Optimising Fine-Grained Access Control Policy Enforcement for Database Queries. A Model-Driven Approach

Hoang Phuoc-Bao Nguyen · Manuel Clavel

Received: date / Accepted: date

Abstract Recently, we have proposed a model-driven approach for enforcing fine-grained access control (FGAC) policies when executing SQL queries. More concretely, we have defined a function \( \text{SecQuery}() \) that, given an FGAC policy \( \mathcal{S} \) and a SQL select-statement \( q \), generates a SQL stored-procedure \( \downarrow \text{SecQuery}(\mathcal{S}, q) \downarrow \), such that: if a user \( u \) with role \( r \) is authorised, according to \( \mathcal{S} \), to execute \( q \) based on the current state of the database, then calling \( \downarrow \text{SecQuery}(\mathcal{S}, q) \downarrow (u, r) \) returns the same result as when \( u \) executes \( q \); otherwise, if the user \( u \) is not authorised, according to \( \mathcal{S} \), to execute \( q \) based on the current state of the database, then calling \( \downarrow \text{SecQuery}(\mathcal{S}, q) \downarrow (u, r) \) signals an error. Not surprisingly, executing the query \( q \) takes less time than calling the corresponding stored-procedure \( \downarrow \text{SecQuery}(\mathcal{S}, q) \downarrow \). Here we propose a model-based methodology for optimising the stored-procedures generated by \( \text{SecQuery}() \). The idea is to eliminate authorisation checks in the body of the stored-procedures generated by \( \text{SecQuery}() \), when they can be proved to be unnecessary. Based on our previous mapping from the Object Constraint Language (OCL) to many-sorted first-order logic, we can attempt to prove that authorisation checks are unnecessary by using SMT solvers. We include a case study to illustrate and show the applicability of our methodology.

Keywords Model-driven security · Fine-grained access control · Database access control · Access control optimisation
1 Introduction

Model-driven security (MDS) \[4,2\] specialises model-driven engineering for developing secure systems. In a nutshell, designers specify system models along with their security requirements and use tools to automatically generate security-related system artifacts, such as access control infrastructures.

MDS has been applied with encouraging results to the development of data-centric applications \[3\]. These applications are focused around actions that create, read, update, and delete data stored in a database. Data-centric applications are typically built following the so-called three-tier architecture. According to this architecture, applications consist of three layers: presentation layer, application layer, and data layer. The presentation layer helps to shape the look of the application. The application layer handles the application’s business logic: it defines the core functionality, and it acts as the middle layer connecting the presentation layer and the data layer. Lastly, the data layer is where information is stored through a database management system.

When the data stored is sensitive, then the user’s actions on these data must be controlled. If the access control policies are sufficiently simple, as in the case of role-based access control (RBAC) \[8\] policies, it may be possible to formalise them declaratively, independent of the application’s business logic. In contrast, fine-grained access control (FGAC) policies may depend not only on the user’s credentials but also on the satisfaction of constraints on the data stored in the database. In such cases, authorisation checks are often implemented programmatically, by encoding them at appropriate places in the application layer. In our opinion, the following three reasons are recommended against this common practice. First of all, in order to perform the authorisation checks, the application layer must have full access (potentially) to the data stored in the database. Secondly, in the case of FGAC policies, the application layer must perform the authorisation checks (potentially) for every row/cell, negatively impacting the overall performance of the application. Thirdly, changes in the access control policy will necessarily imply non-trivial changes in the application layer.

In our opinion, a better approach for enforcing FGAC policies in data-centric applications is to perform the authorisation checks in the data layer for the following reasons. First of all, sensitive data will not be retrieved from the database in an uncontrolled way for the purpose of performing authorisation checks at the application layer. Secondly, FGAC checks will perform more efficiently at the database layer, leveraging on the highly sophisticated optimisations for filtering data. Thirdly, changes in the access control policy will

---

1 About the importance of supporting FGAC at the database level, we basically agree with \[9\]: “Fine-grained access control [on databases] has traditionally been performed at the level of application programs. However, implementing security at the application level makes management of authorization quite difficult, in addition to presenting a large surface area for attackers — any breach of security at the application level exposes the entire database to damage, since every part of the application has complete access to the data belonging to every application user.”
certainly imply changes in the data layer, but not in the application layer, which fits very well with the typical modularity and separation of concerns of a three-tier architecture.

Unfortunately, database-management systems do not currently provide built-in features for enforcing FGAC policies. Broadly speaking, in the case of relational database-management systems, the solutions currently offered are either (i) to manually create appropriate “views” in the database and to modify the queries to reference these views; or (ii) to use non-standard, proprietary enforcement mechanisms. These solutions are far from ideal. In fact, they are inefficient, error-prone, and scale poorly, as argued in [15].

We have proposed in [15] a model-driven approach for enforcing FGAC policies when executing SQL queries. In a nutshell, we have defined a function \text{SecQuery()} that, given an FGAC policy \( S \) and a SQL select-statement \( q \), generates a SQL stored-procedure \( \text{SecQuery}(S, q) \), such that: if a user \( u \) with role \( r \) is authorised, according to \( S \), to execute \( q \) based on the current state of the database, then calling \( \text{SecQuery}(S, q)(u, r) \) returns the same result as when \( u \) executes \( q \); otherwise, if the user \( u \) is not authorised, according to \( S \), to execute \( q \) based on the current state of the database, then calling \( \text{SecQuery}(S, q)(u, r) \) signals an error. The key features of our approach are the following: (i) The enforcement mechanism leaves unmodified the underlying database, except for adding the stored-procedures that configure the FGAC enforcement mechanism. (ii) The FGAC policies and the database queries are kept independent of each other, except that they refer to the same underlying data model. This means, in particular, that FGAC policies can be specified without knowing which database queries will be executed, and vice versa. (iii) The enforcement mechanism can be automatically generated from the FGAC policies.

There is, however, a clear drawback in the approach proposed in [15]. As mentioned before, FGAC policies depend not only on the assignments of users and permissions to roles, but also on the satisfaction of authorisation constraints on the current state of the database. Thus, a “secured” query generated by \text{SecQuery()} will typically include expressions in charge of checking that the relevant authorisation constraints are satisfied in the current state of the database. Unavoidably, executing these expressions will cause a performance penalty, greater or lesser depending on the “size” of the database and the “complexity” of the corresponding authorisation constraints. There are, however, situations in which (some of) these authorisation checks seem unnecessary.

In this article we propose a model-based methodology for optimizing the stored-procedures generated by the function \text{SecQuery()}. The idea is to eliminate authorisation checks from the body of the stored-procedures generated by \text{SecQuery()}, when they can be proved to be unnecessary, for which we propose to use SMT solvers. We report on a case study that illustrates the applicability of our methodology.
In Sections 2–4 we recall our model-driven approach for enforcing FGAC policies when executing database queries. In particular: in Section 2 we introduce FGAC security models; in Section 3 we discuss FGAC authorisation for database queries; and in Section 4 we consider enforcing FGAC authorisation for database queries. The emphasis in these sections is about the key components that conform to our model-driven approach, and about their expected properties. To illustrate and exemplify our approach, we provide concrete details of how these components are realised in SQLSI — a methodology for enforcing FGAC policies when executing SQL queries. The interested reader can find the formal definitions of the SQLSI’s key components in [15].

