7-1-2016

Automated code extraction from packed android applications.

Abhishek Vasisht Bhaskar
Syracuse University

Abstract

Software packing is a method employed by malicious applications to hide their original intent. Extracting the original intent of an application from its application bundle, whether to perform a security analysis on it, to search for security flaws(or bugs) or simply for educational purposes is a key requirement for the security community. With the fluidity provided by the Android app store coupled with a complete application-framework based environment for a malicious user to employ as an attack space, it is of great importance to examine Android applications and extract their intent. For basic applications, simple reverse engineering tools can be used to extract a semantic view of the application very close to the original source code of the application. However for applications, which have been deliberately packaged/packed in such a way that their original intent cannot be extracted by simply reverse-engineering them, we need a more intricate procedure to extract enough information to be able to reproduce the original intent of the application. These applications are packaged such that the actual code is hidden/encrypted and only during run-time is the actual code unpacked and executed. To unpack such applications, we present `DroidUnpack`, a tool based on dynamic program analysis, which is able to extract the original intent of the application, generically. `DroidUnpack` is designed by exploiting some fundamental features of the Android Runtime which cannot be mutated by a malicious user to unpack the application. We also attempts to alleviate tedious manual analysis required by a user to analyze different types of packed applications, by providing a generalized tool which is able to unpack android applications, regardless of the packing technique used.

Automated code extraction from packed android applications.

by

Abhishek Vasisht Bhaskar

B.E., PESIT, Bangalore, India, 2014

Dissertation Submitted in partial fulfillment of the requirements for the degree of

Master of Science in Computer Engineering.

Syracuse University

July 2016

Acknowledgements

Most importantly, I would like to thank my advisor, Dr. Heng Yin, who has guided me at each step of the problem and provided constant motivation and push to keep going. Thank you professor, for helping me grow and encouraging my work at all times. Secondly, I would like to thank my mum and dad, although not in the same contnent they have been giving be constant moral support for all the time during my thesis research.Thirdly, I would like to thank Dr. James Fawcett, Dr. Kevin Du and Dr. Richard Tang who took time out of their schedules to be a part of my defence and provided me with a lot of insight and advice on the problem. Lastly, I would like to thank all the members of the System Security Lab headed by my advisor Dr. Heng Yin, all of you have been very helpful and fourthcoming whenever I had any techinal doubts.

Contents

List of Figures

List of Tables

Listings

Acronyms

APK Android application package

ART Android run-time

VMI Virtual machine introspection

SLOC Source lines of code

DVM Dalvik virtual machine

AOT Ahead-of-Time

OS Operating System

GC Garbage Collector

ASM Assembly

API Application Program Interface

TB Translated Block

CB callback

BB basic-block

Chapter 1

Introduction

Software obfuscation or Run-time packing is a intricate tool used by attackers and software vendors alike to protect their code. Although it can be an absolute boon for software vendors, helping them protect their closed source code base, it can be an absolute nightmare for security analysts when they encounter malicious application which are obfuscated or packed. Simple reverse engineering of such applications proves ineffective and more complex mechanisms are needed to extract meaningful code belonging to these applications.

Binary packing on desktop computers, being a very old problem has been extensively studied since its discovery and various solutions haven been designed to accordingly handle these packed application and extract meaningful source code from them. Although this is the case, the problem of handling binary samples from the wild was scarcely addressed as highlighted very recently by **"SoK: Deep packer inspection: A longitudinal study of the complexity of run-time packers"**(17).

With the onset of smart-phones, there had to be a reinvention of the run-time environment to adapt to a completely different user interface and hardware structure than a desktop computer. On Android, a virtual-machine based sandbox-styled interpreted environment based on `dalvik` byte-code, very similar to `java byte-code` was designed. As these systems were designed, new packing techniques were introduced and classic binary unpacking solutions were no longer applicable to them. Various projects in the recent years have attempted to unpack these android applications to diverse degrees. Although a portion of them produce very accurate results, their extraction processes are based on explicit packing features, modeled around some of the state of the art packers available for Android applications. Dynamic analysis based unpackers usually insert hook-points in the run-time and/or kernel source code to extract files from memory when certain trigger features are met. Albeit they result in successful code extraction for applications packed with any of the known packers, a smart malicious agent could easily subvert these detectors by changing the packing design ever so slightly. Moreover, with the advent of the ART, where most/all of the `dalvik` functions are translated into native code, the problem of unpacking becomes even more complex as simple tap points fail to provide complete coverage of the executed code. We take a brand new perspective to solve the problem of generic code unpacking by considering factors which cannot be manipulated by these packers. We register for key events which represent `java/dalvik` method dispatch points in perspective of the run-time and excerpt information for the particular method from the guest memory by, reading 'state information from run-time data structures for `dalvik` interpreted methods' and 'native code from the `oat file` for ART native methods' both of which remain accurate regardless of the packing technique used. We first design and implement a dynamic analysis platform for the new ART based on **"Droidscope: seamlessly reconstructing the os and dalvik semantic views for dynamic android malware analysis"**(18), which provides various Virtual machine introspection (VMI) tools and finally we present `DroidUnpack`, a plug-in, about 703 Source lines of code (SLOC) of C++, which performs generic code extraction from packed android applications.

Chapter 2

Background and solution overview

2.1 APK packing

Run-time packing or Executable compression is a process where the the code and/or data of an application is compressed/encrypted to various degrees and a run-time element, usually a shared library or such is used to dynamically decompress/decrypt the original code and execute it. This process is employed by malicious users to hide their program's original intent. Even after years of arduous research on trying to propose a generic method of unpacking, Ugarte-Pedrero et al. (17), after conducting a through study on the complexity of run-time packers showed that a great majority of samples employ a multi-layered packing mechanism, whereas most solutions only expect simple single-layered code unpacking and are ill-equipped to handle different/complex packer designs. This paper importantly highlights the lack of a stable generic unpacking scheme.

While still based on the same core principles as its binary predecessors, android APK packers have starkly different designs. Most of the run-time packers, start with the APK, which is merely a set of `.dex` files and resources corresponding to the particular application and encrypt each of the `.dex` file and create a new APK which contains a single `.dex` file (which would act as a launchpad for the application), an obfuscated native library and file-chunks corresponding to the original `.dex` files. The new application starts up from the single `.dex` file which then loads the obfuscated native library. This library is the main unpacking agent which performs all the necessary steps to correct the file-chunks to form a verifiable `.dex` file/s representing the original application, load it into memory and start executing the application. While this a commonly followed design, most packers differ in that they 1. employ different ways to obfuscate/unobfuscate `.dex` files, 2. different ways of launching the application which affects the complete execution pattern of the application… .To cover their tracks these packers employ various techniques like 1. deleting any corrected `.dex` file they drop into memory as soon as it is loading 2. skewing the `.dex` file backing data structure of the run-time in memory to hinder debuggers 3. hooking various system functions to detect if being tracked… which make it especially hard for a security analyst to deduce their original intent. Many of these packers now fully support the new ART, which is much more sophisticated than the older `dalvik` run-time causing a bigger challenge. In essence, apart from the fundamental principle of the ART mechanisms which are built in, anything that the packer can control can be fair gain for implementing packing features. The next section talks about some of the unpackers which exist and goes on to highlight the need for a generic unpacking mechanism.

2.2 APK unpackers

There have been many projects and publications alike attempting to solve the problem of packed android APKs and many of them are successful for particular samples sets. In general, for a packed APK they start off by manually investigating the behavior of the packed application under execution, noting down techniques used by the packer. Once this is done, some of them propose an automatic framework to extract `.dex` files and others manually do so, both relying on the behavioral aspects of the packer which they deduced in the previous step. This investigation is then repeated for a suit of know packers. Since these packed applications are virtually impossible to extract using any known static analysis based approaches, all the unpackers (which intend to handle complex packed applications) are based on different dynamic program analysis techniques. Nasim et al. (14) perform unpacking by performing a memory dump when a new module is loaded by the application, using either a kernel module or a `ptrace` based method and then a python script to parse the memory to the find the `.dex` file corresponding to the application and extract it. Modern packers are very advanced in that they have anti-debug features built into them to detect `ptrace` based tracking methods. They also hook common functions used to read into the memory and suspend the process if they observe that they are being tracked or another program is attempting to read their memory space, hence easily evading this unpacking scheme. Kim et al. (13) develop another such a similar unpacker project which attempts to dump the memory but instead uses a method whereby they change the source code of the DVM and add hook functions into a function `dvmFexFileOpenFromFd` which is used to load the `.dex` file, and at that point dump the memory belonging to the `.dex` file data structure passed onto the function. `.dex` files are often mangled by a packer and during the time of loading to memory are not completely reliable, in that their contents are not accurate and cannot be assumed to be complete. The DVM does not perform any code verification, but instead just checks if the different headers and offsets in the `.dex` file hold good when loading it. Some packers take advantage of this and have a child process dedicated to correcting the `.dex` file during the runtime. This would mean that the a `.dex` file collected during load time may be incorrect. **"Android packers: facing the challenges**(19) is another work which uses **"LiME"**(16) to read into the memory and **"volatility"**(11) plug-ins to perform memory forensics on the collected memory dumps. **"General unpacking method for Android Packer(NO ROOT)"**(15) is another project which hooks functions, in their case they hook different functions for different packers, to perform a memory dump. Keeping all these problems in mind, Zhang et al. (20) take a slightly different approach to unpacking by identifying known packers using 1. inserted classes 2. `location_` for ART and `fileName` for DVM. The former is used to identify the packer while the latter is used to get an idea of the location of the `.dex` file for the `dalvik run-time` or the ART to extract it.

These solutions suffer from the same issues where the packer's features need to be studied before hand to get a fair idea of what functions are to be hooked etc. They also suffer from the fact that more advance packers perform complex selective code unpacking, which means that these unpackers unload a `.dex` file into memory and start up the application, but the `dex` code of all of the methods in the `.dex` file are encrypted or obfuscated, and a runtime library belonging to the library performs selective unpacking where in it decrypts the `.dex` code of the method right before this method is called defeating any unpacking attempts where the unpacking scheme which performs a memory dump at only one specific point in the application life-time.

With all these things in mind, there was a recent work by Bodong et al. (10) which attempts to address the problem of generality in unpacking. They go about their work by hooking into all the functions which are responsible to interpret `dalvik` code in the DVM (source code) and in their callback function, they read the `DexMethod` data structure and extract `dex` code specific to each method. Although feasible, this scheme will not work for the ART because of several reasons,

1. There is very minimal interpreted code in ART and a majority of the code is compiled Ahead-of-Time (AOT), hence hooking any particular method in the ART library will not provide complete code coverage.

2. Once an ART native method is dispatched from the run-time from a particular function, calls to other ART native methods, within that module, from that point on, need not trap back to the run-time

2.3 Solution Overview.

There are many challenges facing APK unpacking as we saw in the previous sections. Packed samples are completely immune to static analysis. They have anti-debug features which render unpackers which attempt to read `.dex` files from the memory via system calls or `ptrace` based methods useless. Some packers mutate the `.dex` file contents in memory, which means that even after getting a memory dump, an analyst cannot successfully find or extract the actual code. Finally, with 69% of the android users now using `KitKat` Operating system or above, all of which are based on the new Android run-time (ART), an unpacker must be able to support it.

To accommodate to these shortcomings we look at the problem from a different perspective. Regardless of what packer is used to pack an application, what features it implements, because applications on the android phone are run and managed by a standard ART run-time, they have no control of the execution engine of the run-time. For ART compiled native methods, there are some data-structures which hold important data, like the offset of these methods in a module and for interpreted `.dex` methods, there are data-structures which hold the `dalvik` byte-code corresponding to each method, in the run-time, both of which are not in the packer's control. Execution of an android application (albeit benign or malicious), whose core logic has been written in Java and compiled into an APK and then packed, has to resemble that of the unpacked application and to satisfy this, the packer cannot mutate certain structures in the ART run-time at any cost.

Acknowledging these facts we first design a system which is able to provide us with a platform to perform unpacking. We build this platform as an upgrade to (18), which is based on the Android emulator (which is based on QEMU). It is designed such that it can support the new Android emulator as well as the recent ART run-time. This emulator based dynamic analysis tool provides us full control of the guest system and all the necessary features to perform the unpacking. The unpacking process itself is done by carefully studying the ART run-time and extracting information from some key data-structures in the run-time at key events (/hook-points) during the execution of the application. We are able to produce a code extraction of all the native/interpreted methods that belong to the application during the lifetime of the application accurately defeating run-time packers, hence providing a security analyst with a block by block trace of the application for further analysis.

2.4 Contributions

1. A complete dynamic analysis platform which supports various virtual machine introspection features like

   (a) native-call tracing

   (b) native-instruction tracing

   (c) java function tracing

   (d) memory read/write tracing ...

   for the new ART run-time, based on `Droidscope`, a similar such tool for the DVM run-time .And in doing so a good overview of the working of the Android run-time (ART) for interested researchers.

2. An unpacker, implemented as a plug-in for the above-mentioned tool, which performs a very generic unpacking procedure which is able to successfully extract accurate code from any packed application, regardless of what packing mechanism was used.

3. A case study of some special known packers

4. A platform for an security analyst to perform further analysis (apart from just code extraction) on the behaviour of these packed applications from the wild.

Chapter 3

The Android run-time (ART)

Before we begin speaking about the unpacker, it is important to understand the new Android run-time (ART) to help the reader in getting a firm grip of this system as well as lay the ground for the later sections. The Android run-time (ART) is the application run-time environment used by the Android operating system since version 4.4 `"KitKat"`.

3.1 History

Before ART, the android Operating System (OS) was based on a `process virtual machine`, whereby source code of an application was written in Java, and the Java classes which belonged to an application were compiled into `dalvik` byte-code (similar to java byte-code). Each `.java` file was compiled into a `.dex` file (similar to `.class` files) and these `.dex` files were combined together with the resources required by the application (like images. . .) and an Android application package (APK) was released for the user to install. During installation, further platform/hardware specific optimization was performed on the the `.dex` files and `.odex` files were produced. For execution, the Dalvik virtual machine (DVM) would load these `.odex` files into memory and execute the `dalvik` byte-code in them by interpreting them one-by-one. Each `dalvik` byte-code is provided an `instruction handler`. These `instruction handlers` are basically written in `C` and/or in assembly for every architecture. Each `instruction handlers` is like an offset of a computer goto -like implementation with the byte-code being the selection mechanism. Depending on architecture, instruction-to-instruction transitions may be done as either computed goto or jump table. In the computed goto variant, each instruction handler is allocated a fixed-size area (e.g. 64 byte). "Overflow" code is tacked on to the end. In the jump table variant, all of the instructions handlers are contiguous and may be of any size. A Java function in invoked by the DVM (the run-time) via a function `dvmCallMethod`, which essentially pulls the byte-code corresponding to the particular method from the `.odex` file (which is loaded onto the memory) and begins interpreting them one-by-one. Figure 3.1 (Source: Wikipedia) shows a good graphical interpretation of the APK of the DVM.

