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State Of The ART

Exploring The New Android KitKat Runtime

Agenda

Introduction

Ahead of time compilation

OAT file format

Security implications

Reverse engineering

Background

- Introduced in Android KitKat 4.4 back in October, 2013

- Still in experimental stage

- Poised to replace Dalvik

Background

- Dalvik
  - Dexopt
  - Just-in-time (JIT) compilation
- ART
  - Ahead-of-time (AOT) compilation
  - Dalvik bytecode -> Native code

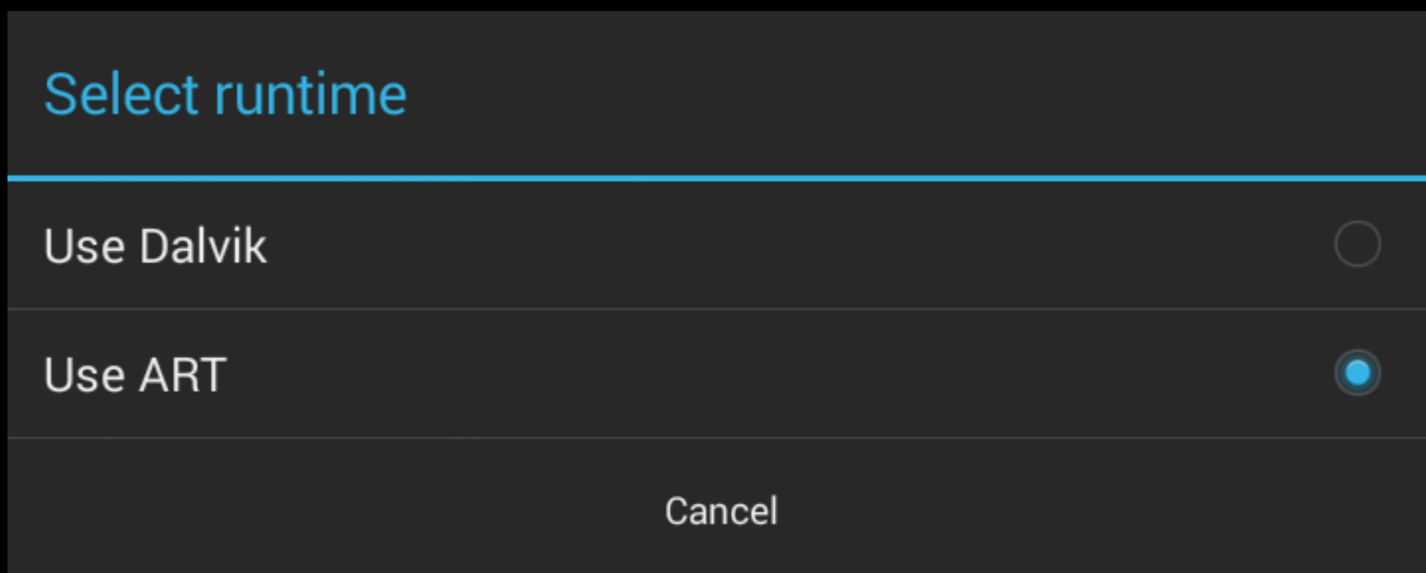
Background

- Advantages
  - Better performance
  - Better battery life

- (slight) Disadvantages
  - More storage space
  - Longer installation time

Turning on ART

- Settings > Developer options > Select runtime



Turning on ART

- Runtime selection is not possible on some devices using official releases
  - 2012 Nexus 7
  - Nexus 10
- Third-party ROMs
- Build from AOSP

Turning on ART

- To check which runtime is enabled

```
getprop persist.sys.dalvik.vm.lib.1
```

- Returns “libart.so” if ART is enabled
- Returns “libdvm.so” if Dalvik

Before we proceed

- ART is still under heavy development
- Some parts of this talk may change
- In some parts will focus on the fundamental principles versus details that may change

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When?

