DataProVe: A Data Protection Policy and System Architecture Verification Tool

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Abstract

In this paper, we propose a tool, called DataProVe, for specifying high-level data protection policies and system architectures, as well as verifying the conformance between them in a fully automated way. The syntax of the policies and the architectures is based on semi-formal languages, and the automated verification engine relies on logic and resolution based proofs. The functionality and operation of the tool are presented using different examples.

1 Introduction

The new General Data Protection Regulation (GDPR) took effect in May 2018, and hence, designing compliant data protection policies and system architectures seem became even more important for organizations to avoid penalties. Unfortunately, the regulation given in a textual format is sometimes ambiguous and can be misinterpreted by the policy and system designers.

In [1], we proposed a semi-formal policy and an architecture language, presented their syntax and semantics, as well as the compliant operation traces and inference rules for reasoning about the privacy and data protection properties. The policy specification concept in [1] is based on our previous work [2], but with modified and extended syntax and semantics elements, specifically for modelling personal data protection properties. Similarly, the architecture language is a modified and extended version of the architecture language outlined in [3,4] with different syntax and semantics elements.

DataProVe follows the policy and architecture specification concept proposed in [1], but with some simplification on the original syntax to make it more user and text editor friendly. It is written in Python and supports graphical user interface (GUI). A user can specify a high-level data protection (or privacy) policy and a system architecture, then verify different conformance properties between the specified architecture and the high-level policy in a fully automated way. With this tool, for instance, one can compare different system architectures based on the same policy.

The main goals of the tool include helping a system designer at the higher level specification (compared to the other tools that mainly focus on the protocol level), such as with the policy and architecture design. This design step can be useful to spot any potential errors before going ahead with the concrete lower level system specification. In addition, the tool could be useful for education purposes, as it can be used to explain properties about data protections and system design.

The verification engine of DataProVe is based on logic, combining both the so-called backward and forward search strategies of resolution based proofs.
In DataProVe, a user can specify a “fine-grained” data protection policy through seven sub-policies, namely, the data collection, data usage, data storage, data retention, data transfer, data possession and data connection sub-policies.

In addition, DataProVe supports three types of conformance properties: (i) privacy conformance, (ii) conformance with regards to the data protection regulation (which we refer to as DPR conformance in this paper), and (iii) functional conformance.

The rest of this paper is structured as follows: In Sections 2-3 we outline the syntax of the policy and architecture language, respectively, on which DataProVe relies. The automated conformance verification approach used by DataProVe is detailed in Section 4. In Section 5 we present the tool itself and its features. Finally, in Section 6 we discuss the operation of the tool using some simple examples.

2 The Specification of a Data Protection Policy

The high-level data protection policy is defined from the perspective of the data controller. Here, we assume that the data controllers are service providers who collect, store, use or transfer the personal data about the data subjects. The data subjects in our case are system users whose personal data is/will be collected and used by the data controller.

A policy is composed of seven sub-policies defined on the data collection, usage, storage, retention, and transfer procedure, as well as the data possession and data connection sub-policies. The syntax presented here is a simplified version of the policy language proposed in [1].

2.1 Policy Syntax

A policy of a service provider SP, is defined on a finite set of entities EntitySet$_{pol}^{SP} = \{e_1, \ldots, e_n\}$, and a finite set of supported data types DataTypes$_{pol}^{SP} = \{\theta_1, \ldots, \theta_m\}$. In the following, we provide a definition for a set of data protection policies.

Definition 1 (Data Protection Policy). The syntax of the data protection policies are defined as the composition of seven sub-policies, namely:

\[
POL = Pol_{Col} \times Pol_{Use} \times Pol_{Str} \times Pol_{Del} \times Pol_{Fw} \times Pol_{Has} \times Pol_{Link}.
\]

where

1. Pol$_{Col}$ = Cons$_{col}$ × CPurp. (Data Collection Sub-policy)
2. Pol$_{Use}$ = Cons$_{use}$ × UPurp. (Data Usage Sub-policy)
3. Pol$_{Str}$ = Cons$_{str}$ × Where$_{str}$. (Data Storage Sub-policy)
4. Pol$_{Del}$ = Where$_{del}$ × Ret$_{delay}$. (Data Retention Sub-policy)
5. Pol$_{Fw}$ = Cons$_{fw}$ × List$^{3rd}$. (Data Transfer Sub-policy)
6. Pol$_{Has}$ = Who$_{canhave}$. (Data Possession Sub-policy)
7. Pol$_{Link}$ = Who$_{canlink}$. (Data Connection Sub-policy)

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Footnote 1: For convenience purpose, the user does not need to specify all the seven sub-policies in one run (which may take a long time). For convenience purposes, DataProVe is able to check the conformance of an architecture against a “partially complete” policy, and also supports a save functionality.
The data collection sub-policy includes whether a collection consent is required (Cons\_col) and a set collection purposes (CPurp). The data usage sub-policy specifies whether a usage consent is required (Cons\_use) for data usage, and the purposes of the data usage (UPurp). The data storage sub-policy specifies whether a storage consent is required (Cons\_str) for storing a piece of data, and where the data can be stored (Where\_str). The data deletion sub-policy specifies from where the data can be deleted (Where\_del), alongside the corresponding retention period (Ret\_del). The data transfer sub-policy involves whether a transfer consent is required (Cons\_fw), and all the third party entities to which the data can be transferred (List\_3rd).

A policy is defined on a data type ($\theta$), specifically, let $\pi_{\theta} \in \text{POL}$, be a policy defined on a data type $\theta$, and the seven sub-policies $\pi_{\text{col}} \in \text{Pol}_{\text{Col}}$, $\pi_{\text{use}} \in \text{Pol}_{\text{Use}}$, $\pi_{\text{str}} \in \text{Pol}_{\text{Str}}$, $\pi_{\text{del}} \in \text{Pol}_{\text{Del}}$, $\pi_{\text{fw}} \in \text{Pol}_{\text{Fw}}$, $\pi_{\text{has}} \in \text{Pol}_{\text{Has}}$, $\pi_{\text{link}} \in \text{Pol}_{\text{Link}}$, where

$$\pi_{\theta} = (\pi_{\text{col}}, \pi_{\text{use}}, \pi_{\text{str}}, \pi_{\text{del}}, \pi_{\text{fw}}, \pi_{\text{has}}, \pi_{\text{link}}),$$

and each sub-policy of $\pi_{\theta}$ is defined as follows:

1. $\pi_{\text{col}} = (\text{cons}, \text{cpurp})$, with $\text{cons} \in \{Y, N\}$. This specifies that if a consent is required to be collected from the data subjects (Y for Yes) or not (N for No) for this type of data, and $\text{cpurp}$ is a set of collection purposes. Purposes can be text strings that uniquely define the purpose.

2. $\pi_{\text{use}} = (\text{cons}, \text{upurp})$, with a consent collection requirement, $\text{cons} \in \{Y, N\}$, and $\text{upurp}$, a set of usage purposes.

3. $\pi_{\text{str}} = (\text{cons}, \text{wh})$, where $\text{wh}$ is a set of places where a piece of data can be stored, for instance, in a device of a customer (e.g. denoted by custloc), with a third party cloud service provider (thirdpartycloud), or in the service provider’s main or backup storage places (denoted by mainstorage, backupstorage).

4. $\pi_{\text{del}} = (\text{fromwhere}, \text{deld})$, with
   - $\text{fromwhere}$ defines the locations from where a piece of data can be deleted. This is closely related to the storage locations defined in the storage policy (point 3).
   - $\text{deld}$ represents the delay for the deletion. The value of this delay can be either $t_{NS}$, which refers to a “Non Specific time”, or a specific “numerical” time value (e.g., 1 day, 10 minutes, 5 years, etc.).

5. $\pi_{\text{fw}} = (\text{cons}, \text{3rdparty})$, where $\text{cons}$ captures if consent is required or not, and $\text{3rdparty}$ is a set of third party entities (e.g. authorities, companies, organisations) to whom the data can be transferred.

6. $\pi_{\text{has}} = \text{whocanhave}$, where $\text{whocanhave}$ is a set of entities in the system that are allowed to be able to have or possess a piece of data of type $\theta$. We we forbid for a given entity to be able to have a given data type, then that entity should never be able to have it (e.g. by obtaining, calculation, interception).

7. $\pi_{\text{link}} = \text{whocanlink}$, where $\text{whocanlink} = \{(e_1, \theta_1), \ldots, (e_k, \theta_k)\}$, is a set of pairs of entities and data types defined in the system. Each pair $(e, \theta)$ specifies that $e$ is allowed to be able to link two pieces of data of types $\theta$ and $\theta_i$. For instance, whether a service provider is allowed to be able to link a disease with a work place.