Then, in Section 5 we present our approach for optimising FGAC authorisation enforcement for database queries, and discuss its realization in SQLSI. Finally, in Section 6 we report on a concrete case study showing how our approach can be applied for optimising SQLSI FGAC policies enforcement, for different SQL queries and FGAC policies. We conclude with related work and future work, in Sections 7 and 8.

2 FGAC security models

A model-driven approach for enforcing FGAC policies for database queries requires, in particular, that FGAC policies are specified using models and that the corresponding policy-enforcement artifacts are generated from these models.

FGAC security models typically specify the resources to be protected, the scenarios on which resources occur, the actions on these resources to be controlled, and the authorisation constraints to control these actions. FGAC security models also typically specify the users that can attempt to access the resources, and the roles that can be assigned to them. In our general approach, we assume that authorisation constraints are specified using expressions, possibly containing keywords denoting the resources being accessed and the user accessing it. Moreover, we assume that authorisation constraints are specified using expressions, possibly containing keywords denoting the resources being accessed and the user accessing it. Moreover, we assume that there exists a Boolean function $Eval()$ such that, for any scenario $O$, any authorisation constraint $auth$, any user $u$, and any list of concrete resources $\vec{w}$, the function call $Eval(O, auth[u, \vec{w}])$ returns either true ($\top$) or false ($\bot$), where $auth[u, \vec{w}]$ denotes the expression $auth$ after substituting its keywords by the corresponding values in $u$, $\vec{w}$.

In our general approach, we assume that each FGAC security model defines a Boolean function $Auth()$ such that, for any scenario $O$, any user $u$, any role $r$, any action $a$, and any list of concrete resource $\vec{w}$, the function call $Auth(O, u, r, a, \vec{w})$ returns either true ($\top$) or false ($\bot$), indicating whether the user $u$, with role $r$ is authorised or not to perform the action $a$ on the concrete resources $\vec{w}$ in the scenario $O$. Typically, the function $Auth()$ will call the function $Eval()$ for checking if the corresponding authorisation constraint is satisfied or not.
In SQLSI we use SecureUML [11,4] for modelling FGAC policies. SecureUML is an extension of Role-Based Access Control (RBAC) [8]. In RBAC, permissions are assigned to roles, and roles are assigned to users. In SecureUML, on the other hand, one can model access control decisions that depend on two kinds of information: the assignments of users and permissions to roles; and the satisfaction of authorisation constraints by the current state of the database.

In SQLSI we model the resources to be protected using data models, which consist of classes and associations, and we model scenarios as instances of these data models. Currently, we do not support class generalisations, and we only consider read-actions on class attributes and association-ends as actions to be controlled.

Example 1 As a basic example, we introduce in Figure 1 the data model University. It contains two classes, Student and Lecturer, and one association Enrolment between both of them. The classes Student and Lecturer have attributes name, email, and age. The class Student represents the students of the university, with their name, email, and age. The class Lecturer represents the lecturers of the university, with their name, email, and age. The association Enrolment represents the relationship between the students (denoted by students) and the lecturers (denoted by lecturers) of the courses the students have enrolled in.

In SQLSI we model authorisation constraints using the Object Constraint Language (OCL) [17]. Authorisation constraints can contain keywords referring to resources — namely, to the object whose attribute is being accessed (denoted by the keyword self), or to the objects linked by the association that is being accessed (denoted by the corresponding association-ends). Authorisation constraint can also contain keywords referring to users — namely, to the user who is attempting to access the resources (denoted by the keyword caller). For the sake of clarity, in SQLSI we underline keywords when they appear in authorisation constraints.

As expected, in SQLSI the function Eval() corresponds to evaluating the given authorisation constraint in the given scenario according to the standard semantics of OCL.
Example 2 Consider the following security model $\text{SecVGU#A}$ for the data model $\text{University}$.

- Roles. There is only one role, namely, the role $\text{Lecturer}$. Lecturers are assigned to this role.
- Permission:
  - $\text{Any lecturer can know his/her students}$. More formally, for a user $\text{caller}$ with role $\text{Lecturer}$ to read the resources linked by the association $\text{Enrolment}$, the following OCL constraint must be satisfied:
    $\text{lecturers} = \text{caller}$.
    in which, as explained before, $\text{lecturers}$ is a keyword denoting any lecturer linked by the association $\text{Enrolment}$ at its association-end $\text{lecturers}$.
  - $\text{Any lecturer can know his/her own email, as well as the emails of his/her students}$. More formally, for a user $\text{caller}$ with role $\text{Lecturer}$ to read the email of a lecturer’s resource $\text{self}$, the following OCL constraint must be satisfied:
    $\text{caller} = \text{self}$.
  - $\text{Any lecturer can know the emails of his/her students}$. More formally, for a user $\text{caller}$ with role $\text{Lecturer}$ to read the email of a student’s resource $\text{self}$, the following OCL constraint must be satisfied:
    $\text{caller.students} \rightarrow \text{includes(self)}$.

3 FGAC-authorisation for database queries

As expected, in our general approach we assume that databases are used for storing information, and that they provide different means to manage this information. In particular, we assume that they support queries for information retrieval. More specifically, we assume that there exists a function $\text{Exec()}$ such that given a database instance $\text{db}$ and a query $\text{q}$, the function call $\text{Exec(db,q)}$ either returns the result of executing the query $\text{q}$ in the database instance $\text{db}$, or it returns an error.

In our general approach, we assume that there exists a Boolean function $\text{AuthQuery()}$ such that, given an FGAC security model $\mathcal{S}$, a query $\text{q}$, a database instance $\text{db}$, a user $\text{u}$, and a role $\text{r}$, the function call $\text{AuthQuery(}\mathcal{S},\text{u},\text{r},\text{q,db})$ returns either true ($\top$) or false ($\bot$), indicating whether the user $\text{u}$, with role $\text{r}$ is authorised or not to execute the query $\text{q}$ in the database instance $\text{db}$.

FGAC-authorisation for database queries in SQLSI

In SQLSI we consider SQL queries. The SQLSI’s definition of the function $\text{AuthQuery()}$ [15] is based on the following consideration. A user can be authorised to execute a query on a database if the execution of this query does not leak confidential information, according to the given FGAC policy. However,
Fig. 2: Example queries

(a) The query Query#1.

```
SELECT email FROM Lecturer WHERE Lecturer_id = 'Huong'
```

(b) The query Query#2.

```
SELECT DISTINCT email FROM Lecturer
JOIN (SELECT * FROM Enrolment
    WHERE students = 'Thanh' AND lecturers = 'Huong') AS TEMP
ON TEMP.lecturers = Lecturer_id
```

(c) The query Query#3.

```
SELECT DISTINCT email FROM Lecturer
JOIN (SELECT huong_enrolments.lecturers AS lecturers
    FROM (SELECT * FROM Enrolment
        WHERE lecturers = 'Manuel') AS manuel_enrolments
    JOIN (SELECT * FROM Enrolment
        WHERE lecturers = 'Huong') AS huong_enrolments
    ON manuel_enrolments.students = huong_enrolments.students
) AS TEMP
ON TEMP.lecturers = Lecturer_id
```

this typically implies much more than simply checking that the final result satisfies the given FGAC policy, since a clever attacker can devise a query such that the simple fact that a final result is obtained may reveal some confidential information. To illustrate this point, consider the select-statements in Figures 2a–2c. Suppose that, for a given scenario, the three select-statements return the same final result, namely, a non-empty string, representing an email, which is not considered confidential. On a closer examination, however, we can realise that, for each of these select-statements, the final result is revealing additional information, which may in turn be confidential. In particular,

- Query#1 reveals that the returned email belongs to Huong.
- Query#2 reveals not only that the returned email belongs to Huong, but also that Thanh is enrolled in a course that Huong is teaching.
- Query#3 reveals that the email belongs to Huong, and that Huong and Manuel are “colleagues”, in the sense that there are some students who have both Huong and Manuel as their lecturers.

