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Data in the Cloud: Authentication without Leaking
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DATA IN THE CLOUD: AUTHENTICATION WITHOUT LEAKING

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Dedicated to

My Beloved Parents

Aniruddha and Brundabati

and Grandparents Uday and Menaka

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गुरुर्ब्रह्मा गुरुर्विष्णुः गुरुर्देवो महेश्वरः ।
गुरुरेव परं ब्रह्म तस्मै श्रीगुरवे नमः ॥
gururbrahmā gururviṣṇuḥ gururdevo maheśvaraḥ |
gurureva paraṁ brahma tasmai śrīgurave namaḥ ||

Translation from Sanskrit:
"Salutations to that Guru, who is the Creator,
Sustainer and Destroyer, who is the limiteless one."

Adi Shankaracharya (788–821 CE)

Here is another night, quietly passing by. Perhaps, the last night of my pursuit of the degree, that degree, for which I started this marathon in 2005 – the highest academic degree of Ph.D. In the air, there is a feeling of nostalgia, a feeling of emptiness, alongwith, of course, a great sense of joy and perhaps, relief. A great number of individuals have contributed to my successful run at Ph.D. and to this feeling of mine today. I wish I could mention each one of them with honor and gratitude here. Alas! This night may not last that long. But I would give it a try.

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PREFACE

Take up an idea, devote yourself to it,
struggle on in patience, and the sun will rise for you.
Swami Vivekananda [133]

No Words – Acts.
The Mother (Pondicherry, 1969)

Since my first semester, I was in search of an important problem that would form the core of my doctoral thesis. I knew of one problem in language security, from my work at IBM Research; however, I was not sure if that was of the right depth and breadth to become a topic of doctoral research.

During the Fall 2005, I was taking the class of Information Security offered by Prof. Elisa Bertino. During the discussion of secure XML dissemination in the class, I found that existing schemes leak information, especially structural information. I discussed this problem with Prof. Bertino, who suggested me to study it further as a course project. Thus I started working on the problem of "Authentication of trees without leaking".

Our first paper in this topic was on secure dissemination of XML documents using randomized traversal numbers, which received the Best Student Paper at IEEE Enterprise Computing (2006). We were encouraged by this interest in the community, and wanted to explore this problem further. At this point, with the advice of my advisor Prof. Bertino, we decided to take this problem as the topic of my doctoral research. We developed a scheme for leakage-free authentication of trees, following which we asked ourselves – can we solve the problem for graphs, or is it the end of this problem? It seemed to be more challenging, especially for cyclic graphs. Since we found that the problem had enough depth and breadth for the purpose of doctoral research, we continued working on it.

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ABBREVIATIONS

PON	Post-Order Number
RON	Pre-Order Number
ION	In-Order Number
RPON	Randomized Post-Order Number
RRON	Randomized Pre-Order Number
RION	Randomized In-Order Number
IV	Integrity Verifier
CRSA	Condensed-RSA
BGLS	Boneh Gentry Lynn Sacham (Aggregate signature scheme)
POPF-CCA	Pseudo-random Order-Preserving Function Chosen Ciphertext Attacks
IND-CCA	Indistinguishability against Chosen Ciphertext Attacks
EU-CMA	Existentially Unforgeable against Chosen Message Attacks

ABSTRACT

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Third party data distribution frameworks such as the cloud are increasingly being employed in order to store, process, and publish sensitive information such as healthcare and finance information, belonging to individuals and enterprises. Such data objects are often organized as trees, graphs or even forests (e.g., XML). In third party frameworks, not only authentication of data is important but also protection of privacy and assurance of confidentiality are important. Moreover, data authenticity must be assured even when the data object that a user has access to consists of subset(s) of the signed data.

Existing solutions such as Merkle hash technique and the redactable signature schemes lead to leakages of structural information, which can be used to infer sensitive information, which in turn would lead to privacy and confidentiality breaches. So the question is: can we authenticate subset(s) of signed data objects without leaking, and if so, how efficiently such authentication can be carried out? We have reported a positive result by presenting efficient and provably secure solutions not only for trees, but also graphs and forests. We have presented a scheme that computes only one signature per tree, graph or forest.

Our schemes support encrypted data to be stored at third-party services. Our schemes can also be used to automatically recover from structural errors in tree-structured data, and for leakage-free authentication of paths (e.g., XPaths). Further, as the applications of our schemes, we have also developed a publish/subscribe model for XML – Structure-based routing, and a scheme for authentication of objects.

1 INTRODUCTION

A man provided with paper, pencil, and rubber,
and subject to strict discipline, is in effect a universal machine.
Alan M. Turing [130]

Third-party model of data distribution and computing has been of growing interest to the enterprises and businesses over the past decade. Such a model helps organizations achieve economies-of-scale while focusing on their core competencies, and deliver better products/services. The explosive growth in the amount of data that needs to be collected, stored, processed, analyzed, distributed, displayed, and even destroyed as and when needed, requires significant amount of technological and financial investment on the part of enterprises. Such an investment spans over the lifetime of the deployment of several technological products and services, and thus puts a continuous strain on the enterprises and their revenue. The third-party model provides viable and cost-effective alternatives for the said requirements while minimizing such strains and allowing enterprises focus on their core-competencies. As a result, recently, *cloud computing* [132] has emerged as the umbrella area that covers all the business and computing aspects of third party data distribution and computing models.

In the emerging cloud-computing paradigms, which are increasingly being employed in order to store, process, and distribute sensitive information belonging to individuals and enterprises, protection of privacy and confidentiality are as important as assuring authenticity of such data (e.g., [7, 24]). As it is, privacy is an important problem in data publishing itself(e.g., [91, 93]). In a third-party model, there is an authorized owner of the data, which maybe the source of the data, one or more third-party services (or distributors), and one or more queriers/subscribers (collectively called as users or data consumers). In the cloud, the distribution of data is carried out by third party services (such as in "Database as a Service" [69]). Such third-

party services may not be trusted (e.g., Amazon EC2 and Amazon Web Services: AWS [1]). In such third-party data distribution setting, an important requirement is to assure data authenticity. An authentication scheme is used to verify (1) the integrity of data, and (2) that the claimed owner is in fact the authorized owner of the data. Authenticity is typically assured by message authentication codes or digital signatures computed by the authorized owner of the data, which in third-party distribution setting, are different from the party distributing the data (referred to as distributor). Data objects in the context of third-party architectures are very often organized as *trees*, *graphs* or even *forests* (set of disconnected trees/graphs); for example, data organized according to XML schemas. Often users receive part of the data that is stored at the database(s), as users maybe authorized to access only a subset of the data. For example, a querier receives a part of an XML document or a relational table from a database instead of the complete XML document or the table. Consequently, data authenticity must be assured even when the data that a user can access, is a subset of the signed data. A crucial requirement is to ensure that the techniques are used for verifying the data authenticity do not result in data leakages in order to protect privacy of the users and confidentiality of data. Such leakages can be used to infer sensitive information that is not part of the received data, which in turn would lead to privacy and confidentiality breaches.

When addressing the problem of authentication of trees, graphs and forests, it is important to notice that each node may contain some contents and that the edges and ordering between nodes may establish some relationships between the contents in these nodes. Such relationships may be defined according to properties such as classification, indexing, temporal-orientation and sensitivity of the contents [60]. Integrity of such edges and ordering between the nodes is referred to as *structural integrity*, whereas the integrity of the contents is referred to as *content integrity*. An authentication scheme for tree structures must thus preserve both content and structural integrity. An additional requirement for authentication of sensitive data is to maintain the confidentiality of the content and the structural information [134]. By

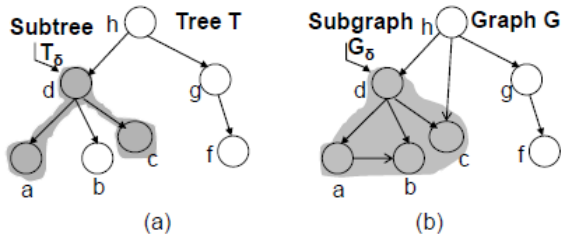


Figure 1.1. (a) Tree T and subtree T_δ. (b) Graph G and subgraph G_δ.

confidentiality, we mean that: (i) a user receives only those subtree(s) that the user is authorized to access, according to the stated access control policies, (ii) a user should not receive nor should be able to infer any information about the nodes and edges that the user is not authorized to access. Nodes and edges that are in a tree/graph but not in the subtree(s)/subgraph(s) that a user receives are referred to as *extraneous information*. Let us consider two application scenarios.

Healthcare: XML is the de-facto standard for specification of healthcare records. A doctor's system uploads an XML-based healthcare record to a third-party service, and a query from an end-user such as nurse would be processed by the third-party service. The query result may be one or more sub-documents in the XML document. In such a scenario, the user should be able to verify the authenticity of the query result, and due to privacy requirements (such as HIPAA [2] requirements), the user should not be able to infer any information about the remaining nodes (diseases/treatments) and edges (types of diseases) in the source XML healthcare record.

Finance: XML is used to specify financial information of individuals and financial accounts. When a user receives part of the financial document of another individual or enterprise, she should not be able to infer existence of any other nodes (bank accounts/credit cards/loans) and edges (types of accounts/cards/loans) in the source financial record.

Before we describe the problem, let us describe the third-party model informally. The formal security model is given elsewhere (Chapter 4).

Data

Trees, Graphs and Forests: A directed (rooted) tree $T(V, E)$ or a directed graph $G(V, E)$ is a data object, where V and E are the sets of vertices and edges in T. A node x represents an atomic unit of the data referred to as c_x. $e(x, w)$ represents a directed edge from x to node w. The fact that x precedes one of its siblings y in a DAG is denoted by $x \prec y$. A subtree $T_\delta(V_\delta, E_\delta)$ that is shared with a user as a result of a query on the tree $T(V, E)$ is a subtree $T_\delta(V_\delta, E_\delta) \subseteq T(V, E)$. Likewise, a subgraph $G_\delta(V_\delta, E_\delta) \subseteq$ graph $G(V, E)$. $\Upsilon(V, E)$ represents either a tree or a graph.

Third-Party Model

Authorized owner: Alice, the authorized owner of one or more data object(s) digitally signs each data object. The signature is referred to as $\sigma_{\Upsilon(V,E)}$, where $\Upsilon(V, E)$ denotes the data object. After signing Υ, *Alice* may delegate the job of publishing Υ or processing queries over Υ to one or more *third-party distributors* D (such as a cloud server).

Users: A user (also referred to as *Bob*) receives a subtree/subgraph/sub-forest from a third-party distributor and verifies its authenticity.

Third-party distributors: A third-party distributor D processes queries from a client/user *Bob* on the data objects, and sends the query result(s) to *Bob*. The data object that a user receives as a result of its query on a tree or a graph is a subtree or a subgraph, respectively. D also sends a signature σ_{Υ_δ} for Υ_δ so that the user can verify the authenticity of the Υ_δ.

Authorized owner is trusted. The third-party distributors are untrusted in the following sense: a distributor can carry out data tampering attacks, it maybe vulnerable to disasters or security compromises, and it does not have any signature authority on behalf of the authorized owner.

Threats

Throughout the dissertation, we assume a probabilistic polynomial time (PPT) adversary [61]. There are two types of threats.

1. *Data tampering attack*: by an adversary over the communication channel: main-in-the-middle attack or at the distributor. The adversary may tamper the content of one or more nodes, the structural order and/or the type of structural relation (edge) between two or more nodes of a tree/subtree.

2. *Inference attack*: A user, who receives Υ_δ that is a portion of the data object Υ, infers information (at least one bit of information) about $(\Upsilon \setminus \Upsilon_\delta)$ from the signature σ_Υ for Υ_δ that it receives from D.

In order to protect from data tampering attacks as well as inference attacks, we need to develop "leakage-free" data authentication schemes.

1.1 The Problem

The problem is how does *Alice* (the data owner) sign the data (a tree, a graph, or a forest) *once*, so that the authenticity of a subset of the data (subtree(s)/subgraph(s)/sub-forest(s)) can be verified without leaking any information about the remaining part of the data. A leakage-free signature scheme must make it possible for the receiver of one or more subtree(s)/subgraph(s)/sub-forest(s) in order to verify the authenticity of data with the following crucial requirement: the receiver should not be able to infer any extraneous information; extraneous information in a tree/graph/forest $\Upsilon(V, E)$ with respect to its subset $\Upsilon_\delta(V_\delta, E_\delta)$ comprises of $(\Upsilon \setminus \Upsilon_\delta)$ the nodes and edges that

are in Υ but not in Υ_δ (such as b, f, g and h, edges: $e(d,b)$, $e(h,d)$, $e(h,g)$, and $e(g,f)$ w.r.t. T_δ in Figure 1.1).

Consider the tree in Figure 1.1(a) and suppose that the user receives the subtree T_δ. The user should neither receive nor should be able to infer anything about the nodes b, f, g and h, and edges $e(d,b)$, $e(h,d)$, $e(h,g)$, and $e(g,f)$. In the case of graphs, another basic form of leakage is about immediate ancestors of a node. For example, assume that the user receives G_δ, subgraph of G in Figure 1.1(b). The user should not learn that node c has another immediate ancestor other than d (which is h), which is in G_δ. For nodes a, b and d, the user should not learn whether they have any other immediate ancestors in the graph.

The notion of redactable signatures and sanitizable signatures are used for authentication of subsets of a data object that is signed by an authorized owner. However, existing solutions (See Chapter 2) leak structural information; so does the widely used Merkle Hash Technique, which is used for authentication of trees and has also been extended for DAGs.

A Straightforward Scheme: A straightforward scheme for trees and graphs is to sign each node as well as each edge (Brzuska *et al.* [29] proposed such a scheme for trees). When a user has access to a subgraph (including a subtree), the signatures of the nodes and edges in the subgraph are also sent to the user. However, such a scheme has two major drawbacks: (1) If the graph has an ordering between the siblings, it would not be possible for the user to verify such ordering; (2) the total number of signatures computed and stored in the worst case is $O(n^2)$, where n is the number of nodes in the graph. This is because, a graph may have $O(n^2)$ number of edges. For a graph of even medium size such as one thousand nodes, about a million signatures need to be stored and managed by the distributor, which is quite large. For a tree, it would have $2n - 1$ signatures. The question is can we support (1) while using less number of signatures?

1.2 Contributions

Highlights of our contributions are as follows. As far as we know, this work is the first such work that addresses authentication of data (ordered trees and graphs) and the related leakage-free requirements in a holistic manner.

1. We have characterized several inference attacks that can be carried out on the widely used Merkle hash technique [87].

2. We have shown that leakages of structural information can lead to privacy and confidentiality breaches, in several scenarios such as in healthcare. We have demonstrated such leakages and breaches in the context of healthcare scenarios [84, 86].

3. Existing formal models in security do not cover the notion of leakage-free authentication of trees, graphs and forests. We have provided the first formal security model for leakage-free redactable signatures. Security notions of unforgeability, privacy and transparency have been formally defined as part of this model [81].

4. A signature scheme called as "structural signatures" based on the traversal numbers of a tree has been proposed that can be used to authenticate a subtree of a tree in a leakage-free manner. For this purpose, we have defined the notion of randomized traversal numbers [84]. Structural signatures scheme can be used for leakage-free authentication of induced subtrees.

5. Structural signature schemes for graphs – both directed acyclic graphs, and graphs with cycles, have been proposed that facilitate authentication of a subgraph in a leakage-free manner [86].

6. In order to facilitate the leakage-free authentication of multiple subtrees/subgraphs, the notion of secure names have been developed and a cryptographic construction has been presented [80].

7. Based on the secure names and an existing redactable signature scheme for sets, we have defined a highly efficient and generic leakage-free redactable signature scheme that can be used not only for trees, but also for graphs and forests. Our scheme compute only one signature for any tree/graph/forest, thus is an optimal leakage-free redactable signature scheme [81].

8. Our schemes for leakage-free authentication can also be used when for encrypted data, when nodes are encrypted.

9. We have shown how the structural signatures can be used to automatically recover from structural errors in tree-structured data. Such a scheme has applications in several scenarios such as satellite-based data transmission and sensors [87].

10. Our schemes can be used for leakage-free authentication of paths, and has applications in secure evaluation of XPath [6] queries.

11. As an application of the structural signatures, we have developed a publish/subscribe scheme for XML distribution called as "structure-based routing", which uses randomized traversal numbers not only for verification structural integrity, but also for efficient routing of contents [82, 83].

12. Objects are a primary model of data representation in object-oriented software, web services, and object-oriented databases. Serialized objects are stored and/or transmitted in environments that involves untrusted third-party entities. In such scenarios, leakage-free authentication of objects is an important security requirement. We have applied our signature schemes in this context, and have developed the first such scheme for this problem [85].

13. We have presented the security analysis, and performance analysis of the proposed signature schemes wherever it is required.

1.3 Dissertation Roadmap

Chapter 2 describes the related works. Inference attacks on the Merkle hash technique, and leakages of structural information in trees and graphs in a health-care context are described in the next chapter - Chapter 3. A formal security model for leakage-free redactable signatures with the notions of unforgeability, privacy and transparency, is presented in Chapter 4, which also describes the formal notion of secure names. Structural signatures for trees are described in the next chapter, and structural signatures for graphs are given in Chapter 6. Leakage-free redactable signatures for trees, graphs and forests are given in the next Chapter 7. An application of structural signatures: structure-based routing of XML documents in a publish/-subscribe model is given in Chapter 8, and a scheme for authentication of objects using the Merkle hash technique and our leakage-free scheme is given in Chapter 9. Chapter 10 summarizes the dissertation, describes some open problems and future research directions.

2 RELATED WORKS

An algorithm must be seen to be believed.
Donald E. Knuth [77]

2.1 Merkle Hash Technique

Merkle [99, 100] proposed a digital signature scheme based on a secure conventional encryption function over a hierarchy (tree) of document fragments. Since then, this technique has been used widely, but always with an authentication path of logarithmic size to verify even a single document fragment. It also leads to leakage of information (discussed in Section 3.1). Buldas and Laur [32] have also found that Merkle trees are binding (integrity-preserving) but *not* hiding (confidentiality-preserving).

The use of commutative hash operations (one-way accumulators [17, 65]) to compute the Merkle hash signature prevents leakage related to the ordering among the siblings. However it cannot prevent the leakage of signatures of a node and the structural relationships with its descendants or ancestors. Moreover, one-way accumulation is very expensive (due to modular exponentiation) in comparison to the one-way hash operation. By salting [76], the Merkle hash of each node is secured against the known-plaintext and known-ciphertext inference attacks. However, salting cannot prevent structural inference attacks completely even when coupled with one-way accumulators, because structural information would still be leaked. There have been several works [18, 73, 94] in order to optimize traversal of Merkle hash trees so that the auxiliary information required for authentication can be determined efficiently. Improved (more efficient) versions of MHT have also been proposed [31].

The MHT has been widely used for data authentication [19,53,54,68,92,113,124]. Bertino *et al.* [20] proposed a technique based on the Merkle hash technique for selective dissemination of XML data in a third party distribution framework. In [19], Bertino *et al.* have defined an authentication scheme using MHT for UDDI repositories towards building secure web services directories. Using techniques from incremental cryptography, Naor and Nissim [106] dynamize hash trees to support the insertion and deletion of elements. In their scheme, the source and the directory maintain identically implemented $2-3$ trees. Each leaf of such a $2-3$ tree stores an element of set, and each internal node stores a one-way hash of its children's values. Hence the source-to-directory communication is reduced to $O(1)$ items, but the directory-to-user communication remains at $O(logn)$. Thus, their solution is however not size oblivious. Martel *et al.* [98] proposed an authentication technique for data structures - directed acyclic graphs referred to as "Search DAGs" in third party distribution frameworks. However their technique uses Merkle hash technique [100], which leaks information during authentication [32, 82–84, 87]. Moreover the "Search DAGs" technique only covers DAGs, not the general directed graphs. For secure multicast, Perrig uses static data ordering over symmetric encryption [117]. Li *et al.* [92] propose a scheme for trustworthy verification (authentication) of write-only read-many data based on the MHT. Singh and Prabhakar [124] developed an authentication scheme for uncertain databases using MHT. Kocher [78] presented a scheme using Merkle hash technique for data distribution using third party models.

2.2 Authenticated data structures

Authenticated data structures (ADS's) have been used to verify the authenticity of data in a static as well as in the dynamic context. Goodrich and Tamassia [63] proposed authenticated dictionaries using skip lists and commutative hashing (one-way accumulators). Goodrich *et al.* [67] proposed techniques to authenticate graphs with specific path queries and geometric searching. Goodrich *et al.* [67] define a generalized

Merkle Hash tree for paths in graphs, and propose a mechanism for authenticating path queries in graphs. They leak structural information because their notion of "path hash accumulator" and their use of generalized merkle hash technique. Martel *et al.* also proposed Search DAGs [98] using the Merkle hash technique, which however leaks information. Papamanthou *et al.* [115] propose authenticated hash tables, where leakage-free property is not achieved, rather efficiency is of primary concern. Goodrich *et al.* [67] provides an excellent related works section on authenticated data structures and we refer interested readers to this paper. Atallah *et al.* [8] have developed a scheme for authentication of 2-dimensional data using only one aggregate signature. Atallah *et al.* [9] developed schemes for covering a tree with minimum number of paths such that the total number of nodes in all the paths is minimized. Such a scheme has applications in verification of integrity of trees and paths. However, it is not obvious on how to develop a leakage-free authentication scheme for trees or paths using such solutions.

2.3 Transitive Signatures

Transitive signatures were originally conceptualized by Rivest in his seminal talk in 2001 [119], and a concrete scheme for undirected graphs were developed by Micali and Rivest [102]. In such signature schemes, the objective is to use the signatures of two or more messages and compute the signature of the messages that is derived from these messages. For example, in a binary tree (in a network route topology), given the signature of two child nodes (routers), the objective is to compute the signature of their parent node (router) [42].

The notion of transitive signatures by Micali and Rivest [102] helps computing a graph in a dynamic manner from authenticated nodes and edges so that the graph built at any point of time is an authenticated one. There are a number of interesting works on directed trees and their transitive signatures. However, they leak information about the history of the transitive signature - from the paths it has been

computed [14, 15, 108, 135, 136]. By history independence, it means that verification of a transitive signature for (i, k) would not leak information about node j and/or its signature. The latest paper by Xu [135] use the notion of RGGMs developed for redactable signatures by Chang *et al.* [41] in order to develop transitive signatures on a path, where it is history independent. However, it uses RGGM trees and thus are quite expensive: for a given path, it computes one RGGM tree.

2.4 Redactable Signatures

Redactable signature schemes (e.g., [74]) inspired by transitive signatures support computation of valid signatures for modified messages from the signatures of the source messages. Anyone with the knowledge of a message, its signature and the associated public key can compute a signature of a redacted message. (In contrast, in case of sanitizable signatures, only a designated sanitizer can compute such a signature.) However, such schemes have been developed only for documents that are linear sequences of sub-documents, and leak structural information. On exception is the redactable signature scheme for sets by Johnson *et al.* [74]. They use RSA-based one-way accumulators and compute a single signature for any set, which allows anyone to computed the signature of the subset without leaking any information about the remaining elements. In this dissertation, we have developed leakage-free redactable signatures for non-linear and complex data objects such as trees and graphs.

Formalization of our work: Brzuska *et al.* [29] extended our work [84] and attempted to formalize the notion of structural signatures for trees. However, their formal model is quite restrictive: does not support query results to be disconnected subtrees, and do not address graphs and forests. Moreover, its definition of integrity is flawed: it claims to support security as strong as "existentially unforgeable under adaptive chosen message attack", which however cannot be supported by redactable signatures as shown by Johnson *et al.* [74]. Moreover, their construction is quite expensive: computes a linear number of signatures for the tree, and for authenticating

the ordering among sibling, computes a quadric number of signatures. An open problem Brzuska *et al.* pose is to find a more efficient solution for trees, which we solve in this dissertation.

Content Extraction Signatures Steinfeld [126] proposed content extraction signatures in which they use RSA homomorphic property to build a redactable signature on documents: the messages are deleted but the *structural position is leaked*. This scheme is a form of redactable signatures. Bull *et al.* [33] proposed content extraction signatures for XML documents, which however, leaks structural information.

2.5 Sanitizable Signatures

: There are two types of sanitization of documents, where a document is a collection of several messages/sub-documents: one that allows modification of messages in a document (e.g., [10], [30]), and another that allows only deletion of the messages [103]. Such signature schemes focus on hiding only the messages being sanitized, but not their structural position in the document and the structural relationships they have with other messages. Brzuska *et al.* [30] propose a notion of "unlinkability" between sanitized documents. Unlinkability means that the hidden/sanitized messages in a sanitized version cannot be recovered even with the knowledge of two or more sanitized versions of the same document. On the other hand, our notion of "leakage-free" signatures focus on hiding not only contents (nodes as messages) but also structure of the original document. Moreover, some of these schemes have a designated entity called "sanitizers". Leakage-free signatures are redactable in nature: applicable to a more relaxed notion of security models that involve untrusted third-parties. Haber *et al.* [68] proposed a signature scheme that allows redaction, and pseudonymization of parts of data (messages/sub-documents), as well as controls redaction of a document by prohibiting it. It does not leak information about messages that have been redacted/pseudonymized, however it leaks information about the existence of such

messages and their structural positions. Hiding not only the messages but also the structural information is the purpose of our leakage-free signature scheme.

2.6 Commitment Schemes

Commitment schemes [116] are not signature schemes. Let c is a commitment of value m; c is not a signature of m, because (1) m remains hidden until c is opened; (2) c can be forged easily as everyone knows the public key being used to compute c from m; (3) in order to verify the so called "signature" c of m, the signer has to release its private key, which is not a case in digital signatures. Set commitment schemes prove that an element is in fact an element of a set in a zero knowledge manner [101]. In commitment schemes, an important issue is who generates the commitment key pair `(pk, sk)`: is it the sender (who commits), the recipient (who receives) or a trusted third party. There are solutions using trusted third party. But in our setting in the dissertation, third party is not "trusted". The primary objective is hiding, and then proving, whereas in a signature scheme, the primary objective is proving.

2.7 Proxy Signatures

There have been several works on proxy signatures (e.g., [27, 88, 97]), where the data owner delegates the signing of a data object to a proxy, who computes a proxy signature of the data. A verifier uses the public key of the proxy and validates the data against the proxy signature. Such a model is similar but different from the third-party model that is being used in this work. One can assign a proxy key pair to each third party server, who would sign each subtree/subgraph that is the result of the graph (that it has not signed earlier). However, the proxy in the signature may not be trusted but not malicious as the third-party servers in our model are assumed to be. Moreover, signing each subtree/subgraph as a query result on behalf of the data owner dynamically exposes the server to side channel attacks, key recovery attacks as well as denial of service attacks.

2.8 Zero-Knowledge Sets and Membership Queries

ZKS (Zero-Knowledge Sets) have been proposed by Micali, Rabin and Killian [101], later extended by [40]. The setting of ZKS has a prover and a verifier engaging in non-interactive zero-knowledge proofs about membership of a value in a set. The prover commits a set, and then generates proof for an element without revealing anything about the other elements, even the size of the set. Such a scheme comes quite close to what we want to achieve, but there are several differences: (1) the setting is different: in our case, the data owner needs to sign a tree/graph and give it to an untrusted server(s), who then evaluate queries from users. (2) the user needs proofs of subtree/subgraph relationships instead of a set membership. (3) we need a digital signature instead of a commitment scheme. (4) In our case, the untrusted server should be able to compute a proof for the subtree/subgraph the user receives using the digital signature computed by the owner, and should not be able to forge such proofs.

Membership queries and associated proofs of their answers have been studied by [101]. Ostrovsky *et al.* [111] proposed a consistency proof for membership queries in a database that also protects privacy. In their model, a database is a set of key-value pairs. Privacy means that the user can only know the answer it receives and it cannot learn any other information about the other key-value pairs in the database. However, they cannot hide the size of the database ([111]: Page: 7). Our leakage-free signatures achieve this: hiding the size of a tree/graph or a database of trees/graphs. They also use a notion of "explicit hashing" which is constructed such that the user always learns that the same number of paths irrespective of the query it issues. It is achieved by issuing dummy pre-images. Moreover, their protocol is used for membership queries in sets and range queries. It is not trivial as how to apply their scheme to solve the problem for trees and graphs. Moreover, their scheme is a commitment scheme, which is different from digital signature schemes.

2.9 Hashing and Accumulation Schemes

Merkle-Damgard [50, 99] (MD) model of hash functions (conceptually modeled as random oracles [16]) is widely used in designing modern hash functions such as SHA1 and MD5. Their proposal is to divide an arbitrary length message into blocks of identical size k (pad the last block if necessary), and apply a compression function such as a block cipher on the blocks sequentially with the output of the compression of block b_i given as an input to the compression of the next block b_{i+1}. At the end, a finalization stage that appends bits and information related to the size of the entire message to the output compression of the last block b_n. Coron *et al.* [46] define a new security notion for random oracles and the hash functions defined thereof: for a hash function $\mathcal{H}$ to behave as a random oracle, the underlying fixed-size block cipher must behave as a random oracle as well. Such a property is stronger than the standard collision resistant property of hash functions. Coron *et al.* show that the MD model does not satisfy this property of hash function. Dodis *et al.* [56] show that a pre-image attack can be carried out on MD-hash functions by knowing the padding used. They propose a methodology for how to strengthen the one-way compression function in order to prevent such attacks.

Accumulators: Exponential accumulators have been proposed by Benaloh and Mare‘ [17]. The core scheme works as follows: a seed y_0 is used such that $y_0 > 1$, y_0 and N are relatively prime, $N = pq$, as in RSA. Accumulator $\mathcal{H}(y_0, x_1) = y_0^{x_1} \ mod \ N$; $\mathcal{H}(y_{i-1}, x_i) = (y_{i-1})^{x_i} \ mod \ N$. It is commutative, but not associative [63]. So incremental computations are not feasible. It is important for its implementation that the seed y_0 of the accumulator should be relatively prime to the RSA primes p, and q [121]. This work has been improved by Baric and Pfitzmann [13] with efficient constructions using strong RSA assumptions. Baric and Pfitzmann developed two RSA-based accumulators: one without random oracles, and the other one using random oracles and they prove that they are collision-resistant assuming that the RSA is

an one-way function. They also proposed fail-stop signature schemes based on the accumulators. The public keys are accumulated and the messages are also accumulated, if there are more than one message. However, the update operations on such accumulators were not size-oblivious (size of the set being accumulated). Camenisch and Lysyanskaya [34] made the update operations size-oblivious. Li *et al.* [90] built upon this work and developed accumulators using which non-membership can be proven efficiently, and memberships can be revoked in anonymous manner.

2.10 Traversal numbers

Traversal numbers have been used for querying and navigation of XML data by Zezula *et al.* [137]. However, they do not address any security issues. Wang *et al.* [134] have used a notion similar to traversal numbers in defining the structural index in XML databases in order to be able to locate encryption blocks as well as their unencrypted data nodes that satisfy user query. They use real intervals $[0, 1]$ for root and every child of the root is assigned a sub-interval such as $[0.5, 0.6]$. The first entry in the interval can be assumed to be referring to the pre-order number and the second one to the post-order number. However, they do not derive such an interval from traversal numbers nor do they use traversal numbers for signing trees. None of the previous approaches propose the use of randomized traversal numbers for the signature of trees. As such, the previous approaches do not include security analysis, performance evaluations nor detailed comparison with the MHT and other secure data publishing techniques derived from the MHT.

2.11 RSA Signatures

The Condensed-RSA signature scheme by Mykletun *et al.* [105] is an aggregate signature scheme. They compare Condensed-RSA and the aggregate signature scheme by Boneh *et al.* [28] in order to efficiently authenticate outsourced databases. Condensed-RSA is secure as against another similar signature scheme: Batch-RSA.

Batch verification of RSA signatures were first proposed by Harn [70] and was thought to support secure signature aggregation. However, such a scheme is insecure (Hwang *et al.* [72] first showed a forgery attack). Later in another paper [71] Hwang *et al.* proposed a new scheme overcoming the weakness of Harn's scheme. However, Bao *et al.* [12] have shown that even this scheme is not secure. The scheme proposed in [12] has also not been proven to be secure. The Condensed-RSA signature scheme is secure under the RSA assumption, because the user does not receive individual signatures [105]. The aggregate signature scheme by Boneh *et al.* [28] is based on elliptic curves and bilinear maps, and is proven to be secure.

2.12 Privacy-preserving Authentication of Query Results

Confidentiality and authenticity are important requirements in secure data management and publishing [22, 25]. Some of the other notable authentication schemes in the literature are by Li *et al.* [89], Mouratidis *et al.* [104], Pang and Mouratidis [113], and by Pang and Tan [114]. The authentication scheme for completeness of query results proposed by Pang *et al.* [112] leaks even in the simple case of "greater than" predicates. In their scheme, if a_3, a_4, and a_5 satisfy a the "greater than" predicate among elements $a_1, a_2, \ldots, a_{10}$, then the user uses auxiliary information *about* a_2 and of a_6 in order to authenticate the results; such extra information leads to leakage about the existence and structural position of these two elements in the data object, which as we have seen earlier could be sensitive information or could lead to inference of sensitive information. Mykletun *et al.* [105] use aggregation of signatures for efficient authentication of tuples in outsourced databases. Ma *et al.* [96] proposes an approach using Merkle hash technique and aggregate signatures [28, 105] in order to authenticate query results in databases. It computes an attr-MHT for each tuple and signs the Merkle hash for the tuple; signatures of the tuples are aggregated to compute the signature of the whole table. However, this scheme leaks: consider the case in which a querier does not receive all (possibly some of these are sensitive at-

tributes), but receives only some attributes of a tuple in the result set. Narasimha and Tsudik [107] proposed another scheme for authenticated database outsourcing. However, this solution computes a signature for each tuple: a hash $\mathcal{H}$ is signed where $\mathcal{H}$ is the hash of the concatenation of the hash of the tuple and hash of each its immediate preceding tuple in each searchable dimension. Clearly this scheme also leaks: consider the case when a querier has access to only on tuple, but it receives auxiliary information and learns about other tuples. Even though each of these techniques provides authenticity, yet they leak. Moreover, none of these works address the problem of authentication of tree structures.

The PADS framework by Thompson *et al.* [128] uses Pedersen's homomorphic commitment scheme [116], Shamir's k-out-of-n secret sharing scheme [123] and Merkle hash technique in order to prevent leakage of micro-data (value of an attribute) while (1) carrying out aggregate query evaluation at multiple third-party servers (in a privacy-preserving manner) and (2) supporting authentication of query results by the client. However, the PADS scheme leaks information about the size of the table and about the existence and positions of other attributes in the table that are not part of the query evaluation. Pang *et al.* [112] propose completeness verification and authentication of data without revealing micro-data, however, they still leak structural information.

Chatvichienchai and Iwaihara [43] proposed mechanisms for secure updates of XML, without leading to information leakages. However such mechanism does not address the problem of information leakages during verification of integrity of partial XML documents. Wang *et al.* [134] treat structure and content as first-class protection units. However they focus on a sharing model, in which the receiver of the data has access to only the content (nodes) and *not* to the structural relationship between them. The paper proposed a scheme for securing structural information in XML databases: how to process queries on an encrypted XML database such that individual element content and structural relations are kept confidential if the security constraint

specified requires so. In our case, we allow the receiver to have access to both nodes and the structural relationships between them.

Graphs are commonly used to model relationships between data items such as documents such as text, XML, richtext, images [58], geographic information [118], healthcare and biological data [57]. Querying, management [44, 57, 129] and mining [59, 122] of graph-structured data as well as privacy-preserving graph publishing and mining techniques [95, 139] have recently emerged as important topics in both academia and industry.

2.13 Secure Publish/Subscribe

The main research efforts related with our work are in the area of secure dissemination of XML data and in the area of secure publish-subscribe systems.

In the first area, the only approach supporting access control in both pull and push based distribution of data has been proposed by Bertino and Ferrari [21]. Such an approach relies on encrypting different portions of the data with different keys and then distributing the keys to data consumers according to the access control policies. Bertino *et al.* [20] have also investigated the problem of integrity of XML data by using the notion of Merkle hash. Those approaches have however some major drawbacks in that they are not scalable and do not remove extraneous data from contents. These drawbacks are fully addressed by the approach proposed in this paper.

In the second area, several approaches have been proposed to address efficiency issues concerning pub/sub systems ([37–39, 47–49, 52, 110]). Several highly efficient publish/subscribe systems (e.g., IBM Gryphon [127], JMS-based systems) have been developed. Multicast-based content dissemination [11, 109] techniques have been developed in order to support efficient dissemination of contents to subscribers. Most approaches (e.g., [38, 48, 49]) use a spanning tree structure for event routing. In order to reduce the matching that has to be performed by brokers from the root to the leaves, several optimization techniques have been proposed. Virtual groups are

used to reduce the matching performed by brokers [138]. However, security issues in content-based pub/sub systems have not been investigated. The only exceptions are the approaches by Srivatsa and Liu [125], that focuses only on resiliency, and by Opyrchal and Prakash [110], which is very inefficient and is not flexible with respect to access control policies. By contrast our approach addresses a larger spectrum of security requirements while being at the same time efficient and scalable.

3 STRUCTURAL LEAKAGES AND PRIVACY

Not all bits have equal values.
CARL SAGAN [120]

Structural information is leaked when existing data authentication schemes such as Merkle hash technique is used. Most existing works are not designed to protect such information with the assumption that structural information does not lead to any privacy/confidentiality breaches. In this chapter, we have demonstrated the relationship between privacy and structural leakages in the healthcare context. We have also described the possible inference attacks on Merkle Hash Technique, which is widely used for authentication of tree-structured, and graph-structured data.

3.1 Inference Attacks on Merkle Hash Technique

In the MHT, a tree is signed by signing the Merkle hash (MH) of its root, which is computed as described below. Common notations are defined in Table 1. In what follows, $\|$ denotes concatenation.

The MHT works bottom-up. For a node x in tree $T(V, E)$, it computes a MH $mh(x)$ as follows: if x is a leaf node, then $mh(x) \leftarrow \mathcal{H}(c_x)$; else $mh(x) \leftarrow \mathcal{H}(mh(y_1) \| \ldots \| mh(y_m))$, where $y_1, \ldots, y_m$ are the m children of x in T in that order from left to right. For example, the MH of the tree in Figure 3.1(a) is computed as follows. The MHes of e and f are: $\mathcal{H}(c_e)$ and $\mathcal{H}(c_f)$, respectively, which are then used to compute the MH of d as $mh(d) \leftarrow \mathcal{H}(mh(e) \| mh(f))$. The MH of b is $\mathcal{H}(mh(d))$. Similarly, the MHes of c and a are computed as $\mathcal{H}(c_c)$ and $\mathcal{H}(mh(b) \| mh(c))$, respectively.

By using such a technique, only the contents of the leaf nodes can be authenticated. In case, the non-leaf (root/intermediate) nodes have contents, the computation of the

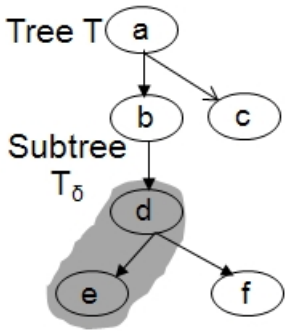


Figure 3.1. An example tree with each node having some content.

MH of a non-leaf node x involves the MH of all of its children, and either (a) the content of x, or (b) hash of the content of x (used for Figure 3.1(a)).

3.1.1 Leakages during Authentication using MHT

Let T_δ be a subtree of tree T to be shared with *Bob*. *Bob* needs the following *auxiliary information* for authentication of T_δ. Such auxiliary information constitute the information leakages by MHT (Figure 3.1). The user then computes the MH of the whole tree using such information (the subtree and auxiliary information) and verifies the signature of the original tree using this MH.

1. Let x be a node in T_δ. The MH of each sibling of x that is in T but not in T_δ. (e.g., $mh(f)$ w.r.t. e.)

2. The MH of each sibling y of each ancestor of x, such that y is not in T_δ. (E.g., $mh(c)$ and $mh(f)$ w.r.t. e.)

3. The hash of the content of each ancestor of x. (e.g., $\mathcal{H}(c_a)$ and $\mathcal{H}(c_b)$ with respect to x.)

4. (i) The structural order between x and its those sibling(s) that are not in T_δ, and (ii) the structural order between those siblings of x that are not in T_δ. (e.g., (i) the order between e and f, and (ii) the order between b and c.)

5. (i) The parent-child/ancestor-descendant relationship(s) between a node in T_δ and another node not in T_δ, and (ii) those between the nodes that are not in T_δ. (e.g., the relationships (i) between b and d, (ii) between a and b, and between a and c).

6. The fact that a given node is the root of the tree T (even if it is the root of T_δ).

3.1.2 Inference Attacks

The attacks on the MHT are based on the set of *auxiliary information* sent to the user. By exploiting these leakages, the following inference attacks can be carried out on MHT.

- *Dictionary attack-1*: It exploits the information (1), (2), (3), and (6). By comparing the MH of a node e in the shared subtree with the MH of another node f received as part of the auxiliary information, the user can infer whether contents of e is same as that of f and if the subtree with root e is identical to the subtree with root f. With the auxiliary information (6), the user can also infer (a) whether the received subtree is in fact the original tree, and (b) whether the root of received subtree is in fact the root of the tree.

- *Dictionary attack-2*: It exploits the information (1), (2), (3), and (6). By comparing the Merkle hashes of two nodes (c and f) that are received as part of the auxiliary information, the user can infer whether the contents of c is same as that of f and whether the subtree with root c is identical to the subtree with root f. With the auxiliary information (6), the user can also infer whether the received subtree is in fact the original tree.

- *Structural inference attack*: It exploits the information (1), (2), (3), and (5). The user infers the number of nodes that are not in the received subtree, and the structure of the original tree from the auxiliary information and shared subtree. If the user receives non-empty auxiliary information, then it infers

that the shared subtree is a proper subtree of the original tree and there are nodes it has not received. In some cases, the user can also infer the exact size of the original tree (such as in the case of our example in Figure 3.1).

- *Missing-siblings inference attack*: It exploits the information (1) and (2). From the auxiliary information, the user infers the number of siblings of a received node e that are not in the shared subtree. If the shared subtree has x and y as siblings, the user also infers the number of siblings that are not in the shared subtree but are to the right of x and to the left of y in the original tree.

- *Structural-order inference attack*: It exploits the information (4) and (5). The user infers structural order between siblings involving one or more nodes that the user does not have access to. In our example, the user learns that b and e are left siblings of c and f, respectively.

- *Parent-child inference attack*: It exploits the information (4) and (5). The user infers the parent-child relationships involving one or more nodes that the user does not have access to. In our example, the user learns that b and d are the parents of e and f, respectively. The user also learns that b is an ancestor of e and f.

The MHT requires certain auxiliary information about the contents and/or the structure of the signed tree in order to authenticate a subtree. This inherent requirement leads to leakages and cannot be completely prevented by the use of salting, or of one-way accumulators. In the next section, we give examples in order to illustrate the significance of such leakages and related inference attacks.

3.2 Structural Leakages in Tree-structured Data

Our running example is in the area of XML data management. XML organizes data according to the tree structure; integrity and confidentiality of XML data is an important requirement, given the widespread adoption of XML for distributed

```
<HealthRecord>
    ...
    <PatientID id=2345S> ... </PatientID>
    <Contact> ... </Contact>
    <CriticalDiseases>
        <Disease name=Cancer>
            <Surgery> ... </Surgery>
            <Chemotherapy>
                <Treatment instance=1>
                    <Doctor name=Dr. S. Stevens/>
                    <DateTime date=...time=.../>
                </Treatment>
                <Treatment instance=2>
                    <Doctor name=Dr. M. Paul/>
                    <DateTime date=...time=.../>
                </Treatment>
            </Chemotherapy>
            <Medication> ... </Medication>
        </Disease>
        <Disease name=KidneyFailure> ... </Disease>
    </CriticalDiseases>
    ...
</HealthRecord>
```

Figure 3.2. XML-based Health-care record of a patient.

web-based applications. As such, XML is an important application domain for the techniques presented in the paper.

