An Activity-Based Model for Separation of Duty

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ABSTRACT
This paper offers several contributions for separation of duty (SoD) administration in role-based access control (RBAC) systems. We first introduce a new formal framework, based on the so-called activity concept. This notion helps organizations define SoD constraints in terms of business requirements and reduces management complexity in large-scale RBAC systems. The model enables the definition of a wide taxonomy of conflict types. In particular, object-based SoD is introduced using the SoD domain concept, namely the set of data in which transaction conflicts may occur. Together with the formalization of the above properties, in this paper we also show the effectiveness of our proposal: we have applied the model to a large, existing organization; results highlight the benefits of adopting the proposed model in terms of reduced administration cost.

1. INTRODUCTION

Role-based access control (RBAC) [2] is a well known and recognized good security model for enterprise access control management. Central to the model is the role concept (a set of access permissions) with users assigned to roles based on duties to fulfill. One of the main benefits related to adopting the RBAC model is the abstraction level introduced by a role. Roles help organizations manage complex structures and large number of identities and permissions within their IT systems. Indeed, a role represents an intermediate layer between permissions (typically managed by IT staff) and users (typically managed by business staff). This helps organizations prevent users from accessing information at their own discretion. In this sense, the role is a business concept although not the only one to be considered when addressing access control. Other business elements, such as business processes or organization structure, should be included in the overall access control model. To date only a few implementations extend the RBAC model with other business properties.

Another important benefit related to RBAC is represented by its simple security administration. RBAC is universally recognized as a policy-neutral access control model in the sense that using hierarchies and constraints, a wide range of security policies can be expressed, including discretionary access control (DAC), mandatory access control (MAC), and user-specific access control [6, 14]. Among all possible aspects of security policy, separation of duty (SoD) is probably the most important. Alternatively indicated as “conflict of interest” or “mutual exclusion”, SoD usually refers to the identification of operations which should not be granted to an individual user. For instance, an employee acting as a financial manager may not be allowed to act as a financial auditor at the same time. There are several types of frameworks proposed in literature for SoD administration [1, 4, 7, 9, 10, 17, 18, 20, 21]. Nevertheless, when thousands of users, roles, and permissions have to be managed, such frameworks do not scale well, so that administering SoD in large-scale RBAC systems is still quite challenging. Moreover, existing frameworks do not leverage business elements to simplify the SoD administration in complex environments.

This paper describes a new framework for administering separation of duty constraints, particularly suitable for large-scale RBAC systems. The framework is based on the following steps: first, the business processes are decomposed into business activities; this may be entirely done by business staff. Then, access permissions supporting all the activities are identified by IT staff. Potential conflicts among activities are also provided, again by business staff, leveraging a business perspective. Such information is used to compute conflicts among RBAC entities—permissions, roles and users. We show how the proposed model offers a natural way to define SoD constraints and to reduce management complexity in large-scale RBAC systems. The proposed model allows a wide taxonomy of conflict types; in particular, we introduce the SoD domain concept as the set of data in which transaction conflicts may occur. Introducing SoD domains makes it possible to easily define more expressive constraints such as object-based separation of duty. Finally, we have applied the proposed model on real data from a large organization. Results confirm that our proposal greatly reduces the administration cost required to manage RBAC systems.

The remainder of the paper is organized as follows: Section 2 offers a survey of state of the art as for SoD constraint and role administration techniques. Section 3 summarizes the main RBAC concepts needed to formally analyze the problem. Section 4 provides a theoretical analysis of the problem, introducing both the activity and the SoD domain concepts. Section 5 offers a trivial usage example of the proposed model. Section 6 shows an application of the model to a large, actual organization. Finally, Section 7 offers some final considerations.

2. RELATED WORK

Separation of privilege is one of the founding principles for the protection of information according to Saltzer and
Schroeder [16]. Further, Clark and Wilson [3] identified separation of duty as one of the two major mechanisms that can be implemented to ensure data integrity. At the policy level, processes can be divided into steps, with each step being performed by a different agent.

