Redactable Signatures on Data with Dependencies

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ABSTRACT

The storage of personal information by service providers entails a significant risk of privacy loss due to data breaches. One way to mitigate this problem is to limit the amount of personal information that is provided. Our prior work on minimal disclosure credentials presented a computationally efficient mechanism to facilitate this capability. In that work, personal data was broken into individual claims, which could be released in arbitrary subsets while still being cryptographically verifiable. In expanding the applications for that work, we encountered the problem of connections between different claims, which manifest as dependencies on the release of those claims. In this new work, we provide an efficient way to provide the same selective disclosure, but with cryptographic enforcement of dependencies between claims, as specified by the certifier of the claims. This constitutes a mechanism for redactable signatures on data with release dependencies. Our scheme was implemented and benchmarked over a wide range of input set sizes, and shown to verify thousands of claims in tens to hundreds of milliseconds. We also describe ongoing work in which the approach is being used within a larger system for holding and dispensing personal health records.

Categories and Subject Descriptors

K.6.5 [**Security and Protection**]: Authentication

General Terms

Algorithms, Performance, Design, Security, Verification

Keywords

Identity management, signature scheme, redactable, hash-tree, Merkle tree, dependency

1. INTRODUCTION

The amount of personal information that is supplied by individuals and stored electronically by other entities, primarily service providers, is enormous and growing. This information ranges from basic (and yet still sensitive) attributes such as name, address, date of birth, and social security number to payment information, e.g. credit card numbers and expiration dates, to much more comprehensive personal information such as detailed financial records and medical records. Unauthorized disclosure of this personal information is a major problem that has been steadily increasing in severity over the last several years.

The overarching goal of our research is to give users more control over their personal information, while also providing trust in the information that is supplied. An important component of our approach is the principle of "least disclosure", i.e. that an entity requesting personal information should be given the minimum amount of information required to authorize the necessary operation or transaction. Our prior work developed new redactable signature schemes that were used to design *minimal disclosure digital credentials*, which combine a large set of attributes into a digital credential with one signature, which can be used to verify any subset of the attributes [1]. As opposed to a single "all-or-nothing" credential, this allows the user flexibility to provide some attributes, while hiding the remaining ones, but it still allows the credential recipient to verify cryptographically and efficiently the provided attributes. This type of credential can also be used with policy-driven trust negotiation to reduce further the amount of personal information that is disclosed [12].

While digital credentials are one application area for minimal disclosure technology, it can also be applied to the general area of disclosure of sensitive personal information, e.g. financial records or medical records. Medical record protection is the subject of the MedVault project [8], which is a joint undertaking between Georgia Tech and Children's Healthcare of Atlanta. Each individual element of personal information that can be disclosed is referred to as a claim. In credentials, claims are attribute values. In medical records, a claim is an individual component of the record, e.g. an X-ray image or doctor's notes about an office visit. In a document that is to be redacted, claims are words.

In certain contexts, claims might be inter-dependent. For example, a health care provider might not be willing to release doctor's notes containing a medical diagnosis unless the test results on which the diagnosis is based are also released. In this paper, we consider how to handle claim dependencies in a minimal disclosure mechanism based on redactable sig-

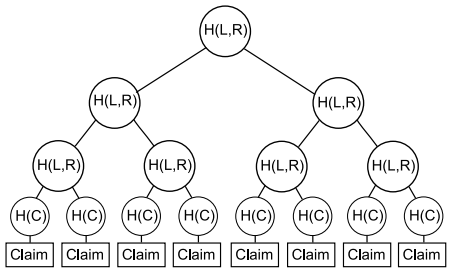


Figure 1: Basic Merkle Hash Tree

natures. We present the design of a scheme for handling claim dependencies, and we evaluate both its worst-case complexity, through analytical evaluation, and its execution time, through measurement on an actual implementation. The results show that the efficiency of simple hash-tree-based redactable signatures can be maintained while handling a useful category of claim dependencies. We close with discussion of an architecture for use of our mechanism in a source-verifiable selective-disclosure personal health record repository.

2. BACKGROUND

2.1 Scenario and Terminology

We consider a scenario with three types of entities: a prover, a verifier, and a certifier. A prover holds records that are certified (cryptographically signed) by a certifier. The prover wants to convince the verifier that the certifier did indeed certify the records. However, the prover does not wish to release all of the records, but just some subset of them. Additionally, the certifier wishes to restrict the manner in which the records can be released. "Released" here refers only to releasing records with evidence that they are certified (ie, cryptographic proof). The prover can freely forge (uncertified) records, so the verifier will accept only certified documents. We refer to an indivisible piece of a record as a claim, following our earlier credential work.

2.2 Redactable Signature Schemes

This problem arose out of our previous work on minimal disclosure credentials. [1] In that work, we presented a credential system based on Merkle hash trees and public-key infrastructure (PKI) certificates, which allows some attribute values to be hidden on a given use of the credential. We also extended the approach to allow attributes certified by different identity providers to be combined into a single credential, while still allowing the selective disclosure of attributes in the credential.

