Good Intentions

Intent-based Vulnerabilities on the Android Platform

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ABSTRACT

In this paper we intend to investigate Intent-based attack surfaces on the Android platform. We address exploits in two ways, focusing on both detection and prevention. First, we implemented a static analysis tool which reports vulnerabilities in an input file. Secondly, we implemented an Android library which provides a mechanism for restricting the origin of Intents to trusted applications.

1. BACKGROUND

Intents allow for inter and intra process communication between Android applications. In the this section we discuss the various classes of Intent exploits. Hijacking attacks intercept Intents and launch malicious components. Spoofing attacks control applications that are meant to be hidden from other applications, allowing an attacker to use the priviledges associated with the application.

Activity Hijacking.

Activity Hijacking happens when an Intent is sent out implicitly and a malicious attacker happens to filter for that Intent. For example, in an application where a user searches for a product on Amazon, and the application opens up the Amazon search results in a browser, the hijacker will intercept the URL before passing the Intent to the real browser. The attacker can now track user activity and any data associated with the URL. Another form of attack is when an application imitates the UI and name of a trusted application. Android presents the user a choice of what application to use. Once the user accidentally chooses the malicious app, the attacker is now in control of all the data being sent through Intents.

Service Hijacking.

Service hijacking attacks have the potential to be especially problematic because services are run in the background, so the user will have no idea that anything is wrong. They are much more difficult to pull off than other types of hijacking attacks, but the result can be worse. This is because when multiple services can handle an Intent the system resolves the destination not by prompting the user, but rather based on which app was installed first. However, it is still possible for an attacker to get a malicious app onto the phone before the legitimate app, in which case it would intercept any and all relevant Intents and could access data, spoof results, and any other actions the original developer did not intend.

Broadcast Hijacking.

Broadcasted Intents can easily be captured by malicious application/component when the right precautions are not made. Specifically, Android Broadcasts that do not require a Receiver signature or those that fail to set the Receiver priority in the manifest can easily be manipulated by malicious software. Broadcast Hijacking attacks can range from a simple denial of service to a more serious case of data theft.

Activity Intent Spoofing.

When an application leaves its activities public or exported, it is then open to accept Intents from outside the application. This leads to attackers being able to send malformed data or request to an Activity. Depending on the tasks that an Activity performs, the attacker can make an app behave erroneously. The problem here is that the receiver of the Intent has no way of verifying if the Intent came from a trusted source.

Android Service Intent Spoofing.

Like spoofing activities, a service that is exported or left public can be manipulated or called by an outside application. Malicious components can bind to a service by sending an implicit Intent and exploit all its capabilities. Additionally, malicious information can be fed into the service that may cause it to die or behave unexpectedly.

Broadcast Intent Spoofing.

A spoofed broadcast Intent involves crafting an Intent that is broadcasted to a victim application's Broadcast Receiver component in an attempt to feed it malicious information or otherwise trigger unintended behavior. BroadcastReceivers, by their nature, need to be made publicly accessible, so they are often an obvious choice for an attack method. If a BroadcastReceiver needs to receive Intents outside of its own package, it must declare exported="true", making it a candidate for a spoofing attack victim. The effectiveness of this attack depends entirely upon what sort of functionality is contained within the victim BroadcastReceiver. The only broadcast Intents that cannot be spoofed are system Intents with actions such as "ACTION_BATTERY_LOW," which only the Android OS can send. However, BroadcastReceivers can always be triggered by the use of an explicit Intent, which explicitly specifies what component it wants to target.

The Goals.

Our goal is to both detect Intents using static analysis, and prevent attacks by exposing a secure API to the Android developer. Our analysis tool focuses on detection of implicit Intents. It uses interprocedural control flow to track Intents.

2. GOOD INTENTIONS LIBRARY

The API was originally intended to be a secure library, abstracting away Intents from developers. After further analysis of the Android architecture, it was proven that the API provides secure ways to handle most of the problems above. Those ways are described below. What is lacking, however, is a way to verify Intent origin to prevent against spoofing attacks. We therefore focused on developing a library that developers can use in order to verify Intent origin.

Activity Hijacking.