Several attempts to formally define separation of duty constraints can be found in literature, especially in role-based access control [4,9,17,18]. Simon and Zurko [20] provide a comprehensive classification, enumerating the different kinds of conflicts. Kuhn [7] proposes mutual exclusion of roles as a separation of duty mechanism; SoD requirements are categorized according to the time mutual exclusion is applied. Also Nyanchama and Osborn [10] describe a way to implement various types of conflicts; they evaluate the effect of role hierarchies in terms of their role-graph model. Alm and Sandhu [1] define the RSL99 language for specifying separation of duty constraints.

All the aforementioned works are mainly based on the core RBAC entities, namely permissions, roles, sessions, and users, missing other business elements. Yet, since SoD is a business requirement, other business aspects affecting SoD are expected to be identified. For instance, although a user’s privileges are often granted based on the tasks the user is expected to fulfill, the concept of tasks is usually not explicitly modeled in access control [5]. Perelson and Botha [15] provide a solution for the specification of static separation of duty requirements in role-based workflow environments. The authors identify the impact of SoD on work process models. Then they extend the typical RBAC model to include the notion of task. Although tasks are taken into consideration during conflict analysis, they are not used as elements for defining conflicts. Likewise, Irwin et al. [5] introduce the task concept as a means to determine users’ privileges and use tasks to define some security properties. Other works attempt to highlight the importance of business information in role-based access control, but they principally address role administration and definition, not always considering SoD. For example, Oh and Park [12] highlight how, in real implementations, users must have permissions to complete a task. Their T-RBAC model [11] is an example of RBAC extension that introduces “task” as a business concept. Schaaf and Moffett [19] propose the Aloy language to model organizational control principles, such as those expressed in separation of duty, supervision and delegation. While other important frameworks for administering RBAC systems strive to include business elements as well [10,13,22], SoD administration based on a modeling of business is not always provided.

3. BACKGROUND

This section offers some of the concepts in the RBAC model [2] that will be used in the following. The entities of interest for the present analysis are:

- **PERMS**, the set of all possible access permissions;
- **USERS**, the set of all system users;
- **ROLES** ⊆ **PERMS**; the set of all roles;
- **UA** ⊆ **USERS** × **ROLES**, the set of all role-user relationships;
- **PA** ⊆ **PERMS** × **ROLES**, the set of all role-permission relationships;
- **RH** ⊆ **ROLES** × **ROLES**, the set of hierarchical relationships between roles.

The symbol “≥” indicates an ordering operator representing a path of direct relationships in RH. If r₁ ≥ r₂, then r₁ is referred to as the child or the senior of r₂. Similarly, r₂ is the parent or the junior of r₁.

The following functions are also provided:

- **ass_users**: ROLES → 2**USERS** to identify users assigned to a role and to none of its senior roles, according to UA.
- **ass_users**: ROLES → 2**USERS** to identify users assigned to a role or to at least one of its seniors, according to UA and RH.
- **ass_perms**: ROLES → 2**PERMS** to identify permissions assigned to a role and to none of its senior roles, according to PA.
- **ass_perms**: ROLES → 2**PERMS** to identify permissions assigned to a role or to at least one of its seniors, according to PA and RH.

In applying dynamic security policies, the session concept should be taken into account. Each session identifies the set of active roles for a given user. A user may be associated with multiple sessions at any moment in time. This feature supports the principle of least privilege: that is, a user assigned to multiple roles may activate any subset of these roles to perform his/her tasks. This may be used in support of dynamic separation of duty policies. According to the RBAC standard, the function **session_roles**: SESSIONS → 2**ROLES** identifies the set of active roles for the user associated to the given session.

Finally, note that according to the standard, a permission is an abstract concept that refers to the arbitrary binding of operations and objects. This means that elements of **PERMS** are actually pairs (o,m), where o ∈ **OBS** indicates the object and m ∈ **OPS** the way in which the object is accessed—where **OBS** and **OPS** indicate, respectively, the set of objects and operations monitored by the access control system. In this paper permissions are always considered as a single unit, except when referred to SoD domains (see Section 4.3), where objects are used to group permissions.

4. MODEL DEFINITION

This section illustrates a new SoD model, where conflicts are not directly defined among permissions or roles, but among business activities. The rationale is that large companies typically have hundreds of thousands of permissions and roles, while possessing only a few hundred activities. Therefore, managing activities is often easier than managing other RBAC entities. Tasks are a natural way to think about user actions and their contexts [5], making the identification of users performing conflicting activities more intuitive than the identification of users assigned to conflicting roles or possessing conflicting permissions.

