Northeastern University
Systems Security Lab

Android DDI: Introduction to Dynamic Dalvik Instrumentation

Hack in the Box
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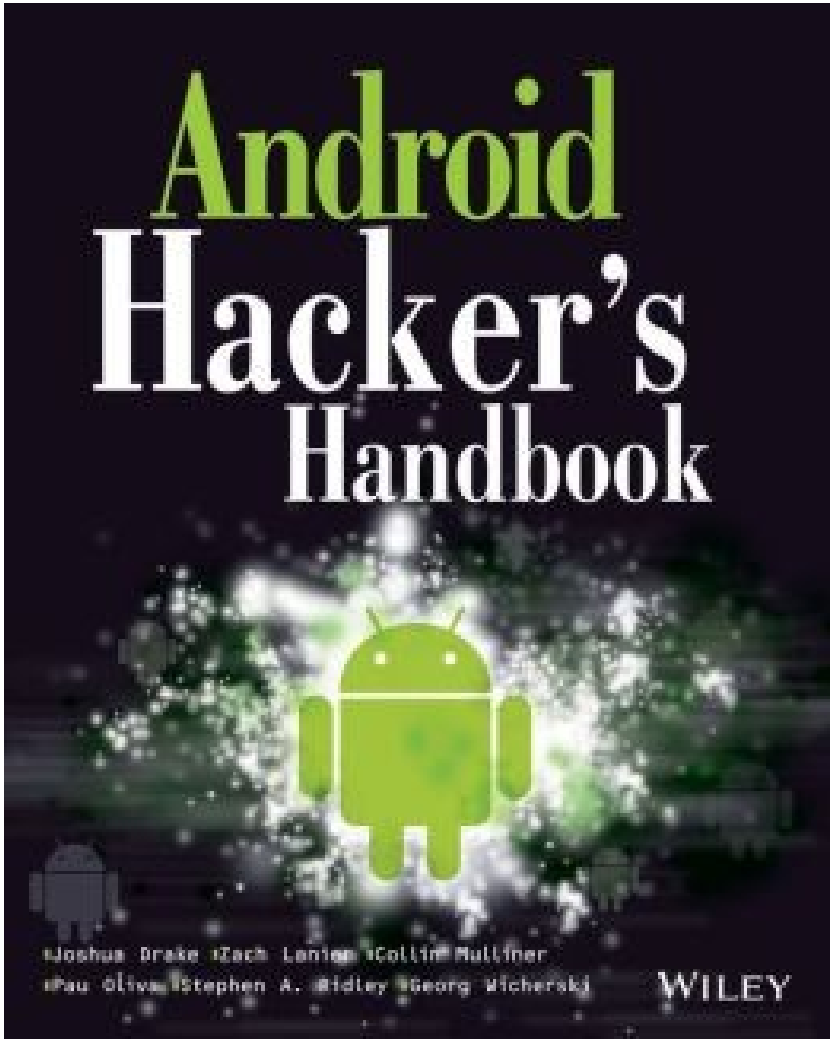
- 'postdoc' Security Researcher
  - $HOME = Northeastern University, Boston, MA, USA
  - `cat .project`
    specialized in *mobile handset security*
- Current work
  - Android security
- Past work
  - Bluetooth security
  - A lot on SMS and MMS security
  - Mobile web usage and privacy
  - Some early work on NFC phone security

Android Hackers Handbook



ETA: April 2014

Introduction

- Android Application Security
  - Find vulnerabilities (audit)
  - Analyze malware
  - RE … what is this application doing
  - ATTACK stuff

- What does this thing do? How does this thing work?
  - Disassemble → look at smali code
  - Run in emulator/sandbox → look at traces / network
  - (Static) instrumentation → look at app while it runs

Introduction

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- **This talk is about Dynamic Instrumentation**
  - **Instrumentation at the Dalvik level**
    (but not bytecode!)

Related Work

- Cydia Substrate for Android
  - Tailored towards building app extensions
  - Powerful but complex
  - http://www.cydiasubstrate.com

- Xposed framework
  - Designed for app & system mods
  - http://forum.xda-developers.com/showthread.php?t=1574401

- My DDI framework is small, easy to understand, easy to use and built for security work

Static Instrumentation on Android

- Unpack APK
  - Convert manifest back to plain text, ...
- Disassemble DEX classes
  - Get smali code
- Instrument smali code
  - Modify smali code, add own code
- Repackage application
  - Compile code, Sign, etc...
- Install and run
  - Hope it works... (bug in patch, self integrity check, ...)

Dynamic Instrumentation

- Change/modify application code at runtime
  - Allows to add and remove code/hooks on-the-fly
  - Technique has been around for many years
- Instrument library calls: quick overview what happens
  - No disassembly needed
- Still need to disassemble for target specific stuff
  - Find the interesting stuff to instrument

