Non-repudiable provenance for clinical decision support systems *

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Abstract. Provenance templates are now a recognised methodology for the construction of data provenance records. Each template defines the provenance of a domain-specific action in abstract form, which may then be instantiated as required by a single call to the provenance template service. As data reliability and trustworthiness becomes a critical issue in an increasing number of domains, there is a corresponding need to ensure that the provenance of that data is non-repudiable. In this paper we contribute two new, complementary modules to our template model and implementation to produce non-repudiable data provenance. The first, a module that traces the operation of the provenance template service itself, and records a provenance trace of the construction of an object-level document, at the level of individual service calls. The second, a non-repudiation module that generates evidence for the data recorded about each call, annotates the service trace accordingly, and submits a representation of that evidence to a provider-agnostic notary service. We evaluate the applicability of our approach in the context of a clinical decision support system. We first define a policy to ensure the non-repudiation of evidence with respect to a security threat analysis in order to demonstrate the suitability of our solution. We then select three use cases from within a particular system, CONSULT, with contrasting data provenance recording requirements and analyse the subsequent performance of our prototype implementation against three different notary providers.

Keywords: data provenance · non-repudiation · health informatics · decision support systems

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1 Introduction

The provenance of a data resource describes the entities, activities and agents that have influenced it over time [21]. Provenance templates are a methodology for the construction of data provenance records. A template is an abstract provenance document which may be later instantiated, as many times as required, usually in the context of a larger document, to produce a concrete provenance document [5]. Each template is designed to represent a discrete, domain-specific action which can be recorded as a single call to a provenance template service [6].

Provenance tools are now being used widely in scientific domains, where trust in the provenance records constructed is essential [19]. A lack of transparency, which implies a lack of trust, is considered one of the main reasons for the poor uptake of clinical decision support systems (DSS) [22]. In response to this issue, there has been a recent movement towards secure provenance, for example [16].

One key security objective is non-repudiation, which is defined as preventing the denial of previous commitments or actions [17]. In this paper, we focus specifically on non-repudiation of origin – preventing an author from falsely denying the act of creating content or sending a message – referred to simply as non-repudiation in the remainder of the text.

Whilst the correctness of the operations commonly used to achieve non-repudiation at the cryptographic level can be formally proven, at the practical level, the broader context needs to be taken into account, such as international regulations related to digital signatures and communications, or current threats relevant to specific systems, which evolve over time. For example, applying a digital signature to a message, which is a common way to ensure its authenticity, means only that a cryptographic operation was performed by a piece of hardware or software on behalf of a person. In a real-world scenario, we might then presume that that person is the real author of a message, because we have assumed that the corresponding private key is known only to them. However, this might not hold true; there is always a chance that confidentiality of a private key can be violated (for example, by malware) and there is no guaranteed mechanism to prevent such an event.

To address this challenge, we first perform a threat analysis for the non-repudiation of recommendations made by a DSS, and define a non-repudiation policy which can be later used during an adjudication process. We then use this policy to guide the design of a provenance-based model for the representation of the evidence required for non-repudiation, and implement this as an optional feature within our provenance template service. We then evaluate our solution using three different evidence storage solutions that satisfy our policy requirements, in the context of a DSS, Consult.

2 Related Work

Authenticity, commonly defined as corroboration of a claimant’s identity, has long been considered distinct from non-repudiation [23,17]. The former is considered a simpler security requirement than the latter, which is typically a more
complex, protocol-based security service [9] and is also defined as one of nine security principles in [2]. The current ISO standard for non-repudiation [12] explicitly states that non-repudiation can only be provided within the context of a clearly defined security policy for a particular application and legal environment. Detailed discussion about why non-repudiation and related evidence management must be designed in advance can be found in the thesis of Roe [25].

To our knowledge, secure provenance and related challenges were discussed for the first time in 2007 [10] and were focused on its integrity, availability and confidentiality. Another paper [3] discussed related challenges in a more detailed way and explained that existing security models do not fit to graph structures, which is the standardized representation of provenance information.

The use of a notary service within a system to ensure the integrity and non-repudiation of biomedical knowledge retrieval requests and responses from a database has already been implemented [14] but differs from our solution by employing a so-called in-line notary. This work does not however include an analysis of possible threats or define tactics for their mitigation, which is crucial in the context of achieving non-repudiation. The authors also mention that to the best of their knowledge there currently exists no other work using blockchain-based technology to manage biomedical evidence integrity and non-repudiation. This is supported by a scoping review [11] which references the former as the only paper within the domain of healthcare or health sciences to address the property of non-repudiation.

