

Practical Foundations of History Independence

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Abstract—The way data structures organize data is often a function of the sequence of past operations. The organization of data is referred to as the data structure’s state, and the sequence of past operations constitutes the data structure’s history. A data structure state can therefore be used as an oracle to derive information about its history. As a result, for history-sensitive applications, such as privacy in e-voting, incremental signature schemes, and regulatory compliant data retention; it is imperative to conceal historical information contained within data structure states.

Data structure history can be hidden by making data structures history independent. In this paper, we explore how to achieve history independence.

We observe that current history independence notions are significantly limited in number and scope. There are two existing notions of history independence – weak history independence (WHI) and strong history independence (SHI). WHI does not protect against insider adversaries and SHI mandates canonical representations, resulting in inefficiency.

We postulate the need for a broad, encompassing notion of history independence, which can capture WHI, SHI, and a broad spectrum of new history independence notions. To this end, we introduce Δ history independence (Δ HI), a generic game-based framework that is malleable enough to accommodate existing and new history independence notions.

As an essential step towards formalizing Δ HI, we explore the concepts of abstract data types, data structures, machine models, memory representations and history independence. Finally, to bridge the gap between theory and practice, we outline a general recipe for building end-to-end, history independent systems and demonstrate the use of the recipe in designing two history independent file systems.

Index Terms—History independence, data structures, regulatory compliance

I. Introduction

Data structures are commonly used constructs to store and retrieve data in systems. However, data structures carry more information than the raw data they organize. One aspect of this information is the history leading to the data structure’s current state [1].

Concealing historical information contained within data structure states is necessary for incremental signature schemes [2] and for privacy in voting systems [2], [3], [4], [5]. Therefore, the need arises for data structures that reveal no information about the history that led to their current state other than what is inherently visible from the data. History independence [6] has been devised to enable the design of such data structures and they are termed as “*history independent data structures*”.

We have identified the role of history independence in designing systems that are compliant with data retention regulations [7]. Retention regulations desire that once data

is deleted, no evidence about the past existence of deleted data must be recoverable. Such a deletion cannot be achieved by simply overwriting data as in secure deletion [8]. This is because overwriting does not eliminate the effects that previous existence of delete data leaves on the current system state. Even after secure deletion, the current state can be used as an oracle to derive information about the past existence of deleted records. For example, the current organization of data blocks on disk is a function of the sequence of previous writes to file system or to database search indexes. The organization could be different depending on whether a particular record was deleted in the past or was never inserted in the data set. Therefore, questions about history, such as “was John’s record ever in the HIV patients’ dataset” can be answered much more accurately than guessing by simply looking at the search index organization on disk since the organization could be different depending on whether John has previously been in the data set or not. The inference of past existence of deleted data violates data retention regulations.

However, in order to architect systems with history independent characteristics and to prove history independence, we need a formal notion of data structures, of data structure states, and of history independence itself. In this paper we first formalize all necessary concepts and understand history independence from a theoretical perspective (Sections III - V). Then, in Section VIII and IX, we use the theoretical results to design two history independent file systems.

II. A Quick Informal Look at HI

History independence (HI) is concerned with the historical information preserved within data structure states. The preserved history may be illicitly used by adversaries to violate regulatory compliance. For example, an adversary may breach data retention laws by recovering deleted data. Therefore, to understand history independence, we need to specify what we mean by state, what we mean by history, and what an adversary can do.

What is state?

A data structure’s state is an organization of data on a physical medium such as memory or disk.

What is history?

History is the sequence of operations that led to the current data structure state.

What is the threat?

For many existing data structures, the current state is a function of both data and history [1]. Hence, by analyzing the current state an adversary can derive the state’s history. Depending on the application the historical information includes the following:

- Evidence of past existence of deleted data [10].

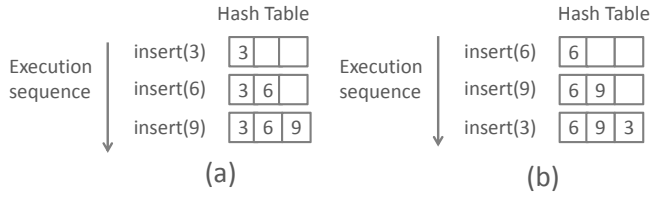


Fig. 1. A history dependent hash table organizes the same data set differently depending on the sequence of operations (i.e., history). In this example, the hash table uses linear probing [9]. The number of hash table buckets is 3 and the hash function is modulo 3.

- The order in which votes were cast in a voting application [2], [3].
- Intermediate versions of published documents [2].

To illustrate, consider the sample hash table data structure of Figure 1. The sample hash table organizes the same data set differently depending on the sequence of operations used. Hence, an adversary that looks at the system memory can potentially detect which operation sequence was used to get to the current hash table state.

What is history independence?

History independence is a characteristic of a data structure. A data structure is said to be history independent if from the adversary’s point of view, the current data structure state is a function of data only and not of history. Thus, the current state of a history independent data structure reveals no information to the adversary about its history other than what is inherently visible from the data itself. We emphasize that history independence is concerned with historical information that is revealed from data organization and not from the data.

Are there different kinds of history independence?

Naor et al. [11] introduced two notions of history independence – weak history independence (WHI) and strong history independence (SHI).

WHI and SHI differ in the number of data structure states an adversary is permitted to observe. Under WHI, an adversary is permitted to observe only the current data structure state. For example, as in case of a stolen laptop. Under SHI, an adversary is permitted several observations of data structure states throughout a sequence of operations. For example, as in case of an insider adversary who can obtain a periodic memory dump. For SHI, the adversary should be unable to identify which sequence of operations was applied between any two adjacent observations.

A. Our Contributions

WHI assumes a weak adversary while SHI is a very powerful notion of history independence, secure even against a computationally unbounded adversary [1]. Currently, applications are restricted to using data structures with either WHI or SHI characteristics. However, applications that do not fit into either WHI or SHI do exist. For example, a journaling system that reveals no historical information other than the last k

operations¹. Further, WHI does not protect against insider adversaries and SHI results in inefficiency [12]. Hence, there is a necessity for new notions of history independence targeted towards specific application scenarios.

In this paper we take the first steps towards better understanding the history independence spectrum and its applicability to systems. The contributions of this paper are:

- The exploration of abstract data types, data structures, machine models, and memory representations (Section III). This is an essential step towards formalizing history independence.
- New game-based definitions of weak and strong history independence (Sections IV-A and IV-B) that are more appropriate for the security community as compared to existing terminology [11], [6].
- A new notion of history independence termed Δ history independence (Δ HI). Δ HI centers around a generic game-based definition of history independence and is malleable enough to accommodate WHI, SHI, and a broad spectrum of new history independence notions (Section V-A). In addition, Δ HI helps to quantify the history revealed or hidden by existing data structures most of which have been designed without history independence in mind.
- A general recipe for designing history independent systems and the recipe’s use in designing a history independent file system (Section VIII).
- The design and evaluation of delete agnostic file system (DAFS). In DAFS, we re-design the file system layer to support new history independence notions. DAFS also increases file system resilience via journaling in the presence of history independence.

III. Preliminaries

Formalizing history independence requires an understanding of data structures. A data structure itself can be viewed as an implementation of an abstract data type (ADT) on a machine model [1]. An abstract data type (ADT) is a specification of operations for data organization while a machine model represents a physical computing machine.

In the following, we provide an overview of ADTs, data structures, machine models, and memory representations as proposed in [1] that are relevant to history independence. Then, in Section IV we formalize history independence.

A. Abstract Data Type (ADT)

The specification of data organization techniques is often done via abstract data types. The key characteristic of an ADT is that it specifies operations independently of any specific implementation. We use the concept proposed by Golovin et al. [1], wherein an ADT is considered as a set of states together with a set of operations. Each operation maps the current state to a new state.

Definition 1. Abstract Data Type (ADT)

An ADT \mathcal{A} is a pentuple $(\mathcal{S}, s_\phi, \mathcal{O}, \Gamma, \Psi)$, where \mathcal{S} is a set of

¹We give additional examples in Section V-A.

states; $s_\phi \in \mathcal{S}$ is the initial state; \mathcal{O} is a set of operations; Γ is a set of inputs; Ψ is a set of outputs; and each operation $o \in \mathcal{O}$ is a function ² $o : \mathcal{S} \times \Gamma_o \rightarrow \mathcal{S} \times \Psi_o$, where $\Gamma_o \subseteq \Gamma$ and $\Psi_o \subseteq \Psi$.

The ADT is initialized to state s_ϕ . When an operation $o \in \mathcal{O}$ with input $i \in \Gamma_o$ is applied to an ADT state s_1 , the ADT outputs $\tau \in \Psi_o$ and transitions to a state s_2 . The transition from s_1 to s_2 is denoted as $o(s_1, i) \rightarrow (s_2, \tau)$.

The necessity of ADTs. History independence requires that from an adversary's point of view, the current data structure state is a function of data only and not of history. In the context of history independence, an ADT models the history revealed by data only. Since we view a data structure as an ADT implementation (Section III-C), the ADT helps to clearly identify what the data structure is permitted or not permitted to reveal about past operations. Any history revealed by an ADT state can be revealed by the corresponding data structure state. Any history hidden by an ADT state must be hidden by the corresponding data structure state.

ADT as a graph. We can imagine the ADT to be a directed graph \mathcal{G} , where each vertex represents an ADT state and each edge is labeled with an ADT operation along with an ADT input and an ADT output. The label for an edge between two vertices represents the operation that causes the transition between the corresponding states. We call the graph \mathcal{G} , the state transition graph of the ADT.

Viewing an ADT as a graph will be particularly useful when we take a deeper look into history independence in Section III-D.

B. Models of Execution

An ADT is only a specification of operations for organizing data. For more practical use, such as for efficiency analysis, concrete implementations of the ADT operations are required. ADT implementations are provided via programs that can be executed on a given machine model. An ADT's implementation in a given machine model is a data structure (Section III-C).

RAM Model of Execution. The RAM model of execution models a traditional serial computer. The model consists of two components, a central processing unit (CPU) and a random access memory (RAM). Both the CPU and RAM are finite state machines (FSM) [13].

The RAM consists of $m = 2^u$ storage locations. Each location is a b -bit word and has a unique $\log_2 m$ bit address associated with it³. Two operations are permitted on a storage location in the RAM. First, a load operation to access the b -bit word stored at the location. Second, a store operation that copies a given b -bit word to the location. Typically, the b -bit words are copied to or copied from CPU registers.

The CPU consists of n b -bit registers and operates on a fetch-and-execute cycle [13]. The CPU has an associated set of

instructions that it can perform. CPU instructions are specified in a programming language. A program in a RAM model is a finite sequence of programming language instructions.

A machine model can itself be considered as an ADT [1]. In this case, the set of ADT states is the set of all machine states, and the set of ADT operations is the set of all machine programs. For the RAM model, the set of ADT states, the set of inputs, and the set of outputs are all represented as bit strings.

Definition 2. Bounded RAM Machine Model

A bounded RAM machine model \mathcal{M} with m b -bit memory words and n b -bit CPU registers is a pentuple $(\mathcal{S}, s_\phi, \mathcal{P}, \Gamma, \Psi)$, where $\mathcal{S} = \{0, 1\}^{b(m+n)}$ is the set of machine states; $s_\phi \in \mathcal{S}$ is the initial state; \mathcal{P} is the set of all programs of \mathcal{M} ; $\Gamma = \{0, 1\}^*$ is a set of inputs; $\Psi = \{0, 1\}^*$ is a set of outputs; and each program $p \in \mathcal{P}$ is a function $p : \mathcal{S} \times \Gamma_p \rightarrow \mathcal{S} \times \Psi_p$, where $\Gamma_p \subseteq \Gamma$ and $\Psi_p \subseteq \Psi$.

\mathcal{M} is initialized to state s_ϕ . If a program $p \in \mathcal{P}$ with input $i \in \Gamma_p$ is executed by the CPU when \mathcal{M} is in state s_1 , \mathcal{M} outputs $\tau \in \Psi_p$ and transitions to a state s_2 . The transition from s_1 to s_2 is denoted as $p(s_1, i) \rightarrow (s_2, \tau)$.

C. Data Structure

An implementation for an ADT in a given machine model is obtained as follows.

- A machine representation is chosen for each ADT input and output.
- For each ADT operation a machine program is selected that provides the functionality desired from the ADT operation.
- A unique machine state is selected to represent the initial ADT state.

We encapsulate the above steps in the following data structure definition.

Definition 3. Data Structure

A data structure implementation of an ADT \mathcal{A} in a bounded RAM machine model \mathcal{M} is a quadruple $(\alpha, \beta, \gamma, s_0^{\mathcal{M}})$, where $\mathcal{A} = (\mathcal{S}, s_\phi, \mathcal{O}, \Gamma, \Psi)$ as per definition 1, $\mathcal{M} = (\mathcal{S}^{\mathcal{M}}, s_\phi^{\mathcal{M}}, \mathcal{P}^{\mathcal{M}}, \Gamma^{\mathcal{M}}, \Psi^{\mathcal{M}})$ as per definition 2, $\alpha : \Gamma' \rightarrow \Gamma^{\mathcal{M}}$, $\beta : \Psi' \rightarrow \Psi^{\mathcal{M}}$, $\gamma : \mathcal{O} \rightarrow \mathcal{P}^{\mathcal{M}}$, $s_0^{\mathcal{M}} \in \mathcal{S}^{\mathcal{M}}$, $\Gamma' \subseteq \Gamma$ and $\Psi' \subseteq \Psi$.

