Delegation in Role-Based Access Control

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Abstract. User delegation is a mechanism for assigning access rights available to a user to another user. A delegation operation can either be a *grant* or *transfer* operation. Delegation for role-based access control models have extensively studied grant delegations. However, transfer delegations for role-based access control have largely been ignored. This is largely because enforcing transfer delegation policies is more complex than grant delegation policies. This paper, primarily, studies transfer delegations for role-based access control models. We also include grant delegations in our model for completeness. We present various mechanisms that authorise delegations in our model. In particular, we show that the use of administrative scope for authorising delegations is more efficient than using relations. We also discuss the enforcement and revocation of delegations. Finally, we compare our work with relevant work in the literature.

1 Introduction

Role-based access control (RBAC) is being increasingly recognized as an efficient access control mechanism that facilitates security administration [1]. *Roles* are identified with various job functions in an organization and users are assigned to roles based on their job responsibilities and qualifications. Permissions are associated with roles. Users acquire permissions through the roles allocated for them. This feature of role-based models greatly simplifies the management of permissions.

Delegation is a mechanism of assigning access rights to a user. Delegation may occur in two forms: *administrative* delegation and *user* delegation. An administrative delegation allows an administrative user to assign access rights to a user and does not, necessarily, require that the administrative user possesses the ability to use the access right. A user delegation allows a user to assign a subset of his available rights to another user. However, a user delegation operation requires that the user performing the delegation must possess the ability to use the access right. Furthermore, like Schaad, we believe that an administrative delegation operation is often long-lived and more durable (permanent) than a user delegation operation that is short-lived (temporary) and intended for a specific purpose [2, Chapter 7, Page 117]. This paper studies user delegation. In the rest of the paper, ‘delegation’ is always understood to be as ‘user delegation’ unless stated otherwise. The user who performs a delegation is referred to as a ‘delegator’ and the user who receives a delegation is referred to as a ‘delegatee’.

Rights can be delegated in two ways in RBAC: by delegating *roles* or by delegating individual *permissions*. Delegating a permission p gives the delegatee the ability to use p . However, delegating a role r gives the delegatee the ability to act in role r . That is, the delegatee is authorized for role r (and thereby gains the ability to use permissions assigned to role r and roles that are junior to r). In particular, we note that *individually* delegating all permissions explicitly assigned to a role r does not authorize the delegatee to act in role r .

Broadly, delegation of privileges may be classified into (at least) two kinds: *grant* and *transfer* [3]. A *grant delegation* model, following a successful delegation operation, allows a delegated access right to be available to both the delegator and delegatee. As such, this is a *monotonic* model, in which available authorizations are only increased due to successful delegation operations. However, in *transfer delegation* models, following a successful delegation operation, the ability to use a delegated access right is transferred to the delegatee; in particular, the delegated access right is no longer available to the delegator.

Grant delegation models are, primarily, concerned with allowing the delegatee to use the delegated access right. However, in transfer delegation models, besides allowing the delegatee to use the delegated access right, we must prevent the use of the delegated access right by the delegator. It is this feature that makes it more difficult to enforce transfer delegation policies in most access control frameworks [2, 4]. Furthermore, it can be easily seen that, in grant delegation models the availability of access rights increases monotonically with delegations. While some business requirements may support grant delegations, it is often desirable that sensitive access rights may not be available to a large number of users (at any given time). Such requirements are usually expressed as cardinality constraints in an access control policy [5, 6]. Transfer delegation policies prove to be more useful when an access control policy specifies cardinality limits on the availability of access rights between users.

Consider, for example, an access control policy that requires the co-operation of k users to accomplish a given task. The unavailability of (at least) one of the users, which can be for several reasons, makes it impossible to complete the task. A desirable solution would be for users to be able to delegate the access right to another user, who may act on behalf of the former user. In the above example, when assumed that the access control policy specifies that the right r , that is required to complete the task, is available to no more than k users, the reference monitor will always deny an attempt to delegate the right r , using *grant delegation*, to another user to prevent violation of the policy. Such scenarios require that the delegation be made using *transfer delegation*.

Most works that studied delegation in the context of role-based models are grant delegation models [3, 7, 8, 9, 10, 11, 12, 13]. To our knowledge no work has studied temporary transfer delegation for role-based models. This paper, primarily, aims to study transfer delegation for role-based models. Role hierarchies are an important reason for the wide interest in role-based models. Hence, it is natural to consider role hierarchies when studying any aspect of role-based models. The semantics of transfer delegations become more complex when

role-hierarchies are considered. We develop a comprehensive delegation model for role-based systems that provides support for both grant and transfer delegation policies. In this paper, we study delegation in the context of both RBAC₀ model (flat roles) and RBAC₁ model (hierarchical roles) of the RBAC96 family of models [1].

The rest of the paper is organized as follows. In the next section, we develop the background for the rest of the paper and define semantics for grant and transfer delegations. Section 3 describes the mechanism for authorising delegations. Section 4 presents enforcement of delegations. A comparison of our work with related work in the literature is given in Sect. 5. We conclude this work and discuss future work in Sect. 6.

2 Role-Based Delegation

The theoretical development of role-based access control and its standardization has been strongly influenced by the RBAC96 family of models [1]. For this reason, we consider delegation within the context of the RBAC96 family of models. In the next section, we introduce some important prerequisite concepts, including the relevant features of RBAC96 and the concept of administrative scope, which is the building block of the RHA family of administrative models [14].