2.2.1 Basic Scheme

A Merkle hash tree is a binary tree where each internal node holds the hash of the concatenated values of its two children nodes. Ralph Merkle first introduced this structure as a way to efficiently handle a large number of Lamport one-time signatures.[9] It has since been adapted for uses such as the large-scale time-stamping of documents [2] and tracking data in peer-to-peer networks [3]. A basic tree is shown in Figure 1.

By the collision-resistance property of a cryptographic hash function, it should not be possible to find two inputs that give the same output (under reasonable computational limits, of course). Therefore, each internal node uniquely fixes the values of its two children nodes. Extrapolating, the single root value uniquely fixes the value of all internal and leaf nodes in the tree. Additionally, it is not necessary to have all nodes of the tree in order to compute its root value. Specifically, verifying that a given value for a leaf node of the tree is correct requires an additional number of nodes equal to the height of the tree minus one ($\mathbf{O}(log(n))$ with respect to the size of the tree). Having a trusted authority digitally sign the root value of the tree provides the equivalent of a trusted signature on everything in the tree. Replacing a simple digital signature with a full PKI certificate containing a public key and meta-data ties the contents of the tree to a private key through a trusted signature; in short, a digital credential. Each leaf node in the tree is a claim of a particular attribute value, which can be verified independently of all of the other claims in the tree. This basic scheme is essentially equivalent (modulo minor implementation details) to the redactable signature scheme proposed in [7].

2.2.2 Extension to Multiple Authorities

Credentials in general are issued by many different authorities. For example, various government agencies issue driver's licenses, passports, business licenses, building permits, etc. Corporations such as insurance companies, private colleges, independent testing agencies, and medical providers all issue different types of certified claims about customers. It can be advantageous to combine together credentials issued by different authorities for reasons of organization, consistency, and/or (as in our system) computational efficiency. Even when considering personal information such as health records, this information can come from a variety of sources, such as different health care providers and/or doctor's offices where a patient has been treated, or from medical devices installed in a patient's home, or from personal medical devices carried by the patient, etc.

In our extended redactable signature scheme, records issued by multiple authorities can be combined together by modifying the hash tree structure slightly. In the modified tree, certain nodes have three branches, instead of the normal two. The third branch, shown as the middle branch in the example of Figure 2, contains a PKI certificate that applies to all nodes below the three-branched node. These three-branched nodes correspond to the root nodes of the records that were combined together. The whole structure must be signed by a trusted authority. However, that authority does not need to see (let alone verify) any of the claims in any of the sub-trees. Rather, this top-level authority only needs to certify that the structure of the tree is correct.

2.3 Motivation for Dependencies

From a basic credential system, we expanded the scope of our uses for the credential construct to hold arbitrary records. In doing so, the issue of dependencies between different data items or between different whole records arose. Data seldom exists in isolation. Individual pieces of data are combined to form data, which are combined to form datasets. Data can be connected via many relationships, and releasing individual pieces of data ignorant of those relationships often makes no sense. So, we wish to provide a way for the certifier of data to prevent data from being re-

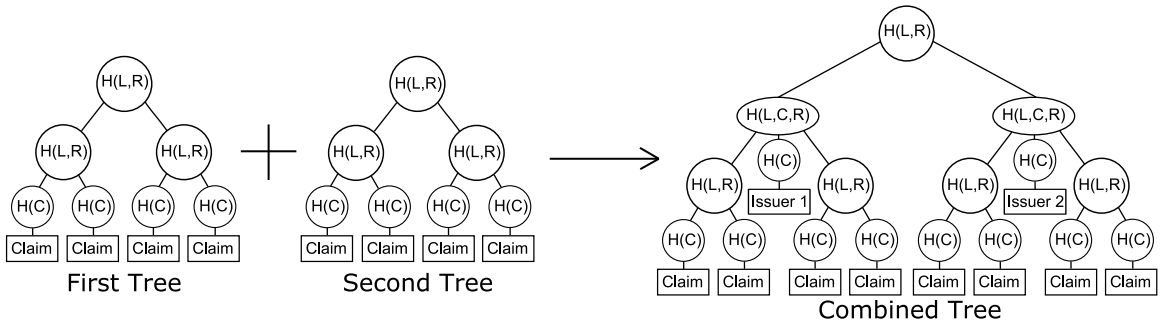


Figure 2: Combining Signed Trees from Multiple Authorities

leased without respecting the relationships between different pieces of data. As mentioned previously, "released" refers only to releasing the data in a certified form. Uncertified data is not considered. In this work, relationships between data are reduced to dependencies between data that must be satisfied for the data to be released.

3. RELATED WORK

While we are not aware of any other attempts to address this specific problem of dependencies in releasing certified data, this work is still related to, or dependent upon, various prior works.

The most closely related works using graphs or circuits of dependencies all seem to involve fulfilling such dependencies under a significantly different threat model, for example [5]. In our system, the most difficult threat is the prover and verifier collaborating to cheat the certifier. And the threshold of that cheating is low, since the result only has to be trusted by the verifier, and not by any honest party.

