of all labels and locations (left or right) of all siblings of nodes on the path from the element to the tree root.

Tree-based authenticated dictionaries reminiscent of Merkle's hash trees are most notably proposed for the distribution of certificate revocation records, first by Kocher [13], and then in an incrementally updatable version by Naor and Nissim [18]. Buldas et al. obviate the need for trusting the dictionary maintainer to keep the dictionary sorted, by introducing the *authenticated search tree* [6, 7]. Authenticated search trees are like hash trees, but all nodes, leaves and internal nodes alike, contain data set elements. The label of the node is a hash not only of the labels of its children, but also of the element of the node. Existence proofs contain node elements in addition to nodes' siblings' labels on the path from the element in question to the root. In this manner, an existence proof follows the same path that the tree maintainer must take to find a sought element; as a result, clients need not unconditionally trust that the tree maintainer keeps the tree sorted, since given a root hash, there is a unique descent path that follows the standard traversal of search trees towards any single element.

Authenticated dictionaries have also been proposed based on different data structures. Buldas et al. [8] describe several tree-like "binary linking schemes." Goodrich et al. [10] propose an authenticated skip list that relies on commutative hashing.

In the recent literature, the maintenance of authenticated but persistent dynamic sets [9, p. 294] has received some attention. Persistent dynamic sets allow modifications of the elements in the set, but maintain enough information to recreate any prior version of the set. Anagnostopoulos et al. [1] propose and implement persistent authenticated skip lists, where not only older versions of the skip list are available, but they are each, by themselves, an authenticated dictionary. In the same work, and also in work by Maniatis and Baker [16], persistent authenticated dictionaries based on red-black trees are sketched in some detail, although the resulting designs are different. Specifically, in the former work, although multiple versions of the authenticated red-black tree are maintained, the collection of versions is itself not authenticated; the latter work uses a second, non-persistent authenticated dictionary to authenticate the tree versions.

3 Secure Timelines

We define a secure timeline within a *service domain.* A service domain comprises a system offering a particular service—the *service* of the domain—and a set of clients who use that system for that service—the *clients* of the domain. Such a service domain could be, for example, the file server and all clients of a secure file system, or an enterprise-wide certification authority along with all certificate subjects within that enterprise.

Within the context of a service domain, a secure timeline is a tamper-evident, temporally-ordered, append-only sequence of the states taken by the service of that domain. In a sense, a secure timeline defines an authenticated logical clock for the service. Each time step of the clock is annotated with the state in which the service is at the time, and an authenticator. The authenticator is tamper-evident: given the authenticator of the latest time step of the timeline, it is intractable for the service or for any other polynomially-bound party to "change history" unobtrusively by altering the annotations or authenticators of past time steps.

In this work, we consider secure timelines based on one-way (second pre-image-resistant) hash functions. Assuming, as is common, that one-way hash functions exist, we use such functions to define the "arrow of time." In other words, given a presumably one-way hash function h such as SHA-1 [19], if $b = h(a)$, then we conclude that value a was known before value b, or *a temporally precedes b*, since given b the probability of guessing the right a is negligible.

A simple recursive way to define a secure timeline is as follows: if at logical time i the clock has authenticator T_i, then at the next logical time step $i + 1$, the hash function h is applied to the previous clock authenticator T_i and to the next state of the system S_{i+1}. Assuming that f is a one-way digest function from system states to digests, then $T_{i+1} = h(i + 1 \| T_i \| f(S_{i+1}))$, where $\|$ denotes concatenation. Given T_{i+1}, it is intractable to produce appropriate α such that $T_{i+1} = h(i + 1 \| T_i{}' \| \alpha)$, so as to make an arbitrary authenticator $T_i{}' \neq T_i$ appear as the timeline authenticator of logical step i, from the second pre-image resistance of the hash function. Similarly, for a given T_{i+1} only a unique state digest $d_{i+1} = f(S_{i+1})$ is probable, and, from the one-way property of the state digest function f, only a unique system state S_{i+1} is probable. Therefore, authenticator T_{i+1} is, in a sense, a one-way digest of all preceding authenticators and system states, as well as of their total temporal ordering.

Many existing accountable services match the secure timeline paradigm, since secure timelines are a generalization of secure time stamping services (TSS) [11]. The service state of a TSS is an authenticated dictionary of all document digests sub-

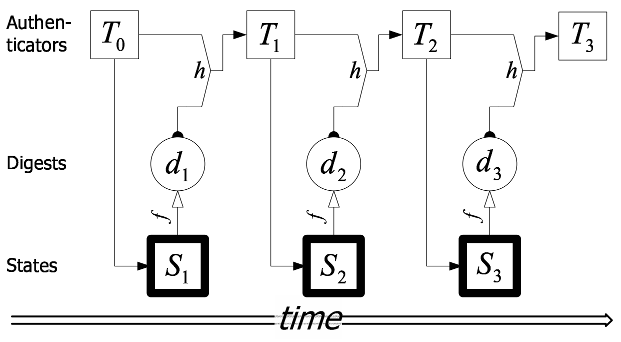


Figure 1: The first few steps of a secure timeline. Time flows from left to right. Note that the current authenticator of the timeline is an input to the next state of the system. We explain one way to accomplish this in Section 5.2.

mitted to it during a time stamping round. The Key Archival Service (KAS) by Maniatis and Baker [16] is another service with a timeline, where the service state is a persistent authenticated dictionary of all certificates and revocation records issued by a Certification Authority. Similarly, any service that maintains one-way digests of its current state can be retrofitted to have a secure timeline. Consider, for example, Kocher's Certificate Revocation Trees (CRT) [13]. The state of the service at the end of each publication interval consists of a hash tree of all published revocation records. The root hash of the CRT is a one-way digest of the database. Consequently, a secure timeline for the revocation service can easily follow from the above construction.

Figure 1 illustrates the first few time steps of a secure timeline. In the figure, the new timeline authenticator is also fed into the new state of the system. Depending on the definition of the state digest function, a new state of the service can be shown to be *fresh*, i.e., to have followed the computation of the authenticator for the previous time step. In Time Stamping Services, this places the time stamp of a document between two rounds of the service. In the Key Archival Service, this bounds the time interval during which a change in the Certification Authority (new certificate, revocation, or refresh) has occurred. In a CRT timeline system, this bounds the time when a revocation database was built. Some authenticated dictionaries can be shown to be fresh(e.g., [8]), and we explain how we handle freshness in Section 5.2.

Secure timelines can be used to answer two basic kinds of questions: *existence questions* and *temporal precedence* questions. Existence questions are of the form "is S the i-th system state?", and are used to establish that the service exhibited a certain kind of behavior at a particular phase in its history. In the time stamping example, an existence question could be "is d the round hash at time i?" A positive answer allows a client to verify the validity of a time stamp from round i, since time stamps from round i are authenticated with the root hash of that round. Temporal precedence questions are of the form "did state S occur before state S'?". In time stamping, answers to precedence questions can establish precedence between two time stamped documents.