2.1 Preliminaries

RBAC96. RBAC₀ is the simplest model and defines a set of roles R , a set of permissions P , a set of users U , a permission-role assignment relation $PA \subseteq P \times R$, and a user-role assignment relation $UA \subseteq U \times R$. We denote the set of roles explicitly assigned to a user u by R_u ; that is, $R_u = \{r \in R : (u, r) \in UA\}$ and the set of roles explicitly assigned to a permission p by R_p ; that is, $R_p = \{r \in R : (p, r) \in PA\}$.

RBAC₁ introduces the concept of a *role hierarchy* $RH \subseteq R \times R$. The graph of the relation RH is acyclic and the transitive reflexive closure of RH defines a partial order on R .

We write $r \leq r'$ in preference to $(r, r') \in RH^*$ (the transitive reflexive closure of RH). We may also write $r' \geq r$ whenever $r \leq r'$. We write $\downarrow r$ to denote the set $\{r' \in R : r' \leq r\}$ and $\downarrow R'$ to denote $\bigcup_{r' \in R'} \downarrow r'$. We write $\uparrow r$ to denote the set $\{r' \in R : r' \geq r\}$ and $\uparrow R'$ to denote $\bigcup_{r' \in R'} \uparrow r'$.

Access control decisions are granted within the context of a *user session*, which is determined by the set of roles that a user activates. This set of roles is a subset of the roles for which the user is authorized directly by the UA relation and indirectly by the role hierarchy. We denote a session for user u by $S_u \subseteq \downarrow R_u$. A user u is permitted to invoke a permission p if there exists an activated role $r \in S_u$ and a role $r' \in R$ such that $(p, r') \in PA$ and $r' \leq r$.

Administrative scope. While RBAC96 is widely regarded as the *de facto* standard for role-based access control, there is less consensus regarding role-based administration. There are three approaches that are regarded as being

relatively mature and sophisticated [15]: the ARBAC97 model [16], which is the administrative counterpart of RBAC96; the RHA family of models [14]; and the role control center [15]. Since delegation can be regarded as “lightweight user-based administration”, it is natural that ideas from role-based administration may be useful in models for delegation. Indeed, the `can_delegate` relation in RDM2000 is very similar in structure and meaning to the `can_assign` relation from ARBAC97 [12]. In this section, we introduce the concept of administrative scope from the RHA model and generalize its definition for use in our delegation model.

Definition 1 (Crampton and Loizou [14]). *Let $r \in R$ and define $\sigma(r) = \{s \leq r : \uparrow s \subseteq \downarrow r \cup \uparrow r\}$. We say that $\sigma(r)$ is the administrative scope of r .*

In Fig. 1(a), for example, $\sigma(b) = \{d\}$; $g \notin \sigma(b)$, because $e > g$ and e is not comparable to b . Administrative scope defines a sub-hierarchy forming a natural unit of administration for the role r .

The success of any administrative operation in the RHA model is determined by the inclusion (or otherwise) of any role parameters in the requesting role’s administrative scope. Hence, a user assigned to role b could add a new role i with parent role d , for example, but could not add a new role k with parent role g .

Administrative scope has been shown to be a far more flexible approach to role-based administration than ARBAC97 [14]. As such, it is unsurprising that it turns out to have considerable advantages in role-based delegation. However, it will be necessary to compute the administrative scope of a role in different partially ordered sets, each of which is a sub-hierarchy of the role hierarchy. Hence, we extend our notion of administrative scope to include two parameters: a partially ordered set X and an element $x \in X$. We write $\sigma(x, X)$ to denote the administrative scope of x computed in partially ordered set X . In practice X will be a subset of R . We now discuss the two most important cases.

- If a user u is assigned to a set of roles R_u , this induces a *user view* $\downarrow R_u$ of the role hierarchy containing all the roles to which u is implicitly assigned (via the user-role and role hierarchy relations). This user view is important in defining which roles a user retains following the delegation of a role. In this case, when u delegates r , we compute $\sigma(r, \downarrow R_u)$ (see Proposition 2).
- Similarly, a set of activated roles $S_u \subseteq \downarrow R_u$ defines a *session view* $\downarrow S_u$, which is useful in defining the roles available to a user following certain types of transfer delegation. In this case, when u delegates r , we compute $\sigma(r, \downarrow S_u)$ (see Proposition 3).

2.2 Delegation Operations

We now describe the characteristics of delegation operations in RBAC96. The grant operation is well understood and has been described in several earlier papers [3, 7, 8, 9, 10, 11, 12, 13]. We include it here for completeness. We define three different types of transfer operations in the context of RBAC₁.

RBAC₀.

- grantR₀(u, v, r):** The delegator u grants the role r to delegatee v . The delegator may continue to use r .
- grantP₀(u, v, p):** The delegator u grants the permission p to delegatee v . The delegator may continue to use p .
- xferR₀(u, v, r):** The delegator u transfers the role r to delegatee v . The delegator may no longer use r .
- xferP₀(u, v, p):** The delegator u transfers the permission p to delegatee v . The delegator may no longer use p .

RBAC₁.