This work can be considered the core of a specialized redactable signature scheme, although it is meant to be embedded into a separate redactable signature, specifically, our previous work described in the next section. Redactable signatures were introduced by Johnson, et al., in [7] as one example of a larger class of homomorphic signatures. While the targeted use of the schemes is very different—Johnson, et al., describe a scenario where the majority of a document is shown, with a small part redacted, while our work describes showing a small amount of data and redacting the majority—the core mechanism is the same.

Privacy preserving trust negotiations associated with the disclosure of sensitive attributes also have disclosure dependencies among attributes. The user can set up policies where the other negotiating party has to disclose some attributes before a particular attribute of the user can be released. We review some related contributions in this area and contrast between dependencies in trust negotiation and dependencies in data disclosure.

In [18], one of the earliest works on negotiating disclosure of sensitive credentials is presented. This work proposed eager and parsimonious strategies and compare their performance. [16] presented a framework for negotiating release of sensitive attributes. They discuss several interoperable negotiation strategies for improving privacy. [15] argued that access control policies protecting sensitive credentials are themselves sensitive and their disclosure should be limited. [19] discuss safety in trust negotiations. They present a formal framework for trust negotiation and analyze safety of credentials under different negotiation strategies.

One major difference between all these trust negotiation systems and our proposed system is that the trust negotiation systems are online where they expect the other party to release credentials online to satisfy the dependencies as opposed to our offline system where the dependencies are enforced cryptographically. Another difference is that in trust negotiation systems both parties try to satisfy each other's policies at run time, whereas in our system the policies result from natural dependencies in the data set that must be preserved to release the information in the correct context.

Other systems attempt to limit the disclosure of personal information/credentials in different ways. For example, in role-based access control, only a user's role needs to be disclosed and not a more specific identifier [14]. Alternately, by adding context to role-based access control, policies for access can be tightened and made more fine grained, thereby reducing the amount of unnecessary personal information retrieved [6]. In a different use of context information, [13] uses context information (about both the subject and the querier) to determine what information can be released for any request. These works do not consider the issue of verifiability of the data being provided nor its inherent data dependencies.

4. SYSTEM DESCRIPTION

Our redactable signature with dependencies consists of several parts. The first two parts are the PKI certificate and Merkle hash tree as used in our prior work and described in the previous section. The interesting and novel part is the handling of the dependencies.

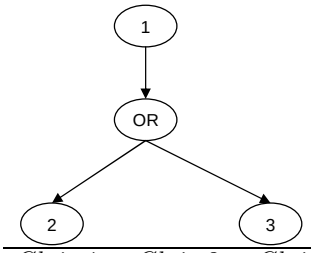
4.1 Dependency Graph

Dependencies between data can come in many forms. The simplest form is a single "depends upon" relationship, such as "claim 1 depends upon claim 2", which means that "claim 1" should not be released without also releasing "claim 2". The next simplest form is a chaining of dependencies, such as "claim 1 depends upon claim 2, and claim 2 depends upon claim 3". These chains can be handled by creating one node per claim in the chain, with each node containing its corresponding claim and all subsequent claims in the chain. Less simple is when there are OR options, such as "claim 1 depends upon either claim 2 or claim 3". In small numbers, these OR options can be handled by just enumerating the possible combinations as if they were chains, but for large systems, that is extremely inefficient.

Simple OR dependencies will be represented by a directed

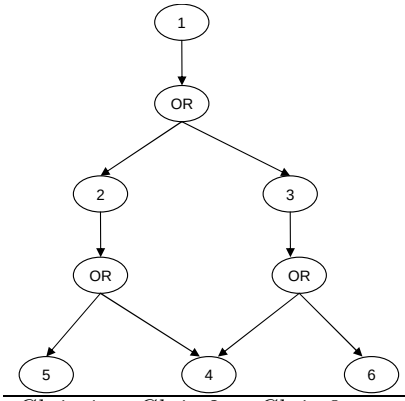
$\rightarrow$ is used for depends upon
$A \rightarrow B$ is read "A depends upon B",
and A is called a parent of B
+ indicates concatenation
{} indicates a set of values, concatenated together
$S(x)$ is the string for vertex x, and is defined as
$S(x) = H(\{$ parent vertices strings $\} + x)$

Figure 3: Generic Dependency Form



$Claim1 \rightarrow Claim2$ or $Claim3$
$S(Claim1) = H(Claim1)$
$S(Claim2) = H(S(Claim1) + Claim2)$
$S(Claim3) = H(S(Claim1) + Claim3)$
$Output = S(Claim2) + S(Claim3)$

Figure 4: Simple Dependency Example



$Claim1 \rightarrow Claim2$ or $Claim3$
$Claim2 \rightarrow Claim4$ or $Claim5$
$Claim3 \rightarrow Claim4$ or $Claim6$
$S(Claim1) = H(Claim1)$
$S(Claim2) = H(S(Claim1) + Claim2)$
$S(Claim3) = H(S(Claim1) + Claim3)$
$S(Claim4) = H(S(Claim2) + S(Claim3) + Claim4)$
$S(Claim5) = H(S(Claim2) + Claim5)$
$S(Claim6) = H(S(Claim3) + Claim6)$
$Output = S(Claim4) + S(Claim5) + S(Claim6)$