Preventing Activity Hijacks is simple. A developer just needs to make sure that the startActivity call contains an explicit Intent, especially if the Intent contains private information. This will guarantee that the Intent will only be read or received by the intended receiver. When sending an implicit Intent, the contents of the Intent should not contain confidential data.

Service Hijacking.

Like other security problems, there are multiple ways to prevent malicious applications from using your service. First, in the <service> tag of the manifest, you can specify properties such as the permissions required to start/bind to the service. Next, by not defining Intent filters your service can only be started by an explicit Intent. This prevents untrusted applications accessing the service. Additionally, to ensure that your service is private to your application, you should set the "exported" attribute in the manifest to false.

Broadcast Hijacking.

Android specifies the security implications of sending Broadcasts and it provides a robust API to mitigate or eliminate security problems in its documentation. The following mechanisms can and should be used to prevent Intent exploits:

- LocalBroadcastManager - This class is to be used when you are sending broadcasts inside your application. It guarantees that the broadcasted Intent does not leave your application.

- sendBroadcast(Intent, receiverPermission) and the like - When sending broadcasts, this enforces receiverPermission be declared through the <uses-permission> tag in the manifest by the broadcastReceiver that intends to receive an Intent when sending broadcasts.

- registerReceiver - Supplying a non-null permission when registering a receiver restricts the broadcasted Intents that will be received to those matching the permission.

- Intent Spoofing (Activities, Services, Broadcasts) - All three have similar solutions. If a developer does not intend the component to receive external Intents, the above components can be made private to the app by declaring the "exported" attribute to be false. Otherwise, the developer needs to check the caller's identity of the Intent or verify that the Intent received is not malicious. Android, however, does not provide a way to verify the origin of an Intent. But, if a developer knows which applications or components to trust, we can then verify the origin of the Intent before receiving it. This solution is described in depth below.

Based on all these analyses we see that Android provides a secure API for application developers to prevent malicious attackers. It is almost always the developer's responsibility to make sure that the application is secure and that methods being used to send Intents are the appropriate ones for the type of data being sent. Furthermore, because the Intent system is so flexible it is very difficult to distinguish between legitimate and malicious functionality. Any attempt to create a comprehensive "secure library" would thus consist of little more than renaming methods that already exist!

2.1 Design

We therefore decided to fully shift our focus to a functionality that we had originally conceived of as part of the library. The idea is to provide a mechanism for components that receive Intents to restrict what apps they will accept Intents from. One cause of potential security vulnerabilities that we identified was the fact that Android does not provide origin information for Intents. This can be problematic in cases where a component is intended to provide sensitive functionality for a known subset of external applications, but must not be used by untrusted apps. In the absence of origin information Intents can be easily spoofed, causing the target app to leak data, give malicious apps unauthorized permissions, or be subject to any other Intent-based exploit. We set out to prevent this.

Because modifying the Android OS was beyond the scope of this project, we had to think creatively about possible solutions within the existing framework. We carefully considered a lot of different ways to do this, and finally settled on the following model because it provides the best balance of ease of use and security. The idea is that a receiving component can define a list of trusted packages, and will only respond to Intents from components within them by requiring some form of identification. Note that any mechanism that relies on secret keys will not work, as an attacker can simply decompile the code to obtain it. The key must be generated randomly and sent to authorized apps. We do this by taking advantage of one of the most fundamental Android security guarantees - that an explicit Intent will reach its target without being intercepted - to allow the receiving component to give keys to only those apps it trusts.

Our system was designed to be easily usable, without requiring the developer to understand anything about how it works. All they need to do is extend an abstract class and register a component in the manifest. The functionality is implemented in the form of two abstract Service classes, to be extended by the developer in both the sending and receiving apps. These are called the Solicitor (sender) and the Bouncer (receiver). The components that use these to communicate will be referred to as the sending and receiving components. The developer of the receiving component must extend the Bouncer, register it as a service, and implement an abstract method specifying which packages should be trusted. The receiving component must not be exported; it will only receive Intents through the Bouncer. The developer of the sending component must do the same for the Solicitor, extending and registering it. When the sending component intends to send an Intent to the receiving component, it simply calls a method in its local Solicitor and everything is taken care of securely. When the Solicitor is invoked it is passed the Intent object that the sending component intends to send to the receiver. It stores the object in memory for later use and then begins the process by contacting the receiving app's Bouncer with a normal call to startService(). Contained in this call is origin information provided by the Solicitor, which is then checked by the Bouncer against its list of authorized packages. If the check passes, the Bouncer then binds to the Solicitor Service explicitly. The Solicitor uses the binding interface to send along the original Intent, which the Bouncer passes along to the receiving component.