- grantR₁(u, v, r):** The delegator u grants the role r to delegatee v . The delegator may continue to use r . The delegatee acquires the right to use all roles in $\downarrow r$.
- grantP₁(u, v, p):** The delegator u grants the permission p to delegatee v . The delegator may continue to use p .
- xferP₁(u, v, p):** The delegator u transfers the permission p to delegatee v . The delegator may not continue to use p .
- xferRstrong(u, v, r):** The delegator u transfers the role r to delegatee v . The delegator may not use any role in $\downarrow r$. The delegatee acquires the right to use all roles in $\downarrow r$. We call this *strong transfer* of a role from the delegator to the delegatee.
- xferRstatic(u, v, r):** The delegator u transfers the role r to delegatee v . The delegator may not use $x \in \downarrow r$ *unless there exists a role r' such that $(u, r') \in UA$ and $x \leq r'$* . (Informally, u retains the use of a role x if there is an alternative path from x to a role to which u is assigned.) We call this *static weak transfer* of a role from the delegator to the delegatee. As before, the delegatee acquires the right to use all roles in $\downarrow r$.
- xferRdynamic(u, v, r):** The delegator u transfers the role r to delegatee v . The roles available to the delegator are determined by the roles he activates in a session. The delegator may not use $x \in \downarrow r$ *unless there exists a role r' such that u has activated r' in the current session and $x \leq r'$* . (Informally, u regains the use of a role x if there is an alternative path from x to a role that u has activated in her session.) We call this *dynamic weak transfer* of a role from the delegator to the delegatee. As before, the delegatee acquires the right to use all roles in $\downarrow r$.

Given the above definitions, the following results are used as a basis for deciding whether the delegator is allowed to use a role following a successful transfer delegation operation. We discuss the enforcement of the consequences of transfer delegations in Sect. 4.

Proposition 2. *If u has performed a static weak delegation of role r , then u is denied access to all roles in $\sigma(r, \downarrow R_u)$, where R_u denotes the set of roles assigned to u .*

Proof. Suppose u cannot use role x . Then $x \leq r$ and there does not exist a role r' such that $(u, r') \in UA$ and $x \leq r'$. Hence, $\uparrow x \subseteq \downarrow r \cup \uparrow r$ in $\downarrow R_u$. The result follows.

Proposition 3. *If u has performed a dynamic weak delegation of role r , then u is denied access to all roles in $\sigma(r, \downarrow S_u)$, where S_u is the set of roles activated by u .*

Proof. The proof is analogous to that of Proposition 2.

Proposition 4. *Let R_{strong} , $R_{dynamic}$ and R_{static} denote the set of roles denied to a user following the operations $\mathbf{xferRstrong}(u, v, r)$, $\mathbf{xferRdynamic}(u, v, r)$ and $\mathbf{xferRstatic}(u, v, r)$, respectively. Then $R_{strong} \subseteq R_{dynamic} \subseteq R_{static}$.*

Proof. $R_{strong} = \downarrow R_u \setminus \downarrow r$, $R_{dynamic} = \downarrow R_u \setminus \sigma(r, \downarrow S_u)$ and $R_{weak} = \downarrow R_u \setminus \sigma(r, \downarrow R_u)$. Now $\sigma(r) \subseteq \downarrow r$ irrespective of the sub-hierarchy in which σ is computed. Hence $R_{strong} \subseteq R_{dynamic}$. Moreover, $S_u \subseteq R_u$ and it is easy to see that this implies that $\sigma(r, \downarrow R_u) \subseteq \sigma(r, S_u)$ (since if $r' \geq x$ for some $x \in \downarrow r$ and some $r' \in S_u$, then $r' \in R_u$).

Consider the role hierarchy depicted in Fig. 1. We assume that some user u is assigned to roles b and f . In the diagram, unfilled nodes represent roles that are available to u (and filled nodes represent nodes that are not available). Each diagram represents different views of the role hierarchy: Fig. 1(a) illustrates the whole hierarchy; Fig. 1(b) illustrates u 's view of the hierarchy; and Figs. 1(d) and 1(e) illustrate two different session views, one in which only role b is activated and one in which only role f is activated.

The user delegates role d , represented by the square node, to another user. Figure 1(b) illustrates the roles that are denied to the user in the event that strong transfer is used to delegate the role. If we are using dynamic weak transfer, then the ability to use role h is determined by whether the user activates role f , as shown in Fig. 1(d) and Fig. 1(e). If we are using static weak delegation, the role h is always available, as depicted in Fig. 1(c).

3 Controlling Delegation

We assume that an access control policy specifies whether delegation of a role or permission is permitted. We also assume the presence of a reference monitor that evaluates such access control policies to determine whether a delegation operation is permitted. There are two issues involved in the specification of delegations:

- Is a user (delegator) authorized to delegate a role or permission that is available to him?
- Can a role or permission be delegated to a user (delegatee)?

In this section, we describe two new mechanisms for authorizing delegations, and discuss their advantages over existing approaches.

Fig. 1. Transfer delegation patterns for role d

3.1 Delegation Relations

Role delegation relation. We introduce two relations that authorize role delegations in a role-based system: **can-delegate** and **can-receive**. The binary relation **can-delegate** specifies the set of roles that can be delegated by a delegator and the relation **can-receive** authorizes delegation of a role to a delegatee.

