Jif: Language-based Information-flow Security in Java

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Abstract—In this report, we examine Jif, a Java extension which augments the language with features related to security. Jif adds support for security labels to Java’s type system such that the developer can specify confidentiality and integrity policies to the various variables used in their program. We list the main features of Jif and discuss the information flow problem that Jif helps to solve. We see how the information flow problem occurs in real-world systems by looking at two examples: Civitas, a ballot/voting system where voters do not necessarily trust voting agents, and SIF, a web application container implemented using Jif. Finally, we implement a small program that simulates information flow in a booking system containing sensitive data and discuss the usefulness of Jif based on this program.

Index Terms—security, information flow, java, jif, confidentiality, integrity

I. INTRODUCTION

Jif is a Java extension which augments the language with features related to security. Primarily, it helps developers enforce information flow security constraints at the code level by using specific Jif annotations and constructs. Jif is available on http://www.cs.cornell.edu/jif/ and in this report we review the extension. In this report we aim to,

- give a detailed description of the main features offered by Jif and the problems that they solve,
- implement a practical example using these features and critique the Jif extension with regards to its suitability as a solution for security related application concerns.

We first give an overview of Jif and its features including how it augments Java’s type system so that developers can explicitly state confidentiality and integrity policies for the data in their programs. We also look at how Jif can be used for two real-world cases, namely a voting/ballot system and a general web framework.

We also present a small program implemented using Jif which will also be used for critiquing Jif towards the end of the report.

II. RELATED WORK

Jif is one of multiple projects that attempt to solve the information flow security problem. FlowFox, for example, is a web browser implemented to take information flow into consideration and protect the user’s sensitive data [4]. A type system for a modified version of JavaScript has been proposed by Hedin and Sabelfeld to introduce information flow security in web scripts [7]. Both these proposals are relevant because they encounter the same problems which will be described later in this report and which apply similarly to Java.

The idea of a security label lattice which is subsequently used by Jif comes from Denning [5]. Denning proved that a lattice can be used to verify the information flow security of a program. Denning & Denning also point out that this verification can be done statically by a compiler [6] which is the primary motivation for developing information flow type systems in languages.

Sabelfeld and Myers discuss information flow security as it pertains to programming languages in their paper and also point out the more subtle problems related to language-based information flow [8]. These include the fact that modern languages are becoming increasingly more expressive and more concurrent.

III. BACKGROUND: THE JIF EXTENSION

In this section, we introduce Jif and its main features. All the information here is from the Jif reference manual available online [1]. We will focus on the basic features that Jif provides and how they can be used to solve common security issues when developing software applications.

A. Information flow

The information flow problem is a common problem in software development concerning the leaking of sensitive information to unauthorised people or entities. This typically occurs not because of a malicious intent by the software developer but due to bugs and errors introduced in the system during development stage. A web application might inadvertently keep sensitive information in memory longer than necessary which is later leaked out as a response to a user request. This is clearly a very dangerous issue and tools like Jif are meant to help tackle and reduce the likelihood of something like this occurring.

B. Principals, security policies & labels

Jif is concerned about information flow between so-called principals. Principals are the entities involved with the system. They can represent a single human user, for example, or even a whole group of users. Jif defines a relation between principals called the acts for relation. For instance, if a given
principal, Alice, can act for another principal, Bob, (written $Alice \geq Bob$) then Bob delegates all of his authority to Alice. Jif also defines a top principal, $\top$, which acts for all principals ($\forall p: Principals - \top \geq p$) and a bottom principal, $\bot$, which allows all principals to act for it ($\forall p: Principals - p \geq \bot$).

Jif extends the Java type system so that types can be declared along with a security label. This security label describes a pair (ie. 2-tuple) made up of a confidentiality policy and an integrity policy. Each policy is owned by a principal. A confidentiality policy specifies which principals the owner allows to read a particular data variable. Likewise, an integrity policy specifies which principals the owner allows to modify a piece of data. For example, the confidentiality policy, $Alice \rightarrow Bob$, means that the data to which this policy applies is owned by Alice and can be read by Alice herself, Bob and any other principal that can act for any of them. Likewise, $Charles \leftarrow Bob$ is the integrity policy, owned by Charles, which allows Charles, Bob and anyone who can act for them to modify the associated data.