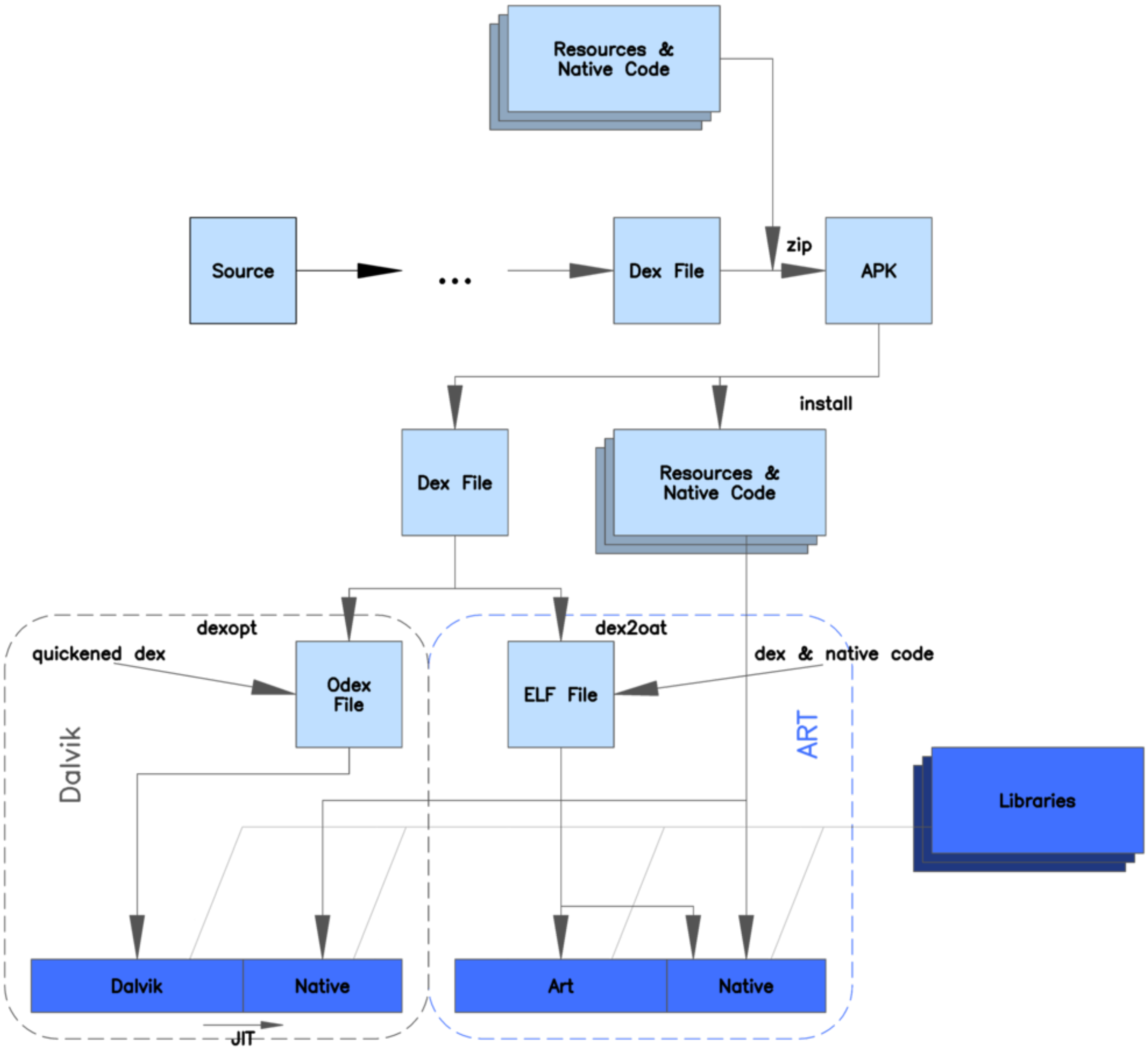


Figure 3.1: A comparison of APK file structure in ART and the older DVM (Source: Wikipedia)

3.2 What is the new Android run-time (ART)?

Interpreting methods tends to make a system significantly slower, to improve on performance Android made a big decision to adopt native code. For backward compatibility, the APK structure had to remain the same, hence none of the Java code could be compiled to native code during release time. This cannot done, also because the target architecture of an application is unknown at release time, this data is only known during install time. During the installation of the application, a tool called `dex2oat` is invoked which compiles every single Java/dalvik method, one class after the other for all classes in the `.dex` file (present in the APK) one-by-one into native code specific to the architecture of the device. After compilation, its back-end `oatwriter`, combines the older .dex files with the compiled native code and creates an `OAT` file. As we see in Figure 3.2, the OAT file is essentially an ELF file (on the older DVM runtime, there was no executable code in an `.odex` file as all the code was interpreted, so the whole file could be loaded onto memory as read/write, but the `.oat` file requires a `.text` section which had to be executable, hence promoting an ELF based file design). For backward compatibility and because of the constraint that some `dalvik` byte-code just CANNOT be compiled into native code and HAVE to be interpreted, the Android run-time (ART) had to still keep the `.dex` files with the original dalvik byte-code. **Every Java method of a class can be either compiled to native code, also known as 'quick code' or not, in which case it is interpreted. Henceforth any reference made to quick code or intepreted code refers to the Java functions which were compiled accordingly.** Hence each class which is written to the `.oat` file gets a label 1. kOatClassAllCompiled - All functions of the class is compiled into native code. 2. kOatClassSomeCompiled - Some of the functions of the class are compiled to native code. 3. kOatClassNoneCompiled - None of the functions are compiled to native code and all of them have to be interpreted. `OatDexFile` is used to hold information about a corresponding .dex file as well as to point to all the OatClasses which belong to the particular file. `DexFile` is the exact same data structure used in the DVM based android, more about this will be explained in the later sections in detail as and when required but it is important to note that a .dex file is unaware of the presence of any native code and is an independent entity (this is important because a user cannot have a reference to a .dex file based data structure and derive the offset of the corresponding native code is a straightforward manner, this will be dealt with in the later sections). `OatClass` is data which can be reached via the `OatDexFile` and holds a list of offsets corresponding to the compiled methods of the particular class. Following this is space for other important run-time information like bitmaps for the Garbage Collector (GC), `VmapTables` which map the Virtual registers to memory addresses etc.. Following this is the quick/native code, which can only be referenced via the offset information in the `OatClass`, they contain a minimalistic header called the `OatMethodHeader`, which holds information like code_size, code_offset, gc_map_offset etc...

Figure 3.3 shows the memory dump of an OAT file, in this case the `system@framework.oat` file where we observe the layout as described in Figure 3.2. Now that we have a good overview of the file structure let us explore the run-time!

ELF Header Magic "0x7f ELF"

Simple ELF header with section information.

OAT Header Magic "OAT \n 039 \0"

variable length with count of D OatDexFiles.

OatDexFile[0] OatDexFile[1] ... OatDexFile[D]	one variable sized OatDexFile with offsets to Dex and OatClasses
DexFile[0] DexFile[1] ... DexFile[C]	one variable sized DexFile for each OatDexFile. These are literal copies of the input .dex files. Here exists the dalvik byte code corresponding to each .dex file.
OatClass[0] OatClass[1] ... OatClass[C]	one variable sized OatClass for each of C DexFile::ClassDefs. Contains OatClass entries with class status, offsets to code, etc. This is important because it holds the offset into the native code for each method

GcMaps, VmapTables, MappingTable and padding as following this will be the native code which needs to be aligned

OatMethodHeader[0] MethodCode[0] (native) ... OatMethodHeader[N] MethodCode[N] (native)	fixed size header for a CompiledMethod including the size of the MethodCode. One variable sized blob with the code of a CompiledMethod. Pairs are deduplicated.

Figure 3.2: OAT File Layout

```
@csrgyin-lab: ~/android_unpacker_project/MalShare-Toolkit
00000000  7f 45 4c 46 01 01 01 03  00 00 00 00 00 00 00 00  |.ELF............|
00000010  03 00 28 00 01 00 00 00  00 00 00 00 34 00 00 00  |..(.........4...|
00000020  84 c4 08 03 00 00 00 05  34 00 20 00 05 00 28 00  |........4. ...(.|
00000030  09 00 08 00 06 00 00 00  34 00 00 00 34 90 0d 91  |........4...4...|
00000040  34 90 0d 91 a0 00 00 00  a0 00 00 00 04 00 00 00  |4...............|
00000050  04 00 00 00 01 00 00 00  00 00 00 00 00 90 0d 91  |................|
00000060  00 90 0d 91 00 80 ab 01  00 80 ab 01 04 00 00 00  |................|
00000070  00 10 00 00 01 00 00 00  00 80 ab 01 00 10 b9 92  |................|
00000080  00 10 b9 92 98 7e 4b 01  98 7e 4b 01 05 00 00 00  |.....~K..~K.....|
00000090  00 10 00 00 01 00 00 00  00 00 f7 02 00 90 04 94  |................|
000000a0  00 90 04 94 38 00 00 00  38 00 00 00 06 00 00 00  |....8...8.......|
000000b0  00 10 00 00 02 00 00 00  00 00 f7 02 00 90 04 94  |................|
000000c0  00 90 04 94 38 00 00 00  38 00 00 00 06 00 00 00  |....8...8.......|
000000d0  00 10 00 00 00 00 00 00  00 00 00 00 00 00 00 00  |................|
000000e0  00 00 00 00 01 00 00 00  00 a0 0d 91 00 70 ab 01  |.............p..|
000000f0  11 00 04 00 09 00 00 00  00 10 b9 92 98 7e 4b 01  |.............~K.|
00000100  11 00 05 00 11 00 00 00  94 8e 04 94 04 00 00 00  |................|
00000110  11 00 05 00 00 6f 61 74  64 61 74 61 00 6f 61 74  |.....oatdata.oat|
00000120  65 78 65 63 00 6f 61 74  6c 61 73 74 77 6f 72 64  |exec.oatlastword|
00000130  00 62 6f 6f 74 2e 6f 61  74 00 00 00 02 00 00 00  |.boot.oat.......|
00000140  04 00 00 00 03 00 00 00  01 00 00 00 00 00 00 00  |................|
00000150  02 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  |................|
00000160  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  |................|
*
00001000  6f 61 74 0a 30 33 39 00  61 bd 88 7f 03 00 00 00  |oat.039.a.......|
00001010  00 00 00 00 0e 00 00 00  00 70 ab 01 01 70 ab 01  |.........p...p..|
00001020  09 70 ab 01 11 70 ab 01  21 70 ab 01 29 70 ab 01  |.p...p..!p..)p..|
00001030  31 70 ab 01 39 70 ab 01  41 70 ab 01 49 70 ab 01  |1p..9p..Ap..Ip..|
00001040  51 70 ab 01 00 a0 5b 00  00 00 00 00 00 00 00 00  |Qp....[.........|
00001050  2c 09 00 00 64 65 78 32  6f 61 74 2d 63 6d 64 6c  |,...dex2oat-cmdl|
00001060  69 6e 65 00 2d 2d 72 75  6e 74 69 6d 65 2d 61 72  |ine.--runtime-ar|
00001070  67 20 2d 58 6d 73 36 34  6d 20 2d 2d 72 75 6e 74  |g -Xms64m --runt|
00001080  69 6d 65 2d 61 72 67 20  2d 58 6d 78 36 34 6d 20  |ime-arg -Xmx64m |
00001090  2d 2d 69 6d 61 67 65 2d  63 6c 61 73 73 65 73 3d  |--image-classes=|
000010a0  66 72 61 6d 65 77 6f 72  6b 73 2f 62 61 73 65 2f  |frameworks/base/|
000010b0  70 72 65 6c 6f 61 64 65  64 2d 63 6c 61 73 73 65  |preloaded-classe|
000010c0  73 20 2d 2d 64 65 78 2d  66 69 6c 65 3d 6f 75 74  |s --dex-file=out|
000010d0  2f 74 61 72 67 65 74 2f  63 6f 6d 6d 6f 6e 2f 6f  |/target/common/o|
000010e0  62 6a 2f 4a 41 56 41 5f  4c 49 42 52 41 52 49 45  |bj/JAVA_LIBRARIE|
000010f0  53 2f 63 6f 72 65 2d 6c  69 62 61 72 74 5f 69 6e  |S/core-libart_in|
00001100  74 65 72 6d 65 64 69 61  74 65 73 2f 6a 61 76 61  |termediates/java|
00001110  6c 69 62 2e 6a 61 72 20  2d 2d 64 65 78 2d 66 69  |lib.jar --dex-fi|
00001120  6c 65 3d 6f 75 74 2f 74  61 72 67 65 74 2f 63 6f  |le=out/target/co|
00001130  6d 6d 6f 6e 2f 6f 62 6a  2f 4a 41 56 41 5f 4c 49  |mmon/obj/JAVA_LI|
00001140  42 52 41 52 49 45 53 2f  63 6f 6e 73 63 72 79 70  |BRARIES/conscryp|
00001150  74 5f 69 6e 74 65 72 6d  65 64 69 61 74 65 73 2f  |t_intermediates/|
00001160  6a 61 76 61 6c 69 62 2e  6a 61 72 20 2d 2d 64 65  |javalib.jar --de|
00001170  78 2d 66 69 6c 65 3d 6f  75 74 2f 74 61 72 67 65  |x-file=out/targe|
00001180  74 2f 63 6f 6d 6d 6f 6e  2f 6f 62 6a 2f 4a 41 56  |t/common/obj/JAV|
00001190  41 5f 4c 49 42 52 41 52  49 45 53 2f 6f 6b 68 74  |A_LIBRARIES/okht|
000011a0  74 70 5f 69 6e 74 65 72  6d 65 64 69 61 74 65 73  |tp_intermediates|
000011b0  2f 6a 61 76 61 6c 69 62  2e 6a 61 72 20 2d 2d 64  |/javalib.jar --d|
000011c0  65 78 2d 66 69 6c 65 3d  6f 75 74 2f 74 61 72 67  |ex-file=out/targ|
000011d0  65 74 2f 63 6f 6d 6d 6f  6e 2f 6f 62 6a 2f 4a 41  |et/common/obj/JA|
000011e0  56 41 5f 4c 49 42 52 41  52 49 45 53 2f 63 6f 72  |VA_LIBRARIES/cor|
```

Figure 3.3: Framework OAT file memory dump

3.3 `libart.so`: the heart of ART and its execution mechanism.

This section will serve as a bedrock for the later sections.`libart.so`, written in C++, is the main run-time library which handles and executes an android application. When the application starts up, via any entry point, `libart.so` starts off by locating the .oat file belonging to the process to be started, checks its sanity and loads it onto memory and starts executing the application. It spawns certain essential threads, each thread corresponding to a thread on the Java side. The main application starts thread as soon as it spawns, calls the Java function `void java.lang.Thread.run()` starts up and initializes all the required framework classes. Once this is done the `<clinit>` function belonging to the application is invoked, which initializes classes belonging to the application and starts executing the application. This is a view from the java perspective, but how does the `libart.so` handle function invocation?. As we discussed earlier, Java methods are compiled into `quick code` or `interpreted code`. Once the .oat file is parsed and loaded onto memory, it initializes and populates data structures in the run-time(`libart.so`) which mirror features on the Java side. By Java features we mean Thread, Objects, Classes, Java methods... are all mirrored on the run-time. To study method invocation behavior, of particular interest to us is the `ArtMethod ((2))` class in `libart.so` which essentially mirrors a Java Method. Now, an instance of the ArtMethod might be either compiled into quick code, or may not have any quick code. An ArtMethod is invoked in ART runtime via a two key functions, `void ArtMethod::Invoke(Thread* self, uint32_t* args, uint32_t args_size, JValue* result, const char* shorty)`, belonging to ArtMethod **OR** `bool DoCall(ArtMethod* method, Thread* self, ShadowFrame& shadow_frame, const Instruction* inst, uint16_t inst_data, JValue* result)`. The former is used to handle functions compiled as quick-code/native-code, while the latter is used for interpreted code(called using handlers of `invoke-XXX/range` dalvik instructions). The

Thread data structure, which mirrors a java thread, holds a managed stack of all the invoked (java) methods belonging in it. `ArtMethod::Invoke` performs the following functions

1. performs some security checks to make sure there were no overflows etc ..

2. checks if the ArtMethod contains native code and if checks pass, invoke `art_quick_invoke_stub`

3. `art_quick_invoke_stub` is a architecture specific Assembly (ASM) method which sets up the stack frame and registers, extracts the method offset form the ArtMethod data structure and jumps to this offset. The Stack and registers for the method are laid out as shown in Figure 3.4

`DoCall` on the other hand, is used to handle interpreted `.dex` methods and works by allocating and setting up a shadow stack for the target method and then, the dalvik byte-code corresponding to the ArtMethod, which is actually stored in a data structure called, `Dex::CodeItem` is extracted for the particular method and submitted to the interpreter functions, which interprets and executes each of the instruction one by one based the goto-implementation based method we spoke about earlier. A layout of `Dex::CodeItem` is shown in Figure 3.5. This is a key data structure as it points us to the dalvik byte-code corresponding to the particular method.

3.4 Final words.

Now that we have a fair idea about the execution pattern of the Android run-time (ART), we can begin to model our dynamic analysis tool to support some of the features we require to perform unpacking.

Quick invocation stub internal.
On entry
r0 = method pointer
r1 = argument array or null for no argument methods
r2 = size of argument array in bytes
r3 = (managed) thread pointer
[sp] = JValue result
[sp + 8] = core register argument array
[sp + 12] = fp register argument array

uint32_t * fp_reg_args uint32_t * core_reg_args result_in_float Jvalue* result	<- Caller frame
lr r11 r9 r4	<- r11
uint32_t out[n-1] .. .. uint32_t out[0] ArtMethod*	Output args <- SP

Figure 3.4: Quick invoke, stack and register layout

registers_size_	ins_size_
outs_size_	tries_size_
insns_size_in_code_units_	
insns_	

Figure 3.5: 32-bit code layout of the Dex::CodeItem data structure which holds the dalvik byte-code.

