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# Secure Object Flow Analysis for Java Card


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## Abstract

The access control exercised by the Java Card firewall can be bypassed by the use of shareable objects. To help detecting unwanted access to objects, we propose a static analysis that calculates a safe approximation of the possible flow of objects between Java Card applets. The analysis deals with a subset of the Java Card bytecode focusing on aspects of the Java Card firewall, method invocation, field access, variable access, shareable objects and contexts. The technical vehicle for achieving this task is a new kind of constraints: quantified conditional constraints, that permits us to model precisely the effects of the Java Card firewall by only producing a constraint if the corresponding operation is authorized by the firewall.


## 1 Introduction

The Java Card language is a subset of Java, tailored to the limited resources available on today's smart cards. Java Card keeps the essence of Java, like inheritance, virtual methods, overloading, but leaves out features such as large primitive data types (`long`, `double` and `float`), characters and strings, multidimensional arrays, garbage collection, object cloning, security managers [1, 10]. Given the security-critical application areas of Java Card, the language has been endowed with an elaborate security architecture. *A priori*, applets are separated by a *firewall* which prevents one applet from accessing objects owned by another applet. Thus, even if a foreign applet obtains a reference to an object with confidential information this does not imply that the information is leaked. In order to provide a means of communication between separated applets, objects can be marked as *shareable*. This allows to grant access to (a subset of) the methods of the objects through the firewall. The problem is that marking an object as shareable means that its shared methods can be accessed by *all* applets that manage to get a reference to the object. To counter this problem, Java Card offers a limited form of stack inspection, allowing a "server" applet to know the identity of a "client" object which invoked a particular method. This, however, must be programmed explicitly by the application programmer. These mechanisms (described in detail in section 2) allow the design of secure applications but do not themselves guarantee security. Further code analysis must be employed to establish that the checks programmed in the server applet guarantee that confidential data is not leaked via shared objects. To summarize:

> The Java Card firewall can be bypassed by using shareable objects. Data flow analysis permits to calculate a safe approximation to the access control actually implemented by a set of applets, and thus to verify that a given access policy is respected.

This paper presents a flow analysis for Java Card programs. The analysis is *constraint-based* in that for each instruction of the program it generates a set of constraints describing the data flow of the instruction. The resolution of this system permits to find the possible values of the variables used in the program and the called method. The analysis relies on a novel technical device, *quantified conditional constraints* (*QCC*s), that allows to generate the set of constraints of a program *on demand*. This way of generating constraints is useful and natural when analyzing object-oriented languages where the control flow and the data flow are inter-dependent. It generalizes the conditional constraints proposed by Palsberg and Schwartzbach [20] for object-oriented type analysis.

The paper is organized as follows. Section 2 introduces the central features of the Java Card 2.1.1 firewall and provides a detailed example. Section 3 defines our representation of the Java Card bytecode. The abstract domains used in the analysis are given in Section 4 and Section 5 defines the set of quantified conditional constraints generated for each type of instruction. Section 6 shows how these *QCC*s can be solved iteratively and Section 7 shows how the analysis performs on the example from Section 2. Section 8 and Section 9 discuss related works and directions for extending this work.

## 2 The Java Card firewall

The Java Card platform is a multi-application environment in which an applet's sensitive data must be protected against malicious access. In Java, this protection is achieved using class loaders and security managers to create private name spaces for applets. In Java Card, class loaders and security managers have been replaced with the Java Card firewall. The separation enforced by the firewall is based on the Java Card's package structure (the same as Java's) and the notion of *contexts* (in Java Card, this notion is called *group context*).

When an applet is created, the *Java Card Runtime Environment* (`JCRE`) assigns it a unique applet identifier (AID). If two applets are instances of classes coming from the same Java Card package, they are said to belong to the same context, identified by the package name. In addition to the contexts defined by the applets executed on the card, there is a special "system" context, called the `JCRE` context. Applets belonging to this context can access objects from any other context on the card. Thus, the set of Java Card contexts is defined by:

*Java Card contexts =*
$\{$ `JCRE` $\} \uplus \{$ *pckg: a package name* $\}$

Every object is assigned a unique *owner context viz.*, the context of the applet which created the object. A method of an object is said to execute in the context of its owner[1]. It is with this context that the `JCRE` determines whether an access to another object will succeed. The firewall isolates the contexts in the sense that a method executing in one context cannot access any fields or methods of objects belonging to another context.

There are two ways for the firewall to be bypassed: via `JCRE` entry points and via shareable objects. `JCRE` entry points are objects owned by the `JCRE` that have been specifically designated as objects accessible from any context. The most prominent example is the *Application Protocol Data Unit* (APDU) buffer in which commands sent to the card are stored. This object is managed by the `JCRE`, and in order to allow applets to access this object, it is designated as an entry point. Other entry points can be the elements of the table containing the AIDs of the applets installed on the card. Entry points can be marked as *temporary*. References to temporary entry points cannot be stored in objects (this is enforced by the firewall).

Two applets in different contexts may want to share some information. Java Card offers a sharing mechanism, called *shareable objects*, that gives limited access to objects across contexts. An applet can allow another applet to access an object's methods from outside its context. The mechanism is restricted to methods and cannot be applied to fields. It uses a shareable interface, that is an interface which extends `javacard.framework.Shareable`. In this interface, the applet gives the list of the method's signatures it wants to share. The class of the object to share must implement this interface. The "server" applet defines a method, `getShareableInterfaceObject`, called when an applet is asked to provide a shared object. The method receives the AID of the "client" applet which requested the shared object. Based on this information, the server decides what to return to the client, thus it is possible to share different objects with different client applets.

### 2.1 An example using shareable objects

Figure 1 contains an example illustrating the sharing mechanisms of the firewall. We have 3 applets: Alice, Bob and Charlie. Alice imple-

[1] In the case of a static call, the execution is in the caller's context.

ments a shareable interface `MSI` (we assume an interface `MSI` that extend `Shareable` in which the signature of the method `foo` is given) and is prepared to share an object `MSIO` (an instance of the class that implements the interface `MSI`) with Bob. When Alice receives a request for sharing (via a call to her method `getSIO`[2]) by the `JCRE`, she verifies that the caller is Bob. If it is Bob, she returns `MSIO` else she returns *Null*.

Bob can ask for a shareable object from Alice using the `JCRE` method `getASIO`[3]. Assume now that Bob (inadvertently) leaks a reference to `MSIO` to the third applet Charlie. Since the firewall only checks that the object is shared before granting access, Charlie can invoke the same methods of the `MSIO` object as Bob. Alice knows this so she decides to verify, at each access to one of her shared methods, the identity of the caller. Java Card offers a method for obtaining the AID of the context in operation before the last context switch, here called `getPrevCxt`[4]. Using this information Alice can discover when applets from contexts other than Bob's attempt to access the `MSIO` object.

