

Cryptographic Role-Based Access Control, Reconsidered [★]

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Abstract. The heavy reliance on reference monitors is a significant shortcoming of traditional access control mechanisms since monitors are single points of failure that need to run in protected mode and have to be permanently online to deal with every access request. Cryptographic access control offers an alternative solution that provides better scalability and deployability. It relies on security guarantees of the underlying cryptographic primitives and also the appropriate key distribution/management in the system. In order to rigorously study security guarantees that a cryptographic access control system can achieve, providing formal security definitions for the system is of great importance, since the security guarantee of the underlying cryptographic primitives cannot be directly translated into those of the system.

In this paper, we follow the line of the existing study on cryptographic enforcement of Role-Based Access Control (RBAC). Inspired by the study of the relation between the existing security definitions for such systems, we identify two different types of attacks which cannot be captured by the existing ones. Therefore, we propose two new security definitions towards the goal of appropriately modeling cryptographic enforcement of Role-Based Access Control policies and study the relation between our new definitions and the existing ones. In addition, we show that the cost of supporting dynamic policy updates is inherently expensive by presenting two lower bounds for such systems which guarantee the correctness and secure access.

1 Introduction

Traditional access control mechanisms heavily rely on reference monitors, meaning single points of failure operating under protected mode. This approach must be critically re-examined, while permanently online access control mechanisms are necessary in order to serve all access requests by users. The mechanism inherent limitations greatly affect application scalability and deployability. This issue can be addressed with the help

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of cryptographic techniques by enforcing access control policies with the help of cryptographic primitives. This alternative approach is referred to as cryptographic access control. It aims at reducing or even eliminating monitor reliance, since in cryptographic access control policy enforcement is achieved in an indirect way: the data is protected by cryptographic primitives and the policies are enforced by distributing the appropriate keys to the appropriate users.

A main concern in the existing cryptographic access control studies is the gap between the specifications of access control policies enforced and the actual implementation of the access control systems. In traditional monitor-based access control mechanisms, the correct enforcement of access control policies holds by design. However, in cryptographic access control, the issue becomes more complex. The enforcement relies on security guarantees by underlying cryptographic primitives and also on the appropriate key distribution/management. Even though some advanced cryptographic primitives are seemingly well-suited for cryptographic access control, their security guarantees cannot be directly translated to security guarantees for the entire system. It is a common understanding that there is often a gap between primitives and the applications motivating them. The gap is obscured by uses of similar terms and jargon at both the application and the primitive level. It is unfortunate that in the case of primitives, the security of the motivating application is often omitted.

Formal security definitions for cryptographic access control systems are of crucial importance in order to bridge this gap. However, formal security definitions is often neglected in the existing research on cryptographic access control. There have been some initial works in this area that focus on new primitives motivated by access control systems [7, 2, 13] and on access control systems based on said primitives [9, 12, 14, 6].

Throughout the literature, rigorous definitions that examine the security of systems for access control have only been heuristically studied. In the aim of reasoning about the confinement problem, Halevi et al. proposed a simulation-based security definition for access control on a distributed file storage system [5]. Their result concerns a particular system rather than a general one. Ferrara et al. defined a precise syntax for cryptographic role-based access control (cRBAC) systems and proposed a formal security definition with respect to secure read access in [4]. Following, they extend their results in a setting that supports write access [3], their goal being to reduce the need for trusted monitors mediation for every write access request. Liu et. al. studied security of cRBAC systems in the UC framework [10]. They proposed a UC security definition for such systems and also showed an impossibility result that such security cannot be achieved due to the commitment problem.

Garrison III et al. studied the practical implications of cryptographic access control systems implementing RBAC policies [8]. They analysed the computational costs of two different constructions of cryptographic role-based access control systems via simulations with the use of real-world datasets. Their results indicate that supporting a dynamic access control policy enforcement may prove prohibitively expensive, even under the assumption that write access is enforced with the minimum use of reference monitors.

NEW SECURITY DEFINITIONS. The results presented in [10] show a gap between game-based and simulation-based security definitions for cRBAC systems, which raises the following question:

Do the existing security definitions appropriately capture the secure enforcement of access control policies?

The first security definition is called *past confidentiality* and refers to security concerns by users, who acquire unauthorised read access to the previous file versions. It serves as a refinement to the existing definition of read security for cRBAC systems. In traditional monitor-based access control, when a user acquires access to the authorised file, only the current content will be available. By "previous contents" we refer to previous file versions written in the past and not considered a part of the current content of the file. In cryptographic access control, due to the file system's public accessibility, users can easily obtain previous file versions (even in an encrypted form) by simply monitoring the state of the file system. Therefore, a user recently granted the read permission of a file might retrieve previous contents written at a time when it did not have access permission - this can be considered as a violation of the implemented access control policy.

Game-based security definitions in the existing work do not appropriately capture the security concern mentioned above [4, 3]. One should keep in mind that in games that define security with respect to read access, the adversary is not allowed read access to challenge files at any point during the game. This restriction on the adversary leads to the attack mentioned above not being ruled out. In fact, the attack can be easily carried out in the constructions proposed in [4, 3]. Interestingly, some recently proposed constructions of cryptographic access control systems pose a similar security concern [1, 8, 11], though they have been proven to securely enforce the corresponding access control policies within their individual frameworks.

LOWER BOUNDS FOR SECURE CRBAC SYSTEMS. Garrison III et al. studied the practical implications of using cryptography to enforce RBAC policies in their recent work [8]. They considered a system model making the necessary use of reference monitors to enforce access control on write access and to maintain the metadata of each file in the file system. For this purpose, they developed two different constructions of cryptographic RBAC systems: one is developed with identity-based encryption (IBE) and identity-based signature (IBS) schemes, while the other one is based on traditional public key cryptography and makes use of public key infrastructure (PKI). In order to analyse construction costs they carried out the simulation over real-world RBAC datasets to generate traces. Their experimental results show that even with the minimum use of reference monitors, the computational costs of the cryptographic RBAC systems supporting the idea of a dynamic policy update are still prohibitively expensive.

Motivated by Garrison III et al.'s work, we study lower bounds for secure cRBAC systems to locate the source of the inefficiency. We show that the costs are inherent in secure cRBAC systems and also in those cryptographic access control systems that greatly or solely rely on cryptographic techniques to enforce access control on both read and write access. The main idea is, since the manager is not involved in any read and

write operation in the file system, both the users' local states and the file system should reflect the enforcement of the access control policy. Whenever a policy update occurs, the system may inevitably require re-keying and re-encryption to preserve secure access and system correctness. We present two lower bounds for secure cRBAC systems. Our results can be valuable in the design of such systems for practical purposes.

2 Preliminaries

2.1 Notations

For assignment, we write $x \leftarrow y$ to denote the assignment of the value y to the variable x . If S is a set, $x \leftarrow S$ denotes that x is being assigned with a value selected uniformly at random from S . Let \mathcal{A} be an algorithm, $x \leftarrow \mathcal{A}(y)$ denotes the assignment of x with the output of running it on the input y , if \mathcal{A} is deterministic, while we write $x \leftarrow_S \mathcal{A}(y)$ for the assignment, if \mathcal{A} is probabilistic.

For any integer $n \geq 0$, we write 1^n to denote the string of n 1s. If S is a set, $|S|$ denotes its size. If s is a string, $|s|$ denotes its length. Given two strings s_0 and s_1 , $s_0||s_1$ denotes their concatenation. ϵ denotes the empty string. \perp denotes an error, though its meaning depends on the context: it could indicate a decryption error or an error returned by an oracle due to an invalid oracle query.

We say f is a *negligible function*, if for every positive polynomial p , there exists an integer N such that for all integers $n > N$, it holds that $f(n) < \frac{1}{p(n)}$.

2.2 Role-Based Access Control

Role-Based Access Control (RBAC) is one of the most popular access control models adopted in large-scale systems. RBAC introduces the significant concept of *roles*, which are typically associated to a collection of job functions. Roles allow for specifying access control policies that naturally map the organisation structures and therefore reduce complexity when administering permissions. RBAC policies are decomposed into two assignments: the user-role assignment and the permission-role assignment. A user is authorised to a permission, if a user role has been assigned with the permission. In this paper, we will only focus on core RBAC, as it is the most common between the standard models.

