
Recent Advances in Access Control

S. De Capitani di Vimercati, S. Foresti, and P. Samarati

Dipartimento di Tecnologie dell'Informazione
Università degli Studi di Milano
26013 Crema, Italy
`{decapita,foresti,samarati}@dti.unimi.it`

Summary. Access control is the process of mediating every request to resources and data maintained by a system and determining whether the request should be granted or denied. Traditional access control models and languages result limiting for emerging scenarios, whose open and dynamic nature requires the development of new ways of enforcing access control. Access control is then evolving with the complex open environments that it supports, where the decision to grant an access may depend on the properties (attributes) of the requestor rather than her identity and where the access control restrictions to be enforced may come from different authorities. These issues pose several new challenges to the design and implementation of access control systems. In this chapter, we present the emerging trends in the access control field to address the new needs and desiderata of today's systems.

1 Introduction

Information plays an important role in any organization and its protection against unauthorized disclosure (*secrecy*) and unauthorized or improper modifications (*integrity*), while ensuring its availability to legitimate users (*no denials-of-service*) is becoming of paramount importance. An important service in guaranteeing information protection is the *access control* service. Access control is the process of mediating every request to resources and data maintained by a system and determining whether the request should be granted or denied. An access control system can be considered at three different abstractions of control: access control *policy*, access control *model*, and access control *mechanism*. A policy defines the high level rules used to verify whether an access request is to be granted or denied. A policy is then formalized through a *security model* and is enforced by an access control *mechanism*. The separation between policies and mechanisms has a number of advantages. First, it is possible to discuss protection requirements independently of their implementation. Second, it is possible to compare different access control policies as well as different mechanisms that enforce the same policy. Third, it is possible to design access control mechanisms able to enforce multiple policies.

In this way, a change in the access control policy does not require any changes in the mechanism. Also, the separation between model and mechanism makes it possible to formally prove security properties on the model; any mechanism that correctly enforces the model will then enjoy the same security properties proved for the model.

The variety and complexity of the protection requirements that may need to be imposed in today's systems makes the definition of access control policies a far from trivial process. An access control system should be simple and expressive. It should be simple to make easy the management task of specifying and maintaining the security specifications. It should be expressive to make it possible to specify in a flexible way different protection requirements that may need to be imposed on different resources and data. Moreover, an access control system should include support for the following features.

- *Policy combination.* Since information may not be under the control of a single authority, access control policies information may take into consideration the protection requirements of the owner, but also the requirements of the collector and of other parties. These multiple authorities scenario should be supported from the administration point of view providing solutions for modular, large-scale, scalable policy composition and interaction.
- *Anonymity.* Many services do not need to know the real identity of a user. It is then necessary to make access control decisions dependent on the requester's *attributes*, which are usually proved by *digital certificates*.
- *Data outsourcing.* A recent trend in the information technology area is represented by data outsourcing, according to which companies shifted from fully local management to outsourcing the administration of their data by using externally service providers [1, 2, 3]. Here, an interesting research challenge consists in developing an efficient mechanism for implementing selective access to the remote data.

These features pose several new challenges to the design and implementation of access control systems. In this chapter, we present the emerging trends in the access control field to address the new needs and desiderata of today's systems. The remainder of the chapter is organized as follows. Section 2 briefly discusses some basic concepts about access control, showing the main characteristics of the discretionary, mandatory, and role-based access control policies along with their advantages and disadvantages. Section 3 introduces the problem of enforcing access control in open environments. After a brief overview of the issues that need to be addressed, we describe some proposals for trust negotiation and for regulating service access. Section 4 addresses the problem of combining access control policies that may be independently stated. We first describe the main features that a policy composition framework should have and then illustrate some current solutions. Section 5 presents the main approaches for enforcing selective access in an outsourced scenario. Finally, Sect. 6 concludes the chapter.

	Document1	Document2	Program1	Program2
Ann	read, write	read	execute	
Bob	read	read	read, execute	
Carol		read, write		read, execute
David			read, write, execute	read, write, execute

Fig. 1. An example of access matrix

2 Classical Access Control Models

Classical access control models can be grouped into three main classes: *discretionary access control* (DAC), which bases access decisions on users' identity; *mandatory access control* (MAC), which bases access decisions on mandated regulations defined by a central authority; and *role-based access control* (RBAC), which bases access decisions on the roles played by users in the models. We now briefly present the main characteristics of these classical access control models.

2.1 Discretionary Access Control

Discretionary access control is based on the identity of the user requesting access and on a set of rules, called *authorizations*, explicitly stating which user can perform which action on which resource. In the most basic form, an authorization is a triple (s, o, a) , stating that user s can execute action a on object o . The first discretionary access control model proposed in the literature is the *access matrix model* [4, 5, 6]. Let S , O , and A be a set of subjects, objects, and actions, respectively. The access matrix model represents the set of authorizations through a $|S| \times |O|$ matrix \mathcal{A} . Each entry $\mathcal{A}[s, o]$ contains the list of actions that subject s can execute over object o . Figure 1 illustrates an example of access matrix where, for example, user **Ann** can **read** and **write** **Document1**.

The access matrix model can be implemented through different mechanisms. The straightforward solution exploiting a two-dimensional array is not viable, since \mathcal{A} is usually sparse. The mechanisms typically adopted are:

- *Authorization table*. The non empty entries of \mathcal{A} are stored in a table with three attributes: **user**, **action**, and **object**.
- *Access control list (ACL)*. The access matrix is stored by column, that is, each object is associated with a list of subjects together with a set of actions they can perform on the object.
- *Capability*. The access matrix is stored by row, that is, each subject is associated with a list indicating, for each object, the set of actions the subject can perform on it.

Figure 2 depicts the authorization table, access control lists, and capability lists corresponding to the access matrix of Fig. 1.

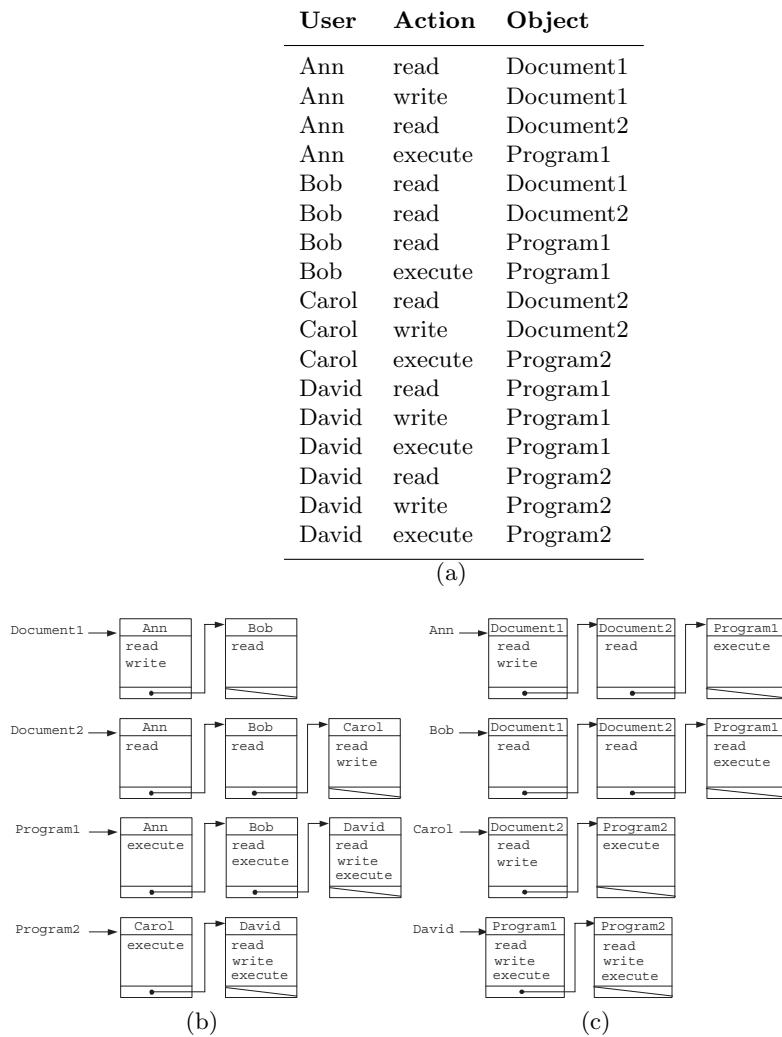


Fig. 2. Access matrix implementation mechanisms

From the access matrix model, discretionary access control systems have evolved and they include support for the following features.

