Dependent Types for Enforcement of Information Flow and Erasure Policies in Heterogeneous Data Structures

Gordon Stewart
Princeton University
jseven@cs.princeton.edu

Anindya Banerjee
IMDEA Software Institute
anindya.banerjee@imdea.org

Aleksandar Nanevski
IMDEA Software Institute
aleks.nanevski@imdea.org

ABSTRACT

We consider verification of information flow and erasure properties in programs with heterogeneous heap-based data structures, in the presence of procedures with local state. A heterogeneous data structure, such as a hash table implementing a medical record database, may store both secret and public data simultaneously. In contrast, extant work primarily focuses on homogeneous data structures which store data of a uniform security level. Heterogeneity, however, does not come for free. For example, standard implementations of hash tables do not support heterogeneity, and may leak sensitive information easily owing to hash collisions. In this paper we identify unique representation as a sufficient condition for a heterogeneous data structure to be leak-free, while simultaneously supporting abstraction and modularity in verification. As a case study, we implement and verify a novel uniquely-represented variant of heterogeneous hash tables. Furthermore, we demonstrate modular reasoning by showing how specifications of the hash table methods can be used in a client application; we thereby obtain abstract and concise formal proofs of erasure. We formalize our work in Relational Hoare Type Theory (RHTT), an expressive, higher-order imperative language and program logic embedded in the Coq proof assistant.

Categories and Subject Descriptors

D.3.1 [Programming Languages]: Formal Definitions and Theory — Semantics; D.4.6 [Security and Protection]: Access Controls, Information Flow Controls, Verification; F.3.1 [Logics and Meanings of Programs]: Specifying and Verifying Reasoning about Programs — Assertions, invariants, logics of programs, pre- and post-conditions.

General Terms

Security, Verification, Languages

Keywords

Dependent Type Theory, Verification, Information Flow, Erasure, Data Structures

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1. INTRODUCTION

This paper considers verification of information flow and erasure policies in programs that manipulate mutable, heap-based, data structures. One of the challenges for programming and enforcement of security policies in this setting is that data structures often need to be heterogeneous, i.e. store data of different security levels. For example, a patient record in a medical database may contain public (or low security) data, such as patient name and address, as well as confidential (or high security) data, such as diagnosis.

Extant type systems and logics for information flow security primarily target homogeneous data structures, where the data stored in the structures is either all low, or all high. A medical database, as in the example above, therefore must be factored into two separate parts, one for storing low fields and the other for storing high fields of the patient records. Moreover, the relationship between the two parts must be maintained in order to match patient names and addresses with diagnoses. Even if this can be done using current database technology, it leads to code which violates data abstraction: the factoring propagates throughout client programs. For example, a client program that stores a patient record into a hash table also must be factored. It has to introduce two hash tables, one for the low and another for high security fields, and then somehow maintain the connection between the two hash tables.

1. INTRODUCTION

In this paper we study heterogeneous data structures in order to circumvent the above problems. Heterogeneity, however, does not come for free. To illustrate the difficulties that arise, consider the following scenario with two program modules A and B. A has some private state, a salary, which it is prepared to share with module B in order for B to compute A’s tax rate via a method called compute_tax. B would like to store A’s salary into a heterogeneous hash table in B’s local state. A allows this storage, but wants to make sure that upon termination of compute_tax, no information about its salary can be leaked from B’s local state. A’s policy therefore allows B to access the secret salary provided B proves (i.e., provides evidence) that compute_tax erases A’s salary and all results that depend on the salary, upon return.

However, forcing B to remove the salary from the hash table, and to erase any results that may depend on it, is itself insufficient to prevent leakage of information about the salary. Due to hash collisions, the insertion of the salary into the hash table may influence the positions of subsequently inserted low entries. Thus even if the salary is eventually removed, an attacker that can traverse the hash table, say via a computation that follows pointers into the data structure or via pointer arithmetic, may be able to reverse-engineer useful information about the salary simply by inspecting the relative positions of the surviving low elements. For example, in an open-addressing hash table with linear probing, collision of a newly
inserted low security element with a high security entry already in the table will change the index at which the low element is placed. A concrete attacker program could follow pointers into the hash table to get access to its secret, and we want to prevent this. Unfortunately, proofs about concrete heaps (Sec. 6 and Sec. 7) demonstrate how the multilevelUR hash tables of Sec. 7 can be used in a medical database application. To the best of our knowledge, this is the first formal static (as opposed to run-time) verification of a security property for a non-trivial data structure (but see Sec. 8 for discussion).

Uniquely represented data structures have been considered before in the algorithms and complexity communities, by Golovin [15], Naor and Teague [25] and others [8, 16, 20, 30]. In each of these cases, the data structures were motivated by the need to prevent an observer with access to the final state of a computation from reconstructing its history, and thus uncovering information that should remain private. In this paper, we show a different application of unique representation, namely, as a tool for verifying programs that manipulate heterogeneous heap-based data structures for conformance with information flow and erasure policies.

We use Relational Hoare Type Theory (RHTT, [24]) for both programming and proof throughout this paper. RHTT is a programming language and logic for specifying and enforcing expressive, state-based access control and information flow policies of imperative programs. Although RHTT is implemented as a domain-specific language in the Coq interactive theorem prover, we do not assume previous knowledge of either interactive theorem proving or of Coq. Sec. 3 presents all the features of RHTT necessary to understand the code in this paper. Our code and proofs are available at http://www.cs.princeton.edu/~jsseven/papers/ur.

2. ATTACK MODEL

For the purposes of this paper, attackers are well-typed RHTT programs that can read from the public components of initial and final (but not intermediate) states of a computation. For example, in the above case with A and B, we will consider B’s hash table to be public in the end, on account of erasure of A’s secret. Therefore, the attacker can observe the layout of the hash table, e.g., by following pointers into the data structure, after compute_tax has terminated, although during the tax computation the hash table may still contain secret data.

Technically, by “states” we mean the source-level representation of heaps given by the semantics of standard sequential program execution; we do not address erasure in compiled code, nor low-level erasure in hardware, or from cache lines, etc. in this paper. Following Nanevski et al. [24], we assume heaps are indistinguishable iff they are exactly equal, i.e., they contain equal addresses, storing equal values. Thus we also guard against attackers that can distinguish concrete representations of pointers as integer addresses, and perform pointer arithmetic.

3. BACKGROUND: RHTT

We briefly recapitulate the main components of the RHTT framework introduced by Nanevski et al. [24]. Fundamentally, RHTT is based on the following aspects of dependent type theory: dependent function types, inductive types and module systems. Dependent function types describe how a function body depends on its arguments; inductive types are needed to specify data structures
such as lists, trees, graphs, etc.; module systems including abstract types and predicates are needed for information hiding. Nanevski et al. show that these aspects jointly give RHTT the power to specify and verify flexible security policies; for example, one can specify the erasure-dependent access policy "A grants B the right to read its salary provided B proves that its code will erase all copies of the salary before termination." In Sec. 4, we adapt a medical records system from Borgström et al. [9] to incorporate erasure policies such as the one above. First we provide basic intuitions.