The relation $\text{can-delegate} \subseteq R \times R$ specifies whether a user is authorized to delegate a role. $(r, r') \in \text{can-delegate}$ specifies that a user u is authorized to delegate role r' , if $r \in R_s$, where R_s denotes the set of roles that are active in u 's current session s . For example, in Fig. 1(a), if $(b, d) \in \text{can-delegate}$ then u may delegate role d if $b \in R_s$.

We define a constraint on the tuples in the **can-delegate** relation that guarantees that no user can delegate a role r that the user is not assigned to. Specifically, we require that if $(r, s) \in \text{can-delegate}$ then $r \geq s$. In our example, in Fig. 1(a), an attempt to add the tuple (b, d) to the **can-delegate** relation will succeed since $b \geq d$. However, an attempt to add the tuple (d, c) to the **can-delegate** relation will fail since $d \not\geq c$.

A delegatee must satisfy a set of conditions, usually role memberships, in order to be authorized to receive a delegation. A *delegation condition* specifies the conditions that must be satisfied by the delegatee to receive a delegation. We adopt the notation of a SARBAC constraint to model a delegation condition [14]. Let $R' = \{r_1, \dots, r_k\}$ be a subset of R and let $\bigwedge R'$ denote $r_1 \wedge \dots \wedge r_k$. We model a delegation condition as $\bigwedge C$ for some $C \subseteq R$. A delegation condition $\bigwedge C$ is said to be *satisfied* by a user v if $C \subseteq \downarrow R_v$. In other words, the condition $\bigwedge C$ is satisfied by the delegatee if he is assigned to all the roles in C . The relation $\text{can-receive} \subseteq R \times C$ specifies whether a user is authorized to receive a role delegation. $(r, C) \in \text{can-receive}$ means a delegatee v may receive a delegation of role r provided that v satisfies $\bigwedge C$.

It may be more efficient to limit the set of roles that a delegatee may receive due to a successful delegation. For example, in Fig. 1(a), is it reasonable for a delegation request to succeed that delegates a role c to a delegatee v who currently is assigned to role g ? We may often require that such delegations are not allowed, since v may lack sufficient expertise to efficiently perform the job requirements of role c . Essentially, we require that a delegation always results in a natural progression for the delegatee with respect to the role hierarchy. We formalize the above requirement by defining the following constraint on the tuples in the can-receive relation: $(r, C) \in \text{can-receive}$ then for all $r' \in C$ we require that $r' \leq r$. Note that this constraint does not apply if r has no junior roles (that is, r is a leaf node in the hierarchy). In our example, $(c, \{g\})$ is not a permissible entry in can-receive ; $(c, \{f\})$, in contrast, is a permissible entry.

In summary, the role-based reference monitor refers to the can-delegate and can-receive relations to establish whether a delegation operation can succeed. A request by u to delegate r to v will succeed only if there exists $(r', r) \in \text{can-delegate}$ such that $r' \in R_s$, where s is u 's current session and a tuple $(r, C) \in \text{can-receive}$ such that v satisfies $\bigwedge C$. In our example, let us assume that $(b, d) \in \text{can-delegate}$, $(d, \{g\}) \in \text{can-receive}$, $(u, b) \in UA$ and $(v, g) \in UA$. Then an attempt by u to delegate role d to v will succeed.

Permission delegation relation. We define a relation $\text{can-delegatep} \subseteq R \times P$ that specifies the set of permissions that can be delegated by a user u . $(r, p) \in \text{can-delegatep}$ specifies that a delegator u may delegate a permission p provided that there exists $r \in R_s$. Similar to the can-delegate relation, we define a constraint on the can-delegatep relation that guarantees that no user u can delegate a permission p that is not available to u . In other words, we require that if $(r, p) \in \text{can-delegatep}$ then there exists a role r' such that $(p, r') \in PA$ and $r' \leq r$.

The relation $\text{can-receivep} \subseteq P \times C$ specifies whether a user is authorized to receive a permission delegation, where C is a delegation condition as defined above. $(p, C) \in \text{can-receivep}$ means that a delegatee v is authorized to receive a delegation of a permission p if v satisfies $\bigwedge C$. Similar to the can-receive relation, we define a constraint on the can-receivep relation that ensures that a delegation always results in a natural progression for the delegatee with respect

to the role hierarchy. If $(p, C) \in \text{can-receive}$ then there must exist $r' \in C$ and $r \in R$ such that $(p, r) \in PA$ and $r' \leq r$.

3.2 Using Administrative Scope

The use of relations for controlling delegations, discussed above, has been used extensively in the literature mainly perhaps because of its simplicity [7, 12, 13]. The use of relations is simple, if we assume that RBAC relations, such as the role hierarchy relation RH , remain static. However, updates to the RBAC relations may lead to inconsistencies in the can-delegate and can-receive relations. Such inconsistencies are explained in detail in Sect. 3.3. For now, we note that the dynamic nature of various RBAC components increases the complexity of managing the relations that are used for controlling delegations. It is our belief that the mechanism used for controlling delegations must be simple and able to implicitly handle any updates to RBAC relations. In this section, we suggest an alternative method for controlling delegations, which dynamically handles updates to RBAC relations using the concept of administrative scope [14].