- *Conditions.* To make authorization validity depend on the satisfaction of some specific constraints, today's access control systems typically support conditions associated with authorizations. [5]. For instance, conditions impose restrictions on the basis of: object content (content-dependent conditions), system predicates (system-dependent conditions), or accesses previously executed (history-dependent conditions).

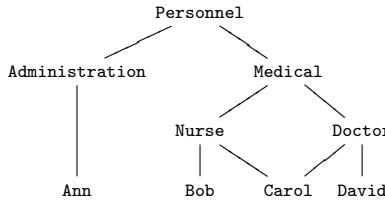


Fig. 3. An example of user-group hierarchy

- *Abstractions.* To simplify the authorization definition process, discretionary access control supports also *user groups* and *classes of objects*, which may also be hierarchically organized. Typically, authorizations specified on an abstraction propagate to all its members according to different *propagation policies* [7]. Figure 3 illustrates an example of user-group hierarchy. Here, for example, an authorization specified for the **Nurse** group applies also to **Bob** and **Carol**.
- *Exceptions.* The definition of abstractions naturally leads to the need of supporting exceptions in authorization definition. Suppose, for example, that all users belonging to a group but u can access resource r . If exceptions were not supported, it would be necessary to associate an authorization with each user in the group but u , therefore not exploiting the possibility of specifying the authorization of the group. This situation can be easily solved by supporting both *positive* and *negative* authorizations: the system would have a positive authorization for the group and a negative authorization for u .

The introduction of both positive and negative authorizations brings to two problems: *inconsistency*, when conflicting authorizations are associated with the same element in a hierarchy; and *incompleteness*, when some accesses are neither authorized nor denied.

Incompleteness is usually easily solved by assuming a *default policy*, open or closed (this latter being more common), where no authorization applies. In this case, an open policy approach allows the access, while the closed policy approach denies it.

To solve the inconsistency problem, different *conflict resolution policies* have been proposed [7, 8], such as:

- *No conflict.* The presence of a conflict is considered an error.
- *Denials take precedence.* Negative authorizations take precedence.
- *Permissions take precedence.* Positive authorizations take precedence.
- *Nothing takes precedence.* Conflicts remain unsolved.
- *Most specific takes precedence.* An authorization associated with an element n overrides a contradicting authorization (i.e., an authorization with the same subject, object, and action but with a different sign) associated with an ancestor of n for all the descendants of n . For instance, consider the user-group hierarchy in Fig. 3 and the autho-

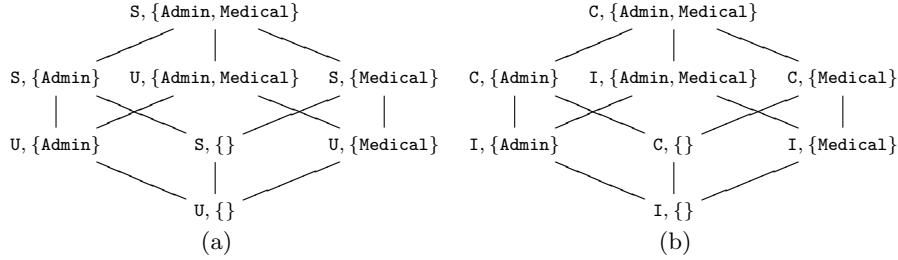


Fig. 4. An example of security (a) and integrity (b) lattices

rizations (`Medical,Document1,+r`) and (`Nurse,Document1,-r`). Carol cannot read `Document1`, since the `Nurse` group is more specific than the `Medical` group.

- *Most specific along a path takes precedence.* An authorization associated with an element n overrides a contradicting authorization associated with an ancestor n' for all the descendants of n , only for the paths passing from n . The overriding has no effect on other paths. For instance, with respect to the previous example, Carol gains a positive authorization from the path `(Medical,Doctor,Carol)`, and a negative one from path `(Nurse,Carol)`.

While convenient for their expressiveness and flexibility, in high security settings discretionary access control results limited for its vulnerability to *Trojan horses*. The reason for this vulnerability is that discretionary access control does not distinguish between *users* (i.e., human entity whose identity is exploited to select the privileges for making the access control decision) and *subjects* (i.e., process generated by a user and that makes requests to the system). A discretionary access control system evaluates the requests made by a subject against the authorizations of the user who generated the corresponding process. It is then vulnerable from processes executing malicious programs that exploit the authorizations of the user invoking them. Protection against these processes requires controlling the flows of information within processes execution and possibly restricting them. Mandatory policies provide a way to enforce information flow control through the use of labels.

2.2 Mandatory Access Control

Mandatory security policies enforce access control on the basis of regulations mandated by a central authority. The most common form of mandatory policy is the *multilevel security policy*, based on the classifications of subjects and objects in the system. Each subject and object in the system is associated with an *access class*, usually composed of a *security level* and a set of *categories*. Security levels in the system are characterized by a total order relation, while

categories form an unordered set. As a consequence, the set of access classes is characterized by a partial order relation, denoted \geq and called *dominance*. Given two access classes c_1 and c_2 , c_1 *dominates* c_2 , denoted $c_1 \geq c_2$, iff the security level of c_1 is greater than or equal to the security level of c_2 and the set of categories of c_1 includes the set of categories of c_2 . Access classes together with their partial order dominance relationship form a *lattice* [9].

Mandatory policies can be classified as secrecy-based and integrity-based, operating in a dual manner.

Secrecy-Based Mandatory Policy [10, 11, 12, 13]. The main goal of secrecy-based mandatory policies is to protect data confidentiality. As a consequence, the security level of the access class associated with an object reflects the sensitivity of its content, while the security level of the access class associated with a subject, called *clearance*, reflects the degree of trust placed in the subject not to reveal sensitive information. The set of categories associated with both subjects and objects defines the area of competence of users and data. A user can connect to the system using her clearance or any access class dominated by her clearance. A process generated by a user connected with a specific access class has the same access class as the user.

The access requests submitted by a subject are evaluated by applying the following two principles.

No-Read-Up. A subject s can read an object o if and only if the access class of the subject dominates the access class of the object.

No-Write-Down. A subject s can write an object o if and only if the access class of the object dominates the access class of the subject.

Consider, as an example, the security lattice in Fig. 4(a), where there are two security levels, **Secret** (S) and **Unclassified** (U), with $S > U$, and the set of categories {Admin, Medical}. Suppose that user **Ann** has clearance $\langle S, \{\text{Admin}\} \rangle$ and she connects to the system as the $\langle S, \{\} \rangle$ subject. She is allowed to read objects $\langle S, \{\} \rangle$ and $\langle U, \{\} \rangle$. She can write objects with access class $\langle S, \{\} \rangle$, $\langle S, \{\text{Admin}\} \rangle$, $\langle S, \{\text{Medical}\} \rangle$, and $\langle S, \{\text{Admin, Medical}\} \rangle$.

