Back To The Future
Going Back In Time To Abuse Android's JIT

$ whoami

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- Android
- **@rotlogix**

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Agenda

- Inspiration and Overview
- Android 4.4.4 JIT Internals & Abuse
- Android 7.1.1 JIT Internals & Abuse
- Android Oreo
- Tools
- Future Challenges
- Conclusion

~~*Back To The Future*~~

Going Back In Time To Abuse Android's JIT

Making Android Malware Great The First Time

On The Shoulders Of Giants

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On the Shoulders of Giants

FRIDAY, APRIL 5, 2013

Shellcode Execution in .NET using MSIL-based JIT Overwrite

@mattifestation

@rwincey

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Java Shellcode Execution

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Shellcode Execution in .NET using MSIL-Based JIT Overwrite

- **@mattifestation** discovered the **CPBLK** opcode, which is effectively the MSIL equivalent to **memcpy**
- He used to this opcode to overwrite a JIT'ed .NET method with shellcode
- https://www.exploit-monday.com/2013/04/MSILbasedShellcodeExec.html

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Java Shellcode Execution

- **@rwincey** uses the Unsafe API to overwrite a JIT'ed Java method with shellcode
- https://www.slideshare.net/RyanWincey/java-shellcodeoffice

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On the Shoulders of Giants

- After absorbing Matt and Ryan's research, I was left with one question

… " Is this also possible in Android? " …

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Motivation

- These techniques discussed today are **post-exploitation** in nature
- We already have installed a malicious application or gain code execution in Java through an arbitrary application
- Our goal is to execute shellcode in memory entirely through Java without loading additional shared-libraries, or utilizing JNI

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Motivation

- This means that a simple ***"application"*** can have a self-contained solution for loading shellcode from memory into memory
- This only relies on having access to a runtime and nothing more
- The technique results in zero disk presence, which eliminates the need packaging up shared-libraries or other executable payloads

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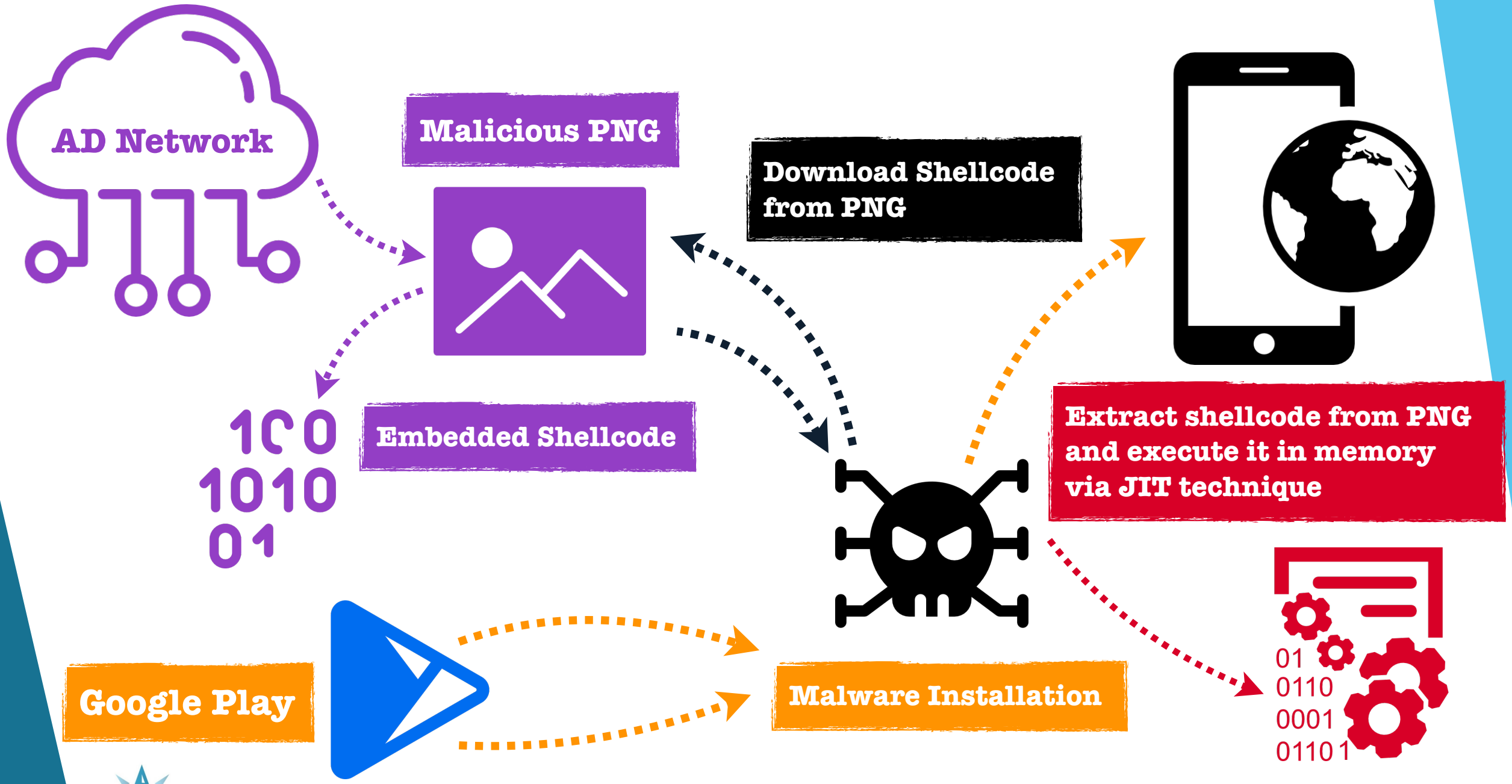
AD Network
Malicious PNG
Download Shellcode from PNG
Embedded Shellcode
Extract shellcode from PNG and execute it in memory via JIT technique
Google Play
Malware Installation