In fact, the SQLSI’s function AuthQuery() is defined in such a way that any information that may be used to reach the final result of a query (in particular, any information involved in subqueries, where-clauses, and on-clauses) is checked for policy-compliance. In this way, for example, if a user is not

\footnote{For the sake of readability, we have formalised these queries using the names of the students and the lecturers, instead of their database ids.}
authorised to know whether Huong is Thanh’s lecturer or not, then he/she will not be authorised to execute Query\#2, even when he/she may be authorised to access Huong’s email. Similarly, if a user is not authorised to know whether Huong and Manuel are “colleagues” or not, then he/she will not be authorised to execute Query\#3, even when he/she may be authorised to access lecturers’ emails.

4 Enforcing FGAC-authorisation for database queries

In our general approach, the FGAC enforcement mechanism for database queries consists of generating “secured” versions of the given queries, and then executing these “secured” versions instead of the given queries. More specifically, we consider the following notion of “secured” queries. Given an FGAC model $S$, a database query $q$, and a database instance $db$, we say that $q^\flat$ is a secured version of a query $q$, if and only if, for any user $u$, and any role $r$:

- if $\text{AuthQuery}(S, u, r, q, db) = \bot$, then $\text{Exec}(db, q^\flat)$ returns an error.
- otherwise, $\text{Exec}(db, q^\flat) = \text{Exec}(db, q)$.

In our general approach, we assume that there exists a function $\text{SecQuery}()$ such that, given an FGAC security model $S$ and a database query $q$, the function call $\text{SecQuery}(S, q)$ returns a “secured” version of the query $q$.

Enforcing FGAC-authorisation for SQL queries in SQLSI

In SQLSI, given an FGAC security model $S$ and a SQL query $q$, the function $\text{SecQuery}()$ generates a SQL stored-procedure $\text{⌜SecQuery}(S, q)⌝$ that implements the authorisation checks required by the SQLSI’s function $\text{AuthQuery}()$ to comply with policy $S$ when executing the query $q$.

5 Optimising FGAC policy enforcement for database queries

As explained before, FGAC policies depend not only on the assignments of users and permissions to roles, but also on the satisfaction of authorisation constraints on the current state of the system. Therefore, in our general approach, we assume that the “secured” queries generated by $\text{SecQuery}()$ include expressions in charge of checking that the relevant authorisation constraints are satisfied in the current state of the database. More specifically, we assume, first of all, that there exists a one-to-one correspondence between the data model’s scenarios and the database instances. We also assume that there exists a one-to-one correspondence between the users and roles declared in the

---

3 The SQLSI’s function $\text{AuthQuery}()$ does not preclude the possibility that, if an attacker knows the specific FGAC policy being enforced, he/she can devise a query such that a “non-authorised” response may still leak confidential information.
Optimising FGAC Policy Enforcement for Database Queries

FGAC security model and those declared in the database. Then, we assume that there is a function \text{map()} such that, for any authorisation constraint \text{auth}, \text{map(auth)} returns a correct implementation of \text{auth}, in the following sense: for any scenario \(O\), any user \(u\), any concrete resources \(\vec{w}\), and any assignment \(\sigma = \{\text{caller} \mapsto u, \vec{k} \mapsto \vec{w}\}\),

\[
\text{Eval}(O, \sigma(\text{auth})) = \top \iff \text{Exec}_\sigma(O, \text{map}(\text{auth})) = \text{TRUE}
\]  

where \(O\) denotes the database instance corresponding to the scenario \(O\), and \(\text{Exec}\) denotes the execution-context where the keywords in \(\text{auth}\) are assigned values according to the assignment \(\sigma\).

Consider now the cost of executing the “secured” queries generated by \text{SecQuery()}. As mentioned before, these queries include expressions generated by \text{map()} for checking that the relevant authorisation constraints are satisfied in the current state of the database. Unavoidably, these expressions cause a performance penalty at execution-time, greater or lesser depending on the “size” of the database and on their own “complexity”. There are, however, situations in which these expensive authorisation checks seem unnecessary. Notice, in particular that, for any authorisation constraint \(\text{auth}\), we can safely eliminate the authorisation check \text{map(auth)} — based on the correctness assumption (1) —, if we can prove that, for any scenario \(O\), any user \(u\), any concrete resources \(\vec{w}\), it holds that \(\text{Eval}(O, \sigma(\text{auth})) = \top\). Interestingly, \(\text{Eval}(O, \sigma(\text{auth})) = \top\) may only hold for scenarios \(O\) which satisfies certain known properties: for example, that every student is over 21 years old. In these cases, the elimination of the authorisation check \text{map(auth)} is only safe if the aforementioned properties can be guaranteed to be satisfied by the database when the query is executed. Similarly, \(\text{Eval}(O, \sigma(\text{auth})) = \top\) may only hold for users \(u\) and/or resources \(\vec{w}\) which satisfies certain known properties: for example, that the lecturer attempting to execute the query is the oldest lecturer in the university, or that the query is only about students enrolled in some classes of the lecturer attempting to execute the query. As before, the elimination of the authorisation check \text{map(auth)} is only safe if the aforementioned properties can be guaranteed to be satisfied by the database when the query is executed.

Optimising FGAC policy enforcement for database queries in SQLSI

The SQLSI’s mapping from data models to SQL schemas is defined in [15]. In a nutshell, classes are mapped to tables, attributes to columns, and many-to-many associations to tables with the corresponding foreign-keys, in such a way that objects and links can be stored, respectively, in the tables corresponding to their classes and the tables corresponding to their associations. Tables corresponding to classes contain an extra column to store the objects’ unique identifiers. The name of this extra column is the table’s name followed by \_id.

As for the function \text{map()}, in charge of implementing in SQL the OCL authorisation constraints, we can reuse, of course, the available mappings from
OCL to SQL — for example [14]. However, for the sake of execution-time performance, we recommend manually implementing in SQL the OCL authorisation constraints, and to take responsibility for its correctness.

Finally, we propose to use the mappings from OCL to many-sorted first-order logic (MSFOL) introduced in [6] for proving that authorisation checks are unnecessary in the “secured” queries generated by SecQuery(), and therefore can be safely removed. In a nutshell, [6] defines the following mappings: (i) a mapping map() from data models to MSFOL theories; (ii) a mapping intr() from scenarios to MSFOL interpretations; and (iii) a mapping maptrue() from OCL boolean expressions to MSFOL formulas. In the case of an expression exp containing collection sub-expressions, the formula maptrue(exp) will contain the corresponding predicate expressions; the conjunction of formulas defining these predicates is generated by a mapping mapdef() which is defined along with the mapping maptrue().