### 2.2 Limitations of the firewall

The Java Card firewall has several shortcomings, as analysed in detail by Montgomery and Krishna [18]. One potential difficulty with the Java Card firewall is that shareable objects can be accessed by any applet and not only by the applet to which the reference was given, as illustrated by the example above. Since references can be passed from one applet to another, this opens up the possibility for methods in shared objects to be invoked by applets other than those for which they were intended. To protect applets against unwanted access, Java Card offers a limited form of the stack inspection mechanism that underlies the Java 2 security architecture. The system method `getPrevCxt` can be called to get access to the last context switch that took place. When a method is called from another applet, this context switch indicates the identity of the caller. This information can then be used to decide what value the method should return to the caller. It is, however, up to the programmer to implement this correctly. If the security mechanisms provided by the language are not used properly, unwanted information flow can arise as a result of objects flowing from one applet to another. In order to verify the access control actually implemented by a set of Java Card applets we have developed a static analysis that calculates, for each variable in a program, an approximation of the set of values that will be stored in this variable. This static approximation allows

- to signal potential data flow between applets that violates a given access control policy,
- or, if no such flow is detected, to provide a proof that all data flow respects the policy.

The analysis is based on a constraint-based type analysis for Java-like languages, but is modified to keep an accurate account of the Java Card specificities (like context and firewall). Indeed, since the security of an applet to a large extent relies on the use of the `getPrevCxt` method, the analysis must be able to model calls to this method precisely.

## 3 A representation of Java Card bytecode

To simplify the presentation, we work with a "three-address" representation of Java Card bytecode where arguments and results of an instruction are fetched and stored in local variables instead of being popped and pushed from a stack. This format is similar to the intermediate language *Jimple* used in the Java tool *Soot* [23] and the transformation of code into this format is straightforward. We furthermore assume that the constant pool has been expanded *i.e.* that indices into the constant pool have been replaced by the corresponding constant. For example, the bytecode instruction `invokevirtual` takes as parameter the signature of the method called, rather than an index into the constant pool. The formal representation of Java Card bytecode can be found in [17].

[2] In reality, this method is called `getShareableInterfaceObject` and is invoked by the `JCRE` that mediates all requests for shared objects.
[3] In reality, the method `JCSystem.getAppletShareableInterfaceObject`.
[4] In reality, this method is called `JCSystem.getPreviousContextAID`.

```
public interface MSI extends Shareable {
   Secret foo (); }
```

```
public class Alice extends Applet implements MSI {
   private Secret ObjectSecret;
   public Shareable getSIO (AID Client) {
      if (Client.equals (BobAID))
         return (this);
      return null; }
   public Secret foo () {
      AID Client;
      Secret Response;
      Client = getPrevCxt();
      if (Client.equals (BobAID))
         Response = ObjectSecret;
      return Response; } }
```

```
public class Bob extends Applet {
   public static MSI AliceObj;
   public void bar () {
      AliceObj = (MSI) getASIO
         (AliceAID); } }
```

```
public class Charlie extends Applet {
   private static MSI AliceObj;
   private static Secret AliceSecret;
   public void bar () {
      AliceObj = Bob.AliceObj;
      AliceSecret = AliceObj.foo (); } }
```

Figure 1: Example of shareable objects

### 3.1 Notations

The term $\mathcal{P}(X)$ denotes the power set of *X*: $\mathcal{P}(X) \equiv \{S \mid S \subseteq X\}$. A product type $X = A \times B \times C$ is sometimes treated as a labeled record: with an element *x* of type *X*, we can access its fields with the names of its constituent types ($x.A$, $x.B$ or $x.C$). A list is defined by enumeration of its elements: $x_1 :: \cdots :: x_n$. List elements can be directly accessed giving their position ($v(i)$ for the $i^{th}$ element). Lists can be concatened: $(x_1 :: \cdots :: x_n) ::: (x_m :: \cdots :: x_p) = x_1 :: \cdots :: x_n :: x_m :: \cdots :: x_p$. $X^*$ denotes the type of finite lists, whose elements are of type *X*. The symbol $\rightarrow$ is used to form the type of partial functions: $X \rightarrow Y$. The $\bar{v} \in \bar{E}$ notation denotes the formula $v_1 \in E_1 \wedge \cdots \wedge v_n \in E_n$.

### 3.2 Abstract syntax

Our program representation is a modified version of that of Bertelsen [5, 6]. We use $Id_p$, $Id_{ci}$, $Id_f$ and $Id_m$ to denote the set of qualified name of a package, of a class or an interface, of a field and of a method, respectively[5]. $Id_v$ is the set of (unqualified) names of variables. To extract name information from an identifier, we use the notation $\lceil Id \rceil^x$, where *Id* is a qualified name and *x* the type of the projection[6]. We assume a set `AID` which contains the possible applet identifiers of the applets installed on a card. This set contains a special AID, written `JCRE`, for the Java Card Runtime Environment.

**Classes and Interfaces** A class or an interface descriptor consists of a set of the access modifiers ($\mathcal{P}(Mod_{ci})$), the name of the class or interface ($Id_{ci}$), the name of the direct superclass or the names of direct super-interfaces (*Ext*), the name of the interfaces that the class implements (*Imp*), the name of its package ($Id_p$), field declarations (*Fld*), method declarations and implementations (*Mtd*). A class must have one superclass, the default being `java.lang.Object`, but an interface can have zero or more super-interfaces. Only a class can implement an interface, so for an interface this set is empty. The fields are described by a map from field names ($Id_f$) to a pair consisting of a set of access modifiers ($\mathcal{P}(Mod_f)$) and a type descriptor (*Type*). The type of a field is either a primitive type (`boolean`, `short`, `byte`, `int`) or the name of a class or an interface. All of this information are stored in the class hierarchy ($E_{ci}$).

**Methods** The methods are described by a map that to a method signature (*Sig*) associates a method descriptor ($\mathrm{Desc}_m$). This structure consists of a set of access modifiers ($\mathcal{P}(Mod_m)$), the code of the method (*Code*), a description of the formal parameters (*Param*), optionally a description of the variable used to return a value (*Res*) and the local variables of the method (*Varl*). A signature is the name of the method ($Id_m$) and the list of type descriptors for its parameters ($Type^*$). Code is a list whose elements consist of a pro-

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[5] The qualified name of an entity is the complete name. For a class, it is *p.c* where *p* is the name of the package and *c* the (unqualified) name of the class. For a method (*c.m*) or a field (*c.f*), it is the qualified name of the class and the (unqualified) name of the method or field.