Figure 5: Multiple Parents

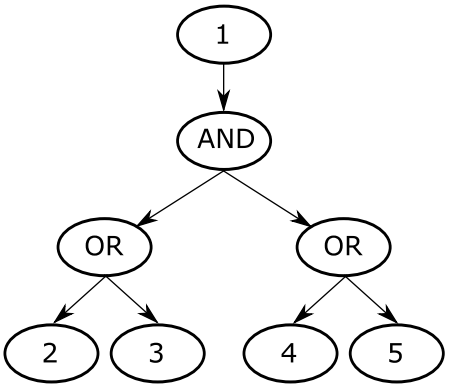
acyclic graph (DAG). To handle these dependencies efficiently, a secure hash function is used to create a path whereby a claim is proven valid at the same time as the next node in the graph is proven valid. We call a node that is dependent upon another node a parent of the latter node. The node that is depended upon is called the child node. A node is assigned a "string" value, which is a hash of the string values of its parent nodes and its actual data value. Calculating a node's string therefore requires having the data for that node. Just as the node (hash) values in the Merkle hash tree define a unique set of children, each node's string value defines a unique set of parent nodes and its data value. In order to tie the entire DAG down to a single value, an output value is created, which is simply the set of string values of all of the leaf nodes of the DAG.

Figure 3 shows the notation that we use, while Figure 4 shows the example described above. The example in Figure 5 shows that multiple parent nodes are efficiently handled. In general, the size of the node's value will grow sublinearly with the number of parents, as the extra parent strings are amortized by the node's actual data content.

Sets of dependencies that cannot be represented by a DAG are not yet handled by our scheme. This includes sets of dependencies with cycles, negative dependencies, and operations that cannot be represented as a combination of ANDs and ORs (discussed next). We do not believe that negative dependencies between released claims is meaningful, since the prover could always perform multiple, independent showings of the signed documents. Cycles are prohibited because we do not yet have an efficient, general way of dealing with them, although a simple cycle that is not interdependent on other sets of claims can be handled easily by collapsing the entire cycle into a single claim.

Moving on to more general forms of dependencies, we wish to handle arbitrary combinations of AND and OR operations. For example, "Claim 1 depends upon one of Claim 2 or Claim 3 and upon one of Claim 4 or Claim 5", alternately written "Claim 1 depends upon (Claim 2 or Claim 3) and (Claim 4 or Claim 5)". The AND operations are handled by adding special AND nodes to the DAG. Placeholder OR nodes are also added to the graph for convenience, but they don't necessarily show up in analysis or implementation. This example is shown in Figure 6. The AND node has two branches for its two children. A different string is given to each branch, represented by AND1_1 and AND1_2. (The two AND pieces are shown without the S(x) notation, because they aren't actual vertex nodes in the graph.) When the two branches are XORed together, the result is the actual value of the AND node. For an n-input AND, this is done by generating n-1 random values (each the size of the output of the hash function) and using them as the values for the first n-1 branches. The final branch is the XOR of the rest of the branches and the AND node's value. All of the randomly generated values are included in the string that is hashed to get the AND node's value (to prevent any linear combination attacks against the XOR combination). The example also shows how the OR nodes disappear, because their value is equal to their parents' value. This is still true (if slightly more complex) when such an OR node has multiple parents; the parent values are simply concatenated, in the same way multiple parents of any other node are handled.

As an example of requiring combined AND and OR dependencies, imagine a table of claims, with each column containing a different type of claim. Consider the rule that to access an element of the first column requires also showing (at least) one element of every other column. Using our method, this requires a graph containing one node for every element in the table, a single AND node, and one OR



$Claim1 \rightarrow (Claim2$ or $Claim3)$ and
$(Claim4$ or $Claim5)$
Is transformed into:
$Claim1 \rightarrow AND1$
$AND1 \rightarrow OR1$ and $OR2$
$OR1 \rightarrow Claim2$ or $Claim3$
$OR2 \rightarrow Claim4$ or $Claim5$
$S(Claim1) = H(Claim1)$
$S(AND1) = H(S(Claim1) + AND1\_1)$
$AND1\_1$ = Random value, of size $|H|$
$AND1\_2 = S(AND1)$ xor $AND1\_1$
$S(OR1) = AND1\_1$
$S(OR2) = AND1\_2$
$S(Claim2) = H(S(OR1) + Claim2)$
$= H(AND1\_1 + Claim2)$
$S(Claim3) = H(S(OR1) + Claim3)$
$= H(AND1\_1 + Claim3)$
$S(Claim4) = H(S(OR2) + Claim4)$
$= H(AND1\_2 + Claim4)$
$S(Claim5) = H(S(OR2) + Claim5)$
$= H(AND1\_2 + Claim5)$
$Output = S(Claim2) + S(Claim3) +$
$S(Claim4) + S(Claim5)$

Figure 6: Combining AND and OR

Prover provides:
$Output = S(Claim2) + S(Claim3) +$
$S(Claim4) + S(Claim5)$
$S(Claim2) = H(AND1\_1 + Claim2)$
$S(Claim4) = H(AND1\_2 + Claim4)$
$S(AND1) = H(S(Claim1) + AND1\_1)$
$S(Claim1) = H(Claim1)$

Verifier checks:
$Output$ is signed (in the hash tree)
All hash values are correct
$S(AND1) = AND1\_1$ xor $AND1\_2)$

Figure 7: Showing claims 1, 3, and 4

node for each column but the first two. Additionally, the OR nodes can be removed, because they are not necessary, as mentioned previously.

