

# **Data Traffic Analysis for Android Applications**

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THESIS

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*To my family and Giulia*

*To everyone that supported me and my studies*

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## LIST OF ABBREVIATIONS

**AOSP** Android Open Source Project. vii, 1–3, 61

**API** Application Programming Interface. vii, 12

**boot loaders** a boot loader is a piece of code that is executed before any Operating System starts to run. It can be exploited to change the Operating System to run. vii, 16

**CSRF** Cross-site request forgery. vii, 24

**HTTP** Hyper Text Transfer Protocol. vii, 34

**IFDS/IDE** interprocedural, finite, distributive, subset/interprocedural distributive environment. vii, 46

**JIT** just-in-time. vii, 4

**LGPL** Lesser General Public Licence. vii, 43

**NDK** Native Development Kit. vii, 2

**SDK** Software Development Kit. vii, 2

**UI** User Interface. vii, 16, 20

**VM** Virtual Machine. vii, 2



## SUMMARY

In this thesis I present the design and the implementation of a tool to analyze the paths that information exchanged by different process on the phone takes, in order to automatically detect vulnerabilities that may come out from bad programming practices or simple distractions while implementing Android applications.

The goal of this work is to produce a tool, targeted to every developer who wishes to test his application. It aims to be intuitive and simple to use.

The tool implements a static code analyzer able to take in input Android application packages and produce as output precise security reports on the analyzed application. The analysis performed focuses its attention to the facilities provided by Android to easily enable applications subprocesses to communicate.

This work was originally ideated after some manual exploration in real Android applications, downloaded from the store. This exploration confirmed that in several cases even the most simple isolation principles were violated, even by popular and broadly used applications.

## CHAPTER 1

### INTRODUCTION

#### 1.1 Android OS Overview

In the past years Android OS had became the most widespread mobile operative system in the world surpassing all the competitors in market shares.<sup>[1]</sup>

One of the reasons for Android success is its *open-source* nature. The Android Open Source Project (AOSP) code is entirely available for download at AOSP download page. In particular, it has to be noticed that every phone manufacturer can easily customize and adapt to its needs an already cooked operative system, without the need to develop a new one from scratch, determining drop in development costs, and a consequent drop in the final product price. Of course this possibility is not restricted to manufacturing companies, but everyone can change and build the code for various purposes such as bug fixing, development contribution or personal curiosity.

This exposition of the code, although, may lead into security problems: a clear sketch of the security features of the operative system can easily be delineated, leading to a easier to access and broader knowledge of the security issues the operative system could have. This knowledge might be exploited for benign purposes such as fixing, but also maliciously, endangering the final phones users.

When a security issue is detected and correctly fixed by the community, the propagation of this patch is, in practice, difficult for two main reasons: first, due to the high fragmentation in Android versions, it might become complicated to detect all the versions in which the bug is present. Then the modification performed by the manufacturers on the actual deployed versions of the operating system might be significant, leading into substantial differences with respect to the official AOSP branch. This misalignment, usually makes difficult for the manufacturer to keep their deployed versions up to date.

#### **1.1.1 Android OS Architecture**

Android OS is a comprehensive operative system built on the top of the Linux Kernel. It is structured as a stack consisting of four logical layers, composed by different modules written in Java, C++ and C.

- **Applications:** these are the actual programs the user interact with. Applications can be written either in *Java* with the support of the official Android SDK, or in *C++* over the official Android NDK.
- **Application Framework:** this is a set of services handling applications life-cycle, message passing and content sharing between applications and managing application specific resources such as images and localized strings.
- **Libraries and Runtime:** Libraries are a collections of facilities available for both application framework components and applications. They provide an unified way to access database storage, web browsing components, media players and so on. The runtime enables each application to run in its own instance of Dalvik VM.

- **Linux Kernel:** this is the lower layer of the infrastructure. In addition to the Linux Kernel, in this layer are also present hardware drivers, in charge of communicating directly to the phone's physical components. These drivers are clearly device specific and there exist phone specific build types in AOSP, containing specific driver binaries (sources are usually not available).

In Figure 1 is represented the complete OS architecture along with all the macro-components.

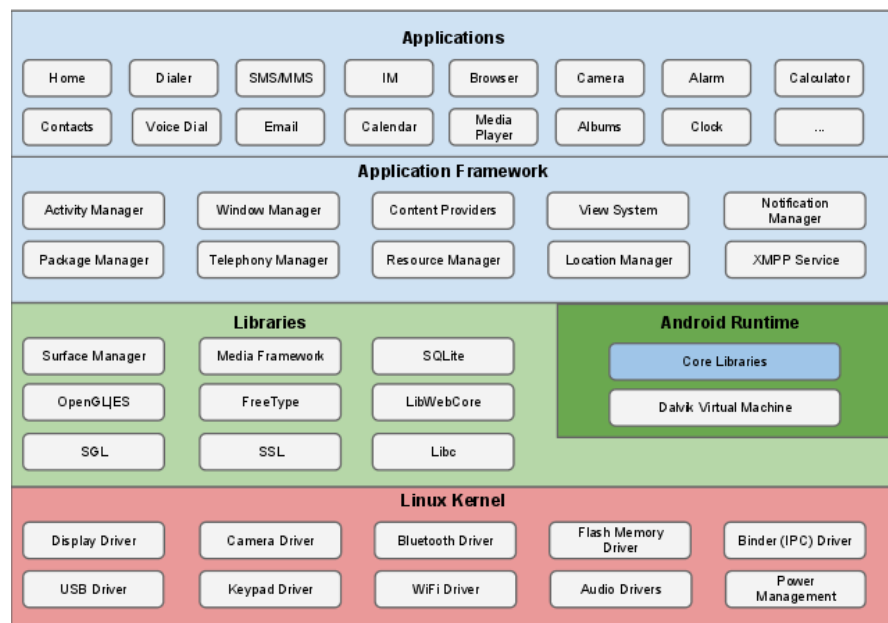


Figure 1: Android OS architecture. Source: <http://source.android.com/tech/security/index.html#android-platform-security-architecture>

Applications and libraries Java code is compiled into Dalvik bytecode, after being compiled into the classical Java bytecode. This bytecode was specifically designed to run on mobile devices (ARM processors), carrying some specific optimizations. Its main characteristic is to be register-based, unlike the classical Java bytecode which is stack-based. The Dalvik VM was designed to run efficiently multiple VM instances so to guarantee isolation among processes. From version 2.2 of Android it has also been added to the Dalvik virtual machine a built-in just-in-time (JIT) compiler, in order to speed up the runtime execution of Android applications.

This thesis focuses the attention on the first two layers of the described hierarchy, i.e. the *applications layer* and the *application framework layer*.

### **1.1.2 Android OS Security Model**

Android claims to be designed to be the most secure and usable mobile operating system providing automatic mechanisms to guarantee user data and resources protection along with application isolation.

The OS strongly relies on the consolidated Linux security model in which process isolation is guaranteed by design, except for a (reduced) set of privileged code fragments that run with root privileges. Linux policies on user resources ensure that *user A*, will not access CPU resources, memory, files or devices belonging to *user B*. The concept of user isolation is exploited by Android in order to provide a complete application isolation (*application Sandboxing*). Differently from the traditional Linux implementation, in Android, it is assigned to each application a unique user ID. Each application will then run into a

separate process belonging to its user. This ensures that no unauthorized data access can occur at native code level.

As mentioned above the application Sandboxing is also ensured by the fact that completely separated instances of Dalvik VMs are started for each new application that is launched. This guarantees complete isolation also at Java code level.

Together those two isolation should prevent memory corruptions to compromise the security of the device. Nevertheless application Sandboxing is breakable on a non properly configured device.

Another higher level security feature that Android OS provides is the so called *Application Permission Model*. By default applications can access a quite limited number of resources. Most of those can only be accessed through OS calls. Applications, in order to access non-default features must declare their intention of usage: a misdeclaration of a requested resource causes a security exception, raised by the application framework, leading into a failure of serving such request. The *Application Permission Model* contains a fine grained, hierarchical list of capabilities applications can declare. The choice between allowing or not applications to access the declared resources is demanded to the final user at installation time. Unfortunately the capabilities cannot be partially accepted/unaccepted, so the only way a user has to prevent an application not to access a specific capability is not to install the application at all. This choice is presented to the user both when installing applications downloaded from the official Google Play Store and when installing other applications from unknown sources.

### 1.1.3 Android OS interprocess communication

A single Android application package can contain several (independent) components. Each of those components, along with its type has to be declared in a *manifest* file. Components can belong to one of the following categories:

- **Activities:** Activities generally contain the code for one single user-focused task. Activities have associated UI components the user can interact with. Typically, the main entry point for an application is a distinguished activity (declared in the manifest file).
- **Services:** Services are pieces of code that run in background independently from the current context presented to the user. Services communicate with the external environment via interfaces available through remote procedure calls.

Due to Application Sandboxing, application's components cannot directly share information or send messages ones to the others. In order to make available the possibility for such isolated processes to communicate, the OS has to provide a controlled mechanism. Android interprocess communication is made available by the help of the following three elements:

- **Binder:** It is a lightweight procedure call mechanism mostly used when the communication demand high performance communication. It is implemented using a custom Linux driver. Exploiting Binder, the Services discussed above can efficiently exchange informations.

- **Intents:** Intents are objects representing simple messages that can be exchanged by different processes. The name Intent was chosen because of the fact that these messages usually are sent when a process has an *intention* to interact with another process. Intent messages either carry information on a specific destination or manifest that some generic request needs to be served by some process able to manage such specific request. Intents can also act as broadcast messages informing a set of interested processes that some status change has occurred (i.e. a network status change information may be interesting for both a browser and a chat application that could notify the user in case of a connection drop, or resume a paused operation after the network status returns available).
- **Content Providers** Content providers is the name given to the interfaces used to expose some particular data, generally directly available for all the processes. An application may want to expose some data it controls to other applications; this can be done by the exposer application by implementing a content provider interface, in which the process specifies its behavior in response to queries from the outer world.