We limit the extent to which a user can delegate roles and permissions using the administrative scope of the role(s) activated by the user. Specifically, we define the administrative scope of a session s to be

$$\sigma(s) = \bigcup_{r \in S} \sigma(r).$$

Then in order for the delegation of role r by user u to succeed we require that $r \in \sigma(s)$, where s is u 's current session. In other words, u can only delegate roles that are within his administrative scope. Similarly, in order for the delegation of permission p by user u to succeed we require that there exists $r \in s$ such that $(p, r) \in PA$ and $r \in \sigma(s)$.

We now consider what criteria the delegatee must satisfy to be able to receive a delegation. Informally, for the delegation of r to v to succeed, we require that v is already "sufficiently authorized". Now, the delegation of role r means that the delegatee is authorized for all roles $r' \leq r$. These observations lead to the idea that the delegatee should already be assigned to any roles outside the delegator's administrative scope that the delegatee will acquire as a result of the delegation. More formally, for the delegation of role r to user v by user u to succeed we require that for all $r' < r$ such that $r' \notin \sigma(s)$, there exists r'' such that $r' \leq r''$ and $(v, r'') \in UA$.

In our example, Fig. 1(a), u (who is assigned to b and f) may delegate role d since $d \in \sigma(b)$. Moreover, the delegation of d to user v will only succeed if v is already assigned to role g . Note, however, that a user w who is assigned (only) to role f will not be able to receive the delegated role d (from u) because $g \notin \sigma(s)$, $g < d$ and w is not assigned to g .

Administrative scope implicitly deals with any updates to various RBAC relations, in particular the role hierarchy relation RH , since administrative scope of a session s is computed, dynamically, with respect to the role hierarchy. Consider, for example, Fig. 2(a) and Fig. 2(b) that depicts our original role hierarchy

and a role hierarchy that is obtained after deleting an edge between roles d and b . In the original hierarchy, if a user u has activated b in a session s then u is authorized to delegate role d since $d \in \sigma(s)$. However, following the edge deletion operation, u is no longer able to delegate d since $d \notin \sigma(s)$. In other words, the success of delegation operations adapts in a natural and transparent way to changes in the structure of the role hierarchy. Figure 2(c) depicts the role hierarchy obtained after deleting an edge between roles g and d . In the original hierarchy, the delegatee v , who is assigned to role g , can receive a delegation of role d since $g < d$. Following the edge deletion operation, v will not be able to receive a delegation of d because $g \not< d$. Note that in Fig. 2(c) there are no roles less than d . This observation leads to the result that no user can receive a delegation of a role $\{r \in R : \downarrow r \subseteq \uparrow r \cap \downarrow r\}$.

Fig. 2. Role hierarchies *before* and *after* edge deletion

3.3 Discussion

Most work in the literature uses a single relation to control delegation [7, 12, 13]. This relation encodes conditions on both the delegator and delegatee. We have proposed an alternative approach where the above issues are dealt with independently. There are several advantages in dealing with these issues separately. Primarily, it eases the management of delegation specification. Furthermore, such an approach employs separation of tasks, thus, making the model less error prone while updating delegation policies. For example, if we wish to revoke the authority of a role r to perform any delegations, then appropriate tuples are deleted from the **can-delegate** relation. Note that such an operation does not require any updates to the **can-receive** relation that authorizes a delegation to the delegatee. Similarly, if we require that a permission p may no longer be delegated to a delegatee who satisfies a condition $\bigwedge C$, we only delete necessary tuples from the **can-receive** relation.

The use of relations to control delegation is common to most existing approaches, mainly perhaps because of its simplicity [7, 12, 13]. The use of relations

is appropriate, if we assume that RBAC structures such as the role hierarchy remain static. However, updates to the role hierarchy may lead to inconsistencies in the **can-delegate** and **can-receive** relations. Consider, for example, Fig. 2(a) and Fig. 2(b) that depict an original role hierarchy and a role hierarchy obtained after deleting an edge between roles d and b . If $(b, d) \in \text{can-delegate}$ it will need to be *explicitly* deleted following the deletion of this edge. Similar considerations apply to the operations that involve revocation of a permission p assigned to b . Similarly, if $(b, \{d\}) \in \text{can-receive}$, then we must delete this entry following the deletion of the edge between b and d . In summary, the **can-delegate** and **can-receive** relations must be updated after updates to certain RBAC relations to prevent inconsistencies.

Hence the advantages of using relations for controlling delegations are limited if we allow updates to RBAC relations. In contrast, administrative scope is a *dynamic* model and *implicitly* deals with any updates to RBAC relations. It is important to note that, following successful updates to RBAC relations, no explicit updates are required with the use of administrative scope to resolve any inconsistencies involved in controlling delegations. This is because administrative scope (and hence delegation) is determined by the structure of the role hierarchy. In short, the use of administrative scope greatly simplifies delegation in the presence of dynamic RBAC structures.

Furthermore, the administrative scope model for controlling delegations preserves the separation of conditions on delegator and delegatee that we introduced in our relation-based model. The issues that are involved in controlling delegations, such as specifying the roles that a user is authorized to delegate and receive, are still dealt with independently. Note also that the constraint we use to limit the increase of power of the delegatee can be framed very elegantly using administrative scope and existing RBAC relations.