Another survey paper [27] describes and compares existing methods to ensure integrity, authenticity, non-repudiation and proof of existence in the long-term. The authors make no distinction between the terms authenticity and non-repudiation, which would have dramatic consequences in a real-world use case. The same is true for the proposed secure provenance schemes in [1] and [13] that claim that non-repudiation can be ensured by applying digital signatures, but any further discussion about what aspects of non-repudiation are achieved is omitted.

3 A Non-repudiation Policy for Decision Support

A clinical decision support system (DSS) is a software tool that evaluates a set of health data inputs and makes recommendations to support clinical decision making. These recommendations range from treatment suggestions to establishing a diagnosis, and are provided to a patient, among other users. Because the recommendation generation process should be transparent [5], information about that process (evidence) is often provided to a patient together with a recommendation, so they can check, for example, whether valid data about their diagnosis and health condition was used (a form of Explainable AI (XAI) [18]). In other words, a patient can, either themselves or via an authorised entity, check the provenance of a recommendation generation process, given that the evidence provided describes the creation and evolution of a particular recommendation. Evidence is particularly useful if harm is caused to a patient as the result of a
particular recommendation, perhaps due to an error in the DSS’s implementa-
tion or design, when it may, for example, be required in a legal context. In order
for evidence to be used in this way, it must be irrefutable at the practical level,
meaning that it is sufficiently convincing; it is clear that it really came from
the system and it was not later changed by anyone to subvert the adjudication
process.

We refer to these concerns as threats, and identify them within a DSS by
examining the following general requirements for irrefutable evidence [17]:

1. The authenticity and integrity of the provided evidence need to be estab-
lished, such that the alleged author of the evidence cannot later deny that
authenticity.
2. Responsibilities and rules related to evidence generation, storage and verifi-
cation must be defined in order to enable all participating parties to behave
responsibly, in accordance with these rules. Violating these rules can lead to
decreased trust in the system.
3. Authenticity and integrity verification information must be available during
a pre-defined period of time, according to a time period for which non-
repudiation should be achieved (achieving non-repudiation for an unlimited
period, if feasible, is likely to be expensive). The evidence verifier must be
able to verify the evidence.
4. If a dispute related to the origin of evidence occurs, trusted timestamps are
required to reconstruct past events.

When applying these requirements to a DSS we observe, for example, that
while a DSS is generally motivated to maintain evidence in order to demonstrate
that the decision generation process is compliant with standards and clinical
practice, if harm were to be caused to a patient, a DSS creator or owner then
has a motive to falsify, modify or destroy generated incriminating evidence –
such as timestamps, in order to discredit the reconstruction of past events –
to protect themselves, particularly if a corresponding authority, responsible for
maintaining said standards and practice, is involved. There are also external
entities with a motive to disrupt evidence, such as insurance companies, who
may wish to avoid making a payment to an injured patient or a DSS provider.

To address these threats, we define a non-repudiation policy, given as a set of
mandatory requirements for the evidence generation process, in order to ensure
that the evidence produced by a DSS both engenders trust, and can also be later
used by a patient during an adjudication process in case of a future dispute.
These requirements are presented along with brief rationale:

1. A DSS is the only party able to generate valid evidence, thus all of evidence
needs to be digitally signed. Authenticity and integrity of the evidence is
achieved by this rule.
2. Cryptographic operations performed by the DSS are realised using a special
piece of hardware, which provides additional protection against private key
disclosure. The reason for applying this rule is that protection of the key
needs to be established.
3. Despite additional protection of private keys, there is always a chance that the confidentiality of a particular private key is compromised. For that reason, a private key owner should define a certain amount of time to report a confidentiality violation of the private key used for creating digital signatures (this time period is called the clearance period \[17\]). If the clearance period expires, all digital signatures created before are considered valid. Since this is a processional part of the non-repudiation and it is not important from architecture point of view, we will not address it in our solution.

4. A timestamp describing the token generation must be generated by a trusted third party. Integrity and authenticity of the timestamp need to be ensured. Due to the importance of the timestamp, we propose this measure in order to build additional trust in reconstructed events, especially if a signing key had been revoked or expired before a dispute arose.

5. Because a DSS could have a motive to disrupt or destroy existing evidence, it cannot be the only party responsible for storing and maintaining it.

6. The evidence used should be held in storage that is able to prevent the modification of stored content. The reason for applying this rule is to raise the level of trust concerning evidence integrity.