[6] To extract a (unqualified name), we use *p* for a package, *c* for a class or an interface, *m* for a method and *f* for a field. To extract a qualified name, we combine the symbols so, for example, $\lceil Id \rceil^{p.c}$ will extract a qualified name of a class (or interface) from the qualified name *Id*.

gram counter value ($Pc$[7]) and the instruction at this address (*Bytecode*). The set of local variables is the list of all variable names ($Id_v$) with their type descriptor (*Type*).

**Bytecode** Due to space limitations, in this paper, we only consider a subset of Java Card byte code. The subset is nevertheless sufficient to illustrate the different features of our analysis; see [16] for a treatment of the full language. In the following, $T_i$ range over local variables and $S_i$ is used to give the list of the type of the parameters for a call (which can be found in the constant pool).

The main departure from standard bytecode is the introduction of the construct `ifAID` $T \in S$ *BCinst*. This specialized if-instruction takes as argument a variable $T$ that contains an AID, a set $S \in \mathcal{P}(\texttt{AID})$ and executes the instruction `BCinst` if the AID belongs to the set $S$. We have introduced this instruction to make explicit how the analysis takes information about AIDs into account. Ordinary bytecode can be transformed to use the `ifAID` instruction by identifying those conditional instructions that make test of the form $Aid \in S$. Most of such tests are syntactically explicit in Java Card source programs or can be identified by simple intra-procedural flow analysis.

$$Bytecode = \texttt{ifAID}\ T \in S\ BCinst \mid BCinst$$

The Java Card bytecode is transformed into a "three-address" like language. We will not describe this program transformation any further.

$$
\begin{array}{lll}
BCinst = & & \\
& & T := \texttt{getstatic}\ f \\
& \mid & T_0 := \texttt{invokeinterface}\ m\ T_1 \\
& & T_2 \cdots T_n\ S_2{::}\cdots S_n{::}S_{n+1} \\
& \mid & T := \texttt{invokestatic}\ getPrevCtx \\
& \mid & T_1 := \texttt{load}\ T_2 \\
& \mid & T := \texttt{new}\ Id_c \\
& \mid & \texttt{putstatic}\ f\ T \\
& \mid & T_1 := \texttt{store}\ T_2
\end{array}
$$

$T$: =`getstatic` $f$ loads the value contained in the static field $f$ of the class $\lceil f \rceil^{p.c}$ and stores it in $T$. $T_0$: =`invokevinterface` $m\ T_1\ T_2 \cdots T_n\ S_2{::}\cdots{::}S_n{::}S_{n+1}$ invokes the interface method $m$ with the signature $S_2{::}\cdots{::}S_{n+1}$ on the object contained in $T_1$ with parameters $T_2 \cdots T_n$ and the result is stored in the variable $T_0$ with type $S_{n+1}$. $T$: =`invokestatic` *getPrevCtx* retrieves the AID of the last active context before the last context switch and stores it in $T$. $T_1$ := `load` $T_2$ loads the value contained in $T_2$ and stores it in $T_1$. $T$: =`new` $C$ stores a reference to the object created at this program point in $T$. `putstatic` $f\ T$ loads the value contained in the variable $T$ and stores it in the static field $f$ of the class $\lceil f \rceil^{p.c}$. $T_1$ := `store` $T_2$ loads the value contained in $T_2$ and stores it in $T_1$.

[7] We assume furthermore a set $Pc$ of program counters. A program counter identifies an instruction within the whole class hierarchy and not just a method.

### 3.3 Auxiliary functions on the class hierarchy

We define three predicates to determine if a class member (the second parameter) is visible from a given instruction (the first parameter). We have *CI_Visibility?* for a class or an interface, *Method_Visibility?* for a method and *Field_Visibility?* for a field. We must keep this test in the constraint because in some cases, like for the modifier `protect`, we need information about its dynamic values.

*CI_Visibility?:*
$Id_c \times Id_{ci} \times E_{ci} \rightarrow Boolean$
*Method_Visibility?:*
$Id_c \times Id_c \times Desc_m \times E_{ci} \rightarrow Boolean$
*Field_Visibility?:*
$Id_c \times Id_f \times E_{ci} \rightarrow Boolean$

The function *Lookup* models the dynamic search of methods underlying the virtual method calls. It takes as arguments the signature of a method, the class in which the method is declared, the class in which the invocation are made and the class hierarchy. It returns a set of fully qualified method names of the implementations of the method designated by the signature.

$$Lookup: Sig \times Id_{ci} \times Id_{ci} \times E_{ci} \rightarrow \mathcal{P}(Id_m)$$

A full description of the Java visibility rules and method resolution would be quite lengthy due to the non-trivial semantics of these two language features. We refer instead to the literature [12, 15, 14].

## 4 Abstract domains

**Owners and contexts** An object is owned by an applet (or the `JCRE`) thus an owner is uniquely identified by an AID. Since an AID does not directly specify the package to which the applet belongs, we add this information for convenience. Thus, the set of object owners is defined by:

$$\mathit{Owner} = \mathit{Id}_p \times \texttt{AID}$$

We define an abstract context to be an abstraction of the call stack in which a method is executed (these contexts should not be confused with the Java Card notion of context). Our abstract contexts are designed to provide exactly the information that can be obtained by a call to the stack-inspecting method `getPrevCxt` (*cf.* Section 2). More precisely, the abstract context in which a method $m$ is analyzed consists of a pair *(Prev,App)* where the first component *Prev* is the last active Java Card context before the last context switch and the second component *App* is the Java Card context of the *caller* (*i.e.*, the active context that invoked $m$). Formally we define:

$$\mathit{Context} = \mathit{Owner} \times \mathit{Owner}$$

**Values** We are primarily interested in modeling the object structure and ownership so we abstract primitive values such as booleans and integers to their type. To model the heap of objects, we adopt a common approach (going back to at least [13]) in which all objects created by the same `new` instruction are identified by one object. We refine this by keeping the owner as part of the abstract object. More precisely, a reference (*Ref*) to an object (*Obj*) is abstracted into the instruction that created the object and the owner of the object. We suppose we have a special *Null* reference.

$$\mathit{Ref} = (\mathit{Pc} \times \mathit{Owner}) \uplus \{ \mathit{Null} \}$$

We have three kinds of abstract values: references, applet identifiers and primitive values which as mentioned above are abstracted by their type.