Time Travel

Time Travel

- Unfortunately the existence of a JIT compiler is not in every major version of Android
- Up until **KitKat**, Android utilized Dalvik, which is a JIT based VM
- When the Android Runtime (ART) was introduced in **Lollipop** it replaced the Dalvik VM
- The Android Runtime itself relies on Ahead-of-Time (AOT) compilation

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Time Travel

- Things change in **Android Nougat**, when a new JIT compiler is introduced with code profiling
- This is meant to improve the performance of applications when running in the ART

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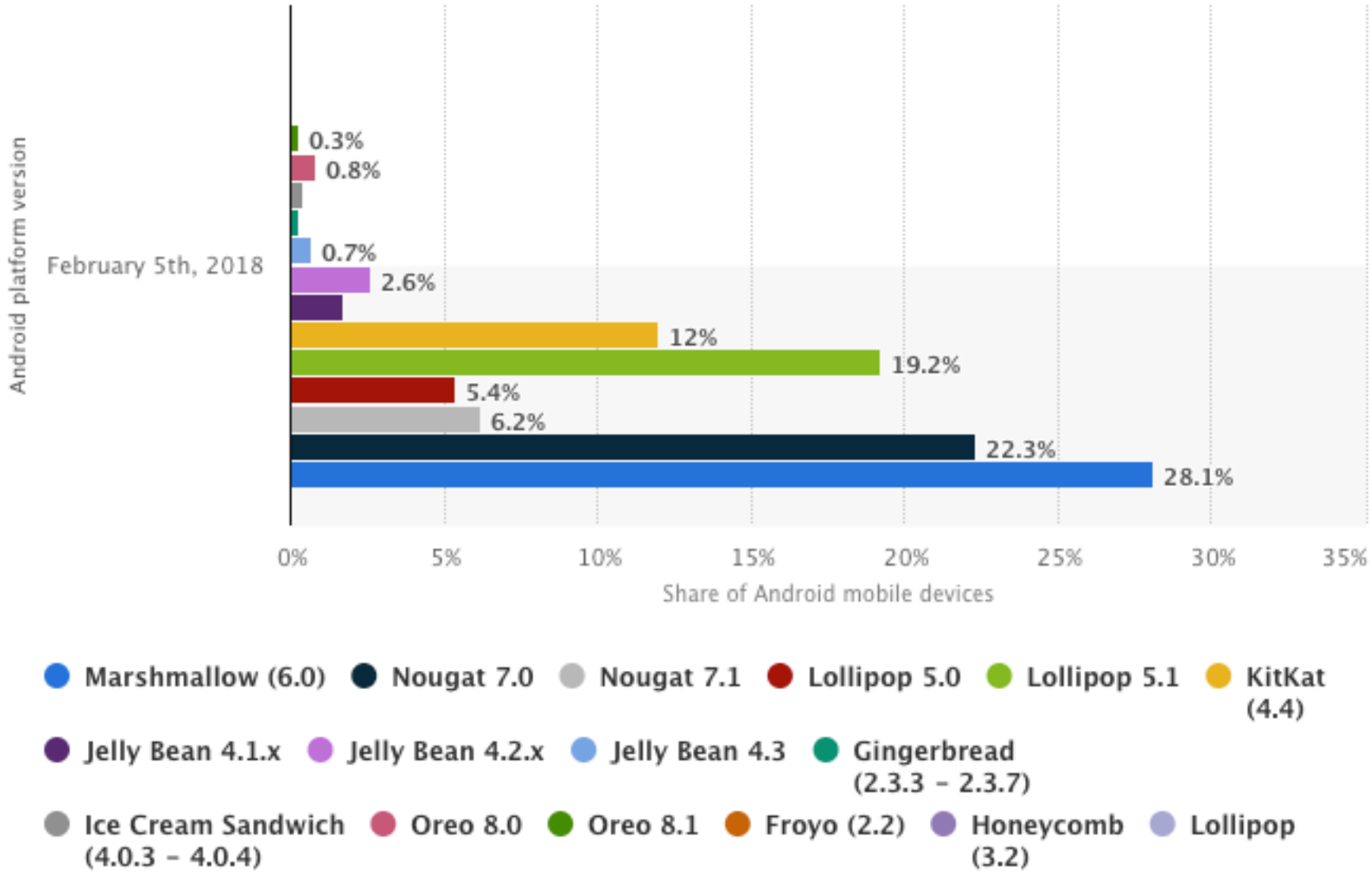
Android platform version
February 5th, 2018
0.3%
0.8%
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6.2%
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Share of Android mobile devices
Marshmallow (6.0)
Nougat 7.0
Nougat 7.1
Lollipop 5.0
Lollipop 5.1
KitKat (4.4)
Jelly Bean 4.1.x
Jelly Bean 4.2.x
Jelly Bean 4.3
Gingerbread (2.3.3 – 2.3.7)
Ice Cream Sandwich (4.0.3 – 4.0.4)
Oreo 8.0
Oreo 8.1
Froyo (2.2)
Honeycomb (3.2)
Lollipop

Overview

- This research predominantly focuses on **Android KitKat** and **Android Nougat**
- We are going to deep dive the internals of Dalvik's JIT implementation and the JIT compiler running in version 7.1.1
- Our main goal is to abuse each implementation in order to execute shellcode directly from memory
- This research was performed on a **Nexus 5 running 4.4.4** and a **Nexus 5X running 7.1.1**

Dalvik JIT Internals

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Dalvik JIT Internals

- The first question we need to answer is the following
- **How does a Dalvik method in its bytecode form, become Just-in-Time compiled?**
- For this research I care less about the ***"why"*** and more about the ***"how"***