- Upon reboot after ART is enabled
  - Creates boot.oat and boot image
  - All installed apps will be compiled
  - May take a while
- App installation
- When it meets certain criteria based on profiling results

Dex2oat

- Dex2oat
  - Ex:
    ```
    /system/bin/dex2oat --zip-fd=6 --zip-location=/system/app/Email.apk --oat-fd=7 --oat-location=/data/dalvik-cache/system@app@Email.apk@classes.dex --profile-file=/data/dalvik-cache/profiles/com.android.email
    ```
- Resulting OAT file will be placed in /data/dalvik-cache

Dex2oat

- Retrieve classes.dex from APK
- Verify each class
- Verify each method
- Verify each Dalvik instruction
- Compile bytecode in all methods in each class into native code
  - Except class initializers (<clinit>)

Boot.oat

- system@framework@boot.oat
- Contains libs and frameworks in boot class path
  - To be pre-loaded in all apps

```
/system/bin/dex2oat --image=/data/dalvik-cache/system@framework@boot.art --runtime-arg
-Xms64m --runtime-arg -Xmx64m --dex-file=/system/framework/core-libart.jar --dex-file=/
system/framework/conscrypt.jar --dex-file=/system/framework/okhttp.jar --dex-file=/
system/framework/core-junit.jar --dex-file=/system/framework/bouncycastle.jar --dex-
file=/system/framework/ext.jar --dex-file=/system/framework/framework.jar --dex-file=/
system/framework/framework2.jar --dex-file=/system/framework/telephony-common.jar --
dex-file=/system/framework/voip-common.jar --dex-file=/system/framework/mms-common.jar
--dex-file=/system/framework/android.policy.jar --dex-file=/system/framework/
services.jar --dex-file=/system/framework/apache-xml.jar --dex-file=/system/framework/
webviewchromium.jar --oat-file=/data/dalvik-cache/system@framework@boot.oat --runtime-
arg -implicit-checks:none --instruction-set=arm --instruction-set-features=default --
base=0x70000000 --image-classes-zip=/system/framework/framework.jar
```

Boot.oat

- /system/framework/core-libart.jar
- /system/framework/conscrypt.jar
- /system/framework/okhttp.jar
- /system/framework/core-junit.jar
- /system/framework/bouncycastle.jar
- /system/framework/ext.jar
- /system/framework/framework.jar
- /system/framework/framework2.jar
- /system/framework/telephony-common.jar
- /system/framework/voip-common.jar
- /system/framework/mms-common.jar
- /system/framework/android.policy.jar
- /system/framework/services.jar
- /system/framework/apache-xml.jar
- /system/framework/webviewchromium.jar

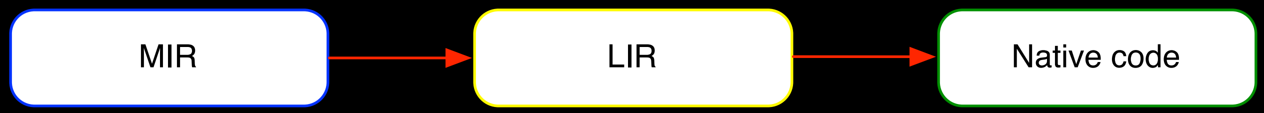
Boot image

- system@framework@boot.art
- Contains absolute pointers for methods in boot.oat
- boot.oat contain absolute pointers to methods in the boot image
- Loaded by zygote along with boot.oat

Compilation

- Compiler backends:
  - Quick
  - Optimizing
  - Portable
- “-compile-backend” option for dex2oat
- Current default is Quick

Quick Backend



- Medium level IR (DEX bytecode)
- Low level IR
- Native code
- Some optimizations at each stage

Optimizing backend

- Basically Quick with additional optimizations
- Still in heavy development

Portable backend

- Uses LLVM bitcode as its LIR
- Optimizations using LLVM optimizer
- Code generation is done by LLVM backends

Profiling

- By default, ART compiles methods regardless of impact on performance

- Profiling feature allows ART to be more selective on which methods to compile

Profiling

- Currently disabled by default
- To enable:

```
setprop dalvik.vm.profiler 1
```

- No AOT compilation upon app install
  - Reduced install time
  - Save on disk space