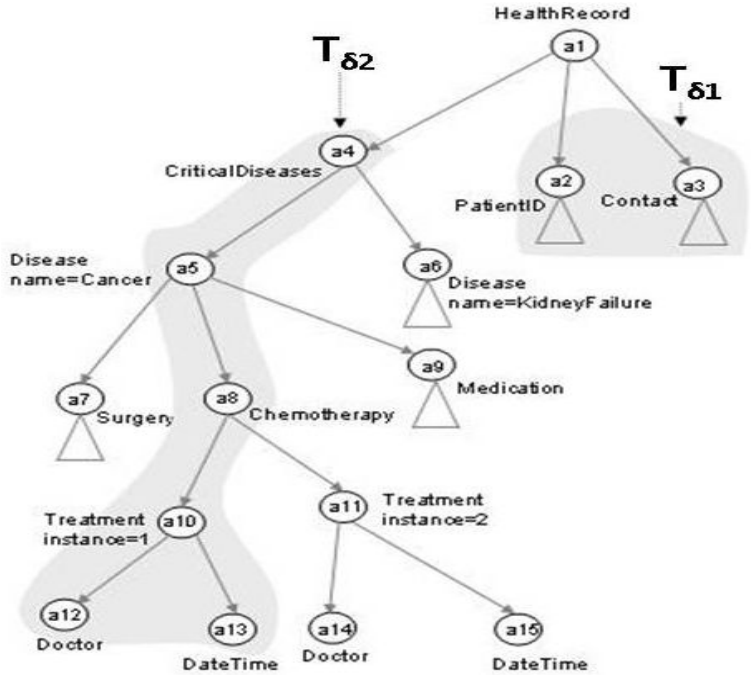


Figure 3.3. The tree representation of the HealthRecord in Figure 3.2.

The XML document in Figure 3.2 is a fictitious health-care record of a patient and thus contains sensitive information. Assume that such record is stored in a hospital database and that its schema, referred to as *HealthRecord*, is defined as follows. The *HealthRecord* element, that is, the root of the tree has a child for each of the following elements: *CriticalDiseases*, *PatientID*, and *Contact*. The *CriticalDiseases* element lists all the critical diseases a patient suffers from; information about a specific critical disease is specified as its child by the element *Disease*. Each *Disease* element lists the types of treatment that the patient has gone through for that same disease. For *Cancer*, the types of treatment are specified by the following elements: *Surgery*, *Chemotherapy*, and *Medication*. Each type of administered treatment is specified as a child node of the node specific to the treatment type and is an instance of *Treatment* element. It contains an attribute *instance*, which refers to the specific instance of the treatment, and child elements to specify the date and time of administering (*DateTime*), and the name of the doctor who administered the treatment (*Doctor*).

Table 3.1
Leakage during authentication of $T_{\delta 2}$ using MHT

Node x	*Nodes whose MH used in this order to compute* $MH(x)$	*Distinct leakages during computation of* $MH(x)$
a_{13}	a_{13}	none
a_{12}	a_{12}	none
a_{10}	a_{12}, a_{13}, a_{10}	none
a_8	a_{10}, a_{11}, a_8	hash of a_{11}, a_{11} is sibling of a_{10}, a_{11} is child of a_8 , a_{11} is to the right of a_{10}
a_5	a_7, a_8, a_9, a_5	a_7-*specific leakage*: hash of a_7, a_7 is sibling of a_8, a_7 is child of a_5, a_7 is to the left of a_8; a_9-*specific leakage*: hash of a_9, a_9 is sibling of a_8, a_9 is child of a_5, a_9 is to the right of a_8
a_4	a_5, a_6, a_4	hash of a_6 a_6 is sibling of a_5, a_6 is child of a_4, a_6 is to the right of a_5

A patient may have received treatments from different doctors, each related to a different instance of the same type of treatment or instance of a different type of

Table 3.2
Inference of sensitive information from leakages (Continued to Table 3.3)

Leakage during computation of $MH(x)$	*Inference from the leakage in the health-care context*
a_8: hash of a_{11} `AND` (a_{11} is sibling of a_{10} `OR` a_{11} is child of a_8)	Patient has gone through another Chemotherapy.
a_8: a_{11} as to the right of a_{10}	If sibling-order represents certain information such as temporal order, then it can be inferred if the chemotherapy referred to by node a_{11} was administered earlier or later than the one referred to by a_{10}.
a_5: hash of a_7 `AND` (a_7 is sibling of a_8 `OR` a_7 is child of a_5)	Patient has gone through another type of treatment; also inferred is: it is either Surgery or Medication.
a_5: a_7 is to the left of a_8	More leakage related to the order such as temporal order.
a_5: hash of a_9 `AND` (a_9 is sibling of a_8 `OR` a_9 is child of a_5)	Patient has gone through another type of treatment; also inferred is: it is either Surgery or Medication.
a_5: a_9 is to the right of a_8	More leakage related to the order such as temporal order.

treatment. For expository purposes, we associate a label with each node in the health record in Figure 3.3; for example, the node *Chemotherapy* is labeled by a_8.

Table 3.3
Inference of sensitive information from leakages (Continued from Table 3.2)

Leakage during computation of $MH(x)$	*Inference from the leakage in the health-care context*
a_4: hash of a_6 `AND` (a_6 is sibling of a_5 `OR` a_6 is child of a_4)	Patient suffers from another critical disease, whose type can be inferred from the hospital specialization.
a_4: a_6 is to the right of a_5	More leakage related to the order such as temporal order: time of treatment of this disease in this hospital relative to the time of treatment of Cancer.

The hospital database, which can be accessed remotely, stores all such patient health records. The Merkle hash technique is used to sign the tree and support authentication of the data by users. Table 3.1 lists the details about how to compute and verify the Merkle hash for each node in the tree in Figure 3.3. The third column of such table also lists the information which is leaked when the integrity of a node is verified. Table 3.2 lists the inference attacks that can be carried out due to the leakages.

Consider the following scenario. A cashier has access to the subtree $T_{\delta 1}$, shown in Figure 3.3, including the root a_1, that is essential for financial and administrative purposes. She does not have access to a_4 and its content that refers to *CriticalDiseases*. An access to the health-record in Figure 3.2 leads to the integrity verification of this portion of the health record at the side of the cashier. During this process, the cashier receives the Merkle hash of a node a_4 and she also receives the following information: a_4 is a child of a_1 and is on the left side of a_2 and a_3. By knowledge of

the schema, the cashier determines that a node at such position must be the *CriticalDiseases* node. Thus the cashier infers that the patient is definitely suffering from some critical disease. If the hospital specializes in some specific critical disease(s), the cashier can further infer which (possible) disease the patient is suffering from. Each of these inferences leads to disclosure of information that is sensitive for the patient.

We now consider another scenario, which leads to leakage of more detailed sensitive information. A nurse has access to $T_{\delta 2}$ and a_1 from the record in Figure 3.2. He has access to $T_{\delta 2}$, because he works with the doctor *S. Stevenson*, who prescribed the administering of this treatment. The nurse receives $T_{\delta 2}$ and a_1, and the corresponding hashes from the remote database. In order to be able to verify the integrity of $T_{\delta 2}$, he also receives the hashes of a_6, a_7, a_9 and a_{11}.

The schema of *HealthRecord* specifies that a child of *CriticalDiseases* refers to a critical disease from which a patient suffers from. By receiving the hash for a_6, which is a child of the node a_4 (element *CriticalDiseases*), the nurse infers that the patient is suffering from another critical disease different from cancer. This is a disclosure of private information, to which the nurse does not have access to. Assume that the hospital of our example specializes on the treatment of only a limited number of critical diseases. It is thus easy to infer what the other disease is. Furthermore, by inferring that a_8 has two siblings, that is, a_7 and a_9, the nurse is able to infer that the patient has gone through two other treatments other than chemotherapy. Such inference may easily lead to determine the seriousness of the illness. In addition, from the schema, the nurse can infer that these nodes refer to *Surgery* and *Medication*, which reveals that the patient has been received either or both of these treatments. If the hospital has two doctors who specialize in *Surgery* or *Medication*, then the knowledge that the patient has been treated with *Surgery* or *Medication* leads to more information, such as that he has been treated by more than one doctors and who (possibly) has been his doctor.

Furthermore, by the disclosure of the hash of node a_{11} and its structural relationship with a_8 as its child, and by knowing that children of a *Chemotherapy* element refer

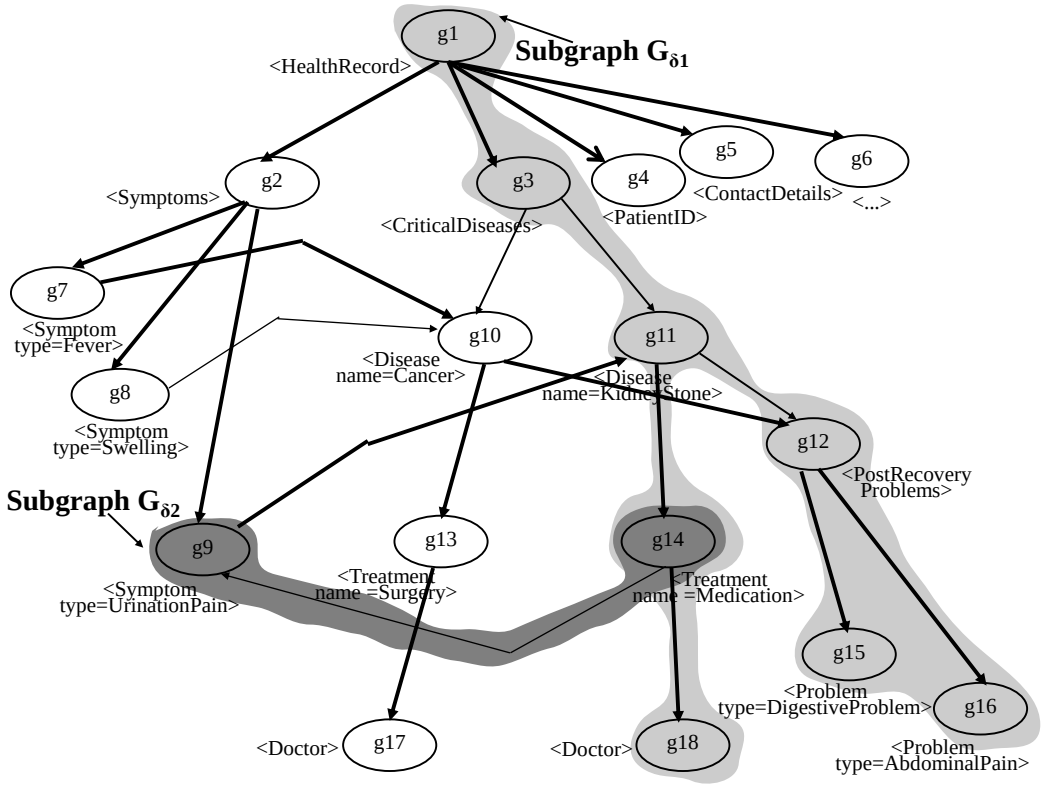


Figure 3.4. A health-record graph; tree-edges in bold.

to the treatment instances, the nurse is sure that the patient went through another Chemotherapy treatment and possibly with another doctor. Additional knowledge about doctors and the hospital could lead to more leakage.

3.3 Structural Leakages in Graph-structured Data

The "IDREF" attribute or a user-defined attribute in XML is used to refer to another element (node) in an XML document, which leads to a non-tree edge (either a back-edge, cross-edge, or a forward-edge). The data object in Figure 3.4 is a graph-based representation of XML-based health-care record of a patient, which typically contains sensitive information. The XML schema elements are described in Table 3.4. The hospital database, which can be accessed remotely, stores all such patient health records.

Table 3.4
XML elements for the healthcare records

Element	*Semantics*
HealthRecord	Root of the XML document
Symptoms	Lists the symptoms of a patient
CriticalDiseases	Critical diseases the patient suffers/suffered from.
Symptom	Specifies a symptom. Attributes. *type* refers to the type a symptom. *idref* refers to the related disease.
Disease	Information about a specific critical disease; Attributes: *idref* refers to PostRecoveryProblems.
Treatment	Type of treatment administered on the patient. Attributes: *name* specifies the treatment. *idref* refers to the symptom that a medication may affect.
Doctor	Name of the doctor who administered the treatment.
PostRecovery-Problems	Post-recovery problems that a patient goes through. The node is created only once for the first recovery. For any later disease and recoveries from it, this node is referred to from that Disease node.
Problem	A post-recovery problem. Attribute: *type* specifies the type of the problem.
PatientID	Identifier of the patient. Attributes: *id* and *name*
ContactDetails	Contact details of the patient.

Consider the following scenario. An insurance manager handling the insurance claim specifically towards the treatment of the disease *KidneyStone* has access to

Table 3.5
Leakage via cross-edge $e(g_{11}, g_{12})$, subgraph: $G_{\delta 1}$.

Distinct leakages	*Related sensitive information leaked*
In-degree of $g_{12} \geq 2$	The patient has suffered from at least one more disease.
There is at least one more path from the node *CriticalDiseases* to g_{12}	(1) This disease is a critical disease. (2) The patient has already recovered from this disease.
The graph is larger than $G_{\delta 1}$	(1) The patient has been treated by another doctor. (2) She has been associated with this hospital earlier. (3) HealthRecord contains more disease-related data.

subgraph $G_{\delta 1}$. As a result of querying the database, the manager receives $G_{\delta 1}$ and a set of authenticity verification items. This portion includes the nodes g_1, g_3, g_{11}, g_{12}, g_{14}, g_{15}, g_{16} and g_{18}. One of the cross-edges received is $(e(g_{11}, g_{12}))$. By knowing that $e(g_{11}, g_{12})$ is a cross-edge, the manager also learns that there is a tree-edge (to which the manager has no access) to the node representing *PostRecoveryProblems*, which implies that the patient has also suffered from another disease.

By knowledge of the schema, the insurance manager determines that an edge to such a node must be from a Disease node, which is a child of the *CriticalDiseases* node. Thus the manager infers that the patient is definitely suffering from some other critical disease. If the hospital specializes in some specific critical disease(s), which is mostly the case in reality, the manager can further infer which (possible) disease the patient is suffering from. Moreover, the manager can definitely infer that

Table 3.6
Leakage via back-edge $e(g_{14}, g_9)$, subgraph: $G_{\delta 2}$.

Distinct leakages	*Related sensitive information leaked*
(a) There is at least one cycle in the graph; (b) so there is at least one path from g_9 to g_{14}	(1) Symptom *UrinationPain* led to a disease, which is being treated with medication. (2) Since the treatment is medication, with high probability, this disease is not in a serious stage.
The graph is larger than $G_{\delta 2}$	HealthRecord contains more disease-related data.

such a disease was cured (and thus diagnosed) before the *KidneyStone* disease; this is because the node of *PostRecoveryProblems* already exists. Each of these inferences leads to disclosure of information that is sensitive for the patient. Leakages inferred from the knowledge that $e(g_{11}, g_{12})$ is a cross-edge are listed in Table 3.5.

We now consider another scenario, which also leads to leakage of some sensitive information by the knowledge that an edge is a back-edge. A pharmacist has access to $G_{\delta 2}$ from the record in Figure 3.4. She has access to $G_{\delta 2}$, because she provides this medication (specified by node g_{14}) to the patient. The pharmacist receives $G_{\delta 2}$ and the corresponding verification items from the remote database to verify authenticity. If she somehow learns that the $e(g_{14}, g_9)$ is a back-edge from the received information, she would learn that there is a path from g_9 to g_{14} in the health-record. The schema of *HealthRecord* specifies that a symptom node is related to a critical disease from which a patient suffers from, that is there is an edge from the symptom node to a disease node. The disease node further has an edge to the *Medication* node. The only path that can exist from g_9 to g_{14} is through a disease node. It is thus apparent

that the patient suffers from a critical disease related to the symptom *UrinationPain*. The symptom name further leads to the possible name of the disease. If the hospital specializes in a limited number of critical diseases, the pharmacist can determine the name of the disease. The treatment type may easily lead to determine the seriousness of the illness (Table 3.6).

4 FORMAL MODEL OF LEAKAGE-FREE REDACTABLE SIGNATURES

One of the greatest lessons I have learnt in my life
is to pay as much attention to the means of work as to its end.
Swami Vivekananda (Los Angeles, California, January 4, 1900)

In this chapter, we propose the formal model of leakage-free redactable signatures that is general and supports not only trees, but also for graphs and forests; moreover, it supports authentication of disconnected subtrees/subgraphs/sub-forests.

4.1 Preliminaries

Trees and Graphs: A directed (a directed graph $G(V, E)$ is a set of nodes (or vertices) V and a set of edges E between these nodes: $e(x, y)$ is an edge from x to y, $(x, y) \in V \times V$. A node x represents an atomic unit of the data, which is always shared as a whole or is not shared at all. A node x is called the ancestor of a node y iff there exists a path consisting of one or more edges from x to y. Node x is an immediate ancestor of y in G iff there exists an edge $e(x, y)$ in E. Nodes having a common immediate ancestor are called siblings. If there is a specific order between siblings in G, then G is an ordered graph. The fact that x precedes one of its siblings y in an ordered graph is denoted by $x \prec y$; i.e., x is to the left of y. The contents, if any, of a node x is referred to as c_x. A *redacted subgraph* graph $G(V, E)$ is denoted by $G_\delta(V_\delta, E_\delta)$, and $G_\delta(V_\delta, E_\delta) \subseteq G(V, E)$. $G_\delta(V_\delta, E_\delta) \subseteq G(V, E)$ if and only if $V_\delta \subseteq V$ and $E_\delta \subseteq E$. $G_\delta(V_\delta, E_\delta) \subset G(V, E)$ if and only if $V_\delta \cup E_\delta \subset V \cup E$. Redacted subgraph $G_\delta(V_\delta, E_\delta)$ is derived from the graph $G(V, E)$ by redacting the set of nodes $V \setminus V_\delta$ and the set of edges $E \setminus E_\delta$ from G. A directed tree $T(V, E)$ is a directed graph with the following constraint: removal of any edge $e(x, y)$ from E leads to two disconnected trees with no edge or path between nodes x and y. Two nodes are siblings, if they

have a common parent; x is a parent of node y iff there is an edge $e(x, y)$ in T; y is called the child of its parent x. In a tree, a parent node is nothing but the immediate ancestor of all its child nodes. An ordered tree is one where each pair of siblings have an order between them. A rooted tree has a special node called root, for which there is no parent node. As in the case of graphs, a redacted subtree of tree $T(V, E)$ is denoted by $T_\delta(V_\delta, E_\delta)$ such that $T_\delta(V_\delta, E_\delta) \subseteq T(V, E)$. $T_\delta(V_\delta, E_\delta) \subseteq T(V, E)$ denotes that $V_\delta \subseteq V$ and $E_\delta \subseteq E$. Redacted subgraph $T_\delta(V_\delta, E_\delta)$ is derived from the tree $T(V, E)$ by redacting the set of nodes $V \setminus V_\delta$ and the set of edges $E \setminus E_\delta$ from T. Two trees/graphs/forests with the same nodes and edges, but *different ordering* between at least one pair of siblings are different trees/graphs/forests. In the rest of the paper, a trees refers to an ordered directed rooted tree, and a graph refers to an ordered directed graph, a subtree/subgraph refers to a redacted subtree/subgraph of a tree/graph unless otherwise stated. $\Upsilon(V, E)$ refers to either a tree $T(V, E)$ or a graph $G(V, E)$.

4.1.1 Signature Schemes

In this section, we review the standard definition of digital signatures (adopted from [76]). A standard digital signature scheme Π is a tuple (`Gen`, `Sign`, `Vrfy`).

Definition 4.1.1 (Standard digital signature scheme) *A digital signature scheme* $r\Pi$ *consists of two probabilistic polynomial-time algorithms and one deterministic polynomial-time algorithm* $\Pi \equiv$ *(*`Gen`*,* `Sign`*,* `Vrfy`*) satisfying the following requirements:*

KEY GENERATION: *The probabilistic key generation algorithm* `Gen` *takes as input a security parameter* 1^n *and outputs a pair of keys* `(pk, sk)`*, where* `pk` *and* `sk` *are the public and private keys, respectively. We assume for convention that each of these keys has length* n *bits, and that* n *can be determined from* `(pk, sk)`*.*

$$(\mathtt{pk}, \mathtt{sk}) \leftarrow \mathtt{Gen}(1^n).$$

SIGNING: *The probabilistic signing algorithm* `Sign` *takes as input a private key* `sk` *and a message* M*, and outputs a signature* σ*.*

$$\sigma \leftarrow \texttt{Sign}_{\texttt{sk}}(M)$$

VERIFICATION: *The deterministic verification algorithm* `Vrfy` *takes as input a public key* `pk`*, a message* M*, and a signature* σ*, and outputs a bit* b*, with* $b = 1$ *meaning* `valid` *(i.e.,* σ *is a valid signature of message* M*), and* $b = 0$ *meaning* `invalid` *(i.e.,* σ *is not a valid signature of message* M*).*

$$b \leftarrow \texttt{Vrfy}_{\texttt{pk}}(\sigma, M)$$

4.1.2 Forgery

The strongest form of security for a digital signature scheme Π is *existentially unforgeable against chosen message attack* (EU-CMA). The following experiment $\texttt{Sig-Forge}^{eu-cma}_{\mathcal{A},\Pi}(\lambda)$ and definition review the unforgeability property of digital signatures (originally defined in [62]).

Unforgeability: Let us consider the following signature forging experiment. $\mathcal{A}$ is a probabilistic polynomial time (PPT) adversary with the knowledge of `pk`.

Signature Forging Experiment: $\texttt{Sig-Forge}^{eu-cma}_{\mathcal{A},\Pi}(\lambda)$

1. $\texttt{(pk, sk)} \leftarrow \texttt{Gen}(1^\lambda)$
2. $\mathcal{A}$ may know `pk` and has oracle accesses to $\texttt{Sign}_{\texttt{sk}}(\cdot)$ and $\texttt{rVrfy}_{\texttt{sk}}(\cdot)$. Let $\mathcal{Q}$ be the set of messages for which $\mathcal{A}$ queries $\texttt{Sign}_{\texttt{sk}}(\cdot)$.
3. $\mathcal{A}$ outputs (σ, M), where $M \notin \mathcal{Q}$.
4. The output of the experiment is 1 if and only if $\texttt{Vrfy}_{\texttt{pk}}(\sigma$,M) outputs 1, else the experiment outputs 0.

Definition 4.1.2 *The digital signature scheme* Π *is* $(t, q, \epsilon) - secure$ *if the experiment* $\texttt{Sig-Forge}^{eu-cma}_{\mathcal{A},\Pi}(\lambda)$ *outputs 1 with probability* $\epsilon(\lambda) = \frac{1}{2} + \epsilon(\lambda)$*, where* $\epsilon(\lambda)$ *is a negligible function in terms of* λ*; i.e.,*

$$Pr[\texttt{Sig} - \texttt{Forge}^{eu-cma}_{\mathcal{A},\Pi}(\lambda) = 1] \leq \ \epsilon(\lambda) = \frac{1}{2} + \epsilon(\lambda)$$

4.2 Leakage-Free Redactable Signatures

In this section, we present the formal model of the leakage-free redactable (LFR) signatures for trees, graphs and forests.

4.2.1 Why a New Model?

The standard notion of digital signatures (Section 4.1) has several shortcomings in our context. (1) It is not suitable for cases when a user has access only to a part of the message, and not the full message. (2) It is not suitable for messages that are trees, graphs or forests. Therefore, they also do not define the notion of "leakage-free". Redactable signatures have been proposed to address the first shortcoming. Such schemes allow signature of (a designated) part of a message to be computed from the signature of the complete message using the knowledge of the public key. Existing models for redactable and sanitizable signatures do not capture all our requirements in a holistic manner, and thus their security definitions are not applicable here as they are.

Brzuska et al [29] have defined formal security definitions of redactable structural signatures for tree data structures. Their definition is restrictive and cannot be applied to our general case. First of all, their scheme is defined only for trees, and can support neither graphs nor forests. Second, their scheme is restrictive for trees as well. They define an operation called $sCut(\cdot)$, which "cuts" a leaf node from a tree, and can be applied multiple times in o order to compute the redacted subtree and its signature. However, by this cut operation, a tree can be reduced to only a connected

subtree, not to a set of disconnected subtrees. The cases, in which a receiver that must receive multiple disconnected subtrees of a tree and verify their authenticity cannot be supported by such a definition. For example, consider the tree in Figure 1.1(a). Consider that a query on tree T evaluates to a subtree T_δ that is verified by the querier for its authenticity. By the definition of Brzuska et al., the $sCut(\cdot)$ operation is applied on leaf b, and iteratively on leaf f. It then results on the subtree T_δ as shown shaded in the figure. The signature of T_δ is computed from the signature of the T without the knowledge of the secret key, with which T was signed. Now consider another scenario – a query on tree T evaluates to two disconnected subtrees: T_δ and the subtree – $g \rightarrow f$. Such a scenario *cannot* be modeled by this definition. However, such scenarios occur quite frequently in practical usages and databases, and cannot be ignored by a security model. Therefore, there is a need for a completely general security model, which should also support graph-structured data (XML graphs, biological and genetic data, which have private and sensitive information encoded in them).

4.2.2 Definition of a General Scheme

In the following definition, $\Upsilon(V, E)$ refers to a tree, a graph, or a forest (a set of disconnected trees/graphs) with the set of vertices and edges being denoted by V and E, respectively.

Definition 4.2.1 (Leakage-Free Redactable Signature Scheme $r\Pi$) *A leakage-free redactable signature scheme $r\Pi$ consists of four polynomial algorithms $r\Pi \equiv$ (*`rGen`*,* `rSign`*,* `rRedact`*,* `rVrfy`*) satisfying the following requirements. Let $\Upsilon(V, E)$ refer to either a tree, graph, or a forest, and let $\Upsilon_\delta(V_\delta, E_\delta) \subseteq \Upsilon(V, E)$, i.e., $\Upsilon_\delta(V_\delta, E_\delta)$ is a redacted subtree/subgraph/sub-forest derived from $\Upsilon(V, E)$.*

KEY GENERATION: *A key generation algorithm* `rGen` *takes as input a security parameter 1^λ and outputs a pair of keys* `(pk, sk)`*, where* `pk` *and* `sk` *are the*

public and private keys, respectively. We assume for convention that each of these keys has length λ, and that λ can be determined from `pk` *and* `sk`*.*

$$(\texttt{pk}, \texttt{sk}) \leftarrow \texttt{rGen}(1^{\lambda}).$$

SIGNING: *The signing algorithm* `rSign` *takes as input a private key* `sk` *and a tree/graph/forest $\Upsilon(V, E)$, where the content c_x of each node $x \in V$ is such that $c_x \in \{0,1\}^*$. It outputs a signature σ_Υ.*

$$(\sigma_\Upsilon, \Upsilon(V, E)) \leftarrow \texttt{rSign}_{\texttt{sk}}(\Upsilon(V, E)).$$

REDACTION: *The redaction algorithm* `rRedact` *takes as input $\Upsilon(V, E)$, its signature σ_Υ, and a set of nodes V'_δ and edges E'_δ, where $V'_\delta \subset V$ and $E'_\delta \subseteq E$.* `rRedact` *outputs a redacted signature $\sigma_{\Upsilon_\delta(V_\delta, E_\delta)}$ for $\Upsilon_\delta(V_\delta, E_\delta)$, where $\Upsilon_\delta(V_\delta, E_\delta)$ is a tree/graph/forest derived from $\Upsilon(V, E)$ consisting of vertices in $V_\delta = V \setminus V'_\delta$, and edges $E_\delta = E \setminus E'_\delta$.*

$$(\sigma_{\Upsilon_\delta}, \Upsilon_\delta(V_\delta, E_\delta)) \leftarrow \texttt{rRedact}(\texttt{pk}, \sigma_\Upsilon, \Upsilon(V, E), V'_\delta)E'_\delta$$

VERIFICATION: *The verification algorithm* `rVrfy` *takes as input a public key* `pk`*, a tree/graph/forest $\Upsilon(V, E)$, whose authenticity needs to be verified, and a signature σ. It outputs a bit b, with $b = 1$ meaning* `valid` *(i.e., σ is a valid signature of $\Upsilon(V, E)$) and $b = 0$ meaning* `invalid` *(i.e., σ is not a valid signature of $\Upsilon(V, E)$).*

$$b \leftarrow \ \texttt{rVrfy}_{\texttt{pk}}(\sigma, \Upsilon(V, E))$$

An LFR signature scheme is correct if the following properties hold.

Signing Correctness: For any tree/graph/forest $\Upsilon(V, E)$, any positive integer value of λ, any key pair `(pk, sk)` $\leftarrow$ `rGen`(λ), and any $(\sigma_{\Upsilon(V,E)}, \Upsilon(V, E)) \leftarrow$ $\texttt{rSign}_{\texttt{sk}}(\Upsilon(V, E))$, $\texttt{rVrfy}_{\texttt{pk}}(\sigma_{\Upsilon(V,E)}, \Upsilon(V, E))$ always outputs 1.

Redaction Correctness: For any tree/graph/forest $\Upsilon(V, E)$, any positive integer value of λ, any key pair $(\mathtt{pk}, \mathtt{sk}) \leftarrow \mathtt{rGen}(\lambda)$, any $(\sigma_{\Upsilon(V,E)}, \Upsilon(V, E)) \leftarrow \mathtt{rSign}_{\mathtt{sk}}(\Upsilon(V, E))$, any subset of vertices $V'_\delta \subset V$, any subset of edges $E'_\delta \subseteq E$ such that $V_\delta = V \setminus V'_\delta$, and $E_\delta = E \setminus E'_\delta$, and any $(\sigma_{\Upsilon_\delta}, \Upsilon_\delta(V_\delta, E_\delta)) \leftarrow \mathtt{rRedact}(\mathtt{pk}, \sigma_\Upsilon, \Upsilon(V, E), V'_\delta)E'_\delta$, $\mathtt{rVrfy}_{\mathtt{pk}}(\sigma_{\Upsilon_\delta}, \Upsilon_\delta(V_\delta, E_\delta))$ always outputs 1.

4.3 Security of Leakage-Free Redactable Signatures

In this section, we define the security requirements of the leakage-free redactable signature scheme $r\Pi$. Informally, these requirements are:

Unforgeability: Someone who does not know the secret key and does not know a valid signature for a tree/graph/forest Υ should not be able to compute a valid signature for Υ provided that (s)he does not know the valid signature for any tree/graph/forest Υ' such that $\Upsilon \subset \Upsilon'$. This is a bit different from the traditional notion of EU-CMA (More on this in Section 4.3.1).

Privacy: Someone who has access to $\Upsilon \subset \Upsilon'$ but not to Υ' should not be able to infer any information about the redacted nodes and edges (in Υ' but not in Υ) from the leakage-free redactable signature of Υ.

Transparency: Someone who has access to $\Upsilon \subset \Upsilon'$ but not to Υ' should not be able to infer whether the signature of Υ has been computed from scratch or through the process of redaction.

4.3.1 Unforgeability

In standard digital signature schemes, only the signer can compute the signature of a given message. However, a redactable signature scheme allows "anyone" with the public key $\mathtt{pk}$ to be able to compute the signature of a (designated) part of the data (In contrast, for sanitizable signatures, a designated sanitizer can only compute

signatures on altered documents). Redactable signatures by Johnson et al. [74] compute the signature of a message M, which consists of n parts: $m_1, m_2, m_3, \ldots, m_n$. It allows anyone, who has a knowledge of the public key to compute the signature of a redacted document M' that consists of a subset of m_i's. Due to such a property, redactable signature schemes cannot support the strongest notion of unforgeability, i.e., existentially unforgeable under adaptive chosen-message attack, as it is. It has to be adapted (in other words, weakened) in order incorporate the fact that the signatures of any redacted sub-document M' can be "legally forge" with respect to the operation that can be used to compute these sub-documents from the original document M (cf., [74]). Therefore, the notion of unforgeability proposed by Brzuska et al ([29]: Definition 3) for redactable structural signatures for trees, is rather too strong to be supported by any redactable signature scheme. Moreover, their definition does not formally define what a "tree attack" means.

In what follows, we make use of the results of Johnson et al. [74] in defining the notion of unforgeability for the leakage-free redactable signature scheme $r\Pi$ defined in the previous section. The operation related to our notion of redaction is the subset $\subset$ operation: a redacted subtree T_δ is a tree with *subsets* of nodes and edges of the original tree T. Intuitively this notion means that if an adversary $\mathcal{A}$ has the knowledge of a subtree/subgraph/sub-forest Υ_δ, its valid signature σ_{Υ_δ}, and the public key, then $\mathcal{A}$ can in fact compute the valid signature of any subtree/subgraph/subforest of Υ_δ, and these are the *only* "messages" for which $\mathcal{A}$ can "forge" a signature without the knowledge of the secret key.

Existentially unforgeable under adaptive chosen-message attack with respect to the $\subset$ operation (EU-CMA-$\subset$): Let us consider the following signature forging experiment. As earlier, $\mathcal{A}$ is a PPT adversary has access to the signing oracle $\texttt{rSign}_{\texttt{sk}}(\cdot)$ with the knowledge of $\texttt{pk}$. $\mathcal{A}$ should not be able to forge a valid signature σ for a "new" tree/graph/forest even after it has adaptively queried the signing oracle $\texttt{rSign}_{\texttt{sk}}(\cdot)$. A "new" tree/graph/forest denotes a tree/graph/forest Υ', for which the $\mathcal{A}$ has not received a valid signature from the signing oracle and Υ' is not a redacted

subtree/subgraph/sub-forest of another Υ for which $\mathcal{A}$ has received a valid signature from the signing oracle.

Signature Forging Experiment: $\texttt{Sig-Forge}^{eu-cma-\subset}_{\mathcal{A},r\Pi}(\lambda)$

1. $\texttt{(pk, sk)} \leftarrow \texttt{Gen}(1^\lambda)$
2. $\mathcal{A}$ is given the $\texttt{pk}$, and is allowed oracle accesses to $\texttt{rSign}_{\texttt{sk}}(\cdot)$, $\texttt{rRedact}_{\texttt{pk}}(\cdot,\cdot)$, and $\texttt{rVrfy}_{\texttt{sk}}(\cdot)$. Let $\mathcal{Q}$ be the set of all trees/graphs/forests for which $\mathcal{A}$ queries $\texttt{rSign}_{\texttt{sk}}(\cdot)$ for their signatures.
3. $\mathcal{A}$ outputs $(\sigma,\ \Upsilon')$, such that
   (a) $\Upsilon' \notin \mathcal{Q}$: Υ' is a tree/graph/forest whose signature the $\mathcal{A}$ has not queried from the signing oracle, and
   (b) $\Upsilon' \notin \cup_{\Upsilon\in\mathcal{Q}}\Theta_\Upsilon$, where $\Theta_\Upsilon = \{\Upsilon''|\Upsilon'' \subset \Upsilon\}$: Υ' is not a subtree/subgraph/ sub-forest of any $\Upsilon(V,E)$, whose signature has been queried by $\mathcal{A}$ from $\texttt{rSign}_{\texttt{sk}}(\cdot)$.
4. The output of the experiment is 1 if and only if $\texttt{Vrfy}_{\texttt{pk}}(\sigma,\Upsilon') = 1$, else the experiment outputs 0.

Definition 4.3.1 (LFR Signature: Integrity) *The leakage-free redactable signature scheme $r\Pi$ is existentially unforgeable under adaptive chosen-message attack over $\subset$ operation, if the experiment* $\texttt{Sig-Forge}^{eu-cma-\subset}_{\mathcal{A},r\Pi}(\lambda)$ *outputs 1 with probability* $\epsilon(\lambda) = \frac{1}{2} + \epsilon(\lambda)$*:*

$$Pr(\texttt{Sig} - \texttt{Forge}^{eu-cma-\subset}_{\mathcal{A},r\Pi}(\lambda) = 1) \leq \epsilon(\lambda) = \frac{1}{2} + \epsilon(\lambda).$$

4.3.2 Leakage-Free Properties

There are two leakage-free properties: privacy and transparency. Transparency is the stronger property and subsumes privacy.

4.3.3 Privacy

An LFR signature scheme supporting privacy does not lead to leakage of the contents of the nodes that have been redacted. Given a redacted subtree/subgraph/subforest and its LFR signature, one cannot infer any of the contents of the redacted nodes. For example, given a subtree from a financial XML document that lists credit-card information, and given two source XML documents, one cannot identify which source tree the subtree has been redacted from.

In the following adversarial experiment, a PPT adversary $\mathcal{A}$ outputs two trees/-graphs/forests Υ_0 and Υ_1 such that (a) $\mathcal{A}$ has not queried the signatures for them nor has queried signatures for super-trees/super-graphs/super-forests of them; (b) redacting a given set of vertices V'_δ and edges E'_δ from either of them lead to the same subtree/subgraph/sub-forest $\Upsilon'_\delta(V'_\delta, E'_\delta)$. The experiment randomly chooses either Υ_b (b = 0 or 1) to be signed, and then computes the signature for the redacted subtree Υ'_δ. A challenge consisting of the redacted subtree and its signature is given to the adversary. The experiment is successful, if the adversary can infer the Υ_b from which Υ'_δ has been redacted with a probability non-negligibly larger than $\frac{1}{2}$.

Privacy Experiment: $\texttt{Sig-Priv}^{priv}_{\mathcal{A},r\Pi}(\lambda)$ Let us consider the following experiment on privacy of the LFR signature scheme $r\Pi$:

1. $\texttt{rGen}(1^\lambda)$ is run to obtain keys `(pk, sk)`.
2. Probabilistic polynomial-time adversary $\mathcal{A}$ is given `pk` and oracle access to $\texttt{rSign}_{\texttt{sk}}(\cdot)$, $\texttt{rRedact}(\cdot)$ and $\texttt{rVrfy}_{\texttt{pk}}(\cdot)$. Let $\mathcal{Q}$ be the set of all trees/graphs/forests for which $\mathcal{A}$ queries $\texttt{rSign}_{\texttt{sk}}(\cdot)$ for their signatures.
3. $\mathcal{A}$ outputs two trees/graphs/forests $\Upsilon_0(V_0, E_0)$, and $\Upsilon_1(V_1, E_1)$, and $\Upsilon_\delta(V_\delta, E_\delta)$, where $\Upsilon_\delta(V_\delta, E_\delta) \subset \Upsilon_0(V_0, E_0)$ and $\Upsilon_\delta(V_\delta, E_\delta) \subset \Upsilon_1(V_1, E_1)$.
4. Draw a random b uniformly from {0,1}. $(\sigma_{\Upsilon_b}, \Upsilon_b(V_b, E_b)) \leftarrow \texttt{rSign}_{\texttt{sk}}(\Upsilon_b(V_b, E_b))$. The signature for redacted subtree Υ_δ is computed from σ_{Υ_b}: $(\sigma_{\Upsilon_\delta}, \Upsilon_\delta) \leftarrow \texttt{rRedact}(\texttt{pk}, \sigma_{\Upsilon_b}, \Upsilon_b(V_b, E_b), V_b \backslash V_\delta) E_b \backslash E_\delta$. Then the *challenge* $(\sigma_{\Upsilon_\delta}, \Upsilon_\delta)$ is given to $\mathcal{A}$.

5. The adversary $\mathcal{A}$ continues to have oracle access to $\texttt{rSign}_{\texttt{sk}}(\cdot)$, $\texttt{rRedact}_{\texttt{pk}}(\cdot,\cdot)$, and $\texttt{rVrfy}_{\texttt{pk}}(\cdot)$. Eventually, $\mathcal{A}$ outputs a bit b' (for the *challenge* $(\sigma_{\Upsilon_\delta}, \Upsilon_\delta)$).
6. The output of the experiment is 1 if $b' = b$, and 0 otherwise.

Definition 4.3.2 (LFR Signature: Privacy) *The LFR signature scheme $r\Pi$ preserves privacy if $Pr($*$\texttt{Sig-Priv}^{priv}_{\mathcal{A},r\Pi}(\lambda)$*$=1) \leq \frac{1}{2} + \epsilon(\lambda)$.*

4.3.4 Transparency

In this section, we formally define a transparent LFR scheme. In many applications, it is expected that the end-user should not be able to infer whether the received subtree/subgraph/sub-forest is a redacted one or not. If such information can be inferred, the adversary can learn that the source tree/graph/forest has a higher number of vertices/edges (which might represent the number of bank accounts one has, or the number of critical diseases one has suffered from). Therefore, the leakage-free redactable signature scheme should prevent inference of such information.

A similar notion exists in the literature for sanitizable signatures in the name of "signature transparency" [74], which however, is different from our notion of signature-indistinguishability in the sense that in our case, the adversary should not be able to infer any extraneous information (either contents or structural) in Υ with respect to Υ_δ (extraneous information is defined in Section 4.2). The existing notion transparency does not capture leakage of structural information.

In the following adversarial experiment, a PPT adversary $\mathcal{A}$ outputs two trees/-graphs/forests Υ_0 and Υ_1 such that $\Upsilon_0 \subset \Upsilon_1$. The experiment randomly chooses either Υ_b (b = 0 or 1) to be signed; if Υ_1 is signed, then the signature for Υ_0 is computed by redaction from that of Υ_1. A challenge consisting of Υ_0 and its signature is given to the adversary. The experiment is successful (returns 1) if the adversary can infer whether the signature of Υ_b was computed by the signing oracle or by the redaction oracle, with a probability non-negligibly larger than $\frac{1}{2}$.

Transparency Experiment: $\texttt{Sig-Transp}^{transp}_{\mathcal{A},r\Pi}(\lambda)$ Let us consider the following experiment on transparency of the LFR signature scheme $r\Pi$:

1. $\texttt{rGen}(1^\lambda)$ is run to obtain keys `(pk, sk)`.

2. Probabilistic polynomial-time adversary $\mathcal{A}$ is given `pk` and oracle access to $\texttt{rSign}_{\texttt{sk}}(\cdot)$, $\texttt{rRedact}(\cdot)$ and $\texttt{rVrfy}_{\texttt{pk}}(\cdot)$. Let $\mathcal{Q}$ be the set of all trees/graphs/forests for which $\mathcal{A}$ queries $\texttt{rSign}_{\texttt{sk}}(\cdot)$ for their signatures.

3. $\mathcal{A}$ outputs two trees/graphs/forests $\Upsilon_0(V_0, E_0)$, and $\Upsilon_1(V_1, E_1)$, such that $\Upsilon_0(V_0, E_0) \subset \Upsilon_1(V_1, E_1)$.

4. Draw a random b uniformly from {0,1}. $(\sigma_{\Upsilon_b}, \Upsilon_b(V_b, E_b)) \leftarrow \texttt{rSign}_{\texttt{sk}}(\Upsilon_b(V_b, E_b))$. If b=1, then the signature for $\Upsilon_0(V_0, E_0)$ is computed from σ_{Υ_1}: $(\sigma_{\Upsilon_0}, \Upsilon_0(V_0, E_0))$ $\leftarrow \texttt{rRedact}(\texttt{pk}, \sigma_{\Upsilon_1}, \Upsilon_1(V_1, E_1), V_1 \backslash V_0) E_1 \backslash E_0$. Then the *challenge* $(\sigma_{\Upsilon_0}, \Upsilon_0(V_0, E_0))$ is given to $\mathcal{A}$.

5. The adversary $\mathcal{A}$ continues to have oracle access to $\texttt{rSign}_{\texttt{sk}}(\cdot)$, $\texttt{rRedact}_{\texttt{pk}}(\cdot, \cdot)$, and $\texttt{rVrfy}_{\texttt{pk}}(\cdot)$. Eventually, $\mathcal{A}$ outputs a bit b' (for the *challenge* $(\sigma_{\Upsilon_\delta}, \Upsilon_\delta)$).

6. The output of the experiment is 1 if $b' = b$, and 0 otherwise.

Definition 4.3.3 (LFR Signature: Transparency) *The LFR signature scheme* $r\Pi$ *preserves transparency, if* $Pr(\texttt{Sig-Transp}^{transp}_{\mathcal{A},r\Pi}(\lambda)=1) \leq \frac{1}{2} + \epsilon(\lambda)$.

4.3.5 Relationships of Privacy and Transparency

In this section, we analyze the relationships between the two leakage-free properties of LFR signature schemes: privacy and transparency. In whatever follows, any mention of tree/subtree can be substituted by the term graph/subgraph or forest/subforest without any change to the semantics of the context.

Proposition 4.3.1 *Privacy $\not\Rightarrow$ Transparency.*

Consider two trees: Υ_1: x is the parent of y and z, and $y \prec z$; Υ_2: x is the parent of y and w, and $y \prec w$. Consider the case in which a party receives subtree x, y, and the edge from x and y, and its signature. If the signature scheme supports privacy, the signature does not leak contents of z or w, but may provide the fact that y has a right sibling. Such a scheme is privacy-preserving, but not transparent, because someone who knows Υ_1, and the subtree and its signature, can infer that the signature is a redacted signature from Υ_1.

Proposition 4.3.2 *Transparency $\Rightarrow$ Privacy.*

Someone who cannot determine if a signature is a redacted signature, cannot in fact determine if the subtree is a redacted subtree or a source tree by itself. By taking negation of the implication, if an LFR scheme does not support privacy, then one can determine the source tree from whose signature, the signature of a subtree has been derived. Such inference in fact implies that the signature of the subtree has not be computed from scratch, but is a redacted signature, which is why transparency also does not hold for such a scheme. *The transparency property of a redactable signature scheme is indeed its leakage-free property.*

4.4 Secure Names

We would now define a formal notion of secure names, and secure naming schemes. Secure names are assigned with nodes in order to prove/disprove the allged ordere between a pair of nodes.