The mappings introduced in [6] satisfy the following property: let D be a data model, and let O be a scenario of D. Let exp be a ground (i.e., no free variables) boolean OCL expression. Then, the following holds:

\[ \text{intr}(O) \models (\text{mapdef}(\text{exp}) \Rightarrow \text{maptrue}(\text{exp})) \iff \text{Eval}(O, \text{exp}) = \top. \quad (2) \]

Hence, when deciding whether the authorisation check corresponding to an authorisation constraint auth is unnecessary and therefore can be safely removed from the “secured” queries generated from the SecQuery(), we can reduce the problem of proving that for any scenario O, any user u, any concrete resources \( \vec{w} \), and any assignment \( \sigma = \{\text{caller} \mapsto u, \vec{k} \mapsto \vec{w}\} \) holds that:

\[ \text{Eval}(O, \sigma(\text{auth})) = \top, \]

to the problem of proving that the following MSFOL theory is unsatisfiable:

\[ \text{map}(D, \sigma) \land \text{mapdef}(\text{auth}) \land \neg(\text{maptrue}(\text{auth})), \quad (3) \]

where map(D, \sigma) simply adds to the MSFOL theory map(D) the constant symbols caller and \( \vec{k} \), with the appropriate sort declarations. Then, if (3) is unsatisfiable, we can safely conclude that the authorisation check corresponding to the constraint auth is indeed unnecessary, since auth cannot be false in any scenario.

In the following section we present a case study in which we apply the above methodology to safely eliminate unnecessary authorisation checks from “secured” queries generated by the SQLSI’s function SecQuery(). Interestingly, the authorisation checks that we consider in our case study seem to be unnecessary only for scenarios, users, or resources that satisfy certain known properties. As expected, to prove that they are indeed unnecessary in these cases we formalise the known properties as OCL boolean expressions, map these expressions into MSFOL formulas, and join (with a conjunction) these formulas to the corresponding satisfiability problem.
6 Case study

In this section we apply to different FGAC policies, different users, and different queries the methodology introduced above for optimising “secured” queries generated by the SQLSI’s function SecQuery().

We first introduce two different policies for the data model University shown in Figure [1]

- The policy SecVGU#1 contains the following clauses: (i) a lecturer can know the age of any student, if no other lecturer is older than he/she is; and (ii) a lecturer can know the students of any lecturer, if no other lecturer is older than he/she is. This policy can be modelled in SQLSI as follows:

roles = \{Lecturer\}
auth(Lecturer, read(Enrolment))
  = Lecturer.allInstances() → select(l | l.age > caller.age)
  → isEmpty()
auth(Lecturer, read(Student : age))
  = Lecturer.allInstances() → select(l | l.age > caller.age)
  → isEmpty()

- the policy, SecVGU#2 contains the following clauses: (i) a lecturer can know the age of any student, if the student is his/her student; (ii) a lecturer can know his/her students; and (iii) a lecturer can know the students of any lecturer if the student is his/her student. This policy can be modelled in SQLSI as follows:

roles = \{Lecturer\}
auth(Lecturer, read(Enrolment))
  = caller.students → exists(s | s = self)
auth(Lecturer, read(Student : age))
  = (caller = lecturers) or
    (caller.students → exists(s | s = students))

Next we introduce three different SQL queries for the database corresponding to the data model University.

- the query Query#4 that asks the number of students whose age is greater than 18. This query can be expressed in SQL as follows:

\[
\text{SELECT COUNT(*) FROM Student WHERE age > 18}
\]

- the query Query#5 that asks the number of enrolments. This query can be expressed in SQL as follows:

\[
\text{SELECT COUNT(*) FROM Enrolment}
\]

- the query Query#6 that asks the age of the students of the user assigned to the variable caller. This query can be expressed in SQL as follows:
SELECT age FROM Student
JOIN (SELECT * FROM Enrolment
       WHERE lecturers = caller) AS my_enrolments
ON my_enrolments.students = Student_id

Finally, in order to follow the case study, we recall here the main “features” of the stored-procedures generated by the SQLSI’s function SecQuery(). The interested readers can find the full definition of the SQLSI’s function SecQuery() in [15]. A stored-procedure generated by SecQuery() has two parameters caller and role, which represent, respectively, the user executing the given query and the role of this user when executing this query. The body of the stored-procedure creates a list of temporary tables and, if successful, it executes the original query. These temporary tables correspond to the conditions that need to be satisfied for the user, with the given role, to be authorised to execute the given query. The definition of each temporary table is such that, when attempting to create the table, if the corresponding condition is not satisfied, then an error is signalled. The reason for using temporary tables instead of subqueries is to prevent the SQL optimiser from “skipping” the authorisation checks that SecQuery() generates. These authorisation checks are implemented using case-expressions. Each of these case-expression calls a function AuthFunc(), which implements the authorisation constraint controlling the access to the corresponding resource (attribute or association). If the result of this function call is TRUE, then the case-expression returns the requested resource; otherwise, it signals an error. As expected, for each authorisation constraint auth, the function AuthFunc() executes map(auth), i.e., the provided implementation in SQL of the OCL constraint auth.

6.1 Case 1: Query#4

Let S be an FGAC security model. We show below the stored-procedure generated by the SQLSI’s function SecQuery() for Query#4.
CREATE TEMPORARY TABLE TEMP1 AS (
    SELECT * FROM Student
    WHERE CASE "AuthFunc(S,Student : age)"(caller, role,
        Student_id) WHEN 1 THEN age ELSE throw_error() END > 18
    );

CREATE TEMPORARY TABLE TEMP2 AS (
    SELECT Student_id AS Student_id FROM TEMP1
);

IF _rollback = 0 THEN SELECT COUNT(*) from TEMP2;
END IF;
END

Notice that, when creating the temporary table TEMP1 in lines 15–19, the SQL function "AuthFunc(S,Student : age)" is called for each row contained in the table Student. Therefore, the execution-time for "SecQuery(S,Query#4)" will increase depending on the "size" of the table Student and the "complexity" of the SQL expression map(auth(S,r,read(Student : age))).

Consider the case of the policy SecVGU#1. Recall that the authorisation constraint auth(SecVGU#1,Lecturer,read(Student : age)) is specified in OCL as follows:

Lecturer.allInstances()→ select(l | l.age > caller.age)→ isEmpty()

Suppose that we implement this constraint in SQL as follows:

```
(SELECT MAX(age) FROM Lecturer)
  = (SELECT age FROM Lecturer WHERE Lecturer_id = caller)
```

Notice then that, when executing

"SecQuery(SecVGU#1,Query#4)"(caller,"Lecturer")

the SQL expression above will be executed for each row in the table Student. Moreover, notice that each time this expression is executed, the clause

WHERE Lecturer_id = caller

will make a search among the rows in the table Lecturer.

Possible optimisations. Suppose that the user attempting to execute Query#4 is the oldest lecturer. In this case, the case-statement in lines 17–18 seems unnecessary, because the policy SecVGU#1 authorises a lecturer to know the age of every student, if no other lecturer is older than he/she is.

Applying the methodology described above, and adding to the corresponding satisfiability problem the fact that the user is the oldest lecturer, we can
prove that the case-statement in lines 17–18 is indeed unnecessary, and therefore can be safely removed, if the user attempting to execute the query is the oldest lecturer. The SMT solver CVC4 \[1\] solves this problem in 0.163 seconds. The interested reader can find in Listing 2 (Appendix A) the input to the CVC4 tool, and in Listing 10 (Appendix B) the optimised stored-procedure \texttt{SecQuery(SecVGU#1, Query#4)}.