Intents are the fundamental communication element in the Android interprocess communication system.

## 1.2 Motivation

In the last few years many researches have highlighted several possible vulnerabilities deriving from poor understanding of the official Android's security guidelines<sup>[2]</sup> and of the Android's security model in general. Android specifically makes interprocess communica-



tion and collaboration one of its main paradigms. Although this communication must be carefully designed by developers, that need to follow some basic design guidelines such as Activity state isolation and so on. Android does not take explicit measures to enforce the design of the applications to be intrinsically secure. This means that the decision of using or not the large amount of security features embedded in Android is left to the final application developer. This philosophy might be slightly optimistic, because it is based on the assumption that every developer has a reasonably good security background to understand and not to underestimate the problems that a non-defensive programming approach can cause.

This work wants to highlight that in several real-world cases this design guidelines are not properly followed, and this “bad behavior” can lead in real threats for the final users.

### **1.3 Contribution of Thesis**

The goal of this thesis is to design and implement a tool capable of automatically detect programming choices, when developing Android applications, that can lead into security risks for the final user. The tool should eventually be able to warn the developer about these risks, and suggest a set of possible solutions. As described in Chapter 2, the subset of programming choices taken into consideration are the ones concerning messages exchanged, in particular accepted, by application’s Activities.

### **1.4 Related Work**

In this section I present three main relevant research areas in Android security.

- **Permission analysis**

When installing an Android application the user is requested to accept and allow the application to access to user and system resources (personal informations, photo camera, GPS location, ...). This is done presenting to the user a list of all the resources required by the application to work. It has been proved that such choice it is not optimal for two main reasons: users might not have an adequate understanding of both the meaning of the entries in such list and the security issues that accepting a given permission can cause. Then even experienced users were found not to pay the required attention to this screen, mainly because is often long and verbose. Other research areas are interested in analyzing the risks and the conceptual flaws of this permission model.<sup>[3][4]</sup>

Other problems when dealing with Android permission raise because of the high usage of inter application communication. An application that has not declared the usage of the system contacts can use another application, enabled to read user's contacts, as proxy for this information, as long as one is installed on the phone. This means that the permission list that the user need to accept might not be exhaustive.<sup>[5][6]</sup>

- **Automatic malware detection**

Android by default allows to install applications only downloaded from trusted sources (Google Play store). Anyway, users can easily install applications coming from arbitrary sources (even email attachments) just by disabling an option in the OS settings. Unfortunately even applications installed from the Google Play Store are in-

adequately controlled for the presence of malicious code. This has pushed a large part of researches in the Android security world to come out with techniques to automatically detect malicious pieces of code in applications. In this area, which is the broadest in Android security, many approaches have been proposed, from the more formal to the more empirical ones.<sup>[7][8][9][10][11]</sup>

- **General security toolkits** Another broad area of research concerns the study of automated systems to automatically detect vulnerabilities in applications that could be exploited by malicious applications to access user's personal data, fake user's behavior or damage the system itself. This toolkits basically can be used to test applications against a certain subset of vulnerabilities.<sup>[12][13]</sup>

This work can be collocated in this last category.

## 1.5 Thesis Organization

The rest of the thesis is organized as follows. Chapter 2 describes more precisely which set of vulnerabilities this thesis deals with. Chapter 3 contains the core idea behind the analyzer. Chapter 4 is an overview of the tools and the techniques, along with design choices made in order to meet the research goal. Chapter 5 is a description of a real-world example of use of the tool. Chapter 6 contains a discussion of the practical benefits deriving by the usage of the tool and about how such tool can be extended to analyze a broader circle of security implications.

## CHAPTER 2

### PROBLEM DEFINITION

#### 2.1 Overview

In order to define the problem I will adopt a model consisting of two activities: the first, identified as *sender*, will produce as output an Intent carrying a set of messages targeted to another Activity, identified as *receiver*. The *receiver*, after being notified that it was a suitable recipient of the Intent, will extract the information in the messages in order to complete the operation specified by the logic of the Activity itself.

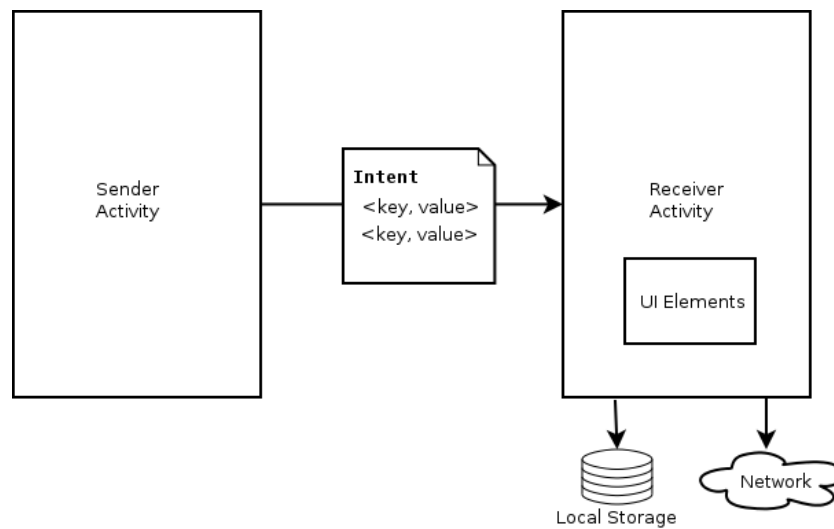


Figure 2: Activity data exchange model

### 2.1.1 Messages as Collections of Parameters

Without loss of generality we can think that an exchanged message consists of a collection of named parameters (*Extras*). The names (keys) uniquely identify a piece of information inside the Intent, therefore the *receiver* usually relies on its prior knowledge about these keys in order to retrieve a particular information. This can be viewed as a protocol that both the *sender* and the *receiver* should implement in order to let the communication succeed.

Given a key, its corresponding payload can have an arbitrary type: the Intent Java API accept all the primitives Java types, but also a generic *Serializable* object. To retrieve these variables, then, the Activity willing to use them, also need to know their exact type. The API provides specific utility methods for each of the primitive types plus a generic *getSerializableExtra(String name)* method that returns an object implementing the *Serializable* interface: the access to the object's informations will be available only after a cast to its original class.

In Table I are listed the main API methods. These functions are also available in their arrayed fashion, allowing extras to carry multiple values under a single key.

The Intent APIs provide reflective interfaces to retrieve all the *Extras* a message includes. The use cases of this approach are however limited mainly to test purposes. It is usually convenient to explicitly name the parameters, providing them an explicit semantic expressed by the name itself.

TABLE I: INTENT API METHODS FOR EXTRA MANIPULATION

Setters	Getters
<i>getBoolean(String key)</i>	<i>putBoolean(String key, boolean value)</i>
<i>getByte(String key)</i>	<i>putByte(String key, byte value)</i>
<i>getChar(String key)</i>	<i>putChar(String key, char value)</i>
<i>getDouble(String key)</i>	<i>putDouble(String key, boolean value)</i>
<i>getFloat(String key)</i>	<i>putFloat(String key, float value)</i>
<i>getInt(String key)</i>	<i>putInt(String key, int value)</i>
<i>getLong(String key)</i>	<i>putLong(String key, long value)</i>
<i>getSerializable(String key)</i>	<i>putSerializable(String key, Serializable value)</i>
<i>getShort(String key)</i>	<i>putShort(String key, Short value)</i>
<i>getString(String key)</i>	<i>putString(String key, String value)</i>

The proposed analysis deals only with primitive types, leaving out the more complex structures such as Objects. In practice, this is not a real limitation, for the reason that strings represent the greatest amount of data exchanged.

### 2.1.2 Activity Lifecycle

Android Activities are managed by the help of a stack structure: the Activity currently running is the one at the top of the stack and it is in a *running state*. When a new Activity is launched the one previously running is moved to either a *paused state* or a *stopped state*.

An Activity becomes paused when the new launched one partially covers it; it instead becomes stopped when it is completely covered. In this case, since the Activity is not visible at all there is no need for it to keep running.

A running garbage collector can ask to both paused and stopped applications to exit their execution, or it can simply kill them.

In Figure 3 is delineated this lifecycle, complete of all the methods that are invoked on the Activity by the system when a status change is requested.

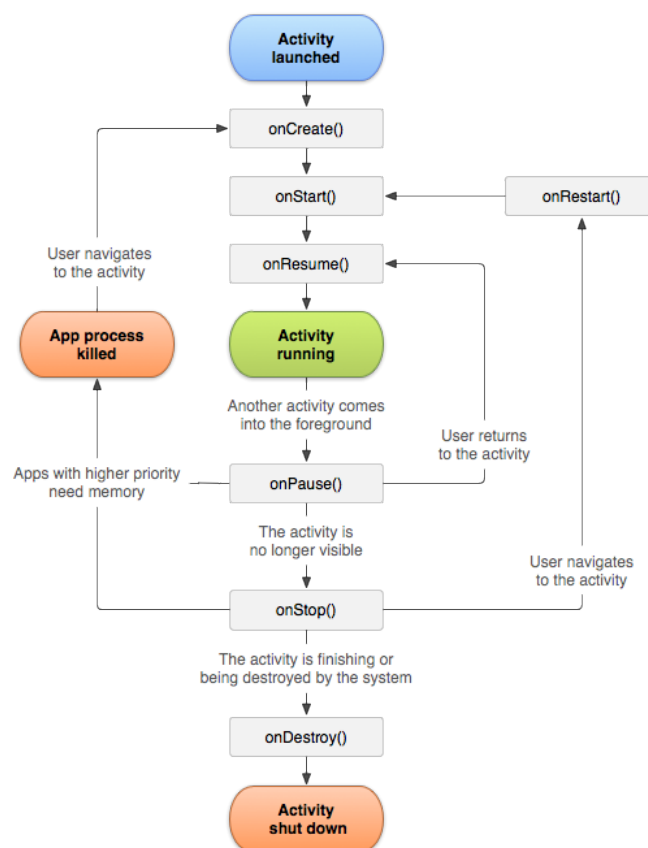


Figure 3: Android Activity Lifecycle Explained. Source: <http://developer.android.com/reference/android/app/Activity.html#ActivityLifecycle>

Whenever there is a match between the Intent recipient and an Activity, this Activity is *always* created and pushed on the top of the stack. Thus the logic for handling the received data has to be encoded starting from the *onCreate()* callback method. The Intent data will also be available after a *onResume()* on a *onRestart()* call since such data will be preserved when the activity is either paused or stopped. Since it is not reasonable for the Activity logic to wait until a stop or a pause request occur to handle the received data, for the following analysis, it will be assumed that *onCreate()* is the single *entry point* for the data and the single point where the operations performed on the data itself start.