$$\mathit{Value} = \mathit{Ref} \uplus \texttt{AID} \uplus \{\texttt{boolean}, \texttt{short}, \texttt{byte}, \texttt{int}\}$$

Concerning the concrete value in memory, we can have a class instance (*Obj*) which contains the name of the class ($\mathit{Id}_{ci}$), the owner of this instance (*Owner*), boolean flags indicating whether or not it is a `JCRE` entry point or a temporary `JCRE` entry point (*cf.* Section 2) and the set of fields (*Fldv*), a function which maps a field name to a set of values.

$$\mathit{Obj} = \mathit{Id}_{ci} \times \mathit{Owner} \times \mathit{JCREep} \times \mathit{tJCREep} \times \mathit{Fldv}$$

$$\mathit{Fldv} = \mathit{Id}_f \rightarrow \mathcal{P}(\mathit{Value})$$

**Firewall checks** The checks made by the firewall are formalized through a collection of predicates. Covering all bytecode instructions would require eight different predicates ([16]); in this paper, we only use two of these predicates:

- The predicate *AccessInterface?* validates the access to methods of an object.

  $$\mathit{AccessInterface?}: \mathit{Ref} \times \mathit{Ref} \times \mathit{Id}_i \times E_{ci} \rightarrow \mathit{boolean}$$

  The first reference represents the current context, the second represents the object on which the call is made and $\mathit{Id}_i$ is the name of the interface which declared the method called. The access is authorized if and only if the context represented by the first reference is the context of the `JCRE` or if the contexts of the two references are the same or if the second reference represents a `JCRE` entry point or if the class of the object represented by the second reference implements a shareable interface and $\mathit{Id}_i$ extends a shareable interface.

- The predicate *AccessPutstatic?* checks the validity of the access to a static field of a class.

  $$\mathit{AccessPutstatic?}: \mathit{Ref} \times \mathit{Value} \rightarrow \mathit{boolean}$$

  The reference represents the current context that wants to store the value in the static field. The access is only authorized if the Java Card context represented by the reference is the context of the `JCRE` or if the value is neither a global object nor a temporary `JCRE` entry point.

## 5 Flow analysis

In this section we describe a data flow analysis to approximate the part of a program's behaviour relevant to security verifications. The main information calculated by our analysis is an approximation of the objects stored in the variables of the program. More precisely, we calculate the following information:

- $\mathcal{V}$ $[\![$*var,m,ctx*$]\!] \in \mathcal{P}$*(Value)*: the set of values stored in the variable *var* of method *m* when this method is called in context *ctx*.
- $\mathcal{SF}$ $[\![Id_{ci}]\!]$ : $Id_f \rightarrow \mathcal{P}$*(Value)*: the possible values of the static fields of a given class.
- *mem* : $Ref \rightarrow Obj$: an approximation of the memory in which an abstract reference of form $(pc, owner)$ is mapped to an abstract object that safely approximates all those concrete objects allocated by instruction at address $pc$ and owned by $owner$.
- $\mathcal{C}$ $[\![$*m,ctx*$]\!] \in \mathcal{P}$*(Ref)*: the set of objects on which a call to method *m* in context *ctx* is made.

It is important to analyze methods for each calling context since this is the information available to the firewall at run-time. An analysis that does not exactly model this information would have poor precision. This information serves two purposes: it permits constructing a control flow graph (by resolving which method is called at a given virtual method call) and it makes explicit if an object owned by an applet is stored in a variable accessible by another applet.

An intra-procedural analysis is required in order to approximate the behaviour of each server applet when it receives a request for a shared object. This analysis is orthogonal to the analysis presented in this paper and will not be described here. We shall assume the function:

$$\textit{Return\_SIO}: \texttt{AID} \times \texttt{AID} \rightarrow \mathcal{P}(\textit{Ref})$$

It takes the AID of a server and the AID of a client and returns a safe approximation of the set of objects that the server accept to share with the client (the set that it returns is equal to or bigger than the set returned during the execution).

### 5.1 Quantified conditional constraints

The analysis will be specified in constraint-based style. We introduce a new type of constraints, the *quantified conditional constraints* (*QCCs*) that can be considered as a constraint scheme from which actual constraints can be generated.

The first kind of constraints used in static analysis is the simple constraint (*SC*). It is used to model the flow and the modification of information. A simple constraint has the form:

$$\text{Expression} \subseteq \text{Variable}$$

An extension of this kind of constraint was used by Palsberg and Schwartzbach [20] for type analysis. They take a simple constraint and add a condition under which the constraint is valid. Such a *conditional* constraint has the form:

$$\text{Class} \in \text{Variable}_1 \rightarrow \text{Expression} \subseteq \text{Variable}_2$$

The $\text{Variable}_2$ have Expression as possible value if and only if Class is a possible value for $\text{Variable}_1$. The simple constraint models an instruction of a method and the condition model the fact that this method can effectively be called.

This kind of constraints solves the problem that the constraints to be generated depend on the actual data flow of the program. The solution has the drawback that it has to generate all possible constraints from the outset and then test for each iteration and for each constraint whether it should be taken into consideration. In the following, we propose to generate the constraints set in an incremental fashion where constraints are only added once the data flow analysis has actually established that the constraints will be activated.

We propose to extend this kind of constraints in the following two ways:

- allow more conditions, to model, for example, the activities of the environment like the firewall checks or the visibility rules,
- produce dynamically the system based on the current value of each variable (instead of generating constraints for all possible values of the domain of the variable).

This new kind of constraints is called *quantified conditional constraints* and has the form:

$$\begin{gathered}\forall\, v_1, \cdots, v_n \in S_1, \cdots, S_n \,\mathbf{:}\\ cond(v_1, \cdots, v_n) \longrightarrow\\ cstr(v_1, \cdots, v_n)\end{gathered}$$

Here, *cstr* is a set of simple constraints parameterized on $v_1, \cdots, v_n$ and *cond* are conditions on the values $v_1, \cdots, v_n$. Evaluation of such a *QCC* results in a set of constraints for each value $v_1, \cdots, v_n \in S_1, \cdots, S_n$ satisfying the condition *cond*. In our analysis, the *QCC*s have a particular structure, as shown below.

- The set *S*, used in the quantification, can be the set of possible values of a variable ($\mathcal{V}$ ⟦*x,m,ctx*⟧), the set of objects on which a call is made ($\mathcal{C}$ ⟦*m,ctx*⟧), the result of the *Lookup* or a constant set.
- The condition *cond* is a conjunction of conditions. It can be a test on the visibility, a firewall check or a test for membership of a constant set.
- A constraint *const* is a set of simple constraint *SC*. *SC* have a form: *Exp* $\subseteq$ *Var*. *Exp* can be a variable, a constant set, a dereferencing of the memory, the set of the values of a static field or the call to *Return_SIO*. *Var* can be a variable, a dereferencing of the memory or the set of the values of a static field.