4 Enforcing Delegation Constraints

Enforcing delegation operations that grant a role or permission to a user is quite straightforward as it is a monotonic action. That is, the set of roles or permissions for each user either stays the same or increases. Delegation operations that transfer a role or permission are rather more difficult. In this section, we introduce three relations that are used to guarantee that delegation operations are enforced correctly. The model described in this section can be used for both grant and transfer delegations. To our knowledge, this is the first treatment of the consequences of temporary transfer delegation policies for access control in role-based systems. This is mainly due to the fact that there is much to say on the subject when grant delegations, but not transfer delegations, are allowed in role-based models.

4.1 The Delegation History Relation

The delegation history (DH) relation is used to record all delegations that have been made. The DH relation is used by the delegators and administrative users

for administrative purposes. Typically, such activities include auditing and re-voking delegations.

A DH tuple has the form (i, u, v, o, C, M) where i is an identifier, u is a delegator, v is the delegatee, o is an object or target of the delegation that can either be a set of roles $R' \subset R$ and/or a set of permissions $P' \subseteq P$, C is the set of conditions, from the **can-receive** relation, that must be satisfied by the delegatee and M is a *delegation mask*. A delegation mask records various internal details of a delegation.

A delegation mask M contains five bits which are used to record certain details of the delegation. More specifically, a delegation mask has the form $b_4b_3b_2b_1b_0$, where $b_i \in \{0, 1\}$, b_4 specifies whether the delegated object can be further delegated¹, b_3 specifies whether the delegated object is a role or permission, b_2 specifies whether the delegation is static or dynamic, b_1 specifies whether the delegation is strong or weak, and b_0 specifies whether the delegation is grant or transfer. The characteristics of a delegation mask are summarized in Table 1, and some examples of masks are shown in Table 2 together with the commands that would give rise to such a mask.

Note that we require the delegator to explicitly set a few values of the bits in the delegation mask while performing a delegation operation. In particular, we require that the bits b_0 , b_1 and b_2 are set by the delegator, while the bits b_3 and b_4 are deduced by the access control enforcement system.

Table 1. Delegation mask bit values

	b_4	b_3	b_2	b_1	b_0
0	undelegatable	role	static	strong	grant
1	delegatable	permission	dynamic	weak	transfer

4.2 Temporary Delegation Relations

We also introduce two relations $tempUA$ and $tempPA$, which record temporary user-role and user-permission assignments that arise from delegation operations. $tempUA$ contains tuples of the form (i, u, r, s) , where $s \in \{-, +\}$ and i identifies a tuple in the DH relation. The meaning of the tuple $(i, v, r, +)$ is analogous to $(v, r) \in UA$; such a tuple would arise as a result of a grant or transfer of role r to the delegatee v . In contrast, a tuple of the form $(i, u, r, -)$ means that u is prohibited from activating role r ; such a tuple only arises when u transfers r to v . The precise set of roles that are unavailable for the delegator u depends on the transfer type used for delegation (strong, weak static or weak dynamic).

$tempPA$ contains tuples of the form (i, u, p, s) , where $s \in \{-, +\}$ and i identifies a tuple in the DH relation. The tuple $(i, v, p, +)$ means that v is allowed

¹ An extra boolean-valued parameter can be added to each of the delegation commands; this parameter would be used to set this bit.

Table 2. Examples of valid delegation mask values, their semantics, and associated commands

Mask	Delegation semantics	Command
00xx0	undelegatable, role, grant	grantR
10x01	delegatable, role, strong, transfer	xferRstrong
00011	undelegatable, role, static, weak, transfer	xferRstatic
10111	delegatable, role, dynamic, weak, transfer	xferRdynamic
11xx0	delegatable, permission, grant	grantP
11x01	delegatable, permission, strong, transfer	xferPstrong
01111	undelegatable, permission, dynamic, weak, transfer	xferPdynamic
11011	delegatable, permission, static, weak, transfer	xferPstatic

to use p ; such a tuple would arise as a result of a grant or transfer of permission p to the delegatee v . A tuple of the form $(i, u, p, -)$ means that u is prohibited from invoking permission p ; such a tuple only arises when u transfers p to v .

For simplicity, we write (i, u, R', s) to denote $\{(i, u, r', s) : r' \in R'\}$. We also write (i, u, P', s) to denote $\{(i, u, p', s) : p' \in P'\}$. We now describe the effects on various relations following the successful execution of a delegation operation. We focus our attention on the more difficult case of RBAC_1 .

Successful delegation operations are recorded in the delegation history relation DH . Hence, following any delegation of o by u to v , we have $DH \leftarrow DH \cup \{(i, u, v, o, C, M)\}$. In addition we have the following operational semantics:

- grantR₁**(u, v, r): u grants role r to v . Such a delegation requires that the delegatee v is allowed to use role r . Hence, $\text{tempUA} \leftarrow \text{tempUA} \cup \{(i, v, r, +)\}$.
- grantP₁**(u, v, p): u grants permission p to the delegatee v . Then, permission p must be available to the delegatee v . Hence, $\text{tempPA} \leftarrow \text{tempPA} \cup \{(i, v, p, +)\}$.
- xferP₁**(u, v, p): delegator u transfers the authority to use permission p to the delegatee v . Hence, we add $\text{tempPA} \leftarrow \text{tempPA} \cup \{(i, v, p, +), (i, u, p, -)\}$.
- xferRstrong**(u, v, r): u performs a strong transfer of role r to v . The delegator u may not use any role in $\downarrow r$ and the delegatee v acquires the right to use all roles in $\downarrow r$. Hence, $\text{tempUA} \leftarrow \text{tempUA} \cup \{(i, v, r, +), (i, u, R', -)\}$, where $R' = \downarrow r$.
- xferRstatic**(u, v, r): u performs a static weak transfer of role r to v . The delegator u may not use a role $x \in \downarrow r$ unless there exists a role r' such that $(u, r') \in UA$ and $x \leq r'$. Hence, by Proposition 2, $\text{tempUA} \leftarrow \text{tempUA} \cup \{(i, v, r, +), (i, u, R', -)\}$, where $R' = \sigma(r, \downarrow R_u)$.
- xferRdynamic**(u, v, r): u performs a dynamic weak transfer of role r to v . The set of roles available to the delegator u are computed by the roles that