Finally, notice that the case-statement in lines 17–18 cannot be removed, however, for the case of the policy \texttt{SecVGU#2}, even if the user who is attempting to execute the query \texttt{Query#4} is the oldest lecturer. The interested reader can find in Listing 3 (Appendix A) the satisfiability problem that corresponds to this case.

### 6.2 Case 2: Query#5

Let \( S \) be an FGAC security model. We show below the stored-procedure generated by the SQLSI’s function SecQuery() for \texttt{Query#5}.  

```sql
CREATE PROCEDURE "SecQuery(S, Query#5)"
  (in caller varchar(250), in role varchar(250))
BEGIN
  DECLARE _rollback int DEFAULT 0;
  DECLARE EXIT HANDLER FOR SQLEXCEPTION
  BEGIN
    SET _rollback = 1;
    GET STACKED DIAGNOSTICS CONDITION 1
    @p1 = RETURNED_SQLSTATE, @p2 = MESSAGE_TEXT;
    SELECT @p1, @p2;
    ROLLBACK;
  END;
  START TRANSACTION;

  CREATE TEMPORARY TABLE TEMP1 AS (
    SELECT Lecturer_id AS lecturers, Student_id AS students
    FROM Lecturer, Student
  );

  CREATE TEMPORARY TABLE TEMP2 AS (
    SELECT * FROM TEMP1
    WHERE CASE "AuthFunc(S, Enrolment)"(caller, role, lecturers, students) WHEN TRUE THEN TRUE
    ELSE throw_error() END
  );

  CREATE TEMPORARY TABLE TEMP3 AS (
    SELECT students FROM Enrolment
  );
```
Notice that, when creating the temporary table TEMP2, the function call \(\text{AuthFunc}(S, \text{Enrolment})\) is executed once for each record contained in the table TEMP1, which is defined as the cartesian product of the tables Student and Lecturer. Therefore, the execution-time for \(\text{SecQuery}(S, \text{Query#5})\) will increase depending on the “size” of the tables Student and Lecturer, and the “complexity” of the SQL expression map(auth(S, r, read(Enrolment))).

Consider the case of the policy SecVGU#2. Recall that the authorisation constraint auth(SecVGU#2, Lecturer, read(Enrolment)) is specified in OCL as follows:

\[
(caller = \text{lecturers}) \text{ or } (\text{caller}.\text{students} \rightarrow \exists s \ (s = \text{students}))
\]

Suppose that we implement this authorisation constraint in SQL as follows:

\[
\begin{align*}
& (\text{caller} = \text{lecturers}) \\
\text{OR } \& \{ \exists s \ (s = \text{students}) \}
\end{align*}
\]

Notice then that, when executing

\[
\text{SecQuery}(\text{SecVGU#2, Query#5})(\text{caller}, \text{"Lecturer"}),
\]

the SQL expression above will be executed once for each row in the table TEMP1, and that each time this expression is executed, the clause

\[
\text{WHERE e.lecturers = caller}
\]

\[
\text{AND e.students = students}
\]

will make a search among the rows in the table Enrolment.

Possible optimisations Suppose now that the user who is attempting to execute the query Query#5 is a lecturer of every student. In this case the case-statement in lines 22–24 seems unnecessary, because the policy SecVGU#2 authorises every lecturer to know the students of any lecturer if they are his/her students.

Applying the methodology described above, adding to the satisfiability problem the fact that the user who is attempting to execute the query is a lecturer of every student, we can in fact prove that the case-statement in lines 22–24 is indeed unnecessary, and therefore can be safely removed if the user attempting to execute the query is a lecturer of every student. The SMT solver CVC4 \[1\] solves this satisfiability problem in 0.046 seconds. The interested reader can find in Listing 4 (Appendix A) the input to the
CVC4 tool, and in Listing 11 (Appendix B) the optimised stored-procedure
⌜SecQuery(SecVGU#2, Query#5)⌝.

Finally, notice that the case-statement in lines 22–24 cannot be removed,
however, for the case of the policy SecVGU#1, even if the user who is attempt-
ing to execute the query Query#5 is a lecturer of every student. The interested
reader can find in Listing 5 (Appendix A) the satisfiability problem that cor-
responds to this case.

6.3 Case 3: Query#6

Let \( S \) be an FGAC security model. We show below the stored-procedure gen-
erated by the SQLSI’s function SecQuery() for Query#6.

```
CREATE PROCEDURE "SecQuery(S, Query#6)"
        (in caller varchar(250), in role varchar(250))
BEGIN
        DECLARE _rollback int DEFAULT 0;
        DECLARE EXIT HANDLER FOR SQLEXCEPTION
        BEGIN
            SET _rollback = 1;
            GET STACKED DIAGNOSTICS CONDITION 1
            @p1 = RETURNED_SQLSTATE, @p2 = MESSAGE_TEXT;
            SELECT @p1, @p2;
            ROLLBACK;
        END;
        START TRANSACTION;
        CREATE TEMPORARY TABLE TEMP1 AS
            SELECT Student_id AS students, Lecturer_id AS lecturers
            FROM Student, Lecturer
            WHERE Lecturer_id = caller
        );
        CREATE TEMPORARY TABLE TEMP2 AS
            SELECT * FROM TEMP1
            WHERE CASE "AuthFunc(S, Enrolment)"(caller, role, lecturers, students) WHEN TRUE THEN TRUE
                ELSE throw_error() END
        );
        CREATE TEMPORARY TABLE TEMP3 AS
            SELECT * FROM Enrolment WHERE lecturers = caller
        );
        CREATE TEMPORARY TABLE TEMP4 AS
            SELECT * FROM Student JOIN TEMP3
```

ON Student_id = students
);

CREATE TEMPORARY TABLE TEMP5 AS (
    SELECT CASE "\(\text{AuthFunc}(S, \text{Student}: \text{age})\)(caller, role, 
        Student_id) WHEN 1 THEN age ELSE throw_error() END as age
    FROM TEMP4
);

IF _rollback = 0
    THEN SELECT age from TEMP5;
END IF;
END

Notice that, when creating the temporary table TEMP2, the function call "\(\text{AuthFunc}(S, \text{Enrolment})\)" is executed once for each record contained in the table TEMP1, which is defined as the subset of the cartesian product of the tables Student and Lecturer that contains only the students of the lecturer attempting to execute the query. Therefore, the execution-time for the stored-procedure "\(\text{SecQuery}(S, \text{Query#6})\)" will increase depending on the "size" of the table Student and the "complexity" of the implemented SQL expression map(auth(S,r,read(Enrolment))).

Similarly, notice that, when creating the temporary table TEMP5, the function call "\(\text{AuthFunc}(S, \text{Student}: \text{age})\)" is executed once for each record contained in the table TEMP4, which is defined as the join of the tables Student and TEMP3, i.e. the students enrolled with the lecturer attempting to execute the query. Therefore, the execution-time for "\(\text{SecQuery}(S, \text{Query#6})\)" will increase depending on the number of students enrolled with the lecturer caller and the “complexity” of the SQL expression map(auth(S,r,read(Enrolment))).