Answers to both existence and temporal precedence questions are provable. Given the last authenticator in the timeline, to prove the existence of a state in the timeline's past I have to produce a *one-way path*—a sequence of applications of one-way functions—from that state to the current timeline authenticator. Similarly, to prove that state S precedes state S', I have to show that there exists a one-way path from state S to state S'. For example, in Figure 1, the path from S_1 to T_1, T_2 and then to S_3 is one-way and establishes that state S_1 occurred before S_3. Extending this path to T_3 provides an existence proof for state S_1, if the verifier knows that T_3 is the latest timeline authenticator.

Secure timelines are a general mechanism for *temporal authentication.* As with any other authentication mechanism, timeline proofs are useful only if the authenticator against which they are validated is itself secure and easily accessible to all verifiers, i.e., the clients within the service domain. In other words, clients must be able to receive securely authenticator tuples of the form $\langle i, T_i \rangle$ from the service at every time step, or at coarser intervals. This assumes that clients have a means to open authenticated channels to the service. Furthermore, there must be a unique tuple for every time step i. Either the service must be trusted by the clients to maintain a unique timeline, or the timeline must be periodically "anchored" on an unconditionally trusted write-once publication medium, such as a paper journal or popular newspaper. The latter technique is used by some commercial time stamping services [25], to reduce the clients' need to trust the service.

For the remainder of this paper, "time i" means the state of the service that is current right before timeline element i has been published, as well as the physical time period between the publication of the timeline authenticators for time steps $i-1$ and i. For service A, we denote time i as $\langle A, i \rangle$, the associated timeline authenticator as T_i^A and the precedence proof from i to j as $P_{A,i}^{A,j}$.

4 Timeline Entanglement

In the previous section, we describe how a secure timeline can be used by the clients within a service domain to reason about the temporal ordering of the states of the service in a provable manner. In so doing, the clients of the service have access to tamper-evident historic information about the operation of the service in the past.

However, the timeline of service A does not carry much conviction before a client who belongs to a different, disjoint service domain B, i.e., a client who does not trust service A or the means by which it is held accountable. Consider an example from time stamping where Alice, a client of TSS A, wishes to know when Bob, a client of another TSS B, time stamped a particular document $\mathcal{D}$. A time stamping proof that links $\mathcal{D}$ to an authenticator in B's timeline only is not convincing or useful to Alice, since she has no way to compare temporally time steps in B's timeline to her own timeline, held by A.

This is the void that *timeline entanglement* fills. Timeline entanglement creates a provable temporal precedence from a time step in a secure timeline to a time step in another independent timeline. Its objective is to allow a group of mutually distrustful service domains to collaborate towards maintaining a common, tamper-evident history of their collective timelines that can be verified from the point of view (i.e., within the trust domain) of any one of the participants.

In timeline entanglement, each participating service domain maintains its own secure timeline, but also keeps track of the timelines of other participants, by incorporating authenticators from those foreign timelines into its own service state, and therefore its own timeline. In a sense, all participants *enforce* the commitment of the timeline authenticators of their peers.

In Section 4.1, we define timeline entanglement with illustrative examples and outline its properties. We then explore in detail three aspects of timeline entanglement: *Secure Temporal Mappings* in Section 4.2, the implications of dishonest timeline maintainers in Section 4.3, and *Historic Survivability* in Section 4.4.

4.1 Fundamentals

Timeline entanglement is defined within the context of an *entangled service set*. This is a dynamically changing set of service domains. Although an entangled service set where all participating domains offer the same kind of service is conceivable—such as, for example, a set of time stamping services—we envision many different service types, time stamping services, certification authorities, historic records services, etc., participating in the same entangled set. We assume that all participating services know the current membership of the entangled service set, although inconsistencies in this knowledge among services does not hurt the security of our constructs below. We also assume that members of the service set can identify and authenticate each other, either through the use of a common public key infrastructure, or through direct out-of-band key exchanges.

Every participating service defines an independent sampling method to select a relatively small subset of its logical time steps for entanglement. For example, a participant can choose to entangle every n-th time step. At every time step picked for entanglement, the participant sends an authenticated message that contains its signed logical time and timeline authenticator to all other participants in the entangled service set. This message is called a *timeline thread*. A timeline thread sent from A at time $\langle A, i\rangle$ is denoted as t_i^A and has the form $[A, i, T_i^A, \sigma_A\{A, i, T_i^A\}]$. $\sigma_A\{X\}$ represents A's signature on message X.

When participant B receives a correctly signed timeline thread from participant A, it verifies the consistency of that thread with its local view of collective history and then archives it. Thread t_i^A is consistent with B's local view of collective history if it can be proved to be on the same one-way path (hash chain) as the last timeline authenticator of A that B knows about (see Figure 2). Towards this goal, A includes the necessary temporal precedence proof, as described in Section 3, along with the thread that it sends to B. In the figure, when thread t_i^A reaches B, the most recent timeline authenticator of A that B knows is T_l^A. Along with the thread, A sends the precedence proof $P_{A,l}^{A,i}$ from its time $\langle A, l\rangle$ to time $\langle A, i\rangle$. As a result, B can verify that the new thread carries a "legitimate" timeline authenticator from A, one consistent with history. If everything checks out, B archives the new timeline authenticator and associated precedence proof in its local *thread archive*.

Thread archives store tuples of the form $[t_i^A, P_{A,l}^{A,i}]$. A thread archive serves two purposes: first, it maintains a participant's local knowledge of the history of the entangled service set. Specifically, it archives proof that every participant it knows about maintains a consistent timeline. It accomplishes this by simply storing the threads, which are snapshots in the sender's timeline, and supporting

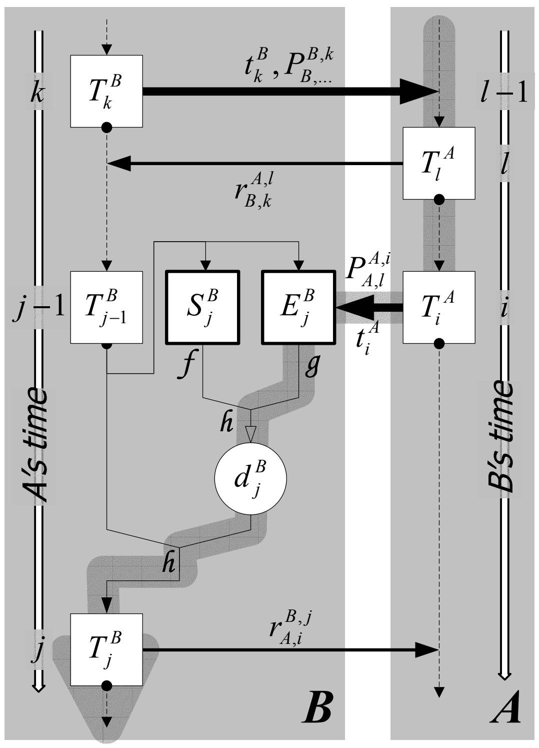


Figure 2: Entanglement exchanges between participants A and B. The workings of B are shown in detail. We show two entanglement exchanges, one of time $\langle B, k\rangle$ with time $\langle A, l\rangle$, and one of time $\langle A, i\rangle$ with time $\langle B, j\rangle$. Thick black horizontal arrows show timeline thread messages. Thin black horizontal arrows show entanglement receipt messages. Vertical black arrows show one-way operations. The thick shadowed arrow shows the temporal ordering effected by thread t_i^A and its receipt $r_{A,i}^{B,j}$.

precedence proofs, which connect these snapshots in a single one-way chain. The second purpose of the thread archive is to maintain temporal precedence proofs between every foreign thread it contains and local timeline steps. It accomplishes this by constructing a one-way digest of its contents as they change, and then using that digest along with the system state digest, to derive the next local timeline authenticator (Section 5.2 describes how the thread archive is implemented). In the figure, B's system state S_j^B and updated thread archive E_j^B are combined into d_j^B, which then participates in the computation of the next timeline authenticator T_j^B.