The state of a (core) RBAC system consists of:

- U : a finite set of users,
- R : a finite set of roles,
- O : a finite set of objects,
- P : a finite set of permissions, where each permission is an *object-operation* pair,
- $UA \subseteq U \times R$: a relation modelling the user-role assignment,
- $PA \subseteq P \times R$: a relation modelling the permission-role assignment,

For simplicity we assume that the set of roles R is fixed, since role structures in organisations are less frequent to change. Therefore, the state of an RBAC system over a fixed role set R is a tuple (U, O, P, UA, PA) . We describe an RBAC system in terms

of a state-transition system. We define the set of state-transition rules **RULES** as the RBAC administrative commands. Given two states $S = (U, O, P, UA, PA)$ and $S' = (U', O', P', PA', UA')$, there is a *transition* from S to S' with $q \in \mathbf{RULES}$ denotes $S \xrightarrow{q}_{\mathcal{S}} S'$, if one of the following conditions holds:

- **[AddUser]** $q = (\text{AddUser}, u)$, $u \notin U$, $U' = U \cup \{u\}$, $O' = O$, $P' = P$, $PA' = PA$ and $UA' = UA$;
- **[DelUser]** $q = (\text{DelUser}, u)$, $u \in U$, $U' = U \setminus \{u\}$, $O' = O$, $P' = P$, $PA' = PA$ and $UA' = UA \setminus \{(u, r) \in UA \mid r \in R\}$;
- **[AddObject]** $q = (\text{AddObject}, o)$, $o \notin O$, $O' = O \cup \{o\}$, $U' = U$, $P' = P \cup \{(o, \text{read}), (o, \text{write})\}$, $PA' = PA$ and $UA' = UA$;
- **[DelObject]** $q = (\text{DelObject}, o)$, $o \in O$, $O' = O \setminus \{o\}$, $U' = U$, $P' = P \setminus \{(o, \cdot)\}$, $PA' = PA \setminus \{(o, \cdot), r) \in PA \mid r \in R\}$ and $UA' = UA$;
- **[AssignUser]** $q = (\text{AssignUser}, (u, r))$, $u \in U$, $r \in R$, $U' = U$, $O' = O$, $P' = P$, $PA' = PA$ and $UA' = UA \cup \{(u, r)\}$;
- **[DeassignUser]** $q = (\text{DeassignUser}, (u, r))$, $u \in U$, $r \in R$, $U' = U$, $O' = O$, $P' = P$, $PA' = PA$ and $UA' = UA \setminus \{(u, r)\}$;
- **[GrantPerm]** $q = (\text{GrantPerm}, (p, r))$, $p \in P$, $r \in R$, $U' = U$, $O' = O$, $P' = P$, $PA' = PA \cup \{(p, r)\}$ and $UA' = UA$;
- **[RevokePerm]** $q = (\text{RevokePerm}, (p, r))$, $p \in P$, $r \in R$, $U' = U$, $O' = O$, $P' = P$, $PA' = PA \setminus \{(p, r)\}$ and $UA' = UA$.

An execution of an RBAC system is a finite sequence of transitions $S_0 \xrightarrow{q_0}_{\mathcal{S}} S_1 \xrightarrow{q_1}_{\mathcal{S}} \dots \xrightarrow{q_n}_{\mathcal{S}} S_{n+1}$, where S_0 is called the *initial* state of the RBAC system.

We denote the *read* permission and the *write* permission of a file $o \in O$ by (o, read) and (o, write) respectively. A predicate $\text{HasAccess}(u, p)$ reflects that a user u has sym-bolicalaccess to a permission p . It is defined as follows:

$$\text{HasAccess}(u, p) \Leftrightarrow \exists r \in R : (u, r) \in UA \wedge (p, r) \in PA$$

2.3 System Model and Syntax

The system model we consider in this paper is the one proposed by Ferrara et al. in [3]. In their system model, a versioning append-only file system is employed for enforcing access control on (quasi-) unrestricted read and write access to the files. Hence, the need for online monitors is eliminated.

It should be noted that using a file system of this kind, does not consist a limitation. In contrast, it allows for modelling a *general* class of access control systems. Since the file system itself does not implement any access control mechanisms and the enforcement of access control policies on files is handled using cryptography solely, it can be used to apprehend data outsourcing scenarios, where hosting trusted reference monitors is impossible. Users may even be able to keep track of files (e.g. storing data on public clouds, repositories, decentralised distributed storage networks, etc.).

We consider a cRBAC system as consisting of three main entities: a *manager*, a *file system* and a set of *users*.

The manager is responsible for the administration of access control policies. More specifically, it is in charge of executing RBAC administrative commands that could involve key management/distribution and data encryption/re-encryption. In contrast to the traditional access control policy enforcer (i.e. the reference monitor) that has to be placed in the critical path to check whether an access request is considered compliant to the policy, the manager does not involve any read and write access to the file system. In addition, the manager is assumed to be a trusted party.

The *file system* is tasked with storing the files subjected to access control and it is publicly accessible to users. In the implementation phase, the system could contain arrays of encrypted files and the related metadata. The file system is assumed to be untrusted in terms of data privacy, but it guarantees availability of the data it stores. Consider that if users are provided unrestricted write access to the file system, no amount of cryptographic techniques can prevent a malicious user from overwriting the existing contents. Therefore, the file system is further assumed to be append-only and supporting versioning. In this case, users can only append contents but not delete any. The append operations can be interpreted as logical writes to the files. When reading a file, a user first needs to fetch the file versions and then identifies the most recently "validated" one to retrieve the content. As the data owner, the manager may have richer interfaces to the file system than users. Therefore, it can overwrite the file contents and add/delete files.

Users may have (quasi-) direct and unrestricted read and write access to the file system without involving the manager. Since the enforcement of access control policies solely relies on cryptographic primitives and the file system does not implement any access control functionality, only the users with appropriate keys can get authorised access to the files.

Secure channels are assumed between each of any two entities. For simplicity, the execution of any RBAC administrative command is assumed to be implemented by non-interactive multi-party computations. That is, when executing any RBAC command, the manager carries out some local computation according to the command to produce update messages for users and potentially updates the file system. Following, update messages will be sent to the users via secure channels. Once a user receives said message from the manager, it updates its local state accordingly. The file system proceeds with the update in a similar manner.

The global state of a cRBAC system at any point during its execution is a tuple $(st_M, fs, \{st_u\}_{u \in U})$, where st_M is the local state of the manager, fs is the state of the file system and st_u is the local state for each user $u \in U$ in the system. Since the manager is tasked with the access control policy administration, the symbolic RBAC state $S = (U, O, P, UA, PA)$ is considered to be a part of st_M . Let $\phi(st_G)$ denote the RBAC state of the global state st_G .

A cRBAC system is defined by a cRBAC scheme which consists of the following algorithms:

- Init, the **initialisation** algorithm: A probabilistic algorithm that takes the security parameter 1^λ and a set of roles R as input and outputs the initialised global state of the cRBAC system.
- AddUser, DelUser, AddObject, DelObject, AssignUser, DeassignUser, GrantPerm, RevokePerm, the **RBAC administrative** algorithms: Probabilistic algorithms that

implement the corresponding RBAC administrative commands. As mentioned, they are non-interactive multi-party computations. Each of the algorithms takes the state of the manager st_M , the state of the file system fs and the additional argument for the command arg as input and outputs the updated state for the manager and the file system as well as a set of update messages $\{msg_u\}_{u \in U}$ for each user $u \in U$.

- Read, the **read** algorithm: A deterministic algorithm that allows a user to retrieve the current content of a file. It takes the local state of a user st_u , the current state of the file system fs and a file name o as input and outputs the current content of the file o , if the user has the read permission. If not or if the file is empty, the algorithm returns an error \perp .
- Write, the **write** algorithm: A probabilistic algorithm that allows a user to write content to a file. It takes the local state of a user st_u , the current state of the file system fs , a file name o and the content m as input and outputs the updated file system.
- Update, the **update** algorithm: A deterministic algorithm that takes the local state of a user st_u and an update message msg_u received from the manager and outputs the updated local state.

