Interactive Access Control for Autonomic Systems: From Theory to Implementation

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Autonomic communication and computing is a new paradigm for dynamic service integration over a network. An autonomic network crosses organizational and management boundaries and is provided by entities that see each other just as partners. For many services no autonomic partner may guess a priori what will be sent by clients nor clients know a priori what credentials are required to access a service.

To address this problem we propose a new *interactive access control*: servers should interact with clients, asking for missing credentials necessary to grant access, whereas clients may supply or decline the requested credentials. Servers evaluate their policies and interact with clients until a decision of grant or deny is taken.

This proposal is grounded in a formal model on policy-based access control. It identifies the formal reasoning services of deduction, abduction and consistency. Based on them, the work proposes a comprehensive access control framework for autonomic systems. An implementation of the interactive model is given followed by system performance evaluation.

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1. INTRODUCTION

Controlling access to services is a key aspect of networking and the last few years have seen the domination of policy-based access control. Indeed, the paradigm is broader than simple access control and one may speak of *policy-based self-management networks* (see Sloman and Lupu [1999]; Lymberopoulos et al. [2003]; or the IEEE Policy Workshop series[1]). The intuition is that actions of nodes controlling access to services are automatically derived from policies. The nodes look at events, requested actions and credentials presented to them, evaluate the policy rules according to those new facts and derive the actions [Sloman and Lupu 1999; Smirnov 2003]. Policies can be simple `iptables` configuration rules for Linux firewalls[2] or complex logical policies expressed in languages such as Ponder [Damianou et al. 2001] or a combination of policies across heterogeneous systems as in the OASIS XACML[3] framework.

Dynamic coalitions and autonomic communication add new challenges: an autonomic network comprises nodes that are no longer within the boundary of a single enterprise that could deploy its policies on each and every node and guarantee interoperability. An autonomic network is characterized by properties of self-awareness, self-management and self-configuration of its constituent nodes. In an autonomic network, nodes are like partners that offer services and lightly integrate their efforts into one, hopefully coherent, network.

Since access to network services is offered by autonomic nodes on their own and to potentially unknown clients, the decision to grant or deny access is based on credentials sent by a client. Decentralized applications such as grid systems require support of credentials issued by certificate authorities belonging to distinct administrative domains; require support of delegation of authority based on certified attributes; require collection of credentials located on distributed repositories. This aspect has emerged as the notion of distributed access control, also referred in the literature as trust management [Weeks 2001].

Credentials themselves convey sensitive information and often become subject to unauthorized misused and disclosure. Recent years have seen the emergence of a new concept called trust negotiation [Seamons and Winsborough 2002; Winslett et al. 2002]. It is a policy-based technique that provides clients with the right to protect their own credentials and to negotiate with servers, access to those credentials. Thus trust negotiation allows two network entities (nodes) to mutually establish requirements to access a resource by requesting each other's sensitive credentials until sufficient trust is established.

Although several efficient and powerful negotiation systems have been developed so far [Bonatti and Samarati 2002; Yu et al. 2003; Bertino et al. 2004; Nejdl et al. 2004; Constandache et al. 2007], they focus on specific policy definitions and evaluation of policy requirements. In contrast, we abstract from specific policy settings and provide meta-level access control driven by two logic reasoning services. The logical model presented in the article fills an important gap between policy specification and enforcement. The meta-level

[1]http://www.policy-workshop.org
[2]See http://www.netfilter.org
[3]http://www.oasis-open.org/committees/xacml

approach allows us to cover a wide range of policy specifications (assuming datalog compliant policy) having hundreds of rules, access constraints, complex role hierarchies and nonmonotonic behavior.

In an autonomic communication scenario a client might have all the necessary credentials to access a service but may simply not know it. Equally, it is unrealistic to assume that servers will publish their security policies on the Web so that clients can do policy evaluations themselves. So, it should be possible for a server to ask a client on the fly for additional credentials, whereas the client may disclose or decline to provide them. Next, the server re-evaluates the client's request, considering the newly submitted credentials, and computes an access decision. The process iterates between the server and the client until a final decision of grant or deny is taken. We call this modality *interactive access control*.

Part of these challenges can be solved by using policy-based self-management of networks but not all of them. Indeed, if we abstract away the details of the policy implementation, one can observe that the only reasoning service that is actually used by policy-based approaches is *deduction*: given a policy and a set of additional facts find out all consequences (actions or obligations) from the policy according to the facts. We simply look at whether granting the request can be deduced from the policy and the current facts. Policies could be different [Bertino et al. 2001; Li et al. 2003; Bonatti and Samarati 2002; Winslett et al. 2005; Li et al. 2005] but the kernel reasoning is the same.

Access control for autonomic communications needs another reasoning service: *abduction* [Shanahan 1989]. Loosely speaking, we could say that abduction is deduction in reverse: given a policy and a request to access a network service we want to know what are the credentials (facts) that would grant access. Logically, we want to know whether there is a possibly minimal set of facts that added to the policy would entail (deduce) the request.

If we look again at our intuitive description of the interactive access control, it is immediately seen that abduction is the core service needed by the policy-based autonomic servers to reason for missing credentials.

1.1 Article Contribution

We present a model for reasoning about access control for autonomic communication. The model abstracts from a specific policy language and provides an algorithm based on deduction and abduction reasoning services for policy evaluation and enforcement. The key aspect of the algorithm is that if a client does not have enough access rights the algorithm computes on the fly, missing credentials necessary for the client to get access. Thus a server interacts with a client asking for possible solutions that unlock a service.

Further the article explores the interactive access control model from theoretical and practical aspects. It analyzes the behavior of the model when applied to monotonic and nonmonotonic policies and against cooperative and malicious clients. Technical guarantees of correctness and completeness are proven against monotonic and nonmonotonic policies, called well-behaved policies. An implementation of the model is given together with its performance evaluation.

(1) check if $\mathcal{P}_\mathcal{A}$ and $\mathcal{C}_p$ entail r,
(2) if the check succeeds then `grant` access
(3) else `deny` access.

Fig. 1. Traditional access control.

Results presented in the article can be applied to multi-agent systems or distributed systems comprising communications among autonomic nodes (software agents, network servers, or mobile devices) having their own resources, processing capabilities, and computing power.

The article follows by introducing the starting point of interactive access control and comparing it with existing approaches. Section 3 presents the semantics of the logical model and identifies the different reasoning services used in the model. Section 4 introduces the interactive access control algorithm followed by an example scenario in Section 5. Section 6 formally defines and proves the model's guarantees of correctness and completeness. Section 7 describes in detail, the interactive access control prototype, called iAccess. Next, Section 8 presents the prototype performance evaluation. Section 9 concludes the article. The appendix shows proofs of theorems stated in the article.

2. FROM ACCESS CONTROL TO INTERACTION

We will introduce the concept of interactive access control by evolving existing access control frameworks. Let us start with traditional access control. A server has a *security policy for access control* $\mathcal{P}_\mathcal{A}$ that is used when taking decisions about the use of services offered by a service provider. A user submits a set of credentials $\mathcal{C}_p$ and a service request r in order to execute a service. We say that policy $\mathcal{P}_\mathcal{A}$ and credentials $\mathcal{C}_p$ entail r meaning that request r should be granted by policy $\mathcal{P}_\mathcal{A}$ and the presented credentials, $\mathcal{C}_p$.

Figure 1 shows the traditional access control decision process [De Capitani di Vimercati and Samarati 2001]. Whether the decision process uses Role-Based Access Control [Ferraiolo et al. 2001], Simple Public Key Infrastructure [SPKI 1999], RT framework [Li et al. 2002] or other trust management frameworks it is immaterial at this stage: they can be captured by suitably defining $\mathcal{P}_\mathcal{A}$, $\mathcal{C}_p$, and the entailment operator.

A number of works have deemed such blunt denials unsatisfactory. Bonatti and Samarati [2002] and Yu et al. [2003] proposed sending back to clients some of the policy rules that are necessary to gain additional access. Subsequent promising approaches [Bertino et al. 2004; Nejdl et al. 2004; Kapadia et al. 2004; Constandache et al. 2007] have developed their own polices and mechanisms for deriving and negotiating policy rules.

Bonatti and Samarati's approach defines that governing access to services is composed of two parts: prerequisite rules and requisite rules. Prerequisite rules specify the requirements that a client should satisfy before being considered for the requirements stated by the requisite rules, which in turn grant access to services. Their approach does not decouple policy disclosure from policy satisfaction, as noted in Yu and Winslett [2003].

Yu and Winslett [2003] overcome this limitation and propose treating policies as first class resources: each policy protecting a resource is considered as a sensitive resource itself, whose disclosure is recursively protected by another policy, called meta-policy.

The meta-policy approach is also used in Bertino et al. [2004]. In this work, each resource is protected by one or more disclosure policies. Each disclosure policy has its policy preconditions and the policy content is revealed if one of the preconditions is satisfied. Each policy precondition has as its own policy precondition that at least one of them must be satisfied before the policy content is released.

If we look at the underlying policy models one can find that either of the approaches requires policies to be flat: a policy protecting a resource must contain all credentials needed to allow access to that resource. As a result, it calls for structuring of policy rules counter-intuitive to the access control point of view. For instance, a policy rule may say that for access to the full text of an online journal article, a requester must satisfy the requirements for browsing the journal's table of contents plus some additional credentials. A rule detailing access to the table of contents could then specify another set of credentials. Even this simple scenario is not intuitive in either formalism.

Further, constraints that would make policy reasoning nonmonotone (such as separation of duties) require looking at more than one rule at a time. So, if the policy is not flat, it has constraints on the credentials that can be presented at the same time, or if a more complex role hierarchy is used, these systems would not be complete.

The work by Kapadia et al. [2004] proposes inferring possible alternatives from failed requests based on the policy scheme of Yu and Winslett. The work uses ordered binary decision diagrams (OBDDs) to represent a resource's policy and its meta-policies. The root of the diagram is the resource itself, and its successors are the policy requirements protecting the resource. The policy requirements have further successors that are the meta-policy requirements and so on. Upon the failure of a request, the approach traverses the diagram from the root to its true state (representing grant status) and finds all alternatives that would satisfy the request.