*QCC:* $\forall\ \overline{value} \in \overline{S}$ **:**
  *cond*($\overline{value}$) $\longrightarrow$
  *cstr*($\overline{value}$)
*S:* $\mathcal{V}$ ⟦*x,m,ctx*⟧ | $\mathcal{C}$ ⟦*m,ctx*⟧ | *Const Set* |
  *Lookup (Sig,* $Id_{ci}$*,* $Id_{ci}$*,* $E_{ci}$*)*
*cond:* $H_1 \wedge \cdots \wedge H_n$
*Condition (H):*
  *CI_Visibility? (*$Id_c$*,*$Id_{ci}$*)* |
  *Method_Visibility? (*$Id_c$*,*$Id_c$*,*$Desc_m$*)* |
  *Field_Visibility? (*$Id_c$*,*$Id_f$*)* |
  *AccessInterface? (Ref,Ref,*$Id_i$*)* |
  *AccessPutstatic? (Ref,Value)* |
  *value* $\in$ *Const Set*
*cstr:* $\mathcal{P}$*(SC)*
*Constraint (SC): Exp* $\subseteq$ *Var*
*Exp: Const Set* | $\mathcal{V}$ ⟦*x,m,ctx*⟧ | $\mathcal{SF}$ ⟦$Id_{ci}$⟧*(*$Id_f$*)* |
  $\mathcal{C}$ ⟦*m,ctx*⟧ | *mem(Ref).Fldv(*$Id_f$*)* |
  *Return_SIO* (`AID`,`AID`)
*Var:* $\mathcal{V}$ ⟦*x,m,ctx*⟧ | $\mathcal{SF}$ ⟦$Id_{ci}$⟧*(*$Id_f$*)* | $\mathcal{C}$ ⟦*m,ctx*⟧ |
  *mem(Ref).Fldv(*$Id_f$*)*

### 5.2 Analysis

The analysis generates, for each method and for an execution context *ctx*, a set of *QCC*s that describes the data flow of the method in this context. The set of constraints for a method is the union of the set of constraints for each instruction. The function to analyze an instruction is:

$$\mathcal{A}_{Inst}\text{: } Inst \times Id_m \times Context \rightarrow \mathcal{P}(QCC)$$

This function takes three parameters: the instruction to analyze, the current method, and the context in which the method is analyzed. An instruction is just a program counter and the bytecode instruction at this address. In the following we define this function for each bytecode instruction.

**getstatic** The `getstatic` instruction loads a value stored in a static field of a class or interface and stores it into a local variable. The value in the field *C.f* is stored in the local variable *T* if and only if the field exists and the field is visible at instruction *Inst* (figure 2).

**invokeinterface** The `invokeinterface` instruction makes a call to an interface method. We calculate the set of methods to which the method signature *sig* can be resolved

*Lookup (sig,mem(o).Type,*$\lceil p \rceil^{p.c}$*,*$E_{ci}$*)*

together with the context in which the methods called will be analyzed *(Prev,App)*. If the call is accepted by the firewall (*AccessInterface? (r,o,*$\lceil p \rceil^{p.c}$*,*$E_{ci}$*)*), we add constraints to simulate this call. We create constraints to simulate the transfer of the actual parameters to the formal parameters:

$\mathcal{V}$ ⟦$T_i$*,m,ctx*⟧ $\subseteq$ $\mathcal{V}$ ⟦$P_i$*,q,(Prev,App)*⟧,

and add a constraint to retrieve the value returned by the method called

$\mathcal{V}$ ⟦$T_0$*,m,ctx*⟧ $\supseteq$ $\mathcal{V}$ ⟦*R,q,(Prev,App)*⟧.

Finally, we add the object *o* in $\mathcal{C}$ ⟦*q,(Prev,App)*⟧ to indicate that the method *q* was invoked on this object (figure 3).

**load** The `load` instruction loads value contained in a variable and stores it in an other variable. The values contained by the variable $T_2$ are transfered into the variable $T_1$ (figure 4).

**new** The `new` instruction simulates the creation of a new class instance and stores a reference to it into a variable. If the class is visible by the instruction, we store in $\mathcal{V}$ ⟦T,m,ctx⟧ the reference to the created object (figure 5).

**putstatic** The `putstatic` instruction stores a value in a static field. The value contained in variable *T* is stored in the static field *f* of the class $\lceil f \rceil^{p.c}$ if the field is visible by the instruction and if the firewall accepts this access (figure 6).

$$\mathcal{A}_{Inst}\ ((pc, T := \texttt{getstatic}\ f), m, ctx) = \begin{array}{l} \forall\,(r) \in \mathcal{C}\,[\![m, ctx]\!] : \mathit{Field\_Visibility?}(mem(r).Id_{ci}, f, E_{ci}) \\ \quad \longrightarrow\ \{\,\mathcal{V}\,[\![T, m, ctx]\!] \supseteq \mathcal{SF}\,[\![\lceil f \rceil^{p \cdot c}]\!](f)\,\} \end{array}$$

Figure 2: Getstatic

$$\mathcal{A}_{Inst}\ ((pc, T_0 := \texttt{invokeinterface}\ p\ T_1\ T_2\ \cdots\ T_n\ S_2 :: \cdots :: S_n :: S_{n+1}), m, ctx) =$$

$$\begin{array}{l} \forall\,(r, o, q) \in \mathcal{C}\,[\![m, ctx]\!] \times \mathcal{V}\,[\![T_1, m, ctx]\!] \times \mathit{Lookup}(sig, mem(o).Type, \lceil p \rceil^{p \cdot c}, E_{ci}) \\ \quad : \mathit{AccessInterface?}(r, o, \lceil p \rceil^{p \cdot c}, E_{ci}) \\ \quad \longrightarrow \left\{ \begin{array}{l} \mathcal{V}\,[\![T_1, m, ctx]\!] \subseteq \mathcal{V}\,[\![P_1, q, ctx']\!], \\ \ldots \\ \mathcal{V}\,[\![T_n, m, ctx]\!] \subseteq \mathcal{V}\,[\![P_n, q, ctx']\!], \\ \mathit{Init\_Var}(E_{ci}(\lceil q \rceil^{p \cdot c}).Mtd((\lceil q \rceil^{m}, S_2 :: \cdots :: S_{n+1})).Varl, q, ctx') \\ \mathcal{C}\,[\![q, ctx']\!] \supseteq \{o\} \\ \mathcal{V}\,[\![T_0, m, ctx]\!] \supseteq \mathcal{V}\,[\![R, q, ctx']\!] \end{array} \right\} \end{array}$$