7. All information needed for integrity and authenticity of the evidence verification should be sealed as part of the evidence. This rule is intended to simplify additional evidence management.

8. After a decision is made and particular provenance is generated, the patient can verify its meaningfulness, authenticity and integrity, and can store it for prospective future claims. The assumption here is that the non-repudiation of the provenance is in the best interest of the patient, since their health condition is affected by particular decision. This reflects a current movement in healthcare whereby patients are custodians of their own data \[3\] and reduces trust assumptions about a third party, which would otherwise have to verify it instead of the patient.

9. The generated evidence must contain an identifier for the particular patient. By applying this rule, the patient may be certain that a generated decision and its evidence was not intended for a different person.

10. The evidence generated during a decision generation contains additional information about time when the request from user and when other inputs for the decision generation were obtained.

This policy is used in the following sections to define a secure process for evidence generation, storage and verification within a DSS. In the following section, we show how some of these requirements can be addressed as a provenance-based model.

4 A Provenance-based Model for Non-repudiable Evidence

The granularity of the provenance template methodology fits the design of an architecture for non-repudiable evidence perfectly. The fact that each template
represent a single, yet complete, domain-specific action within the client system allows evidence to be generated and presented at a meaningful, yet manageable scale. However the direct use of provenance data generated from templates as evidence is insufficient, because it provides no information regarding its use within the construction of the parent document. Thus in order to achieve non-repudiation within a client domain, we have first added the facility to record a provenance trace of the workflow of the provenance template service itself; we call this data \textit{meta-provenance}.

The meta-provenance trace generated for a document constitutes a wholly reproducible record of the construction of that document and is described in detail in Subsection 4.1. This data, later appended with records of the non-repudiable evidence generated at each point in the workflow as formalised in Subsection 4.2, also allows us to present clients with a comprehensive survey of provenance actions carried out on their behalf and to later validate their authenticity.

4.1 Templates for Meta-provenance

Each call to the provenance template service, besides some necessary administrative functionality, represents an action to be executed in the life-cycle of a provenance document under construction. We begin, therefore, by recalling the typical workflow for the construction of a document using the service in Figure 1.

1. \texttt{newTemplate} (one or more times) to upload templates to the server
2. (a) \texttt{newDocument} (once) to begin a new document
   (b) \texttt{addNamespace} (zero or more times) to add a namespace to the document
   (c) \texttt{registerTemplate} (one or more times) to associate a template with the document
   (d) \texttt{generate} (one or more times) to use a substitution to instantiate a template, and merge it into the document
   (e) i. \texttt{generateInitialise} (once) to use a substitution to instantiate a template with zones as a fragment
      ii. \texttt{generateZone} (zero or more times) to use a substitution to instantiate a subsequent iteration of a zone within the fragment
      iii. \texttt{generateFinalise} (once) to check and merge the fragment into the document

\textbf{Fig. 1.} How to construct a document using the provenance template service

We now describe how to formalise instances of this workflow and other important meta-data relating to the operation of the service, by recording provenance traces of the execution of the actions contributing to the life-cycle of a document. Recording the life-cycle of documents not only produces valuable metadata regarding the construction of a document, but is a necessary prerequisite to enabling the non-repudiation and later verification of the data generated.
These traces are recorded in meta-level history documents, one for each standard or object-level document under construction. History documents are valid provenance documents created and maintained by the new meta-provenance module, and stored within the server providing the service. Following the creation of new object-level document by the the document management module, the meta-provenance module will create a new history document. Each service call has a corresponding provenance template defined within the meta-provenance module. When the web service receives a request, following a successful execution of the request at the object-level by the document management module, the request data is sent to the meta-provenance module, which builds a substitution for the respective template. This is then instantiated within the corresponding separate history document. The templates for the newDocument and addNamespace service calls are shown by way of example in Figure 2.

The meta-provenance templates use annotations in the meta namespace. The object document being tracked is represented as an entity of type meta:Document and each action executed upon that document as an activity of meta:Action type. Each action is annotated with its name (meta:actionName) and given a numeric value (meta:actionNumber), corresponding to its order in the trace. The time that the execution of the action was completed is also recorded as the end time of the activity. Templates are recorded as entities of type meta:Template and fragments as entities of meta:Fragment. Object documents, templates and fragments are all annotated with the meta:identifier attribute which contains their unique document identifier within the server.