Participant B responds to the newly reported timeline authenticator with an *entanglement receipt.* This receipt proves that the next timeline authenticator that B produces is influenced partly by the archiving of the thread it just received. The receipt must convince A of three things: first, that its thread was archived; second, that the thread was archived in the latest—"freshest"—version of B's thread archive; and, third, that this version of the thread archive is the one whose digest is used to derive the next timeline authenticator that B produces. As a result, the entanglement receipt $r_{A,i}^{B,j}$ that B returns to A for the entanglement of thread t_i^A consists of three components: first, a precedence proof $P_{B,k}^{B,j-1}$ from the last of B's timeline authenticators that A knows about, T_k^B, to B's timeline authenticator T_{j-1}^B right before archiving A's new thread; second, an existence proof showing that the timeline thread t_i^A is archived in the latest, freshest version E_j^B of B's thread archive after the last authenticator T_{j-1}^B was computed; and, third, a one-way derivation of the next timeline authenticator of B from the new version of the thread archive and the current system state S_j^B. It is now A's turn to check the validity of the proofs in the entanglement receipt. If all goes well, A stores the proof of precedence and reported timeline authenticator from B in its *receipt archive.* This concludes the entanglement process from time $\langle A, i\rangle$ to time $\langle B, j\rangle$.

The receipt archive is similar to the thread archive; it stores entanglement receipts that the participant receives in response to its own timeline threads.

After the entanglement of time $\langle A, i\rangle$ with time $\langle B, j\rangle$, both A and B have in their possession portable temporal precedence proofs ordering A's past before B's future. Any one-way process at A whose result is included in the derivation of T_i^A or earlier timeline authenticators at A can be shown to have completed before any one-way process at B that includes in its inputs T_j^B or later timeline authenticators at B.

In this definition of timeline entanglement, a participating service entangles its timeline at the predetermined sample time steps with all other services in the entangled service set (we call this *all-to-all entanglement*). In this work we limit the discussion to all-to-all entanglement only, but we describe a more restricted, and consequently less expensive, entanglement model in future work (Section 7).

The primary benefit of timeline entanglement is its support for *secure temporal mapping.* A client in one service domain can use temporal information maintained in a remote service domain that he does not trust, by mapping that information onto his own service domain. This mapping results in some loss of temporal resolution—for example, a time instant maps to a positive-length time interval. We describe secure temporal mapping in Section 4.2.

Timeline entanglement is a sound method of expanding temporal precedence proofs outside a service domain; it does not prove incorrect precedences. However it is not complete, that is, there are some precedences it cannot prove. For example, it is possible for a dishonest service to maintain clandestinely two timelines, essentially "hiding" the commitment of some of its system states from some members of the entangled service set. We explore the implications of such behavior in Section 4.3.

Finally, we consider the survivability characteristics of temporal proofs beyond the lifetime of the associated timeline, in Section 4.4.

4.2 Secure Temporal Mapping

Temporal mapping allows a participating service A to map onto its own timeline a time step $\langle B, i\rangle$ from the timeline of another participant B. This mapping is denoted by $\langle B, i\rangle \mapsto A$. Since A and B do not trust each other, the mapping must be secure; this means it should be practically impossible for B to prove to A that $(\langle B, i\rangle \mapsto A) = (\langle A, j\rangle, \langle A, k\rangle]$, if $\langle B, i\rangle$ occurred before or at $\langle A, j\rangle$, or after $\langle A, k\rangle$.

Figure 3 illustrates the secure temporal mapping $\langle B, 2\rangle \mapsto A$. To compute the mapping, A requires only local information from its thread and receipt archives. First, it searches in its receipt archive for the latest entanglement receipt that B sent back before or at time $\langle B, 2\rangle$, receipt $r^{B,1}_{A,1}$ in the example. As described in Section 4, this receipt proves to A that its time $\langle A, 1\rangle$ occurred before B's time $\langle B, 1\rangle$.

Then, A searches in its thread archive for the earliest thread that B sent it after time $\langle B, 2\rangle$, which is thread t^B_3 in the example. This thread proves to A that its time $\langle A, 5\rangle$ occurred at or after time $\langle B, 3\rangle$. Recall, also, that when A received t^B_3 in the first place, it had also received a temporal precedence proof from $\langle B, 1\rangle$ to $\langle B, 3\rangle$, which in the straightforward hash chain case, also includes the system state digest for $\langle B, 2\rangle$. Now A has enough information to conclude that $(\langle B, 2\rangle \mapsto A) = (\langle A, 1\rangle, \langle A, 5\rangle]$.

Since A has no reason to believe that B maintains its timeline in regular intervals, there is no more that A can assume about the temporal placement of state S^B_2 within the interval $(\langle A, 1\rangle, \langle A, 5\rangle]$. This results in a *loss of temporal resolution*; in the figure, this loss is illustrated as the difference between the length on B's timeline from $\langle B, 1\rangle$ to $\langle B, 2\rangle$ (i.e., the "duration" of time step $\langle B, 2\rangle$) and the length of the segment on A's timeline from $\langle A, 1\rangle$ to $\langle A, 5\rangle$ (the duration of $\langle B, 2\rangle \mapsto A$). This loss is higher when A and B exchange thread messages infrequently. It can be made lower, but only at the cost of increasing the frequency with which A and B send threads to each other, which translates to more messages and more computation at A and B. We explore this trade-off in Section 6.

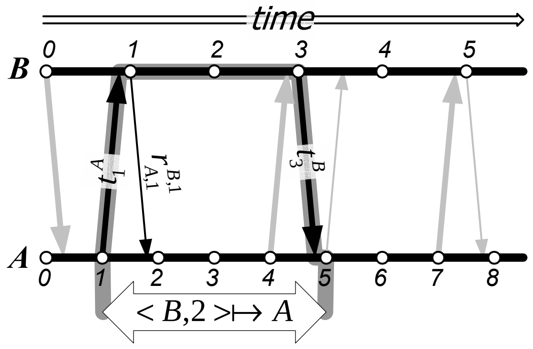


Figure 3: Secure mapping of time $\langle B, 2\rangle$ onto the timeline of A. Thick arrows indicate timeline threads. Thin arrows indicate entanglement receipts (only the relevant entanglement receipts are shown). Irrelevant thread and receipt messages are grayed-out. The dark broken line illustrates the progression of values that secure the correctness of the mapping.

Secure time mapping allows clients within a service domain to determine with certainty the temporal ordering between states on their own service and on remote, untrusted service domains. Going back to the time stamping example, assume that Alice has in her possession a time stamp for document $\mathcal{C}$ in her own service domain A, which links it to local time $\langle A, 7\rangle$, and she has been presented by Bob with a time stamp on document $\mathcal{D}$ in his service domain B, which links Bob's document to time $\langle B, 2\rangle$. Alice can request from A the time mapping $\langle B, 2\rangle \mapsto A$, shown above to be $(\langle A, 1\rangle, \langle A, 5\rangle]$. With this information, Alice can be convinced that her document $\mathcal{C}$ was time stamped after Bob's document $\mathcal{D}$ was, regardless of whether or not Alice trusts Bob or B.