where we have used the following abbreviations:

$$\begin{aligned} sig &= (\lceil p \rceil^{m}, S_2 :: \cdots :: S_n) \\ P_1 :: \cdots :: P_n &= (E_{ci}(\lceil q \rceil^{p \cdot c}).Mtd)((q, S_2 :: \cdots :: S_n)).Param \\ ctx' &= (Prev, App) \\ App &= (mem(r).Owner.Id_p, mem(r).Owner) \\ Prev &= \begin{cases} ctx.Prev \text{ if } ctx.App.Id_p = App.Id_p \\ ctx.App \text{ otherwise} \end{cases} \\ R &= (E_{ci}(\lceil q \rceil^{p \cdot c}).Mtd)((q, S_2 :: \cdots :: S_n)).Res.Id_v \end{aligned}$$

Figure 3: Invokeinterface

$$\mathcal{A}_{Inst}\ ((pc, T_1 := \texttt{load}\ T_2), m, ctx) = \ \longrightarrow\ \{\,\mathcal{V}\,[\![T_1, m, ctx]\!] \supseteq \mathcal{V}\,[\![T_2, m, ctx]\!]\,\}$$

Figure 4: Load

$$\mathcal{A}_{Inst}\ ((pc, T := \texttt{new}\ c), m, ctx) = \begin{array}{l} \forall\,(r) \in \mathcal{C}\,[\![m, ctx]\!] : \mathit{CI\_Visibility?}(mem(r).Id_{ci}, c, E_{ci}) \\ \quad \longrightarrow\ \{\,\mathcal{V}\,[\![T, m, ctx]\!] \supseteq \{(pc, r.Owner)\}\,\} \end{array}$$

Figure 5: New

$$\mathcal{A}_{Inst}\ ((pc, \texttt{putstatic}\ f\ T), m, ctx) =$$

$$\begin{array}{l} \forall\,(r, v) \in \mathcal{C}\,[\![m, ctx]\!] \times \mathcal{V}\,[\![T, m, ctx]\!] \\ \quad : \mathit{Field\_Visibility?}(mem(r).Id_{ci}, f, E_{ci}) \wedge \mathit{AccessPutstatic?}(r, v) \\ \quad \longrightarrow\ \{\,\mathcal{SF}\,[\![\lceil f \rceil^{p \cdot c}]\!](f) \supseteq \{v\}\,\} \end{array}$$

Figure 6: Putstatic

$$\mathcal{A}_{Inst}\ ((pc, T_1 := \texttt{store}\ T_2), m, ctx) = \ \longrightarrow\ \{\,\mathcal{V}\,[\![T_1, m, ctx]\!] \supseteq \mathcal{V}\,[\![T_2, m, ctx]\!]\,\}$$

Figure 7: Store

$$\mathcal{A}_{Inst}\ ((pc, T := \texttt{invokestatic}\ \mathit{getPrevCtx}), m, ctx) =$$

$$\left\{ \begin{array}{l} \forall\,(r) \in \mathcal{C}\,[\![m, ctx]\!] : ctx.App.Id_p = mem(r).Owner.Id_p \\ \quad \longrightarrow\ \{\,\mathcal{V}\,[\![T, m, ctx]\!] \supseteq ctx.Prev.AID\,\} \\ \\ \forall\,(r) \in \mathcal{C}\,[\![m, ctx]\!] : ctx.App.Id_p \neq mem(r).Owner.Id_p \\ \quad \longrightarrow\ \{\,\mathcal{V}\,[\![T, m, ctx]\!] \supseteq ctx.App.AID\,\} \end{array} \right\}$$

Figure 8: getPrevCtx

Let $\mathcal{A}_{Inst}$ $((pc, BCinst), m, ctx) = \forall\,\bar{v} \in \bar{E} : cond \longrightarrow \{C\}$. Then
$\mathcal{A}_{Inst}$ $((pc, \texttt{ifAID}\ T \in S\ BCinst), m, ctx) =$

$$\forall\,(\bar{v}, a) \in \bar{E} \times \mathcal{V}\,[\![T, m, ctx]\!] : cond \wedge a \in S \longrightarrow\ \{\,C\,\}$$

Figure 9: ifAID

Figure 10: Examples of *QCC*s

**store** The `store` instruction stores the value contained in variable $T_2$ in variable $T_1$. This data flow is modeled by a simple set inclusion: values contained in variable $T_2$ may also be contained in variable $T_1$ (figure 7).

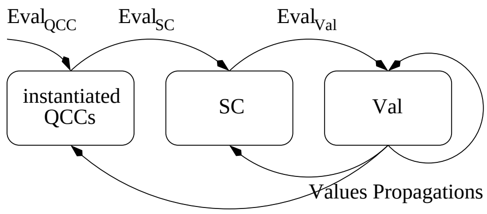
**getPrevCtx** The instruction `invokestatic` *getPrevCtx* makes a call on the static method *JCSystem.getPreviousContextAID*. The method *getPrecCtx* serves to find the AID of the active applet before the last context switch. The first constraint is activated when the active context is the context of the caller, in which case they have the same previous context. The second one is activated when the active context differs from the context of the caller. In that case the previous context is the context of the caller (figure 8).

**ifAID** The *QCC* used in this construct is the one analyzed for the *BCinst* instruction. A condition is added such that the constraints are only generated if the condition in the test is true (figure 9).

## 6 Resolution

The resolution of quantified conditional constraints can be done iteratively as an ordinary fix point computation. The main difference with a "classic" system is that the set of constraints and the values of variables in the constraints evolve together. Hence, the iteration sequence consists of triples *(qcc,sc,val)* where *qcc* is the current set of quantified conditional constraints instantiated for particular contexts, *sc* is the current set of simple constraints and *val* is a valuation that to each variable associates its current value.

Suppose that we have a program *P* consisting of a set of applets (*Aplt*) and a set of methods (*Meth*). Let *Q* be the set of (uninstantiated) *QCC*s obtained by analyzing *P* (with functions $\mathcal{A}_{Class}$ for a class or an interface, $\mathcal{A}_{Meth}$ for a method and $\mathcal{A}_{Inst}$ for an instruction). During the resolution of *Q*, we compute the new set of instantiated *QCC*s, $\mathcal{P}(QCC)$, with the function $Eval_{QCC}$, the new set of simple constraints *SC*, $\mathcal{P}(SC)$, with the function $Eval_{SC}$ and the new valuation *Val* with the function $Eval_{Val}$, as defined below.