4.4.1 Secure Naming Schemes

Each secure (i.e., leakage-free) naming scheme $rN \equiv$ (`rNameGen`, `rNameVrfy`) has two components: generation of secure names and verification of the order between secure names, and is defined as follows.

Definition 4.4.1 (Secure Naming Scheme rN) *A leakage-free naming scheme rN consists of two polynomial algorithms $rN \equiv$ (*`rNameGen`*,* `rNameVrfy`*) satisfying the following requirements. Let V refer to a set of vertices such that $V = \{x_i | 1 \leq i \leq |V|\}$, and $x_i \prec x_j$, for all $1 \leq i < j \leq |\Theta|$. Let $V_\delta \subseteq V$, i.e., V_δ is a redacted set of vertices derived from V.*

NAME GENERATION: *A name generation algorithm* `rNameGen` *takes as input two or less security parameters 1^{λ_1}, and 1^{λ_2} and V and outputs a set of $\Theta = \{\eta_i | 1 \leq i \leq |V|\}$such that η_i is a secure name for node x_i. We assume for convention that each of these secure names has length λ, and that λ can be determined from η_i's. In case of one security parameter, 1^{λ_2} would just be replaced by 0.*

$$\Theta \leftarrow \texttt{rNameGen}(1^{\lambda_1}, 1^{\lambda_2}, V).$$

ORDER VERIFICATION: *The order verification algorithm* `rNameVrfy` *takes as input two or less security parameters 1^{λ_1}, and 1^{λ_2} and two pairs (x_i,η_i) and (x_j,η_j), where a pair is: (node x, secure name η_x), and outputs a bit b, with $b = 1$ meaning* `valid` *(i.e., $x_i \prec x_j$) and $b = 0$ meaning* `invalid` *(i.e., $x_i \not\prec x_j$).*

$$b \leftarrow \texttt{rNameVrfy}(1^{\lambda_1}, 1^{\lambda_2}, (x_i, \eta_i), (x_j, \eta_j))$$

An LFR signature scheme is correct if the generated secure names are verified to be order-preserving.

Naming Correctness: For any set of vertices V such that between a pair of vertices $x, y \in V$, $x \prec y$, any positive integer values of λ_1, and λ_2, and any $\Theta \leftarrow$ $\texttt{rNameGen}(1^{\lambda_1}, 1^{\lambda_2}, V)$, $\texttt{rNameVrfy}(1^{\lambda_1}, 1^{\lambda_2}, (x, \eta_x), (y, \eta_y))$ always outputs 1.

4.4.2 Security of Naming Schemes

In this section, we define the security requirement of the secure names. Informally, this requirement is as follows.

Name-Transparency: Someone who has access to an ordered set of secure names $\Theta_\delta \subset \Theta$ but not to Θ should not be able to infer whether $\Theta = \Theta_\delta$ or $\Theta \neq \Theta_\delta$.

Let us formally define a transparency notion for secure names. Such a notion is similar to that of transparency (Section 4.3.4).

In the following adversarial experiment, a PPT adversary $\mathcal{A}$ outputs two sets of vertices V_0 and V_1 such that $V_0 \subset V_1$, and $x_i \prec x_j$, where $1 \leq i < j \leq |V_1|$. The experiment randomly chooses either V_b (b = 0 or 1) for which secure names are to be generated; if V_1 is chosen, then the secure names for the vertices in V_0 are selected from V_1 . A challenge consisting of V_0 and its set of secure names Θ_0 is given to the adversary. The experiment is successful (returns 1) if the adversary can infer whether the secure names in Θ_0 of Υ_b was computed from scratch or was selected from the Θ_1 after computing Θ_1, with a probability non-negligibly larger than $\frac{1}{2}$.

Name-Transparency Experiment: $\texttt{Name-Transp}^{transp}_{\mathcal{A},rN}(\lambda)$ Let us consider the following experiment on name-transparency of the secure names $r\Pi$:

1. Probabilistic polynomial-time adversary $\mathcal{A}$ is given oracle access to $\texttt{rNameGen}(\lambda_1, \lambda_2, \cdot)$ and $\texttt{rNameVrfy}(\lambda_1, \lambda_2, \cdot)$.

2. $\mathcal{A}$ outputs two sets of vertices V_0, and V_1, such that $V_0 \subset V_1$.

3. Draw a random b uniformly from {0,1}. $\Theta_b \leftarrow \texttt{rNameGen}(1^{\lambda_1}, 1^{\lambda_2}, V_b)$. If $b = 1$, then the set of secure names Θ_0 for the vertices in V_0 are selected from Θ_1. Then the *challenge* (Θ_0,V_0) is given to $\mathcal{A}$.

4. The adversary $\mathcal{A}$ continues to have oracle access to $\texttt{rNameGen}(\lambda_1, \lambda_2, \cdot)$ and $\texttt{rNameVrfy}(\lambda_1, \lambda_2, \cdot)$. Eventually, $\mathcal{A}$ outputs a bit b' (for the *challenge* (Θ_0,V_0).

5. The output of the experiment is 1 if $b' = b$, and 0 otherwise.

Definition 4.4.2 (Secure Naming Scheme: Name-Transparency) *The secure naming scheme rN preserves transparency, if* $Pr($$\texttt{Name-Transp}^{transp}_{\mathcal{A},rN}(\lambda)$*=1)* $\leq \frac{1}{2} + max(\epsilon(\lambda_1), \epsilon(\lambda_2))$*, where* $max(i, j)$ *returns the larger of* i *and* j*.*

4.5 Summary

Redactable signatures for linear-structured data such as strings have been studied. Redactable signatures for non-linear-structured data such as trees and graphs have also been recently developed with a stronger security requirement - that is - such signatures should be completely leakage-free. However, it is restrictive and is flawed. We proposed the first fully general formal model for leakage-free redactable signatures for trees, graphs and forests. We also defined a notion of security of secure names for ordered vertices.

5 STRUCTURAL SIGNATURES FOR TREES

Whether you can observe a thing or not depends on the theory which you use. It is the theory which decides what can be observed.

Albert Einstein (during Heisenberg's 1926 lecture at Berlin)

In this chapter, we present a solution to our problem of leakage-free authentication of trees, for scenarios when a user receives "only one subtree". This scheme is based on the notion of randomized traversal numbers and post-order/pre-order/in-order traversals of trees, and aggregate signature schemes. We then provide security analysis, and complexity as well as performance analysis of this scheme.

For scenarios, in which a receiver receiver receives more than one subtrees as a result of one or more queries, this scheme leaks path-related information between each pair of subtrees.

5.1 Review of Tree Traversals

Post-order, pre-order, and in-order tree traversals are defined in [77]. While post-order and pre-order traversals are defined for all types of trees, in-order traversal is defined only for binary trees. Binary trees are the trees in which each non-leaf node has at most two children, and they are left and right children. A node can have a right child without having a left child and vice versa. In each of these traversals, the first node visited is assigned 1 as its *visit count*. For every subsequent vertex visited, the *visit count* is incremented by 1 and is assigned to the vertex. This sequence of numbers is called the sequence of post-order (PON), pre-order (RON), or in-order (ION) numbers for the tree T, depending on the particular type of traversal.

Properties of traversal numbers: The post-order number of a node is smaller than that of its parent. The pre-order number of a node is greater than that of its parent.

The in-order number of a node in a binary tree is greater than that of its left child and smaller than that of its right child. A specific traversal number of a node x is always smaller than that of its right sibling y. The distribution and range of the traversal numbers are uniform and deterministic ($[1, 2, \ldots, |V|]$). The determinism of the distribution and range of the traversal numbers make them unsuitable for our purposes as they reveal information about the approximate size of the data and the position of the subset of data in the data set. It is possible for an adversary to exploit this information and replace a signed node with a compromised or a different node altogether by assigning to it the original pre-order number. Siblings can be interchanged and the corresponding visit counts could also be interchanged while satisfying the specific properties. A non-binary tree can be uniquely reconstructed from the sequences of pre-order and post-order numbers of its nodes. A binary tree can be uniquely reconstructed from the sequences of in-order and either pre-order or post-order numbers of its nodes.

In order to overcome the above limitations of the traversal numbers, we propose the notion of *randomized traversal numbers*.

5.2 Randomized Traversal Numbers

We transform a set of traversal numbers (of a specific traversal) into a set of distinct random numbers such that the order between the traversal numbers is preserved. By preserving the order of their original counterparts, these randomized traversal numbers (RTNs) preserve their properties. The distribution and range of randomized traversal numbers is non-uniform and non-deterministic. The randomized post-order, pre-order and in-order numbers are called randomized post-order (RPON), randomized pre-order (RRON), and randomized in-order (RION) numbers. RPON, RRON, and RION for a node x are denoted by p_x, r_x and i_x, respectively.

Before we define the randomized traversal numbers formally, we would need to introduce the security notion of POPF-CCA introduced by Boldyreva et al. [26] in

order to develop secure order-preserving encryption schemes. Boldyreva et al observe that the standard indistinguishability notion of IND-CCA (*indistingushable against chosen-ciphertext attack*) cannot be supported by any order-preserving encryption (OPE), because any OPE scheme (1) has to be deterministic in order to support determination of equality among plaintexts, (2) leaks equality, and (3) order among plaintexts. Our notion of randomized traversal numbers in fact can be defined to be the ciphertexts of such OPE scheme that is secure under the new notion of *indistinguishability* as defined in [26]: *pseudo-random order-preserving function against chosen-ciphertext attack* (POPF-CCA). We should note that POPF-CCA is weaker than the strongest notion of indistinguishability - *indistingushable against chosen-ciphertext attack* (IND-CCA). We refer the reader to [26] for detailed description on this notion.

Definition 5.2.1 *Let $T(V, E)$ be a tree. Let V_δ be a subset of V. Let o_x be the traversal number of a node $x \in V$, $O_V = \{o_x | x \in V\}$. Let $O'_V = \{o'_x | x \in V\}$, where o'_x is the randomized traversal number associated with o_x for node x if and only if the following hold true. Let $\odot$ denote either $<, =, >$.*

1. *$o_x \odot o_y \Leftrightarrow o'_x \odot o'_y$.*
2. *Let $Enc_K(\cdot)$ be a POPF-CCA secure order-preserving encryption, which is used as follows: $O'_V \leftarrow Enc_K(O_V)$.*

From the definition, it is clear that given the knowledge of any subset O'_{V_δ} of randomized traversal numbers O'_V in a tree $T(V, E)$, a PPT adversary $\mathcal{A}$ has a negiblible advantage (as defined in [26]) in determining whether $V \setminus V_\delta$ is empty or non-empty under the POPF-CCA notion of security. In other words, $Enc_K(\cdot)$ is transparent (Section 4.3.4).

The following lemmas provide the basis for developing the structural signatures for trees.

Lemma 5.2.1 *The pair of randomized in-order number and either post-order or pre-order number for a node in a binary tree correctly and uniquely determines the position of the node in the structure of the tree, where the position of a node is defined by its parent and its status as the left or right child of that parent.*

Proof From the in-order and either post-order or pre-order traversal sequences of the vertices, it is possible to *uniquely* re-construct a binary tree [75]. Thus from these sequences or from their randomized counterparts, for a node, it is possible to correctly identify its parent and its status as left or right child of that parent in the tree. Thus the lemma is proven. Follows from [75]. ■

Lemma 5.2.2 *The pair of randomized post-order number and pre-order number for a node in a (non-binary) tree uniquely determines the position of the node in the structure of the tree, where the position of a node is defined by its parent and its siblings to its immediate left and right in the tree.*

Proof Follows from [51]. ■

5.2.1 Computation of randomized traversal numbers

In order to compute the randomized traversal numbers, we refer to the secure scheme presented in the literature.

1. By using Boldyreva et al's order-preserving encryption: Boldyreva et al. [26] recently developed a symmetric order-preserving encryption (OPE) scheme that is secure with respect to a security notion - POPF-CCA This scheme is based on hypergeometric (HG) and negative hypergeometric (NHG) probability distributions, and their relation with order-preserving encryption. For our purpose, let $Enc_K([i, j])$ refer to the randomized order-preserving encryption of the list of integers $[i, j]$ using OPE scheme and the key K. For our purpose, we just

need to carry out verification of the order among them, there is no decryption of the encrypted integers. These encrypted numbers can be used as the randomized traversal numbers. However, order-preserving encryption is more expensive than (1) and (2) as it provides a trapdoor to compute the plaintext from the ciphertext. We do not need such a property here. We should note that Boldyreva et al. have not characterized the leakage and its amount due to their OPE scheme ([26]: page: 5). However, this is the state-of-the art scheme. Existing order-preserving hash functions are not related to security in any sense ([26]: page: 5).

2. *Not provably secure*: One scheme is to draw as many randoms as the number of the nodes, and sort them. The sorted (increasing-order) random numbers are assigned as the randomized post-order numbers. This process is repeared for randomized pre-order numbers.

We mention of the second scheme because we believe that it provides security for trees with small arity such as 2 (however, we note that we do not have a proof of security in terms of transparency as of now).

5.3 Structural Signatures

In this section, we develop the protocol of structural signature scheme for trees. Structural signatures for non-binary trees are based on post-order and pre-order numbers, and those of binary trees are defined identically to that of non-binary trees except that in-order traversals are used in place of either the post-order and pre-order traversals (Lemma 5.2.1). For simplicity of exposition, we focus primarily on non-binary trees. The structural signature scheme is referred to as $r\Pi \equiv$ (`rGen`, `rSign`, `rRedact`, `rVrfy`), and is presented in the following sections.

5.3.1 Signing (`rSign`)

Structural Position: A structural position uniquely identifies a node in a tree structure. It is defined as a pair of the RPON and the RRON of a node and for binary trees it is defined as a pair of the RION and RPON (or RRON) of the node (Definition 5.3.1). An integrity verifier (IV) is different from an authenticity verifier ($\mathcal{VO}$), in the sense that the latter is defined from IVs, and can be used to verify authenticity of a subtree (as described later). A structural position is essential a secure-name of a node.

Definition 5.3.1 (Structural Position and Integrity Verifier) *Let x be a node in tree $T(V, E)$. Its structural position, denoted by η_x, is defined as a pair of its RPON p_x and RRON r_x, that is, $\eta_x = (p_x, r_x)$. Let c_x denote the content of node x. Its structural integrity verifier (IV) denoted by ξ_x, is defined as: $\xi_x = \mathcal{H}(\eta_x \| c_x)$.*

Using the IVs, we define the structural signature $\sigma_{T(V,E)}$ of $T(V, E)$. Such signatures are leakage-free. In cases when "the received subtree (sent to the user) is the same as the original tree" is a sensitive information, the signature of a tree may be salted using a random value in order to protect this fact. The (salted) tree signature is publicly available or passed to the user alongwith the subtree that the user has access to. $\sigma_{T(V,E)}$ is an aggregate signature, computed over the IVs of its nodes. We define two types of signatures for trees: one based on the condensed-RSA signatures [105] and the other based on bilinear maps [28].

Definition 5.3.2 (Structural Signature using CRSA) *Let $T(V, E)$ be a tree. Let $\mathcal{H}$ denote a random oracle. Let the RSA signature σ_x of each node x be defined as follows $\sigma_x \leftarrow \xi_x^{\bar{d}} \ mod \ \bar{n}$, where ξ_x is the IV of x. Let ω_T be a random. The leakage-free signature of T, denoted by $\sigma_{T(V,E)}$, is defined as*

$$\sigma_{T(V,E)} = (\omega_T \prod_{x \in V} \xi_x)^{\bar{d}} \ \ (mod \ \bar{n}). \tag{5.1}$$

`rSign`: Sign tree $T(V, E)$.

1. Compute the post-order and pre-order numbers for each node in T.
2. For each node x in T: transform the post-order and pre-numbers into post-order and pre-order numbers denoted, respectively, as p_x and r_x
3. For each node x,
   (a) Assign (p_x, r_x) to x as its structural position η_x.
   (b) Compute the *IV* ξ_x of x: $\xi_x \leftarrow \mathcal{H}(\eta_x \| c_x)$.
4. Compute the leakage-free signature $\sigma_{T(V,E)}$ using either Condensed-RSA (Eq.5.1) or BGLS (Eq.5.2).

Figure 5.1. Algorithm to sign a tree.

Definition 5.3.3 (Structural Signature using BGLS) *Let $T(V, E)$ be a tree. Let $\mathcal{H}$ denote a random oracle. Let the RSA signature σ_x of each node x be defined as follows $\sigma_x \leftarrow \mathtt{sk}\xi_x$, where ξ_x is the IV of x. Let ω_T be a random. The leakage-free signature of T, denoted by $\sigma_{T(V,E)}$, is defined as*

$$\sigma_{T(V,E)} \leftarrow (\mathtt{P}, \mathtt{sk}(\omega_{\mathtt{T}} + \sum_{\mathtt{x} \in \mathtt{V}} \xi_{\mathtt{x}})). \tag{5.2}$$

The signing algorithm for a tree $T(V, E)$ is given belowin Figure 5.1.

5.3.2 Distribution of a Subtree (`rRedact`)

Suppose that Bob receives $T_\delta(V_\delta, E_\delta)$, a subtree of $T(V, E)$. $T_\delta(V_\delta, E_\delta)$ can be shared with Bob according to two different strategies: (1) by sharing the signed subtree - its nodes and the structure; (2) by sharing the signed nodes in the subtree

and letting Bob reconstruct the subtree using the RPON's and RRON's of the nodes. We describe both options in the following sections. By use of either CRSA or BGLS, the distributor D needs to only send $O(1)$ authenticity verifiers to the user.

5.3.3 Distribution of a Subtree along with its Structure

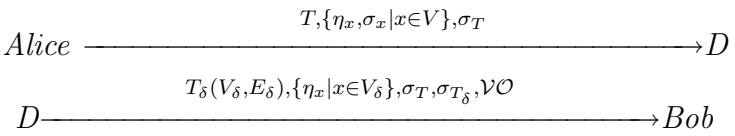


Figure 5.2. Protocol for trees.

Let $T_\delta(V_\delta, E_\delta)$ be the subtree of $T(V, E)$ that is to be shared with user Bob by the distributor. The distributor D sends the information about the parent-child relationships and ordering between siblings (e.g. as an adjacency matrix) in $T_\delta(V_\delta, E_\delta)$ and σ'_{T_δ} to Bob: $\sigma'_{T_\delta} = (\sigma_{T(V,E)}, \sigma_{T_\delta}, VO, \{\eta_x, \sigma_x | x \in V_\delta\})$. The redaction procedure is given in Figure 5.3.3.

The purpose of sending σ_{T_δ} to each user is to prevent injection of spurious nodes to the subtree either at the distributor (cloud server), and/or in the communication channel. The purpose of sending the verification object VO is to prevent an attacker from deleting nodes from the subtree.

5.3.4 Authentication (`rVrfy`)

Figure 5.2 summarizes the interactions between *Alice*, D and *Bob*. *Bob* receives the subtree $T_\delta(V_\delta, E_\delta)$ (with a different name in order avoid any ambiguity), the structural position η_x of each node x, VO, and the signature of the tree σ_T. It verifies the authenticity of the contents; if they are authentic then the integrity of structural relations are verified.

`rRedact`: Compute signature of subtree(s) $T_\delta(V_\delta, E_\delta) \subset T(V, E)$.

1. Aggregate signature of the nodes: σ_{T_δ} computed as follows: in CRSA, $\sigma_{T_\delta} = \prod_{x \in (V_\delta)} \sigma_x \ mod \ \bar{n}$; in BGLS, $\sigma_{T_\delta} = (\mathtt{P}, \sum_{x \in (V_\delta)} \sigma_x)$.

2. Verification object VO computed as follows:
   CRSA: $VO \leftarrow \omega_T \prod_{x \in (V - V_\delta)} \sigma_x \ mod \ \bar{n}$;
   BGLS: $VO \leftarrow \omega_T + \sum_{x \in (V - V_\delta)} \sigma_x$.

Figure 5.3. Algorithm to compute the redacted signature of a subtree $T_\delta(V_\delta, E_\delta) \subseteq T(V, E)$.

Authentication of Contents: Authentication of contents and structural positions of the subtree received verifies (1) its integrity and, (2) the authorized owner (signer) of the subtree. Verification of structural relations is carried out in the next step.

Verification of Structural Relations: The integrity verification of structural relations in a tree involves traversing the tree and comparing the RPON (RRON) of each node with the RPON (RRON) of its parent or its sibling (Figure 5.3.4).

5.3.5 Sharing a Subtree – Only the Nodes

An advantage of the use of structural signatures is that there is no need to supply the user with the structure of the subtree it is receiving. It reduces the amount of data that needs to be transmitted from the distributor to the users and thus improves the efficiency of the data distribution. The structure can be reconstructed from the pre-order and post-order traversals (for non-binary trees [51]) (in-order and pre/post-traversals for binary trees [75]).

Authentication and Reconstruction of a Subtree: If all the node contents are verified to be authentic, the subtree T_δ is re-constructed using RPONs and RRONs using the algorithm in Figure 5.3.5. Structural integrity is automatically verified during the subtree re-construction process. This algorithm has a *lower-bound* complexity of $O(nlogn)$ due to sorting.

`rVrfy`: Verify authenticity of $T_\delta(V_\delta, E_\delta)$.

1. Authentication of contents:
   (a) For each $y \in V_\delta$(received nodes), $\xi_y \leftarrow \mathcal{H}(\eta_y \| c_y)$.
   (b) CRSA: $\prod_{y \in V_\delta} \xi_y \stackrel{?}{=} (\sigma_{T_\delta})^{\bar{e}} \ mod\ \bar{n}$.
   BGLS: $(\mathtt{Q}, \sum_{\mathtt{y} \in \mathtt{V}_\delta} \xi_\mathtt{y}) \stackrel{?}{=} \sigma_{\mathtt{T}_\delta}$.
   (c) CRSA: $VO \prod_{y \in V_\delta} \xi_y \stackrel{?}{=} (\sigma_T)^{\bar{e}} \ mod\ \bar{n}$.
   BGLS: $(\mathtt{Q}, \mathtt{VO} + \sum_{\mathtt{y} \in \mathtt{V}_\delta} \xi_\mathtt{y}) \stackrel{?}{=} \sigma_\mathtt{T}$.
   (d) If (b) and (c) are true, the contents and structural positions of $T_\delta(V_\delta, E_\delta)$ are authenticated.
   (e) Else if (c) is true and (b) is false, at least one of the nodes in V_δ is an unauthorized node.
   (f) Else if (b) is true and (c) is false, at least one of the nodes in $T(V, E)$ has been dropped in an unauthorized manner from V_δ or from the computation of $\mathcal{VO}$.
2. Verification of structural relations:
   (a) Carry out a pre-order traversal on T_δ.
   (b) Let x be the parent of z; if (($p_x \leq p_z$) or ($r_x \geq r_z$)), then parent-child relationship between x and z is incorrect.
   (c) For ordered trees, let y be the right sibling of z; if (($p_z \geq p_y$) or ($r_z \geq r_y$)), then the left-right order among the siblings y and z is incorrect.

Figure 5.4. Algorithm to verify the authenticity of a redacted subtree $T_\delta(V_\delta, E_\delta)$.

1. Initialize a stack S_p, and subtree T_δ as empty.
2. $SortedV \leftarrow$ Sort the vertices with increasing RRONs.
3. $x \leftarrow$ remove first item from $SortedV$.
4. Push(S_p, x). Assign x as the root of T_δ.
5. $y \leftarrow$ remove next item from $SortedV$; (i.e., $r_y > r_x$).
6. Push(S_p, y). Create edge $e(x, y)$.
7. While $SortedV$ is not empty
   (a) $z \leftarrow$ remove next item from $SortedV$.
   (b) Let y refer to the item on top of S_p.
   (c) If $p_y > p_z$, create $e(y, z)$.
   (d) Else Pop(S_p, y), and repeat from Step 7(b).
   (e) Push(S_p, z).

Figure 5.5. Algorithm to reconstruct the structure of a tree given the set of structural positions.

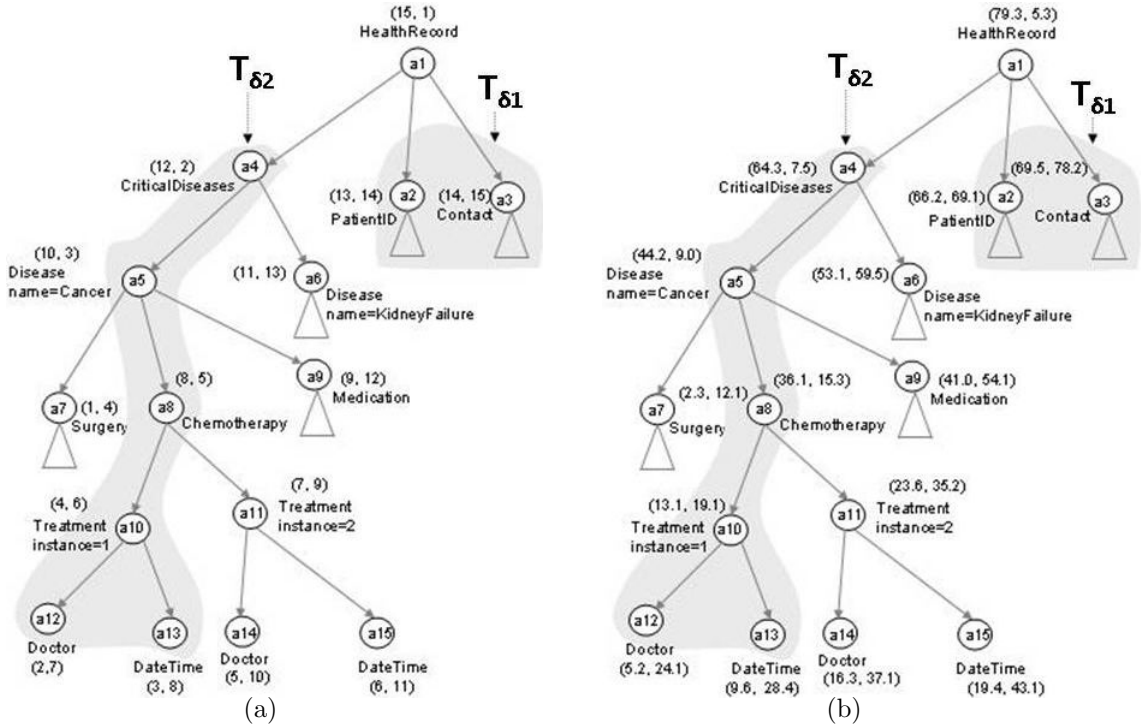


Figure 5.6. (a) Post-order and pre-order numbers assigned to the healthcare record as (PON, RON). (b) Randomized post-order and pre-order numbers assigned to the healthcare record as (RPON, RRON).

5.3.6 Illustration

Consider the tree in our running example (Figure 3.3) and suppose that the tree has been assigned post and pre-order numbers (Figure 5.6(a)) and their randomized counterparts (Figure 5.6(b)). Since the IVs and the hash values are large bit strings (e.g., 256 bits for SHA2), we do not show their actual values. The document $T(V, E)$, its signature $\sigma_{T(V,E)}$, the structural position of each node η_x, and the salt ω_T, if any, are then stored at the database server (distributor).

The cashier has access to subtree $T_{\delta 1}$. The database server D sends two nodes - a_2 and a_3, their structural positions, the tree-signature σ_T, and VO. VO is computed by D from the IVs (ξ_x) of the remaining nodes. The cashier receives two nodes a_2 and

a_3. She applies the authentication procedure which includes computing the IV of a_2 by computing the hash of the (66.2, 69.1) and c_2 (and similarly that of a_3). If the authentication is successful, then the integrity verification of structural relationships and orderings is carried out. Then because a_2 and a_3 were sent as siblings, the cashier verifies whether p_2 (=66.2), the RPON of a_2 is smaller than p_3(=69.5), the RPON of a_3; if so, then a_3 is an ancestor or a right sibling of a_2. However since r_2 (=69.1) $<$ r_3 (=78.2), a_3 is not an ancestor of a_2. Thus their relationship is correctly verified.

In the second scenario, the nurse is authorized to access $T_{\delta 2}$; however suppose he receives a tampered $T_{\delta 2}$, such that in the tampered tree, a_{10} is the child of a_5 and a left sibling of a_8. Such a violation of structural integrity can be detected by comparing the structural positions of the nodes as discussed in Section 6.2.3. The RRON of node a_{10} is greater than that of a_8, which means that a_{10} cannot be a left sibling of a_8. If a_{10} is received as the right sibling of a_8, the structural integrity is violated. Such violation is detected, because the RPON of a_{10} is smaller than that of a_8, which means that a_{10} cannot be a right sibling of a_8.

5.4 Security Analysis

This section analyzes the security of the structural signature scheme in terms of its authenticity and confidentiality guarantees with respect to information leakage defined earlier.

Lemma 5.4.1 (Name-transparency) *Under the assumption that Boldyreva et al.'s order-preserving encryption scheme OPE [26] is POPF-CCA secure, structural positions as secure names are name-transparent.*

Proof Follows from [26]. ■

Lemma 5.4.2 (Authenticity) *Under the random oracle hypothesis, and the assumption that the RSA problem is hard, $r\Pi$ = (*`rGen`*,* `rSign`*,* `rRedact`*,* `rVrfy`*) is existentially unforgeable under chosen-message attacks over subset operation over trees/graphs/forests.*

Proof [Sketch] The signature $\sigma_{T(V,E)}$ of a tree $T(V, E)$ is unforgeable under adaptive chosen message attack (CRSA under strong RSA assumption [105], or BGLS under the assumption that computational Computational Diffie-Hellman problem is hard [28]). Thus any violation to the authenticity of contents and structural positions would be detected by the structural signature scheme. Consider that an adversary $\mathcal{A}$ can compromise the content c_x or the structural position η_x of a node x in T without invalidating the structural signature of the tree, then $\mathcal{A}$ has successfully found a collision in $\mathcal{H}$, which not feasible under the random oracle hypothesis, or or $\mathcal{A}$ has been able to solve the RSA problem or the computation Diffie-Hellman problem (BGLS: [28]), efficiently, which contradicts our assumption.

Structural integrity: Any unauthorized re-ordering of two or more nodes (violation of structural integrity) can be detected using the RPON's and RRON's (Lemma 5.2.2). By the Random Oracle Hypothesis [16], it is not feasible one to find a collision in $\mathcal{H}$ function, which is why one cannot replace a node by an unauthorized one (or else the integrity verifier would be invalidated).

However, anyone can compute the signature $\sigma'_{T_\delta(V_\delta,E_\delta)}$ of a subtree T_δ of tree $T(V, E)$, without the knowledge of the secret key. Therefore, the signature scheme is existentially unforgeable against chosen message attacks over the $\subset$ operation. ■

Lemma 5.4.3 (Transparency) *Under the assumption that the order-preserving encryption scheme is POPF-CCA-secure, then $r\Pi$ preserves transparency.*

Proof [Sketch] Consider the experiment for transparency: $\texttt{Sig-Transp}^{transp}_{\mathcal{A},r\Pi}(\lambda)$ Experiment 4.4.2. The adversary $\mathcal{A}$ invokes the signing oracle, with two trees: $T(V, E)$: that x as a root of $w \prec y \prec z$; and $T_\delta(V_\delta, E_\delta)$: that x as a root of $w \prec z$; i.e., y is not

present in $T_\delta(V_\delta, E_\delta) \subset T(V, E)$. Let $\Upsilon_0(V_0, E_0)$, and $\Upsilon_0(V_0, E_0)$ refer to $T_\delta(V_\delta, E_\delta)$ and $\Upsilon_0(V_0, E_0)$ refer to $T(V, E)$.

1. $\texttt{rGen}(1^\lambda)$ is run to obtain keys `(pk, sk)`.

2. Probabilistic polynomial-time adversary $\mathcal{A}$ is given `pk` and oracle access to $\texttt{rSign}_{\texttt{sk}}(\cdot)$, $\texttt{rRedact}(\cdot)$ and $\texttt{rVrfy}_{\texttt{pk}}(\cdot)$. Let $\mathcal{Q}$ be the set of all trees/graphs/forests for which $\mathcal{A}$ queries $\texttt{rSign}_{\texttt{sk}}(\cdot)$ for their signatures.

3. $\mathcal{A}$ outputs two trees/graphs/forests $\Upsilon_0(V_0, E_0)$, and $\Upsilon_1(V_1, E_1)$, such that $\Upsilon_0(V_0, E_0) \subset \Upsilon_1(V_1, E_1)$.

4. Draw a random b uniformly from {0,1}. $(\sigma_{\Upsilon_b}, \Upsilon_b(V_b, E_b)) \leftarrow \texttt{rSign}_{\texttt{sk}}(\Upsilon_b(V_b, E_b))$. If $b = 1$, then the signature for $\Upsilon_0(V_0, E_0)$ is computed from σ_{Υ_1}: $(\sigma_{\Upsilon_0}, \Upsilon_0(V_0, E_0)) \leftarrow \texttt{rRedact}(\texttt{pk}, \sigma_{\Upsilon_1}, \Upsilon_1(V_1, E_1), V_1 \backslash V_0) E_1 \backslash E_0$. Then the *challenge* $(\sigma_{\Upsilon_0}, \Upsilon_0(V_0, E_0))$ is given to $\mathcal{A}$.

5. The adversary $\mathcal{A}$ continues to have oracle access to $\texttt{rSign}_{\texttt{sk}}(\cdot)$, $\texttt{rRedact}_{\texttt{pk}}(\cdot, \cdot)$, and $\texttt{rVrfy}_{\texttt{pk}}(\cdot)$. Eventually, $\mathcal{A}$ outputs a bit b' (for the *challenge* $(\sigma_{\Upsilon_\delta}, \Upsilon_\delta)$).

6. The output of the experiment is 1 if $b' = b$, and 0 otherwise.

Consider that $\texttt{Sig-Transp}^{transp}_{\mathcal{A}, r\Pi}(\lambda)$ returns 1. For $\texttt{Sig-Transp}^{transp}_{\mathcal{A}, r\Pi}(\lambda)$ to return 1, $\mathcal{A}$ determined the correct value of b, which in turn implies that a node (i.e., y) is missing from the set of children of x, and that w is left of this missing node, which is left of z. In other words, $\mathcal{A}$ has managed to break the POPF-CCA security of Bondyreva et al.'s symmetric order-preserving encryption, which is against our assumption. So the lemma is proven that $r\Pi$ is transparent. ■

5.5 Complexity and Performance Analysis

In this section, we present the complexity and performance analysis of the structural signatures for trees.

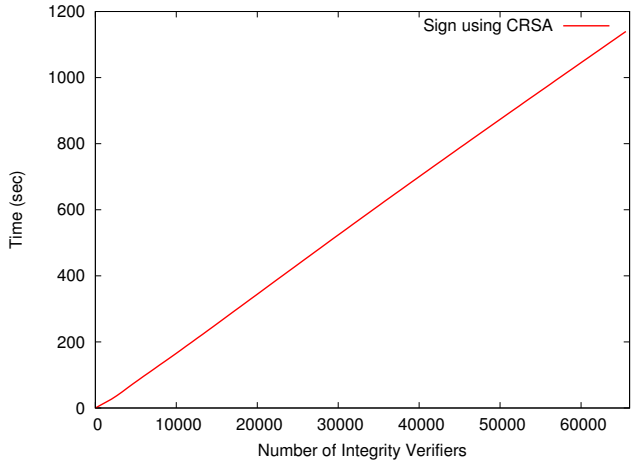


Figure 5.7. CRSA: Average time to sign versus number of IVs.

5.5.1 Complexity Analysis

Trees: The cost of signing a tree $T(V, E)$ is $O(|V|)$. The number of signatures that is computed is $|V|+1$. The number of structural positions that a user receives is the number of nodes in T_δ. The number of signatures that need to be sent to a user is 1 irrespective of the size of the subtree $T_\delta(V_\delta, E_\delta)$ that a user receives. The time to compute this aggregate signature of the subtree at the distributor is $O(|V_\delta|)$. The user receives 1 signature for the subtree $T_\delta(V_\delta, E_\delta)$, 1 signature for the complete tree, and 1 verification object VO. The verification cost for content/structural integrity is linear in terms of the size of the received subtree, that is, $O(|V_\delta|)$. The cost of comparison of RPON's and RRON's (and RIONs for binary trees) is constant.

5.5.2 Performance

We implemented the structural signature scheme and the Merkle hash technique in Java 1.6 and JCA 6.0 (Java Cryptography Architecture) APIs. The experiments were carried out on a IBM Thinkpad T61 with the following specification: 32-bit Linux (Ubuntu 10.04) on Intel Core 2 Duo CPU with 3GB RAM (2560MB as the maximum heap size for Java). Performance analysis of our BGLS-based authentication scheme

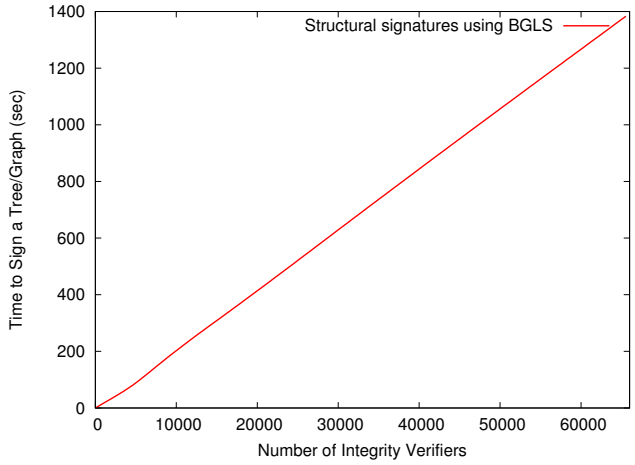


Figure 5.8. BGLS: Average time to sign versus number of IVs.

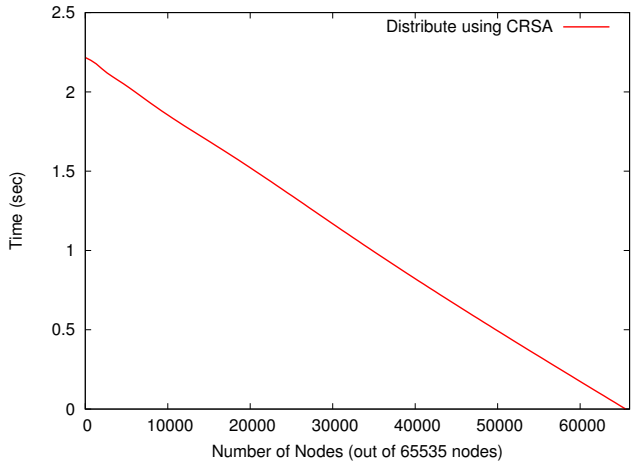


Figure 5.9. CRSA: Average time to distribute versus number of IVs.

is based on a C++ implementation. We used the implementation of pairing-based cryptography (PBC) from Stanford, OPENSSL and GMP[1].

Experiments Our experiments are on complete trees. The trees are 2-ary with the height from 1 to 16. The number of nodes in the largest tree is 65535. The subtrees used for authentication are complete left-most subtrees in a tree with the height varying from 1 to 16. We carried two experiments: one for the time taken to

[1]PBC and GMP are available at http://crypto.stanford.edu/pbc and http://gmplib.org, respectively.

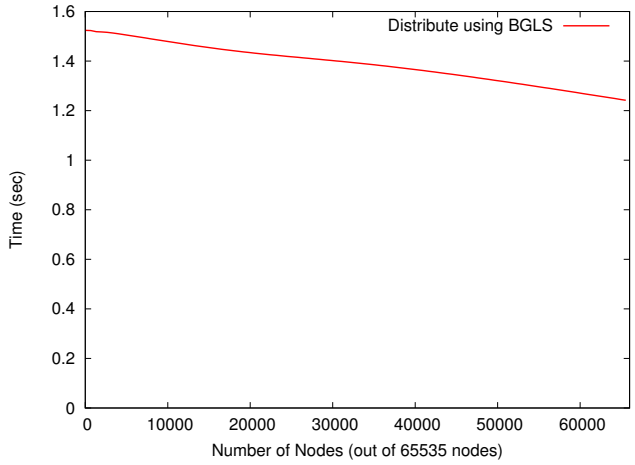


Figure 5.10. BGLS: Average time to distribute versus number of IVs.

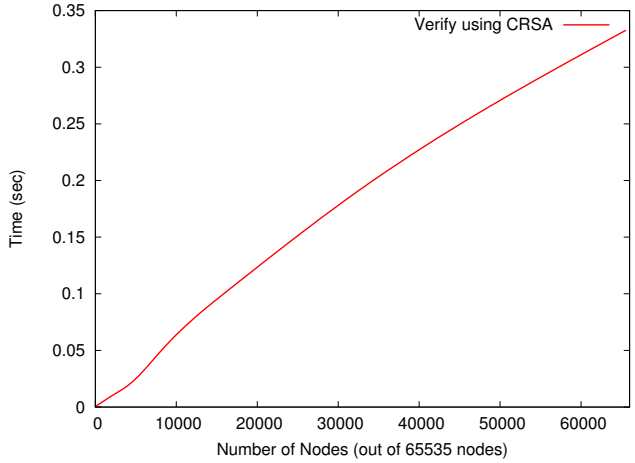


Figure 5.11. CRSA: Average time to verify versus number of nodes.

sign using CRSA-based structural signature and another using BGLS-based structural signatures. The size of RSA keys is 1024-bits and SHA1 as the hash function. We have also implemented the BGLS scheme.

CRSA Vs. BGLS The BGLS authentication scheme is much more expensive for trees than the CRSA-based scheme. This is expected [105] as the BGLS aggregate signature scheme is based on elliptic curves and bilinear maps. We proposed the use of the BGLS scheme in the paper, because cryptosystems developed on elliptic

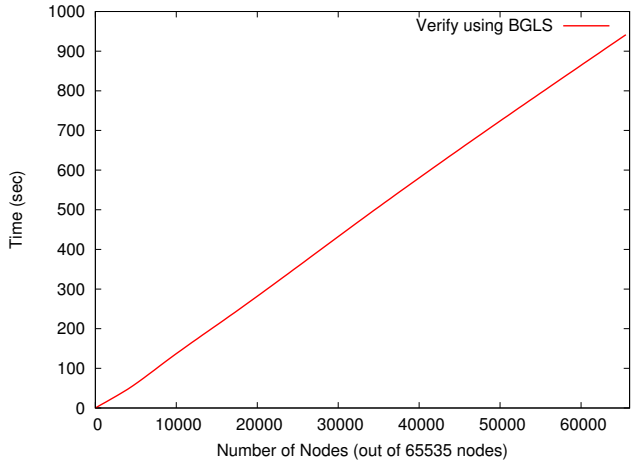


Figure 5.12. BGLS: Average time to verify versus number of nodes.

curves have already been in use as an alternative to the RSA cryptosystems. In case of BGLS however, signing a tree of n nodes and verification of a tree of the same number nodes n take the same amount of time. This can be explained by considering the cost of the bilinear operation, which is much higher than any other cost such as verification of structural relationships.

Signing: Figure 5.7 presents the performance of computing the signature of a tree using CRSA, and Figure 5.8 presents signing using BGLS based structural signatures. As mentioned above, it takes more time to compute the BGLS signatures than the CRSA signatures. Each node has one integrity verifier in a Ltree. In comparison, the less secure Merkle Hash Technique incurs much less cost (about two seconds to sign 65535 integrity verifiers using RSA) for signing a tree (the common tradeoff of cost Vs. security) as it computes a single signature. However, the cost of signing a tree with structural signatures is not an issue especially when the structural signature is computed *once* and re-used *many times* for *any* subtree.

Distribution: Figure 5.9 presents the performance of distributing subtrees with height from 1 to 16 using CRSA, and Figure 5.10 presents distribution using BGLS based structural signatures. The larger the subtree of a tree with 65535 nodes being distributed by a server, the less the number of nodes over which the verification object

VO being computed, and more the number of nodes over which the condensed (aggregate) signature is being computed. Therefore, as the size of the subtree increases (number of nodes), the cost of distribution decreases. The cost of distribution for CRSA is slightly less than that for BGLS. Pre-computed integrity verifiers of nodes are stored at the distributor, and are used in distribution.

Verification: Figure 5.11 presents the performance of verifying subtrees (that are distributed) with height from 1 to 16 using CRSA, and Figure 5.12 presents performance of verification using BGLS based structural signatures. The amount of time taken for verification using our structural signature scheme using CRSA is much less than the time required by the BGLS. BGLS takes more time than CRSA because two bilinear maps are to be applied and m number of elliptic curve computations are needed to be carried out, while for CRSA only m modular multiplications and two modular exponentiations are needed to be carried out. MHT takes more time (about 2.25 seconds for 65535 nodes) than the CRSA based structural signatures, but less than BGLS. Even small overhead in verification is significant because: (1) the time taken for user-side authentication affects the end-to-end response time at the user side, and (2) since authentication would be carried out by many users, the collective overhead would be very high, (3) for energy-constrained devices, the processing overhead of even 2.25 seconds should be avoided.