The provenance template model adds three special attributes (start, end, time) to the prov namespace in order to allow the start and end times of activities, and the times of influences to be instantiated as template value variables. These attributes are translated in the document model into the respective PROV timings. This is necessary because the PROV data model only allows these timings to be of type xsd:dateTime and so cannot be replaced by a variable name directly.

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**Fig. 2.** newDocument (left) and addNamespace (right) templates
Substitutions given as input to generation actions, that is, *generate*, (see Figure 3) *generateInit*, or *generateZone* are now also persisted as meta-level provenance documents called *substitution* documents. A history document together with its associated substitution documents together form the complete, reproducible meta-provenance record of the construction of an object document. The translation of standard substitutions into substitution documents is carried out by the meta-provenance module again by use of templates, given in Figure 4. A substitution is created using the *newSubstitution* template, and then each binding added using *addBinding*. These operations instantiations are executed in-memory by the server, and the final document is persisted by the server, under a system-generated identifier. The substitutions documents thus created during the recording of generation actions are referenced in the meta-provenance templates as entities of type *meta:Substitution* and again, being valid documents, annotated by their identifier. The fine granularity of these operations anticipates future improvements to the provenance template service, whereby substitutions may be submitted to the service over time down to the level of a single variable binding.

Any remaining data provided as part of an action, document, is stored as annotations upon the action activity, given in the *meta* namespace. The *meta:defaultUrl* attribute in the *newDocument* template shown in Figure 2 is one such example.

A meta-provenance record is sufficient to reconstruct an object-level provenance document in its entirety. In order to reproduce the construction of a particular document, its history document is first exported, and the chain of recorded actions then replicated with reference to the necessary substitution documents. This facility allows object documents to be recorded by the server at the meta-level alone, to be expanded at a later date. After the fact document reconstruction from meta-provenance offers the possibility of reducing storage requirements for object documents. Partial reconstruction of documents between specific time points would also reduce the computational requirements for the analysis of object documents.
4.2 A Template for Non-repudiable Evidence

An important requirement of our solution is the capture of the evidence required to achieve the non-repudiation of the provenance data being recorded. The meta-provenance data recorded by each template instantiation within a history document as described in Subsection 4.1 forms the core of this evidence. However, extra data concerning the security and cryptographic operations later carried out upon each addition to the meta-provenance record must also be stored in order for the evidence to provide a guarantee of non-repudiation. We record this extra data using the template shown in Figure 5.

The var:action activity represents the document management action described in Section 4.1 and is instantiated with the same identifier as used for the instantiation of the activity element of the meta-provenance template corresponding to that action. It thus serves as the graft point in the history document between the meta-provenance data recorded about the action and its evidentiary form and required security attributes, as given by the evidence template. The var:serviceCall entity represents the service call that requested the document management action, and holds information about the client application and user that made the request. The var:tokenHeader entity represents the meta-data required for achieving non-repudiation of the service call and the consequent management action. The token header contains a trusted timestamp, which is generated by a trusted timestamping authority. The header is identified by a unique system-generated identifier. The var:tokenContent entity holds a representation of the associated management action, corresponding to the provenance data generated by the meta-provenance module. The var:signature entity represents the digital signature of the required evidence, generated by the var:signToken activity. The certificate needed to verify the signature is given as the value of meta:certificate.

5 A Non-repudiation Architecture for Decision Support

The goal of the proposed solution is to provide a patient with irrefutable evidence that a recommendation made by the DSS and the provenance data recording
the generation of that recommendation originated from the DSS. There are four actors present in our solution:

1. A **patient** using the DSS during their treatment process and acting on diagnostic recommendations generated by the system.
2. A **decision support system** consisting of client and server applications, and an instance of the provenance template service, provided by and referred to below as the **provenance server**. A patient will use the client application to request recommendations from the server-side, which in turn may request one or more provenance template actions to be carried out by the provenance server, for which it will generate non-repudiable evidence that is later returned to the patient together with the recommendation.
3. A **trusted timestamping authority service** which provides signed timestamps. These timestamps are included within the required evidence generated to confirm its existence from a specific instant in time.
4. A **trusted notary service** which stores the required evidence. If a dispute about the origin of the provenance data later arises, the notary may be queried to either support or contradict a particular claim.

In the remainder of this section we describe how we use the provenance evidence model given in Section 4 to design an extended DSS architecture that
meets the policy requirements outlined in Section 4 and thus ensures non-repudiation of the recommendation-making process.