The function $Eval_{QCC}$ uses the current valuation to instantiate the *QCC*s in the set *Q* and adds the corresponding constraints to the current set of constraints. This is where the resolution becomes context-sensitive: if a method is not called in a particular context, no constraints for this method will be generated in that particular context.

$$Eval_{QCC}: \quad \mathcal{P}(QCC) \times Val \rightarrow \mathcal{P}(QCC)$$

$$Eval_{QCC}\,(qcc,val) = qcc \cup \bigcup_{\substack{m \in Meth \\ ctx \in Context}} \left\{ ctr \;\middle|\; \begin{array}{l} o \in \mathcal{C}\,[\![m,ctx]\!] \\ \wedge\ ctx' = CalcCtx\,(o,ctx,val) \\ \wedge\ ctr \in \mathcal{A}_{Meth}\,(m,ctx') \end{array} \right\}$$

where the function for calculating the context of the call is given by

$$CalcCtx: \quad Ref \times Context \times Val \rightarrow Context$$

$$CalcCtx\,(r,c,v) = (Prev, App) \quad \textbf{where}$$

$$App = (v(mem))(r).Owner$$

$$Prev = \begin{cases} c.Prev \ \textbf{if}\ c.App.Id_p = App.Id_p \\ c.App \ \textbf{otherwise} \end{cases}$$

The function $Eval_{SC}$ uses the current valuation to verify the condition for each constraint in the set of instantiated *QCC*s and adds the corresponding simple constraints to the current set of constraints. This evaluation permits to restrict the production of the simple constraints that model the effect of an instruction that "executed". We use the notation $[\![\mathrm{Exp}]\!]_V$ to denote the evaluation of the expression *Exp* with the values contained by the valuation *V*.

$$Eval_{SC}: \quad \mathcal{P}(QCC) \times \mathcal{P}(SC) \times Val \rightarrow \mathcal{P}(SC)$$

$$Eval_{SC}\,(qcc,sc,val) = sc \cup \left\{ ctr[\overline{v}/\overline{x}] \;\middle|\; \begin{array}{l} \forall\, \overline{x} \in \overline{X} : cond \longrightarrow ctr \in qcc \\ \wedge\ \overline{v} \in [\![\overline{X}]\!]_{val} \\ \wedge\ cond[\overline{v}/\overline{x}] \end{array} \right\}$$

The function $Eval_{Val}$ is the standard evaluation function associated to a constraint set. For every constraint $exp \subseteq var$ in the current constraint set *cs* we evaluate the expression with the current valuation and add the new value in *val(var)*.

$Eval_{Val}$:
  $\mathcal{P}(SC) \times Val \rightarrow Val$
$Eval_{Val}$ (sc,val) =
  $val[var \mapsto val(var) \sqcup [\![exp]\!]_{val}]$
    **with**
  $exp \subseteq var \in sc$

ALGORITHM
$Q := \bigcup_{A \in Aplt} \mathcal{A}_{Class}\ (A)$ ;
$qcc' := \mathcal{A}_{Class}\ (JCRE)_{(JCRE,JCRE)}$ ;
sc, sc′, qcc := $\emptyset$ ;
val := $\perp$ ;
val′ := $val_0$[8] ;
**while** qcc $\neq$ qcc′ **or** sc $\neq$ sc′ **or** val $\neq$ val′ **do**
  qcc := qcc′ ; sc := sc′ ; val := val′ ;
  qcc′ := $Eval_{QCC}$ *(qcc,val)* ;
  sc′ := $Eval_{SC}$ *(qcc,sc,val)* ;
  val′ := $Eval_{Val}$ *(sc,val)* ;
**endwhile**
END

**Proposition 6.1** *This algorithm terminates with a correct solution to Q.*

The proof of Proposition 6.1 is an extension of the standard argument based on Tarski's theorem [24, 11]. The specificity of the proof is to take into account that the system evolves (in a monotonic fashion!) during the computation. The formal proof (termination and correctness) can be found in [16].

Establishing a start state for the iteration requires special attention in Java Card because there is no `main` to initialize the analysis. The sequence of operations is given by the `JCRE` and the user. We model this interaction with the card by adding an artificial `JCRE` applet that is analyzed like the others. For the `JCRE` we know its context (it is (`JCRE`,`JCRE`)) which permits the algorithm to produce the initial set of instantiated *QCC*s. The initial valuation $val_0$ links each element with its default value. For each $\mathcal{V}$ [\![x,m,ctx]\!] and $\mathcal{C}$ [\![m,ctx]\!] the default value is $\emptyset$. For each $\mathcal{SF}$ $[\![Id_{ci}]\!]$ the default value is the function which links each static field of $Id_{ci}$ with its default value ($\emptyset$ for a reference and $\{P\}$ for a primitive *P*). Finally, we initialize the abstract memory (*mem*) with the undefined abstract objects for each abstract reference.

[8]The definition of the initial value $val_0$ comes after the algorithm.

# 7 An example analysis

In figure 11, we present a variation of the example given in section 2.1, in which the firewall and Alice can not prevent the flow of the Alice secret to Charlie. Here, Bob implements a shareable object and passes a reference to it to Charlie. In this case, the invoke at *Alice.foo* is valid at runtime, because for Alice the caller is always Bob. Here, we only present the transformation of this example in our language in the figure 12. The constraints are neither generated nor solved automatically yet, but we work on an implementation of the previously presented algorithm. During the resolution, each "variable" received the possible values that it can contain. In this example, the important value is the secret of Alice (represented by the reference $(p, AliceAID)$) and the important variable is the static field `AliceSecret` of Charlie. The resolution gives, as a part of the global solution, the following possible value for the static field of Charlie:

$$(\mathbf{p}, \mathbf{AliceAID}) \in \mathcal{SF}\ [\![\mathbf{Charlie}]\!](\mathbf{Charlie.AliceSecret})$$

This result proves that there is an illegal object flow with the secret of Alice.

# 8 Related works

The formalization of the Java Card firewall has been the object of several works. Motré [19] has formalized the firewall with the B method. She defines a machine for the firewall and an operation for each check of the firewall. This modeling provides a formal description of the firewall that is used to ensure that the firewall verifications are sufficient to fulfill the security policy. In addition, successive refinements lead to a reference implementation of the firewall. More traditional operational semantics for modeling the firewall checks have been given by Éluard *et al.* [17]. Siveroni *et al.* [22] show how to integrate this into an operational semantics for Java Card. For the modeling of the `JCRE` it is necessary to be able to "execute" the differents applets. We choose to follow the approach used by Attali *et al.* [3, 4] and model the `JCRE` by an applet. With this approach, we can adapt the `JCRE` to obtain either exactly the execution we want or all possible executions.