Dynamic Instrumentation on Android

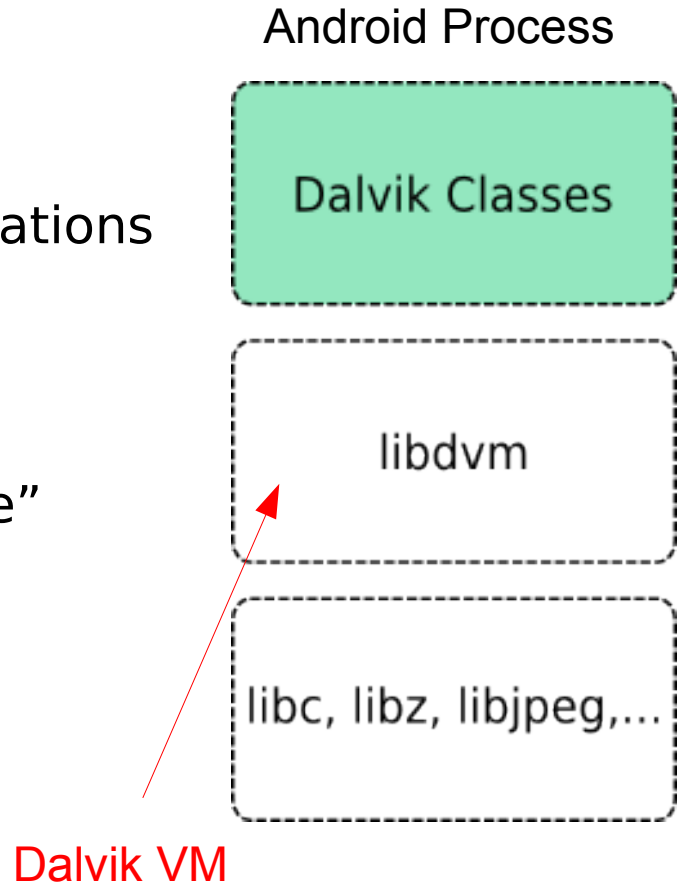
- Not needed: unpacking, disassemble, modify, compile, repacking
  - Saves us time
- APK not modified
  - Defeat 'simple' integrity checks
- But Android Apps are written in Java and run in a VM...

Android


APPLICATIONS
Home
Contacts
Phone
Browser
...
APPLICATION FRAMEWORK
Activity Manager
Window Manager
Content Providers
View System
Notification Manager
Package Manager
Telephony Manager
Resource Manager
Location Manager
XMPP Service
LIBRARIES
Surface Manager
Media Framework
SQLite
OpenGL|ES
FreeType
WebKit
SGL
SSL
libc
ANDROID RUNTIME
Core Libraries
Dalvik Virtual Machine
LINUX KERNEL
Display Driver
Camera Driver
Bluetooth Driver
Flash Memory Driver
Binder (IPC) Driver
USB Driver
Keypad Driver
WiFi Driver
Audio Drivers
Power Management

Android Runtime

- Dalvik Virtual Machine (DVM)
  Core Libraries (java.x.y)
  - Executes: Framework and Applications
- Application
  - Process for “MainActivity”
  - Additional process(s) for “Service”
- Framework works in the same way!
  - zygote
  - system_server
  - ...



Dalvik Instrumentation – The Basic Idea

- Convert Dalvik method to native (JNI) method
  - We get control of the execution
- Call original Dalvik method from native method
  - This creates an in-line hook of the Dalvik method
- Implement instrumentation code using JNI
  - Access to everything
    (private, protected doesn't exist in the land of C)

Java Native Interface (JNI) super quick intro

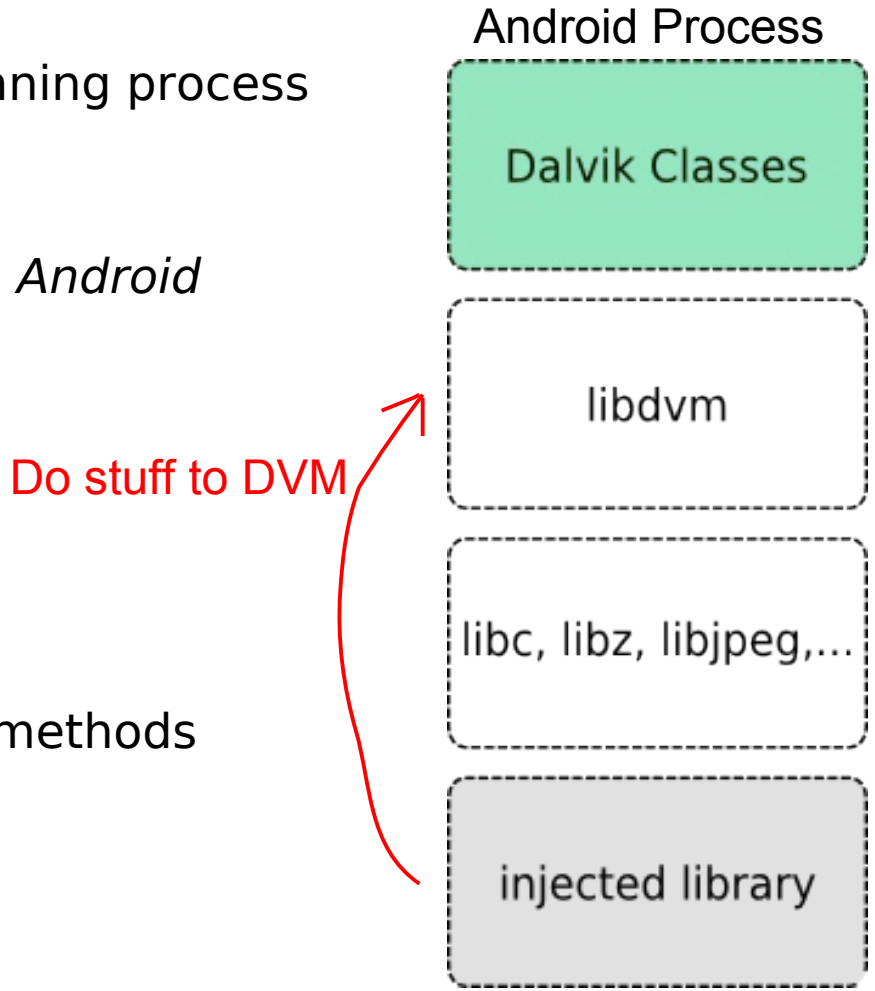
- C API to interact between the Java and C/native world
  - You can write any type of java code using JNI ;-)
- JNI function, signature: `result name(JNIEnv *env, …)`
  - Callable from the Java world
- JNI is essential for our instrumentation!
  - Need to know this in order to do instrumentation! (but not to understand the talk!)

```
FindClass()         // obtain class reference
NewObject()         // create a new class object
GetMethodId()       // get method
CallObjectMethod() // call a method
...
```