In the general case, not all time steps in one timeline map readily to another timeline. To reduce the length of temporal precedence proofs, we use hash skip lists (Section 5.1) instead of straightforward hash chains in Timeweave, our prototype. Temporal precedence proofs on skip lists are shorter because they do not contain every timeline authenticator from the source to the destination. In timelines implemented in this manner, only time steps included in the skip list proof can be mapped without the cooperation of the remote service. For other mappings, the remote service must supply additional, more detailed precedence proofs, connecting the time authenticator in question to the time authenticators that the requester knows about.

4.3 Historic Integrity

Timeline entanglement is intended as an artificial enlargement of the class of usable, temporal orderings that clients within a service domain can determine undeniably. Without entanglement, a client can determine the provable ordering of events only on the local timeline. With entanglement, one-way paths are created that anchor time segments from remote, untrusted timelines onto the local timeline.

However, the one-way properties of the digest and hash functions used make timelines secure only as long as everybody is referring to the same, single timeline. If, instead, a dishonest service maintains clandestinely two or more timelines or branches of the same timeline, publishing different timeline authenticators to different subsets of its users, then that service can, in a sense, revise history. Just [12] identified such an attack against early time stamping services. Within a service domain, this attack can be foiled by enforcing that the service periodically commit its timeline on a write-once, widely published medium, such as a local newspaper or paper journal. When there is doubt, a cautious client can wait to see the precedence proof linking the timeline authenticator of interest to the next widely published authenticator, before considering the former unique.

Unfortunately, a similar attack can be mounted against the integrity of collective history, in an entangled service set. Entanglement, as described in Section 4, does not verify that samples from B's timeline that are archived at A and C are identical. If B is malicious, it can report authenticators from one chain to A and from another to C, undetected (see Figure 4). In the general case, this does not dilute the usability of entanglement among honest service domains. Instead, it renders unprovable some interactions between honest and dishonest service domains. More importantly, attacks by a service against the integrity of its own timeline can only make external temporal precedence information involving that timeline inconclusive; such attacks cannot change the temporal ordering between time steps on honest and dishonest timelines. Ultimately, it is solely the clients of a dishonest service who suffer the consequences.

Consider, for instance, the scenario of Figure 4. Dishonest service B has branched off its originally unique timeline into two separate timelines at its time $\langle B, 2\rangle$. It uses the top branch, with times $3'$, $4'$, etc., in its entanglements with service C, and its bottom branch, with times 3, 4, etc., in its entanglements with service A. From A's point of view, event

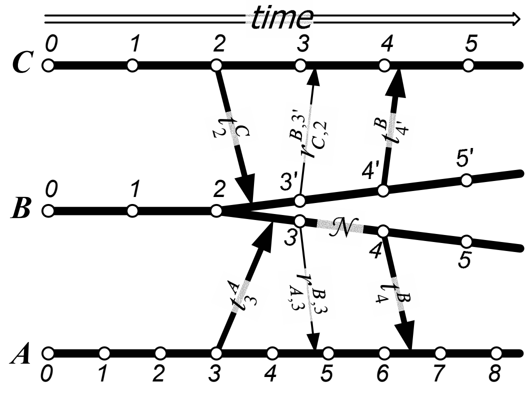


Figure 4: An example showing a dishonest service B that maintains two timelines, entangling one with A and another with C. Event $\mathcal{N}$ is committed on the bottom branch of B's timeline, but does not appear on the top branch.

$\mathcal{N}$ is incorporated in B's state and corresponding timeline at time $\langle B, 4\rangle$. From C's point of view, however, event $\mathcal{N}$ seems never to have happened. Since $\mathcal{N}$ does not appear in the branch of B's timeline that is visible to C, C's clients cannot conclusively place event $\mathcal{N}$ in time at all. Therefore, only the client of B who is responsible for event $\mathcal{N}$ suffers from this discrepancy. C does not know about it at all, and A knows its correct relative temporal position.

We describe briefly a method for enforcing timeline uniqueness within an entangled service set in Section 7.

4.4 Historic Survivability

Historic survivability in the context of an entangled set of services is the decoupling of the verifiability of existence and temporal precedence proofs within a timeline from the fate of the maintainer of that timeline.

Temporal proofs are inherently survivable because of their dependence on well-known, one-way constructs. For example, a hash chain consisting of multiple applications of SHA-1 certainly proves that the result of the chain temporally followed the input to the chain. However, this survivability is moot, if the timeline authenticators that the proof orders undeniably can no longer be interpreted or associated with a real time frame.

Fortunately, secure temporal mapping allows a client within a service domain to fortify a temporal proof that he cares about against the passing of the local service. The client can accomplish this by participating in more service domains than one; then, he can proactively map the temporal proofs he cares about from their source timeline onto all the timelines of the service domains in which he belongs. In this manner, even if all but one of the services with which he is associated become unavailable or go out of business, the client may still associate his proofs with a live timeline in the surviving service domain.

Consider, for example, the scenario illustrated in Figure 5. David, who belongs to all three service domains A, B and C, wishes to fortify event $\mathcal{N}$ so as to be able to place it in time, even if service B is no longer available. He maps the event onto the timelines of A and C—"mapping an event $\mathcal{N}$" is equivalent to mapping the timeline time step in whose system state event $\mathcal{N}$ is included, that is, $\langle B, 2\rangle$ in the example. Even though the event occurred in B's timeline, David can still reason about its relative position in time, albeit with some loss of resolution, in both the service domains of A and C, long after B is gone. In a sense, David "hedges his bets" among multiple services, hoping that one of them survives. Note also that the fortification of even $\mathcal{N}$ can occur long after its occurrence. The use of temporal mapping in this context is similar in scope to the techniques used by Ansper et al. [2] for fault-tolerant time stamping services, although it assumes far less mutual trust among the different service domains.

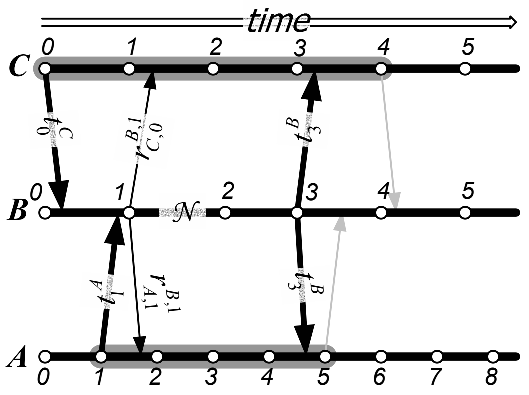


Figure 5: An example of mapping event $\mathcal{N}$ onto two other timelines, to obtain a survivable proof of its temporal position. The top shaded line represents $(\mathcal{N} \mapsto C)$ and the bottom shaded line represents $(\mathcal{N} \mapsto A)$.