α is a mapping from ADT inputs to machine inputs. That is, for any ADT input i , $\alpha(i)$ is the machine representation of the input. Similarly, β is the mapping from ADT outputs to machine outputs. γ is the mapping from ADT operations to machine programs. For an ADT operation o , $\gamma(o)$ is the machine program implementing o . Finally, just as the ADT \mathcal{A} is initialized to a unique state s_ϕ , a unique machine state $s_0^{\mathcal{M}}$ is selected to represent the initial data structure state.

Data Structure State. A data structure state is a machine state. The set of all data structure states consists of all machine states that are reachable from the initial data structure state via execution of machine programs implementing the ADT operations.

State Transition Graph For Data Structure. A data structure can be considered to be a directed graph \mathcal{G} , where each vertex

²For brevity, we model each ADT operation with an input and an output. ADT operations may accept no inputs or produce no outputs. Hence, an ADT operation can also be modeled as the following functions: $o : \mathcal{S} \rightarrow \mathcal{S}$, $o : \mathcal{S} \rightarrow \mathcal{S} \times \Psi_o$, or $o : \mathcal{S} \times \Gamma_o \rightarrow \mathcal{S}$.

³This is a bounded-memory RAM.

TABLE I
SAMPLE PATHS FROM ADT AND DATA STRUCTURE STATE TRANSITION
GRAPHS .

Path	From Figure
$p_A = s_\phi \rightarrow \{1\} \rightarrow \{1, 3\} \rightarrow \{1, 3, 6\}$	2(a)
$p'_A = s_\phi \rightarrow \{1\} \rightarrow \{1, 6\} \rightarrow \{1, 3, 6\}$	2(a)
$p_D = s_\phi^M \rightarrow \langle\langle _, 1, _ \rangle\rangle \rightarrow \langle\langle 3, 1, _ \rangle\rangle \rightarrow \langle\langle 3, 1, 6 \rangle\rangle$	2(b)
$p'_D = s_\phi^M \rightarrow \langle\langle _, 1, _ \rangle\rangle \rightarrow \langle\langle 6, 1, _ \rangle\rangle \rightarrow \langle\langle 6, 1, 3 \rangle\rangle$	2(b)

represents a data structure state and each edge is labeled with a machine program implementing an ADT operation along with a machine input and a machine output. The label for an edge between two vertices represents the program that causes the transition between the corresponding states. We call the graph \mathcal{G} , the state transition graph of the data structure.

D. A Semi-Formal Look At HI

The non-isomorphism problem. In Section II we introduced the two existing history independence notions – weak history independence (WHI) and strong history independence (SHI)⁴.

Non-isomorphism between the state transition graph of an ADT and of its data structure implementation breaks SHI. WHI on the other hand can be achieved even when the ADT and data structure state transition graphs are non-isomorphic. First, we look at how non-isomorphism breaks SHI and then we discuss how to achieve WHI in the presence of non-isomorphism.

Why non-isomorphism breaks SHI? Non-isomorphism and thus the need for SHI arises when an ADT state has multiple memory representations⁵. We will precisely define memory representations for ADT states in Section III-E. For now, it suffices to say the following: A memory representation for an ADT state that is reachable from the initial ADT state via a sequence of ADT operations is the machine state reachable from the initial data structure state via the corresponding program sequence. For example, in Figure 2, the data structure states $\langle\langle 3, 1, 6 \rangle\rangle$ and $\langle\langle 6, 1, 3 \rangle\rangle$ are memory representations of the ADT state $\{1, 3, 6\}$.

To illustrate how non-isomorphism breaks SHI, consider the example graphs from Figure 2, example paths from Table I, and an adversary with access to the initial ADT state s_ϕ , the initial data structure state s_ϕ^M , the current ADT state $\{1, 3, 6\}$, and the current data structure state which is either $\langle\langle 3, 1, 6 \rangle\rangle$ or $\langle\langle 6, 1, 3 \rangle\rangle$.

By looking at the ADT states alone, the adversary cannot determine which sequence of ADT operations was used to arrive at the current ADT state $\{1, 3, 6\}$. This is because there are two paths p_A and p'_A between the ADT states s_ϕ and $\{1, 3, 6\}$. Moreover, the ADT states carry no information about the exact path used to transition from s_ϕ to $\{1, 3, 6\}$. Hence,

the data alone gives the adversary no advantage in guessing which sequence of ADT operations was applied in the past.

Now, by looking at the current data structure state, the adversary can clearly identify which sequence of machine programs was used to arrive at the current data structure state. The current data structure state is either $\langle\langle 3, 1, 6 \rangle\rangle$ or $\langle\langle 6, 1, 3 \rangle\rangle$. There is a unique path from initial data structure state s_ϕ^M to each of the states $\langle\langle 3, 1, 6 \rangle\rangle$ and $\langle\langle 6, 1, 3 \rangle\rangle$. Hence, by observing the current data structure state, the adversary can identify whether path p_D or path p'_D was used to transition from state s_ϕ^M to the current data structure state. Identification of the path in the data structure state transition graph informs the adversary of the program sequence used. Knowledge of the program sequence used in-turn tells the adversary the sequence of ADT operations used. In conclusion, the data structure implementation gives the adversary an advantage in guessing the history of past execution, thereby breaking history independence.

How can we achieve history independence? The two known ways to make data history independent:

- 1) *For SHI, make the ADT and the data structure state transition graphs isomorphic:*
Data structures with state transition graphs isomorphic to their ADT's state transition graph are referred to as canonically represented data structures. We discuss the necessity of canonical representations for SHI in Section IV-D. SHI implies WHI.
- 2) *For WHI, make the data structure state transitions randomized:*

Randomization here refers to the selection of the data structure state representing the corresponding ADT state. To illustrate, consider the example graphs from Figure 2. Both data structure states $\langle\langle 3, 1, 6 \rangle\rangle$ and $\langle\langle 6, 1, 3 \rangle\rangle$ are valid memory representations of the ADT state $\{1, 3, 6\}$. For WHI, the choice between data structure states $\langle\langle 3, 1, 6 \rangle\rangle$ and $\langle\langle 6, 1, 3 \rangle\rangle$ to represent the ADT state $\{1, 3, 6\}$ must be random.

As shown in Figure 3, randomization translates to addition of new paths in the data structure state transition graph to ensure the following: For any two ADT states s_0 and s_1 , if there is a path in the ADT state transition graph between s_0 and s_1 , then, there must be a path from all memory representations of ADT state s_0 to all memory representations of ADT state s_1 in the data structure's state transition graph. The choice of path in the data structure state transition graph between representations of ADT states s_0 and s_1 is then made at random.

From the adversary's point of view randomization makes all memory representations of an ADT state equally likely to occur. Hence, observation of a specific representation gives the adversary no advantage in guessing the sequence of machine programs that led to the current data structure state. Since the adversary cannot identify the sequence of machine programs used, the adversary is also unable to identify the sequence of ADT operations that led to the current ADT state.

⁴Both WHI and SHI are formalized in Section IV.

⁵Many existing data structures have this property and are hence, not history independent. Common examples include the linked list, hash tables and B-Trees. In these data structures different insertion order of the same set of data elements (i.e., the same ADT state) results in different memory representations.

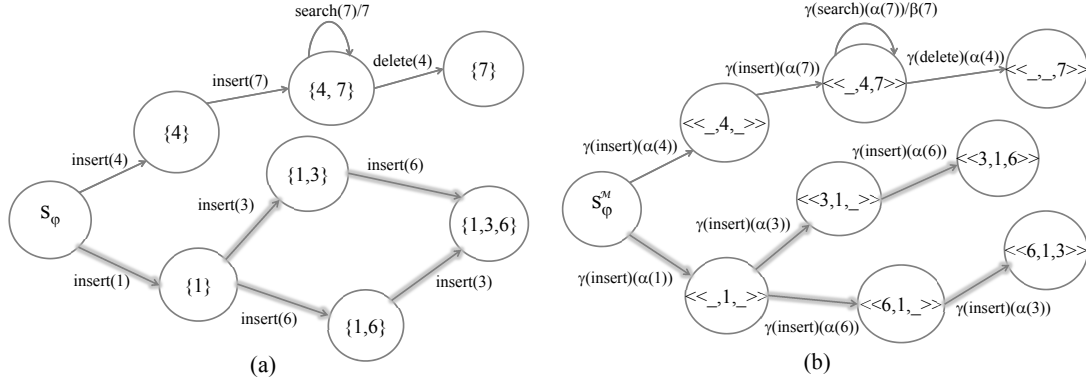


Fig. 2. Example of non-isomorphism between ADT and data structure state transition graphs. (a) Partial state transition graph for sample hash table ADT. (b) Partial state transition graph for sample array-based hash table data structure implementation using linear probing. Number of hash table buckets is 3 and the hash function is $h(\text{key}) = \text{key} \% 3$. $\gamma(\text{insert})$, $\gamma(\text{search})$ and $\gamma(\text{delete})$ denote the machine programs implementing the ADT operations insert, search and delete, respectively. $o(i)/t$ denotes that ADT operation o takes input i and produces output t . Similarly, $\gamma(o)(\alpha(i))/\beta(t)$ denotes that program $\gamma(o)$ takes input $\alpha(i)$ and produces output $\beta(t)$. $\alpha(i)$ and $\beta(t)$ are the machine representations of the ADT input i and ADT output t , respectively. Note that the vertices in figure (b) represent data structure states. In the RAM model these will be bit strings. However, to convey data semantics we denote the hash table array as $\langle\langle a_0, a_1, a_2 \rangle\rangle$, where a_0 , a_1 , and a_2 are elements at buckets 0, 1 and 2, respectively. Underscore denotes an empty bucket. Highlighted paths are referenced in Table I, and in Section III-D

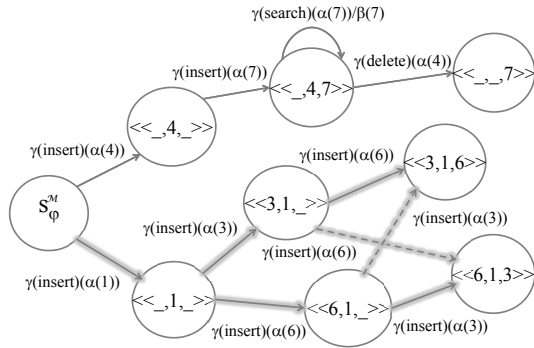


Fig. 3. Using randomization to achieve history independence. The dotted lines indicate new transitions added to the hash table data structure state transition graph. Amongst all edges with the same starting node and the same label, the choice of edge for state transition is made at random.

E. Memory Representations

In the discussion of nonisomorphism and history independence above, we informally introduced memory representations for ADT states. We also showed that history independence comes into picture when an ADT state has multiple memory representations. In short, the memory representation for an ADT state that is reachable from the initial ADT state via a sequence of ADT operations, is the machine state reachable from the initial data structure state via the corresponding program sequence. We formally define memory representations here and use them later in Section IV for the game-based definitions of history independence.

Let $\delta = \langle o_1, o_2, \dots, o_n \rangle$ be a sequence of ADT operations and $I = \langle i_1, i_2, \dots, i_n \rangle$ be a sequence of ADT inputs. We denote by $\mathbb{O}(\delta, s_0, I)$ the application of the ADT operation sequence δ on ADT state s_0 .

$$\mathbb{O}(\delta, s_0, I) = \begin{cases} s_0 & \text{if } |\delta| = 0 \\ (s_n, \tau_n) | o_k(s_{k-1}, i_k) \rightarrow (s_k, \tau_k); \\ 1 \leq k \leq n & \text{otherwise} \end{cases}$$

If δ is empty no state transition occurs and no outputs are produced. For nonempty sequence δ , s_n and τ_n denote the ADT state and the ADT output, respectively, produced by the final operation in sequence δ .

To summarize, we denote by $\mathbb{O}(\delta, s_0, I) \rightarrow (s_n, \tau_n)$ that the ADT operation sequence δ when applied to the ADT state s_0

with ADT input sequence I , results in the ADT state s_n and ADT output τ_n .

Now, let $\delta^M = \chi(\delta) = \langle \gamma(o_1), \gamma(o_2), \dots, \gamma(o_n) \rangle$ be a sequence of machine programs corresponding to the ADT operation sequence δ . $\gamma(o_k)$ is the machine program implementing the ADT operation o_k . Then, we denote by $\mathbb{O}^M(\delta^M, s_0^M, I)$ the application of program sequence δ^M on a machine state s_0^M .

$$\mathbb{O}^M(\delta^M, s_0^M, I) = \begin{cases} s_0^M & \text{if } |\delta^M| = 0 \\ (s_n^M, \beta(\tau_n)) \\ |\gamma(o_k)(s_{k-1}^M, \alpha(i_k)) \rightarrow \{s_k^M, \beta(\tau_k)\}; \\ 1 \leq k \leq n & \text{otherwise} \end{cases}$$

Here, $\alpha(i)$ and $\beta(\tau)$ denote the machine representations for an ADT input i and an ADT output τ , respectively. s_n^M and $\beta(\tau_n)$ are the machine state and the machine output, respectively, produced by the final program in sequence δ^M .

In summary, we denote by $\mathbb{O}^M(\delta^M, s_0^M, I) \rightarrow (s_n^M, \tau_n^M)$ that a program sequence δ^M when applied to a machine state s_0^M with an ADT input sequence I , results in a machine state s_n^M and a machine output τ_n^M .