5.1 Non-repudiable evidence generation and recording process

The proposed architecture is illustrated in Figure 5. The process begins with a request from a DSS client to the DSS service (1) that initiates the generation of a recommendation by the system (2). The recommendation-making process will then in turn request one or more provenance actions to be performed by the provenance server (3). The provenance server first executes the requested action upon the object-level document as usual (4). In the standard architecture this is the point at which the DSS would simply return the recommendation to the user. In the extended architecture however it then records the action as part of the meta-provenance record for the document (5.1) as described in Subsection 4.1.

The provenance server then constructs a non-repudiation token (5.3.1). The token is made up of two parts, the token header and the token payload. The header contains a system-generated identifier for the token, an identifier for the patient who made the request, an identifier for the DSS service, a signed timestamp requested by the server from a trusted timestamping authority (5.2.1), an identifier for that timestamping authority, an identifier for the trusted notary that the evidence is to be later sent to for storage, and the digital certificates required to verify all signatures within the token. The payload consists of data representing the meta-provenance recorded for a provenance action within the recommendation generation process. In the case of a registerTemplate action, this data includes a hash of a normalised and ordered representation of the template used. Similarly, in the case of generation actions, the data includes a hash of an ordered representation of the substitution data used. The token contains all the information required to resolve potential disputes and addresses policy requirements 7, 9, and 10. The use of a trusted timestamping authority addresses policy requirement 4.

The token is then signed using a private key belonging to the server (5.3.2). This addresses policy requirement 4. The signed token is now stored as an instance of the non-repudiable evidence template shown in Figure 5 within the appropriate meta-provenance record for the requested provenance action (5.4). The signed copy of the token will later be provided to a patient as the irrefutable evidence of the recommendation generation process. Since the provenance data used as evidence contains sensitive information about a patient’s health and this information should thus not be provided directly to the notary, we store a signed hash of the signed token only. The server therefore now generates a hash of the signed token (5.5.1) and signs that hash with a second private key (5.5.2). This second signature is important for preventing the generation of false hashes. The signed hash is then sent to the trusted notary (5.6) where it is stored (6).

A copy of the signed token for the provenance action is now returned to the DSS (7). The service then returns the generated recommendation along with all signed tokens created during recommendation process to the client (8). The identifier of each signed token is generated by the DSS and is included in the
token header, so that a patient can access the stored signed token from the meta-
provenance record whenever they desire. This reflects the current movement in
healthcare whereby patients are custodians of their own data [8] and addresses
policy requirements 5 and 8.

Fig. 6. The non-repudiable DSS recommendation process

5.2 Non-repudiable Evidence Verification Process

Once evidence is presented to a patient, according to our policy, its validity
must then be checked. The patient or an authorised agent acting on their behalf,
must verify both the integrity and authenticity of the evidence, which consists
of the token and its signature. First, they must verify the content of the token.
In particular, they need to ensure that the token payload contains the correct
information relating to their medical condition, that the timestamps included
in the token are valid, and that there is a link in the token payload to their
identity; that is, that they are the correct recipient of the evidence. They must
then retrieve the token identifier from the token and look up the corresponding
record in the trusted notary. They need to check whether the digital signature
of the stored hash was created by the DSS, that it is valid, and that the stored
hash is the same for the token that was received from the DSS. Checking the
validity of the signatures involves not only verifying the correct computation of
the signatures, but also checking the revocation and expiration information of the
keys, the size of the keys and the algorithms used to make sure that the signatures
are secure. If these checks succeed, the patient has complete certainty that the
provenance data is authentic and that there is a witness (the notary) confirming
that fact. If any inconsistency is detected, or one of the digital signatures is
invalid, this fact must be reported to the DSS and the patient must not follow
the recommendation provided alongside the evidence.
6 Implementation

We have implemented a prototype version of the non-repudiation architecture described in Section 4. This involved the development of two new modules for the provenance server. The first, a meta-provenance module, carries out the construction of meta-provenance records as detailed in Subsection 4.1. The second, a non-repudiation module, performs the necessary security and cryptographic operations upon each addition to a meta-provenance record, generates the necessary non-repudiable evidence, and appends it to the stored trace. The functionality of both modules is controlled by the web service during the handling of relevant incoming requests to the server. The use of both modules is optional, however, note that whilst meta-provenance may be generated without the addition of non-repudiable evidence, the opposite is not true. Hashing and signing operations are performed using reference implementations of algorithms compliant with the PKCS 11 API standard [7], addressing policy requirement 2. The prototype does not currently make use of a trusted timestamping authority, and instead generates timestamps locally. This will however be implemented in the near future, following the RFC 3161 standard [28]. The overall architecture of the server in the context of this paper is shown in Figure 7.

