Regulating Service Access and Information Release on the Web*

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ABSTRACT

The widespread use of Internet-based services is increasing the amount of information (such as user profiles) that clients are required to disclose. This information demand is necessary for regulating access to services, and functionally convenient (e.g., to support service customization), but it has raised privacy-related concerns which, if not addressed, may affect the users disposition to use network services. At the same time, servers need to regulate service access without disclosing entirely the details of their access control policy. There is therefore a pressing need for privacy-aware techniques to regulate access to services open to the network.

We propose an approach for regulating service access and information disclosure on the Web. The approach consists of a uniform formal framework to formulate—and reason about—both service access and information disclosure constraints. It also provides a means for parties to communicate their requirements while ensuring that no private information be disclosed and that the communicated requirements are correct w.r.t. the constraints.

Categories and Subject Descriptors

H.2.7 [**Database Management**]: Database Administration—*Security, integrity, and protection*; K.4.4 [**Computers and Society**]: Electronic Commerce—*Security*; K.6.5 [**Management of Computing and Information Systems**]: Security and Protection

General Terms

Security

Keywords

Access control, privacy, digital certificate.

*The work reported in this paper was partially supported by the European Community within the Fifth (EC) Framework Programme under contract IST-1999-11791 – FASTER project.

CCS '00, Athens, Greece.

1. INTRODUCTION

We are moving towards a Globally Internetworked Infrastructure connecting remote parties through the use of large scale networks, such as the World Wide Web. Execution of activities at various levels is today based on the use of remote resources and services, and on the interaction between different, remotely located parties that may know little about each other. In such a scenario, traditional assumptions for establishing and enforcing access control regulations do not hold anymore. For instance, service requests may be presented by remote, previously unknown parties, not just by the local community of users. The assumption that a server be able to identify and authenticate each of these possible parties seems not applicable anymore. This paradigm shift is witnessed by a large body of work moving towards alternative approaches for establishing identities or properties of requesters (e.g., [2, 7, 8, 11]). These proposals are based on the use of digital certificates (or credentials), representing statements certified by given entities (e.g., certification authorities), which can be used in establishing properties of their holder (such as identity, accreditation, or authorizations). Besides users, also the traditional concept of access requests changes in this new scenario, and the separation between actions (access modes) and passive objects results limiting. A broader concept of service, encompassing actions and objects on which they are executed, seems to be needed to capture general applications, where traditional objects are just one of the parameters of the application. The overall interaction process between different parties also becomes more complex, moving towards a broader notion of negotiation [14], possibly carried out through software components such as browsers, agents, or wrappers [17, 18].

In a framework embracing this new paradigm, we can imagine parties interacting with each other in order to obtain or offer services and/or information. The process of completing a service often requires communicating information not related to the service itself, but related to additional restrictions on its execution. The certificates mentioned above are one type of such information. In addition, other uncertified declarations (i.e., not signed by any authority) are usually communicated during negotiations. For instance, we may be requested our credit card number in order to perform an electronic purchase; we may be requested to fill in a profile when using public or semipublic services (e.g., browsing for flight schedules) for the purpose of access control or service customization. Such information com-

munication makes the picture even more complex since, on the client's side, releasing information to possibly unknown servers, and losing control on its further dissemination, is raising several concerns [6]. Debates about the need to regulate collection and dissemination of personal information is everyday news, and techniques and policies to satisfy it are being investigated [5, 13]. On the client side, too, there may therefore be the need to impose restrictions on the communication of credentials and declarations to other parties. For this purpose, a client may—like a server—require the counterpart to fulfill some requirements. For instance, a client may be willing to release a AAA membership number only to servers supplying a credential stating that the travel agent is approved by AAA.

In this paper we propose a uniform framework for regulating service access and information disclosure in an open, distributed network system like the Web. Like recent proposals (e.g., [14, 16, 20]) we depart from the classical authorization triple and from the assumption that access requesters be known at the server. We base regulations on the use of credentials—the traditional local authentication assumption being one specific case of this scenario. Going a step beyond previous proposals, we also include treatment of declarations (meaning by this any information required by the access control system that is not presented in the form of a certificate). Moreover, we provide a means for parties to regulate when and how credentials and declarations can be disclosed to other parties they may become involved with. Our framework, by providing the client with the ability to present counter-requests to servers and put restrictions on information disclosure, can be used to support privacy-related constraints of the sort advocated in recent proposals such as P3P [13] and OPS, as well as mechanized use of privacy notices publicized by servers [6]. Note that we are not interested in modeling negotiations and communications themselves [12, 14] but only in establishing regulations restricting the exchanges that can take place in negotiations, from the point of view of protecting service access and information disclosure. Issues related to term translation, involving, for instance, dictionaries, ontologies, and brokers [4, 18] are out of the scope of this paper. Also, our work addresses only information disclosure between the parties directly involved in a negotiation; the problem of controlling subsequent flow of information (to which techniques such as watermarking pertain) lies beyond the scope of this work.

Previous work closest to ours is the work by Winslett et al. [16, 20] who were probably the first to investigate the application of credential-based access control regulating access at a server. However, although the use of a logic language was proposed to express regulations, no specific model or language was presented. Also, their work focussed on protecting service access and did not investigate privacy protection of a party's information, or filtering and transformation issues related to communication of policies between the parties. Subsequent work [19, 21] investigated trust negotiation issues and strategies, more or less protective of a party's privacy, that a party can apply to select credentials to submit to the opponent party in a negotiation. This work is complementary to the work presented in this paper, focussed on expressing, communicating, and enforcing, in a privacy-preserving way, service access and credential submission policies.

The contributions of this paper can be summarized as follows. First, we present a uniform framework and model to reason about service access and information disclosure constraints. Second, we present a language for the specification of such constraints together with its formal semantics. Third, we study the problem of the communication between parties, covering both privacy protection (the access control policy being also considered private w.r.t. to all parties that do not need to know it) and enforcement of the established constraints, on both sides. For this purpose, we introduce a requirement communication mechanism based on a policy filtering and renaming process, that is proven to be correct w.r.t. the specifications. We also discuss privacy protection issues. Proofs of theorems, omitted from the paper for space constraints, can be found in [3].