Note that a user is allowed to connect to the system at different access classes to the aim of accessing information at different levels (provided that she is cleared for it). Otherwise, these accesses would be blocked by the no-write-down principle.

The principles of the secrecy-based mandatory policy prevent information flows from high level subjects/objects to subjects/objects at lower (or incomparable) levels, thus preserving information confidentiality. However, these two principles may turn out to be too restrictive. For instance, in a real scenario data may need to be downgraded (e.g., this may happen at the end of the embargo). To consider also these situations, the secrecy-based mandatory models can allow exceptions for processes that are *trusted* and ensure that the information produced is *sanitized*.

Integrity-Based Mandatory Policy [14]. The main goal of integrity-based mandatory policies is to prevent subjects from *indirectly* modifying information they cannot write. The integrity level associated with a user reflects the degree of trust placed in the subject to insert and modify sensitive information. The integrity level associated with an object indicates the degree of trust placed on the information stored in the object and the potential damage that could result from unauthorized modifications of the information. Again, the set of categories associated with both subjects and objects defines the area of competence of users and data.

The access requests submitted by a subject are evaluated by applying the following two principles.

No-Read-Down. A subject s can read an object o if and only if the integrity class of the object dominates the integrity class of the subject.

No-Write-Up. A subject s can write an object o if and only if the integrity class of the subject dominates the integrity class of the object.

Consider, as an example, the integrity lattice in Fig. 4(b), where there are two integrity levels **Crucial** (C) and **Important** (I), with $C > I$, and the set of categories {Admin, Medical}. Suppose that user Ann connects to the system as the $\langle C, \{\text{Admin}\} \rangle$ subject. She can read objects having integrity class $\langle C, \{\text{Admin}\} \rangle$ and $\langle C, \{\text{Admin, Medical}\} \rangle$ and she can write objects with integrity class $\langle C, \{\text{Admin}\} \rangle$, $\langle C, \{\} \rangle$, $\langle I, \{\text{Admin}\} \rangle$, and $\langle I, \{\} \rangle$.

These two principles are the dual with respect to the principles adopted by secrecy-base policies. As a consequence, the integrity model prevents flows of information from low level objects to higher objects. A major limitation of this model is that it only captures integrity breaches due to improper information flows. However, integrity is a much broader concept and additional aspects should be taken into account [15].

Note that secrecy-based and integrity-based models are not mutually exclusive, since it may be useful to protect both the confidentiality and the integrity properties. Obviously, in this case, objects and subjects will be associated with both a security and an integrity class.

A major drawback of mandatory policies is that they control only flows of information happening through *overt channels*, that is, channels operating in a legitimate way. As a consequence, the mandatory policies are vulnerable to *covert channels* [16], which are channels not intended for normal communication but that still can be exploited to infer information. For instance, if a low level subject requests the use of a resource currently used by a high level subject, it will receive a negative response, thus inferring that another (higher level) subject is using the same resource.

2.3 Role-Based Access Control

A third approach for access control is represented by *Role-Based Access Control* (RBAC) models [17, 18]. A *role* is defined as a set of privileges that any

user playing that role is associated with. When accessing the system, each user has to specify the role she wishes to play and, if she is granted to play that role, she can exploit the corresponding privileges. The access control policy is then defined through two different steps: first the administrator defines roles and the privileges related to each of them; second, each user is assigned with the set of roles she can play. Roles can be hierarchically organized to exploit the propagation of access control privileges along the hierarchy.

A user may be allowed to simultaneously play more than one role and more users may simultaneously play the same role, even if restrictions on their number may be imposed by the security administrator.

It is important to note that roles and groups of users are two different concepts. A group is a named collection of users and possibly other groups, and a role is a named collection of privileges, and possibly other roles. Furthermore, while roles can be activated and deactivated directly by users at their discretion, the membership in a group cannot be deactivated.

The main advantage of RBAC, with respect to DAC and MAC, is that it better suits to commercial environments. In fact, in a company, it is not important the identity of a person for her access to the system, but her responsibilities. Also, the role-based policy tries to organize privileges mapping the organization's structure on the roles hierarchy used for access control.

3 Credential-Based Access Control

In an open and dynamic scenario, parties may be unknown to each other and the traditional separation between *authentication* and *access control* cannot be applied anymore. Such parties can also play the role of both client, when requesting access to a resource, and server for the resources it makes available for other users in the system. Advanced access control solutions should then allow to decide, on one hand, which requester (client) is to be granted access to the resource, and, on the other hand, which server is qualified for providing the same resource. *Trust management* has been developed as a solution for supporting access control in open environments [19]. The first approaches proposing a trust management solution for access control are PolicyMaker [20] and KeyNote [21]. The key idea of these proposals is to bind public keys to authorizations and to use credentials to describe specific delegations of trust among keys. The great disadvantage of these early solutions is that they assign authorizations directly to users' keys. The authorization specification is then difficult to manage and, moreover, the public key of a user may act as a pseudonym of herself, thus reducing the advantages of trust management, where the identity of the users should not be considered.

The problem of assigning authorizations directly to keys has been solved by the introduction of *digital certificates*. A digital certificate is the on-line counterpart of paper credentials (e.g., a driver licence). A digital certificate is a statement, certified by a trusted entity (the certificate authority), declaring

a set of properties of the certificate's holder (e.g., identity, accreditation, or authorizations). Access control models, by exploiting digital certificates for granting or denying access to resources, make access decisions on the basis of a set of properties that the requester should have. The final user can prove to have such properties by providing one or more digital certificates [22, 23, 24, 25, 26].

The development and effective use of credential-based access control models require however tackling several problems related to credential management and disclosure strategies, delegation and revocation of credentials, and establishment of credential chains [27, 28, 29, 30]. In particular, when developing an access control system based on credentials, the following issues need to be carefully considered [22].

- *Ontologies.* Since there is a variety of security attributes and requirements that may need to be considered, it is important to guarantee that different parties will be able to understand each other, by defining a set of common languages, dictionaries, and ontologies.
- *Client-side and server-side restrictions.* Since parties may act as either a client or a server, access control rules need to be defined both client-side and server-side.
- *Credential-based access control rules.* New access control languages supporting credentials need to be developed. These languages should be both expressive (to define different kinds of policies) and simple (to facilitate policy definition).
- *Access control evaluation outcome.* The resource requester may not be aware of the attributes she needs to gain access to the requested resource. As a consequence, access control mechanisms should not simply return a permit or deny answer, but should be able to ask the final user for the needed credentials to access the resource.
- *Trust negotiation strategies.* Due to the large number of possible alternative credentials that would enable an access request, a server cannot formulate a request for all these credentials, since the client may not be willing to release the whole set of her credentials. On the other hand, the server should not disclose too much of the underlying security policy, since it may contain sensitive information.

In the following, we briefly describe some proposals that have been developed for trust negotiation and for regulating service access in open environments.

3.1 Overview of Trust Negotiation Strategies

As previously noted, since the interacting parties may be unknown to each other, the resource requester may not be aware of the credentials necessary for gaining access privileges. Consequently, during the access control process,

the two parties exchange information about the credentials needed for access. The access control decision comes then after a complex process, where parties exchange information not only related to the access itself, but also to additional restrictions imposed by the counterpart. This process, called *trust negotiation*, has the main goal of establishing trust between the interacting parties in an automated manner. A number of trust negotiation strategies have been proposed in the literature, which are characterized by the following steps.

- The client first requests to access a resource.
- The server then checks if the client provided the necessary credentials. In case of a positive answer, the server grants access to the resource; otherwise it communicates the client the policies that she has to fulfil.
- The client selects the requested credentials, if possible, and sends them to the server.
- If the credentials satisfy the request, the client is granted access to the resource.