Chapter 4

DroidScope:ART

4.1 Overview and older `Droidscope`

`DroidScope` (18) is a dynamic program analysis tool developed on top of the Android emulator which provides a user with a host of very useful Virtual machine introspection (VMI) tools like basic-block tracing, native call tracing, dalvik call tracing, native instruction tracing, dalvik instruction tracing.... `DroidScope` reconstructs both the OS-level and Java-level semantics simultaneously and accurately. It provides a platform for the user to dynamically load and unload plug-ins and a set of Application Program Interface (API)s to be used in the plug-ins to which expose its various features. Basic block level callbacks are implemented by hooking key points in the in the Translated Block (TB) translation is the android emulator (for more information please refer to (18), (12), (9)). Native-level API callbacks are implemented on top of Basic-block callback (this will be explained in more detail in the following section). Dalvik method callbacks are implemented by hooking the `dvmCallMethod` function in the Dalvik virtual machine (DVM) and reading data about the method like name, dalvik byte-code... from the `Method` data structure. Dalvik instruction callbacks are implemented by hooking a range of functions which correspond to the interpretation of all the dalvik byte-code, once execution reaches any of these functions, the contents of the `DexPc` is read and disassembled. This older version of `Droidscope` supported android versions "4.2"-, and only the Dalvik virtual machine (DVM).

4.2 The new `Droidscope` with ART support

To accommodate to a completely different run-time in ART, we have had to comprehensively re-work `DroidScope` to still be able to accurately recover both Java and Native level semantic features. This section will provide an expansive overview of how we achieved this step-by-step and a lot of implementation detail will be based off of the details discussed in chapter 3.

4.2.1 Recovering Native semantics.

Below is a list of linux-level semantic information that Droidscope provides along with a very brief summary of how they are implemented. We will not dive deep into this as it is covered in detail in (18), (12), although a basic overview is imperative to understand the higher level working of the system. All or most of the these features were ported from the older version of `Droidscope` with changes as and when required.

1. **Basic block entry/exit callback** - This is a very important concept and will be repeated several times while discussing the implementation. A basic block is defined as a block of ARM(this can be any architecture) instructions terminated by a jump or by a virtual CPU state change which the translator cannot deduce statically. A basic block begin/end is when code jumps into/out of a piece of code form another basic block. This is captured by hooking the translation procedure of QEMU((18), (12), (9)). This is a very powerful tool because a function begin is in essence a basic block begin, hence native functions tracing is built on top of basic block begin tracing as well as a host of other features.

2. **Process map** - A list of all processes running on the guest system and some information like PID, PGD, memory modules loaded. . . for each process. This information

is collected by hooking the `fork` system call (or a variant) of the Linux kernel and reading the kernel's process linked list and looking for newly added processes.

3. **Memory-mapped modules for each process** - All code (+data) required for each process is loaded from the file-system onto memory to be executed. A process's `vm_area_struct` holds a linked list of all loaded modules for the process. We hook kernel functions which mutate this list, and at these hooks, detect new module loads, and collect information like (a) base address at which module is loaded (module_base_address) (b) size of the module (c) name of the module (d) inode_number corresponding to each module etc....

4. **Native function tracing** - On the new version of `Droidscope` we develop a new method of Native function tracing, whereby for each loaded native module, which is basically an ELF binary, or an ELF shared library (essentially the only two places where executable native code exists), as required, we use a file system forensics tool called **"Sleuthkit"**(7) to dump the file corresponding to the inode_number of the module into our host system, use a simple elf disassembler and collect offsets of all exported functions/symbols belonging to the module. Now, (module_base_address + offset) of a function is equal to the address of the function in memory and during a basic block begin callback, when the program counter is equal to (module_base_address + offset) for any function, then that basic block is the beginning of the particular native function. This is a very useful feature and will be used extensively in the sections to come.

5. Apart from these, `Droidscope` provides various other features like, native instruction begin/end callbacks, memory read/write callbacks, module load/unload callbacks, wrapper functions to read a blob of memory from the guest ram etc...

4.2.2 Recovering Java semantics : Introduction

Now that we have a good understanding of how native level semantics are recovered in `Droidscope`, let us discuss how we designed our system on top of these features to give us the same flexibility and features from a Java point-of-view for the new Android run-time (ART). Let us first take up process/java application creation callbacks. Java applications, like native applications are spawned by `forking`, but they differ in that the application name is not resolved when a fork takes places, hence we employ a different approach to track the creation of these processes by 1. making a list of all processes which have been `forked` by an application called `main`, which is the `init` process for every android application. All processes on this list are not android application 2. we hook a function in the `libcutils.so` library called `set_process_name` which is used to set the name of a particular android application. In this hook function we check if the process currently calling `set_process_name` is on our list, if so, we upgrade the process data structure with the name of the application and invoke our android application process begin callback with the accurate name of the application. This is an important tool as a user can now begin tracing of a program by its name.

Next task is recovering java function level semantics, or a Java function callback. During the installation of an application, as discussed before, a compiler/tool `dex2oat` is invoked on the APK to compile it into an ART specific `OatFile`, and one of the arguments that can be passed to this compiler is `dalvik.vm.dex2oat-filter`, the options for which are either `"speed"` or `"interpret-only"`, the former instructs the compiler to translate AS MANY functions as possible into native code leaving the others as interpreted functions, and the latter, commonly used for debugging instructs the compiled to not compile ANY function to native code. By default this argument is set to `"speed"`. **For all intents and purposes, from now on we will consider function tracing as obtaining a trace/names of every single Java function executed by an single application. No packing behavior is expected from the application and that problem will be dealt with after this section, building upon this.** Since there is not really one single function on the Android run-time (ART), as we saw in the previous chapter, we need to come up with a more sophisticated technique to handle both quick code or compiled methods and interpreted methods, in separate independent methods. Let us look at an overview of each implementation following the general algorithm used.

4.2.3 Compiled ART methods

Referring to Figure 3.2 we see that the compiled native methods corresponding to Java methods are present in the very end of the oatfile, and observe that they are laid out very similar to how native functions would be laid out in an executable or native shared library. Hence to trace there methods, we can take a similar approach as tracing native methods, by collecting the offsets of all the compiled methods and corresponding each offset to a Java method (we can collect the name for reference). For native binaries/shared libraries, as their formats are pretty simple, extracting offsets from them is a fairly easy process BUT for oatfiles, we need to follow a different process. The general idea is to obtain the the oatfile belonging to the method, and extract offsets from it.

We know from our discussion in chapter 3 that the function, `void ArtMethod::Invoke (Thread* self, uint32_t* args, uint32_t args_size, JValue* result , const char* shorty)` from `libart.so` is usually used to dispatch a 'compiled method', this by no means covers all compiled methods, but it is sufficient for us to use as a hook point to perform offset extraction from the OatFile belonging to the called ArtMethod. Then next challenge is to discover which module the called ArtMethod belongs, because as we recall the function call is in `libart.so` and ArtMethod is a very simplistic data structure which does not contain any back reference to the originating module. We can reach the DexFile data structure from the ArtMethod data structure and this method will be used for both compiled and native code extraction. Let us discuss that and come back to the offset extraction problem.

`DexFile` data structure form `ArtMethod`

It is important to note that because we are using a dynamic analysis platform, and performing analysis in a plug-in running on the host system and profiling the guest android system, all pointers to these data structures point to memory on the guest RAM and not the host RAM. They cannot be dereferenced directly nor can be used to invoke any class functions, to read field data form a pointer to a data structure in the guest memory, we first need to read a block of memory starting from the pointer upto a size equal to the size of the data structure. We can then cast this block to a pointer to the original data structure and read data from it, BUT caution is be taken as only POD - based data structure can be read with this method, if there are more pointers in the data structure, this process has to be repeated. A sample of this process can be seen in Code Listing 4.1.

Listing 4.1: Sample code showing how guest data structures are read from memory

```
// The ArtMethod is read off of r0
target_ulong called_art_method = env->regs[0];

// Get the ArtMethod from guest memory.
art::mirror::ArtMethod *methodzz;
char block1[SIZEOF_TYPE(art::mirror::ArtMethod)];
DECAF_read_mem_with_pgd(env, pgd_strip(cr3), called_art_method, block1,
            SIZEOF_TYPE(art::mirror::ArtMethod));
methodzz = (art::mirror::ArtMethod *)(block1)
```

Back to the problem at hand, our goal is to find out the module to which this particular ArtMethod belongs to so that we can perform offset extraction form this module, and as the ArtMethod itself does not hold any clue to this, we aim to extract the DexFile Data structure, which holds the base address of the DexFile, and as Figure 3.2 shows us, if we find out which module the DexFile belongs to, and since the DexFile is embedded inside the OAT file, we find the module loaded into memory corresponding to the OatFile. To move from the ArtMethod to the DexFile we follow the following steps

1. The ArtMethod data structure has a field called `HeapReference<Class> declaring_class_;` which is a pointer to the mirror data structure of the class to which this method belongs to. `HeapReference` is just a wrapper around the pointer to the class which is technically on the Java heap. As this data structure is laid out in the class memory completely as a value type, we use the same method as shown in Code Listing 4.1 to first read the ArtMethod from the guest memory and then read the class pointer.

2. Once we have a pointer to the class data structure which was wrapped inside the `HeapReference`, this too does not contain a direct reference to the `DexFile` to which the class belongs to but it contains a `DexCache` data structure which basically holds resolved copies of strings, fields, methods, and classes from the dexfile as well as a pointer to the `DexFile` data strucutre to which this class belongs to (Voila!). We extract the `DexCache` and finally the pointer to the `DexFile` using similar methods explained above.

3. Once we have the `DexFile` pointer, we dump and read the whole `DexFile` data structure. In benign circumstances, the `DexFile` data structure is a treasure which contains a lot of important data required for Virtual machine introspection (VMI), but right now we are only concerned with `const byte* const begin_;` which points, in the guest memory, where the `DexFile` starts.

Offset extraction from the `OatFile`

As mentioned earlier, `DroidScope` provides an API which, given a particular process and an address, returns the module to which this address belongs to. Once we have this information, we dump the `OatFile` from memory completely and extract the offsets based on Algorithm 1. This is a fairly complicated and intricate process were we iterate through essentially each of the `DexFiles` present inside the `OatFile` and then walk each class of every `DexFile`. Then for each class, we do sanity checks to verify the class and finally for each method (`OatMehod`), which contains compiled code, we extract it along with the name of the function and add it to our internal map as seen in Line 30 in Algorithm 1. We internally maintain a data structure such as

MAP[module_base -> MAP[code_offset -> method_name]]

Final `Java` function tracing for native ART methods.

This works well because performing the particular parsing every single time would be highly time consuming and to solve that every module's OatFile offsets are extracted once. Now that we have a all the offsets of `compiled code` in an `OatFile` we can now trace native code execution for the particular application to retrieve `Java` level function call tracing. To achieve this we register for a `Basic Block` begin callback, in which we check first the current module to which this `Basic Block` belongs to, then if this module is an `OatFile` and has offsets extracted for it, we check if the current Program Counter is equal to { `module_base + offset` } for any of the extracted offsets, if so then this is the start of a `Java` function pointed to by the `method_name` corresponding to the `offset` in the MAP.

4.2.4 Interpreted Java methods

Depending on certain options, a large/small part of an android APK is still interpreted. This means that tracing `Java` functions should include tracing of `dalvik` interpreted methods. As discussed in Chapter chapter 3, interpreted methods are ALL dispatched via a function call, `bool DoCall(ArtMethod* method, Thread* self, ShadowFrame& shadow_frame, const Instruction* inst, uint16_t inst_data, JValue* result)` in the Android run-time (ART). Simply hooking this function and employing a simple process to extract the name of the method from the `ArtMethod` will be sufficient.

Algorithm 1 Extract offsets of each compiled method from the OatFile

```
procedure EXTRACT_ART_OFFSETS__(module_base, module_size, module_name, process_identifier)
    if module_base == extracted then
        Return
    end if
    oat_file_contents ← ReadGuestMemory(process_identifier
                                        , module_base, module_size)
    oat_file_valid ← CheckOatMagic(oat_file_contents)
    if oat_file_valid == false then
        Return
    end if
    host_oat_file_dump ← DumpContentsToFile(oat_file_contents
                                            , module_name)
    oat_file ← artOatFileOpenMemory(oat_file_contents, host_oat_file_dump)
    if OatFile == nullptr then
        Return
    end if
    oat_dex_files_ ← oat_file->GetOatDexFiles()
    for each oat_dex_file_ in oat_dex_files_ do
        dex_file ← oat_dex_file_->OpenDexFile()
        class_defs ← dex_file->GetClassDefs()
        for each class_def in class_defs do
            oat_class ← oat_dex_file_->GetOatClass(class_def)
            class_data ← dex_file->GetClassData(class_def)

            if class_data != nullptr then
                oat_methods ← oat_class->GetOatMethods()
                for each oat_method in oat_methods do
                    method_name ← PrettyMethod(oat_method)
                    code_offset ← oat_method->GetCodeOffset()
                    AddOffsetAndNameToMap(module_base, method_name
                                          , code_offset)
                end for
            end if
        end for
    end for
end procedure
```

Java Function name from `ArtMethod`

Since just hooking the above mentioned function will give us full coverage of all interpreted functions, we can go ahead by extracting the function name. To do so we can start with the first argument, the `ArtMethod`. In an android APK, the `DexFile` present inside the `OatFile` is the only location where strings like method names, class names, parameter list... are present. The `DexFile` contains a field `MethodId` for all methods present in the file, this contains offsets into the `DexFile` to other important data structures like the class to which the method belongs to, the name of the method.... The `DexFile` also contains an array of `StringId` data structure for all strings present in the file, were each `StringId` essentially contains the offset to the particular string from the beginning of the `DexFile` and any other data structure in the `DexFile`, which needs to point to a string, hold a reference into this array. Hence to extract the name we perform the following steps

1. Extract the `DexFile` from the `ArtMethod` as described in section 4.2.3.

2. Read the `dex_method_index_` field from the `ArtMethod` which is essentially an index into the `MethodId` array pointing to the `MethodId` for this particular method.

3. Read that particular `MethodId` from the `DexFile` and extract the `name_idx_` field in it, which is essentially an index into the `StringId` array pointing to the name of this particular method.

4. Read the particular `StringId`, which contains a field `string_data_off_` which is the offset of a `leb128 encoded` string from the beginning of the `DexFile`

5. Decode and read the string present at the address (`dex_file_begin_ + string_data_off_` and print/dump out the function name.

4.2.5 Recovering Java semantics : Final Picture

Now, in this section we combine the algorithms from subsection 4.2.3 and subsection 4.2.4 into a single algorithm and showcase its implantation on `Droidscope`. Algorithm-2 summarizes the process of java api tracing by covering both interpreted and native java functions in an abstract view. The process is implemented in a `basic-block (BB)` begin callback (CB) function in `Droidscope:ART`. As discussed in subsection 4.2.1, a `basic-block (BB)` is defined as a block of ARM(this can be any architecture) instructions terminated by a jump or by a virtual CPU state change which the translator cannot deduce statically and a basic block begin/end is when code jumps into/out of a piece of block of code from another basic block. We begin in the callback to check if the CB belongs to the process being tracked, if so we extract the native function call correspond to this BB (only if the BB is the first one of a function then that is a function call). If this a call to `doCall...` or `ArtMethod::Invoke`, the two functions that we have talked about, then we follow the process described in section 4.2.3 to extract the `DexFile` from the `ArtMethod`. Once we have the `DexFile`. If the function call was to `ArtMethod::Invoke`, then we go ahead and extract all the compiled method offsets from the particular `DexFile`'s `OatFile`. If the function call was to `doCall...` then we go ahead and extract the function name for the particular `ArtMethod` with the process as described in section 4.2.4 and dump it.

After this is done, we check if the the current module, to which this basic block belongs is an `OatFile` of which he have extracted offsets for. If so, we check if the current program counter is equal to the sum of the module's base address plus one of these offsets. If so, we extract the function name corresponding to the offset and dump this.

Algorithm 2 JAVA API Call tracer for `Droidscope : ART`

```
procedure BLOCK_BEGIN_CB(cpu_state_information)
    current_pc ← GetCurrentPc(cpu_state_information)
    current_cr3 ← GetCurrentCr3(cpu_state_information)
    if (current_cr3! = tracked_cr3) then
        Return
    end if
    current_module ← GetCurrentModule(cpu_state_information)
    if (current_module == "libart.so") then
        current_function ← GetCurrentFucntion(cpu_state_information)
        if (current_function == ("doCall..."||"ArtMethod :: Invoke...") then
            dex_file ← GetDexFileFromArtMethod()(section 4.2.3)
            dex_file_module ← GetModuleForAddress(dex_file.begin_)
            if (current_function == "ArtMethod :: Invoke...") then
                EXTRACT_ART_OFFSETS__(dex_file_module)[Function − 1]
                Return
            else
                dex_method_name ← GetDexMethodName(dex_file, art_method)
                                                            (section 4.2.4)
                DUMP_FUNCTION_NAME(dex_method_name)
                Return
            end if
        end if
    end if
    if (ArtOffsetsForModuleBase(dex_file.begin_) == TRUE) then
        dex_method_name ← GetDexMethodNameForOffset(current_pc)
        DUMP_FUNCTION_NAME(dex_method_name)
        Return
    end if
end procedure
```

Chapter 5

DroidUnpack

Now that we have a solid understanding of the execution environment on the Android runtime (ART) and a reliable analysis engine which is able to get a complete execution trace of Java function calls made by an application, we can build our unpacker on top of it. Before we proceed we present a series of objectives that we want to be able to achieve with this unpacker.