5 Implementation

We have devised two new, to our knowledge, disk-oriented data structures for the implementation of Timeweave, our timeline entanglement prototype. In Section 5.1, we present authenticated append-only skip lists. These are an efficient optimization of traditional hash chains and yield precedence proofs with size proportional to the square logarithm of the total elements in the list, as opposed to linear. In Section 5.2, we present RBB-Trees, our disk-based, persistent authenticated dictionaries based on authenticated search trees. RBB-Trees scale to larger sizes than current in-memory persistent authenticated dictionaries, while making efficient use of the disk. Finally, in Section 5.3, we outline how Timeweave operates.

5.1 Authenticated Append-only Skip Lists

Our basic tool for maintaining an efficient secure timeline is the authenticated append-only skip list. The authenticated append-only skip list is a modification of the simplistic hash chain described in Section 3 that yields improved access characteristics and shorter proofs.

Our skip lists are deterministic, as opposed to the randomized skip lists proposed in the literature [20]. Unlike the authenticated skip lists introduced by Goodrich et al. [10], our skip lists are append-only, which obviates the need for commutative hashing. Every list element has a numeric identifier that is a counter from the first element in the list (the first element is element 1, the tenth element is element 10, and so on); the initial authenticator of the skip list before any elements are inserted is element 0. Every inserted element carries a data value and an authenticator, similarly to what was suggested in Section 3 for single-chain timelines.

The skip list consists of multiple parallel hash chains at different levels of detail, each containing half as many elements as the previous one. The basic chain (at *level 0*) links every element to the authenticator of the one before it, just like simple hash chains. The next chain (at level 1) coexists with the level 0 chain, but only contains elements whose numeric identifiers are multiples of 2, and every element is linked to the element two positions before it. Similarly, only elements with numeric identifiers that are multiples of 2^i are contained in the hash chain of level i. No chains of level $j > \log_2 n$ are maintained, if all elements are n.

The authenticator T_i of element i with data value d_i is computed from a hash of all the partial authenticators (called *links*) from each basic hash chain in which the element participates. Element $i = 2^l k$, where 2 does not divide k, participates in $l + 1$ chains. It has the $l + 1$ links $L_i^j = h(i, j, d_i, T_{i-2^j})$,

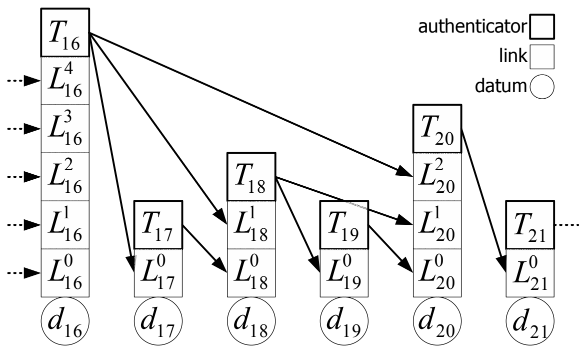


Figure 6: Six consecutive skip list elements, element 16 to element 21. Arrows show hash operations from previous authenticators to links of an element. The top of each tower is the resulting authenticator for the element, derived by hashing together all links underneath it.

$0 \leq j \leq l$, and authenticator $T_i = h(L^0_i \| \ldots \| L^l_i)$. Figure 6 illustrates a portion of such a skip list. In the implementation, we combine together the element authenticator with the 0-th level link for odd-numbered elements, since such elements have a single link, which is sufficient as an authenticator by itself.

Skip lists allow their efficient traversal from an element i to a later element j in a logarithmic number of steps: starting from element i, successively higher-level links are utilized until the "tallest element" (one with the largest power of 2 in its factors among all element indices between i and j) is reached. Thereafter, successively lower-level links are traversed until j is reached. More specifically, an iterative process starts with the current element $c = i$. To move closer to the destination element with index j, the highest power 2^z of 2 that divides c is picked, such that $c + 2^z \leq j$. Then element $k = c + 2^z$ becomes the next current element c in the traversal. The iteration stops when $c = j$.

The associated temporal precedence proof linking element i before element j is constructed in a manner similar to the traversal described above. At every step, when a jump of length 2^z is taken from the current element c to $k = c + 2^z$, the element value of the new element d_k is appended to the proof, along with all the associated links of element k, except for the link at level z. Link L^z_k is omitted since it can be computed during verification from the previous authenticator T_c and the data value d_k.

In the example of Figure 6, the path from element 17 to element 21 traverses elements 18 and 20. The corresponding precedence proof from element 17 to element 21 is $P^{21}_{17} = \{d_{18}, L^1_{18}; d_{20}, L^0_{20}, L^2_{20}; d_{21}\}$. With this proof and given the authenticators T_{17} and T_{21} of elements 17 and 21 respectively, the verifier can successively compute $T'_{18} = h(h(18\|0\|d_{18}\|T_{17})\|L^1_{18})$, then $T'_{20} = h(L^0_{20}\|h(20\|1\|d_{20}\|T'_{18})\|L^2_{20})$ and finally $T'_{21} = h(21\|0\|d_{21}\|T'_{20})$—recall that for all odd elements i, $T_i = L^0_i$. If the known and the derived values for the authenticator agree ($T_{21} = T'_{21}$), then the verifier can be convinced that the authenticator T_{17} preceded the computation of authenticator T_{21}, which is the objective of a precedence proof.

Thanks to the properties of skip lists, any of these proofs contains links and data values of roughly a logarithmic number of skip list elements. The worst-case proof for a skip list of n elements traverses $2 \times \log_2(n)$ elements, climbing links of every level between 0 and $\log_2(n)$ and back down again, or $\log^2_2(n)$ link values and $\log_2(n)$ data values total. Assuming that every link and value is a SHA-1 digest of 160 bits, the worst case proof for a timeline of a billion elements is no longer than 20 KBytes, and most are much shorter.

Our skip lists are fit for secondary storage. They are implemented on memory-mapped files. Since modifications are expected to be relatively rare, compared to searches and proof extractions, we always write changes to the skip list through to the disk immediately after they are made, to maintain consistency in the face of machine crashes. We do not, however, support structural recovery from disk crashes; we believe that existing file system and redundant disk array technologies are adequate to prevent and recover all but the most catastrophic losses of disk bits.

5.2 Disk-based Persistent Authenticated Dictionaries

This work uses authenticated persistent dictionaries based on trees. A persistent dictionary maintains multiple versions (or *snapshots*) of its contents as it is modified. In addition to the functionality offered by simple authenticated dictionaries, it can also provably answer questions of the form "in snapshot t, was element d in the dictionary?".

The dictionaries we use in this work can potentially grow very large, much larger than the sizes of current main memories. Therefore, we have extended our earlier work on balanced persistent authenticated search trees [16] to design on-disk persistent authenticated dictionaries. The resulting data structure, the *RBB-Tree*, is a binary authenticated search tree [6, 7] embedded in a persistent B-Tree [4][9, Ch. 18]. Figure 7 shows a simple RBB-Tree holding 16 numeric keys.