Dalvik Instrumentation – Overview

- Inject 'shared object' (.so) into running process
  - Provides the native code
  - My talk: *Dynamic Binary Instrumentation on Android (SummerCon 2012)*

- Native code 'talks to the DVM'
  - Resolve symbols from DVM
  - Call DVM functions to:
    - Lookup classes and methods
    - Hook method
    - Call original method



Hooking a Dalvik Method 1/3

- Find loaded class
- Find method by name and signature
- Change method parameters
- Convert to JNI method

```
cls = dvmFindLoadedClass(“Ljava/lang/String;”);
met = dvmFindVirtualMethodHierByDescriptor(cls, “compareTo”,
                                           “(Ljava/lang/String;)I”);
```

*if direct method use: dvmFindDirectMethodByDescriptor()

Hooking a Dalvik Method 2/3

- Method parameters (interesting for our task)

```
insSize             // size of input parameters
outSize             // size of output
registersSize       // size of method bytecode
insns               // bytecode
JniArgInfo          // argument parsing info (JNI)
access flags        // public, protected, private, native :-)
```

- *insSize* and *registersSize* are set to a specific value (next slides)
- *outSize* = 0
- *insns* is saved for calling original function (next slides)
- *JniArgInfo* = 0x80000000 (→ parse method arguments)
- *access flags* = access flags | 0x0100 (make method native)

Hooking a Dalvik Method 3/3

- Convert to JNI method

```
int dalvik_func_hook(JNIEnv *env, jobject this, jobject str)
{
 ...
}


dvmUseJNIBridge(met, dalvik_func_hook);
```

- Every call to `java.lang.String.compareTo(String)` is now handled by `dalvik_func_hook()`

Method Parameter Manipulation : the details

- The DVM needs to know how *big* the method arguments are
  - insSize
  - We also set registersSize == insSize

- Argument size calculation
  - Every argument adds one (1) to the input size
  - J (a double) adds two (2)
  - For methods of object classes (non static classes) add one (1) for the instance (this)

```
java.lang.String.compareTo(“Ljava/lang/String;)I
insSize == 2
```

Calling the Original Method

- Lookup class + method (or used saved values from hooking)
- Revert method parameters (or used saved values)
- Call method → inspect result → hook method again

```
int dalvik_hook_func(JNIEnv *env, jobject this, jobject str)
{
    jvalue args[1];
    args[0].l = str;
    int res = (*env)->CallIntMethodA(env, this, meth, args);
    return res;
}
```

LibDalvikHook 1/2

- Easy to use Dalvik hooking library
  - Provides: hooking, unhooking, calling original method

```
struct dalvik_hook_t h;   // hook data, remembers stuff for you

// setup the hook
dalvik_hook_setup(
   &h,                          // hook data
   "Ljava/lang/String;",        // class name
   "compareTo",                 // method name
   "(Ljava/lang/String;)I",     // method signature
   2, // insSize (need to calculate that in your head! LOL)
   hook_func_compareto          // hook function
);

// place hook
dalvik_hook(&libdhook, &h);
```

LibDalvikHook 2/2

- Calling the original method

```
int hook_func(JNIEnv *env, …)
{
  dalvik_prepare(
    &libdhook,      // library context
    &h,             // hook data
    env             // JNI environment
  );
  // use JNI API to call method
  args[0].l = x;
  CallXXMethod(env, obj, h.mid, args); // h.mid → method

  dalvik_postcall(&libdhook, &h);
}
```

- Unhook by simply only calling **dalvik_prepare()**

Injecting the Instrumentation Library 1/2

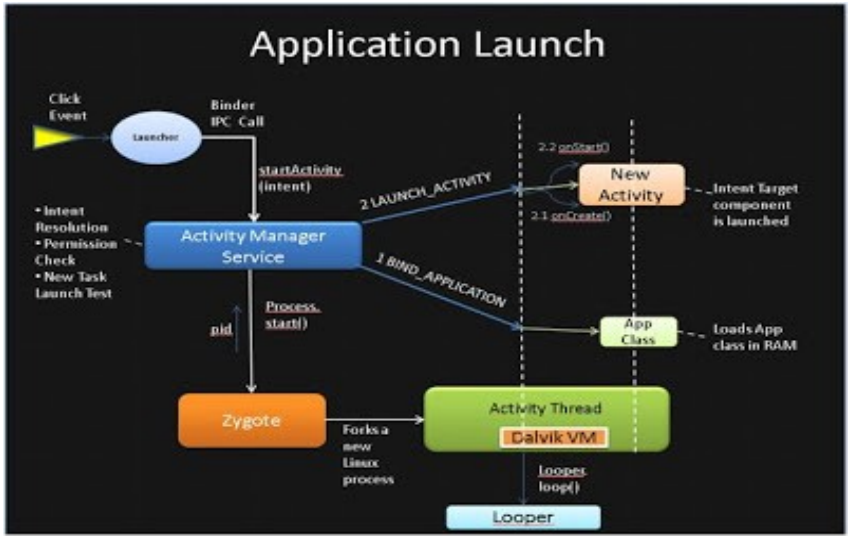
- hijack tool from my talk about native Android instrumentation
  - SummerCon 2012