Consider the case of the policy SecVGU#2. Recall that the authorisation constraint auth(SecVGU#2, Lecturer, read(Enrolment)) is specified in OCL as follows:
\[(\text{caller} = \text{lecturers}) \text{ or } (\text{caller} \to \text{students} \rightarrow \exists s \mid \text{s} = \text{students})\].

Suppose that, as before, we implement this authorisation constraint in SQL as follows:

\[(\text{caller} = \text{lecturers}) \text{ OR } (\exists \text{e} \mid \text{e.lecturers} = \text{caller} \text{ AND e.students} = \text{students})\]

Notice then that, when executing
\[\text{"\(\text{SecQuery}(\text{SecVGU#2, Query#6})\)(caller, \text{Lecturer})\)},\]
the SQL expression above will be executed once for each row in the table TEMP2, which is defined as the subset of the cartesian product of the tables Student
and Lecturer that contains only the students of the lecturer attempting to execute the query, and that each time this expression is executed, the clause

```
WHERE e.lecturers = caller
AND e.students = students
```

will make a search among the rows in the table Enrolment.

Moreover, recall that the authorisation constraint auth(SecVGU#2, Lecturer, read(Student : age)) is specified in OCL as follows:

\[ \text{caller.students} \rightarrow \exists s \mid s = \text{self}. \]

Suppose that this authorisation constraint is implemented in SQL as follows:

```
EXISTS (SELECT 1 FROM Enrolment e
WHERE e.lecturers = caller
AND e.students = self)
```

Notice then that, when executing

\[ \text{SecQuery(SecVGU#2, Query#6)}(\text{caller, “Lecturer”}), \]

the SQL expression above will be executed once for each row in the table TEMP4, which is defined as the join of the tables Student and TEMP3, i.e. the students enrolled with the lecturer attempting to execute the query, and that each time this expression is executed, the clause

```
WHERE e.lecturers = caller
AND e.students = self
```

will make a search among the rows in the table Enrolment.

Possible optimisations Suppose that the user attempting to execute the query has the role Lecturer. In this case, the case-statement in lines 23–25 seems unnecessary, because:

– SecVGU#2 authorises a lecturer to know his/her students,
– the temporary table TEMP1 only contains students of the lecturer attempting to execute the query.

Applying the methodology described above, we can prove that, in this case, the case-statement in lines 23–25 can be securely removed. The SMT solver CVC4 \[1\] solves this satisfiability problem in 0.057 seconds. The interested reader can find in Listing 6 (Appendix A) the input to the CVC4 solver, and in Listing 12 (Appendix B) the optimised version of the stored-procedure "SecQuery(S, Query#6)".

Moreover, the case-statement in lines 38–39 also seems unnecessary, because:

– SecVGU#2 authorises a lecturer to know the age of any student, if the student is his/her student, and
the temporary table TEMP4 only contains students of the lecturer attempting to execute the query.

Applying the methodology described above, and adding the fact that the temporary table TEMP4 only contains students of the lecturer attempting to execute the query, we can prove that, in this case, the case-statement in lines 38–39 can also be securely removed. The SMT solver CVC4 solves this satisfiability problem in 0.038 seconds. The interested reader can find in Listing 5 (Appendix A) the input to the CVC4 solver, and in Listing 12 (Appendix B) the optimised stored-procedure "SecQuery(S, Query#6)".

Notice that the case-statements in lines 23–25 and 38–39, cannot be removed, however, for the case of the policies SecVGU#1. The interested reader can find in Listings 7 and 9 (both in Appendix A) the satisfiability problems that correspond to these cases.

7 Related work

The work presented here optimises our model-driven approach for enforcing FGAC policies when executing database queries. To the best of our knowledge, no directly related work exists yet. Nevertheless, we discuss below indirectly related work: namely, proposals related with our general approach for enforcing FGAC policies. To make this comparison concrete, we consider the implementation of our general approach in SQLSI.

The first feature of our model-driven approach is that it does not modify the underlying database, except for adding the stored-procedures that configure our FGAC-enforcement mechanism. This is in clear contrast with the solutions offered by the major commercial RDBMS, which either recommend — like in the case of MySQL or MariaDB — to manually create appropriate views and modify the queries so as to referencing these views, or they request — like Oracle, PostgreSQL, and IBM — to use non-standard, proprietary enforcement mechanisms. As argued in [16], the solutions currently offered by the major RDBMSs are far from ideal: in fact, they are time-consuming, error-prone, and scale poorly.

The second feature of our model-driven approach is that FGAC policies and SQL queries are kept independent of each other, except for the fact that they refer to the same underlying data model. This means, in particular, that FGAC policies can be specified without knowing which SQL queries will be executed, and vice versa. This is in clear contrast with the solution recently proposed in [12] where the FGAC policies must be (re-)written depending on the SQL queries that are executed. Nevertheless, the approach proposed in [15] certainly shares with [12], as well as with other previous approaches like [10], the idea of enforcing FGAC-policies by rewriting the SQL queries, instead of by modifying the underlying databases or by using non-standard, proprietary features.

The third feature of our model-driven approach is that the enforcement mechanism can be automatically generated from the FGAC-policies, by using
available mappings from OCL to SQL — for example [13] — in order to implement the authorisation constraints appearing in the FGAC policies. However, for the sake of execution-time performance, we recommend manually implementing in SQL the authorisation constraints appearing in the FGAC policies.

8 Conclusions and future work

In [16] we proposed a model-driven approach for enforcing fine-grained access control (FGAC) policies when executing SQL queries. In a nutshell, we defined a function SecQuery() that, given a policy $\mathcal{S}$ and a query $q$, it generates a SQL stored-procedure, such that: if a user is authorised, according to $\mathcal{S}$, to execute $q$, then calling this stored-procedure will return the same result as executing $q$; otherwise, if a user is not authorised, according to $\mathcal{S}$, to execute $q$, then calling the stored-procedure will signal an error.

Since the stored-procedures generated by SecQuery() perform at execution-time the authorisation checks required by the given FGAC policy, not surprisingly, there is a significant loss in performance when executing “secured” queries — i.e., the stored-procedures generated by SecQuery() — with respect to executing “unsecured” queries. There are situations, however, in which performing some authorisation checks may seem to be unnecessary.

In this article we have presented a general, model-based approach that optimises the “secured” queries generated by SecQuery() by removing those authorisation checks that can be proved to be unnecessary. Moreover, we have presented a concrete realisation of this approach for our SQLSI methodology for enforcing FGAC policies when executing SQL queries. To prove in SQLSI that an authorisation check is unnecessary, and therefore that it can be removed, we formulate the corresponding problem as a satisfiability problem in many-sorted first-order logic, and use SMT-solvers like CVC4 [1] to try to solve it. To illustrate this approach we have provided a non-trivial case study involving different FGAC policies, users, and queries.

We recognise that the SQLSI methodology needs to be further developed, in several dimensions. First of all, from the languages point of view: we plan to extend our definition of data models to include class generalisations; we also plan to extend our definition of FGAC security models to include role hierarchies and permissions for other types of actions, besides read actions; and we plan to extend our definition of SecQuery() to cover as much as possible of the SQL language, including, in particular, left/right-joins and group-by clauses. Secondly, from the code-generation point of view, we plan to extend SQLSI to cover also insert, update, and delete statements. Thirdly, from the correctness point of view, we plan to develop a methodology for proving that OCL authorisation constraints are correctly implemented in SQL. Finally, from the applicability point of view, we are interested in developing a methodology à la SQLSI for enforcing FGAC policies in the case of NoSQL databases.
Conflict of interest

The authors declare that they have no conflict of interest.