### 2.1.3 Activity Accessibility

While same-application Activities can always exchange data, due to application isolation and sandboxing, Activities are not allowed, by default, to receive data by processes not belonging to the same application. This intention has to be explicitly declared in one of the ways listed below in the application manifest.

We can easily divide Activities in two macro groups:

- **Intra Application accessible:** those are processes that respond and start only after receiving commands started from processes inside the same application.
- **Inter Application accessible:** those applications can be reached by Intent started by any other process in the system. Android provides two paradigms that activities must follow in order to be world accessible: *Intent Filter* and *Content Provider*.



The paradigm that *Intent Filters* implement mainly consist in functionality delegation: processes delegate to an (a set of) other process a predefined operation that the processes responding to the Intent promise to accomplish.

Content Providers, instead, as already discussed, are a paradigm for data exchange. Although Content Providers are public by default, they can be kept private (only accessed by the application) setting the corresponding option in the application's manifest.

As specified in the *IPC* section of the "Security Tips" section in the Android developer guide, every Activity should be responsible of the received data and should perform input validation, since Intents and Intent filters cannot be considered security features.<sup>[2]</sup>

## **2.2 Android Root Access**

As consequence of the Android's open-source fashion, many communities working around the project have raised. The work of these groups mainly focuses in the modification of the official project, mainly in term of addition of functionalities and specific settings. One of their claims, is manifested in the will of avoiding the control of the phone by the phone's manufacturer or by Google on the users' devices. They see the impossibility of the processes, other than the system ones, to run with root privilege as a fundamental lack of freedom. Beside this, they perceive the locking, by the manufacturers of the boot loaders as a constriction, since the phone users loose the capability of changing the built-in operative system with a desired one.

They started early, with respect to the Android birth, to produce tools able to “jail-break” (or “root”) the phones (removing the constraints applied by the manufacturers) to let the users install any kind of software on their devices (either trusted or untrusted), having the possibility to escalate their privileges to root.

Understanding the impact of the penetration of such communities in the real phone market is although hard. Unfortunately there not exists an official report on the number of rooted devices, or of devices mounting aftermarket Android versions.

We can anyway deduce that the impact is not marginal by taking a look at the number of downloads that both the most famous versions and their related applications received.

TABLE II: ANDROID ROOT MARKET IMPACT

Name	Application/OS	Downloads (thousands)
Superuser	Application	10,000 - 50,000
Rom Manager	Application	5,000 - 10,000
Titanium Backup Root	Application	5,000 - 10,000
CyanogenMod	OS	4,200 *
Wireless Tether for Root Users	Application	1,000 - 5,000
Root Explorer	Application	500 - 1,000

\* *currently installed*

Data updated on March 9, 2013. Sources: Google Play Store, CyanogenMod Statistics.

In a rooted environment, since every candidate process can obtain root privileges, the security risks for the user increase dramatically, since the application sandboxing model is compromised. A root process, in fact, no longer has to obey at the sand-boxed model. Such process can directly access and modify any local data it wishes, it can send to any other process an arbitrary message and it can launch any kind of command. When sending a message to request an other process intervention, this data sent with root privileges will never be ignored, regardless all the security and isolation policies mentioned in the previous paragraph. As consequence of this, developers cannot simply ignore the existence of rooted devices, but they should build applications in a defensive way. Intuitively they should perform sanity checks on the data received even on Activities which access should not be public by specification.

### **2.3 Preliminary Analysis**

The problem presented in the following sections was first noticed by monitoring inter-Activity Intent payloads exchanges from some popular applications downloaded from the Google Play Store.

This simple monitoring was possible with the help of some instrumented classes in the Android libraries, in particular the ones concerning Activity lifecycle and general Activity management.

#### **2.3.1 Instrumentation Class**

The Android Java Core framework provides utility classes to instrument and monitor Activities lifecycle and its interaction with the system. When the instrumentation is enabled,

the Instrumentation class is automatically instantiated before to run the application code. This class is designed to be used by the code in the application itself, i.e. the monitoring logic has to be implemented inside the application.

Since for a preliminary analysis it may result hard and time consuming to inject code in the applications taken in consideration for the analysis, we adopted a naïve approach. We modified the official Instrumentation class code, in order to make it log for us on a phone directory all the Intent data traffic, regardless what application or Activity is currently running.<sup>1</sup> This was obtained enhancing *execStartActivity()*. The method is called exactly before the Activity is created, and thus, exactly before the *onCreate()* method is called on the Activity itself. In this way we have the guarantee that the Intent cannot receive further manipulations, after we capture it.

It has to be noticed that the folder in which the data is saved, must have world writable permissions. This is because the Instrumentation class code runs in the context of the currently running application, so it will become the application itself in charge of writing in the directory.

The recorded data then can be easily dumped off the phone and analyzed off-line.

---

<sup>1</sup>The experiment was done on a custom Android 4.0.2 build, targeted for the Android Emulator (*full-eng*).  
Instrumentation class can be found under `< aosp_root > /frameworks/base/core/java/android/app/`

### 2.3.2 Manual Testing

Android provides several testing and debugging facilities to automatize the testing process with a batched sequence of commands: in particular, *am* was found very useful to emulate sender Activities behavior. *am* is a shell tool to interact with the Android runtime and it can be exploited to create and send Intent populated with Extra parameters.

```
am [start|startservice] -a <action> -n <component> -e <extra_key> <extra_value>
```

The command specified above, launches a generic component (can be either a Service or an Activity), specified in the *-n* option, requesting it to perform an action (*-a*, typically VIEW), passing to it the set of Extra parameters specified with the *-e* option (there exist several *-e* type-specific options, *String* is default).

This allowed us to manually, but easily reproduce a crafted copy of the collected messages, and see how those changes were affecting the execution of the targeted activity, or the internal state of the whole application.

We were eventually able to change elements in the Activities and to actually push text in the application local storage. This meant that no particular check was performed, but the Activities were blindly accepting input strings. In the following section are described the risks that such programming behavior can bring out.

## 2.4 Threat model

In this section are delineated the attacks and the threats to the final user that could come out from a non-defensive approach when dealing with received Intent payloads.

A malicious message could harm or change in an unexpected way the status of the application if one of the following conditions is satisfied:

- **Exposed Activity:** Activities that have explicitly requested to be exposed, for data or functionality sharing, are, in a sense, world-accessible. Their access, can not of course exclude malicious requesters.
- **Unexposed Activity, Root access:** Under this scenario, even not exposed Activities cannot be considered immune with respect to hostile messages. As discussed before, root applications can overcome the limits imposed by the sandboxing.

In particular, as shown in Figure 2, a malicious message can basically be targeted to one of the following resources:

- **Network:** a malicious message can be forwarded to a server. In this case the attack may not directly include the application, but use its code as a bridge to access and modify information on the server.
- **Local Storage:** the message may include parts able not only to store unwanted information on the application's local storage, but also to corrupt previously existing data.
- **UI Elements:** message parts may be used to compose notes aimed to notify the user of a certain situation. Crafted messages may lead the user to have a wrong perception of the current situation.

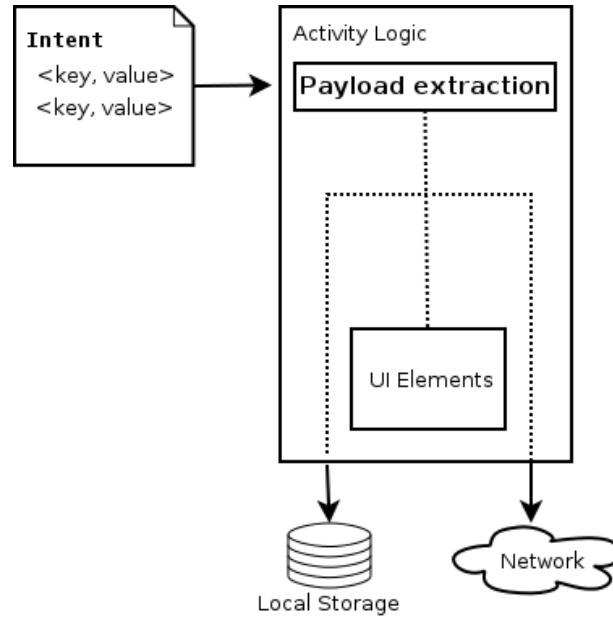


Figure 4: Attack target resources

Intuitively, the resources can be targeted by those kind of attacks, only if the the payload of the Intent is directly used as payload for new piece of information sent to the resource, or if there exist a flow in the code that connects the Intent payload to the resource, and such flow does not include any sanity check neither on the directly involved parameter nor on another related parameter.

#### 2.4.1 Attacker

In this scenario, we can think at an attacker as a normal application, installed on the user's phone, by the user itself, via either the Google Play Store or an another third party source. The application may carry some malicious code along with real functionalities,

used for defacing purposes. The malicious code could remain silent until the user triggers a specific action on the malicious application, believing in the benignity of the used Application.

#### **2.4.2 Victim**

The victim, for this class of attacks, is the final phone user. The user act a fundamental role in this scenario, since he is the one eventually triggering the attack against himself and also that will perceive the changes or the anomalies on its own resources.