- Steps:
  - Push library and DEX file to /data/local/tmp
  - Enable DEX loading (`chmod 777 /data/dalvik-cache/`)
  - hijack -p PID -l /data/local/tmp/lib.so

- Injects the library into running process
  - Works on any process, including system apps + services e.g. zygote, system_server, ... :-)

Injecting the Instrumentation Library 2/2

- We want to inject into processes before they are execute
  - All Dalvik processes are forked from zygote
- hijack zygote and inject when it specializes
  - Need to know the main class of target application

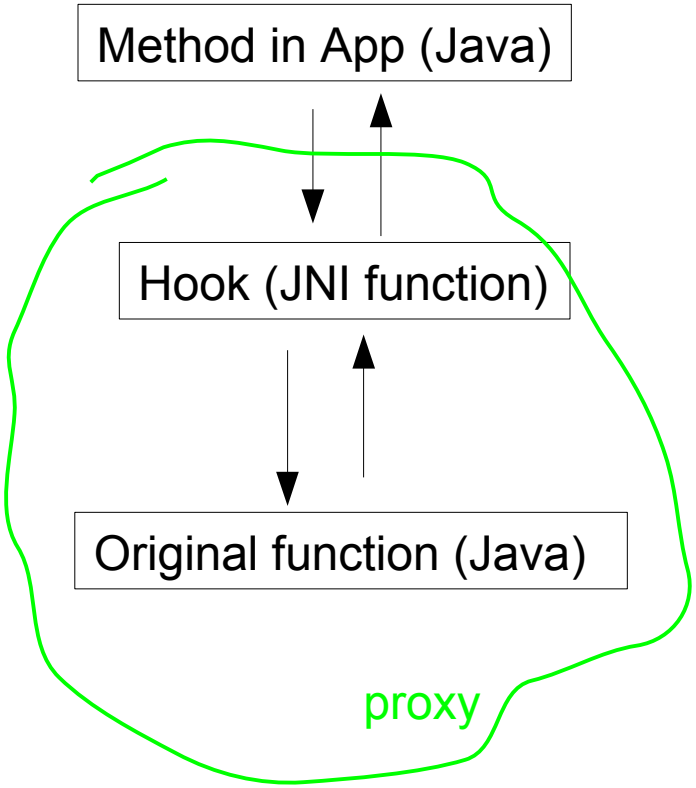



```
hijack -p zygotePID -l lib.so -s org.mulliner.collin.work
```

Hijack's newest Features

- Inject into zygote **-z**
- Inject into new DVM process by class name (combine wit -z)
  -s full.class.name
- Disable calling mprotect() before injecting, old Android versions
  -m
- Debug level switch
  -D <level>

Instrumentation Code Flow (v1)



Monitor / Reverse Applications

- How does the application work?
  - Maybe App is obfuscated, strings are “encrypted”
- Instrument interesting methods to see what App does
  - String operations
  - Reflection
  - …

```
String  java.lang.StringBuffer.toString()
int     java.lang.String.compareTo(..)
int     java.lang.String.compareToIgnoreCase(..)
String  java.lang.StringBuilder.toString()


Method  java.lang.Class.getMethod(..)
```

Attack “Stuff”

- Disable Signature Verification
  - Used for all kinds of things...
  - Patch to always “return true;”
    (used it to attack various things)

```
boolean java.security.Signature.verify(byte[]) { … }
```

Loading Additional Classes

- Sophisticated “instrumentation”
  - way easier done in Java then in C-JNI
  - You really want to be able to write stuff in Java if you want to interact with the Android framework

- Loading classes is supported by LibDalvikHook
  - dexstuff_loaddex()
  - dexstuff_defineclass()