**Noninterference, types, specifications.** The specification of flexible security policies crucially depends on a relational specification of noninterference (NI) which says low outputs of a computation are independent of high inputs [12]. It is independence of flexible security policies crucially depends on a relational specification of noninterference such as lists, trees, graphs, etc.; module systems including abstract types, specifications.

The above program satisfies the policy because the value stored in the two initial heaps are low in the end. This is only possible if the value stored in the location \( x \) is erased, by overwriting it with a constant, or with some other value.

An example erasure policy. Consider the following specification of an erasure policy, and a program conforming to the specification, adapted from Hunt and Sands [13], both presented here in a somewhat stylized RHTT notation. We consider two integer heap pointers \( x \) and \( y \) that are arguments to the program. The contents of \( x \) is initially low, and the contents of \( y \) is initially high. The policy is: the program must erase the high value stored in \( y \). In RHTT, we express this policy with the type

\[ \Pi : y: \text{ptr} \ STsec \ [ \ ] \text{unit} \ (p, q) \]

where the precondition, \( p \), is

\[ \text{fun } i, \exists u : \text{nat}, i = (x \mapsto u \bullet y \mapsto v) \]

and the postcondition, \( q \), is

\[ \text{fun } \tau \ ii \ mm. \ yu \ uu. \ ii \ ((i, x) \Rightarrow uu \bullet (y, y) \Rightarrow vv) \rightarrow u_1 = u_2 \mapsto 3uu' \ vv'. \ mm \ ((i, x) \Rightarrow uu' \bullet (y, y) \Rightarrow vv') \land v_1' = v_2' \]

(Recall our notation: \( uu \) is \( (u_1, u_2) \), \( vv' \) is \( (v_1', v_2') \); We will explain the local context \([\ ]\) momentarily.) The above \( STsec \) type is an instance of a dependent function type; it describes functions with arguments \( x \) and \( y \) of type \( \text{ptr} \) (pointers), as indicated by the variables following the \( \Pi \)-symbol. Such functions produce computations of type \( STsec \) with the listed pre- and postconditions; this type is dependently typed, because the arguments appear in the assertions in order to describe the policy.

The precondition \( p \) states that the program must start with an initial heap \( i \) containing two pointers \( x \) and \( y \), with appropriately-typed contents. Here \( x \mapsto u \) is the singleton heap containing only the location \( x \) storing value \( u \); while \( \bullet \) is disjoint heap union. As \( i \) is the disjoint union of smaller singleton heaps, there is no aliasing between the two pointers \( x, y \). The postcondition binds over three variables \( r: \text{unit} \) and \( ii, mm: \text{heap}^2 \), which are, respectively, the pair of return values, the pair of initial heaps, and the pair of final heaps for the two runs of the program.

The notation \( xz \mapsto uu \) denotes a pair of singleton heaps \( (z_1 \mapsto uu_1, z_2 \mapsto uu_2) \). Similarly \( ii \) lifts \( \bullet \) to pairs; that is, \( jj \mapsto kk \) is \( (j_1 \bullet k_1, j_2 \bullet k_2) \). Thus, the postcondition \( q \) states that if the contents of \( x \) in the two initial heaps are equal (hence low), then the contents of \( y \) are low in the end. This is only possible if the value stored in \( y \) is erased, by overwriting it with a constant, or with some other value computed from the initial (low) contents of \( x \), but not \( y \), as the initial contents of \( y \) are not declared low.

One program satisfying the above policy (i.e. type) is the following.

\[ \text{fun } x, y \text{ do } (u \leftarrow \text{read } x; v \leftarrow \text{read } y; \text{ if } v = 0 \text{ then write } x \text{ (} u + 1 \text{) else skip; write } y \text{ (} u + 2 \text{)}) \]

In this program, in addition to purely functional constructs such as anonymous functions fun, we use side-effecting primitives such as write \( x, n \) which stores the value of \( n \) into the location \( x \); read \( x \), which returns the contents of \( x \); and \( x \leftarrow e_1; e_2 \), which sequentially composes \( e_1 \) and \( e_2 \), substituting the return value of \( e_1 \) for \( x \) in \( e_2 \).

The above program satisfies the policy because the value stored into \( y \) at the end is low (the initial contents of \( x \) incremented by 2). The ending contents of \( x \) are not low, as they depend on the initial contents of \( y \). Our policy, which does not specify the ending security level of the contents of \( x \), allows this flow. Indeed, the program illustrates that the contents of memory cells may change their security level during the program run—a key characteristic of our semantic definition of NI.
Therefore, in RHTT, memory addresses are classified separately from their contents. For example, we can have a low pointer address whose contents is high. While the STsec type of the above program classifies the security of the contents of x and y, it doesn’t classify the pointer addresses themselves, as the latter requires discerning the address names in two different runs. RHTT provides for this possibility by endowing the STsec type with a local context. This is a list of types for the arguments of the computation, whose significance we illustrate by an example.

To reflect that the pointer y is high at the beginning, in addition to having high contents, we change the original STsec type as follows.

\[
\Pi : \text{ptr. STsec [ptr] unit} \\
\quad \text{(fun } y \text{ i. } \exists \text{ u v n. nat.)} \\
\quad \quad \text{fun } y y u v u. \\
\quad \quad \quad \quad \exists u u' v'. \text{mm} = ((x, x) \mapsto uu \bullet yy \mapsto vv) \quad u_1 = u_2 \rightarrow \\
\quad \quad \quad \quad \quad \exists uu' vv'. \text{mm} = ((x, x) \mapsto uu' \bullet yy \mapsto vv') \quad v'_1 = v'_2
\]

Whereas in the original type, the local context was the empty list [], now it contains the element ptr, which is the type of the argument y. Correspondingly, the variable y is pushed into the precondition, and similarly, yy is pushed into the postcondition, so that y_1 and y_2 refer to the addresses of y in two different runs (contrast with (y, y) in the postcondition of the original type). Since the postcondition does not include an equation y_1 = y_2, the address y is high. The program syntax changes too, as the local variables now have to be bound within the scope of do. In other words, our program now looks like:

\[
\text{fun } x. \text{ do (fun } y \text{. } u \leftarrow \text{read } x \text{.} \cdots)
\]

In general, variables bound by I are always low, whereas variables declared in the local context may be low or high, depending on the policy described by the type.

4. ERASURE-DEPENDENT ACCESS CONTROL

The erasure policies we described in the introduction grant one method access to some module’s private data, provided the method access to some module’s private data, provided the method's local state consists of mutable, heap-allocated data structures.

In order to do so, we first survey a database application containing medical records and a database client, both built in RHTT, and inspired by an example from Borgström et al. [2]. We do not describe the complete database system here, though it is fully developed in our Coq scripts. The primary motivation of this section is rather to illustrate how the verification effort required to prove erasure policies scales as the local state maintained by modules evolves, from local scalar variables to heap-allocated data structures such as arrays or hash tables. This section also serves to motivate the use of unique representation.