Profiling

- Profiling data is collected while app is running
- Profile files are placed in /data/dalvik-cache/profiles
- Profile file name is the package name
- Profile data is used to determine if AOT compilation will be done

Profiling

```
42/2/352
android.database.Cursor com.android.email.provider.EmailProvider.uiAccounts(java.lang.String[])/1/128
void com.android.email.NotificationController.ensureHandlerExists()/1/37
int com.android.email.provider.EmailProvider.getFolderTypeFromMailboxType(int)/2/56
boolean com.android.mail.browse.ConversationCursor$ConversationProvider.onCreate()/1/49
com.google.common.collect.ImmutableList com.google.common.collect.ImmutableList.of()/1/3
<snip>
```

- First line is the summary information
  – Samples count/Null methods count/Boot path methods count
- Subsequent lines are the profile data
  – Method name/Count/Size

Profiling

- When?
  - Does the app need to undergo dex2oat?
    - Number of methods comprising 90% of called methods has changed by > 10%
  - If yes, which methods are to be compiled?
    - Methods comprising 90% of called methods

Agenda

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OAT file format

Security implications

Reverse engineering

OAT File

- ELF dynamic object
- .oat file extension

▼ struct dynamic_symbol_table	
▶ struct Elf32_Sym symtab[0]	[U] <Undefined>
▼ struct Elf32_Sym symtab[1]	oatdata
▶ struct sym_name32_t sym_name	oatdata
Elf32_Addr sym_value	0x00001000
Elf32_Xword sym_size	892928
▶ struct sym_info_t sym_info	STB_GLOBAL | STT_OBJECT
unsigned char sym_other	0
Elf32_Half sym_shndx	4
▶ char sym_data[892928]	
▼ struct Elf32_Sym symtab[2]	oatexec
▶ struct sym_name32_t sym_name	oatexec
Elf32_Addr sym_value	0x000DB000
Elf32_Xword sym_size	605104
▶ struct sym_info_t sym_info	STB_GLOBAL | STT_OBJECT
unsigned char sym_other	0
Elf32_Half sym_shndx	5
▶ char sym_data[605104]	
▼ struct Elf32_Sym symtab[3]	oatlastword
▶ struct sym_name32_t sym_name	oatlastword
Elf32_Addr sym_value	0x0016EBAC
Elf32_Xword sym_size	4
▶ struct sym_info_t sym_info	STB_GLOBAL | STT_OBJECT
unsigned char sym_other	0
Elf32_Half sym_shndx	5
▶ char sym_data[4]	ðGõç

OAT File

- Dynamic symbol tables pointing to OAT data and code
  - oatdata
  - oatexec
  - oatlastword

▼ struct dynamic_symbol_table	
▶ struct Elf32_Sym symtab[0]	[U] <Undefined>
▼ struct Elf32_Sym symtab[1]	oatdata
▶ struct sym_name32_t sym_name	oatdata
Elf32_Addr sym_value	0x00001000
Elf32_Xword sym_size	892928
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unsigned char sym_other	0
Elf32_Half sym_shndx	5
▶ char sym_data[4]	ðGõç

OAT File

- oatdata -> headers, DEX files
- oatexec -> compiled code
- oatlastword -> end marker