The work inherits the monotonicity limitations of Yu and Winslett's settings. The scheme reasons on a single rule specifying a resource's policy and its relevant meta-policy rules in order to find missing credentials satisfying the request. As such, the approach cannot scale to nonmonotonic access policies because they require looking at more than one rule (often the entire policy) at any time.

In general, protecting resources' policies with meta-policies in the access policy itself, allows a system to have control of when a policy can be disclosed from when a policy is satisfied. However, this approach interlocks access and disclosure reasoning in one security policy setting.

The foundation of our approach is to decouple the decision about access from the decision about disclosure. Resource access is decided by the business logic whereas policy disclosure is due to security and privacy considerations. We first define decision about access: if a requestor has enough access rights to get a

(1) check if $\mathcal{P}_\mathcal{A}$ and $\mathcal{C}_p$ entail r,
(2) if the check succeeds then `grant` access else
  (a) compute a set $\mathcal{C}_\mathcal{M}$ such that:
    – $\mathcal{P}_\mathcal{A}$ together with $\mathcal{C}_p$ and $\mathcal{C}_\mathcal{M}$ entail r, and
    – $\mathcal{P}_\mathcal{A}$ together with $\mathcal{C}_p$ and $\mathcal{C}_\mathcal{M}$ preserve consistency.
  (b) if $\mathcal{C}_\mathcal{M}$ exists then `ask` $\mathcal{C}_\mathcal{M}$ to the client and iterate
  (c) else `deny` access.

Fig. 2. Basic idea of interactive access control.

resource according to an access policy. If access fails then it is necessary to decide about disclosure and the necessity of information to explain why access failed. If enough information is disclosed to justify the necessity of additional requirements (what is missing to grant access) then ask for these requirements, otherwise if there is not enough information to justify access failure, then deny access.

The important aspect here is that the decision about disclosure comes only if the decision about access fails as opposed to the current approaches.

2.1 Intuition 1: Advanced Reasoning Service Abduction

If we abstract the above approaches, the only reasoning service used for access control is *deduction*—check if the request follows from a security policy and presented credentials.

We identify the need of another reasoning service, called *abduction*—check what missing credentials are necessary so that the request can follow from the policy and the presented credentials. Thereupon, we present the basic idea of interactive access control shown in Figure 2.

The "compute a set $\mathcal{C}_\mathcal{M}$ such that ..." (step 2a) is exactly the operation of abduction, formally defined in Section 3. An essential part of the abduction reasoning is the computation of a set of missing credentials that is a solution for the request and, at the same time, is consistent with the policy state. The consistency property gives us strong guarantees for the missing set of credentials when applying the algorithm on nonmonotonic policies. Section 6 examines in detail the algorithm's properties.

Challenge. Having abduction as a tool for finding missing credentials we face a new challenge: how do we decide the potential set of missing credentials?

It is clearly undesirable to disclose all credentials occurring in $\mathcal{P}_\mathcal{A}$ and, therefore, we need a way to define how to control the disclosure of such a set.

2.2 Intuition 2: Disclosure Control Policy

We need two policies: one for granting access to one's own resources and one for disclosing the need of foreign (someone else's) credentials. Therefore, we introduce a *security policy for disclosure control* $\mathcal{P}_\mathcal{D}$. The policy for disclosure control identifies the credentials whose need can potentially be disclosed to a client. In other words, $\mathcal{P}_\mathcal{A}$ protects partner's resources by stipulating what

(1) check if $\mathcal{P}_\mathcal{A}$ and $\mathcal{C}_p$ entail r,
(2) if the check succeeds then `grant` access else
  (a) compute a set of disclosable credentials $\mathcal{C}_\mathcal{D}$ entailed by $\mathcal{P}_\mathcal{D}$ and $\mathcal{C}_p$,
  (b) compute a set of missing credentials $\mathcal{C}_\mathcal{M}$ out of the disclosable ones ($\mathcal{C}_\mathcal{M} \subseteq \mathcal{C}_\mathcal{D}$) such that
    – $\mathcal{P}_\mathcal{A}$ together with $\mathcal{C}_p$ and $\mathcal{C}_\mathcal{M}$ entail r, and
    – $\mathcal{P}_\mathcal{A}$ together with $\mathcal{C}_p$ and $\mathcal{C}_\mathcal{M}$ preserve consistency.
  (c) if $\mathcal{C}_\mathcal{M}$ exists then `ask` $\mathcal{C}_\mathcal{M}$ to the client and iterate
  (d) else `deny` access.

Fig. 3. Interactive access control with controlled disclosure.

credentials a requestor must satisfy to be authorized for a particular resource while, in contrast, $\mathcal{P}_\mathcal{D}$ defines what credentials among those occurring in $\mathcal{P}_\mathcal{A}$ are disclosable (i.e. can be asked) to the requestor. We note that $\mathcal{P}_\mathcal{D}$ may also identify credentials that do not occur in $\mathcal{P}_\mathcal{A}$ but are required for fine-grained disclosure protection.

Figure 3 shows the refined algorithm with controlled disclosure.

Yu and Winslett's policy scheme determines whether a client is authorized to be informed of the need to satisfy a given policy. While, in our case, having a separate disclosure control policy allows us to determine whether a client is authorized to see the need for single credentials. One can approach a fine-grained disclosure control by defining the disclosure of entire policies as single units as well as the disclosure of single credentials composing those policies.

Stepwise Disclosure Control. Having a separate disclosure policy allows us to have additional reasoning on the policy that helps us to disclose credentials in a stepwise fashion. The basic intuition is that the logical policy structure itself tells us what credentials must be disclosed to obtain the information that other credentials are missing. The negotiation model presented in Koshutanski and Massacci [2007] extends the interactive algorithm with an additional functionality of computing stepwise sets of missing credentials and requesting them gradually until a solution is agreed that grants a resource. In other words, the `ask`($\mathcal{C}_\mathcal{M}$) function of the interactive algorithm is replaced with a stepwise disclosure of requirements by observing $\mathcal{P}_\mathcal{D}$ structure so that at the end $\mathcal{C}_\mathcal{M}$ is disclosed to a client.

In this article we will abstract from the stepwise disclosure functionality and treat a set of missing credentials, $\mathcal{C}_\mathcal{M}$, as a single unit of disclosure. One can well apply the stepwise approach on top of the results achieved in the article.

Let us look at Yu and Winslett's own example [Yu and Winslett 2003, p. 4].

Example 2.1 (*McKinley Clinic*). [Access Scenario] McKinley clinic makes its patient records available for online access. Let r be Alice's record. To gain access to r a requester must either present Alice's patient ID for McKinley clinic ($C_{AliceID}$), or present a California social worker license (C_{CSWL}), and a release-of-information credential (C_{RoI}) issued to the requester by Alice.

[Disclosure Scenario] Alice wants to keep the latter constraint inaccessible to strangers as it may help them to infer that Alice has mental or emotional

problems. However, employees of McKinley clinic ($C_{McKinleyEmployee}$) should be allowed to see the contents of this policy.

[Security Policy]

$\mathcal{P}$: $r : P$
$P \leftrightarrow P_1 \vee P_2$ and $P : true$
$P_1 \leftrightarrow C_{AliceID}$ and $P_1 : true$
$P_2 \leftrightarrow C_{CSWL} \wedge C_{RoI}$ and $P_2 : true$
$P_2 : P_3$
$P_3 \leftrightarrow C_{McKinleyEmployee}$ and $P_3 : true$

P, P_1, P_2 and P_3 are policy identifiers. r and P_2 are protected sensitive resources.

[Example formalization as two logic programs]

$\mathcal{P}_A$: $r \leftarrow C_{AliceID}.$
$r \leftarrow C_{CSWL}, C_{RoI}.$

$\mathcal{P}_D$: $C_{AliceID}.$
$C_{CSWL} \leftarrow C_{McKinleyEmployee}.$
$C_{RoI} \leftarrow C_{McKinleyEmployee}.$

$\mathcal{P}_A$ states that access to r is granted either to Alice or to California social workers that have a release-of-information credential issued by Alice.

$\mathcal{P}_D$ states that the disclosure of Alice's ID is not protected and potentially released to anybody. The need for credentials C_{CSWL} and C_{RoI} is disclosed only to users who have already presented their $C_{McKinleyEmployee}$.

The motivation for using metapolicies is to protect sensitive access policies from being learned by unauthorized clients: those clients who do not comply with the disclosure requirements. In our case, since we first define a decision about access, one would argue that an opponent can probe an access policy by sending different sets of credentials and monitoring the behavior of the system.

Since the access control model enforces a meta-level interaction process, driven by deduction and abduction reasoning, one can address specific disclosure requirements by properly defining the structure of the access and disclosure policies. For example, one can add to all resources' policies a guarding primitive that its satisfaction requires a certain set of credentials to be presented by an opponent (e.g., $r \leftarrow \mathcal{P}_r, guard\,.\,guard \leftarrow \mathcal{P}_{guard}$) in order to learn actual access information. In this way, the primitive causes access failure, even if a resource's policy is satisfied, until the guarding primitive's policy is satisfied. Then, how the guarding requirements are disclosed to the opponent is also the matter of a disclosure policy structure.

Winsborough and Li [2006] postulate a property for safety in automated trust negotiation that further justifies the importance of well-designed access and disclosure policies for protecting the behavior of a system.

A question that would come up is whether the disclosure policy is resource aware—whether we could have an association between resources and credentials protecting resources within $\mathcal{P}_D$. For example, let us have a second resource r_2 protected by credential C_{CSWL} the disclosure of which does not depend on the presence of $C_{McKinleyEmployee}$, but which is the case for r.

Example 2.2 (*Fine-grained disclosure control*).

$\mathcal{P}_A$: $r \leftarrow C_{AliceID}$. $r \leftarrow C_{CSWL}, C_{RoI}$. $r_2 \leftarrow C_{CSWL}$.