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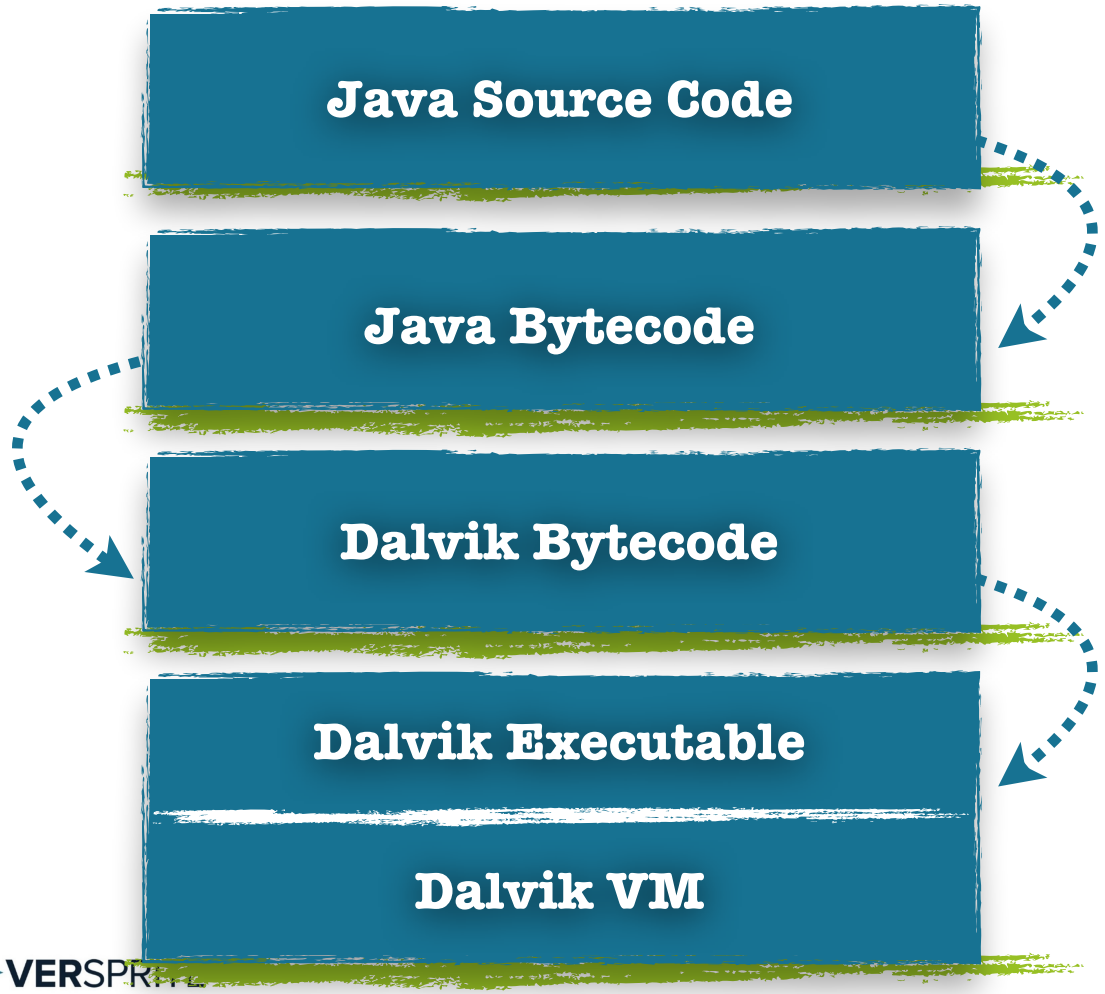
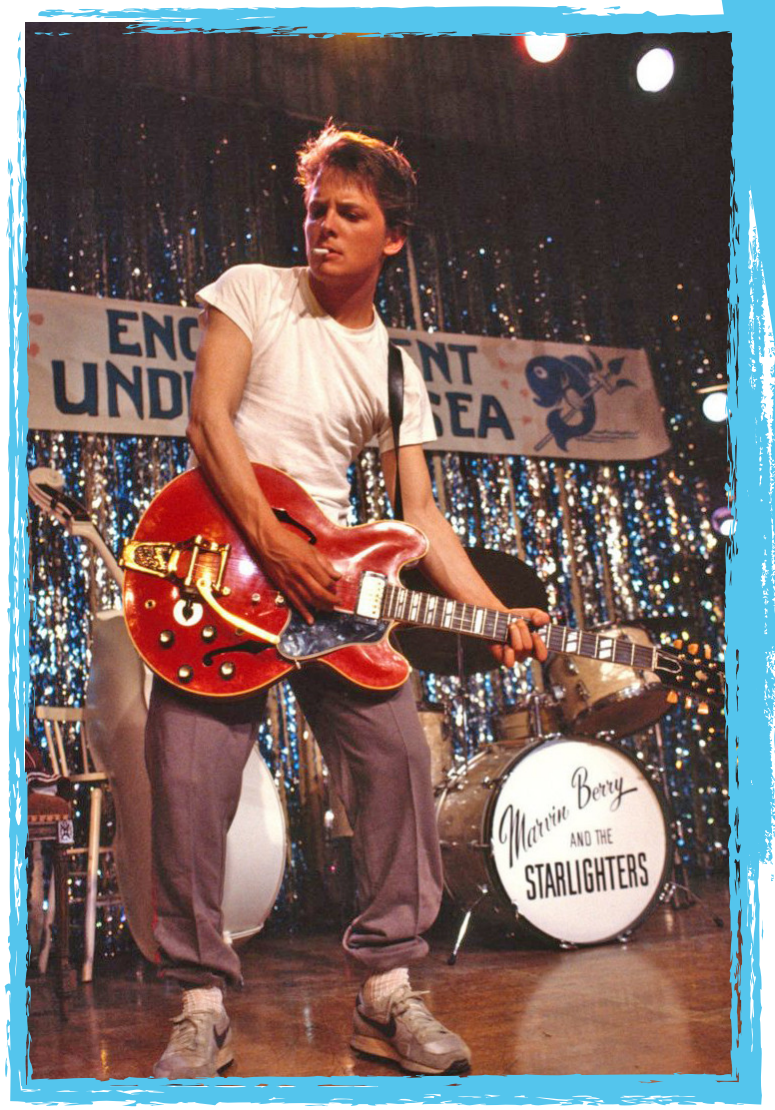
Dalvik JIT Internals