4.1 Example: Data Store for Medical Records

Our medical database application grants access to patient records via the method read_emr (Fig.1), which stands for “read electronic medical record.” The access policy for this method requires that its caller owns a token, called can_read_emr, for the patient whose records it wishes to access. Access to this token is limited to methods of modules from an appropriate group of users (e.g., doctor) who have previously requested (and been granted) permission by
the patient. With this in mind, consider the following generalization of the policy, along the lines of the policy on A’s salary from the introduction: a client method may read confidential patient records even without the can_read_emr token, but only if it erases any data derived from these records before it terminates.

To conservatively enforce that a client method does not steal patient records, the medical records database could require that the clients deallocate all local state on function return, and thereby ensure that the client methods steal nothing, but this is prohibitively expensive. If a client makes many thousands of calls to the database, allocating and then deallocating local state on each call becomes infeasible. Requiring deallocation also prohibits the client methods from maintaining persistent, but innocuous, local state, e.g., statistics about the CPU usage. In general, any client local state not derived from the confidential data should be allowed to escape a call to the database. In RHTT, higher-order STS sec types allow us to formulate such permissive policies.

Fig. 4 gives the database-specific routines required to support erasure-dependent access control: namely, the function endorse; while Fig. 2 presents a client method that calls endorse in order to access confidential patient medical records. The endorse function is parametric in several arguments, which the client methods instantiate to their choosing.

- Type \( R \) circumscribes the shape of the client method’s local heap, typically by encoding the number of required root pointers (e.g., \( R \) equals \( ptr \) if the client’s local heap requires a single root pointer, \( ptr^2 \) for two root pointers, etc.)

- Type \( G \) defines what kind of values are stored in the client method’s local state. For example, \( G \) may equal \( int \) if the local state encodes a single integer value, or \( G \) may be list \( int \), if the local state stores integers in a linked list, etc.

- Predicate \( ccshape \) describes the shape in which the data (of type \( G \)) is layed out in the client method’s local heap, starting from the root pointers as given by the type \( R \). The predicate \( ccshape \) is relational (i.e., its arguments are “squared”), so that it can specify the security levels of the pointer addresses and their contents in the client’s local heap. In Fig. 4 we also make use of the relational predicate \( sshape \) which represents the shape and security levels of the local state of the database, similar to how \( ccshape \) does so for the clients. The \( sshape \) predicate is local to the database module, but is not a parameter of endorse, as it is not something that the clients can choose.

- Function \( cmp \) defines how the values given by \( G \) evolve after each call to the database. For example, letting \( G = int \) and \( cmp = fun \ g \ g + 1 \) corresponds to the client method storing an integer count \( g \) as its local state which increments \( g \) after each call.

The body of endorse’s specification puts everything together. It takes as argument an STS sec computation of type \( T \) and produces a computation of type \( S \). The precondition in \( T \) demands that the computation works over the local states of the database and the client only. It does so by requiring that the initial heap \( i \) can be split into disjoint parts \( j \) and \( t \). \( j \) “belongs” to the shape predicate of the database, and \( t \) “belongs” to the shape predicate of the client. Here shape and \( ccshape \) are non-relational versions of shape and \( ccshape \), respectively. For example

\[
ccshape \ r \ g = fun \ i. \ (i, i) \in ccshape \ (r, r) \ (g, g)
\]

Importantly, the precondition in \( T \) requires a proof of the abstract predicate can_read_emr, which serves as a permission, or a token, necessary to call the database function read_emr. The precondition of \( S \) is similar to \( T \), except that it omits the token can_read_emr. Thus, while the input to endorse is a method that requires a permission, and could ordinarily be executed only by a call from a method of a user (e.g., a doctor) that has been granted the token, the output is a method which needs no permission.

Crucially, endorse will only accept as input those client methods which come with a proof that the client’s final local state does not depend on any secrets that the method computed during the call (the “no leakage of high data” condition). We express this requirement in the postcondition of \( R \): if the client method’s local heaps \( t_1 \) and \( t_2 \) were equal initially (low), then the client method’s final heaps \( t'_1 \) and \( t'_2 \) must also be equal in the two runs \( (t_1 = t_2 \rightarrow t'_1 = t'_2) \).

The proof of such a property is derived by applying relational Hoare-style reasoning (omitted here, but present in our Coq scripts) on the code of the client method. In case the client method contains outgoing calls to functions from its own module, or potentially other modules, we use the specification of each function to verify that the client method satisfies the erasure property, and separately prove that each of the functions that is called satisfies its specification.

**Counting Client.** Fig. 2 defines a client which maintains as local state a count of the number of times it has been called. The type \( R = ptr \) declares a single root pointer, which is a pointer to this count. The shape invariant \( ccshape \) specifies that the heaps \( i_1 \) and \( i_2 \) in the two runs (recall that \( \Rightarrow \) operates on pairs of pointers and values) are singleton heaps from \( r_1 \) and \( r_2 \) to the integer counts \( g_1 \) and \( g_2 \) respectively. The function \( cmp \) just increments the count after each call.

The client program \( prog \) operates as follows: it first reads the medical record of a patient, \( pat \), from the database and stores the resulting value in the variable \( emr \). Next, it dereferences the pointer \( r \) into a second local variable \( g \), for safekeeping. It now stores an integer hash of the medical record \( emr \) into \( r \). If \( prog \) were to return at this point, it would not satisfy the required noninterference property (i.e., \( t'_1 \neq t'_2 \)) since \( emr \) is confidential data and therefore not known to be equal in the two runs. To ensure that \( t'_1 \neq t'_2 \)—and that the count is properly updated—\( prog \) overwrites the value in the client local heap a second time with \( g + 1 \), the incremented count. It then returns \( f_2 \ emr \), a second integer hash of \( pat \)’s medical record.

The program counting_client applies endorse to \( prog \). On its own, \( prog \) would have had to request permission from a patient in order to call \( read_emr \), thereby establishing the function’s precondition. By endorsing \( prog \), we avoid the need to establish this precondition, but at the expense of the additional proof obligation \( t_1 = t_2 \rightarrow t'_1 = t'_2 \). In this case, demonstrating that \( prog \) meets this specification is straightforward: even though the program stores the confidential value \( f_1 \ emr \) into local state at an intermediate point during the computation, it overwrites this value with a low value \( (g + 1) \) before function return. Because counting_client’s local state consists of a single pointer to a scalar value, proving that \( t'_1 = t'_2 \) is relatively easy. Indeed, this proof in RHTT is only a few lines.