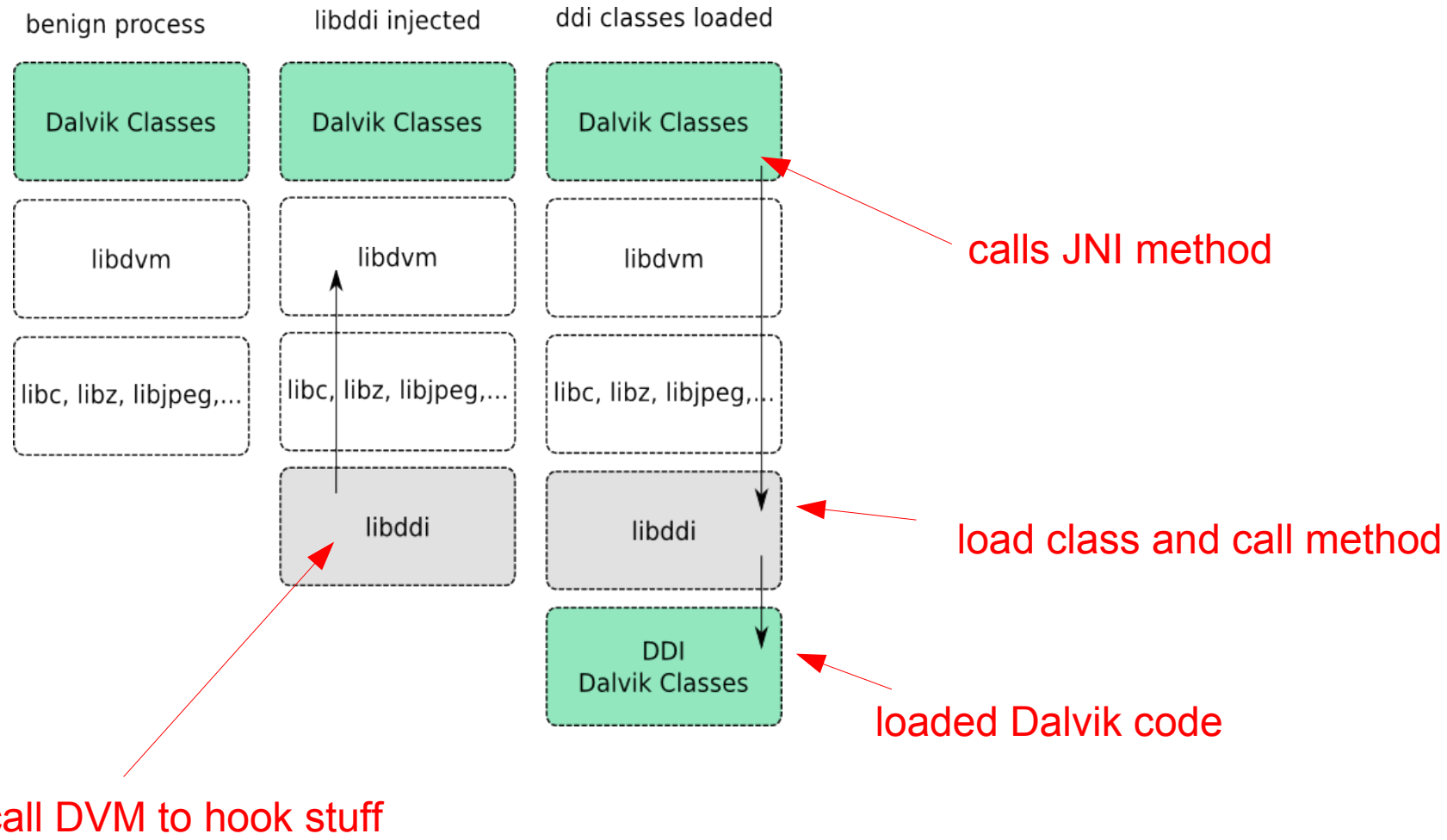
Loading Classes 1/3

- Load DEX file into DVM
- Define classes, tell DVM what classes to load from DEX file
  - Get class loader...

```
args[0].l = "PATH/classes.dex"; // must be a string object
cookie = dvm_dalvik_system_DexFile[0](args, &pResult);

// get class loader
Method *m = dvmGetCurrentJNIMethod();
// define class
u4 args[] = {
  "org.mulliner.collin.work", // class name (string object)
  m->clazz->classLoader,      // class loader
  cookie                      // use DEX file loaded above
};
dvm_dalvik_system_DexFile[3](args, &pResult);
```