$\mathcal{P}_D$: $C_{AliceID} \leftarrow r$. $C_{McKinleyEmployee} \leftarrow r$. $P_1 \leftarrow C_{McKinleyEmployee}, r$. $C_{RoI} \leftarrow P_1$. $C_{CSWL} \leftarrow P_1$. $C_{CSWL} \leftarrow r_2$.

$\mathcal{P}_D$ states that the disclosure of Alice's ID is potentially released to anybody having requested resource r. The need for credential $C_{McKinleyEmployee}$ is released to anybody requesting r. P_1 is a policy identifier encapsulating disclosure of C_{CSWL} and C_{RoI}. The need for credentials C_{CSWL} and C_{RoI} is disclosed only to those who have already presented $C_{McKinleyEmployee}$ and requested resource r. Alternatively, the need for C_{CSWL} is released to those clients who have requested r_2.

To make the interactive algorithm behave as expected, we have to include the service request as a fact when computing the disclosable credentials. Thus, step 2a becomes "compute a set of disclosable credentials $\mathcal{C}_D$ entailed by $\mathcal{P}_D$, r, and $\mathcal{C}_p$."

In the rest of the article, without loss of generality, we assume that the disclosure policy is resource aware and whenever $\mathcal{P}_D$ is involved it implies $\mathcal{P}_D \cup \{r\}$.

Now, if we add the two rules $\{C_{RoI} \leftarrow r.\ C_{CSWL} \leftarrow C_{RoI}, r.\}$ to $\mathcal{P}_D$, then we are able to provide another solution to the example problem that is not intuitive in the policy scheme of Yu and Winslett. We allow a client to know the need for a release-of-information credential issued by Alice without revealing the need of C_{CSWL} (inferring Alice has a mental problem). On the other side, C_{CSWL} is disclosed only if a client has C_{RoI} presented to the system. Thus ensuring only clients evidenced by Alice will know the need for C_{CSWL}.

Example 2.3 (*Rental car service* [*Bertino et al. 2004, p. 832*]).

$\mathcal{P}$: $pol_1 = (\{\}, Rental\_Car \leftarrow C_{corrier\_employee}, C_{ID\_card})$. $pol_2 = (\{\}, Rental\_Car \leftarrow C_{driving\_license})$. $pol_3 = (\{pol_2\}, Rental\_Car \leftarrow C_{credit\_card})$. $pol_4 = (\{pol_3, pol_1\}, Rental\_Car \leftarrow DELIV)$.

Policy pol_4 says that either pol_3 or pol_1 must be satisfied before granting (delivering) the service $Rental\_Car$. pol_3 states that the release of the need for a credential for a credit card will be shown to those who satisfy pol_2. pol_2 has no preconditions and releases its content to anybody: the need for a drivers license credential. pol_1 has also no preconditions and discloses the need for an employee certificate at Corrier company and credential for an ID card potentially to any client.

[Example formalization as two logic programs]

$\mathcal{P}_A$: $Rental\_Car \leftarrow C_{driving\_license}, C_{credit\_card}$. $Rental\_Car \leftarrow C_{corrier\_employee}, C_{ID\_card}$.

$$\mathcal{P}_D: \left| \begin{array}{l} C_{corrier\_employee} \leftarrow Rental\_Car. \\ C_{ID\_card} \leftarrow Rental\_Car. \\ C_{driving\_license} \leftarrow Rental\_Car. \\ C_{credit\_card} \leftarrow C_{driving\_license}, Rental\_Car. \end{array} \right.$$

If we consider dynamic environments where network (privacy) settings continuously change, one can even define a set of disclosure policies each corresponding to a particular network/system state. For example a disclosure policy may consider a set of environmental factors like time, work load, or other system conditions that could enforce additional disclosure control. These dynamic conditions are likely to be the case in autonomic communication networks. Once the access control algorithm is run it could dynamically select a disclosure policy best suited to the current system state. Having multiple disclosure policies for particular access control requirements is not scalable in the current approaches because they tie access and disclosure requirements into one security policy setting.

2.3 Intuition 3: Extension to Automated Trust Negotiation

A question that would come up when introducing interactive access control is what happens on the client side once the computed missing credentials are requested by a server. The work in Koshutanski and Massacci [2007] extends the interactive model to function on both client and server sides. The intuition is that by mirroring the access control algorithm on the client side, the client is also able to abduce what missing credentials need to be requested to a server in order to disclose its own credentials.

The work proposes a negotiation scheme that builds a negotiation protocol on top of the interactive algorithm. The negotiation protocol allows two entities in a network to mutually establish sufficient access rights needed to grant a resource. The protocol runs on two sides so that entities understand each other and automatically interoperate.

This article examines in detail, the guarantees the interactive model provides when applied to monotonic and nonmonotonic access policies. So one could run a trust negotiation over a nonmonotonic policy domain and still guarantee completeness and correctness of the negotiation process.

Since the negotiation protocol is driven by abduction and deduction reasonings one can accommodate negotiation strategies on top of it, so that missing sets of requirements are released (negotiated) according to some high-level goals. The work by Baselice et al. [2007] proposes a general framework for specifying high-level negotiation strategies abstracting from a specific policy language.

3. POLICY SYNTAX AND SEMANTICS

Policies are written as normal logic programs [Apt 1990]. A normal logic program is a set of rules of the form:

$$A \leftarrow B_1, \ldots, B_n, not\ C_1, \ldots, not\ C_m, \tag{1}$$

where A, B_i and C_i are possibly ground predicates. A is called the head of the rule; each B_i is called a positive literal; and each *not* C_j is a negative literal, whereas the conjunction of B_i and *not* C_j is called the *body* of the rule. If the body is empty the rule is called a fact.

In the framework, we also need constraints that are rules with an empty head.

$$\leftarrow B_1, \ldots, B_n, not\ C_1, \ldots, not\ C_m. \tag{2}$$

One of the most prominent semantics for normal logic programs is the stable model semantics proposed by Gelfond and Lifschitz [1988]. The intuition is to interpret the rules of a program, P, as constraints on a solution set, S (a set of ground atoms), for the program itself. So, if S is a set of atoms, rule (1) is a constraint on S stating that if all B_i are in S and none of C_j are in it, then A must be in S. A constraint, (2), is used to rule out from the set of acceptable models, situations where all B_i are true and all C_j are false.

We give the formal definitions for the basic reasoning services:

Definition 3.1 (*Logical Consequence and Consistency*). Let $\mathcal{P}$ be a logic program and L be a positive ground literal. L is a *logical consequence* of $\mathcal{P}$, symbolically $\mathcal{P} \models L$, if L is true in every stable model of $\mathcal{P}$. $\mathcal{P}$ is *consistent*, $\mathcal{P} \not\models \bot$, if there is a stable model for $\mathcal{P}$.

Definition 3.2 (*Security Consequence*). A request, r, is a security consequence of a policy, $\mathcal{P}$, if (1) $\mathcal{P}$ is logically consistent, and (2) r is a logical consequence of $\mathcal{P}$.

Definition 3.3 (*Abduction*). Let $\mathcal{P}$ be a logic program, H a set of ground atoms (called hypotheses or abducibles), L a ground literal (called observation), and $\prec$ a partial order over subsets of H. A solution of the abduction problem $\langle L, H, \mathcal{P}\rangle$ is a set of ground atoms E such that:

(i) $E \subseteq H$,
(ii) $\mathcal{P} \cup E \models L$,
(iii) $\mathcal{P} \cup E \not\models \bot$,
(iv) any set $E' \prec E$ does not satisfy all conditions above.

Traditional partial orders are subset containment or set cardinality.

Definition 3.4 (*Solution Set for a Resource*). Let $\mathcal{P}$ be an access policy and r be a resource. A set of credentials, $\mathcal{C}_S$, is a *solution set* for r according to $\mathcal{P}$ if r is a security consequence of $\mathcal{P}$ and $\mathcal{C}_S$: $\mathcal{P} \cup \mathcal{C}_S \models r$ and $\mathcal{P} \cup \mathcal{C}_S \not\models \bot$.

Definition 3.5 (*Monotonic and Nonmonotonic Policy*). A policy $\mathcal{P}$ is *monotonic* if whenever a set of statements $\mathcal{C}$ is a solution set for r according to $\mathcal{P}$ ($\mathcal{P} \cup \mathcal{C} \models r$), then any superset $\mathcal{C}' \supset \mathcal{C}$ is also a solution set for r according to $\mathcal{P}$ ($\mathcal{P} \cup \mathcal{C}' \models r$).

In contrast, a nonmonotonic policy is a logic program in which if $\mathcal{C}$ is a solution for r there may exist $\mathcal{C}' \supset \mathcal{C}$ that is not a solution for r, i.e. $\mathcal{P} \cup \mathcal{C}' \not\models r$

Input: r, $\mathcal{C}_p$;
Output: grant/deny/ask($\mathcal{C}_\mathcal{M}$);

(1) update $\mathcal{C}_\mathcal{P} = \mathcal{C}_\mathcal{P} \cup \mathcal{C}_p$,
(2) update $\mathcal{C}_\mathcal{N} = \mathcal{C}_\mathcal{N} \cup (\mathcal{C}_\mathcal{M} \setminus \mathcal{C}_p)$, where $\mathcal{C}_\mathcal{M}$ is from the last interaction,
(3) verify if the request r is a security consequence of $\mathcal{P}_\mathcal{A}$ and $\mathcal{C}_\mathcal{P}$, namely $\mathcal{P}_\mathcal{A} \cup \mathcal{C}_\mathcal{P} \models r$ and $\mathcal{P}_\mathcal{A} \cup \mathcal{C}_\mathcal{P} \not\models \bot$,
(4) if the check succeeds then return ***grant*** else
  (a) compute a set of disclosable credentials $\mathcal{C}_\mathcal{D}$ as
  $\mathcal{C}_\mathcal{D} = \{c \mid c \text{ credential that } \mathcal{P}_\mathcal{D} \cup \mathcal{C}_\mathcal{P} \models c\} \setminus (\mathcal{C}_\mathcal{N} \cup \mathcal{C}_\mathcal{P})$,
  (b) compute a minimal set of missing credentials $\mathcal{C}_\mathcal{M} \subseteq \mathcal{C}_\mathcal{D}$ such that
  $\mathcal{P}_\mathcal{A} \cup \mathcal{C}_\mathcal{P} \cup \mathcal{C}_\mathcal{M} \models r$ and
  $\mathcal{P}_\mathcal{A} \cup \mathcal{C}_\mathcal{P} \cup \mathcal{C}_\mathcal{M} \not\models \bot$,
  (c) if $\mathcal{C}_\mathcal{M}$ exists then return ***ask($\mathcal{C}_\mathcal{M}$)*** and iterate,
  (d) else return ***deny***.