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Dalvik JIT Internals - Put in Work

- When a Dalvik method has been selected for JIT compilation, the compiler spins up and goes to work
- Once the JIT compiler has finished its compilation operations for the given Dalvik method, it calls the **dvmJitSetCodeAddr** function
- The compiler passes the target Dalvik method's bytecode pointer and the JIT code address as arguments to **dvmJitSetCodeAddr**

```
void dvmJitSetCodeAddr(const u2* dPC, void *nPC, JitInstructionSetType set,
                       bool isMethodEntry, int profilePrefixSize)
{
    JitEntryInfoUnion oldValue;
    JitEntryInfoUnion newValue;
    /*
     * Get the JitTable slot for this dPC (or create one if JitTable
     * has been reset between the time the trace was requested and
     * now.
     */
    JitEntry *jitEntry = isMethodEntry ?
        lookupAndAdd(dPC, false /* caller holds tableLock */, isMethodEntry) :
                    dvmJitFindEntry(dPC, isMethodEntry);
```

Bytecode and JIT Code Pointers

Dalvik JIT Internals - Lookup & Add

- **dvmJitSetCodeAddr** is then responsible for calling and passing the **dPC** to **lookupAndAdd**
- **lookupAndAdd** handles the ***"Lookup & Add"*** JIT operations

```
/*
 * Find an entry in the JitTable, creating if necessary.
 * Returns null if table is full.
 */
static JitEntry *lookupAndAdd(const u2* dPC, bool callerLocked,
                              bool isMethodEntry)
{
    u4 chainEndMarker = gDvmJit
    u4 idx = dvmJitHash(dPC);
```

dPC -> Dalvik Method Bytecode

Dalvik JIT Internals - Lookup & Add

- **lookupAndAdd** is responsible for finding available **"JitEntry"** slots in the **"JitTable"**
  - **pJitEntryTable** - Hash table structure that contains one or more JitEntry structures
  - **JitEntry** - Structure that contains a pointer to the Dalvik method's bytecode and a pointer to its translated JIT code

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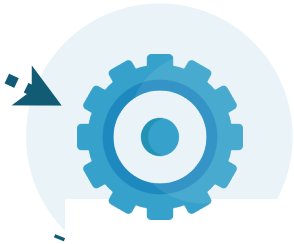
Dalvik JIT Internals - Lookup & Add

An available **JitEntry** slot within the **pJitEntryTable** hash table is updated with the hash of the target **dPC**



The **JitEntry** is populated with the code address for the target Dalvik method

The translated address member is initialized and the **JitEntry** is returned

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Dalvik JIT Internals - Lookup & Add

- Within the **dvmSetCodeAddr** function the translated address is then used to fill out the **JitEntry's codeAddress** member

```
JitEntry *jitEntry = isMethodEntry ?
    lookupAndAdd(dPC, false /* caller holds tableLock */, isMethodEntry) :
                    dvmJitFindEntry(dPC, isMethodEntry);
assert(jitEntry);
/* Note: order of update is important */
do {
    oldValue = jitEntry->u;
    newValue = oldValue;
    newValue.info.isMethodEntry = isMethodEntry;
    newValue.info.instructionSet = set;
    newValue.info.profileOffset = profilePrefixSize;
} while (android_atomic_release_cas(
            oldValue.infoWord, newValue.infoWord,
            &jitEntry->u.infoWord) != 0);
jitEntry->codeAddress = nPC;
```

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Dalvik JIT Internals - JIT Entries

- The **pJitEntryTable** is a member of a global structure called **DvmJitGlobals** which is defined as **gDvmJit**
- The **JitEntry** structure is compromised a few different things including the **JitEntryInfoUnion** union and **JitEntryInfo** structure

```
struct JitEntryInfo {
    unsigned int            isMethodEntry:1;
    unsigned int            inlineCandidate:1;
    unsigned int            profileEnabled:1;
    JitInstructionSetType   instructionSet:3;
    unsigned int            profileOffset:5;
    unsigned int            unused:5;
    u2                      chain;                  /* Index of next in chain */
};

union JitEntryInfoUnion {
    JitEntryInfo info;
    volatile int infoWord;
};

struct JitEntry {
    JitEntryInfoUnion   u;
    const u2*           dPC;            /* Dalvik code address */
    void*               codeAddress;    /* Code address of native translation */
};
```

Pointers of Interest

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Dalvik JIT Internals - JIT Cache

- JIT code is memory mapped and a pointer to the beginning of the memory map is stored in the **gDvmJit** global structure's **codeCache** member

```
/* Compiled code cache */
void* codeCache;
```

```
77159000-7717b000 rw-p 00000000 00:00 0          [anon:libc_malloc]
7717b000-7795b000 rw-s 00000000 00:08 5315       anon_inode:dmabuf
7795b000-77ad2000 r-xp 00000000 00:04 97676      /dev/ashmem/dalvik-jit-code-cache (deleted)
77ad2000-782b2000 rw-s 00000000 00:08 5315       anon_inode:dmabuf
782b2000-78576000 r--p 00000000 b3:1c 89671      /data/data/com.versprite.targetapp/app_outdex/lejit.
```

The translated JIT code pointer within a JitEntry will point somewhere in the JIT Code Cache