▼ struct dynamic_symbol_table	
▶ struct Elf32_Sym symtab[0]	[U] <Undefined>
▼ struct Elf32_Sym symtab[1]	oatdata
▶ struct sym_name32_t sym_name	oatdata
Elf32_Addr sym_value	0x00001000
Elf32_Xword sym_size	892928
▶ struct sym_info_t sym_info	STB_GLOBAL | STT_OBJECT
unsigned char sym_other	0
Elf32_Half sym_shndx	4
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unsigned char sym_other	0
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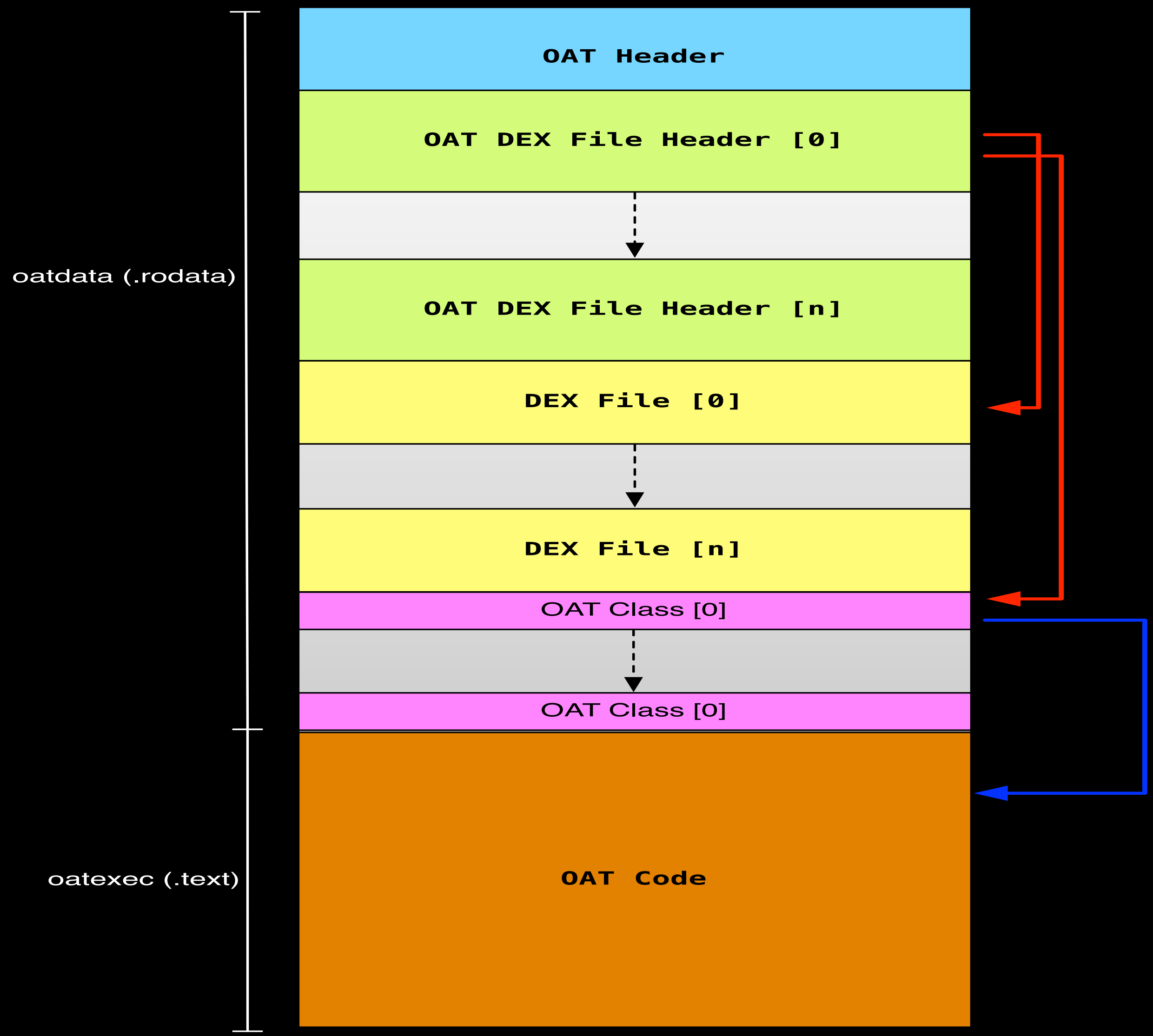
unsigned char sym_other	0
Elf32_Half sym_shndx	5
▶ char sym_data[4]	ðGõç

OAT File


oatdata (.rodata)
oatexec (.text)
OAT Header
OAT DEX File Header [0]
OAT DEX File Header [n]
DEX File [0]
DEX File [n]
OAT Class [0]
OAT Class [0]
OAT Code