Finally, let us assume a finite set $\{\theta_1, \ldots, \theta_m\}$ of all data types supported by the service of a given provider $SP$.

The semantics of the policy is defined based on events. For more details about the semantics, we refer the reader to the policy language proposed in [1].
Then, the data protection (DPR) policy for \( SP \) is defined by the set
\[
\mathcal{PL} = \{ \pi_{\theta_1}, \ldots, \pi_{\theta_m} \}.
\]

## 3 The Corresponding Architecture Level

Below, we provide the definition of system architectures, and outline the syntax elements. Again, the syntax we present here is a simplified version of the architecture language proposed in [1]. While a high-level policy abstracts away from the relationship of the system components/entities and the messages exchange among them, a system architecture focus on these aspects. System architectures describe how a system is composed of components and how these components communicate with each other, however, they abstract away from the specific implementation details, such as the specific cryptographic algorithms, the specific order and concrete timing of the messages.

### 3.1 Architectures Syntax

In line with the policy specification, a system architecture is defined on a set of components/entities and data types. We assume that an architecture for a service provider \( SP \) is composed of a finite set of components/entities, \( \text{EntitySet}^{SP}_{arch} = \{E_{i_1}, \ldots, E_{i_m}\} \). Let \( \text{DataType}^{SP}_{arch} = \{\theta_1, \ldots, \theta_m\} \) be the set of all the supported types in an architecture. We assume a finite set of variables \( \text{Var}, X \in \text{Var} \), and values \( \text{Val}, D \in \text{Val} \).

\[
\begin{align*}
\text{HasAccessTo}: & \quad \text{HasAccessTo}: E_c \in \text{EntitySet}^{SP}_{arch} \rightarrow \{E_c \in \text{EntitySet}^{SP}_{arch}\} \\
\text{Terms}: & \quad T ::= X_\theta | V_\theta | V_{\text{purp}} | \text{Func} \\
& \quad T_i ::= \text{dd} | \text{TT} \\
\text{Func} ::= & \quad F(X_{\theta_1}, \ldots, X_{\theta_n}) | \text{Time}(T_i) | \text{Cconsent}(X_\theta) | \text{Uconsent}(X_\theta) | \text{Sconsent}(X_\theta) | \text{Fwconsent}(X_\theta, E_{\text{towhom}}) \\
\text{Destructor application}: & \quad G(T_1, \ldots, T_n) \rightarrow T \\
\text{Type}: & \quad TYPE(T) ::= \theta, \text{ where } \theta \in \text{DataType}^{SP}_{arch}.
\end{align*}
\]

Figure 1: Terms, Destructors and Types.

**HasAccessTo**: \( \text{HasAccessTo} \) is a function that expects an entity as input and returns a set of other entities defined in the same architecture. It specifies which entity can have access to the data handled/stores/collected by which other entities. For example, if \( E_m \) and \( E_p \) represent a smart meter, and a digital panel (tablet), respectively, and we want to specify that the service provider, \( E_{sp} \), can have access to the panel and the meter, then, we define the relation \( \text{HasAccessTo}(E_{sp}) = \{E_m, E_p\} \).

**Terms**: Terms model any data defined in the architecture, and is defined as shown in Figure 1.
A term can be a variable \((X_\theta)\) that represents some data of type \(\theta\), and it can also be a data constant \((V_\theta)\) of a type \(\theta\).

For each entity \(E\), we define a finite set of variables (i.e., data) \(\text{Var} = \{ X | \text{TYPE}(X) = \theta, \theta \in \text{TYPE}_{TPA}^E \}\) of type \(\theta\) that it owns or inputs into the system. A variable \(X_\theta \in \text{Var}\) represents any kind of data of type \(\theta\) supported by a service provider, such as the users’ personal information, photos, videos, posts, energy consumption data, insurance number, etc. Similarly, a data type can be anything, such as basic personal information, energy consumption data, etc. \(F(X_{\theta_1}, \ldots, X_{\theta_n})\) is a function on some pieces of data that can be, for instance, (symmetric, asymmetric, homomorphic) encryption, cryptographic hash and MAC functions.

The special function \(\text{Time}(Ti)\) specifies the time with either a non-specific time value \(TT\) or a numerical delay value, \(dd\). \(\text{Cconsent}(X_\theta)\), \(\text{Uconsent}(X_\theta)\) and \(\text{Sconsent}(X_\theta)\) specify a piece of data of type collection, usage, storage consent, respectively, on a piece of data of type \(\theta\). Finally, \(\text{Fconsent}(X_\theta, \text{E_{towhom}})\) specifies a type of data transfer consent of a piece of data of type \(\theta\), alongside an entity to whom the data can be forwarded.

A variable \(X_\theta\) will be given specific data value \(V_\theta\) during an instance of system run. The special constants are defined to captures values of special types, such as a purpose value \((V_{\text{purp}})\), a deletion delay value \((dd)\), or the so-called non specific time value \((TT)\). While \(dd\) captures a numerical time value such as 3 years, 2 months, etc, the value \(TT\) is not numerical, and is used to express the informal term “sometime” or “at some point”.

**Destructors:** A destructor represents an evaluation of a function, used to model a verification procedure. For instance, if the function \(F\) is an encryption or a digital signature, then the corresponding destructor \(G\) is the decryption or signature verification procedure. More precisely, if \(X_{\text{enc}} = \text{Enc}(X_{\text{name}}, X_{\text{Skey}})\) that represents the encryption of data \(X\) with the server key \(X_{\text{Skey}}\), and \(X_{\text{Skey}}\) represents a symmetric key, then \(G(X_{\text{enc}}, X_{\text{Skey}}) \rightarrow X\) is \(\text{Dec}(\text{Enc}(X_{\text{name}}, X_{\text{Skey}}), X_{\text{Skey}}) \rightarrow X_{\text{name}}\). Note that not all functions have a corresponding destructor, e.g., in case \(X_{\text{hash}}\) is a one-way cryptographic hash function, \(X_{\text{hash}} = \text{Hash}(X_{\text{password}})\), then due to the one-way property there is no destructor (reverse procedure) that returns \(X_{\text{password}}\) from the hash \(X_{\text{hash}}\).

The corresponding entity and data type specifications of DataProVe can be found in Sections [5.1.2] and [5.3] respectively.

**The definition of a system architecture:** An architecture \(TPA\) is defined as a set of actions (denoted by \(\{F\}\)). The formal definition of privacy architectures is given as follows:

\[
\begin{align*}
\mathcal{PA} &::= \{F\} \\
F &::= \text{OWN}_E(X_\theta) \\
&| \text{CALCULATE}_E(X_\theta = BT) \\
&| \text{CALCULATEAT}_E(X_\theta = BT, \text{Time}(TT)) \\
&| \text{CREATE}_E(X_\theta = BT) \\
&| \text{CREATEAT}_E(X_\theta = BT, \text{Time}(TT)) \\
&| \text{RECEIVE}_E(X_\theta) \\
&| \text{RECEIVEAT}_E(\text{Cconsent}(X_\theta), \text{Time}(TT)) \\
&| \text{RECEIVEAT}_E(\text{Uconsent}(X_\theta), \text{Time}(TT)) \\
&| \text{RECEIVEAT}_E(\text{Sconsent}(X_\theta), \text{Time}(TT)) \\
&| \text{RECEIVEAT}_E(\text{Fconsent}(X_\theta, \text{E_{towhom}}), \text{Time}(TT)) \\
&| \text{STORE}_{\text{Places}}(X_\theta) \\
&| \text{STOREAT}_{\text{Places}}(X_\theta, \text{Time}(TT)) \\
&| \text{DELETE}_{\text{Places}}(X_\theta) \\
&| \text{DELETETHROUGH}_{\text{Places}}(X_\theta, \text{Time}(dd)).
\end{align*}
\]

Figure 2: The table shows the syntax of a system architecture consisting of allowed actions between components/entities. The indices \(E, E_1, E_2\) refer to the entities.
• Action $OWN_E(X_\theta)$ captures that $E$ can own the data variable $X$ of type $\theta$.

• $CALCULATE_E(X_\theta = BT)$ captures that an entity $E$ can calculate the variable $X_\theta$ based on the equation $X_\theta = BT$.

• Similarly, $CREATE_E(X_\theta = BT)$ specifies that $E$ can create a piece of data of type $X_\theta$, which is equal to $BT$.

• $RECEIVE_E(X_\theta)$ specifies that $E$ can receive $X_\theta$.

• The action $STORE_{\text{Places}}(X_\theta)$ says that a piece of data of type $\theta$ can store $X_\theta$ in the set of places $\text{Places}$, where $\text{Places}$ is a set of entities $E \in \{E_{\text{Main}}, E_{\text{BackUp}}\}$. $E_{\text{Main}}$ represents a collection of main storage places such as main servers, while $E_{\text{BackUp}}$ represents a collection of back up storage places (back up servers).