Most of the existing SoD models are characterized by defining conflicts among permissions or roles. For instance, Kuhn [7] proposes mutual exclusion of roles (i.e., roles which should not be simultaneously assigned to a user) as a separation of duty mechanism. But defining SoD conflicts among roles could lead to inconsistent constraint definitions. This is because user’s capabilities are vested in permissions, not roles. For instance, suppose we have roles r₁, r₂, and r₃ where only r₁ and r₂ are specified as being mutually exclusive. However, r₂ and r₃ might be assigned with the same permission set (i.e., ass_perms(r₂) = ass_perms(r₃))
or, more generally, they might share the same permissions which generate conflicts with role \( r_1 \) (i.e., capabilities provided by \( \text{ass-perms}^*(r_2) \)) and \( \text{ass-perms}^*(r_3) \) are conflicting with capabilities provided by \( \text{ass-perms}^*(r_1) \)). According to this observation, both pairs \( \{r_1, r_2\} \) and \( \{r_1, r_3\} \) would provide a user with the same conflicting permissions. While no user could be assigned to both \( r_1 \) and \( r_2 \) at the same time, a user could be simultaneously assigned to \( r_1 \) and \( r_3 \) since these are not defined as conflicting at the role level, tough providing a user with equal conflicting permissions. This illustrates how defining conflicts among roles can easily lead to ill-defined SoD constraints or, even worse, allows to entirely bypass other constraints.

According to the previous observation, the correct approach should be to define conflicting permissions, namely sets of permissions which should not be simultaneously possessed by the same user. If permission conflicts are known, it will be possible to deduce role conflicts: conflicting roles would be those having conflicts in the union of their assigned permissions. Therefore, specifying conflicts among permissions provides a finer granularity as opposed to specifying conflicts at the role level. Yet, in large organizations there could be hundreds of thousands of permissions, leading to an unmanageable situation. Besides this, it is usually difficult to find a user within the organization who has both the business and the IT knowledge required to identify conflicting permissions.

In order to reduce complexity of SoD constraint description, we propose an alternative approach where conflicts are not directly defined among permissions or roles. Before explaining how the proposed model addresses this problem, it is necessary to introduce the activity concept.

### 4.1 Business Activities

Activities are identified by decomposing business processes of an organization. From an access control point of view, an activity is a set of permissions necessary to perform a certain task. In this sense, the activity and role concepts are similar in that they both group permissions, but do have some important differences:

- **Meaning.** Roles group permissions to be assigned to a user in order to support the work he/she has to do, but do not always directly map to specific business activities. Some roles having no business meaning could simply be defined out of convenience. For example, when the hierarchical RBAC model is adopted, a so called “connector role” represents the intersection of permissions assigned to all the derived roles; but the connector role may have no business meaning. Additionally, some RBAC implementations offer a way to define IT and business roles. Business roles are typically established by the business (e.g., Employee, President, Trader, etc.) whereas IT roles are established by the application owners (e.g., admin, user, auditor, etc.). In these systems, it is expected that mapping business roles to IT roles would simplify policy specification. In such case, IT roles exist only to reduce the overall system administration effort, while business roles could allow to perform more than one business activity.

- **Cardinality.** A typical large-scale organization could have thousands of roles defined in its access control system, while having no more than a few hundred business activities. In any organization, activities depend on company objectives, not organizational structure or headcount. For instance, suppose two sales management roles \( \text{na_sales_mgr} \) and \( \text{mea_sales_mgr} \) are assigned different permission sets as they are related to different markets. Despite the need for two distinct roles, they likely allow the same kind of activities to be performed. While new roles are created in response to new sales markets, no new activities will be required. Thus, working with activities instead of roles (whenever the problem permits this replacement) allows an organization to better address its growth.

- **Abstraction.** A role is defined to manage permissions, while an activity is a business concept independent from permissions. Activity constraints could be identified by business staff who have no knowledge of access control. Instead, the role constraint definition could require a joint effort between business and IT.