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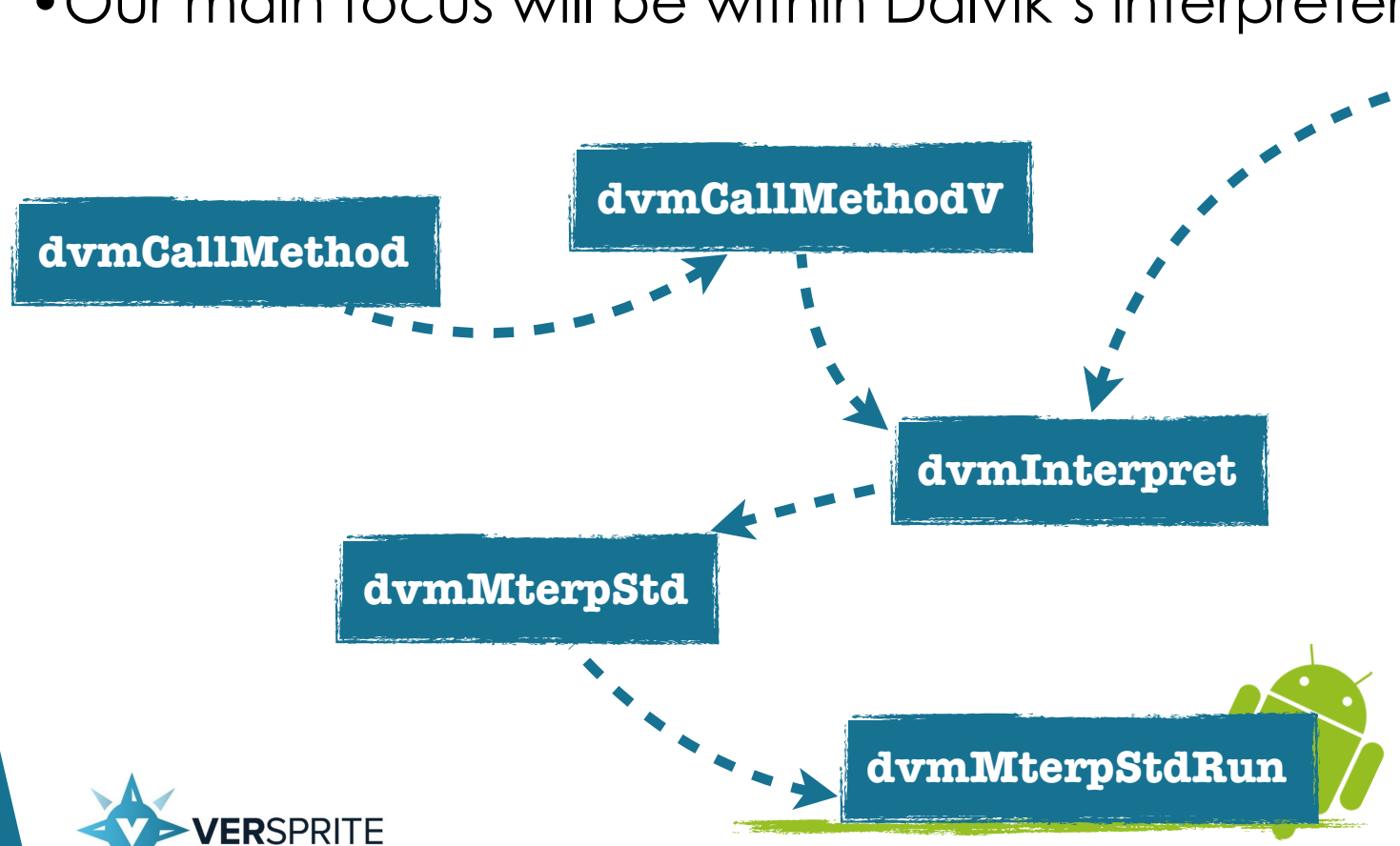
Dalvik JIT Internals - JIT Execution

- There are a lot of moving parts in the Dalvik VM when a method is invoked
- Our main focus will be within Dalvik's interpreter



Dalvik JIT Internals - JIT Entries

- **dvmMterpStdRun** is implemented entire in assembly
- This function is responsible for loading the current PC and executing it
- If that method is JIT'ed the PC will be pointing to the translated code within a thread structure passed in as an argument to the function
- There are multiple global entry points back into the interpreter from JIT code

Abusing Dalvik(s) JIT

- My goal hopefully has become relatively clear at this point
- I want the ability to hijack a **JitEntry** for a target method with a pointer to shellcode

Abusing Dalvik(s) JIT

- The biggest challenge was finding a way to read, write and map memory from Java
- My first idea was to explore the **Unsafe API** included within Android
- This did not prove to be fruitful
- After digging through Android's internals, I stumbled on the **libcore** package

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Abusing Dalvik(s) JIT

- I was pleasantly surprised when I found that **libcore** contain a class called **libcore.io.Posix**
- This class implements the **libcore.io.OS** interface, and contains the methods **mmap** and **munmap** !
- Basically all of the posix methods in the **libcore.io.Posix** class are JNI methods that call their native counterpart.
- These methods can easily be accessed via Java reflection!
- Now we have a mechanism for mapping **RWX** shellcode

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Abusing Dalvik(s) JIT

- I also discovered the **libcore.io.Memory** and **libcore.io.MemoryBlock** classes, which provides methods for reading and writing to memory through different forms
- **peekInt**, **pokeInt**, and **pokeByteArray** specifically were used to read from and write to our shellcode and other memory in the virtual machine

Abusing Dalvik(s) JIT

```
public final void pokeByte(int offset, byte value) {
    Memory.pokeByte(address + offset, value);
}

public final void pokeByteArray(int offset, byte[] src, int srcOffset, int byteCount)
    Memory.pokeByteArray(address + offset, src, srcOffset, byteCount);
}

public final void pokeCharArray(int offset, char[] src, int srcOffset, int charCount,
    Memory.pokeCharArray(address + offset, src, srcOffset, charCount, swap);
}
```

