Static Enforcement of Role-Based Access Control

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We propose a new static approach to Role-Based Access Control (RBAC) policy enforcement. The static approach we advocate includes a new design methodology, for applications involving RBAC, which integrates the security requirements into the system's architecture. We apply this new approach to policies restricting calls to methods in Java applications. We present a language to express RBAC policies on calls to methods in Java, a set of design patterns which Java programs must adhere to for the policy to be enforced statically, and a description of the checks made by our static verifier for static enforcement.

1 Introduction

The objectives of an access control system are often described in terms of protecting system resources against inappropriate or undesired user access. When there is a request for a resource, the system must check who triggered the request *(authentication)*, check if that user has the permission for the request to be fulfilled (*authorisation*) and as a result allow or deny the request *(enforcement)*. Thus, an implementation of access control requires a specification of the rights associated to users in relation to resources *(a policy)*. For this, several models of access control have been defined, from simple access control lists giving for each user the list of authorised operations, to more abstract models, such as the popular Role-Based Access Control (RBAC) model [7].

Our focus is on enforcement, for which there exist two main approaches, static and dynamic, with a recently emerged third approach combining the two: the hybrid approach. The static approach performs all access checks at compile time, whereas the dynamic approach performs these at run time. In short, the static approach enables policy violations to be detected earlier, facilitating debugging and reducing the impact on testing, and usually involves a lower run-time cost. However, the kinds of policies enforceable statically are not as expressive nor as flexible as those enforceable by the dynamic approach. We refer to [12] for a more detailed comparison; see also [3] for hybrid analysis of programs, although not directly applicable to our problem (discussed further in Section 8).

The overall goal of our work is to enforce general access control policies using a hybrid approach, that is, using a combination of compile-time and run-time checks. In this paper, we present the first stage of our work, which is focused solely on static enforcement. Our main result is a mechanism to fully verify RBAC policies statically. More precisely, we consider implementations of RBAC policies in Java, where policies restrict method invocations, and present a static source-code verifier to enforce the policies. Our static verifier ensures that validated programs contain no unauthorised method invocations.

RBAC is a widely used policy specification model. Our static program analysis is applicable to RBAC implementations under certain important conditions. The first of these is that the source code must be available at compile time. Secondly, the code should not be modified at run time through mechanisms such as reflection, therefore our system is aimed at non-malicious programmers. Thirdly, the policy should not change at run time nor should it rely on dynamic information (which changes throughout execution). The latter condition holds for the first and second 'levels' of the standardised RBAC models:

flat-RBAC and *hierarchical-RBAC* [8], if we disallow administrative changes to the policy (Section 7 discusses in more detail these restrictions and our plans to relax them in future work). We therefore provide a policy specification language which supports resource, permission and role definitions, and also role hierarchies. To the best of our knowledge, these kinds of policies are typically enforced dynamically in today's available RBAC systems (e.g., Java Web Security amongst others [1, 10]). One significant reason for this is that during static analysis, it is difficult to know which regions of code are accessible by users with which roles. This is because the roles are not usually part of the application at the design and source level – they exist only at run time as part of the (dynamic) security context information. We have solved this problem through the use of a program design methodology, which integrates the RBAC model in the system's architecture.

To highlight the problem, consider the following Java code [11]:

```
if(securityContext.isUserInRole(''admin'' )) wipeData();
```

These kinds of code snippets are common in RBAC implementions. In such cases, a programmer would want to be sure that only the authorised role ('admin', in this example) can invoke the security-critical, or *protected* method ('wipeData', in this example). This would usually be done using a dynamic check – the *if* statement (which in this case utilises Java Servlet API's *isUserInRole()* method [11]), before any such method invocation. The program would then have to be rigorously tested to ensure that each role can reach only those invocations that it is allowed to. It would be reasonable to assume that the number of test cases needed would increase as the number of roles increases and the number of protected invocations in the program increases.

Catching errors at an early stage statically aids debugging and reduces testing time. So, since a hierarchical-RBAC (and also flat-RBAC) policy is static (with administrative changes disabled), a program implementing this policy should be able to be checked at compile time for policy compliance. Having said that, just because the policy is static does not mean it is trivial to statically check the program for policy compliance. Let us start by removing the dynamic check in our example code – the *if* statement – leaving just the invocation of the protected method. We now need to know statically which roles can perform the invocation. The difficulty is that the active role exists only in the security context of the program's execution. In this paper, we show that it is indeed possible to statically enforce hierarchical (or flat) RBAC policies. Moreover, only the assignment of permissions to roles is assumed to be static, user-role assignments can change, providing more flexibility.

Summarising, we propose a static solution to RBAC policy enforcement for Java programs through the use of new *RBAC MVC* design patterns combined with a set of static verification checks made by our static verifier. The patterns integrate roles into the program as a set of Model-View-Controller (MVC) [13] components (i.e. classes) for each role. Each role's associated MVC classes act as a role-specific interface to accessing resources – protected methods in resources are invoked in these role classes only. The flow of the program directs users to the set of role classes associated to their active role. Finally, the protected invocations are checked statically for policy compliance. We present a static verifier, which performs syntactic checks and call graph analysis to ensure the invocations to methods belonging to resource classes are made only in role classes, such invocations are permitted according the policy and role classes do not invoke methods of components belonging to other roles.