Users usually tend to trust applications downloaded from the Google Play Store, because the common sense suggest it to be a “safe” source. In reality, uploaded applications are not exhaustively tested and verified in actual environments by the Google Play Store staff, so there is not an actual guarantee that applications, even if they are distributed by a certified entity, do not embed malicious code fragments.

One may think that malicious applications could be considered suspicious because they may declare unusual or apparently not required permissions. It has been shown that, in practice, the effectiveness of such declarations is pretty low and that users, even if they are actually able to understand them, tend just to ignore the permission screen prompted on application installation.<sup>[4]</sup>

### **2.5 Characterization of the Attacks**

The exploitation of this class of vulnerabilities result in a very broad set of use cases. The attacks can be classified in three categories, accordingly to the resource they target:

- **Server attacks**



- **Database attacks**
- **Phishing attacks**

### **2.5.1 Server Attacks**

The attacks described in this section can be compared to web attacks. In attacks, the attacker makes use of a script or a crafted resource source URL in the page (typically an image) to induce the browser to directly or indirectly send a request to the server. The sent request is usually targeted to a route on the web server that accept GET parameters in input (usually to target of some form in the web application) to change the status of the server itself.

```

```

In this example, if we assume that the goal of the attack is to transfer money from Alice to Bob and the example image tag is somehow rendered by Alice's browser along with all other DOM elements of the Alice bank page, such browser will send the request to the server, believing to retrieve an image. Instead of responding with an image, the server will change its status if no extra check is performed on the logic in charge of serving the request: the attack will succeed.

The attack relies on the fact that since the resource is requested to be loaded in the same context (domain) of the rest of the application, in particular of the attacker target URL. In this scenario the user session identifier for the application will be also sent along with the request produced by the attacker. This implies that if the authorization security

control in the target page only relies on the user session identifier, such page will have no way to distinguish between a request performed in the normal flow and another forged by an attacker.

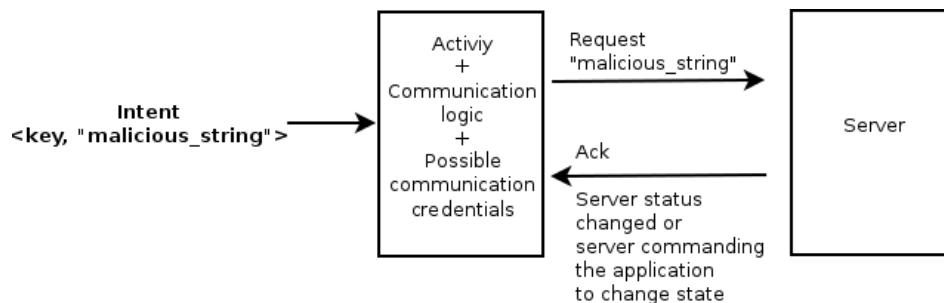


Figure 5: Server attack schema

We can think our Activity attack as a special CSRF attack where a malicious application is sending an Intent message to a target Activity he knows it will perform a request on the server. If this request will be created embedding some of the received Intent extras, an attacker may accurately change the extra values in order to manipulate the state of the server. Again, similarly to CSRF attacks, the request will produce the desired result, because it will be populated by the Activity, with all the session identifiers equivalent that the Activity use to attach when normally requested to perform this action. Also in this

case, if no extra security mechanism is implemented, nor the Activity, nor the server will be able to distinguish between a normal and a malicious request.

The example below shows the Activity equivalent of the previous bank example.

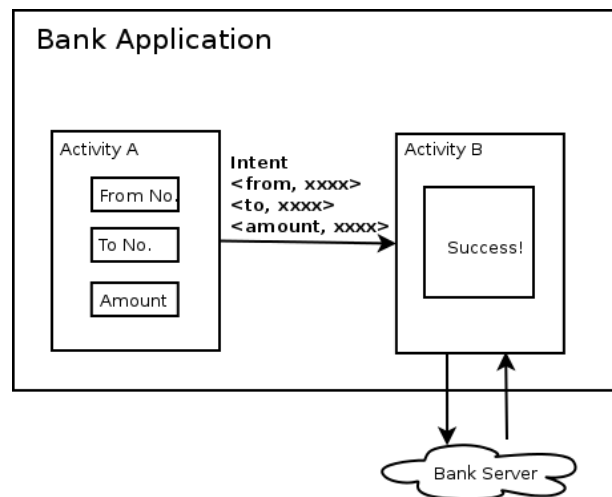


Figure 6: Server attack example

Suppose to have a bank application where the money transaction is implemented by the use of two Activities and they behave in the following way: the first Activity collects recipient and amount data from the users and sends these data to a second Activity via an Intent message. Suppose then that this second Activity (processing Activity) is the

one in charge of sending the transaction to the bank server, showing a load indicator and eventually a success message.

If no extra security mechanism is provided (such as a request validation token), an attacker may send to the processing Activity a message commanding it to perform a transaction of an arbitrary amount to an arbitrary recipient. This transaction will be prepared by the Activity and successfully sent to the bank server. Of course this attack relies on the fact that there is an active user session in the bank application at the moment of the attack.

This class of attacks is anyway harder to perform, since their intrinsic architecture is more convoluted, even if they can directly exploit application local knowledge such as authentication tokens and so on.

### **2.5.2 Database Attacks**

Under the usual assumption that no check is performed on the data extracted from the Intent, and that such data flows to the database, here classical SQL injection attacks can be performed.

Android offers APIs to deal with SQLite databases. The API are designed to strongly recommend the developer to use prepared statement (one for each insert, update, delete operations) so to explicitly prevent most of the SQL injections risks. It anyway offers a method to execute arbitrary SQL code: *execSQL(String sql)*. As shown in Figure 7, a malicious string that flows from an Intent message to the database, without passing through

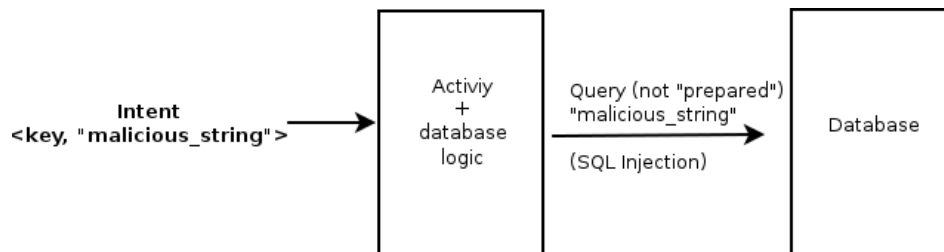


Figure 7: Database attack schema

any prepared statement or extra sanity checks, could eventually damage or compromise user's local data.

I will now show with an example how not even prepared statements are enough to defend the application logic. Suppose an application storing sensitive data that requires a PIN to be accessed.

Suppose that, similarly to the previous example, the “change PIN” feature is implemented by two different Activities, the first requiring the user to insert the PIN and the second performing the update of the PIN on the local database and showing a success dialog. Of course there is no need for this Activity to be exposed to the outer world, since a PIN change is a typical internal operation. Suppose the application is installed on a rooted phone and the attacking application has obtained root rights. Under these assumptions, the attacker may send a message to the second activity that will change the local value of the PIN number into an arbitrary one. The application will then deny further user accesses to the application because she will not have any idea of what the new set PIN is.

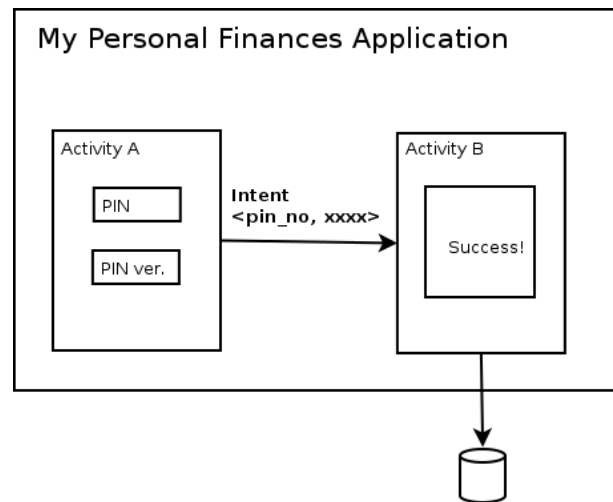


Figure 8: Database attack example

One may say that there is no need to pass through an Activity to access local data, if the intentioned Activity has the rights to do so (root). This is generally true if the application's local data are not encrypted. An attack that flows through the Activity, will easily overcome the encryption, because it will directly exploit the code of the Activity, executed in its specific context, that should have been designed to cope with encryption.

### 2.5.3 Phishing Attacks

This class of attacks can be performed whereas the Activity presents some received payload data to the user.

In this an attacker may use application visible context to let the user believe some convenient (for the attacker) fact, or to give to the user a wrong perception of the status of the application.

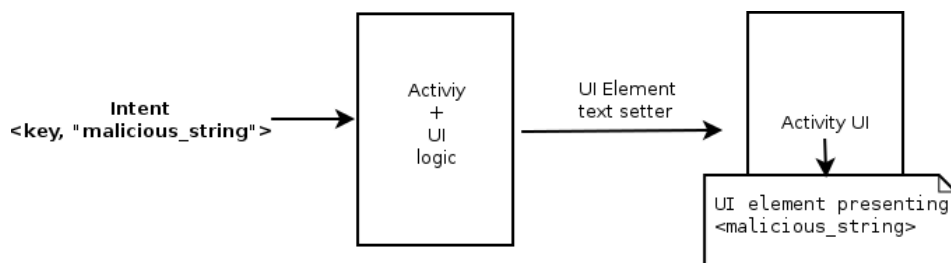


Figure 9: Phishing attack schema

Suppose there is a given application that contains an Activity used to notify the user or to give to her some information about the status of the application itself. Suppose this Activity is just used by the application to display messages that it receives in input with an Intent message, i.e. it has not any kind of logic. An attacker could start this activity feeding it with arbitrary strings that will be prompted to the user.

