A Precedent Approach to Assigning Access Rights

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Abstract. To design a discretionary access control policy, a technique is proposed that uses the principle of analogies and is based on both the properties of objects and the properties of subjects. As attributes characterizing these properties, the values of the security attributes of subjects and objects are chosen. The concept of precedent is defined as an access rule explicitly specified by the security administrator. The problem of interpolation of the access matrix is formulated: the security administrator defines a sequence of precedents, it is required to automate the process of filling the remaining cells of the access matrix. On the family of sets of security attributes, a linear order is introduced. The principles of filling the access matrix on the basis of analogy with the dominant precedent in accordance with a given order relation are developed. The analysis of the proposed methodology is performed and its main advantages are revealed.

1. Introduction

Discretionary access control policy (DAC) implies arbitrary access control: the administrator must define access rights for each subject-object pair. Obviously, even for small local systems, the number of rules that need to be considered is estimated at tens of thousands. Such an access control policy can not be set completely by the administrator. If we consider that the number of objects and subjects in the computer system tends to increase, then the complexity of the task of complete administration of the system exceeds practical possibilities.

A common approach for modern operating systems was the approach based on assigning default access rights at the stage of object creation. The algorithm is that all objects created by a specific subject are assigned the same access rights. In the future, if necessary, these rights can be changed by the administrator. For example, in the Windows family of operating systems, the default rights are extracted from the context of the process that creates the file. This approach is based on the assumption that the same process works with objects that have the same security requirements. Thus, an approach based on the analog (precedent) method is used: if some rights are set for one object created by this subject, then all objects created by this subject should have similar access rights. The main drawback of this approach is that the analogy is built exactly on one feature – the owner of the object.

In this article, we propose an algorithm for constructing DAC using the same analog (precedent) method, but based on the properties of objects and on the properties of subjects. As parameters characterizing the properties of objects and subjects, the values of their attributes are chosen.

Building an access control policy based on the attributes of files and processes was investigated in a number of works. So, in the article [1] the HRU discretionary model was expanded and a typed access matrix was constructed, in which, in addition to object identifiers, their type is also used. The expansion of this model to the case of a dynamically changing object type was carried out in [2]. These results were generalized taking into account not the type, but the attributes of the object in the ABAM model [3]. Also, the influence of attributes on role-based access policy was investigated [4–7]. The influence of attributes on the authorization model was investigated in [8]. These works were
developed as an attribute-based access control model (ABAC). Access control standards based on the attributes of subjects and objects were documented in NIST [5]. Unlike previous studies, we consider an algorithmic approach to the formation of an access matrix and use the attributes of subjects and objects as input data. Note that the approach implemented in the ABAC model is closer to role-based access differentiation, whereas the proposed algorithm remains within the discretionary model.

2. Sequence of precedents

2.1. Access matrix

When building a DAC, it is necessary to determine the access permission for each subject to each object, starting from some formal rules that have a formal form.

Let $S$ be the set of subjects, $O$ be the set of objects, $P$ be the set of access rights. To define a DAC policy, it is necessary to set for each pair $(S_i, O_j) \in S \times O$ a certain set of allowed access rights $\alpha \subseteq P$, that is, to define an access rule $(S_i, O_j, \alpha)$. Such rules are conveniently organized in a two-dimensional table of dimension $|S| \times |O|$, in which each subject has its own row, each object has its own column, and a set of allowed access rights $\alpha$ is indicated at their intersection. The constructed table is usually called an access matrix, in what follows we denote it by $M$. The access matrix defines a discrete map

$$M: S \times O \to 2^P.$$ 

The mapping $M$ is the decision function to allow or deny access and is called the access function.

It should be noted that when the DAC policy is implemented in practice, for each "subject-object" pair $(S_i, O_j)$ not an allowed set of access rights, but prohibited one may be specified. To distinguish these cases, we introduce the following notation:

- access rule $(S_i, O_j, \alpha)\ (\ [M]_{ij} = \alpha)$ means that access $\alpha$ of the subject $S_i$ to the object $O_j$ is allowed;
- access rule $(S_i, O_j, \overline{\alpha})\ (\ [M]_{ij} = \overline{\alpha})$ means that access $\alpha$ of the subject $S_i$ to the object $O_j$ is prohibited.