5.1 Objectives

1. A generic unpacker which is able to dump/log the code execution of every single Java function for a packed android application regardless of features used by a packer.

2. Furthermore, the unpacker should be able to log all memory writes made by the application and automatically detect if any of these regions in memory was executed.

5.2 Code Extraction

Although we were able to implement Java function call tracing successfully, special care must be taken to track the execution of packed applications. Runtime packers try very hard to obfuscate their true intentions and make it very hard for a security analyst to study execution flow of the application. Additional to this we need to extract code, `dalvik` byte-code for interpreted method and `arm` instructions for native ART methods as function names are sometimes simply obfuscated/mangled by a packer and hence simply extracting function name is insufficient for a security analyst to perform further evaluation. What data structures to read and how to do so from memory should be carefully chosen because runtime packers sometimes perform selective unpacking, header mangling etc which means that the extraction technique must be immune to these features. The following approach is used for native and interpreted method,

1. Native methods: One of the challenges of the new Android run-time (ART) was to study the execution of native code in a Java context. Every time we detect the beginning of a compiled ART function, because we have extracted the offsets beforehand from the `OatFile` we have also collected the size in memory of these methods. We go ahead and dump the native code from the start to its end. For good analysis it is preferred to have `dalvik` byte code for all functions rather than native code to keep things consistent, but this is a harder challenge because strict checks are performed on the ART native code, but no strict checks are performed on the byte code during installation. Hence a packer can, after installation wipe out all the dalvik byte-code from the dex files in memory, because they are not required for the execution of the application. The only option to make the most generic would be to disassemble the native code into byte-code, this is a particularly challenging problem and is under our future plans.

2. Interpreted functions: Interpreted methods are comparatively easier in that, each interpreted functions is assigned a data structure in the Android run-time (ART), called DexFile::CodeItem, shown in Listing 5.1. Similar to extracting the name of the function for interpreted functions, the `ArtMethod` data structure holds an reference its `CodeItem` data structure present in its `DexFile`. We proceed by extracting this data structure and disassembling/logging `insns_size_in_code_units_` number of

instructions starting from `insns_` as seen in `CodeItem`.

Listing 5.1: DexFile::CodeItem

```
// Raw code_item.
struct CodeItem {
  uint16_t registers_size_;
  uint16_t ins_size_;
  uint16_t outs_size_;
  uint16_t tries_size_;
  uint32_t debug_info_off_;
          // file offset to debug info stream
  uint32_t insns_size_in_code_units_;
          // size of the insns array, in 2 byte code units
  uint16_t insns_[1];
};
```

5.3 Unpacking algorithm and other features.

The unpacker is essentially a plugin on `Droidscope:ART` which is developed on top of the Java API tracer plugin we described previously with some additional features added. With very little addition to the JAVA API tracer, we are able to implement a generic, robust unpacker for the latest Android run-time (ART) as seen in Algorithm-3. We insert an additional memory write callback, which essentially records all memory writes made by an application. Since these packers tend to dynamically write into the target `OatFile` to correct portions of the code before execution, we can study such behavior with the help of this callback. Apart from this the only additional features is the code extraction which is performed for each method, as described in section 5.2.

Algorithm 3 `DroidUnpack` plugin for `Droidscope:ART`

```
procedure MEMORY_WRITE_CALLBACK(virtual_address, cpu_state_information)
    current_cr3 ← GetCurrentCr3(cpu_state_information)

    if (current_cr3! = tracked_cr3) then
        Return
    end if
    RecordAddressWrite(virtual_address)
end procedure

procedure BLOCK_BEGIN_CB(cpu_state_information)
    current_pc ← GetCurrentPc(cpu_state_information)
    current_cr3 ← GetCurrentCr3(cpu_state_information)

    if (current_cr3! = tracked_cr3) then
        Return
    end if

    current_module ← GetCurrentModule(cpu_state_information)

    if (current_module == "libart.so") then

        current_function ← GetCurrentFucntion(cpu_state_information)

        if (current_function == ("doCall..."||"ArtMethod :: Invoke...") then

            dex_file ← GetDexFileFromArtMethod()(section 4.2.3)
            dex_file_module ← GetModuleForAddress(dex_file.begin_)

            if (current_function == "ArtMethod :: Invoke...") then

                if (art_offsets_extracted(dex_file_module) == TRUE)OR
(dirty_memory_write_in_module(dex_file_module == TRUE) then
                    EXTRACT_ART_OFFSETS__(dex_file_module)[Function − 1]
                end if
                Return
            else
                dex_method_name ← GetDexMethodName(dex_file, art_method)
                                                    (section 4.2.4)
                DUMP_FUNCTION_NAME(dex_method_name)
                dex_code_item ← GetDexCodeItem(dex_file, art_method)
                DUMP_CODE_CODE(dex_code_item)
                Return
            end if
        end if
    end if
```

```
    if (ArtOffsetsForModuleBase(dex_file.begin_) == TRUE) then
        dex_method_name ← GetDexNativeMethodNameForOffset(current_pc)
        dex_method_size ← GetDexNativeMethodSizeForOffset(current_pc)
        dump_function_name(dex_method_name)
        if (DirtyMemoryInRange(current_pc, current_pc+dex_method_size) == TRUE) then
            dump_dirty_code_metadata()
        end if
        Return
    end if
end procedure
```

Chapter 6

Results

6.1 Overall results

We conduct a simple evaluation to measure the veracity of our work, by running the same unpacker plugin, unchanged on 10 applications each packed by 6 standard commercial packers, **" Alibaba Inc."**(1), **" Qihoo360 Inc."**(6), **"Tencent Inc."**(8), **"Bangcle Inc."**(4), **"Baidu Inc."**(3) and **"Ijiami Inc."**(5), as well as on the unpacked application. Verifications was done manually on the results (function call and code dumps) comparing the result of each packer with the that from the unpacked application. We were successfully able to extract code from 5 of the 6 packers we tested with for all applications except for the `Qihoo360 Inc` packer which incorporates an anti-emulation feature. The results are seen in Table 6.1. We compare each of the packer with data extracted from the original unpacked version of the application present 3 parameters, `Code unpacked %(CU)`, which is simply amount of original function flow we could extract from the packed samples, `Dirty Native Code %`, which was the percentage of compiled native java functions which were dynamically mutated by the application during the runtime of the application and finally `Dirty Dalvik Code %`, a similar parameter which indicates the percentage of interpreted Dalvik functions which were dynamically mutated. In the next section we take a look at all these packers

Table 6.1: Overall Comparison

			Packers					
			Alibaba Inc	Baidu Inc	Bangcle Inc	Ijiami Inc	Qihoo360 Inc	Tencent Inc
Applications	com.banasiak.coinflip	CU % [1]	100	100	100	100	-	100
		DNC[%] [2]	X	X	✓[89.41]	X	X	X
		DDC[%] [3]	✓[100]	✓[70.37]	✓[13]	✓[3.57]	X	X
	io.github.sanbeg.flashlight	CU %	100	100	100	100	-	100
		DNC[%]	X	X	X	X	X	X
		DDC[%]	✓[100]	✓[62.5]	✓[3.59]	✓[20]	X	X
	com.frankcalise.h2droid	CU %	100	100	100	100	-	100
		DNC[%]	X	X	✓[90]	X	X	X
		DDC[%]	✓[100]	✓[89.47]	✓[2.08]	✓[9.52]	X	X
	com.tortuca.holoken	CU %	100	100	100	100	-	100
		DNC[%]	X	X	✓[85.33]	X	X	X
		DDC[%]	✓[100]	✓[16.98]	✓[8.51]	✓[3.64]	X	X
	ru.gelin.android.browser.open	CU %	100	100	100	100	-	100
		DNC[%]	X	X	✓[3.8]	X	X	X
		DDC[%]	✓[65.06]	✓[10.86]	✓[4.64]	✓[4.17]	X	X
	edu.killerud.fileexplorer	CU %	100	100	100	100	-	100
		DNC[%]	X	X	✓[13.63]	X	X	X
		DDC[%]	✓[100]	✓[55.55]	✓[3.59]	✓[18.18]	X	X
	edu.killerud	CU %	100	100	100	100	-	100
		DNC[%]	X	X	✓[15]	X	X	X
		DDC[%]	✓[100]	✓[71.42]	✓[1.7]	✓[22.22]	X	X
	de.boesling.hydromemo	CU %	100	100	100	100	-	100
		DNC[%]	X	X	✓[97.36]	X	X	X
		DDC[%]	✓[100]	✓[31.25]	✓[7.45]	✓[11.11]	X	X

individually, for one of the applications, `com.banasiak.coinflip`.

[1] Code Unpacked %.
[2] Dirty Native Code[%]
[3] Dirty Dalvik Code[%]

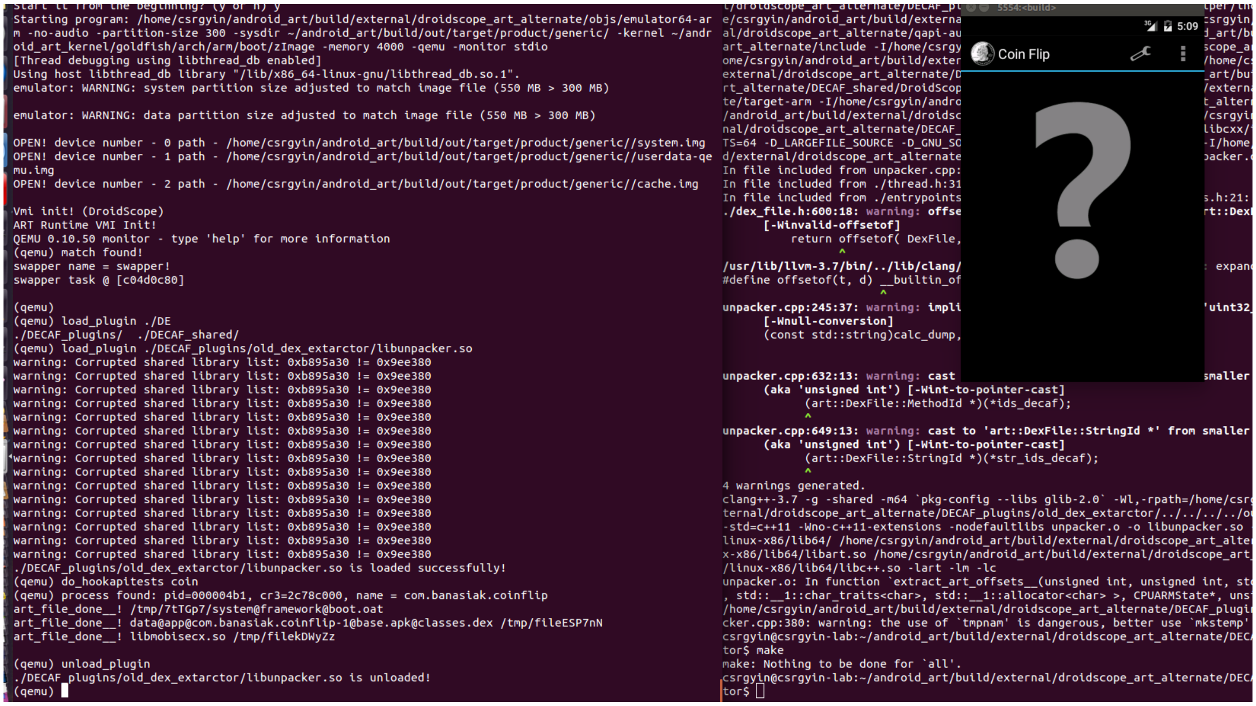


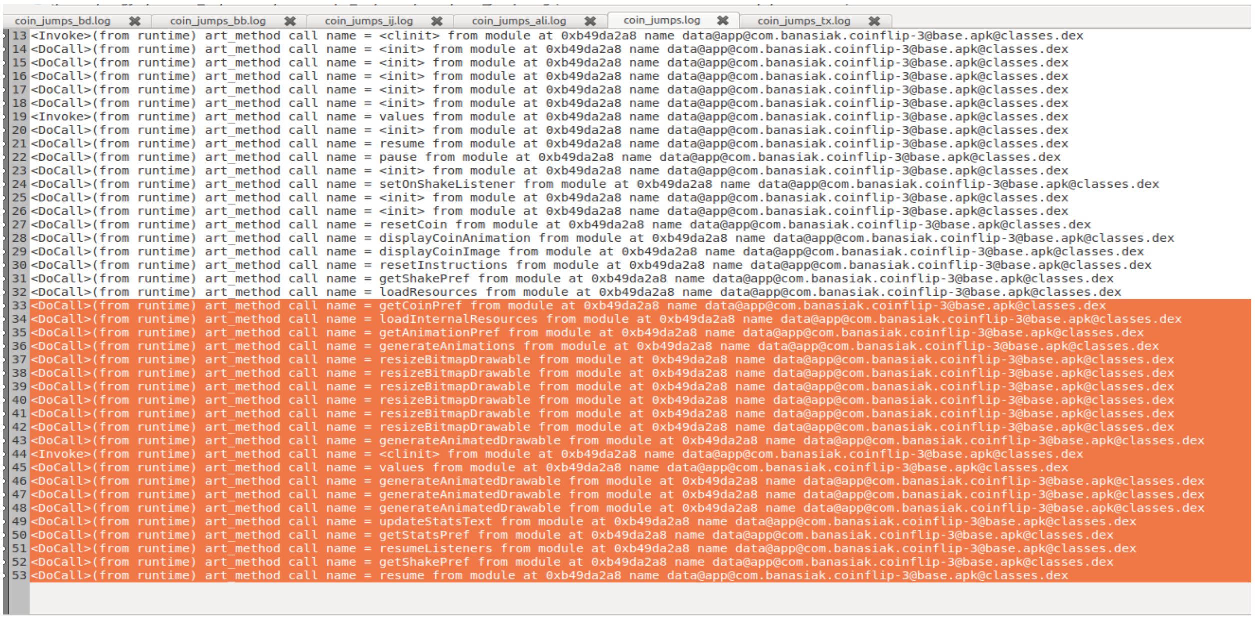
Figure 6.1: Behavior of the Alibaba packer.

6.2 Case Studies

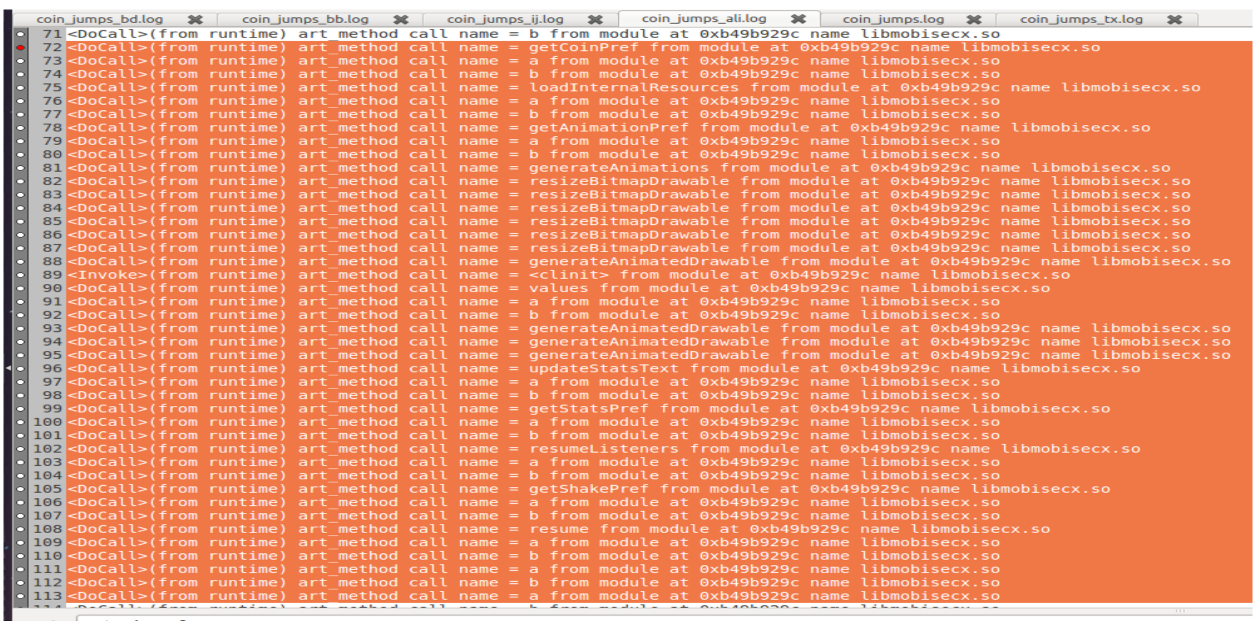
6.2.1 Alibaba Inc.

