Memory Analysis of the Dalvik (Android) Virtual Machine

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Who Am I?

- Security Analyst at Digital Forensics Solutions
  - Also perform wide ranging forensics investigations
- Volatility Developer
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Agenda

- What is Dalvik / why do we care?
- Brief overview of memory forensics
- Extracting allocated and historical data from Dalvik instances
- Target specific Android applications

What is Dalvik?

- Dalvik is the software VM for all Android applications
- Nearly identical to the Java Virtual Machine (JVM) [1]
- Open source, written in C / Java

Why do we care?

- Android-based phones leading in US mobile market
  - Which makes for many phones to investigate
- Memory forensics capabilities against Android applications have numerous uses/implications
- Entire forensics community (LEO, .gov, private firms) already urging development of such capabilities

Memory Forensics Introduction

- Memory forensics is vital to orderly recovery of runtime information
- Unstructured methods (strings, grep, etc) are brittle and only recover superficial info
- Structured methods allow for recovery of data structures, variables, and code from memory
- Previous work at operating system level led to recovery of processes, open files, network connections, etc [4,5]

Memory Analysis Process

- First, need to acquire memory
  - Acquisition depends on environment [6]
- Next, requires locating information in memory and interpreting it correctly
  - Also requires re-implementing functionality offline
- Then it needs to be displayed in a useful way to the investigator

Dalvik Memory Analysis

Acquiring Memory – Approach 1

- The normal method is to acquire a complete capture of physical RAM
- Works well when analyzing kernel data structures as their pages are not swapped out
- Allows for recovery of allocated and historical processes, open files, network connections, and so on

Approach 1 on Android

- Without /dev/mem support, need a LKM to read memory
- No current module works for Android (ARM)
- We developed our own (mostly by @jtsylve)
- Benefits of full capture:
  - Can target any process (including its mappings)
  - Can recover information from unmapped pages in processes

Acquiring Memory – Approach 2

- Memory can be acquired on a per-process basis
- Ensures that all pages of the process will be acquired
- Easiest to perform with memfetch[8]
  - After a few small changes, was statically compiled for ARM
- No unmapped pages will be recovered though
  - Heap and GC don’t munmap immediately

Analyzing C vs Java

- Most previous forensics research has had the “luxury” of analyzing C
  – Nearly 1:1 mapping of code/data to in-memory layout
- Declaration of a C “string”
  – char buffer[] = “Hello World”;
- Memory Layout (xxd)
  – 4865 6c6c 6f20 576f 726c 6400 Hello World.

A Dalvik String in Memory

- First, need the address of the “StringObject”
- Next, need the offsets of the “java/lang/String” *value* and byte *offset* members
- StringObject + value offset leads us to an “ArrayObject”
- ArrayObject + byte offset leads to an UTF-16 array of characters
- … finally we have the string (in Unicode)

Now for the memory analysis…

- The real goal of the research was to be able to locate arbitrary class instances and fields in memory
- Other goals included replicating commonly used features of the Android debugging framework

Locating Data Structures

- The base of Dalvik loads as a shared library (libdvm.so)
- Contains global variables that we use to locate classes and other information
- Also contains the C structures needed to parse and gather evidence we need

Gathering libdvm's Structures

1) Grab the shared library from the phone (adb)

2) Use Volatility's *dwarfparse.py*:

- Builds a profile of C structures along with members, types, and byte offsets
- Records offsets of global variables

3) Example structure definition

```
'ClassObject': [ 0xa0, {
    'obj': [0x0, ['Object']],
```

Volatility Plugin Sample

- Accessing structures is as simple as knowing the type and offset

  intval = obj.Object(“int”, offset=intOffset, ..)