### 4.2 Activity Concept Formalization

Activities are obtained by decomposing business processes into more elementary components, resulting in a tree structure formally described as follows:

- the set \( \text{ACTVT} \) contains all activities obtained by decomposing business processes;
- the set \( \text{ACTVT-H} \subseteq \text{ACTVT} \times \text{ACTVT} \) defines a partial order on the hierarchy tree; \( (a_p, a_c) \in \text{ACTVT-H} \) means that the activity \( a_p \) is the parent of the activity \( a_c \), also represented by \( a_c \rightarrow a_p \);
- the activity tree has only one root;
- \( \forall a \in \text{ACTVT}, \) the activity \( a \) has only one direct parent, namely \( \forall a_p, a_c \in \text{ACTVT} : a_c \rightarrow a_p \implies \exists ! a_p \in \text{ACTVT} : a_p \neq a_p : a_c \rightarrow a_p \).

Activity hierarchy is described using the concept of generalization, that is, using an “is-a” relation [8]. Given two activities \( a_p, a_c \in \text{ACTVT} \), then \( a_c \rightarrow a_p \) indicates that \( a_p \) is more general than \( a_c \). This relationship, represented with the notation \( a_c \rightarrow a_p \), also defines a partial order; thus, \( a_c \geq a_p \) indicates the existence of a hierarchical relationship pathway of “\(-\rightarrow\)” from \( a_c \) to \( a_p \). Note that, without loss of generality, it is always possible to individuate a unique root for a set of activities; for example, a virtual activity “collecting” all the high level activities of the organization could be always defined.

Each activity is supported by sets of permissions, which allow activities to be performed. To obtain a greater level of flexibility, the permission grouping concept has been introduced into the model. Instead of assigning permissions directly to activities, permissions are first grouped into one or more subsets. For a user to perform a given activity, such user must have all the permissions associated to at least one activity-related grouping. This models situations where harmful activities are not defined by a single action. If a user is assigned all the permissions of a grouping, it is possible to assert that the user performs the activity associated to such a grouping. More precisely, a set of permission groupings is attached to each activity and can be formalized as follows:

- \( \text{GRPS} \subseteq 2^{\text{PERMS}} \) represents the possible permission groupings which can be assigned to activities.
- \( \text{ACTVT-G} \subseteq \text{ACTVT} \times 2^{\text{GRPS}} \) expresses the origin of a permission grouping in a given activity.
The function $\text{actvt}_{\text{grps}} : \text{ACTVT} \rightarrow 2^{\text{GRPS}}$ provides the set of groupings associated to an activity. Given an activity $a \in \text{ACTVT}$, it can be formalized as

$$\text{actvt}_{\text{grps}}(a) = \{ g \in \text{GRPS} \mid \exists (a, g) \in \text{ACTVT-G} \}.$$  

The previous function can be extended to take into account the activity breakdown structure, namely

$$\text{actvt}_{\text{grps}}^*(a) = \{ g \in \text{GRPS} \mid \exists a' \in \text{ACTVT} : a' \supseteq a, \langle a', g \rangle \in \text{ACTVT-G} \}$$

provides all the groupings assigned to $a$ and its children.

Notice that activities and groupings can be seen as specialization of roles. In particular, assume the role entity is enriched with a new attribute making a distinction among regular roles, activities, and groupings. Therefore, $\text{ACTVT} \subseteq \text{ROLES}$ and $\text{GRPS} \subseteq \text{ROLES}$, ensuring that elements in $\text{ACTVT}$ and $\text{GRPS}$ are unassignable. Similar to users assigned to hierarchical-related roles, a user performing an activity could also perform all parent activities in the activity tree. Moreover, the set $P_A$ will be used to assign permissions to groupings, while $RH$ will be used to define the activity structure with groupings as leaves of the tree. Constraint formalization and mechanisms defined for roles may also be used among activities and groupings.

The following sections formalize SoD conflicts within the model. Because of the analogy between roles and activities, such definitions can be directly derived from SSD (Static Separation of Duty) and DSD (Dynamic Separation of Duty) constraint definitions of [2].

4.3 Conflict Definition

Potential SoD conflicts are identified among activities, namely from a business perspective. The set $\text{SoD-G} \subseteq 2^{\text{ACTVT} \times \mathbb{N}}$, describing activity conflicts, is a collection of pairs $(A, n)$ where each $A$ is an activity set, while $n \geq 2$. No user should perform more than $n$ activities in $A$ for each $(A, n) \in \text{SoD-G}$. Since activities are hierarchically related, users should not perform neither activities in $A$ nor parent activities of $A$.