A comment should be made about the updated file system, forming the output part of some of the algorithms outlined above. More specifically, the algorithms produce update instructions to be carried out on the file system. For example, after running the Write algorithm, a user will get the update instruction $info$ that includes the information of the file name and also the content to be appended to the file system. Then the user uploads $info$ to the file system and the latter gets updated accordingly. The manager proceeds similarly, but the update instructions might be different from that of the users due to the data owner privilege. For simplicity, we will let those algorithms output the updated file system. In terms of effect, all the above algorithms except Read can potentially update the global state of the cRBAC system. Therefore, we may write the execution of a cRBAC algorithm in the following form:

$$st_G \xrightarrow{Q} st'_G \Leftrightarrow st'_G \leftarrow A(st_G, arg),$$

where A is one of the algorithms defined above (except for Read), arg is its arguments, Q is an implementation of the algorithm, st_G and st'_G are the global states of the cRBAC system.

Let $\vec{Q} = (Q_0, \dots, Q_n)$. We write the execution trace of the cRBAC system as:

$$st_{G_0} \xrightarrow{\vec{Q}} st_{G_{n+1}} \Leftrightarrow st_{G_0} \xrightarrow{Q_0} st_{G_1} \xrightarrow{Q_1}, \dots, \xrightarrow{Q_{n-1}} st_{G_n} \xrightarrow{Q_n} st_{G_{n+1}},$$

where $\{st_{G_i}\}_{i \in \{0, \dots, n+1\}}$ are global states of the cRBAC system.

We say a sequence of operations is *efficient*, if the length of its execution trace is polynomially bounded.

We also introduce the following two notations \mathbb{P}_r and \mathbb{O}_r . \mathbb{P}_r is the set of objects the read permissions of which a user has been “symbolically” assigned at a certain point. Let $S = (U, O, P, UA, PA)$ be the RBAC state of a system:

$$\mathbb{P}_r(S, u) \Leftrightarrow \{o | \text{HasAccess}(u, (o, \text{read}))\}.$$

\mathbb{Q}_r is the set of objects of which a user has “*computational*” read access to, i.e. the objects whose contents can be retrieved by performing the read operations with the user’s local state. Consider that some file might be empty (i.e. it contains no content) after the initialisation, while a user could be granted the read permission of that file. Therefore, we define \mathbb{Q}_r as the set of objects so that if any user u' with write permissions writes some contents to them at this point, u will be able to read those contents. Let st_G be the global state of a cRBAC system. \mathbb{Q}_r is defined as:

$$\mathbb{Q}_r(st_G, u) \Leftrightarrow \{o \mid \forall u' \in U, m \in \{0, 1\}^\lambda : \text{HasAccess}(u', (o, \text{write})) \wedge (fs' \leftarrow \text{Write}(st_{u'}, fs, o, m), m' \leftarrow \text{Read}(st_u, fs', o) : m' = m)\}$$

3 Security Definitions

In this section, we present our formal security definitions of correctness, past confidentiality and local correctness for cRBAC systems.

3.1 Correctness

Correctness was first proposed by Ferrara et al. in [4], but it was omitted in their later work [3], where a new system model was introduced to support write access. Therefore, we will need to reintroduce the definition of correctness.

Intuitively, a cryptographic access control system is said to be *correct*, if every user in the system can get access to the resources to which it is authorised according to the symbolic state of the system. In a cRBAC system enforcing access control on both read and write access to a publicly accessible file system, the correctness requirements are specialised as follows:

1. any user that has the read permission of a file should be able to retrieve the current content of the file by reading it, and
2. the current content of a file written by a user with a write permission will be correctly read by any user who has a read permission of the file.

We formalise the two requirements above via a game between a challenger, who acts as a manager of a cRBAC system defined by cRBAC scheme \mathcal{H} and a polynomial-time adversary \mathcal{A} that attacks the system. The adversary is allowed to request the manager to execute any RBAC administrative command, such that the symbolic state of the system evolves according to its queries. The adversary can also request a user to write to the file system and to query the current state of the file system. At some point of the game, \mathcal{A} needs to show that there exists some user, who cannot correctly retrieve the current content of a file to which it has read access.

More specifically, we define the following experiment $\text{Exp}_{\mathcal{H}, \mathcal{A}}^{\text{cor}}$. The experiment maintains the symbolic RBAC state of the system $State$, which is set to be $(\emptyset, \emptyset, \emptyset, \emptyset, \emptyset)$ initially, and an object-indexed list T to record the contents written to the files by authorised users.

After the initialisation of the cRBAC system with a fixed set of roles R , the adversary can ask for the execution of any RBAC administrative command by calling the

oracle CMD. Upon receiving a query that consists of an RBAC command Cmd and its arguments arg , the oracle will execute the command symbolically and run the algorithm Cmd , which implements the command. Then the adversary will be provided the current state of the file system fs as a response. The oracle WRITE allows the adversary to request a user u to write some content m to a specified file o . If u has the write permission of o , the oracle runs the write algorithm $Write$ to carry out the write operation and then sets $T[o] \leftarrow m$. In addition, the adversary can check the current state of the file system by calling the oracle FS with the query “STATE”.

In this experiment, the adversary is not allowed to take over any user in the system nor to update the file system on its own. At some point, \mathcal{A} outputs a user-object pair (u^*, o^*) and the experiment terminates here. In the case that u^* has the read permission of o^* but the content that it can retrieve from o^* by running the read algorithm $Read$ does not match the record in $T[o^*]$, the adversary wins the game. Correctness is defined by requiring any probabilistic polynomial-time adversary cannot win the above game with probability greater than 0.

Definition 1 (Correctness). A cRBAC system Π defined by a cRBAC scheme for a fixed set of roles R is **correct** if for any probabilistic polynomial-time adversary \mathcal{A} , it holds that

$$\text{Adv}_{\Pi, \mathcal{A}}^{\text{corr}}(\lambda) := \Pr [\text{Exp}_{\Pi, \mathcal{A}}^{\text{corr}}(\lambda) \rightarrow \text{true}]$$

is 0, where the experiment $\text{Exp}_{\Pi, \mathcal{A}}^{\text{corr}}$ is defined as follows:

$\text{Exp}_{\Pi, \mathcal{A}}^{\text{corr}}(\lambda)$

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 $T \leftarrow \emptyset$ ;  $State \leftarrow (\emptyset, \emptyset, \emptyset, \emptyset, \emptyset)$ 
 $(st_M, fs, \{st_u\}_{u \in U}) \leftarrow \text{Init}(1^\lambda, R)$ 
 $(u^*, o^*) \leftarrow \mathcal{A}(1^\lambda : \mathcal{O}_{\text{corr}})$ 
if  $\text{HasAccess}(u^*, (o^*, \text{read})) \wedge T[o^*] \neq \text{Read}(st_{u^*}, o^*, fs)$  then
  return true
else return false

```

The oracles $\mathcal{O}_{\text{corr}}$ that the adversary has access to are specified in Figure 1.

<p><u>CMD(Cmd, arg)</u></p> <pre> $State \leftarrow Cmd(State, arg)$ $(st_M, fs, \{msg_u\}_{u \in U}) \leftarrow Cmd(st_M, fs, arg)$ foreach $u \in U$: $st_u \leftarrow Update(st_u, msg_u)$ return fs </pre>	<p><u>WRITE(u, o, m)</u></p> <pre> if $\neg \text{HasAccess}(u, (o, \text{write}))$ then return \perp $fs \leftarrow Write(st_u, fs, o, m)$ $T[o] \leftarrow m$; return fs </pre> <p><u>FS($query$)</u></p> <pre> if $query = \text{“STATE”}$ then return fs </pre>
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Fig. 1. $\mathcal{O}_{\text{corr}}$: Oracles for defining the experiment $\text{Exp}_{\Pi, \mathcal{A}}^{\text{corr}}$.

3.2 Past confidentiality

In the extended cRBAC system model, the enforcement of access control on write access is supported by employing a versioning file storage, where users can append contents only. The versioning file storage allows users to have (quasi-) unrestricted read and write access to the file system, but it is also accompanied by subtle security issues, though the file system itself does not implement any access control mechanism. One of the security issues relates to unauthorised access to the previous contents. This is a severe security concern in cryptographic access control, but not when concerning traditional mechanisms. Unfortunately, the existing game-based security definitions for secure read access do not suffice to capture this security concern. We propose the following security definition called *past confidentiality* which is improved over the one presented in [3].

The security property is formalised via the following experiment $\text{Exp}_{II, \mathcal{A}}^{\text{pc}}$, which proceeds similarly to the experiment that defines read security in [3]. However, the adversary here is allowed to corrupt the users, who have the read permission of the challenge files under certain conditions. More specifically, the adversary is not allowed to corrupt any user in a position to read the challenge contents (rather than the challenge files in the read security game), until said challenge contents are no longer the current contents of the files. The adversary's goal is still to determine a random bit $b \leftarrow_{\$} \{0, 1\}$, which is selected at the beginning of the game.

The experiment maintains the symbolic RBAC state of the system *State* initialised as $(\emptyset, \emptyset, \emptyset, \emptyset, \emptyset)$ and updated according to \mathcal{A} 's request for the execution of RBAC commands. The experiment maintains the following lists during the execution: *Cr* for the corrupt users, *Ch* for the files of which some contents have been specified as challenges, *L* for the users who have read access to the challenge contents and *Ud* for the files of which the current contents are specified as challenges.

In the experiment, the adversary can request any RBAC administrative command for execution, taking over users and requesting an honest user to write to a file with the content it specifies. The adversary can query the current state of the file system and also write (append) some new content to it. \mathcal{A} can ask for a challenge by specifying a tuple (u, o, m_0, m_1) , where u is a user that has the write permission of the file o , m_0 and m_1 are two messages of the same length. Then the challenger will carry out $\text{Write}(st_u, o, m_b)$ and provide the current state of the file system to the adversary as the response. \mathcal{A} can ask for multiple challenges. When \mathcal{A} terminates with an output b' , it wins the game if $b' = b$.

To prevent the adversary from winning the game trivially by corrupting a user, with-read access to the challenge contents, the experiment maintains the following invariants:

1. No user in *Cr* can have read access to any file o in *Ud*: the adversary is not allowed to request read permission of any file from a corrupt user, if the file's current content is specified as a challenge.
2. No user in the list *L* can be corrupted: any user with direct access to the challenge contents cannot be taken over by the adversary.

Definition 2 (Past Confidentiality). A cRBAC system *II* defined by a cRBAC scheme for a fixed set of roles *R* is said to preserve *past confidentiality* when for any proba-

bilistic polynomial-time adversary \mathcal{A} , it holds that

$$\mathbf{Adv}_{\Pi, \mathcal{A}}^{pc}(\lambda) := \left| \Pr[\mathbf{Exp}_{\Pi, \mathcal{A}}^{pc}(\lambda) \rightarrow \text{true}] - \frac{1}{2} \right|$$

is negligible in λ , where the experiment $\mathbf{Exp}_{\Pi, \mathcal{A}}^{pc}$ is defined as follows:

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ExpΠ, Apc(λ)
  b ←ₛ {0, 1}; Cr, Ch, L, Ud ← ∅
  State ← (∅, ∅, ∅, ∅, ∅)
  (stM, fs, {stu}u ∈ U) ←ₛ Init(1λ, R)
  b' ←ₛ A(1λ : Opc)
  return (b' = b)

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The oracles \mathcal{O}_{pc} that the adversary has access to are specified in Figure 2 and discussed below.

The oracle CMD allows the adversary to request for the execution of any valid RBAC command. When \mathcal{A} 's query leads to an update to Cr , Ch , L or Ud , the lists get updated accordingly. When a user in L loses the read permission of any file in Ch , the file will be removed from the list L . When \mathcal{A} requests to grant an honest user with a read permission for the files in Ud , the user will be added to L .

When the adversary requests an honest user to write content to a file, the current content of which is specified as a challenge, the file will be removed from the list Ud . From then on, the file's read permission can be granted to a corrupt user. When \mathcal{A} requests to place a challenge by calling the oracle CHALLENGE, the oracle returns an error, if there exists some corrupt user that has read access to the specified file. Otherwise, it carries out the write operation and adds the file to lists Ch and Ud .

Compared to the adversary in the game that defines the read security of a cRBAC system, the adversary in the past confidentiality game is obviously more powerful, as it has the ability to take over the users who can acquire read access to the challenged files under certain restrictions. The following theorem confirms the implication between the two security definitions.