5.6 Dynamic Trees

Updates to a tree include insertions, deletions or a combination of insertions and deletions. An update to the tree is reflected by a new signature such that replay attacks cannot be carried out. If the signature does not reflect the updates, a replay attack on the authentication of dynamic trees can be carried out easily. When the owner *Alice* updates the tree $T(V, E)$ to $T'(V', E')$, a malicious distributor may continue distributing or processing queries on an older version; this can be prevented if

some extra authentication information is supplied to the user alongwith the signature. Certification validation and revocation are used in this context.

In our solution, whenever *Alice* signs an updated tree, she includes the hash of the current timestamp in the computation of the signature. In order to make all the previous signatures invalid, *Alice* publishes the latest timestamp when the current signature was computed. A signature is valid, if it contains the latest timestamp.

Insertion of nodes: Upon insertion of a node z, its structural position η_z is computed such that the RPON p_z and RRON r_z preserve correct relationships with the parent and siblings of the node. Insertion of a subtree is carried out as a sequence of insertions.

Leaf-level updates: Let z be the new leaf node in T' added as the child of x, a leaf in T. Let the lowest RPON in T be p_u, and the largest RRON in T be r_v. RPON p_z should satisfy $p_u < p_z < p_x$, and RRON r_z should satisfy $r_x < r_z < r_v$.

Root-level updates: Let x be the root node and z be the new root node added as the parent of x. RPON p_z should satisfy $p_x < p_z$, and RRON r_z should satisfy $r_z < r_x$.

Updates in-between two siblings: Let z be inserted as a new node between two siblings x and y such that x is to the left of y. RPON p_z should satisfy $p_x < p_z < p_y$, and RRON r_z should satisfy $r_x < r_z < r_y$.

Updates in-between parent and child: Let z be inserted as a new node between parent x and child y such that x is to the left of y. RPON p_z should satisfy $p_y < p_z < p_x$, and RRON r_z should satisfy $r_x < r_z < r_y$.

Let (L_p, R_p), and (L_r, R_r), respectively be the intervals in which the RPON p_z and RRON r_z of z should be in (as specified above). Computation of the RPON and RRON can be carried out as follows: repetitively select a secure random number η until $L_p < \eta < R_p$; η is assigned to p_z.

Deletion of nodes: Upon the deletion of a node or a subtree, only the signature needs to be recomputed on the remaining set of nodes (V'). The structural positions of nodes that are remaining from the old tree are not modified.

Insertion and deletion of edges: Deletion of an edge is generally followed by a insertion of a new edge and vice versa, in order to maintain the structural properties typical of trees to remain connected and to have $n-1$ edges for n nodes. If $e(x, y)$ is removed and $e(z, y)$ is inserted, then the structural position η_y of y (and all its children, if any) needs to be re-computed with respect to z. It is similar to deletion of y and then insertion of y as a child of z. The subtree rooted at y remains rooted at y. Such a process leads to re-computation of RPON and RRON of y, and the nodes in its subtree in the same manner as it is done for insertion of nodes.

Incremental computation of the signatures: *Alice* may store the current σ_x for each node $x \in V'$, so that it can be re-used during the next computation of the signature. As seen earlier, it might be necessary to re-compute RPONs and RRONs after a large number of insertions (in the order of millions for 512-bit RPONs and RRONs) between nodes. In practice, such re-computations would not occur frequently and thus are not a major concern, because in large trees (with millions of nodes), insertions get distributed over various parts of the tree. For small trees, signing (includes computation of RPONs and RRONs) is not expensive (corroborated by our experimental results). If a node is dropped, the multiplicative inverse (CRSA) or additive inverse (BGLS) of its signature (signatures in case of cyclic graphs) is computed and is used to cancel out the corresponding signature(s) of the node in the signature of the tree/graph.

Complexity: Insertion or update of a node and a subtree that has m nodes incurs $O(1)$ and $O(m)$ cost, respectively including the cost of computing one signature. Deletion of a node or a subtree incurs only the cost of computation of the signature. In con-

trast, in the case of Merkle Hash technique, an insertion or deletion of a single node z in a tree of n nodes incurs $O(log(n))$ cost in average. This is because, the Merkle hashes of all the ancestors of z are affected due to that operation (even though only one signature has to be computed). Insertion or deletion of a subtree of m nodes incurs $O(mlog(n))$ cost in the MHT.

5.7 Applications

The structural authentication scheme facilitates structural recovery of trees, which is of importance in data recovery and in digital forensics.

5.7.1 Automatic Recovery from Structural Errors

Consider the case in which the nodes (contents and structural positions) in a tree are not compromised, but their structural integrity is compromised by compromising the edge relationships and sibling orderings (as specified in the adjacency list or other means). From the structural positions (RPONs and RRONs), the correct structure of the tree can be easily re-constructed. Such a capability helps automatic correction of data without any interaction with the distributor. The cost of such re-construction is $O(|V|)$ for a tree $T(V, E)$.

For example, suppose that two nodes x and y are received and are authenticated against the signature. However, the structural integrity is found to be invalid. Suppose that the ordering that y is left of x is the received (but incorrect) order for these nodes in a subtree. The user tests using the structural positions if x is left of y. If the test succeeds, the correct order is recovered. If there are many nodes with their structural integrity found to be invalid, the reconstruction algorithm is applied to re-construct the structure of the subtree.

Structure-based Routing: Secure Publish/Subscribe of XML: The structural signature scheme can be used for secure dissemination of XML documents (and of data

objects organized as trees, in general) in a publish-subscribe model. Chapter 8 describes this scheme of structure-based routing in detail.

5.8 Summary

In this chapter, we proposed the notion of structural signatures in order to assure authenticity of subtrees and subgraphs without leaking. The notion of structural signatures for trees is based on the simple notion of tree traversals and the fact that a combination of two tree traversals - post-order and pre-order can be used to uniquely re-construct a tree and any of its subtrees. The number of signatures computed is linear in the number of nodes. However, the number of signatures that are sent to the user by the distributor is constant: 2. In terms of complexity, the scheme for trees incurs $O(n)$ cost for time and storage (n is the number of nodes in a tree). In this chapter, we have also discussed two important applications of the proposed structural signatures scheme for trees. One in the area of automatic data recovery from errors - our scheme is capable of automatic correction of structural errors in the data with no extra overhead. The other application is the secure publish/subscribe of XML documents using structure-based routing. This technique is an extension to our earlier work, and is more secure and efficient.

6 STRUCTURAL SIGNATURES FOR GRAPHS

The origins of graph theory are humble, even frivolous.
N. Biggs, E. K. Lloyd, and R. J. Wilson [23]

In the previous chapter, we have described a scheme for authentication of a single subtree that is based on the notion of depth first traversal numbers - pre-order numbers and post-order numbers. However, this scheme cannot be directly applied to graphs, because graphs are structurally different from trees, and graphs with cycles cannot be topologically sorted.

In this chapter, we propose two schemes on how to *authenticate* DAGs and directed cyclic graphs *without leaking*, which are the first such schemes in the literature. It is based on the structure of the graph as defined by depth-first graph traversals and aggregate signatures. Graphs are structurally different from trees in that they have four types of edges: tree, forward, cross, and back-edges in a depth-first traversal. The fact that an edge is a forward, cross or a back-edge conveys information that is sensitive in several contexts. Moreover, back-edges pose a more difficult problem than the one posed by forward, and cross-edges primarily because back-edges add bidirectional properties to graphs. We prove that the proposed technique is *both* authenticity-preserving and non-leaking. While providing such strong security properties, our scheme is also efficient, as supported by the performance results. The common notations used in this chaper are given in Table 6.

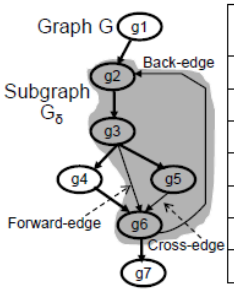
6.1 Background

Graphs contains edges that can be organized into four different types based on a specific depth first traversal of the graph: tree-edges, forward-edges, cross-edges and back-edges (related to cycles), while trees have only one type of edges: tree-

Table 6.1
Acronyms and notations

Notation/Acro.	*Meaning*
α	Related to *forward*, the direction of forward-, cross- and tree-edges.
β	Related to *backward*, the direction of back-edges. Used in the context of β-nodes and β-*reachable* nodes.
f, χ, τ	For forward-, cross- & tree-edges.
q_x^{χ}, r_x^{χ}	χ-RON of x, χ-RRON of x.
$o_x^{\beta:u\to v}$, $p_x^{\beta:u\to v}$, $q_x^{\beta:u\to v}$, $r_x^{\beta:u\to v}$	β-PON, β-RPON, β-RON, β-RRON, resp. of x with respect to a *not-*β*-covered* back-edge $e(u,v)$.
η_x^{τ}, η_x^{χ}	Structural position of τ- or χ-node x.
$\eta_x^{\beta:u\to v}$,$\sigma_x^{\beta:u\to v}$	Structural position/signature resp., of a β-node or β-*reachable* node x, with respect to a *not-*β*-covered* back-edge $e(u,v)$.
σ_x^{α}	Forward structural signature of x. (same as α-signature of x).
σ_G^{α}	Structural signature of DAG G. Also referred to as α-signature of G.
σ_G	Structural signature of graph G.
$\overset{\cup}{\leftarrow}$	Union of the left set with the right set followed by the assignment of the result to the left set.

edges [77]. Depth-first traversal numbers are used to determine the type of an edge for that specific traversal Such numbers are assigned to a node in the order in which



Node	Post-order	Pre-order
g1	7	1
g2	6	2
g3	5	3
g4	3	4
g5	4	7
g6	2	5
g7	1	6

Figure 6.1. A graph with depth-first tree in bold.

they are visited in a specific traversal; for example, post-order and pre-order numbers are assigned to the nodes in post-order and pre-order traversals, respectively. (For more details, the reader is referred to [77]). The various types of edges in a graph are defined below using the notion of traversal numbers.

Definition 6.1.1 *Let τ be the depth-first tree (DFT) of a directed graph $G(V, E)$. Let x, $y \in V$, and $e(x, y) \in E$. Let o_x and q_x refer to post-order number and pre-order number of node x, respectively. With respect to the DFT τ, $e(x, y)$ is a (1) tree-edge, iff $o_x > o_y$, and $q_x < q_y$; (2) forward-edge, iff there is a path from x to y consisting of more than one tree-edges, $o_x > o_y$, and $q_x < q_y$; (3) cross-edge, iff $o_x > o_y$, and $q_x > q_y$; (4) back-edge, iff $o_x < o_y$, and $q_x > q_y$.*

An example of depth-first tree, types of edges are given in Figure 1.1 with the post- and pre-order numbers for each node being given in the table in the figure. An authenticity-preserving and confidentiality-preserving scheme for graph data must not convey the knowledge of whether a given edge is a forward-edge (edge $e(g_3, g_6)$), a cross-edge (edge $e(g_5, g_6)$) or a back-edge (edge $e(g_6, g_2)$), unless the user is authorized to access a corresponding tree-edge(s) or the associated cycle, respectively. The information leakages due to the knowledge about the type of the edge are listed in Table 6.1. Such leakages are described in detail in the context of health information in Section 3.3. Whether an edge is a back or a cross-edge can be determined using both post-order and pre-order numbers [77], as the above definition specifies.

Table 6.2
Information leakages via edge-types.

Type of $e(x, y)$	*Associated information leakages*
Forward-edge	(i) in-degree of $y \geq 2$. (ii) ≥ 2 edges e' incident on y. (iii) e' is a tree-edge. (iv)≥ 2 nodes w, such that $x \ldots w \ldots y$ is a simple path. (v) G is larger than the G_δ.
Cross-edge	(i), (ii), (v).
Back-edge	(a) ≥ 1 simple path from y to x. (b) ≥ 1 cycle in the graph, (c) one cycle between x, y; (d) (v).

In the remaining sections of this chapter, we first propose the structural signatures for DAGs, and then the structural signatures for graphs with cycles.

6.2 DAGs

In this section, we develop structural signatures for DAGs. Table 6.1 summarizes the common acronyms and notations that are used for DAGs and graphs. Consider a user authorized to access one or more cross-edges incident upon a node x, but not the associated tree-edge(s). With reference to Figure 3.4, the user has access only to $e(g_{11}, g_{12})$, which is a cross-edge. One way to share a forward or cross-edge with the user, without leaking it to the user the type of the edge (such as the fact that "$e(g_{11}, g_{12})$ is a cross-edge") is to convey to the user that it is a tree-edge. By concealing the original type of an edge (such as forward or cross-edge) and conveying to the user that any edge it receives is of type tree-edge, unless the user also receives the associated tree-edge(s), we can prevent leakages associated with cross-edges. Note

that the structural signature makes use of the notion of traversal numbers, and that post-order and pre-order numbers allows one to detect whether an edge is a cross-edge or not (Definition 6.1.1). Moreover, such numbers cannot be used to differentiate a forward-edge from a tree-edge.

We thus need to define a different notion of traversal numbers so that a cross-edge would be verified by Bob as a *tree-edge*. In that context, we refer to the end-point of cross-edge(s) as a χ-node. By Definition 6.1.1, it is the pre-order number (and not the post-order number) of a χ-node that violates the behavior of pre-order numbers that is exhibited in case of tree-edges. We first define a variant of the pre-order numbers denoted by χ-pre-order numbers (in short, χ-RONs) (Definition 6.2.2) specifically for χ-nodes. Using a randomized notion of such variants of pre-order numbers, denoted by χ-randomized pre-order numbers (in short, χ-RRONs), we define a structural position of a χ-node that satisfies the constraints of a tree-edge in terms of traversal numbers (Definition 6.1.1). Such a notion of structural position is then used to compute the aggregate signature for the DAG. Since the definitions of χ-RONs and χ-RRONs are specific to cross-edges and χ-nodes only, tree-edges are always conveyed as they are.

Given that the tree-edges, forward-edges, and cross-edges have the same direction, we refer to the signatures for DAGs as *forward-signatures* (denoted by α-signatures). A node that is not a χ-node such as g_3 in Figure 3.4, is referred to as a tree-node (in short, τ-node).

Definition 6.2.1 (χ-node) *A node x in a connected directed acyclic graph $G(V, E)$ is a χ-node, iff there exists an edge $e(w, x)$ in G such that $e(w, x)$ is a cross-edge.*

Definition 6.2.2 (χ-RONs) *Let x be a χ-node in a connected directed acyclic graph $G(V, E)$. Let $e(w, x)$ and $e(x, y)$ be two edges in G. The χ-pre-order numbers of x and w denoted by q_x^χ and q_w^χ are defined such that they satisfy the following conditions:(1) $q_x^\chi > q_x^\tau$; (2) if w is a χ-node, $q_x^\chi > q_w^\chi$, else $q_x^\chi > q_w^\tau$; (3) $q_x^\chi < q_y^\tau$; (4) $q_u^\chi < q_x^\chi < q_v^\chi$, where u, x, and v are siblings and $u \prec x \prec v$.*

Since a DAG can be topologically-ordered, the properties of a χ-pre-order number can be satisfied. For a χ-node x, its χ-randomized pre-order number (χ-RRON) is the randomized version of q_x^χ and is denoted by r_x^χ. It is defined in the same way RPON is defined for PON and RRON for RON.

In our running example (Figure 3.4), g_{10} and g_{12} are χ-nodes; $r_{g_{10}}^\chi$ and $r_{g_{12}}^\chi$ are the χ-RRONs of g_{10} and g_{12}. The notions of τ-structural and χ-structural position (τ-position and χ-position in short, respectively) of a τ-node and a χ-node, respectively are defined by the following definitions.

Definition 6.2.3 (τ-structural position) *Let x be a node in a connected DAG $G(V, E)$. Its τ-structural position, denoted by η_x^τ, is defined as: η_x^τ=(p_x^τ, r_x^τ).*

Definition 6.2.4 (χ-structural position) *Let x be a χ-node in a connected DAG $G(V, E)$. Its χ-structural position, denoted by η_x^χ, is defined as: η_x^χ=(p_x^τ, r_x^χ).*

In our running example (Figure 3.4), the τ-structural position of node g_3 is $\eta_x^\tau = (p_{g_3}^\tau, r_{g_3}^\tau)$; for χ-node g_{10}, its χ-structural position is $\eta_x^\chi = (p_{g_{10}}^\tau, r_{g_{10}}^\chi)$.

6.2.1 Signing a DAG

The algorithm to sign a DAG is described in Figure 6.2.

Definition 6.2.5 (Integrity Verifier of a Node) *Let x be a node in a connected DAG $G(V, E)$. Let $\mathcal{H}$ denote a one-way cryptographic hash function. The integrity verifier ξ_x of x is defined as follows: $\xi_x = \mathcal{H}(\eta_x \| c_x)$, where: if x is a χ-node, η_x is equal to η_x^χ, else it is equal to η_x^τ.*

Definition 6.2.6 (Signature of a DAG using CRSA) *Let $\mathcal{H}$ denote a random oracle, and ω_G be a random. The signature σ_x of a node x is defined as: $\sigma_x \leftarrow \xi_x^{\bar{d}} \bmod \bar{n}$, where ξ_x is the IV of x. The structural signature of a graph $G(V, E)$, denoted by $\sigma_{G(V,E)}$, is defined as follows:*

$$\sigma_{G(V,E)} \leftarrow (\omega_G \prod_{x \in V} \xi_x)^{\bar{d}} \pmod{\bar{n}}. \tag{6.1}$$

Definition 6.2.7 (Signature of a DAG using BGLS) *Let $\mathcal{H}$ denote a random oracle, and ω_G be a random. Let* sk *be the private key and* P *be defined as in an aggregate signature framework. Let ω_G be a random. The signature σ_x of a node x is defined as: $\sigma_x \leftarrow \mathtt{sk}\xi_x$. The structural signature of a graph $G(V, E)$, denoted by $\sigma_{G(V,E)}$, is defined as follows:*

$$\sigma_{G(V,E)} \leftarrow\ e(\mathtt{P}, \mathtt{sk}(\omega_{\mathtt{G}} + \sum_{\mathtt{x} \in \mathtt{V}} \xi_{\mathtt{x}})). \tag{6.2}$$

6.2.2 Distribution

Let $G_\delta(V_\delta, E_\delta)$ be an arbitrary weakly connected subgraph of the weakly connected DAG $G(V, E)$. A weakly connected (directed) graph is one in which if all the edges are changed from being directed to undirected, the graph turns into a connected one [45]. D sends the following items to *Bob*: (1) $G_\delta(V_\delta, E_\delta)$, and (2) $\sigma'_{G_\delta} = (\{\eta_x, \sigma_x | x \in V_\delta\}, \sigma_G, \sigma_{G_\delta}, VO)$ the set of verification units $\mathcal{VO}_{G_\delta(V_\delta, E_\delta)}$ consisting of the signature of the DAG σ_G, the integrity verifier of the subgraph ξ_{G_δ}, and aggregate signature of the subgraph σ_{G_δ}. ξ_{G_δ} and σ_{G_δ} are computed as follows. The computation of one bilinear map in the BGLS step is to balance the work done between the distributor and the user(s). If the distributor does not carry out the bilinear mapping, then the user has to carry out two mappings.

6.2.3 Authentication

Figure 6.4 summarizes the interactions between *Alice*, *D* and *Bob*. A user *Bob* receives (1) a subgraph $G_\delta(V_\delta, E_\delta)$, (2) the signature of the DAG σ_G, and (3) the verification object $\mathcal{VO}$ of the subgraph from the distributor *D*. The verification process goes as follows.

Verification of Contents: If (2) (or 4) is invalid and (1) (resp., 3) is valid, then some nodes have been dropped from the subgraph (i.e., G_δ does not contain some

`rSign`:

1. Execute a depth-first traversal of $G(V, E)$.
2. For each node $x \in V$, compute its post-order number o_x^τ and pre-order number q_x^τ.
3. If $e(w, x) \in E$ is such that $(o_w^\tau > o_x^\tau)$ and $(q_w^\tau > q_x^\tau)$, then mark $e(w, x)$ as a χ-edge and x as a χ-node.
4. For each χ-node, compute its χ-RON $q_\cdot^\chi$
5. For all nodes in V, transform the traversal numbers into traversal numbers, that preserve the order.
6. For a χ-node x, $\eta_x^\chi \leftarrow (p_x^\tau, r_x^\chi)$.
7. For each x that is *not* a χ-node, assign (p_x^τ, r_x^τ) to x as its structural position η_x^τ.
8. For each node x in V, compute its integrity verifier ξ_x:
   (a) If x is a cross-node, $\eta_x \leftarrow \eta_x^\chi$; Else $\eta_x \leftarrow \eta_x^\tau$.
   (b) $\xi_x \leftarrow \mathcal{H}(\eta_x \| c_x)$.
9. Choose a random ω_G.
10. Compute the signature of the DAG either using CRSA (equation 6.1) or using BGLS (equation 6.2).

Figure 6.2. Algorithm to sign a DAG.

of the nodes), ξ is tampered with, and/or the signature σ_G has been tampered with. Otherwise if (1) (or 3) is invalid, and (2) (resp., 4) is valid then some nodes in G_δ are not authentic.

rRedact:

1. CRSA: $\mathcal{VO} \leftarrow \omega_G \prod_{y \in (V - V_\delta)} \xi_y \ mod \ \bar{n}.$
2. CRSA: $\sigma_{G_\delta} \leftarrow \prod_{y \in (V)} \sigma_y \ mod \ \bar{n}.$
3. BGLS: $\mathcal{VO} \leftarrow \omega_G + \sum_{y \in (V - V_\delta)} \xi_y.$
4. BGLS: $\sigma_{G_\delta} \leftarrow e(\mathtt{P}, \sum_{\mathtt{y} \in (\mathtt{V}_\delta)} \sigma_{\mathtt{y}}).$

Figure 6.3. Algorithm to redact a DAG.

$$Alice \xrightarrow{G(V,E),\{\eta_x^\tau \ or \ \eta_x^\chi,\sigma_x | x \in V\},\sigma_G} D.$$

$$D \xrightarrow{G_\delta(V_\delta,E_\delta),\sigma'_{G_\delta}=(\{\eta_x,\sigma_x | x \in V_\delta\},\sigma_G,\sigma_{G_\delta},\mathcal{VO})} Bob.$$

Figure 6.4. Protocol for DAGs.

Verification of Structural Relations Verification of structural relations in a DAG involves traversing the DAG and comparing the RPON (RRON) of each node with the RPON (RRON) of its parent or its sibling. The steps are given in Figure 6.2.3.

Example: Suppose that the back-edge $e(g_{14}, g_9)$ did not exist in our running example (Figure 3.4), thus turning this graph into a DAG. In such a DAG, the cross-edges are $e(g_{11}, g_{12})$, $e(g_8, g_{10})$, and $e(g_3, g_{10})$. Consider the cross-edge $e(g_{11}, g_{12})$ and the cross-node g_{12}. The α-structural signatures for this DAG are computed such that r^χ_{g12} is larger than r^χ_{g11} and p^τ_{g12} is smaller than p^τ_{g11}, which conveys that $e(g_{11}, g_{12})$ is a tree-edge and conceals the fact that it is a cross-edge.

`rVrfy`:

Authentication of contents:

1. CRSA: $\prod_{y \in V_\delta} \xi_y \ mod \ \bar{n} \stackrel{?}{=} \sigma_{G_\delta}$.
2. CRSA: $\mathcal{VO} \prod_{y \in V_\delta} \xi_y \ mod \ \bar{n} \stackrel{?}{=} \sigma_G$
3. BGLS: $e(\mathtt{Q}, \sum_{\mathtt{y} \in \mathtt{V}_\delta} \xi_\mathtt{y}) \stackrel{?}{=} \sigma_{\mathtt{G}_\delta}$.
4. BGLS: $e(\mathtt{Q}, \Omega + \mathcal{VO}) \stackrel{?}{=} \sigma_\mathtt{G}$, where $\Omega \leftarrow \sum_{y \in V_\delta} \mathcal{H}(\eta_y \parallel c_y)$.

Verification of structural relations:

1. Execute a depth-first traversal of G_δ.
2. Let x be an immediate ancestor of z; if ($p_x \leq p_z$) or ($r_x \geq r_z$), then this relationship between x and z is incorrect.
3. For ordered-DAGs, let y be the right sibling of z; if ($p_z \geq p_y$) or ($r_z \geq r_y$), then the left-right order among the siblings y and z is incorrect.

Figure 6.5. Algorithm to authenticate a DAG.

6.3 Graphs with Cycles

In this section, we build on the solution for DAGs and present the general solution for graphs with cycles that handles all the four types of edges. Like in the case of DAGs, in our scheme, a user verifies a back-edge as a tree-edge, in order to conceal the fact that it is a back-edge and thus it prevents the leakages associated with it.

A back-edge (such as $e(g_{14}, g_9)$ in the graph in Figure 3.4) should be presented to the user as a tree-edge unless the user has access to an cycle associated with the back-edge also. Following Definition 6.1.1, both the post-order and pre-order numbers of a node (e.g., g_{14}), which is the origin of a back-edge (denoted by β-nodes), violate

the behavior of the respective numbers that is exhibited in case of tree-edges. In order to handle back-edges, we define a notion of β-post-order number (β-PON) and β-pre-order number (β-RON) for each node that either is a β-node or is reachable from a β-node over a simple path. Nodes that are reachable from a β-node x over a simple path over a β-edge $e(x, w)$, also need to be considered for the following reason. The integrity verifier of such nodes must be such that when they are presented to an authenticity prover along-with the related back-edge $e(x, w)$, they should not leak the fact that $e(x, w)$ is a back-edge; rather they should be consistent with the information presented to the prover that $e(x, w)$ is a tree-edge. Examples of *β-reachable* nodes from the β-node g_{14} in Figure 3.4 are g_9, g_{11}, g_{12}, g_{15} and g_{16}.

We define the notion of β-nodes like the notion of χ-nodes. β-nodes are nodes that are origins of back-edges (Definition 6.3.1). We then define the notion of *β-reachable* nodes (Definition 6.3.2). Our goal is to be able to provide the prover with a set of verification items about back-edges and *β-reachable* nodes such that the prover would learn that all the edges it received are tree-edges (since she does not have any right to learn otherwise). In order to define such signatures, we define a variant of PON and RON for such nodes (Definition 6.3.4). Such variants satisfy the property of tree-edges in terms of traversal numbers.

Definition 6.3.1 (β-node) *A node x in a graph $G(V, E)$ is a β-node, iff there exists an edge $e(x, w)$ in G such that $e(x, w)$ is a back-edge.*

Definition 6.3.2 (β-reachable) *Let node x be a β-node in a graph $G(V, E)$ and let $e(x, w)$ be a back-edge. A node y is said to be* β-reachable *from x (over $e(x, w)$) in G iff either y is w or there exists a simple path $sp(x, y)$ from x to y in G such that $sp(x, y) = x \rightarrow w \ldots \rightarrow y$.*

Unlike the case of cross-edges (Section 6.2), in the case of back-edges, a β-node or a *β-reachable* node has the following position(s) and integrity verifier(s): (1) β-structural; and (2) χ-structural, if it is a χ-node, τ-structural, otherwise. A β-node, or a node that is *β-reachable*, may have multiple β-structural positions (β-positions

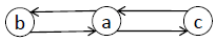


Figure 6.6. Illustration of not-β-covered edges.

in short) and integrity verifiers. A given node may be reachable from multiple back-edges over a simple-path. We only need to consider a minimal set of such edges, which are not covered by other back-edges in a simple-path. Such back-edges are called *not-β-covered* (Definition 6.3.3). The number of such positions and integrity verifiers for a node is the same as the number of *not-β-covered* back-edges (Definition 6.3.3) from which it is reachable over a simple path. However, a user receives *one* position per node. If a user does not have access to a cycle, but to the associated back-edge, the β-structural position and signature are sent to the user. However, if she has access to the cycle, conveying the fact that one of the edges in the cycle is a back-edge does not leak any information. In what follows, $x \rightarrow y$ denotes the edge $e(x, y)$ and $y \ldots \rightarrow z$ denotes the simple path $sp(y, z)$ from y to z.

In a graph, a node maybe *β-reachable* from many back-edges. The question is do we need to consider only one of them or "some" of them in order to minimize the number of β-positions. Consider the graph in Figure 6.6 with a as the root of the depth-first tree; edges $e(a, b)$ and $e(a, c)$ are the tree-edges. Edges $e(b, a)$ and $e(c, a)$ are back-edges. Both b and c are β-nodes. a is *β-reachable* from both b and c. The question is would there be one or two β-positions for a. If a user has access to all nodes and only the back-edges, then how would both of them be proven as tree-edges. To this end, let us first define β-covered and not-β-covered edges.

Definition 6.3.3 (β-covered, not-β-covered) *A back-edge $e(u, v)$ is said to be "β-covered" by another back-edge $e(x, y)$ in graph $G(V, E)$ iff there is a simple path $sp(x, v)$ in G such that $sp(x, v) = x \rightarrow y \ldots \rightarrow u \rightarrow v$. A back-edge $e(u, v)$ is said to be "not-β-covered" iff there exists no such back-edge $e(x, y)$ in G.*

β-structural positions are assigned to nodes as follows: for each node x that is β-reachable from a not-β-covered back-edge $e(u, v)$, a β-position is assigned to x for each such $e(u, v)$. In order to define the constituents of a β-position, we define β-PONs and β-RONs next.

Definition 6.3.4 (β-PONs, β-RONs) *Let $e(x, w)$ and $e(y, z)$ be back-edges in graph $G(V, E)$. Let $e(x, w)$ be not-β-covered and $e(y, z)$ be β-covered by $e(x, w)$. The β-post-order (β-pre-order) numbers of x, w, y and z with respect to $e(x, w)$, denoted by $o_x^{\beta:x\to w}$, $o_w^{\beta:x\to w}$, $o_y^{\beta:x\to w}$, and $o_z^{\beta:x\to w}$, respectively ($q_x^{\beta:x\to w}$, $q_w^{\beta:x\to w}$, $q_y^{\beta:x\to w}$, and $q_z^{\beta:x\to w}$, respectively) satisfy the following conditions:*
(1) $o_x^{\beta:x\to w}$=o_x^{τ}; if x is a χ-node $q_x^{\beta:x\to w}$= q_x^{χ}, else $q_x^{\beta:x\to w}$= q_x^{τ};
(2) $o_w^{\beta:x\to w}$< $o_x^{\beta:x\to w}$; $q_w^{\beta:x\to w}$ > $q_x^{\beta:x\to w}$;
(3) $o_z^{\beta:x\to w}$<$o_y^{\beta:x\to w}$<$o_w^{\beta:x\to w}$; $q_z^{\beta:x\to w}$>$q_y^{\beta:x\to w}$>$q_w^{\beta:x\to w}$.

For a β-node x, the randomized versions of its β-post-order number with respect to $e(x, w)$ $o_x^{\beta:x\to w}$ and β-pre-order number $q_x^{\beta:x\to w}$ are denoted by $p_x^{\beta:x\to w}$ and $r_x^{\beta:x\to w}$, respectively and are defined in the same manner as RPON is defined for PON and RRON for RON. In order to define α-signatures for non-acyclic graphs, the χ-pre-order-numbers for χ-nodes are defined below with an additional constraint related to back-edges, but without changing their properties in Definition 6.2.2. Difference from Definition 6.2.2 is "such that neither of them is a back-edge".

Definition 6.3.5 (χ-RONs) *Let x be a χ-node in a connected directed graph $G(V, E)$. Let $e(w, x)$ and $e(x, y)$ be edges in G "such that neither of them is a back-edge". The χ-pre-order number of x and w denoted by q_x^{χ} and q_w^{χ}, respectively, satisfy the following conditions:(1) $q_x^{\chi} > q_x^{\tau}$; (2) if w is a χ-node, $q_x^{\chi} > q_w^{\chi}$, else $q_x^{\chi} > q_w^{\tau}$; and (3) $q_x^{\chi} < q_y^{\tau}$.*

Definition 6.3.6 (β-structural position) *Let x be a node, which is* β-reachable *from y over the not-β-covered back-edge $e(y, z)$ in a graph $G(V, E)$. The β-structural*

position of x with respect to $e(y,z)$ denoted by $\eta_x^{\beta:y\rightarrow z}$, is defined as the pair of its β-RPON $p_x^{\beta:y\rightarrow z}$ and β-RRON $r_x^{\beta:y\rightarrow z}$, that is, $\eta_x^{\beta:y\rightarrow z} = (p_x^{\beta:y\rightarrow z}, r_x^{\beta:y\rightarrow z})$. Similarly, the β-structural position of y with respect to $e(y,z)$ denoted by $\eta_y^{\beta:y\rightarrow z} = (p_y^{\beta:y\rightarrow z}, r_y^{\beta:y\rightarrow z})$.

If a node is a β-node, it is also a τ-node or a χ-node. However if a node is a χ-node it is not a τ-node and vice versa. The integrity verifiers associated with β-nodes, *β-reachable* nodes and back-edges are called backward signatures (β-integrity verifier in short). Each node has a α-integrity verifier. Moreover, if a node x is *β-reachable* from a not-β-covered back-edge $e(y,z)$ in G, it has a β-integrity verifier $\sigma_x^{\beta:y\rightarrow z}$.

Definition 6.3.7 (β-integrity verifier of a Node) *Let x be a node and $e(y,z)$ be a not-β-covered edge in a weakly connected directed graph $G(V,E)$ such that x is β-*reachable *from y over $e(y,z)$. The β-structural integrity verifier of x, denoted by $\xi_x^{\beta:y\rightarrow z}$, is defined as $\xi_x^{\beta:y\rightarrow z} = \mathcal{H}(\eta_x^{\beta:y\rightarrow z}\|c_x)$. The β-structural signature of the β-node y, denoted by $\xi_y^{\beta:y\rightarrow z}$, is defined as $\xi_y^{\beta:y\rightarrow z} = \mathcal{H}(\eta_y^{\beta:y\rightarrow z}\|c_y)$.*

Definition 6.3.8 (Signature of a Graph using CRSA) *Let $\mathcal{H}$ denote a random oracle, and ω_G be a random. The signature σ_x of a node x is defined as: $\sigma_x \leftarrow \xi_x^{\bar{d}} \bmod \bar{n}$, where ξ_x is the IV of x. The structural signature of a graph $G(V,E)$, denoted by $\sigma_{G(V,E)}$, is defined as follows:*

$$\sigma_{G(V,E)} \leftarrow (\omega_G \prod_{x\in V} \xi_x^{\alpha} \prod_{x\in V} \prod_{e(y,z)\in S_x} \xi_x^{\beta:y\rightarrow z})^{\bar{d}} \bmod \bar{n}. \tag{6.3}$$

Definition 6.3.9 (Signature of a Graph using BGLS) *Let ω_G be a random. The signature σ_x of each node x is defined as: $\sigma_x \leftarrow \mathtt{sk}(\xi_x^{\alpha} + \sum_{e(y,z)\in S_x} \xi_x^{\beta:y\rightarrow z})$. Let S_x be the set of not-β-covered edges from each of which x is β-reachable. The structural signature of a graph $G(V,E)$, denoted by $\sigma_{G(V,E)}$, is defined as follows:*

$$\sigma_{G(V,E)} \leftarrow e(\mathtt{P}, \mathtt{sk}(\omega_{\mathtt{G}} + \sum_{\mathtt{x}\in\mathtt{V}} \xi_{\mathtt{x}}^{\alpha} + \sum_{\mathtt{x}\in\mathtt{V}} \sum_{\mathtt{e(y,z)}\in\mathtt{S_x}} \xi_{\mathtt{x}}^{\beta:\mathtt{y}\rightarrow\mathtt{z}})). \tag{6.4}$$

6.3.1 Signing a Graph

The steps that the trusted owner Alice uses to sign and share a graph $G(V, E)$ with Bob are presented in Figure 6.7. How the set of not-β-covered back-edges are determined is stated by Lemma 6.3.1. *Answer freshness* can be achieved by using a timestamp in the computation of the signature, which would deter replay attacks.

Lemma 6.3.1 *In a graph G, the β-node u that has the lowest o_u^τ among all β-nodes is such that a back-edge $e(u, v)$ in G is* not-β-covered *by any other back-edge.*

Proof Let w be a node and $e(w, x)$ be a back-edge in G such that $e(u, v)$ is β-covered by $e(w, x)$. In such a case, by the property of post-order numbers, the depth-first traversal would assign a post-order number o_w^τ to w such that $o_w^\tau < o_u^\tau$, which is a contradiction. ■

6.3.2 Distribution

In this section, we show how to provide an optimal distribution technique that sends only $O(1)$ integrity verifiers to the user.

D sends the following items to *Bob*: $G_\delta(V_\delta, E_\delta)$, the signature of the graph σ_G, and a verification object of the subgraph $\mathcal{VO}$. The set of verification units $\sigma_{G_\delta(V_\delta, E_\delta)}$ = $\{\sigma_G,\ \mathcal{VO},\ \sigma_{G_\delta}\}$. $\mathcal{VO}$ is computed as shows in Figure 6.9, which is continued in Figure 6.10.

6.3.3 Authentication

Figure 6.11 summarizes the interactions between *Alice*, *D* and *Bob*. *Bob* receives (1) a subgraph $G_\delta(V_\delta, E_\delta)$, (2) the signature of the graph σ_G, and (3) σ'_{G_δ}. The user verifies the authenticity of the contents as well as the structural position of the nodes in G_δ by using the aggregate signature $\sigma_{G_\delta(V_\delta, E_\delta)}$. The process for verification

of contents is same as the process described in Section 6.2.3. The algorithm given in Figure 6.12 are used to verify the contents authenticity of structural relations.

Using the depth-first traversal carried out during authentication of structural relations, it is easy to determine if x is a β-node or $e(x, z)$ is a β-edge in $G_\delta(V_\delta, E_\delta)$ (Definition 6.1.1). We just need to initialize a pair of new pre-order and post-order numbers of each node to -1. These numbers are different than the ones that have been received as signature items. For each edge $e(x, z)$, if the PON of z is already computed (i.e., its value is larger than -1), then $e(x, z)$ is not a back-edge, which implies that x is not a β-node.

Example: Consider our running example in Figure 3.4. Edge $e(g_{14}, g_9)$ is a back-edge; g_{14} is a β-node but is not *β-reachable* (and is the one with minimum p^{τ}_{g14}) (Lemma 6.3.1). Therefore the computation of β-signatures, i.e. step 2(a) starts from g_{14}. The *β-reachable* nodes are g_9, g_{11}, g_{12}, g_{15} and g_{16}. Notice that nodes g_{11} and g_{12} are also χ-nodes. β-structural signatures are defined for each of these nodes. χ-structural signatures are defined for g_{11} and g_{12} and τ-structural signatures are defined for g_{14}, g_9, g_{15} and g_{16}. The information that (1) $p^{\beta:g_{14}\rightarrow g_9}_{g14}$ is larger than $p^{\beta:g_{14}\rightarrow g_9}_{g9}$ and (2) $r^{\beta:g_{14}\rightarrow g_9}_{g14}$ is smaller than $r^{\beta:g_{14}\rightarrow g_9}_{g9}$, convey the prover that $e(g_{14}, g_9)$ is a tree-edge. Similarly consider that a prover has access to the edges $e(g_{14}, g_9)$ and $e(g_9, g_{11})$. The signatures of g_9 and g_{11} are computed such that (a) $p^{\beta:g_{14}\rightarrow g_9}_{g9}$ is larger than $p^{\beta:g_{14}\rightarrow g_9}_{g11}$ and (b) $r^{\beta:g_{14}\rightarrow g_9}_{g9}$ is smaller than $r^{\beta:g_{14}\rightarrow g_9}_{g11}$; (a) and (b) convey that $e(g_9, g_{11})$ is a tree-edge. The same can be verified for other structures.

`rSign`: Sign a graph $G(V, E)$.

1. Forward pass on graph $G(V, E)$.
   (a) Execute a depth-first manner traversal on $G(V, E)$.
   (b) For each node $x \in V$, compute o_x^τ and q_x^τ.
   (c) If $e(w, x) \in E$, and
      i. If $((o_w^\tau > o_x^\tau)$ and $(q_w^\tau > q_x^\tau)$, then mark $e(w, x)$ as a cross-edge and x as a χ-node.
      ii. If $(o_w^\tau < o_x^\tau)$ and $(q_w^\tau > q_x^\tau)$, then mark $e(w, x)$ as a back-edge and w as a β-node.
   (d) For each χ-node, compute its $q_\cdot^\chi$
2. Backward pass on graph $G(V, E)$.
   (a) Let V^β be the set of all back-nodes in G.
   (b) Let $y \in V^\beta$ such that $o_y^\tau < o_u^\tau$, $\forall\ u \in (V^\beta - \{y\})$
   (c) For each back-edge $e(y, z)$ from y, execute a depth-first traversal of the graph from z.
   (d) For each w *β-reachable* from y over $e(y, z)$,
      i. If w is not visited earlier from y, compute $o_w^{\beta:y\to z}$ and $q_w^{\beta:y\to z}$.
      ii. Else compute $o_w^{\beta:y\to z}$ and $q_w^{\beta:y\to z}$, such that $o_w^{\beta:y\to z}$ is less than and $q_w^{\beta:y\to z}$ is larger than the respective values computed in the previous visit.
      iii. if w is a back-node, $V^\beta \leftarrow V^\beta - \{\mathrm{w}\}$.
   (e) Goto step (a) until V^β is empty.

Figure 6.7. Algorithm to sign a graph (continued to Figure 6.8).

`rSign`(Continuted):

3. For each node $x \in V$, transform the traversal numbers into traversal numbers, so that they preserve the order.

4. For each node $x \in V$ that is a χ-node, assign $(p_x^\tau,\ r_x^\chi)$ to x as its structural position η_x^χ.

5. For each node $x \in V$ that is *not* a χ-node, assign $(p_x^\tau,\ r_x^\tau)$ to x as its structural position η_x^τ.

6. For each node $x \in V$, and for each not-β-covered back-edge $e(y, z)$ such that x is *β-reachable* from y over $e(y, z)$, $\eta_x^{\beta:y\to z} \leftarrow (p_x^{\beta:y\to z},\ r_x^{\beta:y\to z})$.

7. For each node $y \in V$ such that $e(y, z)$ is a not-β-covered back-edge, $\eta_y^{\beta:y\to z} \leftarrow (p_y^{\beta:y\to z},\ r_y^{\beta:y\to z})$.

8. For each node $x \in V$:

   (a) If x is a χ-node, $\eta_x \leftarrow \eta_x^\chi$ else $\eta_x \leftarrow \eta_x^\tau$.

   (b) Compute the α-signature $\xi_x^\alpha \leftarrow \mathcal{H}(\eta_x \| c_x)$.

   (c) If x is *β-reachable* from a not-β-covered back-edge $e(y, z)$, compute the β-signature $\xi_x^{\beta:y\to z} \leftarrow \mathcal{H}(\eta_x^{\beta:y\to z} \| c_x)$.

   (d) If x is such that $e(x, w)$ is a *not-β-covered* back-edge, compute the β-signature $\xi_x^{\beta:x\to w} \leftarrow \mathcal{H}(\eta_x^{\beta:x\to w} \| c_x)$.

9. Choose a secure random ω; Let $\omega_G \leftarrow \mathcal{H}(\omega)$.

10. Compute the signature of the graph $G(V, E)$ either using CRSA (equation 6.3) or using BGLS (equation 6.4).

Figure 6.8. Algorithm to sign a graph (continued from Figure 6.7).

`rRedact`:

1. $\vartheta \leftarrow \emptyset$.
2. Let ψ be a set: $\psi \leftarrow \{\langle x, \eta_x, \xi_x\rangle | \forall x \in V$, η_x is a structural position of x, and ξ_x refers to the authentication unit of x associated with $\eta_x\}$.
3. If no edge in G_δ is a back-edge in G, For each node x in G_δ,
   (a) If x is a cross-node, $\eta_x \leftarrow \eta_x^\chi$. Else $\eta_x \leftarrow \eta_x^\tau$.
   (b) $\vartheta \overset{\cup}{\leftarrow} \langle x, \eta_x, \xi_x^\alpha\rangle$.

   Else proceed to the next step.
4. For each $e(x, y)$ in G_δ that is a *not-β-covered* back-edge in G,
   (a) For each node z in G_δ such that z is either x or is *β-reachable* from x over $e(x, y)$ in G_δ, $\vartheta \overset{\cup}{\leftarrow} \langle z, \eta_z^{\beta:x\rightarrow y}, \xi_z^{\beta:x\rightarrow y}\rangle$. Flag z as *visited*.