An observation key is that, since activities identify permission sets, it is possible to derive conflicting permissions from conflicting activities. For example, let us assume the activities “Invoice Creation” and “Invoice Approval” conflict; further, assume permissions \{new_inv1, new_inv2, new_inv3\} are needed to complete the activity “Invoice Creation” and \{app_inv1, app_inv2\} to complete the activity “Invoice Approval”. Thus, there should not be any user possessing permissions \{new_inv1, new_inv2, new_inv3, app_inv1, app_inv2\} since these permissions allow users to perform conflicting activities, namely creating and approving an invoice by oneself. Based on this observation, the following are different kinds of conflicts among RBAC entities that can be identified when adopting the proposed model.

Conflicting and illegal permissions. Permissions conflict when they allow execution of conflicting activities. Formally, given a set $P \subseteq \text{PERMS}$, permissions in $P$ conflict if the following holds:

$$\exists (A, n) \in \text{SoD-G}, \exists A' \subseteq A : |A'| \geq n \implies \forall a \in A', \exists P' \subseteq P : P' \in \text{actvt}_{\text{grps}}^*(a). \quad (1)$$

When $|P| = 1$, the permission $p \in P$ is illegal, meaning that the permission allows the execution of conflicting activities by itself. This happens whenever an application does not allow the execution of different activities recurring to different functionalities (e.g., the application offers only one functionality for the “Invoice Creation” and “Invoice Approval” activities).

Conflicting and illegal roles. Roles are conflicting when the union of their assigned permissions allow execution of conflicting activities. Formally, given a set $R \subseteq \text{ROLES}$, roles in $R$ conflict if the following holds:

$$\exists (A, n) \in \text{SoD-G}, \exists A' \subseteq A : |A'| \geq n \implies \forall a \in A', \exists P' \subseteq \bigcup_{r \in R} \text{ass_perms}(r) : P' \in \text{actvt}_{\text{grps}}^*(a). \quad (2)$$

When $|R| = 1$, the role $r \in R$ is illegal, namely it contains conflicting or illegal permissions. In order to consider the role hierarchy, Equation (2) can be easily extended using $\text{ass_perms}^*(r)$ instead of $\text{ass_perms}(r)$. Note that Equation (2) is derived from Equation (1) by substituting the set of all conflicting permissions $P$ with the union of permissions assigned to roles in $R$.

Conflicting and illegal users. Users conflict when the union of permissions assigned to their roles allows execution of conflicting activities. Formally, given a set $U \subseteq \text{USERS}$, users in $U$ conflict if the following holds:

$$\exists (A, n) \in \text{SoD-G}, \exists A' \subseteq A : |A'| \geq n \implies \forall a \in A', \exists P' \subseteq \bigcup_{u \in U} \text{ass_users}(r) : P' \in \text{actvt}_{\text{grps}}^*(a). \quad (3)$$

When $|U| = 1$, the user $u \in U$ is illegal, namely it is assigned to conflicting or illegal roles. In order to consider the role hierarchy, Equation (3) can be easily extended using $\text{ass_users}^*(r)$ instead of $\text{ass_users}(r)$ and $\text{ass_perms}^*(r)$ instead of $\text{ass_perms}(r)$.

Conflicting and illegal sessions. Sessions conflict if the union of permissions assigned to their users allows execution of conflicting activities. Formally, given a set $S \subseteq \text{SESSIONS}$, sessions in $S$ conflict if the following holds:

$$\exists (A, n) \in \text{SoD-G}, \exists A' \subseteq A : |A'| \geq n \implies \forall a \in A', \exists P' \subseteq \bigcup_{s \in S} \text{ass sessions}(s) : P' \in \text{actvt}_{\text{grps}}^*(a). \quad (4)$$

According to the RBAC model, a session is related to a single user. In order to consider role hierarchy, the previous equation can be easily extended using $\text{ass_users}^*(r)$ instead of $\text{ass_users}(r)$ and $\text{ass_perms}^*(r)$ instead of $\text{ass_perms}(r)$.