OAT Header

Name	Format	Description
magic	ubyte[4]	Magic value. "oat\n"
version	ubyte[4]	OAT version.
adler32_checksum	uint32	Adler-32 checksum of the executable code data
instruction_set	uint32	Instruction set architecture
instruction_set_features	uint32	Bitmask of supported features per architecture
dex_file_count	uint32	Number of DEX files in the OAT
executable_offset	uint32	Offset of executable code section from start of oatdata
interpreter_to_interpreter_bridge_offset	uint32	offset from oatdata start to interpreter_to_interpreter_bridge stub
interpreter_to_compiled_code_bridge_offset	uint32	offset from oatdata start to interpreter_to_compiled_code_bridge stub
jni_dlsym_lookup_offset_	uint32	offset from oatdata start to jni_dlsym_lookup stub
portable_imt_conflict_trampoline_offset	uint32	offset from oatdata start to portable_imt_conflict_trampoline stub
portable_resolution_trampoline_offset	uint32	offset from oatdata start to portable_resolution_trampoline stub
portable_to_interpreter_bridge_offset	uint32	offset from oatdata start to portable_to_interpreter_bridge stub
quick_generic_jni_trampoline_offset	uint32	offset from oatdata start to quick_generic_jni_trampoline stub
quick_imt_conflict_trampoline_offset	uint32	offset from oatdata start to quick_imt_conflict_trampoline stub
quick_resolution_trampoline_offset	uint32	offset from oatdata start to quick_resolution_trampoline stub
quick_to_interpreter_bridge_offset	uint32	offset from oatdata start to quick_to_interpreter_bridge stub
image_file_location_oat_checksum	uint32	Checksum of image file's path
image_file_location_oat_data_begin	uint32	The virtual address of the image file's oatdata section
image_file_location_size	uint32	The length of the image file's path

OAT Header

- Supported instruction sets
  - ARM
  - ARM64
  - Thumb2
  - X86
  - X86_64
  - Mips

OAT DEX File Header

Name	Format	Description
dex_file_location_size	uint32	Length of the original input DEX path
dex_file_location_data	ubyte[dex_file_location_size]	Original path of input DEX file
dex_file_location_checksum	uint32	Checksum of path string
dex_file_pointer	uint32	Offset of embedded input DEX
classes_offsets	uint32[DEX.header.class_defs_size]	List of offsets to OATClassHeaders

- The original DEX file is embedded in the OAT data section

OAT Class Header

Name	Format	Description
status	uint16	State of class during compilation
type	uint16	Type of class
bitmap_size	uint32	Size of methods bitmap
bitmap_pointer	uint32	Offset to methods bitmap
methods_pointer	uint32	Offset to methods

- Status
  - kStatusError
  - kStatusNotReady
  - kStatusIdx
  - kStatusLoaded
  - kStatusResolved
  - kStatusVerifying
  - kStatusRetryVerificationAtRuntime
  - kStatusVerifyingAtRuntime
  - kStatusVerified
  - kStatusInitializing
  - kStatusInitialized

OAT Class Header

Name	Format	Description
status	uint16	State of class during compilation
type	uint16	Type of class
bitmap_size	uint32	Size of methods bitmap
bitmap_pointer	uint32	Offset to methods bitmap
methods_pointer	uint32	Offset to methods

- Type
  - kOatClassAllCompiled
  - kOatClassSomeCompiled
  - kOatClassNoneCompiled

OAT Class Header

- kOatClassAllCompiled
  – All methods in the class were compiled
- kOatClassSomeCompiled
  – Some of the methods in the class were compiled
- kOatClassNoneCompiled
  – None of the methods in the class were compiled

OAT Class Header

Name	Format	Description
status	uint16	State of class during compilation
type	uint16	Type of class
bitmap_size	uint32	Size of methods bitmap
bitmap_pointer	uint32	Offset to methods bitmap
methods_pointer	uint32	Offset to OatMethodOffsets list

- Bitmaps are used to represent which methods are compiled
- Each bit represents every method in the class, starting with direct methods, then virtual methods
- If bit it is set, the method was compiled

OAT Method

- OatMethodOffset

Name	Format	Description
code_offset	uint32	Offset of compiled code from start of oatdata
frame_size_in_bytes	uint32	Frame size for this method when executed
core_spill_mask	uint32	Bitmap of spilled machine registers
fp_spill_mask	uint32	Bitmap of spilled floating point machine registers
gc_map_offset	uint32	Offset to the GC map