We will now discuss what makes this system secure. Most importantly, the receiving component is not exported, which means that only components within the same package can contact it. This ensures that all communication must go through the developer's extension of our Bouncer class, which is in the same package. The Bouncer will only forward Intents to the receiver after it has determined that it is from a trusted package, which is achieved through the combination of checking the origin info against a list and binding to it explicitly. It is important to note that the check itself provides no security, as the origin field can be easily spoofed. The security guarantee comes from the fact that the Bouncer binds to the Solicitor explicitly, which means it specifically targets the trusted package. The Android system can be trusted to carry this out without the possibility of interception. If a malicious app spoofs the origin package, the Bouncer will end up binding to a trusted app's Solicitor, which will simply refuse the connection because it knows it has no pending requests. Security is thus ensured. We successfully devised and implemented a system that provides a guarantee of origin for Intents.

See figure 2 for a graphical representation.

3. USAGE

To use this Intent proxy system, the developers of the two applications must agree to allow communication between their components. Both parties import the Intent proxy library in their projects. If application A intends to send Intents targeted at application B's components, A will fill out a stub class "DevAppSolicitorImpl" which extends the Solicitor class.

```
DevAppSolicitorImpl:

package dev.app.testsender;
import good.intentions.proxy.Solicitor;
public class DevAppSolicitorImpl extends Solicitor {}
```

And application B will fill out a stub class "DevAppBouncerImpl" which extends the Bouncer class. Here, B must implement the setTrustedPackages() method, and add trusted package names to the trustedPackages field.

```
DevAppBouncerImpl:

package dev.app.testreceiver;
import good.intentions.proxy.Bouncer;
public class DevAppBouncerImpl extends Bouncer {
  @Override
  public void setTrustedPackages() {
    trustedPackages.add("dev.app.testreceiver");
  }
}
```

When A wants to send B an Intent, it will craft an Intent as usual, but instead of launching it with the Android's conventional methods (e.g. startActivity()), it will call one of our safe static methods, safeStartActivity(), safeStartService(), or safeSendBroadcast(), defined in the GIProxy class.

```
Intent intent = new Intent();
intent.setClassName("dev.app.testreceiver",
    "dev.app.testreceiver.DevAppTestReceiverActivity");
GIProxy.safeStartActivity(this, intent);
```

4. STATIC ANALYSIS

4.1 Introduction

Our goal is to write a static analysis tool that warns the user about any potentially dangerous Intents that could be sent by the target application. IntentAnalyzer is a command line tool written in Python that performs such analysis. IntentAnalyzer uses inter-procedural control flow analysis to track all delivered Intents. Information about delivered Intents helps IntentAnalyzer decide if the application is sending Intents safely. For instance, IntentAnalyzer is able to differentiate between implicit and explicit Intents by checking whether or not the Intent contains a Component field. By default, IntentAnalyzer flags all implicit Intents as dangerous.

4.2 Approach

To begin, we had to decide on a data structure which would suit our purposes for analyzing the control flow of a program. We researched existing static analysis frameworks, and decided to use a *control flow graph* to represent execution flow. We followed a set of distinct steps to construct a control flow graph from a raw Dex file.

Parsing.

While Java programs are compiled and run in a Java VM, Android programs are run using a Dalvik VM. This means that a Dalvik Executable is generated by the Android compiler (.dex extension) which allows the Dalvik virtual machine to run the application. This .dex file is packaged in an Android .apk file. To make our task easier, we used a customized version of DexDump to process a raw Dex file into an XML format. Our project utilizes this existing Dex to XML converter, which separates classes, methods, and instructions into XML tags. Since Python already includes a rich library for parsing XML, converting the XML into native Python data structures and custom classes was an easy task.