This packer adds two shared libraries, `libmobisec.so` and `libmobisecx.so` into the APK. The original `.dex` file is packed and encrypted and its replaced by a standard custom made `.dex` file which acts as a launchpad to bring up their shared library, `libmobisec.so`, which performs bulk of the unpacking. This library itself is obfuscated and it corrects itself, extracts the the original `.dex` file and loads the it into the shared library `libmobisecx.so`, which is under its control which can be observed in Figure 6.1. We see that three `ART/OAT files` were loaded, the first one being the `framework` file, the second being their launchpad file and the third the actual application. We can verify this is the java function traces.

We see in Figure 6.2 the comparison of the java api trace between the `Alibaba` packer and the unpacked application. We see that we have been able to successfully get the same functions flow as the unpacked application even with this application being packed. Also, it is interesting to see that every function call made to the original `.dex` file is followed and preceded by custom function calls. The packer has inserted these functions calls to inject a form of indirection which would render many analysis techniques fruitless. Also interesting to note is that as we observed before, the `.dex` file is actually embedded in their own shared library. This is a clever strategy as it gives the packer full control of the read/write into the code, but as we discussed in the our motivation section, we rely on the fact that the for the application to execute naturally, it has to adhere to certain constraints imposed by the Android run-time (ART), meaning that some data structures in the run-time can never be mutated and we exploit this to unpack there applications.



(a) JAVA function call trace from the unpacked application.



(b) JAVA function call trace from the application packed with ALI.

Figure 6.2: Comparing the JAVA api traces between the unpacked and the packed application output both obtained from our unpacker plugin.

6.2.2 Baidu Inc.

Similar to the previous packer, `Baidu` includes a custom shared library `libbaiduprotect.so` which performs the similar role of decrypting/unloading and starting the application. Here as seen in Figure 6.3, the packer spawn another child process where the actual application is executed. We also observe that the framework, the launchpad and the actual `ART/OAT` files were successfully loaded and the target file is actually present in the heap. Let us now have a look at the java api calls.

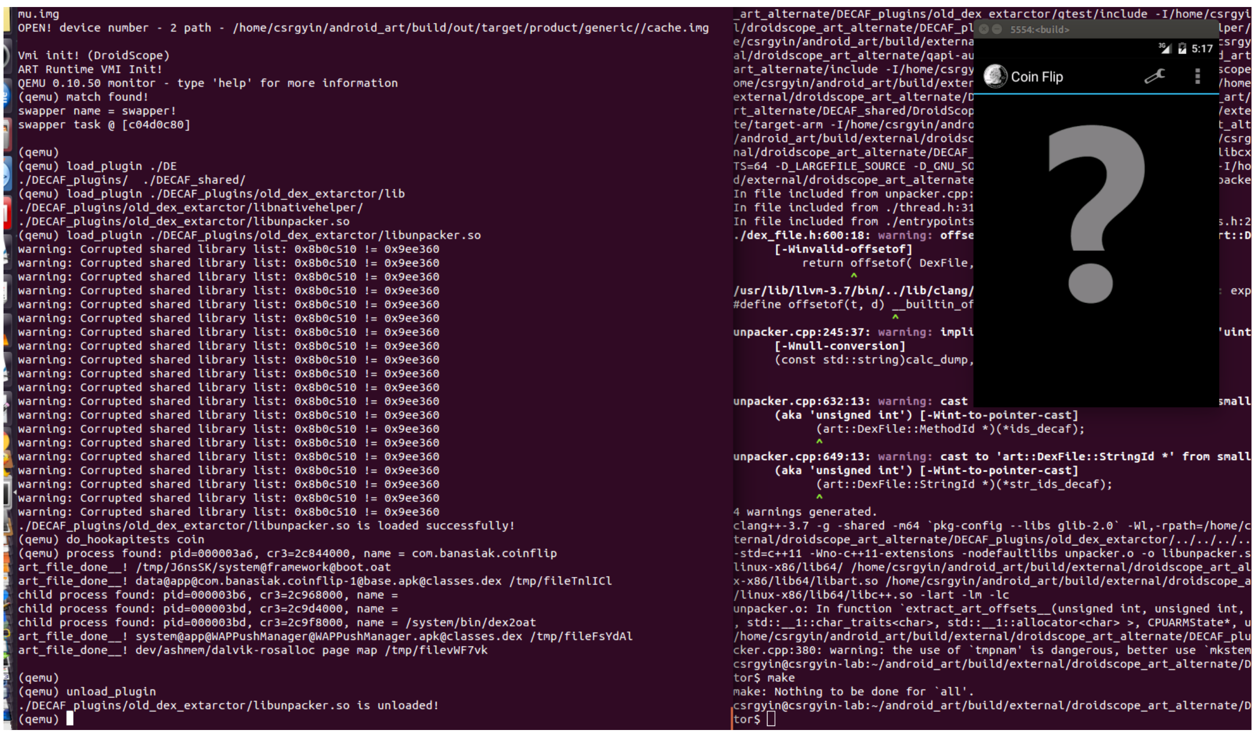
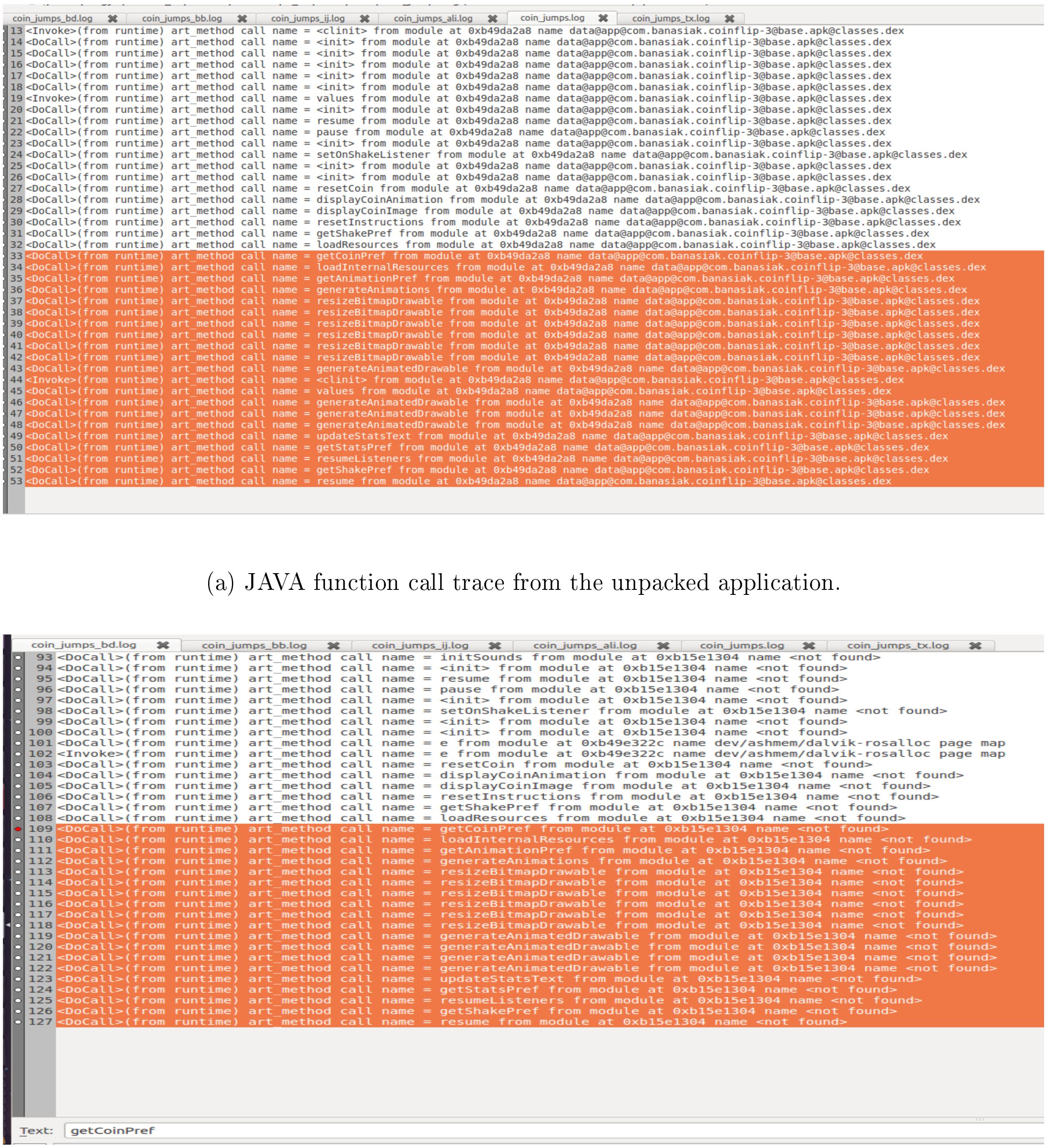


Figure 6.3: Behavior of the Baidu packer.

As we observe the java api calls in the compare them with the the unpacked application, in Figure 6.4 we see that again we are able to successfully unpack the application. It is interesting to note here that the target application is actually loaded somewhere on the heap/dynamically allocated memory.



(a) JAVA function call trace from the unpacked application.

(b) JAVA function call trace from the application packed with Baidu.

Figure 6.4: Comparing the JAVA api traces between the unpacked and the packed application output both obtained from our unpacker plugin.

6.2.3 Bangcle Inc.

Bangcle was one of the more sophisticated packers, with more packing features employed than others. The shared library used was `libsecexe.so` which performed the unpacking. The actual code was contained in a `classes.dex` file which was dynamically recovered and loaded into memory to start the application. The packer employed sever child process, one of them to observe for p-trace based debugging detection and the other where the application was actually loaded. The interesting part of this packer is that it employed another `.dex` file, called `container.dex` which actually performed runtime unpacking of the application as it executed (more on this in the next paragraph). Also interesting to note was that unlike other packers that we studied, Bangcle's target/actual application had all of its functions compiled into native ART functions. We see this behavior in Figure 6.5. Now lets take a look at some of the more interesting features employed by this packer.

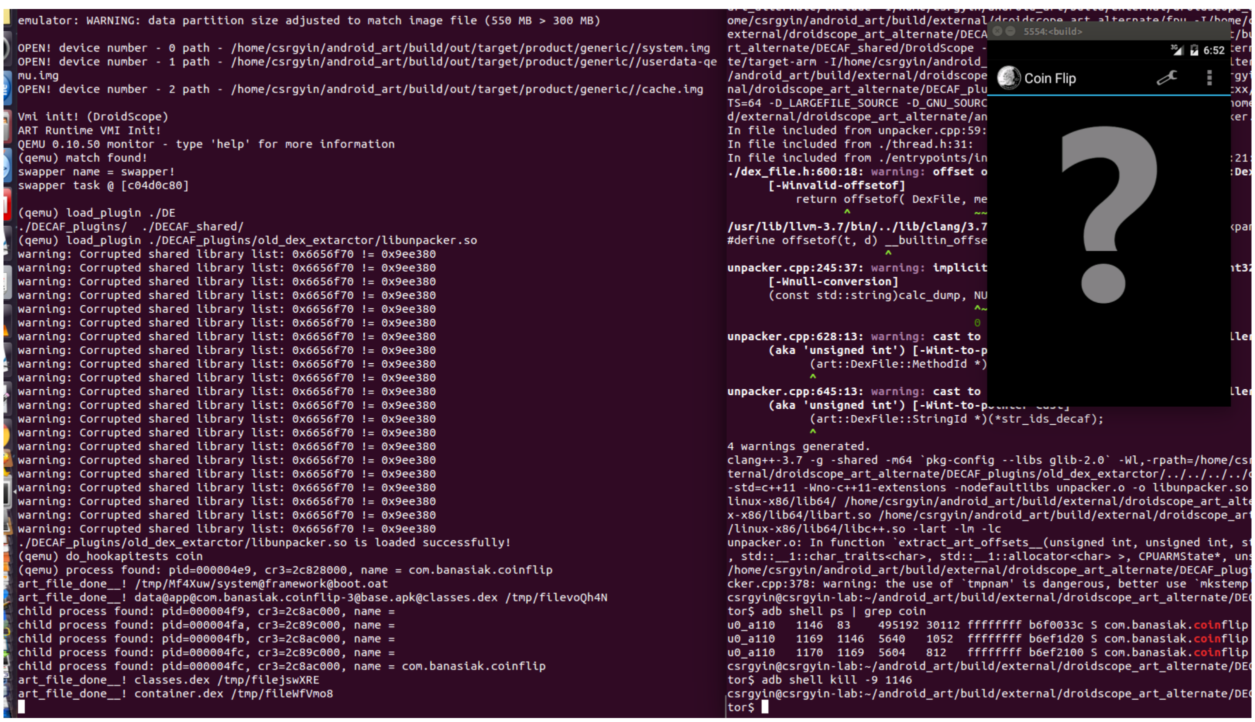


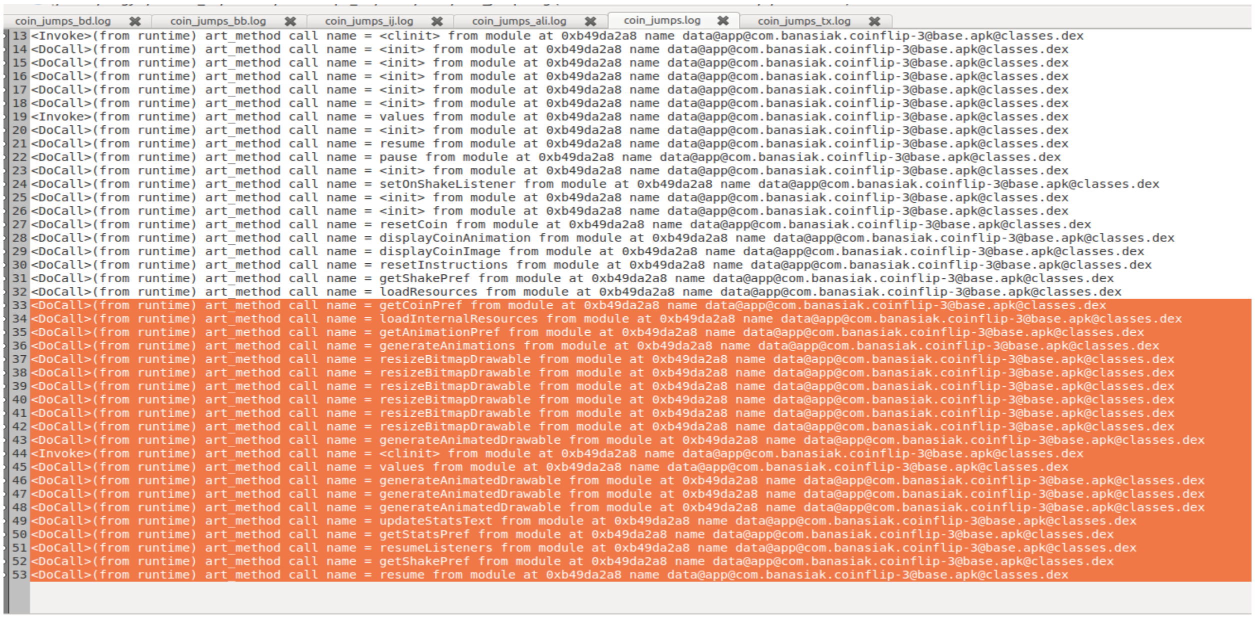
Figure 6.5: Behavior of the Bangcle packer.