References

1. Barrett, C.W., Conway, C.L., Deters, M., Hadarean, L., Jovanovic, D., King, T., Reynolds, A., Tinelli, C.: CVC4. In: G. Gopalakrishnan, S. Qadeer (eds.) Computer Aided Verification - 23rd International Conference, CAV 2011, Snowbird, UT, USA, July 14-20, 2011. Proceedings, Lecture Notes in Computer Science, vol. 6806, pp. 171–177. Springer (2011)

2. Basin, D.A., Clavel, M., Egea, M.: A decade of model-driven security. In: R. Breu, J. Crampton, J. Lobo (eds.) 16th ACM Symposium on Access Control Models and Technologies, SACMAT 2011, Innsbruck, Austria, June 15-17, 2011, Proceedings, pp. 1–10. ACM (2011)

3. Basin, D.A., Clavel, M., Egea, M., de Dios, M.A.G., Dania, C.: A Model-Driven Methodology for Developing Secure Data-Management Applications. IEEE Transactions on Software Engineering 40(4), 324–337 (2014)

4. Basin, D.A., Doser, J., Lodderstedt, T.: Model driven security: From UML models to access control infrastructures. ACM Transactions on Software Engineering and Methodology 15(1), 39–91 (2006)

5. Browder, K., Davidson, M.A.: The virtual private database in Oracle9iR2. Tech. rep., Oracle Corporation (2002). https://www.oracle.com/pdf/VPD9ir2tp.pdf

6. Dania, C., Clavel, M.: OCL2MSFOL: a mapping to many-sorted first-order logic for efficiently checking the satisfiability of OCL constraints. In: B. Baudry, B. Combemale (eds.) Proceedings of the ACM/IEEE 19th International Conference on Model Driven Engineering Languages and Systems, Saint-Malo, France, October 2-7, 2016, pp. 65–75. ACM

7. Row and column access control support in IBM DB2 for i. Tech. rep., International Business Machines Corporation (2014). https://www.redbooks.ibm.com/redpapers/ pdfs/redp5110.pdf/

8. Ferraiolo, D.F., Sandhu, R., Gavrila, S., Kuhn, D.R., Chandramouli, R.: Proposed NIST Standard for Role-Based Access Control. ACM Transactions on Information and System Security 4(3), 224–274 (2001)

9. Kabra, G., Ramamurthy, R., Sudarshan, S.: Redundancy and Information Leakage in Fine-Grained Access Control. In: Proceedings of the 2006 ACM SIGMOD International Conference on Management of Data, SIGMOD ’06, pp. 133–144. Association for Computing Machinery, New York, NY, USA (2006)

10. LeFevre, K., Agrawal, R., Ercogovac, V., Ramakrishnan, R., Xu, Y., DeWitt, D.: Limiting Disclosure in Hippocratic Databases. In: Proceedings of the Thirtieth International Conference on Very Large Data Bases, VLDB ’04, vol. 30, pp. 108–119. VLDB Endowment (2004)

11. Lodderstedt, T., Basin, D.A., Doser, J.: SecureUML: A UML-based modeling language for model-driven security. In: J. Jézéquel, H. Hußmann, S. Cook (eds.) UML 2002 - The Unified Modeling Language, 5th International Conference, Dresden, Germany, September 30 - October 4, 2002, Proceedings, Lecture Notes in Computer Science, vol. 2460, pp. 420–441. Springer (2002)

12. Mehta, A., Elnikety, E., Harvey, K., Garg, D., Druschel, P.: Qapla: Policy compliance for database-backed systems. In: E. Kirda, T. Ristenpart (eds.) 26th USENIX Security Symposium, USENIX Security 2017, Vancouver, BC, Canada, August 16-18, 2017, pp. 1463–1479. USENIX Association (2017)

13. Montee, G.: Row-level security in MariaDB 10: Protect your data (2015). https://mariadb.com/resources/blog/
A Case study. Satisfiability problems

In this appendix we include the satisfiability problems discussed in our case study (Section 6). Notice that these problems refer to the same underlying data model, namely, the data model University (Figure 1). We show in Listing 1 below the MSFOL theory corresponding to the data model University.

```lisp
; sort declaration
(declare-sort Classifier 0)

; null and invalid object and its axiom
(declare-const nullClassifier Classifier)
(declare-const invalClassifier Classifier)
(assert (distinct nullClassifier invalClassifier))

; null and invalid integer and its axiom
(declare-const nullInt Int)
(declare-const invalInt Int)
(assert (distinct nullInt invalInt))

; null and invalid string and its axiom
(declare-const nullString String)
(declare-const invalString String)
(assert (distinct nullString invalString))

; unary predicate Lecturer(x) and its axiom
(declare-fun Lecturer (Classifier) Bool)
(assert (not (Lecturer nullClassifier))
(assert (not (Lecturer invalClassifier))))

; unary predicate Student(x) and its axiom
(declare-fun Student (Classifier) Bool)
(assert (not (Student nullClassifier))
(assert (not (Student invalClassifier))))

; axiom: disjoint set of objects of different classes
(assert (forall ((x Classifier))
  (=> (Lecturer x) (not (Student x)))))
(assert (forall ((x Classifier))
  (=> (Student x) (not (Lecturer x)))))

; function get the age of lecturer and its axiom
(declare-fun age_Lecturer (Classifier) Int)
```
(assert (= (age_Lecturer nullClassifier) invalInt))
(assert (= (age_Lecturer invalClassifier) invalInt))
(declare-fun age_Student (Classifier) Int)
(assert (forall ((x Classifier))
  (=> (Student x) (distinct (age_Student x) invalInt))))

; function get the email of lecturer and its axiom
(declare-fun email_Lecturer (Classifier) String)
(assert (= (email_Lecturer nullClassifier) invalString))
(assert (= (email_Lecturer invalClassifier) invalString))
(declare-fun email_Student (Classifier) String)
(assert (forall ((x Classifier))
  (=> (Student x) (distinct (email_Student x) invalString))))

; function get the name of lecturer and its axiom
(declare-fun name_Lecturer (Classifier) String)
(assert (= (name_Lecturer nullClassifier) invalString))
(assert (= (name_Lecturer invalClassifier) invalString))
(declare-fun name_Student (Classifier) String)
(assert (forall ((x Classifier))
  (=> (Student x) (distinct (name_Student x) invalString))))

; binary predicate of the Enrolment association and its axiom
(declare-fun Enrolment (Classifier Classifier) Bool)
(assert (forall ((x Classifier))
  (=> (Enrolment x y) (and (Lecturer x) (Student y))))))

Listing 1: University data model theory
Case 6.1

; the generated theory for data model is exactly as in Listing 1
; constant symbol of caller and its axiom
(declare-const caller Classifier)
(assert (Lecturer caller))

; constant symbol of self and its axiom
(declare-const self Classifier)
(assert (Student self))

; caller property: caller is indeed the oldest lecturer
; Lecturer.allInstances()->forAll(l|l.age <= caller.age)
(assert (forall ((l Classifier))
  (and (=> (Lecturer l)
  (and (<= (age_Lecturer l) (age_Lecturer caller))
  (not (or (= (age_Lecturer l) nullInt)
  (= 1 nullClassifier))
  (= (age_Lecturer caller) nullInt)
  (or (= caller nullClassifier)
  (= caller invalidClassifier)))))))