• $DELETE_{\text{Places}}(X_\theta)$ captures that $X_\theta$ can be deleted from the places in the set $\text{Places}$.

• $CALCULATEAT_E(X_\theta = BT, Time(TT))$ captures that an entity $E$ can calculate the variable $X_\theta$ at some non-specific time $TT$.

• Similarly, $CREATEAT_E(X_\theta = BT, Time(TT))$ specifies that $E$ can create a piece of data of type $X_\theta$, which is equal to $BT$.

• $RECEIVEAT_E(\text{Consent}(X_\theta), Time(TT))$ says that a collection consent on $X_\theta$ can be received at some non-specific time $TT$. The case of $U\text{con}sent$ and $S\text{con}sent$ are similar.

• $RECEIVEAT_E(F\text{w\text{cons}ent}(X_\theta, E_{\text{towhom}}), Time(TT))$ says that a transfer consent on $X_\theta$ and $E_{\text{towhom}}$ can be received at some non-specific time $TT$.

• The action $STOREAT_{\text{Places}}(X_\theta, Time(TT))$ says that $X_\theta$ can be deleted at some non-specific time $TT$.

• $DELETEWITHIN_{\text{Places}}(X_\theta, Time(dd))$ captures that $X_\theta$ must be deleted from the places within a certain time delay $dd$ (recall that $dd$ is a numerical time value).

The specification of the corresponding action in DataProVe can be found in Section 5.1.1. The semantics of the architectural elements is defined based on states and compliant trace. For more details, again, we refer the reader to the architecture language proposed in [1].

3.2 The Conformance Between Policies and Architectures

We distinguish three types of conformance: (i) privacy conformance, (ii) conformance with regards to the data protection regulation (which we refer to as DPR conformance in this paper), and (iii) functional conformance.

Privacy conformance compares a policy and an architecture based on the privacy properties, namely, if at the policy level (based on a defined policy) an entity is not allowed have or posses a given piece of data, then this is also true in the corresponding architecture, and vice versa. It also says that if at the policy level an entity is not allowed to be able to link two pieces of data of two different types, then this is also the case in the architecture.

The DPR conformance deals with data protection requirements, such as appropriate consent collection, satisfaction of the defined deletion/retention delay, appropriate storage and transfer of a piece of data of given type.

Finally, the functional conformance compares a policy and an architecture based on what certain entities can have or link which two data types. Namely, which entities at the policy level and their corresponding entities at the architecture level are allowed to have/posses the same data type, as well as be able to link two pieces of data of different types. Essentially, in this case we aim at comparing them from the operational perspectives, as in real life, sometimes we would require
a system to be able to provide certain services. This conformance can help a system designer to find an appropriate trade-off between functionality and privacy.

A more formal and detailed discussion of the different forms of conformance can be found in Section 5.3.

4 The automated verification engine

The verification engine of DataProVe is based on logic and resolution based proofs. Below, we define the inference rules that will be used in the inference algorithm in Algorithm 1.

**Definition 2** An inference rule $R$ is denoted by $R = H \vdash T_1, \ldots, T_n$, where $H$ is the head of the rule and $T_1, \ldots, T_n$ is the tail of the rule. Each element $T_i$ of the tail is a fact.

$$
\begin{align*}
D1. & \text{FWCONSENTCOLLECTED}(E1,Y1,Third) \vdash \text{RECEIVEAT}(E1,\text{Fwconsent}(Y1,Third),\text{Time}(T)), \text{RECEIVEAT}(Third,Y1,\text{Time}(T)) \\
D2. & \text{CCONSENTCOLLECTED}(QQ,S) \vdash \text{RECEIVEAT}(QQ,\text{Cconsent}(S),\text{Time}(TM)), \text{RECEIVEAT}(QQ,S,\text{Time}(TM)) \\
D3. & \text{UCONSENTCOLLECTED}(LL,UU) \vdash \text{RECEIVEAT}(LL,\text{Uconsent}(UU),\text{Time}(TI)), \text{CREATEAT}(LL,UU,\text{Time}(TI)) \\
D4. & \text{UCONSENTCOLLECTED}(LA,UA) \vdash \text{RECEIVEAT}(LA,\text{Uconsent}(UA),\text{Time}(TA)), \text{CALCULATEAT}(LA,UA,\text{Time}(TA)) \\
D5. & \text{STRCONSENTCOLLECTED}(LS,US) \vdash \text{RECEIVEAT}(LS,\text{Sconsent}(US),\text{time}(TS)), \text{STOREAT}(LS,US,\text{time}(TS))
\end{align*}
$$

Figure 3: Inference rules for DPR conformance check.

Figure 3 includes the rules used in the verification of the DPR conformance properties. For instance, rule $D1$ says that if an entity $E1$ can receive a consent for the transfer of a piece of data of type $Y1$ to an entity Third at some non-specific time $T$, and Third can receive this data at the same time (or earlier), then $E1$ can collect the transfer consent of $Y1$ to Third.

The arguments in the inference rules are the entity and data type variables, which can be bound to constants (a specific entity and a data type) during the resolution based proofs/unifications.

Figure 4 includes the rules used in the verification of the privacy conformance property (regarding the HAS, i.e. data possession, property). For instance, rule $P1$ says that if the entity $RR$ can store a piece of data of type $NN$, and can delete this data within time $TT$, then the entity can have this data up to $TT$ time. Rule $P3$ says that if a trusted authority/organisation has any data that contains of pseudonymised version of DS, with some other data, then the trusted authority can also have the same data that contains the “real” DS. Finally, Rule $P7$ says that if an entity $X$ can receive a piece of data of type $D$, then it can have this data.

The arguments in the inference rules are the entity and data type variables, which can be bound to constants (a specific entity and a data type) during the resolution based proofs/unifications.

Figure 5 includes the rules used in the verification of the privacy conformance property (regarding the linkability, i.e. data connection, property). For instance, rule $L1$ says that if the entity $O$ can have any data that contains two pieces of data of types $B$, and $U$ alongside with any other data (denoted by $M1@$ and $M2@$), and any data that contains two pieces of data of types $J$ and $U$, then $O$ is be able to link $B$ and $J$. Note that this is not an “unique” link, meaning that $O$ cannot be sure that $B$ and $J$ belong to the same individual.

Similar to Figure 5, Figure 6 includes the rules used in the verification of the privacy conformance property (but this time, regarding the unique linkability property). For instance, rule $U1$ says that if an entity $O$ can have any data that contains two pieces of data of types $B$, and $U$
| Rule | Premise | Conclusion |
|------|---------|------------|
| P1. | `HASUPTO(RR,NN,Time(TT))` | `STORE(RR,NN), DELETEWITHIN(RR,NN,Time(TT))` |
| P2. | `HASUPTO(RL,NL,Time(TL))` | `STOREAT(RL,NL,Time(AT)), DELETEWITHIN(RL,NL,Time(TL))` |
| P3. | `HAS(trusted,Anydata(DS,M@))` | `HAS(trusted,Anydata(M@,P(DS)))` |
| P4. | `HAS(trusted,Anydata(DS,M@))` | `HAS(trusted,Anydata(P(DS),M@))` |
| P5. | `HAS(trusted,Anydata(M@,DS))` | `HAS(trusted,Anydata(M@,P(DS)))` |
| P6. | `HAS(trusted,Anydata(M@,DS))` | `HAS(trusted,Anydata(P(DS),M@))` |
| P7. | `HAS(X,D)` | `RECEIVE(X,D)` |
| P8. | `HAS(XD,DD)` | `RECEIVEAT(XD,DD,Time(TD))` |
| P9. | `HAS(Y,A)` | `STORE(Y,A)` |
| P10. | `HAS(YA,AA)` | `STOREAT(YA,AA,Time(TY))` |
| P11. | `HAS(T,F)` | `OWN(T,F)` |
| P12. | `HAS(Z,E)` | `CREATE(Z,E)` |
| P13. | `HAS(ZE,EE)` | `CREATEAT(ZE,EE,Time(TE))` |
| P14. | `HAS(ZC,EC)` | `CALCULATE(ZC,EC)` |
| P15. | `HAS(ZZ,EZ)` | `CALCULATEAT(ZZ,EZ,time(TZ))` |
| P16. | `HAS(Z,E)` | `COLLECT(Z,E)` |
| P17. | `HAS(L,G)` | `HAS(L,Senc(G,I)),HAS(L,I)` |
| P18. | `HAS(VV,WW)` | `HAS(VV,Mac(WW,LW)), HAS(VV,LW)` |
| P19. | `HAS(PV,QQ)` | `HAS(PV,Aenc(QV,TV)), HAS(PV,Sk(TV))` |

Figure 4: Inference rules for privacy conformance check (HAS property). The last three rules capture cryptographic operations (symmetric encryption, MAC function, and asymmetric encryption, respectively). These three are the so-called destructor application defined in Figure 1.
L1. \( \text{LINK}(O,B,J) \vdash \text{HAS}(O,\_\text{Anydata1}(B,M1@,U)), \text{HAS}(O,\_\text{Anydata2}(J,M2@,U)) \)

L2. \( \text{LINK}(O,B,J) \vdash \text{HAS}(O,\_\text{Anydata1}(B,M1@,U)), \text{HAS}(O,\_\text{Anydata2}(U,M2@,J)) \)

L3. \( \text{LINK}(O,J,B) \vdash \text{HAS}(O,\_\text{Anydata1}(B,M1@,U)), \text{HAS}(O,\_\text{Anydata2}(J,M2@,U)) \)

L4. \( \text{LINK}(O,J,B) \vdash \text{HAS}(O,\_\text{Anydata1}(B,M1@,U)), \text{HAS}(O,\_\text{Anydata2}(U,M2@,J)) \)

Figure 5: Inference rules for privacy conformance check (Linkability).