The document model is graph-based and supports both the OPM [20] and PROV [24] provenance specifications. The document persistence module defines an interface for storing documents, and provides a number of backends. The model was designed with graph databases in mind, and our core storage backend is Neo4j (https://neo4j.com), but we also support those that follow the
Tinkerpop (https://tinkerpop.apache.org) standard, and provide a baseline relational implementation. The construction of documents is controlled through the document management module, which is accessed as a web service.

As shown in Figure 7, our prototype system provides three trusted notary implementations, each of which exhibits the required properties of data immutability and data auditability, and meets policy requirement 6. Our chosen implementations are a distributed ledger, with hashed blocks and a public ledger (Hyperledger Fabric, https://www.hyperledger.org/projects/fabric); a single store object service, with single-write functionality and object access (MinIO, https://min.io); and a file secured by an append-only access control policy (SELinux, http://www.selinuxproject.org). Our notaries are accessed as a web service, providing calls to add, and validate the presence of, data within each notary.

7 Evaluation

We hypothesise that each notary implementation is likely to affect the performance of the provenance server differently, depending on the domain within which the server is deployed. Therefore, by providing multiple implementations, our aim is to allow a user to select the notary that works best with the server within a given domain. In order to produce a set of heuristics for notary selection, we now examine the performance of the server when attached to each notary in three use cases with distinct characteristics for the construction of provenance information. These use cases exist within the CONSULT architecture, a DSS designed to support stroke patients in self-managing their treatments [4].

Fig. 8. Sample of rules used to capture provenance data in the recommendation service

At the core of the CONSULT system is an argumentation-based recommendation service, which takes facts about a patient and their preferences, and, using a computational form of clinical guidelines, determines a treatment path for them [15]. This first use case is characterised by a high computation time. In this instance, provenance data provides the aforementioned insight into the recommendations provided by this service. To extract this data, we augment the service’s rule-base with an additional set of rules, which are satisfied when the system makes particular decisions, and thus output the required provenance data. We structure these rules in the style of [20], and an example is given in Figure 8.

5 https://github.com/kclhi/nr
The facts used by the recommendation service are based upon sensor data (and a patient’s EHR), which the CONSULT system gathers from wearable devices. This second use case is characterised by high volumes of data. Here, provenance data is useful for auditing purposes, for example to aggregate sensor data and identify erroneous readings, before subsequently tracking them back to the device from which they originate. To extract this data, we examine the sensor readings that arrives at a central service in the CONSULT system.

To interface with the CONSULT system, users engage with a chatbot. This chatbot is able to provide the patient with healthcare information, which includes the information provided by the recommendation service, although we do not consider this interaction as a part of this third use case. This aspect of the system is characterised by its non-determinism, as we cannot know, prior to the execution of the chatbot, which answers a user will provide. Much like the recommendation service, in this situation provenance data provides insight into the decisions made by the chatbot, and various parts of the CONSULT chatbot logic are augmented to extract this data.

The output from each of these use cases is used as the basis for constructing substitutions for a set of templates designed for the CONSULT DSS. These templates capture the key agents (e.g. a patient), entities (e.g. a sensor reading or a clinical guideline) and activities (e.g. the generation of a recommendation), in the DSS. In the case of the chatbot, each substitution is constructed and submitted incrementally as zones, as the interaction with the chatbot progresses.

### 7.1 Experiments and Results

We now examine the performance of the provenance server when attached to each notary, within each of these use cases. To do so, we further augment the CONSULT system in order to simulate patients interacting with each use case. The results of these simulations are shown in Table 1, which reflects the average response time, and related statistical tests, of each call to the server from CONSULT, over 1000 simulations \((N = 1000)\). Note that these experiments were performed before the completion of the prototype but still offer a relative comparison of performance.

Examining first the performance of different notaries against one another, we note that the introduction of a ledger-based notary results in the most significant overhead in terms of response time, which is to be expected, given that speed is a common criticism of the technology. While this may make a ledger appear to be the least attractive option, it may still be a consideration when deploying

| Notary | Recommendation | Sensor | Chatbot |
|--------|---------------|--------|---------|
| Ledger | 7.04 (.05,.05; .05,.05) | 6.25 (.05,.05; .05,.05) | 3.02 (.05,.05; .05,.05) |
| Object | 0.56 (.05,.05; .6,.6) | 0.56 (.05,.05; .6,.6) | 0.55 (.05,.05; .4,.6) |
| File | 1.17 (.05,.05; .05,.05) | 1.36 (.05,.05; .05,.05) | 0.82 (.05,.05; .05,.05) |

Table 1. Average response time of provenance server (seconds) using different notaries in different CONSULT use cases, and associated (maximum) \(p\)-values (other notaries; other use cases).
the provenance server, as the use of a ledger brings additional benefits, such as decentralisation, which may outweigh the impact of an increased response time. Of the remaining two notaries, the use of single-write object store offers the best performance, over an append-only file, which is interesting given the low-level nature of the latter, and suggests that, when linked to our server, a notary technology optimised for the storage of client data is more efficient.