Fig. 4. Interactive access control algorithm.

Definition 3.6 (*Resource r Additive Policy*). A policy $\mathcal{P}$ is *a resource r additive* if for any two solution sets $\mathcal{C}_\mathcal{S}$ and $\mathcal{C}_\mathcal{S}'$ for r where $\mathcal{C}_\mathcal{S} \not\subset \mathcal{C}_\mathcal{S}'$ and $\mathcal{C}_\mathcal{S}' \not\subset \mathcal{C}_\mathcal{S}$, then $\mathcal{C}_\mathcal{S} \cup \mathcal{C}_\mathcal{S}'$ is also a solution set for r according to $\mathcal{P}$.

Definition 3.7 (*Resource r Subset Consistent Policy*). A policy $\mathcal{P}$ is a *resource r subset consistent* if for every solution set $\mathcal{C}_\mathcal{S}$ for r it holds that any $\mathcal{C} \subseteq \mathcal{C}_\mathcal{S}$ preserves consistency in $\mathcal{P}$, i.e. $\mathcal{P} \cup \mathcal{C} \not\models \bot$.

Definition 3.8 (*Well-behaved Policy*). A policy $\mathcal{P}$ is *well-behaved* if for all resources $r \in \mathcal{P}$

(i) $\mathcal{P}$ is *resource r additive* and
(ii) $\mathcal{P}$ is *resource r subset consistent*.

Section 6 shows how the interactive access control model guarantees completeness and correctness when applied on well-behaved policies.

4. INTERACTIVE ACCESS CONTROL ALGORITHM

We now summarize all the information we need to state the interactive access control algorithm, shown in Figure 4.

—$\mathcal{P}_\mathcal{A}$ a security policy governing access to resources,
—$\mathcal{P}_\mathcal{D}$ a security policy controlling the disclosure of foreign (missing) credentials,
—$\mathcal{C}_p$ a set of credentials presented by a client in a single interaction,
—$\mathcal{C}_\mathcal{P}$ a set of active credentials presented by a client during an interactive access control process,
—$\mathcal{C}_\mathcal{N}$ a set of credentials that a client has declined to present during an interactive process.

When a client initially requests a service, the server creates a client profile corresponding to a new session. The profile consists of $\mathcal{C}_\mathcal{P}$ and $\mathcal{C}_\mathcal{N}$ initially set

up as empty sets. A client requests a service by submitting a request r and a set of presented credentials $\mathcal{C}_p$. $\mathcal{C}_p$ is optional and could be an empty set.

Steps 1 and 2 update the client profile with newly presented credentials as follows. Active credentials $\mathcal{C}_\mathcal{P}$ are updated with $\mathcal{C}_p$. Declined credentials $\mathcal{C}_\mathcal{N}$ are updated with the missing credentials ($\mathcal{C}_\mathcal{M}$) the client was asked for in the last interaction set. $\mathcal{C}_\mathcal{M}$ is initially set up to an empty set.

Once the profile is updated, the algorithm checks whether the request, r, is granted by $\mathcal{P}_\mathcal{A}$ according to $\mathcal{C}_\mathcal{P}$ (step 3). If the client does not have enough access rights then the algorithm computes all credentials disclosable from $\mathcal{P}_\mathcal{D}$ according to $\mathcal{C}_\mathcal{P}$ and removes all already declined and presented credentials from the resulting set (step 4). The latter step is used to avoid dead loops, asking something already declined or presented.

Next, the algorithm computes all subsets of $\mathcal{C}_\mathcal{D}$ that are consistent with $\mathcal{P}_\mathcal{A}$ and satisfy r. Out of all these sets (if any) the algorithm selects the minimal one (step 4a) to be asked of a client.

Remark 4.1. Using declined credentials is essential to avoid dead loops in the process and to guarantee successful interactions in presence of disjunctive information.

We point out that minimality criteria play an important role in selecting a missing set of credentials when addressing the principle of least privilege [Saltzer and Schroeder 1975]. Set cardinality criterion does not fully apply mainly because credential sensitiveness plays the more important role than cardinality. The role minimality criterion is more adequate when dealing with role-based access control models. If we have attribute-based access control, one can associate values to attributes (e.g. level of sensitiveness) so that one can perform minimality reasoning on them. Additionally, one can accommodate sequences of criteria for filtering missing sets depending on particular access control requirements.

In cases of more than one equally minimal computed solution, the algorithm picks one as a solution to be asked of a client. However, one can slightly modify the algorithm so that it returns all equally minimal solutions as disjunctive information. Then, on the next iteration the declined credentials are computed as the union of all missing sets asked in the last iteration set different from the ones presented in the current step.

The interactive algorithm assumes stateless systems where access control depends only on policies, presented credentials, and the service request. In Koshutanski and Massacci [2005] we propose an extension of the framework that copes with stateful systems, especially with automated conflict detection and resolution. Stateful systems are systems where access decisions change depending on past interactions or past presented credentials. Such systems can become inconsistent with respect to a client's set of presented credentials mainly because access policies may forbid the presentation of a credential if other, currently active, credentials have been presented in the past. The extended model postulates that in the stateful system domain one needs to reason not only about missing credentials allowing access but also about what excess (conflicting) credentials make the policy state inconsistent.

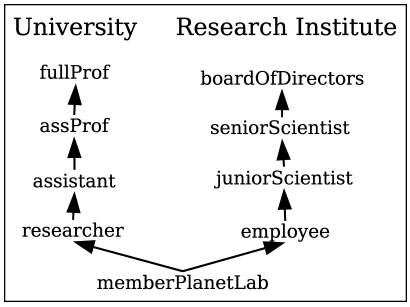


Fig. 5. Planet-Lab hierarchy model.

5. AN EXAMPLE SCENARIO

Let us consider a shared overlay network, Planet-Lab, between Italian universities and German research institutions. For the sake of simplicity assume that there are three main access types to resources: *disk*—read access to data residing on Planet-Lab machines; *run*—read access to data and run processes on the machines; and *conf*—configure access to data including the previous two types of access plus the possibility of configuring network services on machines.

Figure 5 shows the hierarchy and granularity of roles considered for universities and research institutions, respectively. The partial order of roles is indicated by arcs, where the higher the role in the hierarchy, the more powerful it is. A role dominates another role if it is higher in the hierarchy and there is a direct path between them.

The access policy of the Planet-Lab network specifies that:

—`disk` access is allowed to any role of the Planet-Lab hierarchy,

—`run` access is allowed to any employee or higher role at a German research institute, or to any researcher or higher role at an Italian university,

—`conf` access is allowed to junior scientists or higher role at a German research institute, or to any assistant or higher role at an Italian university.

There is a preprocessing step that validates and transforms certificates to predicates suitable for the formal model: credential (*HolderID*, *AttrName*, *IssuerID*) if attribute certificate; certificate (*SubjectID*, *IssuerID*) if identity certificate. There is a mapping from the trusted public keys of SOAs (Source of Authorities) or CAs (Certificate Authorities) to their internal policy identifiers represented by *IssuerID* value. Using a second predicate, IssuerType(*IssuerID*), one can classify which SOAs and CAs are considered trusted to issue particular types of attributes and identity certificates.

We represent variables starting with a capital letter (e.g. Holder, Attr, Issuer) while constants start with a lower case letter (e.g., planetLab_Class1SOA, accredited, juniorScientist). A variable indicates any value in its field and is valid within the rule it appears.

Figure 6 shows the formalization of Planet-Lab access and disclosure policies. Following is the functional explanation of the policies.

Access Policy:

(1) issuerPlanetLab ($planetLab\_Class1SOA$).
(2) issuerAccredInstDE ($deutschAkkred\_Class1SOA$).
(3) issuerAccredUnivIT ($crui\_class1SOA$).
(4) issuerUnivIT ($govitaliane\_class1CA$).
(5) issuerInstDE ($govdeutsch\_class1CA$).
(6) assign ($disk$) $\leftarrow$ credential ($Hol, memberPlanetLab, Iss$), issuerPlanetLab ($Iss$).
(7) assign ($disk$) $\leftarrow$ assign (run).
(8) assign (run) $\leftarrow$ credential ($Hol, Attr, Univ$), $Attr \succeq researcher$, certificate ($Univ, IssUniv$), issuerUnivIT ($IssUniv$), credential ($Univ, accredited, IssAcc$), issuerAccredUnivIT ($IssAcc$).
(9) assign (run) $\leftarrow$ credential ($Hol, Attr, Inst$), $Attr \succeq employee$, certificate ($Inst, IssInst$), issuerInstDE ($IssInst$), credential ($Inst, accredited, IssAcc$), issuerAccredInstDE ($IssAcc$).
(10) assign (run) $\leftarrow$ assign ($conf$).
(11) assign ($conf$) $\leftarrow$ credential ($Hol, Attr, Univ$), $Attr \succeq assistant$, certificate ($Univ, IssUniv$), issuerUnivIT ($IssUniv$), credential ($Univ, accredited, IssAcc$), issuerAccredUnivIT ($IssAcc$).
(12) assign ($conf$) $\leftarrow$ credential ($Hol, Attr, Inst$), $Attr \succeq juniorScientist$, certificate ($Inst, IssInst$), issuerInstDE ($IssInst$), credential ($Inst, accredited, IssAcc$), issuerAccredInstDE ($IssAcc$).