To make this attack more effective, an attacker application may have been designed to launch a series of target application's Activities that exactly reconstruct and reproduce the normal navigation flow of the application. Doing so the user will be induced to think

that she was the author of the flow of actions leading in this last screen, sometimes in the past.



## CHAPTER 3

### DESIGN

#### 3.1 Overview

As introduced in the previous chapter, Android does not explicitly force developers to design applications in a defensive way. Most of the problems described can be solved just by designing applications in a more conscious way, following the design guidelines indicated in the official developer guide and using Intent extra messages to exchange information only when strictly necessary.

For instance, thinking at the scenario described in Section 2.5.3, a different approach to avoid to transmit text to be displayed into Intent extras exists. We can think at two different use cases where Intents are convenient here. One where there is a set of pre-defined messages that are all eventually prompted in the same Activity, as a general information displaying screen, useful to reuse UI components. The other where the Activity is used to provide notifications to the user, and the text of the notification changes every time because, for example, it contains parts of an e-mail, or the event that required the user to be notified. In both of the cases can be convenient to design lightweight Activities that simply takes an arbitrary set of strings in input and place them on the screen. These Activities can be simply launched and populated through an Intent call.

A more clean and safe solution for the first case could be to directly hard code all the possible messages in the displaying Activity binding them to a meaningful ID. When there is the need to display a specific message other Activities can make use of this ID to command to the displayer which message has to be prompted. In this way we ensure that all the messages displayed to the user can not come from an untrusted source.

Unfortunately, if the messages to be shown are variable by nature, this approach does not apply. In this case the “clean” alternative to the one described above, could be to create a queue of messages to be dispatched in the local storage, that the notifying Activity consumes when notified. Here an Activity willing to use the notifying Activity communicate to the user can store the message in the local database and command the second Activity to consume the last message in the queue, using it to populate the UI. If this part of the storage is reliable (encrypted, and not vulnerable to what described in section 2.5.2), is guaranteed that only notification generated from trusted sources will eventually be displayed.

This is just an example to show that a safe data handling strategy is possible.

### **3.2 Goals of the Analysis**

The goal of this work is to design and provide a tool, that by statically analyzing the code, can tell to the developer, what kind of bad behavior is encoded in the application, and where exactly it occurs, so a responsible programmer can go back and immediately fix it.

The problem can be transposed to a statical code analysis problem, aimed to analyze the control flows that Activity extra parameter values take when received by an Activity. A demonstration of a vulnerability is obtained when there exist a control flow leading a parameter value to a set of API calls labeled as vulnerable. This set of API calls includes requests population (network), database non-prepared statements calls and UI elements text setters. A control flow is took into consideration, only when such flow does not include sanity checks on the parameter value.

The static analysis should then be able to:

- **Detect Starting Points:** detect the code instructions after the parameter values are delivered to the Activity (the Intent management is delegated by the Activity Manager to the matching Activity)
- **Follow variables control flow:** follow and track all the statements that include or use the values for further computation
- **Deal with aliased variables:** follow and track also all the variable that aliases the variables containing the parameter values
- **Deal with branching:** effectively and smartly deal with branching and different control flow
- **Deal with different scopes:** deal with method calls that receive values as parameter, by following the control flow of these parameters

### 3.3 Entry Points Definition

As described in Section 2.1.2, we can consider a single entry point for the Intent to enter the Activity, i.e. the *onCreate()* method. Every time an Activity needs to handle an Intent message, it is newly created and the corresponding creation handler method is invoked by the Activity Manager.

This ensures that defining entry points for the analysis for all the *onCreate()* methods present in the application is an exhaustive assumption.

```
1. public void onCreate(Bundle savedInstanceState) {  
2.     super.onCreate(savedInstanceState);  
3.     String paramValue = getIntent().getStringExtra("A_PARAMETER");  
4.     doSomethingWith(paramValue);  
5. }
```

The variable *paramValue* defined at line 3, is a suitable candidate for the analysis, so the specified *onCreate()* method will be used as entry point.

### 3.4 Data Flow Analysis

In this section are described all the problems the analyzer has to deal with when analyzing the code.

### 3.4.1 Variable Path Following

We are interested in tracking every statement that uses one of the variables labeled as *entry point candidate*. The concept of using a variable, given a statement, can be seen as checking whether a given statement contains that variable on the right hand side of the assignment or not, and if no assignment is included in the statement, check id there is a method call that contains the variable in its argument list.

So we reduce the problem of following the flow paths taken by the data as tracking all the statements that uses the variable containing such data.

TABLE III: EXAMPLE OF RELEVANT STATEMENTS

Statement Type	Statement	Tracked
Assignment	<i>int b = doSomethingWith(a);</i>	Yes
Assignment	<i>int c = a;</i>	Yes
Assignment	<i>int c = a + 7;</i>	Yes
Method Call	<i>doSomethingWith(a);</i>	Yes
For	<i>for (int i = 0; i &lt; a.size(); i ++);</i>	No
If	<i>if (a &gt; 0);</i>	No
Suppose that only variable <i>a</i> is being tracked		

In Table III are listed a set of statements that can be relevant or not to track in the analysis.

In order to be able to communicate to the user which is the vulnerable piece of code, and more precisely, which is the parameter that causes the vulnerability, during the analysis, all the tracked statements must be related to the variable that caused them to be tracked.

After this phase the tool should produce a data structure of the type  $\langle parameter\_variable, [statements] \rangle$  for each parameter that needs to be tracked.

### 3.4.2 Variable Aliasing

Since there is no guarantee of the fact that originally tracked parameters will not be identically assigned to new variables in the code, the analyzer, while executing, must dynamically add to its tracking set also all the variables that aliases the base ones. The algorithm of the analyzer should be general enough to treat generally both base parameters and the ones added during the execution.

In addition, for each aliasing variable, it has to be provided a reference to the original variable. For this reason we introduce a slightly modified version of the previous structure including the reference:  $\langle aliasing\_variable, variable\_ref, [statements] \rangle$

The reconstruction and the union of the statements that either directly or indirectly reference a parameter is left to further steps of the analysis.

### 3.4.3 Inter Procedural Analysis

In order to provide correct and exhaustive results, the analysis has to take care of methods calls and therefore of different variable scopes.

One approach might be to treat function parameters as special case of aliasing variables, where their traceability is limited to a specific call context occurred with a specific argument list. This means that for two different calls of the same method, with two different tracked variables passed, has to produce two completely separated statement lists. Similarly, two different methods that locally share the same variable name, called with the same value, must produce two completely separated sets: no overlap can occur.

To do so we need to augment the previously described structure with an additional information: a method identifier. The resulting structure has this shape:

*< aliasing\_variable, variable\_ref, method\_id, [statements] >.*

The structure is instantiated when the method call occurs binding the argument (*variable\_ref*) with the corresponding parameter (*aliasing\_variable*). It has to be noticed that this approach is general enough to deal with nested method calls. The binding with the original parameter, when it is passed through multiple method calls can be obtained by navigating the *variable\_ref* chain until a non-aliased variable is encountered.

### 3.5 Vulnerability Testing

As last step of the analysis, the remaining thing that has to be done is to check the statement lists of all the tracked variables against a *vulnerable list*. This list includes the methods signatures of all the API calls considered dangerous for our purposes.

Whereas a match is found in the list of statements corresponding to a parameter, that statement is marked as vulnerable and as consequence a warning presenting both the statement and the parameter is generated.

### 3.6 Example

Below is presented an example of the analysis performed on a small piece of code.

```

1. public void onCreate(Bundle savedInstanceState) {
2.     super.onCreate(savedInstanceState);
3.     String paramValue = getIntent().getStringExtra("A_PARAMETER");
4.     doSomethingWith(paramValue);
5. }
6.
7. public void doSomethingWith(String value) {
8.     doSomethingElse(String value);
9. }
10.
11. public void doSomethingElse(String v) {
12.     doSomethingBad(v);
13. }

```

The analysis, after line 3, will have a list of solutions containing *paramValue* and an empty parameter statement list.

When the analyzer encounter line 4 the solution set will contain two elements, shown in Table IV:

Something similar will happen encountering line 8, in this case the binding is done between variables *value* and *v*.



TABLE IV: SOLUTIONS AFTER LINE 4

<code>&lt;paramValue, [doSomethingWith(paramValue);]&gt;</code> <code>&lt;value, @paramValue, []&gt;</code>
--

In Table V are listed the results obtained at the end of the analysis.

TABLE V: RESULTS AT THE END OF THE ANALYSIS

<code>&lt;paramValue, [doSomethingWith(paramValue);]&gt;</code> <code>&lt;value, @paramValue, [doSomethingElse(value);]&gt;</code> <code>&lt;v, @value, [doSomethingBad(v);]&gt;</code>
---

In the end, supposing that *doSomethingBad()* is a method contained in the vulnerable method list, such statement will be marked, so will be *v*. The marking will be propagated through *value* and eventually to *paramValue* which is a *base* parameter value.

A report will be eventually produced, carrying *A\_PARAMETER* as a vulnerable parameter and that the vulnerable call for such parameter occurred at line 12.

## CHAPTER 4

### IMPLEMENTATION

#### 4.1 Overview

In this Chapter are described the tools and the techniques adopted to develop and implement the tool.

The tool is designed to be simple to use. It takes as input an Android application package (APK file) and passing through various analysis phases it produces as output security warnings, aimed to notify the user that a suspicious behavior has been encountered in the code. In addition the tool produces a set of example commands that can run on on the phone in order to effectively demonstrate the weakness in the code.

The code contained in the package, in form of Dalvik executable bytecode (dex), is decompiled and transformed into an higher level intermediate representation. This representation can be placed in between the bytecode and the actual Java since it is more human readable than the bytecode, but less complex and structured than the actual Java code.

This intermediate code, passes through a preliminary analysis aimed to detect the entry points, and collect informations used for further analysis. This step also includes a partial computation of the example commands.