This straightforward trust negotiation process suffers of privacy problems, since both the server discloses its access control policy entirely and the client exposes all her certificates to gain access to a resource. To solve such an inconvenience, a *gradual trust establishment* process can be enforced [31]. In this case, upon receiving an access request, the server selects the policy that governs the access to the service and discloses only the information that it is willing to show to an unknown party. The client, according to its practices, decides if it is willing to disclose the requested credentials. Note that this incremental exchange of requests and credentials can be iteratively repeated as many times as necessary.

PRUDent NEgotiation Strategy (PRUNES) is another negotiation strategy whose main goal is to minimize the number of certificates that the client communicates to the server [30]. It also ensures that the client communicates her credentials to the server only if the access will be granted. Each party defines a set of *credential policies* on which the negotiation process is based. The established credential policies can be graphically represented through a tree, called *negotiation search tree*, composed of two kinds of nodes: *credential nodes*, representing the need for a specific credential, and *disjunctive nodes*, representing the logic operators connecting the conditions for credential release. The root of the tree represents the resource the client wants to access. The negotiation process can be seen as a backtracking operation on the tree. To the aim of avoiding the cost of a brute-force backtracking, the authors propose the *PRUNES* method to prune the search tree without compromising completeness or correctness of the negotiation process. The basic idea is that if a credential has just been evaluated and the state of the system has not changed too much, then it is useless to evaluate again the same credential.

A large set of negotiation strategies, called *disclosure tree strategy* (DTS) family [32], has been also defined and proved to be closed. This means that,

if two parties use different strategies from the DST family, they will be able to negotiate trust. A *Unified Schema for Resource Protection* (UniPro) [33] has been proposed to protect the information specified within policies. UniPro gives (opaque) names to policies and allows any named policy P_1 to have its own policy P_2 , meaning that the content of P_1 can only be disclosed to parties who satisfy P_2 . Another solution is the *Adaptive Trust Negotiation and Access Control* (ATNAC) approach [34]. This method grants (or denies) access on the basis of a *suspicion level* associated with subjects. The suspicion level is not fixed but may vary on the basis of the probability that the user has malicious intents.

It is important to note that in recent, more complicated, scenarios disclosure policies can be defined both on resources and on credentials [22]. In this case, the client, upon receiving a request for a certificate, can answer with a counter-request to the server for another certificate.

3.2 Overview of a Credential-Based Access Control Framework

One of the first solutions providing a uniform framework for credential-based access control specification and enforcement was presented by Bonatti and Samarati [22]. The proposed access control system includes an access control model, a language, and a policy filtering mechanism.

The paper envisions a system composed of two entities: a *client* and a *server*, interacting through a predefined negotiation process. The server is characterized by a set of resources. Both the client and the server have a *portfolio*, which is a collection of credentials (i.e., statements issued by authorities trusted for making them [35]) and declarations (statements issued by the party itself). Credentials correspond to digital certificates and are guaranteed to be unforgeable and verifiable through the public key of the issuing authority.

To the aim of performing gradual trust establishment between the two interacting parties, the server defines a set of *service accessibility rules*, and both the client and the server define their own set of *portfolio disclosure rules*. The service accessibility rules specify the necessary and sufficient conditions for accessing a resource, while portfolio disclosure rules define the conditions that govern the release of credentials and declarations. Both the two classes of rules are expressed by using a logic language. A special class of predicates is represented by *abbreviations*. Since there may exist a number of alternative combinations of certificates allowing access to a resource, *abbreviation predicates* may be used for reducing the communication cost of such certificates. The predicates of the language adopted exploit the current *state* (i.e., parties' characteristics, certificates already exchanged in the negotiation, and requests made by the parties) to take a decision about a release. The information about the state is classified as *persistent state*, when the information is stored at the site and spans different negotiations, and *negotiation state*, when it is acquired during the negotiation and is deleted when the same terminates.

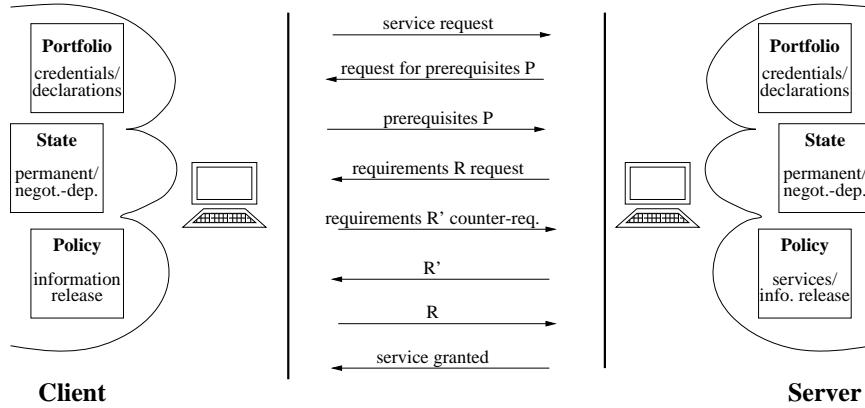


Fig. 5. Client-server negotiation

The main advantage of this proposal is that it maximizes both server and client's privacy, by minimizing the set of certificates exchanged. In particular, the server discloses the minimal set of policies for granting access, while the client releases the minimal set of certificates to access the resource. To this purpose, service accessibility rules are distinguished in *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 allow the service request to be successfully granted. Therefore, the server will not disclose a requisite rule until the client satisfies a prerequisite rule. Figure 5 illustrates the resulting client/server interaction. It is important to highlight here that, before releasing rules to the client, the server needs to evaluate state predicates that involve private information. For instance, the client is not expected to be asked many times the same information during the same session and if the server has to evaluate if the client is considered not trusted, it cannot communicate this request to the client itself.

4 Policy Composition

In many real word scenarios, access control enforcement needs to take into consideration different policies independently stated by different administrative subjects, which must be enforced as if they were a single policy. As an example of policy composition, consider an hospital, where the global policy may be obtained by combining together the policies of its different wards and the externally imposed constraints (e.g., privacy regulations). Policy composition is becoming of paramount importance in all those contexts in which administrative tasks are managed by different, non collaborating, entities.

Policy composition is an orthogonal aspect with respect to policy models, mechanisms, and languages. As a matter of fact, the entities expressing the

policies to be composed may even not be aware of the access control system adopted by the other entities specifying access control rules. The main desiderata for a policy composition framework can be summarized as follows [36].

- *Heterogeneous policy support.* The framework should support policies expressed in different languages and enforced by different mechanisms.
- *Support of unknown policies.* The framework should support policies that are not fully defined or are not fully known when the composition strategy is defined. Consequently, policies are to be treated as black-boxes and are supposed to return a correct and complete response when queried at access control time.
- *Controlled interference.* The framework cannot simply merge the sets of rules defined by the different administrative entities, since this behavior may cause side effects. For instance, the accesses granted/denied might not correctly reflect the specifications anymore.
- *Expressiveness.* The framework should support a number of different ways for combining the input policies, without changing the input set of rules or introducing ad-hoc extensions to authorizations.
- *Support of different abstraction levels.* The composition should highlight the different components and their interplay at different levels of abstraction.
- *Formal semantics.* The language for policy composition adopted by the framework should be declarative, implementation independent, and based on a formal semantic to avoid ambiguity.

We now briefly describe some solutions proposed for combining different policies.