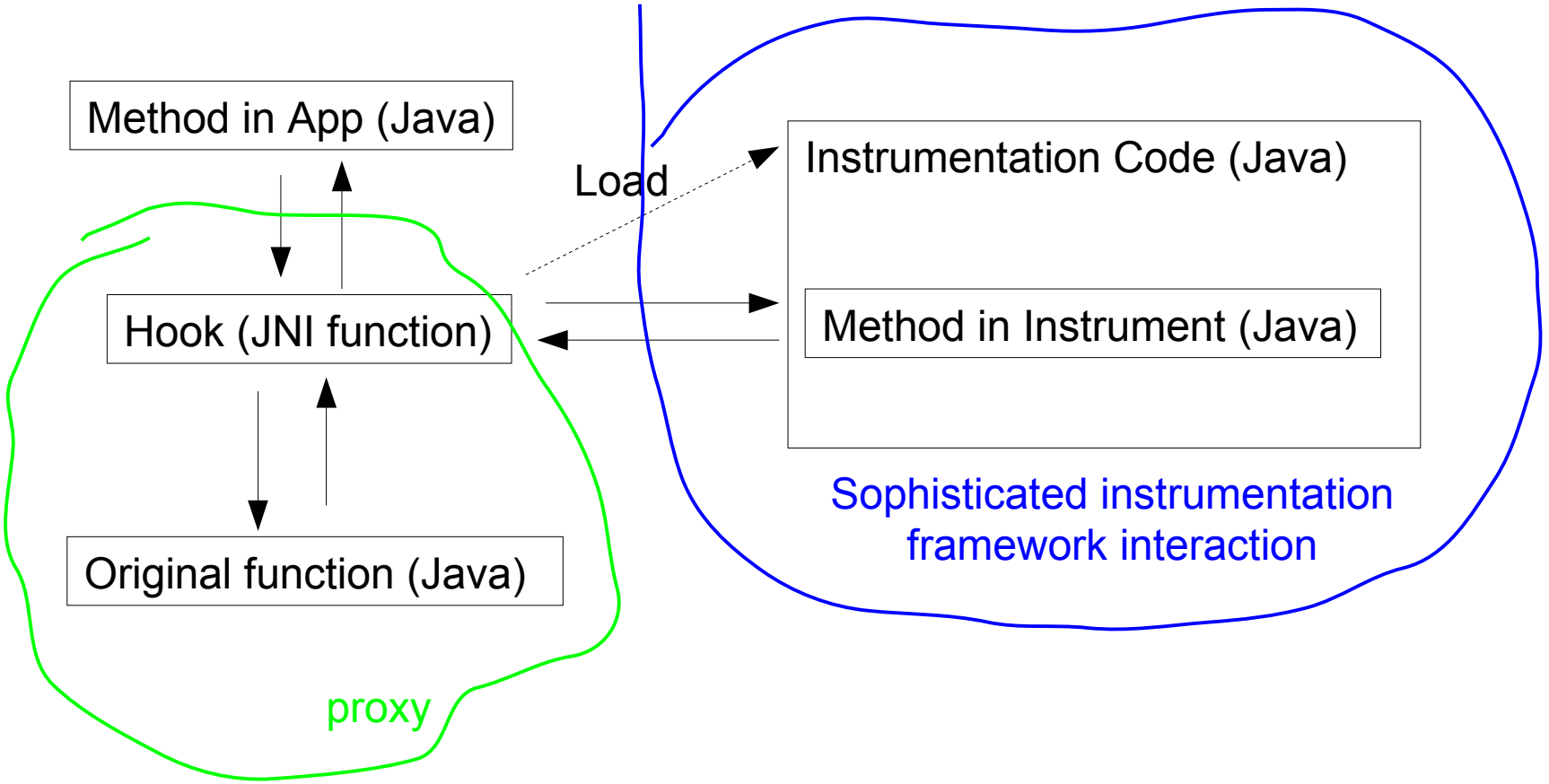
Loading Classes 2/3



Loading Classes 3/3

- The loaded classes can be used like any other class
  - Using C-JNI or Java code
- Each class has to be defined (incl. all inner classes), yes really!
  - e.g. `org.mulliner.collin.work$really`
- Dalvik cache at: `/data/dalvik-cache`
  - Needs to be made world writable
    Required for class loader to write **odex** file
  - **odex** file needs to be deleted on class update
    `rm /data/dalvik-cache/data@local@tmp@classes.dex`

Instrumentation Code Flow (v2)



Interacting with the Target Application

- Our (java) code runs inside the target process, yay!
  - But how do we interact with it?

- Access target's objects (class instances)
  - Scrape them from method parameters

```
int somemethod(Intent x, CustomClass y)
```

- Access the Application Context (android.content.Context)
  - Interact with the Android framework: send Intents, ... (next slides)

Field Scraping 1/2

- Access fields (class variables)
  - Manipulate and/or extract data

- Steps
  - Acquire class object (e.g. thru method hook)
  - Know the field name and type
    (source or disassembly of target class)
  - Access field (JNI GetXField)

```
jobject some_method(JNIEnv *env, jobject obj, …)
{
  cls = FindClass(env, "org/mulliner/collin/work");
  fid = GetFieldID(env, cls, “fieldname",
            "Landroid/content/Context;");
  jobject = GetObjectField(env, obj, fid);
```

Field Scraping 2/2 (for java nerds)

- Inner vs. outer Class
  - Sometimes you will have access to wired stuff but not the stuff you are looking for
  - e.g access to some inner class (ending with `$Name`) you want the outer class or some member of it

- Java generates synthetic member variables for you
  - Inner class has access to the outer class via `this$0`

```
org.mulliner.collin.work & org.mulliner.collin.work$harder

Access only to object of type $harder

FindClass(env, "org/mulliner/collin/work$harder);
GetFieldID(env, cls, “this$0", "Lorg/mulliner/collin/work");
```

Access to Application Context

- Scrape fields of type: Service, Application, …
  - Say hi to your disassembler :)

- Use the ActivityThread
  - Usable from any UI thread

```
Class<?> activityThreadClass =
                Class.forName("android.App.ActivityThread");

Method method =
        activityThreadClass.getMethod("currentApplication");

Application app =
          (Application) method.invoke(null, (Object[])null);
```

Rapid Prototyping of Framework Modifications

- Defense against SMS OTP stealing Trojans [1]
  - Change local SMS routing based on SMS content
- For the prototype we needed to change code in the framework

```
com/android/internal/telephony/SMSDispatcher.java
protected void dispatchPdus(byte[] pdus) { … }
```

- Instead of recompiling Android just replace the method
  → save a lot of time
  → test on many different devices without custom compile

[1] *SMS-based One-Time Passwords: Attacks and Defense (short paper)* Collin Mulliner, Ravishankar Borgaonkar, Patrick Stewin, Jean-Pierre Seifert
In the Proceedings of the 10th Conference on Detection of Intrusions and Malware & Vulnerability Assessment
(DIMVA 2013) Berlin, Germany, July 2013

Using DVM internal functions, for profit

- Dump list of loaded classes in current VM
  - Useful to find out which system process runs a specific framework service

```
dvmDumpAllClasses(level);
// level  0 = only class names 1 = class details
```

- Dump details of specific class
  - All methods (incl. signature), fields, etc...

```
cls = dvmFindLoadedClass("Lorg/mulliner/collin/work");
dvmDumpClass(cls, 1);
```