**Issues with Extending to Hash Tables.** Now consider the situation in which \( r \) is not an integer pointer but a hash table, and the sequence \( \text{write} \ r \ (f_1 \ emr); \text{write} \ r \ (g + 1) \) is replaced by

\[
\text{insert} \ r \ (f_1 \ emr); \text{insert} \ r \ (g + 1); \text{remove} \ r \ (f_1 \ emr).
\]

If \( emr \) is not known to be equal in the two runs, then \( (f_1 \ emr) \) may equal \( g + 1 \) in one run—leading to a collision—but not the
other, leading to two different hash table layouts in the two runs. In general, operation sequences on data structures that are invertible at the level of the data structure interface—such as insertions of key-value pairs into a hash table followed by their removal—can leave traces in the underlying heap representation, and therefore make it difficult to prove noninterference.

For the enforcement of erasure properties, it therefore becomes important to impose additional conditions on the data structure implementation. In particular, we must know that any series of invertible data structure operations leaves the underlying heap representation unchanged. Otherwise, the mere erasure of items from the structure can leak information through the layout, as we discussed previously. In the next section, we focus on unique representation as a particularly simple property to enforce and verify of a data structure, which guarantees the above behavior.

Unique representation alleviates the problem just described by making it possible to reason symbolically about (the absence of) such flows: by ensuring that logical equality of the data structure states in two runs implies actual equality of the underlying heaps, it reduces noninterference proofs to arguments about equalities of symbolic, mathematical representations. This reasoning can often be performed elegantly, through the application of algebraic laws. Moreover, proofs constructed in this way are portable to future implementations satisfying the mathematical interface.

In the next two sections, we first introduce unique representation more formally, then present a UR variant of open-addressing hash tables. First, we develop general definitions.

**Data Structures.** A data structure ties a logical interface (an abstract type and operations on that type) to a concrete implementation of the interface. One can model a data structure mathematically as a tuple consisting of the type $G$—of logical or abstract states—and the type of concrete states. For us, the concrete states will always be heaps, whereas logical states may range from integers (as in Sec. 4), to vectors that model arrays, to finite key-value maps that model data structures such as hash tables. As in Sec. 4, we also need a third type, $R$, to store the root pointers of the structure.

Each pair of a data structure’s logical states and root pointers defines a set of concrete states that implement it. When a root pointer $r$ and logical state $g$ are implemented by heap $h$, we say that the shape of $r$ and $g$ is $h$. The predicate

$$\text{shape} : R \rightarrow G \rightarrow \text{heap} \rightarrow \text{prop}$$

on representation types $R$, logical states $G$, and heaps, gives the formal definition of the shape relation in our development.

**Unique Representation.** A UR data structure is uniquely represented iff for all root pointers $r$, logical states $g$ and heaps $h_1$ and $h_2$, if $h_1 \in \text{shape } r \ g$, and $h_2 \in \text{shape } r \ g$, then $h_1 = h_2$.

As an example of a shape predicate that is naturally UR, consider the definition of shape for standard imperative arrays. Arrays are the simplest UR data structures, and will be the basic building block for all the other UR structures in the paper.

$$\text{shape} (r: \text{array } n \ T) (g: I_n \rightarrow T) (h: \text{heap}) \equiv$$

$$h = (r + 0 \mapsto g(0)),$$

$$r + 1 \mapsto g(1),$$

$$\ldots$$

$$r + (n - 1) \mapsto g(n - 1)).$$

$n$ is the size of the array, and is a parameter of the definition, as is the type $T$ of elements stored in the array. The finite type $I_n = \{0..n - 1\}$ enumerates the indices of the array. The root type $R = \text{array } n \ T$ is implemented as a single pointer $r$ storing the base of the array. The type of logical states $G$ is $I_n \rightarrow T$, so that $g: I_n \rightarrow T$ logically represents the contents of the array as a finite function (i.e., vector) of $n$, $T$-typed elements. The predicate shape on heaps asserts that the array consists of contiguous memory blocks rooted at a pointer $r$; $h$ is the heap that contains value $g(0)$ at location $r + 0$, $g(1)$ at location $r + 1$, and so on. This shape predicate is naturally UR: for a given $r$ and $g$, the heap $h$ that results is always uniquely determined.

**Security Implication of UR.** Why is unique representation a useful property for security? The answer is: An attacker with access to the concrete representation of a UR data structure can learn no more than an attacker constrained by the data structure’s public interface. In other words, different sequences of operations that result in the same logical state leave no trace of the history of operations that got them there. In particular, any sequence of operations that is then reversed (e.g., a series of insertions in an array followed by removals of all these inserted elements) is equivalent, at the level of concrete heaps, to having never performed the operations in the first place.

### 5. UNIQUE REPRESENTATION

In this section, we formally define unique representation and explore its implications. We then describe an implementation of insert-only bounded multisets as an example of a naturally UR data structure. Sec. 6 presents our implementation of a UR variant of open-addressing hash tables. First, we develop general definitions.

**Data Structures.** A data structure ties a logical interface (an abstract type and operations on that type) to a concrete implementation of the interface. One can model a data structure mathematically as a tuple consisting of the type $G$—of logical or abstract states—and the type of concrete states. For us, the concrete states will always be heaps, whereas logical states may range from integers (as in Sec. 4), to vectors that model arrays, to finite key-value maps that model data structures such as hash tables. As in Sec. 4, we also need a third type, $R$, to store the root pointers of the structure.

Each pair of a data structure’s logical states and root pointers defines a set of concrete states that implement it. When a root pointer $r$ and logical state $g$ are implemented by heap $h$, we say that the shape of $r$ and $g$ is $h$. The predicate

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on representation types $R$, logical states $G$, and heaps, gives the formal definition of the shape relation in our development.

**Unique Representation.** A UR data structure is uniquely represented iff for all root pointers $r$, logical states $g$ and heaps $h_1$ and $h_2$, if $h_1 \in \text{shape } r \ g$, and $h_2 \in \text{shape } r \ g$, then $h_1 = h_2$.

### 5.1 Example: Insert-only Bounded Multisets

Molnar et al. [32] describe the architecture of a vote storage unit that achieves operation-order independence, and thus voter anonymity, by storing votes in insert-only bounded multisets. In this section, we illustrate an RHTT implementation of insert-only bounded multisets as another example of a UR data structure, which builds on arrays.

We implement multisets whose elements are integers bounded by $n$, as arrays with $n$ cells, each containing a natural number. The value of the natural number at each index $i$ in the array denotes the number of times element $i$ appears in the multiset, or its multiplicity.

Fig. 3 gives the signature and RHTT implementation of the insert-only bounded multisets module. The type $\text{mset}$ is an alias for arrays with size $n$ and cells of type nat. The predicate shape takes a multiset $r$—a pointer to the base of the array—and a finite function $g$ as arguments. The latter encodes the multiplicity of each multiset element. The shape predicate is implemented by calling the corresponding shape predicate of the array module, which specifies that $r$ is the base of a contiguous memory region of size $n$ with contents given by $g$.