Basic Blocks.

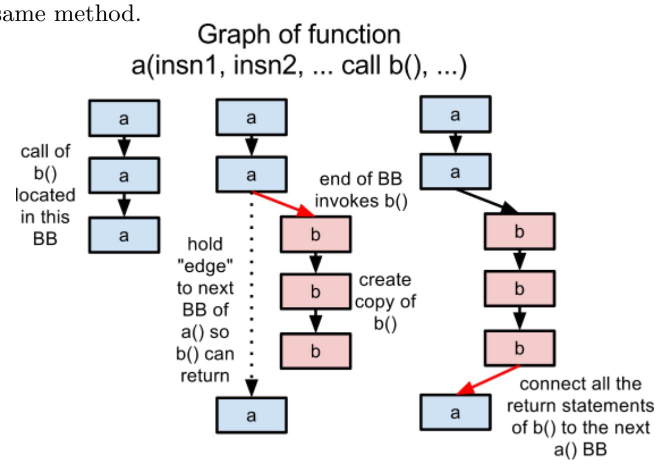
The next task is to separate instructions into basic blocks. Basic blocks constitute the "nodes" of our analyzer - each basic block is a consecutive set of instructions that consists of one entry point and one exit point. When the first instruction of a basic block is executed, the rest of the instructions in the block are always executed in order. We wrote a subroutine which takes in an instruction stream, and outputs an ordered list of basic blocks. Basic blocks are created by examining the instruction stream, and marking instructions which start new basic blocks, such as jump targets, or instructions that follow untaken branches. Then the instructions are separated into basic blocks by emitting a new basic block every time a new entry point instruction is encountered.

Intraprocedural Graph.

Now that we have basic blocks, each basic block is connected to the appropriate successor basic blocks. The connectivity for each basic block depends on the last instruction. For instance, basic blocks that end with a branching instruction may have multiple successors blocks. We implemented this approach by creating a mapping between basic blocks and jump targets. Basic block nodes that end with method invocations are simply connected to the next sequential basic block at this step, but are expanded in the next step.

Interprocedural Graph.

Initially, we construct a control flow graph for each method. Starting with an entry point method, we "expand" method invocation nodes until the graph reaches a fixed point. From here, we identify the entry point methods (for example Android activities start with onCreate). For each entry point method, each method call in the graph is unrolled, in essence creating a union of the graph of the caller and callee method. For every basic block node which ends with an invoke instruction, we delete the edge between that node and the next node. Then we create a copy of the callee's control flow graph. The node that invokes a method is connected to the entry point of this new graph (the first instruction). The basic block that makes a call to a method is now linked to a new instance of the entry basic block of the method. All return statements in the called method are then linked back to the basic block that immediately follows the calling basic block (a directed edge points out of the return statement blocks). In essence each invoke node can be "expanded" an arbitrary amount of times. Therefore, our interprocedural analysis algorithm has an unlimited call depth. In particular, it is important to note that when the same method is called multiple times, each "expansion" generates a new graph, despite the fact that they were generated from the same method.



All Simple Paths.

Given a completely "expanded" graph data structure, we now can build a static analysis algorithms on top of this framework. In particular, we want to track Intents as they are instantiated, until they are passed into a "sink", a method which initiates the IPC process between Android components. An example sink that launches a new Android application is startActivity, or bindService. These sink methods take in an Intent as a parameter.

We enumerated all paths from entry points of the application, to all sinks of the application. Each path defines a single Intent that could possibly be sent from this application, and is essentially a sequential, ordered list of nodes, and each node decomposes into a linear sequence of instructions. However, enumerating all non-cyclic paths in this manner can take a very long time to complete. The running time is non-polynomial, O(n!). Therefore, some graphs can take minutes to complete analysis, while others can take seconds.

At the end of this process, the paths represent all possible flows of execution through the program which end with a sink. All branches are followed, giving an upper bound on the number of paths through the program because even impossible branches are followed, since the tool does not perform constraint satisfaction.

Transfer Functions.