The rest of the paper is organised as follows. After recalling the basic notions in RBAC and the concept of a design pattern in Section 2, we give an overview of the approach in Section 3, followed by the definition of the policy language in Section 4. Section 5 introduces the RBAC MVC patterns and Section 6 describes the static verifier. The implementation is described in Section 7. Section 8 discusses related work and Section 9 concludes and discusses future work.

2 Preliminaries

Role-Based Access Control is a mechanism to protect resources from unauthorised use in an organisation, where instead of specifying all the accesses each user is allowed to execute, access authorisations on objects are specified for roles [7]. Each role is given a set of access rights, and each user is given a set of roles so that only authenticated users who have activated the required role can access and use the restricted resources. Roles can be arranged in a hierarchy, where a more senior role 'subsumes' another; the senior role inherits the permissions of the subsumed role and can be assigned further permissions.

A *design pattern* describes a particular recurring design problem that arises in a specific design context, and presents a generic scheme for its solution [6]. Patterns are usually described using the semi-formal Unified Modelling Language (UML) notation, showing its constituent components, their responsibilities and relationships, and the way in which they collaborate. The goal of patterns is to provide a mechanism to guide the implementation of a solution to a specific problem.

Our work utilises concepts from the well known and widely used *Model-View-Controller (MVC) pattern*. This pattern achieves separation of concern for user interaction [13], separating data processing from user interaction, allowing both to be modified independently. Data processing is handled by *model* components, data presentation and user-interaction are handled by *view* components and the communication between these two is handled by *controller* components.

3 Conceptual Overview of Approach

Programs that restrict access to resources from users typically involve an initial user authentication phase, where users log in and retrieve their access rights, then allowing users to undertake user tasks which may involve accessing resources, and finally logging out of the system. We present a simplified model of the general flow of a program which implements RBAC in the left-hand side of Figure 1. In RBAC, authentication also involves retrieving and activating the role(s) associated to the user, and logging out also involves deactivating the role(s). Controlling access most commonly takes place between 'Tasks' and 'Resources', for example through a reference monitor intercepting all access requests made to resources at run time, stopping those requests which are unauthorised.

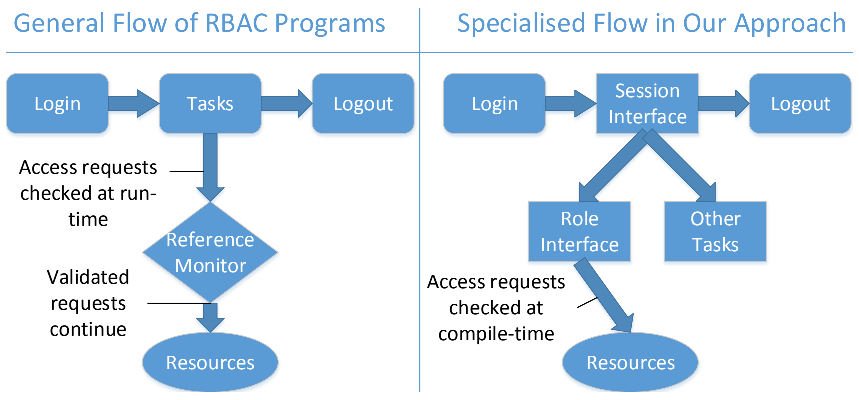

General Flow of RBAC Programs
Specialised Flow in Our Approach
Login
Tasks
Logout
Access requests checked at run-time
Reference Monitor
Validated requests continue
Resources
Login
Session Interface
Logout
Role Interface
Other Tasks
Access requests checked at compile-time
Resources

Figure 1: General and specialised flow of programs that enforce RBAC

In our approach, we divide user tasks into three groups: *role tasks* that users with certain roles in the system can perform (these may access resources), *other tasks* that the policy is not directly concerned with and *session tasks* related to the functioning of the session. After a successful log-in, users are presented with a *session interface*. This is made up of MVC components that implement session tasks e.g. log-out. The session interface will retrieve and hold a list of all the roles assigned to the user in the policy. From here, the user can choose to perform role tasks by selecting one of the retrieved roles, resulting in the session interface displaying the *role interface* for the selected role. Each role has an associated role interface which implements its role tasks through a set of MVC components: a set of view components, one controller and one model component. Direct access to resources is prevented; resources can only be accessed through a role interface. The user interacts with a *Role View* which communicates with its *Role Controller*, which communicates with its *Role Model* which finally may access a resource. In this way, if an access request is found at compile time in a class that is part of a role interface, then the role that the interface belongs to is the role that can reach and execute this request. Our *RBAC MVC* patterns guide the implementation of the program to achieve this flow.

We now define the core concepts in our approach.

Definition 1 (Resource)**.** A *resource* is realised as a *resource class* containing some methods whose invocation needs to be restricted. Invocations are restricted for instances of resource classes.

Methods in resource classes are categorised as follows.