U1. \( \text{LINKUNIQUE}(O,B,J) \vdash \text{HAS}(O,\_\text{Anydata1}(B,M1@,U)), \text{HAS}(O,\_\text{Anydata2}(J,M2@,U)), \text{UNIQUE}(U) \)

U2. \( \text{LINKUNIQUE}(O,B,J) \vdash \text{HAS}(O,\_\text{Anydata1}(B,M1@,U)), \text{HAS}(O,\_\text{Anydata2}(U,M2@,J)), \text{UNIQUE}(U) \)

U3. \( \text{LINKUNIQUE}(O,J,B) \vdash \text{HAS}(O,\_\text{Anydata1}(B,M1@,U)), \text{HAS}(O,\_\text{Anydata2}(J,M2@,U)), \text{UNIQUE}(U) \)

U4. \( \text{LINKUNIQUE}(O,J,B) \vdash \text{HAS}(O,\_\text{Anydata1}(B,M1@,U)), \text{HAS}(O,\_\text{Anydata2}(U,M2@,J)), \text{UNIQUE}(U) \)

Figure 6: Inference rules for privacy conformance check (Unique linkability).
alongside with \( M \@ \) (that represents any other data), and any data that contains two pieces of data of types \( J \) and \( U \), and the data \( U \) is unique, then \( O \) is be able to link \( B \) and \( J \). Moreover, \( O \) can be sure that they belong to the same individual.

Note: For simplicity, there are inference rules that can be used to deduce trivial HAS, LINK, \( \text{LINKUNIQUE} \) properties that we use in our tool, but are not included in the Figures.

Let us define the following rule sets that we will use in the inference algorithms, namely:

- \( \text{DPRRules} = \{ D1, \ldots, D5 \} \).
- \( \text{HasUpToRules} = \{ P1, P2 \} \).
- \( \text{HasRules} = \{ P3, \ldots, P19 \} \).
- \( \text{LinkRules} = \{ L1, \ldots, L4 \} \).
- \( \text{LinkUniqueRules} = \{ U1, \ldots, U4 \} \).

To speed up the verification process, we also divide the actions defined in an architecture to four subsets, specifically, \( \text{ArchTime} \), \( \text{ArchPseudo} \), \( \text{ArchMeta} \), and \( \text{Arch} \). \( \text{ArchTime} \) includes the actions that contains the \( \text{Time()} \) construct, \( \text{ArchPseudo} \) includes the actions that contains the \( \text{P()} \) construct for pseudonymised data, \( \text{ArchPseudo} \) includes the actions that contains the \( \text{Meta()} \) construct for metadata, and finally, \( \text{Arch} \) is a set of actions without any specific construct above.

### 4.1 Automated conformance check

The automated conformance verification is based on the execution of resolution steps and backward search (this is also combined with a forward search strategy when verifying trivial properties, such as one can link all the data in a message it can receive, to speed up the process). Resolution is well-known in logic programming and is widely supported in logic programming languages. Intuitively, a resolution step can be seen as a deduction made based on a fact in one logic rule and a goal in another rule. Specifically, we input two logic rules and get either a new rule or a fact as a result.

The formal definition of resolution is based on the so-called substitution and unification steps. A substitution binds some value (aka. pattern) to some variable, and we denote it by \( \sigma \) in this paper.

**Definition 3** A substitution \( \sigma \) is the most general unifier of a set of facts \( \mathcal{F} \) if it unifies \( \mathcal{F} \), and for any unifier \( \mu \) of \( \mathcal{F} \), there is a unifier \( \mu \) such that \( \mu = \mathcal{F} \sigma \).

Note that two facts may have several unifiers but only one most general unifier.

**Definition 4** Given two rules \( R_1 = H_1 \vdash T_1 \), and \( R_2 = H_2 \vdash T_2, T_3 \), where \( T_2 \) is unifiable with \( H_1 \) with the most general unifier \( \sigma \), then the resolution \( R_1 \circ_{(H_1,T_2)} R_2 \) results in a new rule \( H_2 \sigma \vdash T_1 \sigma \land T_3 \sigma \) (after the unification of \( H_1 \) and \( T_2 \)).

The search process is based on a sequence of resolution steps, each of the form \( R \circ_{T} T \), between a rule \( R \) and a fact \( T \), where \( R = H \vdash T_1, \ldots, T_n \), and \( T \) is unifiable with the head \( H \) with \( \sigma \).
the result of \(R \circ_{(H,T)} T\), \(H\) and \(T\) are eliminated and we receive \(T_1\sigma, \ldots, T_n\sigma\).

Algorithm 1: ConformanceCheck(initgoal, Architecture, Rulesets, N)

Result: Conformance (1) /Violation of conformance (0)

Inputs:
Rule sets = \{DPRRules, HasUpToRules, HasRules, LinkRules, LinkUniqueRules\}
Architecture = \{ArchTime, ArchPseudo, ArchMeta, Arch\}.

Goal: initgoal.

Allowed layers of nested crypto functions: \(N\);
if the predicate of initgoal matches the predicate of a head of a rule in RS, RS \(\in\) Rulesets
then
  for rule in RS do
    isSuccessful[(rule, initgoal)] = Verify(rule, initgoal, Architecture, Rulesets, N)
  end
if for all rule in RS: isSuccessful[(rule, initgoal)] == 0 then
  return 0
else
  return 1
end

In a policy, each definition of a sub-policy will generate a goal (denoted by initgoal). initgoal can be a so-called HAS goal, e.g., HAS(sp,name) if we allow for the service provider to be able to have a data type name. In addition, initgoal can be a LINK or LINKUNIQUE goal, or one of the a FWCONSENTCOLLECTED, CCONSENTCOLLECTED, UCONSENTCOLLECTED, or STR-CONSENTCOLLECTED goals, depending on which sub-policy definition it has been generated
Algorithm 2: Verify(rule, goal, Architecture, Rulesets, N)

\[ \text{GoalsToBeProved} = \{ \text{goal} \} ; \]

if the predicate of goal matches the predicate of an action in AS, AS \( \in \) Architecture then

\[ \text{for arch in AS do} \]

| if arch \( \circ \) (arch, goal) goal is successful then
| \( \text{The Derivation Was Successful}[(\text{rule, goal, arch})] = 1 \)
| else \( \text{The Derivation Was Successful}[(\text{rule, goal, arch})] = 0 \)
| end

\[ \text{if for all arch in AS: The Derivation Was Successful}[(\text{rule, goal, arch})] == 0 \] then
| return 0
| else
| return 1
| end

end

else

if the predicate of goal matches the predicate of a rule head in RS, RS \( \in \) Rulesets then

\[ \text{for nextrule in RS do} \]

| if nextrule \( \circ \) (head of nextrule, goal) goal is successful then
| \( \exists \) goal in nextrule \( \circ \) (head of nextrule, goal) goal that contains more than \( N \) nested layers of crypto functions then
| skip to the following rule in RS;
| else
| remove goal from GoalsToBeProved;
| add the facts in nextrule \( \circ \) (head of nextrule, goal) goal to GoalsToBeProved;
| for nextgoal in GoalsToBeProved do
| if Verify(nextrule, nextgoal, Architecture, Rulesets, N) == 1 then
| return 1
| else
| return 0
| end
| end
| end
end

end

Algorithm 1 defines the process of checking whether the input architecture Architecture is fulfilling the "initial" goal, initgoal, based on the pre-defined inference rule set Rulesets and a pre-defined natural \( N \) that specifies a limit on nested layers of cryptographic functions used in a message. ConformanceCheck(initgoal, Architecture, Rulesets, N) returns either 1 for a conformance, and 0 for a non-conformance (violation). Algorithm 2 defines a recursive verification procedure of the initial goal through the sub-goals resulted from each resolution step.