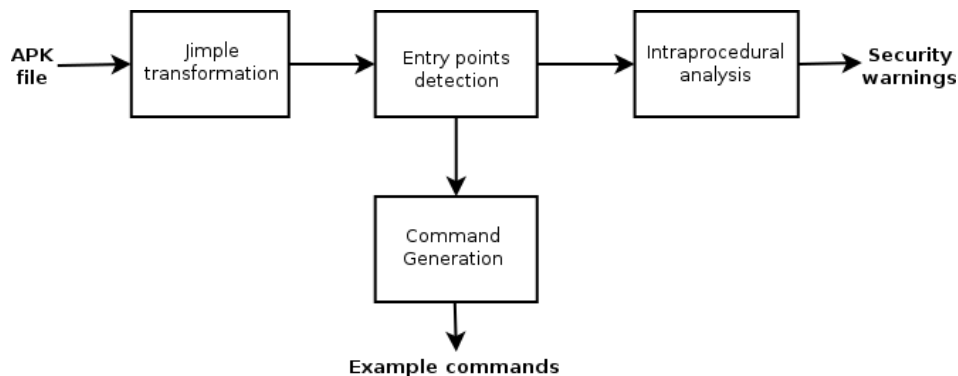


Figure 10: Analysis workflow

The code is then sent to the last step of the analysis, where are extracted the sequence of operations that have a direct or transitive relation with the extracted entry points. Eventually, these sequences are checked against a list of potentially dangerous operations. Every time a match between an element in the sequence and an element in the list is found, a report to the user is produced. For this analysis, the entry points are the values accepted as input by the activities and the list contains a set of methods concerning network request creation, database storage and UI presentation.

The tool is written in Java, and it makes use of both Soot<sup>1</sup> and Heros<sup>2</sup> frameworks to transform and analyze the code. The first is a well consolidated framework and the second

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<sup>1</sup><http://www.sable.mcgill.ca/soot/>

<sup>2</sup><http://sable.github.io/heros/>

was recently developed in order to complete some of the lacks of Soot. They are open source projects distributed under GNU Lesser General Public Licence (LGPL).

## 4.2 The Soot Framework

Soot was first presented between years 1999 and 2000 by members of Sable Research Group at McGill University as master thesis by Vallée-Rai<sup>[14]</sup> and with the more famous paper by the whole research group<sup>[15]</sup>.

Soot is a Java static analyzer, that enables manipulation and optimization of the Java bytecode. The bytecode is transformed in a series of four intermediate representations designed for different objectives. These representations can be sorted from the ones closer to the bytecode to the furthest:

- **Baf** is a streamlined representation of the bytecode
- **Jimple** is a 3-addressed readable representation
- **Shimple** is a version of Jimple in *static single assignment form*
- **Grimp** is an aggregated version of Jimple

One of the main characteristic of Soot is its modularity. Soot is designed to be modular and highly adaptable to solve the set of problems it is aimed to. It relies on a singleton object, the Scene (accessible via *Scene.v()*), that is initially populated when the code is given as input, after being parsed. The Scene offers a large set of APIs to programmatically access classes and methods of the populated objects. A large set of tools is provided to analyze the Scene. Soot offers pre-implemented algorithms to perform call graph analysis,

domination analysis or context-sensitive point-to point analysis. Soot also comes with a package manager that can be used to handle a chain of modules (as phases) which the code is eventually sent to. This allows to attach to the execution chain, external or custom transformations of analyzers.

Soot can run either as command line tool or as embedded Java library to satisfy needs that require more complex customizations.

#### **4.2.1 Jimple Intermediate Representation**

For the purposes of our analysis we adopted Jimple as intermediated representation. This choice was not driven by a special need, but we made it because of the wide support that this representation has obtained. Jimple has become the most popular intermediate representation and it can be considered as a kind of standard when performing static code analysis and optimization.

Here below is presented an example of method in its Jimple representation:

```

protected void onCreate()
{
    [...]

    $z1 == 0 goto label4;

    $r4 = $r0.<com.dropbox.client2.android.AuthActivity: java.lang.String consumerKey>;

    label4:

        virtualinvoke $r3.<android.content.Intent: android.content.Intent
            putExtra(java.lang.String,java.lang.String)>("CONSUMER_KEY", $r4);

    [...]
}

```

Jimple is a 3-addressed representation. It consists of a reduced set of statements (12), that limit the complexity of the analysis without reducing its expressibility in terms of readability. It also completely masks the underlining stack representation (as in the bytecode) by the use of local variables so not to cope with location of non-explicit variables in the stack. As can be noticed in the example above, it preserves the original Java types, complete with their namespace.

#### **4.2.2 Soot with Dalvik Bytecode**

It has recently been announced the integration in Soot of Dexpler<sup>1[16]</sup>, adding to Soot the ability to transform the Dalvik bytecode into a Jimple representation and vice-versa.

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<sup>1</sup>Instrumenting Android Apps with Soot - <http://www.bodden.de/2013/01/08/soot-android-instrumentation>

This transformation may seem simple to perform, since Dalvik bytecode is register based, and there is a remarkable similarity between Dalvik registers and Jimple local variables. However, registers and constants in Dalvik are untyped, and their types has to be computed in order to complete the Jimple transformation (as seen before Jimple variables preserves the original Java types).

Thank to this addition we were able to analyze the code without any further decompilation. This of course highly simplified the whole process. Unfortunately Dexpler has been pushed only to the development branch of Soot, so it is only included in the nightly build.

#### **4.2.3 Heros Framework and IFDS**

Unfortunately Soot does not provide a precise method for inter-procedural analysis. To overcome this lack, Eric Bodden, one of the Soot's current main contributors, has designed Heros<sup>[17]</sup>.

Heros does not rely neither on Soot nor on any kind of Soot's intermediate representation to perform the analysis. It is also language-agnostic, in the sense that it can be used to analyze any language. It is written in Java and it accepts generics types representing statements, methods and data facts.

Heros is an interprocedural, finite, distributive, subset/interprocedural distributive environment (IFDS/IDE) general purpose solver. IFDS/IDE frameworks are class of algorithms to solve in polynomial time inter-procedural finite data-flow analysis.

IFDS is a general algorithm that allow to reduce a inter-procedural data-flow analysis into a graph reachability problem.<sup>[18]</sup> It solves problems in which flow functions can

be expressed as distributive functions. Many data-flow problems can be defined with distributive flow functions, and thus be solved with the IFDS/IDE framework such as defining truly-live variables, variables typestate and information-flow.

The IFDS algorithm extracts from the program's inter-procedural control-flow graph a, so called, "exploded super graph". In this graph, a node  $(s, d)$  is reachable from a selected

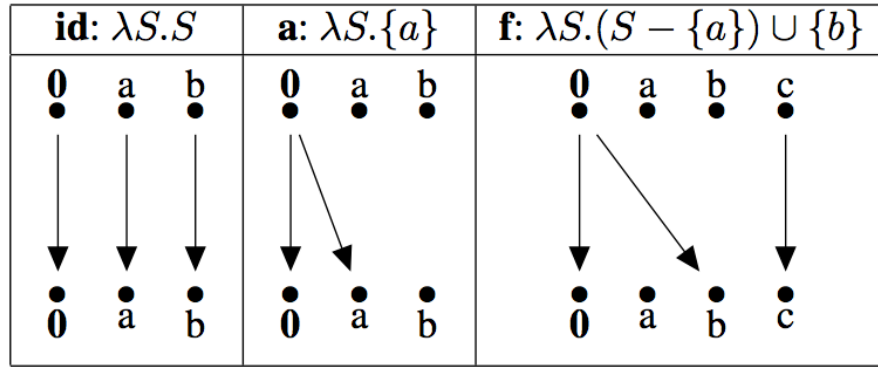


Figure 11: IFDS flow functions, reproduced from<sup>[18]</sup>

start node  $(s_0, 0)$  if and only if the data-flow fact  $d$  holds at  $s$ , where  $s$  is a program state-ments. As "fact" is intended any logical statement, such as variable  $x$  has been declared, initialized or has passed through a series of defined computations. The algorithm makes use of data-flow functions to connect different nodes. As sketched in Figure 11 the function **id** is the identity function, mapping each data-flow fact before a statement into itself.



The value **0** represents an empty fact that is always valid. This **0** value is used to generate data-flow facts unconditionally. Function **a** adds *a* to the set of facts by connecting **0** to *a*, and at the same time removes *b* and other facts not explicitly connected. Function **f** adds *b*, removes *a* and leaves *c* untouched.

Heros solves arbitrary IFDS problems defined by implementing the `IFDSTabulationProblem<N,D,M>` interface, where *N* are node types (statements), *D* are data-fact types and *M* are method types. By implementing this interface the programmer has to define the chosen value for zero data-facts, provide a set of entry points for the analysis and define the behavior of the flow functions. Defining the flow functions means to implement four callback methods, one for each different inter-procedural behavior:

- `getNormalFlowFunction(N curr, N succ)`
- `getCallFlowFunction(N callStmt , M destinationMethod)`
- `getReturnFlowFunction(N callSite , M calleeMethod , N exitStmt , N returnSite)`
- `getCallToReturnFlowFunction(N callSite , N returnSite)`

For each of these functions (each of them representing a generic flow function) the programmer has to implement a inner callback method that will be called for each data-fact present at a given computation moment: `Set<D> computeTargets(D source)`. In this way one or more facts can be generated specifically from a specific fact.

As can be noticed Heros is a precise and close implementation of the originally propose IFDS algorithm.

### 4.3 Entry Points Detection and Command Generation

IFDS algorithm has a worst-case complexity of  $O(N^3)$  where  $N$  is the number of instructions in the analyzed domain. It is not reasonable to perform the analysis with data facts produced from any point in the program. To prevent this we need to collect a subset of methods (entry points) from which the analysis can begin.