Definition 4. Memory Representations

The set of memory representations of an ADT state s , denoted by $m(s)$, is the set of data structure states, defined as

$$m(s) = \begin{cases} s_0^M & \text{if } s = s_\phi \\ s^M | \mathbb{O}^M(\delta_k^M, s_0^M, I_k) \rightarrow \{s^M, \beta(\tau_{|\delta_k|})\}; \\ 1 \leq k \leq n & \text{otherwise} \end{cases}$$

where, s_0^M is the initial data structure state; I_1, I_2, \dots, I_n are sequences of ADT inputs; $\delta_1, \delta_2, \dots, \delta_n$ are ADT operation sequences, each of which when applied to the initial ADT state s_ϕ results in state s , that is $\mathbb{O}(\delta_k, s_\phi, I_k) \rightarrow (s, \tau_k)$; $\delta_k^M = \chi(\delta_k)$ denotes the program sequence corresponding to ADT operation sequence δ_k ; $|I_k| = |\delta_k|$; $1 \leq k \leq n$.

Here m is the mapping $m : \mathcal{S} \rightarrow 2^{\mathcal{S}^D}$, where \mathcal{S} is the set of all ADT states, \mathcal{S}^D is the set of all data structure states, and $2^{\mathcal{S}^D}$ denotes the power set of \mathcal{S}^D .

1) Dealing With Infinite ADT State Space

The set of machine states for the bounded RAM model is finite since there are finite number of available bits. Hence, a

data structure implementation on a bounded RAM model can only have a finite number of data structure states. The set of ADT states on the other hand can be infinite. For an ADT with infinite states, a data structure implementation will be unable to uniquely represent all the ADT states. The case of infinite ADT states is of particular importance for canonically represented data structures that require the state transition graphs of the ADT and of the data structure to be isomorphic, that is, each ADT state has a unique memory representation.

We will look at canonical representations in detail within the context of history independence in Section IV-D. Here, we list two work-arounds to dealing with infinite ADT state space.

- 1) Redefine the ADT, such that the number of ADT states is less than or equal to the number of machine states.
- 2) Design each machine program implementing an ADT operation, such that the program produces a special output when an ADT state cannot be represented using the available machine bits. For example, an out-of-memory error.

IV. History Independence

Now that we are equipped with the necessary concepts (ADT, RAM machine model, data structure, and memory representations), we proceed to formalize history independence. We give new game-based definitions for both WHI and SHI (Sections IV-A and IV-A). The new definitions are equivalent to existing proposals [2], [6] but more appropriate for the security community since they follow the game-based construction of semantic security. Further, our new definitions naturally extend to accommodate other notions of history independence beyond WHI and SHI.

A. Weak History Independence (WHI)

WHI was introduced for scenarios wherein an adversary observes only the current data structure state. For example, as in the case of a stolen laptop.

Informally, a data structure is said to be weakly history independent if for any two sequences of ADT operations δ_1 and δ_2 , that take the ADT from initialization to a state s , observation of any memory representation of state s gives the adversary no advantage in guessing whether sequence δ_1 or δ_2 was used to get to s .

We define weak history independence (WHI) by the following game:

Let $\mathcal{A} = (\mathcal{S}, s_\phi, \mathcal{O}, \Gamma, \Psi)$ be an ADT, $\mathcal{M} = (\mathcal{S}^{\mathcal{M}}, s_\phi^{\mathcal{M}}, \mathcal{P}^{\mathcal{M}}, \Gamma^{\mathcal{M}}, \Psi^{\mathcal{M}})$ be a bounded RAM machine model, and $\mathcal{D} = (\alpha, \beta, \gamma, s_0^{\mathcal{M}})$ be a data structure implementing \mathcal{A} in \mathcal{M} , as per definitions 1, 2 and 3, respectively.

- 1) A probabilistic polynomial time-bounded adversary selects the following: An ADT state s ; two sequences of ADT operations δ_0 and δ_1 ; and two sequences of ADT inputs I_0 and I_1 ; such that $\mathbb{O}(\delta_0, s_\phi, I_0) \rightarrow (s, \tau)$ and $\mathbb{O}(\delta_1, s_\phi, I_1) \rightarrow (s, \tau)$. Both δ_1 and δ_2 take the ADT from the initial state s_ϕ to state s producing the same output τ .
- 2) The adversary sends $s, \delta_0, \delta_1, I_0$ and I_1 to the challenger.
- 3) The challenger flips a fair coin $c \in \{0, 1\}$ and computes $\mathbb{O}^{\mathcal{M}}(\delta_c^{\mathcal{M}}, s_0^{\mathcal{M}}, I_c) \rightarrow (s^{\mathcal{M}}, \tau^{\mathcal{M}})$, where $\delta_c^{\mathcal{M}} = \chi(\delta_c)$ and

$\tau^{\mathcal{M}} = \beta(\tau)$. That is, the challenger applies the program sequence $\delta_c^{\mathcal{M}}$ corresponding to the ADT operation sequence δ_c to the data structure initialization state $s_0^{\mathcal{M}}$, resulting in a memory representation $s^{\mathcal{M}}$ of ADT state s and a machine output $\tau^{\mathcal{M}}$.

- 4) The challenger sends the memory representation $s^{\mathcal{M}}$ to the adversary.
- 5) The adversary outputs $c' \in \{0, 1\}$.

The adversary wins the game if $c' = c$.

\mathcal{D} is said to be weakly history independent if the advantage of the adversary for winning the game, defined as $|\Pr[c' = c] - 1/2|$ is negligible (where “negligible” is defined over any implementation-specific security parameters of the programs in $\mathcal{P}^{\mathcal{M}}$).⁶

Since WHI permits the adversary to make a single observation, the adversary is allowed to choose the end state only in step 1. The starting state for the chosen ADT operation sequences is always the initial ADT state s_ϕ . Recall from the data structure definition (Section III-C) that the initial ADT state has a fixed memory representation, which is the initial data structure state $s_0^{\mathcal{M}}$. Hence, in step 3, the challenger applies the adversary-selected sequence to the memory representation $s_0^{\mathcal{M}}$ of s_ϕ .

If the adversary is able to identify the ADT operation sequence chosen by the challenger in step 3, then the adversary wins the game. Winning the game implies the adversary was able to determine the operation sequence that led to the current ADT state by observing the state’s memory representation, thereby breaking WHI.

B. Strong History Independence (SHI)

Unlike WHI, SHI is applicable when an adversary can observe multiple memory representations throughout a sequence of operations. For example, as in case of an insider who can obtain a periodic memory dump. SHI requires that the adversary must not gain any additional information about the sequence of operations between any two adjacent observations than what is inherently available from the corresponding ADT states.

Informally, a data structure is said to be strongly history independent if for any two sequences of ADT operations δ_1 and δ_2 , that take the ADT from a state s_1 to a state s_2 , observations of any memory representations of states s_1 and s_2 give the adversary no advantage in guessing whether sequence δ_1 or δ_2 was used to go from s_1 to s_2 .

We define strong history independence (SHI) by the following game:

Let $\mathcal{A} = (\mathcal{S}, s_\phi, \mathcal{O}, \Gamma, \Psi)$ be an ADT, $\mathcal{M} = (\mathcal{S}^{\mathcal{M}}, s_\phi^{\mathcal{M}}, \mathcal{P}^{\mathcal{M}}, \Gamma^{\mathcal{M}}, \Psi^{\mathcal{M}})$ be a bounded RAM machine model, and $\mathcal{D} = (\alpha, \beta, \gamma, s_0^{\mathcal{M}})$ be a data structure implementing \mathcal{A} in \mathcal{M} , as per definitions 1, 2 and 3 respectively.

- 1) A probabilistic polynomial time-bounded adversary selects the following.
 - Two ADT states s_1 and s_2 ; two sequences of ADT operations δ_0 and δ_1 ; and two sequences of ADT inputs I_0 and I_1 ; such that $\mathbb{O}(\delta_0, s_1, I_0) \rightarrow (s_2, \tau)$ and $\mathbb{O}(\delta_1, s_1, I_1) \rightarrow (s_2, \tau)$.

⁶For example PRNG seeds when using randomization, or keys when using encryption.

Both δ_1 and δ_2 take the ADT from state s_1 to state s_2 producing the same output τ .

- A memory representation $s_1^{\mathcal{M}}$ of ADT state s_1 .
- 2) The adversary sends $s_1, s_1^{\mathcal{M}}, \delta_0, \delta_1, I_0$ and I_1 to the challenger.
- 3) The challenger flips a fair coin $c \in \{0, 1\}$ and computes $\mathbb{O}^{\mathcal{M}}(\delta_c^{\mathcal{M}}, s_1^{\mathcal{M}}, I_c) \rightarrow (s_2^{\mathcal{M}}, \tau^{\mathcal{M}})$, where $\delta_c^{\mathcal{M}} = \chi(\delta_c)$ and $\tau^{\mathcal{M}} = \beta(\tau)$. That is, the challenger applies the program sequence $\delta_c^{\mathcal{M}}$ corresponding to the ADT operation sequence δ_c to the data structure state $s_1^{\mathcal{M}}$, resulting in a memory representation $s_2^{\mathcal{M}}$ of state s_2 and a machine output $\tau^{\mathcal{M}}$.
- 4) The challenger sends the memory representation $s_2^{\mathcal{M}}$ to the adversary.
- 5) The adversary outputs $c' \in \{0, 1\}$.

The adversary wins the game if $c' = c$.

\mathcal{D} is said to be strongly history independent if the advantage of the adversary for winning the game, defined as $|Pr[c' = c] - 1/2|$ is negligible (where “negligible” is defined over any implementation-specific security parameters of the programs in $\mathcal{P}^{\mathcal{M}}$).

Winning the game means that the adversary was able to determine the operation sequence that took the ADT from state s_1 to state s_2 , thereby breaking SHI.

SHI implies WHI. If the ADT state s_1 chosen by the adversary in step 1 is the initial ADT state s_ϕ , then the SHI game reduces to the WHI game of Section IV-A.

C. Equivalence to Existing Definitions

WHI and SHI were first introduced by Naor et al. [11]. Later, Hartline et al. [6] introduced new definitions for WHI and SHI. However, Hartline et al. showed that their definitions although less complex are equivalent to the ones proposed by Naor et al. Our game-based definitions of WHI and SHI (Sections IV-A and IV-B) differ slightly from the definitions by Hartline et al. Specifically, Hartline et al. assume a computationally unbounded adversary. We address history independence in the presence of computationally bounded adversaries to be more in-line with reality. Further, new definitions were necessary to overcome impreciseness in existing definitions and to develop a framework for new history independence notions beyond WHI and SHI. We detail in the following.

Hartline et al. defined weak history independence as follows.

Definition 5. Weak History Independence (WHI)

A data structure implementation is weakly history independent if, for any two sequences of operations X and Y that take the data structure from initialization to state A , the distribution over memory after X is performed is identical to the distribution after Y . That is:

$$(\phi \xrightarrow{X} A) \wedge (\phi \xrightarrow{Y} A) \implies \forall \mathbf{a} \in A, \Pr[\phi \xrightarrow{X} \mathbf{a}] = \Pr[\phi \xrightarrow{Y} \mathbf{a}]$$

In the above definition, $\phi \xrightarrow{X} B$ denotes that a operation sequence X when applied to the initial state ϕ , results in state A . The notation $\mathbf{a} \in A$ means that \mathbf{a} is a memory representation of state A . $\Pr[\phi \xrightarrow{X} \mathbf{a}]$ denotes the probability that a sequence X when applied to initial state ϕ , results in representation \mathbf{a} .

Reconciling terminology

Hartline et al. do not formalize the concepts of data structure, data structure state and memory representations. A data structure’s state is referred to as the data structure’s content. Memory representation of a data structure state is the physical contents of memory that represent that state. We note that Naor et al. also used the same terminology in their definitions.

The WHI definition by Hartline et al. is imprecise in the following.

- Operation inputs and outputs are not considered.
- The same operation sequences are considered applicable to both data structure states and to memory representations. The mechanisms for the applicability are not specified.
- The connection between a data structure’s state and the state’s memory representations is not precisely specified.

Following Golovin et al. [1] we use the ADT concept to model logical states (or content) and define a data structure as an ADT’s implementation (Sections III-A - III-C). A data structure state is therefore the memory representation of an ADT state. Separating ADT and data structure concepts enables us to precisely define memory representations (Section III-E) for various machine models; understand history independence from the perspective of state transition graphs; and to build a framework for defining new history independence notions other than SHI and WHI (Section V).

To summarize the differences in terminology, what Hartline et al. refer to as data structure state in definition 6 is an ADT state in our model. Further, we refer to a memory representation in definition 6 as a data structure state.

For WHI, Hartline et al. require a data structure implementation to satisfy the following:

$$(\phi \xrightarrow{X} A) \wedge (\phi \xrightarrow{Y} A) \implies \forall \mathbf{a} \in A, Pr[\phi \xrightarrow{X} \mathbf{a}] = Pr[\phi \xrightarrow{Y} \mathbf{a}]$$

Our game-based definition of WHI poses the following slightly relaxed requirement:

$$(\phi \xrightarrow{X} A) \wedge (\phi \xrightarrow{Y} A) \implies \forall \mathbf{a} \in A, |Pr[\phi \xrightarrow{X} \mathbf{a}] - Pr[\phi \xrightarrow{Y} \mathbf{a}]| \text{ is negligible}$$

We will show that the game-based WHI definition (Section IV-A) is equivalent to statement IV-C, that is, a data structure preserves WHI only if statement IV-C is true. However, before we show the equivalence we point out the necessity for the difference between conditions IV-C and IV-C.