By combining a confidentiality policy together with an integrity policy, we get a security label of the form $\{c:d\}$ where $c$ is a confidentiality policy and $d$ is an integrity policy. A label is added to a variable declaration to specify the security policies that govern access to the contained data. So, for example, we can declare an integer variable which everyone can read but only Alice can write to as follows,

$$\text{int}\{Alice\rightarrow_; Alice\leftarrow*\} \text{ secret}$$

**C. Method labels**

During execution, Jif maintains a program counter which keeps track of the most restrictive security policy in effect. If the program attempts to access data with a less restrictive policy than the one in the program counter, the compiler will generate an error warning the developer that information is being leaked at that particular point in the program.

By using a begin-label on a method, we instruct Jif to check that the program counter has the appropriate security policy before execution starts inside the method. It also enforces that write attempts that happen inside the method conform to the active integrity policy.

An example of a method declaration with labels, taken from the Jif reference manual, is shown below,

```java
public void setElementAt{L}(Object{L} o, int{L} i) { }
```

$L$ here is a previously defined label parameter which works similarly to generics. The begin-label of the method `setElementAt` is given in braces just after the method name.

**D. Authorities**

A principal may also give authority to a method to act for it using the `authority` construct. An example from the Jif reference manual is given below,

```java
class Game authority(referee) {
    void start() where authority(referee) {
        // this entire method body has the
        // authority of referee
        ...
    }
```

In this snippet, the class declares that its methods can act for a principal called `referee` in its signature. Then, each one of its methods may add that it acts with the authority of `referee` by adding the clause `authority(referee)` in its signature. Now, each time the system queries the active security policy in the program counter, it will do so with the authority of the `referee` principle.

**E. Other features**

Jif supports other advanced features which we will not cover in this report as we will not use them in the demonstration in section [Ⅳ]. Notably, Jif supports polymorphism with parametrized classes (which works similarly to generics), dynamic labels which store label information at runtime and extensible principals allowing developers to define their own principal types.

**IV. JIF IN ACTION**

We now look at two example applications of Jif. Each paper referenced here has been published by Jif’s creators to promote Jif. We review their arguments for applying Jif in two particular situations with commonly occurring real-world equivalents.

**A. Civitas: a voting system**

**Civitas** is a voting system built using Jif [Ⅲ]. The authors state that in an election, both integrity of the whole balloting process and confidentiality of the individual votes are necessary. They say that, traditionally, each one of these can be solved at the expense of the other. So, for example, integrity can be achieved during an election if everyone publicly states their own vote; this method, though, forgoes confidentiality because everyone’s vote becomes public knowledge.

Civitas makes use of a log service shared across four different types of voting agents. Voting agents are the entities running and organising the election process separate from the electorate. A log service allows data insertion signed using a secure digital signature (prevents forging additional messages). The bulletin board, used by the agents to tally votes, and the individual ballot boxes, used by voters to submit their vote, are all instances of the aforementioned log service.

Using Jif, security policies can be enforced on all the various components of the arrangement mentioned above to ensure that no unintended information flow occurs in the system.

In the system mentioned above, a registration teller agent issues credentials which a voter must use when submitting their vote. When the credentials are created in the system, the registration teller then labels the credentials with a confidentiality policy of $RT \rightarrow voter$. This means that the owner of the policy (the RT or registration teller principal) also allows the voter principal to read the credentials.
Another example given by the authors is that of the integrity policy $TT \leftarrow Sup$ applied to ballot boxes. This label means that the tabulation teller (TT) will consider that the ballot box’s integrity has been compromised if someone else other than the supervisor (Sup) or the tabulation teller themselves has affected the value of the ballot box.

Using a modified version of Jif called Jif$_E$, the system also declares multiple declassification and erasure policies which state the conditions that must hold before a confidentiality policy can be relaxed or made more restrictive. In the Civitas system, each registration teller must store a private credential share that will be requested by the voter as described above. By using an erasure policy, the authors declare that the registration teller must erase the private share component once it is handed to the voter. In this way, we have a provably correct piece of code which is clearly destroying the sensitive data: there is no way that the private credential component will be leaked to unintended entities because the erasure policy mandates its destruction.

B. SIF: Servlet Information Flow framework

SIF is a framework built using Jif, on top of the Java Servlet Framework, used for creating servlet-based web applications [2]. Chong et al. discuss how web applications suffer from multiple threats due to their nature. Specifically, web applications must frequently communicate with potentially unknown clients. These clients are not necessarily benign and may take advantage of vulnerabilities to retrieve sensitive data which they are not authorised to access.