4.1 Overview of Policy Composition Solutions

Various models have been proposed to reason about security policies [37, 38, 39, 40]. In [37, 39] the authors focus on the secure behavior of program modules. McLean [40] introduces *the algebra of security*, which is a Boolean algebra that enables to reason about the problem of policy conflict, arising when different policies are combined. However, even though this approach permits to detect conflicts between policies, it does not propose a method to resolve the conflicts and to construct a security policy from inconsistent sub-policies. Hosmer [38] introduces the notion of meta-policies, which are defined as policies about policies. Metapolicies are used to coordinate the interaction about policies and to explicitly define assumptions about them. Subsequently, Bell [41] formalizes the combination of two policies with a function, called *policy combiner*, and introduces the notion of *policy attenuation* to allow the composition of conflicting security policies. Other approaches are targeted to the development of a uniform framework to express possibly heterogeneous policies [42, 43, 44, 45, 46].

A different approach has been illustrated in [36], where the authors propose an algebra for combining security policies together with its formal semantics. Here, a policy, denoted P_i , is defined as a set of triples of the form (s, o, a) , where s is a constant in (or a variable over) the set of subjects S , o is a constant in (or a variable over) the set of objects O , and a is a constant in (or a variable over) the set of actions A . Policies of this form are composed through a set of *algebra operators* whose syntax is represented by the following BNF:

$$\begin{aligned} E ::= & \mathbf{id}|E + E|E \& E|E - E|E \wedge C|o(E, E, E)|E * R|T(E)|(E) \\ T ::= & \tau \mathbf{id}.E \end{aligned}$$

where **id** is a unique policy identifier, E is a policy expression, T is a construct, called *template*, C is a construct describing constraints, and R is a construct describing rules. The order of evaluation of algebra operators is determined by the precedence, which is (from higher to lower) τ , \cdot , $+$ and $\&$ and $-$, $*$ and \wedge .

The semantic of algebra operators is defined by a function that maps policy expressions in a set of ground authorizations (i.e., a set of authorization triples). The function that maps policy identifiers into sets of triples is called *environment*, and is formally defined as follows.

Definition 1. *An environment e is a partial mapping from policy identifiers to sets of authorization triples. By $e[X/S]$ we denote a modification of environment e such that*

$$e[X/S](Y) = \begin{cases} S & \text{if } Y = X \\ e(Y) & \text{otherwise} \end{cases}$$

The semantic of an identifier X in the environment e is denoted by $\llbracket X \rrbracket_e = e(X)$.

The operators defined by the algebra for policy composition basically reflect the features supported by classical policy definition systems. As an example, it is possible to manage exceptions (such as negative authorizations), propagation of authorizations, and so on. The set of operators together with their semantic is briefly described in the following.

- *Addition* (+). It merges two policies by returning their union.

$$\llbracket P_1 + P_2 \rrbracket_e = \llbracket P_1 \rrbracket_e \cup \llbracket P_2 \rrbracket_e$$

Intuitively, additions can be applied in any situation where accesses can be authorized if allowed by any of the component policies (maximum privilege principle).

- *Conjunction* ($\&$). It merges two policies by returning their intersection.

$$\llbracket P_1 \& P_2 \rrbracket_e = \llbracket P_1 \rrbracket_e \cap \llbracket P_2 \rrbracket_e$$

This operator enforces the minimum privilege principle.

- *Subtraction* ($-$). It deletes from a first policy, all the authorizations specified in a second policy.

$$\llbracket P_1 - P_2 \rrbracket_e = \llbracket P_1 \rrbracket_e \setminus \llbracket P_2 \rrbracket_e$$

Intuitively, subtraction operator is used to handle exceptions, and has the same functionalities of negative authorizations in existing approaches. It does not generate conflicts since P_1 prevails on P_2 by default.

- *Closure* (*). It closes a policy under a set of derivation rules.

$$\llbracket P * R \rrbracket_e = \mathbf{closure}(R, \llbracket P \rrbracket_e)$$

The closure of policy P under derivation rules R produces a new policy that contains all the authorizations in P and those that can be derived evaluating R on P , according to a given semantics. The derivation rules in R can enforce, for example, an authorization propagation along a pre-defined subject or object hierarchy.

- *Scoping Restriction* (\wedge). It restricts the applicability of a policy to a given subset of subjects, objects, and actions of the system.

$$\llbracket P_1 \wedge c \rrbracket_e = \{t \in \llbracket P \rrbracket_e \mid t \text{ satisfy } c\}$$

where c is a condition. It is useful when administration entities need to express their policy on a confined subset of subjects and/or objects (e.g., each ward can express policies about the doctors working in the ward).

- *Overriding* (o). It overrides a portion of policy P_1 with the specifications in policy P_2 ; the fragment that is to be substituted is specified by a third policy P_3 .

$$\llbracket o(P_1, P_2, P_3) \rrbracket_e = \llbracket (P_1 - P_3) + (P_2 \& P_3) \rrbracket_e$$

- *Template* (τ). It defines a partially specified (i.e., parametric) policy that can be completed by supplying the parameters.

$$\llbracket \tau X. P \rrbracket_e(S) = \llbracket P \rrbracket_{e[S/X]}$$

where S is the set of all policies, and X is a parameter. Templates are useful for representing policies as black-boxes. They are needed any time when some components are to be specified at a later stage. For instance, the components might be the result of a further policy refinement, or might be specified by a different authority.

Due to the formal definition of the semantic of algebra operators, it is possible to exploit algebra expressions to formally prove the security properties of the obtained (composed) policy.

Once the policies have been composed through the algebraic operators described above, for their enforcement it is necessary to provide executable specifications compatible with different evaluation strategies. To this aim, the authors propose the following three main strategies to translate policy expressions into logic programs.

- *Materialization.* The expressions composing policies are explicitly evaluated, by obtaining a set of ground authorizations that represents the policy that needs to be enforced. This strategy can be applied when all the composed policies are known and reasonably static.
- *Partial materialization.* Whenever materialization is not possible since some of the policies to be composed are not available, it is possible to materialize only a subset of the final policy. This strategy is useful also when some of the policies are subject to sudden and frequent changes, and the cost of materialization may be too high with respect to the advantages it may provide.
- *Run-time evaluation.* In this case no materialization is performed and run-time evaluation is needed for each request (access triple), which is checked against the policy expressions to determine whether the triple belongs to the result.

The authors then propose a method (*pe2lp*) for transforming algebraic policy composition expressions into a logic program. The method proposed can be easily adapted to one of the three materialization strategies introduced above. Basically, the translation process creates a distinct predicate symbol for each policy identifier and for each algebraic operator in the expression. The logic programming formulation of algebra expressions can be used to enforce access control. As already pointed out while introducing algebra operators, this policy composition algebra can also be used to express simple access control policies, such as open and closed policy, propagation policies, and exceptions management. For instance, let us consider a hospital composed of three wards, namely *Cardiology*, *Surgery*, and *Orthopaedics*. Each ward is responsible for granting access to data under its responsibility. Let $P_{Cardiology}$, $P_{Surgery}$ and $P_{Orthopaedics}$ be the policies of the three wards. Suppose now that an access is authorized if any of the wards policies state so and that authorizations in policy $P_{Surgery}$ are propagated to individual users and documents by classical hierarchy-based derivation rules, denoted R_H . In terms of the algebra, the hospital policy can be represented as follows.

$$P_{Cardiology} \& P_{Surgery} * R_H \& P_{Orthopaedics}$$

Following this work, Jajodia et al. [47] presented a propositional algebra for policies with a syntax consisting of abstract symbols for atomic policy expressions and composition operators.