Theorem 1. *Past confidentiality is strictly stronger than secure read access.*

Proof sketch. First, we briefly show that any cRBAC system preserving past confidentiality is secure in terms of read access. Given any adversary \mathcal{A} attacking a cRBAC system with respect to read security, an adversary \mathcal{B} for past confidentiality can be easily constructed. After the initialisation of the cRBAC system in its own game, \mathcal{B} runs a local copy of \mathcal{A} with the input of the file system's initial state received from the challenger. Then \mathcal{B} starts to simulate the read security game for \mathcal{A} with the use of the oracles it has access to. During the simulation, \mathcal{B} does not maintain the global state of the cRBAC system. It only keeps the two lists: Cr for corrupt users and Ch for the challenge files, as defined in the read security game. Following, \mathcal{B} simply forwards any query received from \mathcal{A} , to the same oracles in its game and replies \mathcal{A} with the response it received. If \mathcal{A} 's query violates the restrictions of the read security game (i.e. by granting any user in Cr the read permission of the files in Ch), \mathcal{B} responds with an error and

<p><u>CMD(<i>Cmd</i>, <i>arg</i>)</u> $(U', O', P', UA', PA') \leftarrow \text{Cmd}(\text{State}, \text{arg})$ foreach $(u, o) \in Cr \times Ud$: if $\exists r \in R: (u, r) \in UA'$ $\wedge ((o, \text{read}), r) \in PA'$ then return \perp $\text{State} \leftarrow (U', O', P', UA', PA')$ $(st_M, fs, \{msg_u\}_{u \in U}) \leftarrow \text{Cmd}(st_M, fs, \text{arg})$ foreach $u \in U \setminus L$: if $\exists o \in Ud : \text{HasAccess}(u, (o, \text{read}))$ then $L \leftarrow L \cup \{u\}$ foreach $u \in L$: if $\nexists o \in Ch : \text{HasAccess}(u, (o, \text{read}))$ $\forall u \notin U$ then $L \leftarrow L \setminus \{u\}$ foreach $o \in Ch$: if $o \notin O$ then $Ch \leftarrow Ch \setminus \{o\}; Ud \leftarrow Ud \setminus \{o\}$ foreach $u \in U \setminus Cr$: $st_u \leftarrow \text{Update}(st_u, msg_u)$ return $(fs, \{msg_u\}_{u \in Cr})$</p>	<p><u>WRITE(<i>u</i>, <i>o</i>, <i>m</i>)</u> if $u \in Cr$ then return \perp if $\neg \text{HasAccess}(u, (o, \text{write}))$ then return \perp $fs \leftarrow \text{Write}(st_u, fs, o, m)$ if $o \in Ch$ then $Ud \leftarrow Ud \setminus \{o\}$ return fs</p> <p><u>CHALLENGE(<i>u</i>, <i>o</i>, <i>m</i>₀, <i>m</i>₁)</u> if $\neg \text{HasAccess}(u, (o, \text{write}))$ then return \perp if $m_0 \neq m_1$ then return \perp foreach $u' \in Cr$: if $\text{HasAccess}(u', (o, \text{read}))$ then return \perp $fs \leftarrow \text{Write}(st_u, fs, o, m_b)$ foreach $u' \in U$: if $\text{HasAccess}(u', (o, \text{read}))$ then $L \leftarrow L \cup \{u'\}$ $Ch \leftarrow Ch \cup \{o\}; Ud \leftarrow Ud \cup \{o\}$ return fs</p>
<p><u>CORRUPTU(<i>u</i>)</u> if $u \notin U \vee u \in L$ then return \perp $Cr \leftarrow Cr \cup \{u\};$ return st_u</p>	<p><u>FS(<i>query</i>)</u> if $query = \text{"STATE"}$ then return fs if $query = \text{"APPEND}(\textit{info})"$ then $fs \leftarrow fs \parallel \textit{info};$ return fs</p>

Fig. 2. \mathcal{O}_{pc} : Oracles for defining the experiment $\text{Exp}_{\text{cRBAC}, \mathcal{A}}^{\text{pc}}$.

ignores the query. Whenever \mathcal{A} outputs a guess of the random bit, \mathcal{B} outputs the same bit in its game.

We will now argue that the simulation \mathcal{B} provides is perfect. First, the global states in both \mathcal{B} 's game and the simulated game are identical. Secondly, not all of \mathcal{A} 's oracle queries will violate the restrictions of the game that defines past confidentiality, since queries from \mathcal{A} not violating the invariant in the read security game will not violate the invariants in the past confidentiality game. Moreover, the simulated game fully depends on the random bit chosen in \mathcal{B} 's game, thus \mathcal{B} wins its game with the same probability as \mathcal{A} wins the simulated game. Therefore, any cRBAC system not secure with read access does not preserve past confidentiality.

In addition, the construction of cRBAC scheme presented in [3] has been proven to be secure with respect to read access. But clearly it does not preserve past confidentiality, because granting the read permission of any file to a user will allow it to access

the previous contents encrypted under the same public key. Therefore, we can conclude that past confidentiality is strictly stronger than secure read access. \square

3.3 Local Correctness

The *local correctness* of a cRBAC system can be considered as a sort of correctness, though it is not implied by correctness. It captures the threat from “insiders” with respect to data availability. The append-only versioning file system allows users to get (quasi-) unrestricted write access to the files, but it also poses a new security concern: a user who has the write permission of a file might be able to invalidate the file’s future versions written by authorised users. Local correctness guarantees that these systems thwart.

This security requirement is formalised via the following experiment $\mathbf{Exp}_{\Pi, \mathcal{A}}^{\text{l-corr}}$ that involves an adversary \mathcal{A} . The experiment maintains a list Cr to record the corrupt users and another object-indexed list T to record the contents written to files by the honest users. After the initialisation of the cRBAC system, the adversary can request the execution of any RBAC administrative command, taking over any user and writing content to a file on behalf of any honest user. \mathcal{A} can also query for the current state of the file system and request to append arbitrary content to it.

The use of the list T here is to record whether the files have been unauthorised touched (rather than authorised write access) or not. When an honest user writes some content to a file o , the content will be recorded in $T[o]$. If the adversary requests to update the file by appending any entry to it, $T[o]$ will store a special value adv , which means the file has been touched after the previous authorised write access.

The experiment terminates when the adversary outputs a user-object pair (u^*, o^*) , where u^* has the read permission of o^* . \mathcal{A} wins the game if the content of o^* read by u^* is different from the record in $T[o^*]$ while $T[o^*]$ cannot be the special value adv .

Definition 3 (Local Correctness). A cRBAC system Π defined by a cRBAC scheme for a fixed set of roles R is said to preserve *local correctness*, if for any probabilistic polynomial-time adversary \mathcal{A} , it holds that

$$\mathbf{Adv}_{\Pi, \mathcal{A}}^{\text{l-corr}}(\lambda) := \Pr [\mathbf{Exp}_{\Pi, \mathcal{A}}^{\text{l-corr}}(\lambda) \rightarrow \text{true}]$$

is negligible in λ , where $\mathbf{Exp}_{\Pi, \mathcal{A}}^{\text{l-corr}}$ is defined as follows:

```

 $\mathbf{Exp}_{\Pi, \mathcal{A}}^{\text{l-corr}}(\lambda)$ 
   $T, Cr \leftarrow \emptyset; \text{State} \leftarrow (\emptyset, \emptyset, \emptyset, \emptyset)$ 
   $(st_M, fs, \{st_u\}_{u \in U}) \leftarrow \text{Init}(1^\lambda, R)$ 
   $(u^*, o^*) \leftarrow \mathcal{A}(1^\lambda : \mathcal{O}_{\text{l-corr}})$ 
  if  $T[o^*] \neq \text{adv} \wedge T[o^*] \neq \text{Read}(st_{u^*}, o^*, fs)$  then
    return true
  else return false

```

The oracles $\mathcal{O}_{\text{l-corr}}$ that the adversary has access to are specified in Figure 3.

We further show that the cRBAC construction proposed by Ferrara et al. in [3] preserves this security property.

<p><u>CMD(Cmd, arg)</u></p> <p>$State \leftarrow Cmd(State, arg)$ $(st_M, fs, \{msg_u\}_{u \in U}) \leftarrow Cmd(st_M, fs, arg)$ foreach $u \in Cr$: if $u \notin U$ then $Cr \leftarrow Cr \setminus \{u\}$ if $Cmd = \text{“DELOBJECT”}$ then Parse arg as o; $T[o] \leftarrow \emptyset$ if $Cmd = \text{“DELUSER”}$ then Parse arg as u; $Cr \leftarrow Cr \setminus \{u\}$ foreach $u \in U \setminus Cr$: $st_u \leftarrow Update(st_u, msg_u)$ return $(fs, \{st_u\}_{u \in Cr})$</p>	<p><u>CORRUPTU(u)</u></p> <p>if $u \notin U$ then return \perp $Cr \leftarrow Cr \cup \{u\}$; return st_u</p> <p><u>WRITE(u, o, m)</u></p> <p>if $u \in Cr$ then return \perp if $\neg HasAccess(u, (o, write))$ then return \perp $fs \leftarrow Write(st_u, fs, o, m)$ $T[o] \leftarrow m$; return fs</p> <p><u>FS($query$)</u></p> <p>if $query = \text{“STATE”}$ then return fs if <math>query = \text{“APPEND($info$)”}</math> then Parse $info$ as (o, c) $T[o] \leftarrow adv$; $fs \leftarrow fs info$ return fs</p>
--	--

Fig. 3. \mathcal{O}_{l-corr} : Oracles for defining the experiment $\text{Exp}_{\Pi, \mathcal{A}}^{l-corr}$.

Theorem 2. *If both the predicate encryption scheme and the digital signature scheme are correct, the construction in [3] preserves local correctness.*

Proof sketch. We will show that in this cRBAC construction, no matter how the adversary touches a file, any content written by an authorised user will be correctly retrieved by another user, with the read permission of the file.

The specification of their write algorithm `Write`, shows us that the algorithm will come up with a new entry to be appended to the file. The content of the new entry is completely independent from any of the previous entries and it only depends on the next available index of the file versions and also the metadata stored in the header of said file. Since the file system is assumed to preserve correct ordering of the file and the metadata can only be updated by the manager, these two parameters will not be affected by any corrupt user’s behaviours to the file system. In case, a different option would be that the predicate encryption scheme or the signature scheme are not correct therefore the authorised user cannot correctly retrieve the content written to the target file. Thus, we can conclude that the construction preserves local correctness under the assumption that both the predicate encryption scheme and the digital signature are correct. \square

4 Lower Bounds for secure cRBAC systems

In this section, we present two lower bounds for secure cRBAC systems. By lower bounds, we refer to the efficiency implications of secure cRBAC systems. To some extent, our results explain why cRBAC systems supporting dynamic policy updates may

be prohibitively expensive: permission revocation can be costly. Prior to presenting our results, we will introduce a technical term called *Permission Adjustment* for an RBAC system. Informally, permission adjustment is a sequence of administrative commands changing the access rights of some users with respect to a set of permissions. In comparison with any sequence of typical RBAC administrative commands that might not bring any change to the access matrix of the system, permission adjustment emphasises the *change* it will bring to the access matrix. The term can be better understood using the following example. Consider that a user that has been deassigned from a reviewer role still has access to the conference papers, as the user may also serve as a programme committee member. This allows the user to get authorised access. However, for the permission adjustment of cancelling its access to the papers, the user will no longer be able to do so due to the change on the access control policy.

Definition 4. (*Permission Adjustment*) Let $S_0 = (U, O, P, UA, PA)$ be the state of an RBAC system over a set of roles R . Given a set of users $\tilde{U} \subseteq U$ and a set of permissions $\tilde{P} \subseteq P$, where both \tilde{U} and \tilde{P} are non-empty, a sequence of RBAC administrative commands $\vec{q} = (q_0, \dots, q_n)$ is called a **permission adjustment** for S_0 with respect to \tilde{U} and \tilde{P} :

- (1) if $\forall u \in \tilde{U}, p \in \tilde{P} : \neg \text{HasAccess}(u, p)$ holds for S_0 and after a sequence of transitions $S_0 \xrightarrow{q_0}_{\mathcal{S}} S_1 \xrightarrow{q_1}_{\mathcal{S}} \dots \xrightarrow{q_{n-1}}_{\mathcal{S}} S_n \xrightarrow{q_n}_{\mathcal{S}} S_{n+1}$, $\forall u \in \tilde{U}, p \in \tilde{P} : \text{HasAccess}(u, p)$ holds for S_{n+1} or
- (2) if $\forall u \in \tilde{U}, p \in \tilde{P} : \text{HasAccess}(u, p)$ holds for S_0 and after a sequence of transitions $S_0 \xrightarrow{q_0}_{\mathcal{S}} S_1 \xrightarrow{q_1}_{\mathcal{S}} \dots \xrightarrow{q_{n-1}}_{\mathcal{S}} S_n \xrightarrow{q_n}_{\mathcal{S}} S_{n+1}$, $\forall u \in \tilde{U}, p \in \tilde{P} : \neg \text{HasAccess}(u, p)$ holds for S_{n+1} .

We denote the set of all possible \vec{q} in case (1) by $\tilde{U} \uparrow \tilde{P}(S_0)$ and the set of all possible \vec{q} in case (2) by $\tilde{U} \downarrow \tilde{P}(S_0)$.

In addition, we introduce two key properties with respect to efficiency.

Definition 5. Let $st_G = (st_M, fs, \{st_u\}_{u \in U})$ be the global state of a cRBAC system over a set of roles R at some point during its execution. Given a sequence of RBAC administrative commands $\vec{q} = (q_0, \dots, q_n)$ and a sequence of efficient operations $\vec{Q} = (Q_0, \dots, Q_n)$ such that for each $i \in \{0, \dots, n\}$: Q_i implements the command q_i . After carrying out \vec{Q} :

- (1) if the state of the file system remains unchanged, we say that \vec{q} is **file system pre-serving** for st_G . It is reflected by the following predicate:

$$\text{FSP}(\vec{q}, st_G) \Leftrightarrow \Pr[\forall \vec{Q} : st_G \xrightarrow{\vec{Q}} st'_G; fs = fs'] = 1,$$

where $st'_G = (st'_M, fs', \{st'_u\}_{u \in U'})$ and $\phi(st'_G) = (U', O', P', UA', PA')$;

- (2) if the local states of a set of users \mathbb{U} remain unchanged, we say that \vec{q} is **\mathbb{U} -user local state preserving** for st_G . It is reflected by the following predicate:

$$\text{LSP}(\vec{q}, st_G, \mathbb{U}) \Leftrightarrow \Pr[\forall \vec{Q} : st_G \xrightarrow{\vec{Q}} st'_G; \forall u \in \mathbb{U} : st_u = st'_u] = 1,$$

where $st'_G = (st'_M, fs', \{st'_u\}_{u \in U'})$, $\phi(st'_G) = (U', O', P', UA', PA')$ and $\mathbb{U} \subseteq U'$.

Finally, we introduce the concept of *non-trivial execution* for a cRBAC system. A non-trivial execution consists of a sequence of operations such that after executing every operation in order, for each file in the system, there should exist at least a user that has the read permission for it and also exist at least a user that has the write permission for it. The non-trivial execution serves as a mild assumption on the execution of a cRBAC system, for the purpose of studying the lower bound of cRBAC systems which are commonly used in practice. Also, non-trivial execution can prevent trivial implementations of a cRBAC system. For example, in a cRBAC system that only exists users who are authorised to read but no user can write to the file system, there is no need to worry about unauthorised read access because no content will be written to the file system. Similar situation holds for the case of write security.

Before introducing the lower bounds, we first present following auxiliary results.

Lemma 1. *For any correct cRBAC system, it holds that:*

$$\Pr[st_G \leftarrow_s \text{Init}(1^\lambda, R); st_G \xrightarrow{\vec{Q}} st'_G; \forall u \in U : \mathbb{P}_r(\phi(st'_G), u) \subseteq \mathbb{Q}_r(st'_G, u)] = 1,$$

where \vec{Q} an efficient non-trivial execution and $\phi(st'_G) = (U, O, P, UA, PA)$.