Disclosure Policy:

(1) credential ($Hol, memberPlanetLab, planetLab\_Class1SOA$).
(2) credential ($Hol, Attr, Inst$) $\leftarrow Attr \succeq employee$.
(3) credential ($Hol, Attr, Univ$) $\leftarrow Attr \succeq researcher$.
(4) certificate ($Univ, govitaliane\_class1CA$).
(5) certificate ($Inst, govdeutsch\_class1CA$).
(6) credential ($Univ, accredited, crui\_class1SOA$).
(7) credential ($Inst, accredited, deutschAkkred\_class1SOA$).

Fig. 6. Planet-Lab access and disclosure control policies.

Access policy:

—Rule (1) defines the trusted SOA issuing Planet-Lab membership certificates. Rule (2) defines the trusted SOA accrediting German research institutes and rule (3) defines the trusted SOA accrediting Italian universities. Rules (4) and (5) specify trusted CA certifying identities of Italian universities and German research institutions, respectively.

—Rule (6) grants `disk` access to the shared network to any entity (holder *Hol*) presented *memberPlanetLab* role credential issued by the trusted Planet-Lab SOA.

—Rule (7) grants `disk` access to anybody who has `run` access permission.

—Rule (8) grants `run` access to any holder of an attribute higher or equal to a researcher position issued by an Italian university. To validate an italian university, Planet-Lab policy requires two additional certificates: an identity certificate identifying the university entity as a legal key holder and an attribute certificate attesting the university entity as accredited Italian university. The former case is validated by the two predicates certificate (*Univ*, *IssUniv*) and issuerUnivIT(*IssUniv*), while the latter case by the two predicates credential (*Univ*, *accredited*, *IssAcc*) and issuerAccredUnivIT(*IssAcc*). Together all the predicates in the body of rule (8) validate an Italian university and implicitly delegate its right to state who has what position at the university.

—Rule (9) grants `run` access to any holder of a credential certificate with an attribute role higher than or equal to an employee position at any German research institute. Planet-Lab policy requires two additional certificates to validate a research institution: an identity certificate identifying the institution as a legal key holder and an attribute certificate attesting to the institution as being accredited.

—Rule (10) grants `run` access to anybody who has `conf` access permission.

—Rule (11) grants `conf` access to any holder of a credential with a position equal to or higher than assistant and issued by an Italian university. University validation follows analogously to rule (8).

—Rule (12) grants `conf` access to any holder of a credential certificate with a role higher than or equal to a junior scientist position issued by a German research institute. Institute validation follows analogously to rule (9).

Disclosure policy:

—Rule (1) discloses the need for a Planet-Lab membership credential and specifies the intended credential issuer. Rule (2) discloses the need for credentials attesting employee, junior scientist, senior scientist, and board of directors, respectively. Rule (3) discloses the need for credentials attesting roles-researcher, assistant, associate, and full professor, respectively.

—Rule (4) discloses the need for a certificate identifying Italian universities, and specifies the intended certificate issuer. Rule (5) discloses the need for a certificate identifying German research institutes, and specifies the intended certificate issuer.

—Rules (6) and (7) disclose the need for a credential certifying Italian universities as accredited institutions, and a credential certifying German institutions as accredited, respectively.

Access control scenario 1. Alice is a senior scientist at Fraunhofer institute in Berlin. She has been issued two certificates one for an employee at the research institute and another one attesting that she is a senior scientist, both issued by a Fraunhofer certificate authority.

Now, Alice wants to run a service located at the Planet-Lab network. For doing so she presents her employee certificate at access time

$$\mathsf{credential}\,(\mathit{alice\_milburk}, \mathit{employee}, \mathit{fraunhofer\_Inst\_Berlin})$$

presuming it is enough, as she knows that Planet-Lab is a joint network between German and Italian institutions.

According to the access policy (rule 9) any employee at a German research institute is allowed *run* access to the network but additionally they must present a certificate identifying Fraunhofer as a legal key holder and a certificate attesting Fraunhofer as a legal (accredited) German research institute.

Alice's credentials are not enough to get `run` access and the request would be denied. Then, the interactive algorithm (step 4a) computes the set of disclosable credentials as all credentials disclosed from rules (1) to (7) of the disclosure

policy to compare with Alice's presented credentials—the credential for an employee.

Next, abduction computation (subset minimal) finds the following missing set that satisfies the request:

{certificate (*Inst*, *govdeutsch_class1CA*),
credential (*Inst*, *accredited*, *deutschAkkred_class1SOA*)}

There is a post processing step that maps the internal policy identifiers of SOAs and CAs (like *govdeutsch_class1CA*) to their high-level descriptions that are to be returned back to the client.

Alice receives the missing set of credentials, then she consults the Fraunhofer authority that issued her employee certificate in order to obtain the missing credentials. Next interaction, she requests the service presenting the missing set of credentials and the system grants her access.

Access control scenario 2. Alice wants to configure an online system for paper submissions of a workshop. She submits her employee certificate together with the two certificates identifying Fraunhofer institute as a legitimate key holder and as an accredited institution. Formally, the initial set of credentials is:

{credential (*alice_milburk*, *employee*, *fraunhofer_Inst_Berlin*),
{certificate (*fraunhofer_Inst_Berlin*, *govdeutsch_class1CA*),
{credential (*fraunhofer_Inst_Berlin*, *accredited*, *deutschAkkred_class1SOA*)}.

Looking at the access policy rule (12), configure access is allowed to junior scientists or higher role positions. The algorithm computes the set of disclosable credentials and removes all that have been already presented by Alice. Next, abduction reasoning finds the following sets of missing credentials:

{credential (*Hol*, *juniorScientist*, *Inst*)}
{credential (*Hol*, *seniorScientist*, *Inst*)}
{credential (*Hol*, *boardOfDirectors*, *Inst*)}.

Now, using the role minimality criterion, the algorithm selects the set {credential(*Hol, juniorScientist, Inst*)} as the minimal one and returns it to the client.

Since Alice is a senior scientist she declines to present the requested credential and returns the access request but with no entry for presented credentials. The algorithm updates Alice's profile marking the requested credential as declined. The difference comes when the algorithm recomputes the disclosable credentials as all disclosable credentials from the disclosure policy set difference between Alice's presented and her declined credentials. Out of those, abduction finds the following missing sets:

{credential (*Hol*, *seniorScientist*, *Inst*)}
{credential (*Hol*, *boardOfDirectors*, *Inst*)}.

The algorithm selects the need for senior scientist and returns it to Alice. On the next interaction, Alice presents her senior scientist credential and gets the service request granted.

The interactive steps in access scenario 1 can be leveraged in two ways. First by using the credential chain discovery algorithm as a preprocessing step to

the interactive algorithm—discovering all relevant credentials before getting a decision. Second, by using a postprocessing step that returns to a client the need for credentials only relevant to the subject attributes and gathering the remaining credentials directly from predefined certificate authorities' public repositories. The latter case outlines potential work on extending the model to reason on automated credential discovery.

6. ACCESS CONTROL GUARANTEES

We define below the main guarantees the access control framework provides.

Definition 6.1 (*Soundness*). If a client is granted a service request then he has a solution for the request.

Definition 6.2 (*Completeness*). If a client has a solution for a service then he will be granted the service.

To prove the guarantees, we first look at the policies underlying our model and especially what would be reasonable access and disclosure policies that support these guarantees.

Definition 6.3 (*Fair Access*). Let $\mathcal{P}_\mathcal{A}$ be an access control policy and let $\mathcal{C}_{\mathcal{P}_\mathcal{A}}$ be the set of ground instances of all credentials occurring in $\mathcal{P}_\mathcal{A}$. The policy $\mathcal{P}_\mathcal{A}$ *guarantees fair access* if for any request r there exists a set $\mathcal{C}_\mathcal{S} \subseteq \mathcal{C}_{\mathcal{P}_\mathcal{A}}$ that is a solution for r.

Definition 6.4 (*Fair Interaction*). Let $\mathcal{P}_\mathcal{A}$ and $\mathcal{P}_\mathcal{D}$ be access and disclosure control policies, respectively. The policies *guarantee fair interaction* if

(1) $\mathcal{P}_\mathcal{A}$ guarantees fair access, and
(2) if $\mathcal{C}_\mathcal{S}$ is a solution for a request r, then $\mathcal{C}_\mathcal{S}$ is disclosable by $\mathcal{P}_\mathcal{D}$: $\forall c \in \mathcal{C}_\mathcal{S},\ \mathcal{P}_\mathcal{D} \models c$.

The intuition of fair interaction is that any solution for a request should be potentially visible to clients. The property essentially defines the conditions for granting services to clients. It does not imply that the service disclosure policy is trivial but rather defines the decision of successful start-up of any interaction process. The property is evident in all trust negotiation models: if there is a policy protecting a resource then the policy (and its meta-policy requirements) should be negotiated with an opponent in order to provide access. How the requirements are negotiated (disclosed) is a matter of concrete trust negotiation settings/strategies. In our case, on top of the property, one can protect a solution set by means of stepwise disclosure control (ref. Example 2.2).

The interactive algorithm itself provides a tool for validating the fair access and interaction properties. Indeed, one can set up the disclosable credentials to all credentials $\mathcal{C}_{\mathcal{P}_\mathcal{A}}$ and run the interactive algorithm for any resource $r \in \mathcal{P}_\mathcal{A}$ with no entry for initial credentials. If for all requests the algorithm returns $\texttt{ask}(\mathcal{C}_\mathcal{M})$, then the fair access property holds. If for some r it returns deny, then the property fails. For example the policy $\mathcal{P}_\mathcal{A} = \{r_0 \leftarrow C_A.\ r_1 \leftarrow r_0, C_B.\ r_2 \leftarrow r_1, \mathit{not}\ C_A.\}$ does not satisfy fair access.