   Flag $e(x, y)$ as *visited*.
5. Let $E_0^\beta \leftarrow \{e(x, y) | e(x, y)$ is in G_δ and is not *visited*, $e(x, y)$ is a back-edge in G and is *not-β-covered* in $G_\delta\}$.
6. For each $e(x, y) \in E_0^\beta$,
   (a) Let be the back-edge $e(u, v)$ in G but not in G_δ such that $e(x, y)$ is *β-covered* by $e(u, v)$ in G.
   (b) For each node z such that z is in G_δ, z is *not visited*, z is either x or *β-reachable* from x over $e(x, y)$ in G_δ, $\vartheta \overset{\cup}{\leftarrow} \langle z, \eta_z^{\beta:u\rightarrow v}, \xi_z^{\beta:u\rightarrow v}\rangle$. Flag z as *visited*.

Figure 6.9. Algorithm to distribute a subgraph (continued to Figure 6.10).

`rRedact`(Continued from Figure 6.9):

7. For each node w that is *not visited* and has a simple path $w \ldots \rightarrow x$ in G_δ, If w is β-*reachable* from u over $e(u,v)$, and $e(u,v)$ is in G, but not in G_δ, $\vartheta \overset{\cup}{\leftarrow} \langle w, \eta_w^{\beta:u\rightarrow v}, \xi_w^{\beta:u\rightarrow v}\rangle$. Flag w as *visited*.

8. For each node w in G_δ that is *not visited*,
   If w is a χ-node, $\vartheta \overset{\cup}{\leftarrow} \langle w, \eta_w^{\chi}, \xi_w^{\alpha}\rangle$. Else $\vartheta \overset{\cup}{\leftarrow} \langle w, \eta_w^{\tau}, \xi_w^{\alpha}\rangle$.

9. Compute $\xi_{G_\delta(V_\delta,E_\delta)}$ and $\sigma_{G_\delta(V_\delta,E_\delta)}$ as follows:

10. CRSA:

    (a) $\xi_{G_\delta} \leftarrow \prod_{\langle x,\eta_x,\xi_x\rangle \ \in \psi-\vartheta} \xi_x \ mod \ \bar{n}$.

    (b) $\sigma_{G_\delta} \leftarrow \prod_{\langle x,\eta_x,\xi_x\rangle \ \in \psi-\vartheta} \sigma_x \ mod \ \bar{n}$.

11. BGLS:

    (a) $\xi_{G_\delta} \leftarrow \sum_{\langle x,\eta_x,\xi_x\rangle \ \in (\psi\vartheta)} \xi_x$.

    (b) $\sigma_{G_\delta} \leftarrow e(\mathtt{P}, \sum_{\langle \mathtt{x},\eta_\mathtt{x},\xi_\mathtt{x}\rangle \ \in (\psi\vartheta} \sigma_\mathtt{x})$.

Figure 6.10. Algorithm to distribute a subgraph (continued from Figure 6.9).

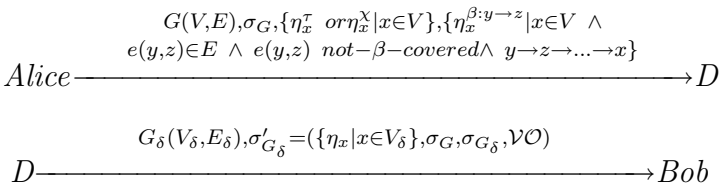


Figure 6.11. Protocol for graphs.

Authentication of contents:

1. CRSA: $\prod_{y \in V_\delta} \xi_y \ mod \ \bar{n} \ \stackrel{?}{=} \sigma_{G_\delta}$.
2. CRSA: $\mathcal{VO} \prod_{y \in V_\delta} \xi_y \ mod \ \bar{n} \ \stackrel{?}{=} \sigma_G$
3. BGLS: $e(\mathtt{Q}, \sum_{\mathtt{y} \in \mathtt{V}_\delta} \xi_{\mathtt{y}}) \stackrel{?}{=} \sigma_{\mathtt{G}_\delta}$.
4. BGLS: $e(\mathtt{Q}, \Omega + \mathcal{VO}) \stackrel{?}{=} \sigma_{\mathtt{G}}$, where $\Omega \leftarrow \sum_{y \in V_\delta} \mathcal{H}(\eta_y \parallel c_y)$.

Verification of structural relations:

1. Execute a depth-first traversal of G_δ. Let the structural position of each node x be denoted by $\eta_x = (p_x, r_x)$.
2. For edge $e(x, z)$, if $(p_x < p_z)$ **and** $(r_x > r_z)$, then if x is not a β-node in G_δ, then $e(x, z)$ is not a back-edge (there is no cycle in G_δ involving x and z), so the parent-child relationship between x and z is incorrect.
3. Else if $(p_x \leq p_z)$ **or** $(r_x \geq r_z)$, then parent-child relationship between x and z is incorrect.

Figure 6.12. Algorithm to verify the structural integrity of a graph.

6.4 Security Analysis

The proposed schemes for DAGs/graphs with cycles support *non-repudiation* primarily because both the CRSA and BGLS schemes support non-repudiation. Moreover, the proposed schemes for DAGs and graphs with cycles are "existentially unforgeable under adaptive chosen-message attack". In what follows, we provide proof sketches for the security of the proposed schemes.

Lemma 6.4.1 (Authentication (DAGs)) *Under the random oracle model, any authenticity violation of a graph can be detected by using the structural signatures for DAGs.*

Proof [Sketch] Let $\xi_{G'_\delta(V',E')}$ and $\sigma_{G'_\delta(V',E')}$ be the authentication units received by a *Bob*, who receives the $G'_\delta(V', E')$, subgraph of $G(V, E)$. Suppose that the authenticity verification scheme in Section 6.2.3 authenticates a graph, $G''_\delta(V'', E'')$ different from G_δ, to G, using $\xi_{G'_\delta(V',E')}$ and $\sigma_{G'_\delta(V',E')}$. By Definitions of χ-RONs, τ-PONs and τ-RONs, the relationship between the nodes in G''_δ must be identical to that of G'_δ(Section 6.2.3), otherwise the randomized traversal numbers are not secure, which is a contradiction. Contents of G''_δ would be authenticated iff Verification of G''_δ is satisfied, which implies that the random oracle $\mathcal{H}$ incurred a collision, and the CRSA/aggregate signature scheme and $\mathcal{H}$ are not secure, which is a contradiction, under the random oracle hypothesis [76] and hardness of computational Diffie-Hellman problem [28]. Thus the lemma is proven. ■

Lemma 6.4.2 (Non-leakage (DAGs)) *Under the random oracle model, the structural signature of a DAG do not lead to any leakage of any extraneous information.*

Proof [Sketch] A user receiving a sub-DAG $G'_\delta(V', E')$ of DAG G should not be able to infer any extraneous information of G from (1) the signature σ_G, (2) set of verification units $\mathcal{VO}_{G'_\delta}$, and (3) the τ- and χ-structural positions of the nodes in G'_δ. Due to the properties of Bilinear maps and aggregate signatures, (1) and (2) do not leak any information (i.e., the probability of leakage is negligible) [28]. We now would prove that (3) does not leak. (Forward-edges:) The τ-structural positions of nodes in a forward-edge are identical to the rules of tree-edge (Definition 6.1.1); therefore an edge $e(x, y)$ that is a forward-edge in G

but not a forward-edge in G'_δ would be verified by the user as a tree-edge. (Cross-edges:) By Definitions 6.2.2 and 6.2.4, a χ-node x has a structural position such that r_x^χ is larger than the r_w^τ for each w that has a cross-edge incident on x. By Definition 6.1.1, the user would only know that $e(w, x)$ is a tree-edge and thus cannot learn whether it is a cross-edge (Definition 6.1.1). Thus the lemma is proved. If the signature of the DAG and the integrity verifier of the subgraph leak extraneous information, then $\mathcal{H}$ incurred a collision, and the aggregate signature scheme and $\mathcal{H}$ are not secure, which is a contradiction, under the random oracle hypothesis [76] and hardness of computational Diffie-Hellman problem [28]. Thus the lemma is proven. ■

Lemma 6.4.3 (Authentication (Graphs with Cycles)) *Under the random oracle model, any authenticity violation of a graph can be detected by using the structural signature scheme for connected directed graphs.*

Proof [Sketch] Let $G(V, E)$ be a directed connected graph and x be a node in it.

Content authenticity: Any compromise of the content c_x or the structural position (either τ, χ, or β) of a node x in G would invalidate the structural integrity verifier ξ_x, which is a hash of a message that contains c_x and structural position of x as defined by Definitions 6.2.4, and 6.3.6, unless the hash function $\mathcal{H}$ encounters a collision, which contradicts our assumption and the random oracle hypothesis. Moreover, if a node/edge is added to or dropped from the received subgraph $G'_\delta(V', E')$, it would invalidate the received integrity verifier of the subgraph $\xi_{G'_\delta(V',E')}$. If $\xi_{G'_\delta(V',E')}$ does not get invalidated, then either $\mathcal{H}$ is not a random oracle or the CRSA/BGLS scheme is not secure – both are contradictions.

Structural authenticity: The signature of a node in a graph is a forward-signature, if it is not reachable from a back-edge. Such a signature is with respect to the DFT obtained from a forward traversal of the graph. Any unauthorized re-ordering between two or more nodes (violation of structural integrity) in such a DFT can be detected using the randomized traversal numbers. If a node is a β-node or is reachable from a back-edge, then such a node also belongs to the DFT obtained from a depth-first traversal carried out from β-node(s) over back-edges. Any unauthorized re-ordering would be detected here as well. Suppose x belongs to another tree G', but claimed to belong to G. By the arguments similar to the one in the proof of Lemma 6.4.1, it is not possible.

■

Lemma 6.4.4 (Non-leakage (Graphs with Cycles)) *Under the random oracle model, the structural signatures for connected directed graphs do not lead to any leakage of any extraneous information.*

Proof [Sketch] A user receiving a subgraph $G'_\delta(V', E')$ of graph G should not be able to infer any extraneous information of G from (1) the signature σ_G, (2) set of verification units $\mathcal{VO}_{G'_\delta}$, and (3) the τ-, χ-, and β-structural positions of the nodes in G'_δ. Due to the properties of Bilinear maps and aggregate signatures, (1) and (2) do not leak any information (i.e., the probability of leakage is negligible) [28]. We now would prove that there is no leakage due to (3).

In order to be confidentiality-preserving, an authentication scheme must not leak any extraneous information about (a) cross-edges, (b) forward-edges, (c) back-edges. Following Lemmas 6.4.2, the authentication scheme for connected directed graphs does not leak

any information about (a) and (b). The scheme does not leak any information via the back-edges or β-structural positions proven as follows.

Let $e(x, w)$ be a *not-β-covered* back-edge in graph $G(V, E)$ (e.g., $e(g_{14}, g_9)$ in Figure 3.4). By Definitions 6.3.4 and 6.2.4, the β-node x has a β-structural position such that $p_x^{\beta:}$ and $r_x^{\beta:}$ are larger and smaller than the $p_w^{\beta:x\rightarrow w}$ and $r_w^{\beta:x\rightarrow w}$, respectively. By Definition 6.1.1, the user would only verify that $e(x, w)$ is a tree-edge and cannot learn whether it is a back-edge.

The following cases arise when a user is authorized to access a connected subgraph that includes a back-edge $e(x, w)$, which is *not-β-covered* in the subgraph; the subgraph may also include: (I) nodes reachable from w, (II) nodes reachable from x and (III) nodes x is reachable from.

Case I: Nodes reachable from w: The user is authorized to access the back-edge $e(x, w)$ and the edge $e(w, y)$ (e.g., $e(g_9, g_{11})$ in Figure 3.4). By Definition 6.3.2, y is *β-reachable* from x. Further by Definitions 6.3.4 and 6.2.4, $p_x^{\beta:x\rightarrow w}$ and $r_x^{\beta:x\rightarrow w}$ are larger and smaller than the $p_y^{\beta:x\rightarrow w}$ and $r_y^{\beta:x\rightarrow w}$, respectively. By Definition 6.1.1, the user would only verify that an edge $e(w, y)$ is a tree-edge and cannot learn from it whether $e(x, w)$ is a back-edge.

Case II: Nodes reachable from x: The user is authorized to access the back-edge $e(x, w)$ and the edge $e(x, y)$ (e.g., $e(g_{14}, g_{18})$ in Figure 3.4).

- y is not *β-reachable* and x is not *β-reachable*: By sending τ-position and τ-signatures for both x and y and β-position and β-signatures for w, the edges would be verified as tree-edges. This is because, $p_x^\tau = p_x^{\beta:x\rightarrow w}$ and $r_x^\tau = r_x^{\beta:x\rightarrow w}$ (Definition 6.3.4) and thus the τ-signature for x are same as its β-signature.

- y is not *β-reachable* and x is *β-reachable*: Not possible by the definition of the notion of *β-reachable*.

- y is *β-reachable* and x is not *β-reachable*: By sending τ-position and τ-signatures for y and β-position and β-signature for x and w, both the edges $e(x, w)$ and $e(y, x)$ are verified by the user as tree-edges, thus hiding the original type of $e(x, w)$. This is because, since x is not *β-reachable*, by Definition 6.3.4, $p_x^\tau = p_x^{\beta:x\rightarrow w}$ and $r_x^\tau = r_x^{\beta:x\rightarrow w}$. Thus and by the properties of post-order and pre-order numbers, since $e(y, x)$ is a tree-edge in G, $p_y^\tau > p_x^{\beta:x\rightarrow w}$ and $r_y^\tau < r_x^{\beta:x\rightarrow w}$.

- y is *β-reachable* and x is *β-reachable*: By sending β-positions and β-signatures for both y, x and w, the edges would be verified as tree-edges. This is because, by Definition 6.3.4, $p_y^{\beta:x\rightarrow w} > p_x^{\beta:x\rightarrow w} > p_w^{\beta:x\rightarrow w}$ and $r_y^{\beta:x\rightarrow w} < r_x^{\beta:x\rightarrow w} < r_w^{\beta:x\rightarrow w}$.

Case III: Nodes from which x is reachable: The user is authorized to access the back-edge $e(x, w)$ and the edge $e(y, x)$ (e.g., $e(g_{11}, g_{14})$ in Figure 3.4). Four cases arise:

- y is not *β-reachable* and x is not *β-reachable*: Proof is identical to this condition in Case-II.

- y is not *β-reachable* and x is *β-reachable*: By sending τ-positions and τ-signatures for y and β-positions and β-signatures for x and w, the edges would be verified as tree-edges. This is because, for an x that is *β-reachable* and a β-node, $p_x^{\beta:x\rightarrow w} < p_x^\tau$ and $r_x^{\beta:x\rightarrow w} > r_x^\tau$. Since $e(y, x)$ is an edge in the graph, $p_x^\tau < p_y^\tau$ and $r_x^\tau > r_y^\tau$.

- y is *β-reachable* and x is not *β-reachable*: Proof is identical to this condition in Case-II.

- y is *β-reachable* and x is *β-reachable*: Proof is identical to this condition in Case-II.

The above arguments can be easily extended to multiple *not-β-covered* back-edges in the graph. Consideration of one *not-β-covered* back-edge takes care of all other back-edges

that are it covers. So the argument also extends to multiple *β-covered* and *not-β-covered* back-edges.

Suppose that a user Bob has access to G'_δ, a subgraph in G. Bob receives the structural signature of G, the node signatures of G'_δ and their structural positions. Any leakage would be a direct leakage through these information or an inference from them.

Direct leakage: Clearly (as per Definitions 6.2.7, 6.2.5, 6.3.9 and 6.3.7, and the protocols specified in Sections 6.2.2 and 6.3.2) Bob does not need the integrity verifier of any node u that is in G but not in G'_δ. He therefore does not need to know any of the structural relationships and ordering that exist in G, but not in G'_δ. Therefore none of (3), (4), (5) and (6) is directly leaked to Bob; he does not learn any extra information from the authentication process.

Indirect leakage through the signature of the graph and integrity verifier for G'_δ: Under the Random Oracle Hypothesis and the hard-ness of Computational Diffie-Hellman problem, the structural signature of the tree reveals neither (3) the signature of u, nor (4) the existence of u. Similarly, the structural signature of a node leaks neither (3) nor (4). Therefore (5) – the structural relations (edges or paths) and (6) – the structural order among nodes in G'_δ and u are also not revealed by the signatures.

In addition, the structural positions of the nodes in G'_δ do not reveal any information [84]: because the probability of inference (and leakage) about (2) – the existence of node u between two immediate siblings from such randoms is negligible. Therefore structural positions of nodes cannot be used to determine the structural signature of u. Since (3) and (4) cannot be inferred from the RPON's and RRON's, (5) and (6) also cannot be inferred from the structural position of a node. ■

6.5 Complexity and Performance Results

In the following sections, we analyze the complexity and performance of the proposed schemes.

6.5.1 Complexity

Signature Generation Complexity. The pre-order and post-order numbers can be generated by a single traversal of the graph $G(V, E)$. The traversal complexity is thus $O(|V|+|E|)$. In the signing scheme of graphs (Section 6.3.1), a graph is traversed once forward, a number of times backward, and once for computing the signatures in the end. The number of backward traversals is the number of *not-β-covered* back-edges d, which is in $[0, |V|-1]$ (0 in case of DAGs and $(|V|-1)$ in case of complete graphs). In case of signing DAGs, the scheme requires only two traversals (no backward traversal is required here). Therefore, the complexity for signing a DAG is $O(|V|+|E|)$. In case of graphs with cycles, the scheme requires d number of backward traversals, where d is the number of not-β-covered back-edges.

The number of authentication items that need to be *computed*, and *stored* is $(|V|*(2 + 2d))$ as explained below by assuming that the sizes of the secure random number and the cryptographic hash are identical. In the worst case (when the graph is a complete graph), each node is a β-node; so each node has one forward and d backward positions. Each structural position involves two secure random numbers. Therefore, the *storage complexity* of structural signatures is $O(|V|$*d).

Distribution Complexity. Let the signed subgraph that needs to be shared with a user be $G'_\delta(V', E')$. In the worst case ($G'_\delta(V', E')$ is a complete graph), the distributor has to send $(2 * |V'|)$ number of signature items as follows. Each node in such a subgraph is a β-node; thus the β-structural position (two authentication items) of each node is sent to the user. Therefore the distribution complexity of structural signatures is $O(|V'|)$.

Integrity Verification Complexity. The procedure for the verification of content integrity incurs a cost linear in terms of the size of the subgraph $G'_\delta(V', E')$ received, that is, $O(|V'| + |E'|)$. It accounts for one hashing for each node. The cost of verification of structural integrity is also linear: $O(|V'| + |E'|)$, as the cost of comparison of randomized traversal numbers is constant.

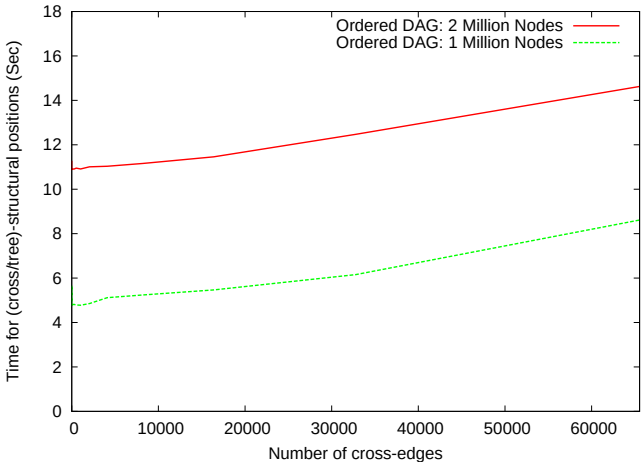


Figure 6.13. Average time in seconds to compute the χ- and τ-structural positions vs. the number of cross-edges in each ordered-DAG.

6.5.2 Performance Results

We implemented the two schemes - DAG and graphs in Java 1.6 and JCA 6.0 (Java Cryptography Architecture) APIs. The experiments were carried out on a desktop with the following specification: 64-bit Linux (Ubuntu 8.10) on Intel Core 2 Duo CPU with 4GB RAM. For signing using aggregate signatures and bilinear maps, we used the C implementation of bilinear maps [3]. The performance metrics measured are: time to compute the χ-, τ-structural positions and β-structural positions (for graphs) versus the number of cross-edges, back-edges in the DAG and the graphs. The other performance metric that we have evaluated the schemes against is time taken for signing and verification.

Time to Compute Structural Positions: The process of computing appropriate structural positions of each node in either a DAG or a graph is part of the one-time process of signing. Figure 6.13 shows that the time for computation of χ- and τ-structural positions for DAGs is very efficient (linear). For DAGs of size about 2 million nodes, it takes only 14 seconds. Figure 6.14 shows that the time to compute all the structural positions for all the nodes in a graph with respect to the number of

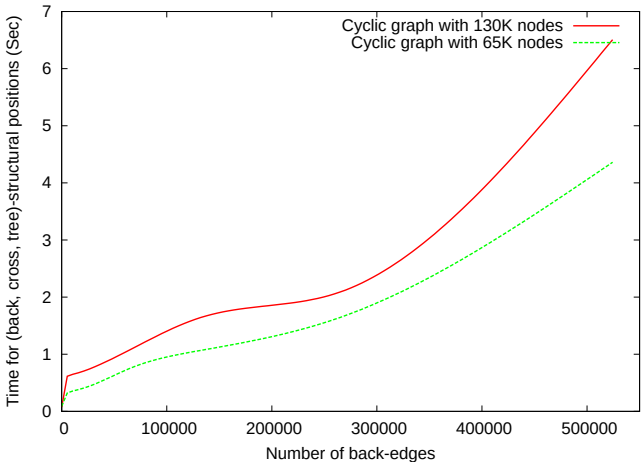


Figure 6.14. Average time in seconds to compute the β-,χ- and τ-structural positions vs. the number of back-edges in a graph with cycles.

back-edges in the graph is also highly efficient - for more than 0.5 million back-edges, it takes 6.5 seconds.

The performance of signing a graph, redaction and verification of a subgraph is same as that of the trees. This is primarily beacause computation of various structural positions in case of a graph is what is the major difference between trees and graphs. However such a cost as shown in the previous paragraph is almost negligible in comparison to the cost of signing, which is in thousands of seconds. Such high cost of signing and verification is due to involvement of modular exponentiations. Our performance results are in terms of the number of integrity verifiers; in case of trees, the number of integrity verifiers per node is one, whereas in a graph, it is more especially for nodes involved in cycles.

6.6 Summary

In this chapter, we proposed two schemes in order to address the problem of leakage-free authentication - one for DAGs and another for graphs with cycles. The proposed schemes are based on structure of graphs and aggregate signatures.

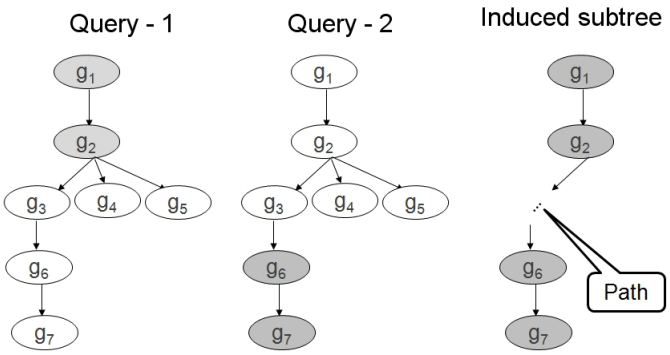


Figure 6.15. Leakages in structural signature scheme for trees.

A graph contains nodes and tree-edges, forward-edges, cross-edges and back-edges. The fact that an edge is a forward-, cross- or a back-edge in a depth-first traversal conveys information that is sensitive in several contexts. Moreover, back-edges pose a more difficult problem than the one posed by forward- and cross-edges (i.e. DAGs) primarily because back-edges add a bidirectional nature to the graph, which turns graphs into complex structures, which in turn makes the problem of authentication with confidentiality of such structures a hard one.

Our schemes prevent leakage of information while facilitating authentication of content as well as the structure of trees and graphs. The security of such schemes are based on the security of cryptographic hash functions (random oracles) and aggregate signatures (Computational Diffie-Hellman problem). In terms of complexity, the schemes for DAGs and graphs with cycles incur $O(n)$ and $O(n * d)$, respectively, for time and storage (n is the number of nodes in the graph). Performance of our schemes on large DAGs and on graphs as large as 0.5-million back-edges nodes show that our scheme is efficient. Further, experimental results show that our technique for graphs with cycles performs linearly – better than the complexity analysis.

Limitations of Structural Signatures Structural signature schemes for trees and graphs are however not secure when the user receives more than one subtrees/subgraphs of a tree/graph. A user can infer about the existence of path relationship

between nodes that are different subtrees. In Figure 6.15, we show that a user receives first and second subtrees as the results of query-1 and query-2, respectively. As part of this process, the user also receives the randomized post-order and pre-order numbers of these nodes. Since post-order (pre-order) number of an ancestor is larger (resp., smaller) than that of the descendant. In this example, the post-order (pre-order) number of g_2 is greater (resp., smaller) than that of g_6, which why, the user can infer that there exists a path between between these two nodes in the original trees. This maybe a sensitive information in many scenarios, such as, healthcare (disease is denoted by g_2 and patient is referred to by g_6), in finance (a specific loan is denoted by g_2 and an individual is referred to by g_6).

In the next chapter, we have presented a scheme that is leakage-free even when a user has access to multiple subtrees/subgraphs.

7 LEAKAGE-FREE REDACTABLE SIGNATURES

The only truly secure system is one that is powered off,
cast in a block of concrete and sealed in a lead-lined room
with armed guards – and even then I have my doubts.

EUGENE H. SPAFFORD [55]

The structural signature scheme described in the previous chapters can authenticate only "single" subtrees, and will leak when "multiple" subtrees are results of one or more queries. Moreover, structural signatures compute a linear number of signatures for the trees and at least a linear number of signatures for graphs. In this chapter, we present a scheme that computes only one signature for a tree/graph/forest, is generic for trees, graphs, and forests, and can be used to authenticate multiple subtrees/subgraphs without leaking.

7.1 Trees

In this section, we propose a leakage-free signature scheme $r\Pi$ for trees. It relies on the notion of "secure names" that are assigned to the nodes in a tree.

The purpose of secure names is to convey the order of siblings (which node is to the left of which other node) without leaking anything else (e.g., whether they are adjacent siblings, how many other siblings are between them, etc). For example, in Figure 1.1(a), a, b, and c are siblings such that $a \prec b \prec c$. Secure names η_a, η_b, and η_c are assigned to a, b, and c, respectively. Given η_a, and η_c, alongwith a and b, a user can establish the fact that $a \prec c$. But it cannot learn anything about b, or its existence (extraneous information).

The signing procedure traverses a tree $T(V, E)$ bottom-up, and assigns an N-bit secure name η_x to each node x in the tree, and then computes the signature σ_T of the tree using these secure names. Using the secure names of the nodes in a tree,

an "integrity verifier" for each node is computed, which in turn is used to define the signature of the tree $\sigma_{T(V,E)}$. A user that receives a subtree T_δ also receives the signature of the tree, and a verification object ($\mathcal{VO}$) in order authenticate the integrity and the origin of this subtree. $\mathcal{VO}$ is computed using the integrity verifiers of those nodes that are not in the subtree T_δ. The user verifies the signature of the tree using the $\mathcal{VO}$ and the received subtree together. The structural relationships between the nodes and the order between the siblings in T_δ are verified using their secure names.

In the following sections, we have shown how to compute the signature of a tree, and distribute, and how to authenticate a subtree. To ease the exposition, we first introduce a preliminary approach for naming the nodes, which is easier to understand and is secure but is not efficient - it has an exponential complexity. We then present the efficient solution that is both secure and efficient for trees with large branching factor.

7.1.1 Preliminary Scheme (Scheme-1)

Our approach for generating secure names follows a bottom-up strategy. Let $v_1, \ldots, v_k$ be a list of siblings listed in left to right order. Let $lsb(s)$ denote the least significant bit of the bit-string s. The secure names of siblings v_i and v_{i+1} are computed such that the least significant bits of the hash of $\eta_{v_i} \| \eta_{v_{i+1}}$ *and* the hash of $\eta_{v_{i+1}} \| \eta_{v_i}$ are 1 and 0, respectively. We call this as the *ordering property* of secure names. This scheme is given in Figure 7.1.

Example: In the tree in Figure 1.1(a), N-bit secure names η_a, and η_b, are assigned to a, and b, respectively. η_a is a assigned as a random. η_b is computed such that $lsb(\mathcal{H}(\eta_a \parallel \eta_b)) = 1$ and $lsb(\mathcal{H}(\eta_b \parallel \eta_a)) = 0$. This process is repeated for each set of siblings.

`rNameGen`: Compute the secure names for siblings $v_1, v_2, \ldots, v_k$, children of node x, where $v_i \prec v_j, i < j$.

1. For the root node *root* of T, assign a random to $\eta_{\hat{p}_{root}}$.
2. Repeat the following statements for each $x \in V$. Let $v_1, v_2, \ldots, v_k$ be the set of the children of x.
3. Generate a random permutation π of the integers $\{1, \ldots, k\}$.
4. Set $\eta_{v_{\pi(1)}}$ to be any random.
5. For $i = 2, \ldots, k$, compute $\eta_{v_{\pi(i)}}$ as follows.
   (a) Choose a random r.
   (b) For $j = 1, \ldots, i-1$, do the following:
      i. $\lambda_{\prec} \leftarrow \mathcal{H}(\eta_{v_{\pi(j)}} \parallel r)$.
      ii. $\lambda_{\succ} \leftarrow \mathcal{H}(r \parallel \eta_{v_{\pi(j)}})$.
      iii. If $v_{\pi(i)}$ is to the left (resp., right) of $v_{\pi(j)}$, then check whether $lsb(\lambda_{\prec})$ is 1 (resp., 0) and $lsb(\lambda_{\succ})$ is 0 (resp., 1).
      iv. If the answer is "yes" for all j, then $\eta_{v_{\pi(i)}} \leftarrow r$.
      v. Else go back to Sub-step 5(a).

`rNameVrfy`: Verify the order between two nodes $v_i \prec v_j$, using their secure names η_{v_i} and η_{v_j}.

1. $v_i \prec v_j \Leftrightarrow lsb(\mathcal{H}(\eta_{v_i} \parallel \eta_{v_j}))= 1 \wedge lsb(\mathcal{H}(\eta_{v_j} \parallel \eta_{v_i})) = 0$.

Figure 7.1. Algorithm to compute secure names for $T(V, E)$ (Scheme-1).

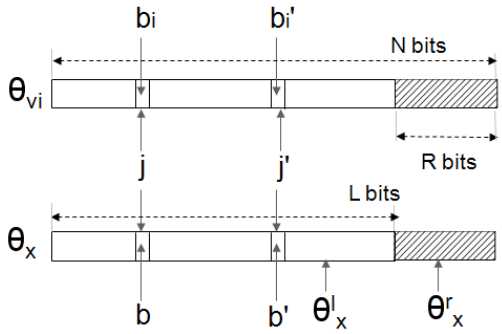


Figure 7.2. Secure names η_{V_i} and η_x of siblings V_i and x in the context of the efficient naming scheme.

Complexity

Scheme-1 takes $O(n)$ time, where n is the number of nodes in the tree. The probability that a particular choice of r is found suitable for $\eta_{v_{\pi(i)}}$ is 4^{-i+1}, and the average number of r values generated for the selection of such an η_{v_i} is 4^{i-1}. The expected time to compute the secure names all k siblings is therefore: $\sum_{i=1}^{k} 4^{i-1} = (4^k - 1)/3$, and the average time to compute all secure names is $(n - \ell) * (4^k - 1)/3$. Note that, although it is quite unlikely to happen, it is nevertheless possible that two non-sibling nodes receive the same secure name. In such a case, step 5(a) should be repeated.

7.1.2 Efficient Scheme (Scheme-2)

The main drawback of the Scheme-1 is the fact that the worst-case time to compute an η_x, when x is the $(j+1)$'th leftmost child of its parent, is exponential in j (Step 3 in Section 7.1.1). This section describes an improved scheme that does not suffer from this drawback. As earlier, a non-leaf node in a tree has k number of children.

7.1.3 Secure Names

The idea is, as before, to compute the η_x's (secure names) bottom-up and, within a set of siblings, in left-to-right order. The main difference is how a secure name η_x is computed. This scheme (Scheme-2) is given in Figure 7.3.

In this approach, we split the N-bit long secure name η_x of a node x into two disjoint parts: η_x^l and η_x^r of sizes L and R refer to the left and right parts of η_x, respectively (Figure 7.2). If x is the leftmost child (i.e., the first child) of its parent then η_x is selected randomly. If x is $(m+1)$'th leftmost child of its parent, then η_x depends on the secure names of its left siblings. Let w be a left sibling of x: $w \prec x$. Two bits (b_w and b'_w) in η_w^l and two bits (b_x and b'_x) in η_x^l are selected and their values are set such that $b_w \oplus\ b_x < b'_w \oplus\ b'_x$. b_w and b_x are the j'th leftmost bit in w and x, respectively, where j is computed using η_w^r and η_x^r in this order (because $w \prec x$). Similarly b'_w and b'_x are the (j')'th leftmost bit in w and x, respectively, where j' is computed using η_w^r and η_x^r in the reverse order. This is the *ordering property* of secure names computed in this fashion. Alongwith N, $(L - 2 * k)$, and R are sufficiently large as security parameters.

Example: For $N = 512$, choose L=360 for $k \leq 100$, and R=152 in the context of current computational power. In the tree in Figure 1.1(a), secure names η_a, and η_b, are assigned to a, and b, respectively. η_a is an N-bit random and each bit of η_a^l is marked as *not-used*. η_b is computed as follows. η_b^r is an R-bit random and η_b^l is initialized to 0. Each bit of η_b^l is marked as *not-used*. j is computed as $(1 + \mathcal{H}(\eta_a^r \parallel \eta_b^r) \bmod\ L)$. Since j'th leftmost bits of η_a^l and η_b^l referred to as b_i and b, respectively, are marked as *not-used*, j' is computed as $(1 + \mathcal{H}(\eta_b^r \parallel \eta_a^r) \bmod\ L)$. If $(j \neq\ j')$ and the (j')'th leftmost bits of η_a^l and η_b^l referred to as b'_i and b', respectively, are marked as *not-used*, then proceed as follows. Assign either (0,0) or (1,1) to (b_i,b'_i) in η_a^l, and (0,1) or (1,0) to (b,b') in η_b^l. Such an assignment assures that $b_i \oplus b(=0) < b'_i \oplus b'(=1)$. The j'th and (j')'th bits of η_a and η_b are marked as *used*. η_c depends on both η_a and η_b. This process is repeated for each set of siblings.

`rNameGen`: Compute the secure name for x such that $v_1, v_2, \ldots, v_k, x$ are siblings, where $v_i \prec v_j \prec x, i < j$.

1. Choose a sufficiently large N. Choose L and R are such that (a) $N = L + R$, (b) $R \geq \log(L)$, and (c) $(L - 2 * k)$ and R are sufficiently large as security parameters. Let η_x^r and η_x^l refer to the right-part consisting of R and left-part consisting of L bits of the secure name η_x of x.

2. Assign random values to η_x^r, and zero values to η_x^l. Associate with each bit of η_x^l a status that is initially set to *not-used*.

3. Compute secure names of siblings in the left-to-right order of the siblings. Let $v_1, \ldots, v_k$ be the siblings to the left of x, where v_i is the ith leftmost one. (Each of the η_{v_i}'s of these k siblings of x have already been computed.)

4. For $i = 1$ to k do the following.

   (a) $\lambda_\prec \leftarrow \mathcal{H}(\eta_{v_i}^r \parallel \eta_x^r)$; $j \leftarrow 1 + (\lambda_\prec \mod L)$. Let b_i (resp., b) denote the jth leftmost bit of $\eta_{v_i}^l$ (resp., η_x^l). If the status of b is *not-used* then continue with the next step, else go back to step (2).

   (b) $\lambda_\succ \leftarrow \mathcal{H}(\eta_x^r \parallel \eta_{v_i}^r)$; $j' \leftarrow 1 + (\lambda_\succ \mod L)$. Let b_i' (resp., b') denote the (j')'th leftmost bit of $\eta_{v_i}^l$ (resp., η_x^l).

   (c) If $(j \neq j')$ and the status of b' is *not-used* then proceed to the next step, else go back to step (2).

   (d) Set b and b' such that $b_i \oplus b < b_i' \oplus b'$.

   (e) Change the status of b and b' from *not-used* to *used*.

Figure 7.3. Efficient algorithm to compute secure names for tree $T(V, E)$ (Scheme-2) (Continued to Figure 7.4).

`rNameVrfy`: Verify whether $y \prec z$, using their secure names η_y and η_z.

1. $j \leftarrow 1 + (\mathcal{H}(\eta_y^r \parallel \eta_z^r) \bmod L)$
2. $j' \leftarrow 1 + (\mathcal{H}(\eta_z^r \parallel \eta_y^r) \bmod L)$
3. Let b_y and b_z be the j'th, and b'_y and b'_z are the (j')'th bits in η_y and η_z, respectively.
4. Check the following: $y \prec z \Leftrightarrow b_y \oplus b_z < b'_y \oplus b'_z$.

Figure 7.4. Efficient algorithm to compute secure names for tree $T(V, E)$ (Scheme-2) (Continuted from Figure 7.3).

Complexity

The above algorithm translates into a simple and constant-time test of which of two given siblings is to the left of the other. But we need to analyze the expected number of re-starts. Suppose that the size L of the left part (η_x^l) of a secure name is 500. The probability of a "collision" and re-start at Step (1) is the probability that $2k$ numbers drawn randomly from the 500 choices $[1, 500]$ are not all distinct, i.e., that at least 2 of them are equal. This is the classic birthday problem, and the probability of a re-start is (assuming $2k \leq 500$): $1 - \prod_{j=1}^{2k-1}\{(1 - (j/500))\} \approx 1 - e^{-(2k)(2k-1)/1000}$. For $2k = 50$ this probability is 0.91, hence the expected number of re-starts is $(1/(1 - 0.91) = 11$, which is much better than the preliminary scheme where the expected number of re-starts would have been proportional to 4^{25}. Scheme-2 incurs linear cost $O(n)$ in terms of the number of nodes in the tree.

7.1.4 Leakage-Free Signatures of Trees (`rSign`)

In this section, we describe the signature, distribution and verification protocols for trees. Prior to computing the signatures, a dummy node is inserted by splitting an edge: if $e(x, y)$ is an edge in the original tree, add a node w such that $e(x, w)$ and $e(w, y)$ are the new edges in the modified tree. Secure name η_w of each inserted node w is a random. Such node w when given to a user only when the user has access to *both* x and y. The ordering between them is not needed to be verified by secure names.

Integrity Verifiers

An integrity verifier (IV) of a node is the hash of the secure name of its parent, its secure name and its contents. In case of inserted nodes, no contents is used in IV. Using the IVs, we define a signature $\sigma_{T(V,E)}$ (also referred to as σ_T) for $T(V, E)$. In cases when "the received subtree (sent to the user) is the same as the original tree" is

a sensitive information, the signature of a tree may be salted using a random value in order to protect this fact. The (salted) tree signature is publicly available or passed to the user alongwith the subtree that the user has access to. $\sigma_{T(V,E)}$ is an aggregate signature, computed over the IVs of its nodes. We define two types of signatures for trees: one based on the condensed-RSA signatures [105] and the other based on bilinear maps [28].

Definition 7.1.1 (Integrity Verifier) *Let x be a node in tree $T(V, E)$, and c_x be the content of node x. Its integrity verifier (IV) denoted by ξ_x, is defined as: $\xi_x \leftarrow \mathcal{H}(\eta_{\hat{p}_x} \| \eta_x \| c_x)$.*

In this section, we define the signature of a tree based on Condensed-RSA signature scheme [105] and aggregate signatures [28].

Definition 7.1.2 (Signature of Trees using CRSA) *Let $T(V, E)$ be a tree. Let $\mathcal{H}$ denote a random oracle. Let the RSA signature σ_x of each node x be defined as follows $\sigma_x \leftarrow \xi_x^{\bar{d}} \bmod \bar{n}$, where ξ_x is the IV of x. Let the salt be ω_T be a random, and let $\Omega_T \leftarrow {\omega_T}^{\bar{d}} \bmod \bar{n}$. The signature of T, denoted by σ_T, is defined as*

$$\sigma_T = \Omega_T \prod_{x \in V} \sigma_x \bmod \bar{n}. \tag{7.1}$$

Definition 7.1.3 (Signature of Trees using BGLS) *Let $T(V, E)$ be a tree. Let $\mathcal{H}$ denote a random oracle. Let the salt be ω_T. The signature σ_x of each node x is defined as $\sigma_x \leftarrow \mathtt{sk}\xi_x$. The signature of T, denoted by σ_T, is defined as*

$$\sigma_T \leftarrow (\mathtt{P}, \mathtt{sk}(\omega_\mathtt{T} + \sum_{\mathtt{x} \in \mathtt{V}} \xi_\mathtt{x})). \tag{7.2}$$

7.1.5 Distribution (`rRedact`)

The distributor D sends the following items to Bob, who has access to $T_\delta(V_\delta, E_\delta)$, a subtree of tree $T(V, E)$: $(T_\delta(V_\delta, E_\delta), \mathcal{VO}_{T_\delta}, \sigma_T)$, where $\mathcal{VO}_{T_\delta(V_\delta, E_\delta)}$ (also referred to as $\mathcal{VO}_{T_\delta}$) is the verification object of T_δ, and σ_T the signature of the $T(V, E)$. The

`rSign`: Sign tree $T(V, E)$.

1. For each node $x \in V$, compute its secure name η_x, and compute its IV : $\xi_x \leftarrow \mathcal{H}(\eta_{\hat{p}_x} \| \eta_x \| c_x)$.
2. Assign a salt ω_T to T.
3. If CRSA is used, compute the "signature of the tree" $\sigma_{T(V,E)}$ as follows:
   (a) For each $x \in V$, $\sigma_x \leftarrow (\xi_x)^{\bar{d}} \; mod \; \bar{n}$.
   (b) Compute the signature σ_T by evaluating Eq. 7.1, where $\Omega_T \leftarrow {\omega_T}^{\bar{d}} \; mod \; \bar{n}$.
4. If BGLS is used, compute the signature of each node, and compute "signature of the tree" σ_T by evaluating Eq. 7.2.

Figure 7.5. Algorithm to sign a tree.

following steps show how to compute $\mathcal{VO}_{T_\delta}$. D computes two collective integrity verifiers σ_{T_δ} and Δ_{T_δ} as part of $\mathcal{VO}_{T_\delta}$ over the integrity verifiers of all the nodes that are not in the subtree and also includes the salt.

$\mathcal{VO}$ is used to verify the signature of the tree, and is used to detect if any node(s) has been dropped form T_δ in an unauthorized manner. σ_{T_δ} is used to verify the signature of all the nodes in the subtree in an aggregate manner, and is used to detect if any node(s) has been injected form T_δ in an unauthorized manner. η_x is the secure name of x.

7.1.6 Authentication (`rVrfy`)

Bob receives the subtree $T_\delta(V_\delta, E_\delta)$, the signature of the tree σ_T, and the verification object $\mathcal{VO}$. As part of the content authentication process, Bob computes the

`rRedact`: Computed signature of the redacted subtree $T_\delta(V_\delta, E_\delta) \subseteq T(V, E)$.

1. $\sigma'_{T_\delta} \leftarrow \langle \sigma_{T_\delta}, \mathcal{VO}, \Theta_{T_\delta} \rangle$, computed as follows.
2. Θ_{T_δ} is the set of all secure names of the nodes and their respective parents in T_δ: $\Theta_{T_\delta} \leftarrow \{(\eta_x, \eta_{\hat{p}_x}) | x \in V_\delta\}$.
3. Compute the collective integrity verifier $\mathcal{VO}$ as follows.
   (a) CRSA: $\mathcal{VO} \leftarrow \omega_T \prod_{x \in (V - V_\delta)} \xi_x \ mod \ \bar{n}$;
   $\sigma_{T_\delta} \leftarrow \prod_{x \in V_\delta} \sigma_x \ mod \ \bar{n}$.
   (b) BGLS: $\mathcal{VO} \leftarrow \omega_T + \sum_{x \in (V - V_\delta)} \xi_x$;
   $\sigma_{T_\delta} \leftarrow (\mathtt{P}, \sum_{\mathtt{x} \in \mathtt{V}_\delta} \sigma_{\mathtt{x}})$.

Figure 7.6. Algorithm to redact a subtree.

integrity verifiers of the nodes in V_δ and combines them with the received collective integrity verifier $\mathcal{VO}$. If the contents of the nodes are valid, the structural integrity is verified with the help of secure names: the parent-child relationship, and the order among the siblings. Authentication of contents and structural positions of the subtree received includes (1) verification of integrity and, (2) verification of the source of the subtree. The integrity verification of structural relations in a tree involves traversing the tree and using the secure-name of two siblings of its parent or its sibling. The user can carry out verification of integrity of a n'-node subtree in $O(n')$-time. The verification procedure is given in Figure 7.7.

`rVrfy`: Verify authenticity of subtree $T_\delta(V_\delta, E_\delta)$.