We have the following three properties for the conformance verification procedure:

**Property 1 (Correctness)**

We distinguish several cases based on the nature of initgoal:

1. If initgoal is a HAS goal, and corresponds to the option ‘Y’ in a data possession sub-policy, then whenever ConformanceCheck(initgoal, Architecture, Rulesets, N) == 1, the architecture (defined by Architecture in Algorithm 1) functionally conforms with this requirement of the policy.
2. If initgoal is a HAS goal, and corresponds to the option ‘N’ or left blank in a data possession sub-policy, then whenever $\text{ConformanceCheck}(\text{initgoal}, \text{Architecture}, \text{Rulesets}, N) == 1$, the architecture violates the privacy conformance with the policy.

3. If initgoal is a LINK or LINKUNIQUE goal, and corresponds to a link permit sub-policy, then whenever $\text{ConformanceCheck}(\text{initgoal}, \text{Architecture}, \text{Rulesets}, N) == 1$, the architecture functionally conforms with this link policy.

4. If initgoal is a LINK or LINKUNIQUE goal, and corresponds to a link forbid sub-policy, then whenever $\text{ConformanceCheck}(\text{initgoal}, \text{Architecture}, \text{Rulesets}, N) == 1$, the architecture violates the privacy conformance with the policy.

5. If initgoal is a FWCONSENTCOLLECTED, CCONSENTCOLLECTED, UCONSENTCOLLECTED, or STRCONSENTCOLLECTED goal, and corresponds to the option ‘Y’ in the forward, collection, usage, and storage sub-policy, respectively, then the architecture DPR conforms with the actual sub-policy whenever $\text{ConformanceCheck}(\text{initgoal}, \text{Architecture}, \text{Rulesets}, N) == 1$.

**Property 2 (Termination up-to $N$)**

Let $N$ be the maximum number of nested layers of cryptographic functions the verification engine will examine. Beside a finite $N$, the verification procedure never gets into an infinite loop.

The completeness property can be stated as a consequence of the termination property (Property 2), as follows:

**Property 3 (Completeness)**

The following points are valid if all the data types specified in Architecture (see Algorithm 7) contain at most $N$ layers of nested cryptographic functions, for some finite $N$:

1. If initgoal is a HAS goal, and corresponds to the option ‘Y’ in a data possession sub-policy, then whenever $\text{ConformanceCheck}(\text{initgoal}, \text{Architecture}, \text{Rulesets}, N) == 0$, the architecture does not functionally conform with the policy.

2. If initgoal is a HAS goal, and corresponds to the option ‘N’ or left blank in a data possession sub-policy, then whenever $\text{ConformanceCheck}(\text{initgoal}, \text{Architecture}, \text{Rulesets}, N) == 0$, the architecture functionally conforms with the policy.

3. If initgoal is a LINK or LINKUNIQUE goal, and corresponds to a link permit sub-policy, then whenever $\text{ConformanceCheck}(\text{initgoal}, \text{Architecture}, \text{Rulesets}, N) == 0$, the architecture does not functionally conform with the policy.

4. If initgoal is a LINK or LINKUNIQUE goal, and corresponds to a link forbid sub-policy, then whenever $\text{ConformanceCheck}(\text{initgoal}, \text{Architecture}, \text{Rulesets}, N) == 0$, the architecture functionally conforms with the policy.

5. If initgoal is a FWCONSENTCOLLECTED, CCONSENTCOLLECTED, UCONSENTCOLLECTED, or STRCONSENTCOLLECTED goal, and corresponds to the option ‘Y’ in the forward, collection, usage, and storage sub-policy, respectively, then the architecture does not DPR conform with the policy whenever $\text{ConformanceCheck}(\text{initgoal}, \text{Architecture}, \text{Rulesets}, N) == 0$.

Property 3 says that completeness can only be “achieved” up to the maximum allowed nested layers of cryptographic functions, $N$.

## 5 Implementation

DataProVe is written in Python, and is available for download from GitHub[2]

[2]https://github.com/vinhgithub83/DataProVe
5.1 The System Architecture Specification Page

After launching the tool, as depicted in Figure 7, the default page can be seen, where the user can specify a system architecture. DataProVe supports two types of components, the so-called main components, and the sub-components. The main components can represent an entire organisation, system or entities that consists of several smaller components, such as a service provider, a customer, or authority (trusted third-party organisation). Sub-components are elements of a main component, for example, a service provider can have a server, a panel, or storage place. A main component usually has access to the data handled by its own sub-components, but this is not always the case, for instance, two main components can share a sub-component and only one main-component has access to its data. This can happen, for example, when a service provider operates a device of a trusted third party, but it does not have free access to the content of the data stored inside the device.

Figure 7: After launching DataProVe, the system architecture specification page can be seen.

In the first version of DataProVe (v0.9), main components are represented by rectangular shapes, while sub-components are represented by circles. Examples can be seen in Figures 8-11.

In this report, we will interchange between the two terms entity and component, because the term entity has been used in our theoretical papers, while the tool uses the term component more. They refer to the same thing in our context.

In DataProVe one can specify which main-component can have access to which sub-component. An example can be seen in Figure 12, where we specified the relation between sp and server, meter, as well as between the authority auth and meter, socialmediapage.

In Figure 13 a new text box is created with the name recvdmsg1, which denotes that the server receives a message called msg1. Its content (depicted in Figure 14) says that sp can receive a reading that contains the energy consumption (energy) and the customer ID (custID).

In the architecture level, we distinguish entity/component, actions and data, where actions specify what an entity/component can do on a piece of data (it may not perform this action eventually during a low-level system run, but there are instances of the system run that where this action happens), except for DELETEWITHIN, as we will see later.
5.1.1 ACTIONS

Based on the definition of actions and architectures in Figure 2, we propose their corresponding formats that can be given in the text boxes/text editor in DataProVe.

Actions are words/string of all capital letters, and DataProVe supports the actions 'OWN', 'RECEIVE', 'RECEIVEAT', 'CREATE', 'CREATEAT', 'CALCULATE', 'CALCULATEAT', 'STORE', 'STOREAT', 'DELETE', 'DELETEWITHIN'. The syntax of each action in DataProVe is as follows.

Note: no space character is allowed when specifying the actions in the bullet points below.

The reserved/pre-defined keywords are highlighted in bold, while the non-bold text can be freely defined by the user:

- **OWN**(component,Datatype) :
  This action defines that a component (e.g., sp, auth, server, meter etc.) can own a piece of data of type Datatype. For example, **OWN**(server,spkey) say they server can own the a piece of data of type service provider key (spkey).
• **RECEIVE**(component, Datatype):
  This action defines that a component can receive a piece of data of type Datatype, for example, **RECEIVE**(server, Sicknessrecord(name, insurancenumber)) says that server can receive a sickness record that contains a piece of data of type name and insurance number.

• **RECEIVEAT**(component, Datatype, Time(t)):
  This action is similar to the previous one, except that here we also need to define the time when the data can be received. Since at the architecture level we do not intent to specify the concrete time value, the generic time construct, denoted by the keyword **Time(t)** specifies that component can receive a piece of data of type Datatype at some (not specific) time $t$. **RECEIVEAT** is used to define when a consent ($Cconsent$(Datatype), $Uconsent$(Datatype), $Sconsent$(Datatype), $Fwconsent$(Datatype)) is received.

• **CREATE**(component, Datatype):
  This action defines that a component can create a piece of data of type Datatype, for instance, **CREATE**(sp, Account(name, address, phone)) defines that a service provider $sp$ can create an account that contains three pieces of data of types name, address and phone number.
Figure 12: Specify which main component has access to the data in which sub component (sp has access to server and meter, while auth has access to meter and socialmediapage).

Figure 13: Draw an arrow from the component meter to server.

- CREATEAT\textup{(}component,\textup{Datatype, Time(t)})\textup{:}
  
  This action defines that a component can create a piece of data of type Datatype at some (not specific) time $t$. For example, \texttt{CREATE(sp,Account(name,address,phone),Time(t))}.

- CALCULATE\textup{(}component,\textup{Datatype)}:
  
  This action defines that a component can calculate a piece of data of type Datatype, for instance, \texttt{CALCULATE(sp,Bill(energyconsumption))} defines that a service provider \texttt{sp} can calculate a bill using a piece of data of type energy consumption.
Figure 14: Specify the message content of recvmsg1 (through the action RECEIVE).

- **CALCULATEAT**(component, Datatype, Time(t)):
  This action defines that a component can calculate a piece of data of type Datatype at some (not specific) time \( t \). For example, \( \text{CALCULATE}(sp, \text{Bill(energyconsumption)}, \text{Time}(t)) \).