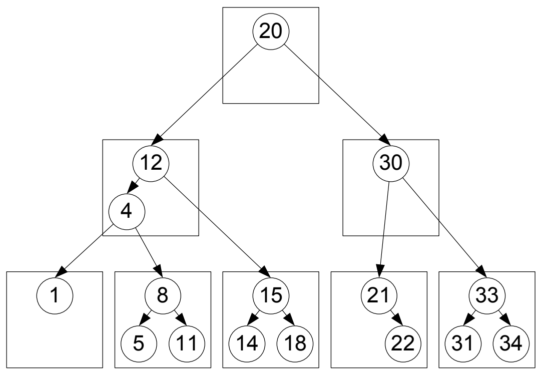


Figure 7: An RBB-Tree. Boxes are disk blocks. In this example, each non-root disk block contains a minimum of 1 and a maximum of 3 keys. The authentication labels of the embedded binary tree nodes are not shown; the label of any key node is the hash of the label of its left child, its own key, and the label of its right child, as in [6, 7]. We do not show the "color" attribute of the keys in the per-node red-black trees, since they have no bearing in our discussion.

RBB-Trees, like B-Trees, are designed to organize keys together in efficient structures that result in few disk accesses per tree operation. Every tree node is stored in its own disk block, contains a minimum of $r-1$ and a maximum of $2r-1$ keys, and has between r and $2r$ children (the root node is only required to have between 1 and $2r-1$ keys). Parameter r is the *order* of the B-Tree.

Unlike traditional B-Trees, RBB-Tree nodes do not store their keys in a flat array. Instead, keys within RBB nodes are organized in a balanced binary tree, specifically a red-black tree [3][9, Ch. 13]. We consider RBB-Trees "virtual" binary trees, since the in-node binary trees connected to each other result in a large, piecewise-red-black tree, encompassing all keys in the entire dictionary.

It is this "virtual" binary tree of keys that is authenticated, in the sense of the authenticated search trees by Buldas et al. [6, 7]. As such, the security properties of RBB-Trees are identical to those of authenticated search trees, including the structure of existence/non-existence proofs.

Since the RBB-Tree is a valid B-Tree, it is efficient in the number of disk block accesses it requires for the basic tree operations of insertion, deletion and modification. Specifically, each of those operations takes $\mathcal{O}(\log_r n)$ disk accesses, where n is the total number of keys in the tree. Similarly, since the internal binary tree in each RBB-Tree node is balanced, the virtual embedded binary tree is also loosely balanced, and has height $\mathcal{O}((\log_r n)(\log_2 r))$, that is, $\mathcal{O}(\log_2 n)$ but with a higher constant factor than in a real red-black tree. These two collaborating types of balancing applied to the virtual binary tree—the first through the blocking of keys in RBB nodes, and the second through the balancing of the key nodes inside each RBB node—help keep the length of the resulting existence/non-existence proofs also bounded to $\mathcal{O}(\log_2 n)$ elements.

The internal key structure imposed on RBB-Tree nodes does not improve the speed of search through the tree over the speed of search in an equivalent B-Tree, but limits the length of existence proofs immensely. The existence proof for a datum inside an authenticated search tree consists of the search keys of each node from the sought datum up to the root, along with the labels of the siblings of each of the ancestors of the sought datum up to the root [6]. In a very "bushy" tree, as B-Trees are designed to be, this would mean proofs containing authentication data from a small number of individual nodes; unfortunately, each individual node's authentication data consist of roughly r keys and r siblings' labels. For example, a straightforwardly implemented authenticated B-Tree storing a billion SHA-1 digests with $r = 100$ yields existence proofs of length $\lceil \log_r 10^9 \rceil \times (r \times (160 + 160))$ bits, or roughly 160 KBits. The equivalent red-black tree yields existence proofs of no more than $2 \times \lceil \log_2 10^9 \rceil \times (160 + 160)$ bits, or about 18 KBits. RBB-Trees seek to trade off the low disk access costs of B-Trees with the short proof lengths of red-black trees. The equivalent RBB-Tree of one billion SHA-1 digests yields proofs no longer than

$$\overbrace{\lceil \log_r 10^9 \rceil}^{\text{B}-\text{Tree height}} \times \overbrace{2 \times \lceil \log_2 r \rceil}^{\text{max red}-\text{black tree height}} \times \overbrace{(160 + 160)}^{\text{key and label}}$$

bits or roughly 22 KBits, with disk access costs identical to those of the equivalent B-Tree.

We have designed dynamic set persistence [9, p. 294] at the granularity of both the RBB node and the embedded key node (see Figure 8). As long as there is key-node space available within an RBB node, new snapshots of the key tree within that node are collocated with older snapshots. This allows multiple snapshots to share unchanged key nodes within the same RBB node. When, however, all available key-node space within an RBB node is exhausted, subsequent snapshots of the key tree inside that node are migrated to a new, fresh RBB node.

The different persistent snapshot roots of the RBB-Tree are held together in an authenticated linked list—in fact, we use our own append-only authenticated skip list from Section 5.1.

Since each snapshot of the RBB-Tree is a "virtual" binary authenticated search tree, the root la-

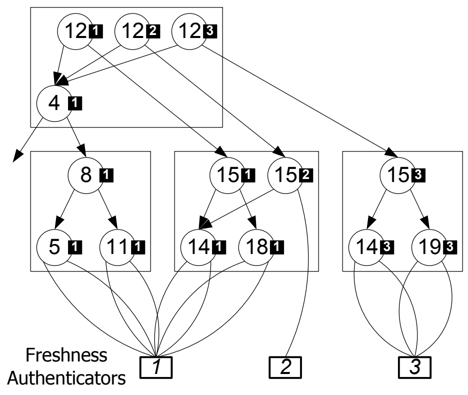


Figure 8: A detail from the tree of Figure 7 illustrating dynamic set persistence. Each key node (circle) indicates the snapshot to which it belongs (small black box). The subtree below the 12 key node of snapshot 1 is identical to that of the original tree in Figure 7. Snapshot 2 occurs when key 18 is removed from snapshot 1. As a result, snapshot 2 has its own key nodes for 12 and 15. Snapshot 3 occurs when key 19 is inserted into snapshot 2. The RBB node previously holding 14 and 15 has no more room for key nodes, so a new RBB node is created to hold the new key nodes 14, 15 and 19 in snapshot 3. At the bottom, the freshness authenticators for each of the three snapshots are shown. A key node without children uses the freshness authenticator of its snapshot when calculating its hash label.

bel of that tree (i.e., the label of the root key node of the root RBB node) is a one-way digest of the snapshot [6, 7]. Furthermore, the authenticated skip list of those snapshot root labels is itself a one-way digest of the sequence of snapshot roots. As a result, the label of the last element of the snapshot root skip list is a one-way digest of the entire history of operations of the persistent RBB-Tree. The snapshot root skip list subsumes the functionality of the Time Tree in our earlier persistent authenticated red-black tree design [16].

In some cases the “freshness” of an authenticated dictionary snapshot has to be provable. For example, in our description of secure timelines, we have specified that the system state must depend on the authenticator of the previous timeline time step. When the system state is represented by an authenticated dictionary, an existence proof within that dictionary need not only show that a sought element is part of the dictionary given the dictionary digest (root hash), but also that the sought element was added into the dictionary *after* the authenticator of the previous time step was known.