Authentication of nodes:

1. For each node $y \in V_\delta$, compute $\xi_y \leftarrow \mathcal{H}(\eta_{\hat{p}_y} \| \eta_y \| c_y)$.
2. CRSA: Verify (a) and (b):
   (a) $(\sigma_{T_\delta})^{\bar{e}} \stackrel{?}{=} \prod_{y \in V_\delta} \xi_y \ (mod\ \bar{n})$, *and*,
   (b) $(\sigma_T)^{\bar{e}} \stackrel{?}{=} \mathcal{VO} \prod_{y \in V_\delta} \xi_y \ (mod\ \bar{n})$.
3. BGLS: Verify (a) and (b):
   (a) $(\sigma_{T_\delta}) \stackrel{?}{=} (\mathtt{Q}, \sum_{y \in V_\delta} \xi_y))$, *and*,
   (b) $(\sigma_T) \stackrel{?}{=} (\mathtt{Q}, (\mathcal{VO} + \sum_{y \in V_\delta} \xi_y))$.
4. If (a) and (b) are valid, then the contents and secure names of T_δ are authenticated. Otherwise, if (b) is invalid and (a) is valid, then the received nodes are authenticated, but either some nodes have been dropped, or $\mathcal{VO}$ and/or σ_T have been tampered with.

Verification of edges and ordering among siblings:

1. Carry out a depth-first traversal on T_δ.
2. *Parent-child relationship*: Let x be the parent of y in T_δ; if $(\eta_x \neq \eta_{\hat{p}_y})$, then this relationship is incorrect.
3. *Order among siblings*: For ordered trees, in T_δ, let y and z are children of x, and let $y \prec z$.
   (a) For scheme-1 (Section 7.1.1): $y \prec z \Leftrightarrow$
   $(lsb(\mathcal{H}(\eta_y \parallel \eta_z)) = 1) \wedge (lsb(\mathcal{H}(\eta_z \parallel \eta_y)) = 0)$.
   (b) For scheme-2 (Section 7.1.2):
      i. $j \leftarrow 1 + (\mathcal{H}(\eta_y^r \parallel \eta_z^r) \bmod L)$
      ii. $j' \leftarrow 1 + (\mathcal{H}(\eta_z^r \parallel \eta_y^r) \bmod L)$
      iii. b_y and b_z are the j'th, and b'_y and b'_z are the (j')'th bits in η_y and η_z, respectively.
      iv. $y \prec z \Leftrightarrow b_y \oplus b_z < b'_y \oplus b'_z$.

Figure 7.7. Algorithm to verify a subtree.

7.2 Graphs

Our proposed authentication scheme for graphs is a general one. It can be used for trees, DAGs, graphs with cycles as well as forests. However, for trees, it is recommended to use the scheme specifically developed for trees (in Section 7.1), especially when the fact that the data is organized as trees need not be kept as a secret from users. The scheme for trees computes only one signature and is more efficient than that for the graphs (described below). Moreover, as we will see later (Section 7.6.1), the scheme for graphs can be used for signing forests of trees and graphs as well as authenticate such forests in a leakage-free manner.

Consider a simple graph G shown in Figure 1.1(b). It is a directed acyclic graph (DAG) with node c having two immediate ancestors - d and h (this DAG can be turned into a cyclic graph, by adding a back-edge such as one from f to h). Our solution for trees described earlier, does not work for graphs. In case of graphs, a node may have multiple incoming edges (i.e., multiple immediate ancestors such as c), whereas in case of trees, a node has only one parent (immediate ancestor) except for the root, which does not have any parent. Therefore, in the context of graphs, we cannot use the notion of integrity verifiers that is used for trees (Definition 7.1.1). The challenge in designing leakage-free signatures for graphs arises from the fact that the set $\alpha_\delta(x)$ of immediate ancestors of a node x in a subgraph G_δ is a (possibly empty) subset of the set $\alpha(x)$ of immediate ancestors of x in G. The question is how to verify the authenticity of $\alpha_\delta(x)$ without leaking any information about $(\alpha(x) \backslash \alpha_\delta(x))$: whether it is empty or non-empty, what is its size, etc? For example, c has only d as its immediate ancestor G_δ, whereas it has d and h as the immediate ancestors in G. How to authenticate the fact that d in fact is a correct immediate ancestor of c in G_δ, without leaking any information about h.

Ordering among siblings makes sense for graphs with cycles if and only if, the back-edge (or the edge which can be removed to break a given cycle among nodes) need to be of different semantics.

7.2.1 Leakage-Free Signatures for Graphs (`rSign`)

Our proposed scheme computes the integrity verifier of a node independent of the secure name of the parent, and integrity verifiers for edges. It computes secure names for nodes that have specific ordering with their siblings. If in a graph, the ordering between some siblings is not possible, then the secure names of such nodes are just randoms.

Definition 7.2.1 (Integrity Verifier: Node) *Let x be a node in graph $G(V, E)$, and c_x be the content of node x. Its integrity verifier (IV) denoted by ξ_x, is defined as: $\xi_x \leftarrow \mathcal{H}(\eta_x \| c_x)$.*

Definition 7.2.2 (Integrity Verifier: Edge) *Let $e(x, y)$ be an edge in graph $G(V, E)$. Its integrity verifier (IV) denoted by $\xi_{(x,y)}$, is defined as: $\xi_x \leftarrow \mathcal{H}(\eta_x \| \eta_y)$.*

Signature of a graph is then computed as the aggregate signature of the integrity verifiers of nodes and edges. Distribution is similar in the case of trees: if a user has access to a specific set of nodes and edges, signatures of the integrity verifiers of the edges and nodes as well as the secure names of the nodes are given to the user alongwith the nodes and edges. Also the aggregate signature of these IVs are given to the user alongwith the signature of the source graph and the verification object.

The signature scheme has a complexity of $O(|V| + |E|)$. It computes as many signatures as the number of nodes and edges in the graph (as in the case of trees) and another signature for the whole graph.

7.2.2 Distribution of Graphs (`rRedact`)

The distributor D sends the following items to Bob, who has access to $G_\delta(V_\delta, E_\delta)$, a subgraph of graph $G(V, E)$: (G_δ,$\mathcal{VO}_{G_\delta}$,σ_G), where $\mathcal{VO}_{G_\delta}$ (also referred to as $\mathcal{VO}_{G_\delta}$) is a verification object, and σ_G is the signature of G.

`rSign`: Sign a graph $G(V, E)$.

1. For each node $x \in V$,
   (a) For each node x, compute its secure name η_x.
   (b) For each node x, compute its integrity verifier $\xi_x \leftarrow \mathcal{H}(\eta_x \| c_x)$; For each edge $e(x, y)$, compute its integrity verifier $\xi_{(x,y)} \leftarrow \mathcal{H}(\eta_x \| \eta_y)$.
2. Assign a salt ω_G to G.
3. If CRSA is used, compute the signature σ_G:
   (a) For each $x \in V$, $\sigma_x \leftarrow (\xi_x)^{\bar{d}} \ mod \ \bar{n}$; For each edge $e(x, y) \in E$, $\sigma_{(x,y)} \leftarrow (\xi_{(x,y)})^{\bar{d}} \ mod \ \bar{n}$.
   (b) $\Omega_G \leftarrow {\omega_G}^{\bar{d}} \ mod \ \bar{n}$. Compute $\sigma_{G(V,E)} \leftarrow \ \Omega_G \prod_{x \in V} \sigma_x \prod_{e(x,y) \in E} \sigma_{(x,y)} \ mod \ \bar{n}$.
4. If BGLS is used, compute σ_G as follows:
   $\sigma_{G(V,E)} \ \leftarrow \ (\mathtt{P}, \mathtt{sk}(\omega_{\mathtt{G}} + \sum_{\mathtt{x} \in \mathtt{V}} \xi_{\mathtt{x}} + \sum_{\mathtt{e(x,y)} \in \mathtt{E}} \xi_{\mathtt{(x,y)}}))$.

Figure 7.8. Algorithm to sign a graph.

`rRedact`: Computation of the redacted signature of $G_\delta(V_\delta, E_\delta)$:

1. Compute σ_{G_δ} and Δ_{G_δ} as follows.
   (a) CRSA: (a)$\sigma_{G_\delta} \leftarrow \prod_{y \in V_\delta} \sigma_y \ \prod_{e(x,y) \in E_\delta} \sigma_{(x,y)} \ mod \ \bar{n}$.
   (b) $\Delta_{G_\delta} \leftarrow \omega_G \prod_{y \in V - V_\delta} \xi_y \prod_{e(x,y) \in E - E_\delta} \xi_{(x,y)} \ mod \ \bar{n}$.
   (b) BGLS: (a)$\sigma_{G_\delta} \leftarrow \ (\mathtt{P}, \sum_{\mathtt{y} \in \mathtt{V}_\delta} \sigma_{\mathtt{y}} + \sum_{\mathtt{e(x,y)} \in \mathtt{E}_\delta)} \sigma_{\mathtt{(x,y)}})$.
   (b) $\Delta_{G_\delta} \leftarrow \ \omega_G + \sum_{y \in V - V_\delta} \xi_y + \sum_{e(x,y) \in E - E_\delta)} \xi_{(x,y)}$.
2. $\Theta_{G_\delta} \leftarrow \{\eta_x \mid x \in\}$; $\mathcal{VO}_{G_\delta} \leftarrow \langle \sigma_{G_\delta}, \Delta_{G_\delta}, \Theta_{G_\delta} \rangle$.

Figure 7.9. Algorithm to redact a subgraph.

`rVrfy`: Verification of authenticity of subgraph $G_\delta(V_\delta, E_\delta)$

Authentication of contents:

1. For each node $x \in V_\delta$ in a subgraph $G_\delta(V_\delta, E_\delta)$, compute its integrity verifier: $\xi_x \leftarrow \mathcal{H}(\eta_x \| c_x)$.
2. For each edge $e(x, y)$, compute its integrity verifier: $\xi_{(x,y)} \leftarrow \mathcal{H}(\eta_x \| \eta_y)$.
3. CRSA: Compute (a) $((\sigma_{G_\delta})^{\bar{e}} \stackrel{?}{=} \prod_{x \in V_\delta} \xi_x \ (mod\ \bar{n}))$ *and*, (b) $((\sigma_G)^{\bar{e}} \stackrel{?}{=} \Delta_{G_\delta} \prod_{x \in V_\delta} \xi_x \ (mod\ \bar{n}))$.
4. BGLS: (a) $(\sigma_{G_\delta} \stackrel{?}{=} (\mathtt{Q}, \sum_{x \in V'} \xi_x))$ *and*, (b) $(\sigma_G \stackrel{?}{=} (\mathtt{Q}, \Delta_{G_\delta} + \sum_{x \in V'} \xi_x))$.
5. If (a) and (b) are valid, then the contents and secure names of G_δ are authenticated. Otherwise, if (b) is invalid and (a) is valid, then the received nodes are authenticated, but either some nodes have been dropped, Δ_{G_δ} and/or σ_G have been tampered with. *Parent-child relationship* is verified during this process.

Verification of ordering among siblings:

1. Carry out a depth-first traversal on G_δ.
2. *Order among siblings*: In G_δ, let y and z are children of x, and let $y \prec z$.
   (a) For scheme-1 (Section 7.1.1): $y \prec z \Leftrightarrow (lsb(\mathcal{H}(\eta_y \| \eta_z)) = 1) \wedge (lsb(\mathcal{H}(\eta_z \| \eta_y)) = 0)$.
   (b) For scheme-2 (Section 7.1.2):
      i. $j \leftarrow 1 + (\mathcal{H}(\eta_y^r \| \eta_z^r) \bmod L)$
      ii. $j' \leftarrow 1 + (\mathcal{H}(\eta_z^r \| \eta_y^r) \bmod L)$
      iii. b_y and b_z are the j'th, and b'_y and b'_z are the (j')'th bits in η_y and η_z respectively.
      iv. $y \prec z \Leftrightarrow b_y \oplus b_z < b'_y \oplus b'_z$.

Figure 7.10. Algorithm to verify a subgraph.

Δ_{G_δ} is used to verify the signature of the graph, and is used to detect if any node(s) has been dropped form G_δ in an unauthorized manner. σ_{G_δ} is used to verify the signature of all the nodes in the subgraph in an aggregate manner, and is used to detect if any node(s) has been injected form G_δ in an unauthorized manner. η_x is the secure name of x.

Example: D has to send G_δ in our example to Bob. σ_G is a CRSA-signature. D computes the Δ_{G_δ} as a modular multiplication of the salt ω_G, and the integrity verifiers of f, g, and h, because f, g, and h are not in G_δ. Now $\mathcal{VO}_{G_\delta}$ is the tuple consisting of σ_{G_δ}, Δ_{G_δ} and a set consisting of an element for each node in G_δ. D then sends the signature of the graph σ_G and $\mathcal{VO}_{G_\delta}$ alongwith G_δ, to the user.

7.2.3 Authentication (`rVrfy`)

Bob receives the subgraph $G_\delta(V_\delta, E_\delta)$, the secure name η_x of each node x, verification object $\mathcal{VO}_{G_\delta}$, and the signature of the graph σ_G. It verifies the authenticity of the contents; if they are authentic then the structural integrity is verified.

Authentication of the contents of subgraph G_δ

By contents, we mean the contents of each node x as well as η_x. In order to authenticate contents of $G_\delta(V_\delta, E_\delta)$, Bob first computes the integrity verifiers ξ_x for each node, and then combines them appropriately with Δ_{G_δ} in order to verify the signature σ_G. If the signature verifies, the edges and ordering among siblings are also verified. Authentication of contents of $G_\delta(V_\delta, E_\delta)$ has a complexity of $O(|V_\delta| + |E_\delta|)$.

Example: Bob computes the integrity verifiers of a, b, c and d in G_δ in our example. Consider CRSA signatures. Bob computes a modular multiplication of these integrity verifiers together with Δ_{G_δ} received as part of $\mathcal{VO}_{G_\delta}$. Then Bob applies the signature verification process of CRSA on the result of this multiplication and the received signature σ_G of the graph. If the verification turns out to be valid, the contents are authenticated.

Authentication of the structural relationships

In order to verify the integrity of the ordering among siblings (in ordered DAGs), Step 4(a) or 4(b) in Section 6.2.3 can be used for Scheme-1 or Scheme-2, respectively. Verification of immediate ancestors and the structural order between siblings in $G_\delta(V_\delta, E_\delta)$ has a complexity of $O(|V_\delta| + |E_\delta|)$.

7.3 Single Signature Scheme

In this section, we propose a construction of leakage-free redactable signatures for trees that is transparent as well as highly efficient (computes only one signature). The LFR signature scheme is based on the notion of secure names developed earlier in the dissertation, and the redactable set signatures developed by Johnson, Molnar, Song and Wagner (JMSW) [74].

Review of JMSW Redactable Set Signatures: Johnson et al. [74] developed a redactable set signature scheme based on RSA primitives and random oracle. The signature secure (EU-CMA over $\subset$ and $\cup$ operation). Since it is redactable, given the signature of a set, and the elements that are to be removed from the set (that results in the subset), anyone who knows the public key, can efficiently compute the signature of the subset. The signature is history-independent, and thus can be shown to be a leakage-free redactable signature for sets. Let the public key be $\bar{e}$ and the RSA modulus be $\bar{n}$. Some constraints on RSA are that $\bar{n} = \bar{p}.\bar{q}$, where $\bar{p}$ and $\bar{q}$ are "safe primes".

Given a set $S = \{s_1, s_2, \ldots, s_n\}$, its signature σ_S is computed as follows: compute $H(S) = \prod_{1 \leq i \leq n} \mathcal{H}(S_i) \; mod \; \bar{n}$, and $I(S) = H_S^{-1} \; mod \; \phi(\bar{n})$, where $\phi(\bar{n}) = (\bar{p}-1)(\bar{q}-1)$. Signature σ_S is computed as $(\bar{e})^{I(S)}$. Verification proceeds as follows: Given a set S', and a signature σ, one computes the $H(S') = \prod_{1 \leq i \leq |S'|} \mathcal{H}(S'_i)$, where S'_i is the i'th element in S'; And then it is checked if $(\sigma)^H(S')$ is equal to $\bar{e}$. If the equality holds, σ is a valid signature of the set S'. In order to compute the signature of a subset

`rSign`: Sign tree $T(V, E)$. Let $p(x)$ be the parent of node x.

1. For each node w with m children, let x_i be the i'th child, $1 \leq i \leq m$, and $x_j \prec x_{j+1}$, $1 \leq j \leq m-1$.
2. Let η_x refer to the secure name assigned to node x.
3. Add a dummy node dxy to each edge $e(x, y)$, thereby splitting the edge to two edges $e(x, dxy)$ and $e(dxy, y)$. Assign a random η_{dxy} to each dummy node dxy. $V' \leftarrow V \cup \{dxy | e(x, y) \in E\}$.
4. For each node x in V', compute $\theta_x \leftarrow \mathcal{H}(\eta_{p(x)} \parallel \eta_x \parallel c_x)$.
5. $H(V) \leftarrow \prod_{x \in V} \theta_x \ mod \ \bar{n}$.
6. $\sigma_T \leftarrow (\bar{e})^{I(V)} \ mod \ \bar{n}$, where $I(V) \leftarrow H_V^{-1} \ mod \ \phi(\bar{n})$, $\phi(\bar{n}) = (\bar{p}-1)(\bar{q}-1)$.

Figure 7.11. Algorithm to sign a tree.

`rRedact`: Compute signature of subtree(s) $T_\delta(V_\delta, E_\delta) \subset T(V, E)$.

1. $\sigma_{T_\delta} \leftarrow (\sigma_T)^{H(V \backslash V_\delta)} \ mod \ \bar{n}$, where $H(V \backslash V_\delta) \leftarrow \prod_{x \in V \backslash V_\delta} \theta_x \ mod \ \bar{n}$.

Figure 7.12. Algorithm to redact a tree.

$S'' \subset S$, one redacts the hashes of the elements $S \backslash S''$ from the signature σ_S as follows: compute $H(S \backslash S'')$ and $\sigma_{S''}$ is computed as ${\sigma_S}^{H(S \backslash S'')}$.

7.3.1 LFR Signature: $r\Pi$

In this section, we present an LFR signature scheme $r\Pi$ for trees that can be easily extended to graphs/forests. Ordered graphs and forests can be signed using the above scheme. The number of signatures computed is optimal: 1, and the number

Verification (`rVrfy`): Verify $(\sigma,\ T_\delta(V_\delta, E_\delta))$; verifier receives θ_x for each node x in V_δ, and θ_{dxy} for each edge $e(x, y)$ in V_δ.

Verification of Contents:

1. For each node x in V', compute $\theta_x \leftarrow \mathcal{H}(\eta_{p(x)} \parallel \eta_x \parallel c_x)$.
2. $H(V_\delta) \leftarrow \prod_{x \in V_\delta} \theta_x \ mod\ \bar{n}$, $\theta_x = \mathcal{H}(\eta_{p(x)} \parallel \eta_x \parallel c_x)$.
3. If ${\sigma_{T_\delta}}^{H(V_\delta)} \ mod\ \bar{n} = \bar{e}$, all nodes are authenticated.

Verification of Edges and Ordering:

1. Carry out a depth-first traversal on T_δ.
2. *Parent-child relationship*: Let x be the parent of y in T_δ; if $(\eta_x \neq \eta_{\hat{p}_y})$, then this relationship is incorrect.
3. *Order among siblings*: For ordered trees, in T_δ, let y and z are children of x, and let $y \prec z$.
   (a) For Scheme-1 (Section 7.1.1): $y \prec z \Leftrightarrow$
   $(lsb(\mathcal{H}(\eta_y \parallel \eta_z)) = 1) \wedge\ (lsb(\mathcal{H}(\eta_z \parallel \eta_y)) = 0)$.
   (b) For Scheme-2 (Section 7.1.2):
      i. $j \leftarrow 1 + (\mathcal{H}(\eta_y^r \parallel \eta_z^r) \bmod\ L)$
      ii. $j' \leftarrow 1 + (\mathcal{H}(\eta_z^r \parallel \eta_y^r) \bmod\ L)$
      iii. b_y and b_z are the j'th, and b'_y and b'_z are the (j')'th bits in η_y and η_z respectively.
      iv. Check: $y \prec z \Leftrightarrow b_y \oplus b_z < b'_y \oplus b'_z$.
4. If contents, the edges, and the orderings among all siblings are verified to be authentic, return 1, else return 0.

Figure 7.13. Algorithm to verify a tree.

of hashings carried out is $O(|V| + |E|)$. The signing, distribution, and verification schemes are given in Figures 7.11, 7.13, and 7.12, respectively.

7.3.2 Complexity

Single signature scheme: Our single signature scheme takes a single traversal on a tree/graph/forest, and incurs cost of $O(n + m)$, where n and m are number of nodes and edges, respectively. The number of signatures computed is 1, and the number of order-preserving encryptions that are carried out is n/k, as that many groups of siblings are there. The cost of computing a subtree/subgraph/sub-forest of n' nodes and m' edges is $O(n - n' + m - m')$, because $n - n'$ nodes and $m - m'$ edges have to be redacted from the signature. The cost of verifying the integrity of a subtree/subgraph/sub-forest is $O(n' + m')$, but needs to verify only 1 signature. There is no decryption of the encrypted integers.

Brzuska et al's scheme: For trees, it computes n signatures for the tree, and quadratic number of signatures for each group of siblings: $O(k^2)$ (and there are n/k such groups of siblings), k is the arity of the tree. More precisely, it computes $O(n+nk)$ signatures, and incurs cost of $O(n+nk)$. The cost of computing a subtree of n' nodes is $O(n'+n'k)$, because $n'k$ orderings and their signatures have to be selected. The cost of verifying the integrity of a subtree/subgraph/sub-forest is $O(n' + n'k)$: these many signatures are verified.

Comparison: In comparison to our scheme, signing by Brzuska et al's is $n + nk$ times more expensive. For computation of signature of redacted signatures, our scheme requires one modular exponentiation, whereas the other scheme does not need any such operations; however, their scheme incurs $O(nk)$ more traversal cost. Verification of the integrity of a subtree using Brzuska et al's is $(n' + n'k)$ times more expensive than our scheme.

7.4 Security Analysis

We prove the security of the signature schemes by proving the name-transparency of the secure names, unforgeability and transparency of the signature schemes, for both trees and graphs.

7.4.1 Secure Names

Lemma 7.4.1 (Name-transparency) *Under the random oracle hypothesis, secure names computed by Scheme-1 are name-transparent.*

Proof [Sketch] Consider that an adversary $\mathcal{A}$ can determine with non-negligible probability whether a given set of secure names for a subset of siblings V_δ have been computed as part of the computation of secure names of V ($V_\delta \subset V$), or have been computed afresh. Consider the sets of nodes as output from $\mathcal{A}$: $V_0 = \{x,z\}$ and $V_1 = \{x,y,z\}$, $x \prec y \prec z$. b is drawn uniformly and randomly from $\{0,1\}$. The adversary then receives the challenge (V_0, Θ_0). Consider that $b = 1$, and $\mathcal{A}$ outputs $b' = 1$. $\mathcal{A}$ determines that there are one or more siblings in between x and z. It implies that the $j'th$ and (j')'th bit positions for (x,y) pair and/or for (y,z) pair are known to $\mathcal{A}$, which implies that $\mathcal{A}$ has been able to carry out second-preimage attack on $\mathcal{H}$. Therefore, $\mathcal{H}$ is not a random oracle, which contradicts our assumption.

Let all secure names be in the interval $[1 : U]$. Let y be a node with rank i among its siblings and be referred to as v_i (to remain consistent with the terminology used in the scheme). To prove that a secure name η_{v_i} reveals nothing about i, it suffices to prove that the proposed process for secure-name computation is such that the probability of an η_{v_i} being equal to any $u \in [1 : U]$ is independent of i. We write the event $\{\eta_{v_i} = u\}$ as the union of k disjoint events $E_1, \ldots, E_k$ where $E_j = \{\pi(i) = j, \eta_{v_i} = u\}$. We thus have: $Pr(\eta_{v_i} = u) = \sum_{j=1}^{k} Pr(\pi(i) = j, \eta_{v_i} = u) = \sum_{j=1}^{k} (1/k)(1/U)(1/4^{j-1})$ where we used the facts that: (i) $Pr(\pi(i) = j) = 1/k$; (ii) η_{v_i} is u iff Sub-step 3(a) selects u out of the U choices (with probability $1/U$) *and* that choice is not discarded in Sub-step 3(b), i.e., the choice is admissible relative to the $j-1$ other already assigned secure names (probability of non-discard is 4^{-j+1}). Because $\sum_{j=1}^{k} 1/4^{j-1} = (4/3)(1 - 4^{-k})$ we obtain: $Pr(\eta_{v_i} = u) = (4/3kU)(1 - 4^{-k})$, which is independent of i, as required.

The secure names do not leak information on k or m (the number of nodes in the tree) either, because each secure name is drawn uniformly from a subset of $[1 : U]$

that is both large (of size approximately $4U/3k$) and uniform over all such subsets of $[1:U]$, hence indistinguishable from a random choice over $[1:U]$. ■

Lemma 7.4.2 (Name-transparency) *Under the random oracle hypothesis, secure names computed by Scheme-2 are name-transparent.*

Proof [Sketch] Consider that an adversary $\mathcal{A}$ can determine with non-negligible probability whether a given set of secure names for a subset of siblings V_δ have been computed as part of the computation of secure names of V ($V_\delta \subset V$), or have been computed afresh. Consider the sets of nodes as output from $\mathcal{A}$: $V_0 = \{x,z\}$ and $V_1 = \{x,y,z\}$, $x \prec y \prec z$. b is drawn uniformly and randomly from $\{0,1\}$. The adversary then receives the challenge (V_0, Θ_0). Consider that $b = 1$, and $\mathcal{A}$ outputs $b' = 1$. $\mathcal{A}$ determines that there are one or more siblings in between x and z. It implies that the $j'th$ and (j')'th bit positions for (x,y) pair and/or for (y,z) pair are known to $\mathcal{A}$, which implies that $\mathcal{A}$ has been able to carry out second-preimage attack on $\mathcal{H}$. The bits of the secure names are assigned using $\oplus$ operation, and the probability of each bit being assigned 0 or 1 is $\frac{1}{2}$. R: the number of bits on the η_w^r, w is either of x,y, or z, is a security parameter (λ_2). Therefore, $\mathcal{H}$ is not a random oracle, which contradicts our assumption. Otherwise, $\mathcal{A}$ has carried out a brute-force attack by enumerating all possible secure names; however, the number of bits that are never used for any pair of siblings $(L - 2 * k)$ is a large value - a security parameter (λ_1). It implies that $\mathcal{A}$ can carry out such brute force search over an exponential search space, a contradiction to the assumption that $\mathcal{A}$ is a probabilistic-polynomial adversary.

As earlier, let all secure names be in the interval $[1:U]$. To prove that a secure name η_x reveals nothing about its rank i among its siblings, it suffices to prove that the process for secure-name assignment is such that the probability of a bit in η_x being either 0 or 1 is $\frac{1}{2}$, and it is true for all the bits in η_x. We give a proof by induction.

Basis: Case I: x is the left-most child of its parent: η_x is randomly chosen.

Case II: x is the second left-most child of its parent: Let v_1 be the left sibling of

x. The R bits are randomly chosen. Two out of the remaining bits referred to as b and b' are chosen such that $(b_1 \oplus b) < (b'_1 \oplus b')$ (Step 2 of the scheme). However, b_1 and b'_1 are bits in the random v_1, i.e. the probability that the value of b_1 (or b'_1) is either 0 or 1 is $\frac{1}{2}$. Result of the XOR ($\oplus$) of a random number with another (possibly non-random) number is also a random number [76]. Thus b and b' are also random bits. The remaining bits of x are "not used" and randomly chosen. Thus the number $n(x)$) is a random.

Inductive step:

If v_k is the k'th left-most child of its parent and η_{v_k} is a random number, then η_x is also a random number where x is the $(k+1)$'st leftmost child of its parent. $r(v_k)+2(k-1)$ number of bits in η_x are already "used". By Step 2 in the scheme, two bits at positions j and j' that are still unused in η_{v_k} are chosen. The $r(x)$ bits are randoms as well as the two bits at j and j' leftmost positions in η_x are also randoms. The remaining bits are "not used" and chosen randomly. Thus η_x is also a pseudo-random. ■

7.4.2 Trees

Lemma 7.4.3 *The signature scheme* $r\Pi \equiv$ *(*`rGen`*,* `rSign`*,* `rRedact`*,* `rVrfy`*) for trees using either the CRSA or BGLS scheme is existentially unforgeable under the adaptive chosen-message attack over the subset operation.*

Proof [Sketch] Unforgeability of the signature is due to the unforgeability of CRSA or BGLS. If the signature of a tree can be forged by an $\mathcal{A}$, then $\mathcal{A}$ has managed to solve the RSA problem or the Computational Diffie-Hellman problem, which however are assumed to be hard problems.

Given the correctness of the secure names (scheme-1 or scheme-2), the order between siblings can be verified. In case the order between siblings or edge relationship in a tree has been forged, then the hash function $\mathcal{H}$ is not a random oracle, which contradicts our assumption. ■

Lemma 7.4.4 *The signature scheme* $r\Pi \equiv$ *(*`rGen`*,* `rSign`*,* `rRedact`*,* `rVrfy`*) for trees using either the CRSA or BGLS scheme is transparent.*

Proof [(Sketch)] $r\Pi$ is transparent if and only if the secure naming scheme is transparent, which is proven in Lemmas 7.4.1 and 7.4.1. ■

7.4.3 Graphs

Lemma 7.4.5 *The signature scheme* $r\Pi =$ *(*`rGen`*,* `rSign`*,* `rRedact`*,* `rVrfy`*) for graphs using either the CRSA or BGLS scheme is existentially unforgeable under the adaptive chosen-message attack over the subset operation.*

Proof is similar to the proof of Lemma 7.4.3.

Lemma 7.4.6 *The signature scheme* $r\Pi =$ *(*`rGen`*,* `rSign`*,* `rRedact`*,* `rVrfy`*) for graphs using either the CRSA or BGLS scheme is transparent.*

Proof is similar to the proof of Lemma 7.4.4.

7.4.4 Single Signature Scheme

The following lemmas state the security of the proposed construction $r\Pi$.

Lemma 7.4.7 *Under the random oracle hypothesis, and the assumption that the RSA problem is hard, and that the secure naming scheme Scheme-2 is secure,* $r\Pi$ *is existentially unforgeable under chosen-message attack over subset (and union) operation over trees/graphs/forests.*

Proof Suppose that $r\Pi$ can be forged for a subtree T_δ. In one scenario, either a node x can be substituted by another node y in the subtree such that $\theta_x = \theta_y$. It implies that $\mathcal{H}$ has encountered a collision, contradicting the assumption that $\mathcal{H}$ is a random oracle. Similarly, forging a wrong parent-child relationship is not feasible under the

random oracle hypothesis. If forging is carried out by forging the signature of a set (other than subset and union operations), then the JMSW signature scheme has been broken, which implies that the adversary has solved the RSA problem efficiently [74]. The order between two siblings cannot be forged under the random oracle hypothesis (because the $\mathcal{H}$ involves θ_x of each node x). ■

Lemma 7.4.8 *Under the random oracle hypothesis, and the assumption that the RSA problem is hard, then* $r\Pi$ *preserves transparency.*

Proof Suppose that $r\Pi$ is not transparent for a subtree T_δ of tree T. In other words, according to Definition 4.4.2, if T_δ and T are given to the $r\Pi$, the signature that one receives from T_δ leaks the fact whether it was computed from scratch or by redaction from the signature of T. If existence of a sibling in T, but not in T_δ, is leaked by the signature of T_δ, then the plaintext values of the position of a sibling among other siblings has been recovered, i.e., the secure naming scheme Scheme-1 or 2 has computed secure names that are not name-transparent, which however is not true. If a parent-child (edge) relationship between two nodes x and y in T_δ is leaked, then θ_{dxy} is not distinct, which is a contradiction. ■

7.5 Performance Results

We carried out experiments over the two schemes proposed in Sections 7.1.1 and 7.1.2. We implemented these two techniques in Java 1.6 and JCA 6.0 (Java Cryptography Architecture) APIs. The experiments were carried out on a IBM Thinkpad with the following specification: Linux (Ubuntu 8.10) on Intel Core 2 Duo CPU 2.2GHz with 2.98GB RAM. SHA-512 is used as the hash function. We have compared the two secure naming schemes with respect to: (1) the average number of attempts, and (2) the average time needed to successfully compute the secure names. We have carried out performance analysis of signing, distribution and verification.

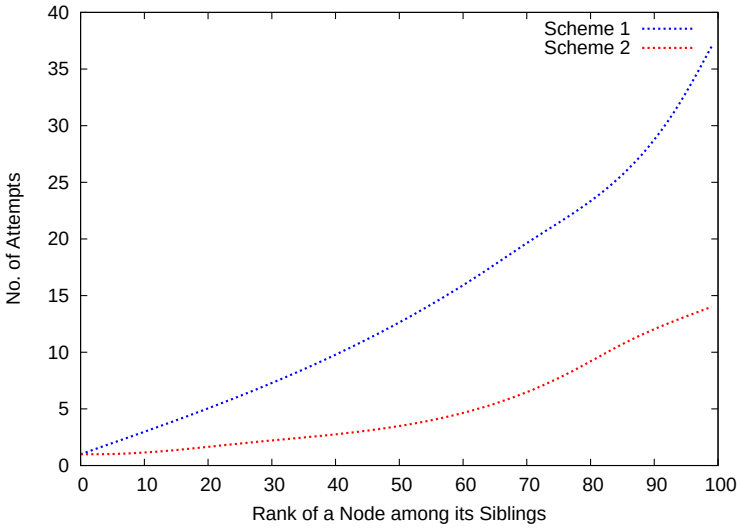


Figure 7.14. Average number of attempts to assign a secure name to a node; branching factor ≤ 100.

Computing Secure Names: We considered trees of branching factor (the number of children a non-leaf node can have) ranging from 1 to 100. Considering the upper limit, a tree that has a breadth of 100 and a height as small as 3, can have as many as 1 million nodes. In the plots, the rank of a child among its siblings (other children of the same parent) is i, $0 \leq\ i \leq 99$. Figures 7.14 and 7.15 refer to the performance results with respect to (1) and (2), respectively. Scheme 1 and 2 respectively refer to the preliminary technique (Sections 7.1.1) and the better technique (Section 7.1.2).

We have also carried out the experiments for branching factor 1 to 300, which requires modification of the size of the secure names (only in the case of the second technique) in order to accommodate the breadth of 300, which could not have been possible with the size of 512-bits for the secure name. 300 is a very large Branching factor; a tree of a small height 3 and branching factor 300 has as many as 27 million nodes. The plots in Figures 7.16 and 7.17 refer to the performance results with respect to the number of attempts to compute a secure name of a node and the time to compute such a secure name, respectively with respect to the position of a node among its siblings.

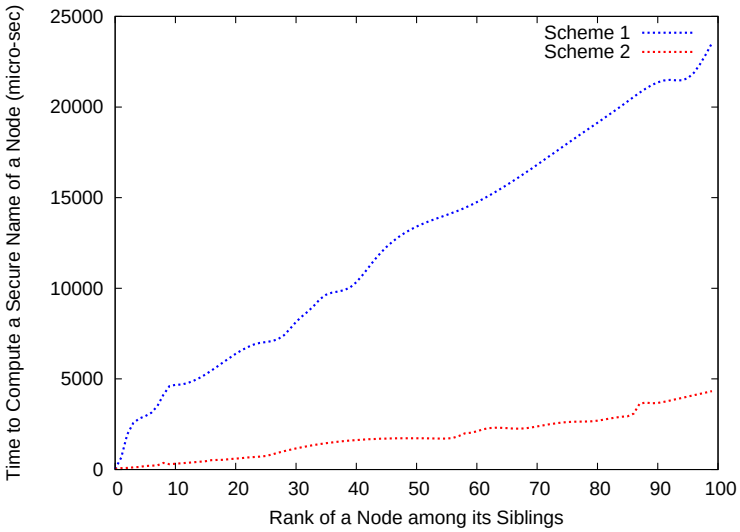


Figure 7.15. Average time in micro-sec to assign a secure name to a node; branching factor ≤ 100.

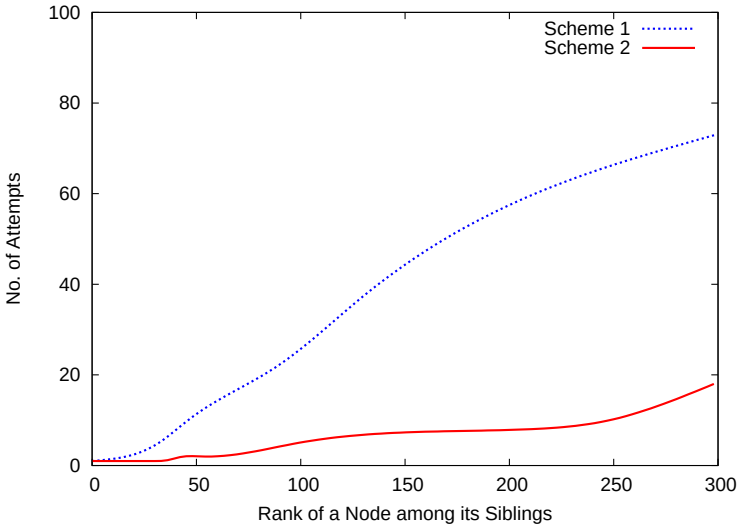


Figure 7.16. Average number of attempts to assign a secure name to a node; branching factor ≤ 300.

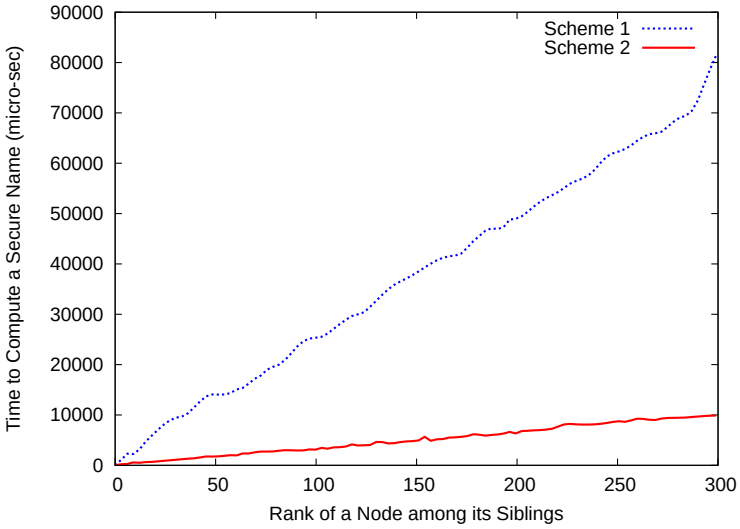


Figure 7.17. Average time in micro-sec to assign a secure name to a node; branching factor ≤ 300.

Our performance results corroborate the theoretical analysis and show that the second technique outperforms the first technique both in the number of attempts and

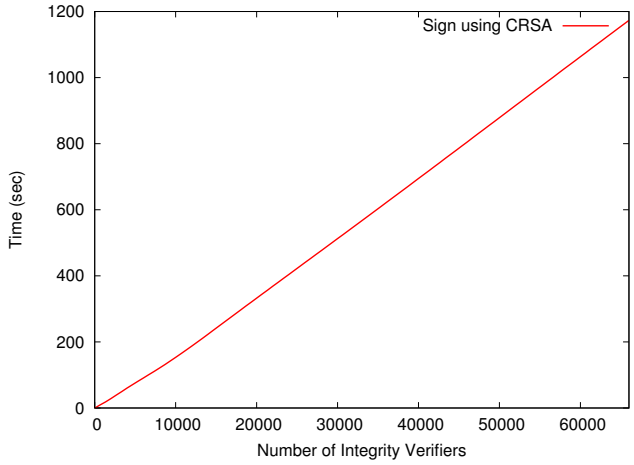


Figure 7.18. CRSA: Time to sign a tree.

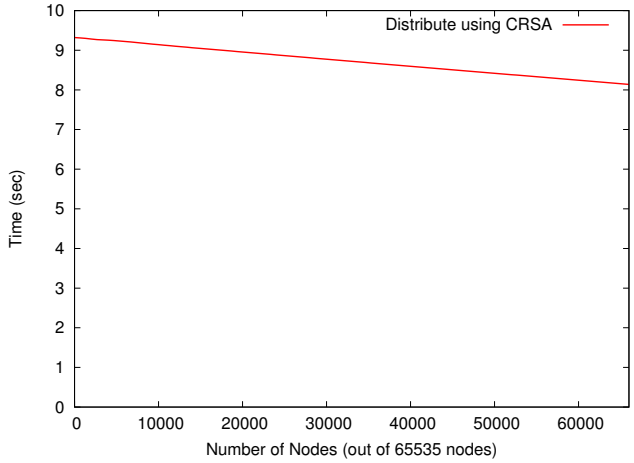


Figure 7.19. CRSA: Time to redact a subtree.

the time required to successfully assign a secure name to a node especially when the breadth of a tree is as high as in the order of hundreds.

7.5.1 CRSA/BGLS-based Schemes

Signing, Distribute, Verify: We have carried out experiments for the efficient scheme. The performances of these algorithms are similar to the performances of

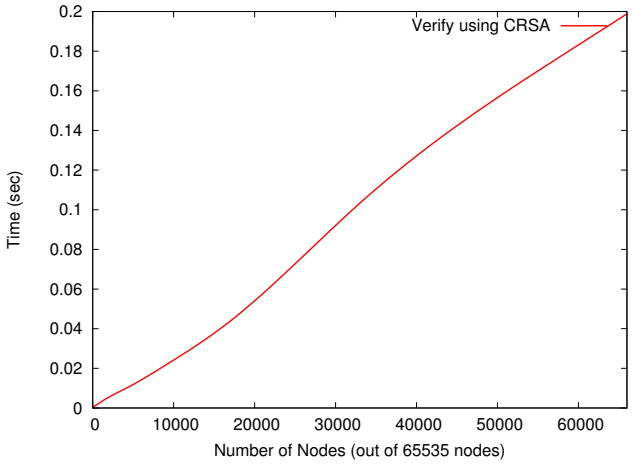


Figure 7.20. CRSA: Time to verify a subtree.

the algorithms in structural signatures. The dominant cost factor in signing, and verification is the modular exponentiation (modular multiplication for distribution) for CRSA, and the bilinear map operation and computation over the elliptic curve group for BGLS (for distribution as well). Verification of structural relationships is quite fast (less expensive than the cost of computing the secure names in the efficient scheme as shown in Figure 7.15), and do not affect the verification cost in any significant way; such cost is not included in the plot for verification. These performance results are applicable for forests as well, as the schemes for them are only different from the tree in the sense of representation of the edges. The BGLS authentication scheme is much more expensive for trees than the CRSA-based scheme [105] as the BGLS aggregate signature scheme is based on elliptic curves and bilinear maps.

7.5.2 Single Signature Scheme

We have implemented a prototype of the JMSW redactable signatures of sets in Java and Java Cryptographic Architecture, and carried out the experiments on a Lenovo Thinkpad T61 with 3GB RAM, of which 2560MB was specified as the

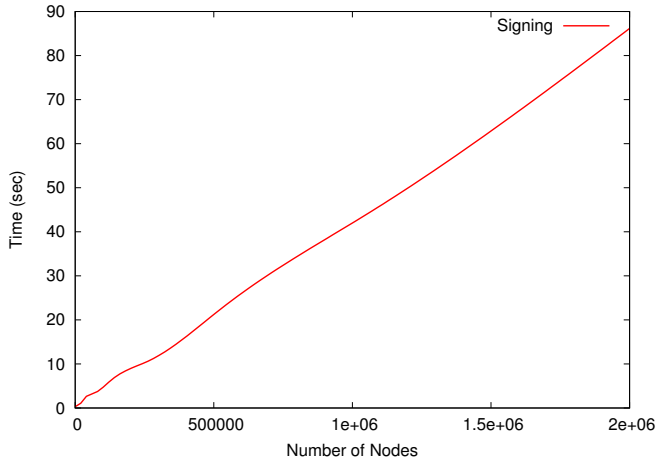


Figure 7.21. Computation of signature of a tree.