Some interesting features

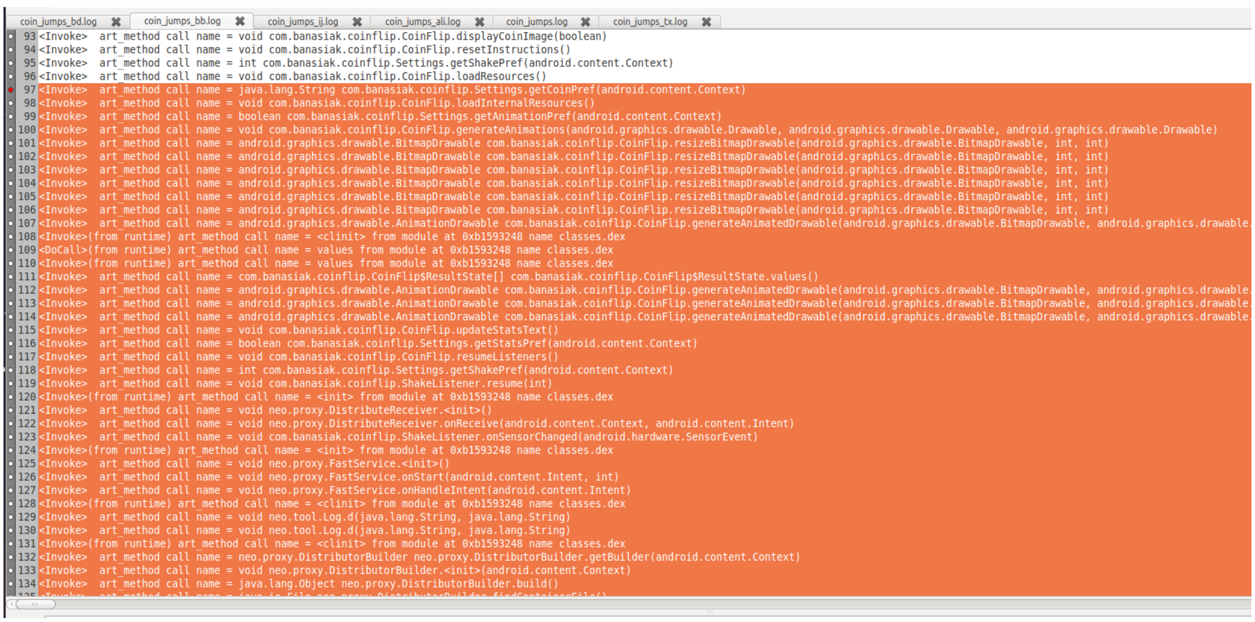
The most interesting feature about the Bangcle packer is the `container.dex`. This is actually an application launched by the parent application (most likely from the shared library) and acts as an ACTUAL container to the original application. What this means is that all data (like strings, classes, resources...) are encrypted when the application starts up and when there is a request to any of these elements, they are trapped by the `container.dex` application which decrypts the required data at runtime and provides it to the application. A more longer version of the api behavior of Bangcle can be found in Appendix for an interested user. Here in the shorter version in Figure 6.6 where we see that despite these efforts by the packer we are able to successfully unpack the application.

6.3 Ijiami Inc.

Similar to the other packers, Ijiami unloads its packed `OAT` file onto a file named `“.1”`, as seen in Figure 6.7 compiles this application (we see the invocation to `dex2oat`) and after the application starts, deletes the backing file making it difficult for a security analyst to unpack the application. In Figure 6.8 we see that we are successfully able to recover the accurate execution trace of the application compared to its unpacked application.



(a) JAVA function call trace from the unpacked application.



(b) JAVA function call trace from the application packed with Bangcle.

Figure 6.6: Comparing the JAVA API traces between the unpacked and the packed application output both obtained from our unpacker plugin.

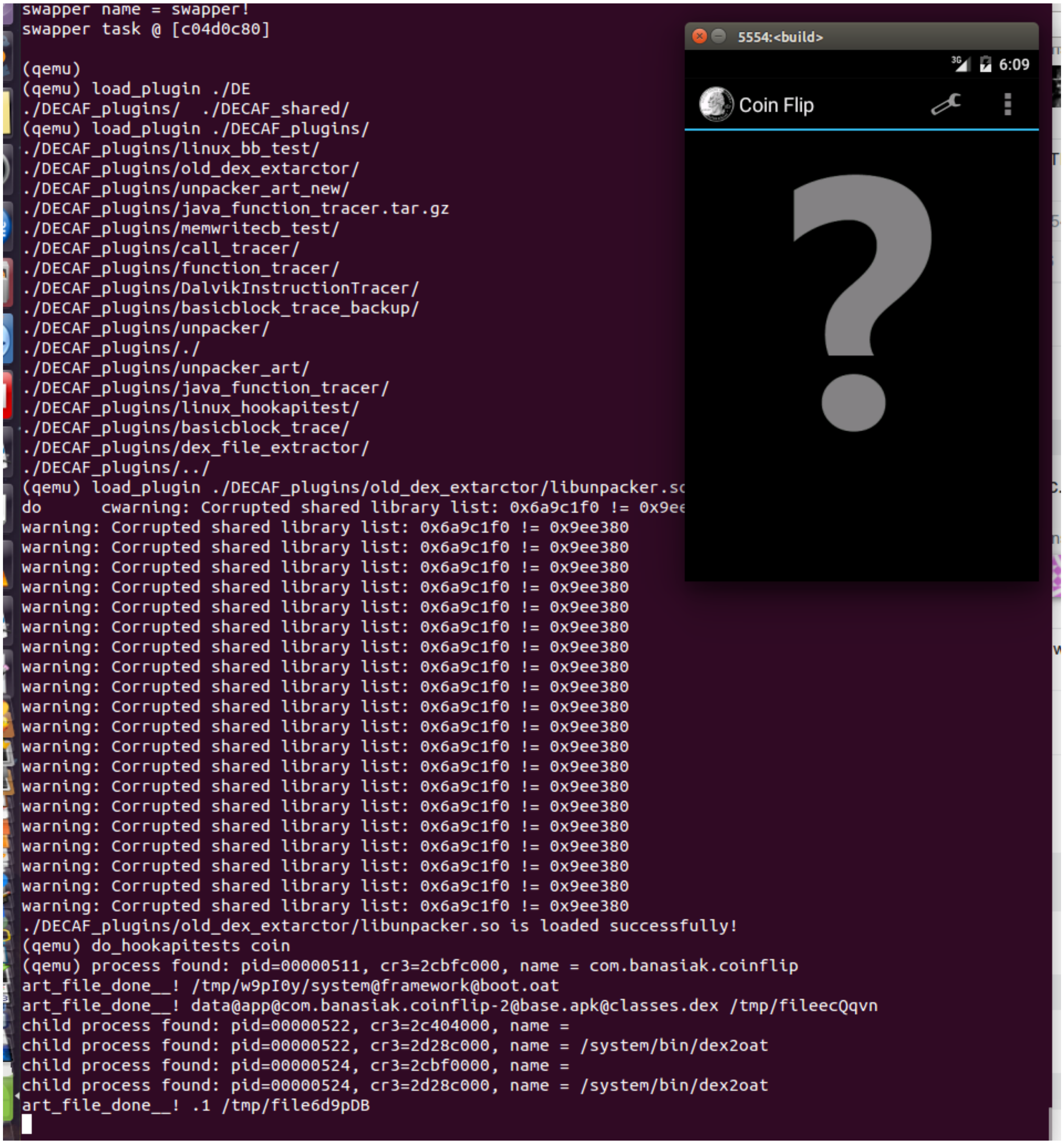
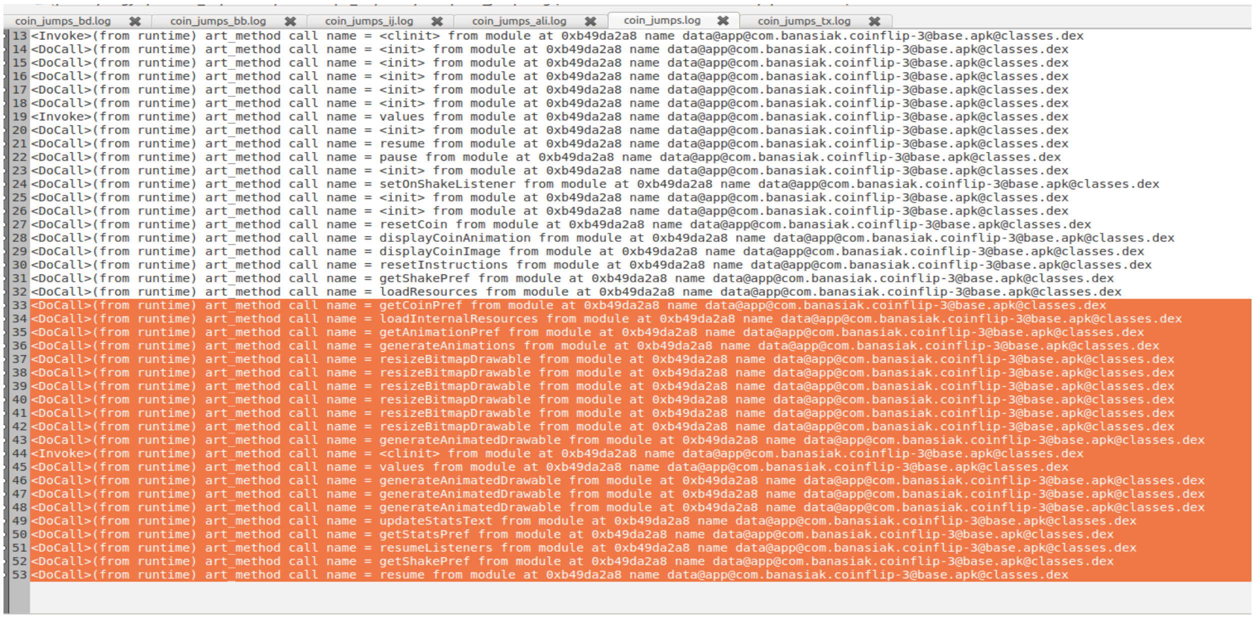
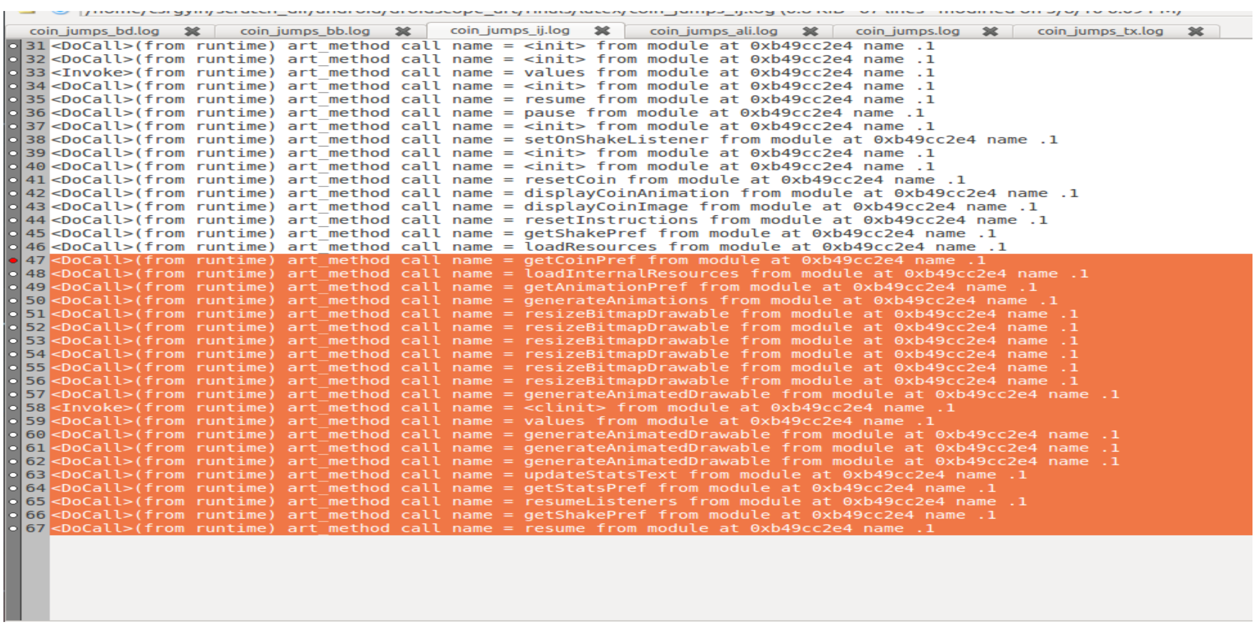


Figure 6.7: Behavior of the Ijiami packer.



(a) JAVA function call trace from the unpacked application.



(b) JAVA function call trace from the application packed with Ijiami.

Figure 6.8: Comparing the JAVA api traces between the unpacked and the packed application output both obtained from our unpacker plugin.

6.4 Qihoo360 Inc.

This unpacker employed an emulator detector which crashes the application on the android emulator. We see in Figure 6.9 that the application actually starts, invokes some shell commands and crashes unexpectedly.

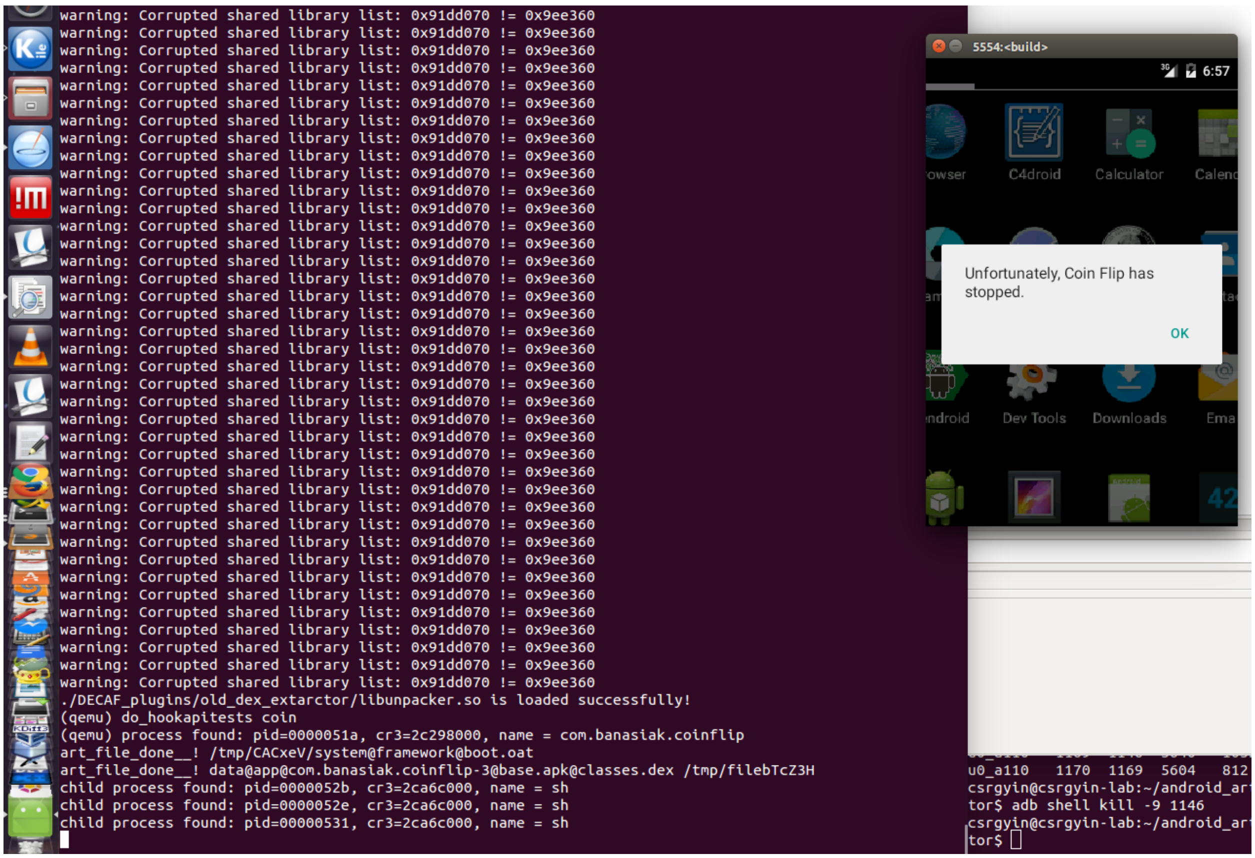


Figure 6.9: Behavior of the Qihoo360 packer.

6.5 Tencent Inc.

Behavior was similar to other packers, the target `ART/OAT` file is loaded onto the dynamic heap and the executed as seen in Figure 6.10 and we see in Figure 6.11, successful code extraction.