The static analysis problem we wish to solve is to determine the state of the Dalvik VM registers right before the sink is executed. Given a linear sequence of instructions represented as a *path*, we can simply follow it and update the register state after each analyzed instruction. To accomplish this, we wrote transfer functions for each instruction. Each instruction that was on the path is passed a "state" data structure, which contained all register mappings and tracked Intents. After passing through every instruction in a path, the state would contain the register mapping right before the execution of the sink instruction. With this information, we can check that the argument register of the sink method contains a reference to an Intent, and output accordingly. For each Intent found, we output all attributes collected along the way, including action string, categories, extra data, target component, and miscellaneous flags.

One challenge we had was tracking state between method calls. Even though we expanded method calls in place, such that the new nodes and edges were connected with the existing graph, each method call produces a *frame* with its own registers mappings. Therefore, we represented the state of the execution as a stack of register mappings. Mappings were pushed and popped from the stack as invoke nodes and return nodes were encountered.

Intent Analysis.

At this stage, we have a list of all the Intents that were detected by our tool. By default, our tool simply flags all implicit Intents as dangerous. Implicit Intents do not specify a target component by the time it reaches the sink. We classify implicit Intents as dangerous, because it renders the application vulnerable to Activity Hijacking, Service Hijacking, and Broadcast Theft. Any malicious app is able to intercept the Intent and read its contents by specifying a matching Intent Filter. Admittedly, this heuristic for flagging dangerous Intents is simple and crude, but more elaborate schemes for identifying dangerous Intents could implemented in the future.

4.3 Limitations

Future revisions of the project may perform constraint analysis on branches to reduce the number of paths, but we believed it to be outside of the scope of the project to track conditions on branches. Similarly, a future revision will implement tracking of switch statements. The final limitation is the computation of all distinct paths between source and sink nodes when enumerating all paths that create and emit Intents. Currently, our search can take O(n!) time in the worst case. This search can possibly be improved by exploiting the properties of directed acyclic graphs.

Our analysis framework is general enough to work for any method defined in the class file, using the push and pop mechanism of register mappings to track state across method calls. However, external methods such as library methods need to be implemented as "stubs", because we can not actually generate their graphs, since their implementations are not in the Dex file. Stubs are Python functions which take state and arguments as parameters, and modify them in a predetermined way. We had to define a new stub for each library method. This is tiresome in general, so we did not cover every single Android API call; we covered the ones relevant to our interests, such as any Intent method which modified the Intent in some way. Therefore, the information we collect on Intents may be incomplete, because not all API methods have stubs.

Finally, we adopted a simple heurustic for flagging dangerous Intents. Intents without components are flagged as dangerous. This could be improved in the future by using a more precise heuristic, such as checking whether or not the action string of the Intent is supported by the Android API, or just internally.

4.4 Improvements Over Comdroid

By building the graph through iterative method unrolling, our project overcomes Comdroid's 1 level function call limit. Furthermore, our analysis splits branches into 2 or more distinct paths that are tracked separately, thereby enumerating over paths that Comdroid does not and allowing the discovery of vulnerable Intents that Comdroid can not find. For example, if one branch creates an implicit Intent, and another creates an explicit Intent, ComDroid will report an explicit Intent, whereas IntentAnalyzer will report both.

4.5 Example Analysis

As an example we will analyze a release of the Opera mobile web browser. Although our tool examines all entry points, here we look at a single entry point, *onPause()*. Figure 1 shows the graph that is generated after the entry point method is expanded. By manual inspection, we can see that block 8292 is a source node, and block 8294 is a sink node, since one allocates a new Intent, and the other delivers it. There is only a single path from source to destination. An Intent is created from this path and we can determine changes to its attributes as it travels along the path. The figure demonstrates that the tracked Intent contains an *action* string and *extra* data. It is implicit because the *classname* and *class* fields are empty. Thus, it is dangerous. It also appears that the action is meant for an internal component, since the string seems to specify an Intent action string specific to Opera. Therefore, we discovered a vulnerability in Opera after running the Dex file through IntentAnalyzer, because any malicious application could potentially intercept this Intent and perform Broadcast Theft.

5. REFERENCES

ComDroid http://www.cs.berkeley.edu/ emc/papers/mobi168-chin.pdf