As with other authenticated dictionaries, we accomplish this by making the hash label of NIL pointers equal to the “freshness” authenticator, so that all existence proofs of newly inserted elements—equivalently, non-existence proofs of newly removed elements—prove that they happened after the given freshness authenticator was known. Note that subtrees of the RBB-Tree that do not change across snapshots retain their old freshness authenticators. This is acceptable, since freshness is only necessary to prove to a client that a requested modification was just performed (for example, when we produce entanglement receipts in Section 4), and is required only of newly removed or inserted dictionary elements. In the figure, the label for key node 19 is derived from the freshness authenticator for snapshot 3, since 19 is added into the tree in snapshot 3. This establishes that the tree changed to receive key 19 after the value of the freshness authenticator for snapshot 3 was known.

In standalone RBB-Trees, the freshness authenticator is simply the last authenticator in the snapshot root list (i.e., the authenticator that resulted from the insertion of the latest closed snapshot root into the skip list). In the RBB-Trees that we use for thread archives in Timeweave (Section 5.3), the freshness authenticator for snapshot i is exactly the authenticator of the previous timeline time step T_{i-1}.

5.3 Timeweave

Timeweave is an implementation of the timeline entanglement mechanisms described in Section 4. It is built using our authenticated append-only skip lists (Section 5.1) and our on-disk persistent authenticated search trees (Section 5.2).

A Timeweave machine maintains four components: first, a service state, which is application specific, and the one-way digest mechanism thereof; second, its secure timeline; third, a persistent authenticated archive of timeline threads received; and, fourth, a simple archive of entanglement receipts received.

The timeline is stored as an append-only authenticated skip list. The system digest used to derive the timeline authenticator at every logical time step is a hash of the concatenation of the service state digest and the digest of the thread archive after any incoming and outgoing threads have been recorded.

The thread archive contains threads sent by remote peers and verified locally. Such threads are contained both in thread messages initiated remotely and in entanglement receipts to outgoing threads. The archived threads are ordered by the identity of the remote peer in the entanglement operation, and then by the foreign logical time associated with the operation. The archive is implemented as an RBB-Tree and has a well-defined mechanism for calculating its one-way digest, described in Section 5.2.

The receipt archive is a simple (not authenticated) repository of thread storage receipts for all outgoing threads successfully acknowledged by remote peers.

The main operational loop of a Timeweave machine is as follows:

1. Handle client requests and update system state digest $f(S)$.
2. Insert all valid, newly obtained timeline threads into thread archive E and update thread archive digest $g(E)$.
3. Hash together the digests to produce system digest $d = h(f(S) \| g(E))$.
4. Append d into the timeline skip list, resulting in a new timeline authenticator T, and sign the authenticator.
5. Set the new timeline authenticator as the freshness authenticator in the next snapshot of the thread archive and, potentially, of the application-specific system state.
6. For all incoming timeline threads just archived, construct and return receipts to thread senders.
7. If it is time to send an outgoing timeline thread, send one to all peers, and store the receipts in the thread and receipt archives.

The Timeweave machine also allows clients to request local temporal mappings of remote logical times and temporal precedences between local times.

6 Evaluation

In this section, we evaluate the performance characteristics of timeline entanglement. First, in Section 6.1, we present measurements from a Java implementation of the Timeweave infrastructure: authenticated append-only skip lists and RBB-Trees. Then, in Section 6.2, we explore the performance characteristics of Timeweave as a function of its basic Timeweave system parameter, entanglement load.

In all measurements, we use a lightly loaded dual Pentium III Xeon computer at 1 GHz, with

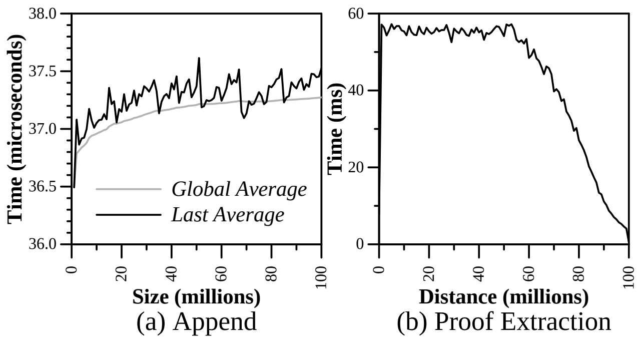


Figure 9: Skip list performance. (a) Append time vs. skip list size. Note that the y axis does not start from 0. "Global average" shows average performance over all operations; "last average" shows performance during the last one million operations for a given size. (b) Proof extraction time vs. proof distance. For each distance, 1,000 proofs from uniformly random starting elements are averaged.

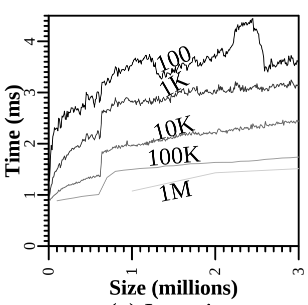
2 GBytes of main memory, running RedHat Linux 7.2, with the stock 2.4.9-31smp kernel and Sun Microsystems' JVM 1.3.02. The three disks used in the experiments are model MAJ3364MP made by Fujitsu, which offer 10,000 RPMs and 5 ms average seek time. We use a disk block size of 64 KBytes. Finally, for signing we use DSA with SHA-1, with a key size of 1024 bits.

6.1 Data Structure Performance

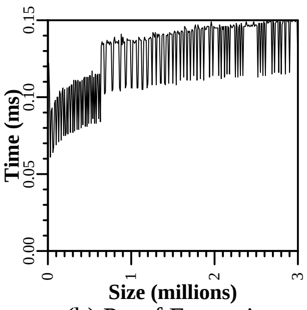
We measure the raw performance characteristics of our disk-based authenticated data structures. Since Timeweave relies heavily on these two data structures, understanding their performance can help evaluate the performance limitations of Timeweave.

Figure 9(a) shows the performance of skip list appends, for skip list sizes ranging from one million to 100 million elements, in increments of one million elements. The figure graphs the time taken by a single append operation averaged over all operations for a given size, and averaged over the last one million operations for a given size. As expected, the time taken by append operations grows logarithmically with the size of the skip list, although for practical skip list sizes, the cost per append operation is virtually constant.

We also measure the performance of skip list proof extraction, in Figure 9(b). The figure graphs the time it takes to extract a precedence proof from a 100-million element skip list for a given distance between the end-points of the proof (the distance between elements i and j is $j - i$ elements). We average over 1,000 uniformly random proof extractions



(a) Insertion



(b) Proof Extraction

Figure 10: RBB-Tree performance for different snapshot sizes. Curve labels indicate the number of keys per snapshot—from 100 keys to one million keys per snapshot. (a) Insertion time vs. tree size. (b) Proof extraction time vs. tree size. The "knee" around 0.8 million elements is due to the overflow of the disk block cache.

Keys per snapshot	100	1K	10K	100K	1M
Tree Size (GB)	18	13	7	2	0.5

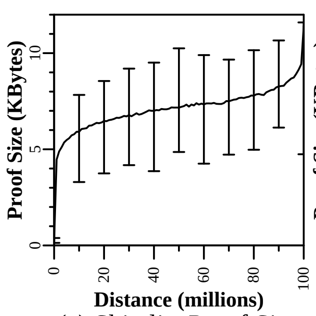
Table 1: RBB-Tree size on disk as a function of the snapshot size used to build it. Sizes shown correspond to trees with three million keys.

per distance. For small distances, different proofs fall within vastly different disk blocks, making proof extraction performance heavily I/O bound. For larger distances approaching the entire skip list size, random proofs have many disk blocks in common, amortizing I/O overheads and lowering the average cost.