If we modify the interactive algorithm to return all missing solutions (subset minimal, $\subseteq$-minimal) in one round then we can extend the validation to check the fair interaction property. Now, for each request r and for each $\mathcal{C}_\mathcal{M}$ returned, we again run the interactive algorithm, but just the section on deduction, on $\mathcal{P}_\mathcal{D}$ instead of $\mathcal{P}_\mathcal{A}$, and specify $\mathcal{C}_\mathcal{M}$ as a request. If for any resource in the access policy, any solution set is granted by the disclosure policy (thus disclosable by $\mathcal{P}_\mathcal{D}$) then access and disclosure policies satisfy fair interaction. One can also approach validation of well-behaved policies by properly employing abduction and deduction reasoning in an algorithm.

One would argue that if it is a fair interaction then why not simply request all credentials allowed by the disclosure policy instead of abducing missing ones. First, the disclosure policy controls the disclosure of all the resources' policies under a partner's domain and so we need to abduce only the relevant information (credentials). Second, by abducing the missing credentials we ensure that at any moment the missing set of credentials is an actual solution, that it is consistent with the access policy.

We make the following policy assumptions.

Remark 6.1 (*Policy Assumptions*). Hereinafter all $\mathcal{P}_\mathcal{A}$ are *well-behaved* policies and all $\mathcal{P}_\mathcal{D}$ are *monotonic* policies.

The well-behaved property ensures that if we have two solutions for a service we can add them and we will still get the service, and if we have a solution for a service, any subset of this solution is consistent with the policy. With the latter requirement we avoid situations where lack of information makes a policy inconsistent.

The set of well-behaved policies resides between monotonic and arbitrary policies.

PROPOSITION 6.1. *All monotonic policies are well-behaved but the converse is not true.*

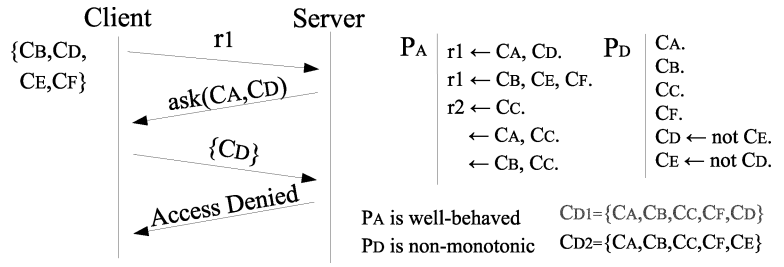
PROOF. In one direction the property is immediate (refer to Definition 3.5). For the other direction we show a counter-example:

$$\begin{aligned} r_1 &\leftarrow C_A. \\ r_1 &\leftarrow C_B. \\ r_2 &\leftarrow C_C. \\ &\leftarrow C_A, C_C. \\ &\leftarrow C_B, C_C. \end{aligned}$$

In our case, having $\{C_A, C_B, C_C\}$ bans the client from getting either of the services, which clearly shows that the example is a nonmonotonic policy. At the same time, for each of the services we have additive and consistent subset properties so that the policy is well-behaved. □

Monotonicity on $\mathcal{P}_\mathcal{D}$ ensures that if a solution is visible to a client then that solution should remain visible during interaction steps. Consider the following example.

Example 6.1 (*Nonmonotonic Disclosure*).



There are two sets of disclosable credentials and either of them contains a solution, set for r_1. If the interactive algorithm selects $\mathcal{C}_{D1}$ then the solution that abduction finds is $\{C_A, C_D\}$. On the next interaction step the client supplies C_D (as he does not have in possession C_A) and gets denial because the presence of C_D bans the disclosure of C_E and abduction cannot find any solution in the new set of disclosable credentials.

The prior example illustrates the necessity of a unique stable model of $\mathcal{P}_\mathcal{D}$ in order to guarantee the fair interaction property during all interactions within an access control session. We define syntactic restrictions on the $\mathcal{P}_\mathcal{D}$ structure to be a stratified logic program [Apt 1990].

Let us look at a client side and define what would be a reasonable client that our framework aims to provide the guarantees for.

Definition 6.5 (*Cooperative Client*). A client with a set of credentials (ability) $\mathcal{C}$ is a *cooperative client* if whenever he receives $\texttt{ask}(\mathcal{C}_\mathcal{M})$, he returns $\mathcal{C}_\mathcal{M} \cap \mathcal{C}$.

The definition captures the practical and intuitive aspect of client's behavior: A client who has the right set of credentials and who is willing to send them to a server will be granted access. We notice that it is fairly difficult to model and prove any results for noncooperative clients.

One can also model a cooperative client as a client who returns the need of $\mathcal{C}_\mathcal{M}$ if and only $\mathcal{C}_\mathcal{M} \subseteq \mathcal{C}$. In this case the server will keep track of any declined set $\mathcal{C}_\mathcal{M}$ during an interactive process and will mark them as constraints (constraint rules of credential combinations) over possible solution sets when performing abduction reasoning. Thus, the server will interact with the client until a $\mathcal{C}_\mathcal{M}$ is requested that matches the client's capability.

However, this level of cooperativeness results in a more expensive interaction process in terms of an increased number of interactions for successful agreement. One can extend the results in this article to also capture this type of cooperative client.

The work in Koshutanski and Massacci [2007] empowers cooperative clients with a negotiation model that allows them to negotiate with a server for additional requirements before presenting the own credentials. Thus, a client and a server become cooperative on that set of credentials on which they have mutually satisfiable requirements.

We assume that a client initiates a service request with an empty set of presented credentials. This assumption is important in order to avoid initial inconsistency and to ensure a successful first step.

The proofs of termination and completeness of the claims stated in the following are based on termination and completeness of the abduction reasoning. We refer the reader to Eiter et al. [1997]; Denecker and Schreye [1998]; and Verbaeten [1999] for a comprehensive analysis of the logic programming abduction problem, its computational complexity, completeness, and termination.

THEOREM 6.1 (SOUNDNESS). *Let $\mathcal{P}_\mathcal{A}$ be an access policy, $\mathcal{P}_\mathcal{D}$ be a disclosure policy, and r a request. If a client gets grant r with the access control algorithm then the client has a solution set $\mathcal{C}_\mathcal{S}$ that unlocks r according to $\mathcal{P}_\mathcal{A}$.*

PROOF. This proof is rather straightforward. The only way to introduce a credential in $\mathcal{C}_\mathcal{P}$ is by step 1 of the algorithm. Since initially $\mathcal{C}_\mathcal{P} = \emptyset$, the client has sent a sequence of sets of credentials $\mathcal{C}_{p_1}, \ldots, \mathcal{C}_{p_n}$ such that $\bigcup_{i=1}^{n} \mathcal{C}_{p_i} = \mathcal{C}_\mathcal{P}$, the client has a set of credentials that unlocks r. □

THEOREM 6.2 (TERMINATION). *The access control algorithm always terminates.*

PROOF. At each interaction the union of presented and declined credentials always increases. Because at each interaction abduction finds a different solution with respect to the preceding ones then the union sets always increase with new credentials occurring in the access policy.

Since the union set is bound by the credentials occurring in the policy then there is always a stage in which either grant (enough presented credentials) or deny (too many declined credentials) is given. □

THEOREM 6.3 (COMPLETENESS FOR A COOPERATIVE CLIENT). *Let $\mathcal{P}_\mathcal{A}$ be an access policy, $\mathcal{P}_\mathcal{D}$ be a disclosure policy, and r a request. If $\mathcal{P}_\mathcal{A}$ and $\mathcal{P}_\mathcal{D}$ guarantee fair access and interaction then if a cooperative client has a set of credentials $\mathcal{C}_\mathcal{S}$ that is a solution for r according to $\mathcal{P}_\mathcal{A}$ then the client always gets grant r with the access control algorithm.*

PROOF. Refer to the appendix. □

7. IMPLEMENTING THE ACCESS CONTROL FRAMEWORK: IACCESS SYSTEM

This section describes an implementation of the access control framework called iAccess.

7.1 Use of Answer Set Programming Solvers (ASP)

With the increase of computational power over the last decade, ASP solvers have become very efficient tools[4] that can compute results with several thousands of

[4]See benchmarks of ASP solvers http://asparagus.cs.uni-potsdam.de

atoms and rules. It makes them suitable for access control engines especially when scaling to hundreds of access rules, constraints, and user roles and tasks.

We use the DLV[5] system [Leone et al. 2006] as a back-end engine for the basic computations of deduction and abduction. DLV is a disjunctive datalog system with negations and constraints under the stable model semantics. DLV provides front-ends facilitating different computations.The two front-ends relevant to our purposes are the disjunctive datalog (the default) used for deductive computations and the diagnosis front-end used for abductive computations.

We use DLV's default front-end to check if a request, marked as a query, is granted by the access policy and presented credentials: if the request is true or false in all stable models of the policy union of the presented credentials. Alternatively, we use the default front-end with an input being a disclosure policy union of a set of presented credentials, in order to compute all disclosable credentials.

We use the diagnosis front-end with input: a service request stored in a file with extension *.obs*, a set of disclosable credentials stored in a file with extension *.hyp*, and the third argument, an access policy union, a set of presented credentials. The file with extension .hyp points to a set of hypotheses and with .obs points to a set of observations. The DLV output of that step are all subsets (subset minimal) of the hypotheses that satisfy the observations.

7.2 Integration with X.509 Standard

We adopted the X.509 [X.509 2005] certificate standard for attesting participants' identities and attributes. There are two certificate types considered by the standard: identity and attribute certificates. An X.509 identity certificate is used to identify entities in a network. The main fields of the certificate's structure are the subject information, the public key identifying the subject (corresponding to the subject's private key), the issuer information, and the digital signature on the document, signed by the issuer with its private key. The X.509 attribute certificate has the same structure as the identity certificate with the difference being that instead of a public key field there is a field for listing attributes and the subject field is called holder (of the attributes).