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Abusing Dalvik(s) JIT

- The **JIT Code Cache** isn't writeable, but this doesn't matter!
- We can use our **read** and **write** primitives for controlling entries in the writeable global **JitTable**
- In order to do this we need to locate the **gDvmJit** global structure in memory
- **gDvmJIT** actually has a symbol reference to it!
- We wrote a basic **process maps** parser for getting the base address of **libdvm**, then simply added the offset

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```
/*
 * JIT-specific global state
 */
struct DvmJitGlobals {
    /*
     * Guards writes to Dalvik PC (dPC), translated code address (codeAddr) and
     * chain fields within the JIT hash table.  Note carefully the access
     * mechanism.
     * Only writes are guarded, and the guarded fields must be updated in a
     * specific order using atomic operations.  Further, once a field is
     * written it cannot be changed without halting all threads.
     *
     * The write order is:
     *    1) codeAddr
     *    2) dPC
     *    3) chain [if necessary]
     *
     * This mutex also guards both read and write of curJitTableEntries.
     */
    pthread_mutex_t tableLock;

    /* The JIT hash table.  Note that for acce
     * are stored in each thread. */
    struct JitEntry *pJitEntryTable;
```

How do we deal with this?

Abusing Dalvik(s) JIT

- We attempted to honor the **tableLock** and whether or not it was being held by checking the **pthread_mutex_t** structure's state member
- If the **tableLock** was not held, we would acquire the lock by setting the state to "locked" in Java through our memory write primitive
- However, we found that the **tableLock** is rarely held when first checked
- Initially we thought racing against the JIT compiler in order to write to the **JitTable** would be required
- We also found this wasn't typically the case

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Abusing Dalvik(s) JIT

- Attacking the **JIT Entry Table** requires overwriting the **codeAddress** field of a **JitEntry** for a method or a partial method
- We were unsuccessful with being able to force a given method to be JIT'ed in a consistent way
- So we focused on scanning the entire **JIT Entry Table** for populated JIT Entries

Abusing Dalvik(s) JIT

- In order to attack a target **JitEntry**, we first needed to know which classes had already been loaded in the VM
- For each method that was extracted from the loaded class, we need to determine if the pointer to that method's Dalvik PC matches the Dalvik PC within the **JitEntry**
- Knowing the target method also allows us to invoke this from Java after we have overwritten the **codeAddress** via reflection

```
/*
 * Loaded classes, hashed by class name.  Each entry is a ClassObject*,
 * allocated in GC space.
 */
HashTable*  loadedClasses;
```

The VM globals contains a hash table for all of the loaded classes

```
/* virtual methods defined in this class; invoked through vtable */
int             virtualMethodCount;
Method*         virtualMethods;

/*
 * Virtual method table (vtable), for use by "invoke-virtual".  The
 * vtable from the superclass is copied in, and virtual methods from
 * our class either replace those from the super or are appended.
 */
int             vtableCount;
Method**        vtable;
```

Each class contains of a vtable of Method structures representing its methods

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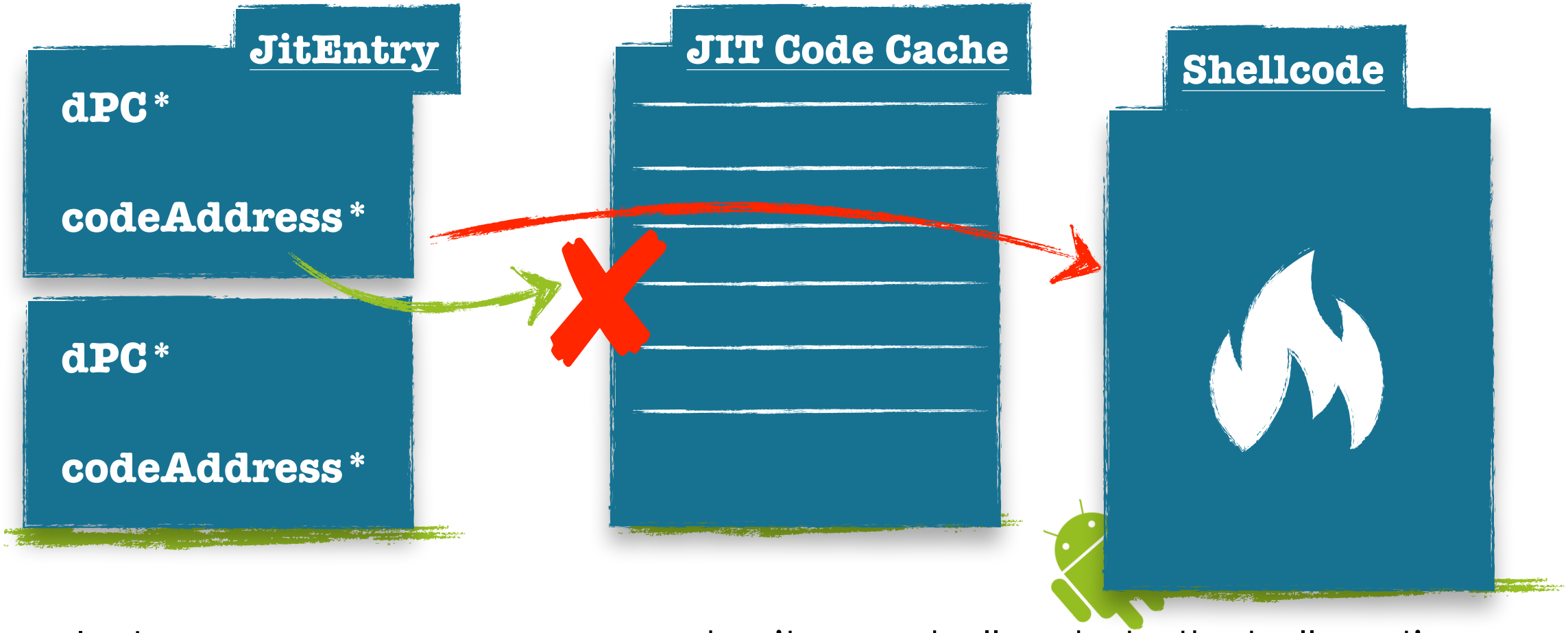
```
/* the actual code */
const u2*        insns;        /* instructions, in memory-mapped .dex */
```

The Method structure contains the **insns** field, which points to the method's Dalvik bytecode