Definition 2 (Actions and Auxiliary Methods)**.** An *action* is a method in a resource class that must only be invoked by those users with the permission to do so. An *auxiliary* method is a method in a resource class that is not part of the policy definition. Such methods are usually required for the correct initialisation and operation of a class, and should not be invoked directly by users.

Definition 3 (Permission)**.** A *permission* is a pair $[res, act]$ where *res* is the name of a resource and *act* is the name of an action of that resource. The action is allowed to be invoked on any instance of that resource class by the role (see Definition 6) which the permission is assigned to.

Definition 4 (Access)**.** An *access to a resource* is an invocation or call to an action method of an instance of a resource class.

Definition 5 (Task)**.** We divide the concept of a user task into three groups as follows. Firstly, a *role task* is an operation, or business function, to be performed by an authorised user in a specific role, which could involve the invocation of one or more actions on resources. Secondly, a *session task* is an operation required to correctly manage the session e.g. log-in and log-out. Thirdly, an *other task* is an operation or function that is executable by all users, regardless of the notion of role as it does not access resources (in the access control sense).

An example of a role task is as follows. A user in an Admin role in a GP surgery may need to perform the task *`registerPatient`*, which would involve a call to an action e.g. *`addPatient`* in the *`Patients`* resource.

Definition 6 (Role)**.** At the policy level, a *role* consists of a name and a list of permissions to access resources.

In the context of our system, a role is implemented by a set of MVC components: a set of Role View components (i.e. classes), a Role Controller class and a Role Model class (as defined below). Together, these provide a *role-specific interface* for the user to perform tasks. We define these components below.

Definition 7 (Role Model)**.** A *Role Model* provides role-task methods which should only call those actions that are permitted for its role. Its name must be prefixed with the name of the role, followed by 'Model'.

Definition 8 (Role Controller)**.** A *Role Controller* acts as an intermediary between the Role Model and View classes. Its name must be prefixed with the name of the role, followed by 'Controller'. Role Controller methods are invoked in Role View classes to communicate with the Controller.

Definition 9 (Role View)**.** A *Role View* provides (part of) the user-interface for users to execute the tasks of their role. Its name must be prefixed with the name of the role, followed by 'View' (followed by any valid Java identifier).

For any role r, its single associated role model class contains the code that performs the tasks r can do in the system. The role's multiple associated role view classes and its single associated role controller class, provide the means for users that have activated this role to access these tasks (and perform them).

An example of a set of role components is as follows. Firstly, a role model class *AdminModel*, which provides a role task `registerPatient()` that calls on the `addPatient()` action in the `Patients` resource. Secondly, a set of role view components *AdminViewPatients, AdminViewAppointments,* e.t.c. Thirdly, a role controller *AdminController* acting as an intermediary between the role view and model components.

Definition 10 (Session)**.** A *session* is the state of the program in which an authenticated user is able to perform the three kinds of tasks in the system. The session has a user interface composed of a session-specific interface, the role-specific interface (made up of Role MVC components discussed above) of the current active role and any interfaces implementing other tasks. The session-specific interface is made up of a set of MVC components: one Session Model, one Session Controller and a set of Session View classes. The Session Model implements the session tasks which are: log-in/authentication, role activation, log-out, calling a role-interface and calling classes that implement other tasks. The Session Views and Controller provide the means for the user to access these session tasks. The session-specific interface is always active so that the session tasks are always available to the user. We, of course, have minimum expectations such as log-out only being available if logged-in and so forth. The session-specific interface also allows the user to interact with the system via their role by calling a role interface, or without their role thus calling other-task implementing classes. Names of session classes start with the string 'Session' followed by either 'Model', 'Controller' or 'View'. For the latter, since there can be many Session View classes, any valid class identifier (in Java) is allowed to follow in the name.

The classes required for the session – Session Classes – constitute part of our Trusted Computing Base (TCB); the other part is the actions, which we trust behave safely. The session classes should contain the minimum code necessary to implement session tasks, so that the TCB is small. We perform few checks, and exercise few constraints, on session classes in order for their implementation to be as flexible as possible. Therefore, we do not deal with authentication in this paper. However, an important aspect of an RBAC system is the *active role*, which is to be implemented by the session classes. We give guidelines for implementing the active role below by first defining the concept of *authenticated user*.

Definition 11 (Authenticated User)**.** An *authenticated user* is a user that passes the authentication process, which is left open and unrestricted for the programmer in our approach except for one condition: after successful authentication, the session model class contains a list *retrievedRoles* containing the names of the roles given to that user in the policy.

Definition 12 (Active Role)**.** The *active role* is the single role r_a selected by the user from the *retrievedRoles* (see Definition 11) whose role interface is being displayed to the user so that they may perform the role tasks associated with r_a. *Role activation* constitutes storing r_a in a field called *activeRole* in the session model class and invoking the role controller of that role. This process is achieved in a method *activateRole()* in the session model class (See Definition 10). This will result in presenting a role view of the active role's role interface to the user by composing it with the session interface.

4 Policy Language: JPol

We define a policy specification language for hierarchical-RBAC, called JPol, where resources, together with their associated lists of actions, and roles, together with their associated permissions, can be declared. To simplify, we assume that only the access requests that are allowed are expressed, so all other requests are not allowed. The policy file will be parsed and represented as a set of tables, to be used only at compile-time by the static verifier in order to perform the access checks.