In terms of the performance of the same notary across different deployment domains, we note that, in addition to offering the best performance, the use of a single-write object store also guarantees consistent performance when operating in domains with differing provenance data collection properties. This may make the object store an attractive option in domains with uncertain properties. In contrast, while responding broadly consistently to the high throughput of data found in the sensor use case, and when working with the complexity of the rule-based recommendation service, both the ledger and file offer improved performance in the chatbot use case. While, in general, this is to be expected, given that a number of smaller submissions are made to the server during the incremental construction of resources, rather than a single larger submission, it is interesting to note that this style of resource construction has the most significant impact on the performance of these two notaries.

8 Conclusions and Future Work

We have identified the importance of the role of provenance data within a DSS, as evidence designed to be used in the resolution of potential disputes about the actions of the system. We have shown that a DSS – the evidence generator – has a motive to disrupt this evidence in order to protect its interests, and thus the authenticity and integrity of the evidence must be established. That is, provenance data used as evidence must exhibit non-repudiation of origin. In order to achieve this goal, we have defined a security policy for non-repudiable evidence in the context of a DSS, developed a fully general provenance-based model to represent such evidence, and then proposed an extended DSS architecture that meets the requirements of our policy.

Our solution allows us to present to the user a comprehensive survey of all provenance actions taken by the system on their behalf and to retrieve and validate the authenticity of that data at any point thereafter.

We have developed a prototype implementation of our architecture, by extending our provenance template service with the functionality described in our evidence model, and creating a web service interface for trusted notary applications. We evaluated the performance of the prototype using three contrasting provenance generation use cases arising within the Consult DSS.

Following further improvements to our prototype, we now intend to investigate how our model may be extended to work within a distributed environment, in which provenance data is being generated by multiple systems working in multiple domains.
References