5 Access Control Through Encryption

Since the amount of data that organizations need to manage is increasing very quickly, data outsourcing is becoming more and more attractive. Data outsourcing provides data storage at a low rate, allowing the data owner to

concentrate its activity on its core business where data are managed by an external service provider. The main drawback of this practice is that the service provider may not be fully trusted. The data owner and final users are usually supposed to trust the provider for managing data stored on its server, and to correctly execute queries on it, but the provider is not fully trusted for accessing data content. To solve this problem, different solutions have been proposed in the literature, mainly based on the use of cryptography as a mechanism for protecting data privacy [1, 2, 3]. Most of the proposals in this area focus on issues related to querying encrypted data, to the aim of avoiding server-side decryption, while minimizing client-side burden in query evaluation. Another drawback of existing proposals is that they assume that any client has complete access to the query results, and therefore the data owner has to be involved for filtering out the data not accessible by the client. This would cause an excessive burden on the owner, thus nullifying the advantages of outsourcing data management. On the other hand, the remote server cannot enforce access control policies, since it may not be allowed to know the access control policy defined by the owner. Since neither the data owner nor the remote server can enforce the access control policy, for either security or efficiency reasons, the data themselves need to implement selective access. This can be realized through *selective encryption*, which consists in encrypting data using different keys and distributing the keys so that users can decrypt only the data they are authorized to access.

The problem of enforcing access control policies through selective encryption has been analyzed both for databases and for XML documents. In the following, we briefly introduce the most important proposals for these two scenarios [48, 49, 50].

5.1 Overview of Database Outsourcing Solutions

Let us consider a system composed of a set \mathcal{U} of users and a set \mathcal{R} of resources. A resource may be a table, an attribute, a tuple, or even a cell, depending on the granularity at which the data owner wishes to define her policy. Since this distinction does not affect access control policy enforcement, we will always refer generically to resources. The access control policy defined by the data owner can be easily represented through a traditional access matrix \mathcal{A} , where each cell $\mathcal{A}[u,r]$ may assume either the value 1, if u can access r , or the value 0, otherwise (currently only read privileges have been considered). Figure 6 represents an example of access matrix, where there are four users, namely A , B , C , and D , and four resources r_1 , r_2 , r_3 , and r_4 .

A first solution that could be adopted for selectively encrypting data for access control purposes consists in using a different key for each resource, and in communicating each user the set of keys used to protect the resources belonging to her capability list (i.e., the set of resources that the user can access). This solution requires each user to keep a possibly great number of

	r_1	r_2	r_3	r_4
A	1	1	0	1
B	1	1	0	0
C	1	0	1	0
D	0	1	1	0

Fig. 6. An example of binary access matrix

(secret) keys, depending on the number of her privileges. To the aim of reducing the number of keys that each user has to manage, *key derivation methods* can be adopted [51]. A key derivation method allows the computation of an encryption key, by proving the knowledge of another secret key in the system. By adequately organizing encryption keys and adopting a derivation method, it is possible to communicate a small number of keys to users, granting them the possibility of deriving from these keys, those needed for accessing data. Typically, these methods assume the existence of a partial order relationship defined on the set of keys. Given the set of encryption keys \mathcal{K} in the system, and a partial order relationship \preceq defined on it, the pair (\mathcal{K}, \preceq) represents the *key derivation hierarchy* of the system, where $\forall k_i, k_j \in \mathcal{K}$, if $k_j \preceq k_i$ then k_j is derivable from k_i . Consequently, by knowing a key k_i , it is possible to compute the value of any k_j such that $k_j \preceq k_i$. Graphically, a key derivation hierarchy can be represented as a graph, with a vertex for each key in \mathcal{K} , and a path from k_i to k_j if $k_j \preceq k_i$. A key derivation hierarchy can however assume three different graphical structures, which in turn influence the key derivation method that can be adopted, as described in the following.

- *Chain of vertexes.* The relation \preceq is a total order relation for \mathcal{K} ; the value of k_i depends only on the value of the key of its (unique) direct ancestor k_j [52].
- *Tree.* The relation \preceq is a partial order relation for \mathcal{K} such that if $k_i \preceq k_j$ and $k_i \preceq k_l$, then either $k_j \preceq k_l$ or $k_l \preceq k_j$; the value of k_i depends on the value of the key of its (unique) direct ancestor k_j , and on the public label l_i associated with k_i [52, 53, 54].
- *DAG.* Different classes of solutions have been proposed for DAGs [51]. In particular, Atallah et al. [55] introduce an interesting solution that allows insertion and deletion of keys in the hierarchy without the need of redefining the whole set of keys \mathcal{K} . This method associates a piece of public information (called *token*) with each edge in the DAG. Given an edge connecting key k_i with k_j , token $T_{i,j} = k_j \oplus h(k_i, l_j)$, where l_j is a publicly available label associated with k_j , h is a secure hash function, and \oplus is the n -ary xor operator.

Damiani et al. [56] propose an access control solution for outsourcing data that is based on the definition of a key derivation hierarchy reflecting the user-group containment relation. Given a set \mathcal{U} of users, a *user-based hierarchy*, denoted UH , is defined as a pair $(P(\mathcal{U}), \preceq)$, where $P(\mathcal{U})$ represents the powerset

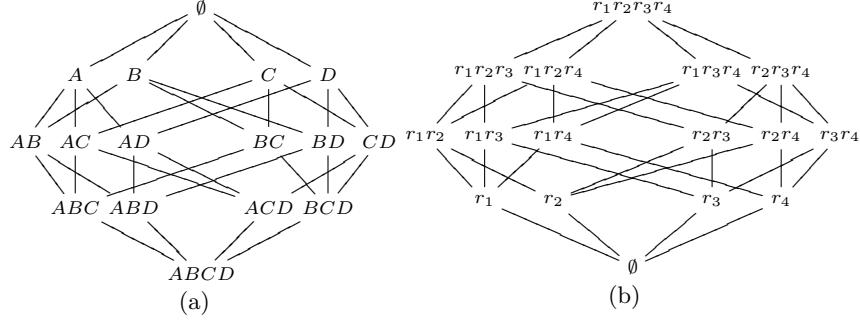


Fig. 7. An example of UH (a) and RH (b)

(i.e., the set of all subsets of \mathcal{U}) of \mathcal{U} , and contains $2^{|\mathcal{U}|}$ items, and \preceq is defined as the set containment relation, that is, $\forall a, b \in P(\mathcal{U})$, $a \preceq b$ if and only if $b \subseteq a$. Each vertex v_i in UH is associated with a private key k_i . Each user $u_i \in \mathcal{U}$ is then communicated key k_i associated with the vertex representing the singleton set $\{u_i\}$. Each resource r_j is instead encrypted with the key k_j associated with the vertex representing its *acl*. Since partial order relation \preceq is defined on the basis of the set containment relation, any user in the system, by knowing the key of vertex $\{u_i\}$, can derive all and only the keys of vertexes representing sets of users including u_i . Figure 7(a) represents the user hierarchy suitable for the access matrix in Fig. 6. To correctly enforce the given access control policy, r_1 is encrypted with the key of vertex ABC , r_2 with the key of vertex ABD , r_3 with the key of vertex CD , and r_4 with the key of vertex A . Due to this key assignment, any user can access exactly the resources in her capability list. As an example, with respect to the hierarchy in Fig. 7(a), it is easy to see that B can derive the key associated with vertexes AB and BD that in turn can be used for deriving the keys associated with vertexes ABC and ABD , this allowing to access r_1 and r_2 , respectively.

In a dual way, it is possible to build a key derivation hierarchy on the basis of the resources in the system. A *resource-based hierarchy*, denoted RH, is defined as a pair $(P(\mathcal{R}), \preceq)$, where $P(\mathcal{R})$ represents the powerset of \mathcal{R} , and \preceq is a partial order relation such that $\forall a, b \in P(\mathcal{R})$, $a \preceq b$ if and only if $a \subseteq b$. To correctly enforce the given policy, each user u_i is assigned the key of the vertex representing her capability list, while each resource r_j is encrypted with the key of the vertex representing the singleton set $\{r_j\}$. Considering again the access matrix in Fig. 6, the corresponding resource hierarchy is represented in Fig. 7(b).