As discussed in Section III-D, there are two known ways to achieve history independence. The first way is to make the ADT and data structure state transition graphs isomorphic. The second way is to make the data structure state transition graph randomized. The requirement for identical memory distributions as per statement IV-C rules out the use of randomization to achieve history independence⁷. A randomized data structure implementation will rely on pseudo random generators. The security of pseudo random generators relies on computational indistinguishability. Therefore, the relaxed

⁷The use of randomization to achieve weak history independence is discussed in Section IV-E.

requirement of negligibility introduced in statement IV-C is in fact not a limitation, but rather a reconciliation of the definition by Hartline et al. with reality where we have computationally bounded adversaries.

Although Naor et al. proposed a WHI definition that requires identical distributions, they also used randomization to design a history independent data structure.

Equivalence of WHI definitions

We now show that our gamed-based WHI definition (Section IV-A) is equivalent to a WHI definition based on statement IV-C.

We rewrite statement IV-C for consistent notations as follows.

$$(s_\phi \xrightarrow{\delta_0} s) \wedge (s_\phi \xrightarrow{\delta_1} s) \implies \forall s^{\mathcal{M}} \in s, |Pr[s_\phi^{\mathcal{M}} \xrightarrow{\delta_0^{\mathcal{M}}} s^{\mathcal{M}}] - Pr[s_\phi^{\mathcal{M}} \xrightarrow{\delta_1^{\mathcal{M}}} s^{\mathcal{M}}]| \text{ is negligible}$$

Here, δ_0 and δ_1 are two ADT operation sequences that take the ADT from initial state s_ϕ to state s . s_ϕ and $s_\phi^{\mathcal{M}}$ are the initial ADT and the initial data structure states, respectively. $\delta_0^{\mathcal{M}}$ and $\delta_1^{\mathcal{M}}$ are the machine programs corresponding to ADT operation sequences δ_0 and δ_1 , respectively.

History independence only considers cases where the condition $(s_\phi \xrightarrow{\delta_0} s) \wedge (s_\phi \xrightarrow{\delta_1} s)$ is true, that is, both sequences δ_0 and δ_1 take the ADT to the same end state s . Otherwise, the ADT states themselves reveal history.

We therefore have two cases to consider

Case 1: The distributions are computationally distinguishable, that is,

$$\exists s^{\mathcal{M}} \in s \text{ such that } |Pr[s_\phi^{\mathcal{M}} \xrightarrow{\delta_0^{\mathcal{M}}} s^{\mathcal{M}}] - Pr[s_\phi^{\mathcal{M}} \xrightarrow{\delta_1^{\mathcal{M}}} s^{\mathcal{M}}]| \text{ is non-negligible.}$$

Now consider the following adversarial strategy. Given a data structure state $s^{\mathcal{M}}$ in step 4 of the WHI game, the adversary outputs c such that $\delta_c^{\mathcal{M}}$ has a higher probability of producing $s^{\mathcal{M}}$. For such an adversarial strategy $|Pr[c' = c] - \frac{1}{2}|$ is non-negligible for some $s^{\mathcal{M}}$. Therefore, the data structure implementation does not preserve WHI.

Case 2: The distributions are computationally indistinguishable, that is,

$$\forall s^{\mathcal{M}} \in s, |Pr[s_\phi^{\mathcal{M}} \xrightarrow{\delta_0^{\mathcal{M}}} s^{\mathcal{M}}] - Pr[s_\phi^{\mathcal{M}} \xrightarrow{\delta_1^{\mathcal{M}}} s^{\mathcal{M}}]| \text{ is negligible}$$

In this case, from a computationally bounded adversary's perspective, the representation $s^{\mathcal{M}}$ received in step 4 of the WHI game is equally likely to have been produced by either $\delta_0^{\mathcal{M}}$ or $\delta_1^{\mathcal{M}}$. Hence, observation of a data structure state gives the adversary a negligible advantage in guessing c . The data structure implementation therefore preserves WHI.

Equivalence of SHI definitions

For strong history independence Hartline et al. proposed the following definition.

Definition 6. Strong History Independence (SHI) *A data structure implementation is strongly history independent if, for any two (possibly empty) sequences of operations*

X and Y that take a data structure in state A to state B , the distribution over representations of B after X is performed on a representation \mathbf{a} is identical to the distribution after Y is performed on \mathbf{a} . That is:

$$(A \xrightarrow{X} B) \wedge (A \xrightarrow{Y} B) \implies \forall \mathbf{a} \in A, \forall \mathbf{b} \in B, \Pr[\mathbf{a} \xrightarrow{X} \mathbf{b}] = \Pr[\mathbf{a} \xrightarrow{Y} \mathbf{b}]$$

In the above definition, $A \xrightarrow{X} B$ denotes that a operation sequence X when applied to state A , results in state B . The notation $\mathbf{a} \in A$ means that \mathbf{a} is a memory representation of state A . $\Pr[\mathbf{a} \xrightarrow{X} \mathbf{b}]$ denotes the probability that a sequence X when applied to memory representation \mathbf{a} , results in representation \mathbf{b} .

Similar to the case for WHI, our game-based SHI definition (Section IV-B) differs from the above definition only by relaxing the requirement for identical distributions. That is, for SHI, we require the following:

$$(A \xrightarrow{X} B) \wedge (A \xrightarrow{Y} B) \implies \forall \mathbf{a} \in A, \forall \mathbf{b} \in B, |\Pr[\mathbf{a} \xrightarrow{X} \mathbf{b}] - \Pr[\mathbf{a} \xrightarrow{Y} \mathbf{b}]| \text{ is negligible}$$

The equivalence of SHI definitions follows similarly to the case of WHI.

Summary of Differences

The main differences between our definitions and the definitions by Hartline et al. are the following

- The definitions by Hartline et al. are imprecise about the concepts of data structures, states, and memory representations. We precisely formalize all of these concepts.
- Hartline et al. do not consider the case of computationally bounded adversaries. We permit computationally bounded adversaries and thus have the negligibility definition instead of equality for memory distributions.

D. Canonical Representations

Canonically (or uniquely) represented data structures have the property that each ADT state has a unique memory representation. Unique representation implies that the ADT and data structure state transition graphs are isomorphic⁸. Canonically represented data structures give very strong guarantees for history independence and in many cases are the only way to achieve history independence.

We first define canonically represented data structures and then discuss several important results pertaining to canonical representations and history independence.

We also summarize (Table II) the scenarios where canonical representations are necessary for history independence across all combinations of types of programs, secrecy of random bits, adversarial computational ability, and the desired notion of history independence.

Definition 7. Canonically represented data structure *A data structure \mathcal{D} implementing an ADT \mathcal{A} on a bounded RAM machine model \mathcal{M} is canonically represented if each ADT state has a unique memory representation, that is, the mapping $m : \mathcal{S} \rightarrow 2^{\mathcal{S}^{\mathcal{D}}}$ is injective and $|m(s)| = 1$, where \mathcal{S}*

⁸Isomorphism is discussed in Section III-D.

TABLE II

IDENTIFICATION OF SCENARIOS WHERE CANONICAL REPRESENTATIONS ARE NECESSARY FOR HISTORY INDEPENDENCE. N/A = NOT APPLICABLE.

Programs of \mathcal{M}	Random bits hidden from adversary	Adversary computationally bounded	History Independence desired	Canonical representations needed?
Randomized	Yes	Yes	WHI	No
N/A	N/A	No	N/A	Yes
N/A	N/A	N/A	SHI	Yes
Deterministic	N/A	N/A	N/A	Yes

is the set of all ADT states, $\mathcal{S}^{\mathcal{D}}$ is the set of all data structure states, and $m(s)$ denotes the set of memory representations of an ADT state $s \in S$ as per definition 4.

1) ADTs with infinite states

The case of infinite ADT states is of particular importance for canonically represented data structure implementations on a bounded RAM machine model. Since the bounded RAM machine model has a finite number of available bits, the machine state space is not large enough to provide a unique representation for each ADT state when the ADT state space is infinite. Impossibility of unique representations clearly suggests that canonical representations for infinite state set ADTs are not possible in practice since machines with infinite state space do not exist in reality. This straight-forwardly leads to the following theorem.

Theorem 1. *Canonically represented data structure implementations for ADTs with infinite states are impossible in practice.*

However, prior work [11], [2], [1] has claimed designs for canonically represented data structures for the RAM model in direct contradiction to Theorem 1. The contradiction arises from the fact that prior work has implicitly considered ADTs with finite state space. Specifically, the ADTs considered have fewer states than the total number of machine states.

2) Canonical Representations and SHI

Since history independence was first proposed [11], it has been known that canonically represented data structures support SHI. An interesting question posed in this context was whether canonical representations are necessary to achieve SHI. The question about the necessity of canonical representations for SHI was answered by Hartline et al. Hartline et al. [6] showed that SHI cannot be achieved without canonical representations.

Theorem 2. *A data structure is strongly history independent iff it is canonically represented.*

Proof. The proof by Hartline et al. [6] builds on the case that if a data structure is not canonically represented, then an adversary can distinguish an empty sequence of operations from a nonempty sequence of operations. In the context of our game based definition for SHI, we provide an equivalent proof for the same.

Consider an ADT \mathcal{A} and a data structure \mathcal{D} implementing \mathcal{A} on a bounded RAM machine model \mathcal{M} . Also assume that \mathcal{D} is not canonically represented. Now, Let Q be an adversary and C be the challenger in our game. Q selects the following

- Two ADT state s_1 and s_2 .
- Two sequence of operations δ_0 and δ_1 ; and two sequences of ADT inputs I_0 and I_1 , such that $\mathbb{O}(\delta_0, s_1, I_0) \rightarrow (s_2, \tau)$ and $\mathbb{O}(\delta_1, s_1, I_1) \rightarrow (s_2, \tau)$.

Let α_1 and α_2 be two distinct memory representations for ADT state s_1 . We show that, with this setup, the adversary Q can distinguish between an empty sequence of operations and a non empty sequence of operations. Consider that Q selects δ_0 to be an empty sequence of operation and δ_1 to be a non empty sequence of operations. In step 2 of the SHI game, the adversary sends $s_1, \delta_0, \delta_1, I_0$ and I_1 to C . In step 3 of the SHI game, C flips a coin and applies either δ_0 or δ_1 to s_1 and returns the memory representation of the output state to Q . There are two possible cases for step 3 -

- 1) C selects δ_0 - there is no change in the ADT state and the corresponding memory representation since an empty sequence of operations does not cause state changes. Hence in step 4, C returns α_1 to Q .
- 2) C selects δ_1 - the final ADT state reached after performing all the operations in δ_1 is s_1 but the memory representation for s_1 in this case may be either α_1 or α_2 . In step 4, if C returns α_2 to Q , then Q can correctly predict with non-negligible probability that C has applied δ_1 on s_1 to reach α_2 . This breaks strong history independence for \mathcal{D} .

□

Canonical representations are not necessary for WHI

In the absence of canonical representations, it has been shown that an adversary can distinguish an empty sequence of operations from a nonempty sequence of operations thereby breaking SHI [6]. If operation sequences are always assumed to be nonempty, canonical representations are not necessary [6]. We will define such a slightly relaxed notion of history independence that permits only nonempty sequences in Section V-A. We show that WHI is preserved even for empty operation sequences in the absence of canonical representations.

Consider the WHI game from Section IV-A. The case in which the adversary selects two empty ADT operation sequences in step 1 is trivial since empty sequences cause no state transitions and hence there is no history to be revealed.

Now, consider the case when the adversary selects an empty sequence δ_ϕ and a nonempty sequence δ_1 of ADT operations. Both δ_ϕ and δ_1 are required to take the ADT from the initial state to the same end state. Since the empty sequence δ_ϕ causes no state transitions, end state for both sequences δ_ϕ and δ_1 will be the initial ADT state.

Then, in step 3, the challenger chooses either δ_ϕ or δ_1 and sends the resulting memory representation to the adversary. Since the end state for the two operation sequences is the initial ADT state, the memory representation sent to the adversary in step 4 will be the data structure initialization state. From the data structure definition (Section III-C), we know that the initial ADT state has a corresponding fixed unique memory representation. Hence, irrespective of the nonempty sequence that the adversary selects in step 1, the adversary receives the initial ADT state’s memory representation in step 4. Since the adversary receives the same representation each time, the adversary gains no advantage in guessing whether δ_ϕ or δ_1 was chosen by the challenger in step 3.

ADT states other than the initial ADT state can have multiple memory representations. Multiple representations for ADT states does not break WHI as long it is ensured that from the adversary’s perspective, all representations of the current ADT state are equally likely to be observed. Randomization achieves equal likelihood for all representations of an ADT state (Section IV-E). In Section III-D we covered the use of randomization for WHI from the perspective of state transition graphs. Later, in Section IV-E we will show how to achieve WHI by randomization in practice, which can be used for WHI. For deterministic machine programs (also described in Section IV-E) WHI too requires canonical representations.

3) Canonical representations and adversary models

Canonically represented data structures are history independent in the strongest sense, secure even against a computationally unbounded adversary [1]. For a computationally unbounded adversary, canonical representations are also necessary for WHI.

E. Randomization and HI

In Section III-D, we introduced the use of randomization for WHI from the point of view of state transition graphs.