The policy language does not support user definitions and user-role assignments, since we do not deal with authentication in this paper. Since with our static verifier, only the roles which have been declared in the policy will be permitted to be assigned to users, the resources will still be protected because each role will have been checked at compile-time to ensure it does not perform any illegal access requests. The proposed approach is flexible: new users can be added to the system and user-role assignments can change depending on changes within the organisation.

4.1 Syntax and Representation

The policy language adopts an object-oriented, Java-like syntax designed to make the policy implementer's transition from target program language, Java, to policy language as effortless as possible. However, as we will see later, the static verifier relies solely on the information generated as a result of parsing the policy file. Thus, the syntax of the policy language can change and be adapted to any environment using hierarchical- (or flat-) RBAC. We could, for instance, use one of the existing RBAC specification languages.

The grammar of the policy language is as follows, where the keyword *subsumes* indicates role inheritance. The abstract syntax of the policy language is illustrated in Figure 2.

```
stmts          ::=  (stmt ';')+
stmt           ::=  decRole | decRoleSubsume | decRes
                    | addActRes | addPermRole
decRole        ::=  'Role' ID '=' 'new' 'Role' name
decRoleSubsume ::=  'Role' ID '=' 'new' 'Role' name
                    'subsumes' ID
decRes         ::=  'Resource' ID '=' 'new' 'Resource' name
addActRes      ::=  ID '.' 'addAction' name
addPermRole    ::=  ID '.' 'addPermission' permission
name           ::=  '(' ID ')'
permission     ::=  '(' ID ',' ID ')'
```

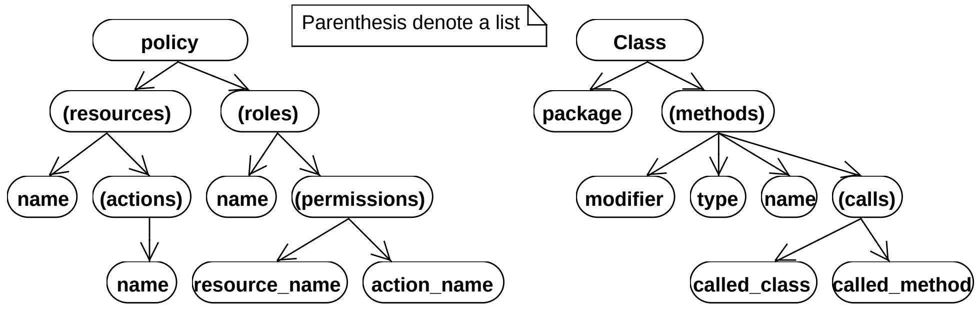


Figure 2: Abstract syntax of policy on the left and a class on the right

The parser for the policy specification language checks that a policy declaration is syntactically correct, producing the Abstract Syntax Tree (AST) shown in Figure 2. It then generates intermediate data structures – tables called ‘Resources’ and ‘Roles’ containing the information needed for the static verifier.

Listing 1 shows an example specification in JPol for patient-related resources and permissions for roles in an example GP/doctor’s surgery, with the resulting tables ‘Resources’ and ‘Roles’ shown in Figure 3.

Listing 1: Example JPol code declaring Resources with their actions and Roles with their permissions

```
Resource nhspatient = new Resource(‘Nhspatient’);
nhspatient.addAction(‘getFirstName’);
Resource privatepatient = new Resource(‘Privatepatient’);
privatepatient.addAction(‘getFirstName’);
Role nhsdoctor = new Role(‘NHSDoctor’);
nhsdoctor.addPermission(‘Nhspatient’, ‘getFirstName’);
Role privatedoctor = new Role(‘PrivateDoctor’);
privatedoctor.addPermission(‘Privatepatient’, ‘getFirstName’);
Role admin = new Role(‘Admin’);
admin.addPermission(‘Nhspatient’, ‘getFirstName’);
admin.addPermission(‘Privatepatient’, ‘getFirstName’);
```

Resources	
name	**actions**
Nhspatient	getFirstName
Privatepatient	getFirstName

Roles	
name	**permissions**
NHSDoctor	Nhspatient, getFirstName
PrivateDoctor	Privatepatient, getFirstName
Admin	Nhspatient, getFirstName
	Privatepatient, getFirstName

Figure 3: Example Roles and Resources Tables Representation

4.2 Semantics

We can state the semantics of the policy language in a concise manner by mapping the abstract syntax to elements of the RBAC model: there is a one-to-one correspondence between the resources, roles and permissions specified in JPol and in the RBAC model. In particular, an ‘addPermission’ statement in JPol syntax (see the grammar rule for ‘addPermRole’ above) corresponds directly to a permission in the RBAC sense. Therefore, we can define policy satisfaction as follows.

Definition 13 (Policy Satisfaction)**.** A Java program satisfies a JPol policy if, for any invocation $res.m$ that exists in the program, where res is an instance of a resource class Res and m an action, only authenticated users with active role r, such that the JPol policy specifies the permission $[Res, m]$ for r, can perform $res.m$.