Although both the models presented for defining a key derivation hierarchy correctly enforce the access control policy defined by the owner, there is an important difference that should be considered when deciding which structure to adopt. As a matter of fact, UH allows resources to share the same encryption key, while each user has her secret key. By contrast, when adopting RH,

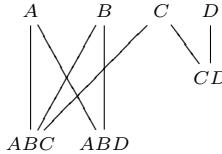


Fig. 8. An example of transformed user hierarchy.

different users can share the same secret key, while resources are all encrypted using a different key. Moreover, since the number of vertexes in the hierarchy depends on the number of users (resources, respectively) in the system, if \mathcal{U} is smaller than \mathcal{R} , UH will be probably more convenient than RH. In the following, we focus on the user-based hierarchy, but the discussion is however applicable also to the resource-based hierarchy.

It is easy to note that UH structure defines a great number of keys, some of which may be useful neither for encryption nor for distribution to users. This causes both an expensive key derivation process on the client side, and an excessive storage workload for the server. As a matter of fact, the length of key derivation paths in UH is linear in $|\mathcal{U}|$, and the number of tokens stored on the server grows with $|\mathcal{U}|$.

To the aim of reducing both key derivation costs and, more generally, the size of the key derivation hierarchy, the authors propose to remove from UH all those vertexes that are not necessary for access control enforcement [48]. Therefore, the vertexes that are maintained in the hierarchy are those that represent singleton sets of users and resources' *acls*. These vertexes are then connected in a new hierarchical structure, according to the \preceq partial order relation. The resulting hierarchy should guarantee that any user u_i can compute, from her private key, the keys used to encrypt all and only the resources belonging to her capability list. To this purpose, the authors propose an algorithm that, starting from the set of required vertexes, builds a key derivation hierarchy on which they apply the Atallah et al. key derivation method. To improve the key derivation process for final users, the algorithm tries to minimize the number of tokens in the system. To this aim, other vertexes besides the necessary ones are possibly added to the hierarchical structure. Considering the user hierarchy in Fig. 7, Fig. 8 illustrates the hierarchy corresponding to the access control policy in Fig. 6, and containing only the vertexes needed for a correct enforcement of the policy.

Zych and Petkovic [49] exploit Diffie-Hellman key generation scheme and asymmetric encryption for enforcing selective access on outsourced data. Given a user-based hierarchy, the authors propose to build a *V-graph* starting from it. For each vertex in the V-graph, the number of incoming edges is either 2 or 0, and for any two vertexes, there is at most one common parent vertex. The resulting structure is a *binary tree*, whose leaves represent singleton sets of users, and whose root represents the group containing all the users

in the system. Also, any user knows the private key of the vertex representing herself in the hierarchy, and each resource is encrypted with the private key associated with the vertex representing its *acl*. However, differently from other proposals, key derivation goes from leaves to the root of the tree.

5.2 Overview of XML Document Outsourcing Solutions

Besides traditional databases, also XML documents can contain sensitive information, and their outsourcing may cause privacy breaches. As a consequence, it is necessary to develop techniques for enforcing access control on outsourced XML data as well. Although some of the approaches presented for the relational database outsourcing scenario are suited for XML data outsourcing, they do not exploit the main characteristics of XML documents (e.g., their tree structure) and different specific approaches have then been proposed. The solutions presented exploit once again selective encryption as a way for enforcing access control when publishing or outsourcing sensitive data.

Miklau and Suciu [50] propose a way for differentiating the encryption of different portions of an XML document, on the basis of users or groups who can access them. The proposed access control mechanism is enriched by adding metadata XML nodes, adopted to enforce access control rules with conditions on the values contained in the document. Wang et al. [57] present an access control system that both protects data stored in the XML document and the associations among data by introducing association constraints that need to be satisfied by the encryption model adopted.

6 Conclusions

This chapter discussed recent trends in the access control field. We described the basic concepts of access control and investigated different issues concerning the development of an access control system. In particular, we outlined the needs for providing means to: support access control in open environments, where the identities of the involved parties may be unknown; combine authorization specifications that may be independently stated; enforce access control through the use of selective encryption. For these contexts, we described recent proposals and ongoing work.

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References

1. Hacigümüs, H., Iyer, B., Mehrotra, S., Li, C.: Executing SQL over encrypted data in the database-service-provider model. In: Proc. of the ACM SIGMOD 2002, Madison, Wisconsin, USA (2002)
2. Hacigümüs, H., Iyer, B., Mehrotra, S.: Providing database as a service. In: Proc. of 18th International Conference on Data Engineering, San Jose, California, USA (2002)
3. Damiani, E., De Capitani di Vimercati, S., Jajodia, S., Paraboschi, S., Samarati, P.: Balancing confidentiality and efficiency in untrusted relational DBMSs. In: Proc. of the 10th ACM Conference on Computer and Communications Security (CCS03), Washington, DC, USA (2003)
4. Graham, G., Denning, P.: Protection- principles and practice. In: Proc. of the Spring Jt. Computer Conference. Volume 40., Montvale, NJ, USA (1972) 417–429
5. Harrison, M., Ruzzo, W., Ullman, J.: Protection in operating systems. Communications of the SCM **19**(8) (August 1976) 461–471
6. Lampson, B.W.: Protection. ACM Operating Systems Review **8**(1) (January 1974) 18–24
7. Jajodia, S., Samarati, P., Sapino, M., Subrahmanian, V.: Flexible support for multiple access control policies. ACM Transaction on Database Systems **26**(2) (June 2001) 214–260
8. Lunt, T.: Access control policies: Some unanswered questions. In: Proc. of IEEE Computer Security Foundations Workshop II, Franconia, New Hampshire (1988)
9. Sandhu, R.: Lattice-based access control models. IEEE Computer **26**(11) (1993) 9–19
10. Bell, D., La Padula, L.: Secure computer systems: A mathematical model. Technical Report MTR-2547, Vol 2, MITRE Corp., Bedford, MA (November 1973)
11. Bell, D., La Padula, L.: Secure computer systems: Mathematical foundations. Technical Report MTR-2547, Vol 1, MITRE Corp., Bedford, MA (November 1973)
12. Bell, D., La Padula, L.: Secure computer systems: A refinement of the mathematical model. Technical Report MTR-2547, Vol 3, MITRE Corp., Bedford, MA (April 1974)
13. Bell, D., La Padula, L.: Secure computer systems: Unified exposition and multics interpretation. Technical Report MTR-2997, Vol 4, MITRE Corp., Bedford, MA (July 1975)
14. Biba, K.J.: Integrity considerations for secure computer systems. MTR-3153 rev., MITRE Corp., Vol 1, Bedford, MA (April 1977)
15. Samarati, P., De Capitani di Vimercati, S.: Access control: Policies, models, and mechanisms. In Focardi, R., Gorrieri, R., eds.: Foundations of Security Analysis and Design. LNCS 2171. Springer-Verlag (2001)
16. McLean, J.: Security models. In Marciniak, J., ed.: Encyclopedia of Software Engineering. John Wiley & Sons (1994)
17. Ferraiolo, D., Kuhn, D.: Role-based access control. In: Proc. of the 15th National Computer Security Conference. (1992)
18. Sandhu, R., Coyne, E., Feinstein, H., Youman, C.: Role-based access control models. IEEE Computer **29**(2) (1996) 38–47