The problems related to the Java Card fire-

```
public class Bob extends Applet
      implements MSI2{
   private static MSI AliceObj;
private void bar () {
   AliceObj=(MSI) getSIO (AliceAID); }
public Secret foo2 () {
   return AliceObj.foo (); } }
```

```
public class Charlie extends Applet {
   private static MSI2 BobObj;
   private static Secret AliceSecret;
private void bar () {
   BobObj=(MSI2) getSIO (BobAID); }
private void foo3 () {
   AliceSecret=BobObj.foo2 (); } }
```

Figure 11: An example of illegal object flow

```
public class Alice extends Applet implements MSI {
   private Secret ObjectSecret;
   public Secret foo () {
      AID Client;
      Secret Response;
      1:T1:=invokestatic getPrevCxt
      2:Client:=store T1
      3:ifAID Client ∈ {BobAID} T2:=getstatic Alice.ObjectSecret
      4:Response:=store T2
      5:Alice.foo_Ret:=load Response
      return Alice.foo_Ret } }
```

```
public class Bob extends Applet
      implements MSI2{
   private static MSI AliceObj;
public Secret foo2 () {
   6:T3:=getstatic Bob.AliceObj
   7:T4:=invokeinterface MSI.foo T3
   8:Bob.foo2_Ret:=store T4
   return Bob.foo2_Ret } }
```

```
public class Charlie extends Applet {
   private static MSI2 BobObj;
   private static Secret AliceSecret;
private void foo3 () {
   9:T5:=getstatic Charlie.BobObj
   10:T6:=invokeinterface MSI2.foo2 T5
   11:putstatic Charlie.AliceSecret T6} }
```

Figure 12: The translation of the three methods of the example in our language

wall have been observed by others, notably Montgomery and Krishna [18], who propose another approach to secure object sharing based on delegates. A server implements a delegate object that mediates access to those methods that the server wants to share with others. The delegate object performs the checks that it deems necessary to grant access. This approach is more flexible than the existing firewall but has the drawback that it requires (minor) changes to the JCVM. This technique permits to use more sophisticated authentication mechanisms than the one based only on AID comparison. In the paper it is shown how to use a protocol based on challenge/response phrases to avoid the problem of AID spoofing. However, no technique is presented for proving that delegates indeed do respect a given security policy. In contrast, our approach works for the standard JCVM and relies on static analysis to check that no unwanted access takes place.

Two works on the verification of applet sharing on Java Card are closely related to ours. Bieber *et al.* [8, 7], as part of the Pacap project [2], have defined an analysis of Java Card applets which can detect illegal information flow. Their approach is based on three elements: an abstraction of values of variables into a *level* that describes the sharing of the value, an invariant that is a sufficient condition the security property to hold and a model checker to verify the invariant. A lattice of levels is used to represent the sharing of objects. If an applet *A* is allowed to share some information with an applet *B*, the level *A*+*B* is entered into the lattice specifying the security policy. Each applet is represented by a call graph and each call graph is transformed into an SMV model. To work with a shareable object, an applet must call an interface method so only call graphs which include an interface method are taken into account. The invariant together with the control flow graphs are given to the SMV model checker for verification. The work presented here complements their work by providing a precise description of how these control and data flow graphs can be calculated, taking into account the firewall and the different calling contexts.

The analysis proposed by Caromel, Henrio and Serpette [9] has as aim to signal whether a security exception might (or will definitely) be raised by the firewall at execution of a set of applets. The analysis thus shares objectives with ours and calculates the same type of information. The differences between the analyses lie in the precision. Caromel *et al.* have opted for a simple, flow-insensitive analysis whereas we can obtain some flow sensitivity through the choice of local variables in our three-address byte code. Instead of modeling the memory state explicitly, they use an alias analysis to track side effects of assignments. The control flow analysis in their analysis is a simple class hierarchy analysis, in contrast to our context-sensitive flow analysis. Indeed, their analysis does not analyze methods separately for each calling context and hence would not be able to deal with the call stack inspection as well as our analysis. Thus, the two analyses can be seen as two extremes of the design space for flow analysis for Java Card.

The quantified conditional constraints (*QCC*s) introduced in Section 5.1 are an extension of the conditional constraints (originally due to Reynolds [21]) that are used in the object-oriented type analysis defined by Palsberg and Schwartzbach [20]. In this analysis, conditions of the form $C \in \mathcal{V}(X)$ are used to guard the constraints generated from class $C$ such that these are only evaluated when class $C$ is actually used. However, it is still necessary to generate the constraints for every class in the hierarchy which leads to scalability problems. The *QCC*s, on the other hand, generate these constraints *on demand*: only when the analysis discovers that a certain class or method is used, the corresponding constraints are generated and added to the current set of constraints.

## 9 Conclusions and future work

The access control exercised by the Java Card firewall is bypassed when invoking methods on shareable objects. In order to determine the access control that is implemented by a given set of Java Card applets we have presented a static analysis that calculates a safe approximation of the flow of objects between applets of a Java Card application. The static analysis is an extension of the constraint-based program analysis framework that allows to generate and solve data flow constraints in a demand-driven fashion.

The information calculated by our analysis has other applications than verifying access control. The data flow information allows to construct a precise *control flow graph* on which other safety-style properties of the application can be verified. Examples of these include verifying that all Java Card transactions are well-formed and that exceptions are properly caught and treated by the application. A verification technique based on model checking using finite automata is detailed in [16].

The present analysis does not deal with the problem of *(indirect) information flow* between applets. In particular, we do not model the flow of primitive values between applets so we cannot detect if applet B transfers data to applet C that contains information obtained from applet A. Analyses for detecting such information flow have been proposed elsewhere (see *e.g.* [25]) in the setting of a simple imperative language. The control and object flow information calculated by our analysis can be used to adapt such analyses to the Java Card language because it allows to eliminate the higher-order and object-oriented features of an application, essentially translating it into an imperative language. This requires an improvement to the abstract domains such that owner information can be attached to primitive values and primitive operations must be adjusted to calculate the possible owners depending on the values used in the operation as well as the applet which does the operation.

Finally, for the moment the analysis does not take into account exceptions other than security exceptions. With the current abstraction of the primitive values it is clear that exceptions related to *e.g.*, array access (index-out-of-bound exceptions) can only be dealt with in a very approximate fashion. Exceptions form an integral part of the control-flow of an application so progress in this direction is desirable.

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