4.4 SoD Domains and Constraint Taxonomy

The introduction of the activity concept allows flexible categorization of several kinds of SoD constraints. For example, the constraint taxonomy proposed in [20] can be extended recurring to the activity concept instead of the role
The first class of constraints is represented by Operational SoD: activities to be considered conflicting, must be completed in all their steps. Therefore, the users are allowed to execute parts of, but not the entire set of conflicting activities. From an access control viewpoint, a step is no more than a set of permissions [11, 12]. In our model, this concept is mapped to permission groupings. If a particular order of execution is required, dynamic session-based mechanisms might be implemented.

Another SoD constraint class is represented by the Object-Based SoD specifying that a user cannot execute conflicting activities on the same object. This kind of constraint is usually not directly supported by RBAC implementations. To support it, we introduce the SoD domain concept in our model. For instance, a SoD domain is a set of data on which a single user should not complete conflicting activities. If a user can perform conflicting activities on different data, then it is probably impossible to configure an illegal action. A SoD domain can be a single row on a DBMS table, or simply the set of all data accessed by a given application. As mentioned in Section 3, a RBAC permission is represented by a couple \((o, m)\), where \(o\) indicates the object and \(m\) the way in which the object is accessed. This means that given a permission, it is possible to determine in which domains the permission operates. Consequently, SoD domains can be formalized as follows:

- **SoD-D** indicates the set of all SoD domains.
- **SoD-D-OBJIS** \(\subseteq \text{SoD-D} \times 2^{\text{OBS}}\) expresses the origin of an object in a given SoD domain.

The function \(\text{perm\_domains}: \text{PERMS} \rightarrow 2^{\text{SoD-D}}\) provides the set of SoD domains a given permission operates. This can be computed from the sets \(\text{SoD-D-OBJIS}\) and \(\text{PERMS}\); given \(p \in \text{PERMS}\) the function can be defined as:

\[
\text{perm\_domains}(p) = \{d \in \text{SoD-D} \mid \exists(d, O) \in \text{SoD-D-OBJIS}, \exists m \in \text{OPS}, \exists o \in O : (o, m) = p\}.
\]

To bring the SoD domain concept in the equations of the previous section, it is required that all conflicting permissions must be confined within the domains contained in set \(D\). Therefore, Equation 1 (conflicting and illegal permissions) becomes

\[
\exists(A, n) \in \text{SoD-G}, \exists A' \subseteq A, \exists D \subseteq (2^{\text{SoD-D}} \setminus \{\emptyset\}) : |A'| \geq n \implies \forall a \in A', \exists P' \subseteq P : P' \in \text{actvt\_grps}^*(a), \bigcap_{p \in P'} \text{perm\_domains}(p) = D.
\] (5)

Similarly, Equation 2 (conflicting and illegal roles) becomes

\[
\exists(A, n) \in \text{SoD-G}, \exists A' \subseteq A, \exists D \subseteq (2^{\text{SoD-D}} \setminus \{\emptyset\}) : |A'| \geq n \implies \forall a \in A', \exists P' \subseteq \bigcup_{r \in \text{ass\_perms}(r)} P' \in \text{actvt\_grps}^*(a), \bigcap_{p \in P'} \text{perm\_domains}(p) = D.
\] (6)

Equation 3 (conflicting and illegal users without sessions) becomes

\[
\exists(A, n) \in \text{SoD-G}, \exists A' \subseteq A, \exists D \subseteq (2^{\text{SoD-D}} \setminus \{\emptyset\}) : |A'| \geq n \implies \forall a \in A', \exists P' \subseteq \bigcup_{r \in \text{ass\_perms}(r)} P' \in \text{actvt\_grps}^*(a), \bigcap_{p \in P'} \text{perm\_domains}(p) = D
\] (7)

while Equation 4 (conflicting and illegal users with sessions)

\[
\exists(A, n) \in \text{SoD-G}, \exists A' \subseteq A, \exists D \subseteq (2^{\text{SoD-D}} \setminus \{\emptyset\}) : |A'| \geq n \implies \forall a \in A', \exists P' \subseteq \bigcup_{r \in \text{ass\_perms}(r)} P' \in \text{actvt\_grps}^*(a), \bigcap_{p \in P'} \text{perm\_domains}(p) = D.
\] (8)

Although defining SoD domains at the object level allows the finest granularity, the resulting complexity could be unmanageable, hence preventing its application. To dominate the curse of complexity, it is often sufficient to define a domain as the set of all data accessed by an application or set of applications. Most of the time, the application to identify data sets provides assurance that users are prevented from executing conflicting actions. It is important to highlight that different data does not necessarily mean different domains. In fact, the same data can belong to multiple SoD domains; moreover, working on one object can have effects over other related objects. For this reason, it would be too restrictive to say that permissions accessing distinct objects cannot cause conflicts between one another. Most of the time, defining SoD domains as all data accessed by an application allows to correctly partition conflicting permissions.