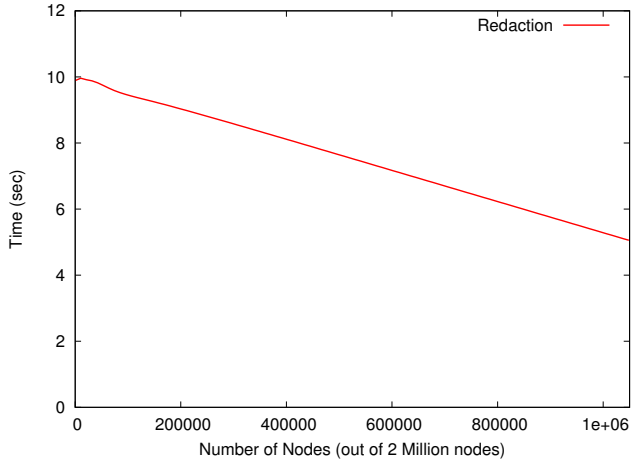


Figure 7.22. Computation of redacted signature of a subtree.

maximum heapsize for the Java Virtual Machine. We used 2-ary trees. Experimental results corroborate our complexity analysis.

Signing a tree using our scheme (that deals with sibling ordering as well) of $2 * 2^{20}$ (more than 2 Million) nodes requires about 70 seconds (Figure 7.5.2), which is in fact quite efficient. For a tree with 65535 nodes, computing the RSA signatures for Brzuska et al's signature scheme takes more than 1100 seconds (even without sibling

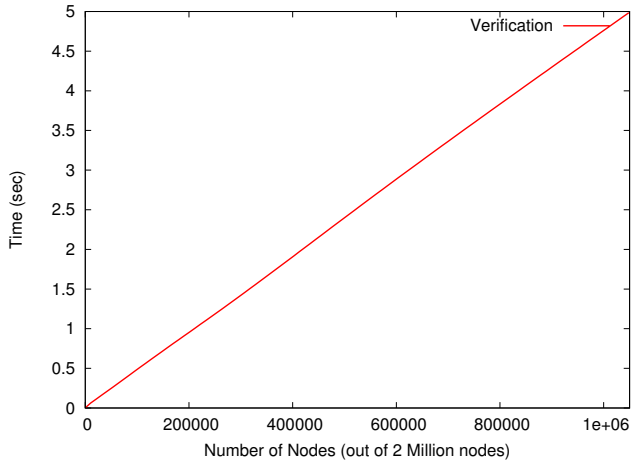


Figure 7.23. Computation of verification of a subtree.

ordering). It is significantly expensive than our signing scheme. The time to compute signatures of redacted subtrees decreases as the size of the redacted subtree increases (Figure 7.5.2), because the number of nodes to be redacted decreases with the increase in the size of the subtree. It takes about 5 seconds to compute the redacted signature of a 1-Million-node subtree (of a 2 Million node tree). It corroborates the fact that redaction of signatures is more efficient than re-computing them. Verification of the signature of a redacted subtree of 1 Million nodes (of a 2 Million node tree) requires about 5 seconds (Figure 7.5.2), which is significantly less expensive than Brzuska et al's scheme: that has to verify 1 Million signatures just for parent-child relationships.

7.6 Discussion

We would now describe how the schemes presented in this chapter can be used for certain other scenarios.

7.6.1 Forests

Our scheme for graphs can be used to sign and authenticate forests, i.e., a set of dis-connected trees/graphs in a leakage-free manner. The idea is to sign the forest as a graph (though disconnected). Our scheme for graphs do not depend on connectedness.

7.6.2 Encrypted Trees, Graphs and Forests

In cloud computing, often plaintext data is not delivered to the cloud servers. If the contents of the nodes are encrypted (but not the structure), out schemes (including the structural signature schemes) can be used directly to such scenarios. The only changes that are needed are (1) Share with the server the integrity verifiers, which are hashed values. (2) use a perfact one-way hash functions [36] to compute the hashes, which can then be hased again to be converted to full-domain hashes. Perfect one-way hash functions do not leak contents of the message being hashed, whereas standard (such as SHA1 pr SHA2) hash functions leak information.

7.6.3 Dynamic Trees, Graphs and Forests

In order to inrementally compute the signature of the updated tree, an insertion (resp., deletion) of a new node requires a new secure name, and leads to a modular multiplication (resp., division) in case of CRSA and an group addition (resp., subtraction) on the elliptic curve followed by a bilinear operation. In an updated graph, the signature of immediate ancestors has also to be updated appropriately. Unlike in the MHT, in our schemes, the updates do not get propagated up in a tree. They do not affect the secure name of other siblings or nodes in Scheme-1; however, in Scheme-2, they affect the secure name of other siblings. The single signature scheme supports both redaction and union of two signatures, which is why, it also supports dynamic updates on trees, graphs and forests.

Computation of a new secure name in the j'th rank among its siblings does not affect any secure names of other siblings in case of Scheme-1. However, in the case of Scheme-2, it affects the secure names of all other siblings.

Answer Freshness and Prevention of Replay Attacks: The proposed authentication schemes prevent replay attacks and guarantee answer freshness by incorporating timestamps in the signatures as an extra element.

7.6.4 Automatic Recovery from Structural Errors

If the contents of a subtree/subgraph is not compromised, but some or all structural relationship and/or order among the nodes have been compromised (maliciously or by communication errors), then the correct parent-child relationship and correct order can be easily recovered using the secure names. Such a capability helps automatic recovery from structural errors without any interaction with the distributor.

For example, suppose that Bob receives a G_δ and authenticates its contents to be valid. However, Bob finds that the received order between two siblings y and z, ($y \prec z$) is incorrect. The correct order between these two siblings can be recovered without communicating with the distributor (server). Verify for the ($x \prec y$) order using the secure names η_x and η_y. If the test succeeds, the correct order is recovered. If such test also fails, then there is no ordering (that is explicitly) imposed on these two nodes in the tree. Similarly, parent-child relationships (for graphs instead of parent, it is immediate ancestor) could be recovered. In order to correct such a relationship between x and y, it is verified whether x is the parent of $y$by $\eta_x \stackrel{?}{=} \eta_{\hat{p}_y}$. If it fails, then the reverse is checked by evaluating $\eta_y \stackrel{?}{=} \eta_{\hat{p}_x}$.

7.6.5 Path Queries

Our scheme for *trees* can be applied to path queries (XPath query) and leakage-free authentication of the results of path queries. Such a result is a set of nodes that form a path in the queried tree. The user should be able to verify that the received

nodes indeed lie on a path, but at the same time should not be able to learn any information extraneous to the received nodes. One important topic in which such a requirement occurs is privacy-preserving data mining. The ordering property of secure names for siblings (in the Scheme-1 or Scheme-2), is used for nodes in a path. Secure names that satisfy such property are assigned to ancestors and descendants in a path. When the user receives two or more nodes claimed to lie on a path: the secure names are used to verify whether they are indeed on a path.

Subsequences and Ordered-Set Queries

Paths or lists can also be seen as representation of subsequences and ordered-sets. The approach for path query verification can be directly applied to the problem of authenticating the subsequence queries and subsets of ordered sets.

7.7 Summary

In this chapter, we solved the problem of how to authenticate multiple sub-trees and sub-graphs without leaking. We proposed two leakage-free authentication schemes: one for trees and another for graphs. The scheme for graphs is a general one: it can be used to authenticate any form data organization structures: trees, DAGs, graphs with cycles, forests of trees and graphs. The schemes compute one signature, irrespective of the number of nodes and edges in the data structure. Our schemes are highly scalable. It is efficient than the latest scheme proposed by Brzuska et al [64].

8 SECURE PUBLISH/SUBSCRIBE OF XML

All parts should go together without forcing. You must remember that the parts you are reassembling were disassembled by you. Therefore, if you can't get them together again, there must be a reason. By all means, do not use a hammer.

IBM Maintenance Manual (1925)

This chapter proposes an approach to content dissemination that exploits the structural properties of XML Document Object Model in order to provide efficient dissemination by at the same time assuring content integrity and confidentiality. Our approach is based on the notion of encrypted post-order numbers that support the integrity and confidentiality requirements of XML content as well as facilitate efficient identification, extraction and distribution of selected content portions. By using such notion, we develop a structure-based routing scheme that prevents information leaks in XML-data dissemination and assures that content is delivered to users according to the access control policies, that is, policies specifying which users can receive which portions of the contents. Our proposed dissemination approach further enhances such structure-based, policy-based routing by combining it with multicast in order to achieve high efficiency in terms of bandwidth usage and speed of data delivery, thereby enhancing scalability. Our dissemination approach thus represents an efficient and secure mechanism for use in applications such as publish-subscribe systems for XML Documents. The publish-subscribe model restricts the consumer and document source information to the routers to which they register with. Our framework facilitates dissemination of contents of varying degrees of confidentiality and integrity requirements in a mix of trusted and untrusted networks, which is prevalent in current settings across enterprise networks and the web. Also it does not require the routers to be aware of any security policy in the sense that the routers do not need to implement any policy related to access control.

8.1 Some Simple Observations

In this section, we discuss the properties of XML data and post-order numbers.

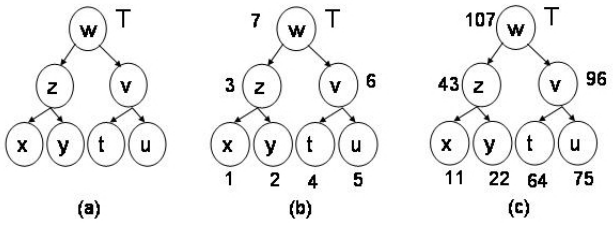


Figure 8.1. (a) A tree: abstract representation of an XML Document, (b) Post-order numbers associated with each node and (c) Randomized post-order numbers associated with each node.

8.2 XML Data Model

DOM is the commonly used model for representing XML-based languages [5]. DOM organizes data as a rooted tree. In what follows *Document* refers to such a tree and *DocumentRoot* refers to its root. Moreover, *Element* refers to an intermediate node in the tree. Content of a node includes *Attr*, *DocumentType*, *DOMImplementation* [5]. Each node that is one of the following - *Text*, *CDATASection*, *ProcessingInstruction*, *Comment*, is a leaf node in the tree. An *Entity* refers a non-root node in the tree.

Let D be an XML data instance organized according to the DOM representation. Let $T(V, E)$ be a tree representing document D (see Figure 8.1; V and E denote the set of nodes (vertices) and of edges of D, respectively. Let x be a node in V. Let D_x denote the subtree of D rooted at x. Some or all the nodes in an XML-data instance contain *content*. Content of a node x is referred to as c_x. c_x contains only the content specific to x and not of other nodes. The relation between parent-child nodes is represented as directed edges, with edges directed from parents to children. In what follows $ancestor(x)$ denotes the set of ancestors of x.

Dissemination of a document exploits the following structural properties in order to meet the requirements of secure and scalable dissemination of XML-data:

- In some scenarios, XML data is order-preserving, that is, nodes x and y have an order among them in D thus they are modeled as ordered trees. In other scenarios, XML data is modeled as unordered trees.
- The unit of data access is the *sub-tree* representation of a sub-document. The smallest unit is a node.
- Any element and its corresponding sub-document is accessible through by themselves or a subtree rooted at any of their ancestors.

These properties are crucial in ensuring that structure-based routing extracts the correct sub-document and routes it to the correct consumer; they are reflected by post-order numbers: We can identify and extract a specific sub-document in a document using a randomized post-order number.

8.3 Document Encoding and Encryption

Each element node in an XML document is signed using structural signatures defined in Chapter 5. The hash of structural position and content of a node x used in its structural signature is referred to as I_x. Table 8.3 shows the encoding of each node in the XML tree in Figure 8.1. For simplicity, the integrity identifier is not enumerated as it involves a hash value. Encryption of the node contents are carried if necessary using standard encryption techniques. If contents are encrypted, then the publisher passes of the perfectly one-way hashes [36] of the nodes to the routers. Such hashes do not leak information.

Table 8.1
Encoding of XML tree in Figure 8.1.

$Node$	$S_x : (e_x, e^x_{lowest})$	Encoding: $\langle C_x, S_z \rangle$
x	$(11, 11)$	$\langle((11, 11), I_x), (43, 11)\rangle$
y	$(22, 22)$	$\langle((22, 22), I_y), (43, 11)\rangle$
z	$(43, 11)$	$\langle((43, 11), I_z), (107, 11)\rangle$
t	$(64, 64)$	$\langle((64, 64), I_t), (96, 64)\rangle$
u	$(75, 75)$	$\langle((75, 75), I_u), (96, 64)\rangle$
v	$(96, 64)$	$\langle((96, 64), I_v), (107, 11)\rangle$
w	$(107, 11)$	$\langle((107, 11), I_w)\rangle$

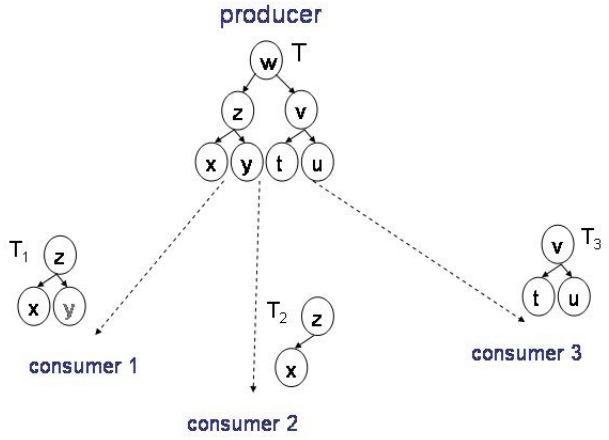


Figure 8.2. Three sub-trees of the content tree are shared with three consumers: consumer 1, 2 and 3.

8.4 Structure-based Routing

We propose a multicast based approach to disseminate XML-based data among the consumers. Figure 8.4 shows multiple consumer requests to access an XML tree. Consumer 1 has access to sub-tree T_1, consumer 2 has access to T_2 and consumer 3 has access to T_3. For dissemination of the sub-trees among various consumers, a multicast

topology based on the structure of the tree is proposed. The multicast topology is built dynamically and asynchronously using a publish-subscribe methodology. The publish-subscribe based multicast network uses structure-based routing.

Structure-based routing involves the following entities: the document source is the document producer or a trusted owner of the document and has full access to the original document and is the root of the multicast overlay network; the publisher publishes the data to a set of subscribers; the subscriber subscribes to the data and sends its request to a router-based publisher; the router routes the specific portion of the data to consumers and other routers. A router is both a publisher and a subscriber. The document source is a publisher. A consumer is a subscriber. A consumer is said to be associated with a router for a specific document if it has subscribed to that document through that router. For simplicity of discussion, we assume one document source; however the proposed solution can handle multiple document sources. A parent router of another router is one from which the latter receives some content. A child router is defined conversely.

We assume that documents are identified by a valid Uniform Resource Identifier - URI [4] or any other naming scheme suitable for the enterprise. The owner of the document can itself carry out publishing or can delegate the publishing functionality to one or more other entities. The publishing routers propagate this information to their neighbor routers.

Let D_z and D_q be sub-documents such that q is a descendant of z. Thus, $D_q \subset D_z$. Let R refer to any router that is reachable from another router R_z. D_z is the *maximal structural block* at a router R_z if and only if R_z or any router R reachable from R_z has only those consumers that have access to only D_z or D_q, for any q that is a descendant of z in D. Each router is aware of the maximal structural block that it is responsible for routing collectively to all the subscribers - consumers and routers.

Example: Let D be represented by the tree T (T is shown in Figure 8.1). Let R_1 be a router. Consumers u_1 and u_2 have subscribed to R_1 for document D. u_1 and u_2

have access to the sub-document represented by T_z and T_x, respectively. Let R_2 be a router reachable from R_1. It has a subscriber u_3. u_3 has access to the sub-document T_x. Therefore the maximal structural block of R_1 is T_z and of R_2 is T_x. If a new consumer subscribes to R_1 with an access to T itself, then the maximal structural block of R_1 becomes T.

The multicast topology with root at router R_z disseminates content to a set of consumers collectively such that none of them has access or has subscribed to a subtree D_m of D where $D_z \subset D_m$. D_z can be identified through the encrypted post-order numbers. Let p_z and p_m be the RPONs of D_z and D_m, respectively; then $p_z < p_m$, by definition of RPON. Router R_z routes (or publishes) only D_z and its sub-trees. R_z identifies its maximal structural block through its RPON e_z, which we call as the *Publishing RPON*.

A Publishing RPON (PRPON) is the encrypted post-order number of a maximal structural block being published from the corresponding router. For router R_z, p_z is a PRPON. Routing is carried on a multicast topology which is of the form: either a tree or a directed acyclic graph (DAG). In Figure 8.3, the PRPON's for the two routers (between the consumer and the producer) are 43 and 96.

Access permissions on the content for a consumer are expressed on a node in the document. Access permissions for a consumer u on a document d denoted by L^u are represented as an *AllowedSet* defined as $\{\eta_x \mid$ consumer has access to node x and η_x is the structural signature of x $\}$.

8.4.1 Content Routers

By content routers, we refer to content distributors of brokers. Such a router is an application level router that routes documents. In what follows, the notation $\{x+\}$ or $\{\langle x\rangle+\}$ denotes a non-empty set of elements of type x. Every router R is aware of the following information:

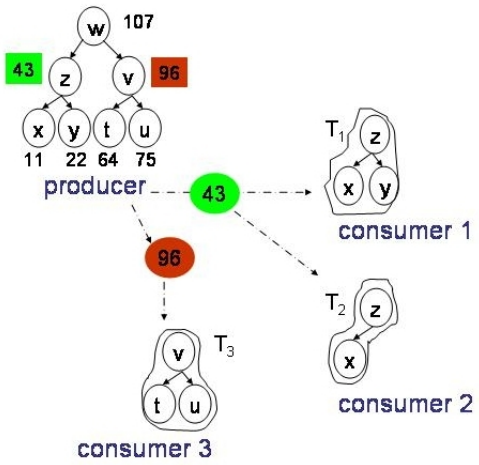


Figure 8.3. Routing of three sub-trees to consumers using RPONs.

- $\{\langle$*c-id, c-credentials, document URI, permissions, callback-address*$\rangle+\}$, where *c-id* is the id of the consumer subscribed to document accessible at *document URI*, *c-credentials* includes parameters needed for authentication of *c-id*, and permissions is the set of the nodes that a consumer has access to in the document (*AllowedSet*). The *callback-address* method provides a mechanism to deliver content to the consumer in case of asynchronous subscription.

- $\{\langle$*parent router,* $\{S_x+\}\rangle+\}$, where x is the root of the maximal structural block the parent router receives and S_x is its structural position (identifier), p_x in S_x is the PRPON of the router.

- $\{\langle$*child router,* $\{S_y+\}\rangle+\}$, where a child router is a router that has subscribed to a sub-document with PRPON S_y from R. The list of child routers with their specific PRPONs are stored at R.

Example Consider Figure 8.3. The router that routes the tree with PRPON 43 has two consumers *consumer* 1 and *consumer* 2. It does not have any parent router nor any child router. The information stored at this router is shown in Table II.

Table 8.2
Information at a router for PEPON 43 in Figure 8.3.

$\langle consumer\ 1, credentials1,$ $URI\ of\ T, \{11, 22, 43\}, callback1\rangle$
$\langle consumer\ 2, credentials2,$ $URI\ of\ T, \{11, 43\}, callback2\rangle$

8.4.2 Dissemination Network

A link in the document dissemination network is between two content routers and might involve intermediate network routers. In this section, we discuss the development of the dissemination network that uses the structural identifier.

Subscription

The subscription process is initiated by a consumer. Upon being successful the process returns the consumer a set of structural signatures for the nodes in the document that the consumer has access to. The set is the *AllowedSet* for the consumer. A consumer determines which router to join for a specific document. A router R upon receiving a request for subscription to a document performs the consumer subscription, if the consumer is authorized.

Link Setup

If a router R does not already have a known path to the document publisher to satisfy the request, it sends subscription requests to some or all other routers it is aware of (neighbor routers). Among many possible protocols, we propose a three-way handshake protocol to establish a subscription link between two routers. Suppose that router R receives positive responses from R_1, R_2. Based on the document prop-

erties, and the path length from document source to each of them, R then determines which one to choose and notify the router(s) accordingly. Several criteria can be used for such selection.

Outline of Link Setup Protocol

1. The consumer sends the subscription request for a document including its consumer id, credentials and callback method to a router R.

2. R authenticates the consumer and determines the list of signatures of the content nodes that the consumer has access to.

3. The router determines the set of sub-documents (sub-trees) from the set of signatures as follows: it sorts the signatures based on the RPON in the signature; if η_x is the signature for x, then the sorting parameter is p_x. Let the sorted set be Q. Let the set of sub-trees be denoted by Γ, initialized as empty. Let the signature with highest RPON in Q be η_z. Remove each signature η_x from Q including η_z such that $p_x \leq p_z$, assign this set of signature to γ_x; add γ_x to Γ and repeat this process until Q becomes empty.

4. If the list of accessible sub-trees Γ includes a subtree with root having RPON p_z (z being the document element) that is subsumed by the content tree served by this router, then the request is processed successfully.

5. Otherwise, the router R sends a subscription request for the subtree rooted at p_z to some or all of its neighboring routers. If the access permissions include multiple sub-trees, the subscription request includes each of these sub-trees.

6. Upon receiving a request from R, a router R_i checks if there exists a PRPON p_x. If so, it returns p_x with success as a response to R, else it recursively repeats the link setup procedure from R_i for p_z to all its neighbors.

7. Upon receiving the responses, the router R selects a parent router; the router registers the consumer and sends the response back to the client.

8. Each router determines if the new node(s) and existing node(s) can be combined together to form a complete sub-tree of the document. If so, then it replaces all the nodes stored in the database by the lowest common ancestor of these sub-trees.

8.4.3 Content Publishing

The document publication process varies based on the recipient - router or consumer. Content is published as follows. Router R receives a set of document nodes N from its ancestor (topology is a tree) or ancestors (topology is a DAG). If R has a non-empty set of consumers for the document, it then forwards the document to the consumers based on the permissions. If there is a non-empty set of routers that are subscribers for some nodes in this document, then R forwards the document to these routers based on their requirements.

Content Delivery to Consumers

For each subscribed consumer the router determines its access permissions for the associated document.

The router identifies to which received content sub-trees, the allowed nodes (included in $AllowedSet$) belong. This is carried out by matching the RPON p_x of each $\eta_x \in AllowedSet$ with the RPON of each of the roots of the received sub-trees. The sub-trees specific for the consumer in Γ are then extracted from the identified content. The router then forwards the subtree to the consumer after encrypting it using the encryption technique in place, if any. In our running example, Figure 8.3 shows how RPONs are used for routing of sub-trees.

Content Delivery to Routers

The process of forwarding the document to a router is as follows. For each router in its subscriber set, a router determines the node(s) it is registered for. It identifies and extracts these document nodes from the respective sub-trees. They are then encrypted and sent to the subscribing router. The next section discusses the technique used for identification and extraction.

Content Identification and Extraction

Content identification and extraction is carried out at each router that has at least one subscriber. Each router has a list of the content sub-trees it receives for a given document. The list is essentially a list of signatures of the roots of these sub-trees (maximal structural blocks) that contain the encrypted post-order numbers (PRPONs) of these roots. The router also keeps track of the list of signatures of the roots of the sub-trees each of its subscribers (consumers or routers) has access to (Section 8.4.1). The identification step determines the *belongs-to* relation among each of the content roots accessible to each consumer and the content sub-trees it receives. An important property of RPONs is reported here from Section 5.2.
Simple RPON Property - any node y that belongs to the subtree rooted at node x is such that the $p_y < p_x$, where p_y and p_x are the RPONs of y and x respectively. The identification technique uses the *Simple RPON Property* while verifying the *belongs-to* relation among the received content and the subscribed content. The worst case complexity of the identification step is $O(mn)$, where m is the number of received content sub-trees and n is the number of subscribers at a given router.

During the extraction step, a depth-first traversal [45] is carried out to determine the subscribed content root. The RPON of the root of the subscribed content root is compared to the RPON of the visited node. If these RPON's match, the corresponding subtree is extracted. The worst case complexity of the extraction procedure is

same as that of the depth-first search - $O(v + e)$, where v is the number of nodes in the received subtree and e is the number of edges in the received subtree.

8.4.4 Document Verification

The security requirements for secure dissemination of XML content are two-fold (Section I): maintaining confidentiality by not sending extraneous data to a consumer (preventing information leaks) and facilitating precise verification of integrity. In this section we focus on integrity verification for the received content at the consumer side.

In order to precisely detect any integrity violations, the following verification steps must be executed at the consumer side:

- if nodes have been dropped: aggregate signatures are used to verify if any nodes have been dropped.
- if the order of the nodes has been changed: using the integrity verification mechanism of structural signatures.
- if the content of a node has been compromised: using the integrity verification mechanism of structural signatures.
- if some nodes have been added in an unauthorized manner: if signed hash is used (in other words $\mathcal{H}$ represents a signed hash), then such unauthorized additions could be verified.
- if the content of one node has been replaced with the content of another node: using the integrity verification mechanism of structural signatures.
- Non-repudiation: signed hash supports complete non-repudiation.

8.4.5 Update Management

This section discusses updates to documents - content and structure in the context of structure-based routing. The updates to the XML tree is carried as per the procedure specified in Section 5.6.

In case of changes that are structurally-invariant, only the data inside a document node changes. Thus only the local hash of the node changes. Only the updates of the changed nodes along with their signatures are forwarded to the routers.

Structural changes have to be reflected in the mapping from user credentials to accessible nodes and their signatures. Therefore the services that implement the mapping function from user credential to structural identifiers need to be notified accordingly with the new EPON's. If it is a distributed hash table, then the document source updates the hash table. The routers are also notified of the modifications. Removal of a subtree is notified to the routers and consumers having the document. In case of addition of a new subtree, the original structure of the document is not affected. Therefore the update is propagated to all the routers that have consumers with access permission to the new subtree. In case of interchanges, the changes need to be propagated to the routers and consumers that are registered for any updated node or an ancestor of that updated node.

8.5 Discussion

In this section, we discuss the requirements for document dissemination and show that our proposed dissemination model addresses all the security requirements of a dissemination model.

Requirements Satisfaction

Integrity: We introduced the notion of encrypted post-order numbers in order to support all the integrity requirements. In Section 8.4.4, we developed techniques based on this notion for content verification and validation.

Access Control and Confidentiality: The structure based routing scheme ensures that a consumer is delivered only the portion of data that it has access to. The notion of maximal structural blocks at routers ensures that the routers have access to only that much amount of data that its consumers collectively have access to. Our post-order numbering based integrity check technique is parallel to the Merkle Hash algorithm. Such a technique requires the hash values of the subtrees that are not accessible to the consumer also to be forwarded, so that the consumer can verify document integrity by computing and matching the final hash value of the complete original tree. Our technique exploits the properties of post-order numbering for the same goal and thus avoids sending the hash values of the subtrees that are not accessible to the consumer, thereby preventing leakage of data. This is an indirect information leak that is prevented by our framework.

Efficiency of Structure-based Routing

The simple notion of post-order numbers in the context of XML-data provides powerful and sound principles for content identification and efficient extraction with linear time complexity. The framework uses an efficient content routing mechanism based on the content structure. The cost of routing is, in the worst case, linear in the document size.

The multicast topology based on structure-based routing for the dissemination model is acyclic. Multicast reduces the network usage, while the cycle-less feature ensures that the number of router hops is finite and proportional to the height of the document tree. Using Pigeonhole principle on the number of content nodes and the

number of consumers in a large dissemination network, there would be overlaps for content accessibility and subscription between consumers.

Given that each path from the document source to a consumer contains a monotonically decreasing sequence of RPON's of the document as PRPON's of the underlying routers and a parent router never has a less RPON as a given router's PRPON, a cycle cannot occur. This makes the multicast topology more efficient in terms of bandwidth usage and dissemination speed. The path from the source of a document to a consumer contains a list of routers. Let the sequence of routers be $R_1 \rightarrow R_2 \rightarrow \ldots \rightarrow R_i \rightarrow R_{(i+1)} \rightarrow \ldots \rightarrow R_n$. Let the publishing RPON for the consumer at each R_i be β_i. The following observations are crucial for the topological efficiency.

- For each $i < j, 1 \leq i, j \leq n$, $\beta_i \leq \beta_j$, that is, the PRPON's have a monotonically decreasing order among them in such a path. This is because a router creates a link to another router during the subscription process, if and only if the router has access to the required sub-tree or a larger sub-tree from the specific document.

- Due to the monotonicity property, the sizes of the subtrees being transmitted along the path $R_1 \rightarrow R_2 \rightarrow \ldots \rightarrow R_n$, also decrease monotonically. In the worst case all subscribers along the path have access to the complete document; however in reality, most subscribers have access to a subset of the document. Therefore the cost of transmission of the content from the source to a consumer is less than the cost incurred in a common star/broadcast topology; or is in the worst case equivalent to such a cost in the latter.

Therefore such a model is efficient in terms of network resource usage, speed of dissemination and thus is more scalable.

8.6 Summary

We showed how the structural properties of the XML Document Object Model can be exploited in order to address issues in data security and dissemination. We used randomized post-order numbers as the content routing parameters. The structure-based routing scheme uses the notion of randomized post-order numbers to prevent information leaks in XML-data dissemination.

We proposed a dissemination model for XML content that combines multicast and structure-based routing in order to improve efficiency in terms of bandwidth usage and speed of data delivery, thereby favoring scalability. The dissemination model combined with techniques for data integrity verification and confidentiality provides a secure publish-subscribe paradigm for XML Documents. The publish-subscribe model restricts the consumer and document source information to the routers to which they register with. Such an approach to XML content dissemination satisfies the requirements of integrity, confidentiality and privacy-preservation in a *holistic manner*.

Structure-based routing provides a modular and flexible model for security enforcements in data distribution. Flexibility in security enforcement is known to be an important requirement in secure system design and implementation. Depending on the degree of trust on the network integrity checks may or may not be enforced. Moreover, the framework facilitates dissemination of contents with varying degrees of confidentiality and integrity in a mix of trusted and untrusted networks, which is so prevalent in current settings across enterprise networks and the web.

9 AUTHENTICATION OF OBJECTS

There are two kinds of cryptography in this world:
cryptography that will stop your kid sister from reading your files, and
cryptography that will stop major governments from reading your files.

Bruce Schneier [121]

A widely used form for representation, storage, query, management and transmission of data is the object-oriented form. With the advent of cloud computing, web services, and JSON-type object forms to transfer data, objects are being increasingly being used information units. In this paper, we define the first schemes for (leakage-free) authentication of objects and of *redacted* objects.

9.1 Introduction

Authentication of data especially in cloud computing paradigms is an important problem, and has been widely investigated [54, 66]. Authentication is a stronger security requirement than integrity assurance. With the advent of cloud computing, web services, and JSON-type object forms to transfer data between a browser and a server, objects are increasingly being used for representation, storage, query, management, and transmission of data. Objects are transferred across organizational and trust boundaries. In such a context, the development of authentication techniques specific to (redacted) objects is an important requirement.

An object might contain sensitive information, which need to be redacted when the object or its copy is sent to another process/service that has a different trust level or that does not need to know such information [79]. The need for authentication and redaction of objects arises in the following three scenarios: $\mathcal{C}'$ is a superclass of $\mathcal{C}$. Process/service P_1 has an object $\mathcal{O}$ of class $\mathcal{C}$. Process/service P_2 (maybe a remote or local) provides a service/functionality that P_1 requires, for which it needs

to have access to an instance of class $\mathcal{C}'$. (1) Process P_1 and Process P_2 have the same level of privilege. (2) Process P_2 has a lower privilege level and thus cannot access the values of all the members in $\mathcal{O}$. (3) $\mathcal{O}$ has one or more members (not inherited from $\mathcal{C}'$) that are privacy-sensitive, and disclosure of even their existence would breach privacy. Process P_2 has a lower privilege level than P_1 and thus should not learn about the existence of such members. For scenario 1, the object needs to be authenticated but not redacted. For scenario 2, the object needs to be redacted such that the values of the sensitive members are hidden/deleted, and the redacted object should be authenticated. For scenario 3, the object needs to be redacted such that the names and values of the sensitive members are hidden/deleted, and the redacted object should be authenticated. Moreover, for the latter two cases, the redacted objects should of type that is a subclass of $\mathcal{C}'$ and defines a behavioral subtype, which is assumed to be satisfied by the process of redaction. P_1 might store $\mathcal{O}$, which would be used by P_2 later. Multiple processes and services can also be included in such scenarios.

In this paper, we define authentication schemes using which the authenticity of an object can be verified. Moreover, we propose the notion of object redactions and redactable signatures for objects such that a public redactor (anyone) can compute the signature of an object $\mathcal{O}'$ that is redacted from $\mathcal{O}$. We assume that the redaction of an object is safe - i.e., the computation with $\mathcal{O}'$ as input would always proceed in the same manner as it would proceed for $\mathcal{O}$ as input (equivalent to behavioral subtyping). We present two schemes for authentication of objects that can be represented as trees and objects redacted from them.

9.2 Objects

Member Fields: An object $\mathcal{O}$ that is an instance of class $\mathcal{C}$ contains a set of members - that are fields representing the state of the object and methods that

represent the messaging constructs. By a member, we denote instance members and not class-specific members (such as static variables and methods in Java).

Inheritance: Inheritance of classes are used to define subclasses. An instance of a subclass contains all the members of all the super-classes as well as its own new members with some exceptions. The exceptions are in the context of methods. Methods can be overridden (such as virtual methods in C++ and non-static methods in Java). Let $\mathcal{C}$ be the class of the object $\mathcal{O}$. A member belongs to the class where it is declared. Therefore, if a member was defined in a superclass $\mathcal{C}'$ of $\mathcal{C}$, then it belongs to $\mathcal{C}'$, and is inherited by $\mathcal{C}$. For an instance method $m()$ that is defined in $\mathcal{C}'$, that specific definition belongs to $\mathcal{C}'$. If $\mathcal{C}$ overrides the definition of the method $m()$, then $\mathcal{C}$ contains this new definition of $m()$, otherwise $\mathcal{C}$ inherits the definition of $m()$. Overloading of methods lead to different method signatures, and thus are treated as different members. For simplicity, we have not explicitly handled constructors, which can be handled in a way similar to that of methods (even though they are not exactly methods).

Example: A class `Emp` (employees) is a superclass of class `RegEmp` (regular employees - eligible for bonuses).

```
public class Emp {
  private int id, pay;
  public Emp(int idv, int payv) {id=idv; pay=payv;}
}
public class RegEmp extends Emp {
  private float bonus;
  public RegEmp(float bonus_pct) {bonus = bonus_pct;}
}
```

9.3 Object Trees

Objects can be represented as trees if each member field is referred to by at most one other member, and it does not have any cyclic references. Each member of such an object is represented as a tree, as specified below (See the object tree of *objRegEmp* - instance of *RegEmp* class in Figure 9.2(b)).

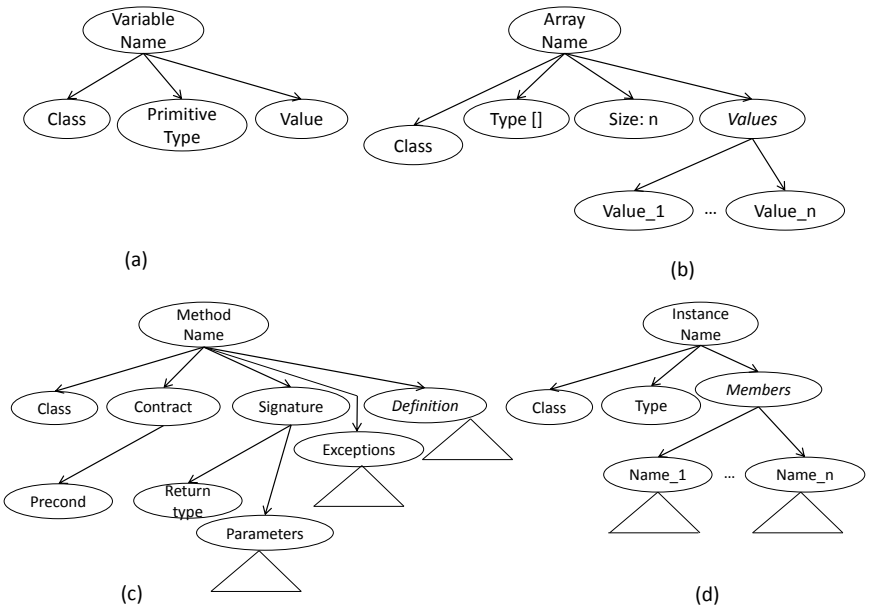


Figure 9.1. Tree representations of members of objects: (a) primitive data type, (b) array of primitive types, (c) methods, and (d) instances of user-defined types.)

Primitive Types: A member variable is represented as a tree (Figure 9.1(a)). Root of the tree specifies the name of the member (e.g., *id*). The first (left) child specifies the class name where this member is declared - in this case it is $\mathcal{C}$. (If a superclass has declared a variable with the same name, then that there would be another entry in the object tree). Next child specifies the type, and the right child specifies the value contained in that variable.

Arrays: The tree for arrays (Figure 9.1(b)) contains the name as the root. The first child is the class name. Next child is the type as "type []" (e.g., int []), the next child of root contains the size of the array. The next child is the root of another subtree. The values in the array are represented as the leaf nodes in the subtree. It can be extended to represent arrays of user-defined types by adding references or pointers to instances in the nodes representing values.

Methods: The tree for methods (Figure 9.1(c)) contains the name of the method as the root node. The name of the class that defines the method is the first left child. The contracts (pre-condition and post-condition in this order) are specified as the next child. The return type and then the definition (method body) are defined as the next children, in this order.

Instances of User Defined Types: A user-defined type (such as class, structures and unions) contains member variables, methods (if it is a class), and class-specific variables and methods. The tree representing an instance of a user-defined type (Figure 9.1(d)) has the name as the root, the class it belongs to is the first left child, and then the nodes/subtrees with respect to each other members. If the object is not contained in another object, then the class name to which it belongs has a value "NONE".

9.4 Redaction of Objects

Consider our example. If an object of `RegEmp` need to be redacted to an instance of type `Emp`, and should not contain the bonus information, then the bonus information, is removed from the object. Notice that if the received process learns that the original object had "bonus" as a member, then it would infer that the "original" object is an instance of `RegEmp` and thus the associated employee is a regular employee. In several contexts, it may breach privacy, and thus the "bonus" field should be hidden completely - even its existence. For the scenario 1 (Section 1), the object in Figure 9.2(b) is sent to the process P_2. For scenarios 2 and 3, the objects sent are in Figure 9.2(c) and (d), respectively.

How Redaction is Carried out: An access control policy $\mathcal{P}$ is applied to the object that specifies the confidentiality levels of each member in-depth in the object, if such a policy is not already applied on a member. Each process has a specific privilege level associated with it. Whenever an object $\mathcal{O}$ (instance of class $\mathcal{C}$) needs to be passed to a process of privilege level L, a redaction is carried out. Suppose the process of

privilege level L expects an instance of class $\mathcal{C}'$. The secure clone can then be an operation of this sort: $\mathcal{O}' = \mathcal{O}.redact(\mathcal{P}, L, \mathcal{C}')$. The formal method signature is given later, which also takes the signature of the object and auxiliary information. This operation creates $\mathcal{O}'$ that contains all members that have a privilege level less than or equal to L. Moreover, the redact() operation is such that it always creates an object that conforms to the behavioral subtyping rule by ensuring that $\mathcal{O}'$ is an instance of a class that is a subclass of $\mathcal{C}'$. The mechanisms of redaction can be carried out by a *secure clone* or *selective clone* operation on the object. Such operations need to be supported, especially, when an $\mathcal{O}'$ needs to be passed to a process/service (or a thread) residing in the same memory. Redaction is also be carried out during the process of serialization/marshaling. Marshalling is required when the object needs (1) to be sent to a remote process/service, or one that is in a separate memory, and/or (3) to be persistently stored.

Secure and Selective Clone: Secure and selective clone operations implement the redaction logic as well. In secure clone: the secure clone can be used as a redaction operation: $\mathcal{O}' = \mathcal{O}.clone(\mathcal{P}, L, \mathcal{C}')$. This operation creates $\mathcal{O}'$ that contains all members that have a confidentiality level less than or equal to L. Moreover, the clone() operation supports behavioral subtyping rules. A selective clone operation does not specify a privilege level, but specifies only the expected type of the object that is returned by the clone operation: $\mathcal{O}' = \mathcal{O}.clone(\mathcal{C}')$. There are several issues such as conflicts in confidentiality levels of members and aliasing that need to be addressed in implementation of policy enforcement on objects and secure clone, which we do not address here.

Redaction During Serialization: An object can be redacted during its serialization according to its expected type and access control policies, if any. Java language supports both standard and custom serialization and deserialization mechanisms via `java.io.Serializable` and `java.io.Externalizable`. The redaction can be implemented in the `WriteObject()` and `WriteExternal()` methods. One way to specify the members that need to be redacted and whether to redact their existence as well is by populating a vector

of such members that would be referred to by these methods during serialization. If the type of the resultant object is defined by a new class that is dynamically created, the definition of the class has to be sent to the recipient first; by doing so, it is ensured that the class is loaded into the memory before deserialization of the actual received object is carried out successfully. Mechanisms for such dynamic class creation needs to be in place and should be secure.

9.5 Authentication of Objects

In this section, we have presented our scheme for objects that can be represented as trees. During serialization, the signature is attached and verification object is computed for the (redacted) object. During deserialization, (1) the object is deserialized first, and then (2) this object is validated against the signature and verification object. Serialization and de-serialization of objects are necessary when the P_1 and P_2 are either remote (do not reside in the same memory). Such operations are order-preserving, that is, the order between the members in which they are serialized into a stream such as file or a network socket connection, is preserved during its de-serialization. In case it is not, de-serialization may fail. Therefore, the authentication mechanism should not only preserve the integrity of the contents but also preserve the order among the members. Moreover, the straightforward scheme of signing nodes and edges in an object tree would not work.

Cryptographic Notations: $\mathcal{H}$ is an one-way collision resistant hash function. `(pk, sk)` is a pair of public and secret key respectively. $(\sigma_{\mathcal{O}},\mathcal{VO}_{\mathcal{O}}) \leftarrow \mathtt{rSign}_{\mathtt{sk}}(\mathcal{O})$ signs an object $\mathcal{O}$ of class $\mathcal{C}$ using the secret key. $\mathcal{VO}_{\mathcal{O}}$ is the auxiliary information for $\mathcal{O}$. $\mathcal{VO}_{\mathcal{O}'} \leftarrow \mathtt{Redact}(\mathcal{O}, (\sigma_{\mathcal{O}}, \mathcal{VO}_{\mathcal{O}}), \mathcal{P}, \mathcal{C}')$ redacts the object $\mathcal{O}$ to $\mathcal{O}'$ with respect to class $\mathcal{C}'$ and returns the redacted verification object $\mathcal{VO}_{\mathcal{O}'}$. The redacted signature of $\mathcal{O}'$ is $(\sigma_{\mathcal{O}'},\mathcal{VO}_{\mathcal{O}'})$. Verification $\mathtt{rVrfy}_{\mathtt{pk}}((\mathcal{O}', \sigma_{\mathcal{O}}, \mathcal{VO}_{\mathcal{O}'})) = 1$ if the signature $(\sigma_{\mathcal{O}'},\mathcal{VO}_{\mathcal{O}'})$ is valid for $\mathcal{O}'$, and 0 otherwise.

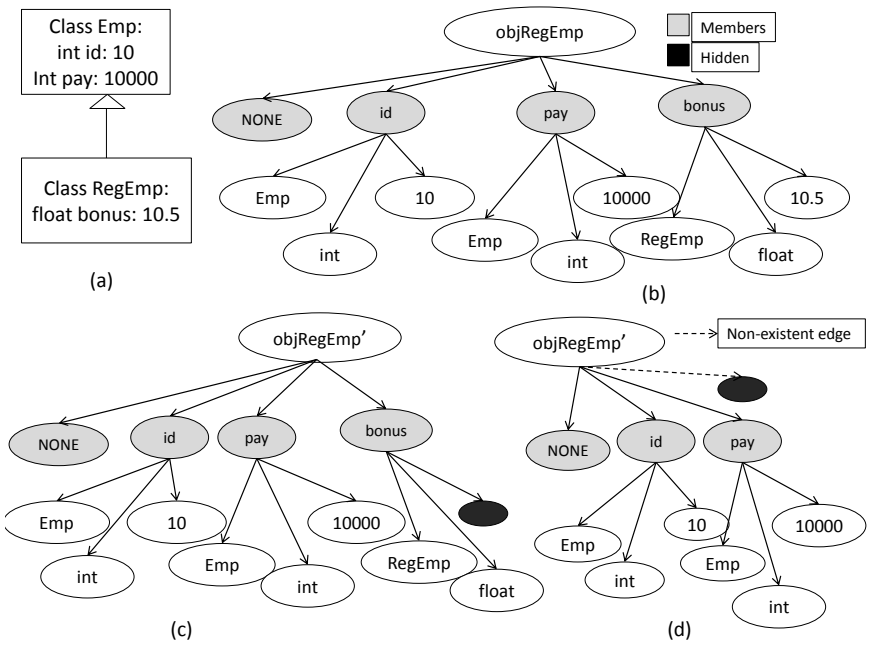


Figure 9.2. (a) Class hierarchy of Emp and RegEmp, (b) Object Tree of objRegEmp1. (c) Redacted object tree for scenario 2, (d) Redacted object tree for scenario 3.