2. REFERENCE SCENARIO AND BASIC CONCEPTS

We consider a network composed of different parties that interact with each other in order to offer (*servers*) or require (*clients*) *services*.[1] Each party has an associated *portfolio* of credentials and declarations; in addition, each server has an associated set of *services* it provides. Release of portfolio information and access to services is regulated by *rules* specified by the parties. Each party also maintains additional information, which we refer to as *state* information. State information can be interaction-specific or persistent, and can be viewed at the abstract level as a set of facts (e.g., user profiles). The reminder of this section discusses *portfolio* and *services* in more details. Release and service access rules will be discussed in Section 4.

2.1 The portfolio

Each party's portfolio contains properties that the party can submit in order to obtain (or offer) services. Among these properties, we distinguish between *data declarations* (e.g., identity, address, and credit card number) and *credentials* (i.e., digital certificates). The difference between them lays in the fact that declarations are statements uttered by the party while credentials are statements uttered and signed (i.e., certified) by authorities trusted for making the statements [8]. As an example, the driver license number maintained as a data value at a party and communicated in a negotiation (e.g., by inserting it in a web interface form) is a declaration. A digital copy of the driver license, released by the DMV to the party, and that the party can submit to a server to prove that it has a driver license or that the DMV certifies some properties (e.g., address), is instead a credential. The portfolio may also represent views of certificates that are not actually stored at the party site but can be obtained if needed [17].

Credentials must be unforgeable and verifiable. Both these goals are achieved through the use of public key encryption: each credential is signed with the *private digital signature key* K^- of the issuing authority [8], which can be successfully verified only with the corresponding *public digital signature verification key* K. Successful verification of a signature therefore proves both the fact that the credential has been released by the authority whose public key is K and that its content has not been altered.

[1] For the sake of simplicity we restrict our scenario to interactions involving two parties, the approach can be extended and applied to cases where more parties are involved.

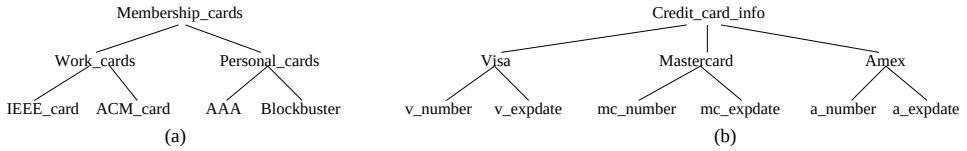

Figure 1: An example of credential (a) and declaration (b) abstractions

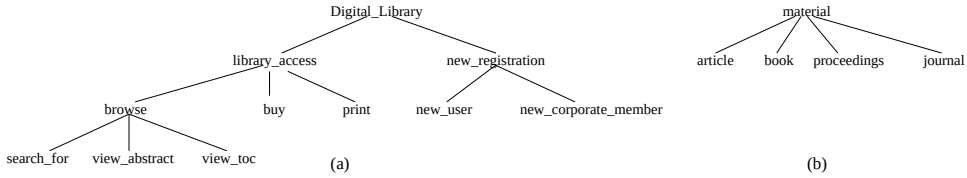

Figure 2: An example of service (a) and value (b) abstractions for a digital library server

At a practical level, we view a credential as characterized by two elements: a *signed content*, and the *public digital signature verification key* to verify the signature. Although there is no specific structure for credentials, or more precisely their content, in the following we assume a *semi-structured* [1] organization of credentials that allows us to query for specific data, such as name or address in a driver license, number or expiration date in a credit card. To refer to specific data in a credential we introduce the definition of credential term.[2]

DEFINITION 2.1 (CREDENTIAL TERM). *A credential term is an expression of the form* credential_name(attribute_list), *where* credential_name *is the name of the credential, and* attribute_list *is a possibly empty list of elements of the form "*attribute_name=value_term*", where value term is either a ground value or a variable.*

Some examples of credential terms, whose interpretation is immediate, are: driver-license(name="`John Doe`"), driver-license(name=X), enrollment_certificate(issuer=I,student_id ="`John Doe`",university=U).

Declarations and credentials in a portfolio may be organized into a partial order $\sqsubseteq_{\mathsf{P}}$ by collecting declarations into classes representing named sets of properties (e.g., "demographic_data" or "personal_data"), and credentials into abstractions. Figure 1 illustrates an example of credential and declaration abstractions regarding membership cards (for credentials) and credit card information (for declarations). Classes and abstractions can be used to refer to a set of declarations or credentials as a whole. The definition of such a partial order, which can be orthogonal to the data model, can be done in different ways [9] (for instance, declarations can be organized into XML documents [1]) and is outside the scope of this paper.

2.2 Services

The functionalities offered by a server are defined by a set of services. Intuitively, each service can be seen as an application that clients can execute (e.g., reserve a flight). Services may be collected into classes. Classes need not be disjoint and may be nested. Intuitively, classes are grouping of services (and classes thereof), which can be used to refer to a set of services as a whole. For instance, at a digital library server, a class "`browse`" may group services "`search_for`", "`view_abstract`", or "`view_toc`". Classes can be used to simplify the specification of security requirements. For instance, a single security constraint associated with service class "`browse`" can be used to restrict access to any such service. Classes are also convenient to model "gradual" access to applications. For instance, a client, guided by a web interface, can request access to class "`browse`" upon which, presented with the specific services to choose from, she can specialize her request. In the following, we use the term service to indiscriminately refer to *basic* services (applications) and classes thereof. We will explicitly distinguish between basic services and classes when needed. The relationship between services and their classes introduces a partial order $\sqsubseteq_{\mathsf{SN}}$ on the set of service names SN. Basic services are minimal elements of the partial order. Figure 2(a) illustrates an example of services and classes thereof for a digital library server.

Each basic service may have attributes associated with it. Attributes play the role of formal parameters and specify inputs to the application implementing the service. Values in the domain of an attribute can be collected into ranges or abstractions partially ordered by relation $\sqsubseteq_{\mathsf{V}}$, where $x \sqsubseteq_{\mathsf{V}} y$ holds if y is a range/abstraction containing x. For instance, as illustrated in Figure 2(b), value `material` can be defined as an abstraction of the set of values `article`, `book`, `journal`, and `proceedings`, denoting the type of a publication. In the following, we use the term "value" to indiscriminately refer to both primitive values and their abstractions. Value abstractions can be used to specify security requirements applicable to different service calls. For instance, the security constraints associated with service buy with parameter `material`, will be applicable to all its specialized values. Note that this feature is particularly important in our model, where the traditional "authorization object", which can be hierarchically organized [9], is embedded as a parameter to the service.