- Corresponds to each compiled method

OAT Method

- OATMethodHeader

Name	Format	Description
mapping_table_offset	uint32	Offset from the start of the mapping table
vmap_table_offset	uint32	Offset form the start of the vmap table
code_size	uint32	Method's code size in bytes

- Appears right before method code

Agenda

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Security implications

Reverse Engineering

Compiler vulnerabilities

- New technology means new code
- New code means more potential mistakes

Fuzzing the AOT compiler

- Used dumb fuzzing methods
- Generated DEX files with mutated method code
- Ran dex2oat against them

Fuzzing the AOT compiler

- Found several crashes
- Did not pursue further due still evolving code in ART
- Viable target once ART stabilizes

User mode rootkits

- Post exploitation scenario
- Attacker already has elevated privileges
- Some past examples in Android
  – Erez Metula in his book “Managed Code Rootkits”
  – Tsukasa Oi’s “Yet Another Android Rootkit” paper

User mode rootkits

- Technologies such as dm-verity introduced in KitKat makes rootkits relying on /system partition modifications obsolete

- No write to /system, or anywhere else except boot.oat, no memory modications, no ptrace

User mode rootkits

- Example idea
  – Parse the boot image to locate address of methods to hook
  – Patch the target compiled method in boot.oat to jump to your code
  – Hide your code inside boot.oat using ELF virus techniques

User mode rootkits

- Ongoing research

ASLR bypass

- Base address of boot image is fixed at 0x700000

```
5d5ba000-5ee19000 r-xp 00000000 b3:03 922        /system/lib/libwebviewchromium.so
5ee19000-5ee1a000 ---p 00000000 00:00 0
5ee1a000-5ef2e000 r--p 0185f000 b3:03 922        /system/lib/libwebviewchromium.so
5ef2e000-5ef48000 rw-p 01973000 b3:03 922        /system/lib/libwebviewchromium.so
5ef48000-5ef64000 rw-p 00000000 00:00 0
5ef64000-6013e000 r--s 00000000 b3:03 1202       /system/usr/icu/icudt53l.dat
6013e000-6073e000 rw-p 00000000 00:04 7375       /dev/ashmem/dalvik-allocspace main rosalloc space live-bitmap 2 (deleted)
6081d000-60e1d000 rw-p 00000000 00:04 7376       /dev/ashmem/dalvik-allocspace main rosalloc space mark-bitmap 2 (deleted)
60e1d000-60e1e000 ---p 00000000 00:00 0
60e1e000-60f21000 rw-p 00000000 00:00 0
60fe0000-60fe1000 ---p 00000000 00:00 0
60fe1000-610e4000 rw-p 00000000 00:00 0
61122000-61123000 ---p 00000000 00:00 0
61123000-61226000 rw-p 00000000 00:00 0
70000000-70b28000 rw-p 00000000 b3:09 425155     /data/dalvik-cache/system@framework@boot.art
70b28000-7286e000 r--p 00000000 b3:09 425271     /data/dalvik-cache/system@framework@boot.oat
7286e000-74257000 r-xp 01d46000 b3:09 425271     /data/dalvik-cache/system@framework@boot.oat
74257000-74258000 rw-p 0372f000 b3:09 425271     /data/dalvik-cache/system@framework@boot.oat
74258000-74687000 rw-p 00000000 00:04 3462       /dev/ashmem/dalvik-zygote / non moving space (deleted)
74687000-74688000 rw-p 00000000 00:04 7377       /dev/ashmem/dalvik-alloc space (deleted)
74688000-77a59000 ---p 00001000 00:04 7377       /dev/ashmem/dalvik-alloc space (deleted)
77a59000-78258000 rw-p 033d2000 00:04 7377       /dev/ashmem/dalvik-alloc space (deleted)
78258000-78459000 rw-p 00000000 00:04 3461       /dev/ashmem/dalvik-main space (deleted)
78459000-90258000 ---p 00201000 00:04 3461       /dev/ashmem/dalvik-main space (deleted)
be94f000-be970000 rw-p 00000000 00:00 0          [stack]
ffff0000-ffff1000 r-xp 00000000 00:00 0          [vectors]
```