As noted in Section 5, we need a way to semantically convert X.509 certificates to internal policy-compliant representation. We adopted the following transformations:

—An identity certificate to `certificate`(subject, `Issuer`: `i`) predicate identifying entity subject stated by authority `i`.

—An attribute certificate to `credential`(holder, `Attr`: a, `Issuer`: i) predicate attesting that the holder has an attribute `a` issued by authority `i`.

The logical model has the following two sets of predefined identifiers regarding credential transformations: `Attr` for attribute identifiers and `Issuer` for certificate authority identifiers. We developed a semantic conversion module

[5]www.dlvsystem.com

that has a predefined database specifying certificate to credential conversions including transformations between public keys of trusted CAs and SOAs and their logical identifiers, as well as transformations between attribute values and their logical representation.

The semantic conversion module also has the responsibility to properly convert internal credential values to values compliant with the external domain a request comes from.

7.3 Integration with SAML Standard

We have adopted the OASIS SAML[6] standard for having standard semantics of authorization statements among participants in an autonomic network. SAML offers a standard way of exchanging authentication and authorization information among online partners. The basic SAML data objects are assertions. Assertions contain information that determines whether users can be authenticated or authorized to use resources. The SAML framework also defines a protocol for requesting assertions and responding to them, which makes it suitable when modeling interactive communications among entities in a distributed environment.

A client uses a SAML Authorization Decision Query statement to specify a resource name, and a resource action when requesting a service. Once a SAML request is received iAccess extracts the Authorization Decision Query and invokes the semantic conversion module for transforming it to a predicate of the logical model. We have adopted the transformation Authorization Decision Query to `grant(Resource`: r, `Action`: p) where `Resource` and `Action` are predefined sets of identifiers considered in the logical model.

Once an access decision is taken, iAccess generates a SAML response part incapsulating a SAML Authorization Decision assertion. The authorization decision assertion has three types of decision values: permit, deny, and indeterminate.

—Permit or Deny decision is used when the access control algorithm explicitly returns grant or deny.

—Indeterminate decision is used when `ask(`$\mathcal{C}_{\mathcal{M}}$`)` is returned.

iAccess uses the SAML standard attribute assertions to list the set of missing credentials. For each certificate (subject, issuer), the semantic conversion module generates a SAML assertion with an authentication statement detailing subject and issuer fields. In the case of a credential (holder, attribute, issuer), the semantic conversion module generates a SAML assertion with an attribute statement.

7.4 iAccess Architecture

To make the access decision engine Web Services compatible we also adopted W3C SOAP[7] as a main transport layer protocol. SOAP is a lightweight protocol

[6]http://www.oasis-open.org/committees/security

[7]http://www.w3.org/TR/soap

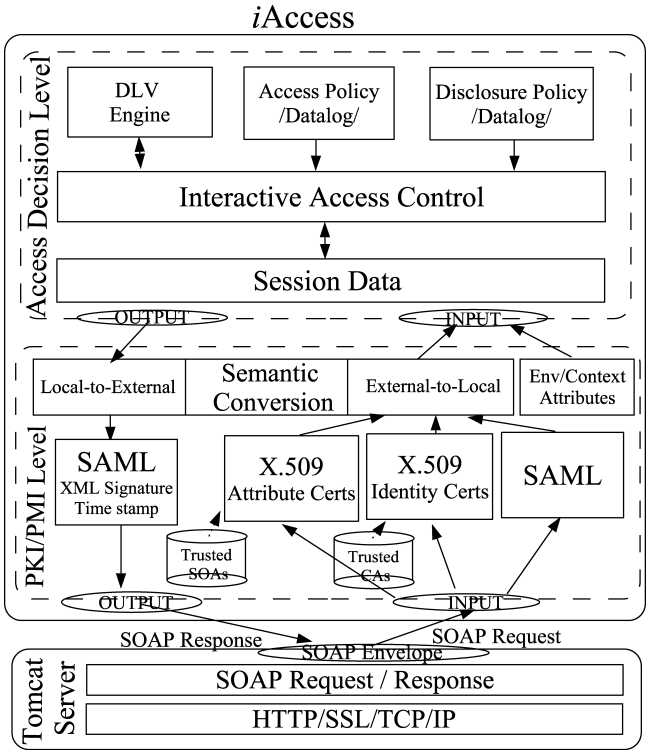


Fig. 7. *i*Access architecture.

for exchanging structured information in a distributed environment. It has an optional Header element and a required Body element. Informally, in the body we specify what information is directly associated with the service request and in the header additional information that should be considered by the end point server.

To request an access decision on a message level one has to:

(1) Place a SAML Request in the SOAP Body thus making it an input to the decision engine being invoked, and
(2) attach X.509 Certificates in the SOAP Header using a WS-Security[8] specification for that.

Figure 7 shows iAccess system architecture. The bottommost layer comprises the integration of the prototype with the Tomcat[9] application server. To ensure message confidentiality on the transport layer, one can perform all interactions over an SSL connection.

When the Tomcat server receives an access request it invokes the iAccess engine for an access decision. iAccess parses the SOAP envelope, containing

[8]http://www.oasis-open.org/committees/wss
[9]http://tomcat.apache.org

the body and the header elements, and extracts X.509[10] certificates and the SAML[11] authorization query.

Next, iAccess validates and verifies the certificates and invokes the semantic conversion module. The verification against trusted CAs and SOAs is to internally identify those authorities that are known and trusted by a server. Authorities unknown to a server are internally represented according to some default criteria, for example, by using authorities' common name (CN) of the X.500 structure.

We note that the semantic conversion database is dynamically allocated and loaded depending on the domain the request comes from.

Once an access decision is taken iAccess invokes the conversion module for transforming grant, deny, or additional credentials onto a SAML decision assertion that is then wrapped in a SAML Response. Next, iAccess places a time-stamp for a validity period on the decision statement and digitally signs it to ensure the integrity of the information. The Tomcat server returns the SAML decision to the entity requesting it. When the SAML assertion is received it becomes an authorization certificate that is to be presented to an application enforcement module for providing access to a resource.

The Envr/Context module provides the environment and context attributes that access and disclosure policies are sensitive against (e.g. system time, state, network endpoint address etc).

8. IACCESS PERFORMANCE EVALUATION

We will present iAccess time response evaluation in three parts: PKI/PMI, access decision, and total time response. PKI/PMI covers the extraction of X.509 certificates and SAML request, certificate validation and verification, and logical predicates transformation. The second part corresponds to the actual interactive access control algorithm functionality. The overall time response includes the time response of PKI/PMI, access decision, and the time response of the conversion module for generating a digitally signed SAML response element containing the access decision.

We run the iAccess system on the access control policies described in Section 5. All the tests have been run on a PC with Windows XP, Intel Pentium 4 processor on 2 Ghz and 512 Mb of RAM.

Figure 8 shows the first set of trials. The performance has been measured in milliseconds and rounded to seconds when displayed on the diagram. We have invoked iAccess server 11 times with a different number of X.509 certificates. For that purpose, we generated X.509 attribute certificates with roles, fraunhofer *employee01* to fraunhofer *employee97*. Each trial has been done with increase of 10 certificates and the last one with as input of 100 certificates.

Each trial had of an input, the three certificates: Alice Milburk employee, Fraunhofer identity certificate, and Fraunhofer accredited institution; and the remaining certificates from the newly generated ones: the first trial with 2 of the new certificates, second with 7, third with 17 and so on, and the last one with

[10]X.509 technology provider: http://www.bouncycastle.org
[11]SAML technology provider: http://www.opensaml.org

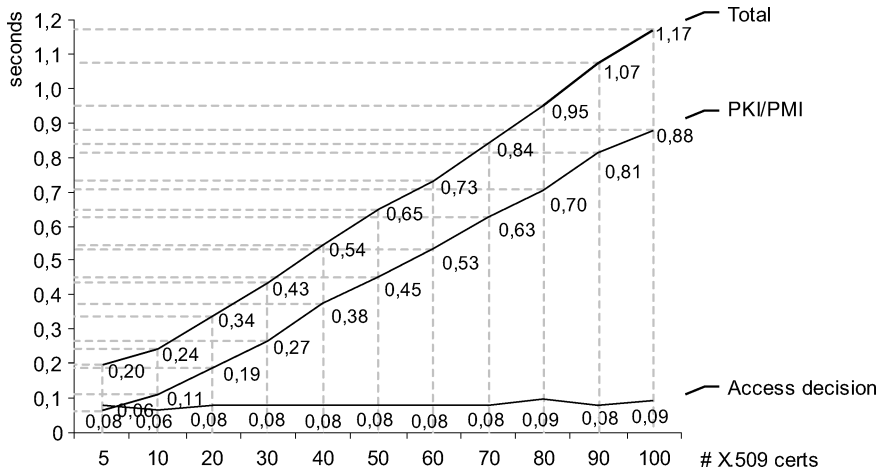


Fig. 8. iAccess performance with increased input of X.509 certificates.

97. Each trial specified access request for *conf* permission so that the system had to compute a set of missing credentials (in our case *juniorScientist*) for every request, thus obtaining the maximum system load.

The positive outcome of the first set of trials is that even with 100 certificates, the iAccess system response time to make a decision is around 1 second. We conclude that the number of certificates and their respective cryptographic operations are not a bottleneck for an iAccess timely decision. The generation of a digitally signed SAML response remained within the range of 70–150 milliseconds for all of the trials.

However, what we observed was that the access decision time remained less than 100 milliseconds for all 11 trials while only the PKI/PMI portion increased with the increased number of certificates. So, the total time response has been influenced mainly by the PKI/PMI portion.

The explanation for that is the way the access decision algorithm functions. If there are not enough access rights the algorithm computes the set of disclosable credentials and then invokes the abduction reasoning with the input being the set of credentials marked as hypotheses. If we look at the disclosure policy (Figure 6), we immediately find out that whatever credentials we input, the disclosure policy releases only the nine roles we have in the hierarchy and the four certificates of trusted CAs and SOAs. Thus with the increased number of clients' certificates, the number of hypotheses input to the abduction engine remained unchanged—10 facts—and the DLV engine took the same time to compute a set of missing credentials. Remember that we remove all presented credentials from the disclosable credentials, in our case the three certificates for an employee, legal key holder, and accredited organization.