The precondition of insert defines when it is safe to execute the method, i.e., shape $r \ g$ must hold of the input heap $h$ and the base
Module MultiSet.

\[\text{mset} \equiv \text{array} \ n \ \text{nat} \]

\[\text{shape} \ (r:\text{mset}) \ (g:\text{L} \rightarrow \text{nat}) \equiv \text{Array.shape} \ r \ g\]

\[\text{bump} \ (k:1) \ (g:\text{L} \rightarrow \text{nat}) \equiv \text{g}[k \rightarrow \text{g}(k) + 1]\]

\text{new} \ : \ \text{STSec[}] \ \text{mset} \ldots

\[\text{insert} \ (r:\text{mset}) : \]

\[\text{STSec} \ \text{[S]} \ \text{unit}\]

\(\text{fun} \ k, i, g, i \in \text{shape} \ r \ g, \) \ text{fun} \ k, k y y y i i \in \text{m}m m \ \text{\forall g}. \ g g \rightarrow \)

\[i i \in \text{shape} \ (r, r) \ g g \rightarrow \]

\[\text{m}m \in \text{shape} \ (r, r) \ (\text{bump} \ k, g_1, \text{bump} \ k_2 \ g_2)) \equiv \]

\[\text{do} \ (\text{fun} \ k, x \leftarrow \text{Array.read} \ r \ k; \)

\[\text{Array.write} \ r \ k \ (x + 1))\]

End Module MultiSet.

Figure 3: Signature and implementation of insert-only multisets. The module is parameterized by \(n : \text{nat}\), which is the bound on the number of elements of the multiset. The specification and implementation of the method \text{new} are elided.

pointers \(r\) for some finite function \(g\). In insert’s postcondition, the proposition \(\text{mm} \in \text{shape} \ (r, r) \ (\text{bump} \ k, g_1, \text{bump} \ k_2 \ g_2)\) states that in the two runs, the output heaps \(\text{mm}\) contain the local state of the multiset \(r\), the contents (i.e., multiplicities) of whose indices \(k_1\) and \(k_2\) have been incremented by 1. In the case of arrays and multisets, the relational predicate \text{shape} is defined as a “duplication” of shape, that is \(\text{shape} \ rr \ g g \ h h = \text{shape} \ r_1 \ g_1 \ h_1 \land \text{shape} \ r_2 \ g_2 \ h_2\).

The code for insert first reads the contents of the array at index \(k\) into \(x\) by calling the array read operation \text{Array.read}. Next, it writes \(x + 1\) at index \(k\) by calling the array write operation \text{Array.write}. In our RHTT implementation of arrays, \text{Array.read} and \text{Array.write} are implemented via pointer arithmetic on the base address.

The proof (in the Coq scripts) that bounded multisets are UR follows from the fact that multisets are implemented as arrays, and the latter are UR as explained previously.

6. MULTILEVEL UR HASH TABLES

Open-addressing hash tables—those that use probing to resolve collisions—are a key imperative data structure with wide-ranging applications. However, such hash tables are unfortunately not UR: key collisions can create different memory layouts depending on the order in which keys are inserted, and thus leak information. When modules use hash tables to store their local state, it therefore becomes quite difficult to prove the sorts of information flow and erasure specifications that appeared in earlier sections of the paper.

Inspired in part by a particular kind of open-addressing hash table, called a filter hash (cf. Fotakis et al. 14), in this section we present a variant of standard open-addressing hash tables, called multilevel UR hash tables, that is uniquely represented. Although we will describe below the filter hash tables of Fotakis et al. in order to introduce our UR multilevel variant, we note at the outset that our UR multilevel hash tables do not have the same complexity profile as the Fotakis et al. filter hash tables. Indeed, the primary purpose of this section is not to demonstrate that UR data structures present efficient alternatives to standard data structures; Golovin, in his Ph.D. thesis 15, has already demonstrated this point by presenting a variety of efficient UR data structures (though the particular hash table variant we implement in this section has not been analyzed before). The purpose of this section is, rather, to demonstrate that it is possible, in a fully mechanized system such as RHTT, to prove nontrivial data structures uniquely represented. Section 7 then revisits how unique representation can be used in practice to prove erasure and information flow properties of modules that employ multilevel UR hash tables in their local state.

6.1 Canonical Representation

Standard filter hash tables were first proposed by Fotakis et al. 14 as a simple yet efficient variant of \(m\)-level cuckoo hash tables. They consist of \(m\) levels, or filters, each of which has an associated hash function hash and an array for storing key-value pairs, just as in standard open-addressing hashing. When a collision occurs in the top filter of the table (i.e., level 0), insertion is reattempted at a lower level (e.g., level 1) until either the insertion succeeds or the table runs out of filters. In the latter case, the item is placed in a secondary key-value map. As we mentioned above, filter hash tables unfortunately suffer from the same kinds of information leaks as standard open-addressing hash tables. It is therefore difficult to prove erasure and information flow specifications of modules that use filter hash tables to define their local state.

Multilevel UR hash tables are just like filter hash tables except that (1) they impose a canonicity invariant on the layout of the keys at each level of the table; and (2) they employ a single hash function across all levels, whereas filter hash tables use \(n\) hash functions for \(n\) levels. Condition (1), the canonicity invariant, is what makes our multilevel hash tables uniquely represented. We explain canonicity in more detail below. Condition (2) is slightly more ad hoc. If our hash table variant did not implement deletion, then condition (2) would be unnecessary. However, as it currently stands condition (2) enables the implementation of efficient deletion, while most likely adversely affecting the space usage of the data structure. We are not aware of a better UR algorithm; this is an open research question.

It is also possible to define uniquely represented chaining hash tables, by ensuring that the linked list that implements each bucket in the table remains sorted at all times. Although RHTT supports dynamic allocation, reconciling allocation with information flow and erasure is quite tricky (cf. Golovin 15). For example, pointer comparisons make even the order in which memory blocks are allocated observable. Considerations such as these prompted our investigation of the multilevel alternative tables we describe in this section.

To get an intuition for the canonicity invariant, imagine an \(m\)-level hash table is split into two parts: (1) the top level \(d_0\) and (2) the remaining levels \(d_1 \ldots d_{m-1}\), together with the auxiliary store \(b\), which we call the “bucket”. Let \(<\) be a total order on keys.

\[\text{Definition 2 (Canonicity). An } m\text{-level hash table is canonical when the following properties hold for all } 0 \leq i < m:\]

\[\text{• For all keys } k \text{ and } k’, \text{ if } (a) \ k \text{ is stored in level } d_i, \text{ (b) } k’ \text{ is stored either in a strictly lower level or in the bucket, } b, \text{ and (c) } \text{hash}(k) = \text{hash}(k’), \text{ then } k < k’.\]

\[\text{• For all indexes } j, \text{ if } d_j{}^\uparrow \text{ is empty, then there is no key } k \text{ such that (a) } \text{hash}(k) = j, \text{ and (b) } k \text{ is stored either in a strictly lower level or in the bucket, } b.\]

In other words, canonicity requires that keys be placed as high up in the multilevel hash table as possible and that whenever there is a collision during insertion, a suitable strict order \(<\) be used to resolve the collision. Of course, deletion must preserve the canonicity invariant as well. One consequence of this property is that all occupied slots in the top level \(d_0\) always contain the minimum key among all keys currently in the table that would also have hashed
to that slot. Nonminimum keys that collided with the minimum key upon insertion must be placed in lower levels of the hash table. Intuitively, canonicity implies unique representation since: (1) the keys in every hash collision path are uniquely ordered by the < relation; and (2) empty slots are always filled in order, topmost first.