1. Ahmed, I., Khan, A., Khan, M.S., Ahmed, M.: Aggregated signatures for chaining: A secure provenance scheme. In: 2016 IEEE Trustcom/BigDataSE/ISPA. pp. 2012–2017 (Aug 2016)
2. Anderson, R.J.: Liability and computer security: Nine principles. In: Gollmann, D. (ed.) Computer Security — ESORICS 94. pp. 231–245. Springer Berlin Heidelberg, Berlin, Heidelberg (1994)
3. Braun, U., Shinnar, A., Seltzer, M.: Securing provenance. In: Proceedings of the 3rd Conference on Hot Topics in Security. pp. 4:1–4:5. HOTSEC’08, USENIX Association, Berkeley, CA, USA (2008)
4. Chapman, M., Balatsoukas, P., Ashworth, M., Curcin, V., Kökciyan, N., Essers, K., Sassoon, I., Modgil, S., Parsons, S., Sklar, E.I.: Computational Argumentation-based Clinical Decision Support. In: Proceedings of the 18th International Conference on Autonomous Agents and MultiAgent Systems. pp. 2345–2347. AAMAS ’19, International Foundation for Autonomous Agents and Multiagent Systems, Richland, SC (2019)
5. Curcin, V., Fairweather, E., Danger, R., Corrigan, D.: Templates as a method for implementing data provenance in decision support systems. Journal of Biomedical Informatics 65, 1–21 (Jan 2017)
6. Fairweather, E., Alper, P., Porat, T., Curcin, V.: Architecture for template-driven provenance recording. In: Belhajjame, K., Gehani, A., Alper, P. (eds.) Provenance and Annotation of Data and Processes. pp. 217–221. Springer International Publishing, Cham (2018)
7. Gleeson, S., Zimman, C.: PKCS #11 cryptographic token interface base specification. Tech. rep., OASIS (Apr 2015)
8. Gordon, W.J., Catalini, C.: Blockchain technology for healthcare: Facilitating the transition to patient-driven interoperability. Computational and Structural Biotechnology Journal 16, 224 – 230 (2018)
9. Hafner, M., Memon, M., Breu, R.: Seaas - a reference architecture for security services in soa. Journal of Universal Computer Science 15(15), 2916–2936 (Sep 2009)
10. Hasan, R., Sion, R., Winslett, M.: Introducing secure provenance: Problems and challenges. In: Proceedings of the 2007 ACM Workshop on Storage Security and Survivability. pp. 13–18. StorageSS ’07, ACM, New York, NY, USA (2007)
11. Hasselgren, A., Kralevska, K., Gligoroski, D., Pedersen, S.A., Faxvaag, A.: Blockchain in healthcare and health sciences - a scoping review. International Journal of Medical Informatics 134, 104040 (2020)
12. ISO/TC JTC1, SC 27: ISO 13888-1:2009 Information technology - Security techniques - Non-repudiation Part 1 - General. Tech. rep., International Organisation for Standardization (2009)
13. Jamil, F., Khan, A., Anjum, A., Ahmed, M., Jabeen, F., Javaid, N.: Secure provenance using an authenticated data structure approach. Computers & Security 73, 34 – 56 (2018)
14. Kleinaki, A.S., Mytis-Gkometh, P., Drosatos, G., Efрайmidis, P.S., Kaldoudi, E.: A blockchain-based notarization service for biomedical knowledge retrieval. Computational and Structural Biotechnology Journal 16, 288 – 297 (2018)
15. Kokciyan, N., Sassoon, I., Young, A., Chapman, M., Porat, T., Ashworth, M., Curcin, V., Modgil, S., Parsons, S., Sklar, E.: Towards an Argumentation System for Supporting Patients in Self-Managing their Chronic Conditions. In: Joint Workshop on Health Intelligence (W3PHIAI) (2018)
16. Massi, M., Miladi, A., Margheri, A., Sassone, V., Rosenzweig, J.: Using PROV and Blockchain to Achieve Health Data Provenance. Tech. rep., University of Southampton (2018)
17. Menezes, A.J., Vanstone, S.A., Oorschot, P.C.V.: Handbook of Applied Cryptography. CRC Press, Inc., Boca Raton, FL, USA, 1st edn. (1996)
18. Miller, T.: Explanation in artificial intelligence: Insights from the social sciences (2019)
19. Moreau, L.: A Canonical Form for PROV Documents and Its Application to Equality, Signature, and Validation. ACM Transactions on Internet Technology 17(4), 1–21 (2017)
20. Moreau, L., Clifford, B., Freire, J., Futrelle, J., Gil, Y., Groth, P., Kwansikowska, N., Miles, S., Missier, P., Myers, J., Plale, B., Simmhan, Y., Stephan, E., Den Bussche, J.: The open provenance model core specification (v1.1). Future Generation Computer Systems 27(6), 743–756 (2011)
21. Moreau, L., Missier, P., Belhajjame, K., B’Far, R., Cheney, J., Coppens, S., Cresswell, S., Gil, Y., Groth, P., Klyne, G., Others: Prov-dm: The prov data model. Retrieved July 30 (2013). W3C (2013)
22. Moxey, A., Robertson, J., Newby, D., Hains, I., Williamson, M., Pearson, S.A.: Computerized clinical decision support for prescribing: provision does not guarantee uptake. Journal of the American Medical Informatics Association 17(1), 25–33 (01 2010)
23. PINTO, F.: Digital time-stamping to support non repudiation in electronic communications. Proc. SECURICOM ’96-14th Worldwide Congress on Computer and Communications Security and Protection pp. 397–406 (1990)
24. Provenance Working Group W3C: W3C-PROV (2011)
25. Roe, M.: Cryptography and evidence. Tech. Rep. UCAM-CL-TR-780, University of Cambridge. Computer Laboratory (May 2010)
26. Toniolo, A., Cerutti, F., Oren, N., Norman, T., Sycara, K.: Making Informed Decisions with Provenance and Argumentation Schemes. In: 11th International Workshop on Argumentation in Multi-Agent Systems. pp. 1–20 (2014)
27. Vigil, M., Buchmann, J., Cabarcas, D., Weinert, C., Wiesmaier, A.: Integrity, authenticity, non-repudiation, and proof of existence for long-term archiving: A survey. Computers & Security 50, 16 – 32 (2015)
28. Zuccherato, R., Cain, P., Adams, D.C., Pinkas, D.: Internet X.509 Public Key Infrastructure Time-Stamp Protocol (TSP). Tech. rep., Internet Engineering Task Force (Aug 2001)