- Volatility code to access ‘descriptor’ of an ‘Object’:

  o = obj.Object("Object", offset=objectAddress, ..)

  c = obj.Object("ClassObject", offset=**o.clazz**, …)

  desc = linux_common.get_string(**c.descriptor**)

gDvm

- *gDvm* is a global structure of type *DvmGlobals*
- Holds info about a specific Dalvik instance
- Used to locate a number of structures needed for analysis

Locating Loaded Classes

- gDvm.*loadedClasses* is a hash table of *ClassObjects* for each loaded class
- Hash table is stored as an array
- Analysis code walks the backing array and handles active entries
  - Inactive entries are NULL or have a pointer value of 0xcbcacccd

Information Per Class

- Type and (often) name of the source code file
- Information on backing *DexFile*
  - *DexFile* stores everything Dalvik cares about for a binary
- Data Fields
  - Static
  - Instance
- Methods
  - Name and Type
  - Location of Instructions

Static Fields

- Stored once per class (not instance)
- Pre-initialized if known
- Stored in an array with element type *StaticField*
- Leads directly to the value of the specific field

Instance Fields

- Per instance of a Class
- Fields are stored in an array of element type *InstField*
- Offset of each field stored in *byteOffset* member
  - Relative offset from *ClassObject* structure

Listing Instance Members

Source file: ComposeMessageActivity.java

Class: Lcom/android/mms/ui/ComposeMessageActivity;

Instance Fields:

name: m_receiver
signature: Landroid/content/BroadcastReceiver;

name: m_filter
signature: Landroid/content/IntentFilter;

name: mAppContext
signature: Landroid/content/Context;

name: mAvailableDirPath
signature: Ljava/lang/String;

Analyzing Methods

- We can enumerate all methods (direct, virtual) and retrieve names and instructions
- Not really applicable to this talk
- Can be extremely useful for malware analysis though
  - If .apk is no longer on disk or if code was changed at runtime

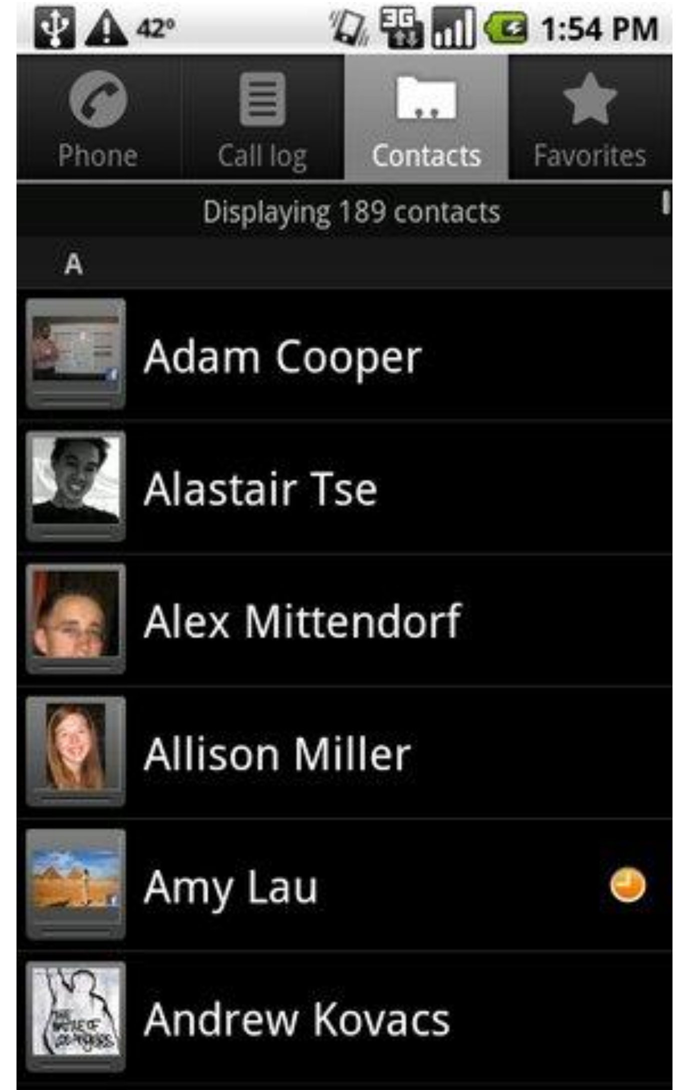
Methods in Memory vs on Disk

- Dalvik makes a number of runtime optimizations [1]
- Example: When class members are accessed (*iget, iput)* the field table index is replaced with the direct byte offset
- Would likely need to undo some of the optimizations to get complete baksmali output