In practice, randomization is achieved using the machine programs implementing the ADT operations. An ADT operation o takes the ADT from a state s_1 to a state s_2 . A machine program implementing o takes the data structure from a memory representation of state s_1 to a memory representation of state s_2 . Since each ADT state can have several memory representations (Section III-D), the program has a choice amongst all representations of state s_2 and picks one representation as the result of a transition. Starting from a fixed memory representation of s_1 , and a fixed input, if the program takes the data structure to a fixed resulting representation of s_2 on each execution, then the program is said to be deterministic. If on each execution the resulting representation is chosen uniformly at random from all possible representations of state s_2 , then the program is said to be randomized.

To illustrate, consider an ADT operation o and a machine program p implementing o . Let $o(s_1, i) \rightarrow (s_2, \tau)$ denote the transition from ADT state s_1 to ADT state s_2 using an ADT input i and producing an ADT output τ . Also, let $m(s_1)$ and $m(s_2)$ denote the set of memory representations of states s_1 and s_2 , respectively. Then, for history independence, the following must hold for program p :

$$\Pr[p(s_1^M, \alpha(i)) \rightarrow (s_2^M, \beta(\tau))] = \frac{1}{|m(s_2)|}, \forall s_1^M \in m(s_1) \\ \text{and } \forall s_2^M \in m(s_2).$$

Here, $\alpha(i)$ and $\beta(\tau)$ are the machine representations of ADT input i and ADT output τ , respectively.

Randomization here refers to the selection of memory representations for ADT states and not to program outputs. A program’s output is the machine representation of the corresponding ADT operation’s output.

If randomization is used for history independence, then random choices made by the machine programs must be hidden from the adversary. If the adversary has knowledge of the random bits, then from the adversary’s point of view the machine programs are deterministic. Data structures with deterministic machine programs require canonical representations.

V. Generalizing History Independence

SHI is a very strong notion of history independence requiring canonical representations [1], [6]. Canonically represented data structures are not efficient [12]. For heap and queue data structures Buchbinder et al. [12] show that certain operations that require logarithmic time under WHI take linear time under SHI. Hence, it is worth to question the need for canonical representations for history independence. Many scenarios may not require such a strong notion rendering SHI data structures with canonical representations inefficient.

Some scenarios that can be efficiently realized by new history independence notions:

- Hiding evidence of specific operations only. For example, hiding only the fact that a specific data item has been deleted in the past, as required by regulations [7]
- A most recently used (MRU) caching or a journaling system by definition reveals the last k operations. Hence, journaling and caching require a new notion of history independence, wherein no history is revealed other than the last k operations [11].
- Revealing only the number of times each operation is performed [1]. For example, in a file-sharing application disclosing file-access counts may be permissible, but not the access order.

A straight-forward way to define new notions of history independence is to provide a new game-based definition for each scenario. However, defining distinct scenario-specific games can quickly become a tedious process. Instead, we introduce a definitional framework that can accommodate a broad spectrum of history independence notions. We term the new framework as Δ history independence (Δ HI), where Δ is the parameter determining the history independence flavor. As we shall see, Δ HI also captures both WHI and SHI. In addition, Δ HI helps to reason about the history revealed or concealed by existing data structures which were designed without history independence in mind.

A. Δ History Independence (Δ HI)

The WHI and SHI games (Sections IV-A and IV-B respectively) are defined over a subset of ADT operation sequences. For WHI, the adversary is permitted to select sequences that

take the ADT from initialization to the same end state. For SHI, the permitted sequences are ones that take the ADT from the same starting state to the same ending state. The selection is made by the adversary in step 1 of both the WHI and SHI games. Hence, the initial selection permitted to the adversary determines the history that is desired to be revealed or hidden. By generalizing the selection step, we can accommodate a broad spectrum of history independence notions. We achieve the generalization in Δ HI, defined by the following game:

Let $\mathcal{A} = (\mathcal{S}, s_\phi, \mathcal{O}, \Gamma, \Psi)$ be an ADT, $\mathcal{M} = (\mathcal{S}^{\mathcal{M}}, s_\phi^{\mathcal{M}}, \mathcal{P}^{\mathcal{M}}, \Gamma^{\mathcal{M}}, \Psi^{\mathcal{M}})$ be a bounded RAM machine model, and $\mathcal{D} = (\alpha, \beta, \gamma, s_0^{\mathcal{M}})$ be a data structure implementing \mathcal{A} in \mathcal{M} , as per definitions 1, 2 and 3, respectively. Also, let ζ be the set of all ADT operation sequences, Υ be the set of all ADT input sequences, and Δ be a function $\Delta : \mathcal{S} \times \mathcal{S} \times \zeta \times \zeta \times \Upsilon \times \Upsilon \rightarrow \{0, 1\}$.

- 1) A probabilistic polynomial time-bounded adversary selects the following.
 - Two ADT states s_1 and s_2 ; two sequences of ADT operations δ_0 and δ_1 ; and two sequences of ADT inputs I_0 and I_1 ; such that $\Delta(s_1, s_2, \delta_0, \delta_1, I_0, I_1) = 1$.
 - A memory representation $s_1^{\mathcal{M}}$ of ADT state s_1 .
- 2) The adversary sends $s_1, s_1^{\mathcal{M}}, \delta_0, \delta_1, I_0$ and I_1 to the challenger.
- 3) The challenger flips a fair coin $c \in \{0, 1\}$ and computes $\mathbb{O}^{\mathcal{M}}(\delta_c^{\mathcal{M}}, s_1^{\mathcal{M}}, I_c) \rightarrow (s^{\mathcal{M}}, \tau^{\mathcal{M}})$, where $\delta_c^{\mathcal{M}} = \chi(\delta_c)$. That is, the challenger applies the program sequence $\delta_c^{\mathcal{M}}$ corresponding to the ADT operation sequence δ_c to the data structure state $s_1^{\mathcal{M}}$, resulting in a memory representation $s^{\mathcal{M}}$, and a machine output $\tau^{\mathcal{M}}$.
- 4) The challenger sends the memory representation $s^{\mathcal{M}}$ and the machine output $\tau^{\mathcal{M}}$ to the adversary.
- 5) The adversary outputs $c' \in \{0, 1\}$.

The adversary wins the game if $c' = c$.

\mathcal{D} is said to be δ history independent if the advantage of the adversary for winning the game, defined as $|Pr[c' = c] - 1/2|$ is negligible (where “negligible” is defined over any implementation-specific security parameters of the programs in $\mathcal{P}^{\mathcal{M}}$).

Function Δ determines the pairs of ADT states, ADT operation sequences, and ADT input sequences that the adversary is permitted to select in step 1 of the Δ HI game. For the adversary-selected ADT states, operation sequences, and input sequences, the Δ HI game can be played and the data structure implementation is required to ensure that the advantage of the adversary is negligible. Thus, for a given ADT, Δ defines two sets,

$$H_\Delta = \{(s_1, s_2, \delta_0, \delta_1, I_0, I_1) \mid \Delta(s_1, s_2, \delta_1, \delta_2, I_0, I_1) = 1\},$$

and

$$\overline{H}_\Delta = \{(s_1, s_2, \delta_0, \delta_1, I_0, I_1) \mid \Delta(s_1, s_2, \delta_1, \delta_2, I_0, I_1) = 0\}.$$

For all tuples in H_Δ , history independence is preserved, that is, neither the ADT nor the data structure implementation reveals the operation sequence selected by the challenger in step 3. For all tuples in \overline{H}_Δ , history independence is not required to be preserved since the ADT itself reveals the sequence of operations used.

A careful choice of Δ allows us to precisely define both SHI and WHI, and a broad spectrum of new history independence notions. In the following, we illustrate the use of Δ HI framework to define some familiar history independence notions and a few previously unconsidered notions of history

independence.

1) Strong History Independence (SHI)

We discussed SHI in Section IV-B. Here, we define the function Δ for SHI.

$$\Delta(s_1, s_2, \delta_0, \delta_1, I_0, I_1) = \begin{cases} 1 & \text{if } \mathbb{O}(\delta_0, s_1, I_0) \rightarrow (s_2, \tau) \text{ and } \mathbb{O}(\delta_1, s_1, I_1) \rightarrow (s_2, \tau) \\ 0 & \text{otherwise} \end{cases}$$

For SHI, the adversary’s advantage in the Δ HI game must be negligible when in step 1, the adversary selects any two ADT operation sequences that take the ADT from a state s_1 to a state s_2 producing the same ADT output τ .

2) Weak History Independence (WHI)

Refer to Section IV-B for discussion on WHI, which requires the following definition of Δ .

$$\Delta(s_1, s_2, \delta_0, \delta_1, I_0, I_1) = \begin{cases} 1 & \text{if } s_1 = s_\phi \text{ and } \mathbb{O}(\delta_0, s_1, I_0) \rightarrow (s_2, \tau) \text{ and} \\ & \mathbb{O}(\delta_1, s_1, I_1) \rightarrow (s_2, \tau) \\ 0 & \text{otherwise} \end{cases}$$

Since WHI permits the adversary to observe a single data structure state, the adversary chooses only the end state s_2 in step 1 of the Δ HI game. The starting state on which sequences δ_0 and δ_1 are applied is the initial ADT state s_ϕ .

3) Null history independence (ϕ HI)

Under null history independence, a data structure conceals no history except for the trivial case when the ADT operation sequences and ADT input sequences selected by the adversary in the Δ HI game are identical. Example of a data structure with ϕ HI is an append-only log. We can reflect ϕ HI using the following.

$$\Delta(s_1, s_2, \delta_0, \delta_1, I_0, I_1) = \begin{cases} 1 & \text{if } \mathbb{O}(\delta_0, s_1, I_0) \rightarrow (s_2, \tau) \text{ and} \\ & \mathbb{O}(\delta_1, s_1, I_1) \rightarrow (s_2, \tau) \\ & \text{and } \delta_1 = \delta_2 \text{ and } I_1 = I_2 \\ 0 & \text{otherwise} \end{cases}$$

4) SHI*

The necessity of canonical representations for SHI was proven by Hartline et al. [6]. The proof by Hartline et al. [6] builds on the case that if a data structure is not canonically represented, then an adversary can distinguish an empty sequence of operations from a nonempty sequence. Hartline et al. [6] then proposed SHI*, which is defined over nonempty ADT operation sequences. SHI* data structures were initially expected to more efficient than data structures providing SHI. However, Hartline et al. [6] found that SHI* still poses very strict requirements on a data structure and may not differ from SHI in asymptotic complexity.

Here, we give the Δ function for SHI*.

$$\Delta(s_1, s_2, \delta_0, \delta_1, I_0, I_1) = \begin{cases} 1 & \text{if } \mathbb{O}(\delta_0, s_1, I_0) \rightarrow (s_2, \tau) \text{ and} \\ & \mathbb{O}(\delta_1, s_1, I_1) \rightarrow (s_2, \tau) \text{ and} \\ & |\delta_0| > 0 \text{ and } |\delta_1| > 0 \\ 0 & \text{otherwise} \end{cases}$$

SHI* closely resembles SHI except that the operations sequences δ_0 and δ_1 must be nonempty.

5) Reveal last k operations (Most Recently Used Cache, Journal)

System features such as caching and journaling by definition reveal the last k operations performed from the ADT state itself. Thus, for caching and journaling, we need to define a Δ function, such that no additional historical information is leaked from the memory representations other than the last k operations. We define the new notion as follows.

Let $\delta[i]$ denote the i^{th} operation in the sequence δ . Also, let $\delta[i, j]$ denote a subsequence of δ , $\{\delta[i], \dots, \delta[j]\}$ with $i \leq j$.

$$\Delta(s_1, s_2, \delta_0, \delta_1, I_0, I_1) = \begin{cases} 1 & \text{if } \mathbb{O}(\delta_0, s_1, I_0) \rightarrow (s_2, \tau) \text{ and} \\ & \mathbb{O}(\delta_1, s_1, I_1) \rightarrow (s_2, \tau) \text{ and} \\ & |\delta_0| \geq k \text{ and } |\delta_1| \geq k \text{ and} \\ & \delta_0[|\delta_0| - k, |\delta_0|] = \delta_1[|\delta_1| - k, |\delta_1|] \\ 0 & \text{otherwise} \end{cases}$$

The adversary is permitted to choose two sequences δ_0 and δ_1 , such that the last k operations in δ_0 and δ_1 are the same. Other than the last k operations, sequences δ_0 and δ_1 may differ. Yet, the adversary should be unable to identify the sequence chosen in step 3.

6) Operation-Agnostic History Independence (OAHI)

Consider a secure deletion application that wishes to destroy any evidence of a delete operation performed in the past. That is, an adversary (by observing the memory representations) should be unable to detect whether a delete operation was performed or not other than guessing. In general, any particular operation may require to be concealed, not just deletes. can be extended to any ADT operation (not just delete) We introduce a new notion of history independence that conceals specific ADT operations. The new notion is referred to as operation-agnostic history independence (OAHI). A data structure that is Δ history independent given the following Δ function guarantees operation-agnostic history independence for an ADT operation o .

$$\Delta(s_1, s_2, \delta_0, \delta_1, I_0, I_1) = \begin{cases} 1 & \text{if } \mathbb{O}(\delta_0, s_1, I_0) \rightarrow (s_2, \tau) \text{ and } \mathbb{O}(\delta_1, s_1, I_1) \rightarrow (s_2, \tau) \text{ and} \\ & o \in \delta_0 \text{ and } o \notin \delta_1 \\ 0 & \text{otherwise} \end{cases}$$

In OAHI, neither the presence of operation o in δ_0 , nor the absence of o in δ_1 gives the adversary any advantage in guessing the sequence chosen by the challenger in step 3 of the Δ HI game.