ASLR bypass

- Base address of boot image is fixed at 0x700000

```
5f0ef000-5f10b000 rw-p 00000000 00:00 0
5f10b000-602e5000 r--s 00000000 b3:03 1202       /system/usr/icu/icudt53l.dat
602e5000-608e5000 rw-p 00000000 00:04 5563       /dev/ashmem/dalvik-allocspace main rosalloc space mark-bitmap 2 (deleted)
608e5000-609d5000 rw-p 00000000 00:04 5566       /dev/ashmem/dalvik-allocspace alloc space mark-bitmap 3 (deleted)
609d5000-609d6000 ---p 00000000 00:00 0
609d6000-60ad9000 rw-p 00000000 00:00 0
60b93000-60b94000 ---p 00000000 00:00 0
60b94000-60c97000 rw-p 00000000 00:00 0
60cbc000-60cbd000 ---p 00000000 00:00 0
60cbd000-60dc0000 rw-p 00000000 00:00 0
60e74000-60e75000 ---p 00000000 00:00 0
60e75000-60f78000 rw-p 00000000 00:00 0
61003000-61004000 ---p 00000000 00:00 0
61004000-61107000 rw-p 00000000 00:00 0
70000000-70b28000 rw-p 00000000 b3:09 425155     /data/dalvik-cache/system@framework@boot.art
70b28000-7286e000 r--p 00000000 b3:09 425154     /data/dalvik-cache/system@framework@boot.oat
7286e000-74257000 r-xp 01d46000 b3:09 425154     /data/dalvik-cache/system@framework@boot.oat
74257000-74258000 rw-p 0372f000 b3:09 425154     /data/dalvik-cache/system@framework@boot.oat
74258000-74687000 rw-p 00000000 00:04 5542       /dev/ashmem/dalvik-zygote / non moving space (deleted)
74687000-74688000 rw-p 00000000 00:04 5564       /dev/ashmem/dalvik-alloc space (deleted)
74688000-77a59000 ---p 00001000 00:04 5564       /dev/ashmem/dalvik-alloc space (deleted)
77a59000-78258000 rw-p 033d2000 00:04 5564       /dev/ashmem/dalvik-alloc space (deleted)
78258000-78459000 rw-p 00000000 00:04 5541       /dev/ashmem/dalvik-main space (deleted)
78459000-90258000 ---p 00201000 00:04 5541       /dev/ashmem/dalvik-main space (deleted)
be9bc000-be9dd000 rw-p 00000000 00:00 0          [stack]
ffff0000-ffff1000 r-xp 00000000 00:00 0          [vectors]
```

ASLR bypass

- Base address of boot image is fixed at 0x700000

```
60405000-60409000 rw-p 00000000 00:00 0
60461000-60464000 rw-p 00000000 00:00 0
60474000-6047a000 rw-p 00000000 00:00 0
60514000-60517000 rw-p 00000000 00:00 0
6053d000-60541000 rw-p 00000000 00:00 0
60601000-60605000 rw-p 00000000 00:00 0
606cf000-606d2000 rw-p 00000000 00:00 0
6076b000-60770000 rw-p 00000000 00:00 0
60770000-60d70000 rw-p 00000000 00:04 6272       /dev/ashmem/dalvik-allocspace main rosalloc space live-bitmap 2 (deleted)
60e68000-61468000 rw-p 00000000 00:04 6273       /dev/ashmem/dalvik-allocspace main rosalloc space mark-bitmap 2 (deleted)
61468000-61469000 ---p 00000000 00:00 0
61469000-6156c000 rw-p 00000000 00:00 0
6156c000-6156d000 ---p 00000000 00:00 0
6156d000-61670000 rw-p 00000000 00:00 0
70000000-70b28000 rw-p 00000000 b3:09 425155     /data/dalvik-cache/system@framework@boot.art
70b28000-7286e000 r--p 00000000 b3:09 425154     /data/dalvik-cache/system@framework@boot.oat
7286e000-74257000 r-xp 01d46000 b3:09 425154     /data/dalvik-cache/system@framework@boot.oat
74257000-74258000 rw-p 0372f000 b3:09 425154     /data/dalvik-cache/system@framework@boot.oat
74258000-74687000 rw-p 00000000 00:04 5472       /dev/ashmem/dalvik-zygote / non moving space (deleted)
74687000-74688000 rw-p 00000000 00:04 6274       /dev/ashmem/dalvik-alloc space (deleted)
74688000-77a59000 ---p 00001000 00:04 6274       /dev/ashmem/dalvik-alloc space (deleted)
77a59000-78258000 rw-p 033d2000 00:04 6274       /dev/ashmem/dalvik-alloc space (deleted)
78258000-78459000 rw-p 00000000 00:04 5471       /dev/ashmem/dalvik-main space (deleted)
78459000-90258000 ---p 00201000 00:04 5471       /dev/ashmem/dalvik-main space (deleted)
bed25000-bed46000 rw-p 00000000 00:00 0          [stack]
ffff0000-ffff1000 r-xp 00000000 00:00 0          [vectors]
```