4.2 Protocols for Usage

In general, a set of claims will have some claims with no dependencies and other groups of claims that are inter-dependent. To handle this situation, we combine the structures described in the previous subsection with the hash-tree-based readactable signature scheme from our prior work. Each group of inter-dependent claims is represented by a DAG and a single signed output value is generated for each such group. Each of these signed output values then becomes a node in the overall hash tree, along with each of the claims that have no dependencies associated with them. As in the prior approach, the certifier signs the root value of this hash tree and places it in a PKI certificate.

To show a claim that has dependencies requires showing more claims to fulfill those dependencies. We refer to a claim and one set of additional claims that fulfills the dependencies as a chain. The term "chain" is not strictly accurate, since the chain will have multiple branches if it has any AND nodes, and those multiple branches may even connect together (ie, not a tree). There can be no loops, per the constraint that dependencies must be in the form of a DAG.

As an example, consider the graph of Figure 6 and the case of showing "Claim1", "Claim3", and "Claim4". The prover must provide to the verifier the input strings that were hashed to create the string values of each of the claims being shown and the AND node on the path, along with the (signed) output value. The input string for a claim node includes the actual data of that claim, so the data for the three claims is included in what is shown. Figure 7 summarizes what the prover shows and what the verifier needs to verify. The only additional values given to the verifier that are not used are $S(Claim4)$ and $S(Claim5)$. These are the string values for the other two leaf nodes, and contain just the hash output. Under the assumption that the hash function is secure (can't be inverted and doesn't leak data), then no data is leaked by these extra strings, except for the knowledge of their existence.

4.3 Relation to prior work

The mechanism for handling dependencies obviously shows a family relationship to the Merkle hash tree. It in fact looks like a backward tree, where instead of a root node verifying the values of many leaf nodes, a set of leaf nodes can verify the value of a set of root nodes (and all of the intermediate nodes as well). In most of our examples, the set of leaf nodes is much larger than the set of root nodes, but that is simply selection bias of the examples.

5. SECURITY

A secure scheme requires some additional details beyond those described in the previous section. First and foremost, the claims must have random padding to prevent a dictionary attack, because the hash value of unreleased claims is necessarily provided to a verifier. Second, and related, is that the values of nodes should be unambiguous about what they contain. Throughout this paper, the value of nodes is represented by a simple concatenation of values. In our actual implementation, we include additional meta-data between the fields.

There is an alternative to the random padding of claims; substituting a collision-resistant message authentication code (MAC) function such as HMAC in place of the plain hash function. In this situation, a unique key must be used for every node, with the key being revealed to the verifier when a node is proven. We do not see any advantage of this method over the random padding of the claims.

The specific attacks the system needs to be secure against include forgery, loss of privacy, and violation of dependencies. Next, we provide informal analyses of the security of the approach against these attacks.

5.1 Forgery

Forgery covers all cases where the verifier is convinced that a claim is certified by a particular entity, when it was not. Forgery covers several different problems, depending on what part of the system is attacked. For example, a forger can try to attack the hash function to create a bad final or intermediate value. A secure hash function will prevent this type of attack.

A forger can try to pass off data as if it were part of the structure, or vice versa. This style of attack is only possible if the construction of nodes' strings is done in a simplistic manner, such as merely concatenating the values. By adding meta-data – such as a count of the number of fixed-sized fields, before the start of the variable-sized data field – the contents of the string can be made unambiguous, clearly demarcating structure and data. Additional meta-data (such as marking whether a node is an AND or data node) can provide further reassurance, and may be necessary for a formal proof of security. Meta-data might also be required in specific applications of the approach. For example, if applied to documents, the order of the claims (words) is important and this information can be provided in the meta-data in the form of sequence numbers. If knowing the sizes of the gaps in the provided text is important, contiguous sequence numbers are used. Otherwise, random increments between consecutive sequence numbers can avoid release of extra information such as the precise number of words that were redacted from a particular section.

A forger could also try to fake a valid looking AND node. The AND node construct of XORed masks is a trivial secret sharing scheme, while having the masks inside of the hashed string is a constraint on the values of shares that are accepted. This constraint is necessary to eliminate the possibility of generalized birthday attacks [17], although we hope that these attacks would not be practical on the system even without such a constraint. The problem of faking an AND node can be reduced to the problem of creating a collision in a hash function defined as $H(x + \{y_i\}) = H'(x + \{y_i\})$ xor $\{y_i\}$, where $H'(x)$ is an assumed to be secure hash function and $\{y_i\}$ is an arbitrarily sized set of values. We assume this is not possible since breaking this structure is equivalent to breaking the underlying hash function.