5. EXAMPLES

This section introduces some examples illustrating practical applications of the proposed SoD model. For this purpose, Figure 1 shows a possible model instance, depicting relationships among involved entities. It depicts some example permissions \((\text{PERMS} = \{p_1, \ldots, p_9\})\), roles \((\text{ROLES} = \{r_1, \ldots, r_9\})\) and the corresponding permission-role assignments. The “aggregation” concept is used to assign permission sets to roles, while the “generalization” concept is used in defining hierarchical relationships. For example, role \(r_1\)
is a composition of permissions $p_1, p_2$, while role $r_6$ is a composition of permissions $p_1, p_2, p_3, p_4, p_5$ since it is senior of $r_1, r_2, r_3$ from which it inherits permissions $p_1, p_2, p_4, p_5$. The figure also shows how permissions are entirely managed by IT staff, where role definition is a typical joint-task of both business and IT people (sometimes represented by a “security” staff).

Permission groupings (GRPS = \{g_1, \ldots, g_k\}) are simply aggregation of permissions, while activities (ACTVT = \{a_1, \ldots, a_{15}\}) inherit permissions from groupings or other activities. In the figure, activity $a_2$ is performed when a user possesses permissions $p_2, p_4$ (i.e., grouping $g_2$) or permissions $p_3, p_4$ (i.e., grouping $g_3$), namely $\text{actvt} \in \text{grps}(a_2) = \{g_2, g_3\} = \{\{p_2, p_4\}, \{p_3, p_4\}\}$. Instead, activity $a_{10}$ is performed when a user possesses $p_6$ (through the hierarchical relationship with $a_3$ or $a_6$) or $p_9$ (directly through grouping $g_7$). In fact, permission $p_9$ allows not only execution of activities $a_5, a_6$, but also activity $a_{10}$. Similar to a role definition task, security staff are in charge of defining permission groupings as well as role activity identification is a typical task for business staff.

Figure 1 shows two distinct domains (SoD-D = \{d_1, d_2\}). For example, permission $p_6$ is declared to operate in both domains, that is perm\_domains($p_6$) = \{d_1, d_2\}, while permission $p_2$ operates in $d_1$ but not in $d_2$. Permission $p_1$ is not associated to any domain, thus it can never conflict with other permissions; in fact perm\_domains($p_1$) = \{\} and any equation from Sections 4.3 and 4.4 could be satisfied. In the figure, $s_1$ is a graphical representation of a possible SoD constraint in SoD-G, stating that activities $a_2, a_4, a_{10}$ cannot be performed by the same user at the same time. According to Section 4.3 this can be formally represented by the pair $\langle \{a_2, a_4, a_{10}\}, 3 \rangle$. Again, we emphasize the fact that defining SoD constraints is a task for business staff.

Ignoring the SoD domain concept, $\langle \{a_2, a_4, a_{10}\}, 3 \rangle$ makes $r_2, r_5, r_8$ conflict because of Equation 2. In fact, role $r_2$ is assigned with permissions $p_2, p_4$, namely grouping $g_2$, thus supporting activity $a_2$. Role $r_5$ is assigned with permissions $p_7, p_8, p_9$, namely groupings $g_6, g_7, g_8$, thus supporting activities $a_5, a_6, a_{10}$. Note that role $r_5$ allows partial execution of activity $a_4$, since permission $p_6$ is needed to complete grouping $g_6$. Thus, role $r_5$ is required to perform activity $a_4$. Role $r_8$ is also assigned with permission $p_9$ (inherited from role $r_3$) thus allowing execution of activity $a_3$, that has no influence on the analyzed SoD constraint. Permissions $p_2, p_4, p_8, p_9, p_5$ are thus conflicting and any user possessing them (i.e., roles $r_2, r_5, r_8$) would be illegal.