2.2. Security attributes

Assumption 1. We will assume that in the computer system for each subject and each object a set of properties is defined that characterizes the given subject or object and determines its rights in the system. Such a set of properties will be called security attributes.

You should not confuse security attributes with DAC access rights or security labels for a mandatory access policy. Security attributes are an integral part of the object and characterize its contents, type or status in the system. While the access rights are set in the system by the administrator quite arbitrarily. By entering the security attributes, we assume that the access rights to the objects with the same properties will be the same. It should be noted that not all object properties automatically refer to security attributes. Which attributes affect security, and which do not, determines the administrator, based on the properties of the system as a whole.

Let each subject of system $S_i$ from set of subjects $S$ is characterized by a set of security attributes $(a_1^i, ..., a_n^i)$, $a_k^i \in A_k$, $k = 1, ..., n$; and each object of system $O_j$ from set of objects $O$ is characterized by a set of security attributes $(b_1^j, ..., b_m^j)$, $b_s^j \in B_s$, $s = 1, ..., m$.

Assumption 2. If two subjects have the same set of security attribute values, then they have the same access rights in the system.

Assumption 3. If two objects have the same set of security attribute values, then the access rights to them of subjects with the same set of security attribute values are the same.
The last two assumptions introduce an equivalence relation on sets of subjects and objects. By equivalence, we mean sameness of two objects with the same set of values of security attributes of the security subsystem. In the future, all the subjects or objects, which are identical in terms of security, we will refer to the same equivalence class, and a subject or object shall mean the corresponding equivalence classes. Working with equivalence classes significantly reduces the complexity of checking the security of the system state. As is well known, checking the security of an arbitrary system with DAC is not algorithmically solvable [9]. The number of equivalence classes is always finite due to the limited number of security attributes and their values. Thus, each subject is a vector in \( n \)-dimensional feature space: \( S_i \in S \subseteq A_1 \times \ldots \times A_n \), and the object is a vector in the \( m \)-dimensional feature space: \( O_j \in O \subseteq B_1 \times \ldots \times B_m \).

Examples of security attributes of a subject include:
- the user on whose behalf the subject is initialized;
- the process level (kernel level or application level);
- the location of the executable object, etc.

Examples of object security attributes:
- system or not system object;
- the type of the object;
- the owner of the object;
- the location of the object in the file system, etc.

### 2.3. Access rules

**Definition 1.** Let the security administrator explicitly fill in a certain cell of the access matrix, that is, the access rule \((S_i, O_j, \alpha)\) or \((S_i, O_j, \alpha)\) is defined, where \(S_i \in S\), \(O_j \in O\), \(\alpha \subseteq P\) \((\alpha \neq \emptyset)\). Such a triplet will be called a precedent (or an explicit access rule).

The task is to set access rights, which are not explicitly defined by the system administrator, for "subject-object" pairs based on the analysis of the existing precedents. That is, it is necessary to determine the values of the unknown access function \(M\) by some known set of its values. In this formulation, the problem reduces to the interpolation of a discrete function.

**The problem of interpolation of the access matrix.** Let subjects and objects be vectors in the spaces of their attributes. Let the security administrator defines a sequence of precedents \(Q = \{(S_{i1}, O_{j1}, \alpha_1), \ldots, (S_{it}, O_{jt}, \alpha_t)\}\). It is required to fill in the remaining cells of the access matrix, that is, based on the set of given precedents, interpolate the discrete access function.

**Definition 2.** The access rule obtained in the automatic mode will be called an implicit access rule.

In order to avoid contradictions in specifying the values of the cells of the access matrix, there should not be two precedents \(q_a = (S_a, O_a, \alpha_a)\) and \(q_b = (S_b, O_b, \alpha_b)\) in the sequence \(Q\) such that \((S_a = S_b) \land (O_a = O_b) \land (\alpha_a \cap \alpha_b \neq \emptyset)\). Given that the administration process is time-dispersed and the functioning of the computer system can lead to new requirements for access control, the condition on the sequence \(Q\) may be violated. In this case, one of three approaches is possible.

1. A new precedent is adopted and the old one is discarded. That is, it is considered that the administrator by default accepts only correct decisions and the new precedent corresponds to the changed requirements for the access control policy.
2. A new precedent is not adopted. In this case, the access control policy does not change significantly with each succeeding precedent. This approach is necessary in the administration of critical information processing systems.