5.2 Loss of Privacy

A loss of privacy occurs when releasing some claims or data exposes additional claims or data that the holder did not intend to release. In our system, the most obvious way for additional data to leak is through hashes of unreleased data being (necessarily) revealed. Under the assumption of a secure hash function, no information about the data should be directly leaked by its hash value. However, if the data itself is in a guessable form and of low entropy, then a dictionary attack may be performed against the hash. Adding random padding is our recommended solution to this problem. The padding can either be independently generated and stored for each data value, or it can be generated using a pseudorandom function along with a random seed value.

5.3 Violation of Dependencies

A violation of dependencies occurs when a holder is able to release certified data to a verifier in a way that the verifier can determine that it was certified, while not releasing other data as required by the certifier. Please note that in this case, security is done on a "can prove" basis, where it doesn't matter how the certified data is proven. In particular, the verifier does not have to follow established protocols or intentions. (Put simply, we do not assume that the verifier is not an honest player in the system.)

Dependencies are enforced by providing chains, such that each link in the chain must be fully verifiable in order for the next link to be verifiable. Additionally, to verify a (data) link requires the actual data for that node to be known and used by the verifier. These chains overlap, creating the DAG. There are two general ways to violate the dependencies: forging a link in the chain and finding a different way (than following the chain) to prove a claim. The first of those is covered by the subsection on forgery, discussed previously. The second is beyond the scope of this paper, as it covers application-specific side-channels, and is dependent upon the implementation and use of the system.

5.4 Other

There is an additional class of attacks that are of less concern, namely attacks by the certifier of the data. The only meaningful attack we can see is the certifier putting a hidden channel into the signature, without the knowledge of the user. As we generally expect the certifier to provide the data, define the dependencies, and create the actual structures of the signature, we consider attempting to identity and prevent all possible hidden channels as beyond the scope of this paper. Since in all applications we can imagine for the approach, the user has an inherent trust relationship with the certifier, we do not consider this issue a serious one.

6. PERFORMANCE RESULTS

Good performance for large systems of dependencies was a primary goal of this work. Two evaluations of the system in meeting that goal are provided. The first evaluation is in the form of analytical bounds, while the second evaluation is based on experimental results from an implementation of the scheme.

6.1 Analytical Bounds

In addition to being relatively easy to understand, our system as described so far provides clear bounds on space and time complexity. For example, there is exactly one vertex node for each claim, and the actual data of each claim is stored and hashed only once. There is a maximum of one vertex for each AND and OR as well (multiple ANDs and ORs may be combined).

For comparison to our system, consider a brute-force approach to handling dependencies. All possible combinations of claims necessary to satisfy a particular claim's release policy can be combined and treated as a single claim. For small

graphs, this can actually be quite efficient. However, consider the example given before of a table of claims, with the rule that to access an element of the first column requires also showing (at least) one element of every other column. As noted before, the number of nodes in the graph of this example is equal to the number of items in the table plus one (ignoring the removed OR nodes). The approximate total size of data being hashed in the creation of the graph is given in Equation 1, where n is the number of rows, k is the number of columns, and assuming a symmetric table (all columns have the same number of rows).

$$(n * k + n + k - 3) * |H| + |\text{all data items}| \quad (1)$$

Thus, our solution is $\mathbf{O}(n * k)$ in space and time while enumerating all possible combinations is $\mathbf{O}(n^k)$.

6.2 Trade-offs

There are a number of trade-offs that can be made between storage space and speed. For example, separate, smaller DAGs can be calculated and stored for every claim that is involved in a dependency calculation, allowing for quick retrieval and verification of single claims and verification chains. Alternately, a single large DAG (or a small set of medium sized DAGs) can be used, which can greatly increase the amount of data necessary to verify a single claim (and chain), but which is much more efficient to store and verify large sets of claims (with overlapping dependency chains).

The discussion so far has assumed a single, monolithic DAG is used. A single monolithic graph is easier to describe, program, and analyze. However, a multiple graph approach can produce better results in a "best-case" scenario. As such, both a monolithic version and a multiple graph version were implemented for experimental performance testing. To provide the best contrast, the multiple graph version makes and stores a separate DAG for every claim.

6.3 Experimental Setup

A Java implementation of just the dependency handling portion of the system was written and tested. All tests were performed on a Dell PowerEdge 2900 server with dual Xeon 5150 CPUs running at 2.66 GHz using Sun's 64-bit server JVM, version 1.6.0_06. The code was single threaded and the server otherwise idle. The minimum time seen over the course of multiple rounds was recorded, to avoid artifacts from the just-in-time compilation and garbage collection. SHA-256 is used for the hash function [10].

Two styles of input dependency graphs were used, both rectangular tables. Using this format, it was easy to vary the number of rows, number of columns, and size of data in each claim (constant across all claims in a table to make the results more consistent). The first style matched the example analyzed earlier, where a table of claims has the requirement that to release any claim in the first column requires releasing (at least) one value from each of the other columns as well. This graph is fast to process, as would be expected from the earlier bounds discussion and some simple analysis (most of the nodes in the graph are of low degree, with the connections concentrated in the AND and OR nodes).

The second graph is a table where each column is dependent upon the next column in order. More specifically, showing any claim in any column except the final column requires showing at least one claim from the next column.