Introducing SoD domains, roles $r_2, r_5, r_8$ conflict in domain $d_1$. In fact, permissions $p_2, p_4, p_6, p_7, p_8$ can operate in domain $d_1$, while $p_3$ cannot. Although activity $a_{10}$ is not directly supported by $p_8$, both activity $a_5$ and $a_6$ satisfy Equation 2 since $a_5 \geq a_{10}$ and $a_6 \geq a_{10}$. Similarly, roles $r_5, r_6, r_8$ conflict in domain $d_2$.

Note that role $r_5$ inherits permissions from $r_2, r_8$, thus roles $r_5, r_9$ conflict. For the same reason, roles $r_3, r_7, r_8$ conflict as well. If the previous SoD constraint is changed to $\langle \{a_2, a_4, a_{10}\}, 2 \rangle$, role $r_5$ will be illegal. In fact, the constraint requires only two activities to be performed, so that $r_7$ is no longer needed to support $a_{10}$. Adding the constraint $\langle \{a_5, a_6\}, 2 \rangle$, permission $p_9$ will also be illegal as well as role $r_5$.

6. TESTING ON REAL DATA

A large private company has been analyzed to highlight the properties of the proposed SoD model. In particular, the analyzed RBAC system is composed up of 90,287 users, 12,314 permissions (related to 67 different applications), and 16,755 roles.

In accordance to our framework, the business staff identified an activity tree containing 298 nodes. Upon this tree, 437 conflicting activity pairs were defined. To simplify the definition of conflicts, only conflicting activity pairs were considered, namely constraints having the form $\langle A, 2 \rangle \in \text{SoD-G}$. At the same time, 42,515 activity-permission relationships were identified by IT professionals. To simplify this task, it was divided among the owners of the 67 existing applications. Each owner analyzed only permissions related to the administered application. In this way each professional did not have to manage more than a thousand activity-permission relationships. Further, one SoD domain was defined for each application, since activities performed by different applications adopted by the organization do not access the same data set. Note that each identified activity was not necessarily performed recurring to one specific application, namely within a single domain, but it could be performed within different contexts, thus spreading across multiple domains.

In such a scenario, only static SoD conflicts were identified. It was possible to deduce 4,555 illegal roles and 4,037,051 conflicting role pairs, discarding conflicts between illegal and the remaining roles. As for roles, 2,566 illegal permissions and 1,109,541 conflicting permission pairs were identified, discarding conflicts between illegal and remaining permissions. Finally, 7,047 users were found to be performing conflicting activities, potentially able to carry out illegal actions. Without the adoption of the proposed SoD model, such role and permission pairs should have been directly defined, thus requiring more effort from both the business and the IT staff. The results of this experimental activity can be summarized as follows: First, defining SoD conflicts through the activity concept reduced the number of relationships to be managed, thus leading to a reduced administration cost; in place of defining 4,036,908 conflicting role pairs and 4,402 illegal roles, the proposed SoD model required the definition of 437 conflicting activity pairs and 42,515 activity-permission relationships. Second, in our SoD model the relationship identification task may be clearly divided among business (responsible for activity conflicts) and IT users (responsible for activity-permission relationships, further separated among application owners). In most organizations it is unlikely the case where users can establish by their own all possible conflicts among roles, since this task requires a simultaneous good understanding of both IT and business requirements related to such roles. Further, new roles may be defined or existing roles may be reorganized without requiring new SoD constraints nor affecting the existing ones.

7. CONCLUDING REMARKS

This paper formalized a model that allows to analyze SoD constraints adopting a business perspective. In particular, potential SoD conflicts are defined among activities instead of roles or permissions. In this way, it is possible to define SoD constraints in a more natural fashion, and to reduce problem complexity in large-scale RBAC systems. The model also enables the definition of a wide taxonomy of con-
conflict types. Object-based separation of duty is introduced using the SoD domain concept—namely the set of data in which transaction conflicts may occur. Experimental results supported the viability of the proposed approach and confirmed all the claimed benefits.

To the best of our knowledge, this work represents the first attempt to address SoD from a business perspective, yet with an appropriate degree of formalization, that paves the way for further research in the area.

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