- **STORE**(storageplace, Datatype):
  This action defines that a service provider can store a piece of data of type Datatype in storageplace, where storageplace can be **mainstorage**, **backupstorage**. These reserved keywords define a collection of storage place(s) that can be seen as “main” storage, or “backup” storage, respectively.
  For example, \( \text{STORE(mainstorage, Account(name,address,phone))} \) defines that a service provider can store an account that contains name, address and phone number in its main storage place(s).

- **STOREAT**(storageplace, Datatype, Time(t)):
  This action defines that a component can store a piece of data of type Datatype in the place(s) storageplace at some (not specific) time \( t \).
  For example, \( \text{STORE(mainstorage, Account(name,address,phone), Time(t))} \) defines that an account with a name, address and phone number can be stored in the main storage of the service provider at some time \( t \).

- **DELETE**(storageplace, Datatype):
  The action delete is closely related to the action store, as it defines that a piece of data of type Datatype can be deleted from storageplace.
For example, DELETE(mainstorage,Account(name,address,phone)) captures that a service provider can.

- DELETEWITHIN(storageplace,Datatype,Time(tvalue)):
  This action captures that once the data is stored, a component must delete a piece of data of type Datatype within the given time value tvalue (tvalue is a data type for time values).
  Unlike the non-specific Time(t), which is a predefined construct, tvalue is defined by the user, and takes specific time values such as 3 years or 2 years 6 months.
  For example, DELETE(mainstorage,Account(name,address,phone),Time(2y)) defines that the service provider must delete an account from its main storage within 2 years.

5.1.2 COMPONENTS/ENTITY

A component can be specified by a string of all lower case, for example, a service provider can be specified by sp, or a third-party authority by auth (obviously they can be specified with any other string).

DataProVe supports some pre-defined or reserved components/entities, such as sp, trusted, mainstorage, backupstorage.

- sp: this reserved keyword defines a service provider. DataProVe only allows a single service provider at a time (in the specification of a policy and architecture).
- trusted: this reserved keyword defines a trusted authority that is able to link a pseudonym to the corresponding real name.
- mainstorage: this reserved keyword defines the collection of main storage places of a service provider.
- backupstorage: this reserved keyword defines the collection of backup storage places of a service provider.

Note: An entity/component is always defined as the first argument of an action.

5.1.3 DATA TYPES

DataProVe supports two groups of data types, the so-called compound data types, and simple data types.

- Simple data types do not have any arguments, and they are specified by strings of all lower cases, without any space or special character. Example simple data types include name, address, phonenumber, nhsnumber, etc.
- Compound data types have arguments, and they are specified by strings that start with a capital letter followed by lower cases (again without any space or special character). For example, Account(name,address,phone) is a compound data type that contains three simple data types as arguments. Another example compound data type can be Hospitalrecord(name,address,insurance). Any similar compound data types can be defined by the user. We note that the space character is not allowed in the compound data types. Nested compound data types are compound data types that contain another compound data types. For instance, Hospitalrec(Sicknessrec(name,disease),address,insurance) captures a hospital record that contains a sickness record of a name and disease, and an address, and finally, an insurance number.
DataProVe has pre-defined or reserved data types, such as

- The types of consents: **Cconsent**(Datatype), **Uconsent**(Datatype), **Sconsent**(Datatype), **Fwconsent**(Datatype).

  We do not differentiate among the different consent format, it can be e.g. written consent, or online consent form, or some other formats.

  - **Cconsent**(Datatype): This is a type of collection consent on a piece of data of type Datatype. For example, **Cconsent**(illness), **Cconsent**(Account(creditcard,address)) capture the collection consent on the illness information, and the account containing a credit card number and address.

  - **Uconsent**(Datatype): A type of usage consent on a piece of data of type Datatype. For example, **Uconsent**(Energy(gas,water,electricity)), **Uconsent**(address).

  - **Sconsent**(Datatype): A type of storage consent on a piece of data of type Datatype. For example, **Sconsent**(personalinfo), **Sconsent**(Account(creditcard,address)) defines the types of storage consent on a type of personal information and account, respectively.

  - **Fwconsent**(Datatype,component): A type of forward/transfer consent on a piece of data of type Datatype, and a component to whom the data is forwarded/transferred. E.g. **Fwconsent**(personalinfo,auth), **Fwconsent**(Account(creditcard,address),auth) defines the type of forward consent on the type of personal information and account, respectively, as well as a third party authority (auth) to which the given data is forwarded.

- The types of time and time value: **Time(t)** or **Time(t)value**, where **Time()** is a time data type, while the pre-defined special keyword t denotes a type of non-specific time, and tvalue is a type of time value (such as 5 years, 2 hours, 1 minute, etc.). tvalue is a (recursive) type and takes the form of

  \[
  tvalue ::= y \mid mo \mid w \mid d \mid h \mid m \mid numtvalue \mid tvalue + tvalue
  \]

  where y specifies a year, mo a month, w a week, d a day, h an hour and m a minute. Further, numtvalue is the a number (num) before tvalue, for example if num = 3 and tvalue = y, then numtvalue is 3y (i.e. 3 years). Additional examples include tvalue = 5y + 2mo + 1d + 5m.

  It is important to note that **Time(t)value** can only be used in the action **DELETEWITHIN, RECEIVEAT, CREATEAT, CALCULATEAT, STOREAT** must contain the non-specific time **Time(t)**.

  For example, the actions

  - **DELETEWITHIN**(sp.mainstorage,Webpage(photo,job),**Time**(10y+6mo)) Any webpage must be deleted from the main storage of the service provider within 10 years and 6 months.

  - **RECEIVEAT**(sp,**Cconsent**(illness)**,**Time**(t)) The service provider can receive a collection consent on illness information at some non-specific time t.

  - **RECEIVEAT**(sp,**Uconsent**(Webpage(photo,job)),**Time**(t)) The service provider can receive a usage consent on a webpage at some non-specific time t.
- **STOREAT***(sp,backupstorage,Webpage(photo,job),Time(t))** The service provider can store a webpage in its back up storage places at some non-specific time t.

- **CREATEAT***(server,Account(name,address),Time(t))**: The service provider can create an account that contains a name and address in at some non-specific time t.

- **CALCULATEAT***(sp,Bill(tariff,Energy(gas,water,electricity)),Time(t))**: The service provider can create an account that contains a name and address in at some non-specific time t.

- The type of metadata and meta values: **Meta***(Datatype)**.

  This data type defines the type of metadata (information about other data), or information located in the header of the packets, the meta information often travels through a network without any encryption or protection, which may pose privacy concern. Careful policy and system design are necessary to avoid privacy breach caused by the analysis of metadata or header information.

  **Note**: **Meta**(Datatype) is always defined as the last argument in a piece of data.

Example application of metadata includes:

- **RECEIVE**(sp,Sicknessrec(name,disease,Meta(ip))): This action defines that the service provider can receive a packet that containing a name and disease, but the packet also includes the metadata IP address of the sender computer. We note that this syntax is simplified in terms that it aims to eliminate the complexity of nested data type. Specifically, this syntax abstracts away from the definition of the so-called packet data type, an “abbreviation” of the lengthy **RECEIVE**(sp,Packet(Sicknessrec(name,disease),Meta(ip))).

- **RECEIVE**(sp,Sicknessrec(name,disease,Meta(Enc(ip,k)))): This action is similar to the previous one, but now the metadata IP address is encrypted with a key k.

- **RECEIVEAT**(sp,Sicknessrec(name,disease,Meta(ip)),Time(t))**: This action is similar to the first one, but it includes the time data types at the end. It defines that the service provider receives the sickness record along with the IP address of the sender device, at some non-specific time t.

  Obviously, any metadata can be defined instead of IP address in the examples above.

- The type pseudonymous data: **P**(Datatype | component).

  This data type defines the type of pseudonymous data, for example, a pseudonym. The argument can be either a data type or a component. Pseudonym is a means for achieving a certain degree of privacy in practice as the real identity/name and the pseudonym can only be linked by a so-called trusted authority. DataProVe also captures this property, namely, only the component trusted can link the pseudonym to the real name/identity.

  For example,

  - **RECEIVE**(sp,Sicknessrec(P(name),disease)): This action defines that a service provider can receive a sickness record, but this time, the name in the record is not the real name but a pseudonym, hence, the service provider cannot link a real name to a disease.

  \[3\] This would be in the versions above v0.9. In the version 0.9, DataProVe preserves the keyword (all small letters) **ds** for data subject, and the user can define **P**(ds) to specify that the real data subject/identity has been pseudonymised.
- **RECEIVE**(trusted,Sicknessrec(P(name),disease)):
  This is similar to previous case, but the trusted authority can receive a sickness record instead of the service provider.
- **RECEIVE**(sp,Sicknessrec(P(name),disease,Meta(ip))): Again, this is similar to the first case, but with metadata.
- **RECEIVEAT**(sp,Sicknessrec(name,disease,Meta(ip)),Time(t)): This is similar to previous case, but also include the time data type.