Figure 9 shows the second set of trials but this time with an increased number of hypotheses in each trial. We modified the disclosure policy by adding new rules, such that for each presented credential in the range *employee01* to *employee97* the policy discloses a new credential *juniorScientist01* to *juniorScientist97*, respectively. Additionally, we specified that each *juniorScientistXX*

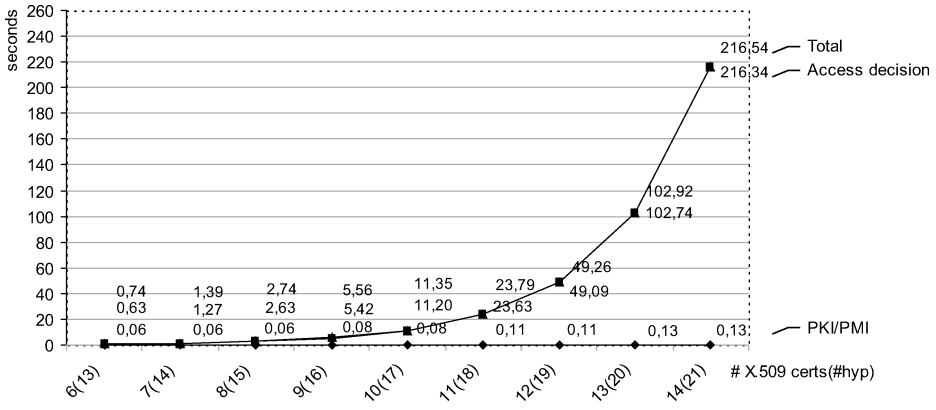


Fig. 9. iAccess performance with an increased number of hypotheses.

dominates the basic role *juniorScientist*. In this way by increasing the number of input certificates we increase the number of hypotheses to the abduction engine.

We have done nine trials, but this time starting with six certificates and increasing with one on each trial. On the horizontal axis we denote the number of input certificates, and in brackets the number of hypotheses, fed to the abduction engine. With 13 hypotheses the access decision time is 630 milliseconds and with 21 hypotheses the time response is approximately $3^1/_2$ minutes. The algorithm performance becomes very sensitive above 13 hypotheses. The PKI/PMI portion remains imperceptible with respect to the access decision time.

The conclusion from the second set of trials is that the number of disclosable credentials forms a critically important factor when designing access and disclosure policies. To mitigate the exponential time growth, one could define (split $\mathcal{P}_\mathcal{D}$ to) a single disclosure policy per resource (or per group of resources) so that the system dynamically loads the relevant policy on request.

The main factor for the potential number of rounds needed to grant a service is the complexity of the access policy and particularly how many possible solutions exist for a service. Another possibility to increase system performance is to enable the server side to cache some client details for subsequent requests.

An interesting idea in Bertino et al. [2004], that could be well used in our setting, is the use of trust tickets. A trust ticket keeps information on recent successful negotiations (interactions) of credential exchange for a given resource. Thus, if a trust ticket is initially introduced (during an introductory phase) for the same resource, then the access process can be speeded up by omitting interactions on those requirements indicated in the trust ticket.

9. CONCLUSIONS

We have proposed a framework for access control for autonomic communication. The key idea is that in an autonomic network a client may have the right set of credentials but may not know it so an autonomic server needs a way to interact and communicate with the client who is missing credentials that grant access.

We have proposed a solution to this problem by extending classical policy-based access control models with an advanced reasoning service: abduction. Built on top of it, we have presented the interactive access control algorithm that computes, on the fly, missing credentials that entail a request.

We enriched the framework over the existing policy-based approaches for access control by introducing the difference between monotonic and well-behaved policies. The distinction extends our work on a wider set of policy languages with respect to the already existing approaches. We have shown that the access control framework is sound and correct. We have presented an implementation of the model and its performance evaluation.

A prerequisite for adoption of the model is the definition of high-level tools for policy specification and automated translation to their formal representation. We refer the reader to ASP RuleML[12] for an approach to adapt RuleML[13] language to express answer-set programs and their automated transformation to/from logic programs.

A complimentary direction to policy specification is the definition of tools for policy analysis. As we have seen, deduction and abduction could be successfully employed as core services for policy analysis. Just recently, abductive techniques have been considered for analyzing authorization policies [Becker and Nanz 2008].

Future work includes the extension of the interactive model to cope with automated credential discovery. The aim is to leverage the interactive process and reduce the number of credentials requested from a client. Another direction of research is what guarantees the interactive framework offers in terms of interoperability when applied to existing negotiation systems such as TrustBuilder [Winslett et al. 2002], Trust-X [Bertino et al. 2004], or PeerTrust [Nejdl et al. 2004].

APPENDIX

APPENDIX (FORMAL PROOFS)

PROOF THEOREM 6.3. We prove the theorem in two parts. The first part proves that in a single interaction, if a cooperative client does not get grant r, he gets $\texttt{ask}(\mathcal{C}_{\mathcal{M}})$: a cooperative client will not be denied access by the algorithm. Second part (rather straightforward) shows that since the access policy is finite, then a cooperative client with a solution set for r will get grant r.

Part 1. Proof by induction on interaction steps:

Interaction 1. Client requests service r together with an initial set of presented credentials $\mathcal{C}_p = \emptyset$. Fair access and interaction properties guarantee that: (1) a solution for r exists according to the access policy $\mathcal{P}_{\mathcal{A}}$, and (2) that the solution is disclosable by the disclosure policy $\mathcal{P}_{\mathcal{D}}$. Therefore, abduction reasoning finds a solution for r and the algorithm returns it to the client.

[12]http://www.kr.tuwien.ac.at/staff/roman/aspruleml
[13]http://www.ruleml.org

Interaction N. Here we use the induction hypothesis that the client fails to get grant r and gets $\texttt{ask}(\mathcal{C}_\mathcal{M})$ at interaction step N-1. Now, suppose that the client fails to get grant r at interaction N. There are two reasons to fail: either there is no solution in the set of active credentials, $\mathcal{C}_\mathcal{P}$, that unlocks the request, or $\mathcal{C}_\mathcal{P}$ makes the access policy state inconsistent so that no solution set in $\mathcal{C}_\mathcal{P}$ entails the request.

The set of active credentials, $\mathcal{C}_\mathcal{P}$, increases only with credentials that are part of other solutions for r: $\mathcal{C}_\mathcal{P} \subset (\mathcal{C}^1_\mathcal{M} \cup \ldots \cup \mathcal{C}^{N-1}_\mathcal{M})$, where $\mathcal{C}^i_\mathcal{M}$ denotes the set of missing credentials returned at each interaction preceding the current one. Here we use the assumption that access policy $\mathcal{P}_\mathcal{A}$ is *well-behaved*. According to Definitions 3.8, 3.7 and 3.6 it follows that $\mathcal{C}_\mathcal{P}$ is a subset of a solution set for r (using the additive property) and is consistent with the access policy.

Therefore, $\mathcal{C}_\mathcal{P}$ preserves consistency in $\mathcal{P}_\mathcal{A}$ and the only reason the client fails to get the grant is that there is no solution for r in $\mathcal{C}_\mathcal{P}$.

In step 3 the algorithm computes the set of disclosable credentials, $\mathcal{C}_\mathcal{D}$. Since $\mathcal{P}_\mathcal{A}$ and $\mathcal{P}_\mathcal{D}$ guarantee fair access and interaction, then the solution set, $\mathcal{C}_\mathcal{S}$, that the client has, is disclosable—$\mathcal{C}_\mathcal{S} \subseteq (\mathcal{C}_\mathcal{D} \cup \mathcal{C}_\mathcal{P})$—and not yet presented—$\mathcal{C}_\mathcal{S} \not\subseteq \mathcal{C}_\mathcal{P}$.

Following that, the abduction reasoning will find a solution for r in step 4b and that solution is guaranteed by the existence of the nonempty set $\mathcal{C}_\mathcal{S} \setminus \mathcal{C}_\mathcal{P}$ justified by:

(i) $(\mathcal{C}_\mathcal{S} \setminus \mathcal{C}_\mathcal{P}) \subseteq \mathcal{C}_\mathcal{D}$ and
(ii) $(\mathcal{C}_\mathcal{S} \cup \mathcal{C}_\mathcal{P}) \subset (\mathcal{C}^1_\mathcal{M} \cup \ldots \cup \mathcal{C}^{N-1}_\mathcal{M} \cup \mathcal{C}_\mathcal{S})$.

Since $\mathcal{P}_\mathcal{A}$ is well-behaved it follows that $\mathcal{C}_\mathcal{S} \cup \mathcal{C}_\mathcal{P}$ does not make $\mathcal{P}_\mathcal{A}$ inconsistent: $\mathcal{P}_\mathcal{A} \cup \mathcal{C}_\mathcal{P} \cup \mathcal{C}_\mathcal{S} \not\models \bot$, and the client gets $\texttt{ask}(\mathcal{C}_\mathcal{M})$ at interaction step N.

Part 2. We proved in Part 1 that in a single interaction step, if a cooperative client does not get grant r he gets $\texttt{ask}(\mathcal{C}_\mathcal{M})$.

There are a finite number of solutions for each request r simply because $\mathcal{P}_\mathcal{A}$ consists of a finite number of access rules. The abduction reasoning service at each interaction computes different solutions with respect to the solutions computed in previous interactions because we remove all credentials that have been already requested to a client from the disclosable credentials (ref. step 4a).

Since there are finite solution sets for r, and since the client has one of them, therefore the client, in a finite number of interaction steps, will be asked to present $\mathcal{C}_\mathcal{S}$, $(\mathcal{C}_\mathcal{S} \subseteq \mathcal{C}_\mathcal{P})$, and will get grant r. □

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