u activates in a session. Hence, by Proposition 3, $tempUA \leftarrow tempUA \cup \{(i, v, r, +), (i, u, R', -)\}$, where $R' = \sigma(r, \downarrow S_u)$.²

4.3 Access Control Decisions

The role-based reference monitor uses the $tempUA$ and $tempPA$ relations, in addition to the UA and PA relations, to make access control decisions. For example, an attempt by a user u to activate a role r is always denied if there exists a tuple $(i, u, R', -) \in tempUA$ such that $r \in R'$; and granted if there exists a tuple $(i, u, r', +) \in tempUA$ or $(u, r') \in UA$ such that $r \leq r'$. Similarly, an attempt to invoke a permission p by u is always denied if $(i, u, p, -) \in tempPA$; and granted if $(i, u, p, +) \in tempPA$ or there exist $r, r' \in R$ such that $(p, r) \in PA$, $(u, r') \in UA$ and $r \leq r'$.

4.4 Revocation

Successful delegations have a specified lifetime or may be revoked before the delegation ends.³ In either case, the $tempUA$ and $tempPA$ relations must be updated to prevent any subsequent use of the delegated access right by the delegatee and, if necessary, to allow the delegator to use the delegated access right. Essentially, we require that when a delegation $d \in DH$ ends or is revoked the tuples $(i, u, R', s) \in tempUA$ and $(i, u, P', s) \in tempPA$ are *deleted*, where i identifies the obsolete delegation d . We now describe the effects on various relations when a delegation ends or is revoked.

grantR₁(u, v, r): When such a delegation ends, the delegatee v is no longer allowed to use role r . Hence, $tempUA \leftarrow tempUA \setminus \{(i, v, r, +)\}$.

grantP₁(u, v, p): permission p must no longer be available for the delegatee v . Hence, $tempPA \leftarrow tempPA \setminus \{(i, v, p, +)\}$.

xferP₁(u, v, p): delegatee v must be prevented from using permission p and the delegator u regains the ability to use the delegated permission p . Hence, $tempPA \leftarrow tempPA \setminus \{(i, v, p, +), (i, u, p, -)\}$.

xferRstrong(u, v, r): u performs a strong transfer of role r to v . The delegator u gets back the right to use any role in $\downarrow r$ and the delegatee v can no longer use any role in $\downarrow r$. Hence, $tempUA \leftarrow tempUA \setminus \{(i, v, r, +), (i, u, R', -)\}$ where $R' = \downarrow r$.

² It is important to note that, following a dynamic weak transfer, the roles that are to be prevented for the delegator u are determined by the roles that are active in u 's current session. Hence, it is necessary to add appropriate tuples to the $tempUA$ relation whenever a session is initiated by a user who has performed a weak dynamic delegation.

³ In a practical implementation, the DH relation would include some information that would determine the lifetime of the delegation: this information might be a start and an end time, or a start time and a duration, for example.

xferRstatic(u, v, r): u performs a static weak transfer of role r to v . Similar to the above delegation, the delegator u gets back the right to use any role in $\downarrow r$ and the delegatee v can no longer use any role in $\downarrow r$. Hence, $tempUA \leftarrow tempUA \setminus \{(i, v, r, +), (i, u, R', -)\}$ where $R' = \sigma(r, \downarrow R_u)$.

xferRdynamic(u, v, r): u performs a dynamic weak transfer of role r to v . Again, the delegator u regains the right to use any role in $\downarrow r$ and the delegatee v can no longer use any role in $\downarrow r$. Hence, $tempUA \leftarrow tempUA \setminus \{(i, v, r, +), (i, u, R', -)\}$ where $R' = \sigma(r, \downarrow S_u)$.⁴

5 Related Work

Several delegation models have been proposed for role-based access control [3, 7, 8, 9, 10, 11, 12, 13]. The early work of Barka and Sandhu was instrumental in identifying the important considerations for delegation in RBAC [3]. This included the concepts of *monotonic* and *non-monotonic* delegation, which correspond to our grant and transfer models. To our knowledge, the work that we present in this paper represents the first attempt to deal properly with the consequences of temporary non-monotonic delegation in RBAC.⁵

Of the work in the literature, the RBDM0, RDM2000 and PBDM models are closest to our work [7, 8, 12, 13]. RBDM0 is a model for delegating roles, and is based on the RBAC₀ model of the RBAC96 family of models [7]. Another role delegation model for role-based access control is presented in [8]. RDM2000 defines a rule-based framework for delegation and revocation [12]. The model considers role hierarchies and also provides support for multi-step delegations. The PBDM model proposes a delegation model for permissions that supports multi-step delegations [13].