- The types of cryptographic primitives and operations: DataProVe supports the basic cryptographic primitives for the architecture. Again, we provide the reserved keywords in bold.
  - Private key: **Sk**(Pkeytype):
    This data type defines the type of private key used in asymmetric encryption algorithms. Its argument has a type of public key (Pkeytype). We note that public key is not a reserved data type.
  - Symmetric encryption: **Senc**(Datatype,Keytype):
    This is the type of the cipher text resulted from a symmetric encryption, and has two arguments, a piece of data and a symmetric key (Keytype).
    For example,
    * **RECEIVE**(sp,Senc(Account(name,address),key)):
      This specifies that a service provider can receive a symmetric key encryption of an account using a key of type key.
    * **RECEIVE**(sp,Senc(Account(Senc(name,key),address),key)):
      This specifies that a service provider can receive a symmetric key encryption of an account that contains another encryption of a name, using a key of type key.
    * **OWN**(sp,key):
      This specifies that a service provider can own a key of type key.
  - Asymmetric encryption: **Aenc**(Datatype,Pkeytype):
    This is the type of the cipher text resulted from an asymmetric encryption, and has two arguments, a piece of data and a public key (Pkeytype).
    For example,
    * **RECEIVE**(sp,Aenc(Account(name,address),pkey)):
      This specifies that a service provider can receive an asymmetric key encryption of an account using a public key of type pkey.
    * **CALCULATE**(sp,Sk(pkey)):
      This specifies that a service provider can calculate a private key corresponding to the public key (of type pkey).
    * **OWN**(sp,pkey):
      This specifies that a service provider can own a public key of type pkey.
  - Message authentication code (MAC): **Mac**(Datatype,Keytype):
    This is the type of the message authentication code that has two arguments, a piece of data and a symmetric key (Keytype).
    For example,
    * **RECEIVE**(sp,Mac(Account(name,address),key)):
      This specifies that a service provider can receive a message authentication code of an account using a key of type key.
  - Cryptographic hash: **Hash**(Datatype):
    This is the type of the cryptographic hash that has only one argument, a piece of data. For example,
* RECEIVE(server, Hash(password)):
  This specifies that a server can receive a hash of a password.
* STORE(sp.mainstorage, Hash(password)):
  This specifies that a service provider can store a hash of a password in its main storage place(s).

5.2 The Data Protection Policy Specification Page

On the data protection policy specification page, we can define a high-level data protection policy (as shown in Figure 15).

Figure 15: The Policy Specification Page.

5.2.1 Entities/Components (the top part)

The policy page has three parts, the top part is to specify the entities/components in the system, such as authority, client etc. On the left side, the user is expected to provide a short notation, and on the right side, the full name/description to help identifying the meaning of the notation. For instance, in Figure 15, the notation is auth, and the description is third party authority. After adding a new entity, it will appear in the drop-down option menu in the bottom part. Note that the entity sp (service provider) is a pre-defined entity that is already added by default (hence, the user does not need to add). The user can specify any other entities.

5.2.2 Data groups/Data types (the middle part)

The middle part in the policy specification page is for defining the data groups and data types. As shown in Figure 16, the user can define a group of data types, for instance, a data group
denoted by `personalinfo` is defined which includes four data types, name, address, `dateofbirth`, and `phonenumber`.

![Figure 16: Specifying data groups (personalinfo) and its data types.](image)

The option menu in the middle (called “IS THIS UNIQUE”) expects the user to provide if the data group together with its data types can be used to uniquely identify an individual. For instance, a name alone cannot be used to uniquely identify an individual, but a name together with an address, date of birth and phone number, can be, so the option “Yes” was chosen. Another example is shown in Figure 17, with the data group called `energy` (refers to energy consumption) and its data types, gas, water, and electricity consumption. This type group together with its types cannot be used to uniquely identify an individual, hence, the option “No” was chosen.

![Figure 17: Specifying data groups (energy) and its data types.](image)

### 5.2.3 Policy specification (the bottom part)

Based on the syntax of the policy language given in Section 2.1, we follow the seven sub-policies. However, here to avoid confusion we divide the last sub-policy, the data connection policy, into two categories, the data connection permit and data connection forbid policies. In the first one the user can specify which data link they allow, while in the second one for which they forbid.

A data protection policy is defined on a data group/type and an entity. In DataProVe, each policy consists of eight sub-policies, to achieve a fine-grained requirement specification (Figure 18). The users do not have to define all the eight sub-policies, but they can if it is necessary. Both the policies and architectures can be saved, and opened later to modify or extend.

The first five sub-policies (collection, transfer) are defined *only from the service provider’s perspective*. For the rest three sub-policies (data possession and the two data connections policies), the user can specify from any entity’s perspective.

The eight sub-policies are data collection, data usage, data storage, data retention, data transfer, data possession and the two data connection sub-policies. Below we only highlight four sub-policies, for the rest four the readers are referred to full manual in the GitHub repository.\footnote{https://github.com/vinhgithub83/DataProVe}
The data collection sub-policy: In the data collection sub-policy window, for a given entity and data group the user can specify whether consent is required to be collection when the selected entity collect a selected data group (Y for Yes/N for No), and then specify the collection purposes.

The collection purposes can be given row by row, each row with a different action in the format of:

\[ \text{action1: data1, data2, \ldots, data_n} \]

where action1 can be any action, while data1, \ldots, data_n are compound data types (note that these compound data types do not need to be specified/added in the policy). For example, in Figure 21, the user sets that consent is required to be collected when the service provider collects the personal information. Then, the collection purpose for personal information is to create an account. The compound type account does not need to be defined in the policy.

The data possession sub-policy:
The data possession sub-policy defines who can have/possess a piece of data of a given group. The users only need to specify who are allowed to have or possess a given data group, DataProVe automatically assumes that the rest entities/components are not allowed to have/possess the selected type of data.

The data connection permitted sub-policy: This sub-policy specifies which entity is permitted to connect or link two types/groups of data.

In the second drop-down option menu, the user can specify further if the selected entity is permitted to be able to link two pieces of data uniquely, meaning that it will be able to deduce that the two pieces of data belongs to the same individual.
For example, in Figure 23 we specified that the service provider is permitted to be able to link the data group energy and the data group personalinfo. However, we do not allow the service provider to be able to uniquely link the two data groups. Obviously, if personalinfo was defined as
unique, then unique link would be possible, so there is chance that the architecture always violates this requirement of the policy.

**The data connection forbidden sub-policy:** This sub-policy is the counterpart of the permitted policy. While in case of the data possession policy, the user only needs to specify which entity is allowed to have or possess certain type of data, and DataProVe automatically assumes that the rest are not allowed, here the user needs to explicitly specify which pair of data types/groups are an entity is forbidden to be able to link together.

For example, in Figure 24, we forbid for the third-party authority to be able to link the data group personalinfo with the data group energy. Here, we forbid the unique link-ability of these two data groups for the third-party authority.

If we choose “No” (Figure 25), then it means that any ability to link any two pieces of data of the given data groups, is forbidden (not just unique link). Hence, this option is stricter than the previously one.

### 5.3 Conformance verification

We define three types of conformance, namely, functional conformance, privacy conformance and the so-called DPR conformance.
5.3.1 Functional conformance

The functional conformance captures if an architecture is functionally conforming with the specified policy. Namely:

1. If in the policy, we allow for an entity to be able to have a piece of data of certain data type/group, then in the architecture the same entity can have a piece of data of the same type/group.

2. If in the policy, we allow for an entity to be able to link/uniquely link two pieces of data of certain types/groups, then in the architecture the same entity can link/uniquely link two pieces of data of the same types/groups.

3. If in the policy, the (collection, usage, storage, transfer) consent collection is not required for a piece of data of given type/group, then in the architecture there is no consent collection.

4. If in the policy, we define

(a) a storage option `Main` and Backup Storage for a piece of data of certain type/group, then in the architecture there is a `STORE` or `STOREAT` action defined for both `mainstorage` and `backupstorage`, and for the same data type/group;
Figure 25: The data connection permission sub-policy.

(b) a storage option \( \text{Only Main Storage} \), then in the architecture there is a \text{STORE} or \text{STOREAT} action defined for only \text{mainstorage}, and for the same data type/group.

(c) If in the policy, we allow a piece of data of certain type/group, data, to be transferred to an entity ent, then in the architecture there is \text{RECEIVEAT}(\text{ent}, \text{data}, \text{Time}(t)) or \text{RECEIVE}(\text{ent}, \text{data}).