B. Measuring History Independence

We have seen that new notions of history independence can be easily derived from Δ history independence by defining the appropriate Δ function. In this section, we present an intuitive way of comparing Δ functions on the basis of the history they require to be concealed or preserved.

For a given Δ function we defined the set H_Δ (Section V-A) that represents all combinations of ADT states, operation sequences, and ADT input sequences for which the adversary's advantage is negligible in the Δ history independence game. That is, for all members of H_Δ , history independence is preserved. One insight is to use the cardinality of H_Δ as a measure of history independence.

Recall from Section III-C that an ADT can have several data structure implementations. Let \mathcal{D} and \mathcal{D}' be two implementations of an ADT \mathcal{A} , such that \mathcal{D} is Δ history independent and \mathcal{D}' is Δ' history independent for two functions Δ and Δ' . Now, we say that \mathcal{D} is more history independent than \mathcal{D}' if $H_{\Delta'} \subset H_\Delta$.

Note that $|H_\Delta| > |H_{\Delta'}|$ alone does not imply that \mathcal{D} is more history independent than \mathcal{D}' since an application may be more sensitive to the history preserved by \mathcal{D}' than the history preserved by \mathcal{D} . Only in the case where $H_{\Delta'} \subset H_\Delta$ can we consider \mathcal{D} to be a more history independent implementation than \mathcal{D}' .

C. Deriving History Independence

In order to provide a history independent implementation for an ADT, we first require the Δ function to be precisely defined. Then, a history independent data structure can be designed that satisfies the Δ function. Satisfying a Δ function means that the adversary's advantage is always negligible in the Δ history independence game. In effect, so far we have approached history independence as a define-then-design process.

However, data structures have been in use for a long time and most data structures have been designed for efficiency or functionality with no history independence in mind. A natural question then arises – are there any meaningful⁹ Δ functions satisfied by existing data structures?.

A data structure can be Δ history independent for several Δ functions. For example, a data structure that satisfies SHI, also satisfies WHI, OAHI, and OIAHI. Hence, for a given data structure \mathcal{D} finding a Δ function may not be a particularly difficult task. It may be more useful instead to determine an uncontained Δ function for \mathcal{D} . We define an uncontained Δ function for a data structure as follows.

Definition 8. Uncontained Δ function

A Δ function for a data structure \mathcal{D} is uncontained if \mathcal{D} is Δ history independent and $\nexists \Delta'$, such that \mathcal{D} is also Δ' history independent and $H_\Delta \subset H_{\Delta'}$, where

$$\begin{aligned} H_\Delta &= \{(s_1, s_2, \delta_0, \delta_1, I_0, I_1) \mid \\ & \Delta(s_1, s_2, \delta_0, \delta_1, I_0, I_1) = 1\}; \\ H_{\Delta'} &= \{(s'_1, s'_2, \delta'_0, \delta'_1, I'_0, I'_1) \mid \Delta'(s'_1, s'_2, \delta'_0, \delta'_1, I'_0, I'_1) = 1\}; \\ & s_1, s_2, s'_1, \text{ and } s'_2 \text{ are ADT states; } \delta_0, \delta_1, \delta'_0, \text{ and } \delta'_1 \text{ are ADT} \\ & \text{operation sequences; and } I_0, I_1, I'_0, \text{ and } I'_1 \text{ are ADT input} \\ & \text{sequences.} \end{aligned}$$

We can determine an uncontained Δ function for existing data structures on a case-by-case basis. An open question is whether there exists a general mechanism for deriving an uncontained Δ function for a given data structure.

VI. From Theory To Practice

A. Defining Machine States

The RAM model of execution described in Section III-B consists of two components, the RAM and the CPU. Hence, the machine state for the RAM model includes bits from both the RAM and the CPU. In general, the machine state

⁹ $\Delta = 0$ is satisfied by all data structures. Hence, we need to determine Δ functions that are more useful in practice.

for a system-wide machine model will comprise all system component states. A system-wide history independent implementation has to then consider each individual component's characteristics along the interaction between the components. Providing system-wide history independence is therefore challenging.

However, in practice an adversary may have access to only a subset of system components. In this case, for the purpose of history independence, the machine state can be defined over the adversary-accessible components only. For example, history independent data structures proposed in existing work (Section X) are designed with the RAM model in mind. However, the machine states considered for history independence only include bits from the RAM and exclude the CPU.

B. Building History Independent Systems

Various techniques for designing history independent data structures for commonly used ADTs such as queues, stacks, and hash tables have been proposed [1]. Our focus on the other hand is designing *systems* with end-to-end history independent characteristics. The difference between history independent implementations for simple ADTs, such as stacks and queues versus a complete system, such as a database, or a file system is a matter of often exponentially increasing complexity. Fundamentally, any system can be modeled as an ADT and an history independent implementation can be sought for the system.

We introduce a general recipe for building history independent systems as follows:

- 1) Model the system as an ADT. For a specific example of file system as an ADT, refer to section VIII.
- 2) Select a machine model for implementation. While defining the machine state identify all machine components that the adversary has access to and define the machine state associated with the adversary-accessible components.
- 3) Depending on the application scenario, fix a desired notion of history independence and the corresponding Δ function.
- 4) Based on the definition of Δ , provide an implementation over the selected machine model. For complex systems, the implementation will likely require the most effort since the machine programs implementing the ADT operations must provably ensure that the advantage of the adversary is negligible in the Δ HI game.

In section VIII, we follow the above recipe to design a history independent file system.

VII. On A Philosophical Note

At a very high level, the motivation for history independence can be stated as follows.

For any logical state S_L , the physical state S_P representing S_L may reveal information about the history leading to S_L , that is otherwise not discernible via solely S_L .

So far, we have considered the logical state to be the ADT state and the physical state to be the underlying machine state

representing the ADT state, that is, the physical state is the set of all bits of the machine. Our selection of logical and physical states seems rather arbitrary. We do this specific selection due to our adversary model, which assumes that the adversary can interpret information at the level of bits. An adversary, that can for example, examine the electric charge in individual capacitors used to represent the bits will require a different choice of logical and physical state descriptions. A straightforward choice would be to consider a bit as a logical state and the precise capacitor state as the physical state.

The following interesting question arises from this discussion – *is history independence only a matter of perspective?*. The short answer is *yes*, history independence is a matter of perspective. There is no universal history independence.

To clarify, consider the universe as a whole from the viewpoint of classical physics. Under the classical viewpoint, knowledge of current state of all objects in the universe enables determination of any past or future universal state since the laws of physics work both forwards and backwards in time. Hence, the past is never hidden and history independence is impossible. For example, using the currently observed movement of galaxies, the past states of the universe can be inferred up to the very initial moments of the big bang.

Physical phenomena at the subatomic scale is explained by quantum physics. At the quantum level, the universe appears nondeterministic. Further, the uncertainty principle [14] restricts the ability to accurately measure the current state of a quantum system. Since the current state cannot be accurately known, it may seem the past states cannot be determined either and history independence can be achieved at the quantum level.

However, even at the quantum level history independence is still a matter of perspective. The perspective is governed by the interpretation of quantum physics used. Under the many-worlds interpretation, the multiverse as a whole is deterministic [15]. The probabilistic nature at the quantum level is only our perception since our observations are limited to a single universe. A hypothetical all-powerful adversary that can view the entire multiverse would have a full view of the past and the future similar to the case of classical physics making history independence in the presence of such an adversary impossible.

VIII. Practical SHI for File Systems

We now apply our theoretical concepts and results towards practical history independent system designs.

Our focus is designing *systems* with end-to-end history independent characteristics. The difference between history independent implementations for simple ADTs, such as stacks and queues [1] versus a complete system, such as a database, or a file system is a matter of often exponentially increasing complexity. Fundamentally, any system can be modeled as an ADT and a history independent implementation can be sought for the system.

We introduce a general recipe for building history independent systems as follows:

- 1) Model the system as an ADT. For a specific example of file system as an ADT, refer to section VIII-A.

- 2) Select a machine model for implementation. While defining the machine state identify all machine components that the adversary has access to and define the machine state associated with the adversary-accessible components.
- 3) Depending on the application scenario, fix a desired notion of history independence and the corresponding Δ function.
- 4) Based on the definition of Δ , provide an implementation over the selected machine model. For complex systems, the implementation will likely require the most effort since the machine programs implementing the ADT operations must provably ensure that the advantage of the adversary is negligible in the Δ HI game.

Using this recipe, we design, implement, and evaluate a history independent file system (HIFS) and a delete agnostic file system (DAFS).

In Sections VIII-A - VIII-C, we describe HIFS, an SHI implementation for file systems. In Section IX, we introduce DAFS (delete agnostic file system). DAFS extends HIFS beyond SHI to implement new history independence notions. DAFS aims to be more efficient for scenarios in which canonical representations can be avoided. Further, DAFS extends functionality and resilience of the FS.

A. HIFS Overview

Existing file systems, such as Ext3 [16] are not history independent because they organize data on disk as a function of both files' data and the sequence of file operations. The exact same set of files can be organized differently on disk depending on the sequence of file system operations that created the set. As a result, observations of data organization on disk can potentially reveal file system's history. Moreover, file system meta-data also contains historical information, such as list of allocated blocks. Therefore, when observations of data organization are combined with file system meta-data, and with knowledge of application logic, significantly more historical information can be derived, for example, full recovery of deleted data. It is therefore imperative to hide file system history.

File system history can be hidden by making file system implementations history independent. A straight-forward way to achieve this is to use existing history independent data structures to organize files' data on disk. Current techniques to make history independent data structures persistent require the use of history independent hash tables [1]. The history independent hash tables [3] in turn use uniform hash functions. The use of uniform hash functions distributes files' data on storage with no consideration to data locality.

Modern filesystems exploit data locality for performance by storing logically related data at nearby physical locations on the storage device. For e.g., blocks of data belonging to the same file may be stored physically close to each other to reduce seek time on traditional storage devices with mechanical parts. This significantly reduces the latency for file access. Consequently, existing history independent data structures which do not preserve data locality cannot be used for practical filesystem design.

In HIFS, we overcome the challenge of providing history independence while preserving data locality.

Model

We assume an insider adversary with full access to the system disk. By analyzing data organization on disk, the adversary aims to derive file system's history. We assume that the adversary can make multiple observations of disk contents. Recall from Section IV-D that thwarting such an adversary requires SHI with canonical representations. Hence, HIFS targets canonical representations for file storage.

Concepts

1) File System ADT

A file system organizes data as a set of files. We consider a file to consist of some meta-data and a bit string. That is, a file $f = \{m_f, b_f\}$, where m_f is the file meta-data and $b_f \in \{0, 1\}^*$. We define a file system ADT using the file type. Refer to Section III-C for a discussion on ADTs and types.

A file system is an ADT, that is, a pentuple $(\mathcal{S}, s_\phi, \mathcal{O}, \Gamma, \Psi)$, where

- $\mathcal{S} = 2^{\mathcal{F}}$, is the set of states. Here \mathcal{F} is the set of all files.
- $s_\phi \in \mathcal{S}$ is the initial state.
- $\Gamma = \mathbb{N} \cup \{0, 1\}^* \cup (\mathbb{N} \times \mathbb{N} \times \mathbb{N}) \cup (\mathbb{N} \times \mathbb{N} \times \mathbb{N} \times \{0, 1\}^*)$ is the set of all possible inputs to the filesystem operations. In other words, the set of all possible inputs is composed of : All possible inputs to the filesystem close operation \cup All possible inputs to the filesystem open operation \cup All possible inputs to the filesystem read operation \cup All possible inputs to the filesystem write operation.
- $\Psi = \mathbb{Z} \cup (\{0, 1\}^* \times \mathbb{Z})$ is the set of all possible outputs from the filesystem operations. In other words, the set of all possible outputs is composed of : All possible outputs of filesystem operations \cup All possible output for filesystem metadata.
- The set of operations $\mathcal{O} = \{\text{open, read, write, delete, close}\}$, such that
 - open : $\mathcal{S} \times \{0, 1\}^* \rightarrow \mathcal{S} \times \mathbb{Z}$.
 - read : $\mathcal{S} \times \mathbb{N} \times \mathbb{N} \times \mathbb{N} \rightarrow \mathcal{S} \times \{0, 1\}^* \times \mathbb{Z}$.
 - write : $\mathcal{S} \times \mathbb{N} \times \mathbb{N} \times \mathbb{N} \times \{0, 1\}^* \rightarrow \mathcal{S} \times \mathbb{Z}$.
 - delete : $\mathcal{S} \times \mathbb{N} \rightarrow \mathcal{S} \times \mathbb{Z}$.
 - close : $\mathcal{S} \times \mathbb{N} \rightarrow \mathcal{S} \times \mathbb{Z}$.

File systems including HIFS support several additional operations. We have included only a small subset of the operations here for brevity.

2) RAMDisk Machine Model

In Section III-B we introduced the RAM machine model. The RAM model consists of two components, a central processing unit (CPU), and a random access memory (RAM). However, a file system is generally used to store and manage data over a secondary storage device. Hence, we define the RAMDisk model which in addition to the CPU and memory also includes the storage disk.