To model partial specifications of services we introduce the concept of *service terms*, and extend to them the partial orders defined on service names and values. A specification is partial if it provides only a subset of the parameters of the

[2] Note that the fact that we allow reference to specific properties within a credential content does not mean that we allow to single them out in the submission process. A credential can only be submitted as a whole. Reference to specific properties within a credential is only needed for the purpose of querying its content.

services and/or provides only partial information on them (e.g., refer to abstract values).

DEFINITION 2.2 (SERVICE TERM). *A service term is an expression of the form* service_name(attribute_list), *where* service_name $\in$ SN *and* attribute_list *is a, possibly empty, list of elements of the form "*attribute_name=value_term*", where* value_term *is either a ground (primitive or abstract) value or a variable.*

DEFINITION 2.3 (SERVICE TERM PARTIAL ORDER). *Given two* ground *service terms $s_1(L_1)$ and $s_2(L_2)$, we write $s_1(L_1) \sqsubseteq_{\mathsf{ST}} s_2(L_2)$ iff both the following conditions hold:* 1) *$s_1 \sqsubseteq_{\mathsf{SN}} s_2$, and* 2) *for each element "$a = V$" in L_2 there exists an element "$a = V'$" in L_1 such that $V' \sqsubseteq_{\mathsf{V}} V$.*

Examples of service terms and relationships between them are: print(year=1990, pub_type=`proceedings`)$\sqsubseteq_{\mathsf{ST}}$ print(pub_type=`proceedings`)$\sqsubseteq_{\mathsf{ST}}$print(pub_type=`material`).

Each basic service may have *facets* associated with it. Facets can capture additional, or alternative (*polymorphic behavior*), functionalities of the service that can be enabled upon presentation of given credentials or declarations. For instance, at an airline server, a flight-reservation service may have facets seat_assignments or lunch_choices that provide additional features (choice of seat and food) enabled only for frequent flyer members, upon insertion of the membership number.

3. BASIC ELEMENTS OF THE REQUIREMENT SPECIFICATION LANGUAGE

We illustrate the basic constructs of the language that will be used to specify service access and information release rules. In the following, we use "term" to denote either a value in a given domain or a variable over it; we use $\vec{x}$ to denote a list $x_1, \ldots, x_n$ of parameters, where the number n of parameters and their type will be clear from the context. The basic predicates of the language are as follows.

1. A binary predicate symbol, credential. The first argument is a credential term (Definition 2.1). The second argument is a public key term. Intuitively, a ground atom credential(c, K) is true iff the current state contains a credential c verifiable with public key K.

2. A predicate symbol, declaration, whose argument is an element of the form "*attribute_name = value_term*". Intuitively, a ground atom declaration(d) is true iff the current state contains declaration d.[3]

3. A binary predicate symbol cert_authority, whose arguments are a certification authority and its public key. Intuitively, predicate cert_authority(CA, K_{CA}) states that the party trusts certificates signed by certification authority CA whose public key is K_{CA}. Note the importance of such a statement: a party usually accepts only certificates signed by authorities that it trusts (or chains of certificates eventually ending with them) [8].

4. A set of non predefined *state* inquiry predicates that evaluate information stored at the site (*persistent state*) or acquired during a negotiation (*negotiation state*). State predicates can also be built-ins or calls to external packages [17]. A typical example of server's persistent knowledge is represented by user *profiles* containing information about different users registered at the server, such as demographic information or preferences. Examples of negotiation state predicates are predicates determining the current service or the credentials/declarations already submitted to the opponent party within a negotiation.

5. A set of non predefined *abbreviation* predicates denoting abbreviation of requirements, e.g., declarations, credentials, and chains thereof.

6. A set of standard built-in mathematic predicates, including $=, \neq, <$.

The above predicates, which we refer to as *basic predicates*, constitute the basic literals that can be used in rules restricting services accessibility and portfolio disclosure. These rules will be discussed in the next section. Abbreviation rules, which have the same form at both the client and the server side, are defined as follows.

DEFINITION 3.1 (ABBREVIATION RULES). *An* abbreviation rule *has the form: $p(\vec{x}) \leftarrow q_1(\vec{x_1}), \ldots, q_n(\vec{x_n})$, where p is an abbreviation predicate, and $q_i, i = 1, \ldots, n$, is a basic predicate.*

Intuitively, abbreviation rules define "macros" that can be used as a shorthand for disjunctions or conjunctions of conditions (those in the body of abbreviation rules).

EXAMPLE 3.1. *The following are examples of abbreviation rules.*

1. info(hobby=X) $\leftarrow$ declaration(name=Y), usr_profile(Y, hobby=X)
2. info(hobby=X) $\leftarrow$ declaration(preferences.hobby=X)
3. principal(P, K) $\leftarrow$ cert_authority(P, K)
4. principal(P, K) $\leftarrow$ credential(belongs_to(issuer=I, principal=P, key=K), K'), principal(I, K')

*Rules 1 and 2 introduce an abbreviation to refer to the hobby of a client, which can be obtained by querying the user's profile, if her identity is known (rule 1), or by explicit declaration by the user (rule 2). Rules 3 and 4 define the association between a principal P and a public key K, when this association is certified by a certification authority (*cert_authority *literals), which the party trusts either directly (rule 3) or through a chain of certificates (rule 4) [8].*

4. SERVICE ACCESSIBILITY AND PORTFOLIO DISCLOSURE RULES

We illustrate the rules that regulate negotiation and client-server interaction. We distinguish two kinds of rules: *service accessibility rules*, used by servers to specify restrictions that clients must satisfy to access a service, and *portfolio disclosure rules*, used by both clients and servers to specify restrictions regulating disclosure of their portfolio. Examples refer to the rules reported in Figure 3, where predicate

[3] For simplicity, in the following we will often use declaration with more than one argument. A declaration literal with n argument is to be interpreted as a shorthand for n declaration literals, one for each of the arguments.