To maintain the canonicity invariant, we ensure that the minimum key for each index is always stored in $d_0$ (and so on for levels 1 through $m - 1$, for the remaining keys). This requires checking whether a newly inserted key $k'$ with hash($k'$) = $j$ is less than the current key in slot $j$ of $d_0$. If it is, then $k'$ is placed in $d_0$ and the current key $k$ in slot $j$ is evicted to a lower level. If $k' > k$ then $k'$ is inserted into a lower level as usual. When $k = k'$, the new value $v'$ associated with $k'$ overwrites the current value $v$ (we do not maintain duplicate keys). Deletion is somewhat trickier: when a key $k$ is removed from slot $j$ in level $d_0$, we must find the smallest key $k'$ at level $d_1$ such that hash($k'$) = $j$ and recursively move this key up into level $d_0$.

Fig. 4 illustrates insertion of the keys GFDBEACIH, paired with their values, into a 4-level UR hash table. Key $G$ is inserted first. Then key $F$ is inserted, causing a collision with $G$ in the topmost level. Since $F < G$ in the usual lexicographic order, $G$ is evicted from $d_0$ and re-inserted into $d_1$. Keys $D$ and $B$ are inserted next, without incident, into level $d_0$. The state of the table after $E$ has been inserted is shown in Panel 1 of the figure.

Next, key $E$ is inserted in slot 1 of $d_0$, causing a second collision with $F$. The eviction of $F$ and its re-insertion into level $d_1$ causes a chained collision with $G$, which is evicted now for the second time into level $d_2$. The state of the table after $E$ has been inserted is shown in Panel 2. Key $A$'s insertion causes the eviction of $D$ into a free slot in level $d_1$ (Panel 3). The rest of the keys are inserted in a similar manner, resulting in the multilevel UR hash table shown in Panel 4 of the figure. Note that the table that results after all keys have been inserted is equivalent to the table resulting from insertion of the keys in order, ABCDEFGHI, or in any other permutation. In Panel 4, key $I$ is placed in the auxiliary key-value map, bucket, since it collided with other keys at every level of the table during insertion. Panels 5 and 6 illustrate deletions. In Panel 5, key $A$ is deleted, causing $D$ to be moved up into level 0. In Panel 6, key $F$ is deleted, causing a chain of three redrawableings: key $G$ is moved from level 2 to level 1, key $H$ is moved from level 3 to level 2 and key $I$ is moved from the bucket into level 3.

Figure 5: Preliminary specifications and definitions for multilevel UR hash tables. The module is parameterized by the types $K$ and $V$, $n : \text{nat}$, and a hash function $\text{hash} : K \rightarrow I_n$. The functions $\text{hashtab}$ and $\text{stash}$ define the reference functional implementation of the partitioning of key-value pairs into the top level and the stash. Functions $\text{find}$, $\text{ins}$ and $\text{rem}$ are for look up, insertion and removal of a key in a finite map such as $g$.

6.2 Preliminary Definitions for Multilevel UR Hash Tables

Now we turn to the definition of multilevel UR hash tables in RHTT. Fig. 5 gives the preliminary RHTT definitions used in our implementation and in the correctness and unique representation proofs. We present these definitions first, before the imperative RHTT code for hash table lookup, insertion and deletion, because the definitions are important for understanding the specifications of these functions.

The function $\text{hash}$ of type $K \rightarrow I_n$ maps keys $k : K$ to indices of type $I_n$. Here $K$ is a type with a built-in order operation. For
Module MultilevelURHashTab.

new \(\equiv\) do \((r_1 \leftarrow \text{Array.new n None;} r_2 \leftarrow \text{Stash.new;}
\text{ret } (r_1, r_2))\)

lookup \((r:\text{hashmap})\) \(\equiv\)
do \((\text{fun } k, o \leftarrow \text{Array.read } r.1 \text{ (hash } k)\);
if isNone o then ret None
else if \((o = [(k', v')] \&\& k = k')\) then \text{ret } [v']
else Stash.lookup r.2 k 2

insert \((r:\text{hashmap})\) \(\equiv\)
do \((\text{fun } k, v \leftarrow \text{Array.read } r.1 \text{ (hash } k)\);
if (isNone o) \((o = [(k', v')] \&\& k = k')\)
then Array.write r.1 (hash k) [(k, v)]
else let \(([(k', v')] =\ o\) in
if \(k < k'\) then Stash.insert r.2 (k', v');
Array.write r.1 (hash k) [(k, v)]
else Stash.insert r.2 k v

remove \((r:\text{hashmap})\) \(\equiv\)
do \((\text{fun } k, o \leftarrow \text{Array.read } r.1 \text{ (hash } k)\);
if \((o = [(k', v')] \&\& k = k')\)
then \(k_{\text{min}} \leftarrow \text{Stash.minkey } r.2 \text{ (hash } k)\)
else let \(\lfloor k_{\text{min}} \rfloor =\ k_{\text{min}}\ in\ [v_{\text{min}}] \leftarrow \text{Stash.lookup } r.2 k_{\text{min}}\):
Stash.remove r.2 k_{\text{min}}
Array.write r.1 (hash k) \([(k_{\text{min}}, v_{\text{min}})]\)
else Stash.remove r.2 k

End Module MultilevelURHashTab.

Figure 6: RHTT implementation of multilevel UR hash tables.
The module is parameterized by \(n : \text{nat}\), which is the size of the levels in the hash table, and a key-value map Stash.

lookup must first check whether \(o\) is None—meaning the toplevel array is empty at position hash \(k\)—before proceeding. If \(o\) is None, then lookup immediately returns None. It can do so because the canonicity invariant implies that \(k\) is not present: if \(k\) were present, it would have been hashed into the empty slot.

The insert function is somewhat more complicated. It takes two local arguments, a key, \(k\), and a value, \(v\). Like lookup, its first step is to look up the current key-value pair, \(o\), at position hash \(k\) in the toplevel array. If \(o\) is None then insert writes the pair \([(k, v)]\) into the array at that position. The canonicity invariant again implies that there are no keys elsewhere in the table that hash to the same slot as \(k\) and yet are less than \(k\) in the order. Likewise, if \(o\) is an actual key-value pair \((k', v')\) such that \(k = k'\), then insert can just overwrite the current value of \(k'\) with the new value, \(v\). Otherwise, \(o\) is a key-value pair \((k', v')\) such that \(k \neq k'\). Now there are two cases: either \((1) k < k'\), or \((2) k < k'\). In case (1), lookup inserts \(k'\) recursively into the key-value map, then overwrites \(k'\) at position hash \(k\) in the toplevel array with \([(k, v)]\). Case (2) is even simpler: \(k'\) stays where it is and \(k\) is inserted recursively into the stash.