Definition 9. RAMDisk Machine Model

A RAMDisk machine model $\mathcal{M}_{\mathcal{D}}$ with m b -bit memory words, n b -bit CPU registers, and c k -bit disk blocks is a pentuple

$(\mathcal{S}, s_\phi, \mathcal{P}, \Gamma, \Psi)$, where $\mathcal{S} = \{0,1\}^{b(m+n)+c \cdot k}$ is a set of machine states, $s_\phi \in \mathcal{S}$ is the initial state, \mathcal{P} is the set of all programs of $\mathcal{M}_{\mathcal{D}}$, $\Gamma = \{0,1\}^*$ is a set of inputs, $\Psi = \{0,1\}^*$ is a set of outputs; each program $p \in \mathcal{P}$ is a function $p : \mathcal{S} \times \Gamma_p \rightarrow \mathcal{S} \times \Psi_p$, where $\Gamma_p \subseteq \Gamma$ and $\Psi_p \subseteq \Psi$.

$\mathcal{M}_{\mathcal{D}}$ is initialized to state s_ϕ . When a program $p \in \mathcal{P}$ with input $i \in \Gamma_p$ is executed by the CPU when $\mathcal{M}_{\mathcal{D}}$ is in state s_1 , $\mathcal{M}_{\mathcal{D}}$ outputs $\tau \in \Psi_p$ and transitions to a state s_2 . This transition is denoted as $p(s_1, i) \rightarrow (s_2, \tau)$.

According to our model (Section VIII-A), the adversary has access to the storage disk. For the purpose of history independence, we need to consider the machine states associated with the adversary-accessible components only. Hence, from this point onwards we refer to the storage device state as the machine state. Since the adversary does not access CPU and RAM components we permit the CPU and RAM states to reveal history.

3) File System Implementation (Data Structure)

The objectives of HIFS design are three-fold.

- 1) For a given set of files, the organization of files' data and files' meta-data on disk must be the same independent of the sequence of file operations. That is, file system implementation must be canonically represented and thereby preserve SHI.
- 2) Despite history independent storage, data locality must be preserved.
- 3) The implementation must be easily customizable to suit a wide range of data locality scenarios.

HIFS is a history independent implementation of the file system ADT from Section VIII-A1. That is, HIFS is a data structure $\mathcal{D} = (\alpha, \beta, \gamma, s_0^{\mathcal{M}})$ obtained as follows.

- For all $n \in \mathbb{N}_b$, $\alpha(n) \in \{0,1\}^b$. Here, $\mathbb{N}_b = \{x | x \in \mathbb{N} \text{ and } x \leq 2^b\}$, b is the machine word length, and $\alpha(n)$ is the bit string representing n . For all $t_s \in \{0,1\}^{c \cdot k}$, $\alpha(t_s) = t_s$ where t_s represents the current disk state in the RAMDisk model. For all $(n_1, n_2, n_3) \in \mathbb{N}_b \times \mathbb{N}_b \times \mathbb{N}_b$, $\alpha((n_1, n_2, n_3)) = \alpha(n_1) || \alpha(n_2) || \alpha(n_3)$. For all $(n_1, n_2, n_3, t_s) \in \mathbb{N}_b \times \mathbb{N}_b \times \mathbb{N}_b \times \{0,1\}^{c \cdot k}$, $\alpha((n_1, n_2, n_3, t_s)) = \alpha(n_1) || \alpha(n_2) || \alpha(n_3) || t_s$.
- For all $z \in \mathbb{Z}_b$, $\alpha(z) \in \{0,1\}^b$. Here, $\mathbb{Z}_b = \{x | x \in \mathbb{Z} \text{ and } x \leq 2^b\}$, b is the machine word length, and $\alpha(z)$ is the bit string representing z .
- $\gamma : \mathcal{O} \rightarrow \mathcal{P}^{\mathcal{M}}$. The programs that we provide for each file system operation are the key to achieving SHI. We discuss the HIFS programs in Section VIII-B.
- The initial data structure state $s_0^{\mathcal{M}}$ corresponding to the initial file system ADT state is obtained by initializing all file system meta-data.¹⁰

B. Architecture

1) Overview

A file system ADT state contains two pieces of information for each file – the file meta-data and the file data. HIFS

¹⁰File system meta-data includes superblock, group descriptors, inode tables, and disk buckets map. Refer to [17] for detailed HIFS architecture. The loading of file system programs and memory management are done by the operating system.

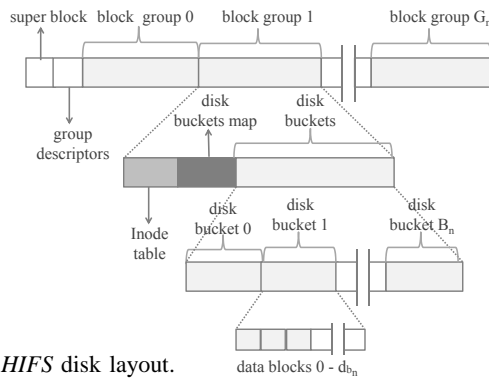


Fig. 4. HIFS disk layout.

supports SHI by providing unique memory representations for each ADT state. To ensure unique representations, we first select an existing SHI data structure implementation for a hash table ADT (Section VIII-B2). Then, we re-design the hash table implementation to endow it with data locality properties (Section VIII-B3). Finally, we use two instances of re-designed hash table implementation to store data on disk, one for files' meta-data and the other for files' data (Section VIII-B4).

We refer the reader to [17] for detailed HIFS architecture. In the following we focus only on the key features that make HIFS history independent and locality preserving.

2) History Independent Hash Table [3]

The SHI data structure of choice is the history independent hash table from [3]. The hash table in [3] is based on the stable matching property of the *Gale-Shapley Stable Marriage* algorithm [18].

SHI Hash Table: [3] uses the stable matching property to construct a canonically represented SHI hash table.

The construction in [3] ensures that for a given set of keys, the hash table data structure state is the same irrespective of the sequence of key insertions and deletions, thereby making the hash table data structure canonically represented¹¹.

3) Key Insights

The SHI hash table of [3] can be used as is to organize file's meta-data and files' data on disk. This will yield a SHI file system implementation. However, doing so does not preserve data locality, which is an important goal in HIFS design. Then a key observation in this context is the following. In the Stable Marriage algorithm each man in M can rank the n women in W in $n!$ ways and vice-versa. Hence, several sets of preferences from keys to buckets and buckets to keys are possible, each resulting in a distinct hash table instance. Therefore, by changing the preference order of keys and buckets we can control the organization of keys within the hash table.

To enable the re-ordering of preferences we re-write the algorithms of [3]. The re-write categorizes hash table operations in two Procedure Sets, a *generic* set and a *customizable* set. The generic procedures implement the overall search, insert, and delete operations, and can be used unaltered for all scenarios. The customizable procedures determine the specific

¹¹Refer to [3] for proof of canonical representation.

key and bucket preferences thereby governing data organization, including canonical representations and data locality. This new procedure classification and rewrite enables HIFS to realize different data locality scenarios for the same data set through modifications of the customizable procedure set only. The generic procedures and the overall file system operations remain unchanged. We note that this customization is achieved while preserving SHI.

Due to space constraints we refer the reader to [17] for complete listing of generic and customizable procedures for several data locality scenarios. In this paper we focus on the scenario of block group locality. Under block group locality, it is desired that blocks of the same file are located close together on disk ideally within the same block group.

4) File Storage

File data is stored in blocks on disk. The blocks are grouped into fixed-size units. Each unit is termed as a disk bucket (Figure 4). Like Ext3 [16], HIFS divides the disk into block groups. Each block group contains an inode table, a disk buckets map, and a set of disk buckets. Each entry within the disk buckets map has a one-one mapping to the corresponding disk bucket within the same block group. The entry in the disk bucket map contains meta-data about the corresponding disk bucket, such as whether the bucket is free or occupied.

5) Achieving SHI With Data Locality

Existing file systems, such as Ext3 [16] maintain a list of allocated blocks within the file inode, which renders the disk space allocation history dependent. HIFS on the other hand does not rely on allocation lists. Instead, in HIFS, locations of data blocks are determined using only the current operation parameters and do not depend on past operations.

In HIFS, the disk bucket maps from all block groups are collectively treated as a single SHI hash table. Then, to achieve canonical representations for file system ADT states, the file system operations are translated in to SHI hash table operations as follows: (a) Keys are derived from the full file path, and from read or write offset parameters to file system operations. (b) The hash table buckets are the disk buckets map entries. (c) Key preferences are set such that each key first prefers all buckets from one specific block group in a fixed order. Then, buckets from the next adjacent block group and so on. This ensures that with high probability blocks of the same file will be located within the same block group. (d) Buckets prefer keys with higher numerical values.

The above translation realizes one data locality scenario referred to as block group locality. In [17] we demonstrate several other scenarios such as sequential file storage and locality based on external parameters.

C. Experiments

A detailed evaluation of HIFS for different application profiles and data locality scenarios is available in [17]. Here, we only list partial results (Figure 5) to give a sense of throughputs that can be achieved under SHI.

We tested HIFS on a file system of size 100 GB with mean file size 1 GB. The experiments were conducted for different

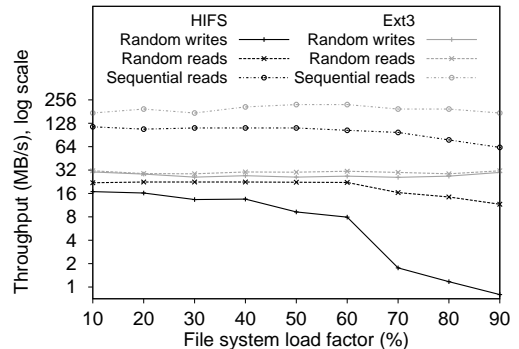


Fig. 5. HIFS experimental throughputs. Load factor = space utilization.

load factors denoted by L^{12} . The tests were conducted on $L \times 100$ files. We used 4 KB disk blocks with 8 block groups and 5120 disk blocks per bucket. The typical inode size used was 281 bytes and IO size was 32 KB.

The performance of HIFS for read operations is comparable to read throughputs of Ext3 for load factors up to 60%. For higher load factors the write operations sustain significant overheads. This is because as the load factor increases, the per write overhead to maintain canonical representations increases exponentially. The overhead is the relocation of existing files' data when a new file is being written or when a file is being resized. However, once the write operations achieve canonical representations with block group locality reads are efficient.

IX. Delete Agnostic File System (DAFS): Journaling and DAHI

The HIFS implementation (Sections VIII-B - VIII-C) supports SHI. As seen from the experimental results (Figure 5), for higher file system load factors, write efficiency is low. This is because SHI strictly requires canonical representations. To ensure canonical representations, HIFS relocates data on each write operation. The amount of data re-located increases exponentially with the file system load factor. Hence, the write throughputs are significantly lower for load factors greater than 60%.

Applications that do not require SHI can be made highly efficient using new targeted history independence notions. In Section V-A, using Δ HI we have defined several new history independence notions that unlike SHI, do not require canonical representations. We have re-designed the file system layer to support such new notions. Further, we have extended both functionality and resilience of the file system. The new file system is called *Delete Agnostic File System (DAFS)*.

Journalled History Independence (JHI). In the event of a system failure, it is imperative that the file system state is not corrupted. To ensure this, file systems typically employ a journal. File system operations are first recorded in the journal and then applied to the file storage area. If a failure occurs while writing to the journal, the operations can be ignored on system recovery. On the other hand, if failure occurs while writing to file storage, then on recovery the operations can be re-played from the journal. Thus each write request to the file

¹²Load factor is the file system disk space utilization.

system causes two disk writes, one to the journal and one to file storage.

DAFS Journaling. In DAFS, a separate region on disk is reserved for a journal in the form of a circular log. The journal contains information for a finite number of file system operations, say k operations. Operations are recorded in the journal in the order in which they are received by the file system. To restore consistency after system failure, it is essential to maintain operation order. Hence, the sequence of k operations recorded in the journal cannot be hidden. The file storage areas, such as the inode tables, disk bucket maps, and the disk buckets provide SHI just as in the case of HIFS. Hence, once a file system operation is applied to file storage and removed from the journal, its timing can no longer be identified.

Apparent paradox: why journaling increases efficiency
History independence relaxations that come with journaling allow significantly more efficient file system operations due to batching. This is explained in the following.

To maintain canonical representations in HIFS, data is potentially re-located on each file system write operation. The frequency of data re-location increases exponentially with the file system load factor. Hence, for higher load factors, the number of disk writes for each write request to the file system is much greater than the two disk writes required for journaling. Further, the same data blocks may be re-located several times in consecutive write operations. If write operations can be batched, then the number of times a data block is re-located can be reduced by avoiding redundant moves.

In DAFS, we choose to use the journal not only for failure recovery but also as a buffer to batch write operations. Write operations are applied to file storage areas only when the journal is full. During this process, redundant disk writes are eliminated significantly improving write throughputs.

A. Delete-Agnostic HI (DAHI)

Regulations [7] that are specifically concerned with irrecoverable data erasure and not with other artifacts of history can be met by systems that support OAH for the delete operation. We refer to this notion of history of independence as delete-agnostic history independence (DAHI). As discussed in Section V-A6, unlike SHI, OAH for deletes can be achieved without canonical representations. Relaxing the requirement to noncanonical representations presents significant efficiency benefits.

To make DAFS preserve DAHI only, we first transform the SHI hash table [3] into an DAHI hash table. Then, we use the DAHI hash table to organize files' data and files' metadata.

1) DAHI hash table

The SHI hash table from [3] can be transformed into an DAHI hash table as follows :

The hash table insert operation is modified to not maintain canonical representations. Instead, the insert operation uses linear probing [9] and inserts a key in the first available bucket.