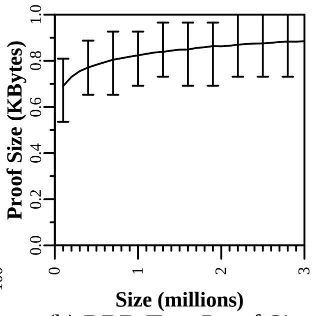
We continue by evaluating the performance characteristics of RBB-Trees. Figure 10 contains two graphs, one showing how insertion time grows with tree size (Figure 10(a)) and another showing how proof extraction time grows with tree size (Figure 10(b)).

Smaller snapshot sizes have two effects: more disk blocks for the same number of elements and more hashing. The number of disk blocks used is higher because some keys are replicated across more snapshots; the amount of hashing is higher since every new copy of a key node must have a new hash label calculated. The first effect is evidenced in Table 1, which shows the disk size of a three-million-key RBB-Tree with varying snapshot sizes. The second effect is evidenced in Figure 10(a), plotting insertion times for different snapshot sizes.

Proof extraction experiments consisted of 1,000 random searches for every size increment. This operation, which consists of a tree traversal from the root of the tree to a leaf, is not affected by snapshot size, but only by tree size (tree height, specifically).



(a) Skip list Proof Size



(b) RBB-Tree Proof Size

Figure 11: Proof sizes (minimum, average, maximum) in skip lists and RBB-Trees. (a) Proof size vs. distance between the skip list proof end points. (b) Proof size vs. RBB-Tree size.

Neither the traversed logical "shape" of the tree, nor the distribution of keys into disk blocks are dependent on how frequently a tree snapshot is archived.

Finally, we graph proof sizes in skip lists (Figure 11(a)) and RBB-Trees (Figure 11(b)). Both graphs show proof sizes in KBytes, over 1,000 uniform random trials in a skip list of 100 million elements and an RBB-Tree of three million elements, respectively. The skip list curve starts out as a regular square logarithmic curve, except for large distances, close to the size of the entire list. We conjecture that the reason for this exception is that for random trials of distances close to the entire list size, all randomly chosen proofs are worst-case proofs, including every link of every level between source and destination, although we must explore this effect further. The RBB-Tree graph shows a regular logarithmic curve.

6.2 System Performance

Although microbenchmarks can be helpful in understanding how the basic blocks of Timeweave perform, they cannot give a complete picture of how the system performs in action. For example, very rarely does a Timeweave machine need to insert thousands of elements into a skip list back-to-back. As a result, the disk block caching available to batched insertions is not available for skip list usage patterns exhibited by Timeweave. Similarly, most proof extractions in timelines only span short distances; for one-second-long timeline time steps with one entanglement process per peer every 10 minutes, a Timeweave machine barely needs to traverse a distance of $10 \times 60 = 600$ elements to extract a precedence proof, unlike the random trials measured in Figure 9.

In this section we measure two performance met-

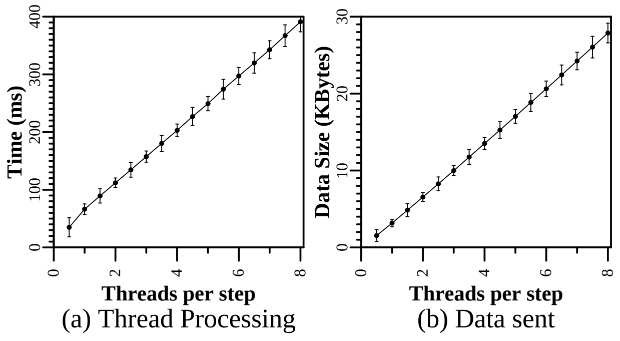


Figure 12: Timeweave performance for different Timeweave loads. The errorbars show one standard deviation around the average. (a) Time taken by Timeweave maintenance per step. (b) Data sent per time step.

rics of a Timeweave machine in action: *maintenance time* and *data transmitted*. Timeweave maintenance consists of the different computations and data manipulations performed to verify, archive and acknowledge timeline threads. Transmitted data consist of new outgoing threads to the peers of the Timeweave machine and receipts for threads received from those peers.

We measure the change of these two metrics as the *load* of a Timeweave machine changes. The load of a Timeweave machine is roughly the number of incoming threads it has to handle per time step. If we fix the duration of each time step to one second, and the entanglement interval to 10 minutes (600 time steps), then a load of 5 means that the entanglement service set consists of $600 \times 5 = 3000$ Timeweave machines and, as a result, every Timeweave machine receives on average 5 threads per second.

Figure 12(a) shows the time it takes a single machine to perform Timeweave maintainance per one-second-long time step. The almost perfectly linear rate at which maintenance processing grows with the ratio of threads per time step indicates that all-to-all entanglement can scale to large entangled service sets only by limiting the entanglement frequency. However, for reasonably large service sets, up to 1000 Timeweave machines for 10-minute entanglement, maintenance costs range between 2 and 8% of the processing resources of a PC-grade server.

Figure 12(b) shows the amount of data sent per time step from a single Timeweave machine. Although the data rate itself is no cause for concern, the number of different destinations for secure transmissions could also limit how all-to-all entanglement scales. Again, for entangled service sets and entanglement intervals that do not exceed two or three threads per time step, Timeweave maintenance should not pose a problem to a low-end server with reasonable connectivity.

7 Conclusion

In this work we seek to extend the traditional idea of time stamping into the concept of a secure timeline, a tamper-evident historic record of the states through which a system passed in its lifetime. Secure timelines make it possible to reason about the temporal ordering of system states in a provable manner. We then proceed to define timeline entanglement, a technique for creating undeniable temporal orderings across mutually distrustful service domains. Finally, we design, describe the implementation of, and evaluate Timeweave, a prototype implementation of our timeline entanglement machinery, based on two novel authenticated data structures: append-only authenticated skip lists and disk-based, persistent authenticated search trees. Our measurements indicate that sizes of several hundred service domains can be efficiently entangled at a frequency of once every ten minutes using Timeweave.

Although our constructs preserve the correctness of temporal proofs, they are not complete, since some events in a dishonest service domain can be hidden from the timelines with which that domain entangles (Section 4.3). We plan to alleviate this shortcoming by employing a technique reminiscent of the signed-messages solution to the traditional Byzantine Generals problem [15]. Every time service A sends a thread to peer B, it also piggybacks all the signed threads of other services it has received and archived since the last time it sent a thread to B. In such a manner, a service will be able to verify that all members of the entangled service set have received the same, unique timeline authenticator from every other service that it has received and archived, verifying global historic integrity.

We also hope to migrate away from the all-to-all entanglement model, by employing recently-developed, highly scalable overlay architectures such as CAN [22] and Chord [24]. In this way, a service only entangles its timeline with its immediate neighbors. Temporal proofs involving non-neighboring service domains use *transitive* temporal mapping, over the routing path in the overlay, perhaps choosing the route of least temporal loss.

Finally, we are working on a large scale distributed historic file system that enables the automatic maintenance of temporal orderings among file system operations across the entire system.

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