To do so, a full scan of the Jimple representation of the program is performed. In this scan we are interested in detecting all the instructions that affect Intents extras, e.g. that both set or retrieve them. Since the set of API calls that Android provides to set and retrieve the extra parameters contained in the Intent message is quite limited and constant between different Android versions, the list of the signatures of this calls is explicitly declared. Whereas one these statements is interesting in the context of our search a data structure is populated wrapping together all the extras that are enclosed in the same Intent. To this data structure is also added other information that is not relevant to the real analysis but is instead necessary to generate the example commands, like class and package names.

In the application there may exists Intent messages targeted to other application's Activities (for example more than one application are included in the scope of the analysis), the tool also produces commands for Intent messages sent, but not received by the same application, as well as received, but never sent within the application. For this reason in this step is collected information both when a creation method callback is encountered

(*onCreate()*) and when a request to start a new Activity is performed. Of course this causes duplicates that are removed afterwards.

As entry points for the real inter-procedural analysis, since we are tracking the programming behavior when receiving data, only the structures populated from receiving methods are considered.

#### **4.4 Inter-procedural analysis**

In this section is presented how the IFDS algorithm is exploited to perform the data flow analysis described in Section 3.4.

IFDS algorithm is well suitable to our analysis objectives, in fact this specific analysis is an instance of an information-flow problem easily describable as an IFDS Tabulation problem.

For our instance of the IFDS problem we use a simple data structure to represent data facts, similar to the one described in Section 3.4.3:

```

        <Value trackedVariable,
            Value baseVariable,
            SootMethod contextMethod,
List<Stmt> trackedStatements>

```

where *trackedVariable* is the variable to which the list of tracked statements corresponds, *baseVariable* is the reference to an aliased variable if any, null otherwise. *contextMethod* is the scope of validity of the variable and *trackedStatements* is the list of all the statements in which *trackedVariable* appears.

Value is a Soot interface that classes can implement to represent a variable, SootMethod is an utility class to access methods information and Stmt is an interface that represents general statements.

#### 4.4.1 IFDS Problem

The problem is expressed as an instance of an Heros problem by implementing the interfaces described in Section 4.2.3. Below is described the logic encoded in the flow functions for each of the normal flow, call flow, return flow and call to return flow callbacks.

As mentioned previously, as soon as the analysis starts is available the list of entry points complete with all the parameters treated in such entry points, namely *base parameters*.

- **Normal flow function** This callback is called when the statement does not include a method call or a return instruction.

When this callback is called on behalf of a statement containing a base parameter reference, if the fact set is empty or it does not contain a fact yet having such base parameter as trackedVariable a new fact is added with the base parameter variable as trackedVariable and a new list of statements is initialized with the current statement.

If the current statement is an assignment and one of the trackedVariable contained in the fact set is present in the right hand side of the assignment a new fact is generated. This fact will contain as trackedVariable the variable in the left hand side and

the previous fact `trackedVariable` as `baseVariable`. Then the current statement is added to the new fact's statement list.

Eventually, if a statement simply uses a variable contained in the `trackedVariable` field of a fact, such statement is added to the list, otherwise the previous facts are simply propagated.

- **Call flow function** This callback is called when a statements include a method invocation.

If the fact set is empty is done something similar to what described for the normal flow callback, i.e. a new fact is generated if the current statement is an assignment that contains on its left hand side a variable containing a base value. Similarly, when the invocation contains as parameter a variable present in the `trackedVariable` field of a fact, if the returned value of the method is assigned to a new variable, a referencing fact is created containing the current statement in the statement list.

Also, whereas a variable in the fact list is passed a parameter, a new fact is generated with `trackedVariable` equal to the local variable, as `baseVariable` equal to the passed parameter and the statement list with the current statement added. In this way is explicitly created a parameter-argument binding for all the method invocations.

The fact list is killed in all the other cases so to avoid to analyze method not relevant in our analysis domain.

- **Return flow function**

Since we are not propagating facts from the body to the method to the one enclosing it when the end of the body is reached, we simply kill all the paths passing by this callback.

- **Call to return function**

We are not interested in propagating back facts binding the local returned variable to an external assignments, since we explicitly binding local and external scopes. This solutions is more robust since it allows to track internal operations performed on non primitive types (that are passed by reference). The flow function for this call back is simply an *identity function* that simply propagates all the facts valid so far.

This analysis will produce a set of all and only interesting variables in the context of the analysis, along with a list of all the statements that used them, or affected them for some reason.

#### **4.4.2 Vulnerability check**

At this point what remains to do is simply to query the IFDS facts for each captured *onCreate()* method (entry points). The complete IFDS facts can be considered the ones corresponding to the last statement for each entry point method.

The list of facts can be used to reconstruct the variable dependencies (aliasing) in order to correlate all the statements to the variables enclosing the base parameter values and build a new list containing only base parameters in the `trackedVariable` field.

Then each of the entries in the statement lists is checked against a list of methods statements considered vulnerable. Every time a match is encountered a security warning is produced and outputted.

## CHAPTER 5

### PROOF OF CONCEPT

#### 5.1 Experimental Setup

In order to demonstrate the effectiveness of our method we choose a set of popular applications from the Google Play Store. We downloaded a sample consisting of 30 middle size applications. For middle size we mean applications with a limited, but significant, number of Activities (8-15) and Services (1-3). This choice was driven by the substantial execution time that the analysis takes. The IFDS solver takes between 2 and 9 minutes to complete the analysis of a single Activity. The variance in this time strongly depends on the number of methods present in the Activity, along with their complexity.

#### 5.2 Results

In Table VI are present the number of paths the tool detected, divided into three sets. These three sets corresponds to the three set of vulnerabilities described in Section 2.4.

Below are listed some remarkable vulnerabilities which effectiveness have been demonstrated by manually creating an exploit that triggers them:

- **Mint** let an attacker load an arbitrary web page in the visual context of the application. Since this application deals with user's personal finance reports it is easy to imagine how an attacker could exploit this capability.



TABLE VI: EXPERIMENTAL ANALYSIS RESULTS

Application Name	Paths to Network	Paths to Database	Paths to UI
Airbnb	0	0	5
Airfrance	0	0	0
Blink	0	0	0
Booking	0	0	4
Craiglist	0	0	1
EF File Manager	0	0	0
Evernote	0	0	1
Expedia	0	0	2
Fancy	0	0	2
FriendCaster	0	0	0
GoChat	0	0	4
Hike	0	1	2
IM+	0	0	2
Imo	0	0	1
Mediolanum	0	0	0
Mint	1	0	1
OpenTable	0	0	1
Poste Italiane	0	0	5
Postepay	0	0	9
Readability	0	0	0
RocketTalk	1	0	8
Seesmic	0	0	1
Skype	0	0	0
Skyscanner	0	0	0
Snapchat	0	0	2
Swissquote	0	0	2
TripIt	0	0	0
Twitter	5	1	10
Wall Street Journal	0	0	0
Waze	0	0	0

- **Poste Italiane/Postepay**: these two applications let an attacker communicate any kind of message to the application user through the applications' modal alert screen. An user may be deceived and induced to perform some dangerous action on its debit card account.
- **Airbnb** let open the modification of the house rules and the FAQ screen.
- in **RocketTalk**, an attacker may specify a chat room (JSON resource) which URL could not belong to the RocketTalk default domain. This fact can be exploited by an attacker to actually manipulate user's chat history.

During the analysis was also found a noteworthy defense mechanism implemented by GOChat. This simple chat application exchanges verification codes for inter-Activity communication. This defense method exploits the Applications shared memory space (shared among all the Activities) to store a token generated from the Intent sender. The Intent receiver then matches the token received in the Intent payload with the one stored in the application shared memory. Every communication request without a valid token will then be discarded.

This simple approach was found to be very effective. In fact we were not able to manually perform any kind of operation on Activities protected by this mechanism. Of course this approach cannot be exploited when a given Activity or Service has to be world accessible by design.

### 5.3 Paths Distribution

As can be noticed in Figure 12 the number of UI paths detected heavily dominates the number of paths in the other two classes. Intuitively we can see the cardinality of these three sets decreasing with the increasing complexity of the threat model.

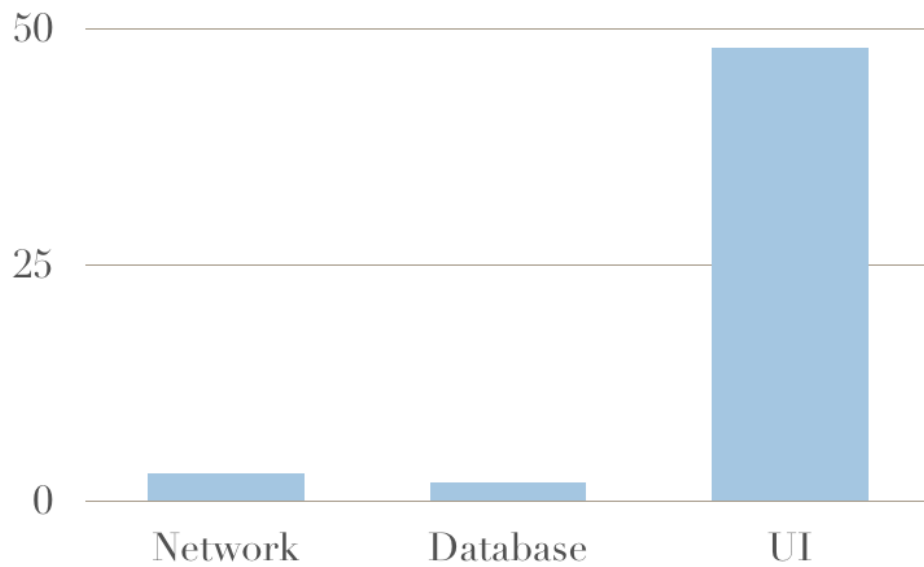


Figure 12: Path distribution histogram

As can be intuitively deduced from an high level reasoning about the use cases and the underlining architectures that let these classes of vulnerability raise, network and database paths are less likely to appear.

To support this thought, we can also rank the three vulnerability classes in order of severity: network vulnerabilities are the most severe since they can impact remote user resources (maybe locally synchronized on many user devices). Then database set that affect the local status of the application and eventually the phishing set which (in theory) should only affect user's current session.