Service accessibility rules (at the digital library server)

1. service_prereqs(library_access()) ← declaration(login=X, passwd=Y) | usr_profile(login=X, passwd=Y).
2. service_prereqs(library_access()) ← credential(affiliation(issuer=I, user=U, user_key=K_U), K_I), principal(I, K_I) | registrations(subscriber=I).
3. service_reqs(new_user()) ← declaration(login=X, passwd=Y, name=Z, affiliation=U), membership(name=Z).
4. service_reqs(print()) ← declaration(copyright="`accept`").
5. service_reqs(print(journal=J, year=X)) ← customer_affiliation(A), subscription(subscriber=A, year=X, journal=J), current_year(Y), $X < Y$.
6. service_reqs(buy()) ← declaration(credit_card_number=X).
7. service_reqs(buy()) ← credential(authorized_to_buy(issuer=I, user=U, user_key=K_U), K_I), current_customer(U), customer_affiliation(I).
8. facet_reqs(buy(material="`proceedings`", conf=C, ass=A), discount) ← current_customer(U) credential(attendance_certificate(issuer=O, attendant=U, conference=C)K_O), accredited_organizer(company=O, association=A), principal(O, K_O).
9. accredited_organizer(company=O, association=A) ← credential(accredited(issuer=A, organizer=O), K_A), principal(A, K_A).
10. membership(name=Z) ← credential(acm_membership(issuer="`ACM`", member=Z), K).
11. membership(name=Z) ← credential(ieee_membership(issuer="`IEEE`", member=Z), K).

Portfolio disclosure rules (at the client)

12. release_reqs(credit_card_info) ← current_service(buy()), declaration(no_disclosure="`accept`").
13. release_reqs(membership_card(issuer=X)) ← credential(certified_server(issuer=X, server=M), K), current_server(M), principal(X, K).

Figure 3: An example of service access and portfolio disclosure rules

principal is defined as in Example 3.1, cert_authority information is assumed given, and the other predicates that do not occur in the head of any rules are state predicates, whose interpretation is immediate.

4.1 Service accessibility rules

Service accessibility rules specify conditions that clients must satisfy to access services. Rules can also be specified with reference to specific facets of services, in which case their satisfaction (lack of, respectively) only affects the enabling (disabling, respectively) of the corresponding facet, not the access to the service itself. Requirements associated with facets are *optional*, and we treat them separately.

We distinguish two kinds of service accessibility rules: *prerequisites* and *requisites*. Prerequisites are conditions that must be satisfied for a service request to be taken into consideration (they do not guarantee that it will be granted); requisites are conditions that must be satisfied for the service request to be successfully granted. The basic motivation for this separation is to avoid unnecessary disclosure of information from both parties, and can therefore be seen as twofold: 1) *server's privacy* and 2) *client's privacy*. Let us first discuss server's privacy. The credentials and declarations required from a client may need to satisfy certain relations with (protected) server's state information. For instance, the login and password supplied by the client must match those registered in the server state; clearly this part of the server state must not be disclosed to the client and the match can be evaluated only after the client itself has provided the information. Through prerequisites, it is also possible to limit the disclosure of the access control policy itself. To illustrate, suppose that a given service is to be made accessible only to users who satisfy all the following conditions: 1) are registered at the server, 2) are US residents, 3) are members of a partner association. Instead of communicating all such requirements to the client, and therefore unrestrictedly disclosing the whole policy, the server could first ask the counterpart for her login name (prerequisite); if she is not registered, there is no reason to proceed further. On the other hand—concerning the client's privacy—it is usually legitimate for the client, after submitting the requested credentials and declarations, to expect a successful completion of the service. If it weren't so, and the server could advance further requests that the client may not be willing or able to fulfill, the initial release of information from the client to the server would prove ineffective from the point of view of getting the service, resulting in an unnecessary disclosure of information (imagine the situation of a user submitting personal and financial information required for a purchase and then being denied it). It is therefore important that servers clearly indicate whether the required credentials and declarations are only a necessary (prerequisite), or also a sufficient (requisite), condition for service access (this assuming, of course, honesty of the server.)

Service prerequisite rules are composed of two parts. The first part states credentials and declarations that the client must submit to have its request considered. The second part states conditions that such credentials and declarations must satisfy for the rule's successful evaluation, and they will be checked by the server after reception of the required credentials and declarations.

DEFINITION 4.1 (SERVICE PREREQUISITE RULES). *A service prerequisite rule is a rule of the form* service_prereqs($s(L)$) ← $q_1(\vec{x_1}), \ldots, q_n(\vec{x_n}) \mid p_1(\vec{y_1}), \ldots, p_1(\vec{y_m})$, *where $s(L)$ is a service term, q_i, $i = 1, \ldots, n$, is a basic predicate, and p_j, $j = 1, \ldots, m$, is either a state predicate or a math built-in.*

Service requisite rules are simpler. Their body is composed of only one part, whose evaluation determines the requirements to be communicated to the client.

DEFINITION 4.2 (SERVICE REQUISITE RULES). *A* service requisite *rule is a rule of the form* $\mathsf{service\_reqs}(s(L)) \leftarrow q_1(\vec{x_1}), \ldots, q_n(\vec{x_n})$, *where* $s(L)$ *is a service term and* q_i, $i = 1, \ldots, n$ *is a basic predicate.*

Consider the rules in Figure 3. Rules 1 and 2 define two (alternative) prerequisite conditions that must be satisfied to get access to a digital library service. Rule 1 applies to users registered as individuals, who must declare their login and password. Rule 2 applies to users affiliated with an organization that is registered as a corporate member, who must present a certificate of affiliation to one such organization.[4] Rules 3 through 7 are examples of service requisite rules. Rule 3 requires new users registering at a service to declare login, password, and affiliation, and to supply a credential issued by either ACM or IEEE stating the user's membership in the association. Rules 4 requires clients to accept a copyright agreement (operation that can be simply accomplished with a click on the "ok" button of a pop up window) in order to access the print service. Moreover, by rule 5, printing of journal articles appeared in old issues is allowed only to those users affiliated with an organization that has a subscription for the considered year. Finally, rules 6 and 7 require buyers to provide either a credit card number (purchase by an individual) or a certificate stating that the purchase is authorized by the buyer's organization subscribed to the service (corporate purchase).

DEFINITION 4.3 (FACET REQUISITE RULES). *A* facet requisite *rule is a rule of the form* $\mathsf{facet\_reqs}(s(L), f) \leftarrow q_1(\vec{x_1}), \ldots, q_n(\vec{x_n})$, *where* $s(L)$ *is a service term,* f *is the name of a facet associated with* s, *and* q_i, $i = 1, \ldots, n$, *is any of the basic predicates.*

Rule 8 in Figure 3 is an example of facet rule. It enables facet `discount` on service buy for `proceedings` material upon presentation of a certificate proving the buyer's attendance to a conference organized by an accredited organization.