9.5.1 Scheme Based on Merkle Hash Technique

`rSign`: The Merkle hash [100] of an object is computed by by carrying out a bottom up and left to right traversal of the object tree, and computing the respective Merkle hashes (MH). The MH of a tree is computed as follows. It computes the hash of the leaves m_i: $h_i \leftarrow \mathcal{H}(m_i)$. It then traverses the tree bottom up and left to right (for children) and computes the MH h_{ij} of node m_{ij} $(j \geq i)$, which is the parent of nodes $m_i, m_{i+1}, \ldots, m_j$ as follows: $h_{ij} \leftarrow \mathcal{H}(h_i \| h_{i+1} \ldots \| h_j)$. The MH of the tree is the MH of its root. The MH of the root of the object tree $h_{\mathcal{O}}$ is signed: $\sigma_{\mathcal{O}} \leftarrow \mathtt{rSign}_{\mathtt{sk}}(h_{\mathcal{O}})$.

`Redact`(:) Let the redacted object be $\mathcal{O}'$ an instance of class $\mathcal{C}'$. Redaction only returns the modified object $\mathcal{VO}_{\mathcal{O}'}$ is the set of the MH of each of the following node x: x is an adjacent sibling of a member in $\mathcal{O}'$ in the tree representation of $\mathcal{O}$. For scenario 2, the member that is redacted is bonus in objRegEmp1. So $\mathcal{VO}_{objRegEmp'} =$

{MH of the value of bonus: 10.5}. (There are hash schemes available in the literature that do not leak information (such as [35]) and can be used here).

`rVrfy`: The receiver computes the MH of the root of the tree for the received object $\mathcal{O}'$ using the $\mathcal{VO}_{\mathcal{O}'}$, and then verifies the signature using $\texttt{rVrfy}_{\texttt{pk}}((\mathcal{O}', \sigma_{\mathcal{O}'}, \mathcal{VO}_{\mathcal{O}'}))$. For example, the MH of the root of the tree in Figure 9.2(c) is computed as earlier, but it uses the MH of the value of bonus: 10.5. The Merkle hash technique leaks information about the existence of the bonus information, and the receiver may infer that this object is for a regular employee. In order to prevent such leakages, we present the following scheme.

9.5.2 Leakage-free Scheme

We would use our leakage-free redactable signature scheme for trees based on JMSW homomorphic signature scheme (Section 7.3). This scheme does not leak any extraneous information that is not in the subtree/subgraph. We can use the signature schemes we have developed based on Mykletun et al's Condensed-RSA or Boneh et al's aggregate signature scheme. However, for efficiency, and simplicity, we would use the single-signature scheme.

`rSign`: Let V be the set of nodes in the object tree of $\mathcal{O}$. A secure name is assigned to each node x or the structural position $\eta_x \leftarrow (p_x, r_x)$ is assigned to x in the object tree, where p_x and r_x are randomized post- and pre-order numbers. Signature of the object $\sigma_{\mathcal{O}}$ is computed as per the signing scheme presented in Section 7.3.

`Redact`: Let the redacted object be $\mathcal{O}'$ – an instance of $\mathcal{C}'$, and V' be the set of nodes in the tree of $\mathcal{O}'$. Redaction scheme in Figure 7.12 computes the modified object and the redacted signature $\sigma_{\mathcal{O}'}$.

`rVrfy`: The receiver of $\mathcal{O}'$ follows the verification procedure outlined in Figure 7.13. It first verifies content authenticity, and then verifies the structural relationships.

Efficiency and Security: Distribution of the object and authenticity verification is carried out without leaking any information. It is important to note that the size of the signature items is size-oblivious ($O(1)$) independent of the sizes of the original and redacted objects. The receiver only receives information about $\mathcal{O}'$ and constant number of verification objects, i.e., it does not learn existence/absence of the nodes in $\mathcal{O}$ that are not in $\mathcal{O}'$.

Object Graphs: Objects in general form are graphs with cycles involved. We can directly apply the leakage-free signature for graphs (Section 4.3.2) for authentication of an object or a sub-object.

9.6 Summary

An authentication scheme is used to verify (1) the integrity of data, and (2) the fact that whether the received data object O is indeed sent by the claimed sender from the claimed data source. An authentication mechanism can help in developing data provenance purposes. A widely used form for representation, storage, query, management, and transmission of data is the object-oriented form. Object-oriented databases have been studied almost a decade ago, and such trends would only influence the revival of such databases and their much more usage.

10 CONCLUSIONS

We can only see a short distance ahead,
but we can see plenty there that needs to be done.
Alan M. Turing [131]

In third party data distribution frameworks such as the "cloud", storage and distribution of data is carried out by third party infrastructures and servers, which may not be trusted. Data objects stored, processed and distributed through third-party architectures are very often organized as *trees*, *graphs* or even *forests* (set of disconnected trees/graphs); for example, data organized according to XML schemas and biological graphs. In such cloud-computing paradigms, which are increasingly being employed in order to store and publish sensitive information, protection of privacy and assurance of confidentiality are as important as verifying authenticity of data. Moreover, data authenticity must be assured even when the data that a user can access is a subset of the signed data, as users maybe authorized to only access a subset of the data.

Existing solutions such as the Merkle hash technique and the redactable signature schemes lead to data leakages that can be used to infer sensitive information that is not part of the received data, which in turn would lead to privacy and confidentiality breaches. Our contributions have been summarized in the following section.

10.1 Research Contributions

In this work, we demonstrated a connection between structural leakages and their implications on privacy and confidentiality. We characterized the inference attacks that can be carried out on the widely used Merkle hash technique. We presented the

first formal security model for leakage-free redactable signatures that defines a notion of unforgeability, privacy and transparency.

In this work, a signature scheme called as "structural signatures" based on the traversal numbers has been proposed that can be used for authentication of a subtree in a leakage-free manner. For this purpose, we defined the notion of randomized traversal numbers. We have also presented the structural signature schemes for graphs – both directed acyclic graphs, and graphs with cycles, that facilitate authentication of a subgraph in a leakage-free manner. In order to support the leakage-free authentication of multiple subtrees/subgraphs, the formal notion of secure names have been developed; we have proposed two constructions of such secure names. Based on the secure names and existing redactable signature scheme for sets, we have defined a highly efficient and generic leakage-free redactable signature scheme that can be used not only for trees, but also for graphs and forests. This scheme is highly efficient – it computes only one signature per tree/graph/forest.

Our schemes for leakage-free authentication can be used for encrypted data (nodes are encrypted), which plays a significant role in enabling security in cloud computing solutions and services. We also showed how the structural signatures can be used to automatically recover from structural errors in tree-structured data. Such a scheme has several applications especially in satellite-based data transmission and in sensors. Our schemes can be used for leakage-free authentication of paths, and has applications in authentication of of XPath query results.

As an application of the structural signatures, we have developed a publish/subscribe scheme for XML distribution known as "structure-based routing", which uses randomized traversal numbers not only for verification structural integrity, but also for efficient routing of contents. In another application scenario, leakage-free authentication of objects is an important requirement. Objects are a primary model of data representation in object-oriented programs, web services, and object-oriented databases. Serialized objects are also stored and/or transmitted in environments that involve untrusted third-party entities. We have developed the first such solution

to this problem. Moreover, in financial scenarios, organizations such as credit-card providers, banks, and tax offices manage, store and process financial information. Given the sensitive nature of such data, it is essential to facilitate authentication of financial data without leaking. Our solutions can be applied in order to address such requirements in the financial domain.

10.2 Open Problems

Completeness verification and leakage-free authentication of query results: The question is can we develop a scheme for trees/graphs so that query results from such databases can be authenticated without leaking, and the completeness of the query results can be verified. We think it is impossible to provide both completeness and leakage-free properties together. The question is quite interesting when a single query results in multiple subtrees/subgraphs; in such a case, what is the lower-bound on the leakage for an authentication scheme that provides verification of completeness?

Optimality of the single-signature solution: In Section 4.3.2, we presented a leakage-free signature that computes only one signature, and carries out $O(n)$ modular multiplications in the RSA system, where n is the number of nodes and edges. The number of signatures is optimal. However, is the number of modular multiplications optimal, or can we find a scheme in which we can compute a leakage-free signature for a tree, graph and/or a forest, where it would lead to a sub-linear number of such operations?

Leakage-free authentication of paths: As we described earlier, the path relationship between two nodes in a tree/graph can be authenticated without leaking. However, when a user receives multiple sub-paths (or sub-sequences) from a path/sequence, the user can learn about the path relationships between the nodes that are belong to different sub-paths. A straightforward solution to this problem is to compute $O(n^2)$ number of signatures for a path consisting of n nodes. There are two questions: can

we develop a scheme that is more efficient than this one, and what is the lower-bound on the number of signatures?

Undecidability of random-ness: We needed a scheme to compute randomized traversal numbers, which led us to the following question: how do we know that a given number is truly a random number or "almost" a random number. There are statistical techniques towards addressing this question, however, there are no schemes that can be used to prove whether a given number is truly random or not. We do not have such a scheme as well. The following conjecture is on this problem.

Conjecture 1. *Determining whether an event or number is truly random, is undecidable.*

10.3 Future Research Directions

Unforgeability of redactable signatures: Redactable signatures as as been noted by Johnson et al [74] can only support a notion of unforgeability weaker than the standard notion - EU-CMA. Johnson et al proposed a redactable signature for sets that is existentially unforgeable against chosen message attacks under the subset and union operations (i.e., one can "legally" forge signatures for a subset (or a union) from the signature of a message (or signatures of messages)). The question is can we have a redactable signature for sets that is leakage-free, and is existentially unforgeable against chosen message attacks under only the subset or the union operation, not both of them. Such a scheme has interesting applications in third-party data distribution. The following conjecture is based on this problem.

Conjecture 2. *A redactable signature scheme supports subset operation iff it supports the union operation.*

Authenticated databases and privacy-preserving operations: Authenticated databases are important especially in a third-party cloud context. Do the schemes proposed in this thesis support any form of authenticity requirements in third-party databases? Moreover, if there are further security and efficiency requirements in such a context, then what they are and how they can be addressed. It is essential to develop schemes, systems and standards towards various levels of security on cloud-based databases. Moreover, privacy-preserving operations on trees, graphs, and forests are gaining importance in both cloud frameworks and two-party frameworks. Such operations are useful in query evaluation on encrypted databases, caching such as of XML data, and in multi-party computation. Solutions to privacy-preserving operations on such data objects enable cloud-based databases of sensitive data such as healthcare, financial as well as biological data.

Composite software and their interactions: Composite software and their execution has three aspects: (1) data, (2) code of the components, and (3) the metadata that specifies the interaction and makes the software discoverable as a service. In the emerging models of composite web services, mobile applications, and cloud computing, each of these aspects should be assured with respect to their integrity and confidentiality. When services/applications from multiple parties are used in developing a single service, it is essential to verify their integrity and authenticity. Authenticated UDDI registries are used to discover web services (Bertino *et al.* [19]). Authentication of web services is essential towards addressing software-based need-to-know attacks [79]. The problem of authenticating all the three aspects in both static workflows/web services (static – no changes in any of these three aspects), and dynamic workflows and web services is important towards realizing a trusted third-party computing framework.

LIST OF REFERENCES

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[1] Amazon Web Services. `http://aws.amazon.com`.

[2] HIPAA: Healthcare privacy in united states. `http://www.hhs.gov/ocr/privacy`.

[3] Implementation of Pairing Based Cryptography. `http://crypto.stanford.edu/pbc`.

[4] URI: Uniform Resource Identifier. `http://www.w3.org/Addressing/URL/url-spec.txt`.

[5] XML: Extensible Markup Language. `http://www.w3.org/XML/`.

[6] XPaths. `http://www.w3.org/TR/xpath`.

[7] M. Armbrust, A. Fox, R. Griffith, A. D. Joseph, R. H. Katz, A. Konwinski, G. Lee, D. A. Patterson, A. Rabkin, and M. Zaharia. Above the clouds: A Berkeley view of cloud computing. Technical report, Technical Report No. UCB/EECS-2009-28, EECS Department, University of California, Berkeley, 2009.

[8] M. J. Atallah, Y.-S. Cho, and A. Kundu. Efficient data authentication in an environment of untrusted third-party distributors. In *Proceedings of the 24th IEEE International Conference on Data Engineering (ICDE)*, pages 696–704, Washington, DC, USA, 2008. IEEE Computer Society.

[9] M. J. Atallah, G. N. Frederickson, and A. Kundu. A tree-covering problem arising in integrity of tree-structured data. *Information Processing Letters*, 109(1):79–82, 2008.

[10] G. Ateniese, D. H. Chou, B. de Medeiros, and G. Tsudik. Sanitizable signatures. In *Proceedings of the 10th European Symposium on Research in Computer Security (ESORICS)*, volume 3679 of *Lecture Notes in Computer Science*, pages 159–177, Milan, Italy, September 12-14, 2005. Springer.

[11] G. Banavar, T. Chandra, B. Mukherjee, and J. Nagarajarao. An efficient multi-cast protocol for content-based publish subscribe systems. In *Proceedings of the 19th IEEE International Conference on Distributed Computing Systems (ICDCS)*, pages 262–272, 1999.

[12] F. Bao, C.-C. Lee, and M.-S. Hwang. Cryptanalysis and improvement on batch verifying multiple RSA digital signatures. *Applied Mathematics and Computation*, 172(2):1195–1200, 2006.

[13] N. Baric and B. Pfitzmann. Collision-free accumulators and fail-stop signature schemes without trees. In *Proceedings of the 16th Annual International Conference on Theory and Application of Cryptographic Techniques (EUROCRYPT)*, pages 480–494, Berlin, Heidelberg, 1997. Springer-Verlag.

[14] M. Bellare and G. Neven. Transitive signatures based on factoring and RSA. In *Proceedings of the 8th International Conference on the Theory and Application of Cryptology and Information Security (ASIACRYPT)*, pages 397–414, London, UK, 2002. Springer-Verlag.

[15] M. Bellare and G. Neven. Transitive signatures: new schemes and proofs. *IEEE Transactions on Information Theory*, 51:2133–2151, 2005.

[16] M. Bellare and P. Rogaway. Random oracles are practical: a paradigm for designing efficient protocols. In *Proceedings of the 1st ACM Conference on Computer and Communications Security (CCS)*, pages 62–73, New York, NY, USA, 1993. ACM.

[17] J. Benaloh and M. de Mare. One-way accumulators: a decentralized alternative to digital signatures. In *Proceedings of the Workshop on the Theory and Application of Cryptographic Techniques on Advances in Cryptology (EUROCRYPT)*, pages 274–285, Secaucus, NJ, USA, 1994. Springer-Verlag New York.

[18] P. Berman, M. Karpinski, and Y. Nekrich. Optimal trade-off for Merkle tree traversal. *Theoretical Computer Science*, 372:26–36, March 2007.

[19] E. Bertino, B. Carminati, and E. Ferrari. Merkle tree authentication in UDDI registries. *International Journal of Web Service Research*, 1(2):37–57, 2004.

[20] E. Bertino, B. Carminati, E. Ferrari, B. Thuraisingham, and A. Gupta. Selective and authentic third-party distribution of XML documents. *IEEE Transactions on Knowledge and Data Engineering*, 16(10):1263–1278, 2004.

[21] E. Bertino and E. Ferrari. Secure and selective dissemination of XML documents. *ACM Transactions on Information and Systems Security*, 5(3):290–331, 2002.

[22] E. Bertino, L.R. Khan, R. Sandhu, and B. Thuraisingham. Secure knowledge management: confidentiality, trust, and privacy. *IEEE Transactions on Systems, Man and Cybernetics, Part A*, 36(3):429–438, May 2006.

[23] N. Biggs, E. K. Lloyd, and R. J. Wilson. *Graph Theory, 1736-1936*. Clarendon Press, New York, NY, USA, 1986.

[24] K. Birman, G. Chockler, and R. van Renesse. Toward a cloud computing research agenda. *SIGACT News*, 40(2):68–80, 2009.

[25] M. Bishop. *Computer Security: Art and Science*. Addison-Wesley, 2002.

[26] A. Boldyreva, N. Chenette, Y. Lee, and A. O'Neill. Order-preserving symmetric encryption. In *Proceedings of the 28th Annual International Conference on Theory and Applications of Cryptographic Techniques (EUROCRYPT)*, pages 224–241, Berlin, Heidelberg, 2009. Springer-Verlag.

[27] A. Boldyreva, A. Palacio, and B. Warinschi. Secure proxy signature schemes for delegation of signing rights. Technical report, Cryptology ePrint Archive, Report 2003/096, International Association for Cryptologic Research, received 20 May 2003, last revised 3 Feb 2008.

[28] D. Boneh, C. Gentry, H. Shacham, and B. Lynn. Aggregate and verifiably encrypted signatures from bilinear maps. In *Proceedings of the 22nd Annual International Conference on Theory and Applications of Cryptographic Techniques (EUROCRYPT)*, 2003.

[29] C. Brzuska, H. Busch, Ö. Dagdelen, M. Fischlin, M. Franz, S. Katzenbeisser, M. Manulis, C. Onete, A. Peter, B. Poettering, and D. Schröder. Redactable signatures for tree-structured data: Definitions and constructions. In *Proceedings of the 8th International Conference on Applied Cryptography and Network Security (ACNS)*, volume 6123 of *Lecture Notes in Computer Science*, pages 87–104. Springer Berlin / Heidelberg, June 22-25, 2010.

[30] C. Brzuska, M. Fischlin, A. Lehmann, and D. Schröder. Unlinkability of sanitizable signatures. In *Proceedings of the 13th International Conference on Practice and Theory in Public Key Cryptography (PKC)*, volume 6056 of *Lecture Notes in Computer Science*, pages 444–461. Springer, May 26-28, 2010.

[31] J. Buchmann, L. C. C. García, E. Dahmen, M. Döring, and E. Klintsevich. CMSS – An improved Merkle signature scheme. In *Proceedings of the 7th International Conference on Cryptology in India (INDOCRYPT)*, pages 349–363, December 11-13, 2006.

[32] A. Buldas and S. Laur. Knowledge-binding commitments with applications in time-stamping. In *Proceedings of the 10th International Conference on Practice and Theory in Public Key Cryptography (PKC)*, pages 150–165, Berlin, Heidelberg, 2007. Springer-Verlag.

[33] L. Bull, P. Stanski, and D. McG. Squire. Content extraction signatures using XML digital signatures and custom transforms on-demand. In *Proceedings of the 12th international conference on World Wide Web (WWW)*, pages 170–177, New York, NY, USA, 2003. ACM.

[34] J. Camenisch and A. Lysyanskaya. Dynamic accumulators and application to efficient revocation of anonymous credentials. In *Proceedings of the 22nd Annual International Cryptology Conference on Advances in Cryptology (CRYPTO)*, pages 61–76, London, UK, 2002. Springer-Verlag.

[35] R. Canetti. Towards realizing random oracles: Hash functions that hide all partial information. In *Proceedings of the 17th Annual International Cryptology Conference on Advances in Cryptology (CRYPTO)*, pages 455–469, London, UK, 1997. Springer-Verlag.

[36] R. Canetti, D. Micciancio, and O. Reingold. Perfectly one-way probabilistic hash functions (preliminary version). In *Proceedings of the 30th Annual ACM Symposium on Theory of Computing (STOC)*, pages 131–140, New York, NY, USA, 1998. ACM.

[37] A. Carzaniga, D. S. Rosenblum, and A. L. Wolf. Design and evaluation of a wide-area event notication service. *ACM Transactions on Computer Systems*, 19(3):332–383, 2001.

[38] A. Carzaniga, M. J. Rutherford, and A. L.Wolf. A routing scheme for content-based networking. In *Proceedings of the 23rd Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM)*. IEEE, March 7-11, 2004.

[39] A. Carzaniga and A. L. Wolf. Forwarding in a content-based network. In *Proceedings of the Conference on Applications, Technologies, Architectures, and Protocols for Computer Communications (SIGCOMM)*, pages 163–174, New York, NY, USA, 2003. ACM.

[40] D. Catalano, D. Fiore, and M. Messina. Zero-knowledge sets with short proofs. In *Proceedings of the 27th Annual International Conference on Theory and Applications of Cryptographic Techniques (EUROCRYPT)*, pages 433–450, Berlin, Heidelberg, 2008. Springer-Verlag.

[41] E.-C. Chang, C. L. Lim, and J. Xu. Short redactable signatures using random trees. In *Proceedings of the The Cryptographers' Track at the RSA Conference on Topics in Cryptology (CT-RSA)*, pages 133–147, Berlin, Heidelberg, 2009. Springer-Verlag.

[42] S. Chari, T. Rabin, and R. L. Rivest. An efficient signature scheme for route aggregation. Manuscript at: `http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.24.8419`, 2002.

[43] S. Chatvichienchai and M. Iwaihara. Detecting information leakage in updating XML documents of fine-grained access control. In *Proceedings of the 17th International Conference of Database and Expert Systems Applications (DEXA)*, volume 4080 of *Lecture Notes in Computer Science*. Springer, 2006.

[44] J. Cheng, J. X. Yu, B. Ding, P.S. Yu, and H. Wang. Fast graph pattern matching. In *Proceedings of the 24th IEEE International Conference on Data Engineering (ICDE)*, pages 913–922, Washington, DC, USA, 2008. IEEE Computer Society.

[45] T. H. Cormen, C. E. Leiserson, R. L. Rivest, and C. Stein. *Introduction to Algorithms*. MIT Press, second edition, 2001.

[46] J.-S. Coron, Y. Dodis, C. Malinaud, and P. Puniya. MerkleDamgård revisited: How to construct a hash function. In *Proceedings of the 25th Annual International Cryptology Conference (CRYPTO)*, volume 3621 of *Lecture Notes in Computer Science*. Springer, August 14-18, 2005.

[47] P. Costa, M. Migliavacca, G. P. Picco, and G. Cugola. Epidemic algorithms for reliable content-based publish-subscribe: an evaluation. In *Proceedings of the 24th IEEE Inernational Conference on Distributed Computing Systems (ICDCS)*, pages 552–561, Washington, DC, USA, 2004. IEEE Computer Society.

[48] P. Costa and G. P. Picco. Semi-probabilistic content-based publish-subscribe. In *Proceedings of the 25th IEEE International Conference on Distributed Computing Systems (ICDCS)*, pages 575–585, Washington, DC, USA, 2005. IEEE Computer Society.

[49] G. Cugola, D. Frey, A. L. Murphy, and G. P. Picco. Minimizing the reconfiguration overhead in content-based publish-subscribe. In *Proceedings of the 19th ACM Symposium on Applied Computing (SAC)*, pages 1134–1140, New York, NY, USA, 2004. ACM.

[50] I. Damgård. A design principle for hash functions. In *Proceedings of the 9th Annual International Cryptology Conference (CRYPTO)*, pages 416–427, London, UK, 1990. Springer-Verlag.

[51] S. K. Das, K. B. Min, and R. H. Halverson. Efficient parallel algorithms for tree-related problems using the parentheses matching strategy. In *Proceedings of the 8th International Symposium on Parallel Processing (ISPP)*, pages 362–367, Washington, DC, USA, 1994. IEEE Computer Society.

[52] A. K. Datta, M. Gradinariu, M. Raynal, and G. Simon. Anonymous publish/-subscribe in p2p networks. In *Proceedings of the 17th International Parallel and Distributed Processing Symposium (IPDPS)*, pages 74.1–, Washington, DC, USA, 2003. IEEE Computer Society.

[53] P. Devanbu, M. Gertz, A. Kwong, C. Martel, G. Nuckolls, and S. G. Stubblebine. Flexible authentication of XML documents. In *Proceedings of the 8th ACM Conference on Computer and Communications Security (CCS)*, pages 136–145, New York, NY, USA, 2001. ACM.

[54] P. Devanbu, M. Gertz, C. Martel, and S. G. Stubblebine. Authentic data publication over the internet. *Journal of Computer Security*, 11:291–314, April 2003.

[55] A. K. Dewdney. Computer recreations: Of worms, viruses and core war. *Scientific American*, page 110, March 1989.

[56] Y. Dodis, T. Ristenpart, and T. Shrimpton. Salvaging merkle-damgård for practical applications. In *Proceedings of the 28th Annual International Conference on Advances in Cryptology (EUROCRYPT)*, pages 371–388, Berlin, Heidelberg, 2009. Springer-Verlag.

[57] B. A. Eckman and P. G. Brown. Graph data management for molecular and cell biology. *IBM Journal of Research and Development*, 50(6), 2006.

[58] P. F. Felzenszwalb and D. P. Huttenlocher. Efficient graph-based image segmentation. *International Journal of Computer Vision*, 59(2):167–181, September, 2004.

[59] L. Getoor and C. P. Diehl. Link mining: a survey. *ACM SIGKDD Explorations Newsletter*, 7(2):3–12, 2005.

[60] S. K. Goel, C. Clifton, and A. Rosenthal. Derived access control specification for XML. In *Proceedings of the ACM workshop on XML security (XMLSEC)*, pages 1–14, New York, NY, USA, 2003. ACM.

[61] S. Goldwasser and S. Micali. Probabilistic encryption. *Special issue of Journal of Computer and Systems Sciences*, 28(2):270–299, April 1984.

[62] S. Goldwasser, S. Micali, and R. L. Rivest. A digital signature scheme secure against adaptive chosen-message attacks. *SIAM Journal of Computing*, 17(2):281–308, 1988.

[63] M. Goodrich and R. Tamassia. Efficient authenticated dictionaries with skip lists and commutative hashing. *Technical Report, Johns Hopkins Information Security Institute*, 2001.

[64] M. T. Goodrich, M. J. Atallah, and R. Tamassia. Indexing information for data forensics. In *Proceedings of the Third International Conference on Applied Cryptography and Network Security, (ACNS)*, volume 3531 of *Lecture Notes in Computer Science*, pages 206–221. Springer Berlin / Heidelberg, June 7-10, 2005.

[65] M. T. Goodrich, R. Tamassia, and J. Hasic. An efficient dynamic and distributed cryptographic accumulator. In *Proceedings of the 5th International Conference on Information Security (ISC)*, pages 372–388, London, UK, 2002. Springer-Verlag.

[66] M. T. Goodrich, R. Tamassia, and N. Triandopoulos. Efficient authenticated data structures for graph connectivity and geometric search problems. *Algorithmica*, pages 1–48, 2009. 10.1007/s00453-009-9355-7.

[67] M. T. Goodrich, R. Tamassia, N. Triandopoulos, and R. Cohen. Authenticated data structures for graph and geometric searching. In *Proceedings of the RSA Conference on the Cryptographers' Track (CT-RSA)*, pages 295–313, Berlin, Heidelberg, 2003. Springer-Verlag.

[68] S. Haber, Y. Hatano, Y. Honda, W. Horne, K. Miyazaki, T. Sander, S. Tezoku, and D. Yao. Efficient signature schemes supporting redaction, pseudonymization, and data deidentification. In *Proceedings of the ACM Symposium on Information, Computer and Communications Security (ASIACCS)*, pages 353–362, New York, NY, USA, 2008. ACM.

[69] H. Hacigumus, S. Mehrotra, and B. Iyer. Providing database as a service. In *Proceedings of the 18th International Conference on Data Engineering (ICDE)*, pages 29–38, Washington, DC, USA, 2002. IEEE Computer Society.

[70] L. Harn. Batch verifying multiple RSA digital signatures. *Electronics Letters*, 34(12), 1998.

[71] M.-S. Hwang, C.-C. Lee, and Y.-L. Tang. Two simple batch verifying multiple digital signatures. In *Proceedings of the 3rd International Conference on Information and Communications Security (ICICS)*, pages 233–237, London, UK, 2001. Springer-Verlag.

[72] M.-S. Hwang, I.-C. Lin, and K.-F. Hwang. Cryptanalysis of the batch verifying multiple RSA digital signatures. *Informatica*, 11(1), 2000.

[73] M. Jakobsson, T. Leighton, S. Micali, and M. Szydlo. Fractal Merkle tree representation and traversal. In *Proceedings of the RSA Conference on the Cryptographers' Track (CT-RSA)*, pages 314–326, Berlin, Heidelberg, 2003. Springer-Verlag.

[74] R. Johnson, D. Molnar, D. Song, and D. Wagner. Homomorphic signature schemes. In *Proceedings of the RSA Conference on the Cryptographers' Track (CT-RSA)*, pages 244–262, London, UK, 2002. Springer-Verlag.

[75] V. Kamakoti and C. Pandu Rangan. An optimal algorithm for reconstructing a binary tree. *Information Processing Letters*, 42(2):113–115, 1992.

[76] J. Katz and Y. Lindell. *Introduction to Modern Cryptography: Principles and Protocols*. Chapman & Hall/CRC, first edition, 2007.

[77] D. E. Knuth. *The Art of Computer Programming: Fundamental Algorithms*, volume 1. Addison-Wesley Professional, 1968.

[78] P. C. Kocher. On certificate revocation and validation. In *Proceedings of the Second International Conference on Financial Cryptography*, pages 172–177, London, UK, 1998. Springer-Verlag.

[79] A. Kundu. SN2K attacks and honest services. In *1st IEEE International Workshop on Security Aspects of Process and Services Engineering (SAPSE)*, pages 445–450. IEEE Computer Society, July 2009.

[80] A. Kundu, M. J. Atallah, and E. Bertino. Leakage-free authentication of trees, graphs and forests. Under Submission, 2010.

[81] A. Kundu, M. J. Atallah, and E. Bertino. Leakage-free redactable signatures. Under Submission, 2010.

[82] A. Kundu and E. Bertino. Secure dissemination of XML content using structure-based routing. In *Proceedings of the 10th IEEE International Enterprise Distributed Object Computing Conference (EDOC)*, pages 153–164, Washington, DC, USA, 2006. IEEE Computer Society.

[83] A. Kundu and E. Bertino. A new model for secure dissemination of xml content. *IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews*, 38(3):292–301, May 2008.

[84] A. Kundu and E. Bertino. Structural signatures for tree data structures. *Proceedings of the VLDB Endowment*, 1(1):138–150, 2008.

[85] A. Kundu and E. Bertino. Authentication of objects. Under Submission, 2010.

[86] A. Kundu and E. Bertino. How to authenticate graphs without leaking. In *Proceedings of the 13th International Conference on Extending Database Technology (EDBT 2010)*, volume 426 of *ACM International Conference Proceeding Series*. ACM, March 22-26, 2010.

[87] A. Kundu and Elisa Bertino. Privacy-preserving authentication of trees and graphs. Under Submission, 2010.

[88] B. Lee, H. Kim, and K. Kim. Strong proxy signature and its applications. In *Proceedings of the Symposium on Cryptography and Information Security (SCIS)*, pages 603–608, 2001.

[89] F. Li, M. Hadjieleftheriou, G. Kollios, and L. Reyzin. Dynamic authenticated index structures for outsourced databases. In *Proceedings of the 2006 ACM SIGMOD international conference on Management of data (SIGMOD)*, pages 121–132, New York, NY, USA, 2006. ACM.

[90] J. Li, N. Li, and R. Xue. Universal accumulators with efficient nonmembership proofs. In *Proceedings of the 5th International Conference on Applied Cryptography and Network Security (ACNS)*, pages 253–269, Berlin, Heidelberg, 2007. Springer-Verlag.

[91] T. Li and N. Li. On the tradeoff between privacy and utility in data publishing. In *Proceedings of the 15th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining (KDD)*, pages 517–526, New York, NY, USA, 2009. ACM.

[92] T. Li, X. Ma, and N. Li. Worm-seal: trustworthy data retention and verification for regulatory compliance. In *Proceedings of the 14th European Conference on Research in Computer Security (ESORICS)*, pages 472–488, Berlin, Heidelberg, 2009. Springer-Verlag.

[93] D. Lin, E. Bertino, R. Cheng, and S. Prabhakar. Location privacy in moving-object environments. *Transactions on Data Privacy*, 2(1):21–46, 2009.

[94] H. Lipmaa. On optimal hash tree traversal for interval time-stamping. In *Proceedings of the 5th International Conference on Information Security (ISC)*, pages 357–371, London, UK, 2002. Springer-Verlag.

[95] K. Liu and E. Terzi. Towards identity anonymization on graphs. In *Proceedings of the ACM SIGMOD International Conference on Management of Data (SIGMOD)*, pages 93–106, New York, NY, USA, 2008. ACM.

[96] D. Ma, R. H. Deng, H. Pang, and J. Zhou. Authenticating query results in data publishing. In *Information and Communications Security (ICICS)*, volume 3783 of *Lecture Notes in Computer Science*, pages 376–388. Springer Berlin / Heidelberg, 2005.

[97] M. Mambo, K. Usuda, and E. Okamoto. Proxy signatures for delegating signing operation. In *Proceedings of the 3rd ACM conference on Computer and communications security (CCS)*, pages 48–57, New York, NY, USA, 1996. ACM.

[98] C. Martel, G. Nuckolls, P. Devanbu, M. Gertz, A. Kwong, and S. G. Stubblebine. A general model for authenticated data structures. *Algorithmica*, 39(1):21–41, 2004.

[99] R. C. Merkle. *Secrecy, Authentication, and Public Key Systems*. Ph.D. Dissertation, 1979.

[100] R. C. Merkle. A certified digital signature. In *Proceedings of the Annual International Cryptology Conference (CRYPTO)*, pages 218–238, New York, NY, USA, 1989. Springer-Verlag New York, Inc.

[101] S. Micali, M. Rabin, and J. Kilian. Zero-knowledge sets. In *Proceedings of the 44th Annual IEEE Symposium on Foundations of Computer Science (FOCS)*, page 80, Washington, DC, USA, 2003. IEEE Computer Society.

[102] S. Micali and R. L. Rivest. Transitive signature schemes. In *Proceedings of the The Cryptographer's Track at the RSA Conference on Topics in Cryptology (CT-RSA)*, pages 236–243, London, UK, 2002. Springer-Verlag.

[103] K. Miyazaki, G. Hanaoka, and H. Imai. Digitally signed document sanitizing scheme based on bilinear maps. In *Proceedings of the ACM Symposium on Information, computer and communications security (ASIACCS)*, pages 343–354, New York, NY, USA, 2006. ACM.

[104] K. Mouratidis, D. Sacharidis, and H. Pang. Partially materialized digest scheme: an efficient verification method for outsourced databases. *The VLDB Journal*, 18(1):363–381, 2009.

[105] E. Mykletun, M. Narasimha, and G. Tsudik. Authentication and integrity in outsourced databases. *ACM Transactions of Storage*, 2(2):107–138, 2006.

[106] M. Naor and K. Nissim. Certificate revocation and certificate update. In *Proceedings of the 7th Conference on USENIX Security Symposium*, pages 17–17, Berkeley, CA, USA, 1998. USENIX Association.

[107] M. Narasimha and G. Tsudik. Authentication of outsourced databases using signature aggregation and chaining. In Mong Lee, Kian Tan, and Vilas Wuwongse, editors, *Database Systems for Advanced Applications (DASFAA)*, volume 3882 of *Lecture Notes in Computer Science*, pages 420–436. Springer Berlin / Heidelberg, 2006.

[108] G. Neven. Note: A simple transitive signature scheme for directed trees. *Theoretical Computer Science*, 396(1-3):277–282, 2008.

[109] L. Opyrchal, M. Astley, J. S. Auerbach, G. Banavar, R. E. Strom, and D. C. Sturman. Exploiting IP multicast in content-based publish-subscribe systems. In *IFIP/ACM International Conference on Distributed systems platforms (Middleware)*, pages 185–207, Secaucus, NJ, USA, 2000. Springer-Verlag New York.

[110] L. Opyrchal and A. Prakash. Secure distribution of events in content-based publish subscribe systems. In *Proceedings of the 10th Conference on USENIX Security Symposium*, pages 21–21, Berkeley, CA, USA, 2001. USENIX Association.

[111] R. Ostrovsky, C. Rackoff, and A. Smith. Efficient consistency proofs on a committed database. In *Proceedings of the 31st International Colloquium on Automata, Languages and Programming (ICALP)*, volume 3142 of *Lecture Notes in Computer Science*. Springer, July 12-16, 2004.

[112] H. Pang, A. Jain, K. Ramamritham, and K.-L. Tan. Verifying completeness of relational query results in data publishing. In *Proceedings of the ACM SIGMOD International Conference on Management of Data (SIGMOD)*, pages 407–418, New York, NY, USA, 2005. ACM.

[113] H Pang and K Mouratidis. Authenticating the query results of text search engines. *Proceedings of the VLDB Endowment*, 1:126–137, August 2008.

[114] H Pang and K Tan. Authenticating query results in edge computing. In *Proceedings of the 20th International Conference on Data Engineering (ICDE)*, Washington, DC, USA, 2004. IEEE Computer Society.

[115] C. Papamanthou, R. Tamassia, and N. Triandopoulos. Authenticated hash tables. In *Proceedings of the 15th ACM Conference on Computer and Communications Security (CCS)*, pages 437–448, New York, NY, USA, 2008. ACM.

[116] T. P. Pedersen. Non-interactive and information-theoretic secure verifiable secret sharing. In *Proceedings of the 11th Annual International Cryptology Conference on Advances in Cryptology (CRYPTO)*, pages 129–140, London, UK, 1992. Springer-Verlag.

[117] A. Perrig. The BiBa one-time signature and broadcast authentication protocol. In *Proceedings of the 8th ACM Conference on Computer and Communications Security (CCS)*, pages 28–37, New York, NY, USA, 2001. ACM.

[118] C. Quix, L. Ragia, L. Cai, and T. Gan. Matching schemas for geographical information systems using semantic information. In *Proceedings on the Workshop On the Move to Meaningful Internet Systems (OTM)*, volume 4278 of *Lecture Notes in Computer Science*, pages 1566–1575. Springer Berlin / Heidelberg, 2006.

[119] R. L. Rivest. Two new signature schemes. Presented at Cambridge Seminar: `http://www.cl.cam.ac.uk/Research/Security/seminars/2000/rivest-tss.pdf`, 2001.

[120] C. Sagan. *COSMOS*. Ballantine Books, 1985.

[121] B. Scheneir. *Applied Cryptography*. John Wiley & Sons, second edition, 1996.

[122] T. E. Senator. Link mining applications: progress and challenges. *ACM SIGKDD Explorations Newsletter*, 7(2):76–83, 2005.

[123] A. Shamir. How to share a secret. *Communications of the ACM*, 22(11):612–613, 1979.

[124] S. Singh and S. Prabhakar. Ensuring correctness over untrusted private database. In *Proceedings of the 11th International Conference on Extending Database Technology (EDBT)*, pages 476–486, New York, NY, USA, 2008. ACM.

[125] M. Srivatsa and L. Liu. Securing publish-subscribe overlay services with EventGuard. In *Proceedings of the 12th ACM Conference on Computer and Communication Security (CCS)*, pages 289–298, New York, NY, USA, 2005. ACM.

[126] R. Steinfeld, L. Bull, and Y. Zheng. Content extraction signatures. In *Proceedings of the 4th International Conference on Information Security and Cryptology (ICISC)*, volume 2288 of *Lecture Notes in Computer Science*, pages 163–205. Springer Berlin / Heidelberg, 2002.

[127] R. E. Strom, G. Banavar, T. D. Chandra, M. Kaplan, K. Miller, B. Mukherjee, D. C. Sturman, and M. Ward. Gryphon: An information flow based approach to message brokering. In *Proceedings of the International Symposium on Software Reliability Engineering*, 1998.

[128] B. Thompson, S. Haber, W. G. Horne, T. Sander, and D. Yao. Privacy-preserving computation and verification of aggregate queries on outsourced databases. In *Proceedings of the 9th International Symposium on Privacy Enhancing Technologies (PETS)*, pages 185–201, Berlin, Heidelberg, 2009. Springer-Verlag.

[129] Y. Tian, J. Patel, V. Nair, S. Martini, and M. Kretzler. Periscope/GQ: A graph querying toolkit. In *Proceedings of the VLDB Endowment*, volume 1, pages 1404–1407. VLDB Endowment, August 2008.

[130] A. M. Turing. Intelligent machinery. Technical report, Report for the National Physical Laboratory, published in Machine Intelligence 7, B. Meltzer and D. Michie, eds. (1969), 1948.

[131] A. M. Turing. Computing machinery and intelligence. *Mind*, 59:430–460, 1950.

[132] L. M. Vaquero, Luis R.-M., J. Caceres, and M. Lindner. A break in the clouds: towards a cloud definition. *ACM SIGCOMM Computer Communication Review*, 39(1):50–55, 2009.

[133] Swami Vivekananda. *The Complete Works of Swami Vivekananda, Volume 6, Notes Of Class Talks And Lectures*. Vedanta Press & Bookshop, 1947.

[134] H. Wang and L. V. S. Lakshmanan. Efficient secure query evaluation over encrypted XML databases. In *Proceedings of the 32nd International Conference on Very Large Databases (VLDB)*, pages 127–138. VLDB Endowment, 2006.

[135] J. Xu. On directed transitive signature. Cryptology ePrint Archive, Report 2009/209, 2009. `http://eprint.iacr.org/`.

[136] X. Yi. Directed transitive signature scheme. In *Proceedings of the The Cryptographers Track at the RSA Conference(CT-RSA)*, volume 4377 of *Lecture Notes in Computer Science*, pages 129–144. Springer Berlin / Heidelberg, 2007.

[137] P. Zezula, G. Amato, F. Debole, and F. Rabitti. Tree signatures for XML querying and navigation. In *Database and XML Technologies*, volume 2824 of *Lecture Notes in Computer Science*, pages 149–163. Springer, September 8, 2003.

[138] R. Zhang and Y. C. Hu. Hyper: A hybrid approach to efficient content-based publish/subscribe. In *Proceedings of the 25th IEEE International Conference on Distributed Computing Systems (ICDCS)*, pages 427–436, Washington, DC, USA, 2005. IEEE Computer Society.

[139] E. Zheleva and L. Getoor. Preserving the privacy of sensitive relationships in graph data. In *Proceedings of the International Workshop on Privacy, Security, and Trust in KDD (PinKDD)*, pages 153–171, Berlin, Heidelberg, 2007. Springer-Verlag.

VITA

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Ashish Kundu was born in Mangalpur in the state of Odisha, India. During his schooling, Ashish attended the Mangalpur Primary School, the Srima Shiksha Sadan Middle English School and the Srima Shiksha Sadan High School at the Sri Aurobindo Nagar near his native place. For higher secondary education (11th and 12th) in science, he studied in the Fakir Mohan College at Balasore in Odisha. During the schooling and undergraduate, Ashish received a Primary School Scholarship of Odisha, National Rural Talent Scholarship of India, and National Merit Scholarship of India. During these years, Ashish has also received several awards for his essay writing and debating abilities.

After his higher secondary education, Ashish joined the Regional Engineering College, Rourkela (now known as the National Institute of Technology, Rourkela) in order to study for the Bachelor of Engineering in Computer Science & Engineering. In 1998, after completing the Bachelor of Engineering with Honors, he went on to study for the degree of Master of Technology in Computer Science at the Indian Institute of Technology Bombay. During the master's program, Ashish worked with Prof. D. M. Dhamdhere, his advisor, and developed the notion of E-Paths and the scheme of E-Path-PRE for efficient partial redundancy elimination in the context of optimizing compilers.

After receiving the master's degree, Ashish joined the IBM Research Lab in Delhi as a Research Staff Member, where his focus of research was primarily on distributed and pervasive systems. During his tenure at IBM Research ($2000 - 2005$), Ashish received a First Invention Achievement award, two Plateau Invention Achievement awards, and a IBM Bravo award.

In 2005, Ashish joined the Department of Computer Science at Purdue University, West Lafayette, in order to pursue a Ph.D. in Computer Science. Since then he has

been affiliated with the Center for Education and Research in Information Assurance and Security (CERIAS) as well. In spring, 2006, he started working with Prof. Elisa Bertino, his advisor, on the problem of "Authentication of Trees and Graphs without Leaking". In his doctoral research, Ashish developed structural signatures and leakage-free redactable signatures for trees, graphs and forests, that have direct applications in the context of cloud computing. The first paper he co-authored with Prof. Bertino on this research topic was adjudged as the Best Student Paper at the 2006 IEEE Enterprise Computing conference. Ashish's work on information leakage in the context of trees/graphs and web services, as well as on dishonest software, have also been recognized as the Best Research Posters at some of the Annual CERIAS Symposia.

In summer 2008, he interned at Google, Mountain View, California, and developed a framework for mobile ad delivery on Android-based smart-phones. In spring 2010, he interned at EMC^2, Santa Clara, California, where his works on dynamic performance tracing in storage kernels were incorporated in a product. While at Purdue, he served on technical program committees of the IEEE EDOC, DEXA and IDEAS. Ashish defended his doctoral dissertation in November 2010, and received the Ph.D. in December 2010.