5.3.2 Violation of the functional conformance

1. In the policy, we allow for an entity to be able to have a piece of data of certain data type/group, but in the architecture the same entity cannot have a piece of data of the same type/group.

2. In the policy, we allow for an entity to be able to link/uniquely link two pieces of data of certain types/groups, but in the architecture the same entity cannot link/uniquely link two pieces of data of the same types/groups.

3. In the policy, the (collection, usage, storage, transfer) consent collection is not required for a piece of data of given type/group, but in the architecture there is a consent collection, namely, an action

- \text{RECEIVEAT}(\text{sp}, \text{Cconsent}(\text{data}), \text{Time}(t)),
Figure 26: To verify the conformance between the specified system architecture and policy.

- RECEIVEAT(sp,Sconsent(data),Time(t)), or
- RECEIVEAT(sp,Uconsent(data),Time(t)), or
- RECEIVEAT(third,Fwconsent(data,third),Time(t)).

4. In the policy, we define
   (a) a storage option ‘Main and Backup Storage’ for a piece of data of certain type/group, but in the architecture, there is STORE or STOREAT action defined for only either mainstorage or backupstorage, or no store action defined at all, for the same data type/group;
   (b) a storage option ‘Only Main Storage’, but in the architecture there is no STORE or STOREAT action defined at all, for the same data type/group.

5. In the policy, we allow a piece of data of certain type/group, data, to be transferred to an entity ent, but in the architecture there is no RECEIVEAT(ent,data,Time(t)) or RECEIVE(ent,data) defined (i.e., data is not transferred to the entity ent).

5.3.3 Privacy conformance

   The privacy conformance captures if an architecture satisfies the privacy requirements defined in the policy. Namely:

   1. If in the policy, we forbid for an entity to be able to have or possess a piece of data of certain type/group, then in the architecture the same entity cannot have or possess a piece of data of the same type/group.
   2. If in the policy, we forbid for an entity to be able to link/uniquely link two pieces of data of certain types/groups, then in the architecture the same entity cannot link/uniquely link two pieces of data of the same types/groups.

5.3.4 Violation of the privacy conformance

   1. In the policy, we forbid for an entity to be able to have or possess a piece of data of certain type/group, but in the architecture the same entity can/is be able to have or possess a piece of data of the same type/group.
2. In the policy, we forbid for an entity to be able to link/uniquely link two pieces of data of certain types/groups, but in the architecture the same entity can/is be able to link/uniquely link two pieces of data of the same types/groups.

5.3.5 DPR conformance
The privacy conformance captures if an architecture satisfies the data protection requirements defined in the policy. Namely:

1. If in the policy, the (collection, usage, storage, transfer) consent collection is required for a piece of data of given type/group, then in the architecture there is a collection for the corresponding consent.

2. If in the policy, we define a (collection, usage, storage) purpose action: data for a piece of data of certain type/group, then in the architecture there is the action action defined on a compound data type data.

5.3.6 Violation of the DPR conformance

1. In the policy, the (collection, usage, storage, transfer) consent collection is required for a piece of data of given type/group, but in the architecture, there is no collection for the corresponding consent.

2. In the policy, we define a (collection, usage, storage) purpose action: data for a piece of data of certain type/group, but in the architecture there is not any action action defined on a compound data type data, or besides action, there are also other actions defined in the architecture on data that are not allowed in the policy.

3. In the policy, we define

   (a) a storage option â€œMain and Backup Storageâ€ for a piece of data of certain type/group, but in the architecture there is a STORE or STOREAT action defined for some storage place, different from mainstorage and backupstorage, for the same data type/group;

   (b) a storage option â€œOnly Main Storageâ€, but in the architecture there is a STORE or STOREAT action defined for some storage place, different from mainstorage, for the same data type/group.

4. In the policy, we define

   (a) a deletion option â€œFrom Main and Backup Storageâ€ for a piece of data of a certain data type/group, data, but in the architecture there is not any of the action

       • DELETE(mainstorage, data) or
       • DELETEWITHIN(mainstorage, data, Time(tvalue)), or
       • DELETE(backupstorage, data) or
       • DELETEWITHIN(backupstorage, data, Time(tvalue));

   (b) a deletion option â€œOnly From Main Storageâ€ for a piece of data of a certain data type/group, data, but in the architecture there is no action DELETE(mainstorage, data) or DELETEWITHIN(mainstorage, data, Time(tvalue)).

5. In the policy, we allow a piece of data of certain type/group, data, to be transferred to an entity ent, but in the architecture there is also an action RECEIVEAT(ent1, data, Time(t)) or RECEIVE(ent1, data) defined for some ent1 to whom we do not allow data transfer in the policy.
6 Application Examples

In this section, we highlight the operation of DataProVe through two very simple examples.

6.1 Example 1 (Data retention policy)

In this example, in the policy we specify a data group called `personalinfo`, which is stored centrally at the service provider, only in the main storage places. In the storage sub-policy, we also set that storage consent is required before the store action takes place. Finally, we do not allow for the service provider (sp) to be able to have the data of type/group `personalinfo`.

As for the deletion policy, we set the retention delay in the main storage to 8 years (i.e. 8y, as shown in Figure 27).

![Figure 27: We set that the data of type/group personal information must be deleted from the main storage places of the service provider within 8 year.](image)

In the architecture level, we add an action that says a piece of data of type personalinfo needs to be deleted from the main storage within 10 years (action `DELETEWITHIN`, in the last line).

| Content of `spmessages`: | `RECEIVEAT(sp,Sconsent(personalinfo),Time(t))` |
| Content of `storagemessages`: | `RECEIVEAT(mainstorage,personalinfo,Time(t))` |
| Content of `storemain`: | `STOREAT(mainstorage,personalinfo,Time(t))` |
| Content of `deletion`: | `DELETEWITHIN(mainstorage,personalinfo,Time(10y))`. |

In the architecture shown in Figure 28, the service provider (sp) can receive a storage consent for `personalinfo` at some non-specific time t. The main storage places of sp can receive the data at some non-specific time and store it. The data of this type/group is deleted within 10 years from the main storage places. In the box above, the content of each text box in Figure 28 can be seen (except for sp and cust, which denote the name of the service provider and customer, respectively).
As a verification result (Figure 29), we got that the architecture violates the privacy conformance, as the architecture allows for sp to have the data of type personalinfo after 8 years, however, in the policy we set it to only 8 years. In the last line of the verification result window, we can also see a DPR conformance property, namely, sp collects storage consent before the data is stored. The first two lines are because we did not specify the collection and usage sub-policies (left blank).

Figure 29: The verification results show the violation of the privacy and DPR conformance properties.

6.2 Example 2 (Data possession and connection policy)

In the second simple example, we focus on the data possession and data connection sub-policies. We present the receive action with the Meta construct (metadata or 'packet' header data such as IP address, source, destination addresses, etc.).

In the policy, we define four data groups, nhsnumber (National Health Service number), name, photo, and address (see Figure 30).

Then, we forbid (any kind of link-ability, not only unique link) for the service provider to be able to link two pieces of data of types nhsnumber, and photo (see Figure 31). Again, we also forbid for the service provider to be able to have all the four data types/groups.
Figure 30: The policy level with the four data types/groups.

Figure 31: The specified data connection sub-policy for example 2.

In the architecture, a service provider collects data from two phone applications (Figure 32). The "HealthXYZ" app sends the service provider a sickness record with an ip address (phone ip) other app, called, "SocialXYZ" also sends the social profile with the same ip address (same phone). Both data types/groups are encrypted (using symmetric encryption) with the service provider keys (sp owns the two keys).
As a result (Figure 33), we got that the service provider not only be able to link the data of types nhsnumber with the data of type photo, but it also has all the data of types nhsnumber, name, photo and address. The reason is that sp will be able to decrypt both messages and link, have the data inside them.
7 Conclusion and Future Work

In this paper we presented DataProVe, a tool for specifying data protection policies and system architectures, as well as verifying their conformance properties in a fully automated way. We also presented the syntax of the policy and architecture languages on which the tool is based. The main goal of the tool is to aid policy and system designer to reason about their designs, and spot any error at an early stage. The tool could be useful for education purposes as well, aide the tutors with explaining about data protections and design. The development of the tool is still at an early stage and ongoing, with many ways to extend and improve it. For example, to include an attacker model, and verify conformance properties in a hostile environment with attackers. In addition, to add more guidance and hints on how to fix the violation of conformance properties. Finally, integrate it with security protocol verification tools such as ProVerif or AVISPA is also an interesting direction, in order to connect all the three levels, namely, the policy level, the architecture level and the implementation level.

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