Prerequisites, requisites, and facet rules, together with abbreviation rules and certification authority information discussed in the previous section, are all is needed to specify service accessibility restrictions at a server. It must be noted, however, that the support of abstractions with the semantics discussed implies that, to access a service, a client must satisfy, beside the accessibility restrictions associated with the service, also the possible restrictions specified at a more abstract level. For instance, a client requesting print(journal="CACM", year="2000") will be required both to accept the copyright agreement (rule 4) *and* to provide a certificate of affiliation with an organization that has a subscription to `CACM` for year 2000 (rule 5).

Additional predefined (meta)rules must then be considered by the access control system to enforce propagation of requisites. This propagation is made explicit by the following definition.[5]

DEFINITION 4.4 (REQUISITE PROPAGATION RULE, Inh). *Let* APol *be a set of requisite rules specified at a server. The* requisite propagation *rules for a given service term* $s(L)$ *and* APol, *denoted by* $\mathsf{Inh}(s(L), \mathsf{APol})$, *are* predefined *rules of the form* $\mathsf{service\_reqs}*(s(L)) \leftarrow \mathsf{service\_reqs}(s_1(L_1)), \ldots, \mathsf{service\_reqs}(s_n(L_n))$, *where* $s_1(L_1) \ldots, s_n(L_n)$ *are all and only the ground instances of the service terms that occur in* APol, *such that the variables are bounded to leaves of the value hierarchy and* $s(L) \sqsubseteq_{\mathsf{ST}} s_i(L_i)$.

DEFINITION 4.5 (REQUISITE SATISFACTION). *A set of credentials/declarations* Info satisfies the requisites for *a service* $s(L)$ *w.r.t. a server state* Σ *iff* $\mathsf{APol} \cup \mathsf{Inh}(s(L), \mathsf{APol}) \cup \Sigma \cup \mathsf{Info} \models \mathsf{service\_reqs}*(s(L))$.

The formal definition of prerequisite and facet requirement satisfaction is analogous. Note that Definition 4.5 yields the traditional closed policy (only accesses explicitly authorized are allowed). Such an option can be easily reversed (open policy) w.r.t. a service $s(L)$ by specifying a rule $\mathsf{service\_reqs}(s(L)) \leftarrow$ `true`. This provides a convenient way to combine the open and closed control policy paradigm [9].

4.2 Portfolio disclosure rules

At each party, release rules regulate the disclosure of declarations and credentials in the portfolio. Although it is natural to think of these rules at the client side, and for concreteness we refer our discussion to those, it is important to note that they can be enforced at any of the parties (server as well) that may release declarations/credentials. For instance, the server of a travel agency can submit to its clients a credential that proves the fact that the travel agent is approved by AAA. Release rules are defined as follows.

DEFINITION 4.6 (RELEASE RULE). *A* release *rule is a rule of the form* $\mathsf{release\_reqs}(o) \leftarrow q_1(\vec{x_1}), \ldots, q_n(\vec{x_n})$, *where* o *is either a credential term* $c(L)$ *or a declaration, and* q_i, $i = 1, \ldots, n$, *is a basic predicate.*

Consider the portfolio disclosure rules in Figure 3. Rule 12 restricts the release of declarations concerning credit card information (Figure 1(b)), allowing their disclosure only in the process of a buy operation and upon presentation of a nondisclosure agreement by the server.[6] Intuitively, rule 12 can be seen as an example of *need to know* principle enforcement: only at the time of a purchase does the server need to know the credit card number of the client. Rule 13 restricts the release of a card proving membership in an organization only to servers certified by that organization.

Similarly to requisites, pre-defined (meta)rules enforce propagation of restrictions to abstraction and class instances.

DEFINITION 4.7 (RELEASE PROPAGATION RULE). *Let* RPol *be a set of release rules and let* o *be an information object, representing either a credential term or a declaration attribute/class. The* release propagation *rule for* o *and* RPol, *denoted by* $\mathsf{Inh}(o, \mathsf{RPol})$, *is a predefined rule of the form* $\mathsf{releasable}*(o) \leftarrow \mathsf{release\_reqs}(o_1), \ldots, \mathsf{release\_reqs}(o_n))$, *where* $o_1, \ldots, o_n$ *are all and only the ground instances of the terms that occur in* RPol, *such that the variables are bounded to leaves of the value hierarchy and* $o \sqsubseteq_{\mathsf{PO}} o_i$, *for* $i = 1, \ldots, n$.

[4] Note the importance of treating this as a prerequisite; the server can control that the organization is a registered member without communicating the list of registered members to the client [3].

[5] The actual implementation of inheritance does not rely on the rules in Definition 4.4, but on a more concise and flexible recursive formulation [3].). The rules in the definition are the simplest description of the declarative semantics of inheritance, that will be needed for reasoning about the correctness of the access control process.

[6] Note that the release of such an agreement by the server, might be conditioned to the enforcement of corresponding release rules at the server side.

Given this, we can now state the condition under which credentials/declarations can be released.

DEFINITION 4.8 (RELEASABLE TERM). *A credential/declaration term o is* releasable *w.r.t. a party's state Σ and a set* Info *of received credentials/declarations iff* $\mathsf{RPol} \cup \mathsf{Inh}(o, \mathsf{RPol}) \cup \Sigma \cup \mathsf{Info} \models \mathsf{releasable}*(o)$.

5. CLIENT-SERVER INTERPLAY

Service execution is regulated by the rules enforced by the two parties. The client-server interplay, depicted in Figure 4, can be summarized as follows. Upon reception of a service request, the server reacts by asking the client for prerequisite information (determined by evaluating the service prerequisite rules), if any. If the client sends back the required prerequisites, and if they satisfy the conditions after the bars, then the server determines (based on its service rules and state) the credentials/declarations that the client must submit to get the service, and communicates them to the client. The client, in turn, evaluates the required credentials and declarations with respect to its own portfolio disclosure rules and possibly presents a counter request R' for credentials/declarations to the server. Upon satisfaction of its request[7], the client will present the server with the requested credentials/declarations, thus gaining access to the service.