Proof. Assume that for a cRBAC system Π , the probability that after carrying out the non-trivial execution \vec{Q} , the system will reach some global state st'_G such that $\mathbb{P}_r(\phi(st'_G), u) \subseteq \mathbb{Q}_r(st'_G, u)$ holds for all user $u \in U$ is $\epsilon < 1$. We show that Π cannot be correct in such case.

Consider the following adversary \mathcal{A} for $\text{Exp}_{\Pi, \mathcal{A}}^{\text{corr}}(\lambda)$. After the system gets initialised, \mathcal{A} is provided λ and then calls the corresponding oracles to carry out \vec{Q} in order. Let st'_G be the current global state of the system. Now \mathcal{A} makes a random guess of a tuple $(u, u', o) \in U \times U \times O$ and also comes up with a message $m \in \{0, 1\}^\lambda$. It then calls the write oracle WRITE with (u', o, m) . If WRITE returns an error, \mathcal{A} just terminates here; otherwise \mathcal{A} terminates with an outputs (u, o) . Since \vec{Q} is a finite sequence of operations, \mathcal{A} is an polynomial-time adversary.

By assumption, the probability of existing a user $\bar{u} \in U$ and a file $\bar{o} \in O$ satisfying both $o \in \mathbb{P}_r(\phi(st'_G), \bar{u})$ and $o \notin \mathbb{Q}_r(st'_G, \bar{u})$ is $1 - \epsilon$. Since \vec{Q} is a non-trivial execution, the condition $o \notin \mathbb{Q}_r(st'_G, \bar{u})$ further implies that there exists a user $\bar{u}' \in U$ has the write permission of \bar{o} such that if the message m is written to \bar{o} by \bar{u}' at this point, it will not be retrieved by correctly by running Read with \bar{u} 's local state. Therefore, if \mathcal{A} made a good guess of such $\bar{u}, \bar{o}, \bar{u}'$, the challenger will not be able to retrieve m . The advantage that \mathcal{A} can gain in the experiment is:

$$\text{Adv}_{\Pi, \mathcal{A}}^{\text{corr}}(\lambda) \geq \frac{1}{|U| \cdot |U| \cdot |O|},$$

which is obviously non-zero. Therefore, Π cannot be correct. \square

Lemma 2. *If a cRBAC system is secure with respect to read access, it holds that:*

$$\Pr[st_G \leftarrow_s \text{Init}(1^\lambda, R); st_G \xrightarrow{\vec{Q}} st'_G; \forall u \in U : \mathbb{P}_r(\phi(st'_G), u) \supseteq \mathbb{Q}_r(st'_G, u)] \geq 1 - \epsilon,$$

where \vec{Q} is an efficient non-trivial execution, $\phi(st'_G) = (U, O, P, UA, PA)$ and ϵ is a negligible function in λ .

Proof. Assume that for a cRBAC system Π , the probability that after carrying out the non-trivial execution \vec{Q} , it will reach some global state st'_G such that for all ϵ , $\mathbb{P}_r(\phi(st'_G), u) \supseteq \mathbb{Q}_r(st'_G, u)$ holds for all $u \in U$ with probability $\epsilon_0 < 1 - \epsilon$. We show that Π cannot be secure with respect to read access.

Consider the following adversary \mathcal{A} for $\text{Exp}_{\Pi, \mathcal{A}}^{\text{read}}(\lambda)$. After being provided the security parameter λ , \mathcal{A} makes queries to the corresponding oracles to carry out \vec{Q} in order. Let st'_G be the current global state of Π . Now \mathcal{A} randomly chooses a user $u \in U$, a file $o \in O$ and another user $u' \in \{u | \text{HasAccess}(u, (o, \text{write}))\}$. It then requests to corrupt u to obtain the local state st_u . Next, \mathcal{A} calls the challenge oracle CHALLENGE with (u', o, m_0, m_1) , where $m_0, m_1 \in \{0, 1\}^\lambda$ are two random messages of the same length. If CHALLENGE returns an error, \mathcal{A} terminates here and outputs a random bit. If CHALLENGE returns the updated state of the file system fs , \mathcal{A} then computes $m^* \leftarrow \text{Read}(st_u, fs, o)$. Finally, it outputs 0 if $m^* = m_0$ and 1 if $m^* = m_1$; otherwise, it just outputs a random bit. Since \vec{Q} is efficient, \mathcal{A} is an polynomial-time adversary.

It is possible that u has the read permission of o , due to the reason that \mathcal{A} chose u and o randomly from all existing users and files in the system. Therefore, the request of taking over u might lead to an error returned by CHALLENGE. Notice that \mathcal{A} can read the content written to the file specified as its challenge only when there exist some user $\bar{u} \in U$ and $\bar{o} \in O$ satisfying both $\bar{o} \notin \mathbb{P}_r(\phi(st'_G), \bar{u})$ and $\bar{o} \in \mathbb{Q}_r(st'_G, \bar{u})$, and \mathcal{A} made a good guess of them. In all the other cases, \mathcal{A} has to output a random bit. By assumption, such \bar{u} and \bar{o} exist with probability $1 - \epsilon_0$. Then we have, the advantage that \mathcal{A} can gain in the experiment is:

$$\begin{aligned} \text{Adv}_{\Pi, \mathcal{A}}^{\text{read}}(\lambda) &\geq \left| (1 - \epsilon_0) \cdot \frac{1}{|U| \cdot |O|} + (1 - \epsilon_0) \cdot \left(1 - \frac{1}{|U| \cdot |O|}\right) \cdot \frac{1}{2} + \epsilon_0 \cdot \frac{1}{2} - \frac{1}{2} \right| \\ &= \left| \frac{1}{2} \cdot \frac{1}{|U| \cdot |O|} - \epsilon_0 \cdot \frac{1}{2} \cdot \frac{1}{|U| \cdot |O|} \right| \\ &= \frac{1}{2} \cdot \frac{1}{|U| \cdot |O|} \cdot (1 - \epsilon_0) > \frac{1}{2} \cdot \frac{1}{|U| \cdot |O|} \cdot \epsilon \end{aligned}$$

which is non-negligible. Hence Π cannot be secure with respect to read access. \square

Now we present our first lower bound for cRBAC systems which are both correct and secure with respect to read access.

Theorem 3. *For any cRBAC system which is **correct and secure with respect to read access**, it holds that:*

$$\Pr \left[st_G \leftarrow \text{Init}(1^\lambda, R); st_G \xrightarrow{\vec{Q}} st'_G; \forall \vec{q} \in U_r \downarrow P_r(\phi(st'_G)) : \text{FSP}(\vec{q}, st'_G) \wedge \text{LSP}(\vec{q}, st'_G, U_w) \right] \leq \epsilon,$$

where \vec{Q} is any non-trivial execution for the system, $st'_G = (st'_M, fs', \{st'_u\}_{u \in U'})$, $\phi(st'_G) = (U', O', P', UA', PA')$, $U_r \subseteq U'$, $P_r \subseteq \{(o, \text{read}) | o \in O'\}$, $U_w =$

$\{u|\forall(o, \text{read}) \in P_r : \text{HasAccess}(u, (o, \text{write}))\}$ and ϵ is a negligible function in λ .

Proof. We prove the theorem by showing that if the above condition is not satisfied, the cRBAC system cannot be both correct and secure with respect to read access. Assume by contradiction that there exists a cRBAC system Π which is correct and read secure, the above condition holds with probability ϵ_0 , which is greater than any ϵ .

Consider the following attack against the system. After Π is initialised with the role set R and then the non-trivially execution \vec{Q} is carried out. Let st'_G be the current global state. Since the cRBAC system is correct, for all users $u \in U_r$, $\mathbb{P}_r(\phi(st'_G), u) \subseteq \mathbb{Q}_r(st'_G, u)$ should hold with probability 1 according to Lemma 1. We let a user $u_0 \in U_r$ keeps its current local state st_{u_0} and refuses to get it updated in future, which means u_0 will ignore all the update messages sent from the manager from now on. After the sequence of RBAC administrative commands in \vec{q} is carried out, the global state becomes st''_G . Now, by assumption, $\text{FSP}(\vec{q}, st'_G)$ and $\text{LSP}(\vec{q}, st'_G, U_w)$ holds with non-negligible probability ϵ_0 . In the case that both of the two properties are satisfied simultaneously, the state of the file system and the local states of the users in U_w remain the same. It implies that $\mathbb{Q}_r(st'_G, u) = \mathbb{Q}_r(st''_G, u)$ but $\mathbb{P}_r(\phi(st''_G), u) \leftarrow \mathbb{P}_r(\phi(st'_G), u) \setminus P_r$ with overwhelming probability, which leads to a violation of the Lemma 2. Therefore, we can conclude that the cRBAC system cannot be both correct and secure with respect to read access.

We have the following lower bound for cRBAC systems which preserve both correctness and write security. The proof of it can be carried out in a similar manner. But it is obtained via a weaken security definition of secure write access where the manager will carry out the read operation to the specified file instead of the user chosen by the adversary.

Theorem 4. For any cRBAC system which is *correct and secure with respect to write access*, it holds that:

$$\Pr \left[st_G \leftarrow \text{Init}(1^\lambda, R); st_G \xrightarrow{\vec{Q}} st'_G; \forall \vec{q} \in U_w \downarrow P_w(\phi(st'_G)) : \text{FSP}(\vec{q}, st'_G) \wedge \text{LSP}(\vec{q}, st'_G, U_r) \right] \leq \epsilon,$$