(listing 2: Case 6.1, SecVGU#1. The user is the oldest lecturer

; this TEMP0 function is the OCL expression
; Lecturer.allInstances()->select(l|l.age > caller.age)
(declare-fun TEMP0 (Classifier) Bool)
(assert (forall ((l Classifier))
  (= (TEMP0 l)
  (and (Lecturer l)
  (and (> (age_Lecturer l) (age_Lecturer caller))
  (not (or (= (age_Lecturer l) nullInt)
  (= 1 nullClassifier))
  (= (age_Lecturer caller) nullInt)
  (or (= caller nullClassifier)
  (= caller invalidClassifier)))))))

; authorisation constraint auth: caller is the oldest lecturer
; Lecturer.allInstances()->select(l|l.age > caller.age)->isEmpty()
; below is the negation of maptrue(auth)
(assert (not (forall ((x Classifier))
  (and (not (TEMP0 x)) (not false))))

; the generated theory for data model is exactly as in Listing 1
; constant symbols of caller, self and its axiom
; are defined as in Listing 2
; caller property: caller is indeed the oldest lecturer
; is defined as in Listing 2
; authorisation constraint auth: a caller can know the age of any student
if the caller is the lecturer of that student
; caller.students->exists(s|s = students)
; below is the negation of maPtrue(auth)
(assert (not (exists ((temp Classifier))
  (and (Enrolment caller temp)
    (= temp self)
    (not (or (= caller nullClassifier)
            (= caller invalidClassifier)))))
  (not (= self invalidClassifier)))))

Listing 3: Case 6.1 SecVGU#2. The user is the oldest lecturer

Case 6.2

; the generated theory for data model is exactly as in Listing 1
(declare-const caller Classifier)
(assert (Lecturer caller))

(declare-const lecturers Classifier)
(assert (Lecturer lecturers))

(declare-const students Classifier)
(assert (Student students))

; caller property: caller is the lecturer of every student
; Student.allInstances()->forall(s|s.lecturers->includes(caller)
(assert (forall ((s Classifier))
  (and (=> (Student s)
    (exists ((temp Classifier))
      (and (Enrolment temp s)
        (= temp caller)
        (not (or (= s nullClassifier)
                (= s invalidClassifier)))
        (not (= caller invalidClassifier)))))
    (not false))))

; authorisation constraint auth: a lecturer can know his/her student and
; can know the students of any lecturer if the student is his/her student
; caller = lecturers or caller.students->includes(students)
; below is the negation of maPtrue(auth)
(assert (not (or (or (= caller nullClassifier)
    (= lecturers nullClassifier))
    (and (= caller lecturers)
      (not (or (= caller nullClassifier)
        (= lecturers nullClassifier))
      (= lecturers invalidClassifier))))
    (exists ((temp Classifier))
      (and (Enrolment temp students)
        (= temp caller)
        (not (or (= students nullClassifier)
Listing 4: Case 6.2 SecVGU#2. The user is the lecturer of every student

```
(= students invalidClassifier))
(not (= caller invalidClassifier))))))))
```

Listing 5: Case 6.2 SecVGU#1. The user is the lecturer of every student

```
Listing 6: Case 6.3 (I), SecVGU#2. The user has role Lecturer

```

Case 6.3

```
Optimising FGAC Policy Enforcement for Database Queries

Listing 7: Case 6.3 (I), SecVGU#1. The user has role Lecturer

Listing 8: Case 6.3 (II), SecVGU#2. The user has role Lecturer
B Optimised stored-procedures

Case 6.1

We can enforce the policy SecVGU#1 by using the following if-then-else (Listing 10): if the user is the oldest lecturer, then we execute the original query Query#4, without further checks; otherwise, we execute the “securized” query corresponding to Query#4.

```sql
% declare and assign the variable caller.
% declare and assign the variable role.
IF (role = 'Lecturer'
  AND ((SELECT MAX(age) FROM Lecturer)
    = (SELECT age FROM Lecturer WHERE Lecturer_id = caller)))
THEN
  % if the condition is satisfied, i.e. caller is the oldest lecturers,
  % then the case-statement is removed.
  CREATE TEMPORARY TABLE TEMP1 AS (
    SELECT * FROM Student WHERE age > 18
  );
ELSE
  % otherwise, the case-statement as before.
  CREATE TEMPORARY TABLE TEMP1 AS (
    SELECT * FROM Student
    WHERE CASE ⌜
      AuthFunc($,Student:age)⌝(caller, role, Student_id)
 WHEN 1 THEN age ELSE throw_error() END > 18
  );
END IF;
```

Listing 10: Case 6.1, SecVGU#1

Case 6.2

We can enforce the policy SecVGU#2 by using the following if-then-else (Listing 11): if the user is a lecturer of every student, then we execute the original query Query#5, without further checks; otherwise, we execute the “securized” query corresponding to Query#5.

```sql
% declare and assign the variable caller.
% declare and assign the variable role.
IF (role = 'Lecturer'
  AND ((SELECT COUNT(*) FROM Student)
    = (SELECT COUNT(*) FROM Enrolment WHERE lecturers = caller)))
THEN
  % if the condition is satisfied, i.e. caller is the lecturer of every student,
  % then the case-statement is removed.
  CREATE TEMPORARY TABLE TEMP2 AS (
    SELECT * FROM TEMP1 WHERE TRUE
  );
ELSE
  % otherwise, the case-statement as before.
  CREATE TEMPORARY TABLE TEMP2 AS (
    SELECT * FROM TEMP1 WHERE CASE ⌜
      AuthFunc($,Student:age)⌝(caller, role, Student_id)
 WHEN 1 THEN age ELSE throw_error() END > 18
  );
END IF;
```

Listing 10: Case 6.1, SecVGU#2
We can enforce the policy SecVGU#2 by using the if-then-else statements shown in Listing 12.

```
% declare and assign the variable caller.
% declare and assign the variable role.
IF (role = 'Lecturer')
THEN
  % if the condition is satisfied,
  % i.e. caller has role Lecturer,
  % then the case-statement is removed.
  CREATE TEMPORARY TABLE TEMP2 AS (
    SELECT * FROM TEMP1
  );
ELSE
  % otherwise, then the case-statement as before.
  CREATE TEMPORARY TABLE TEMP2 AS (
    SELECT * FROM TEMP1
    WHERE CASE 'AuthFunc(S, Enrolment)'(caller, role, lecturers, students) WHEN TRUE THEN TRUE ELSE throw_error() END
  );
END IF;

IF (role = 'Lecturer')
THEN
  % if the condition is satisfied,
  % i.e. caller has role Lecturer,
  % then the case-statement is removed.
  CREATE TEMPORARY TABLE TEMP5 AS (
    SELECT age FROM TEMP4
  );
ELSE
  % otherwise, then the case-statement as before.
  CREATE TEMPORARY TABLE TEMP5 AS (
    SELECT CASE 'AuthFunc(S, Student:age)'(caller, role, Student_id) WHEN 1 THEN age ELSE throw_error() END as age
    FROM TEMP4
  );
END IF;
```

Listing 12: Case 6.3 SecVGU#2