Now the question is: *how should the credential/declaration requests involved in the negotiation be formulated?* To fix the ideas, let us see the problem from the point of view of the server (the client's point of view is symmetrical). The naive way to formulate a declaration/credential request—that is, giving the client a list with all the possible sets of credentials that would enable the service—is not feasible, due to the large number of possible alternatives. In particular, *i)* the precise nature of the credentials might not be known in advance (as it happens with chains of credentials), and *ii)* in the presence of compound credential requests such as "*one* ID *and one* membership certificate from a federated association", there may be a combinatorial explosion of alternatives, as each individual request can potentially be fulfilled in many possible ways. This can be avoided by presenting the client with a compact requirement description, based on the abbreviations (such as 'ID' and 'membership card') defined by abbreviation rules, which are not fully expanded. The client evaluates these rules to find a set Info of credentials and declarations from its portfolio such that Info plus the abbreviation rules entail the abbreviated requirements—then it is guaranteed that Info suffices to enable the desired service. Similar considerations apply to the requirements formulated for *classes* of services and inherited by their subclasses and instances; combinatorial explosion of inherited alternative requirements should be avoided, and the mechanism of rule attachment is a way of achieving this goal.

However, the server cannot simply send its rules to the client. Some rules may query the server's private state information (e.g., to check whether the client is a `good_customer`). Clearly, the server should not send its private information to the client; it should then evaluate state predicates at its side. Moreover, since requisite satisfaction must ensure service access, state predicates must be evaluated *before* sending the requisite request to the client. In principle, other parts of the state, such as the client's preferences need not be hidden from the client, but they should be evaluated anyway before sending the rules to the client. The reason is that the client is not expected to bother with profile information submitted during previous interactions; profiles are maintained by the server precisely for the purpose of making client-server interactions more concise and less redundant.

In this scenario, a crucial property of the requirement request construction is that the *rule manipulation process should not change the original policy*. After selecting the "right" abbreviations to be attached to the requirements, and after the pre-evaluation of those rules, the sets of credentials/declarations Info that satisfy the requirements according to the rules sent to the other party should coincide with the sets Info that satisfy the requirements according to the original policy. To ensure this, a formal account of the policy manipulation process is needed, which we examine next. Such a formal account will also be needed to prove privacy protection results.

5.1 Server's policy filtering mechanism

The process of selecting the rules that should be sent to the client and their partial pre-evaluation yields a form of *filtering*, which is described in detail in the following. We shall prove formally that the original policy is not distorted by filtering, that is, the sets of requirements that enable a service under the original policy coincide with the requirements specified by the filtered rules.

We first consider requisite rules. In order to define the filtering process for them, we introduce an operator Relevant that collects rules and abbreviations that—after partial evaluation—will be returned to the client. Roughly speaking, Relevant selects all the requisite rules for services $s'(L')$ more general than the given request $s(L)$, as well as all rules that define an abbreviation needed by those requisite rules or—recursively—by other needed abbreviations.

DEFINITION 5.1 (Relevant). *Let $s(L)$ be a ground service term, and let* APol *be a set of rules, including both requisite and abbreviation rules. Define* $\mathsf{Relevant}(\mathsf{APol}, s(L))$ *to be the least set satisfying the following closure conditions:*

1. *The hierarchy propagation rule for $s(L)$ (cf. Definition 4.4) is in* $\mathsf{Relevant}(\mathsf{APol}, s(L))$.
2. *For all rules $R = [\mathsf{service\_reqs}(s'(L')) \leftarrow Body]$ in* APol*, and all substitutions θ binding all and only the variables in L' to leaves of the value hierarchy, such that $s(L) \sqsubseteq_{\mathsf{ST}} s'(L')\theta$, $R\theta$ must be in* $\mathsf{Relevant}(\mathsf{APol}, s(L))$.[8]
3. *If some rule in* $\mathsf{Relevant}(\mathsf{APol}, s(L))$ *contains an abbreviation predicate p in the body, then every rule in* APol *with p in the head is in* $\mathsf{Relevant}(\mathsf{APol}, s(L))$.

EXAMPLE 5.1. *Let* APol *be the set of server rules in Figure 3, and let $s(L) =$* print(journal=*"CACM"*, year=*"2000"*)

[7]Although in principle different request/counter-request steps can be imagined, for the sake of simplicity, and practical considerations, we assume the server not to present counter-requests but either satisfy or not satisfy the client requirement.

[8]Operationally, θ is obtained by unifying each variable X in an equality $a = X$ of L' to the value v in the corresponding equality $a = v$ of L. If the latter equality does not exist, then $s(L) \sqsubseteq_{\mathsf{ST}} s'(L')\theta$ cannot possibly hold, and rule R should not be included in $\mathsf{Relevant}(\mathsf{APol}, s(L))$.

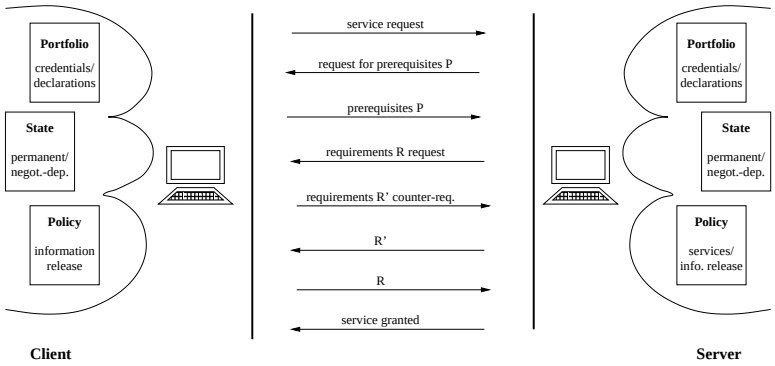

Figure 4: Client/server interplay

be a service request. By condition 1, Relevant(APol, $s(L)$) *contains the rule*

R1) service_reqs*(print(journal="CACM", year="2000")) ←
service_reqs(print(journal="CACM", year="2000")) ,
service_reqs(print()) .

By condition 2, Relevant(APol, $s(L)$) *contains the rules*

R2) service_reqs(print(journal="CACM", year="2000")) ←
customer_affiliation(A), subscription(subscriber=A, year="2000", journal="CACM"), current_year(Y), 2000 < Y .

R3) service_reqs(print()) ← declaration(copyright="accept") .

Consider now the request $s(L)$ = new_user().

Relevant(APol, $s(L)$) *consists of the rules:*

service_reqs*(new_user()) ← service_reqs(new_user()) .
service_reqs(new_user()) ← declaration(login=X, passwd=Y, name=Z, affiliation=U), membership(name=Z) .
membership(name=Z) ←
credential(acm_membership(issuer="CACM", member=Z), K).
membership(name=Z) ←
credential(ieee_membership(issuer="IEEE", member=Z), K).

where the last two rules (defining membership*) are abbreviations.*

It is easy to prove—by means of a standard least fixpoint construction [10]—that the minimality requirement in Definition 5.1 can always be fulfilled, and hence Relevant is well-defined.