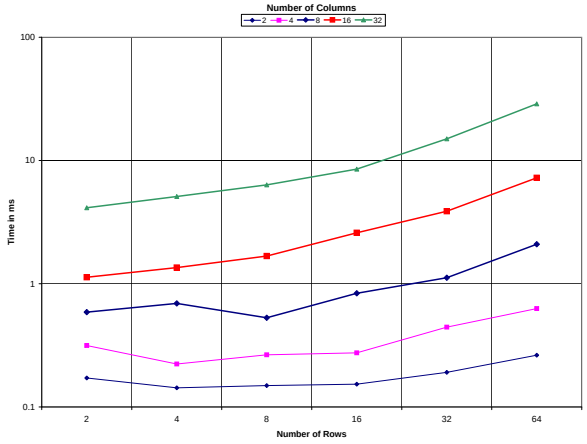


Figure 8: Verifying a Chain in 2nd Graph Style

(For claims in the first column of the table, the behavior of this graph style is the same as for the previous graph style.) This graph is denser in connections than the first graph, with all nodes being of degree n (for the first or last column) or $2 * n$ (for all other columns).

6.4 Experimental Results

6.4.1 *Absolute timings*

Handling of dependencies is efficient for most cases, as can be seen in Table 1, which shows representative timing data for the first graph style. Most of the operations take just milliseconds. However, the largest value in the table is five seconds for verifying *all* claims in the multiple graph representation. Thus, the multiple graph approach can be very inefficient when the number of claims to be verified is very large.

The table shows some oddities, compared to the simple complexity analysis. For example, the monolithic graph is fairly close to linear in the number of rows, but sub-linear in the number of columns. The reason for this is that operations that are ignored in our complexity analysis (i.e., comparing values, identifying which child/parent a node is) dominate the execution time.

This is shown even more clearly by the second style of input. This second style has the same complexity bound as the first style, but is much slower in practice due to the very high density of connections. In particular, the time to pre-generate all of the chains in the multiple graph approach make it impractical, even when the chain verification time is very small. As such, the following figures only show the monolithic graph timings.

Figure 8 shows the time (in milliseconds) for verifying a single chain in a monolithic graph (first timing column in Table 1) using the second style of input. This time is very small (at most tens of milliseconds), even when the numbers of rows and columns become large. Figure 9 shows the time (in milliseconds) for verifying the entire monolithic graph (second column in Table 1) using the same data. This time is also reasonable, being less than one second even for large cases.

6.4.2 *Relative timings*

While absolute timings are important for identifying whether

Input Table Size			Monolithic Graph		Multiple Graph	
Rows	Columns	Data size	Verify chain	Verify all	Verify chain	Verify all
Small inputs						
4	4	10	360	330	120	450
4	8	10	520	460	200	660
4	16	10	960	890	400	1500
4	32	10	1900	1800	950	3600
Medium inputs						
64	16	100	1700	8200	1300	77,000
64	32	100	3400	17,000	4400	280,000
64	64	100	6800	34,000	19,000	1,200,000
64	128	100	15,000	74,000	77,000	5,000,000

Table 1: Timings for first graph style (in μs)

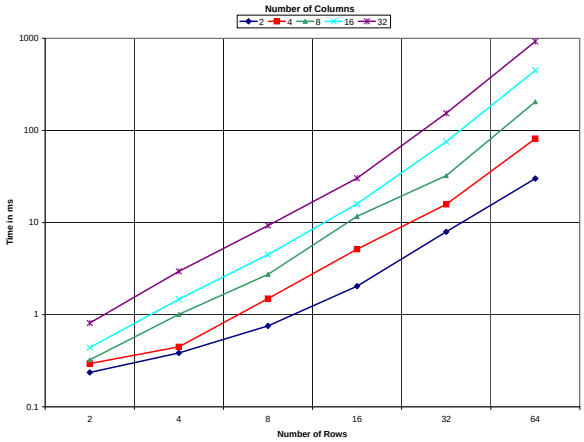


Figure 9: Verifying Full Graph in 2nd Graph Style

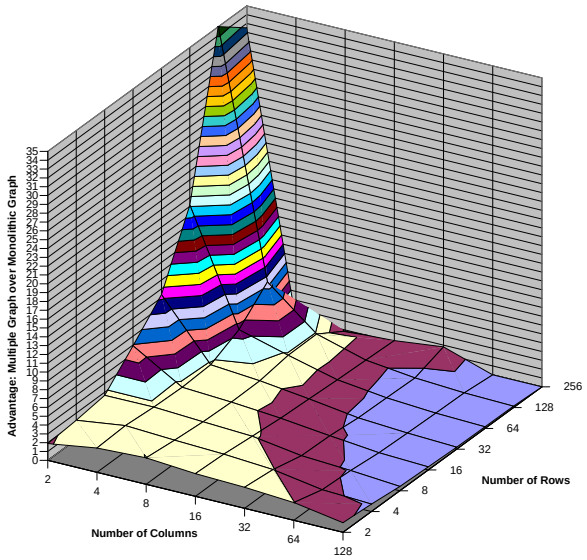


Figure 10: Relative Time to Verify a Single Dependency Chain

the system is viably efficient, relative timing between different options is also instructive.