ASLR bypass

- Base address of boot image is fixed at 0x700000
- Rich source of ROP gadgets
- boot.oat code section has 27 mb of code

```
7286e000-74257000 r-xp 01d46000 b3:09 425154      /data/dalvik-cache/system@framework@boot.oat
```

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Security implications

Reverse engineering

Static analysis

- Still better to read Dalvik bytecode disassembly (unless you're weird)
- If you are, you can use oatdump to dump the native code disassembly
  – You can find it in your ART enabled device

```
oatdump –oat-file=<oat-file>
```

Static analysis

```
DEX CODE:
  00049758: invoke-direct {v0}, void android/app/Activity-><init>() // method@(11, 0x000b)
  0004975e: return-void
COMPILED CODE:
  0x00000000: ldr.w                ip, [sb, #0x78]
  0x00000004: push.w               {r5, r6, lr}
  0x00000008: subs.w               sp, sp, #0x14
  0x0000000c: cmp                  sp, ip
  0x0000000e: blo.w                #0x38
  0x00000012: adds                 r6, r0, #0
  0x00000014: str                  r0, [sp]
  0x00000016: adds                 r5, r1, #0
  0x00000018: movw                 lr, #0xbd05
  0x0000001c: movt                 lr, #0x72f0 ; entryPointFromQuickCompiledCode
  0x00000020: movw                 r0, #0x7528
  0x00000024: movt                 r0, #0x7053 ; void android.app.Activity.<init>()
  0x00000028: adds                 r1, r5, #0
  0x0000002a: blx                  lr
  0x0000002c: subs                 r4, #1
  0x0000002e: beq.w                #0x3e
  0x00000032: add                  sp, #0x14
  0x00000034: pop.w                {r5, r6, pc}
  0x00000038: add                  sp, #0x20
  0x0000003a: ldr.w                pc, [sb, #0x2d8]
  0x0000003e: ldr.w                lr, [sb, #0x2c0]
  0x00000042: blx                  lr
  0x00000044: b                    #0x32
  0x00000046: movs                 r0, r0
```

Static analysis

- oatdump dumps the whole OAT file
- Need to have a tool to dump individual classes or methods and display xrefs
- Or better yet, an IDA plugin

Dynamic analysis

- Debugging Java code
  - ART supports JDWP, so you can use jdb (theoretically, haven't tried)
- Use gdb to debug native code
  - Get address of method using oatdump
  - Set breakpoint
  - trace

Dynamic analysis

- Dynamic instrumentation
  - Cydia Substrate for Android by saurik
  - Xposed Framework by rovo89
- ART not supported yet in these tools
- But work is ongoing

Dynamic analysis

- For now, static instrumentation is still the way to go
  – unpack
  – disassemble
  – add instrumentation
  – assemble
  – repackage

Conclusion

- ART is poised to supersede Dalvik in (hopefully) the near future

- Ripe for more security research

- RE tools need to adapt

Questions?

Thanks for listening!

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