5 Program Design Patterns - RBAC MVC

In order for the target program to be statically checked for policy compliance, it must follow our RBAC MVC Patterns described below.

5.1 RBAC Model, Controller, View and Session Patterns

The class diagrams of the patterns are shown together in Fig. 4. RBAC Model contains only packages with names containing ‘model’, describing the design of resource and role model classes. RBAC Controller adds packages with names containing ‘controller’, describing the design of role controller classes. The empty interface class ‘RoleController’ simply groups all role controllers to simplify the link with session classes. RBAC View adds packages with names containing ‘view.n’ (where *n* represents any valid package identifier in Java) to these, describing the design of sets of role view classes. RBAC Session adds the package ‘session’, to guide the implementation of two key RBAC concepts: activating a role and users having multiple roles being able to switch between them. It also adds the package ‘other’ containing other classes, linking the session classes to them.

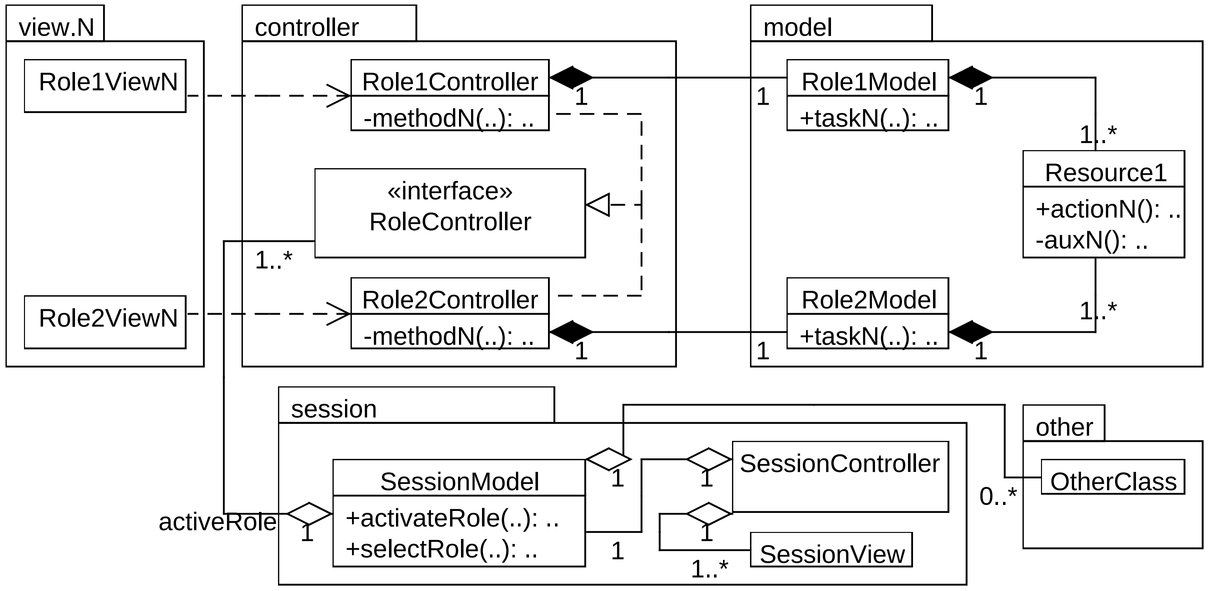


Figure 4: UML Class Diagram of RBAC Model, RBAC Controller, RBAC View and RBAC Session patterns. Note that *N* represents any valid identifier in Java.

6 Static Verification

Our source-level static verifier takes as input a well-formed program, which is defined as follows:

Definition 14 (Well-formed program)**.** A well-formed program consists of a (syntactically correct) JPol policy file and a Java program that implements the RBAC MVC patterns defined in Section 5. Implementing the patterns means: there is a set of session classes (one model, one controller and multiple views associated to the session), a set of resource classes, a set of role classes (sets of one role model, one role controller and multiple role view classes) and a set of classes which do not fit into the other groups. In particular for session classes, they: correctly authenticate users, activate the correct role(s) allowed for the user, switch roles correctly for the retrieved and selected roles.

A well-formed program might contain unauthorised calls to actions on resources. The static verifier should reject a program if an access violation is found, else accept it. In other words, it should only accept programs that satisfy the policy (see Definition 13). In this section, we describe high-level details of the static verifier, which is composed of a parser that generates abstract syntax representations of the policy and program, and populates tables, and a checker that uses the abstract syntax tree and tables to check that the program satisfies the policy.

6.1 Parsing

Section 4.1 described the AST and tables generated by parsing the policy. We now describe the process of parsing the program.

The parser generates an AST for each class using standard parsing rules for Java. Figure 2 (right) shows a simplified AST of a class; note that for the node *called_class*, if it is an object, our parser resolves the object to obtain the name of its class. In addition, the parser groups classes into Resource classes, Role Model classes, Role Controller classes, Role View classes, Session classes and Other classes (the latter are any that do not fit into other groups).