PROPOSITION 5.1. *For all* APol *and* $s(L)$*, there exists a unique minimal set* Relevant(APol, $s(L)$) *satisfying conditions 1 and 2 of Definition 5.1.*

As we anticipated, the rules selected by Relevant must be simplified by evaluating state inquiry predicates and built-in math predicates (when possible). Relation $\leadsto_\Sigma$ defined below captures a single evaluation step, presented as rule transformation. Σ models the server's state information, that here is viewed as a set of ground atoms. Intuitively, we shall write $R_1 \leadsto_\Sigma R_2$ if R_2 is obtained from R_1 by simplifying one of the conditions in R_1's body.

DEFINITION 5.2 ($\leadsto_\Sigma$, $\leadsto^*_\Sigma$, PartEval). *Let Σ be a set of ground state inquiry atoms, and let $H \leftarrow B, q(\vec{x}), C$ be a logic program rule, where B and C are sequences of atoms.*

We write $(H \leftarrow B, q(\vec{x}), C) \leadsto_\Sigma (H \leftarrow B, C)\theta$, if $q(\vec{x})$ satisfies one of the following conditions:

1. *$q(\vec{y})$ is a* "standardized apart variant of an atom in Σ",[9] *and θ is the* "most general unifier" *of $q(\vec{x})$ and $q(\vec{y})$;*
2. *q is a built-in mathematical atom, and $q(\vec{x})$ is ground and true.*

The reflexive and transitive closure of $\leadsto_\Sigma$ will be denoted by $\leadsto^*_\Sigma$.

Given a rule R, PartEval(R, Σ) *denotes the set of rules R' such that $R \leadsto^*_\Sigma R'$ and the body of R' contains no state inquiry predicate and no ground math atoms.*

With abuse of notation, in the following we will often use PartEval(APol, Σ) as a shorthand for $\bigcup\{\text{PartEval}(R, \Sigma) \mid R \in \text{APol}\}$, where APol is a set of rules.

EXAMPLE 5.2. *Suppose that Σ contains the facts:* customer_affiliation("ACME"), subscription(subscriber="ACME", year="2000", journal="CACM"), *and* current_year(2000).

From the second rule of Example 5.1 we have

R2 $\leadsto^*_\Sigma$ service_reqs(print(journal="CACM", year="2000")) ← 2000 < 2000 .

As another example, consider the rules for service new_user() *and abbreviation* membership *in Example 5.1. None of these rules contains a state predicate or any mathematical built-in, and we have only $R \leadsto^*_\Sigma R$, for each of such rules R.*

Note that the evaluation steps are iterated until all the atoms $q(\vec{x})$ with the specified properties have been evaluated. If some of such $q(\vec{x})$ cannot be simplified away, then $q(\vec{x})$ fails, and hence the rule must be deleted, because it is not applicable in the current state Σ.

The filtered policy consists of all the selected and partially evaluated rules of the policy.

DEFINITION 5.3 (POLICY FILTERING). *Let $s(L)$ be a service term,* APol *be a set of rules, and Σ be a set of ground state inquiry atoms. Define:*

Filter(APol, $s(L), \Sigma$) = PartEval(Relevant(APol, $s(L)$), Σ) .

EXAMPLE 5.3. *In the scenario of the last examples, if* $s(L)$ = print(journal="CACM", year="2000") *then* Filter(APol, $s(L), \Sigma$) *consists of the two rules:*

service_reqs*(print(journal="CACM", year="2000")) ←
service_reqs(print(journal="CACM", year="2000")) ,
service_reqs(print()) .

[9] This means that $q(\vec{y})$ is obtained from an atom of Σ by uniformly renaming all variables to fresh variables, not occurring in $(H \leftarrow B, q(\vec{x}), C)$.

$\mathsf{service\_reqs}(\mathsf{print}()) \leftarrow \mathsf{declaration}(\mathsf{copyright}=\texttt{"accept"})$.
If $s(L) = \mathsf{new\_user}()$ *then* $\mathsf{Filter}(\mathsf{APol}, s(L), \Sigma)$ *coincides with* $\mathsf{Relevant}(\mathsf{APol}, \mathsf{new\_user}())$ *(cf. Example 5.1), because those rules contain neither state nor mathematical built-in predicates.*

The partially evaluated service requisite rules in $\mathsf{Filter}(\mathsf{APol}, s(L), \Sigma)$, show the relation between each service term in the head and the associated requirements. In cases where servers wish to hide the details of such correspondence, a renaming mechanism can be applied that transforms each head of the form $\mathsf{service\_reqs}(s_i(L_i))$ into an anonymous abbreviation p_i.

DEFINITION 5.4 (SERVICE RENAMING). *Let ρ be an injective function, called renaming function, mapping each atom* $\mathsf{service\_reqs}(s_i(L_i))$ *occurring in* $\mathsf{Relevant}(\mathsf{APol}, s(L))$ *onto some propositional symbol p_i not occurring in* APol. *The result of substituting* $\rho(\mathsf{service\_reqs}(s_i(L_i)))$ *for* $\mathsf{service\_reqs}(s_i(L_i))$ *in* $\mathsf{Filter}(\mathsf{APol}, s(L), \Sigma)$ $(1 \leq i \leq n)$ *is called a* service renaming of $\mathsf{Filter}(\mathsf{APol}, s(L), \Sigma)$ based on ρ, *and will be denoted by* $\mathsf{RenFilter}(\mathsf{APol}, s(L), \Sigma, \rho)$.

The process above applies to the requisites associated to a given service. The technicalities related to the filtering and renaming of the other server rules—for facet requisites and prerequisites—are very similar, with small differences which we sketch below.

Facet rules are filtered exactly as requisite rules. However, the renaming phase does not hide the facet name. Facet names are not hidden because, in a typical commercial setting, some knowledge about the facet (e.g., the fact that the facet grants a discount) may motivate the client's decision to release optional credentials.

Prerequisite rules is treated in a slightly different way. The selection operator (corresponding to Relevant) must drop the part of the rules following the bar '|'. After that, filtering and renaming proceed in the same way.