A well known information flow attack is SQL injection where a user sends SQL commands to the web application which are sent straight to the underlying RDBMS server without any sanitisation. The RDBMS server will execute the unsanitized command in full and possibly send back information which should not have been accessible to the user.

Jif, instead, protects against more general attacks of a similar nature. A user might know the URL of a particular page on the web application containing sensitive data. Due to human error, the page might have been left accessible without the need for authentication. Using Jif, the sensitive data itself (as opposed to the web page displaying that data) can be labelled and Jif will ensure that such data never leaves the web application as a response unless the authenticated principal is correct. This is somewhat similar, albeit on a smaller scale, to the example implementation given later in section V-A.

SIF makes heavy use of dynamic principals since web applications usually add new users (through some sort of registration process) during their lifecycle. Dynamic principals are a recent addition to Jif; they allow Jif’s type checker to reason about principals which are not yet fully known in advance during compilation.

The authors give an example of a web application, implemented in SIF, providing a calendar service for its users. Users create events which they own and, using different security policies, can share their events with other users and attendees. Using Jif’s integrity policy labels, SIF allows users to express whether they want other users to modify events or just see events that they shared. At a lower level, the system is checking whether the authenticated user can act for an event’s creator or one of the attendees (using a special Jif operator, actsfor).

By labelling the appropriate data in this way, the compiler will statically check that an event object’s information never reaches a user who is not the owner or one of the attendees. A person who is reading the code finds a proof of security in the labels that are specified with each object’s declaration.

V. A Jif Example

In this part of the report, we present a small program written in Jif to demonstrate how security labels can be used to restrict unauthorised information flow. The full program listing is found in Appendix A.

A. Defining sensitive data

For this program, we simulate a small part of a tour booking system. A class Booking represents a booking object created by either one of two users of the system, namely Alice and Bob. Each booking object has a sensitive field of type String called cardNumber which is the 16-digit credit card number used by the customer when paying for the booking. It is extremely important for a system of this sort that the card number is never shown to an unauthorised user. We define the Booking class as well as the cardNumber string as shown in listing 1.

Listing 1. Booking class with sensitive card number.

```
public class Booking{principal Owner,
principal Operator} authority(Owner) {
  private final String(Owner->*) cardNumber;

  // ... Getter methods, etc.
}
```

The class is defined with respect to two principal parameters, the Owner who created the booking and an Operator user who is managing the bookings using the system.

By adding a label {Owner->*} to the cardNumber variable, Jif will make sure that cardNumber is never accessed by any principal which is not the owner of the booking. In fact, the getter function of this variable (getFullCardNumber()) must also have its begin-label set to {Owner->*}: the compiler will check that the program counter has the appropriate security level before any calls to the getter method can go through.

B. Declassifying confidential information

Information sometimes needs to flow from a highly restricted and secure domain to a less restricted domain as part of the business specifications of the system itself. In Jif, this is realised as moving data from a variable with a particular label to another variable with a less restrictive label.

The Jif compiler would normally not allow such an operation and will give an error. An example of this is shown in
The commented line contains a statement where Bob tries to copy Alice’s card number from her booking object into his own notebook. The label on Bob’s notebook, \{Bob→\} is less restrictive than the label on Alice’s card number. In this case, Jif would issue an error at compile time similar to the error in figure 1. Jif stops us from making the critical mistake of inadvertently passing Alice’s card number to Bob.

Finally, Chuck writes Alice’s first six digits from her card number in his notebook. Now, since this is the same information that is coming from Alice’s card number, the label on Chuck’s notebook must be a conjunction of Chuck’s confidentiality policy and Alice’s confidentiality policy on her card number’s first six digits².

VI. REFLECTIONS ON JIF

Our reflection and opinions regarding Jif are based on our experience while working on the example given in the previous section. By using Jif, we believe that protecting crucial sensitive data is much easier provided that the labels are used correctly.

Jif’s labelling system suffers from the same problems apparent in any other type system. Namely, the type system will work as long as the developer uses it correctly. As a type system, such as Jif’s, becomes more complex, the likelihood of making an error becomes greater.