In order to group each class, we use naming restrictions on the package and class names, described informally as follows. Names of resource classes must be the same as the name of a resource given in the policy, names of session classes must begin with string 'Session' and can then be followed by any valid identifier in Java - this applies to session model, session view and session controller classes which are grouped together into one group. Names of role model and role controller classes must begin with the name of a role given in the policy followed by the string 'Model' and 'Controller' respectively. Names of role view classes must begin with the name of the role followed by the string 'View' and can then be followed by any valid identifier in Java.

This phase also generates tables containing the names of all classes in each group except *Other classes*. We call these tables *ResourceClasses*, *RoleModelClasses*, *RoleControllerClasses*, *RoleView-Classes* and *SessionClasses*. This is to simplify the process of looking up called classes in the checks made by the verifier (discussed below).

6.2 Static Verifier Checks

The checks performed on each group of classes are described informally at a high level as follows.

6.2.1 Resource Class Checks

The checks on resource classes, performed by a subprogram of the verifier called *ResourceClassChecks*, are described below.

1. For each method (each element of the node *methods*, see Figure 2), we search the actions sub-table (generated when parsing the policy, see Figures 2 and 3) for *Class.name* (which is the name of a resource) then:
   (a) If the method name is in this sub-table, then the value of the node *modifier* (see Figure 2) must be 'public'.
   (b) Else the value of the node *modifier* must be 'private'.
2. For each call (each element of the node *calls*, see Figure 2) we check that:
   (a) The called class (the node *called_class*) is not the name of a role model class. This is done by searching the names of classes in the table *RoleModelClasses* generated by the parser.

(b) The called class is not the name of a role controller class. This is done by searching the names of classes in the table *RoleControllerClasses* generated by the parser.

(c) The called class is not the name of a role view class. This is done by searching the names of classes in the table *RoleViewClasses* generated by the parser.

(d) The called class is not the name of a session class. This is done by searching the names of classes in the table *SessionClasses*

6.2.2 Role Model Class Checks

The checks on role model classes, performed by a subprogram called *RoleModelClassChecks*, are described below. The role name the class belongs to is obtained by removing the substring 'Model' from *Class.name*.

1. For each call, we check that:

   (a) If the called class is a resource class, then

      i. If the called method (the node *called_method*) is an action, which is done by searching the *actions* sub-table for that resource in the table *Resources* generated when parsing the policy, see Figures 2 and 3, then the pair of values [*called_class*, *called_method*] must appear in the permissions for the associated role of the class (done by searching the *permissions* sub-table of the matching role in table *Roles*)

   (b) The called class is not the name of a different role model class. This is done by checking if the called class contains the substring 'Model', then the name of the class must be the same as the value in the node *Class.name*.

   (c) The subsequent checks are equivalent to Section 6.2.1 Checks 2b, 2c and 2d.

6.2.3 Role Controller Class Checks

The checks on role controller classes, performed by a subprogram called *RoleControllerClassChecks*, are described below. The role name that the class belongs to is obtained by removing the substring 'Controller' from *Class.name*.

1. For each call we check:

   (a) If the method called is an action, we do the same check as Section 6.2.2 Check 1a.

   (b) The called class is not the name of a different role's role model class. This is done by checking if the value of *called_class* contains the substring 'Model', then remove this substring and check that this *called role* matches the role that this role controller class belongs to.

   (c) The called class is not the name of a different role's role controller class. This is done by checking if the value of *called_class* contains the substring 'Controller', then this value must be the same as the value in *Class.name*.

   (d) The called class is not the name of a different role's role view class. This is done by finding the suffix of the value in *called_class* which begins with the string 'View' and ends at the end of the value, then removing this entire suffix. The remaining value must match the role name of this role view class.

   (e) The called class is not the name of a session class.

6.2.4 Role View Class Checks

The checks on role view classes, performed by a subprogram called *RoleViewClassChecks*, are described below. The role name the class belongs to is obtained by finding the suffix of the value in *Class.name* which begins with the string ‘View’ and ends at the end of the value, then removing this entire suffix.

1. For each call we check:
   (a) If the method called is an action, we do the same check as Section 6.2.2 Check 1a.
   (b) The remaining checks are equivalent to Section 6.2.1 Checks 2a and 2d and Section 6.2.3 Checks 1c and 1d.

6.2.5 Session Class and Other Class Checks

For each method invocation within a session class, we check that the method called does not belong to a resource class or role model class (due to Definitions 10 and 12). For each method invocation in an other class, we check that it is not calling a method belonging to resource classes, or to role or session classes. We omit details of these checks due to space restrictions.

6.3 Properties

The static verification checks described in the previous sections ensure that programs that pass the checks do not perform invalid access requests. More precisely, the source code of programs satisfies the propositions stated below, for which we first define the notion of *OK-program*.

Definition 15 (OK-program)**.** A program P is OK, written $OK(P)$, if its actions are ‘public’ and auxiliary methods are ‘private’; resource classes do not invoke methods of a role model, role controller, role view or session class; role model methods do not invoke session classes, role controller classes, role view classes or an action that is not allowed by the policy for the associated role; role controller classes do not invoke session classes or an action that is not allowed by the policy for the associated role; role view methods do not invoke role model or session classes or an action that is not allowed by the policy for the associated role; role classes do not call classes belonging to other roles; session classes do not invoke resource classes or role classes except for role controllers and role views; other class methods do not call role, resource, or session classes.