3. Interactive approach. In the event of a collision, the system in interactive mode asks the administrator which of the precedents, old or new, is considered correct.

In turn, the emergence of a new precedent leads to a redefinition of some of the implicit access rules. In all cases, in addition to the full definition of the access matrix, the matrix $M$ is determined ambiguously since it is possible to find various implicit access rules that satisfy the conditions imposed by a sequence of precedents.

3. Interpolation of the access matrix

3.1. Partial interpolation

To determine implicit access rules, it is necessary to formulate some principles for their building. First of all, we will be guided by the principle of issuing minimum rights, which is that when an uncertainty situation arises, the minimum of permissible sets of access rights is selected. However, if we confine ourselves to only one principle of minimal rights, we get a primitive solution, in which all accesses, except explicitly specified, are prohibited. Consider one of the possible examples of determining implicit access rules.

We assume that at the initial instant of time the access matrix is either filled, based on some a priori information, or, using the thesis "everything that is not allowed is forbidden," all the cells contain only access bans. We will fill the cells of the access matrix that correspond to implicit access rules in accordance with the following reasoning.

**Definition 3.** A precedent that defines an implicit access rule is called dominant. If a dominant precedent $(S, O, \alpha)$ is found for the access of the subject $S_i$ to the object $O_j$, then the implicit access rule is determined by analogy with the dominating precedent as $(S_i, O_j, \alpha)$.

**Assumption 4.** We assume that the subject's security attributes dominate the object's security attributes. Moreover, on the family of attribute sets we introduce a linear order: $A_1 > … > A_n > B_1 > … > B_m$.

A dominant precedent is chosen among the precedents influencing on this implicit access rule. Selection of influencing and dominating precedents is carried out in accordance with the rules of partial interpolation of the access matrix: Доминирующий прецедент выбирается среди прецедентов, влияющих на данное неявное правило доступа. Отбор влияющих и доминирующих прецедентов осуществляется в соответствии с правилами частичной интерполяции матрицы доступов:

1. A precedent can influence on the access rights of subjects to objects only in its own row and in its own column of the access matrix.

2. The precedent $(S_{ip}, O_{jp}, \alpha)$ influence on the access of the subject $S_i$ to the object $O_j$, if:
   - $S_i = S_{ip}$ and for objects $O_j$ and $O_{jp}$ the values of at least one attribute are the same;
   - $O_j = O_{jp}$, and for subjects $S_i$ and $S_{ip}$ the values of at least one attribute are the same.

3. If the access of the subject $S_i$ to the object $O_j$ is influenced by the precedents that specify both access of the subject $S_i$ (the precedents are located in the same row of the access matrix) and access to the object $O_j$ (the precedents are located in the same column of the access matrix), then, since the security attributes of the subject dominate the security attributes of the object, the precedents from the same row of the access matrix are more significant.
4. If the access of the subject $S_i$ to the object $O_j$ is influenced by several precedents that determine the access of the subject $S_i$ (the precedents are located in the same row of the access matrix), then the linear order introduced on the set of security attributes of the object is used to identify the dominant precedent: the precedent dominates with the more significant coinciding attribute of objects.

5. If the access of the subject $S_i$ to the object $O_j$ is influenced by several precedents that determine access to the object $O_j$ (the precedents are located in the same column of the access matrix), then the linear order introduced on the set of security attributes of the subject is used to identify the dominant precedent: the precedent dominates with more significant coinciding attribute of subjects.

The specified rules for filling the access matrix allow us to draw the following conclusion. With partial interpolation, the order of precedents does not affect the resulting access matrix. Indeed, the access of the subject $S_i$ to the object $O_j$ depends only on the precedents that influence on it and does not depend on the previous state of the access matrix cells. The resulting algorithm for partial interpolation of the access matrix is formulated as follows:

1. If the cell of the access matrix is defined by a precedent (an explicit access rule), its contents remain unchanged.

2. If the cell of the access matrix is not defined by the precedent, then an implicit access rule is formed for it based on the analogy (coincidence) with the dominant precedent. Selection of the dominant precedent occurs by comparing attributes in accordance with Assumption 4 and the rules for partial interpolation of the access matrix.