Analyzing Specific Applications

Recovery Approach

- Best approach seems to be locating data structures of UI screens
  - UI screens represented by uniform (single type) lists of displayed information
  - Data for many views are pre-loaded



Finding Data Structures

- Can save substantial time by using *adb's logcat* (next slide)
  - Shows the classes and often methods involved in handling UI events
- Otherwise, need to examine source code
  - Some applications are open source
  - Others can be "decompiled" with baksmali [9]

logcat example

The following is a snippet of output when clicking on the text message view:

D/**ConversationList**(12520): onResume Start

D/**ComposeMessageActivity**(12520): onConatctInfoChange

D/RecipientList(12520): mFilterHandler not null

D/**RecipientList**(12520): get recipient: 0

D/RecipientList(12520): r.name: John Smith

D/RecipientList(12520): r.filter() return result

D/RecipientList(12520): indexOf(r)0

D/RecipientList(12520): prepare set, index/name: 0/John Smith

Phone Call History

- Call history view controlled through a *DialerContactCard$OnCardClickListener*
- Each contact stored as a *DialerContactCard*
- Contains the name, number, convo length, and photo of contact

Per Contact Call History

- Can (sometimes) retrieve call history per-contact
- Requires the user to actually view a contact’s history before being populated

Text Messages

- Recovery through ComposeMessageActivity & TextMessageView
- Complete conversations can be recovered
- Not pre-populated

Voicemail

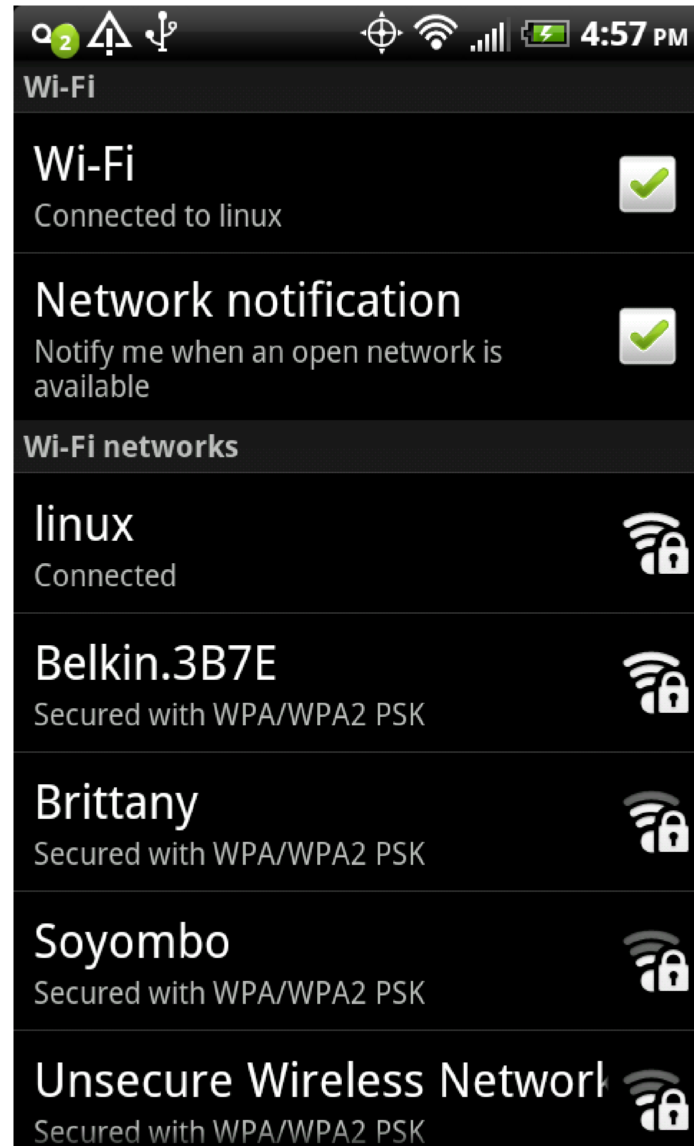
- Audio file is open()’ed
- Not mapped contiguously into the process address space
- No method to recover deleted voicemails..