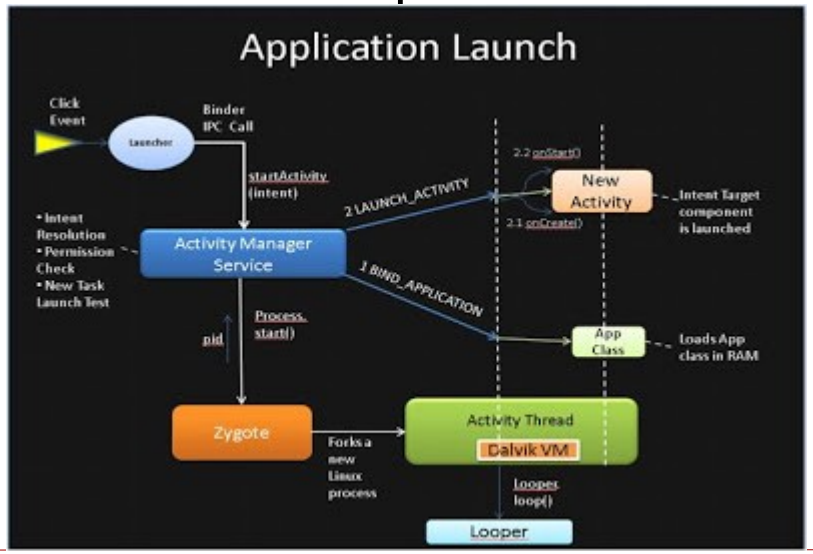
DvmDumpClass output for java.lang.String

```
I/dalvikvm(  410): ----- class 'Ljava/lang/String;' cl=0x0 ser=0x50000016 -----
I/dalvikvm(  410):   objectSize=24 (8 from super)
I/dalvikvm(  410):   access=0x0003.0011
I/dalvikvm(  410):   super='Ljava/lang/Object;' (cl=0x0)
I/dalvikvm(  410):   interfaces (3):
I/dalvikvm(  410):      0: Ljava/io/Serializable; (cl=0x0)
I/dalvikvm(  410):      1: Ljava/lang/Comparable; (cl=0x0)
I/dalvikvm(  410):      2: Ljava/lang/CharSequence; (cl=0x0)
I/dalvikvm(  410):   vtable (62 entries, 11 in super):
I/dalvikvm(  410):     17: 0x56afd4e8            compareTo (Ljava/lang/String;)I
I/dalvikvm(  410):     18: 0x56afd520  compareToIgnoreCase (Ljava/lang/String;)I
I/dalvikvm(  410):     19: 0x56afd558              concat (Ljava/lang/String;)...
I/dalvikvm(  410):     20: 0x56afd590            contains (Ljava/lang/CharSequ...
I/dalvikvm(  410):     21: 0x56afd5c8       contentEquals (Ljava/lang/CharSequ...
. . . .
I/dalvikvm(  410):   static fields (4 entries):
I/dalvikvm(  410):      0:                ASCII [C
I/dalvikvm(  410):      1: CASE_INSENSITIVE_ORDER Ljava/util/Comparator;
I/dalvikvm(  410):      2:     REPLACEMENT_CHAR C
I/dalvikvm(  410):      3:     serialVersionUID J
I/dalvikvm(  410):   instance fields (4 entries):
I/dalvikvm(  410):      0:                value [C
I/dalvikvm(  410):      1:            hashCode I
I/dalvikvm(  410):      2:              offset I
```

Modifying Stuff Globally

- **zygote** is base VM for all processes
  - Code injected into zygote propagates to all newly created processes

- **system_server** handles like everything
  - monitor and/or cross process Intents



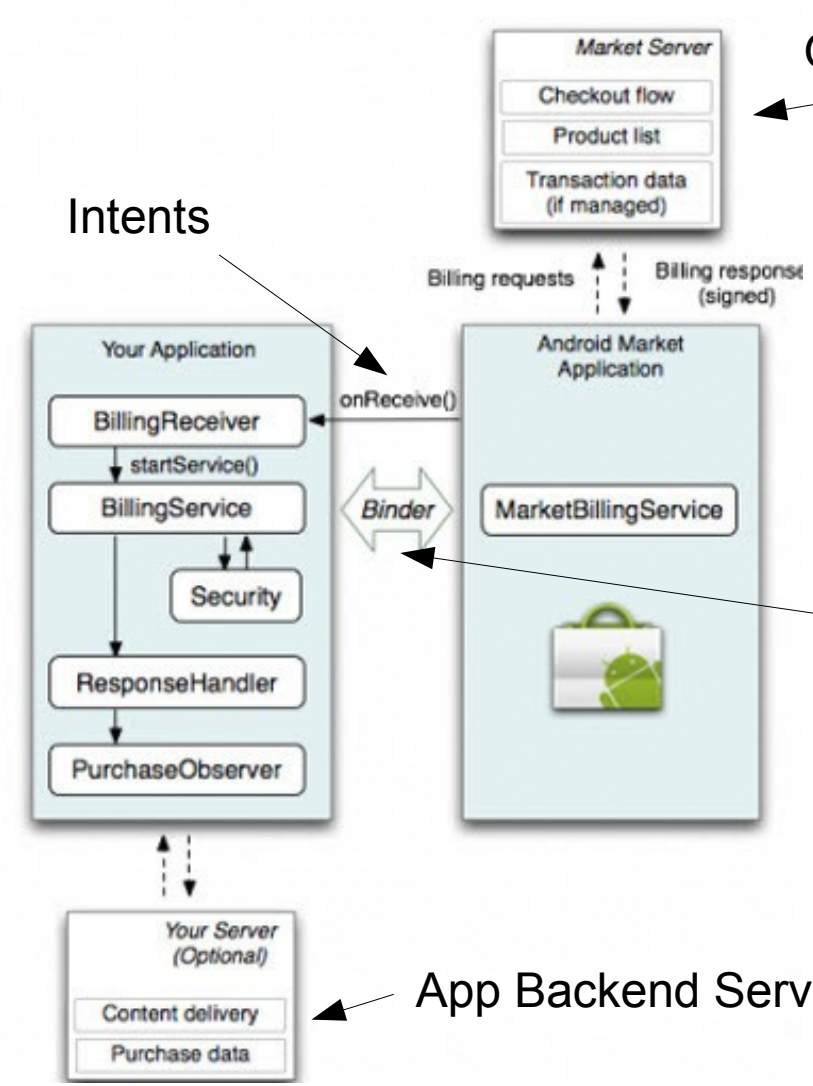
Getting Serious!