While working on the example presented in this report, we encountered multiple issues with regards to selecting the correct labels for the program to compile. Admittedly, this is mostly due to our inexperience of working with Jif and trial-and-error did eventually get the job done. Jif’s lack of widespread adoption and community using the tool is also partly to blame. A more time-constrained developer would have taken the short-cut of simply removing any label constraints which were proving to be a problem until the program compiles: the resultant system would supposedly be resilient to incorrect information flow but in reality, none of Jif’s security features come into play.

In spite of this, we still believe that Jif is a suitable tool with a lot of promise. It has a good span of features which are all documented. Jif’s creators should now focus more on expanding the toolset available for Jif (a Jif file editor with code suggestion is sorely needed, for instance). Also, additional documentation should be provided for troubleshooting common problems as a new programmer using Jif will likely encounter multiple problems when using it for the first few times.

VII. CONCLUSION

In this report, we discussed the information flow problem, a security concern for systems which deal with sensitive data. We gave an overview of the Jif extension for Java which is a

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²This is an ideal example of where we could have considered using an integrity policy instead of combining confidentiality policies. We would keep the operator’s notebook readable only by Chuck but its contents can be affected by Alice: \{Chuck → T; Chuck ← Alice\}.

³“Error” here in the sense that the user does not fully specify the correct types and takes short-cuts.

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Listing 2. Incorrect flow of information. Jif will not compile this method.

```java
public String{Owner->Operator} getFirstSix{Owner->*}() {
    try {
        return cardNumber.substring(0, 6);
    } catch (Exception e) {
        return "N/A";
    }
}
```
Finally, we developed a small example using Jif where we protected sensitive data from accidentally leaking outside its security domain. Using the program we also gave constructive criticism for Jif as a whole. In essence, we have come to the conclusion that Jif is indeed a suitable tool for solving the information flow problem.

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Civitas and SIF were given as examples of systems built using Jif where we see the information flow problem clearly. Civitas, for example, has multiple entities which have to cooperate together but are mutually distrusting of each other. Jif therefore enforces security constraints on the data which the aforementioned entities have to work with. Likewise, SIF implements security constraints for web applications which are repeatedly targeted in information flow attacks where an adversary attempts to extract unauthorised information which they normally should not have access to.

Fig. 1. Compiler error when card number is not declassified first.
### A. Booking.jif

```java
package edu.ac.ed.apl.s1461410.jifdemo;

public class Booking[principal Owner, principal Operator] authority(Owner) {

    private final String{Owner->*} cardNumber;

    public Booking(String{Owner->*} number) {
        this.cardNumber = number;
    }

    public String{Owner->*} getFullCardNumber{Owner->*}() {
        return cardNumber;
    }

    public String{Owner->Operator} getFirstSix{Owner->*}() {
        try {
            String{Owner->Operator} result = "";
            result = declassify(cardNumber, {Owner->*} to {Owner->Operator});
            return result.substring(0, 6);
        } catch (Exception e) {
            return "N/A";
        }
    }

    public String{Owner->Operator} getLastFour{Owner->*}() {
        try {
            String{Owner->Operator} result = "";
            result = declassify(cardNumber, {Owner->*} to {Owner->Operator});
            return result.substring(12, 16);
        } catch (Exception e) {
            return "N/A";
        }
    }

    public String{Owner->Operator} getHashedNumber{Owner->*}() {
        return getFirstSix() + "******" + getLastFour();
    }
}
```

### B. Application.jif

```java
package edu.ac.ed.apl.s1461410.jifdemo;

public class Application authority(Alice, Bob, Chuck) {

    public void execute{Alice->Chuck meet Bob->Chuck meet Chuck->*}() {
        Booking[Alice, Chuck][Alice->Chuck] booking1 = new Booking[Alice, Chuck]("4444333322221111");
        Booking[Bob, Chuck][Bob->Chuck] booking2 = new Booking[Bob, Chuck](*4443333322221111*);
        String[Alice->*] aliceNotebook = booking1.getFullCardNumber();
        // The compiler would issue an error for the line below
        // String[Bob->*] bobNotebook = booking1.getFullCardNumber();
        String[Chuck->*;Alice->Chuck] operatorNotebook = booking1.getFirstSix();
    }

    public static void main{Alice->Chuck meet Bob->Chuck meet Chuck->*}(String[] args) {
        new Application().execute();
    }
}
```