Browser (Opera Mini)

- Opera Mini is the most used mobile browser
- Can recover some session information
  - The history file is always mapped in memory (including information from current session)
- HTTP requests and page information is (possibly) recoverable
  - Can recover <title> information
  - Stored in Opera Binary Markup Language
  - Not publicly documented?

Recovering Wireless Information

- Screenshot on the right shows results of a scan for wireless networks
- Recovery of this view provides the SSID, MAC address, and enc type for routers found
- Recovery of "Connected" routers show which were associated with



Other Wireless Information

- Potentially interesting information:
  - Wireless keys
  - Connection stats
- These are not controlled by Dalvik
  - Keys only initially entered through Dalvik, but then saved
- Stored by the usual Linux applications
  - wpa_supplicant, dhcpd, in-kernel stats

Location Recovery

- Associating location & time not always important
  – But makes for better slides *hint*
- Interesting for a number of reasons
  – Forensics & Privacy concerns
  – Not part of a “standard” forensics investigation

Google Maps

- Did not do source code analysis
  - Most phones won't be using Google Maps while being seized
  - Wanted to find ways to get historical data cleanly
- Found two promising searches
  - mTime=*TIME*,mLatitude=*LAT*,mLongitude=*LON*
  - point: *LAT*,*LON* … lastFix: *TIME*
    - *TIME* is the last location, extra work needed to verify

“Popular” Weather Application

- The weather application uses your location to give you relevant information
- ***http***://vendor.site.com/widget/search.asp?lat=*LAT*&lon=*LON*&nocache=*TIME*

More GPS Fun

- All of the following applications do not clear GPS data from memory, and all send their lat/lon using GET with HTTP
  - Urban Spoon
  - Weather Channel
  - WeatherBug
  - Yelp
  - Groupon
  - Movies

Implementation

- Recovery code written as Volatility [7] plugins
  - Most popular memory analysis framework
  - Has support for all Windows versions since XP and 2.6 Intel Linux
  - Now also supports ARM Linux/Android
- Makes rapid development of memory analysis capabilities simple
- Also can be used for analyzing other binary formats

Testing

- Tested against a HTC EVO 4G
  - No phone-specific features used in analysis
  - Only a few HTC-specific packages were analyzed
- Visually tested against other Dalvik versions
  - No drastic changes in core Dalvik functionality

Research Applications

- Memory forensics (obviously)
- Testing of privacy assurances
- Malware analysis
  - Can enumerate and recover methods and their instructions

Future Avenues of Research

- Numerous applications with potentially interesting information
  - Too much to manually dig through
  - Need automation
  - Baksmali/Volatility/logcat integration?
- Automated determination of interesting evidence across the whole system
  - Combing work done in [2] and [3]

Questions/Comments?

- andrew@digdeeply.com
- @attrc

References - 1

[1] http://bit.ly/dalvikvsjava

[2] Brendan Dolan-Gavitt, *et al*, "Virtuoso: Narrowing the Semantic Gap in Virtual Machine Introspection", IEEE Security and Privacy, 2011

[3] TaintDroid, http://www.appanalysis.org/

[4] http://bit.ly/windowsmemory

[5] http://bit.ly/linuxmem

[6] http://bit.ly/memimaging

[7] http://code.google.com/p/volatility/

[8] http://lcamtuf.coredump.cx/soft/memfetch.tgz

References - 2

[9] baksmali - http://code.google.com/p/smali/