Proposition 1. Let P be a well-formed program. P is accepted by the static verifier if and only if $OK(P)$.

Proposition 2. A well-formed program P accepted by the verifier satisfies the policy (see Definition 13).

We provide an intuitive explanation of the propositions as follows. According to Definition 13 we need to show that only authorised users with active role r having permission $[Res, m]$ can invoke the action m of an instance of Res. Let $res.m$ be a call to m in the program P, for which the parser has identified the called class to be Res and the called method to be an action m. Since P is *well-formed*, by Definition 14 it implements the RBAC MVC patterns. Therefore, the user u executing $res.m$ has been authenticated and is in a session, where by Definition 10, one of u’s roles, say r, has been activated.

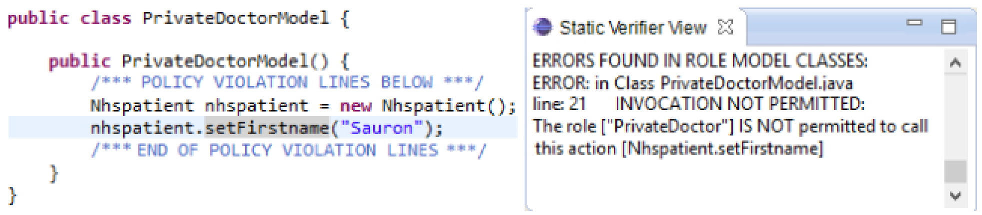
By Definition 12, this implies that r’s role controller has been invoked. Moreover, since P has been accepted by the verifier, by Proposition 1, $OK(P)$. Once the role controller for r has been invoked, by Definition 15 the Java code executed from the role classes associated to r contains only invocations $res.m$ that are authorised by the policy, there are no calls to methods in role classes belonging to other roles, and any call to a method in a class which is not one of r’s role classes (except for a call to a session class) will not contain invocations to actions or to role classes. Note that the only classes outside role classes which could call a role class are session classes, which, since the program is well-formed, must satisfy the requirements of the RBAC-MVC pattern. In particular, we trust the calls to role classes made in session classes.

To provide flexibility to programmers, we have allowed actions to be freely invoked within resource classes. We assume that actions are not restricted in their behaviour (i.e., the policy specifies the actions that a role is allowed to call, and it does not restrict the invocations within those actions). The session classes are the critical part of the program in our approach, in which role class invocations are trusted and not verified. The minimal Trusted Computing Base in our approach is therefore the action methods and the session classes. In future work, we will extend the verifier to include checks within actions, to alert programmers if an action calls another action not allowed by the policy.

7 Implementation and Evaluation

Implementation Our implementation consists of a JPol policy parser, produced using the ANTLR-Works tool [5], and a static analysis program which are both part of a plug-in we have produced for the Eclipse Integrated Development Environment (IDE) [9] [1]. Eclipse plugins are able to use the Java Development Tools (JDT) Application Programming Interface (API) provided by Eclipse, whose benefits include simplifying static code analysis. In Java, there are three ways to invoke a method; either invoking a ('static') method on a class e.g. 'ClassName.methodOne()', invoking a method on a variable e.g. 'x.methodOne()' or invoking a method on the object returned by another method call e.g. 'x.methodOne().methodTwo()'. Using JDT we can get the type binding for variables and method invocation expressions, and so we can check if a resource's actions are being called or if one role's components invoke another role's components. This is sufficient to implement all the static checks discussed in Section 6. We have tested our plug-in on a simple doctor's surgery web database application implemented in Java Enterprise Edition (JEE) (refer to [11] for an overview of JEE). The tool outputs helpful error messages in Eclipse's editor window, consisting of the class name and line number where the error occurs, the kind of error that has occurred (e.g. 'Invocation not permitted') and a description of why that error could have occurred.

See Figure 5 for an example of the verifier catching an error, utilising the policy fragment described in Listing 1.



```
public class PrivateDoctorModel {

    public PrivateDoctorModel() {
        /*** POLICY VIOLATION LINES BELOW ***/
        Nhspatient nhspatient = new Nhspatient();
        nhspatient.setFirstname("Sauron");
        /*** END OF POLICY VIOLATION LINES ***/
    }
}
```

```
ERRORS FOUND IN ROLE MODEL CLASSES:
ERROR: in Class PrivateDoctorModel.java
line: 21     INVOCATION NOT PERMITTED:
The role ["PrivateDoctor"] IS NOT permitted to call
this action [Nhspatient.setFirstname]
```

Figure 5: An example error caught by the static verifier

Evaluation The static approach to access control enforcement has limitations. Firstly, the policy cannot change after compilation, which prevents administrative changes in policies such as changing role permissions. Secondly, permissions cannot be based on any information that changes at run-time. For

[1]The plugin and a sample program can be found at www.inf.kcl.ac.uk/pg/aliasad

flat or hierarchical RBAC policies, this is sufficient. For more general versions of RBAC, these two restrictions can be relaxed by combining the static approach with a dynamic one, which will be the subject of future work. User-to-role assignments can change in our approach and these tend to change more often than permission-to-role assignments. Thirdly, the program code must be available at compile-time in order to analyse it statically.