## CHAPTER 6

### CONCLUSIONS AND FUTURE WORK

#### 6.1 Conclusions

To conclude, the tool is actually able to detect paths on real applications and it does not suffer of false-negatives: this evidence was demonstrated by a manual validation of each of the collected results.

Unfortunately since the tool is not able to cope with application semantic (common trough this class of approaches), it suffers of false-positives. For example, just by looking at the paths it can not be determined if a phishing attach can be considered effective: we can not distinguish between slight modification in the UI (button label changing) and considerable modification that can actually deceive an user. In Section 6.2 is described an evolution of the tool that could help to solve this problem.

The tool could be confidently used in real world development environments to test application's message passing implementation against the tree class of vulnerabilities discussed in this thesis. Of course the results of the tools are indications that should no be blindly accepted.

#### 6.2 Future Work

One of the main lacks of this tool is a complete dynamic test suite that can demonstrate the severity of found vulnerabilities. This problem is, unfortunately, hard, because the anal-

ysis includes a wide set of Android system features, namely interprocess communication, network communication, databases and UI elements.

The only effective way to automatically prove the severity of a given vulnerability is to test it into the application execution context. This requires the ability to instrument the applications at run time, by artificially triggering events that lead the application in the vulnerable state. To have a solid feedback is also needed to monitor the effective changes that occur in the resources, and to bind them to the event that provoked them.

Android debugging tools may not be enough for this purposes due to their incapacity to explicitly track cause-effect events. In addition debugging tools does not provide mechanisms to analyze encrypted network traffic or encrypted data storage. Of course a exhaustive testing can be performed only by having clear access to all the resources of the system.

A solution to this impossibility could be to create a modified build where informations are captured before being encrypted and (in case of the network), leaving the system and responses are captured after entering the system and after being decrypted. This, although, requires a deep knowledge of the Android system, because this approach requires to instrument all the system libraries such as the Activity Manager, the Apache HTTP Library included in Android, the SQLite database drivers and the component rendering library.

Given this omni-comprehensive environment is then possible to perform an active and automatic testing of the severity of the vulnerabilities.

A tool like the one described above could be considered a comprehensive testing framework for Android applications.

## **APPENDICES**



## Appendix A

### IFDS IMPLEMENTATION

---

```
1
2 public class IFDSFollowFlow
3     extends DefaultJimpleIFDSTabulationProblem<IFDSFact, InterproceduralCFG<Unit, SootMethod>> {
4
5     private final Set<Unit> initialSeeds;
6     private final Set<Value> baseValues;
7     private final SootMethod baseContext;
8
9     public IFDSFollowFlow(InterproceduralCFG<Unit, SootMethod> icfg, AbstractTrappedAction receiver) {
10         super(icfg);
11         Set<Unit> seeds = new HashSet<Unit>();
12         baseValues = new HashSet<Value>();
13         baseContext = Scene.v().getMethod(receiver.getMethodSignature());
14         seeds.add(baseContext.getActiveBody().getUnits().getFirst());
15         baseValues.addAll(receiver.getAllValues());
16         this.initialSeeds = seeds;
17     }
18
19     private boolean valueInUseBoxes(Value val, Stmt statement) {
20         for (ValueBox dBox : statement.getUseBoxes()) {
```

## Appendix A (Continued)

```

21     if (dBox.getValue().equivTo(val)
22         && interproceduralCFG().getMethodOf(statement).equals(baseContext)) return true;
23     }
24     return false;
25 }
26
27 @Override
28 protected FlowFunctions<Unit, IFDSFact, SootMethod> createFlowFunctionsFactory() {
29     return new FlowFunctions<Unit, IFDSFact, SootMethod>() {
30
31         @Override
32         public FlowFunction<IFDSFact> getNormalFlowFunction(Unit curr, Unit succ) {
33             if (interproceduralCFG().isStartPoint(curr)
34                 && interproceduralCFG().getMethodOf(curr).equals(baseContext)) {
35                 return new FlowFunction<IFDSFact>() {
36
37                     @Override
38                     public Set<IFDSFact> computeTargets(IFDSFact source) {
39                         if (source == zeroValue()) {
40                             HashSet<IFDSFact> res = new HashSet<IFDSFact>();
41                             for (Value v : baseValues) {
42                                 IFDSFact fact = new IFDSFact(v, baseContext);
43                                 res.add(fact);

```

## Appendix A (Continued)

```

44         }
45         return res;
46     } else {
47         return Collections.emptySet();
48     }
49 }
50 };
51 }
52
53 if (curr instanceof DefinitionStmt) {
54     final DefinitionStmt assignment = (DefinitionStmt) curr;
55     return new FlowFunction<IFDSFact>() {
56         @Override
57         public Set<IFDSFact> computeTargets(IFDSFact source) {
58             // facts have already been initialized
59             if (source != zeroValue()) {
60                 // source base value is assigned
61                 if (source.getValue().equals(assignment.getRightOp())
62                     && interproceduralCFG().getMethodOf(assignment).equals(
63                     source.getContextMethod())) {
64
65                     source.addStatement(assignment);
66                     source.addAlias(assignment.getLeftOp(),

```

## Appendix A (Continued)

```

67         interproceduralCFG().getMethodOf(assignment));
68     return Collections.singleton(source);
69 }
70 // source alias is assigned
71 if (source.hasAlias(assignment.getRightOp(),
72     interproceduralCFG().getMethodOf(assignment))) {
73     source.addAlias(assignment.getLeftOp(),
74         interproceduralCFG().getMethodOf(assignment));
75     source.addStatement(assignment);
76     return Collections.singleton(source);
77 }
78
79 }
80 return Collections.singleton(source);
81 }
82 };
83 }
84
85 return Identity.v();
86
87 }
88
89 @Override

```

## Appendix A (Continued)

```

90  public FlowFunction<IFDSFact> getCallFlowFunction(final Unit callStmt,
91      final SootMethod destMethod) {
92      if (interproceduralCFG().isStartPoint(callStmt)
93          && interproceduralCFG().getMethodOf(callStmt).equals(baseContext)) {
94      return new FlowFunction<IFDSFact>() {
95
96          @Override
97      public Set<IFDSFact> computeTargets(IFDSFact source) {
98          if (source == zeroValue()) {
99              HashSet<IFDSFact> res = new HashSet<IFDSFact>();
100              Set<Stmt> statements = new HashSet<Stmt>();
101              for (Value v : baseValues) {
102                  IFDSFact fact = new IFDSFact(v, baseContext);
103                  res.add(fact);
104              }
105              return res;
106          } else {
107              return Collections.emptySet();
108          }
109      }
110      };
111  }
112  final Stmt stmt = (Stmt) callStmt;

```

## Appendix A (Continued)

```

113     final InvokeExpr invokeExpr = stmt.getInvokeExpr();
114     final List<Value> args = invokeExpr.getArgs();
115     final List<Value> localArguments = new ArrayList<Value>(args.size());
116     for (Value value : args) {
117         if (value instanceof Value)
118             localArguments.add(value);
119         else
120             localArguments.add(null);
121     }
122
123     return new FlowFunction<IFDSFact>() {
124
125         @Override
126         public Set<IFDSFact> computeTargets(IFDSFact source) {
127             if (source == zeroValue()) return Collections.singleton(source);
128             if (localArguments.contains(source.getValue())) {
129
130                 int paramIndex = args.indexOf(source.getValue());
131                 source
132                     .addAlias(
133                         new EquivalentValue(Jimple.v().newParameterRef(
134                             destMethod.getParameterType(paramIndex), paramIndex)),
135                         invokeExpr.getMethod());

```

## Appendix A (Continued)

```

136     source.addStatement(stmt);
137
138     source
139         .addAlias(
140             new EquivalentValue(jimple.v().newParameterRef(
141                 destMethod.getParameterType(paramIndex), paramIndex)),
142                 invokeExpr.getMethod());
143
144     if (callStmt instanceof DefinitionStmt) {
145         DefinitionStmt defStmt = (DefinitionStmt) callStmt;
146         if (defStmt.getLeftOp().getType().toString().equals("java.lang.String")) {
147             source.addAlias(defStmt.getLeftOp(), baseContext);
148         }
149     }
150
151     return Collections.singleton(source);
152 }
153
154 SootMethod contextMethod = interproceduralCFG().getMethodOf(callStmt);
155
156 Value aliasedArg = getValueFromFact(source, contextMethod, localArguments);
157
158 if (aliasedArg != null) {
159     source.addAlias(aliasedArg, invokeExpr.getMethod());
160
161     source.addStatement(stmt);
162
163     if (callStmt instanceof DefinitionStmt) {
164         DefinitionStmt defStmt = (DefinitionStmt) callStmt;
165         if (defStmt.getLeftOp().getType().toString().equals("java.lang.String")) {
166             source.addAlias(defStmt.getLeftOp(), contextMethod);

```

## Appendix A (Continued)

```

159         }
160     }
161     return Collections.singleton(source);
162 }
163 // do not propagate through non-interesting functions
164 return Collections.emptySet();
165 }
166 };
167 }
168
169 @Override
170 public FlowFunction<IFDSFact> getCallToReturnFlowFunction(Unit arg0, Unit arg1) {
171     return Identity.v();
172 }
173
174
175 @Override
176 public FlowFunction<IFDSFact> getReturnFlowFunction(Unit arg0, SootMethod arg1, Unit arg2,
177     Unit arg3) {
178     // no need to propagate local fact
179     return KillAll.v();
180 }
181 };

```



**Appendix A (Continued)**

```
182     }  
183  
184     @Override  
185     public Set<Unit> initialSeeds() {  
186         return initialSeeds;  
187     }  
188  
189     @Override  
190     protected IFDSFact createZeroValue() {  
191         return new IFDSFact(new JimpleLocal("<<zero>>", NullType.v()), baseContext);  
192     }  
193  
194 }
```

---

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