```
struct JitEntry {
    JitEntryInfoUnion   u;
    const u2*           dPC;            /* Dalvik code address */
    void*               codeAddress;    /* Code address of native translation */
};
```

If the method has been JIT'ed, the dPC field in the **JitEntry** should match



- In Java we **mmap** memory and write our shellcode to that allocation
- Through **libcore**, we can access our shellcode's base address
- We save off the original **JitEntry** structure in order to restore it later
- We use the pointer to our shellcode to replace the **codeAddress** within the target **JitEntry**

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Abusing Dalvik(s) JIT - Shellcode

- The Shellcode segment is divided up into two primary sections
  - **TEXT**
  - **STACK**
- Each section is referenced via labels and pc relative addressing
- The stack holds execution context information and arguments which is filled out in Java via the **libcore** API(s)

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Abusing Dalvik(s) JIT - Shellcode

- At a high-level the **TEXT** section is responsible for
  - Immediately reverting changes to the JIT Entry Table
    - Basically we are repopulating the original data
    - In some cases we may have overwritten many **JitEntries**
  - Make room for our function call's stack frame
  - Call **system()** to invoke the **log** command
  - Clean and restore execution context

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Abusing Dalvik(s) JIT - Shellcode

- Clean Up consists of
  - Restore original **`codeAddress`** to the JIT Entry
  - Restore original **`codeAddress`** into registers **`r0`** and **`r1`**
    - **`r0`** and **`r1`** our controlled when our shellcode is first executed and point to our shellcode entry point
  - Branch to the original **`codeAddress`**

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Abusing Dalvik(s) JIT - Shellcode

- Our strategy was basically to target all UI related framework methods, [illegible] we observed they were most likely to be JIT'ed
- We can i[illegible]ages for this framework code via our process[illegible]
- If we find a **JITE[illegible]** [illegible] points into this range
  - We look that method up[illegible]
  - Validate that it matches
  - Hijack the **codeAddress**
  - Execute the method

DEMO

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[redacted]

Nougat JIT Internals

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Nougat JIT Internals

- A JIT compiler was added in Nougat in order to improve performance
- Android maintains a page on the overall JIT workflow itself, which is helpful for visualization
- The internals of Nougat's JIT compilation process is vastly different in comparison to Dalvik
- Again, we care about what happens to a method after it becomes translated and how it gets executed

Nougat JIT Internals

```
class ArtMethod FINAL {
 public:
  ArtMethod() : access_flags_(0), dex_code_item_offset_(0), dex_method_index_(0),
      method_index_(0) { }

  ArtMethod(ArtMethod* src, size_t image_pointer_size) {
    CopyFrom(src, image_pointer_size);
  }
```

In the Android Runtime Java methods are implemented through the ArtMethod C++ class

```
  // Method dispatch from quick compiled code invokes this pointer which may cause bridging into
  // the interpreter.
  void* entry_point_from_quick_compiled_code_;
```

The entry_point_from_quick_compiled_code_ typically points into an ART entry point, unless the method has been JIT'ed

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Nougat JIT Internals

```
JitCodeCache* JitCodeCache::Create(size_t initial_capacity,
                                   size_t max_capacity,
                                   bool generate_debug_info,
                                   std::string* error_msg) {
  ScopedTrace trace(__PRETTY_FUNCTION__);
  CHECK_GE(max_capacity, initial_capacity);

  // Generating debug information is mostly for using the 'perf' tool, which does
```

When a method is JIT'ed, that JIT code is stored as an entry point in the JIT code cache

↓

The JIT code cached maintains r-x permissions

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Nougat JIT Internals

```
uint8_t* JitCodeCache::CommitCodeInternal(Thread* self,
                                          ArtMethod* method,
                                          const uint8_t* vmap_table,
                                          size_t frame_size_in_bytes,
                                          size_t core_spill_mask,
                                          size_t fp_spill_mask,
                                          const uint8_t* code,
                                          size_t code_size,
                                          bool osr) {
```

New JIT code is added through JitCodeCache::CommitCodeInternal

A map is maintained internally which contains the following (ArtMethod, JIT Code)

This map is updated after the translation operations finish

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Nougat JIT Internals

```
  ProfilingInfo* profiling_info = method->GetProfilingInfo(sizeof(void*));
  // Update the entrypoint if the ProfilingInfo has one. The interpreter will call it
  // instead of interpreting the method.
  if ((profiling_info != nullptr) && (profiling_info->GetSavedEntryPoint() != nullptr)) {
    Runtime::Current()->GetInstrumentation()->UpdateMethodsCode(
        method, profiling_info->GetSavedEntryPoint());
  } else {
    AddSamples(thread, method, 1, /* with_backedges */false);
  }
}
```