The remove function is similar in structure to insert. Like both insert and lookup, it first reads the current key-value pair, \(o\), located at position hash \(k\) in the toplevel array. If \(o\) is \([(k', v')]\) such that \(k = k'\), then remove must delete \(k\) from the toplevel array and replace it with the next smallest key that would have hashed to that slot, if one exists. To do so, remove calls Stash.minkey on the stash, returning a value \(k_{\text{min}}\) of type option \(K\). If \(k_{\text{min}}\) is an actual key, then it and its associated value, \(v_{\text{min}}\), are removed.
Module KVMapSig.

sshape : R^2 → (K → fin V ) → heap → prop
shape : R → (K → fin V ) → heap → prop
shape_fun :
∀ g i j.
   i ∈ shape r g →
   j ∈ shape r g → i = j
sshape_shape :
∀ g i j.
   i ∈ sshape r g g →
   j ∈ sshape r g g → i = j
lookup (r kvmap) : STSec [K] (option V )
{ fun k. ∃ g. i ∈ shape r g,
   fun k k y y i mm. y gg .
   i ∈ sshape (r, r) g g →
   mm = i i ∧ yy = (fnd k1 g1, fnd k2 g2) }
insert (r kvmap) : STSec [K, V ] unit
{ fun k v. ∃ g. i ∈ shape r g,
   fun k k v v y y i i mm. v y g .
   i ∈ sshape (r, r) g g →
   mm ∈ sshape (r, r) (ins k1 v1 g1, ins k2 v2 g2) }

... End Module KVMapSig.

Figure 7: Specifications of key-value map lookup and insert. The module is parameterized by the types R, K, and V . The hash table functions of Fig. 6 meet these interfaces, along with similar ones for new, remove, and minkey (elided). The type kvmap is a parameter to the specifications. The predicates shape and sshape are related by laws like sshape_shape above. In addition, shape is required to be a function (shape_fun), thus enforcing that modules matching the key-value map interface, such as the multilevel hash table library of this section, be uniquely represented.

Unique Representation. The unique representation theorem for multilevel UR hash tables follows from the canonicity invariant we defined in Sec. 6.1 (Def. 2) and the definition of the multilevel UR hash table shape predicate (cf. Fig. 5).

THEOREM 1 (UR FOR MULTILEVEL UR HASH TABLES). For all multilevel UR hash tables r, finite maps g : K → fin V and heaps m_1 and m_2, if m_1 ∈ shape r g and m_2 ∈ shape r g then m_1 = m_2.

6.4 Specifying Multilevel UR Hash Tables

Our multilevel hash table implementation satisfies the key-value map interface we first described informally in the previous section. We forgo presenting the entire interface here since most of the specifications are straightforward (please see our Coq scripts for more details, file kvmap.v). Below we focus on a few of the interface functions.

The lookup function, specified by the STSec type given in Fig. 7 and implemented in the previous section by multilevel hash table lookup, takes two arguments, a function argument r defining a key-value map and a local argument of type K providing the key to be looked up. The precondition of lookup states that the heap i satisfies the key-value map shape predicate, which is required to be a function by the interface.

In our multilevel hash table implementation of the key-value map interface, shape is instantiated with the multilevel hash table shape predicate defined in the previous section. The requirement that shape be a function (law shape_fun in Fig. 6) is satisfied by the unique representation proof for multilevel hash tables (Theorem 1). The postcondition of lookup states that lookup leaves the heap unchanged (mm = ii) and that the option values y_1 and y_2 that lookup returns are those discovered when keys k_1 and k_2 are looked up, via fnd, in the mathematical finite maps g_1 and g_2 that represent the key-value map r (ii ∈ sshape (r, r) gg).

Key-value map insert (also shown in Fig. 6) takes three arguments, the map r, a key k, and its new value v. As in lookup, r is a function argument that we assume to be low, whereas k and v are function arguments that are implicitly high, insert’s postcondition states that in the output heap mm, k_1 is mapped to v_1 in one run and k_2 is mapped to v_2 in the other. We model these updates mathematically using the finite map insertion function, ins, which updates a key with a new value in a key-value map.

The interactions among ins, fnd, and rem are governed by several algebraic laws, e.g., rem k (ins k v g) = rem k g. As we described in the introduction, clients of the multilevel UR hash table module will reason using laws of this nature. In particular, client reasoning is entirely independent of the number of levels in the table and other implementation details.

7. ERASURE-DEPENDENT ACCESS CONTROL REVISITED

In Sec. 4 we described an RHTT implementation of a medical database application. One of the distinguishing features of the system was that it supported expressive conditional information flow policies. In particular, the higher-order function endorse grants a client unrestricted access to confidential patient records provided the client could first prove that any confidential data it stored in local state during the computation was erased before its function exited. In Sec. 4 our example client’s local state consisted of a single pointer to an integer; the simplicity of this local state made it quite easy to prove that the client program met the erasure policy required by endorse.

In this section, we revisit the client of Sec. 4 in order to prove erasure policies for more complicated data structures such as the multilevel UR hash tables of Sec. 6. Unique representation is the key property that enables these proofs.

Hashing Client. Fig. 8 presents the RHTT code for our enhanced medical database client. In the original client of Sec. 4 the client’s local state, given by the type R, was a pointer to an integer. Here R is the type of 4-level UR hash tables, defined by the function build_map. This function constructs a multilevel UR hash table with an arbitrary number of levels (4 in this case). The hash function hash is a parameter. The predicate cshape is defined wrt. the multilevel UR hash table’s relational shape invariant, FilterHashPrem.sshape. This shape invariant applies the multilevel UR hash table’s unary shape predicate shape (Sec. 5) to heaps i_1 and i_2 respectively. The function cmp defines how the client’s local state evolves after each call to hashing_client. Here we specify that after each call, the client will have inserted the low key-value pair (18, v), for some v, into (and removed key 17 from) its local hash table. The hashing_client function is similar to the counting_client function of Sec. 4. Within the do block, prog first reads pat’s elec-
Module B′.

\[ R \equiv \text{build\_map\_hash\_4} \]
\[ G \equiv \text{finMap\_K\_V} \]
\[ \text{ccshape}\ (rr:R^2)\ (gg:G^2)\ (ii:heap^2) \equiv \]
\[ \text{Multilevel\_UR\_Hash\_Prelim\_sshape\ rr\ gg\ ii} \]
\[ \text{cmp}\ (g;G) : G \equiv \ins\ 18\ v\ (\text{rem}\ 17\ g) \]
\[ \text{prog}\ (r;R) : T' \equiv \text{do}\ (\text{fun}\ \text{db}\ \text{pat.})\]
\[ \text{emr} \leftarrow \text{read\_emr\ db\ pat.}; \]
\[ \text{Multilevel\_UR\_Hash\_Tab}\ .\text{insert}\ r\ 17\ (f_1\ \text{emr}); \]
\[ \text{Multilevel\_UR\_Hash\_Tab}\ .\text{insert}\ r\ 18\ v; \]
\[ \text{Multilevel\_UR\_Hash\_Tab}\ .\text{remove}\ r\ 17; \]
\[ \text{ret}\ (f_2\ \text{emr}) \}
\[ \text{hashing\_client}\ (r;R) : S' \equiv \text{A}\_\text{endorse}\ R\ G \]
\[ \text{Multilevel\_UR\_Hash\_Prelim\_sshape\ cmp\ prog} \]
End Module B′.