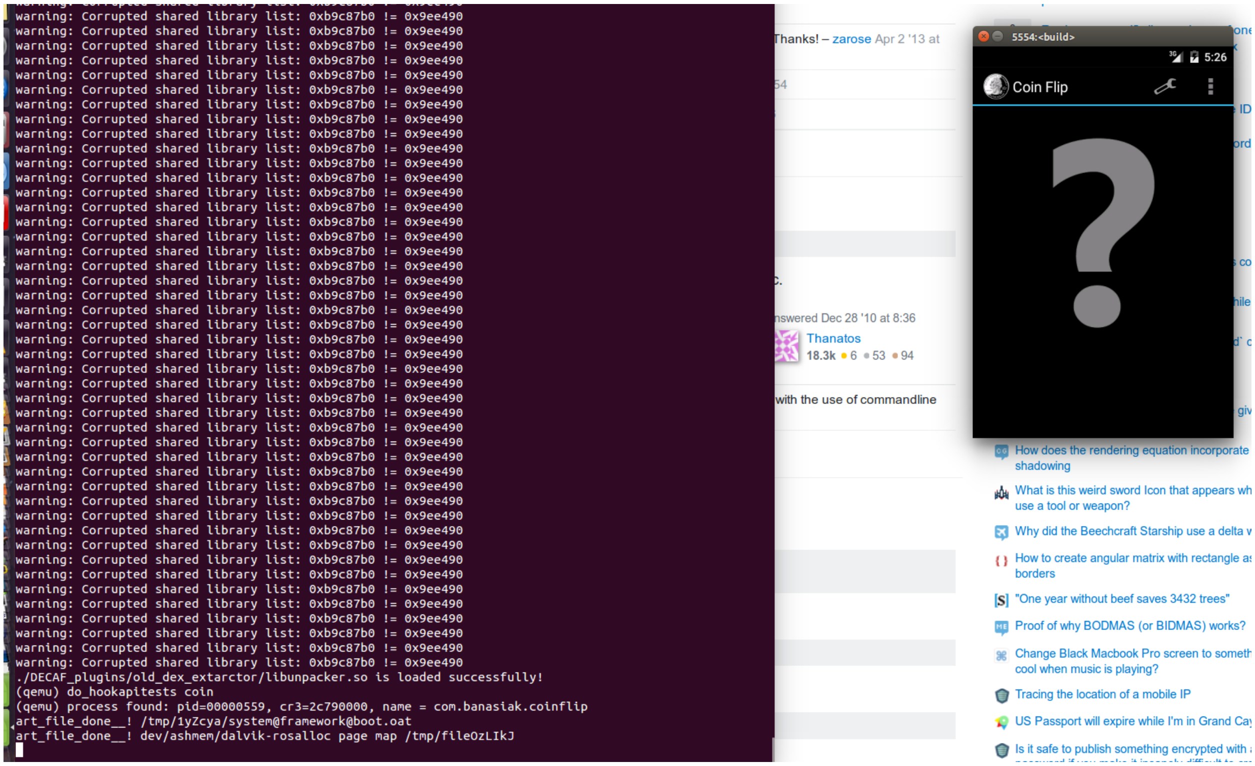
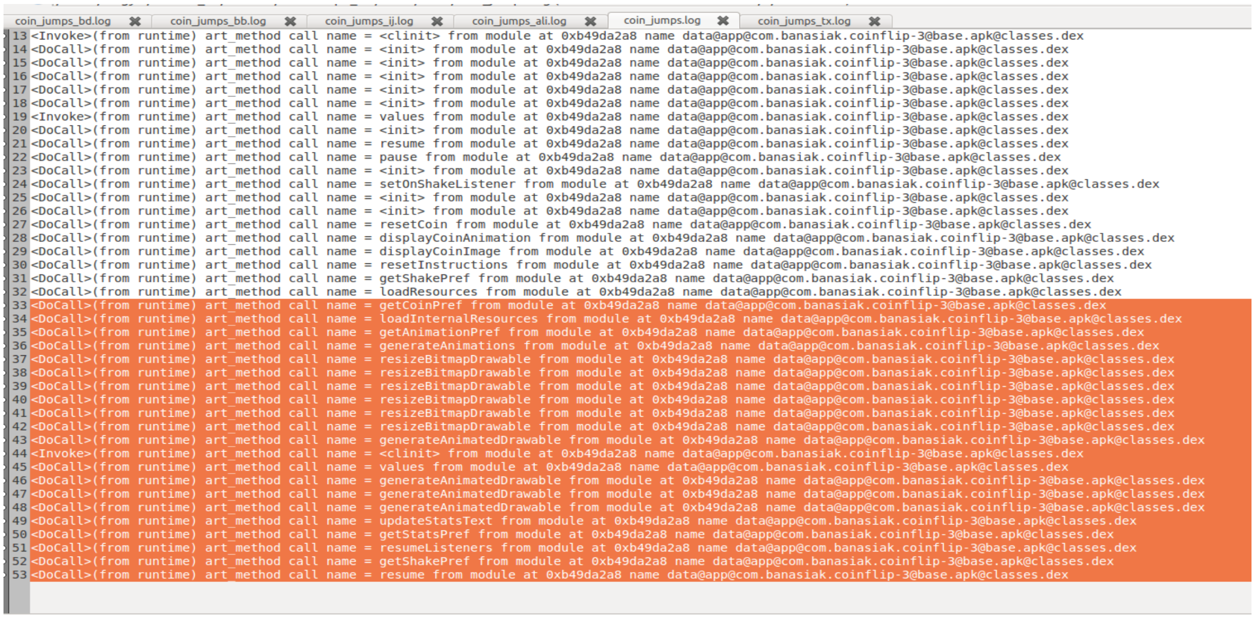
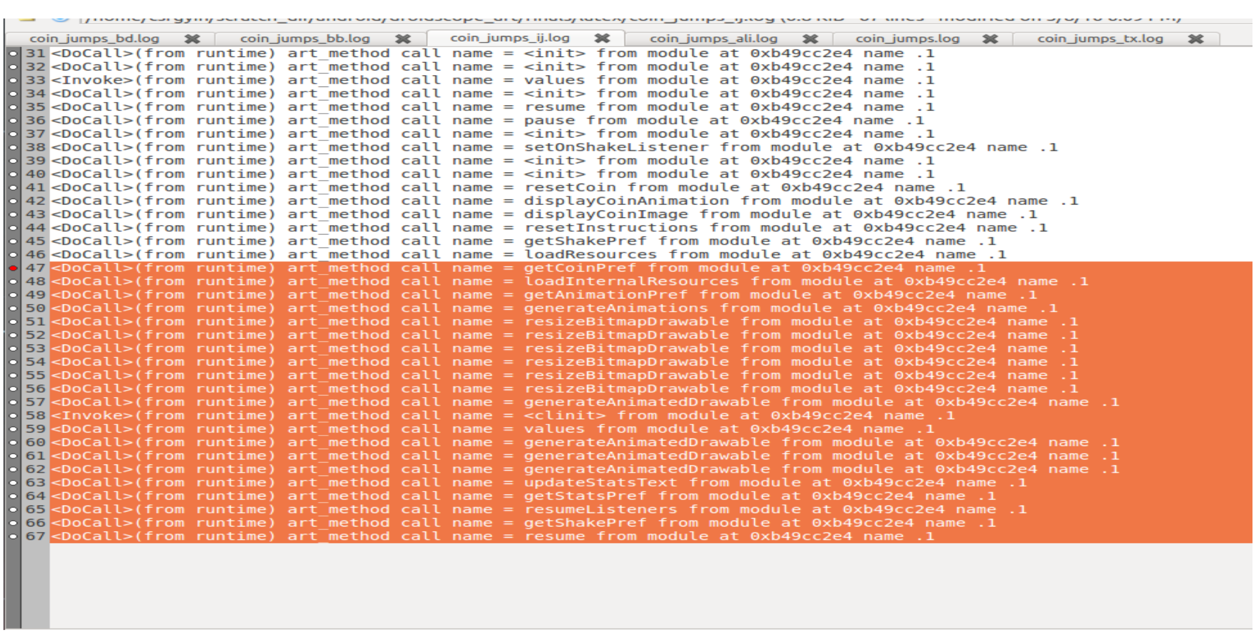


Figure 6.10: Behavior of the Tencent packer.



(a) JAVA function call trace from the unpacked application.



(b) JAVA function call trace from the application packed with Tencent.

Figure 6.11: Comparing the JAVA api traces between the unpacked and the packed application output both obtained from our unpacker plugin.

Chapter 7

Conclusion and Future work

7.1 Conclusion

In the years to come, the android execution environment will shift more towards the design of the new Android run-time (ART) to keep pace with other platforms like the `iOS` who's complete execution is done as native code. In this project, `Droidunpack` we essentially provide a strong dynamic analysis framework, based on the new Android run-time (ART) to set the stage for performing research projects on the framework. In the process of doing so we study the ART in an exhaustive way in all its relevant aspects and present them for an interested security analyst. We then summarize the gist of important features required for us to implement a platform which will provide us with various Virtual machine introspection (VMI) features. Additionally, we are precisely able to recover both native and Java level semantics for Android applications on the new Android run-time (ART).

We lay out the necessary foundations required for the construction of a generic android unpacker. We briefly describe some of the work that has been done on unpacking android applications, their strengths and shortcomings. Acknowledging these factors, we look at the problem from a new perspective. We argue that for any packed android application, with the core of its original application written in java, regardless of what packer was used, has to conform to some strict rules imposed by the Android run-time (ART), in that certain data structures in the run-time are beyond the control of a packer. With this, we design our unpacker by tapping into certain key events in the run-time of an application to successfully perform unpacking of the application. We then evaluate the unpacker against some of the standard commercial packers to verify the working and accuracy of the unpacker.

7.2 Drawbacks

Although we provide a robust and generic unpacking framework, it suffers from some small issues like code-coverage and anti-emulation detection features. We unpack and extract all the code executed by the application, with 'executed' being the key word. Since android is a GUI based environment, simple testing where we start the application, trace it for some fixed time and kill it will cover lesser code than what is actually present. This means that in essence we are not able to cover and unpack the source code of the whole application. This is a particularly difficult problem since packers employ features where they unpack a function right before it is dispatched and decrypt it again after it finishes execution. In such a case, it becomes a lot more difficult to generically unpack the complete application. To address this we present some interesting plans that we mean to implement. Anti-emulation is a bane for dynamic analysis tools based on emulators. Although there are no plain solutions to this problem, there are always anti-anti-emulation tools to help avoid these to an extent.

7.2.1 Breaking out of `DroidUnpack`

One other important topic to think about is how attackers can subvert such an unpacking mechanism. Apart from having anti-emulation stubs installed, an attacker can carefully move the original implementation of the application, into native `JNI` code. Although a sophisticated process, the user can find a way to convert the java/dalvik code present in the APK into a custom representation and move it into shared native libraries, hence breaking out of the the ART runtime.

7.3 Future Work

As next steps in the evaluation of this project we plan to perform more large scale analysis on a huge data-set of malicious/benign Android applications in the wild, to better understand a trend in their design and behavior. To address the problem of code coverage, we plan to design an engine for force execution of java functions combined with the unpacker.

Appendix A

Source code excerpts from the `DroidUnpack` plug-in.

Below is a small cut-down version of the unpacker plug-in. Code Listing A.1 basically provides the implementation of the different algorithms discussed in the document. Only the important callback functions are listed and other parts of the code are omitted to keep it compact.