The RDM2000 model uses a relation $can_delegate \subseteq R \times 2^R \times \mathbb{N}$ to authorize delegations, $\mathbb{N}$ is the set of natural numbers. If $(r, C, n) \in can_delegate$, a delegator acting in role r may delegate any role $r' \leq r$ to a delegatee v provided v satisfies some role assignment conditions specified by C ; n is used to define the maximum depth of a delegation. A major limitation of this relation is that no constraints are defined on the tuples in the $can_delegate$ relation. That is, r and C are not required to have any relationship with each other. What this means is that the delegatee's power can be arbitrarily increased by a successful delegation. In practice, a delegatee can be assigned to roles for which they lack any relevant expertise or experience.

The PBDM model uses a similarly named relation $can_delegate \subseteq R \times R \times P \times \mathbb{N}$. If $(r, r', P', n) \in can_delegate$ then a delegator who is assigned to role r

⁴ Recall that, following a dynamic weak transfer of a role r , we determine the roles that are not available for the delegator u , in a session s , by computing $\sigma(r, \downarrow S_u)$ (see Proposition 3). Hence, it may also be necessary to delete appropriate tuples from the $tempUA$ and $tempPA$ relations when the delegator u deactivates a role.

⁵ Barka distinguishes between temporary and permanent delegation for role-based delegation models [17]. We believe the latter is more correctly viewed as an administrative activity. Barka does not consider temporary non-monotonic delegation policies (which we call transfer delegation policies).

can delegate the set of permissions P' to a user who is assigned to a role r' with a maximum delegation depth of n . Like the RDM2000 model, the *can_delegate* relation does not require that there is any relationship between P' and r , which means that it is possible for a delegator u to delegate a permission p that is not available to u . As we have already noted, these relation-based approaches to delegation are unlikely to be suitable in environments where the role hierarchy may change.

Unlike the above discussed models, which use a single relation for controlling delegations, we use two different relations: **can-delegate** and **can-receive**. Advantages of using different relations for controlling delegations include flexibility, greater control while specifying delegations, ease of management and is less error prone. Furthermore, our model for controlling delegations defines constraints on the **can-delegate** and **can-receive** relations. Such constraints ensure that the tuples that are added to the **can-delegate** and **can-receive** relations does not give the authority for a delegator u to delegate a right that is not available to u and the rights of a delegatee v can only be incrementally increased and are limited by v 's existing rights.

Hence, we believe our delegation specification model is more conservative (and thus safer), more fine-grained and more manageable than these models [7, 8, 12, 13]. However, in Sect. 3.3, we observed that the use of relations for controlling delegations may not be efficient for implicitly handling updates to various RBAC relations. Our model includes an alternative way of controlling delegations using the concept of administrative scope [14]. The administrative scope model is dynamic and implicitly handles any updates to RBAC relations, in particular the role hierarchy relation RH . We have also described the enforcement of both grant and transfer delegations and dealt with revocations.

A delegation model with restricted permission inheritance is proposed in [9]. The model is based on the idea of dividing a role hierarchy into inter-related role hierarchies. A cascaded role delegation model in the context of decentralized trust management systems is presented in [10]. Another model that supports delegation of both roles and permissions is discussed in [11]. We believe that our

Table 3. Delegation characteristics in various delegation models

Characteristic	RBDM0	RDM2000	PBDM	Our model
Role delegation	✓	✓	✓	✓
Permission delegation	✗	✗	✓	✓
Grant delegation	✓	✓	✓	✓
Transfer delegation	✗	✗	✗	✓
Controlling delegations	✓	✓	✓	✓
Implicit updates	✗	✗	✗	✓
Delegation history	✗	✓	✗	✓
Temporary delegation assignments	✓	✓	✓	✓
Revocation	✓	✓	✓	✓

model can easily be extended to incorporate these concepts. However, none of the above work considers transfer delegation for role-based systems. Table 3 compares the support provided for key delegation features by well known delegation models.

6 Conclusions and Future Work

We have developed a comprehensive delegation model for role-based access control that provides support for both grant and transfer delegation policies. This is the first attempt in the literature that extensively studies transfer delegations for role-based access control.

We have discussed two mechanisms for controlling delegations: the relations approach and the administrative scope approach. In particular, we have shown that the concept of administrative scope can be used for authorising delegations and is more effective than relations for delegation in dynamic environments.

We have also presented an enforcement mechanism that supports both grant and transfer delegation policies. Our enforcement model uses a delegation history relation *DH* and temporary delegation relations, *tempUA* and *tempPA*, to guarantee that delegations are enforced correctly. We also discussed various effects on the above relations following a successful delegation operation and corresponding revocations.

An immediate priority in future work is to enrich the revocation mechanism that has been described in this paper. Most importantly, we wish to provide support for cascaded revocations. That is, if a delegation is revoked and this delegation had been used to generate other delegations, then the latter delegations must also be revoked. We may also consider revocation of a delegation when a user is revoked from a role $r \in C$, where C is a delegation condition. Another future work is to consider supporting revocations such as those discussed in [18]. Furthermore, we wish to define necessary commands that provide an option to set the delegatable flag in delegation mask. A long term goal is to develop abstract Java classes that implement our delegation model.

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