**Example 1.** Consider a subsystem that includes three subjects $S_1$, $S_2$, $S_3$ and three objects $O_1$, $O_2$, $O_3$. We confine ourselves to two security attributes for the subjects of the system: $S \subseteq A_1 \times A_2$.

Objects will be characterized by three attributes: $O \subseteq B_1 \times B_2 \times B_3$. The values of the security attributes of subjects $S_1$, $S_2$, $S_3$ and objects $O_1$, $O_2$, $O_3$ are given as follows: $S_1 = (a_1^x, a_2^x)$, $S_2 = (a_1^x, a_3^x)$, $S_3 = (a_2^x, a_3^x)$, $O_1 = (b_1^x, b_2^y, b_3^z)$, $O_2 = (b_1^y, b_2^y, b_3^z)$, $O_3 = (b_1^y, b_2^z, b_3^z)$, with $a_1^x, a_2^x \in A_1$; $a_3^x \in A_2$; $b_1^x, b_1^y \in B_1$; $b_2^x, b_2^y \in B_2$; $b_3^x, b_3^z \in B_3$. Suppose that $P = \{all\}$. Then $[M]_{ij} = 1$ if full access is allowed, and $[M]_{ij} = 0$ if full access is denied. Access permissions or access denials defined by precedents will be marked in square brackets in the access matrix. The default accesses will be denoted by the sign “??”.

Suppose that only one precedent is created: $q_1 = (S_1, O_1, 1)$. Consider the accesses of the same subject to the two remaining objects. Both access $S_1$ to $O_2$ and $S_1$ to $O_3$ will be allowed since the object $O_2$ coincides with $O_1$ by the third attribute $b_3^x$, and $O_3$ coincides with $O_1$ by the first attribute $b_1^x$. The access rights of subjects $S_2$ and $S_3$ to the object $O_1$ will be the same as for the subject $S_1$ since $S_1$ and $S_2$ have the same second attribute $a_2^x$, and for $S_1$ and $S_3$ the first attribute $a_1^x$ coincides (see Table 1).

| Table 1. Partial interpolation of the access matrix for $Q = \{q_1\}$. |
|------------------------------------------|
| $S_1 = (a_1^x, a_2^x)$ | 1 | 1 | 1 |
| $S_2 = (a_1^y, a_3^x)$ | 1 | ? | ? |
| $S_3 = (a_1^x, a_2^x)$ | 1 | ? | ? |

Now suppose that the precedent $q_2 = (S_1, O_3, 0)$ has occurred in the system. The permission to access $S_1$ to $O_2$ is not explicitly specified. The first precedent allows this access, because the third attribute $b_3^x$ is the same, and the second precedent prohibits it, because the second attribute $b_2^y$ is the same. But $B_3 > B_2$, that is, the second attribute is more significant than the third one, so access of $S_1$ to $O_2$ will be prohibited. The access rights of subjects $S_2$ and $S_3$ to the object $O_3$ will be the same as for the subject $S_1$ since $S_1$ and $S_2$ have the same second attribute $a_2^x$, and for $S_1$ and $S_3$ the first attribute $a_1^x$ coincides (see Table 2).
the access rights of subjects to objects not only in its own row and in its own column of the matrix.

Are there other ways of interpolating the access matrix? We require that the precedent can influence each precedent potentially influences on the entire access matrix, the following rules for sequential interpolation of the access matrix can be proposed:

1. Each new precedent can change the accesses in the "own" row. Then accesses in the "own" column can change. That is, the rules of partial interpolation described in the previous section apply to the first stage of processing the precedent.

2. At the second stage, each cell from the precedent’s row that changed its state is considered a precedent for the cells of its column. Here the rules of partial interpolation in the column again apply.

It should be noted that, as in the case of partial interpolation, the resulting access matrix does not depend on the order of precedents.

**Example 2.** Tables 4, 5, and 6 show the result of the rules of sequential interpolation of the access matrix. Angular brackets denote accesses in the cells of the precedent’s row that have changed their state. For example, in Table 5, access of \( S_1 \) to \( O_2 \) is determined by the use of precedent \( q_2 \), and accesses of \( S_2 \) to \( O_2 \) and \( S_3 \) to \( O_2 \) are determined under the influence of access \( S_1 \) to \( O_2 \).
algorithm. Forwarding individual precedents reduces system performance requirements.