Listing A.1: Source code from the `DroidUnpack` plug-in.

```
/*
Copyright (C) <2012> <Syracuse System Security (Sycure) Lab>
This is a plugin of DECAF. You can redistribute and modify it
under the terms of BSD license but it is made available
WITHOUT ANY WARRANTY. See the top-level COPYING file for more details.

For more information about DECAF and other softwares, see our
web site at:
http://sycurelab.ecs.syr.edu/

If you have any questions about DECAF,please post it on
http://code.google.com/p/decaf-platform/
*/
/**
* @author Abhishek VB
* @date June 22 2015
*/

static void SkipAllFields(art::ClassDataItemIterator& it) {
  while (it.HasNextStaticField()) {
```

```
    it.Next();
  }
  while (it.HasNextInstanceField()) {
    it.Next();
  }
}

// Main algorithm which extract offsets of native functions from an OAT file.
static void extract_art_offsets__(target_ulong base_,
                                  target_ulong size,
                                  std::string name,
                                  CPUArchState* env,
                                  target_ulong cr3) {
  if (base_to_offsets.count(base_)) {
    return;
  }

  // Try to grab the memory and open and OAT file
  std::vector<uint8_t> oat_file_contents;

  target_ulong oat_file_end = base_ + size;

  // For the range of module, read it from memory onto a buffer.
  for (target_ulong oat_file_base = base_; oat_file_base != oat_file_end;
       oat_file_base += 1) {
    uint8_t ph = 0;

    DECAF_read_mem_with_pgd(env, cr3, oat_file_base, (void*)&ph,
                            sizeof(uint8_t));

    oat_file_contents.push_back(ph);
  }

  std::string name1 = dex_files_dir + std::to_string(current_dex_file) + ".oat";
  std::string calc_dump = name1;

  // Save the contents as a local file for analysis later.
  binary_save(oat_file_contents, calc_dump);

  // Skip through the ELF header.
  std::vector<uint8_t> elf_magic_needle{ 'E', 'L', 'F', '\0' };
  std::vector<uint8_t>::iterator itt =
  std::search(oat_file_contents.begin(), oat_file_contents.end(),
                  elf_magic_needle.begin(), elf_magic_needle.end());
  if(itt != oat_file_contents.end()) {
    oat_file_contents.erase(oat_file_contents.begin(), itt);
  }
  else {
    // No ELF header, return.
    return;
  }


  ++current_dex_file;

  // Skip over the OAT header.
```

```
std::vector<uint8_t> oat_magic_needle{'o', 'a', 't', '\n',
                                      '0', '3', '9', '\0'};
std::vector<uint8_t>::iterator it =
    std::search(oat_file_contents.begin(), oat_file_contents.end(),
                oat_magic_needle.begin(), oat_magic_needle.end());

oat_file_contents.erase(oat_file_contents.begin(), it);

std::vector<uint8_t>::iterator it1 =
    std::search(oat_file_contents.begin(), oat_file_contents.end(),
                oat_magic_needle.begin(), oat_magic_needle.end());

if (it1 != oat_file_contents.end()) {
  oat_file_contents.erase(oat_file_contents.begin(), it1);
}

std::string error_msg;
std::unique_ptr<art::OatFile> oat_file(
    art::OatFile::OpenMemory(oat_file_contents, calc_dump, &error_msg));
// CHECK(oat_file.get() != NULL) << calc_dump << ": " << error_msg;

if (oat_file.get() == nullptr) {
  if (bad_dex_file_bases.count(base_))
    bad_dex_file_bases[base_]++;
  else
    bad_dex_file_bases[base_] = 1;

  // Ugly!
  auto j3 = json::parse(get_string(json_path));
  j3["dex_file_integrity"] = false;
  std::string s = j3.dump();
  save_string(s, json_path);

  return;
}

monitor_printf(default_mon, "art_file_done__! %s %s\n", name.c_str(),
               name1.c_str());

std::unordered_map<target_ulong, std::string> to_add_offsets;
std::unordered_map<target_ulong, target_ulong> to_add_sizes;
const std::vector<const art::OatFile::OatDexFile*> oat_dex_files_ =
    oat_file->GetOatDexFiles();

for (size_t i = 0; i < oat_dex_files_.size(); i++) {
  const art::OatFile::OatDexFile* oat_dex_file = oat_dex_files_[i];
  CHECK(oat_dex_file != nullptr);
  std::string error_msg;

  const art::DexFile* dex_file = oat_dex_file->OpenDexFile(&error_msg);

  if (dex_file == nullptr) {
    std::cout << "Failed to open dex file '"
              << oat_dex_file->GetDexFileLocation() << "': " << error_msg;
    continue;
  }
```

```
    for (size_t class_def_index = 0; class_def_index < dex_file->NumClassDefs();
         class_def_index++) {
      const art::DexFile::ClassDef& class_def =
          dex_file->GetClassDef(class_def_index);
      const art::OatFile::OatClass oat_class =
          oat_dex_file->GetOatClass(class_def_index);
      const byte* class_data = dex_file->GetClassData(class_def);
      if (class_data != nullptr) {
        art::ClassDataItemIterator it(*dex_file, class_data);
        SkipAllFields(it);
        uint32_t class_method_index = 0;
        while (it.HasNextDirectMethod()) {
          const art::OatFile::OatMethod oat_method =
              oat_class.GetOatMethod(class_method_index++);
          uint32_t code_offset = oat_method.GetCodeOffset();
          to_add_offsets[code_offset] =
              PrettyMethod(it.GetMemberIndex(), *dex_file, true);
          to_add_sizes[code_offset] = oat_method.GetQuickCodeSize();

          it.Next();
        }
        while (it.HasNextVirtualMethod()) {
          const art::OatFile::OatMethod oat_method =
              oat_class.GetOatMethod(class_method_index++);
          uint32_t code_offset = oat_method.GetCodeOffset();
          to_add_offsets[code_offset] =
              PrettyMethod(it.GetMemberIndex(), *dex_file, true);
          to_add_sizes[code_offset] = oat_method.GetQuickCodeSize();
          it.Next();
        }
      }
    }
  }
  base_to_sizes[base] = std::move(to_add_sizes);
  base_to_offsets[base] = std::move(to_add_offsets);
  base_to_oat_file[base] = (void*)oat_file.release();
}

// This is the memory write callback which registers writes made to memory
target_ulong current_cr3 = 0x00, current_pc = 0x00;
CPUArchState* current_env = NULL;
static void hook_writes(DECAF_Callback_Params* params) {
  if (!(targetcr3s.count(current_cr3)))
    return;


  byte_addrs_written.insert(params->mw.vaddr);
}

// This is the heart of the unpacker, as described in the document, a basic-block
// is the piece of code which is terminated by a control-flow transfer instruction
// We hook at the beginnning of each basic block and perform required extraction
// for each basic block.

static void block_begin_cb(DECAF_Callback_Params* param) {
```

```
char modname[1024];
char functionname[1024];
// char process_name[1024];

CPUArchState* env = param->bb.env;

target_ulong cur_pc = param->bb.cur_pc;
target_ulong cr3 = DECAF_getPGD(env);

if (DECAF_is_in_kernel(env) || !(targetcr3s.count(cr3))) {
  current_cr3 = 0x00;
  return;
}
current_env = param->bb.env;
current_cr3 = cr3;
module* art_module = NULL;
art_module = VMI_find_module_by_pc(cur_pc, cr3, &base);

if (art_module != NULL &&
    (strstr(art_module->name, "system@framework@boot.oat") != NULL)) {
  if (!framework_offsets_extracted) {
    char* oat_file_str;
    extract_oat_file(env, base, &oat_file_str);
    extract_art_offsets_framework(base, art_module, env, cr3,
                                  std::string(oat_file_str));
    framework_offsets_extracted = true;
  }

  if (framework_offsets.count((cur_pc - base - 0x1000))) {
    fprintf(log_fd_jumps, "java function call = %s \n",
       framework_offsets[(cur_pc - base - 0x1000)].c_str());
    fflush(log_fd_jumps);
  }
}

if (art_module != NULL && (strstr(art_module->name, "libart") != NULL)) {
  if (funcmap_get_name_c(cur_pc, DECAF_getPGD(env), modname, functionname) ==
      0) {
    int reg_num = is_an_invoke_call(functionname);
    // Extract member offset from invoke.
    if (reg_num != -1) {
      // this pointer! artMethod
      target_ulong dex_cache, declaring_class,
          called_art_method = env->regs[0];

      // We need to dig one level deeper
      if (reg_num == 3) {
        target_ulong actual_art_method = 0x00;
        DECAF_read_mem_with_pgd(env, pgd_strip(cr3), called_art_method,
                                &actual_art_method, sizeof(target_ulong));
        called_art_method = actual_art_method;
      }

      // Get the ArtMethod
      art::mirror::ArtMethod* methodzz;
      char block1[SIZEOF_TYPE(art::mirror::ArtMethod)];
```

```
DECAF_read_mem_with_pgd(env, pgd_strip(cr3), called_art_method, block1,
                        SIZEOF_TYPE(art::mirror::ArtMethod));
methodzz = (art::mirror::ArtMethod*)(block1);

// Get the ArtMethod's declaring class
art::MemberOffset declaring_class_offset =
    methodzz->DeclaringClassOffset();
byte* raw_addr = reinterpret_cast<byte*>(methodzz) +
                 declaring_class_offset.Int32Value();
art::mirror::HeapReference<art::mirror::Class>* objref_addr =
    reinterpret_cast<art::mirror::HeapReference<art::mirror::Class>*>(
        raw_addr);
declaring_class = (target_ulong)objref_addr->AsVRegValue();

art::mirror::Class* clazz = nullptr;
char block2[SIZEOF_TYPE(art::mirror::Class)];
DECAF_read_mem_with_pgd(env, pgd_strip(cr3), declaring_class, block2,
                        SIZEOF_TYPE(art::mirror::Class));
clazz = (art::mirror::Class*)block2;

// Get the Declaring class's DexCache
art::MemberOffset dex_cache_offset = clazz->DexCacheOffset();
raw_addr =
    reinterpret_cast<byte*>(clazz) + dex_cache_offset.Int32Value();
art::mirror::HeapReference<art::mirror::DexCache>*
    dexcache_objref_addr = reinterpret_cast<
        art::mirror::HeapReference<art::mirror::DexCache>*>(raw_addr);
dex_cache = (target_ulong)dexcache_objref_addr->AsVRegValue();

art::mirror::DexCache* dexcachezz = nullptr;
char block3[SIZEOF_TYPE(art::mirror::DexCache)];
DECAF_read_mem_with_pgd(env, pgd_strip(cr3), dex_cache, block3,
                        SIZEOF_TYPE(art::mirror::DexCache));
dexcachezz = (art::mirror::DexCache*)block3;

// Get the DexFile from the DexCache of the declaring class of the
// Artmethod

art::MemberOffset dex_file_offset = dexcachezz->GetDexFileOffset();
raw_addr =
    reinterpret_cast<byte*>(dexcachezz) + dex_file_offset.Int32Value();
uint64_t* dex_file_ref = reinterpret_cast<uint64_t*>(raw_addr);

art::DexFile* dexfilezz = nullptr;
char block4[SIZEOF_TYPE(art::DexFile)];
DECAF_read_mem_with_pgd(env, pgd_strip(cr3), *dex_file_ref, block4,
                        SIZEOF_TYPE(art::DexFile));
dexfilezz = (art::DexFile*)block4;

/*******************************************************************/
/* WE ARE DONE! WE GOT THE DEXFILE! NOW TIME TO GET THE FUNCTION NAME */
/*******************************************************************/
// Try to grab all methods from the dex file!
// This process is simialar to what is done in the DexMethodIterator

raw_addr = reinterpret_cast<byte*>(dexfilezz) + 4;
```

```
uint32_t* begin_decaf = reinterpret_cast<uint32_t*>(raw_addr);
target_ulong dex_begin = (target_ulong)(uintptr_t)(*begin_decaf);

module* dirty_module = VMI_find_module_by_pc(
    reinterpret_cast<target_ulong>(*begin_decaf), cr3, &base);

if (dirty_module != NULL &&
    strstr(dirty_module->name, "framework") == NULL) {
  extract_art_offsets__(base, dirty_module->size,
                        std::string(dirty_module->name), env, cr3);
} else if (dirty_module == NULL) {
  target_ulong prev_end = 0x00;
  // monitor_printf(default_mon, "unknown module %x\n",
  // reinterpret_cast<target_ulong>(*begin_decaf));
  dirty_module =
      VMI_find_next_module(reinterpret_cast<target_ulong>(*begin_decaf),
                           cr3, &base, &prev_end);
  extract_art_offsets__(prev_end, base - prev_end,
                        std::string(dirty_module->name), env, cr3);
}

if (dirty_module && strstr(dirty_module->name, "framework") != NULL)
  return;

if (reg_num == 3)
  return;

/*  Here we try to replicate the process used in
 * DexFile->GetMethodName(MethodId&)
 *  The process goes something like this
 *  -> From MethodId get the offset of the name of method in the
 * StringIds
 *  -> Extract the exact StringId from this offset
 *  -> Use this StringId to find the offset of the actual string
 *       in the DexFile from the base of the dexfile
 *
*/

raw_addr = reinterpret_cast<byte*>(dexfilezz) + 8;
uint32_t* dex_file_size = reinterpret_cast<uint32_t*>(raw_addr);

// Used to extract code item
art::MemberOffset dex_code_item_offset =
    methodzz->GetDexCodeItemOffset();
raw_addr = reinterpret_cast<byte*>(methodzz) +
           dex_code_item_offset.Int32Value();
uint32_t* code_item_offset = reinterpret_cast<uint32_t*>(raw_addr);

// This is the offset of the method in the MethodIds array
art::MemberOffset dex_method_id_offset =
    methodzz->GetDexMethodIndexOffset();
raw_addr = reinterpret_cast<byte*>(methodzz) +
           dex_method_id_offset.Int32Value();
uint32_t* dex_method_id = reinterpret_cast<uint32_t*>(raw_addr);

// This is to get the base of the MethodIds array and add the offset to
```

```
// get the appropriate MethodId member
art::MemberOffset dexfile_method_ids_offset =
    dexfilezz->GetMethodIdsOffset();
raw_addr = reinterpret_cast<byte*>(dexfilezz) + 48;
uint32_t* ids_decaf = reinterpret_cast<uint32_t*>(raw_addr);
art::DexFile::MethodId* temp_id = (art::DexFile::MethodId*)(*ids_decaf);
temp_id = temp_id + *dex_method_id;

art::DexFile::MethodId* idzz;
char block5[SIZEOF_TYPE(art::DexFile::MethodId)];
DECAF_read_mem_with_pgd(env, pgd_strip(cr3),
                        (target_ulong)(uintptr_t)temp_id, block5,
                        SIZEOF_TYPE(art::DexFile::MethodId));
idzz = (art::DexFile::MethodId*)block5;

// Now we have the MethodId in `idzz`, and idzz->name_idx_ holds the
// offset of the StringId

// Proceed getting the StringId
raw_addr = reinterpret_cast<byte*>(dexfilezz) + 48 - 12;
uint32_t* str_ids_decaf = reinterpret_cast<uint32_t*>(raw_addr);
art::DexFile::StringId* temp_str_id =
    (art::DexFile::StringId*)(*str_ids_decaf);
temp_str_id = temp_str_id + idzz->name_idx_;

art::DexFile::StringId* str_idzz;
char block6[SIZEOF_TYPE(art::DexFile::StringId)];
DECAF_read_mem_with_pgd(env, pgd_strip(cr3),
                        (target_ulong)(uintptr_t)temp_str_id, block6,
                        SIZEOF_TYPE(art::DexFile::StringId));
str_idzz = (art::DexFile::StringId*)block6;
// We now have the StringId at str_idzz, PHEW!!

char block7[200];
DECAF_read_mem_with_pgd(env, pgd_strip(cr3),
                        dex_begin + str_idzz->string_data_off_ + 1,
                        block7, 200);
block7[199] = '\0';

if (reg_num == 0) {
  fprintf(log_fd_jumps,
      "java function call = %s \n",
       block7);
  fflush(log_fd_jumps);
  return;
} else {
  fprintf(log_fd_jumps, "java function call = %s\n", block7,
          reinterpret_cast<target_ulong>(*begin_decaf));

  art::DexFile::CodeItem* this_code_item;
  char code_item_block[SIZEOF_TYPE(art::DexFile::CodeItem)];
  DECAF_read_mem_with_pgd(env, pgd_strip(cr3),
                          dex_begin + (target_ulong)(*code_item_offset),
                          code_item_block,
                          SIZEOF_TYPE(art::DexFile::CodeItem));
  this_code_item = (art::DexFile::CodeItem*)code_item_block;
```

```
          uint32_t num_bytes_to_read =
              this_code_item->insns_size_in_code_units_ * 2;

          target_ulong to_check_start =
              dex_begin + (target_ulong)(*code_item_offset);
          target_ulong to_check_end =
              dex_begin + (target_ulong)(*code_item_offset) +
              SIZEOF_TYPE(art::DexFile::CodeItem) + num_bytes_to_read + 4;

          while (to_check_end != to_check_start) {
            if (byte_addrs_written.count(to_check_start)) {
              fprintf(log_fd_jumps, "<dirty_dalvik_code>\n");
              break;
            }
            ++to_check_start;
          }

          fflush(log_fd_jumps);
        }
      }
    }
  }

end:
  if (base_to_offsets.count(base)) {
    std::unordered_map<target_ulong, std::string>& oat_module_offsets =
        base_to_offsets[base];

    std::unordered_map<target_ulong, target_ulong>& oat_module_sizes =
        base_to_sizes[base];

    if (oat_module_offsets.count((cur_pc - base - 0x1000))) {
      increment_something("num_native_methods");
      fprintf(log_fd_jumps, "java function call = %s\n",
              oat_module_offsets[(cur_pc - base - 0x1000)].c_str());

      target_ulong native_method_size =
          oat_module_sizes[(cur_pc - base - 0x1000)];
      target_ulong native_method_end = cur_pc + native_method_size,
                   native_method_begin = cur_pc;

      while (native_method_end != native_method_begin) {
        if (byte_addrs_written.count(native_method_begin)) {
          fprintf(log_fd_jumps, "<dirty_native_code>\n");
          break;
        }
        ++native_method_begin;
      }

      fflush(log_fd_jumps);
    }
  }
}
```

```
static void createproc_callback(VMI_Callback_Params* params) {
  if (targetpid == 0 && strlen(targetname) > 1 &&
      strstr(params->cp.name, targetname) != 0) {
    targetpid = params->cp.pid;
    targetcr3 = params->cp.cr3;
    targetcr3s.insert(targetcr3);

    strncpy(actualname, params->cp.name, strlen(params->cp.name));
    actualname[511] = '\0';

    register_hooks();
    DECAF_printf("process found: pid=%08x, cr3=%08x, name = %s\n", targetpid,
                 targetcr3, params->cp.name);

  } else if (targetpid != 0 && params->cp.parent_pid == targetpid) {
    targetcr3s.insert(params->cp.cr3);
    DECAF_printf("child process found: pid=%08x, cr3=%08x, name = %s\n",
                 params->cp.pid, params->cp.cr3, params->cp.name);
    increment_something("child_processes");
  }
}
```

Appendix B

Results.

The raw results for the experiments can be obtained from `https://gitlab.com/TheLoneRanger14/thesis_results.git`. The password to the zip is ‘droidunpack‘ and the zip contains a REAME describing the structure of the results.

Vita

Abhishek Vasisht Bhaskar, was born in Bangalore, India to parents Girija Bhaskar and H.N.Bhaskar. After finishing his undegraduate program in Telecommmunication engineering at PES University in Bangalore he arrrived at Syracuse, NY to persue graduate studies. As of July 2016 he graduates from a Masters program in Computer engineering from the EECS department at Syracuse University. During his time at Syracuse University, he served as a Research Assistant under Dr. Heng Yin as a part of the Systems Security Lab at Syracuse University for little over a year. This work was thought, implmeneted and verified during the same period.

Current Location: Syracuse, NY 13210.

This thesis was typed by the author.

Bibliography

[1] Alibaba inc. http://jaq.alibaba.com/.

[2] Android art runtime. http://androidxref.com/5.0.0_r2/xref/art/runtime/mirror/art_method.h.

[3] Baidu inc. http://apkprotect.baidu.com/.

[4] Bangcle inc. http://www.bangcle.com/.

[5] Ijiami inc. http://www.ijiami.cn/.

[6] Qihoo360 inc. http://dev.360.cn/protect/welcome.

[7] Sleuthkit. http://www.sleuthkit.org/.

[8] Tencent inc. http://www.qcloud.com/product/product.php?item=appup.

[9] F. Bellard. Qemu, a fast and portable dynamic translator. In *Proceedings of the Annual Conference on USENIX Annual Technical Conference*, ATEC '05, pages 41–41, Berkeley, CA, USA, 2005. USENIX Association. URL `http://dl.acm.org/citation.cfm?id=1247360.1247401`.

[10] L. Bodong, H. Wenjun, & G. Dawu. Appspear: Bytecode decrypting and dex reassembling for packed android malware.

[11] V. Foundation. volatility. https://github.com/volatilityfoundation/volatility, 2015.

[12] A. Henderson, A. Prakash, L. K. Yan, X. Hu, X. Wang, R. Zhou, & H. Yin. Make it work, make it right, make it fast: Building a platform-neutral whole-system dynamic binary analysis platform. In *Proceedings of the 2014 International Symposium on Software Testing and Analysis*, pages 248–258. ACM, 2014.

[13] D. Kim, J. Kwak, & J. Ryou. Dwroiddump: Executable code extraction from android applications for malware analysis. *International Journal of Distributed Sensor Networks*, 2015, 2015.

[14] F. Nasim, B. Aslam, W. Ahmed, & T. Naeem. Uncovering self code modification in android. In *Codes, Cryptology, and Information Security*, pages 297–313. Springer, 2015.

[15] Y. Park. General unpacking method for android packer(no root), 2015. URL `http://tinyurl.com/zj6z2bp`.

[16] D. F. . C. S. Research. Lime. https://github.com/504ensicsLabs/LiME, 2012.

[17] X. Ugarte-Pedrero, D. Balzarotti, I. Santos, & P. G. Bringas. Sok: Deep packer inspection: A longitudinal study of the complexity of run-time packers. In *Security and Privacy (SP), 2015 IEEE Symposium on*, pages 659–673. IEEE, 2015.

[18] L. K. Yan & H. Yin. Droidscope: seamlessly reconstructing the os and dalvik semantic views for dynamic android malware analysis. In *Presented as part of the 21st USENIX Security Symposium (USENIX Security 12)*, pages 569–584, 2012.

[19] R. Yu. Android packers: facing the challenges, building solutions, January 2016. URL `https://www.virusbulletin.com/virusbulletin/2016/01/paper-android-packers-facing-challenges-building-solutions/`.

[20] Y. Zhang, X. Luo, & H. Yin. Dexhunter: toward extracting hidden code from packed android applications. In *Computer Security–ESORICS 2015*, pages 293–311. Springer, 2015.