For example, Table 1 shows little advantage to the multiple graph approach, which is supposed to be a speed-up. Figure 10 provides a different view, showing the relative advantage of the multiple graph over the monograph. (This graph is based on the first input style and a data size of 10 bytes.) It can be clearly seen that the multiple graph approach provides a significant advantage—about 35 times faster for the peak in the figure—for some parameter values. In particular, it does best with a large number of rows and a small number of columns. The area to the right of the first contour line is where the monolithic graph performs better.

Thus, the optimum implementation approach is dependent on the nature of the release dependencies. However, from a worst-case standpoint, the monolithic graph implementation appears to be better.

7. APPLICATION TO PATIENT MEDICAL DATA

One of the application areas where these ideas are being implemented is healthcare, in the Georgia Tech and Children's Healthcare of Atlanta MedVault project [8]. This work is currently in progress and some of the components are ready for integration with the whole system. Dependencies in a patient's medical data may require that certain medical documents not be disclosed unless other related documents are also disclosed. For example, a patient's medical report may not be disclosed unless the doctor's consultation and the clinical lab report are also disclosed. These types of dependencies can be created in the disclosure policy. For implementing these dependencies, the proposed cryptographic scheme can be used.

Figure 11 shows the architecture of a service that maintains a personal health record (PHR) database by aggregating a patient's medical records from various sources. The patient has a personalized agent to provide authorization service for the PHR repository. The authorization scheme is policy based, where the patient can set his disclosure policies. These policies are attribute-based and hence the patient defines a set of attributes that a requester must hold in order to access particular records. The repository holds the PHR which is composed of a number of medical records. The agent and the repository form a single unit as shown in the figure. This architecture is loosely based on the health care use case from [11], which can be considered a specification for systems that permit patients to access their own health records and to specify disclosure policies on those records.

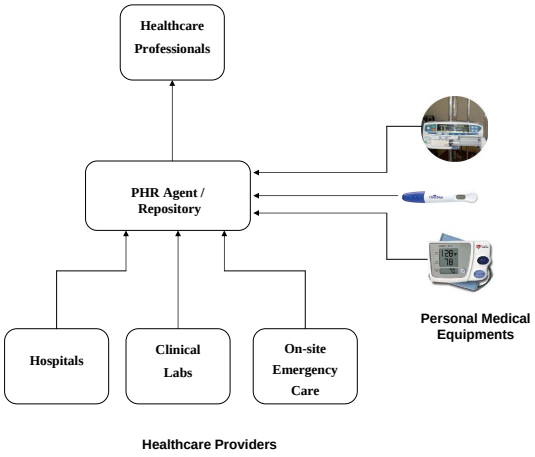


Figure 11: Architecture of the PHR service

Healthcare providers, such as hospitals, clinical labs, on site emergency care units etc., are entities that generate medical records about the patient and these records are added to the repository. These providers are the *certifiers* in our terminology and make use of the proposed dependency-aware redactable signature scheme in order to sign the records that they provide to the repository. The patient's personal medical devices also generate medical records about the patient and are useful in monitoring the patient's condition on a regular basis. The healthcare professionals require these personal health records to provide medical care to the patient. This medical care can be emergency, definitive or general. Healthcare professionals contact the patient's agent and request some records. Upon authentication and checking the authorization policies, the agent retrieves the records from the repository and sends them to the requesting professional. Although the medical records are being provided by the patient himself, the authenticity of the records can be verified as they are digitally signed by the originating entity.

The patient can set attribute-based authorization policies in his personalized agent. He specifies specific sets of verifiable attributes that the requesting medical professional should posses in order to access documents from a particular category. These attributes are provided to the medical professionals by identity agents who assert them by digitally signing them and creating a certified credential. The policy engine is based on the XACML standard [4]. When the patient specifies his policies, the XACML policy description point (PDP) converts them into XACML policy files. When a request for access is made to the agent, the agent responds with a set of attributes required for that access. When the requester provides the credentials, they are verified and the access request and the attributes are given to the policy evaluation point (PEP) in XACML. The PEP evaluates the request based on the patient's policy and responds with approve or deny. In case the request is approved, the agent accesses the appropriate piece of the health record from the repository, along with any other entries that the requested piece is dependent upon, and sends them to the requester.

Using the proposed method, medical data from multiple authorities can be combined together to form an aggregate report to be presented to the healthcare professional. Let's consider the previous example where the patient cannot disclose his medical report unless the doctor's consultation and the clinical lab report are also disclosed. Further assume that the clinical lab report contains the patient's blood pressure and it can be substituted by a report from the patient's personal device. If the medical report is represented by MedReport, the doctor's report by DocReport, the clinical report by ClinReport and the blood pressure device reading by BPReading, then we have the following: "$MedReport \rightarrow DocReport$ and ($ClinReport$ or $BPReading$)"

The policy can be cryptographically encoded so that policy enforcement is done in a natural way. In the present example, even if the medical report is disclosed without its dependencies by mistake, it cannot be verified or trusted by the requester.

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