5.2 Client's policy evaluation

Given the server's requirements $\mathsf{RenFilter}(\mathsf{APol}, s(L), \Sigma, \rho)$, the client searches its portfolio for a set of credentials/declarations Info such that $\mathsf{RenFilter}(\mathsf{APol}, s(L), \Sigma, \rho) \cup \mathsf{Info} \models \mathsf{service\_reqs}*(s(L))$, where $s(L)$ is the service requested by the client. This can be done either by constructing a top-down proof of $\mathsf{service\_reqs}*(s(L))$ and collecting credential and declaration atoms as they are needed, or by collecting the credential and declaration atoms after the proof trees have been constructed [15]. Once the alternative *sets* of credentials that would grant $s(L)$, say $C_1, \ldots, C_n$, have been collected, the client prunes them by using its release rules. Recall that this is done by checking for each credential/declaration o in a C_i whether $\mathsf{releasable}*(o)$ can be derived using the client's release rules and state (the client may send C_i to the server only if $\mathsf{releasable}*(o)$ holds for all $o \in C_i$).[10] In general, the releasability proof may require credentials and/or declarations that are not already available to the client and should therefore be asked to the server (e.g., rules 12 and 13 in Figure 3). As we anticipated, to formulate the client's requests concisely without disclosing private information, the client's release rules and related abbreviations should be filtered and renamed, and the result should be sent to the server as a counter-request. Release rules filtering and renaming are thoroughly analogous to filtering and renaming of service requirement rules. The main differences are: *i)* The analogous of operator Relevant applies to release rules, and makes use of the client's credential/declaration hierarchy, rather than the service term hierarchy; *ii)* Relation $\rightsquigarrow_\Sigma$ and $\mathsf{PartEval}(\mathsf{APol}, \Sigma)$ use as Σ the state information of the client. Since the technical definitions are perfectly analogous to those for service rules, we omit them here.

Note that for how the protocol has been defined, the set of credentials/declarations requested from a client as requisites (as opposed to prerequisites) are sufficient for the client to acquire access to the service. Hence, the client is ensured (of course assuming honesty of the server) that the delivery of the requested credentials/declarations will grant him the service.

[10] Any set of credentials with this property will do. Among the different criteria [19, 21] that can guide the choice, we are investigating *maximally parsimonious information release.* Intuitively, the client may simply rate the releasable sets of credentials $C_1, \ldots, C_k$, and then submit the corresponding requests to the server in order of decreasing parsimony, until the server fulfills a request. The assumption that no counter-counter requests are made by the server guarantees that this simple method yields maximal protection.

6. CORRECTNESS AND COMPLEXITY

The correctness of the techniques introduced comprises of several aspects. A first aspect concerns the *correctness of the policy translation and filtering process.* Filtering and renaming are supposed to protect the server's privacy without changing its policy, so the equivalence of the original policy and the filtered requisites states the *correctness* of the filtering mechanism.

THEOREM 6.1 (CORRECTNESS OF FILTERING/RENAMING). *For all* APol, $s(L)$, Σ, *renaming* $\mathsf{RenFilter}(\mathsf{APol}, s(L), \Sigma, \rho)$, *and sets* Info *of credential and declaration atoms,*

$$\mathsf{APol} \cup \mathsf{Inh}(s(L), \mathsf{APol}) \cup \Sigma \cup \mathsf{Info} \models \mathsf{service\_reqs}*(s(L)) \iff \mathsf{RenFilter}(\mathsf{APol}, s(L), \Sigma, \rho) \cup \mathsf{Info} \models \mathsf{service\_reqs}*(s(L)).$$

To clarify the formal details, recall that $\mathsf{APol} \cup \mathsf{Inh}(s(L), \mathsf{APol}) \cup \Sigma \cup \mathsf{Info} \models \mathsf{service\_reqs}*(s(L))$ on the left of the above equivalence is the condition that must be satisfied for the service $s(L)$ to be accessible. The right-hand side of the equivalence models the check that must be performed by the client. The client, given $\mathsf{RenFilter}(\mathsf{APol}, s(L), \Sigma, \rho)$, should look for a set of credentials/declarations Info such that $\mathsf{RenFilter}(\mathsf{APol}, s(L), \Sigma, \rho) \cup \mathsf{Info} \models \mathsf{service\_reqs}*(s(L))$ holds. Then the client would know that by sending Info to the server, it can obtain service $s(L)$.

A second aspect of correctness concerns the fact that the policy must be respected during client-server interactions. This correctness criterion is the counterpart of access control process correctness in traditional authorization systems [9]. In our case, a correct implementation should ensure that: *1)* a party's declaration/credential term o is disclosed only if it is *releasable* as formalized by Definition 4.8; and *2)* a service request $s(L)$ is granted only if the service prerequisites and requisites are *satisfied* (cf. Definition 4.5).

A further, very important, correctness aspect concerns the protection of a party's private state. The requisites (filtered rules) communicated to a counterpart may reflect a party's current state (e.g., the filtering process may bind some rule variables to terms occurring in the state that then become visible to the other party). In general, this information flow

is inevitable (independently of our approach) as information exchange is necessary for communication to take place, and some state information is supposed to be communicated. As an example, it should be possible for a server to convey the information (stored in its state) that it only accepts `Visa` and `Mastercard`. Given this, it is clear that the protection of state privacy should not be concerned with hiding the whole state, but with clearly identifying the state information conveyed in the communication. There are different possible notions of information protection, with different degrees of paranoia. We are currently considering two different approaches ranging from complete state protection (which is too restrictive in some cases) to identification of the portions of state that may be disclosed to the other party. Such techniques will be the subject of further work.

We close this section with a remark on the complexity of the evaluation process.

THEOREM 6.2. *For fixed service and value hierarchies, and under the assumption that the size of $s(L)$ and the service terms in* APol *are bounded by a fixed constant, the set* $\mathsf{Filter}(\mathsf{APol}, s(L), \Sigma)$ *can be computed in time* $O(n \log n)$*, where* $n = |\mathsf{APol}| + |\Sigma|$.

7. CONCLUSIONS

We introduced a uniform framework and model to regulate service access and information release in large scale networks. The framework comprises a language (with formal semantics) for expressing access and release policies, and a policy filtering mechanism to let the parties exchange their requirements in a compact and privacy preserving way. We investigated the correctness and privacy preserving properties of the filtering process, whose execution has been proved polynomial in the size of the policies. We are currently developing a prototype implementation of our framework in XSB [15], a Prolog system supporting goal tabulation and delay, which is particularly efficient on the computations carried out in our framework. Many aspects have to be investigated in more detail (from negotiations and maximally parsimonious release to the different forms of privacy protection); they will be the subject of further work.

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