As a result of the analysis, policy enforcement is done exclusively at compile-time, aiding debugging since the program requires no run-time checks for policy enforcement.

The limitations of the static approach do not mean that it is not useful. A policy commonly contains some static and some dynamic parts (even though these may not be clearly separated). For example, just after log-in, usually some static part of the policy will be in effect. Therefore, the static approach can be used in combination with dynamic checks within a hybrid checker.

Using our design pattern, it takes an initial effort for an architect/programmer to design/implement an initial set of resource classes and one set of Role MVC classes. After this initial stage, designing/implementing the program becomes easier than without using the patterns. Our patterns help to relate the functionality of the program with the roles that can access that functionality. Adding this related functionality becomes easier - achieved just by adding more sets of Role MVC classes. Our pattern also helps in the design of resources because it helps to clearly separate the resources from the rest of the program. Current limitations of our patterns are that roles that have many similar operations will require completely separate Role MVC classes, possibly duplicating code. Moreover, role hierarchies are declared in the policy but not reflected in the design of the program; the permissions of a subordinate role are copied to the senior one and this data is used in the static analysis only. Reflecting role hierarchies in the program would reduce code duplication, which we intend to address in future work.

Lastly, it is difficult to compare the performance of a program designed using a pattern and the same program designed without using it. Performance is not usually taken into consideration when designing a pattern, especially in the case where performance gains are not the main goal of a pattern - as in our approach. We can be sure that in our approach, policy enforcement will have no impact on run-time resources, since no access-checks will be made at run-time.

8 Related Work

Formal approaches for the verification of properties of access control policies usually rely on purpose-built logics or rewrite-based techniques [4, 16, 15, 2]. In this paper, we have focused on verifying that a program enforces a policy, rather than on proving properties of the policies. Bodden et al. [3] enforce security properties in programs using a hybrid approach. They generate code for run-time checks, then perform compile-time analysis to eliminate some of these. In their approach, the access control enforcement of (static) roles would not be possible at compile-time, because they cannot determine, at compile-time, the access requests that each role can make. Our design pattern solves this. Therefore, in their approach, a static RBAC policy would be enforced dynamically.

In Java Web security, there are two types of access control using roles: declarative and programmatic security. Both of these use dynamic checks to restrict access to methods, the former uses XML based permission declarations whilst the latter uses provided Java methods such as `isUserInRole()` [10], [1]. Our approach requires no dynamic checks.

In design-level security, generally, security restrictions are specified at the design stage of a program's lifecycle. An example is Model Driven Security [1]. In this work, code to perform access checks is generated from access control specified in the UML model of the application. The security code generated for Java utilises Java Web security mechanisms which are dynamic (as discussed above), whereas our approach uses static checks.

There exists a body of work on security patterns. In [14], the authors describe access control, specifically RBAC and Metadata-based Access Control, using patterns and run time checks. Steel, Nagappan and Lai [17] propose several security patterns that are specifically targeted towards securing Java (Enterprise) applications. Their work takes a dynamic approach to enforcement; in fact, all patterns that we have seen that aid in the implementation of a policy rely on dynamic mechanisms. Many patterns in [17] can and should be used in conjunction with our patterns to secure the overall application aside from enforcing RBAC statically.

Zarnett et al. [18] enforce RBAC in Java using proxy objects in Remote Method Invocation. Their work has the effect of removing the need for run-time access control checks, however their approach relies on annotations. Understanding where a specific annotation should go can be a difficult task, especially in large programs. Moreover, specifying the policy via annotations leaves the policy fragmented throughout the program. In our approach, we check that the policy has been implemented correctly, e.g. that all the resources and roles have been implemented, however they have no such verification techniques since there exists no central policy specification, which means that errors are discovered later (at run time). Also, recalling the model in Figure 1, their approach enforces access restrictions at the level of the 'Resources', by creating proxy objects containing only those methods which are authorised for the currently active role. Our approach enforces access control at the level of 'Tasks', where instead of creating proxy objects of each resource for each role, all authorised methods for each role are provided by a role-specific user-interface.

9 Conclusion and Future Work

We have described a new system to statically check that a target program respects its RBAC policy. If the program successfully passes the static verifier's checks, then when using the program, the logged in user can only call those methods that have been authorised for the role currently activated for them. Therefore, no run-time access checks are needed.

In future work, we will develop a hybrid approach for policies with dynamic conditions, inlining code in the program to check these at run-time. This hybrid approach would utilise our concept of implementing the groupings which access rights/users are assigned to in the policy (roles in this paper) as a set of MVC components, and then statically verifying static groups whilst dynamically verifying dynamic groups. The result would allow static parts of the policy to be enforced statically, whilst still allowing dynamic policies to be expressed and then enforced dynamically.

Furthermore, we will consider systems where a policy is defined as a combination of existing policies, extending the approach in order to allow programmers to combine validated RBAC implementations without re-doing all the static checks.

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