Figure 8: A medical database client with a 4-level UR hash table as local state. The module is parameterized by the types K and V.

tronic medical record, then inserts a confidential integer hash of this record \((f_1, \text{emr})\) into the multilevel UR hash table, associated with key 17. prog next inserts the low key-value pair \((18, v)\) into the hash table. Finally, it removes the confidential data it previously inserted at key 17 by calling FilterHashTab.remove \(17\).

To prove that hashing_client meets the erasure policy, we must show that the client’s local heap is low after the function is executed, assuming its local state was low before execution. To do so, we reason in two steps: we first show that symbolically executing prog from equal initial states results in equal symbolic, i.e., logical, final states. That is, inserting the confidential key-value pair \((17, (f_1, \text{emr}))\), the public or low key-value pair \((18, v)\) and then removing the confidential pair \((17, (f_1, \text{emr}))\) to \(g_1\) and \(g_2\) results in final key-value maps \(g_1\) and \(g_2\) that are equal. That this is true can be seen by considering how insert commutes with remove. For example, one such commutation property is \(\text{rem} k (\text{ins} k v g) = \text{rem} k g\). Note that this symbolic proof is performed with respect to the mathematical abstraction of hash tables as key-value maps and therefore is entirely independent of our particular hash table implementation (thus achieving portability to future implementations).

Once we have proved that \(g_1 = g_2\), in the second step we apply the unique representation theorem for multilevel UR hash tables (Theorem 1) to show that equality of the logical states \(g_1\) and \(g_2\) implies equality of the final memory states.

8. RELATED WORK

There has been much work on semantics of noninterference and its relaxations [28,29] as well as enforcement mechanisms based on type systems, logics and other program analyses. Chong and Myers [10,11] study specification and enforcement of erasure policies in the context of a simple imperative language and show how their framework can be implemented in Jil [23]. Their framework handles declassification policies as well: they describe a duality between declassification and erasure where the former can be viewed as a relaxation of noninterference and the latter as a strengthening of noninterference. Hunt and Sands [13] show the close connection between information erasure policies and noninterference in the context of simple imperative as well as interactive programs. Russo et al. [27] employ a flow-sensitive dynamic type system, to perform run-time enforcement of secure information flow in non-UR, but heterogeneous, data structures such as dynamically allocated DOM trees. Further extensions by Hedin and Sabelfeld [17] and by Birgisson et al. [7] consider tracking information flow in heap-based heterogeneous data structures in dynamic languages such as JavaScript. In this line of work, the nodes in a linked structure are assigned several security labels. For example, specifically in [17], each node has one security label for inspecting the existence of the node, another label for changing the structure rooted at the node, and another one for the node’s contents. In a secret control context, addition of new fields to a node is allowed only if the node’s structure label is high. Otherwise, the addition results in run-time error. Similar to this work, RHTT is also a flow-sensitive type system. In contrast, we do not consider security labels, but use a semantic definition of NI. Furthermore, in RHTT we focus on static verification of non-interference and erasure, rather than run-time enforcement.

Swamy et al.’s F* system [31] permits properties of data values to be specified via preconditions and postconditions in the form of dependent types of methods. The verification conditions are discharged automatically by passing them to the SMT solver Z3, though some manual work is usually needed in the course of development, to guide the SMT solver. The assertions on the methods focus on the properties of values only. In this respect, RHTT differs from F*, as we allow arbitrary higher-order logic assertions over heap shapes, and the assertions may, moreover, be relational.

Nanevski et al. [24] consider verification of flexible security policies in possibly heterogeneous linked lists. Such lists may contain mixed high and low data as well as mixed high and low links, although their main example considers low links only. Here we consider more involved data structures such as hash tables and recognize unique representation as a critical property to ensure secure erasure in the presence of adversaries who have access to the concrete memory state.

In the algorithms community, Amble and Knuth [1] studied hash tables without deletions. However, their goal was to develop fast searching algorithms rather than to exploit properties such as history independence. Theoretical work on history independent data structures by Naor and Teague [25], Hartline et al. [16], and Blelloch and Golovin [8,15] has been a primary impetus for our work, which complements the algorithmic approaches by applying unique representation to achieve provable guarantees about the functional correctness and security of programs.

9. DISCUSSION AND FUTURE WORK

This paper proposes unique representation as a means of enforcing expressive information flow and erasure policies in programs with modules and procedures with local state, in the presence of pointers and mutable data structures such as hash tables. To explore the verification of UR data structures, we present a case study in which we (1) formalize a UR variant of hash tables and (2) show how the UR theorem for this data structure can be used to prove noninterference of a medical database client. We believe this is the first verification case study of involved security properties such as NI and erasure that considers non-trivial heap-based data structures and their clients.

Much work remains. One direction to explore is the connection between enforcement of information flow policies in a high-level language (as done in this paper) and their preservation through the compilation toolchain. For example, an information-flow aware compiler must not optimize away operations introduced by the programmer to prevent information leakage (e.g., zeroing out of confidential local variables in the stack frame before function return) just because these operations do not affect a program’s dataflow.
Another direction involves studying interactions between garbage collection and erasure guarantees, especially in the context of timing and other attacks over covert channels. Proper engineering of an incremental garbage collector could ensure that private data is erased, and prevent some timing attacks. However, any end-to-end erasure guarantee of programs composed with the garbage collector would depend on the correctness of the garbage collector itself (cf. McCreight et al. [19]).

The resolution of both of the above issues may require generalizing our specifications so that they express not only properties of the beginning and the end of the computation, but of intermediate points as well. This may require reasoning about traces and temporal properties.

Another direction for generalization involves studying the verification of history independent data structures [16]. History independent structures cannot distinguish different but logically equivalent operation sequences. They generalize UR. Indeed, there are some history-independent data structures that use internal randomization as an implementation strategy, that are not UR. For example, in order to prevent a binary search tree from leaking information through the physical layout, one may consider randomly rebalancing the tree after each operation. Currently, RHHT cannot reason about randomization. In the presence of randomization, we foresee generalizing the notion of indistinguishability of heaps, which feeds into the definition of uniqueness of representation (cf. Definition 1). RHHT currently employs exact equality of heaps, but it may be possible to relax this notion by attaching a random distribution to the set of heaps.

We also plan to study the interplay between UR and parametricity, and consider how internalized reasoning about type abstractions [6] may be used to formally prove that a module interface tightly encapsulates the internal state of the module.

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