The administrator does not need to forward the entire new access matrix, it is enough to send out precedents, on the basis of which all nodes will form access permissions using the same access rules.

Table 5. Sequential interpolation of the access matrix for $Q = \{q_1, q_2\}$.

| $O_1 = (a^1, a^2)$ | $O_2 = (b^1, b^2)$ | $O_3 = (b^1, b^2)$ | $O_4 = (b^1, b^2)$ |
|---------------------|---------------------|---------------------|---------------------|
| $S_1 = (a^1, a^2)$  | $S_2 = (a^1, a^2)$  | $S_3 = (a^1, a^2)$  |
| [1]                 | 1                   | 1                   |
| >0<                 | 0                   | 0                   |
| 0                   | 0                   | 0                   |

Table 6. Sequential interpolation of the access matrix for $Q = \{q_1, q_2, q_3\}$.

| $O_1 = (a^1, a^2)$ | $O_2 = (b^1, b^2)$ | $O_3 = (b^1, b^2)$ | $O_4 = (b^1, b^2)$ |
|---------------------|---------------------|---------------------|---------------------|
| $S_1 = (a^1, a^2)$  | $S_2 = (a^1, a^2)$  | $S_3 = (a^1, a^2)$  |
| [1]                 | 1                   | 1                   |
| 0                   | [1]                 | >1<                 |
| 0                   | 0                   | 0                   |

3.3. Uncertainty situations

For the presented algorithms of interpolation of the access matrix, there can be situations when existing precedents do not allow to determine the type of access for a certain "subject-object" pair. This happens in the following situations:

- there are no precedents influencing on access (see access of subject $S_1$ to object $O_5$ in Table 7);
- from precedents that influence on access you cannot select the dominant one (see access of subject $S_1$ to object $O_7$ in Table 7).

Table 7. Interpolation of the access matrix for $Q = \{(S_1, O_4, 1), (S_1, O_5, 0), (S_1, O_6, 0)\}$.

| $O_4 = (b^1, b^2)$ | $O_5 = (b^1, b^2)$ | $O_6 = (b^1, b^2)$ | $O_7 = (b^1, b^2)$ |
|---------------------|---------------------|---------------------|---------------------|
| $S_1 = (a^1, a^2)$  | $S_2 = (a^1, a^2)$  | $S_3 = (a^1, a^2)$  | $S_4 = (a^1, a^2)$  |
| [1]                 | 1                   | 1                   |
| ?                   | ?                   | ?                   |
| 0                   | 0                   | 0                   |

4. Conclusion

The use of additional security attributes of subjects and objects, determined by the system administrator, significantly expands the options for configuring the DAC policy. The precedent-based approach can be seen as the development and improvement of the default access control system. At the same time, the proposed method of administration the DAC policy refers to decision support methods – algorithms allow to partially automate the process of assigning access rights and provide the administrator with information about access that cannot be determined automatically and require an explicit task.

The developed algorithms do not depend on the order of precedents, which allows you to significantly reduce the amount of memory to store data on the behavior of the system.

It is easy to show that the algorithms for partial and sequential interpolation of the access matrix are polynomial with respect to the quantitative characteristics of the system. Indeed, the implementation of the rules of partial interpolation (rules of the precedent’s influence in the row and in the column) will require no more than $O(m|O|^2 + n|S|^2)$ operations. The complexity of the second stage of the sequential interpolation algorithm does not exceed $O(n|O||S|^2)$. Since the entities of the system are represented by equivalence classes defined by finite sets of values of security attributes, the software implementation of the algorithms for interpolating the access matrix is not difficult.

In the examples given, we limited ourselves to considering only full access. The proposed algorithms can easily be extended to any number of possible accesses. In this case, each precedent specifies its own set of accesses, which either replaces, or does not, the type of access in the cells of the matrix influenced by the precedent.

The use of this approach to the formation of an access matrix may prove to be productive in distributed systems for which there is a problem of reconciling data at different nodes. When changing the access rules, the administrator does not need to forward the entire new access matrix, it is enough to send out precedents, on the basis of which all nodes will form access permissions using the same algorithm. Forwarding individual precedents reduces system performance requirements.
Productivity can also be enhanced by more "soft" formation of access permission when creating new objects and subjects. It is enough for the administrator to set the correct values for the security attributes of the object and the system will independently create access control.

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