where \vec{Q} is any non-trivial execution for the system, $st'_G = (st'_M, fs', \{st'_u\}_{u \in U'})$, $\phi(st'_G) = (U', O', P', UA', PA')$, $U_w \subseteq U'$, $P_w \subseteq \{(o, \text{write}) | o \in O'\}$, $U_r = \{u | \forall(o, \text{write}) \in P_r : \text{HasAccess}(u, (o, \text{read}))\}$ and ϵ is a negligible function in λ .

5 Conclusion

We proposed two new formal security definitions for cRBAC systems in the game-based setting. The first one is called past confidentiality, which captures the security concern of unauthorised access to the previous versions of the files. We show that this security definition is strictly stronger than the existing one for secure read access. The other security definition we proposed is called local correctness, which captures the security concern from the insider of the system which might undermine data availability. We presented two lower bounds for secure cRBAC systems, which explain where the inefficiency stems from in such systems that support for permission revocation.

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A Security definitions of cRBAC schemes in [3]

A.1 Secure Read Access

A cRBAC system is said to be secure with respect to read accesses if no user can deduce any partial content of a file without having the read permission. It is formalised via the following experiment $\mathbf{Exp}_{II,\mathcal{A}}^{\text{read}}$ which involves a challenger who plays as the manager of a cRBAC system and an adversary \mathcal{A} . During the game, the adversary can choose two messages to be written to a file of which it does not have the read permission. Then one of the two messages will be written to that file and \mathcal{A} 's goal is to determine which of the messages it is.

Definition 6 (Secure Read Access). A cRBAC system II defined by the cRBAC scheme (Init, AddUser, DelUser, AddObject, DelObject, AssignUser, DeassignUser, GrantPerm, RevokePerm, Read, Write, Update) is *secure with respect to read access* if for any probabilistic polynomial-time adversary \mathcal{A} , it holds that

$$\mathbf{Adv}_{II,\mathcal{A}}^{\text{read}}(\lambda) := \left| \Pr[\mathbf{Exp}_{II,\mathcal{A}}^{\text{read}}(\lambda) \rightarrow \text{true}] - \frac{1}{2} \right|$$

is negligible in λ , where $\mathbf{Exp}_{II,\mathcal{A}}^{\text{read}}$ is defined as follows:

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 $\mathbf{Exp}_{II,\mathcal{A}}^{\text{read}}(\lambda)$ 
   $b \leftarrow_{\$} \{0, 1\}; Cr, Ch \leftarrow \emptyset$ 
   $State \leftarrow (\emptyset, \emptyset, \emptyset, \emptyset, \emptyset)$ 
   $(st_M, fs, \{st_u\}_{u \in U}) \leftarrow_{\$} \text{Init}(1^\lambda, R)$ 
   $b' \leftarrow_{\$} \mathcal{A}(1^\lambda : \mathcal{O}_{\text{read}})$ 
  return  $(b' = b)$ 

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The oracles $\mathcal{O}_{\text{read}}$ that the adversary has access to are specified in Figure 4.

A.2 Secure Write Access

A cRBAC system is said to be secure with respect to write access if no user can write some content to a file without having the permission. Particularly, in the case of open-accessible file system, the content wrote by an unauthorised user should not be considered as valid. It is formalised by the following experiment $\mathbf{Exp}_{II,\mathcal{A}}^{\text{write}}$. The adversary needs to specify a target file with an honest user and its wins the game if it can manage to write any valid content (read by the honest user) without the help of any authorised user. To prevent trivial wins, from the point when the last write operation to the target file is carried out by an honest user who has the permission till \mathcal{A} generates its output, no corrupt user can get write access to the target file.

Definition 7. A cRBAC system II defined by the cRBAC scheme (Init, AddUser, DelUser, AddObject, DelObject, AssignUser, DeassignUser, GrantPerm, RevokePerm, Read, Write, Update) is *secure with respect to write access* if for any probabilistic polynomial-time adversaries \mathcal{A} , we have

$$\mathbf{Adv}_{II,\mathcal{A}}^{\text{write}}(\lambda) := \Pr[\mathbf{Exp}_{II,\mathcal{A}}^{\text{write}}(\lambda) \rightarrow \text{true}]$$

<p><u>CMD(<i>arg</i>)</u> $(U', O', P', UA', PA') \leftarrow \text{Cmd}(\text{State}, \text{arg})$ foreach $u \in Cr$ AND $o \in Ch$: if $\exists r \in R$: $(u, r) \in UA' \wedge ((o, \text{read}), r) \in PA'$ then return \perp $\text{State} \leftarrow (U', O', P', UA', PA')$ $(st_M, fs, \{msg_u\}_{u \in U}) \leftarrow \text{Cmd}(st_M, fs, \text{arg})$ foreach $u \in Cr$: if $u \notin U$ then $Cr \leftarrow Cr \setminus \{u\}$ foreach $o \in Ch$: if $o \notin O$ then $Ch \leftarrow Ch \setminus \{o\}$ foreach $u \in U \setminus Cr$: $st_u \leftarrow \text{Update}(st_u, msg_u)$ return $(fs, \{msg_u\}_{u \in Cr})$</p>	<p><u>WRITE(<i>u, o, m</i>)</u> if $u \in Cr$ then return \perp if $\neg \text{HasAccess}(u, (o, \text{write}))$ then return \perp $fs \leftarrow \text{Write}(st_u, fs, o, m)$ return fs</p>
<p><u>CORRUPTU(<i>u</i>)</u> if $u \notin U$ then return \perp foreach $o \in Ch$: if $\text{HasAccess}(u, (o, \text{read}))$ then return \perp $Cr \leftarrow Cr \cup \{u\}$; return st_u</p>	<p><u>CHALLENGE(<i>u, o, m₀, m₁</i>)</u> if $\neg \text{HasAccess}(u, (o, \text{write}))$ then return \perp if $m_0 \neq m_1$ then return \perp foreach $u' \in Cr$: if $\text{HasAccess}(u', (o, \text{read}))$ then return \perp $Ch \leftarrow Ch \cup \{o\}$ $fs \leftarrow \text{Write}(st_u, fs, o, m_b)$ return fs</p>
	<p><u>FS(<i>query</i>)</u> if $query = \text{"STATE"}$ then return fs if $query = \text{"APPEND}(info)\text{"}$ then $fs \leftarrow fs \parallel info$; return fs</p>

Fig. 4. \mathcal{O}_{read} : Oracles for defining the experiment $\text{Exp}_{II, \mathcal{A}}^{\text{read}}$.

is negligible in λ , where $\text{Exp}_{II, \mathcal{A}}^{\text{write}}$ is defined as follows:

$\text{Exp}_{II, \mathcal{A}}^{\text{write}}(\lambda)$
 $Cr, T \leftarrow \emptyset$
 $\text{State} \leftarrow (\emptyset, \emptyset, \emptyset, \emptyset)$
 $(st_M, fs, \{st_u\}_{u \in U}) \leftarrow \text{Init}(1^\lambda, R)$
 $o^* \leftarrow \mathcal{A}(1^\lambda : \mathcal{O}_{write})$
if $T[o^*] \neq \text{adv} \wedge T[o^*] \neq \text{Read}(st_M, fs, o^*)$ **then**
 return true
else return false

The oracles \mathcal{O}_{write} that the adversary has access to are specified in Figure 5

<p><u>CMD(<i>Cmd</i>, <i>arg</i>)</u></p> <p><i>State</i> \leftarrow <i>Cmd</i>(<i>State</i>, <i>arg</i>)</p> <p>(<i>st_M</i>, <i>fs</i>, {<i>msg_u</i>}_{<i>u</i> ∈ <i>U</i>}) \leftarrow $\\$ CMD(<i>st_M</i>, <i>fs</i>, <i>arg</i>)</p> <p>if <i>Cmd</i> = “DELOBJECT” then</p> <p style="padding-left: 20px;">Parse <i>arg</i> as <i>o</i>; <i>T</i>[<i>o</i>] \leftarrow \emptyset</p> <p>if <i>Cmd</i> = “DELUSER” then</p> <p style="padding-left: 20px;">Parse <i>arg</i> as <i>u</i>; <i>Cr</i> \leftarrow <i>Cr</i> \setminus {<i>u</i>}</p> <p>foreach <i>o</i> ∈ <i>O</i>:</p> <p style="padding-left: 20px;">if $\exists u' \in Cr : \text{HasAccess}(u', (o, \text{write}))$ then</p> <p style="padding-left: 40px;"><i>T</i>[<i>o</i>] \leftarrow adv</p> <p>foreach <i>u</i> ∈ <i>U</i> \setminus <i>Cr</i>:</p> <p style="padding-left: 20px;"><i>st_u</i> \leftarrow Update(<i>st_u</i>, <i>msg_u</i>)</p> <p>return (<i>fs</i>, {<i>msg_u</i>}_{<i>u</i> ∈ <i>Cr</i>})</p> <p><u>CORRUPTU(<i>u</i>)</u></p> <p>if <i>u</i> \notin <i>U</i> then return \perp</p> <p>foreach <i>o</i> ∈ <i>O</i>:</p> <p style="padding-left: 20px;">if HasAccess(<i>u</i>, (<i>o</i>, write)) then</p> <p style="padding-left: 40px;"><i>T</i>[<i>o</i>] \leftarrow adv</p> <p><i>Cr</i> \leftarrow <i>Cr</i> \cup {<i>u</i>}; return <i>st_u</i></p>	<p><u>WRITE(<i>u</i>, <i>o</i>, <i>m</i>)</u></p> <p>if <i>u</i> ∈ <i>Cr</i> then return \perp</p> <p>if $\neg \text{HasAccess}(u, (o, \text{write}))$ then</p> <p style="padding-left: 20px;">return \perp</p> <p><i>fs</i> \leftarrow $\\$ Write(<i>st_u</i>, <i>fs</i>, <i>o</i>, <i>m</i>)</p> <p>foreach <i>u'</i> ∈ <i>Cr</i>:</p> <p style="padding-left: 20px;">if HasAccess(<i>u'</i>, (<i>o</i>, write)) then</p> <p style="padding-left: 40px;">return <i>fs</i></p> <p><i>T</i>[<i>o</i>] \leftarrow <i>m</i>; return <i>fs</i></p> <p><u>FS(<i>query</i>)</u></p> <p>if <i>query</i> = “STATE” then</p> <p style="padding-left: 20px;">return <i>fs</i></p> <p>if <i>query</i> = “APPEND(<i>info</i>)” then</p> <p style="padding-left: 20px;"><i>fs</i> \leftarrow <i>fs</i> <i>info</i>; return <i>fs</i></p>
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Fig. 5. \mathcal{O}_{write} : Oracles for defining the experiment $\text{Exp}_{II, \mathcal{A}}^{write}$.