```
  } else {
    ClassLinker* class_linker = Runtime::Current()->GetClassLinker();
    if (class_linker->IsQuickResolutionStub(quick_code) ||
        class_linker->IsQuickToInterpreterBridge(quick_code)) {
      new_quick_code = quick_code;
    } else if (entry_exit_stubs_installed_) {
      new_quick_code = GetQuickInstrumentationEntryPoint();
```

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Abusing Nougat(s) JIT

PLAN OF ATTACK

Force JIT a target Java method that we control

Find that target method's ArtMethod object in memory

Overwrite the ArtMethod(s) entry_point with a pointer to our shellcode

Invoke the JIT'ed method from Java

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Abusing Nougat(s) JIT

- Getting a method to JIT reliably worked perfectly in 7.1.1
- We still have our memory **read** and **write** primitives from Java in Nougat through **`libcore`**
- It's difficult to leak an exact **`ArtMethod`** address for a given Java method
- I opted for just scanning the memory maps where allocated **`ArtMethod(s)`** are stored

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Abusing Nougat(s) JIT

- Finding a JIT'ed **ArtMethod** is pretty simple, if the entry point from quick compiled code is an address in the JIT code cache the method becomes a target
- Figuring out if the scanned **ArtMethod** is **THE** target **ArtMethod** proved to be difficult
- This was accomplished in the hardest way possible

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```
// Index into method_ids of the dex file associated with this method.
uint32_t dex_method_index_;
```

The ArtMethod contains the method_ids index for itself in the associated DEX file

We can parse the DEX file mapped into memory for the method name that corresponds with the dex_method_index

Finally we validate its our method!

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Abusing Nougat(s) JIT

- Once we have found our target **ArtMethod**, we overwrite the entry point from quick compiled code with the address of our shellcode already allocated in memory
- Then we use reflection to invoke the method from Java

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What Now?

- Utilizing this technique, an attacker can continue to minimize their presence on disk
  - **_IN_MEMORY_ DEX Loader**
  - **_IN_MEMORY_ ELF Loader**
  - **_IN_MEMORY_ OAT Loader**
- Each version of the operation system provides internal constructs for loading executable types into memory

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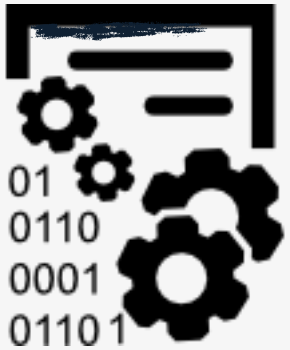
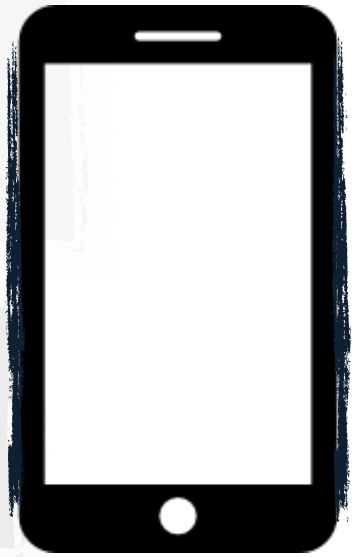
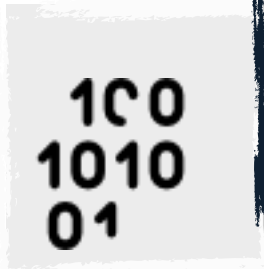
What Now?

Download and Execute Shellcode from Memory







Download and Load DEX into Memory

Infect Device!

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A Better Way Forward and Backward

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```
rotected:
 // Field order required by test "ValidateFieldOrderOfJavaCppUnionClasses".
 // The class we are a part of.
 GcRoot<mirror::Class> declaring_class_;

 // Access flags; low 16 bits are defined by spec.
 // Getting and setting this flag needs to be atomic when concurrency is
 // possible, e.g. after this method's class is linked. Such as when setting
 // verifier flags and  implementation flag.
 std::atomic<std::uint  ags_;
```

ARTMETHOD ADDRESS?

With the ability to write memory method into a JNI method by modifying it's a

With the ability to write memory with M, it's easier to convert a regular method into a JNI method by modifying it's access flags

Once you replace the method's data pointer with your shellcode, you can easily invoke order to achieve native execution

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Android Oreo

java.lang.reflect

```
public final class Method extends Executable  {
    // Android-changed: Extensive modifications made throughout the class for ART.
    // Android-changed: Many fields and methods removed / modified.
    // Android-removed: Type annotations runtime code. Not supported on Android.
    // Android-removed: Declared vs actual parameter annotation indexes handling.
```

```
    /**
     * The ArtMethod associated with this Executable, required for dispatching due to entrypoints
     * Classloader is held live by the declaring class.
     */
    @SuppressWarnings("unused") // set by runtime
    private long artMethod;
```

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Tools

Tools

- A lot of time was spent tracking and tracing the JIT compilation + execution process
- We developed a very robust tool suite on top of **Frida** for all of our dynamic instrumentation needs
- For both 4.4.4 and 7.1.1 we hand rolled ARM 32 and 64 Bit shellcode strategies
- We used **keystone** in order to assemble and wrote a wrapper in Python that convert **keystone's** output into a Java **byte[]**

FRIDA

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Future Challenges

- Android has begun to lock down private API(s) with special access flags
- Cannot be bypassed with reflection
- **libcore** potentially gets scoped into this group
- Will require a bypass in order to access things like **mmap**
- There is a way to (de)restrict private API(s)
- However this requires a native library, so it defeats the purpose

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Future Challenges

- What if the posix interface is removed entirely?
- We can rely on ROP
- Using **DirectByteBuffer** we can build our ROP stack and also have a reference to the allocated address
- Android has added more capabilities to the **Unsafe API** over the years, which in Android 8+ makes it a suitable alternative for wrapping an address and writing directly to memory
- We can use the **Unsafe API** to modify the **ArtMethod** in memory and turn it into a native method

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Conclusion

- For both **4.4.4** and **7.1.1** platforms, this research felt like it took forever
- Hopefully this research demonstrates that offensive techniques seen in other operating systems can also be accomplished on Android
- Special thanks to **@varmintoverflow** for all his assistance and pain endurance
- Shout outs to DS, DH, and DB for challenging me to be better

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Thanks!

@rotlogix

@VerSprite

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