The SHI hash table delete operation¹³ alone provides DAHI. Deletion of a key from the hash table leaves an empty bucket, say bucket b_1 . The delete operation then finds a key that prefers bucket b_1 more than the bucket it is located in according to the the gale-shapely stable marriage algorithm, say bucket b_2 . If such a key is found it is moved from b_2 to b_1 making b_2 empty. The process is then repeated for bucket b_2 , and so on, until no key is found for relocation. The net effect of this process is that a sequence of hash table operations that contains a delete operation results in the same hash table state as an insert-only sequence hiding all evidence of the delete.

Theorem 3. *DAHI hash table preserves delete-agnostic history independence.*

Proof. Consider the Δ history independence game for operation agnostic history independence for deletes played between a challenger \mathcal{C} and an adversary \mathcal{A} . The ADT considered here is the delete-agnostic hash table. \mathcal{A} selects two sequence of operations : δ_0 and δ_1 such that δ_0 inserts and subsequently deletes an element x from the hash table. δ_1 does not contain any delete operations. To ensure indistinguishability between the two sequence, the delete agnostic hash table must ensure that applying both the sequences of operations to the same initial ADT state should result in the same final ADT state.

Now consider that applying δ_0 brings the hash table from an initial state to a given state s with element x placed at position k in the hash table. Also consider that $\delta_0[j] = I(x)$ and $\delta_0[m] = D(x)$, that is, the j^{th} operations in sequence δ_0 inserts x into the hash table and the m^{th} operation deletes x from the hash table.

Consider the elements inserted into the hash table by the operations in δ_0 upto the m^{th} operation. We can divide these elements into three sets as follows

- 1) $A = \{y \mid \delta_0[i] = I(y), i < j\}$.
- 2) $B = \{y \mid \delta_0[i] = I(y), i > j, i < m\}$. Further, $\forall y \in B$, y cannot be mapped to position k in the hash table using linear probing.
- 3) $C = \{y \mid \delta_0[i] = I(y), i > j, i < m\}$. Further, $\forall y \in C$, y can be mapped to position k in the hash table using linear probing.

The three sets are constructed in a way such that the elements of the sets are sorted on the order in which the elements are inserted into the hash table. To illustrate, consider a set $S \in \{A, B, C\}$ and two elements $a, b \in S$ such that $S_i = a$ and $S_j = b$ where S_k is the k^{th} element of set S . Also consider $\delta_0[p] = I(a)$ and $\delta_0[q] = I(b)$. Then, the sorted property of the sets implies that $i < j$ only if $p < q$.

When the delete operation for x is executed in δ_0 , the elements of A and B are not affected due to the design of the hash table. Further by construction, once x is deleted, the first element from C is placed at position k and all other elements already placed in the hash table are remapped (if necessary). If $C = \phi$, then nothing is written to k after the delete. Let $C = \{c_1, c_2, \dots\}$ without loss of generality. Also let $D = \{d_1, d_2, \dots\}$ be the elements inserted into the hash table after x was inserted. Once the delete operation is

¹³For complete listing of SHI hash table operations refer to [17].

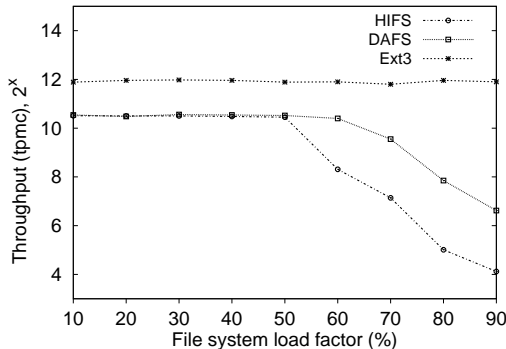


Fig. 6. TPCC throughputs for Ext3, HIFS, and DAFS with file system load factor. Load factor = space utilization.

executed in δ_0 , c_1 will be placed at position k and the elements in D will be remapped to positions in the hash table as if x was never inserted. Since, δ_0 does not contain any other delete operations, the resulting state after applying the sequence of operations on the delete-agnostic hash table is equivalent to the resulting state when an insert-only sequence is applied which does not insert and subsequently delete x from the hash table. Note that the definition of the Δ function for operation agnostic history independence for deletes enforces the adversary to select δ_1 to be exactly such a sequence in step 1 of the game. Hence, applying δ_1 to the delete agnostic hash table will lead to the same modifications to the hash table as δ_0 . This ensures indistinguishability between the two sequences of operations for the adversary and guarantees that the adversary cannot win the operation agnostic history independence game for deletes on the delete agnostic hash table with more than negligible advantage. \square

2) DAHI in DAFS

DAFS uses the DAHI hash table for file storage. The DAHI hash table insert operation is not required to maintain canonical representations. Since the hash table insert operation is used by file system write operation, the overhead of maintaining canonical representations on file writes is eliminated.

When a file is deleted in DAFS, for each disk bucket allocated to the file, the same effect is achieved as that for a key deleted from the DAHI hash table. As a result, no evidence of a delete remains in the file system state and DAHI is preserved.

Changing the history independence notion from SHI in HIFS to DAHI in DAFS has significant potential for efficiency. The number of writes to disk buckets needed for DAHI is significantly lower as compared to the number of writes needed for SHI. This is because write operations are no longer required to maintain canonical representations. As a result, when disk buckets are allocated to a file, other files' data needs no relocation. The relocation of data was precisely the reason for lower throughputs of HIFS writes.

B. Experiments

DAFS implements two new history independence notions, JHI and DAHI. Both JHI and DAHI are aimed to increase file system efficiency. DAFS can be configured to use DAHI and JHI either exclusively or together. If DAFS is configured to use

TABLE III

SUMMARY OF HISTORY INDEPENDENT DATA STRUCTURES. $\alpha \leftarrow$ LOAD FACTOR, $N \leftarrow$ NUMBER OF KEYS, $B \leftarrow$ BLOCK TRANSFER SIZE. ALSO, I : INSERT, L : LOOKUP, D : DELETE, R : RANGE

Data Structure	SHI or WHI?	Year	Ops	Runtime
2-3 Tree [20]	WHI	1997	I,L,D	$O(\log N)$
Hash Table [11]	SHI	2001	I,L	$O(\log(1/(1-\alpha)))$
Hash Table [3]	SHI	2007	I,L,D	$O(1/(1-\alpha)^3)$
Hash Table [2]	SHI	2008	I,L,D	$I,D \rightarrow O(\log N), S \rightarrow O(1)$
B-Treaps [21]	SHI	2009	I,D,R	$O(\log_B N)$
B-SkipList [22]	SHI	2010	I,D,R	$O(\log_B N)$

both JHI and DAHI, then DAFS uses DAFS journaling IX. In this case, if the journal contains an entry for a delete operation then the adversary can learn about this delete from the journal. Thus, DAFS allows the user to configure the filesystem for better performance at the cost of revealing a few deletes to the adversary. In this section, we compare the performance of DAFS and HIFS.

All experiments were conducted on servers with 2 Intel Xeon Quad-core CPUs at 3.16GHz, 8GB RAM, and kernel v3.13.0-24. The storage devices of choice are Hitachi HDS72302 SCSI drives.

DAFS is implemented as a C++ based user-space Fuse file system. All data structures, including DAHI hash table were written from scratch. We tested DAFS on a file system of size 10 GB and mean database size 1 GB. The experiments were conducted on L10 databases. We used 4 KB disk blocks with 4 block groups and 512 disk blocks per bucket. The typical inode size used was 281 bytes.

To experiment for a real-world scenario we use the TPCC [19] database benchmark. The database of choice is SQLite. SQLite data files are stored using HIFS, DAFS (without journaling), and Ext3. The BenchmarkSQL tool is used to generate the TPCC workload.

Each test run commences with an empty file system and creates new databases on file system storage. The number of databases is increased until the file system is 90% full. The TPCC scale factor is 10 giving a size of 1GB for each database. Throughputs are measured at specific load factors, ranging from 10% to 90%.

Figure 6 reports the throughputs for HIFS, DAFS, and Ext3. As per the TPCC specification, throughputs are reported as new order transactions executed per minute (tpmc). As seen, the performance of DAFS is up to 4x times better than HIFS for load factors $>50\%$. Note that the performance of Ext3 is included as a reference. Ext3 does not provide DAHI.

For load factors $\leq 50\%$, HIFS and DAFS exhibit similar performance. At lower load factors fewer collisions occur as new files are added to file system storage. Fewer collisions mean that the frequency of data relocation to maintain canonical representations is low at load factors $\leq 50\%$. Hence, performance of DAFS and HIFS is similar at low load factors.

X. Related Work

Existing history independent data structures are summarized in Table III. The data structures in Table III assume a rewritable storage medium. [4] designed a history independent solution for a write-once medium. The construction is based on the observation from [11] that a lexicographic ordering of elements in a list is history independent. However, write-once

memories do not allow in-place sorting of elements. Instead [4] employs copy-over lists [11]. When a new element is inserted, a new list is stored while the previous list is erased. This requires $O(n^2)$ space to store n keys.

[5] improves on [4] requiring only linear storage. The key idea is to store all elements in a global hash table and for each entry of the hash table maintain a separate copy-over list containing only the colliding elements.

XI. Conclusions

In this paper, we took a deep look into history independence from both a theoretical and a systems perspective. We explored the concepts of abstract data types, machine models, data structures and memory representations. We identified the need for history independence from the perspective of ADT and data structure state transition graphs. Then, we introduced Δ history independence, which serves as a general framework to define a broad spectrum of history independence notions including strong and weak history independence. We also outlined a general recipe for building history independent systems and illustrated its use in designing two history independent file systems.

References

- [1] D. Golovin, "Uniquely represented data structures with applications to privacy," Ph.D. dissertation, 2008, aAI3340637.
- [2] M. Naor, G. Segev, and U. Wieder, "History-independent cuckoo hashing," in *Proceedings of international colloquium on Automata, Languages and Programming, Part II*. Springer-Verlag, 2008, pp. 631–642.
- [3] G. E. Blelloch and D. Golovin, "Strongly history-independent hashing with applications," in *Proceedings of IEEE Symposium on Foundations of Computer Science*, ser. FOCS '07, 2007, pp. 272–282.
- [4] D. Molnar, T. Kohno, N. Sastry, and D. Wagner, "Tamper-evident, history-independent, subliminal-free data structures on prom storage-or-how to store ballots on a voting machine," in *Proceedings of IEEE Symposium on Security and Privacy*, 2006, pp. 365–370.
- [5] T. Moran, M. Naor, and G. Segev, "Deterministic history-independent strategies for storing information on write-once memories," in *Proceedings of International Colloquium on Automata, Languages and Programming*. Springer, 2007, pp. 303–315.
- [6] J. Hartline, E. Hong, A. Mohr, E. E. Mohr, W. Pentney, and E. Roche, "Characterizing history independent data structures," 2002.
- [7] CFR240, "Code of Federal Regulations, Part 240.17a-4," 2010.
- [8] S. M. Diesburg and A.-I. A. Wang, "A survey of confidential data storage and deletion methods," *ACM Comput. Surv.*, vol. 43, no. 1, pp. 2:1–2:37, Dec. 2010.
- [9] D. P. Mehta and S. Sahni, *Handbook Of Data Structures And Applications (Chapman & Hall/Crc Computer and Information Science Series.)*. Chapman & Hall/CRC, 2004.
- [10] S. Bajaj and R. Sion, "Ficklebase: Looking into the future to erase the past," *2013 IEEE 29th International Conference on Data Engineering (ICDE)*, vol. 0, pp. 86–97, 2013.
- [11] M. Naor and V. Teague, "Anti-persistence: History independent data structures," in *In Proceedings of ACM symposium on Theory of computing*. ACM Press, 2001, pp. 492–501.
- [12] N. Buchbinder and E. Petrank, "Lower and upper bounds on obtaining history independence," *Inf. Comput.*, vol. 204, no. 2, pp. 291–337, Feb. 2006. [Online]. Available: <http://dx.doi.org/10.1016/j.ic.2005.11.001>
- [13] J. Savage, "Models of computation: Exploring the power of computing," 1998.
- [14] A. Rae, *Quantum physics: a beginner's guide*, ser. Oneworld beginners' guides. Oneworld, 2005.
- [15] H. Everett, "The theory of the universal wavefunction," 1956, PhD Thesis.
- [16] L. Lu, A. C. Arpaci-Dusseau, R. H. Arpaci-Dusseau, and S. Lu, "A study of linux file system evolution," *Trans. Storage*, vol. 10, no. 1, pp. 3:1–3:32, Jan. 2014.
- [17] S. Bajaj and R. Sion, "HIFS: History Independence for File Systems," in *Proceedings of the 20th ACM Conference on Computer and Communications Security*, ser. CCS '13, 2013.
- [18] D. Gale and L. Shapley, "College admissions and the stability of marriage," *American Mathematical Monthly*, vol. 69, no. 1, pp. 9–15, 1962.
- [19] T. P. P. Council, "TPC-C," Online at <http://www.tpc.org/tpcc/>, 1992, database Benchmark Specification.
- [20] D. Micciancio, "An oblivious data structure and its applications to cryptography," in *In Proceedings of ACM Symposium on the Theory of Computing*. ACM Press, 1997, pp. 456–464.
- [21] D. Golovin, "B-treaps: A uniquely represented alternative to b-trees," in *Proceedings of International Colloquium on Automata, Languages and Programming: Part I*. Springer-Verlag, 2009, pp. 487–499.
- [22] —, "The B-skip-list: A simpler uniquely represented alternative to B-trees," *CoRR*, vol. abs/1005.0662, 2010.