19. Security and trust management (2005)
http://www.ercim.org/publication/Ercim_News/enw63/.
20. Blaze, M., Feigenbaum, J., Lacy, J.: Decentralized trust management. In: Proc. of the 17th Symposium on Security and Privacy, Oakland, California, USA (May 1996)
21. Blaze, M., Feigenbaum, J., Ioannidis, J., Keromytis, A.: The KeyNote Trust Management System (Version 2). Internet RFC 2704 edn. (1999)
22. Bonatti, P., Samarati, P.: A unified framework for regulating access and information release on the web. *Journal of Computer Security* **10**(3) (2002) 241–272
23. Irwin, K., Yu, T.: Preventing attribute information leakage in automated trust negotiation. In: Proc. of the 12th ACM Conference on Computer and Communications Security, Alexandria, VA, USA (2005)
24. Li, N., Mitchell, J., Winsborough, W.: Beyond proof-of-compliance: Security analysis in trust management. *Journal of the ACM* **52** (2005) 474–514
25. Ni, J., Li, N., Winsborough, W.: Automated trust negotiation using cryptographic credentials. In: Proc. of the 12th ACM Conference on Computer and Communications Security, Alexandria, VA, USA (2005)
26. Yu, T., Winslett, M., Seamons, K.: Supporting structured credentials and sensitive policies through interoperable strategies for automated trust. *ACM Transactions on Information and System Security (TISSEC)* **6**(1) (February 2003) 1–42
27. Seamons, K.E., Winsborough, W., Winslett, M.: Internet credential acceptance policies. In: Proc. of the Workshop on Logic Programming for Internet Applications, Leuven, Belgium (July 1997)
28. Seamons, K.E., Winslett, M., Yu, T., Smith, B., Child, E., Jacobson, J., Mills, H., Yu, L.: Requirements for policy languages for trust negotiation. In: Proc. of the 3rd International Workshop on Policies for Distributed Systems and Networks (POLICY 2002), Monterey, CA (June 2002)
29. Winslett, M., Ching, N., Jones, V., Slepchin, I.: Assuring security and privacy for digital library transactions on the web: Client and server security policies. In: Proc. of the ADL '97 — Forum on Research and Tech. Advances in Digital Libraries, Washington, DC (May 1997)
30. Yu, T., Ma, X., Winslett, M.: An efficient complete strategy for automated trust negotiation over the internet. In: Proc. of the 7th ACM Computer and Communication Security, Athens, Greece (November 2000)
31. Seamons, K., Winslett, M., Yu, T.: Limiting the disclosure of access control policies during automated trust negotiation. In: Proc. of the Symposium on Network and Distributed System Security, San Diego, CA (April 2001)
32. Yu, T., Winslett, M., Seamons, K.: Interoperable strategies in automated trust negotiation. In: Proc. of the 8th ACM Conference on Computer and Communications Security, Philadelphia, Pennsylvania (November 2001)
33. Yu, T., Winslett, M.: A unified scheme for resource protection in automated trust negotiation. In: Proc. of the IEEE Symposium on Security and Privacy, Berkeley, California (May 2003)
34. Ryutov, T., Zhou, L., Neuman, C., Leithead, T., Seamons, K.: Adaptive trust negotiation and access control. In: Proc. of the 10th ACM Symposium on Access Control Models and Technologies, Stockholm, Sweden (June 2005)
35. Gladman, B., Ellison, C., Bohm, N.: Digital signatures, certificates and electronic commerce. <http://www.clark.net/pub/cme/html/spki.html>.

36. Bonatti, P., De Capitani di Vimercati, S., Samarati, P.: An algebra for composing access control policies. *ACM Transactions on Information and System Security* **5**(1) (February 2002) 1–35
37. Abadi, M., Lamport, L.: Composing specifications. *ACM Transactions on Programming Languages* **14**(4) (October 1992) 1–60
38. Hosmer, H.: Metapolicies II. In: Proc. of the 15th National Computer Security Conference, Baltimore, MD (October 1992)
39. Jaeger, T.: Access control in configurable systems. *Lecture Notes in Computer Science* **1603** (2001) 289–316
40. McLean, J.: The algebra of security. In: Proc. of the 1988 IEEE Computer Society Symposium on Security and Privacy, Oakland, CA, USA (April 1988)
41. Bell, D.: Modeling the multipolicy machine. In: Proc. of the New Security Paradigm Workshop, Little Compton, Rhode Island, USA (August 1994)
42. Bertino, E., Jajodia, S., Samarati, P.: A flexible authorization mechanism for relational data management systems. *ACM Transactions on Information Systems* **17**(2) (April 1999) 101–140
43. Jajodia, S., Samarati, P., Sapino, M., Subrahmanian, V.: Flexible support for multiple access control policies. *ACM Transactions on Database Systems* **26**(2) (June 2001) 214–260
44. Jajodia, S., Samarati, P., Subrahmanian, V., Bertino, E.: A unified framework for enforcing multiple access control policies. In: Proc. of the 1997 ACM International SIGMOD Conference on Management of Data, Tucson, AZ (May 1997)
45. Li, N., Feigenbaum, J., Grosof, B.: A logic-based knowledge representation for authorization with delegation. In: Proc. of the 12th IEEE Computer Security Foundations Workshop, Washington, DC, USA (July 1999)
46. Woo, T., Lam, S.: Authorizations in distributed systems: A new approach. *Journal of Computer Security* **2**(2,3) (1993) 107–136
47. Wijesekera, D., Jajodia, S.: A propositional policy algebra for access control. *ACM Transactions on Information and System Security* **6**(2) (May 2003) 286–325
48. Damiani, E., De Capitani di Vimercati, S., Foresti, S., Jajodia, S., Paraboschi, S., Samarati, P.: An experimental evaluation of multi-key strategies for data outsourcing. In: Proc. of the 22nd IFIP TC-11 International Information Security Conference (SEC 2007), Sandton, South Africa (May 2007)
49. Zych, A., Petkovic, M.: Key management method for cryptographically enforced access control. In: Proc. of the 1st Benelux Workshop on Information and System Security, Antwerpen, Belgium (2006)
50. Miklau, G., Suciu, D.: Controlling access to published data using cryptography. In: Proc. of the 29th VLDB Conference, Berlin, Germany (September 2003)
51. Crampton, J., Martin, K., Wild, P.: On key assignment for hierarchical access control. In: Proc. of the 19th IEEE Computer Security Foundations Workshop (CSFW'06), Los Alamitos, CA, USA (2006)
52. Sandhu, R.: On some cryptographic solutions for access control in a tree hierarchy. In: Proc. of the 1987 Fall Joint Computer Conference on Exploring Technology: Today and Tomorrow, Dallas, Texas, USA (1987)
53. Gudes, E.: The design of a cryptography based secure file system. *IEEE Transactions on Software Engineering* **6** (1980) 411–420
54. Sandhu, R.: Cryptographic implementation of a tree hierarchy for access control. *Information Processing Letters* **27** (1988) 95–98

55. Atallah, M., Frikken, K., Blanton, M.: Dynamic and efficient key management for access hierarchies. In: Proc. of the 12th ACM conference on Computer and Communications Security (CCS05), Alexandria, VA, USA (2005)
56. Damiani, E., De Capitani di Vimercati, S., Foresti, S., Jajodia, S., Paraboschi, S., Samarati, P.: Selective data encryption in outsourced dynamic environments. In: Proc. of the Second International Workshop on Views On Designing Complex Architectures (VODCA 2006). Electronic Notes in Theoretical Computer Science, Bertinoro, Italy, Elsevier (2006)
57. Wang, H., Lakshmanan, L.V.S.: Efficient secure query evaluation over encrypted XML databases. In: Proc. of the 32nd VLDB Conference, Seoul, Korea (September 2006)