- We can...
  - inject native + Dalvik code into any Android process
  - hook Dalvik methods in Apps, the Framework, and Java core libraries
  - Interact with the Apps and the Android framework
- We did...
  - spy on behavior of Apps API calls
  - changed SMS handling in the Android framework
- **Lets attack real stuff and make some $$$$**

Android In-App Billing

- Sell stuff from within an Android application
  - Upgrade to full version
  - Remove advertisement
  - In-game coins
  - Arbitrary content
- Google takes 30% of all sales
  - Google says they make significant revenue with this

In-App Billing: Overview



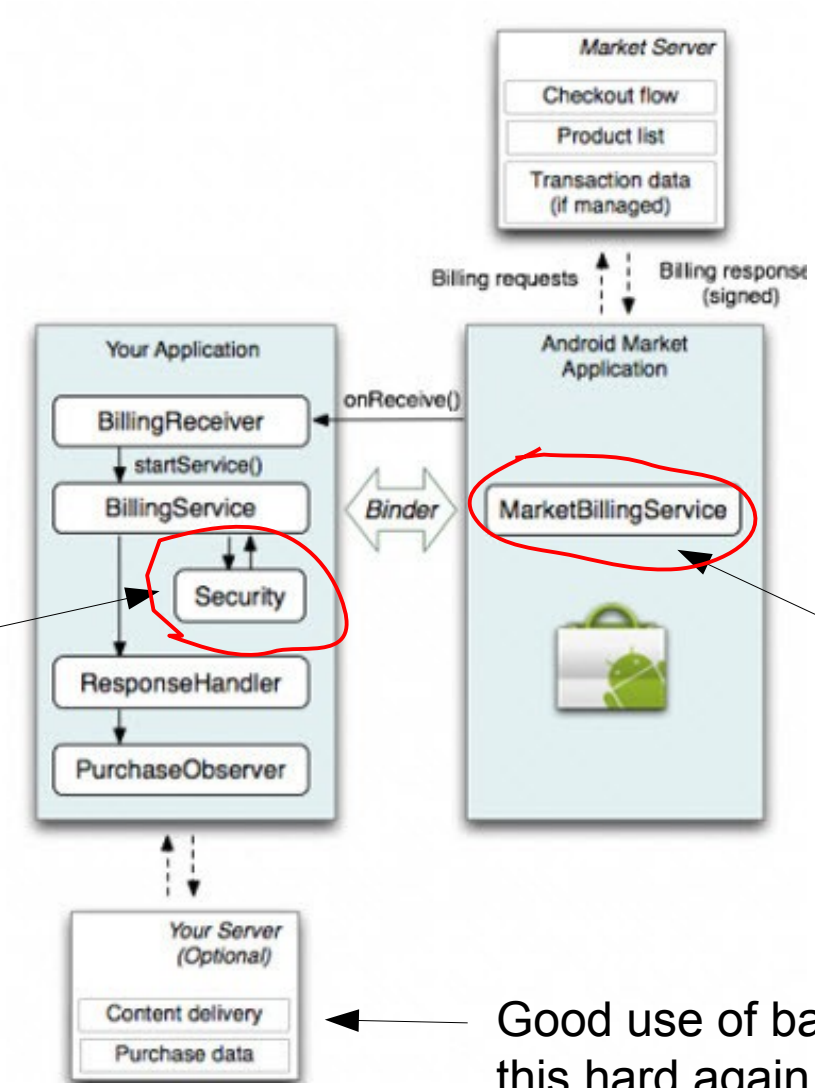
Attacking In-App Billing 1/2

- Goals
  - Unlock full versions, free content, in-game coins :-)
- Previous attacks (according to a friend)
  - **Manually patching**
    - The Apps
      - Remove checks, disable billing code, …
    - the Android Market App
- Problems
  - A lot of work and testing, needs to be for each App
  - Repeat after every update :-(
  - Fucking up your Market App

Attacking In-App Billing 2/2

- Use Dynamic Dalvik Instrumentation (DDI)
- Implement once run anywhere
  - Start / Stop attack on-demand
- No need to manually do anything on per-app basis
- Updates don't bother us
  - (Market API changes do)

The Attack



Disable security. This is a signature check. **Remember signature.verify?** Done in zygote, this is global!

Instrument Market App → only the In-App billing API

Good use of backend makes this hard again

Dog and Pony Show (Demo)

- ...a video

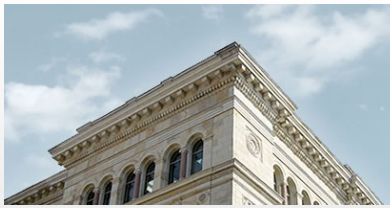
Conclusions

- Dynamic Instrumentation via the Android Runtime allows
  - Modification of Apps and the Framework in memory
  - Doesn't break APK signatures
  - Portable across devices
  - Super stable (not a hack)
  - But can only replace whole functions
    - no bytecode modification
- Possible to stir up Android AppSec quite a bit
  - Obfuscation and use of reflection is kinda useless
- We have various ongoing projects based on this
  - Students doing interesting stuff

DDI Framework Release!

- DDI Framework released in source, of course!
  - Injection tool + libs
  - Including examples
  - No source for GooglePlay attack!

- http://www.mulliner.org/android/ddi/
  - Repo will be on GitHub



EOF

Thank you!

twitter: @collinrm
collin[at]mulliner.org
http://mulliner.org/android
http://seclab.ccs.neu.edu

The Dalvik VM - libdvm

- We interrogate the DVM using dlsym()
  - We just need a small number of symbols

```
// hooking
dvmFindLoadedClass
dvmFindVirtualMethodHierByDescriptor
dvmFindDirectMethodByDescriptor
dvmUseJNIBridge
// class loading
dvm_dalvik_system_DexFile
dvmStringFromCStr
dvmGetSystemClassLoader
dvmGetCurrentJNIMethod
// debugging :)
dvmDumpAllClasses
dvmDumpClass
```